НАУЧНОМ ВЕЋУ ИНСТИТУТА ЗА ФИЗИКУ

Предмет: Молба за покретање поступка за стицање звања научни сарадник

С обзиром да испуњавам критеријуме прописане од стране Министарства просвете, науке и технолошког развоја за стицање звања **научни сарадник**, молим Научно веће Института за физику да покрене поступак за мој избор у наведено звање.

У прилогу достављам:

1. Мишљење руководиоца пројекта са предлогом комисије за избор у звање,
2. Стручна биографија,
3. Преглед научне активности и елементе за квалитативну анализу рада,
4. Елементе за квантитативну анализу рада,
5. Списак објављених радова,
6. Податке о цитираности-Scopus,
7. Копије објављених радова,
8. Решење о претходном избору у звање,
9. Уверење о докторирању

У Београду,

7. септембар 2018.

Никола Веселиновић

Научном већу Института за физику Универзитета у Београду

ПРЕДМЕТ: Мишљење руководиоца пројекта о избору др Николе Веселиновића у звање научни сарадник

Др Никола Веселиновић запослен је у Институту за физику у Београду од 2011. године. Ангажован је на пројекту основних истраживања Министарства просвете, науке и технолошког развоја Републике Србије ОИ171002, под називом *Нуклеарне методе истраживања ретких догађаја и космичког зрачења*. У оквиру пројекта бави се истраживањима у физици космичког зрачења и физици високих енергија, као и нискофонском гама спектроскопијом. С обзиром да испуњава све предвиђене услове за избор у звање вишег научног сарадника, у складу са Правилником о поступку, начину вредновања и квантитативном исказивању научноистраживачких резултата истраживача Министарства просвете, науке и технолошког развоја Републике Србије, сагласан сам са покретањем поступка за избор др Николе Веселиновића у звање научни сарадник.

За састав комисије за избор др Николе Веселиновића у звање научни сарадник предлажем:

1. др Владимир Удовичић, виши научни сарадник, Институт за физику у Београду

2. др Александар Драгић, виши научни сарадник, Институт за физику у Београду

3. проф. др Јован Пузовић, редовни професор, Физички факултет Универзитета у Београду

Руководилац пројекта

проф. др Иштван Бикит

Стручна биографија- Никола Веселиновић

<u>Контакт</u>:
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Телефон: 0642468288
e-mail: veselinovic@ipb.ac.rs

Никола Веселиновић је рођен 10.11.1976. у Београду, где је завршио основну школу и гимназију.
Завршио је Физички факултет, експериментални смер 2008. године. Дипломски рад на тему: "Скалирање приноса неутрона и максималне струје пражњења у деутеријумском плазма фокусу" одбранио је на Физичком факултету са оценом 10 под менторством др. Владимира Удовичића. Од јесени 2008. јестудент докторских студија на Физичком факултету на смеру Физика честица и језгара под менторством др Александра Драгића.
Радио је у Хидрометеоролошком заводу Србије од 2007. године, а од априла 2011. је запослен на Институту за физику у Земуну у оквиру Нискофонске лабораторије за нуклеарну физику, прво као истраживач приправник, а од 2012. године као истраживач сарадник. Ангажован је на пројекту Министарства просвете, науке и технолошког развоја Републике Србије ОИ171002 "Нуклеарне методе истраживања ретких догађаја и космичког зрачења"
Никола Веселиновић је радио на проблемима из области космичког зрачења (Соларна модулација космичких зрака различите енергије, утицај атмосферских параметара на мерење флукса космичког зрачења), ниских активности и фона (космогени радионуклеиди-утицај космичког зрачења на фон, допринос радона фону) и експерименту на уређају Плазма фокус (скалирање приноса неутрона). Био је део је тима из Србије у оквиру SHINE колаборације у CERN-у (2011-2013). Докторску дисертацију под називом: "Реализација детекторског система у подземној лабораторији за изучавање соларне модулације космичког зрачења у хелиосфери" је одбранио јуна 2018. на Физичком факултету у Београду.
Поред овог, Никола Веселиновић је предавао физику по IGCSE програму и IBDP програму у две интернационалне школе. Био је програмски координатор Фестивала науке 2014. године и координатор издања „Српски научници у речи и слици".
Живи са женом и сином у Београду.

Елементе за квалитативну анализу рада

1.1. **Значај научног рада кандидата**

Главна научна активност Николе Веселиновића,као члана Нискофонске лабораторије за нуклеарну физику Института за физику у Земуну, је у области космичког зрачења, поглавито мионске компоненте секундарног космичког зрачења које се детектује на површини и испод површине Земље. Ови резултати су од значаја за изучавање процеса соларне модулације космичког зрачења.

У оквиру овог истраживања, радио је на инсталацији асиметричног мионског телескопа у подземном делу НФ, чиме су значајно проширене могућности НФ за студирање поменутог процеса. Резултати тих активности су објављени у *Nucl.Instrum.Meth. A875 (2017) 10-15*, као и у *Nucl.Instrum.Meth. A745 (2014) 7-11* и *Nuclear Technology & Radiation Protection (2011), Vol. 26, No. 3*, све часописи са импакт фактором преко 1 од који су два М21 а један М22 категорије. Никола Веселиновић је представио резултате ових активности на неколико међународних конференција из области астро-честичне физике и физике космичких зрака као и на неколико домаћих конференција. Поред главног правца истраживања Никола Веселиновић је дао допринос и у другим областима истраживања која се одвијају у оквиру Нискофонске лабораторије за нуклеарну физику Института за физику у Земуну и то у нуклеарној спектроскопији, изради радонске мапе Србије и нуклеарне фузије помоћу уређаја Плазма фокуса. Из ових области учествовао је у изради и дао допринос у чланцима објављеним у *Nukleonika,(2016), vol.61, br.3, str.357-360, M23; Radiation protection dosimetry, (2014), vol. 162 br. 1-2, str. 148-151,M22; Radiation protection dosimetry, (2014), vol. 160 br. 1-3, str. 62-64,M22; Applied radiation and isotopes, (2014), vol. 87 br. , str. 70-72,M22; Nuclear technology & radiation protection, (2014), vol. 29 br. 1, str. 17-23, M22;Romanian journal of physics, (2013), vol. 58 br. , suppl. s, str. s14-s21,M23; Journal of fusion energy, (2011), vol. 30 br. 6, str. 487-489,M21; Radiation protection dosimetry, (2011), vol. 145 br. 2-3, str. 155-158, M22.*

1.2.Параметри квалитета часописа

Кандидат др Никола Веселиновић је објавио укупно 11 радова у међународним часописима (http://kobson.nb.rs/nauka_u_srbiji.132.html?autor=Veselinovic%20Nikola%20B&samoar=&offset=0#.W5EHB8IyWUl) и то :

- 2 рада у врхунском међународном часопису *NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT* (импакт фактор:1,336;1,216)
- 1 рад у врхунском међународном часопису *APPLIED RADIATION AND ISOTOPES* (импакт фактор: 1,231)
- 1 рад у врхунском међународном часопису *JOURNAL OF FUSION ENERGY* (импакт фактор: 0,517)
- 3 рада у истакнутом међународном часопису *RADIATION PROTECTION DOSIMETRY (* импакт фактор: 0,913;0,913;0,822)
- 2 рада у истакнутом међународном часопису *NUCLEAR TECHNOLOGY & RADIATION PROTECTION* (импакт фактор: 0,560;1,159)
- 1 рад у међународном часопису *ROMANIAN JOURNAL OF PHYSICS* (импакт фактор: 0,745)
- 1 рад у међународном часопису *NUKLEONIKA* (импакт фактор: 0,760)

Укупан импакт фактор је 10,169

1.3. Подаци о цитираности

Према бази *Scopus* радови др Николе Веселиновића су цитирани 37 пута од чега 21 пут изузимајући аутоцитате.
Прилог: Цитираност радова према бази *Scopus*.

2. Нормирање броја коауторских радова.

Сви радови кандидата спадају у експерименталне радове у природно-математичким наукама тако да се радови са 7 коаутора узимају са пуном тежином а радови са више (2 чланка из међународних часописа са 8 и један чланак са 9 аутора, као и радови са конференција) се нормирају по формули датој у Правилнику о поступку и начину вредновања, и квантитативном исказивању научноистраживачких резултата истраживача.

3. Учешће у пројктима, потпројектима и пројектним задацима

Кандидат је од од 1.11.2012. ангажован је на пројекту ОИ171002 "Нуклеарне методе истраживања ретких догађаја и космичког зрачења" Министарства просвете, науке и технолошког развоја Републике Србије, чији руководилац је др Иштван Бикит.

4. Активност у научним и научно-стручним друштвима

4.1. Организација научних скупова

Др Никола Веселиновић био је члан организационог одбора два међународна научна скупа:

- 48th MICE Collaboration Meeting (2017.),
- NA61/NA49 Collaboration Meeting (2013.)

4.2. Педагошки рад

-наставник физике у Гимназији Руђер Бошковић, на Програму међународне матуре (IB Diploma Programme) за ученике III и IV и на Међународном Кембриџ програму за ученике I и II разреда гиманзије (Cambridge IGCSE) од школске године 2013/2014.

- наставник физике у British International school на Међународном Кембриџ програму заученике I и II разреда гиманзије (Cambridge IGCSE) од школске године 2009/2010 до 2016/2017.

- ментор ученика полазника Регионалног центра за таленте Београд 1

5. Утицај научних резултата

Списак радова и цитата дат је у прилогу.

6. Конкретан допринос кандидата у реализацији радова у научним центрима у земљи и иностранству

Кандидат је све своје научне активности реализовао у Институту за Физику Београд. Значајно је допринео сваком раду у ком је учествовао. Његов допринос је пре свега у нумеричком симулирању интеракције секундарних космичких зрака са атмосфером, земњиштем и детекторским системима и анализи утицаја космичког зрачења на фон као и на прикупљању и анализи експерименталних података и у писању радова.

Елементи за квантитативну оцену научног доприноса

Остварени М-бодови по категоријама публикација

Категорија Укупно М-бодова	**М-бодова по публикацији**	**Број публикација**	**Број публикација за нормирање**	**Укупно М-бодова**
M21	8	4	1	30,67
M22	5	5	2	22,49
M23	2	2	0	4
M33	1	6	4	5,1
M70	6	1	0	6
M10+M20+M30		17		62,26

Списак радова др Николе Веселиновића

Радови у врхунским међународним часописима (М21):

1. Veselinovic Nikola B,Dragic Aleksandar L,Savic Mihailo R,Maletic Dimitrije M,Jokovic Dejan R,Banjanac Radomir M,Udovicic Vladimir I (2017) *An underground laboratory as a facility for studies of cosmic-ray solar modulation*, NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT, vol. 875, br. , str. 10-15
2. Banjanac Radomir M,Dragic Aleksandar L,Udovicic Vladimir I,Jokovic Dejan R,Maletic Dimitrije M,Veselinovic Nikola B,Savic Mihailo R (2014) *Variations of gamma-ray background in the Belgrade shallow underground low-level laboratory*, APPLIED RADIATION AND ISOTOPES, vol. 87, br. , str. 70-72
3. Banjanac Radomir M,Maletic Dimitrije M,Jokovic Dejan R,Veselinovic Nikola B,Dragic Aleksandar L,Udovicic Vladimir I,Anicin Ivan V (2014) *On the omnipresent background gamma radiation of the continuous spectrum*, NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT, vol. 745, br. , str. 7-11
4. Udovicic Vladimir I,Dragic Aleksandar L,Banjanac Radomir M,Jokovic Dejan R,Veselinovic Nikola B,Anicin Ivan V,Savic Mihailo R,Puzovic Jovan M (2011) *Yield from Proton-Induced Reaction on Light Element Isotopes in the Hydrogen Plasma Focus*, JOURNAL OF FUSION ENERGY, vol. 30, br. 6, str. 487-489

Радови у истакнутом међународном часопису (М22)

1. Maletic Dimitrije M,Udovicic Vladimir I,Banjanac Radomir M,Jokovic Dejan R,Dragic Aleksandar L,Veselinovic Nikola B,Filipovic Jelena Z (2014) Correlative and Multivariate Analysis of Increased Radon Concentration in Underground Laboratory, RADIATION PROTECTION DOSIMETRY, vol. 162, br. 1-2, str. 148-151
2. Udovicic Vladimir I,Filipovic Jelena Z,Dragic Aleksandar L,Banjanac Radomir M,Jokovic Dejan R,Maletic Dimitrije M,Grabez Bojana S,Veselinovic Nikola B (2014) *Daily and seasonal radon variability in the underground low-background laboratory in Belgrade, Serbia*, RADIATION PROTECTION DOSIMETRY, vol. 160, br. 1-3, str. 62-64
3. Maletic Dimitrije M,Udovicic Vladimir I,Banjanac Radomir M,Jokovic Dejan R,Dragic Aleksandar L,Veselinovic Nikola B,Filipovic Jelena Z (2014) *Comparison of Multivariate Classification and Regression Methods for the Indoor Radon Measurements*, NUCLEAR TECHNOLOGY & RADIATION PROTECTION, vol. 29, br. 1, str. 17-23
4. Dragic Aleksandar L,Udovicic Vladimir I,Banjanac Radomir M,Jokovic Dejan R,Maletic Dimitrije M,Veselinovic Nikola B,Savic Mihailo R,Puzovic Jovan M,Anicin Ivan V (2011) *The New Set-Up in the Belgrade Low-Level and Cosmic-Ray Laboratory*, NUCLEAR TECHNOLOGY & RADIATION PROTECTION, vol. 26, br. 3, str. 181-192
5. Udovicic Vladimir I,Anicin Ivan V,Jokovic Dejan R,Dragic Aleksandar L,Banjanac Radomir M,Grabez Bojana S,Veselinovic Nikola B (2011) *Radon Time-series Analysis in the Underground Low-level Laboratory in Belgrade, Serbia*, RADIATION PROTECTION DOSIMETRY, vol. 145, br. 2-3, str. 155-158

Радови у међународним часописима (М23):

1. Filipovic Jelena Z,Maletic Dimitrije M,Udovicic Vladimir I,Banjanac Radomir M,Jokovic Dejan R,Savic Mihailo R,Veselinovic Nikola B (2016) *The use of multivariate analysis of the radon variability in the underground laboratory and indoor environment*, NUKLEONIKA, vol. 61, br. 3, str. 357-360
2. Banjanac Radomir M,Udovicic Vladimir I,Dragic Aleksandar L,Jokovic Dejan R,Maletic Dimitrije M,Veselinovic Nikola B,Grabez Bojana S (2013) *Daily Variations of Gamma-Ray Background and Radon Concentration*, ROMANIAN JOURNAL OF PHYSICS, vol. 58, br. , str. S14-S21

Саопштење са међународног скупа штампано у целини (М33):

1. Banjanac Radomir M,Udovicic Vladimir I,Jokovic Dejan R,Maletic Dimitrije M,Veselinovic Nikola B,Savic Mihailo R,Dragic Aleksandar L,Anicin Ivan V (2015) *Background Spectrum Characteristics of the HPGE Detector Long-Term Measurement in the Belgrade Low-Background Laboratory*, RAD 2015: THE THIRD INTERNATIONAL CONFERENCE ON RADIATION AND APPLICATIONS IN VARIOUS FIELDS OF RESEARCH, vol. , br. , str. 151-153
2. Maletic Dimitrije M,Banjanac Radomir M,Jokovic Dejan R,Udovicic Vladimir I,Dragic Aleksandar L,Savic Mihailo R,Veselinovic Nikola B (2015) *Correlative and Periodogram Analysis of Dependence of Continuous Gamma Spectrum in the Shallow Underground Laboratory on Cosmic Ray and Climate Variables*, RAD 2015: THE THIRD INTERNATIONAL CONFERENCE ON RADIATION AND APPLICATIONS IN VARIOUS FIELDS OF RESEARCH, vol. , br. , str. 47-50
3. Savic Mihailo R,Maletic Dimitrije M,Jokovic Dejan R,Veselinovic Nikola B,Banjanac Radomir M,Udovicic Vladimir I,Dragic Aleksandar L (2015) *Pressure and temperature effect corrections of atmospheric muon data in the Belgrade cosmic-ray station*, 24TH EUROPEAN COSMIC RAY SYMPOSIUM (ECRS), vol. 632
4. Veselinovic Nikola B,Dragic Aleksandar L,Maletic Dimitrije M,Jokovic Dejan R,Savic Mihailo R,Banjanac Radomir M,Udovicic Vladimir I,Anicin Ivan V (2015) *Cosmic Rays Muon Flux Measurements at Belgrade Shallow Underground Laboratory*, EXOTIC NUCLEI AND NUCLEAR/PARTICLE ASTROPHYSICS (V). FROM NUCLEI TO STARS, vol. 1645, br. , str. 421-425
5. Maletic Dimitrije M,Dragic Aleksandar L,Banjanac Radomir M,Jokovic Dejan R,Veselinovic Nikola B,Udovicic Vladimir I,Savic Mihailo R,Puzovic Jovan M,Anicin Ivan V (2013) *Stopped cosmic-ray muons in plastic scintillators on the surface and at the depth of 25 m.w.e.*, 23RD EUROPEAN COSMIC RAY SYMPOSIUM (AND 32ND RUSSIAN COSMIC RAY CONFERENCE), vol. 409
6. Dragic Aleksandar L,Anicin Ivan V,Banjanac Radomir M,Udovicic Vladimir I,Jokovic Dejan R,Maletic Dimitrije M,Savic Mihailo R,Veselinovic Nikola B,Puzovic Jovan M (2013) *Neutrons produced by muons at 25 mwe*, 23RD EUROPEAN COSMIC RAY SYMPOSIUM (AND 32ND RUSSIAN COSMIC RAY CONFERENCE), vol. 409

Подаци о цитираности- база SCOPUS

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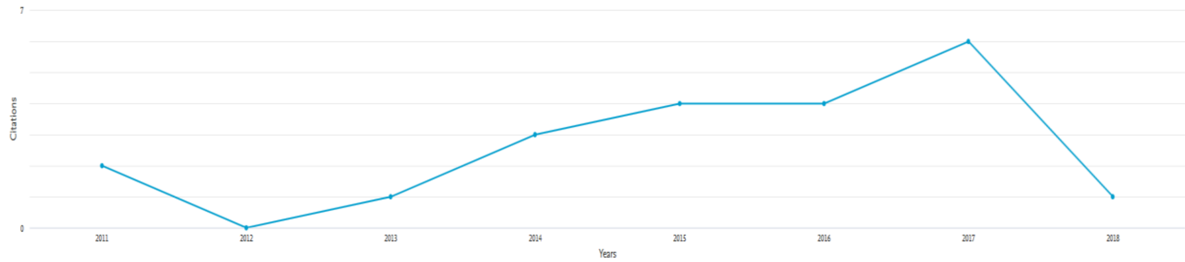

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RADON TIME-SERIES ANALYSIS IN THE UNDERGROUND LOW-LEVEL LABORATORY IN BELGRADE, SERBIA

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Measurements of radon concentration in the underground low-level laboratory in Belgrade, Serbia with a discrete sampling (*T* = 2 h) have been performed. From July 2008 to July 2010, the time-series analysis was carried out. Also, the simultaneous measurements of meteorological parameters (temperature, atmospheric pressure and relative humidity) in the laboratory were done. The simultaneous monitoring of these parameters shows the correlation between temporal variations of radon concentration and meteorological parameters. Also, the radon time-series analysis has been used to study the possible correlation between the anomalous behaviour of the radon concentration and the local seismicity.

INTRODUCTION

Radon is a unique natural element since it is a gas, noble and radioactive in all of its isotopes. As gases, the radon isotopes are mobile and can travel significant distances within the earth and through the atmosphere. The fact that radon is a noble gas means that it is not immobilised by chemically reacting with the medium that it permeates. The only way that radon diminishes is the radioactive decay. Its radioactivity allows radon to be measured with high sensitivity. Unfortunately, the high radon concentrations are a health risk, a cause of lung cancer. The detection and the concentration measurements of radon are one of the most important procedures in the environment protection.

Indoor radon concentration varies daily and seasonally, mainly due to the changes of the atmospheric parameters (temperature, atmospheric pressure and relative humidity) and the exchange rate between indoor and outdoor air. For this reason, it is important to investigate short-term variations of the indoor radon concentrations because the short-term variation during the day may be extreme. The short-term radon measurements were performed in the underground low-level laboratory in Belgrade, Serbia. The laboratory has the system for radon reduction, which provides conditions for the experiments and routine measurements, which require low levels of radon concentration with minimum temporal variations. Also, the simultaneous measurements of meteorological parameters (temperature, atmospheric pressure and relative humidity) in the laboratory were done. In this paper, the radon data obtained with a discrete sampling period of 2 h were spectrally analysed. Short-term radon measurements during 2 y were performed. The radon monitor was set to record, at the same time, the radon concentration, temperature, atmospheric pressure and relative humidity in the laboratory. The seasonal variation can be noticed in the monthly averaged radon data. In the long term a clear correlation occurs between indoor radon concentration and the relative humidity and temperature.

The time-series analysis of the obtained radon data may be used as a possible tool for earthquake prediction. The anomalies in radon time series that are discovered in the past are expected to result from the fluid flow in the ground. This motion can cause a different radon concentration in the measuring place than it would be in the absence of the flow. The famous example of the correlation between radon and earthquake prediction was Kobe earthquake in the Japan in 1995[1]. Also, radon has been recognised for a long time as a detectable component of fluids associated with volcanoes (fumaroles,

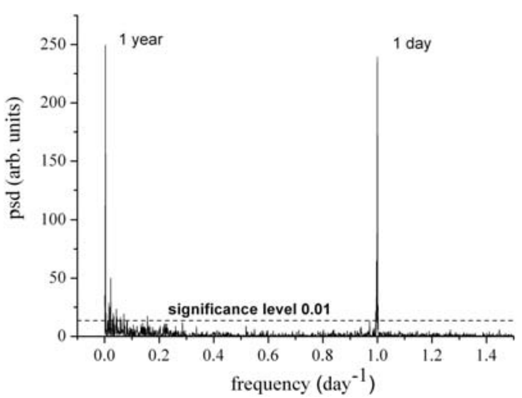

Figure 1. Lomb-Scargle periodogram for a measurement period of 2 y.

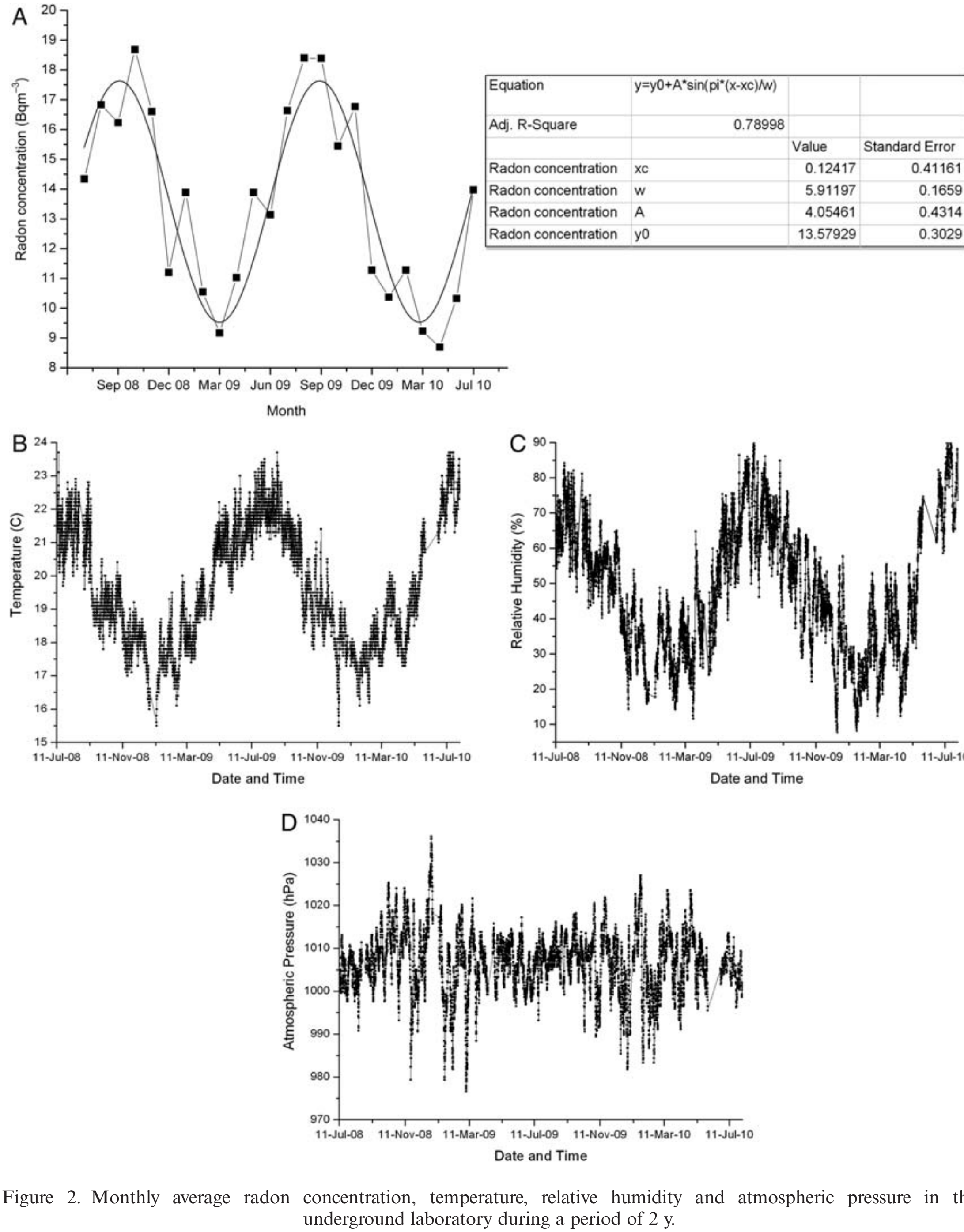

Figure 2. Monthly average radon concentration, temperature, relative humidity and atmospheric pressure in the underground laboratory during a period of 2 y.

groundwaters or soil gas)[2]. In Durrani and Ilić[3] one can find detailed survey about the applications of the radon measurements in the soil, groundwater and air, and in the earth sciences. During the 2 y (from July 2008 to July 2010) of the short-term radon measurements, the authors have tried to find possible

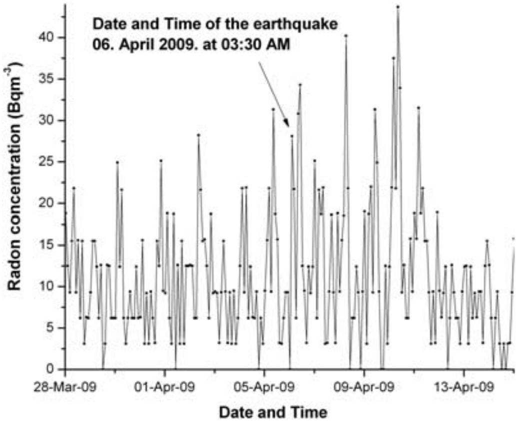

Figure 3. Variations of the radon concentration in the period when the earthquake occured in L'Aquila, Italy (6 April at 03:30 a.m., M_L=6.3, depth=8.8 km).

correlation between the anomalous behaviour of the radon concentration and the local seismicity in the region of the south-east Europe.

EXPERIMENT

The indoor radon measurements were performed in the underground low-level laboratory in Belgrade, Serbia. The laboratory is a shallow underground laboratory (25 m.w.e., a shielding thickness of the overburden soil expressed as water equivalent thickness). Description of the laboratory is presented in more detail elsewhere(4). The system for the reduction of radon concentration in the laboratory is described in Udovičić *et al*.(5) The radon monitor is used to investigate the temporal variations in the radon concentrations. For this type of short-term measurements, the SN1029 radon monitor was used (manufactured by the Sun Nuclear Corporation). The device consists of two diffused junction photodiodes as a radon detector, and is furnished with sensors for temperature, barometric pressure and relative humidity. The user can set the measurement intervals from 30 min to 24 h. The radon monitor device records radon and atmospheric parameters readings every 2 h in the underground laboratory. The data are stored in the internal memory of the device and then transferred to the personal computer. The data obtained from the radon monitor for the temporal variations of the radon concentrations over a long period of time enable the study of the short-term periodical variations. The series taken during the period of 2 y were spectrally analysed by the Lomb-Scargle periodogram method. This method of analysis because it is specially designed for the treatment of unevenly sampled data was chosen, and it is better suited for the case here where some of the data are missing than the common Fourier transformation analysis. Another advantage of the Lomb-Scargle method is a well-defined statistical interpretation of the periodogram.

RESULTS AND DISCUSSION

The Lomb-Scargle periodogram for a measurement period of 2 y is presented in Figure 1.

It is obvious that the Lomb-Scargle periodogram shows very clean peak at 1 d and 1 y period. Average radon concentration in the underground laboratory for 2 y of measurement is found to be a satisfactory low 13.48 Bq m^{-3}, with a standard deviation of 10.07 Bq m^{-3}. The two periodicity of the indoor radon behaviour are correlated with daily and seasonal variations. The maximum radon levels occurred each day in the early morning and the minimum radon concentration was reached in the afternoon hours. In the long term, a clear correlation between monthly average radon concentration and humidity and temperature in the laboratory is obtained (Figure 2.)

Concerning the radon daughters, the relative humidity indoors contributes to the aerosol density and keeps the radon daughters in the indoor air.

During the measurement period, the data about seismic activity in the region from the official site of the seismological survey of Serbia were collected. Fortunately, there was no earthquake with the magnitude higher than M_L=4. The most intense earthquake in the neighbourhood happened in L'Aquila, Italy (6 April at 03:30 a.m., M_L=6.3, depth=8.8 km). Variations of the radon concentration in the period when eartquake occurred are presented in Figure 3. Any anomalous behaviour of radon concentration in that period of time was not observed.

CONCLUSIONS

Indoor radon concentration was measured under controlled experimental conditions (indoor–outdoor air exchange rate was constant; the influence of the behaviour of the people, for example opening and closing the door of the laboratory, was minimised). The short-term measurements have shown that there are temporal variations on daily basis, although the reduction system is in operation. In the long term, a clear seasonal variations of the radon concentration are presented. Since the indoor–outdoor air exchange rate was constant, only relative humidity and the temperature variations in the laboratory are correlated with the daily and seasonal variations of the radon concentration. Also, there were no irregularities in the radon time series, which may be correlated with the earthquakes.

FUNDING

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DAILY VARIATIONS OF GAMMA-RAY BACKGROUND AND RADON CONCENTRATION*

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The reduction of the gamma-ray background contributes to the reduction of statistical errors of low activity measurements, while reduction of time variations of the background leads to lower systematic errors, especially in measurements of activities that coexist in the background. The sources of time variation of the background in a typical measurement of low activity are daily variations of radon concentration and aperiodic variations of cosmic-rays intensity. In this study we investigated the conditions that contribute to variations of radon and background by analyzing their time series in our ground level and shallow underground laboratories.

Key words: Low-level gamma spectroscopy, time-series of radon measurements, time variation of the background, shallow underground laboratory.

1. INTRODUCTION

The most of the low background laboratories that deal with low activity measurements have developed routine measurements of background. The duration of these measurements may be from one day to even a month and they are designed to produce results with sufficiently low statistical errors for the envisaged measurements. These measurements, however, yield only average values of background, what in principle may lead to systematic errors in later measurements of NORM samples. The reason is the time variability of gamma-ray background spectra due to the changes of cosmic-rays intensity and radon concentration. Changes in cosmic ray intensity can usually be neglected since contributions to background, apart from the annihilation line, lie in the continuum.

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Radon concentrations, on the other hand, are known to vary considerably, depending on many parameters that determine this concentration in every particular case. This includes the deposition of radon progenies on the walls of lead castles, what makes even the traditional radon suppression method by flushing the interior of the sample chamber with liquid nitrogen vapor potentially ineffective. It is thus most desirable to know the properties of every particular laboratory regarding the variability of radon concentration. In this case the optimum method for the minimization of this variation could be developed and applied, and the measurement strategy adjusted to these conditions. With this in mind we performed a series of measurements of radon concentration time series in our surface based and in our underground laboratory, where rather special conditions concerning radon concentration exist.

In this paper we present only briefly some results of these measurements, which might be of wider interest. The most informative measurements in this respect are the measurements by the germanium spectrometers. There is a number of studies concerning the long-term stability of the background of gamma-ray spectrometers, [1]. The results of the measurements of radon concentrations for a short and long periods of time for our underground laboratory were already reported, [2]. The aim of the present work was to perform simultaneous measurements of radon concentration and air parameters (temperature, pressure and relative humidity) as well as the gamma-ray background.

2. DESCRIPTION OF THE LABORATORIES

Our *Underground Laboratory* (UL) is presented in more detail elsewhere, [3], and the system for the radon reduction in the laboratory is described in [4]. This system consists of passive and active “radon shield”. The passive shield consists of the 1 mm aluminum sheet which completely covers all the wall surfaces inside the laboratory. It is hermetically sealed with a silicon sealant to prevent diffusion of radon from surrounding soil and concrete walls of the laboratory. As an active radon shield the laboratory is continuously ventilated with fresh air, filtered through one rough filter for dust elimination followed by the active charcoal filters for radon adsorption.

The long-term mean value of temperature inside the UL is 19(4) ^{o}C. The UL has area of 45 m^2 and volume of 135 m^3 that required the rate of air inlet was adjusted to 800 m^3/h. This huge amount of fresh air contributes to greater temperature variability. On the other side the rate of air outlet (700 m^3/h) was adjusted to get the overpressure of about 2 mbar over the atmospheric pressure, what prevents radon diffusion through eventual imperfections in the aluminum layer. The pressure buffer corridor to the laboratory (18 m^2) ensures almost constant value of this overpressure. Relative humidity is controlled by the dehumidifier device what provides that the relative humidity in the underground laboratory does not exceed 60%.

All the measurements presented in this work performed in the underground laboratory were repeated in the *Ground Level Laboratory* (GLL), which is only air-conditioned. This laboratory is situated in two joined standard transportation containers with iron sheet walls, but furnished with quality thermal insulation. The GLL has area of 30 m^2 and volume of 75 m^3.

3. EXPERIMENTAL TECHNIQUES

The radon monitor model SN1029 (manufactured by the Sun Nuclear Corporation, USA) provides the radon concentration together with atmospheric parameters by readings on every two hours. Measuring cycle of two hours duration of data sampling is limited to forty days by the device memory capacity.

Gamma-ray background spectra of two HPGe detectors (of 18% and 35% relative efficiencies) in their 10 and 12 cm thick cylindrical lead castles were recorded at the same time with radon monitor, in the GLL and the UL, respectively. Analyzing devices for both HPGe detectors are flash analog to digital converters (FADC), made by C.A.E.N (type N1728B), which sample at 10 ns intervals into 2^{14} channels. User-friendly software was developed and dedicated to C.A.E.N analyzer data with the possibility to choose integration time for further time-series analysis corresponding to time of readings of radon monitor. The details about digital setup and developed software are described in [5]. The results of digital time spectrometry analyzed by this software are time-series of the selected data, for example of the entire background spectrum or of the prominent peak net areas of radon daughters (^{214}Pb and ^{214}Bi). Time variations of these peaks should follow the changes of radon concentration as well as the fluctuations of ambient temperature and relative humidity but depend on many other parameters (aerosol kind and concentration, rate of surface deposition, etc.).

4. THE RESULTS AND DISCUSSION

The results are separated in two parts. The first one is related to investigation of connection between the measured ambient parameters and the measured daily radon variability inside the different measuring locations. Two hours of data sampling by radon monitor was optimally chosen in order to clearly see daily radon variation and not to have big statistical errors. For each day of all the runs, the difference of maximum to minimum value was calculated, [6]. The Table 1 summarized the most important of these results.

Table 1

The mean values of radon concentration and the averaged difference of its maximum to minimum values with corresponding standard deviations (sd), measured at listed locations (not simultaneously). (*)Averaged values of 3 measuring cycles.

	Outdoor (near the GLL)	*GLL* No air-con	*GLL* Air-con(*)	*SR* Air-con	*UL*
<Rn> (sd) [Bq/m^3]	14(8)	34(22)	54(44)	33(14)	15(9)
<Max-Min> (sd) [Bq/m^3]	13(6)	28(20)	100(60)	39(11)	10(5)

The Pearson correlation coefficient (Pcc) was calculated for all pairs of measured values. All presented results for the Pcc values have statistically significance at the confidence level of 95%.

In absence of air-conditioning inside the GLL, behavior of indoor air parameters is similar to the behavior of the outdoor air with characteristic anticorrelation between relative humidity and temperature. The Pcc(RH,T) is –0.84 and –0.67 for outdoor and „no air-con“ GLL measurement, respectively. In spite of quality wall insulation of the GLL, influence of radon through the ground floor is intensive. We tested the effects of air-conditioning on radon concentration in the GLL, under the conditions of stabilized temperature by one air-conditioning unit. The air-conditioner (12 kBTU) is adjusted to automatically provide temperature of 20 ^{o}C, 23 ^{o}C and 25 ^{o}C, during a full measuring cycle of radon monitor, respectively. For all of these 3 measuring cycles the most significant and surprisingly difference in radon behavior is almost doubled the <Max-Min> value related to the radon mean value and compared to the radon behavior inside the „no air-con“ GLL, Table 1. Radon monitoring inside the GLL demonstrates that one air-conditioner alone cannot stabilize the radon content sufficiently to make the space suitable for any low-level NORM gamma-ray measurements, Figure 1. Otherwise, there is no strong correlation between relative humidity and temperature, the Pcc (RH,T) = +0.18.

In order to decrease daily radon variability we also tested the fluctuation of radon concentration inside the smaller well-insulated and thoroughly air-conditioned room with almost constant temperature. This small room (SR) is situated on the second floor inside the building of the Institute of Physics, has area of 10 m^2 and 12 kBTU air-conditioning unit installed inside was adjusted to 23 ^{o}C. Figure 2 shows that even when the temperature is almost constant (T=23.6(2) ^{o}C), there is a considerable radon fluctuation, but the daily periodical variation is not so visualy obvious compared to „air-con“ GLL, Table 1. The Pcc(RH,T) is +0.53.

As already shown only relative humidity and temperature have statistically significant correlation but no pressure. The Pearson correlation coefficients between radon concentration and ambient parameters (temperature, relative humidity and atmospheric pressure) are negligible except for Pcc(Rn,T) = –0.5 in „air-con“ GLL and Pcc(Rn,RH) = +0.35 in „no air-con“ GLL.

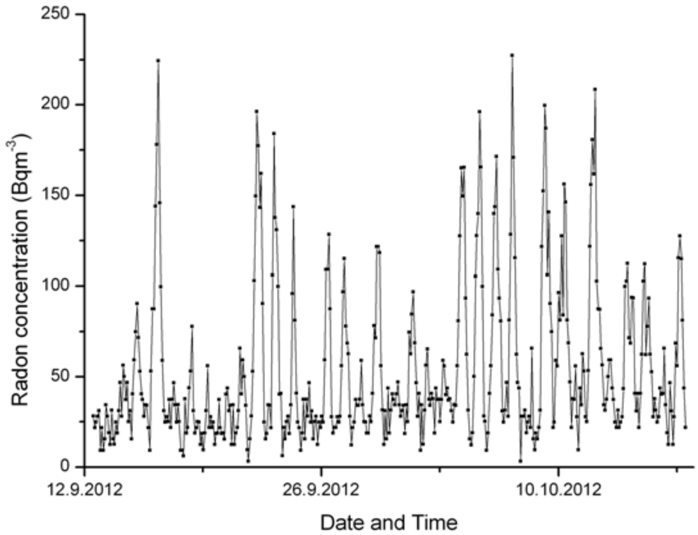

Fig. 1 – Typical radon concentration variability inside the air-conditioned GLL.

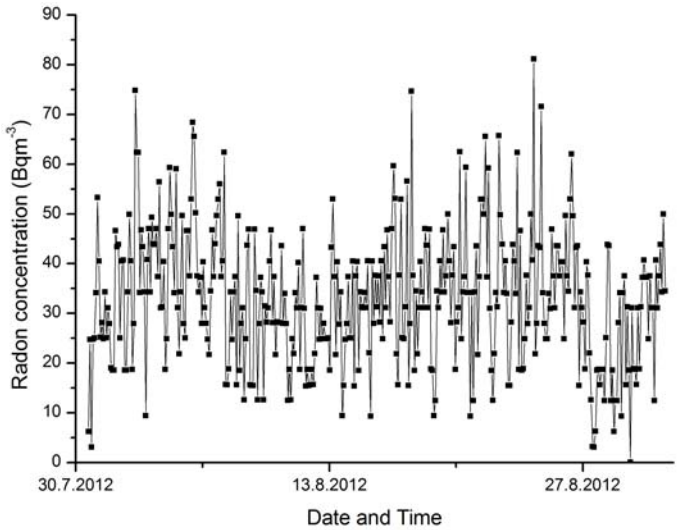

Fig. 2 – Indoor radon concentration in the small air-conditioned room SR.

Stability of radon concentration was also tested in the UL. The mean value of radon concentration averaged for two years of continuous measurement is 13(5) Bqm^{-3}. Due to the huge quantity of fresh air pumped into the UL (800m^3/h), daily variability of radon concentration follows a similar pattern as that in the GLL, though with much smaller amplitude, Table 1. Figure 3 shows this daily periodicity over an averaged day after 2 years of measurement by a radon monitor.

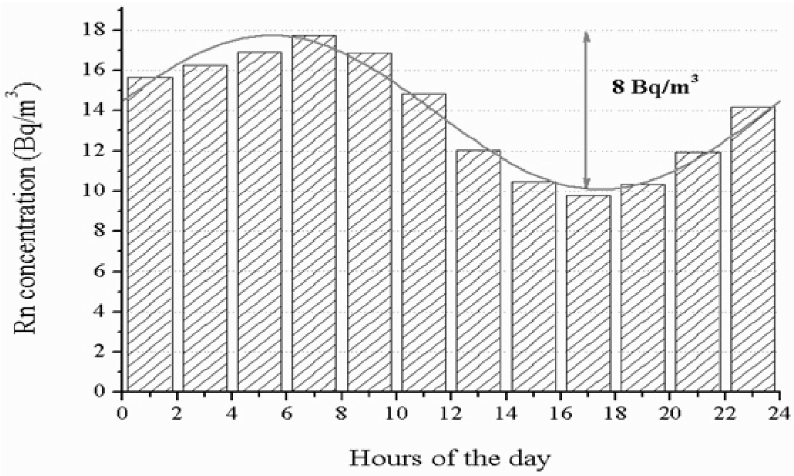

Fig. 3 – Variation of radon concentration in the UL over an averaged day after 2 years of continuous monitoring at two hours intervals.

Relative humidity and temperature show a positive correlation, Pcc(RH,T) = = 0.77 for 2 years of continuous measurement.

The second part of the results is related to simultaneously measurements of radon concentration by radon monitor and gamma-ray background by HPGe detectors. Inside of the sample chamber (SC) of a HPGe gamma-ray detector, radon concentration is influenced, also, by the radon distribution outside the SC, when the SC is not hermetically sealed. The HPGe detector sees the radon daughters (^{214}Pb and ^{214}Bi) not only from the air inside SC but also from surface depositions on detector and passive shield. Figure 4 presents how the summed intensity of the 4 most prominent radon daughter lines varies with time, as viewed by a small shielded HPGe detector (18% relative efficiency) in the „air-con" GLL. This varies almost simultaneously with radon changes, as viewed by the radon monitor positioned inside the SC (air volume of 1 dm^3) following the big <Max-Min> radon value, Table 1.

The Pcc between the summed intensity of the 4 most prominent radon daughter lines and simultaneously measured radon concentration is +0.39. The further investigations must be done in most controlled ambient conditions including the knowledge about many other parameters (aerosol kind and concentration, radon diffusion rates and rate of surface deposition of radon daughters) in order to optimize measuring parameters. This is important especially when deal with NORM low-level measurements of ^{226}Ra in ground level laboratories.

The background measurement in the UL by the HPGe detector (35% relative efficiency), as well as radon monitoring inside the SC, do not show obvious neither radon daughters nor radon daily periodicity.

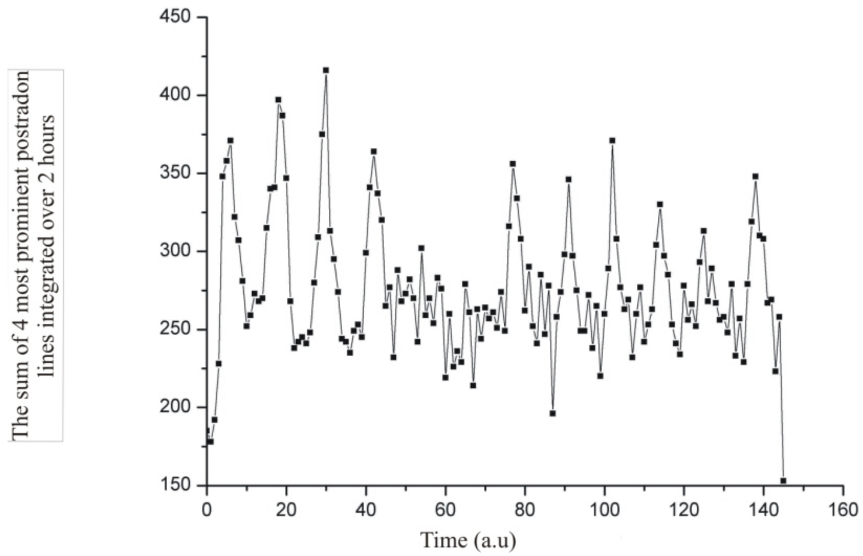

Fig. 4 – Variability of radon daughters inside the GLL viewed by a small HPGe detector.

5. CONCLUSION

The issue of stability of the gamma-ray background requires special attention when low-level ^{226}Ra measurements are performed by HPGe detectors. Main source of systematic error in these measurements is the daily radon concentration variability, which causes daily concentration variability of its daughters inside the sample chamber. Even a small HPGe detector sees significant changes of background, if the mean radon concentration in ambient air is of the order or above 10 Bqm^{-3} and some kind of radon suppression method inside a sample chamber must be applied, [7].

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THE NEW SET-UP IN THE BELGRADE LOW-LEVEL AND COSMIC-RAY LABORATORY

by

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The Belgrade underground laboratory consists of two interconnected spaces, a ground level laboratory and a shallow underground one, at 25 meters of water equivalent. The laboratory hosts a low-background gamma spectroscopy system and cosmic-ray muon detectors. With the recently adopted digital data acquisition system it is possible to simultaneously study independent operations of the two detector systems, as well as processes induced by cosmic-ray muons in germanium spectrometers. Characteristics and potentials of the present experimental setup, together with some preliminary results for the flux of fast neutrons and stopped muons, are reported here.

Key words: underground laboratory, gamma-ray spectroscopy, low-level measurements, cosmic rays

INTRODUCTION

The low-level and cosmic-ray laboratory in Belgrade is dedicated to the measurement of low activities and cosmic-ray (CR) muon components. At the intersection of the two research subjects, the study of muon-induced background in gamma spectroscopy is of particular interest. The laboratory adds to the list of relatively shallow underground laboratories worldwide (see the recent review [1]). It is located on the right bank of the river Danube in the Belgrade borough of Zemun, on the grounds of the Institute of Physics. The ground level portion of the laboratory (GLL), at 75 meters above sea level (m.a.s.l), is situated at the foot of a vertical loess cliff, about 10 meters high. The underground part of the laboratory (UL), useful area 45 m^2, is dug into the foot of the cliff and is accessible from the GLL via a 10 meters long horizontal corridor which also serves as a pressure buffer for a slight overpressure that is constantly maintained in the UL (fig. 1). The overburden of the UL is about 12 meters of loess soil, equivalent to 25 meters of water. The container, which is to accommodate the top laboratory (TL), is situated at the top of the cliff, just above the UL. The GLL and UL have been in some use for a number of years now, while the TL is still not functional.

Continuous measurements of the cosmic-ray muon flux by means of a pair of small plastic scintillators 50 cm 23 cm 5 cm started in the GLL and UL back in 2002 and lasted for about 5 years. These measurements yielded the precise values of the integral CR muon flux at ground level and at the depth of 25 m.w.e. [2]. Different analyses of the time series of these measurements have also been performed [3, 4].

Significant efforts are being made to contain the low radon concentration within the laboratory. The UL is completely lined with a hermetically sealed, 1 mm thick aluminum foil. The ventilation system maintains the overpressure of 2 mbar, so as to prevent radon diffusion from the soil. Fresh air entering the laboratory is passed through a two-stage filtering system. The first stage is a mechanical filter for dust removal. The second one is a battery of coarse and fine charcoal active filters. The concentration of radon is kept at an average value of about 10 Bq/m^3. Throughout the years, certain interesting behaviors of the said concentration have also been reported [5, 6].

The two laboratory spaces have recently been furnished with a new experimental set-up which is now ready for routine measurements. Here presented are some preliminary results of wider interest, ob-

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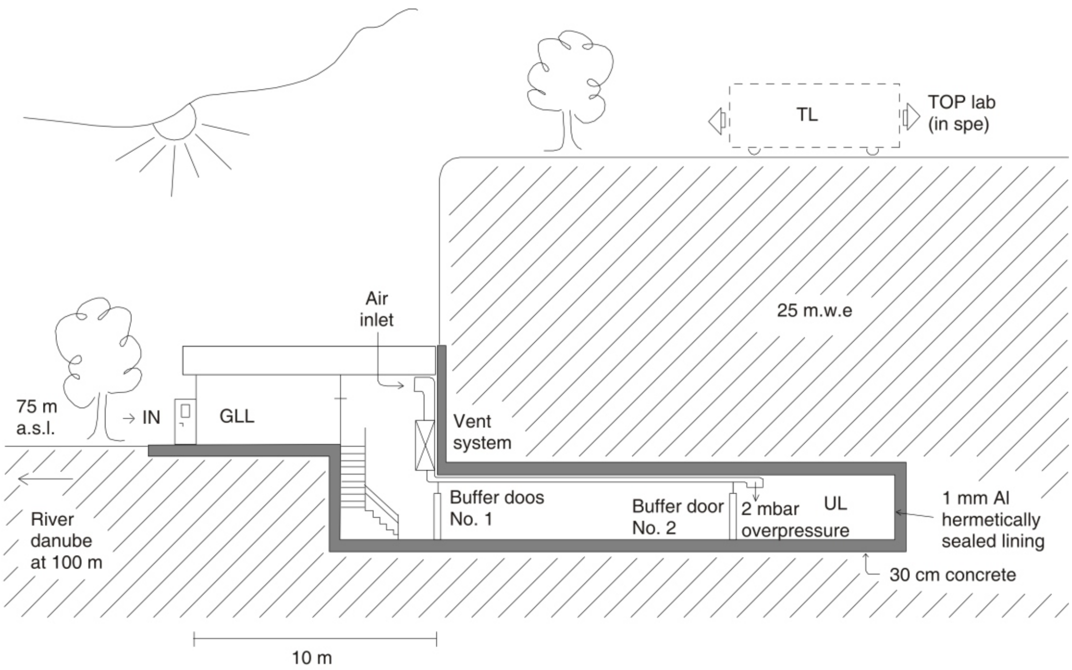

Figure 1. Cross-section of the low-level and CR laboratory at IOP, Belgrade, 44°49'N, 20°28'E, vertical rigidity cutoff 5.3 GV

tained during the testing period of the new equipment and the development of the needed software.

EXPERIMENTAL SET-UP

The equipment now consists of two almost identical sets of detectors and analyzing electronics, one set situated in the GLL, the other in the UL. Each set is composed of muon detectors and a gamma spectrometer.

A pair of plastic scintillator detectors is used for CR muon measurements. One of them is a larger 100 cm 100 cm 5 cm detector, equipped with four PMT directly coupled to the corners beveled at 45°, made by Amcrys-H, Kharkov, Ukraine. The other, a small 50 cm 23 cm 5 cm plastic scintillator detector, with a single PMT looking at its longest side via a Perspex light guide tapering to the diameter of a PMT, made by JINR, Dubna, Russia, and assembled locally. The smaller detector may serve as a check of stability of the muon time series obtained from the larger detector, which is important for long term measurements. It can also be used (in coincidence with the larger detector) for measurements of the lateral spread of particles in CR showers. Plastic scintillation detectors are also employed for active shielding of gamma spectrometers.

In the UL, a 35% efficiency radio-pure p-type HPGe detector, made by ORTEC, in its 12 cm thick cylindrical lead castle, is deployed. Another HPGe detector, of 10% efficiency, is put to use in the GLL. It is shielded with lead of the same origin, parts of a plumbing system collected at a demolition site of an old housing estate. The exact history of this lead is not known, but all the components are known to be older than two half-lives of Pb-210.

At the heart of the data acquisition system are two flash: analog to digital converter (ADC), flash analog to digital converter (FADC), one in each laboratory, made by CAEN (type N1728B). These are versatile instruments, capable of working in the so-called energy histogram mode when performing as digital spectrometers or, in the oscillogram mode, when they perform as digital storage oscilloscopes. In both modes, they sample at 10 ns intervals into 2^{14} channels in four independent inputs. The full voltage range is 1.1 V.

They are capable of operating in the list mode, when every analyzed event is fully recorded by the time of its occurrence and its amplitude. This enables the correlation of events, both prompt and arbitrarily delayed, at all four inputs with the time resolution of 10 ns. Single and coincident data can be organized into time series within any integration period from 10 ns up. The two N1728B units are synchronized, enabling coincidence/correlation of the events recorded in both of them. The flexible software encompassing all above said off-line analyses is user-friendly and entirely homemade.

The usual disposition of FADC inputs is described next. The preamplifier outputs of the PMT of the larger detectors are paired diagonally, the entire detector thus engaging these two inputs of the FADC. Signals from these inputs are later coincided off-line and their amplitudes added to produce the single spectra of these detectors. This procedure results in a practically complete suppression of the uninteresting low-energy portion of the background spectrum (up to some 3 MeV), mostly due to environmental radiation, leaving only high-energy loss events due to CR muons and EM showers that peak at about 10 MeV. The output of the PMT of the smaller detector is fed to the third input. The fourth input is reserved for the HPGe detectors.

In some instances, auxiliary measurements are performed with a different definition of the inputs of the data acquisition system. For example, a (3 3)" NaI detector is used in the GLL to scan the response of the larger detector to CR as a function of the position of the interaction point.

In the UL, the HPGe detector is positioned beneath the center of the larger detector (fig. 2). For the purpose of measuring low activities, the large plastic detector is used in anticoincidence, as a cosmic-ray muon veto detector. In order to study the effects of cosmic rays on the spectra in low-level high-resolution gamma-ray spectroscopy, it is used in coincidence as the trigger for the CR-induced processes. These two functions of the system are performed simultaneously and do not interfere, as they are realized by different off-line analyses of the same set of data.

Figure 2. Detectors in the underground laboratory (UL). The big plastic scintillator is positioned over the HPGe detector, seen in its lead shielding. The small plastic scintillator is in the front upper right corner. A hermetically sealed, 1 mm Al lining covering the entire UL, which enables the doubly filtrated ventilation system to sustain an overpressure of 2 mbar and keeps the radon concentration at an average level of some 10 Bq/m^3, is also shown

TESTING THE SYSTEM AND DEVELOPING THE SOFTWARE

In order to test the performance of the digital spectroscopy system, a series of test measurements with different count rates and different types of radiation detectors at the input of the FADC are performed.

One of the tests is designed to correspond to the real situations where neutrons created by CR muons in the lead shield produce certain effects in HPGe detectors. Neutrons produced by muons in the vicinity of the detector or the surrounding rock mass represent a significant source of background in ultra-low background experiments carried out deep underground, such as those searching for dark matter or double beta decay. In the test, done at the GLL, Cf-252 was used as a neutron source and the small plastic scintillator as a trigger for neutrons. To distinguish between the effects of fast and slow neutrons, some materials common in neutron work, such as rubberized B_4C, Cd sheets, paraffin, lead and iron slabs, were placed around and in between the source and the detectors. In addition to the environmental background, the HPGe spectra consists of different features induced by slow and fast neutrons in the HPGe detector and surrounding materials.

Results of measurements are stored as a list of events represented with their amplitudes, time tags, designation of input channels and some additional information (pile-up event or not, *etc*.). The time tag for every event is determined by the moment of crossing the set-triggering level. In order to minimize the amplitude walk, there is a possibility to choose between different types of triggers, termed here as simple, digital or CFD. We have stuck to the digital trigger which was found to work reliably and, if necessary, to the off-line correction of the amplitude walk [7].

The distribution of time intervals between events in the trigger detector and the HPGe is deduced from the recorded data in off-line analysis. There is no need to implement the hardware tome-to-amplitude converter (TAC). For convenience, in what follows we will refer to this distribution as the TAC spectrum.

As an illustration, the TAC spectrum between events in the plastic scintillator and HPGe is presented here (fig. 3).The prompt-time distribution is seen to be about 90 ns wide, while the tail of delayed coincidences is discernable beyond approx. 100 ns upon the prompt peak. The same time spectrum, off-line corrected for the amplitude walk, according to the procedure described in [7], is presented in fig. 3(b). The full

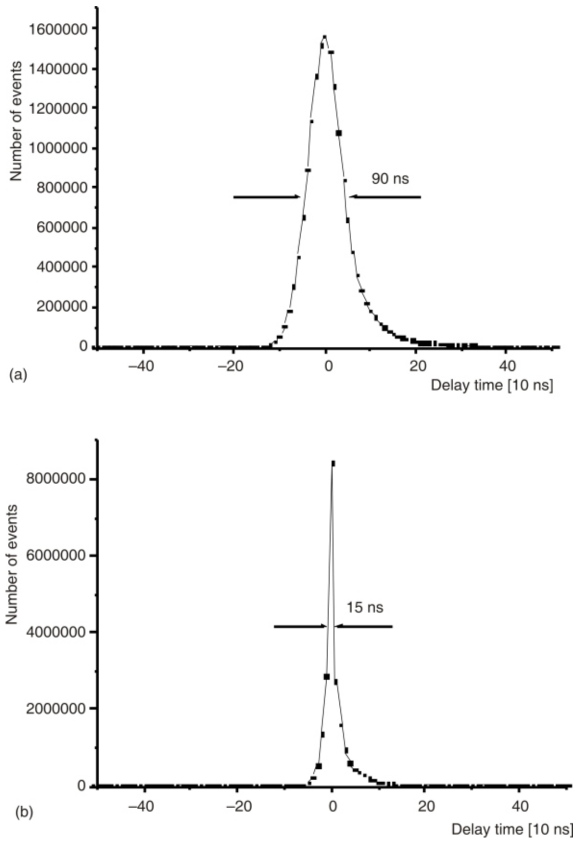

Figure 3. (a) The time spectrum between events in the plastic scintillator and the HPGe; (b) the same time spectrum, but with off-line time corrected for the amplitude walk

with at half maximum (FWHM) is now only 15 ns and delayed coincidences, perhaps, start as early as at approximately 20 ns after the prompt peak. Minding the geometry of our set-up, we expect the effects induced by fast neutrons, both in the environment and the HPGe detector itself, to be within the prompt peak, while those induced by thermalized neutrons should be found in the tail of delayed coincidences.

To illustrate the complete separation of the effects due to fast and slow neutrons, here presented (fig. 4) are the portions of the coincident HPGe spectrum around the spectral lines originating from different processes induced by neutrons in different materials, gated with different portions of the time spectrum – with the prompt peak, tail of delayed events up to one microsecond and the flat portion of random coincidences. Short comments can be found in the caption under fig. 4.

We will now briefly comment on the two well-known structures induced by neutrons in the HPGe detector itself, the structures at 596 keV and 692 keV. Their appearance in the coincidence spectra is depicted in fig. 5. The triangular distributions result from the summing of the radiations depopulating the state ex-

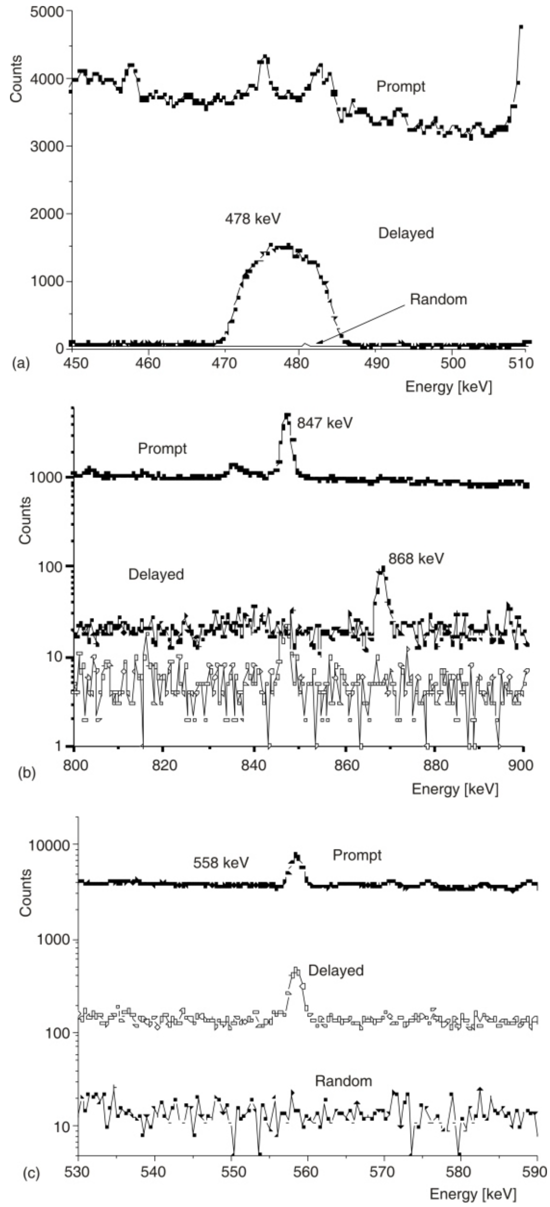

Figure 4. The prompt, delayed (up to 1 μs), and random coincidence spectra of: (a) the 478 keV Doppler-widened line from the (n, α) reaction on ^{10}B which appears only in the delayed spectrum; (b) the 847 keV line from the (n, n') inelastic scattering on ^{56}Fe which appears only in the prompt spectrum; (c) the 558 keV line which appears in both the prompt and delayed spectra, proving that this line originates partly from the usually assumed thermal neutron capture by ^{113}Cd and, depending on the hardness of the neutron spectrum, in part, from the fast neutron (n, n') reaction on ^{114}Cd

cited in inelastic neutron scattering with the energy of the recoiling nucleus. The one at 596 keV appears in the prompt spectrum, since the state at 596 keV in Ge-74 is short-lived. The regular peak of this energy in the delayed spectrum results from the thermal neutron capture by Ge-7, as is the case with the neighboring 609 keV line stemming from the same capture reaction. If the neutron flux at the detector is high, some of the intensity of the ubiquitous background line of 609 keV, usually entirely attributed to ^{214}Bi, is due to this process.

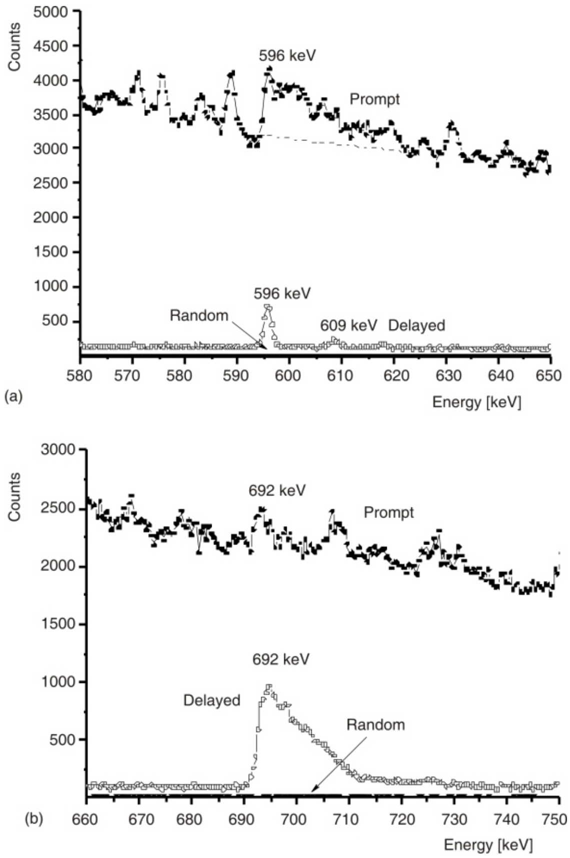

Figure 5. The spectrum of prompt, delayed, and random coincidences (practically negligible) containing: (a) the structure at 596 keV from inelastic fast neutron scattering on Ge-74 in the prompt spectrum, and the line of the same energy from slow neutron capture on Ge-73, in the delayed spectrum; (b) the structure at 692 keV from the inelastic scattering of fast neutrons on Ge-72, this time in the delayed spectrum, due to the finite lifetime of 444 ns at the excited state of 692 keV

The structure at 692 keV, however, appears in the delayed spectrum since the excited state of this energy in Ge-72 is comparatively long-lived, with a half-life of 444 ns, which is long in comparison to the time resolution of our system. As a demonstration of the capabilities of the system, we determined this half-life by setting the software gate to encompass the whole triangular structure in the coincident Ge spectrum, thus producing a time spectrum corresponding to this condition, thanks to which the fit produced a satisfactory value of 447(25) ns for the said half-life.

This particular structure has been studied in detail many times in the past, since 692 keV radiation is pure E0, detectable with 100% efficiency, which is why the integral of the triangular structure is a reliable measure of the fast neutron flux at the position of the detector [8-12]. These studies were performed with analog spectroscopy systems where the integration constants are long and the recoils invariably sum up with the 692 keV pulses. In digital spectroscopy systems, however, there is one important caveat to keep in mind when using the integral of this structure for fast neutron flux determination. It appears that here the shape and the intensity of the distribution strongly depend on the height of the triggering level. The recoil pulse is prompt, while the corresponding 692 keV pulse follows the recoil with delay distributed according to the decay law with the half-life of 444 ns. When the trigger is higher than the height of the recoil pulse, 692 keV pulse sums practically completely with the recoil. When the trigger is lower than the recoil, it will trigger the ADC, and this pulse, together with the following 692 keV pulse, will be rejected by the pile-up rejecting algorithm. This is illustrated in fig. 6 where the same portion of the direct HPGe spectrum is presented, with two different triggering levels. The width of the triangular structure appears proportional to the height of the triggering level. If this structure is to be used for quantitative purposes, the safe height of the triggering level that may be recommended is, thus,

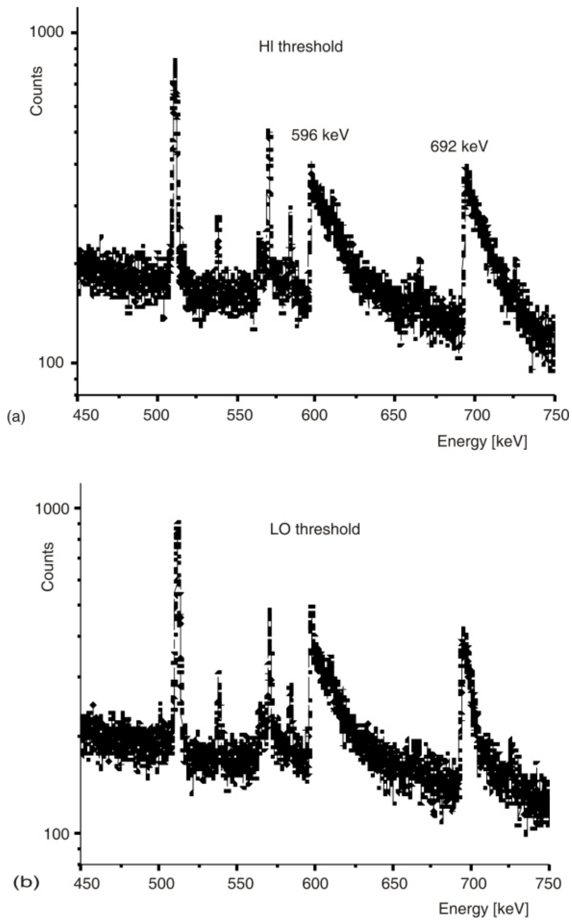

Figure 6. The 692 keV distribution in the direct spectrum with the triggering level set at 50 keV (a) and at 20 keV (b)

perhaps about 50 keV, when the loss of the counts within the structure is expected to be negligible.

After the system satisfactorily passed all the tests, we started some preliminary measurements of the type that we plan to perform in the long run in the future, and it is of these results that we report in what follows.

PLANNED MEASUREMENTS

We plan to continuously collect the background spectra of all detectors in both laboratories, eventually changing only their mutual spatial arrangements. The spectra of the large scintillators will stretch up to a couple of hundreds of MeV, so as to include all multiple CR and shower events, while the one corresponding to the HPGe detector will go up to about 30 MeV, in order to include all possible nuclear radiations induced by CR radiations. Each event is to be recorded in a separate list, in accordance with the time of the occurrence of its trigger (with the resolution of 10 ns) and by its amplitude (in 32 k channels). By off-line analyses of this data we expect to directly obtain:

- the continuous time series of cosmic-ray intensity (muon plus electromagnetic – EM, components) in large and small plastic scintillators at ground level, as well as those generated underground,
- decoherence curves of cosmic-ray coincidence counts and coincidence spectra at different separations of the said detectors, be it at ground level or the underground one, the idea being to first define and, afterwards, separate muon from EM components,
- the spectrum of the HPGe detector in coincidence and anticoincidence with the large plastic scintillator positioned right above it, in the underground, and
- as well as the signatures of the soft component of EM showers in the spectrum of the unshielded NaI detector, taken in coincidence with the plastic detectors.

Since all above mentioned measurements are spectral, we hope to exploit this feature to some advantage, even in the case of rather featureless spectra of plastic scintillators. With the help of MC simulation programs (mainly CORSIKA and GEANT4), we expect to discriminate the signatures of CR muons from those of electromagnetic showers to some degree.

If all the measurements are performed continuously, we estimate that, together, both set-ups will produce about 1 TB of data per year, all of which would be kept permanently for later analyses.

To illustrate the potential of these measurements, we will now briefly report on some preliminary results obtained during a testing period, approximately yearlong. We will first briefly discuss the performance of low-level measurements and then those pertaining to CR measurements.

LOW-LEVEL MEASUREMENTS

Future applications of the low-background gamma spectroscopic system include the study of rare nuclear processes, measurements of environmental radioactivity and radiopurity of materials.

The cylindrical lead shielding of the 35% efficiency radio-pure HPGe ORTEC detector, with a wall thickness of 12 cm and an overall weight of 900 kg, was cast locally out of scratch plumbing retrieved after the demolition of some old housing. The integral background rate in the region from 50 keV to 3 MeV is about 0.5 cps. The lines of Co-60 are absent in the background spectrum, while the line of Cs-137 with the rate of 1 10^{-4} cps starts to appear significantly only if the measurement time approaches one month. Fukushima activities, though strongly present in our inlet air filter samples, did not enter the background at observable levels, in spite of the great quantities of air that we pump into the UL to maintain the overpressure, and it seems that the double air filtering and double buffer door system, along with stringent radiation hygiene measures, is capable of keeping the UL clean in cases of global accidental contaminations (see *e. g.* [13]).

No signatures of environmental neutrons, neither slow nor fast, are present in direct background spectra. The rates of some characteristic background

Table 1. Count rates in some background lines. Rotes are given in counts per second (cps)

Energy [keV]	Count rate [cps]
186.2 (Ra-226)	2.4 10^{-4}
351.9 (Pb-214)	1.1 10^{-3}
583.1 (Tl-208)	6.6 10^{-4}
609.3 (Bi-214)	1.1 10^{-3}
911.1 (Ac-228)	4.5 10^{-4}
1460.8 (K-40)	3.5 10^{-3}
2614.5 (Tl-208)	1.1 10^{-3}

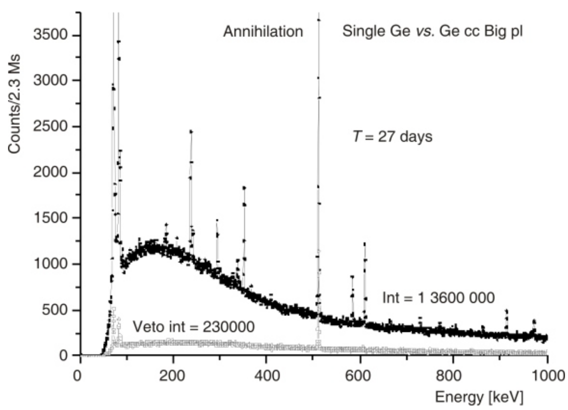

Figure 7. The background spectrum of the HPGe detector in its lead castle in the UL and the part of the spectrum coincident with the large scintillator positioned right above it

lines are listed in tab. 1. With the large plastic scintillator currently positioned rather high over the detector top, at a vertical distance of 60 cm from the top of the lead castle, in order to allow for the placing of voluminous sources in front of the vertically oriented detector, the off-line reduction of this integral count by the CR veto condition is about 18% (see fig. 7). Up to a factor of two might be gained if the veto detector were to be positioned at the closest possible distance over the HPGe detector. This agrees well with simple estimates of the rate of events susceptible to the veto condition [14]. The veto spectrum contains all events, prompt as well as those with delays of up to 10 s, which is why besides the continuum it contains only the lead X-rays and the annihilation line. As we shall see, the selection of delayed events only reveals some other details in this spectrum. Since for the time being we are not able to improve on the intrinsic background of our detector, when analyzing the analytical powers of our system, at present, we do not insist on the lowering of statistical errors which depend on background levels solely and are difficult to reduce further with available means, but rather emphasize its stability due to the low and controlled radon concentration in the laboratory. This is essential, especially in NORM measurements, and makes our system virtually free of systematic errors as compared to systems which operate in environments where radon is not controlled and where the reduction of post-radon background activities is achieved by flushing the detector cavity with liquid nitrogen vapor, where the transient regimes during sample changes and possible deposition of radon progenies [15] may introduce systematic uncertainties which are difficult to estimate.

COSMIC-RAY MEASUREMENTS

Muon spectra and the time series

During the commissioning of the large plastic detectors, we tested the response of these detectors to CR muons and their stability over a prolonged period of time. Certain results of these preliminary studies are presented here.

In fig. 8, we present the spectra of the two diagonals of the large plastic scintillator in the UL. Contrary to the situation in the GLL, the peak of charged particle energy losses situated at about 10 MeV (due to both muons and electrons from EM showers), is not fully separated from the low-energy tail of Compton electrons in the UL, because of gamma-ray interactions (both environmental and from EM showers).

Figure 9 presents the coincident sum spectra of the two diagonals. Energy spectra now contain only the well-defined peak of charged particles energy losses. The offsets are not imposed and occur simply

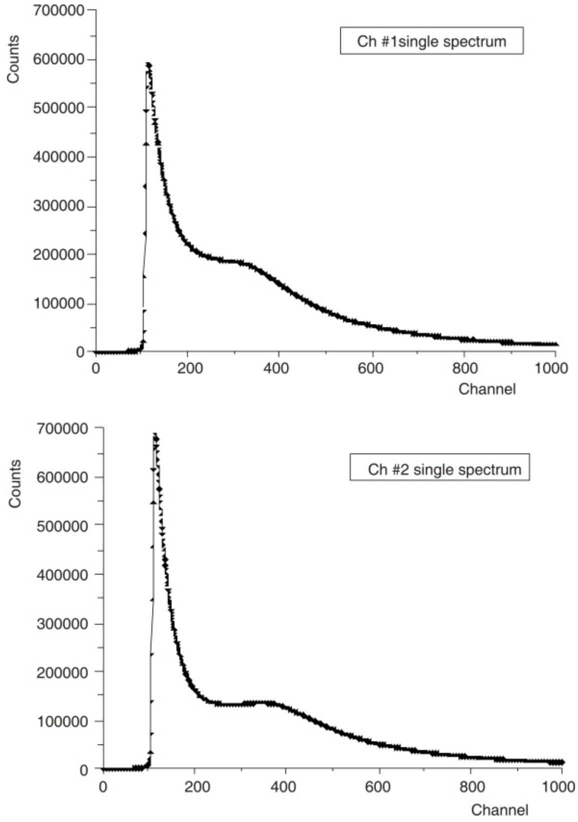

Figure 8. The spectra of two diagonals of the large plastic detector in the UL. Note that the peak of charged particle energy losses of 10 MeV, which corresponds to channel 320, is not separated from the low-energy tail of Compton scattered environmental gamma radiations. When summed, in coincidence they produce the spectrum from fig. 9

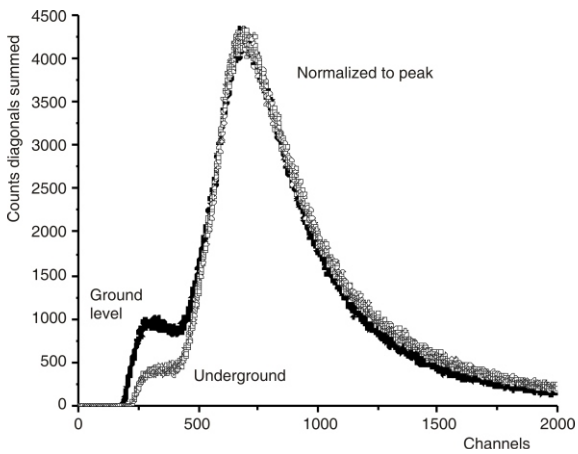

Figure 9. The sum spectra of two diagonals of the large plastic detectors in the UL and GLL. For comparison, the spectra are normalized for the peaks to coincide. Channel 650 now corresponds to the muon energy loss of 10 MeV. The integral of this peaked distribution is taken as the first approximation to the CR muon count by the large detectors

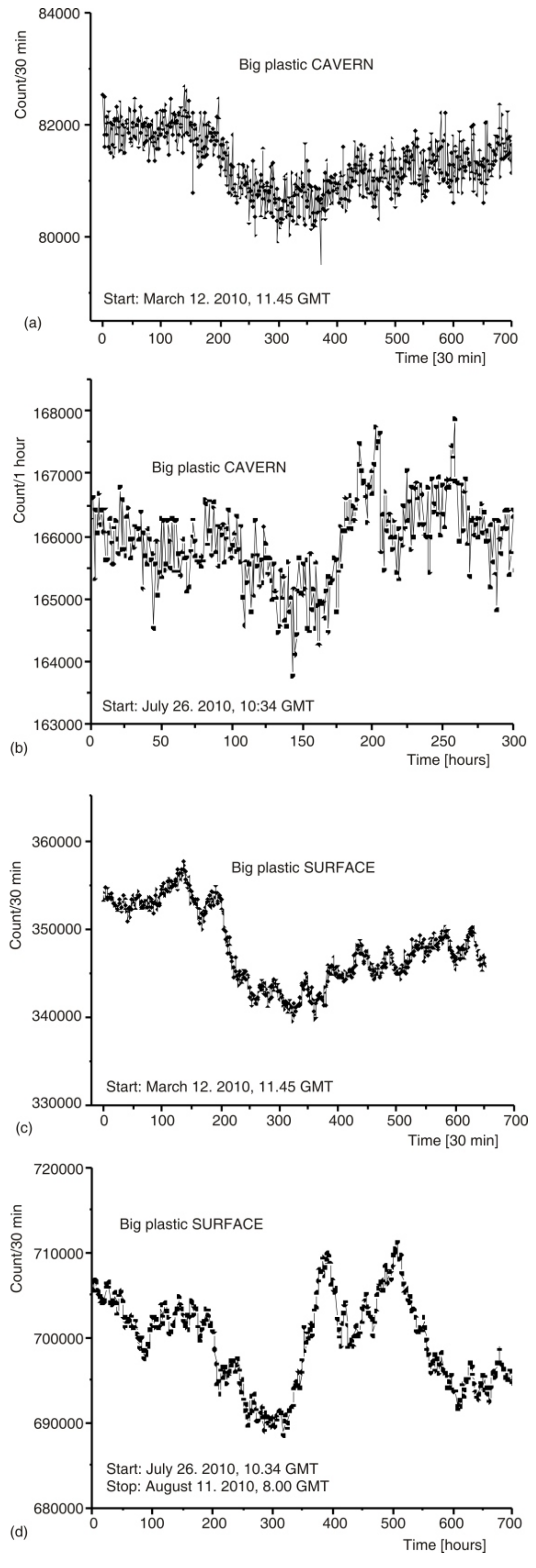

Figure 10. The time series of the CR muon count of the large plastic detector in the UL – (a) and (b) graphs – and GLL (c) and (d) graphs for the period starting with March 12, 2010, averaged to half hour intervals, as opposed to the period starting with July 26, 2010, averaging to one hour intervals. It is evident that the modulation in the two laboratories is correlated and that the amplitude of the modulation in the UL is roughly half

because at low energies there are no coincident events. As the simulations demonstrate, this is so because single Compton electrons do not produce enough light to trigger both diagonals.

The majority of events that produce this peaked distribution are due to CR muons that pass through the detector. We thus form the time series of this spectrum integrated over different time intervals. As an example, in fig. 10 we present the time series of this count in 30-minute intervals, both in the UL and in the GLL, for a period of 16 days in March 2010, and in one-hour intervals for the period starting with July 26, 2010. The data are not corrected either for atmospheric pressure or temperature.

The two series appear highly correlated, the amplitude of the modulation of this count in the UL is about 1.8%, while the corresponding one in the GLL is about 3.5%. At these integrating times, this is already sufficiently statistically significant, even in the UL.

Previous measurements at the same location with the small detectors yielded results for the muon flux of 1.37(6) 10^{-2} per cm^2s in the GLL, and of 4.5(2) 10^{-3} per cm^2s in the UL [2].

NEUTRONS AND STOPPED POSITIVE MUONS IN THE UNDERGROUND LABORATORY

During the testing period, we have accumulated some six months of data-taking in the underground laboratory. The background spectrum of the HPGe de-

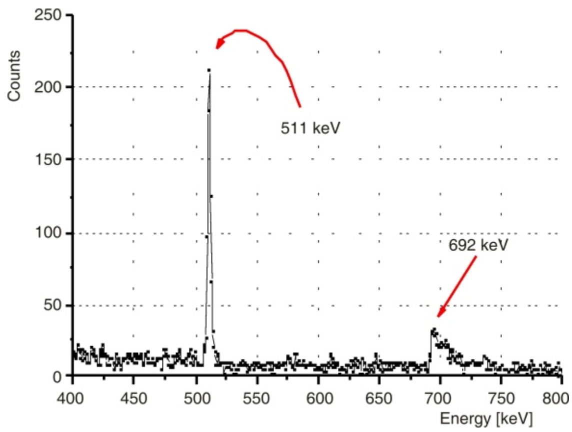

Figure 11. The portion of the background of the HPGe spectrum coincident with the large plastic detector with delays in the range of 1 to 5 μs, after 187 days of measurement time. It shows the annihilation line which is due to the decays of positive muons stopped in the lead castle, and the triangular structure at 692 keV, which is due to inelastic scattering of fast neutrons on 72-Ge, the neutrons originating mostly from direct fast muon interactions with nuclei and certainly less from captures of stopped negative muons. The threshold in this spectrum is sufficiently high to leave this last structure unscathed

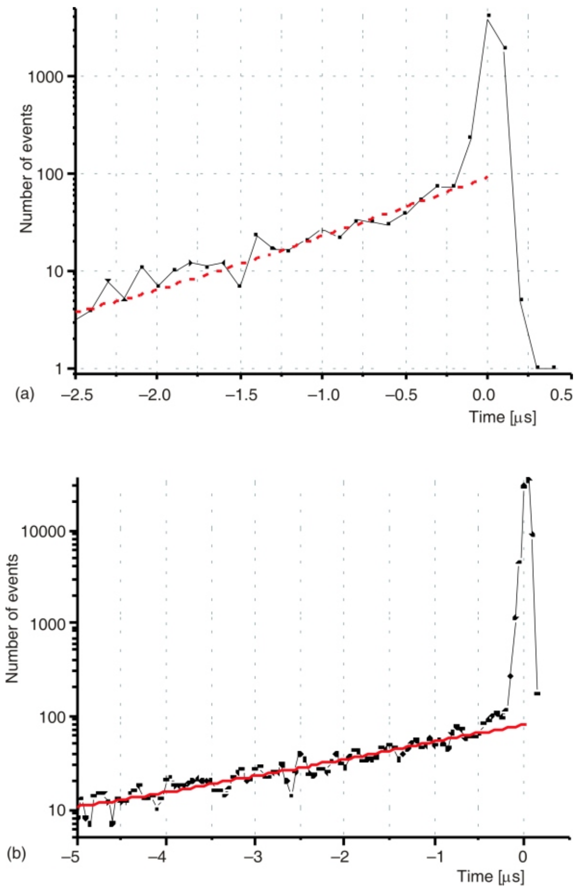

Figure 12. Time distributions of events that belong (a) to the structure of 692 keV, the slope of which yields 500(50) ns for the half-life of the state of this energy in 72-Ge and, (b) that of the annihilation line, which yields 2.24(9) s for the mean life of the muon

tector containing the coincidences with the large plastic scintillator from the delayed tail of the corresponding TAC distribution in the region of 1 to 5 s, shows at this statistics only two interesting features (fig. 11), though some more seem to emerge, but still insufficiently significant. The first is the already discussed triangular structure at 692 keV already discussed, which originates from the inelastic (n, n') scattering exciting the first excited state of the stable Ge-72 within the Ge detector itself. In this case the trigger was sufficiently high, and according to our finding, the intensity of the 692 keV distribution can be reliably used for the estimate of the fast CR-induced neutron flux at the position of the detector. To verify this, we applied the software gate to this structure and obtained the TAC distribution presented in fig. 12(a). Although the statistics is poor, the fit through the tail of delayed coincidences yields the half-life of 500(50) ns, which compares well with the known value of 444 ns. Using the expression from ref. [8], we obtain the value of 4(1) 10^{-7} $cm^{-2}s^{-1}$ for the flux of neutrons of CR origin with energies over 1 MeV. This refers to the flux at the depth of 25 m.w.e., (see *e. g.* [16]) within roughly a ton of lead, a common environment in most measurements of low activities.

The second feature of this spectrum is the annihilation line. The gate put on this line gives the TAC distribution presented in fig. 12(b), where the fit through the tail of delayed coincidences yields the mean life of 2.24(9) s. This justifies the assumption that these events are due to the decays of stopped positive muons. We further assume that the source of these delayed annihilations is homogeneously distributed throughout the volume of the lead castle and use GEANT4 to find the overall detection efficiency. From the intensity of these delayed annihilations, we then obtain that the number of stopped positive muons per kg of lead per second equals 3.0(5) 10^{-4} μ_{stop}/kgs.

We have also been able to estimate the number of stopped muons in the large plastic scintillators themselves, both in the GLL and the UL (*e. g.* [16]). For this

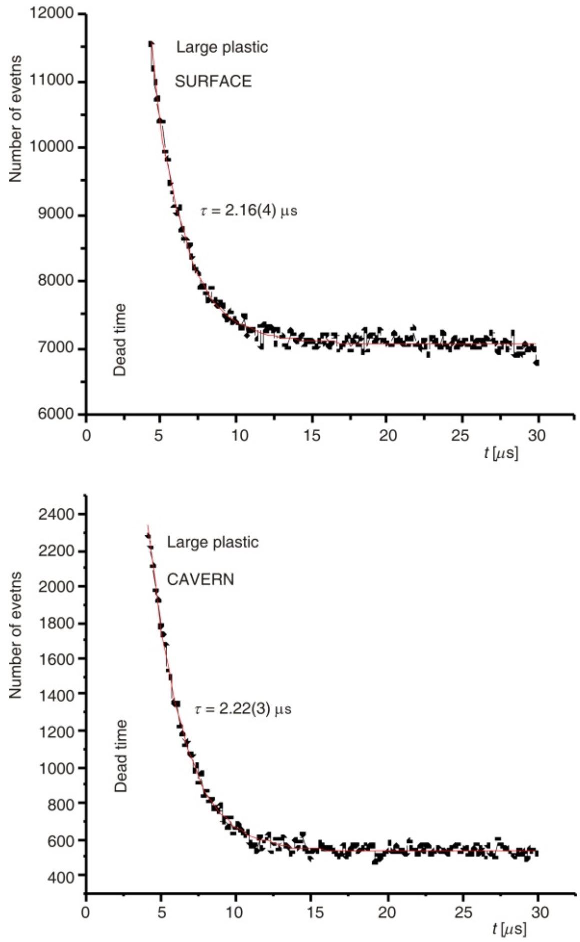

Figure 13. The distributions of short time intervals between successive counts in large plastic scintillators which sit on the distribution of time intervals between successive counts with a long exponential constant that corresponds to the total counting rate and appears flat on this scale. The decay constant of short time interval distributions, however, equals that of a muon mean life. Note that the first two lifetimes are missing, due to the dead time of the system, which in this particular case equals 4 s

purpose, we looked into the distribution of time intervals between the successive counts of these detectors. The gross structure of this distribution is nicely exponential, corresponding to the average CR counting rate and to an average time interval between the counts, reciprocal to the said rate. At short time intervals, however, the distribution strongly departs from this shape (fig. 13).

It is again exponential, now with the time constant of 2.16(4) and 2.22(3) μs in the GLL and UL, respectively, reproducing satisfactorily the muon mean life. This suggests that these events originate from muons that both stop and decay within the detector. Minding that the fiducial volume for this kind of signature has not been estimated, the intensity of this exponential distribution, taking in account the missing events due to the 4 s long dead time, now gives the estimate for the lower limit of the number of muons that stop in 5 cm of plastic per square meter per second, at ground level as 6 10^{-2} $_{\text{stop}}$ per m^2s, and at a depth of 25 m.w.e. as 1.52 10^{-2} μ_{stop} per m^2s. It is interesting to compare those figures with the results obtained recently at Gran Sasso [18, 19].

DECOHERENCE CURVES AND SPECTRA

In test measurements, coincidence spectra between large and small detectors at different separations between the two were recovered in off-line analyses, both in the GLL and the UL. These are predominantly the spectra of EM showers, as seen by respective detectors. The comparison with their direct spectra, which at lower energies are composed mostly of the signatures of environmental gamma radiations and at higher energies of the signatures of CR muons, enables the disentanglement of the signatures of these radiations. As an illustration, fig. 14 presents the spectrum of the large plastic detector in the UL, in coincidence with the small detector, at their smallest possible separation. This is to be compared with the direct spectrum of the large detector, as presented in fig. 9. Reflecting the structure of the EM component at the given location, not only the intensity, but also the shape of the spectrum changes with detector separation, and the differences between these coincidence spectra in the GLL and the UL reflect the difference in the composition of showers on the surface and underground. The simplest integral characteristic of the shower profile is presented by the integral of this coincidence spectrum as a function of detector separation, sometimes referred to as the decoherence curve. Figure 15 shows the decoherence curve at the GLL, fig. 16 the same in the UL.

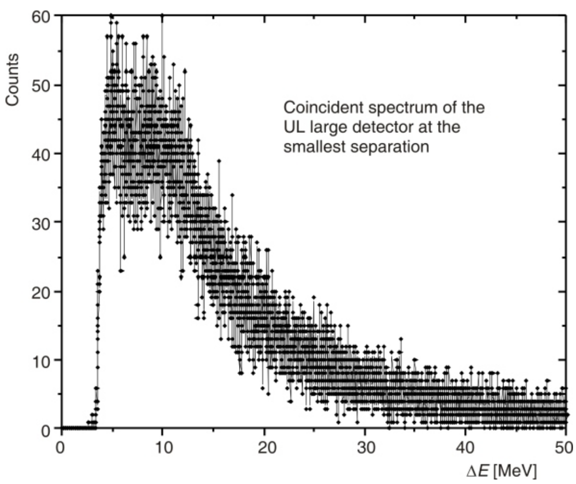

Figure 14. The coincident spectrum of the large plastic detector in the UL, with the small detector at the smallest separation between them. Compare this with the direct spectrum presented in fig. 9

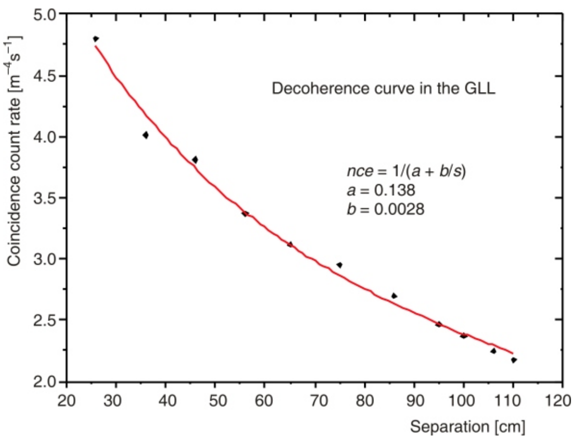

Figure 15. The decoherence curve in the GLL, reflecting the lateral profile of EM showers on the surface; the nce denotes number of coincident events

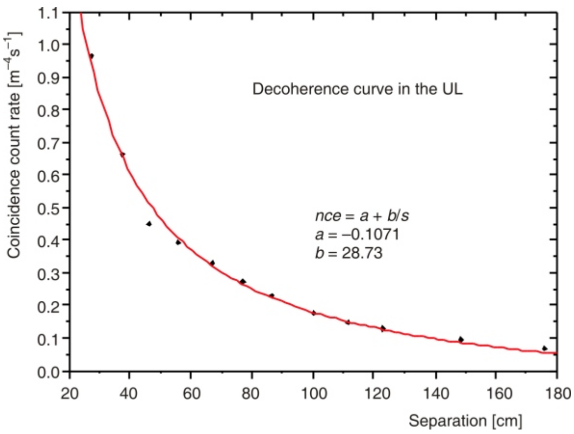

Figure 16. The decoherence curve in the UL, reflecting the lateral profile of EM showers at the equivalent depth of 25 m.w.e; the nce denotes number of coincident events

Note that the two curves cannot be satisfactorily fitted with quite the same type of functional dependence, so that the width of the distributions on the surface and underground cannot be directly compared. The much narrower distribution underground is a result of the harder CR muon spectrum and of the different radiation and attenuation lengths, as well as of the geometry of the shower-producing medium. The ratio of the intensities of the distributions on the surface and underground is roughly twice the ratio of CR muon intensities at two locations. Full interpretation awaits better statistics.

CONCLUSION

We have presented some preliminary results for muon and neutron fluxes at ground level and underground spaces of the Belgrade low-level and CR laboratory, obtained during the commissioning of the new equipment consisting of two scintillation detectors, a HPGe detector, and a digital spectroscopy system based on two CAEN N1728B units. The main advantage of the present set-up is that it enables complex measurements involving routine low activity measurements with modest means, along with some interesting research work related to cosmic-ray physics. We find that the results obtained in this testing phase justify the planned program of measurements and that the future improvement on statistics will contribute not only to the quality of the results already obtained, but furthemore with increased sensitivity new results are also expected to emerge.

ACKNOWLEDGEMENT

The present work was funded by the Ministry of Education and Science of the Republic of Serbia, under the Project No. 171002. The Belgrade Laboratory bears the name of "Dr. Radovan Antanasijević", in honor of its early deceased founder and first director.

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НОВА ОПРЕМА У БЕОГРАДСКОЈ ЛАБОРАТОРИЈИ ЗА МЕРЕЊЕ НИСКИХ АКТИВНОСТИ И КОСМИЧКОГ ЗРАЧЕЊА

Београдска лабораторија састоји се од два лабораторијска простора, једног на површини и једног подземног, на дубини од 25 метара воденог еквивалента. Детаљно су описани и илустровани потенцијали ових лабораторија за мерење ниских активности и за континуирано мерење мионске и електромагнетне компоненте космичког зрачења, као и за студије процеса које ова зрачења индукују у германијумским спектрометрима смештеним у нискофонским подземним лабораторијама. Сва ова мерења се изводе симултано, новим системом за дигиталну спектроскопију, а подаци се записују догађај по догађај, и анализирају после завршених мерења. Такође су приказани прелиминарни резултати који су у фази тестирања опреме добијени за флукс брзих неутрона и заустављених миона у површинској и у подземној лабораторији.

Кључне речи: подземна лабораторија, гама спектроскопија, мерења ниских активности, космичко зрачење

COMPARISON OF MULTIVARIATE CLASSIFICATION AND REGRESSION METHODS FOR THE INDOOR RADON MEASUREMENTS

by

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We present the results of a test usage of multivariate methods, as developed for data analysis in high-energy physics and implemented in the toolkit for multivariate analysis software package, in our analysis of the dependence of the variation of indoor radon concentration on climate variables. The method enables the investigation of the connections of the wide spectrum of climate variables with radon concentrations. We find that multivariate classification and regression methods work well, giving new information and indications, which may be helpful in further research of the variation of radon concentration in indoor spaces. The method may also lead to considerable prediction power of the variations of indoor radon concentrations based on the knowledge of climate variables only.

Key words: radon, multivariate analysis, climate parameter

INTRODUCTION

Radon is a unique natural element since it is a gas, noble and radioactive in all of its isotopes. As noble gases, radon isotopes are mobile and can travel significant distances within the ground and through the atmosphere. Being radioactive, radon makes for about 55% of the annual effective dose received by average non-professional. Indoor radon concentrations vary significantly due to a large number of factors, which include the local geology, soil permeability, building materials and lifestyle characteristics, climate parameters and the exchange rate between indoor and outdoor air. Since both the climate parameters and air exchange rates may significantly vary during a day, it is important to investigate their correlation with short-term variations of indoor radon concentrations. In the past somewhat unusual climate parameters, such as wind speed and cloud cover, were occasionally considered, using a multivariate method [1-3]. We start this analysis with the maximum of 18 climate parameters and use and compare 12 different multivariate methods.

Variations of radon concentration were studied in our laboratory [4] in many details since 1999 [5-8]. Several climate variables, like air temperature, pressure, and humidity were considered [8, 9]. We now make further advance and try to use all publicly available climate variables monitored by, in our case, nearby automatic meteorological station (Automatic Meteorological Station Belgrade-south, Banjica-Trošarina, 44°45'16''N, 20°29'21''E). We want to find the appropriate method out of the wide spectrum of multivariate analysis methods that are developed for the analysis of data from high-energy physics experiments to analyze our measurements of variations of radon concentrations in indoor spaces.

FORMULATION OF THE PROBLEM

The demand for detailed analyses of large amount of data in high-energy physics resulted in wide and intense development and usage of multivariate methods. Many of multivariate methods and algorithms for classification and regression are already integrated into the analysis framework ROOT [10], more specifically, into the toolkit for multivariate analysis (TMVA) [11]. We use these multivariate methods to create, test and apply all available classifiers and regression methods implemented in the TMVA in order to find the method that would be the most appropriate

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and yield maximum information on the dependence of indoor radon concentrations on the multitude of climate variables.

The first step is to calculate and rank the correlation coefficients between all the variables involved, what will help in setting up and testing the framework for running the various multivariate methods contained in the TMVA. Although these correlation rankings will later be superseded by method-specific variable rankings, they are useful at the beginning of the analysis.

The next step is to use and compare the multivariate methods in order to find out which one is best suited for classification (division) of radon concentrations into what would be considered acceptable and what would be considered increased concentration in indoor spaces. Main aim is to find out which method can, if any, on the basis of input climate variables only, give an output that would satisfactorily close match the observed variations of radon concentrations. This would enable the creation of the "radon alarm" using only the multivariate classification of the now widely available records of climate variables. Towards this aim, this work should be considered a preliminary one, for the number of specific cases that should be studied in this way should be much larger, to comprise the multitude of possible representative situations that occur in real life.

In order to be able to use the multivariate classification, the set of input events (values for climate variables for each measurement) used, have to be split into those that correspond to the signal (the radon concentrations that are considered increased) and to the background (consisting of radon concentrations that are declared acceptable). This splitting of the set of input events is for the purposes of this preliminary analysis performed at the limiting value of 40 Bq/m^3. This value is used for most of the analyses, and is selected because this splitting ensures maximum employment of multivariate comparison methods, and this particular value reflects the fact that in our test case the statistics on higher radon concentration values are lower. For the purposes of setting of a sort of a "radon alarm", the value of radon concentration that should be used for splitting of input events is the value for radon concentration recommended by World health organization of 100 Bq/m^3. The method of multivariate regression, however, does not require preliminary splitting of input events, and is therefore a more general one.

EXPERIMENTAL DATA

There are many methods available for measurement of radon concentrations in air. According to the integrating measurement time, these may be divided into the long-term and short-term ones. The first are mostly performed with passive integrating measuring devices based on nuclear track detectors, which are due to their low cost, simplicity, and wide availability well suited for simultaneous collection of data from a large number of measurement points and are thus used in large radon mapping projects. The second group comprises the methods that are performed with more complex and more expensive passive or active (with pumped air sampling) devices. For the short-term measurements of radon concentration in a single-family dwelling house in Belgrade, Serbia, we use the SN1029 radon monitor (manufactured by the Sun Nuclear Corporation, NRSB approval-code 31822). The device consists of two diffused junction photodiodes as a radon detector, and is furnished with sensors for temperature, barometric pressure and relative humidity. The user can set the measurement intervals from 30 minutes to 24 hours. It was set to record simultaneously the radon concentration, temperature, atmospheric pressure and relative humidity.

The selected house to measure the temporal variations of radon concentration is a typical one-family detached dwelling house built with standard construction materials such as brick, concrete, and mortar. The house is thermally insulated with Styrofoam. During the period of measurements (summer), the house was naturally ventilated and air conditioning was used during the hottest days. The indoor radon measurements were performed in the living room, where family spends anything from 16 up to 24 hours during the working days of the week. Radon monitor was measuring radon concentration, temperature, pressure, and humidity at 2 hour intervals, starting from the 3rd of June till the 3rd of July and from the 18th of July till the 11th of August 2013.

The values of climate variables, which will be correlated with radon monitor results, are obtained from a modern automatic meteorological station located some 400 m (GPS coordinates) away from the house where the radon monitor was placed. The wide set of climate variables were used, for the measurements of which were performed at 5 minute intervals during June, July, and August 2013. The fifteen climate parameters used are: outdoor air temperature, pressure and humidity, solar irradiance, wind speed at the height of 10 m above the ground, precipitation, evaporation, and underground temperature and humidity at the depths of 10-30 and 50 cm.

The second site used for the tests is our own ground level laboratory [1], which is air-conditioned and only rarely accessed, thus having much more stable indoor conditions than the dwelling house described. The measurements were performed during September and October 2012. Measurements of climate parameters that will be combined with radon measurements in this case come from the different, and somewhat older automatic metrological station, located about 4 km from the laboratory where the radon monitor was taking data.

MULTIVARIATE METHODS

The TMVA provides a ROOT-integrated environment for the processing, parallel evaluation and application of multivariate classification and multivariate regression methods. All multivariate methods in TMVA belong to the family of "supervised learning" algorithms. They make use of training events, for which the desired output is known, to determine the mapping function that either describes a decision boundary (classification) or an approximation of the underlying functional behavior defining the target value (regression). All MVA methods see the same training and test data. The correlation coefficients of the input variables are calculated and displayed, and a preliminary ranking is derived (which is later superseded by method-specific variable rankings). For standalone use of the trained classifiers, TMVA also generates lightweight C++ response classes that do not depend on TMVA or ROOT, neither on any other external library. As will be demonstrated, the two most important multivariate methods for our purposes are the boosted decision trees (BDT) and the artificial neural networks (ANN) methods.

Boosted decision trees

BDT has been successfully used in high energy physics analysis for example by the MiniBooNE experiment [12]. In BDT, the selection is done on a majority vote on the result of several decision trees. Decision tree consists of successive decision nodes, which are used to categorize the events in sample as either signal or background. Each node uses only a single discriminating variable to decide if the event is signal-like "goes right" or background-like "goes left". This forms a tree like structure with "baskets" at the end (leave nodes), and an event is classified as either signal or background according to whether the basket where it ends up has been classified as signal or background during the training. Typically, BDT is constructed of a forest of such decision trees. The (final) classification for an event is based on a majority vote of the classifications done by each tree in the forest. However, the advantage of the straightforward interpretation of the decision tree is lost. In many academic examples with more complex correlations or real life examples, the BDT often outperform the other techniques. More detailed information about training can be found in [11].

Artificial neural networks

An artificial neural network (ANN) [13] is most generally speaking any simulated collection of interconnected neurons, with each neuron producing a certain response at a given set of input signals. By applying an external signal to some (input) neurons the network is put into a defined state that can be measured from the response of one or several (output) neurons.

ANN in TMVA belong to the class of multilayer perceptrons (MLP), which are feed-forward neural networks. The input layer contains as many neurons as input variables used in the MVA. The output layer contains a single neuron for the signal weight. In between the input and output layers are a variable number of *k* hidden layers with arbitrary numbers of neurons.

All neuron inputs to a layer are linear combinations of the neuron output of the previous layer. The transfer from input to output within a neuron is performed by means of an "activation function". In general, the activation function of a neuron can be zero (deactivated), one (linear), or non-linear. The ANN used for our purposes uses a sigmoid activation function. The transfer function of the output layer is usually linear.

RESULTS

We comment on the results of our analyses divided into cases that differ by the size of the set of climate parameters used, by the indoor space studied, and by the methods of analysis used.

First, we intercompare the multivariate methods used for classification of radon concentrations by using the full set of climate variables as described in previous sections.

We are using the input events (set of climate variables for each measurement) to train, test and evaluate the 12 multivariate methods implemented in TMVA. The graph presenting the receiver operating characteristic (ROC) for each multivariate method (fig. 1) may be considered as the most indicative in comparing the different methods used for classification of radon concentrations using climate variables. On this graph one can read the dependence of background rejection on signal efficiency. The best method is the one that holds maximum value of background rejection for highest signal efficiency, *i. e*. the best method has ROC curve closest to the upper right corner on the graph presented in fig. 1. It turns out that the method best suited for our purpose is the BDT method. This means that BDT gives most efficient classification of input events. This is seen in fig. 2, which shows the distribution of BDT classification method outputs for input signal and background events. The second best method is the implementation of ANN MLP.

In fig. 3, one can see the values of signal and background efficiency and significance. Significance, calculated as

$$\frac{N(\text{signal})}{\sqrt{N(\text{signal}) \quad N(\text{background})}}$$

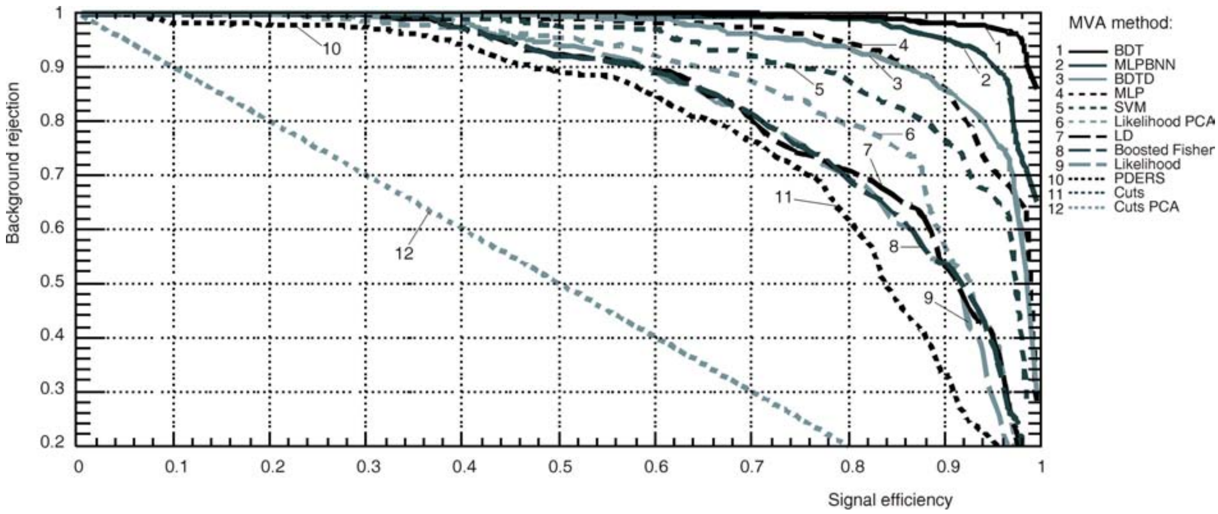

Figure 1. ROC for all multivariate methods used for classification of radon concentration using climate variables

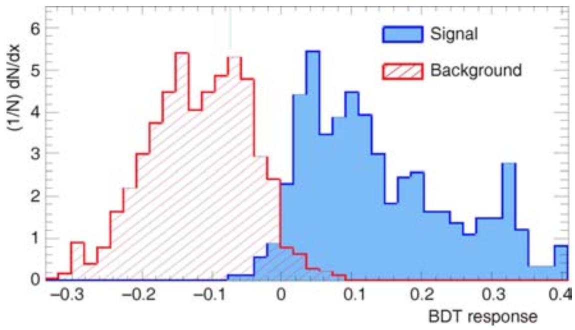

Figure 2. Distribution of BDT classification method outputs for input signal and background events

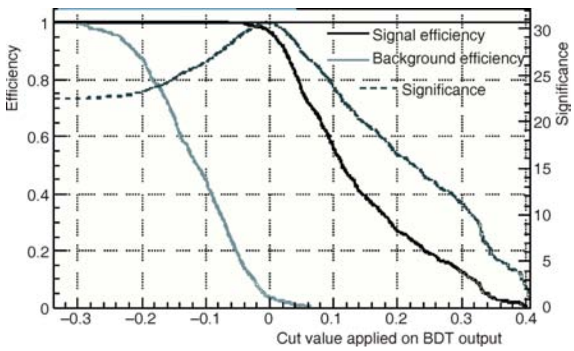

Figure 3. Cut efficiency and optimal cut value of BDT classification MVA method

can be used as the value for comparison of various multivariate methods, and also for comparison of method efficiencies for different sets of input variables. The significance of the BDT method with full set of input climate variables turns out to be 30.6. Ranking of the BDT input variables (tab. 1.) is derived by counting how often the variables are used to split decision tree nodes, and by weighting each split occurrence by the separation it has achieved and by the number of events in the node. As seen from tab. 1, temperature of the soil at the depth of 10 cm appears to be by far the most important variable.

Now we compare the multivariate methods for classification of radon concentration by using the minimum set of climate variables that would give similar results as when using the full set. While searching for the best multivariate method for radon classification indoors in this situation, we found that the BDT method again gives the best result, with the significance of 29.6 as compared to 30.6, when all the available climate variables for training and testing of multivariate methods are used. The climate variables chosen for training and testing in this case were: outdoor air temperature, humidity and pressure, outdoor soil temperature at the depth of 10 cm, differences of

Table 1. Ranking of BDT input variables

Variable	Variable importance
Temperature of soil at depth of 10 cm	1.37e-01*
Outside air temperature	7.40e-02
Evaporation	7.16e-02
Outside air pressure	7.16e-02
P (outside) – P (radon monitor)	6.51e-02
Outside air humidity	6.40e-02
H (outside) – H (radon monitor)	6.12e-02
T (outside) – T (radon monitor)	5.79e-02
Humidity of soil at depth of 10 cm	5.74e-02
Solar irradiance	5.16e-02
Temperature of soil at depth of 20 cm	4.99e-02
Temperature of soil at depth of 50 cm	4.68e-02
Temperature of soil at depth of 30 cm	4.46e-02
Humidity of soil at depth of 20 cm	4.31e-02
Wind speed at height of 10 m	3.87e-02
Humidity of soil at depth of 30 cm	3.41e-02
Humidity of soil at depth of 50 cm	3.13e-02
Precipitation	0.00e+00

*1.37e-01 read as 1.37 10^{-1}

outdoor and indoors temperature, and the indoors humidity and pressure. One important caveat is in place here. It concerns the possibility that the two sets of instruments (for indoor and outdoor measurements) are not identically calibrated, what may especially be the case when two different groups or institutions conduct the indoor and outdoor measurements. It is estimated that these instrumental effects do not influence significantly the results of this study. In the case of calibration of MVA classification method, we need radon monitor apparatus indoors and apparatus for P, H, and T measurements outdoors and an apparatus for measurement of the outdoor soil temperature with the sensor positioned at the soil depth of 10 cm. While aiming at setting a "radon alarm" in this case, we thus have to have two apparatuses for P, H, and T measurements, indoor and outdoor, and an apparatus for measurement of outdoor soil temperature with the sensor positioned at the depth of 10 cm.

Next we compare the uses of multivariate methods for classification of radon concentration indoors when using the simplest possible set of climate variables. The climate variables used for training and testing were: outdoor air temperature, pressure and humidity, and differences of outdoor and indoor temperature, pressure and humidity. That means that we need to have two devices for measurement and recording of temperature, pressure and humidity, both indoors and outdoors at the same time. For calibration and testing of multivariate methods, in case of using this set of climate variables we would need one radon monitor indoors, and an apparatus for measurement of P, H, and T outdoors. For the purpose of seting the radon alarm, we would need to have two apparatuses for P, H, and T measurement. The best multivariate method for radon classification indoors in this case is also BDT method. The resulting significance is 28.2 as compared to 30.6 what we get when using the full set of available climate variables for training and testing of multivariate methods. This testifies that when we drop out many climate parameters in this case of analysis the resulting significance decreases notably, but still leaving MVA classification work good.

We also compared the multivariate methods for classification of radon concentration using the simplest set of climate variables in our Ground level laboratory, which is, as said, an air-conditioned and only seldom accessed space. The climate data are provided by the 4 km away and somewhat older automatic meteorological station. The methods are still found to work satisfactorily – the resulting significance of the BDT method now being 27.6 as compared to 28.2, obtained with the simplest set of variables in the case of the actively inhabited dwelling. The climate variables, requirements for training and testing are the same as in the previous case.

We also tested the simple set of only outdoor measured climate variables consisting of the outdoor air temperature, pressure and humidity, and the outdoor soil temperature at the depth of 10 cm. This means that the devices for measurement and recording of outdoor temperature, pressure and humidity as well as the device for measurement and recording of the outdoor soil temperature at depth of 10 cm are required. The resulting significance is now 27.2 as compared to 30.6 when using the full set of available climate variables, and 28.19 when using the two apparatuses for P, H, and T measurements.

Comparison of multivariate methods for classification of radon concentration indoors

The difference between this case and the previous one with the full set of climate variables is that input events are now split at the value of radon concentration of 100 Bq/m^3, which is the recommended limiting value between the acceptable and increased radon concentration by the World Health Organization (WHO). Previous method had a cut on the value of 40 Bq/m^3, which was found to insure maximum employment of multivariate classifications. This particular value reflects the fact that the statistics on higher radon concentrations are getting progressively lower. In tab. 2, we present the significance and the signal and background efficiency for several best multivariate classifier methods. Again, the BDT (and BDT decorrelated) multivariate method shows the best performance in classifying the events into the categories of increased and acceptable concentrations.

Figure 4 shows the distribution of BDT classification method outputs for input signal and background events. These figures again demonstrate that classification methods work well *i. e.*, that the separation of signal and background works very good. Also, the significance value for BDT is higher for higher cut values for splitting of input events. Interestingly, it appears that other multivariate methods also give better results under these new conditions.

Regression methods

Regression is the approximation of the underlying functional behavior defining the target value. We tried to find the best regression method that will give

Table 2. Significance, signal, and background efficiency for several best multivariate classifier methods in the case of imposed limiting value of 100 Bq/m^3

Classifier	S/sqrt(S + B)	EffSig	EffBkg
BDT	31.1	0.97	0.01
BDTD	30.9	0.98	0.03
MLPBNN	30.6	0.95	0.02
MLP	30.0	0.93	0.04
SVM	29.6	0.93	0.05

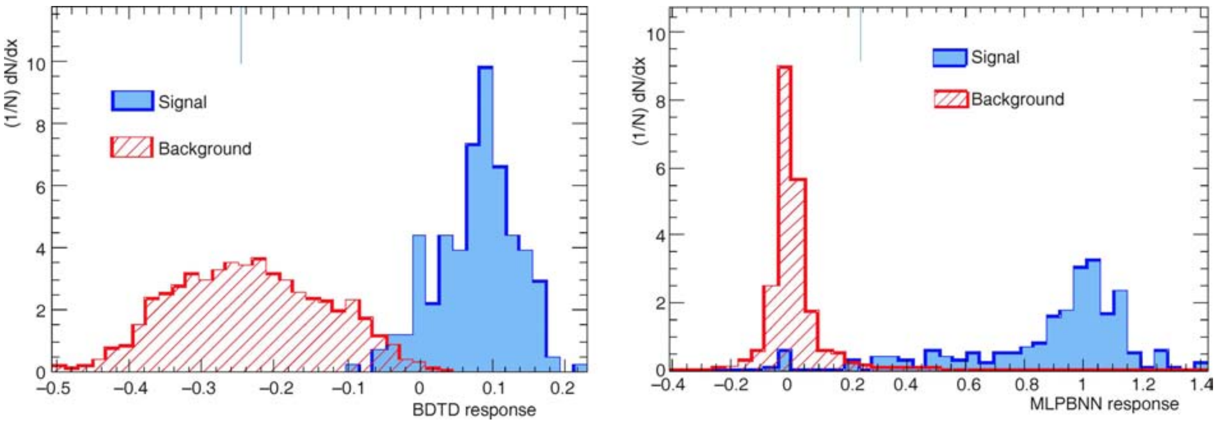

Figure 4. Distribution of BDT and ANN MLP classification method outputs for input signal and background events

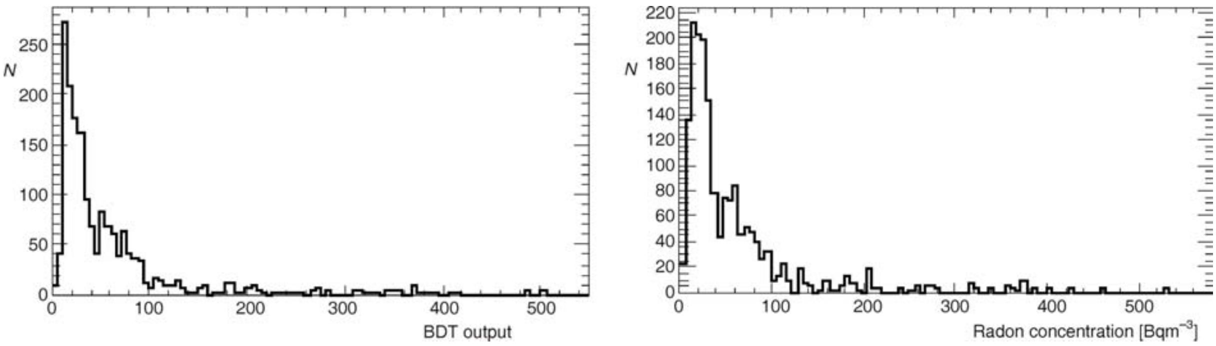

Figure 5. Distribution of radon concentrations and outputs from BDT multivariate method for regression of radon concentration using all climate variables

output values (predicted radon concentration) closest to the actual radon concentration that corresponds to specific input climate variables. The best multivariate regression method is found to be BDT, and the second one is MLP, same as in case of multivariate classifiers. Figure 5 presents the distribution of radon concentrations and outputs from the BDT multivariate method from regression of radon concentration using all climate variables.

To best way to estimate the quality of the method is to look at the differences between the output values from BDT multivariate regression method and the values of measured radon concentrations (fig. 6). The figure indicates the satisfactory predictive power of multivariate regression methods as applied for prediction of variations of indoor radon concentrations based on the full set.

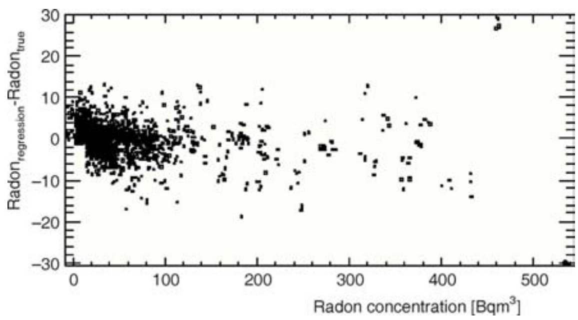

Figure 6. Difference of outputs from BDT multivariate regression method and radon concentrations, *vs.* radon concentration

CONCLUSIONS

The first test of multivariate methods developed for data analysis in high-energy physics and implemented in the TMVA software package applied to the analysis of the dependence of indoor radon concentration variations on climate variables demonstrated the potential usefulness of these methods. It appears that the method can be used with sufficient reliability for prediction of the increase of indoor radon concentrations above some prescribed value on the basis of monitored set of climate variables only. Surprisingly, this set of climate variables does not have to include too many of those which are nowadays widely available. To confirm these promising preliminary findings more case studies of similar character are required.

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AUTHOR CONTRIBUTIONS

The idea for this paper came as a result of discussions of V. I. Udovičić, R. M. Banjanac, D. R. Joković, and D. M. Maletić. Gathering climate data and MVA analysis was done by D. M. Maletić. V. I. Udovičić performed indoor radon measurements. Writing of the paper was done by D. M. Maletić and V. I. Udovičić. A. L. Dragić gave idea about using MVA methods in cosmic and radon measurements. N. B. Veselinović analyzed and validated climate data. J. Z. Filipović helped with MVA analysis. D. R. Joković helped with data analysis and paper technical preparation.

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ПОРЕЂЕЊЕ МУЛТИВАРИЈАНТНИХ МЕТОДА ПРИ КЛАСИФИКАЦИЈИ И РЕГРЕСИЈИ РЕЗУЛТАТА МЕРЕЊА РАДОНА У ЗАТВОРЕНИМ ПРОСТОРИЈАМА

Представљамо резултате тестирања коришћења мултиваријантних метода, развијених за анализу података у физици високих енергија и имплементираних у програмском пакету за мултиваријантну анализу – у нашем проучавању зависности варијација концентрације радона у затвореним просторијама и климатских варијабли. Мултиваријантни методи омогућавају испитивање повезаности широког спектра климатских варијабли и концентрације радона, и онда када међу њима нема значајних корелација. Показали смо да мултиваријантни методи за класификацију и регресију раде добро, дајући као резултат нове информације и индикације које би могле бити корисне у даљем изучавању варијација концентрације радона у затвореним просторијама. Коришћењем ових метода, моћи ће да се дође до релативно добре моћи предвиђања концентрација радона, користећи само податке климатских варијабли.

Кључне речи: радон, мултиваријантна анализа, климатски параметар

Daily and seasonal radon variability in the underground low-background laboratory in Belgrade, Serbia

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DAILY AND SEASONAL RADON VARIABILITY IN THE UNDERGROUND LOW-BACKGROUND LABORATORY IN BELGRADE, SERBIA

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Radon time-series analysis, based on the short-term indoor radon measurements performed worldwide, shows two main periodicity: daily and seasonal. The information obtained from time series of the measured radon values is the results of the complex radon dynamics that arises from the influence of the large number of different parameters (the state of the indoor atmosphere (temperature, pressure and relative humidity, aerosol concentration), the exchange rate between indoor and outdoor air and so on). In this paper we considered daily radon variability in the underground low-background laboratory in Belgrade, Serbia. The results are originated from the radon time-series analysis based on the 3 y of the continuous short-term indoor radon measurements. At the same time, we obtained the time series of the temperature, pressure and relative humidity in the laboratory. We also tried to find the correlation between different time series.

INTRODUCTION

The Low-Background Laboratory for Nuclear Physics at the Institute of Physics in Belgrade is a shallow underground laboratory. The experiments and routine measurements in the underground Low-Background Laboratory for Nuclear Physics require low levels of radon concentration with minimum temporal variations[1, 2]. Unfortunately, in the underground environments, radon level is extremely high (up to several kBq m^{-3}) and temporal variations, especially the daily amplitude, might be very intensive. The radon behaviour in such specific environments is the subject of intensive research. This is confirmed by a number of scientific articles published in last years[3–7]. The radon time-series analysis, based on the 3 y of the short-term radon measurements, has shown that there are two periodicity at 1 d and 1 y. Besides the fact that the laboratory has the system for radon reduction[8], there is a significant 1-d period which is the main subject of this work. The physical origin of the obtained daily variation in the underground laboratory is not straightforward. The daily variability shows the best correlation with the difference of external and internal temperature.

EXPERIMENT

The continuos short-term radon measurements were performed in the underground low-level laboratory in Belgrade. The device for the performed short-term radon measurements is SN1029 radon monitor (manufactured by the Sun Nuclear Corporation, NRSB approval-code 31822) with the following characteristics: the measurement range from 1 Bq m^{-3} to 99.99 kBq m^{-3}, accuracy equal to ± 25 %, sensitivity of 0.16 counts hour per Bq m^{-3}. With these characteristics, SN1029 radon monitor is defined as a high-sensitivity passive instrument for the short-term radon measurements and it is an optimal solution for radon monitoring in the underground laboratory. The measurements covered period from June 2008 to November 2011. The device has sensors for temperature, barometric pressure and relative humidity. The sampling time was set to 2 h. The data are stored in the internal memory of the device and then transferred to the personal computer. The data obtained from the radon monitor for the temporal variations in the radon concentrations over a long period of time enable the study of the short-term periodical variations. The series taken during period of 3 y were spectrally analysed by the Lomb-Scargle periodogram method. After the 2 y, after start of the measurements, the data were analysed and the obtained results were published[9].

RESULTS AND DISCUSSION

The descriptive statistics on the raw radon data are shown in Table 1. The radon data from radon monitor device SN1029 for the period of 3 y are spectrally analysed. The Lomb-Scargle periodogram analysis method has been used in spectral analysis of radon time series. With the better statistics compared with the previous results[9], the obtained periodogram show two periodicity, on the 1 d and 1 y.

In Figure 1, the obtained radon and the difference between outdoor and indoor temperature time series during one calendar year are presented. The results show similar behaviour of the two quantities. Figure 2 shows the correlation between radon and temperature differences.

It is relatively a good correlation and presents the results that may correspond to the previous results[3]. Also, the temperature profile defined two season, cold (winter) and hot (summer). The winter time covered the

Table 1. Descriptive statistics on the raw radon data.

	n	Mean	SD	Median
Radon concentration (Bq m^{-3})	10 090	13.75	9.86	12.4

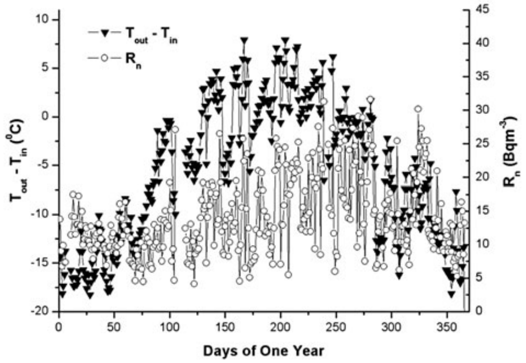

Figure 1. The radon and difference between outdoor and indoor temperature time series during one calendar year.

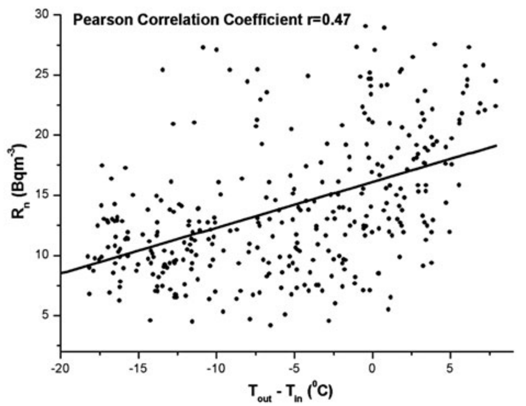

Figure 2. The correlation between radon and temperature differences.

period from December to June and the summer time is the period from June to November. According to that fact, the radon behaviour is presented in Figure 3.

The maximum radon concentration is in the August and the minimum value is in the March. The daily radon variability also has the interesting characteristic.

In Figure 4, the daily radon and the difference between outdoor and indoor temperature variability during 1 d are presented. Two quantities are shifted in phase. This means that, when the difference between the exterior and interior temperature decrease (between 4 and 13 h), the radon level decreases (between 6 and 16 h). The daily radon variability is

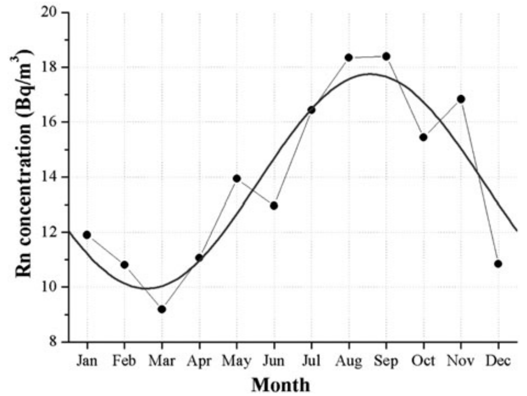

Figure 3. The radon monthly variability in the one calendar year.

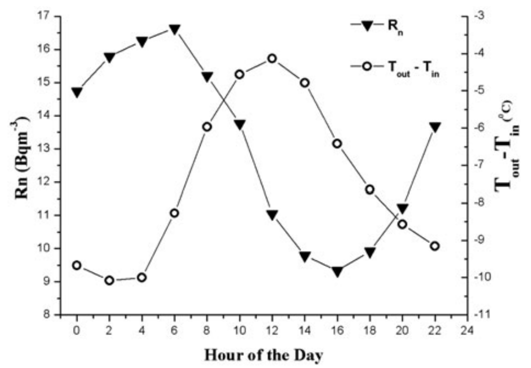

Figure 4. The daily radon and difference between outdoor and indoor temperature variability during one day.

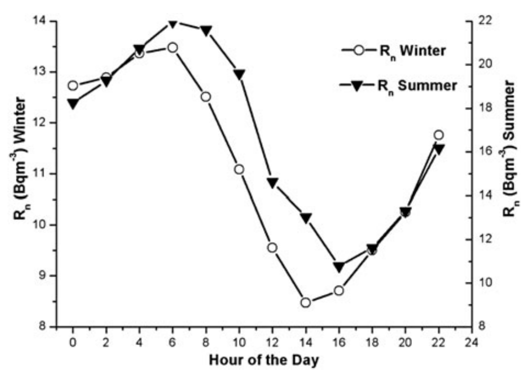

Figure 5. The daily radon variability during two periods, winter and summer.

also analysed due to different periods of the year, winter and summer.

The daily radon variability during two periods, winter and summer, is presented in Figure 5. The positions of the peaks are almost the same, but in the summer, the daily variability is more intensive compared with the winter period.

CONCLUSIONS

It has been shown that the radon behaviour in the underground low-level laboratory in Belgrade has the similar characteristics as in the other underground environment (caves, mines, boreholes and so on), because it has the same source and the places are completely surrounded with the soil. It is also not quite understood the influence of the meteorological parameters on the radon variability. In this work, the correlation between daily radon variation and the difference of external and internal temperature in the UL is pointed out. The further theoretical and experimental research work is necessary to explain physical mechanisms by which the temperature gradient is correlated with radon variations in the underground environments.

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ORIGINAL PAPER

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The use of multivariate analysis of the radon variability in the underground laboratory and indoor environment

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Abstract. The paper presents results of multivariate analysis of variations of radon concentrations in the shallow underground laboratory and a family house, depending on meteorological variables only. All available multivariate classification and regression methods, developed for data analysis in high-energy physics and implemented in the toolkit for multivariate analysis (TMVA) software package in ROOT, are used in the analysis. The result of multivariate regression analysis is a mapped functional behaviour of variations of radon concentration depending on meteorological variables only, which can be used for the evaluation of radon concentration, as well as to help with modelling of variation of radon concentration. The results of analysis of the radon concentration variations in the underground laboratory and real indoor environment, using multivariate methods, demonstrated the potential usefulness of these methods. Multivariate analysis showed that there is a potentially considerable prediction power of variations of indoor radon concentrations based on the knowledge of meteorological variables only. In addition, the online system using the resulting mapped functional behaviour for underground laboratory in the Institute of Physics Belgrade is implemented, and the resulting evaluation of radon concentrations are presented in this paper.

Key words: multivariate analysis • radon variability

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Introduction

The research of the dynamics of radon in various environments, especially indoors, is of great importance in terms of protection against ionizing radiation and in designing of measures for its reduction. Research of radioactive emanations (of radon (^{222}Rn) and thoron (^{220}Rn)) are in the domain of radiation physics, but since a few decades ago, subject of radioactive emanation involves many other scientific disciplines, thus giving a multidisciplinary character to this research. Published results and development of many models to describe the behaviour of indoor radon indicate the complexity of this research, especially with models for the prediction of the variability of radon, simply because the variability depends on large number of variables. Large number of factors (such as local geology, permeability of soil, building materials used to build the buildings as well as the habits of people) impact the variation of radon, and therefore, it is important to study their correlation. In this paper, the results of correlative analysis of indoor radon and meteorological variables are presented. Furthermore, the results of multivariate classification and regression analysis is presented. More details of this study can be found in [1].

Indoor radon variation depends significantly on large number of factors, which include the local geology, soil permeability, building materials, lifestyle characteristics and meteorological variables. In order to analyse the dependence of radon variation on multiple variables, multivariate analysis needs to be used.

The demand for detailed analyses of large amount of data in high-energy physics resulted in wide and intense development and usage of multivariate methods. Many of multivariate methods and algorithms for classification and regression are already integrated into the analysis framework ROOT [2], more specifically, into the toolkit for multivariate analysis (TMVA [3]). Multivariate analysis toolkit is used to create, test and apply all available classifiers and regression multivariate methods implemented in the TMVA in order to find methods that are the most appropriate and yield maximum information on the dependence of indoor radon concentrations on the multitude of meteorological variables. Classification methods are used to find out if it is possible to classify radon concentrations into low and high concentrations, using arbitrary cut value for radon concentrations. Regression methods are used as a next step with a goal to find out which regression method can, if any, on the basis of input meteorological variables only, give an output that would satisfactorily close match the observed variations of radon concentrations. The output of usage of multivariate regression analysis methods is mapped functional behaviour, which can be used to evaluate the measurements of radon concentrations using input meteorological variables only. The prediction of radon concentrations can be an output of mapped function when the prediction of input meteorological variables exists.

Short-term radon measurements in laboratory and real environment

Depending on the integrated measurement time, methods of measurement of radon concentrations in air may be divided into long-term and short-term ones. For the measurements of radon concentration presented in this paper, the SN1029 radon monitor (manufactured by the Sun Nuclear Corporation, NRSB approval-code 31822) has been used as active, short-term measurement device. The device consists of two diffused junction photodiodes as a radon detector and is furnished with sensors for temperature, barometric pressure and relative humidity. The user can set the measurement intervals from 30 min to 24 h. It was set to record simultaneously the radon concentration, temperature, atmospheric pressure and relative humidity.

For the purposes of determining the best multivariate methods to use in the analysis, the results are obtained using radon monitor are from measurements in two locations, the Low-Background Laboratory for Nuclear Physics in the Institute of Physics in Belgrade and in a family house.

The underground Low-Background Laboratory for Nuclear Physics is selected for measurement and analysis because routine measurements in this laboratory require low levels of radon concentration with minimum temporal variations. Low-background laboratory is located on the right bank of the river Danube in the Belgrade borough of Zemun, on the grounds of the Institute of Physics. The ground level portion of the laboratory, at 75 m above sea level, is situated at the foot of a vertical loess cliff, about 10 m high. The underground part of the laboratory, useful area of 45 m^2, is dug into the foot of the cliff. Underground laboratory is surrounded with 30-cm thick concrete wall. The overburden of the underground laboratory is thus about 12 m of loess soil. Significant efforts are being made to contain the low radon concentration within the laboratory. The underground laboratory is completely lined with a hermetically sealed, 1-mm thick aluminium foil. The ventilation system maintains the overpressure of 2 mbar, so as to prevent radon diffusion from the soil. Fresh air entering the laboratory is passed through a two-stage filtering system. The first stage is a mechanical filter for dust removal. The second one is a battery of coarse and fine charcoal active filters. The concentration of radon is kept at an average value of about 10 Bq/m^3.

In the Low-Background Laboratory for Nuclear Physics, radon concentrations were measured in period from 2008 to 2011 and continued later on periodically about a couple of months each year. Measurements of meteorological variables used in the analysis were recorded since 2008 and are taken from the meteorological station located 4 km from the laboratory. Measurements of radon concentrations, room temperature, atmospheric pressure and relative humidity inside the laboratory were obtained using radon monitor. The results obtained from the measurements of radon concentrations and their influence on gamma and cosmic ray measurements in the laboratory were published in several articles in international scientific journals [4–6].

The family house selected for the measurements and analysis of variations of radon concentrations is a typical house in Belgrade residential areas, with requirement of existence of cellar. House is built on limestone soil. Radon measurements were carried out in the living room of the family house, which is built of standard materials (brick, concrete, mortar) and isolated with styrofoam. During the period of measurements (spring–summer), the house was naturally ventilated and air conditioning was used in heating mode at the beginning of the measurement period. During the winter period measurements, the electrical heating was used in addition to air conditioning. Measured radon concentrations, room temperature, atmospheric pressure and relative humidity inside the house were obtained using radon monitor. Values of meteorological variables in measurement period were obtained from an automatic meteorological station located 400 m from the house in which the measurement was performed. We used the following meteorological variables: external air temperature, pressure and humidity, solar radiation, wind speed at a height of 10 m above ground, precipitation, evaporation and temperature and humidity of the soil at a depth of 10, 20, 30 and 50 cm.

Correlation and regression analysis of the results

All multivariate methods implemented in the TMVA are used in our search. All multivariate methods in TMVA belong to the family of 'supervised learning' algorithms [1]. All methods make use of training events, for which the desired output is known, to determine the mapping function that either describes a decision boundary (classification) or an approximation of the underlying functional behaviour defining the target value (regression). Every MVA methods see the same training and test data. The two best performing multivariate methods for our purposes are boosted decision trees (BDT) and artificial neural networks (ANN).

The determination of correlation coefficients between measured radon concentration and meteorological variables serves as a good tool for identifying the variables with strongest correlation, which are not excluded from the analysis later on. Also, correlation coefficient tables gives a good overview of input data and their intercorrelations. In Fig. 1, the correlation matrix of linear correlation coefficients as an overview of intercorrelations of measured radon concentration and all input meteorological variables are shown for underground laboratory. The input variables in case of analysis of underground laboratory are atmospheric pressure, temperature and humidity in laboratory (P_{rm}, T_{rm}, H_{rm}) and outdoor (P, T, H) and differences in measured values of pressure ($P - P_{rm}$), temperature ($T - T_{rm}$) and humidity ($H - H_{rm}$) in laboratory and outdoor. Input meteorological variables in case of family house are the same as the list of measured meteorological variables from nearby meteorological station, with the addition of differences in temperature ($T - T_{rm}$) and humidity ($H - H_{rm}$) from indoor and outdoor values, where indoor measurements results were obtained using radon monitor.

Multivariate methods within the package TMVA in ROOT can search for best multivariate approximation of functional behaviour for the classification function of radon concentration depending on meteorological variables. In the analysis, several multivariate methods were tested, and best performed method was BDT. This can be seen by presenting the receiver operating characteristics (ROC) curve for all tested multivariate methods in case of house measurements (Fig. 2). The BDT method has the highest value of integrated ROC function.

Linear correlation coefficients in%

	T_mm	P_mm	H_mm	T	P	H	T-T_mm	P-P_mm	H-H_m	Radon
Radon	17	4	25	14	5	1	13	5	-14	100
H-H_mm	-81	13	-73	-94	10	79	-94	-8	100	-14
P-P_mm	9	-15	13	1	15			100	-8	5
T-T_mm	80	-14	77	99	-14	-68	100		-94	13
H	-43	3	-18	-65	3	100	-68		79	1
P	-4	95	-12	-13	100	3	-14	15	10	5
T	86	-13	80	100	-13	-65	99	1	-94	14
H_mm	84	-17	100	80	-12	-18	77	13	-73	25
P_mm	-7	100	-17	-13	95	3	-14	-15	13	4
T_mm	100	-7	84	86	-4	-43	80	9	-81	17

Fig. 1. Correlation matrix with linear correlation coefficients as an overview of radon and meteorological variables intercorrelations in case of the Low-Background Laboratory for Nuclear Physics.

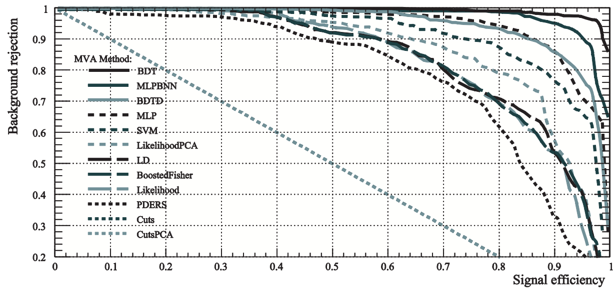

Fig. 2. ROC curve for all multivariate methods in case of house measurements.

BDT has proven to be the most effective method for the classification of radon concentrations in case of data obtained from the house as well as those obtained from measurements in the Low-Background Laboratory for Nuclear Physics.

The next step in the analysis is the regression analysis, which is the way of finding a mapped function behaviour of dependence of radon concentrations and meteorological input variables. The regression analysis was done using the TMVA packages, already used in classification analysis, and for the same set of measured radon concentration and meteorological variables in underground laboratory and a family house in Serbia. Multivariate method BDT was found to be the best suited for regression analysis also, as was the case in classification analysis.

The data of measured radon concentration in house and BDT evaluated values, using only the values of meteorological variables, without the knowledge of measured values (i.e. in the testing set of multivariate analysis), is presented for comparison in Fig. 3.

One of the possible application of having resulting mapped function, given by multivariate regression analysis, is to have prediction of radon concentration values (evaluated) based on meteorological variables alone. The online application of the regression multivariate analysis can be imple-

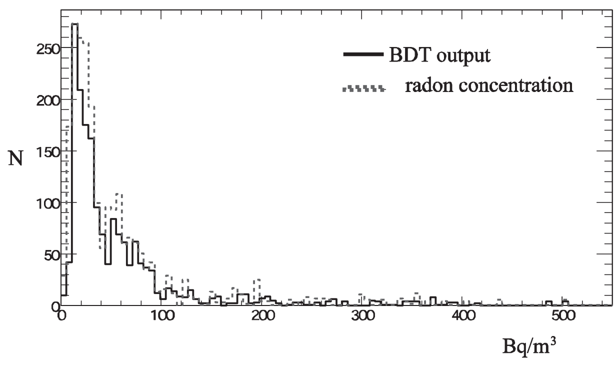

Fig. 3. BDT evaluated (predicted) values of radon concentrations based on meteorological variables using regression analysis within TMVA packages in house (left) and measured values (right).

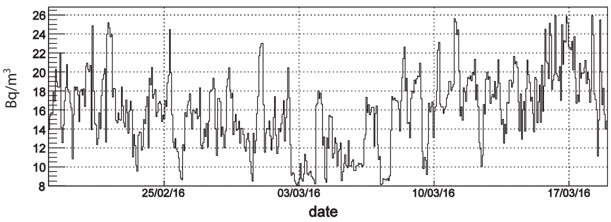

Fig. 4. BDT evaluated (predicted) values of radon concentration, based on meteorological variables alone of underground laboratory posted online and updated daily.

mented, as the one posted online for evaluation (and prediction) based on meteorological variables alone (Fig. 4).

Limitation of multivariate methods

As the multivariate methods used in the analysis are 'supervised learning' algorithms, the performance of the main result of multivariate analysis, the resulting mapped functional behaviour, depends on learning process. Limitation of multivariate analysis in the analysis of radon dependence on meteorological variables are coming from small number of measurements used in learning process, unlike the great number of measurements in high-energy physics experiments. As the next logical step in multivariate analysis presented in this paper should be inclusion of variables such as local geology, permeability of soil, building materials used to build the buildings as well as the habits of people, the requirement for efficient multivariate analysis is to have many measurements in many different houses. Many measurements would help to get good mapped functional behaviour, as opposed to possible existence of theoretical modelling that is independent on number of measurements. In this sense, if the number of measurements is not great, multivariate analysis can be used only as hell to indicate which variables are more important to be used in theoretical modelling, for comparison of mapped and modelled functions, and modelled function test. Another important limitation of multivariate analysis is that no 'straightforward' interpretation of mapped functional behaviour is possible, or simply, the mapped function is a 'black box'. This comes from the fact that the error minimization in learning algorithms, while mapping the functional behaviour, is an important part in learning process.

Conclusions

The paper presents the results of multivariate analysis of variations of radon concentrations in the shallow underground laboratory and a family house, depending on meteorological variables only. This test of multivariate methods, implemented in the TMVA software package, applied to the analysis of the radon concentration variations connection with meteorological variables in underground laboratory (with ventilation system turned on and off) and typical house in Serbia, demonstrated the potential usefulness of these methods. It appears that the method can be used for the prediction of the radon concentrations, on the basis of predicted meteorological variables. The next step in multivariate analysis presented in this paper should be inclusion of variables such as local geology, permeability of soil, building materials used to build the buildings as well as the habits of people. The requirement for efficient multivariate analysis is to have many measurements in many different houses, which makes multivariate method very useful only when having many measurement, for instance, during radon mapping campaigns. Many measurements would help to get good mapped functional behaviour, as opposed to possible existence of theoretical modelling that is independent on number of measurements. Generally, multivariate analysis can be used to help indicate which variables are more important to be used in theoretical modelling, furthermore, for comparison of mapped and modelled functions, and modelled function test.

Another usage of the results of classification multivariate analysis presented in this paper is the implementation of online warning system for possible increased radon concentration in family houses based on meteorological variables only.

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Cosmic Rays Muon Flux Measurements at Belgrade Shallow Underground Laboratory

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Abstract. The Belgrade underground laboratory is a shallow underground one, at 25 meters of water equivalent. It is dedicated to low-background spectroscopy and cosmic rays measurement. Its uniqueness is that it is composed of two parts, one above ground, the other bellow with identical sets of detectors and analyzing electronics thus creating opportunity to monitor simultaneously muon flux and ambient radiation. We investigate the possibility of utilizing measurements at the shallow depth for the study of muons, processes to which these muons are sensitive and processes induced by cosmic rays muons. For this purpose a series of simulations of muon generation and propagation is done, based on the CORSIKA air shower simulation package and GEANT4. Results show good agreement with other laboratories and cosmic rays stations.

Belgrade Cosmic Rays Station

Cosmic rays are energetic particles from outer space that continuously bombard Earth atmosphere, causing creation of secondary showers made of elementary particles. For last hundred years, after Hess' discoveries, cosmic rays (CR) has been studied at almost every location accessible to research, from deep underground to above atmosphere [1]. Low-level and cosmic-ray lab in Belgrade is dedicated to the measurement of low activities and CR muon component. One of the objectives is also intersection of these two fields, namely, muon–induced background in gamma spectroscopy. Belgrade lab is relatively shallow underground laboratory [2] located at the right bank of river Danube on the ground of Institute of Physics in Belgrade. It is located at near-sea level at the altitude of 78 m a.s.l. and its geographic position is 44° 51' N and longitude 20° 23' E with geomagnetic latitude 39° 32' N and geomagnetic vertical cut-off rigidity 5.3 GV. The lab has two portions, ground level portion (GL) is situated at the foot of the vertical loess cliff. Other portion, the underground level (UL) is dug into the foot of the cliff and is accessible from the GL via horizontal corridor as can be seen at Fig.1. Working area of UL has three niches for independent experiments.

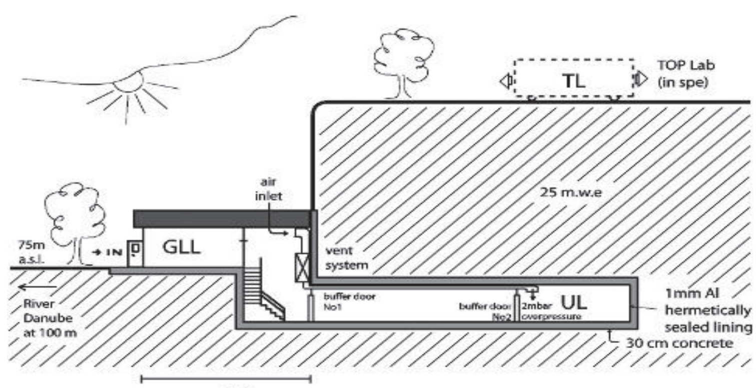

FIGURE 1. Scheme of low-level and CR laboratory at Institute of Physics, Belgrade

The overburden of the UL is about 12 meters of loess soil, which is equivalent to 25 meters of water. The walls are made of 30 cm thick reinforced concrete and covered with the hermetically sealed Al lining 1 mm thick, to

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prevent the radon from the soil to diffuse into the laboratory. The low-level laboratory is equipped with an air ventilation system which keeps 2 mbar overpressure in the UL, in order to minimize radon diffusion through eventual imperfections in the Al lining.

Experimental Set-up

The equipment of the lab consists of two identical set of detectors and analyzing electronics. One set is situated in the GL and other in the UL. Each set is composed of gamma spectrometer and muon detectors. For muon measurements a pair of plastic scintillator detectors is used. One of the detectors is small, 50 cm x 23 cm x 5 cm plastic scintillator detector, with a single PMT looking at its longest side via a Perspex light guide tapering to the diameter of a PMT, made by JINR, Dubna, Russia, and assembled locally. The other, larger one has dimensions of 100 cm x 100 cm x 5 cm, equipped with four PMT directly coupled to the corners beveled at 45°,made by Amcrys-H, Kharkov, Ukraine. The smaller detector may serve as a check of stability of the muon time series obtained from the larger detector, which is important for long term measurements. It can also be used (in coincidence with the larger detector) for measurements of the lateral spread of particles in CR showers and decoherence. Plastic scintillation detectors are also employed for active shielding of gamma spectrometers. In the UL, a 35% efficiency radio-pure p-type HPGe detector, made by ORTEC, 12 cm thick cylindrical lead castle is deployed around the detector. One of the set-ups is presented at Fig.2. Another HPGe detector, of 10% efficiency, is placed in GL.

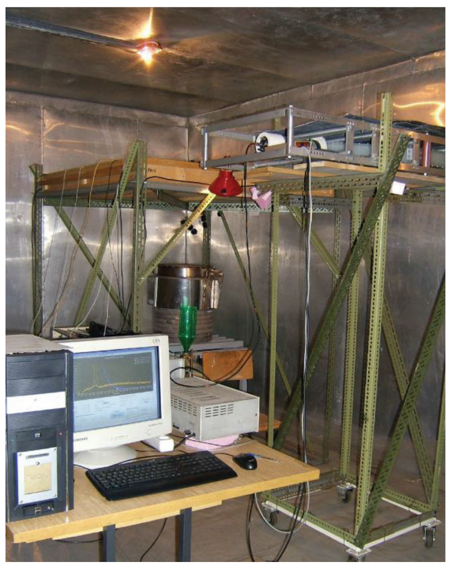

FIGURE 2. Detectors in the underground laboratory. Large scintillator detector is placed above HPGe and small scintillator can change position.

Data acquisition system is identical both in UL and GL and it has two flash analog to digital converter (FADC), one in each laboratory, made by CAEN (type N1728B). These are versatile instruments, capable of working in two modes, energy histogram mode when performing as digital spectrometers or, in the oscillogram mode, when they perform as digital storage oscilloscopes. In both modes, they sample at 10 ns intervals into 2^{14} channels in four independent inputs. The full voltage range is ±1.1 V. They are capable of operating in the list mode, when every analyzed event is fully recorded by the time of its occurrence and its amplitude. This enables the correlation of events, both prompt and arbitrarily delayed, at all four in puts with the time resolution of 10 ns. Single and coincident data can be organized into time series within any integration period from 10 ns up. The two N1728B units are synchronized, enabling coincidence/correlation of the events recorded in both of them. The flexible software encompassing all above said off-line analyses is user-friendly and entirely homemade. The preamplifier outputs of the PMT of the larger detectors are paired diagonally. Signals from these paired inputs are later coincided off-line and their amplitudes added to produce the single spectra. This procedure suppress low-energy portion of the background spectrum (up to some 3 MeV), mostly environmental radiation, leaving only high-energy loss events due to CR muons and EM showers that peak at about 10 MeV, shown at Fig 3. The output of the PMT of the smaller detector is fed to the third input of FADC. [3]

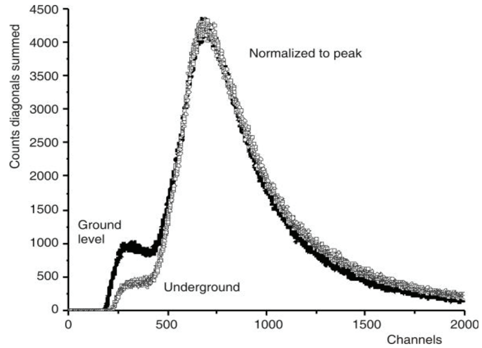

FIGURE 3. The sum spectra of two diagonals of the large plastic detectors in the UL and GLL. For comparison, the spectra are normalized for the peaks to coincide. Channel 650 corresponds to the muon energy loss of 10 MeV.

Simulation and Results

The experimental set-up is rather flexible, thus allowing different studies of the muon and electromagnetic components of cosmic rays at the ground level and at the shallow depth underground. The cosmic-ray muon flux in the underground laboratory has been determined from data taken from November 2008 till June 2013 (there were some small gaps in recording data during this period). These measurements yielded the precise values of the integral cosmic ray muon flux at the location of Belgrade. Measured muon flux is: 137(6) $m^{-2}s^{-1}$ at the ground level and 45(2) $m^{-2}s^{-1}$ at the underground level [4]. Different analyses of time series of these measurements have also been performed. Interpretation and calibration of the experimental spectra has been done using Monte Carlo simulation packages CORSIKA and Geant4 [5, 6]. CORSIKA simulates extensive air showers generated by the primary cosmic-rays in interactions with air nuclei at the top of the atmosphere. It gives spectra of the secondary cosmic-rays at the preferred observation level. These secondary particles, their energy and momentum direction distribution, obtained by CORSIKA, are then used as an input for the Geant4 based simulation of the detectors. In this simulation, particles first traverse through soil and infrastructure of the UL lab before hitting the detector. Then the response of the plastic scintillation detectors is simulated. For the UL scintillators, the simulated spectra are shown in Fig. 4.[7]

They agree very well with the experimental ones, except in the low-energy part where the ambiental gamma radiation is mostly present and where the cuts are applied. We also used these simulation packages to simulate different experimental set-ups and to obtain information about lower cut-of energy of primary cosmic rays at our site and for single muons and muons in coincidence. Energy of the primary particles from which detected muons originate increases for UL compared to GL but also for muons in coincidence compared with single detected muons.

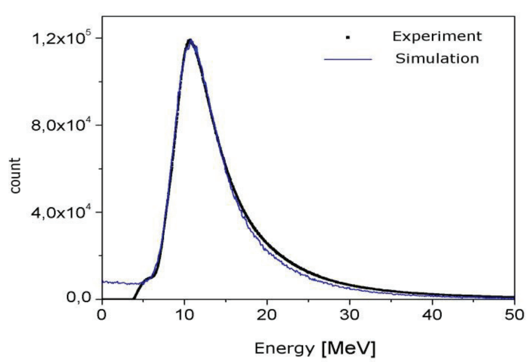

FIGURE 4. Experimental vs simulated spectrum of large plastic scintillator detector at UL

These measurements allow us to study fluctuations in muon flux intensity during the rising phase of Solar Cycle 24 and to make five-minutes or one-hour time series of the flux. The scintillator counts are corrected for atmospheric pressure for the whole period of measurements and, as well, for vertical temperature profile for the period of last six years. The results are compared with other correction methods available. One-hour time series of the cosmic ray muon intensity at the ground level are checked for correlation with European neutron monitors (NM), with emphasis on occasional extreme solar events, e.g. Forbush decreases (FD) in order to investigate claims of influence of cosmic-rays on cloud formation and climate [8,9] In some specific time periods, like during the FD in March 2012, we showed that our muon measurement system has sensitivity comparable to European neutron monitors in this period, but still not as efficient as NM with better geographical position (at high altitude), e.g. Jungfraujoch in the Swiss Alps.These results are presented at Fig. 5. Due to fact that muons detected underground originate from primary particles with energy around and above the limit for solar modulation time series from UL are less sensitive to these Solar events.

FIGURE 5. Time series for March 2012 recorded at NM at Jungfraujoch compared to time series obtained at Belgrade cosmic-rays station

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On the omnipresent background gamma radiation of the continuous spectrum

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ABSTRACT

The background spectrum of a germanium detector, shielded from the radiations arriving from the lower and open for the radiations arriving from the upper hemisphere, is studied by means of absorption measurements, both in a ground level and in an underground laboratory. The low-energy continuous portion of this background spectrum that peaks at around 100 keV, which is its most intense component, is found to be of very similar shape at the two locations. It is established that it is mostly due to the radiations of the real continuous spectrum, which is quite similar to the instrumental one. The intensity of this radiation is in our cases estimated to about 8000 photons/($m^2 s \cdot 2\pi \cdot$ srad) in the ground level laboratory, and to about 5000 photons/($m^2 s \cdot 2\pi \cdot$ srad) in the underground laboratory, at the depth of 25 m.w.e. Simulations by GEANT4 and CORSIKA demonstrate that this radiation is predominantly of terrestrial origin, due to environmental gamma radiations scattered off the materials that surround the detector (the “skyshine radiation”), and to a far less extent to cosmic rays of degraded energy.

1. Introduction

After many comprehensive studies of background spectra of germanium detectors [1,2], it has become common knowledge that the main contributors to these spectra are the gamma radiations of discrete spectrum, that originate from naturally occurring radioactive isotopes dispersed in the environment and in the materials that surround the detector, as well as the complex radiations of mixed composition whose origin can be traced to cosmic rays. Gamma radiations of discrete energies produce the line spectrum but are also partially responsible for the continuum, composed of the Compton distributions of discrete energies that escape total detection. Due to the intrinsically high peak-to-Compton ratio, this continuum is in germanium detectors much lower than in other types of detectors. Vicinity of significant quantities of new lead may be also contributing to the continuum due to the presence of ^{210}Pb [3].

Cosmic-ray muons by direct interactions produce the continuous spectrum of energy losses that, for all detector sizes but for the thinnest ones, peaks at high energies, well beyond the region where the spectrum is usually of interest. The muon secondaries, however, contain significant quantity of low-energy radiations that contribute to the continuum in its portion relevant to spectroscopy. The soft, electromagnetic component of cosmic rays by its scattered and degraded radiations also contributes to the continuous part of the background spectrum, mostly at lower energies, within the region of interest to practical spectroscopy. Neutrons, mostly of cosmic-ray origin, contribute the continuous spectrum of recoils that diverges at lowest energies, though usually of very low intensity. The only spectral line that is attributed to cosmic rays is the annihilation line.

All these results in the instrumental background spectrum that is characteristic of the detector size, shape and the dead layers. The prominent feature common to all instrumental background spectra, however, is that the greatest part of the spectral intensity lies in the low-energy continuum that, depending primarily on the detector size, peaks at around 100 keV. It is an empirical fact that in the background spectra of unshielded High Purity Germanium (HPGe) detectors, depending on their size, the total intensity in the lines makes only some 10–20% of the total intensity in this low-energy continuum. The cause for the particular shape of the continuum is usually found in the similarly shaped energy dependence of detection efficiency curves on germanium detectors. The intensity of the continuum is already by an educated guess well over the expected intensity of all the Compton distributions taken together, what suggests that at least some part of the continuum must be of some other origin, unaccounted for by conventional considerations. To check this, in this work we

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study by means of absorption measurements the background radiations that arrive from the upper hemisphere, which may be suspected responsible for the part of this continuum, with the aim of determining its intensity and origin. This assumption is justified by the fact that majority of germanium detectors are vertically oriented and are by virtue of their construction already of very low detection efficiency for low-energy radiations arriving from the lower hemisphere, e.g. Ref. [4].

2. The experiment

The measurements were performed with a vertically oriented 35% efficiency coaxial type radio-pure HPGe detector mounted in the 1.5 mm thick magnesium housing (of the ORTEC GEM30 type). It was shielded from the radiations coming from the lower hemisphere by the lower half of a heavy lead castle and completely open to those arriving from the upper hemisphere. The cylindrical shield around the detector has the thickness of 12 cm, while that of the layer of lead bricks on which the Dewar vessel sits is 10 cm (Fig. 1).

The same setup was used in both the ground level and in the underground laboratory situated at the depth of 25 m of water equivalent (m.w.e.). The detector is usually used in coincidence/anticoincidence with the 1 m^2 plastic scintillator, and is dedicated to the study of the features that cosmic rays contribute to the background spectra of heavily shielded detectors. The laboratories where the current measurements are performed are described in some detail in Ref. [5]. A set of measurements is performed with lead absorbers of increasing thickness positioned so as to block the way to the radiations coming from above (Fig. 1). The background spectra from such measurements are presented in Fig. 2. Absorber thicknesses range from 0.04 mm (45 mg/cm^2) to 4.5 mm (5 g/cm^2), and are marked in the figures. The figures are presented in two different scales; in the figures on the left to show the general change of spectra upon absorption, and in the figures on the right to emphasize the particularly indicative details around the X-rays of lead.

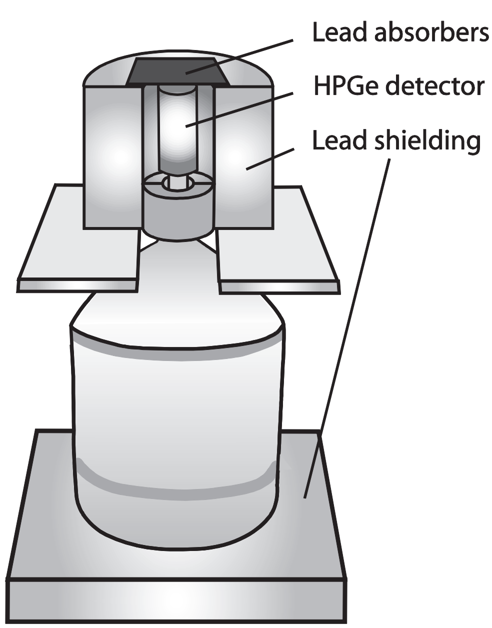

Fig. 1. Detector assembly used in this study.

3. The results and discussion

Visual inspection of the absorption spectra presented in Fig. 2 leads to a number of interesting qualitative conclusions:

1. The spectra taken on the ground level and in the underground exhibit great similarity, the integral intensity of the continuum in the underground being about 1.75 times smaller. At the same time the intensity of cosmic-ray muons in the underground is about 3.5 times smaller [6].
2. The energy, which carries maximum intensity in the continuum, increases with absorber thickness, what is typical of continuous spectra, and is known as the “hardening of the spectrum”.
3. The discontinuity in the absorption spectra on the energy of K_β X-rays of lead (K-absorption edge) reflects the fact that the instrumental continuous spectrum is mostly due to the radiations of the same continuous spectrum, and not due to incomplete detection of radiations of higher discrete energies. If it were due to the distributions of Compton scattered gamma rays of higher energies that have escaped detection, the incoming gamma rays would have been absorbed only weakly by Compton scattering in the absorbers, what would not produce the discontinuity in the spectrum of radiations that reach the detector.
4. Initial increase of the intensity of fluorescent X-rays of lead with absorber thickness again witnesses that the incoming radiation is absorbed by the photoelectric effect. This suggests that the real spectrum of this radiation is similar to the instrumental one, at least up to the energies of about 200 keV, where the photoelectric effect in lead dominates over the Compton effect.
5. Some apparent differences in absorption character of the spectra taken on the ground level and in the underground are to be expected on account of necessarily different composition of the radiations and their different angular distributions at the two locations. The detector in the ground level laboratory virtually has no overhead material, except 1 mm of iron that constitutes the roof of the container, while in the underground laboratory it is surrounded by 30 cm of concrete, that constitutes the walls, the floor and the ceiling of the cavern.

These qualitative conclusions are supported by quantitative analyses of absorption curves at different energies of the continuum. As an illustration, Fig. 3 presents the absorption curves for the count in the channel in the continuum that corresponds to the energy of 89 keV, close to the K-absorption edge in lead. The two well-defined components of very different absorption properties are found. On the surface, the much more intense and less penetrating one by its absorption coefficient corresponds within the errors to the energy close to 90 keV, while the same component in the underground appears of slightly different absorption properties, due to necessarily different composition of the radiations and their different angular distributions. The much less intense and much more penetrating component, both on the surface and in the underground, roughly corresponds to the energy of about 500 keV. The first component thus represents the radiation of the same energy at which it appears in the spectrum, which belongs to the continuum, while the second one represents the sum of Compton distributions of all radiations of higher energies that escape full detection. This last component thus manifests absorption properties of the radiation of an average energy that in our case appears to be around 500 keV.

Since the low-energy component is practically fully absorbed by 1 mm of lead, subtracting the spectrum that corresponds to the absorber of that thickness from the spectrum of the open detector

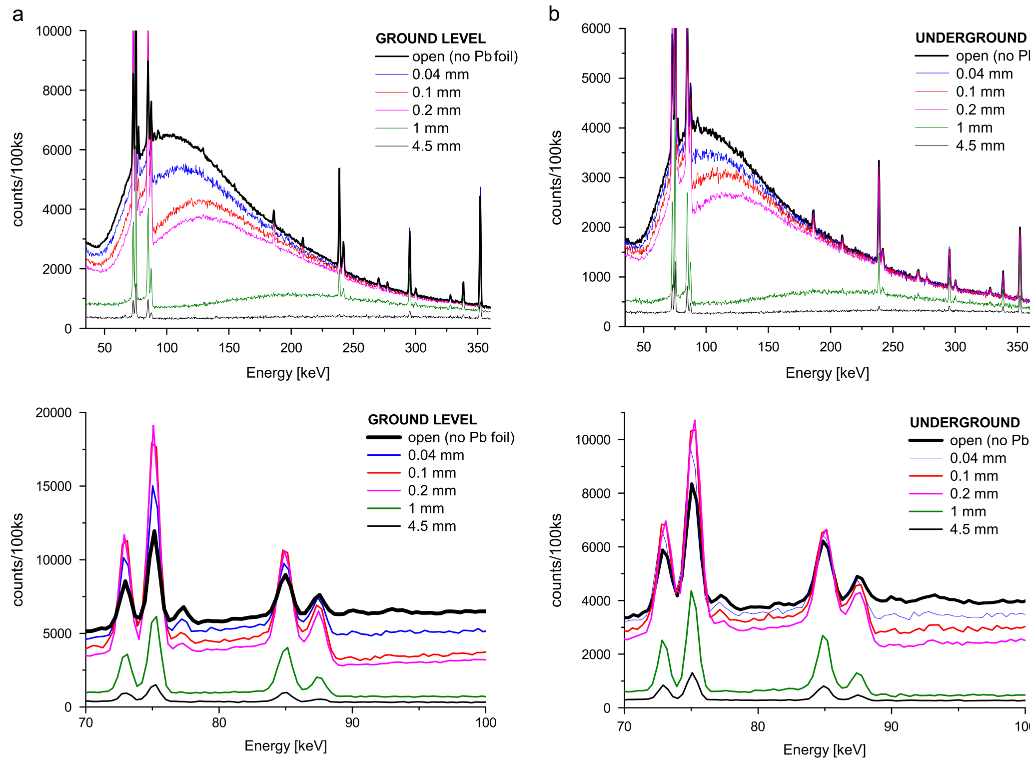

Fig. 2. Experimental low-energy portions of background spectra of the HPGe detector completely shielded from the radiations coming from the lower hemisphere, with a set of lead absorbers of different thicknesses positioned so as to intercept the radiations arriving at the detector from the upper hemisphere: (a) ground level laboratory, (b) underground laboratory at 25 m.w.e. All spectra are normalized to the measurement time of 100 ks.

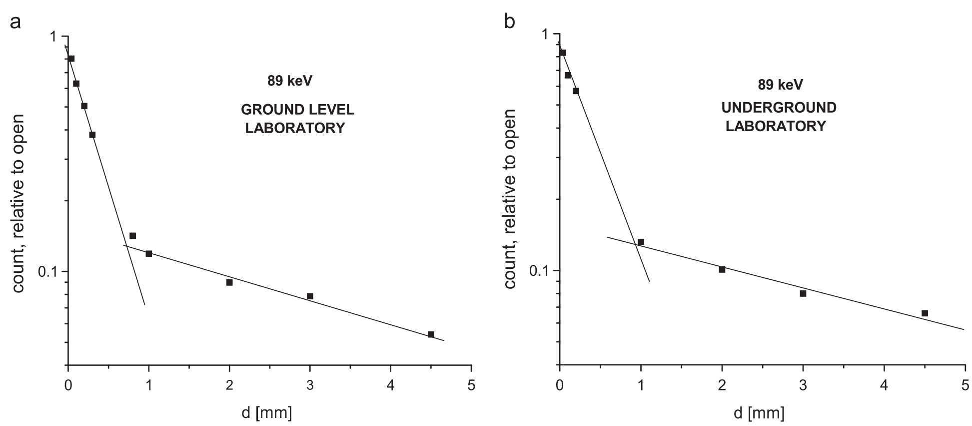

Fig. 3. Absorption curves for the count in the continuum that corresponds to the energy of 89 keV, in the ground-level laboratory (left) and in the underground laboratory at 25 m.w.e. (right). Two distinct components are seen; the first much more intense corresponds rather well to this energy of 89 keV, while the other, much weaker and much more penetrating, approximately corresponds to an average energy of about 500 keV.

would leave predominantly the spectrum of the radiations of the genuinely continuous spectrum, as seen by a given detector. The thus obtained approximate shapes of these instrumental spectra of background radiations arriving at the HPGe detector open towards the upper hemisphere are presented in Fig. 4.

The integrals of these spectra, corrected for absorption in the detector housing and the detector dead layers, yield for the fluxes of these radiations the values of about 8000 photons/($m^2 s \cdot 2\pi \cdot$ srad) on the surface, and about 5000 photons/($m^2 s \cdot 2\pi \cdot$ srad) in the underground. An important property of these spectra is that the maximum of intensity at around 100 keV, as well as the dip of intensity at energy of about 40 keV, is an essential property of the true spectrum of the incoming radiations, and is only partly due to the drop of detection efficiency at these energies. It also seems that the steep increase of intensity below the dip is an intrinsic property of all these spectra. We could not reach this region but there is ample evidence in background spectra taken at other places that this is also their ubiquitous property [7].

All these conclusions are corroborated by the detailed simulations of the experimental situations that might be held responsible for these spectra, using the Monte Carlo simulation packages Geant4 and CORSIKA [8,9]. Two possible contributions to these spectra were considered. The first is the contribution of environmental natural radioactivity via the scattering of discrete energy gamma rays off the air, the walls, and the ceiling, that thus produce the so-called skyshine radiation, which is known to be of spectral shape similar to that of our Fig. 4 [10]. For this simulation, the as realistic as possible distribution of radioactivities in the environment was assumed, in accord with relative intensities of spectral lines in the experimental spectra. Configuration of the HPGe detector assembly was taken into account in detail, according to the manufacturer's technical data specifications. The result of this simulation of very low efficiency is, for the setup in the underground laboratory, presented in Fig. 5 (equivalent of 4000 h of single CPU time went into the production of this figure). Similarity of the continuous low-energy parts of the simulated and experimental spectra (Fig. 2) is obvious, but absolute intensities are, due to the unknown exact distribution of activities, difficult to compare.

On the other hand, the cosmic rays represent a source of background of constant and well-known parameters, and may consequently be used for absolute comparison of simulated and experimental background spectra. Fig. 6 presents the result of the simulation of all the contributions due to cosmic rays to the background spectrum in the underground (recent work by Solc et al. [11] does not pay special attention to the low-energy part of this spectrum). The composition and energy and momentum distributions of cosmic rays at the observation plane at the surface of the Earth were simulated by CORSIKA, while the interactions in the overburden soil and the detector spectrum, were obtained by Geant4 based simulation. It is seen that the shape of the simulated spectrum follows that of the experimental spectrum, though not as closely as the simulated skyshine spectrum. The portion of the spectrum above the 2614 keV line, which is mostly due to cosmic rays, now allows for the normalization of the simulated spectrum to the experimental one. The integration of the thus normalized experimental and simulated spectra in the region of up to 500 keV shows that the cosmic rays at the depth of 25 m.w.e. contribute to the background radiations of the continuous spectrum only about one part in 250 of the scattered environmental radiations.

Finally, we performed the same procedure for the case of the detector setup in the ground level laboratory. Fig. 7 presents the simulated spectrum of cosmic ray contributions normalized to the high-energy portion of the experimental background spectrum for the detector situated in the ground level laboratory. Integration of the spectra shows that at the ground level the cosmic rays contribute to the low energy continuous background spectrum about 60 times less than the skyshine radiation.

Earlier studies implicitly offer controversial arguments as to the nature of this spectrum. For instance, the results of Tsutsumi et al. [4], which nicely reproduce the experimental background spectrum by the inclusion of natural radioactivities only, suggest that the contributions of skyshine radiation greatly overcome that of cosmic rays. On the other hand, the study by Semkow et al. [12], who measured the background spectrum of an unshielded detector in open space, demonstrates that the same shape of the continuum is obtained when only the genuine skyshine radiation,

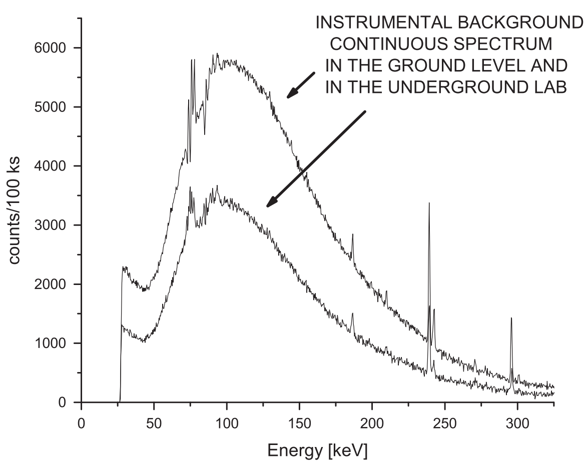

Fig. 4. Instrumental spectra of background radiations of the continuous spectrum arriving at the HPGe detector open towards the upper hemisphere in a ground-level laboratory (upper spectrum) and in an underground laboratory at 25 m.w.e. (lower spectrum). The peaks are residuals due to effects that are unessential here. Integral count rates in these spectra are 21 cps and 12 cps respectively.

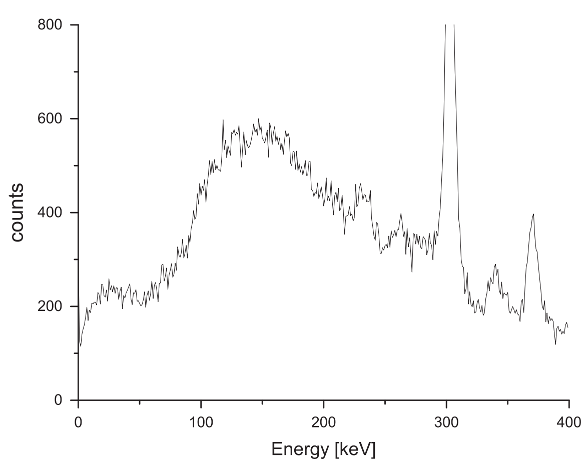

Fig. 5. The simulated "skyshine" radiation spectrum due to environmental radioactivity in the underground laboratory.

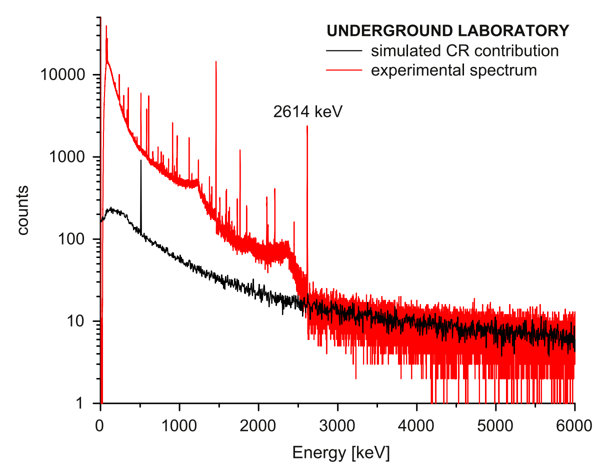

Fig. 6. The simulated contribution of all radiations of cosmic ray origin to the low-energy part of the background spectrum of the detector setup in the underground laboratory, normalized to the high-energy portion of the experimental background spectrum.

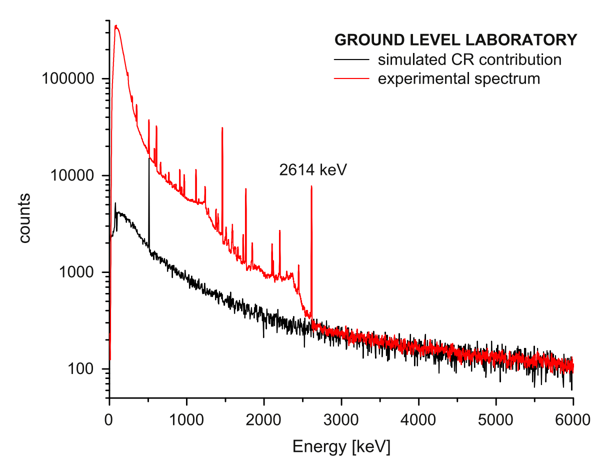

Fig. 7. The simulated contribution of all radiations of cosmic ray origin to the low-energy part of the background spectrum of the detector setup in the ground level laboratory, normalized to the high-energy portion of the experimental background spectrum.

scattered off the open air, is present, as when the detector is situated in the heavily walled building, what now speaks in favor of the non-negligible contribution of cosmic rays. In a comparatively recent study Mitchell et al. [13] find that the cosmic ray contribution constitutes about 1/10 of the skyshine contribution. In their case, however, the results may be prone to systematic error due to possibly high activity of the NaI spectrometer itself. On the basis of our findings we side with the results that support the view that skyshine radiation greatly dominates over the cosmic ray contributions.

4. Conclusion

We have established that the low-energy continuous part of background spectra of germanium detectors open to the upper hemisphere, that peaks around 100 keV, is in greatest part absorbed by 1 mm of lead and that can in a good approximation be considered as being due to the radiations of the similar true continuous spectrum arriving at the detector from the upper hemisphere. This holds true both in a ground level and in the underground laboratory at 25 m.w.e. The origin of this radiation is in the particular situations that we studied found to be predominantly of terrestrial origin. Relative contributions of the radiations of terrestrial and cosmic-ray origin to this spectrum would, however, greatly differ from place to place and from an environment to the other, depending on the quantity and distribution of natural radioactivity in the surroundings of the detector, as well as on the geographic latitude and altitude, which determine the cosmic-ray contribution. It would in this respect be instructive to study the radiations of this continuous spectrum in largely different environments and at different spaces underground.

Acknowledgments

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Variations of gamma-ray background in the Belgrade shallow underground low-level laboratory

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HIGHLIGHTS

- Time variability of Ge detector background was measured in two laboratories.
- Variations of cosmic ray intensity and radon concentration were tested.
- Advantage of an underground laboratory compared to a ground level one was proved.

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Cosmic rays
Radon variability

ABSTRACT

During the last three years we investigated the variations of background simultaneously in two laboratories, the ground level (GLL) and the underground laboratory. The Forbush-like effect from March 2010 was observed in the GLL using a Ge detector and plastic veto scintillator. The underground plastic scintillator saw the same effect but the coincident veto spectrum did not detect the decrease of cosmic-ray intensity. Using a time series analysis of prominent post-radon lines, a significant radon daily variability was detected in the Ge detector background spectrum, but only in the GLL.

1. Introduction

Any long and even short-term gamma-ray background measurement is subject to certain temporal variations due to time variability of two prominent contributors to background—cosmic-ray intensity and radon concentration. The duration of background measurements may be anything from one day to several months, depending on the wanted final statistical accuracy of the envisaged measurements. These measurements, however, yield only average values of the background, what in principle may lead to systematic errors in later measurements, especially of NORM samples.

Radon concentrations are known to vary considerably, depending on many parameters that determine this concentration in every particular case. This includes the deposition of radon progenies on the walls of lead castles and detectors themselves, what makes even the traditional radon suppression method by flushing the interior of the sample chamber with nitrogen potentially ineffective.

On the other side, effective protection of Ge detectors from cosmic-rays is provided by active veto shielding using convenient large area detectors, although all significant periodic and aperiodic variations of cosmic ray intensity can usually be neglected since contributions to background, apart from the annihilation line, lie in the continuum.

2. Description of the laboratories and equipment

The Belgrade underground low-level laboratory (UL), located at a depth of 25 m. w. e (meter water equivalent) is equipped with ventilation system which provides low radon concentration of 13 (5) Bq/m^3, the mean value being obtained from more than two years long-term measurement. The UL is presented in more detail by Antanasijević et al. (1999), and the especially designed ventilation system for radon reduction in the laboratory has been described by Udovičić et al. (2009). This system consists of two “radon shields”—the passive and the active one. The passive shield consists of 1 mm thick aluminum foil which completely covers all the wall surfaces inside the laboratory, including floor and ceiling. It is hermetically sealed with a silicon sealant to prevent diffusion of radon from surrounding soil and concrete walls of the laboratory. As the active radon shield the laboratory is continuously ventilated with fresh air, filtered through one rough filter for dust elimination

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followed by active charcoal filters (cross-section of 60 cm × 60 cm, weight of 40 kg) for radon adsorption.

The UL has an area of 45 m^2 and volume of 135 m^3 what required the rate of air inlet adjusted to 800 m^3/h. This huge amount of fresh air contributes to greater temperature variations and the long-term mean value of temperature inside the UL is 19 (4)°C. On the other side the rate of air outlet (700 m^3/h) was adjusted to get an overpressure of about 2 hPa over the atmospheric pressure, what prevents radon diffusion through eventual imperfections in the aluminum layer. The pressure buffer corridor to the laboratory (18 m^2) ensures almost constant value of this overpressure. Relative humidity is controlled by a dehumidifier device, what provides that the relative humidity in the underground laboratory does not exceed 60%.

All the measurements presented in this work which were performed in the underground laboratory were performed in the ground level laboratory (GLL) as well. The GLL is air-conditioned and represents a typical ground level laboratory. This laboratory is situated in two joined standard transportation containers with iron sheet walls, but furnished with quality thermal insulation. The GLL has an area of 30 m^2 and volume of 75 m^3. It is air-conditioned (average radon concentration of 50(30) Bq/m^3).

The low-level background detector system in the UL includes an intrinsically low-radioactivity level Ge detector (35% relative efficiency, named Ge1) and a plastic veto scintillator (1 m^2, named PS1) situated coaxially above the Ge1 detector. Comparative background study is performed in the GLL which is equipped with a Ge detector (18% relative efficiency and not intrinsically low-radioactivity level, named Ge2) and a small plastic scintillator (0.125 m^2, named PS2) in veto position.

Radon monitoring inside the laboratories was performed by radon monitor, model RM1029 manufactured by Sun Nuclear Corporation, NRSB approval-code 31822. The device consists of two diffused junction photodiodes as a radon detector, and is furnished with sensors for temperature, barometric pressure and relative humidity. The user can set the measurement intervals from half an hour to 24 h. The device has no online option (direct access to data) but the data are stored in the internal memory of the device and transferred to the personal computer after the measurement interval. The data obtained from the radon monitor (RM) for the temporal variations of the radon concentrations over a long period of time enable the study of the short-term periodical variations simultaneously with Ge detectors (Bossew, 2005).

Two flash analog to digital converters (FADC), made by C.A.E.N (type N1728B), which sample at 10 ns intervals into 2^{14} channels were used to analyze spectra from Ge detectors. User-friendly software was developed to analyze the C.A.E.N data with the possibility to choose the integration time for further time-series analysis that correspond to integration time of the radon monitor.

3. Results and discussion

For routine measurements of NORM samples the simplest arrangement of a Ge detector system is required due to frequent samples exchanges.

As the emphasis was on realistic conditions of radon and cosmic-ray influences on the Ge background neither any additional radon suppression method nor the full (2π coverage) veto arrangement were applied.

3.1. Cosmic-ray influence on the Ge detector background spectrum

The periodicities in cosmic-ray intensity variations (1-day and 27-days) are known to have small amplitudes. The Ge detectors can not see these variations neither in the annihilation line nor in the entire spectrum, mostly due to their small active area. Aperiodic variations of cosmic-ray intensity have greater amplitudes like a Forbush effect which typically lasts for several days. During simultaneously background measurements using two veto shielded Ge detectors the most intensive cosmic-ray variation occurred in March 2010. The decrease of cosmic-ray intensity, which lasted about four days, was very similar to characteristic decrease during a real Forbush effect, hence this event is appointed as a Forbush-like effect. Characteristic variation (decrease) of cosmic-ray intensity remains after cosmic-ray data correction on pressure variation (real Forbush effect) or vanishes after this correction (Forbush-like effect). A Ge detector does not recognize the cause of these cosmic-ray variations but it can detect them. The Forbush-like effect from March 2010 was registered in both single PS2 and single PS1 detectors inside the GLL and the UL, respectively. The cosmic-ray intensity decrease was relatively small, about 4% in the GLL and 2.5% as measured in the UL. Even small, it seems that a certain variation in number of coincidences between PS2 and Ge2 was registered, and both spectra followed each other during four days (Fig. 1). Integration time in the time series of the coincidence spectrum was chosen to be 6 h to emphasize the similarity between the two spectra. Strictly speaking it is only the time variation of the well-defined annihilation line, mostly caused by cosmic-ray pair-production, that can reflect the cosmic-ray changes, but its count rate is too low. Similarly, statistics is poor even for the high-energy continuous part of the Ge spectrum. The coincidence veto spectrum in Fig. 1 has no energy cuts and includes all gamma-ray lines what corresponds to the real condition of background measurement without a priori selected energy intervals. The single cosmic-ray spectrum was not corrected for atmospheric pressure and temperature because this represents the realistic situation in a typical ground level laboratory, which is probably without a veto shield.

The big plastic scintillator PS1 inside the UL registered the same Forbush-like effect, but the coincidence spectrum does not show any corresponding changes, Fig. 2. At a depth of 25 m.w.e, the mean energy of cosmic-ray muons is about 5 GeV higher than that of ground level muons, which is why they feel all solar modulation effects far less than the cosmic-rays particles on the ground level.

3.2. Radon influence on the Ge detector background spectrum

The significance of the other time variable background component was tested in simultaneous measurements of radon concentration by RM and gamma-ray background by the Ge detector. Inside the sample chamber (SC) of the Ge detector, in the space between the lead shield and the detector, radon concentration is influenced by the radon distribution outside the SC, when the SC is

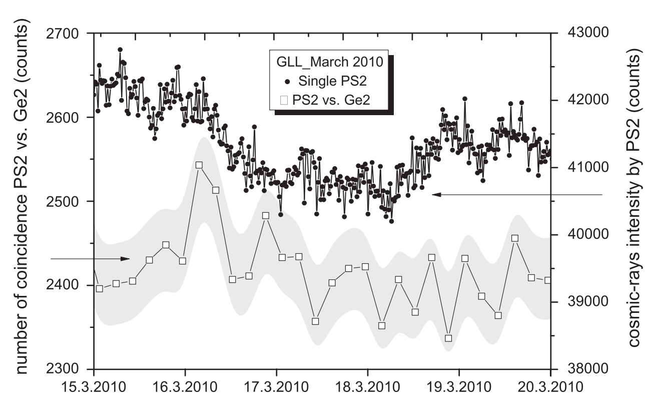

Fig. 1. Single cosmic-ray spectrum (circles) of PS2 and coincidence veto spectrum between PS2 and Ge2 (squares) inside the GLL during the Forbush-like effect in March 2010. The coincidence spectrum includes the error bars (1σ-B-spline).

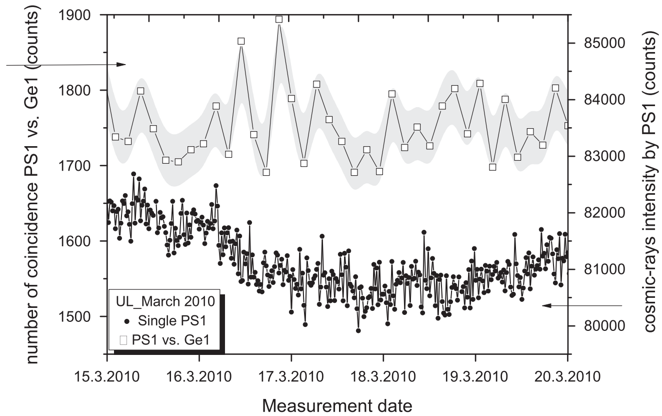

Fig. 2. Single cosmic-ray spectrum (circles) of PS1 and coincidence veto spectrum between PS1 and Ge1 (squares) inside the UL during the Forbush-like effect in March 2010. The coincidence spectrum includes the error bars (1σ-B-spline).

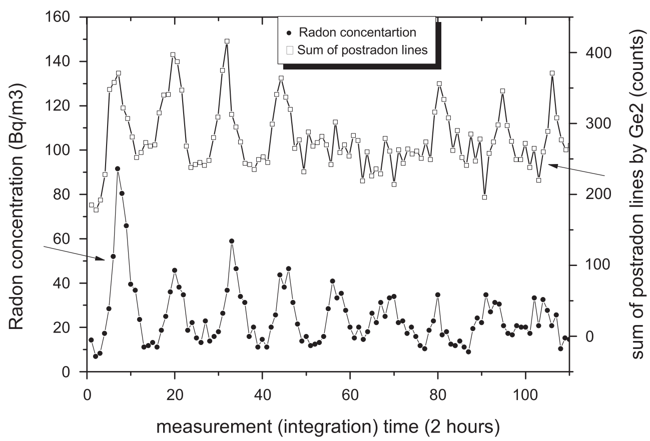

Fig. 3. Variability of radon concentration measured by RM inside the sampling chamber of the Ge2 detector (circles) and the sum of four post-radon lines (squares) measured by Ge2 inside the GLL.

not hermetically sealed. The Ge detector can see the radon daughters (^{214}Pb and ^{214}Bi) not only from the air inside SC but also from surface depositions on the detector and its passive shield.

Fig. 3 presents how the summed intensity of the four most prominent radon daughter lines (295.2 keV and 351.9 keV from ^{214}Pb, 609.3 keV and 1120.3 keV from ^{214}Bi) varies with time, as seen by the small shielded Ge detector (Ge2) inside the air-conditioned GLL. This follows closely the readings of the radon monitor positioned inside the SC (air volume of 1 dm^3). Here, we used the summed intensity of post-radon lines since the detector is small, but for high-efficiency detectors every single line should manifest the same behavior.

The radon monitor recorded radon and atmospheric parameters readings every 2 h and the integration in the time series of post-radon lines was chosen accordingly. This is sufficient to show clearly the one-day radon periodicity (Fig. 3).

Inside the UL, the radon concentration is kept at the low value under stable atmospheric parameters. The variability of radon concentration in the fresh air on the ground level is maximally suppressed in the UL by the ventilation system. The value of the summed post-radon lines inside the UL is almost constant as well as is the radon concentration.

The issue of stability of the gamma-ray background requires special attention when low-level ^{226}Ra measurements are performed by Ge detectors due to radon variability in ground level laboratories and sampling chambers of Ge detectors. Even a small Ge detector can see significant changes of background, if the mean radon concentration in ambient air is of the order or above 10 Bq/m^3 and some kind of radon suppression method inside a sample chamber must be applied (Neumaier et al., 2009).

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An underground laboratory as a facility for studies of cosmic-ray solar modulation

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A R T I C L E I N F O

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Response function

A B S T R A C T

The possibility of utilizing a shallow underground laboratory for the study of energy dependent solar modulation process is investigated. The laboratory is equipped with muon detectors at ground level and underground (25mwe), and with an underground asymmetric muon telescope to have a single site detection system sensitive to different median energies of primary cosmic-ray particles. The detector response functions to galactic cosmic rays are determined from Monte Carlo simulation of muon generation and propagation through the atmosphere and soil, based on CORSIKA and GEANT4 simulation packages. The present setup is suitable for studies of energy dependence of Forbush decreases and other transient or quasi-periodic cosmic-ray variations.

1. Introduction

Galactic cosmic rays (GCR) arriving at Earth after propagating through the heliosphere interact with nuclei in the atmosphere. These interactions of primary CRs lead to production of a cascade (shower) of secondary particles: hadrons, electrons, photons, muons, neutrinos. Ground based CR detectors are designed to detect some species of secondary cosmic radiation. Widely in use are neutron monitors [1,2], muon telescopes [3,4], various types of air shower arrays [5], γ-ray air Cherenkov detectors [6], air fluorescence detectors [7] etc.

The flux and energy spectra of GCR are modulated by the solar magnetic field, convected by the solar wind. Particularly affected are GCR at the low energy side of the spectrum (up to ~100 GeV). Therefore, secondary CRs generated in the atmosphere can be used for studying solar and heliospheric processes. Among the best known effects of the solar modulation are CR flux variations with 11 year period of the solar cycle, 22 year magnetic cycle, diurnal variation and Forbush decrease. The so called corotation with the solar magnetic field results in the flux variation with the 27-day period of solar rotation.

Modulation effects have been studied extensively by neutron monitors (NM) [8,9], sensitive up to several tens of GeV, depending on their geomagnetic location and atmospheric depth. Muon detectors at ground level are sensitive to primary particles of higher energies than NMs. Underground muon detectors correspond to even higher energy primaries. For this reason muon observations complement NM observations in studies of long-term CR variations, CR anisotropy and gradients or rigidity spectrum of Forbush decreases. However, muon observations suffer from difficulties to disentangle variations of atmospheric origin. While the effect of atmospheric pressure is similar to NMs and easy to account for, the temperature effect is more complicated. The entire temperature profile of the atmosphere is contributing, with different net temperature effect on muon flux at different atmospheric layers, as a result of interplay of positive and negative temperature effects. The positive temperature effect is a consequence of reduced atmospheric density with the temperature increase, resulting in less pion interactions and more decays into muons [10]. The negative temperature effect comes from the increased altitude of muon production at the periods of high temperature, with the longer muon path length and the higher decay probability before reaching the ground level [11]. Both effects are accounted for by the integral method of Dorman [12]. The negative temperature effect is dominant for low energy muons (detected at ground level) and the positive for high energy muons (detected deep underground). At shallow depth of several tens of meters of water equivalent both temperature effects contribute to the overall temperature effect. Several detector systems with different sensitivity to primaries at the same location have the advantage of sharing common atmospheric and geomagnetic conditions.

Belgrade CR station is equipped with muon detectors at ground level and at the depth of 25 m.w.e. Underground laboratory is reached only by muons exceeding energy threshold of 12 GeV. The existing detectors are recently amended by additional setup in an attempt to fully exploit laboratory's possibilities to study solar modulation at different

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median rigidities. In the present paper the detector systems at the Belgrade CR station are described. Response functions of muon detectors to galactic cosmic rays are calculated. The detector system represents useful extension of modulation studies with neutron monitors to higher energies, as it is demonstrated in the case of a recent Forbush event.

2. Description of Belgrade CR station

The Belgrade cosmic-ray station, situated at the Low Background Laboratory for Nuclear Physics at Institute of Physics, is located at near-sea level at the altitude of 78 m a.s.l. Its geographic position is: latitude 44°51′N and longitude 20°23′E, with vertical cut-off rigidity 5.3 GV. It consists of the ground level lab (GLL) and the underground lab (UL) which has useful area of 45 m^2, dug at a depth of 12 m. The soil overburden consists of loess with an average density 2.0 ± 0.1 g/cm^3. Together with the 30 cm layer of reinforced concrete the laboratory depth is equivalent to 25 m.w.e. At this depth, practically only the muonic component of the atmospheric shower is present [13].

2.1. Old setup

The experimental setup [14] consists of two identical sets of detectors and read out electronics, one situated in the GLL and the other in the UL. Each setup utilizes a plastic scintillation detector with dimensions 100 cm × 100 cm × 5 cm equipped with 4 PMTs optically attached to beveled corners of a detector. Preamplifier output of two diagonally opposing PMTs are summed and fed to a digitizer input (CAEN FADC, type N1728B). FADC operates at 100 MHz frequency with 14 bit resolution. The events generating enough scintillation light to produce simultaneous signals in both inputs exceeding the given threshold are identified as muon events. The simulated total energy deposit spectrum is presented on the left panel of Fig. 1. After the appropriate threshold conditions are imposed on the signals from two diagonals, the spectrum is reduced to the one represented on the right panel of the same figure. Contribution from different CR components are indicated on both graphs and experimentally recorded spectrum is plotted as well.

Particle identification is verified by a two-step Monte Carlo simulation. In the first step development of CR showers in the atmosphere is traced, starting from the primary particles at the top of the atmosphere by CORSIKA simulation package. CORSIKA output contains information on generated particles (muons, electrons, photons, etc.) and their momenta at given observation level. More details on CORSIKA simulation will be given in Section 3. This output serves as an input for the second step in simulation, based on GEANT4. In the later step energy deposit by CR particles in the plastic scintillator detector are determined, together with the light collection at PMTs. Contributions from different CR components to recorded spectrum are also shown in Fig. 1.

According to the simulation, 87.5% of events in the coincident spectrum originate from muons. To account for the contribution from other particles to the experimental spectrum not all the events in the spectrum are counted when muon time series are constructed. Muon events are defined by setting the threshold corresponding to muon fraction of recorded spectrum. Threshold is set in terms of “constant fraction” of the spectrum maximum, which also reduces count rate fluctuations due to inevitable shifts of the spectrum during long-term measurements.

2.2. Upgrade of the detector system

Existing detectors enable monitoring of CR variations at two different median energies. An update is contemplated that would provide more differentiated response. Two ideas are considered. First one was to extend the sensitivity to higher energies with detection of multi-muon events underground. An array of horizontally oriented muon detectors ought to be placed in the UL. Simultaneous triggering of more than one detector is an indication of a multi-muon event. The idea was exploited in the EMMA underground array [15], located at the deeper underground laboratory in Pyhasalmi mine, Finland, with the intention to reach energies in the so called knee region. For a shallow underground laboratory, exceeding the energy region of solar modulation would open the possibility to study CR flux variations originating outside the heliosphere. Second idea is an asymmetric muon telescope separating muons with respect to zenith angle. Later idea is much less expensive to be put into practice.

Both ideas will be explained in detail and response function to GCR for existing and contemplated detectors calculated in the next section.

3. Calculation of response functions

Nature of variations of primary cosmic radiation can be deduced from the record of ground based cosmic ray detectors provided relation between the spectra of primary and secondary particles at surface level are known with sufficient accuracy. Relation can be expressed in terms of rigidity or kinetic energy.

Total detector count rate can be expressed as:

$$N(E_{th}, h, t) = \sum_i \int_{E_{th}}^{\infty} Y_i(E, h) \cdot J_i(E, t) dE \tag{1}$$

where E is primary particle energy, i is type of primary particle (we take into account protons and α particles), $J_i(E,t)$ is energy spectrum of primary particles, h is atmospheric depth and $Y_i(E,h)$ is the so called yield function. E_{th} is the threshold energy of primary particles. It depends on location (geomagnetic latitude and atmospheric altitude) and detector construction details. At a given location on Earth, only particles with rigidity above vertical rigidity cut-off contribute to the count rate. Also, detector construction often prevents detection of low energy particles. For instance, muon detectors are sometimes covered with a layer of lead. In present configuration our detectors are lead free.

Historically, yield functions were calculated empirically, often exploiting the latitude variations of neutron and muonic CR component [16–18]. With the advancement of computing power and modern transport simulation codes it became possible to calculate yield functions from the interaction processes in the atmosphere [19,20]. The yield function for muons is calculated as:

$$Y_i(E, h) = \int_{E_{th}}^{\infty} \int S_i(\theta, \phi) \cdot \Phi_{i,\mu}(E_i, h, E, \theta, \phi) dE d\Omega \tag{2}$$

where $S(\theta,\phi)$ is the effective detector area and integration is performed over upper hemisphere. $\Phi_{i,\mu}(E_i, h, E, \theta, \phi)$ is the differential muon flux per primary particle of the type i with the energy E_i.

Total differential response function:

$$W(E, h, t) = \sum_i Y_i(E, h) \cdot J_i(E, t) \tag{3}$$

when normalized to the total count rate gives the fraction of count rate originating from the primary particles with the energy in the infinitesimal interval around E. Integration of differential response function gives the cumulative response function.

The response functions of our CR detectors are calculated using Monte Carlo simulation of CR transport through the atmosphere with CORSIKA simulation package. Simulation was performed with protons and α-particles as primary particles. They make ~94% (79% + 14.7%) of all primaries [21]. Implemented hadron interaction models were FLUKA for energies below 80 GeV, and QGSJET II-04 for higher energies. If the old version of QGSJET is used, a small discontinuity in response function is noticed at the boundary energy between two models. Geomagnetic field corresponds to the location of Belgrade B_x = 22.61 μT, B_z = 42.27 μT. Power law form of differential energy spectrum of galactic cosmic rays $J_p(E) \sim E^{-2.7}$ is assumed. Energy range of primary particles is between 1 GeV and $2 \cdot 10^7$ GeV. Interval of zenith angles is $0° < \theta < 70°$. Low energy thresholds for secondary particles are: 150 MeV for hadrons and muons and 15 MeV for electrons

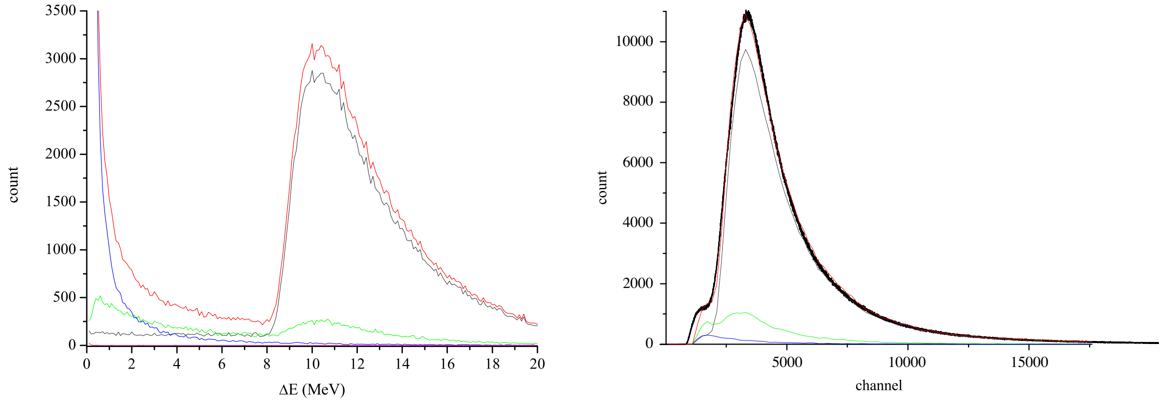

Fig. 1. Left — ΔE spectrum in the plastic scintillator detector, derived from GEANT simulation; right — the same, but for the events exceeding threshold on both diagonals. Contribution of different CR components to the total energy deposit in the detector: muons-gray line, photons-blue line, electrons-green line and sum of all contributions — red line. The black curve on the right panel is the experimental spectrum. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

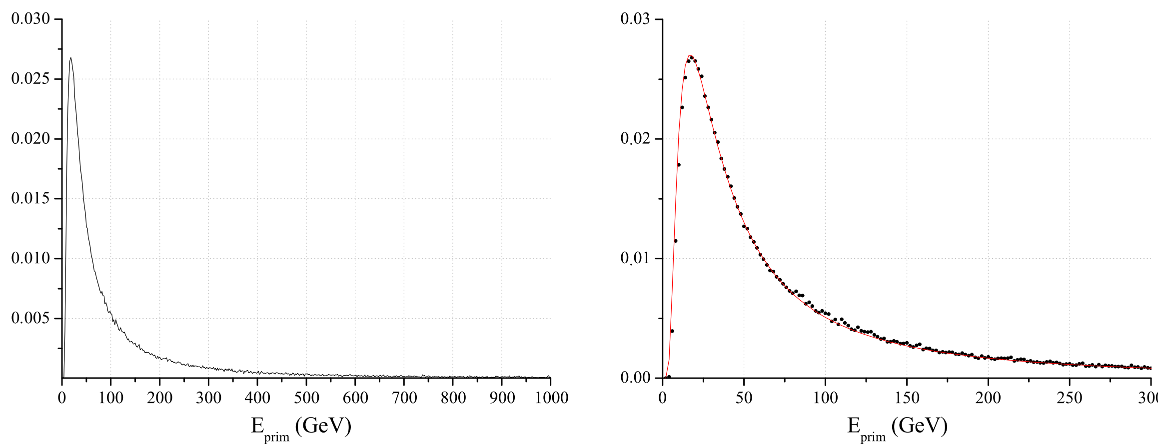

Fig. 2. Left: normalized total response function of ground level muon detector to galactic cosmic rays; right: same as left, fitted with Dorman function (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

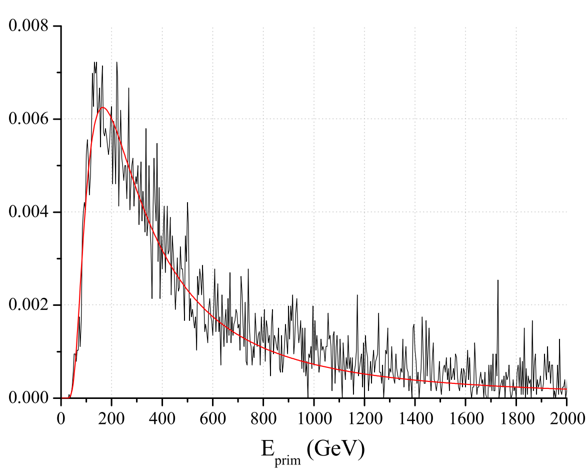

Fig. 3. Response function for multi-muon events in UL to galactic cosmic rays.

and photons. Selected atmospheric model is AT511 (Central European atmosphere for May 11 1993). Observational level is at 78m a.s.l.

For calculation of response functions for underground detectors, simulation of particle propagation through the soil overburden is performed using the code based on GEANT4 package. For precise calculation of energy loss, chemical composition of the soil needs to be known. The composition used in our work is taken from a geochemical study of neighboring loess sections of Batajnica and Stari Slankamen [22]. Most abundant constituents are quartz (SiO_2) 70%, alumina (Al_2O_3) 15% and quicklime (CaO) 10%, while others include Fe_2O_3, MgO, TiO_2, K_2O,…. Inaccuracy of our knowledge of the soil chemical composition should not strongly affect our results since, at relevant energies, dominant energy loss mechanism for muons is ionization which, according to Bethe–Bloch formula depends mostly on $\langle Z\rangle/\langle A\rangle$. Soil density profile is probed during laboratory construction. It varies slowly with depth and average density is found to be (2.0 ± 0.1) g/cm^3.

In the simulation, the effective area and angular acceptance of different modes of asymmetric muon telescope (single, coincident and anticoincident) are taken into account.

According to Dorman [12], response function can be parametrized as:

$$W(E) = \begin{cases} 0, & \text{if } E < E_{th}; \\ \dfrac{a \cdot k \cdot \exp(-aE^{-k})}{E^{(k+1)}(1 - aE_{th}^{-k})}, & \text{otherwise}; \end{cases} \tag{4}$$

with the high energy asymptotics: $W(E) \approx a \cdot k \cdot E^{-(k+1)}$.

3.1. Ground level

Calculated response function for ground level muon detector is presented on Fig. 2, together with fitted Dorman function (4).

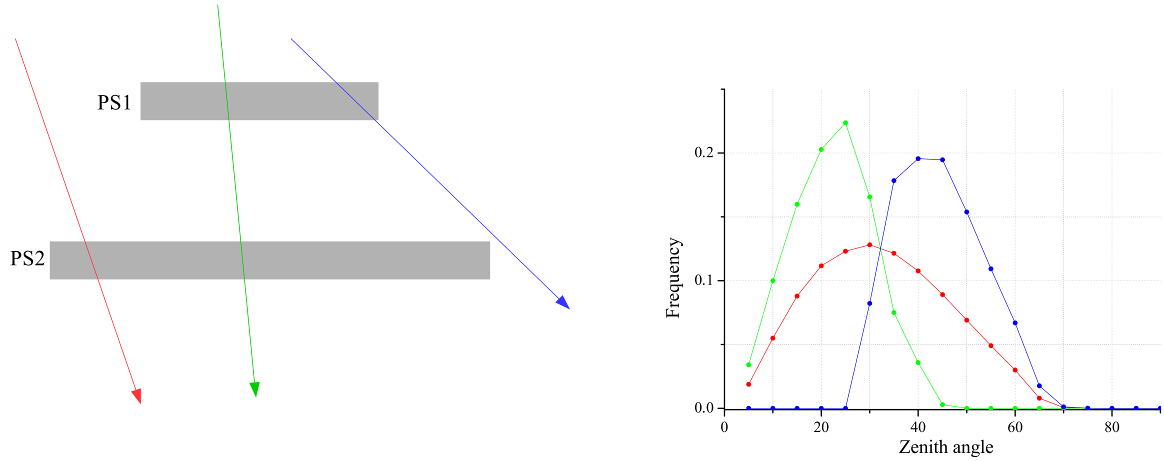

Fig. 4. Left: Schematic view of the asymmetric muon telescope; PS1 — plastic scintillator detector 1, PS2 — plastic scintillator detector 2. Right: angular distribution of detected muons in single mode (red), coincident mode (green) and anticoincident mode (blue), normalized to number of counts in each mode. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

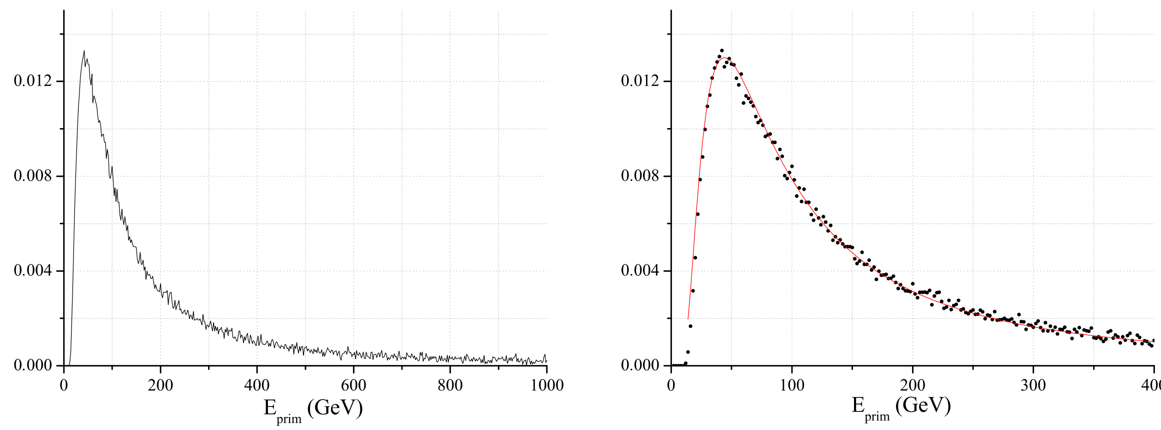

Fig. 5. Response function of single mode of ASYMUT in the UL to galactic cosmic rays. On the right panel the energy interval of interest is enlarged and Dorman function fit is plotted (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

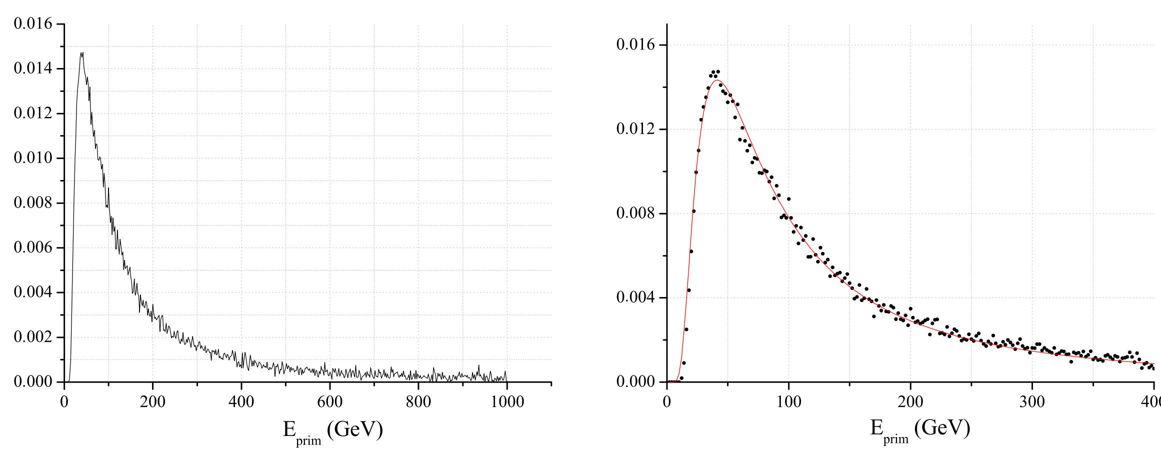

Fig. 6. Response function of coincident mode of asymmetric muon telescope in the UL to galactic cosmic rays. On the right panel the interesting energy interval is enlarged and Dorman function fit is plotted (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Underground

3.2.1. Multi-muon events

Count rate of multi-muon events underground turned out to be too low for the above mentioned array detector experiment to be feasible in our laboratory. To collect enough events for construction of the response function (Fig. 3), allowed muon separation is 200 m, fairly exceeding laboratory dimensions. Under these conditions calculated median energy is 270 GeV.

*3.2.2. **ASY**mmetric **MU**on **T**elescope (ASYMUT)*

Asymmetric muon telescope is an inexpensive detector, constructed from components already available in the laboratory. It consists of two plastic scintillators of unequal dimensions. The lower is identical to the

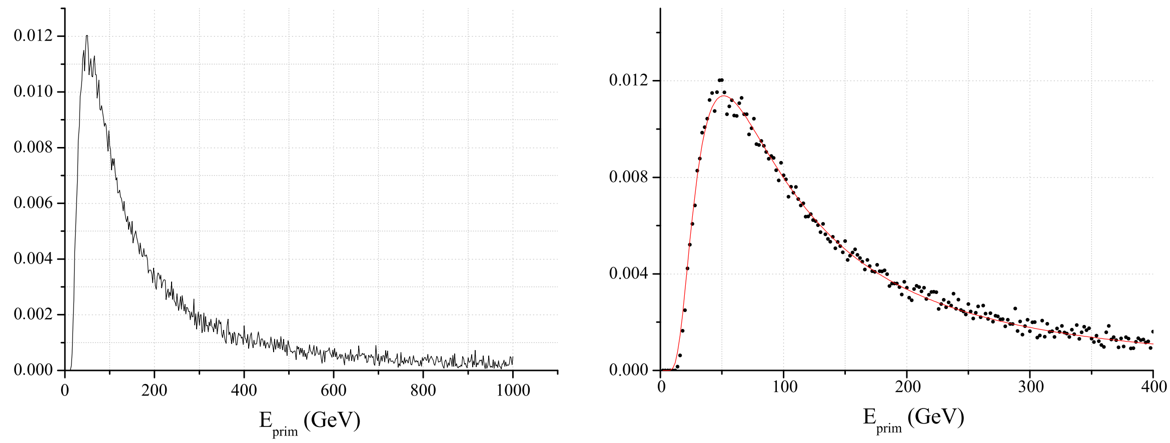

Fig. 7. Response function of anticoincident mode of asymmetric muon telescope in the UL to galactic cosmic rays. On the right panel the interesting energy interval is enlarged and Dorman function fit is plotted (red line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

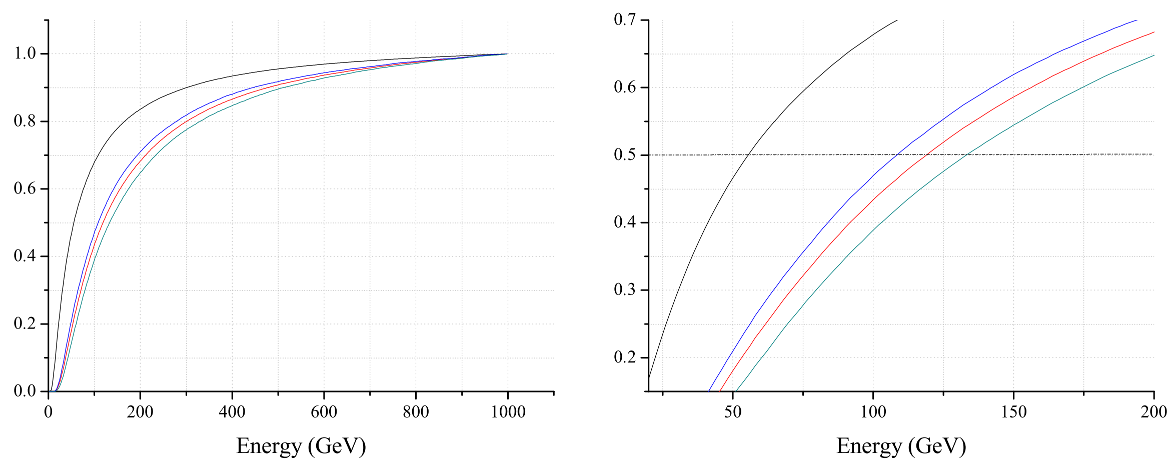

Fig. 8. Cumulative response function to galactic cosmic rays of different muon detectors in the Belgrade CR station: black curve — GLL; red curve — single UL; green curve — CC mode and blue curve — ANTI CC mode of asymmetric muon telescope. The 0.5 level corresponds to median energy. Cumulative response function with enlarged region around this level is shown in the right picture. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

one located in the GLL (100 ×100 ×5 cm) and upper one is 50 ×46 ×5 cm. Detectors are separated vertically by 78 cm, as depicted in Fig. 4, to have roughly the same count rate in the coincident and anticoincident mode. Lower detector in single mode operates in the same manner as the one in the GLL, with wide angular acceptance. The coincident mode is composed of the events registered in both upper and lower detector. In the anticoincident mode, muons passing through the upper but not the lower detector are counted. Therefore, the later mode favors inclined muon paths. Different angular distribution means different path length of muons registered in three modes of ASYMUT (right part of Fig. 4) and also different energy distribution of parental primary particles.

The response functions to GCR of three modes of ASYMUT are shown on Figs. 5–7 and respective cumulative response functions are shown on Fig. 8.

Important parameters describing shapes of response functions are summarized in Table 1. The most often used characteristics of a detector system is its median energy E_{med}. Primary particles with the energy below E_{med} give 50% contribution to detector count rate. The energy interval (($E_{0.05}$, $E_{0.95}$) is responsible for 90% of registered events. Fitted value of the parameter k from Dorman function (Eq. (4)) is also presented. The parameters $E_{0.05}$ and E_{med} are determined with 1 GeV accuracy, while the uncertainty of $E_{0.95}$ is much higher due to small number of very high energy events and is conservatively estimated as 10%.

Table 1
Sensitivity of Belgrade CR detectors (GLL — ground level; UL — underground based ASYMUT single mode; CC — ASYMUT coincident mode; ANTI — ASYMUT anticoincident mode) to GCR primary particles. Primaries with the energy below $E_{0.05}$ (and above $E_{0.95}$) contribute with 5% to the count rate of a corresponding detector. E_{med} is median energy, E_{th} threshold energy and k is Dorman parameter.

det	E_{th} (GeV)	$E_{0.05}$ (GeV)	E_{med} (GeV)	$E_{0.95}$ (GeV)	k
GLL	5	11	59	915	0.894(1)
UL	12	31	137	1811	0.971(4)
CC	12	27	121	1585	1.015(3)
ANTI	14	35	157	2031	0.992(4)

3.3. Conclusions

Usefulness of our setup for solar modulation studies is tested on the example of investigation of a Forbush decrease of 8 March 2012. In the first half of March 2012 several M and X class solar flares erupted from the active region 1429 on the Sun. The strongest were two X class flares that bursted on March 7. The first one is the X5.4 class flare (peaked at 00:24 UT) and the second one is the X1.3 class flare (peaked at 01:14 UT). The two flares were accompanied by two fast CMEs, one of which was Earth-directed [23]. Several magnetic storms were also registered on Earth, and a series of Forbush decreases is registered. The most pronounced one was registered on March 8. Characteristics of this event as recorded by various neutron monitors and our detectors are compared.

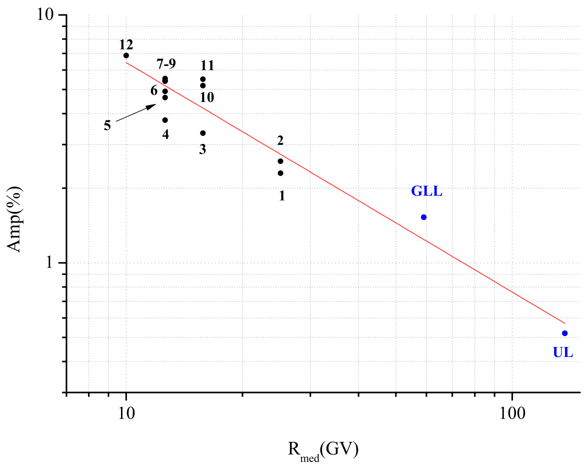

Fig. 9. Rigidity spectrum of FD from 12 March 2012. Black points represent the amplitude of the event as seen by twelve NMs: 1 — Athens, 2 — Mexico City; 3 — Almaty, 4 — Lomnicky stit; 5 — Moscow; 6 — Kiel; 7 — Yakutsk; 8 — Apatity; 9 — Inuvik; 10 — McMurdo; 11 — Thul; 12 — South Pole. Blue points are from Belgrade CR station: GLL — ground level and UL — underground. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Amplitude of a Forbush decrease is one of its main characteristics. Dependence of FD amplitude on median rigidity (or energy) is expected to follow the power law: $\Delta N/N \sim R^{-\gamma}$ [12].

For investigation of rigidity spectrum of mentioned FD data from 12 NMs are combined with the data from our two detectors (GLL and UL) that were operational at the time of the event. Neutron monitor data in the period between 1 March 2012 and 1 April 2012 are taken from the NMDB database (www.nmdb.eu) [24]. The exponent of the rigidity spectrum of this FD γ is obtained by the least-square fitting of the data with the power function (Fig. 9) and found to be $\gamma = 0.92 \pm 0.18$. Presented analysis illustrates applicability of our setup for studies of consequences of CR solar modulation process in the energy region exceeding sensitivity of neutron monitors.

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Neutrons produced by muons at 25 mwe

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Neutrons produced by muons at 25 mwe

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Abstract. The flux of fast neutrons produced by CR muons in lead at the depth of 25 mwe is measured. Lead is a common shielding material and neutrons produced in it in muon interactions are unavoidable background component, even in sensitive deep underground experiments. A low background gamma spectrometer, equipped with high purity Ge detector in coincidence with muon detector is used for this purpose. Neutrons are identified by the structure at 692 KeV in the spectrum of delayed coincidences, caused by the neutron inelastic scattering on Ge-72 isotope. Preliminary result for the fast neutron rate is $3.1(5) \times 10^{-4} n/cm^2 \cdot s$.

1. Introduction

Muons are very penetrating particles, present even in deep underground laboratories. Muons themselves and secondary radiation they produce are important source of background in sensitive experiments hosted in these laboratories. Neutrons produced in muon interactions in rock or detector surroundings are particularly troublesome. In dark matter experiments neutrons can produce recoil signal in detectors, similar to expected signal from WIMPs.

Another example of dangerous background arising from neutrons is in double beta experiments. In $(n, n'\gamma)$ reaction on lead, gamma rays of 2041 KeV energy can be produced, close to Q value for neutrinoless double beta decay in Ge-76[1].

Our measurements are performed in a shallow underground site, but even these measurements are of relevance for deeply underground located experiments [2].

2. Description of the experiment

The Belgrade underground laboratory is located on the right bank of river Danube in the Belgrade borough of Zemun, on the grounds of the Institute of Physics. The ground level part of the laboratory, at altitude 78 m above sea level, is situated at the foot of the vertical loess cliff, which is about 10 meters high. The underground part of the laboratory, of the useful area of 45 m^2, is dug into the foot of the cliff and is accessible from the ground level lab via the 10 meters long horizontal corridor, which serves also as a pressure buffer for a slight overpressure in the laboratory. More detailed description of the laboratory could be find in the ref. [3].

Experimental setup consist of a plastic scintillator detector and HPGe detector operating in coincidence. Scintillator detector with dimensions $100 \times 100 \times 5$cm, equipped with four PMTs directly coupled to the corners bevelled at 45°, is made by Amcrys-H of Kharkov, Ukraine. A radiopure HPGe detector of 35% efficiency and 149 cm^3 volume, made by ORTEC, in its 12 cm thick cylindrical lead castle is positioned beneath the center of the scintillator detector.

The core of digital data acquisition system is a FADC unit with four independent inputs each, made by CAEN, of the type N1728B. It samples signal at 10 ns intervals, into 2^{14} channels.

The preamplifier outputs of the PMTs of plastic scintillator detector are paired diagonally, the whole detector thus engaging the two inputs of the FADC. The third FADC input is reserved for HPGe, and fourth is used by auxiliary detector, unrelated to the present purpose.

Every event in each input channel is fully recorded by the time of its occurrence over the set triggering level, and its amplitude. This enables to off-line coincide the events at all four inputs, prompt as well as arbitrarily delayed.

Plastic scintillator detector serves as a muon flux monitor when its data are organized into time series. In independent operation HPGe detector is a typical low background gamma spectrometer. In anticoincident regime the plastic detector serves as a muon veto for gamma detector.

The coincident mode enables one to study cosmic-ray induced effects in gamma spectrometer. We are particularly interested in the signature of neutrons produced by CR muons in the lead shield.

All the operating modes of the system are performed simultaneously and do not interfere, as they are realized by performing different off-line analyses of the same set of data.

3. Results

After over 35 million seconds (400+ days) of measurements enough data are accumulated to present first results on neutron production from CR muons. Neutron identification is based on the process of inelastic scattering on Ge-72 isotope, within the HPGe detector itself, leading to the excited state at 692 KeV of energy. The abundance of Ge-72 isotope is 27.7% in natural Ge. The 692 keV state is an isomer state, with the half-life of 444 ns, and the depopulating radiation is pure E0, meaning that detection efficiency for the 692 keV radiation is practically 100%.

The spectrum of the HPGe detector containing the coincidences with the plastic scintillator delayed with respect to prompt between 500 ns and 2 μs, shows at this statistics only two interesting features (Fig.1).

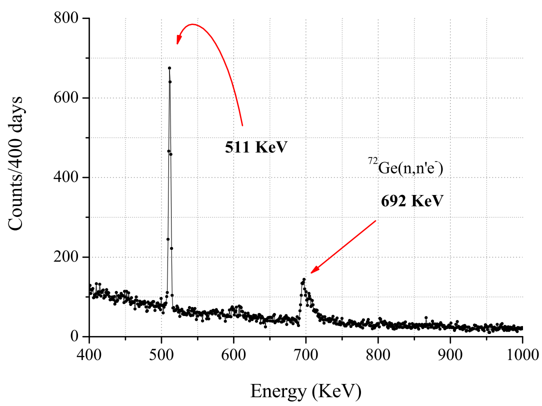

Figure 1. Portion of the background HPGe spectrum coincident with the plastic scintillator with the delays in the range from 100 ns to 2 μs, after 400 days of measurement time. It shows the annihilation line, which is due to the decays of positive muons stopped in the lead castle, and the triangular structure at 692 keV, which is due to inelastic scattering of fast neutrons on Ge-72.

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The first is the quasi-triangular structure at 692 keV, whose shape is a result of summing of the energy of transition radiation with the energy of the recoil of Ge nucleus. This structure has been studied many times [4, 5, 6, 7]. The second is annihilation line originating mainly from the decay of stopped positive muons.

The time spectra, or distribution of time intervals between start and stop signal, with the software gate on these two structures confirms previous statement.

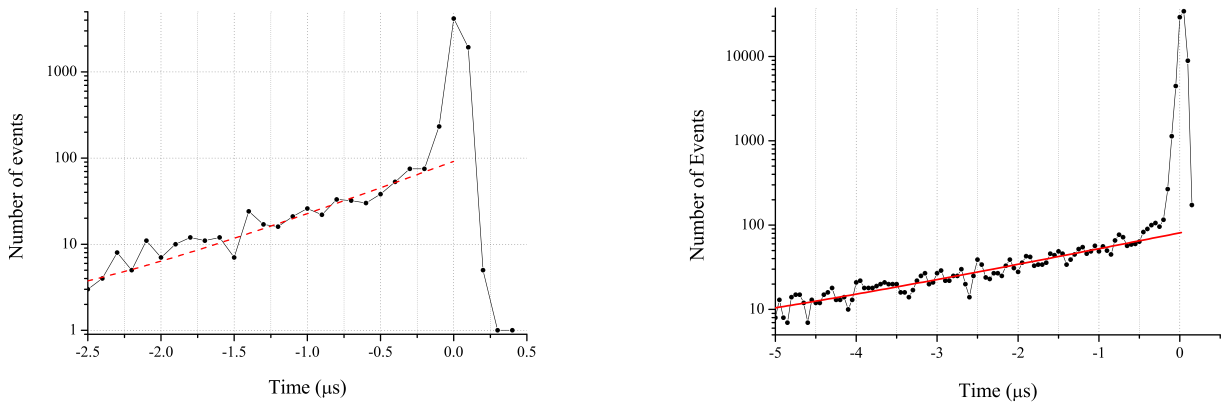

Figure 2. Time distributions of the events from Fig.1 that belong to the structure of 692 keV (left), the slope of which yields 500(50) ns for the half-life, and that of the annihilation line (right), which yields 2.24(9) μs for the mean life of the muon. Note logarithmic scale and interchange of start and stop signals.

With the gate on 692 KeV structure, though the statistics is poor, the fit through the tail of delayed coincidences yields the half-life of 500(50) ns (left panel of Fig2). The gate on 511 KeV line yields the mean life of 2.24(9)μs (right panel of Fig2). It is our intention to use the intensity of 692 KeV structure to estimate the flux of fast neutrons, produced in lead by CR muons, with the energy above the threshold. The empirical relation:

$$\Phi_F = k\frac{I_{692}}{V} \tag{1}$$

introduced by Škoro et al. [8] has been reasonably verified in the past. Here, I_{692} is the count rate in 692 KeV structure in counts per second, V is detector volume in cm^3 and k is parameter found to be (900 ± 150)cm.

This relation has been used before with analog spectroscopy systems, where the integration constants are long and the recoils invariably sum up with the 692 keV pulses. In digital spectroscopy systems, however, one important caveat is in place when using the integral of this structure for fast neutron flux determination. It appears that the shape, and the intensity of the distribution, here strongly depends on the height of the triggering level. When the trigger is higher then the height of the recoil pulse, the corresponding 692 keV pulse sums practically completely with its recoil. When the trigger is lower than the recoil it will trigger the ADC, and this pulse, together with the following 692 keV pulse, will be rejected by the pile-up rejecting algorithm. In our case the trigger was sufficiently high and according to our finding the intensity of the 692 keV distribution can be reliably used for the estimate of the fast CR induced neutron flux at the position of the detector. For the flux of neutrons of CR origin with energies over 1

MeV the value of $3.1(5) \times 10^{-4} n/cm^2 \cdot s$ is obtained. This refers to the flux at the depth of 25 m.w.e., within roughly one ton of lead, which is a common environment in most measurements of low activities.

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Stopped cosmic-ray muons in plastic scintillators on the surface and at the depth of 25 m.w.e

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Stopped cosmic-ray muons in plastic scintillators on the surface and at the depth of 25 m.w.e.

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Abstract. Cosmic ray muons stopped in 5 cm thick plastic scintillators at surface and at depth of 25 m.w.e are studied. Apart from the stopped muon rate we measured the spectrum of muon decay electrons and the degree of polarization of stopped muons. Preliminary results for the Michel parameter yield values lower than the currently accepted one, while the asymmetry between the numbers of decay positrons registered in the upper and lower hemispheres appear higher than expected on the basis of numerous earlier studies.

The laboratory spaces and the apparatus used in this work are described in detail in [1]. Here we first determine the number of stopped positive muons of cosmic-ray origin in our plastic scintillator detectors, which have the vertical thickness of 5 cm and an area of 1 m^2. The pulses from the PMTs are recorded in the event-by-event mode by their amplitude and time of occurrence, with 10 ns resolution. From such a list it is thus possible, among other things, to form the series of time intervals between successive pulses from a single detector. The signature of positive muons which stop and decay in the detector is the succession of pulses – the start pulse which is due to the stopped muon, and the stop pulse which is due to the positron emitted in its decay, which does not necessarily loose all of its energy in the detector (figure 1). The intervals between these start and stop pulses are distributed exponentially, with the constant corresponding to the lifetime of the muon. This distribution sits on another exponential distribution that corresponds to the Poisson count of the through-going muons, with the constant reciprocal to the rate of these events, which is of the order of 100 Hz, and which in the region where the first distribution is present (up to some 20 μs), appears flat (figure 2). In these measurements the dead time of the system was from 1 to 4 μs, and these portions of our time spectra are missing. Integrating this time distribution that corresponds to the stopped and decayed muons, and correcting for the missing events due to the dead time, we obtain the number of stopped muons in the ground level based and in the underground laboratory as:

$$N_{GB}(\mu_{stop}) = 6\cdot 10^{-2}\ \mathrm{m}^{-2}\ \mathrm{s}^{-1} \quad \text{and} \quad N_{UG}(\mu_{stop}) = 1.5\cdot 10^{-2}\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}$$

the errors on these numbers being below the significant figures presented here. Next, we find the amplitude spectra of all the start and of all the stop pulses from two different time intervals – one at the very beginning of the time spectrum (marked I in figure 2), and the other of the same width at the time when the muon decay distribution has practically died out (marked II in figure 2). We now subtract the spectrum of starts that corresponds to region II from that which corresponds to region I, to obtain the true spectrum of starts, which is the spectrum of muon energy losses until they stop in the detector (spectrum designated as “Stopped muons” in figure 3). We thus recover the spectrum of energies that stopped muons have prior to entering our detector. We do the same with the spectra of stops, what produces the spectrum of positron energy losses until they either stop within the detector or until they leave it (the spectrum designated as “Decay positrons” in figure 3). For the purposes of comparison we present in the same figure the much more intense spectrum of energy losses of through-going muons (marked as “Singles”), which peaks at about 10 MeV. It is seen that the spectrum of stopped muons peaks, in spite of the shorter path within the detector, at an energy higher than that at which peak the through-going muons, what is to be expected on the grounds that the muons of energies sufficiently low to stop in the detector have higher specific ionization than the high energy through-going ones, which are practically the minimum ionizing particles. Figure 3b presents the same results for the identical setup situated in the underground laboratory. Comparison between figure 3a and 3b shows the rather unexpected and significant differences between both the spectra of stopped muons and decay positrons on the surface and underground. The differences might be caused by the differences in low-energy parts of the muon spectrum at the two locations and possibly by the different degree of polarization of the stopped muons. This would, by virtue of parity non-conservation in the weak interactions involved, lead to different angular distributions of decay positrons, what would in turn result in the observed differences in their corresponding energy-loss spectra.

To check the above assumption we arranged the triple sandwich arrangement of plastic scintillator detectors, the big plastic detector (1 m^2) sandwiched between the two small ones (0.125 m^2), the pulses from each detector being recorded by their amplitudes and time of occurrence, with 10 ns resolution. All relevant combinations of off-line coinciding and anti-coinciding between the detectors yielded the information that we discuss in what follows.

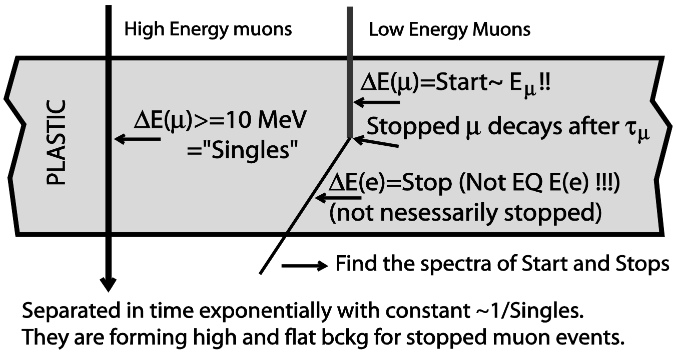

Figure 1. Definitions of the quantities involved in the study of CR muons which stop and decay in plastic scintillator detectors 5 cm thick.

Since the angular distribution of the incoming muons is wide, and the overall geometry of the events included into these spectra is complex, it is not possible to interpret and draw meaningful quantitative conclusions from the significant differences that exist between the two spectra (figure 4). It is, however, evident that the ratio of the number of positrons that are emitted into the upper hemisphere and those that are emitted into the lower hemisphere is significantly bigger than that which might be expected on the basis of the multitude of earlier measurements of this asymmetry (e.g. see [2]). The only possible reason for that might be the different character of the stopping medium, that appears to be different from those used in any of earlier studies. The results of the same measurement underground still do not have sufficient statistics for meaningful conclusions, and the measurements go on.

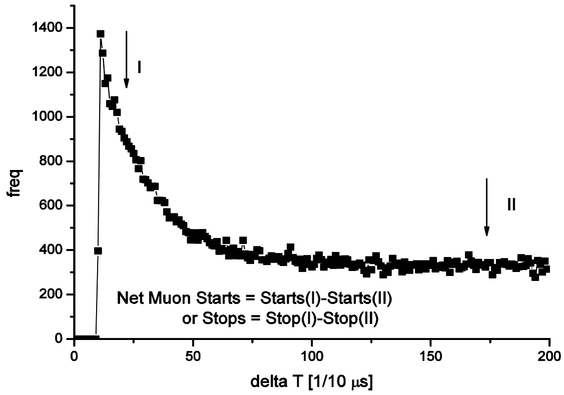

Figure 2. Distribution of time intervals between successive pulses from the 1 m^2 plastic scintillator detector. Region I contains majority of the stopped muon decays, while region II contains only the "background" composed only of time intervals between the through-going high-energy muons.

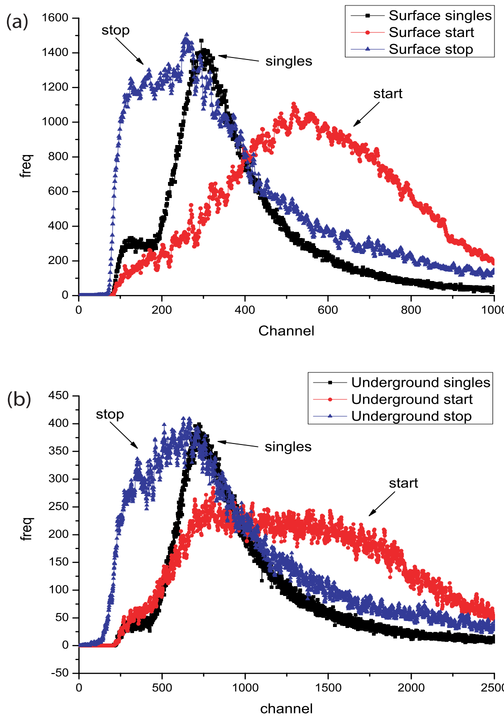

Figure 3. (a) The spectra of through-going muons (Singles), of stopped muons (Starts, or Stopped muons) and of decay positrons (Stops, or Decay positrons), all in the ground level based laboratory (Surface). (b) Same, in the underground laboratory (Cavern).

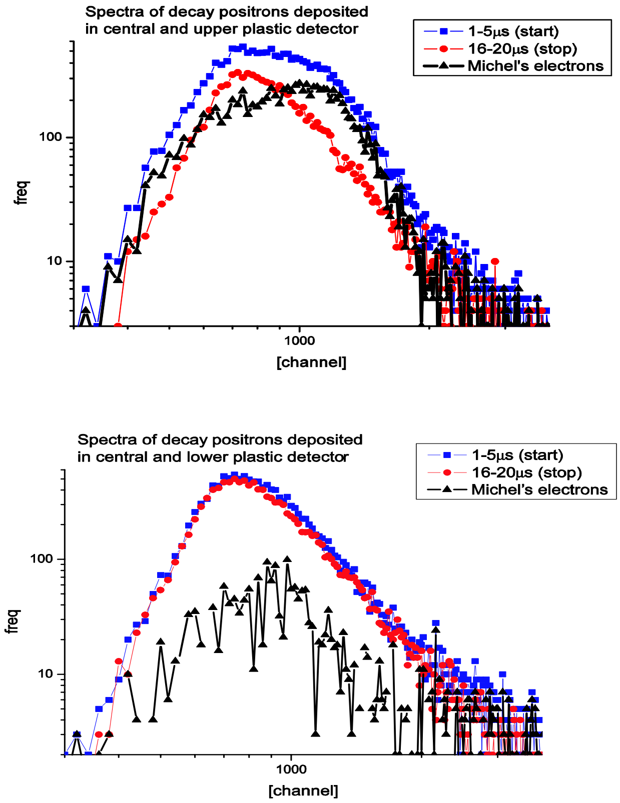

Figure 4. Preliminary results of measurements with the triple sandwich detector arrangement in the ground based laboratory. Spectrum of decay positron energy losses (triangles) in the upper detector (upper image) and in the lower detector (lower image).

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Correlative and multivariate analysis of increased radon concentration in underground laboratory

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CORRELATIVE AND MULTIVARIATE ANALYSIS OF INCREASED RADON CONCENTRATION IN UNDERGROUND LABORATORY

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The results of analysis using correlative and multivariate methods, as developed for data analysis in high-energy physics and implemented in the Toolkit for Multivariate Analysis software package, of the relations of the variation of increased radon concentration with climate variables in shallow underground laboratory is presented. Multivariate regression analysis identified a number of multivariate methods which can give a good evaluation of increased radon concentrations based on climate variables. The use of the multivariate regression methods will enable the investigation of the relations of specific climate variable with increased radon concentrations by analysis of regression methods resulting in 'mapped' underlying functional behaviour of radon concentrations depending on a wide spectrum of climate variables.

INTRODUCTION

Radon is considered to be the main source of human exposure to natural radiation. By the World Health Organization, the greatest exposure is due to the inhalation of indoor short-lived decay products of radon(1). They contribute for about 55 % to the annual effective dose received by the general population. Indoor radon concentrations vary significantly due to a large number of factors. The focus of this work is only on climate parameters by investigating the possible correlation of short-term variations of climate parameters and radon concentrations.

Low Background Laboratory in the Institute of Physics, Belgrade consists of the Ground level laboratory and the Underground level (UL) laboratory, placed 12 m underground. Laboratory is described in details elsewhere(2). During normal working operations, the UL laboratory has an operating ventilation system, which serves two purposes: first one is to exchange air in the laboratory with the outdoor one and the second purpose is to create over-pressurised air in the laboratory in order to help stopping the radon incursion into the laboratory. The ventilation system is constantly switched on, but in some special cases, for a short period of time, like in the case of the study presented in this work, the ventilation system was switched off. In the case of non-over-pressurised and no air exchange conditions in the UL, there is an increase of the radon concentrations. This is a very good condition to look into relations of climate variables and increased radon concentrations.

The goal in this study is a use of the multivariate analysis approach in finding the relations of climate variables and increased radon concentrations in the UL. The first tests of correlative and multivariate analysis of variations of indoor radon concentrations with climate variables were published elsewhere(3).

When the ventilation system in the UL is switched off, radon concentrations increase rapidly, indicated by starting activities from <20 Bq m^{-3}. After a few days, the rapid increase of radon concentrations becomes steady, with values of radon activities reaching as much as 900 Bq m^{-3}, and also, the variability of radon concentrations is much more pronounced. Additional interesting property of the conditions in the UL, while taking into account radon activity measurements, is that during the measurement time, the laboratory is practically not accessed, so air exchanges cannot explain the changes of radon concentrations. This fact alone will improve the chances of finding the stronger correlation of climate variables with radon concentrations. Radon tends to concentrate in enclosed spaces such as underground mines or houses. Soil gas infiltration is recognised as the most important source of residential radon(1). Conditions in the UL with the ventilation system switched off are a close match for such enclosed spaces.

The search for an appropriate analysis method resulted in the selection of multivariate methods. Many multivariate methods and algorithms for classification and regression are already integrated into the analysis framework ROOT(4), more specifically, into the Toolkit for Multivariate Analysis (TMVA)(5).

In the present analysis 12 variables based on outdoor climate variables were used. The outdoor climate variables are temperature, pressure and humidity, the temperatures of ground at two depths of 20 and 50 cm and wind speed. The additional variables are atmospheric pressure, air temperature and humidity measured with a radonometer measuring system and the differences of these values with outdoor measured ones. The analysis starts with comparing the multivariate methods in order to find out which one is best suited for classification (division) of radon concentrations into what would be considered acceptable and what would be considered increased concentration in UL.

EXPERIMENTAL DATA

For measurement of radon concentrations, air temperature, atmospheric pressure and humidity in the UL the SN1029 radon monitor (manufactured by the Sun Nuclear Corporation, NRSB approval-code 31822) is used. This device consists of two diffused junction photodiodes as a radon detector. The radon monitor was used for measuring radon concentration, air temperature, atmospheric pressure and humidity at 2-h intervals during the September and October of 2013.

RESULTS

The results of MVA classification and regression methods are commented.

The start of MVA method-based analysis is done by using the events consisting of one set of all climate variables and the corresponding measured radon activity. For classification methods, all events are split into signal events—a set of events where the measured radon activity is greater than some predefined value (200 Bq m^{-3}) and background ones, the set of events with values less than the predefined value. After the process of training of MVA methods, comparison of their performance in properly splitting the whole set of events into signal and background events is performed. The graph presenting the 'receiver operating characteristic' (ROC) for each multivariate method (Figure 1) may be considered as the most indicative in comparing the different methods used for classification of radon concentrations using climate variables. On this graph one can read the dependence of background rejection on signal efficiency. The best method is the one that holds the maximum value of background rejection for highest signal efficiency, i.e. the best method has an ROC curve closest to the upper right corner on the graph presented in Figure 1.

From Figure 1 it can be seen that the selected 12 MVA methods can very efficiently classify all events into signal and background ones. For all MVA classifiers, the signal efficiency is >85 % for practically 100 % background rejection. The best performing MVA methods are BDT and MVA methods. The response function of the best classifier is shown in Figure 2. From this figure it can be seen that the signal and background events are separated very good.

Classifiers can be very useful, especially from a radiation protection aspect in connection with radon measurements. In radon measurements one can use either long-term measurements or expensive short-term ones. This way, by training the classifiers, it will be achievable to predict short-term variations, which are considered as increased radon activity (>200 Bq m^{-3}), which will otherwise be blended (invisible) in long-term measurements.

Regression

The next step was to try to get more information from MVA methods by trying to 'map' a functional behaviour of radon vs. input climate variables. This is done by using the MVA regression methods. During the tests, the observation was made that not all MVA methods give good evaluation of radon concentrations. In Figure 3 the authors present the initial and corrected values of evaluation of radon concentration for one of the MVA methods.

The distribution of measured radon activities and MVA regression evaluations is shown in Figure 4. From this plot, it is clear that the distribution of MVA evaluations are in good agreement with the experimental values. This also means that it is now possible to calculate the errors of MVA evaluation which is presented in Figure 5. One can see that for the high values of radon concentrations, such as in the UL, the

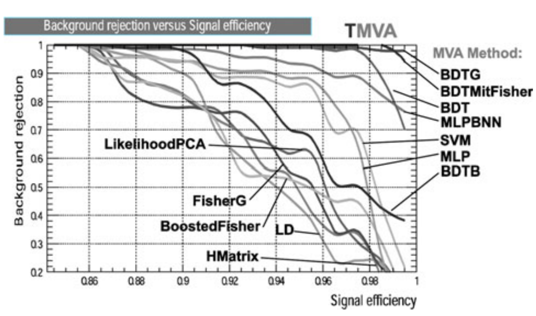

Figure 1. ROC for all multivariate methods used for classification of radon concentration using climate variables.

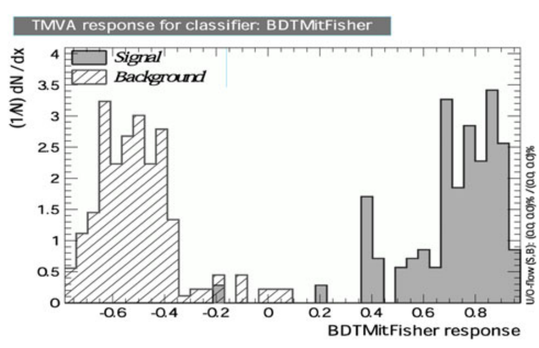

Figure 2. TMVA response for classifier for best performing MVA classifier, a method based on boosted decision trees.

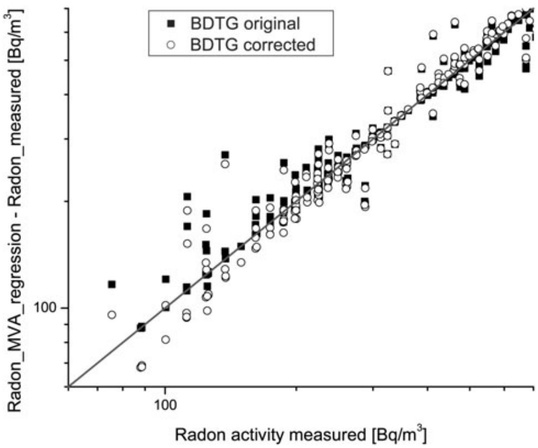

Figure 3. Initial and corrected evaluations of radon activity. After corrections, the difference between measured and corrected evaluation is closer to 0 for a whole range of radon activities.

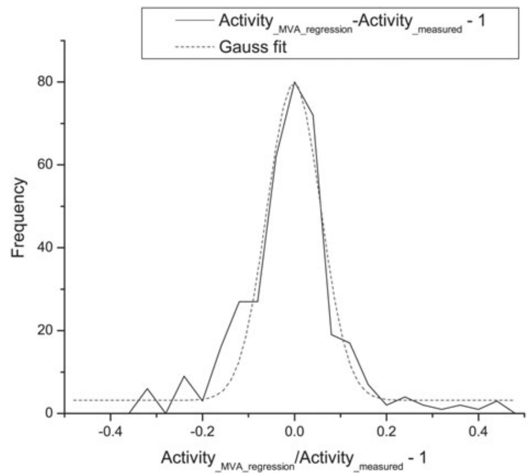

Figure 5. Calculation of relative variations of MVA evaluated values from measured radon activities.

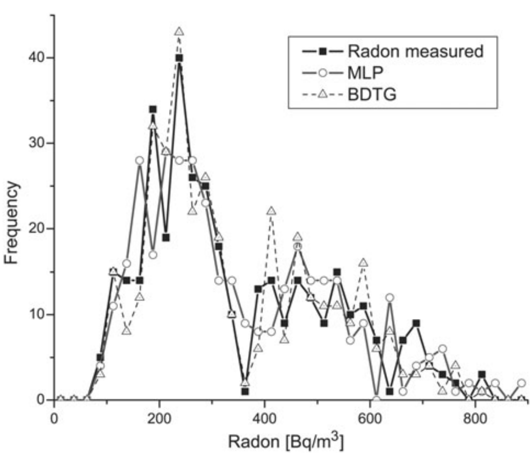

Figure 4. Distribution of the values of radon activity for measured (radon) and MVA regression methods' evaluation values (MLP and DBT methods).

evaluation is better. The error of evaluation is estimated to be ~6 %.

CONCLUSION

The results of analysis of relation of increased radon concentrations in UL and climate variables using multivariate classification and regression methods, as developed for data analysis in high-energy physics and implemented in the TMVA software package are presented. These methods enabled the investigation of the relations of a wide spectrum of climate variables with increased radon concentrations in the UL. Multivariate regression analysis gives a possible choice of several good multivariate methods which can be used for evaluation of increased radon concentration in the UL, with input events based on climate variables. The analysis performed showed that there is a significant relation of climate variables and increased radon concentrations in the UL. As a result of the analysis presented in this work, there is now MVA regression 'mapped' underlying functional behaviour of radon concentrations depending on a wide spectrum of climate variables. Having 'mapped' the functional behaviour of radon concentrations enables analysis with the possibility of exclusion of the inter-correlations of climate variables, which presents one with a new advantage in the analysis of radon concentration relations with climate variables.

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PAPER • **OPEN ACCESS**

Pressure and temperature effect corrections of atmospheric muon data in the Belgrade cosmic-ray station

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Pressure and temperature effect corrections of atmospheric muon data in the Belgrade cosmic-ray station

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Abstract. We present results of continuous monitoring of the cosmic-ray muon intensity at the ground and shallow underground level at the Belgrade cosmic-ray station. The cosmic-ray muon measurements have been performed since 2002, by means of plastic scintillation detectors. The scintillator counts are corrected for atmospheric pressure for the whole period of measurements and, as well, for vertical temperature profile for the period of the last six years. The results are compared with other correction methods available. One-hour time series of the cosmic-ray muon intensity at the ground level are checked for correlation with European neutron monitors, with emphasis on occasional extreme solar events, e.g. Forbush decreases.

1. Introduction

The Belgrade cosmic-ray station, situated in the Low-level Laboratory for Nuclear Physics at Institute of Physics, Belgrade, have been continuously measuring the cosmic-ray intensity since 2002. The station is at near-sea level at the altitude of 78 m a.s.l.; its geomagnetic latitude is 39° 32' N and geomagnetic vertical cut-off rigidity is 5.3 GV. It consists of two parts: the ground level lab (GLL) and the underground lab (UL); the UL is located at a depth of 12 metres below the surface, i.e. 25 metre water equivalent. At this depth practically only the muonic component is present. The cosmic-ray muon measurements are performed by means of plastic scintillation detectors, a pair of which is, along with instrumentation modules for data acquisition, placed in both the GLL and the UL. The set-up is quiet flexible, as the scintillators could be arranged in different ways, which allows conducting different experiments. The analyses of the measurements yielded some results on variations of the cosmic-ray muon intensity and on precise values of the integral muon flux at the ground level and at the depth of 25 m.w.e. [1,2,3,4].

2. Experimental set-up

The experimental set-up in both the GLL and the UL consists of a large plastic scintillation detector (rectangular shape, 100cm x 100cm x 5cm) and a data acquisition system (DAQ). The scintillator is polystyrene based UPS-89, with four 2-inch photomultiplier tubes attached to its corners, so that each PM tube looks at the rectangle diagonal. Preamplifier signals from two PM tubes looking at the same diagonal are summed in one output signal, thus two output signals are led to the DAQ from each scintillator.

The summed signals from the PM tubes on the same diagonal of the detectors are stored and digitized by the DAQ, which is based on 4-channel flash analog-to-digital converters (FADC), made by CAEN (type N1728B), with 100 MHz sampling frequency. The FADCs are capable of operating in the event-list mode, when every analyzed event is fully recorded by the time of its occurrence and its amplitude. This enables the correlation of events, both prompt and arbitrarily delayed, at all four inputs with the time resolution of 10 ns. Single and coincident data can be organized into time series within any desired integration period. The FADCs can also be synchronized with each other for the additional coinciding of the events in the GLL and the UL.

For both the GLL and the UL detector, two input channels on the corresponding FADC are reserved for events recorded by each of detector's diagonals. The cosmic-ray events recorded by a single diagonal are drown in the background. Coinciding of the prompt events from two diagonals within a narrow time window gives the resulting experimental spectrum of the plastic scintillator, which is the energy deposit (*ΔE*) spectrum of the cosmic-ray particles (figure 1). Interpretation of the experimental spectra and their features as well as their calibration have been done using Geant4 based Monte Carlo simulation [4,5]. The spectra peak at ~11 MeV and have the instrumental thresholds at ~4 MeV. Comparing the spectra of the GLL detector and the UL detector one can notice the obvious difference in their shape, especially in the low-energy part below ~6 MeV. This difference points to the contribution of the cosmic-ray electrons and gammas (electromagnetic component) to the *ΔE* spectra at the ground level, which is absent in case of the underground detector.

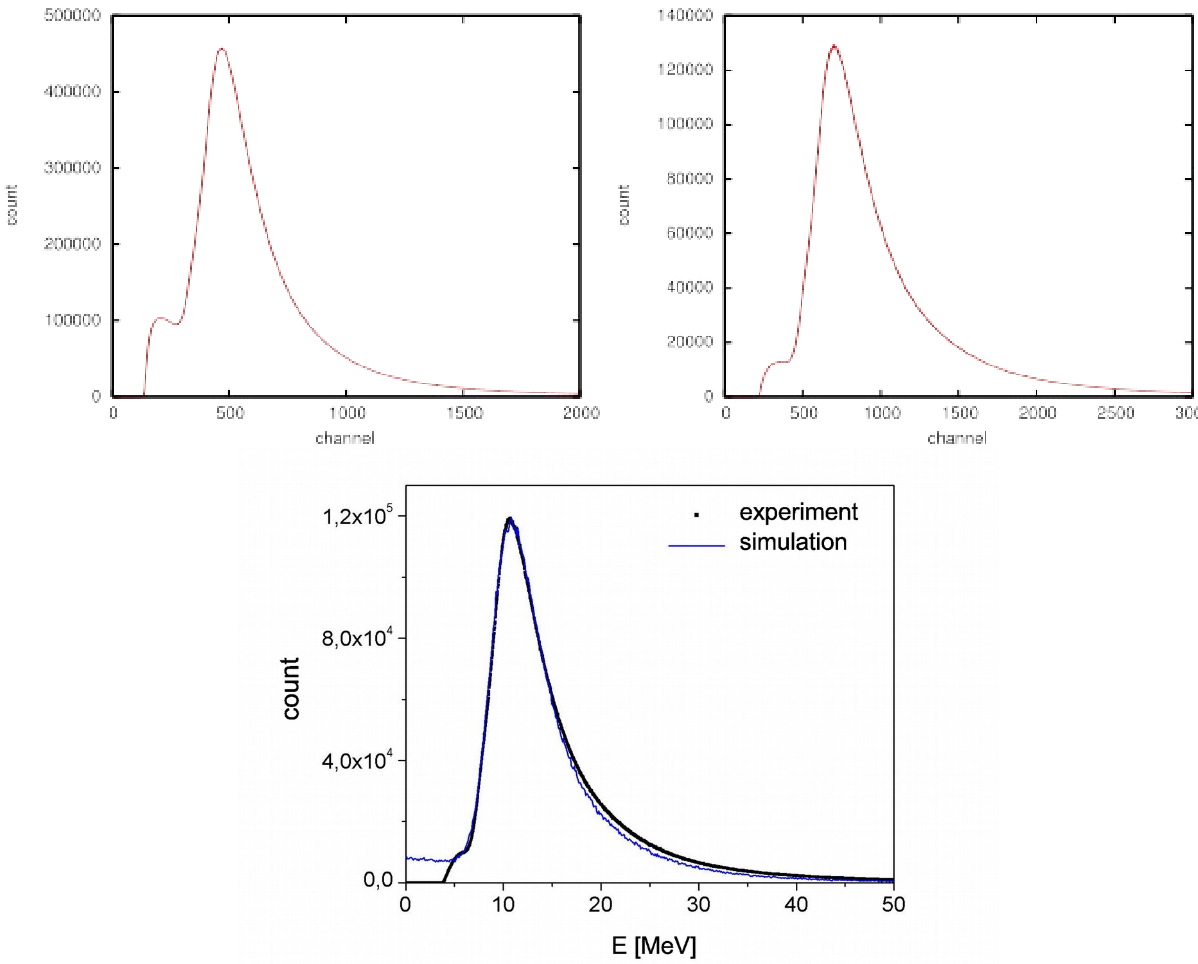

Figure 1. The cosmic-ray *ΔE* spectra of the GLL detector (top left) and the UL detector (top right). Experimental and simulated *ΔE* spectra of the UL detector (bottom).

3. Results and discussion

The cosmic-ray intensity data are automatically processed, using a web-based “robot” developed for this purpose, and published online at www.cosmic.ipb.ac.rs/muon_station. The online available data are raw scintillator counts in time series with resolution of 5 min or 1 h. Time series of the raw data are corrected for pressure and temperature effect; pressure corrections have been done for the whole data taking period and temperature effect corrections have been done for the the time period of the last six years.

3.1. Efficiency corrections

The first data corrections are related to detector assembly efficiency. As mentioned, the instrumental thresholds cut the spectra at ~3 MeV. However, the thresholds may vary, thus changing the initial spectrum and resulting in fluctuations of the integral spectrum count. Related to this, the necessary correction has been done by means of constant fraction discriminator (CFD) function (figure 2); with use of the CFD cut the spectrum fluctuations decreased significantly. The CFD is based on cut on chosen height as a percentage of peak height where the spectrum is cut. The simulation tells us that, for the underground detector, ~6% of muon events is also cut (figure 1).

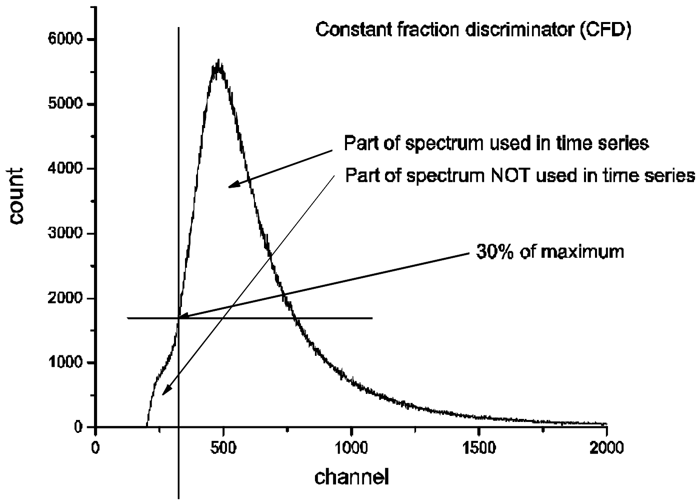

Figure 2. Constant fraction discriminator (CFD) applied in efficiency corrections. The obtained truncated spectrum is used for calculating time series.

The next step in the efficiency corrections is a correction of 5-min count values that are clearly lower than a mean 5-min count in surrounding time intervals. This undershoot comes at the beginning/end of runs, where events are not collected for all 5 min of measurement. The last and smallest correction is a correction of fluctuations of spectrum due to fluctuation in amplification which influence the cut on diagonals and efficiency of coincidence of two diagonals. We found that the CFD cut is proportional to efficiency of coincidence.

3.2. Corrections for atmospheric pressure and for temperature

Significant part of variation of cosmic ray muon component intensity can be attributed to meteorological effects. Here, two main contributors are barometric and temperature effect [6].

Barometric effect is caused by variation of the atmospheric mass above the detector. These pressure corrections are done by finding the linear regression coefficient, using only International Quiet Days, i.e. time series data from periods with more or less constant intensity of galactic cosmic rays, for creation of the distribution of scintillator counts vs. atmospheric pressure. Atmospheric pressure data are available due to on-site continuous measurement.

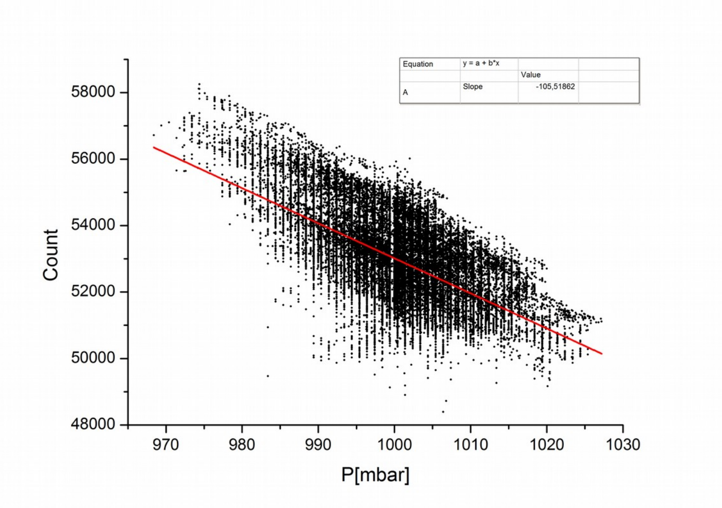

Figure 3. Dependence of 5-min counts on atmospheric pressure.

The temperature effect is related to the variation of the atmospheric temperature profile. The effect is two-fold, as it affects pion decay (positive contribution) as well as muon ionization losses and possible decay (negative contribution). To correct for these effects, integral correction method was applied [6,7]. The variation of the muon intensity due to temperature variations is calculated by using the formula:

$$\delta I_T = \int_0^{h_0} \alpha(h) \cdot \delta T(h) \cdot dh$$

where δI_T is the variation of the muon intensity due to the temperature effect, $\delta T(h)$ is the variation of the atmospheric temperature, which is calculated in reference to the mean temperature value for a given time period (denoted by index M): $\delta T(h) = T_M(h) - T(h)$, where h is atmospheric depth. Temperature coefficient densities $\alpha(h)$ are calculated according to [6].

Available meteorological models make it possible to have hourly atmospheric temperature profiles for 17 standard isobaric levels at the geographic position of the Belgrade muon station, necessary for application of formula shown above. The procedure used here is as described in [7]. Temperature profiles have been obtained from ftp://cr0.izmiran.rssi.ru/COSRAY!/FTP_METEO/blgd_Th/, courtesy of IZMIRAN laboratory.

3.3. Time series of the cosmic-ray intensity

In Figure 4 the count rate time series is shown for all corrections. First, the corrected count rate for efficiency corrected data is shown. Also, the atmospheric pressure and combined atmospheric pressure and temperature corrections time series of count rates are shown.

One-hour time series of the cosmic-ray muon intensity at the ground level are checked for correlation with European neutron monitors (NM), with emphasis on occasional extreme solar events, e.g. Forbush decreases.

In Figure 5 the comparison of time series of pressure corrected and pressure and temperature corrected count rates for the Belgrade muon station and Jungfraujoch, Rome, Baksan and Oulu neutron monitors is presented for Forbush candidate in March 2012. The count rates of neutron monitors are shifted to be close to each-other for visibility. The count rate for the Belgrade station is shown in percentages with additional shift down for visibility. The count rate drop for the neutron monitors is clearly more pronounced than for Belgrade muon monitor.

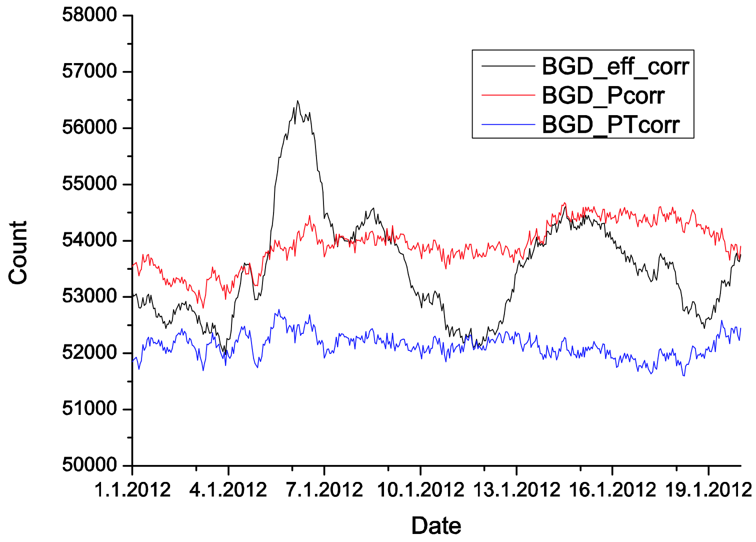

Figure 4. Time series of efficiency corrected, pressure corrected and pressure and temperature corrected counts.

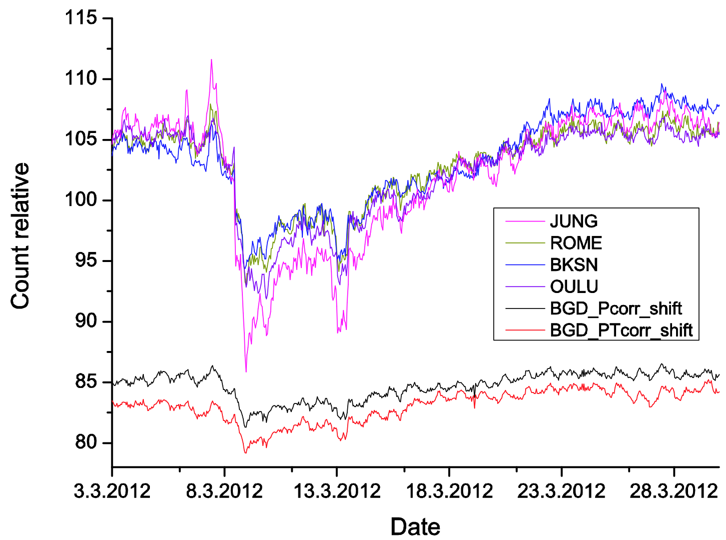

Figure 5. Comparison of time series of pressure corrected and pressure and temperature corrected count rates for the Belgrade muon monitor station and neutron monitors. Count rates are shifted for comparison.

In Figure 6 the comparison of time series of pressure corrected count rates for the Belgrade muon station Jungfraujoch, Rome, Baksan and Oulu neutron monitors is presented. The count rates of neutron monitors are shifted to be close to each-other for visibility. The count rate for Belgrade station is scaled in the way that the drop in count rate is similar to most of the stations (except Jungfraujoch, which is at high altitude). The visual comparison shows the good correlation of the count rates of Belgrade muon monitor and neutron monitors, previously noticed using correlative analyses of count rates. The pressure corrected count rates from Belgrade muon monitor is only dataset used for visual comparison, since neutron monitor data are also only pressure corrected. This was also observed previously using correlative analyses of count rates.

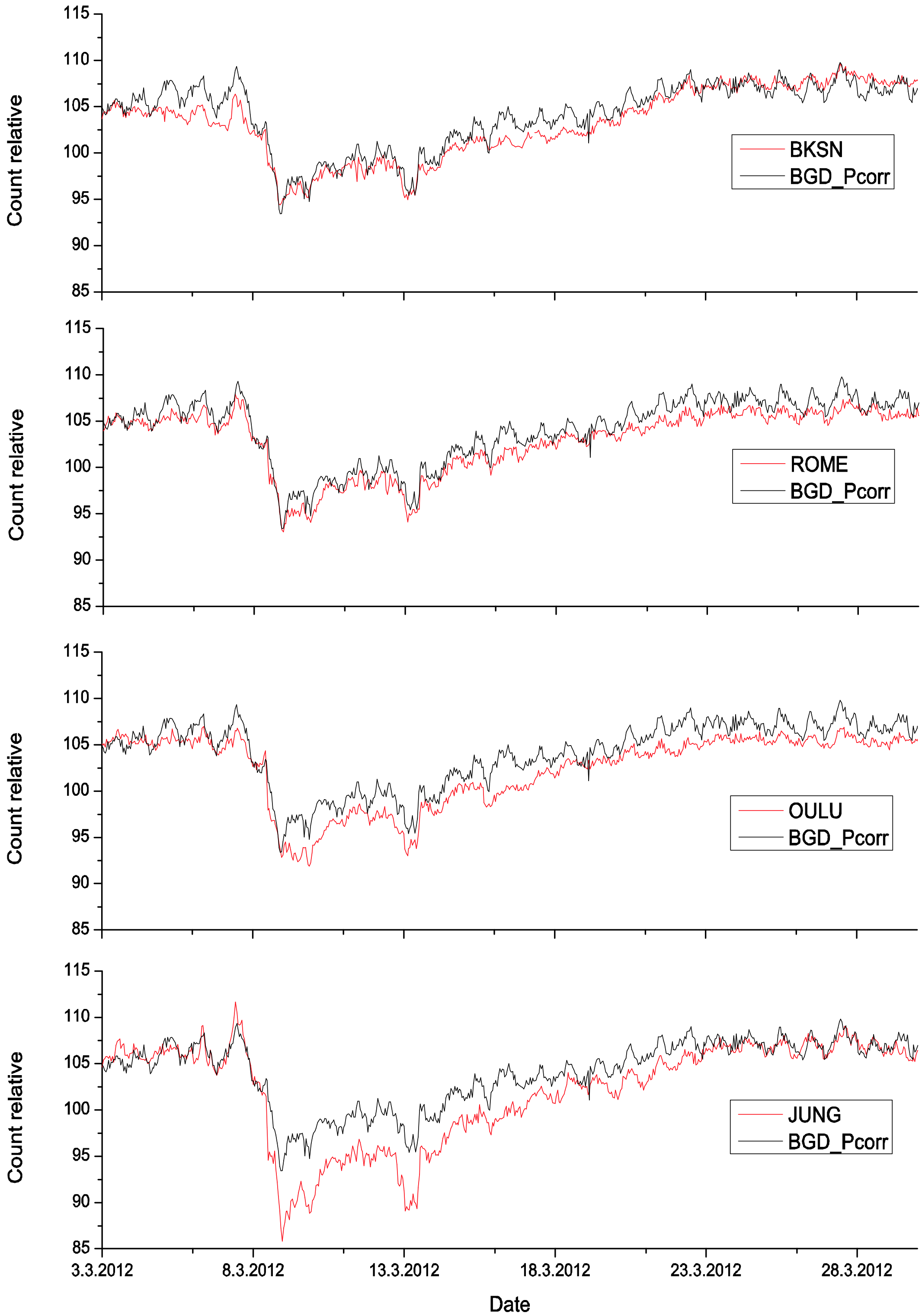

Figure 6. Comparison of time series of pressure corrected count rates for the Belgrade muon monitor station and neutron monitors. Count rates are shifted and scaled for comparison.

4. Conclusions

The results of continuous monitoring of the cosmic-ray muon intensity at the ground and shallow underground level at the Belgrade cosmic-ray station are presented. The scintillator counts are corrected for atmospheric pressure for the whole period of measurements and, as well, for vertical temperature profile for the period of the last six years. The results are compared with other correction methods available and showed excellent agreement. One-hour time series of the cosmic-ray muon intensity at the ground level are checked for correlation with European neutron monitors, with emphasis on occasional extreme solar events, e.g. Forbush decreases. As a result of correlative analysis, the Forbush candidate in March 2012 is the best choice to be used for visual comparison presented in this work. The comparison showed high correlation of the Belgrade muon monitor with neutron monitors, especially geographically closer neutron monitors such as Rome NM. In some specific time periods, like during the Forbush candidate in March 2012, we showed that our muon measurement system has sensitivity comparable to European neutron monitors in this period, but still not as efficient as NM with better geographical position (at high altitude), e.g. Jungfraujoch in the Swiss Alps.

5. Acknowledgements

This work is supported by the Ministry of Education, Science and Technological Development of Republic of Serbia, project no. OI171002. We acknowledge the NMDB database (www.nmdb.eu), founded under the European Union's FP7 programme (contract no. 213007) for providing data. We acknowledge the Department of Physical Sciences, University of Oulu, Finland, as the source of data used in publications. Jungfraujoch neutron monitor data were kindly provided by the Cosmic Ray Group, Physikalisches Institut, University of Bern, Switzerland. We acknowledge the ROME neutron monitor data. SVIRCO NM is supported by IFSI/INAF-UNIRoma3 collaboration. We acknowledge the Baksan Neutrino Observatory of Institute for Nuclear Research of Russian Academy of Science, Moscow, for providing data.

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ORIGINAL RESEARCH

Yield from Proton-Induced Reaction on Light Element Isotopes in the Hydrogen Plasma Focus

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Abstract The high Q-value of some (p,α) fusion reactions is very important in the investigation that can lead to power production with controlled fusion using advanced fuels (hydrogen-lithium-7, hydrogen-boron-11). For this reason, it is crucial to know the rates of these fusion reactions. Unfortunately, in the fusion machines such as plasma focus device, the interaction energy is usually far below the Coulomb barrier. Because of that, direct measurements of the relevant reaction cross sections are practically impossible. A few different indirect approaches have been proposed. In this work the Trojan Horse Method (THM) will be described. On the basis of the results obtained from the THM method and data, which are well-known from our previous work (Banjanac et al. in Radiat Meas 40:483–485, 2005), the reaction rate for proton-induced reaction ^{7}Li(p,α)α produced in the hydrogen plasma focus is calculated. This calculation will be compared with the measurements of α particles production rate using CR-39 detectors.

Keywords Plasma focus · Trojan horse method

Introduction

Proton-induced reaction on light element isotopes play a key role in nucleosynthesis of the elements in the earliest stages of the universe and in all the objects formed thereafter. In a few last years, these fusion reactions became the subject of the investigation because of their high Q-value [3]. Because of this it is very important to know the rates of these nuclear reactions. However, cross sections of reactions with charged particles become very small with decreasing energy and because of that cannot be directly measured. Therefore, the cross section $\sigma(E)$ at low energies is obtained by extrapolating experimental data at higher energies with the well-known astrophysical S factor. In the last ten years, several indirect methods have been developed to extract value for the astrophysical S factor at the low energy limit $S(0)$. One of these indirect methods is a Trojan Horse Method (THM). In this approach the relevant two-body nuclear reaction is replaced by a suitably chosen three-body reaction that is measured under special kinematical conditions [7].

In this work, the THM method will be explained on the example of the ^{7}Li(p,α)α fusion reaction. On the basis of the results obtained from the THM method and data, which are well-known from our previous work [3], the reaction rate for proton-induced reaction ^{7}Li(p,α)α produced in the hydrogen plasma focus can be calculated. This calculation is compared with the measurements of α particles production rate using CR-39 detectors.

Theory

The rates of the charged-particle-induced nuclear reactions for one par of the particles, $\langle\sigma v\rangle$ are well-known from the general theory of the nuclear reactions [6]:

$$\langle\sigma v\rangle = 7.20 \times 10^{-19} \frac{1}{\mu Z_1 Z_2} \tau^2 \exp(-\tau) S(E_0) \qquad (1)$$

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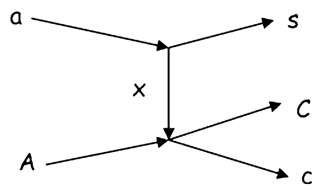

Fig. 1 Pseudo-Feynman diagram representing the quasi-free A + a → c + C +s reaction

where v is the relative velocity of the particles, μ is reduced mass, $\tau = \frac{3E_0}{kT}$ is undimensional parameter, Z_1, Z_2 are the charge numbers of the colliding nuclei and $S(E_0)$ is the astrophysical S factor for the Gamow energy E_0.

Direct measurements of the astrophysical S factor at the Gamow energies for the relevant fusion reactions, such as ^{7}Li(p,α)α are impossible. As it mentioned in the introduction, the powerful indirect method, called THM method has been developed.

The basic idea of the THM relies on the assumption that a three-body reaction a(A,cC)s can proceed via quasi free reaction mechanism that is dominant under particular kinematical conditions. In these conditions, the reaction a(A,cC)s is considered to be described by a polar diagram as it shown in Fig. 1 (pseudo-Feynman diagram). The target nucleus a is assumed to break-up into the clusters x and s, where s is then considered to be a spectator of the A + x → c + C reaction, where c and C are the outgoing particles. In this picture, the cross section of the three-body reaction can be factorized into two terms corresponding to the two vertices of the diagram (Fig. 1). It should be outlined that in order to apply the THM a suitable three-body and proper kinematical conditions should be found. The most relevant results obtained for the fusion reaction ^{7}Li(p,α)α using THM technique are reported [4].

The three-body reaction used in this case is ^{7}Li(d,αα)n, where deuteron is considered as a cluster of proton (interaction particle) and neutron (spectator). In the same work [4], important tests of the THM method have been done studying reaction, ^{11}B(p,α)2^{4}He which present a resonant behaviour. The high Q-value of this fusion reaction is very important in the investigation that can lead to power production with controlled fusion using advanced fuels [5].

All about THM method, including detailed calculations one can found in the review paper [7].

Experiment

In our previous works [2, 3], we have obtained the experimental data for the flux and energy of the accelerated protons (especially the axial protons) emitted from the hydrogen plasma focus. On the basis of these experimental data, we have performed experiment with the lithium target, which was thick wire (thicknesses of about 100 μm) placed on the CR-39 plate (2 × 2 cm). CR-39 nuclear track detectors manufactured by the Intercast were used for the detection of the α particles produced in the ^{7}Li(p,α)α fusion reaction. Both the lithium target and CR-39 plate were placed in one of the diagnostical windows positioned at the top of the plasma focus chamber along the central electrode axis. The fast protons were collimated with integrated collimators, so that the protons bombarded target at right angles.

All the experiments were performed on the Mather-type plasma focus device with hydrogen as a working gas. The gas discharges is produced by capacitator bank with stored energy of 5.76 kJ. After exposure the CR-39 detectors were etched by the similar procedure as in [1]. The CR-39 nuclear track detectors were chemically etched for an etching time of 2.5 h with a solution of 30% KOH at 70°C. The tracks were counted by the semi-automatic track-counting system consisting of a CCD camera and a high-resolution monitor.

Results and Conclusions

In all of the scanned CR-39 detectors, the alpha track density was on the background level (10^2 cm^{-2}). This result is in good agreement with the calculations based on (1) and the value for the astrophysical S factor obtained through THM method for the ^{7}Li(p,α)α fusion reaction [4]. The obtained experimental results and theoretical calculations show that it is not possible to realized ^{7}Li(p,α)α fusion reaction in a small plasma focus device (stored energy of 5.76 kJ).

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CORRELATIVE AND PERIODOGRAM ANALYSIS OF DEPENDENCE OF CONTINUOUS GAMMA SPECTRUM IN THE SHALLOW UNDERGROUND LABORATORY ON COSMIC RAY AND CLIMATE VARIABLES

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***Abstract*. The continuous gamma spectrum, Cosmic ray intensity and climate variables; atmospheric pressure, air temperature and humidity were continually measured in the Underground laboratory of Low Background Laboratory in the Institute of Physics Belgrade. Same three climate variables for outside air were obtained from nearby meteorological station. The obtained gamma spectrum, measured using HPGe detector, is split into three energy ranges, low, intermediate and high ending with energy of 4.4 MeV. For each of the energy intervals periodogram and correlative analysis of dependence of continuous gamma spectrum on cosmic ray intensity and climate variables is performed. Periodogram analysis is done using Lomb-Scargle periodograms. The difference of linear correlation coefficients are shown and discussed, as well as the differences in resulting periodograms.**

Key words: *gamma spectroscopy, surface air, underground laboratory, correlative analysis, periodogram analysis.*

1. INTRODUCTION

The low-level and cosmic-ray laboratory in the Low-Background laboratory for Nuclear Physics in the Institute of Physics Belgrade is dedicated to the measurements of low activities and to the studies of the muon and electromagnetic components of cosmic rays at the ground level and at the shallow depth under-ground, and in particular to the detailed studies of the signatures of these radiations in HPGe spectrometers situated shallow underground. The ground level part of the laboratory (GLL), at 75 m above sea level, is situated at the foot of the vertical loess cliff, which is about 10 meters high. The underground part of the laboratory (UL), of the useful area of 45 m², is dug into the foot of the cliff and is accessible from the GLL via the 10 meters long horizontal corridor, which serves also as a pressure buffer for a slight overpressure in the UL (Fig.1). The overburden of the UL is about 12m of loess soil, equivalent to 25 meters of water. [1]

In the UL laboratory the gamma spectrum is recorded using HPGe detector and fast ADC unit made by CAEN, and analysed using software developed in our laboratory. Besides HPGe measurements the air pressure, temperature and humidity were recorded in UL also. Values for temperature, pressure and humidity of outside air was taken from publicly available web site. The time period from which the measurements were used in this analysis is from beginning of December 2009 till end of April 2010.

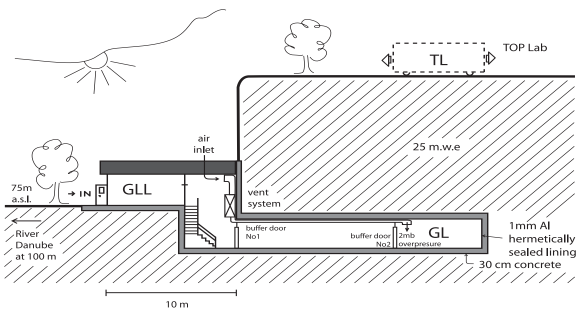

Figure 1. Cross-section of the low-level and CR laboratory at IOP, Belgrade, 44°49'N, 20°28'E, vertical rigidity cut off 5.3 GV.

Continuous Cosmic rays' (CR) spectrum measure-ments by means of a pair of small plastic scintillators [(50x25x5)cm] started in the GLL and UL back in 2002 and lasted for about 5 years. It agrees to the spectrum of relatively shallow underground laboratories worldwide [2]. These measurements yielded the precise values of the integral CR muon flux at the ground level and underground level laboratory, at the location of Belgrade [3]. Different analyses of the time series of these measurements have also been performed [4, 5]. Since the UL is completely lined with the hermetically sealed 1 mm thick aluminum lining, and the ventilation system keeps the overpressure of 2 mbars of doubly filtered air, the concentration of radon is kept at the low average value of about 10 Bq/m³.

BACK

Measurements and analysis of periodicy of gamma-rays in underground laboratory had been reported [6-7], and also for Radon measurements and periodicity [8-9] including advanced Multivariate Analysis tecniques [10-11].

Most recent research done in our laboratory [12] addresses the question of determination of origin of low energy gamma-rays detected by HPGe detector, which are coming either from environmental radiation or from CR. In this paper the correlative analysis is used to address the same question of composition of low-energy gamma-rays spectrum, thus giving us the new approach to the research done in [12].

The correlative analysis in this paper was done using Toolkit for Multivariate Analysis TMVA[13] package as part of the ROOT[14] software, widely used in analysis, especially for High Energy Physics experiments. The TMVA was used for analysis extensively in our laboratory, and it was the natural choice to use the software for correlative analysis also. Lomb-Scargle periodograms were produced using software developed in Low-Background laboratory.

2. EXPERIMENTAL SETUP

In the UL 35% efficiency radiopure HPGe detector, made by ORTEC, is used. The HPGe is sourounded by 12 cm thick cylindrical lead castle. Cosmic ray setup consists of a single [(100x100x5)cm] plastic scintillator detector equipped with four PMTs directly coupled to the corners beveled at 45°, made by Amcrys-H of Kharkov, Ukraine. The signals from HPGe detector and plastic scintillators give output to fast ADC unit with four independent inputs each, made by CAEN, of the type N1728B. CAEN units are versatile instruments capable of working in the so-called energy histogram mode, when they perform like digital spectrometers, or/and in the oscillogram mode, when they perform like digital storage oscilloscopes. In both modes they sample at 10 ns intervals, into 2^{14} channels. The full voltage range is ±1.1V.

CAEN units are capable of operating in the list mode, when every analyzed event is fully recorded by the time of its occurrence over the set triggering level, and its amplitude, in the same PC, which controls their workings. This enables to off-line coincide the events at all four inputs, prompt as well as arbitrarily delayed, with the time resolution of 10 ns, as well as to analyze the time series not only of all single inputs, but also of arbitrary coincidences, with any integration period from 10 ns up. The flexible software that performs all these off-line analyses is user-friendly and is entirely homemade.

The preamplifier outputs of the PMTs of detectors are paired diagonally, the whole detector thus engaging the two inputs of the CAEN unit. The signals from these inputs are later off-line coincided and their amplitudes added, to produce the singles spectra of these detectors. Offline coincidence allows that the high intensity but uninteresting low energy portion of the background spectrum of this detector (up to some 3 MeV), which is mostly due to environmental radiations, is practically completely suppressed, leaving only the high energy-loss events due to CR muons and EM showers that peak at about 10 MeV, as shown in Figure 2.

Since event of HPGe gamma spectrum and Cosmic rays consists of time-stamp and the amplitude, off-line analysis is used to create time series of arbitrary time window with selection of specific part of gamma spectrum as well as the time series of Cosmic ray flux in UL (Figure 3.). This enables that whole gamma spectrum can be divided into energy ranges, and analyze each energy range separately. The spectrum separation is done on channel numbers, and after the energy calibration, the energy ranges used in our analysis are 180-440 keV, 620-1330 keV and 1800-4440 keV. The full gamma spectrum is recorded in range of 180-6670 keV. The part of gamma spectrum of the HPGe is shown in Figure 4.

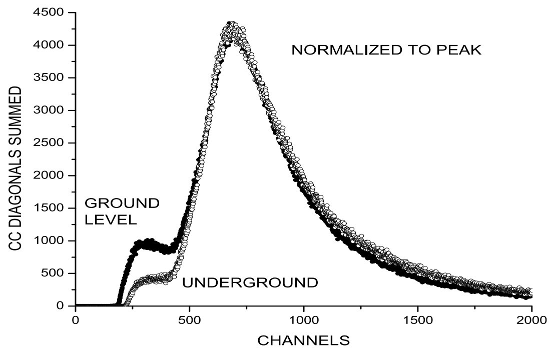

Fig. 2. The sum spectra of two diagonals of big plastic detectors in the UL and GLL .

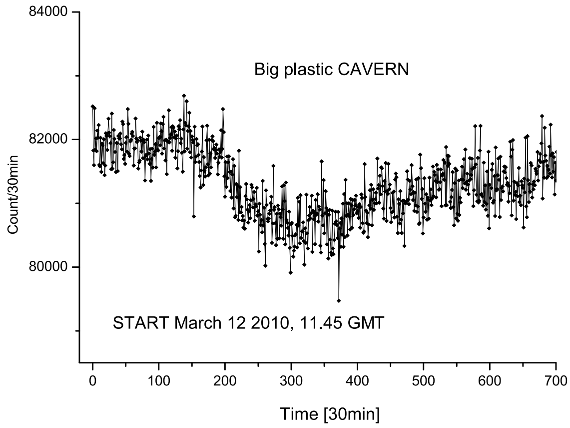

Fig. 3. The time series of the CR muon count of the big plastic detector in the UL.

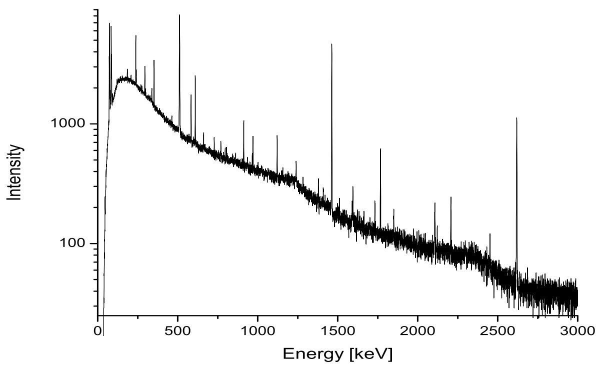

Figure 4. Gamma spectrum of the HPGe detector in 12cm lead castle in the Underground laboratory.

3. Results and discussions

The analysis starts with correlation analysis. The software for correlative analysis is a part of TMVA package. Hourly time series of variables, atmospheric pressure P, temperature T, and humidity H for UL (P_R, T_R, H_R), and outside (P,T,H) are used, Cosmic ray time series (CR) as well as T (DT) and H (DH) difference of UL and outside values make the number of nine input variables. The table summarizing the linear correlation coefficients is shown in Table 1. We can see correlation between each input variable and HPGe gamma spectrum for full energy range in Table 1 also.

DH	-10	69	-9	-86	57	-22	51	-25	-64	100
DT	7	-98	7	60	-30	10	-24	42	100	-64
CR	-14	-42	-65	36	-14	-52	13	100	42	-25
H_R	-2	30	-44	-1	42	-59	100	13	-24	51
P_R	14	-13	80	-8	-22	100	-59	-52	10	-22
T_R	1	43	-16	-41	100	-22	42	-14	-30	57
H	10	-63	-15	100	-41	-8	-1	36	60	-86
P	11	-9	100	-15	-16	80	-44	-65	7	-9
T	-6	100	-9	-63	43	-13	30	-42	-98	69
HPGe	100	-6	11	10	1	14	-2	-14	7	-10
	HPGe	T	P	H	T_R	P_R	H_R	CR	DT	DH

Table 1. Summary table of linear correlation coefficient for all 9 input variables' 1 hour time series and 1 hour time series of HPGe gamma spectrum for full energy range.

Correlation analysis was done also for three mentioned energy ranges, the Table 2. summarizes the results.

	180-6670 keV	180-440 keV	620-1330 keV	1780-4440 keV
T	-0.070	-0.045	-0.041	-0.096
P	**+0.111**	**+0.124**	**+0.033**	**+0.010**
H	+0.106	+0.056	+0.047	+0.101
T_{UG}	+0.013	-0.029	+0.014	-0.012
P_{UG}	+0.149	+0.111	+0.091	+0.061
H_{UG}	-0.029	-0.068	-0.030	+0.028
CR	**-0.140**	**-0.179**	**-0.030**	**+0.036**
T_{UG}-T	+0.076	+0.043	+0.046	+0.100
H_{UG}-H	-0.105	-0.083	-0.055	-0.072

Table 2. Linear correlation coefficients in % for full and three narrower energy ranges.

All the correlation of HPGe gamma spectrum hourly time series and input variables are not significant. The biggest correlation coefficient with HPGe time series is pressure time series measured underground followed by Cosmic ray time series. It is interesting to notice the change of correlation coefficients with HPGe for atmospheric pressure and Cosmic rays time series. While pressure correlation coefficients tend to drop going towards higher gamma energies, Cosmic rays' correlation coefficients are increasing from negative sign to positive one. This observation is in agreement with the fact that the Cosmic rays are contributing more to the the gamma spectrum of higher energies, as it was shown in [12]. Since Cosmic rays and pressure are anti-correlated with correlation coefficient of -65%, as can be seen in Table 1, increase in atmospheric pressure will give negative correlation coefficient of HPGe and Cosmic rays' time series. This can be explained by having in mind that Cosmic rays are contributing insignificantly to gamma spectrum on lower energies [12] behaving like constant in low energy range, while increase in pressure increases the air density, thus more gamma scattering events are contributing to low energy gamma spectrum.

In the periodogram analysis the Lomb-Scargle periodograms were produced for atmospheric variables P, T, H and HPGe gamma spectrum. The periodograms show only daily periodicity of T, H time series as shown on figures 5 and 6. The P periodogram on Figure 7. Shows expected daily and mid-daily periodicity. It is noticeable that the periodogram for P has lowest spectral powers, which means that periodicity of P is less noticeable. Also, the unexpected 1/3 day periodicity is with low spectral power. The periodogram analysis showed that there is no significant periodicity in HPGe gamma spectrum time series, as shown on Figure 8.

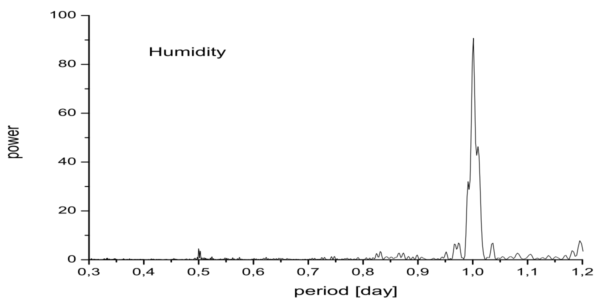

Figure 5. Lomb-Scargle periodogram of air humidity.

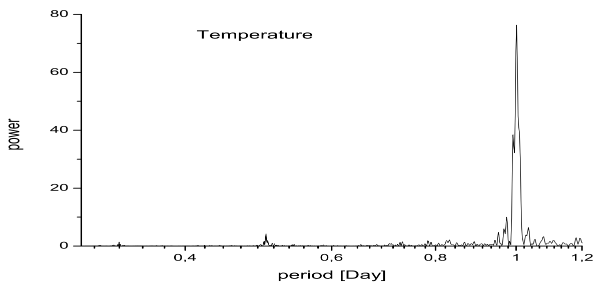

Figure 6. Lomb-Scargle periodogram of air temperature.

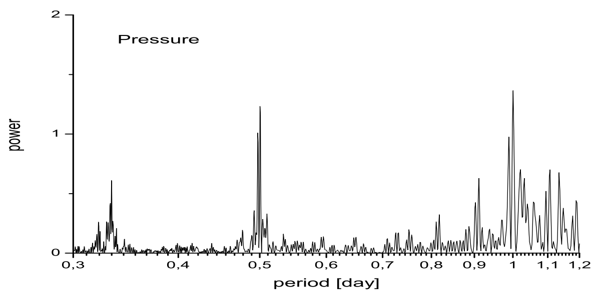

Figure 7. Lomb-Scargle periodogram of air pressure.

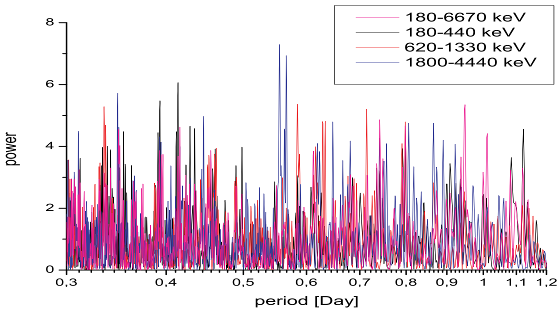

Figure 8. Lomb-Scargle periodogram of full and three different energy range HPGe gamma spectrum time series.

Conclusion

In the Underground laboratory of Low Background Laboratory in the Institute of Physics Belgrade the continuous HPGe gamma spectrum, Cosmic ray intensity and climate variables were continually measured in the period from beginning of December 2009 till the end of April 2010. The HPGe gamma spectrum is split into three energy ranges, low, intermediate and high. For each of the energy intervals periodogram and correlative analysis of dependence of continuous gamma spectrum on cosmic ray intensity time series and climate variables time series is performed. Periodogram analysis is done using Lomb-Scargle periodograms. The correlation coefficient between air pressure and Cosmic rays is -65%. The correlation coefficients between HPGe gamma spectrum and input variables are not significant. The decrease of values of correlation coefficients of gamma spectrum and air pressure is present. The increase of values of correlation coefficients of gamma spectrum and Cosmic rays is present also. Increase in atmospheric pressure is resulting in negative correlation coefficient between HPGe and Cosmic rays' time series for low energy gamma spectrum. The more significant contribution of Cosmic rays in high energy gamma spectrum, as opposite to insignificant contribution of Cosmic rays to low energy gamma spectrum is evident. Lomb-Scargle periodograms showed daily periodicity for air temperature and humidity, and additional mid-daily periodicity for air pressure. There is no noticeable periodicity for each of energy ranges of gamma spectrum.

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BACKGROUND SPECTRUM CHARACTERISTICS OF THE HPGE DETECTOR LONG-TERM MEASUREMENT IN THE BELGRADE LOW-BACKGROUND LABORATORY

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Abstract. *The Belgrade low-level background laboratory, built in 1997, is shallow (25 m.w.e) underground space (45m²) which is constantly ventilated with fresh air against radon. The muon intensity (about 3.5 times less than at ground level), radon concentration (suppressed to averaged value of 15 Bqm⁻³), as well as gamma-ray background are monitoring for more than eight years. After long-term measurement using the radiopure HPGe detector with 35% relative efficiency, the measured data includes radionuclide concentration of detector surroundings, estimation of background time variation due to radon and cosmic-rays as well as MDA values for typical samples of water matrix. The detailed characteristics of gamma-ray background spectra are here presented.*

Key words : *Underground laboratory, Low-level background, long-term gamma-ray measurement*

1. INTRODUCTION

Various experiments which strive for the detection of very rare events require the lowest possible background radiation which can be achieved only in a deep underground laboratory. Some of recent the most interesting are double beta-decay experiments, [1] and dark matter searches, [2]. In any applied measurements of low activities, a goal that is pursued by all gamma spectroscopist is to lower the minimum detectable activity (MDA) of their detection system obtaining more statistical evidence in less time.

But, any long and even short-term gamma-ray background measurement is subject to certain temporal variations due to time variability of two prominent contributors to background, cosmic-rays and radon. The most of the low background laboratories that deal with low activity measurements have developed routine measurements of background. The duration of these measurements may be from one day to even a month and they are designed to produce results with sufficiently low statistical errors for the envisaged measurements. These measurements yield only average values of the background, what in principle may lead to systematic errors in later measurements, especially of NORM samples.

The averaged values of the background, gamma lines and continuum, nuclide concentrations or MDA presenting a "personal card" of used detector system for certain samples in any low-level background laboratory, [3]. Here is attempt to present our low-level background laboratory in a similar way. First of all, the detailed description of the laboratories and used detector system are described.

2. DESCRIPTION OF THE LABORATORIES AND EQUIPMENT

The Belgrade underground low-level laboratory (UL), built in 1997 and located on the right bank of the river Danube in the Belgrade borough of Zemun, on the grounds of the Institute of Physics. The overburden of the UL is about 12 meters of loess soil, equivalent to 25 meters of water. It is equipped with ventilation system which provides low radon concentration of 15(5) Bq/m³. The "passive" shield consists of 1 mm thick aluminum foil which completely covers all the wall surfaces inside the laboratory, including floor and ceiling. As the active radon shield the laboratory is continuously ventilated with fresh air, filtered through one rough filter for dust elimination followed by active charcoal filters for radon adsorption. The UL has an area of 45m² and volume of 135m³ what required the rate of air inlet adjusted to 800m³/h. This huge amount of fresh air contributes to greater temperature variations and the long-term mean value of temperature inside the UL is 19(4)°C. The rate of air outlet (700m³/h) was adjusted to get an overpressure of about 200 Pa over the atmospheric pressure, what prevents radon diffusion through eventual imperfections in the aluminum layer. Relative humidity is controlled by a dehumidifier device, what provides that the relative humidity in the underground laboratory does not exceed 60%. The muon intensity (which is about 3.5 times less than at ground level), radon concentration and gamma-ray background are monitoring for more than eight years. Comparative background study is performing in the GLL (at ground level) which is equipped with a Ge detector (13% relative efficiency and not intrinsically low-radioactivity level, named SGe) and a big plastic scintillator (1m², named BPS) in veto position. The GLL is air-conditioned (average radon concentration of

50(30) Bq/m³) has an area of 30m² and volume of 75m³. The Fig. 1 presents veto arrangement of the HPGe detector (BGe, in 12cm lead shield) and big plastic scintillator, inside the UL.

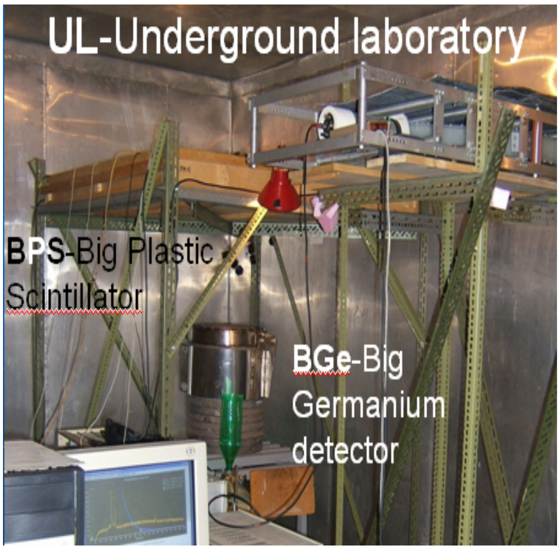

Fig. 1 Veto arrangement of the HPGe detector (BGe) and big plastic scintillator inside the UL

3. DESCRIPTION OF DETECTOR SYSTEMS IN THE UL

The low-level background detector system in the UL includes an intrinsically low-radioactivity level p-type Ge detector (35% relative efficiency, named BGe) and another plastic veto scintillator (1m², named BPS) situated coaxially above the BGe detector. The BGe is a GEM30 model (made by ORTEC) in LB-GEM-SV cryostat configuration with magnesium end cap. The energy resolution at 1332.5keV, measured by analog data acquisition system, is 1.72keV, 0.65keV at 122keV as well as the Peak to Compton ratio at 1332.5keV has value of 68. The cylindrical lead shielding of the BGe, with a wall thickness of 120 mm and an overall weight of about 900kg, was cast locally out of scratch plumbing retrieved after the demolition of some old housing. Radon monitoring inside the laboratories was performed by radon monitor, model RM1029 manufactured by Sun Nuclear Corporation. The device consists of two diffused junction photodiodes as a radon detector, and is furnished with sensors for temperature, pressure and relative humidity. A pair of plastic scintillator detectors is used for CR muon measurements at both laboratories. One of them is a larger (100cmx100cmx5cm) detector (BPS), equipped with four PMT directly coupled to the corners beveled at 45°, made by Amcrys-H, Kharkov, Ukraine. The other, a smaller 50cmx23cmx5cm plastic scintillator detector, with a single PMT looking at its longest side via a Perspex light guide tapering to the diameter of a PMT, made by JINR, Dubna, Russia, and assembled locally. The smaller detector may serve as a check of stability of the muon time series obtained from the larger detector, which is important for long term measurements. Two flash analog to digital converters (FADC), made by C.A.E.N (type N1728B), which sample at 10 ns intervals into 214 channels were used to analyze spectra from Ge detectors as well as corresponding BPS. User-friendly software was developed to analyze the C.A.E.N data with the possibility to choose the integration time for further time-series analysis that corresponds to integration time of the radon monitor. The performances of digital acquisition system as well as software developed for analysis were described in detail, [4].

4. THE RESULTS OF BACKGROUND MEASUREMENTS IN THE UL

Additional to intrinsically low-radioactivity level of the BGe itself, environmental radioactivity is low, too. The UL was built from low activity concrete about 12 Bq/kg of U-238 and Th-232, and of 23 Bq/kg and 30 Bq/kq of surrounding soil, respectively. Radioactivity of aluminum wall-lining is negligible. Pb-210 activity of used lead shield of 30Bq/kg is measured. After long-term cosmic-ray, [5], radon concentration, [6] and gamma-ray background measurements, no significant long-term time variations of gamma background was found, [7]. After several years of almost continuously background measurements, the integral background rate in the region from 40keV to 2700keV has mean value of about 0.5 cps. The lines of Co-60 are absent in the background spectrum, while the line of Cs-137 with the rate of 1×10^{-4} cps starts to appear significantly only if the measurement time approaches one month. Fukushima activities, though strongly presented in our inlet air filters samples, did not enter the background at observable levels, in spite of the great quantities of air that we pump into the UL to maintain the overpressure, and it seems that the double air filtering and double buffer door system, along with stringent radiation hygiene measures, is capable of keeping the UL clean in cases of global accidental contaminations. No signatures of environmental neutrons, neither slow nor fast, are present in direct background spectra.

The Fig. 2 shows a characteristic shape of background spectrum obtained in the UL after about 6 months of measuring, with distinctive Pb X-ray lines at the beginning of the spectrum, annihilation line, and lines from ^{40}K and ^{208}Tl (2614.5keV) at the end of the spectrum with a lot of post-radon lines between them.

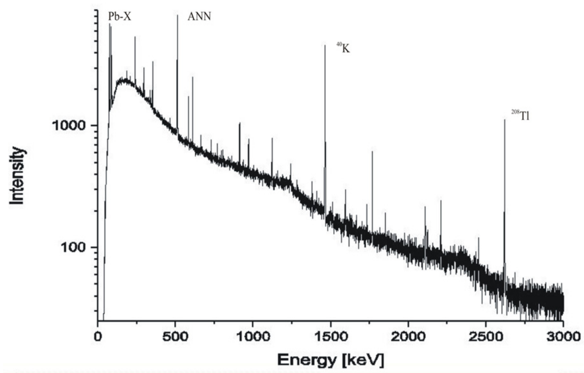

Fig. 2 Background spectrum of the HPGe detector (BGe) inside the UL after about 6 months of measuring

The table 1 in the third column presents gamma-ray background values of typical spectrum measured in the UL using the BGe in direct (no veto) mode. The measurement time was about 6 months.

Table 1 The background characteristics of the BGe inside the UL

Line/ region (keV)	Radionuclide/ series/ nuclear reaction	Intensity (10^{-3} s^{-1})	MDA (mBq) for 100ks Water matrix
40-2700	-	500	-
46.5	Pb-210/U-238	0.38(11)	1500
53.2	U-234	-	9400
63.3	Th-234	-	700
72.8	Pb-X-$K_{\alpha 2}$	3.1(1)	-
75	Pb-X-$K_{\alpha 1}$	6.2(1)	-
84.9	Pb-X-$K_{\beta 1}$	4.2(1)	-
87.3	Pb-X-$K_{\beta 2}$	1.49(6)	-
92.5	Th-234	-	100
143.8	U-235	-	20
163.4	U-235	-	110
200.3	U-235	-	100
238.6	Pb-212/Th-232	0.83(4)	40
242	Pb-214/U-238	0.20(2)	-
295.2	Pb-214/U-238	0.71(4)	40
338.3	Ac-228/Th-232	0.15(2)	-
351.9	Pb-214/U-238	1.26(5)	30
477.6	Be-7	-	40
510.8+511	Tl-208/Th-232/ANN	7.0(1)	-
583.2	Tl-208/Th-232	0.30(3)	56
609.2	Bi-214/U-238	1.08(5)	60
661.7	Cs-137	0.10(5)	9
727.3	Bi-212	-	200
803.3	Pb-206 (n,n^{I}) Pb-206	0.11(2)	-
911.2	Ac-228/Th-232	0.25(2)	110
969	Ac-228/Th-232	0.11(2)	80
1001	Pa-234m	-	1300
1120.4	Bi-214/U-238	0.28(3)	-
1173.2	Co-60	-	19
1332.5	Co-60	-	11
1238.1	Bi-214/U-238	0.09(2)	-
1460.8	K-40	3.27(9)	850
1764.6	Bi-214/U-238	0.49(3)	230
2103.7	2614.5SE/Tl-208	0.13(2)	-
2204.2	Bi-214/U-238	0.15(2)	-
2614.5	Tl-208/Th-232	1.05(5)	-

The fourth column of the same table presents minimum detectable activity (MDA) calculated for predicted measurement time of 100000 seconds (approximately one day) for cylindrical sample (volume of 120cm^3) situated on the top of the detector. Efficiency calibration was obtained by GEANT4 simulation toolkit as well as experimentally using appropriate standard. The difference between the two efficiency calibration curves is less than 5% for sample of water matrix, which MDA is here presented. MDA values are calculated as $MDA=L_D/(t \times Eff \times p)$, where the $L_D=2.71+4.65B^{1/2}$ is detection limit. B is background at the energy of gamma-ray line with absolute detection efficiency Eff and emission probability p. If the predicted measurement time t is valued in seconds then MDA values have Bq unit. The obtained MDA values are presented for water matrix cylindrical samples in bottles with volume of 120cm^3.

With the BPS currently positioned rather high over the detector top, at a vertical distance of 60cm from the top of the lead castle, in order to allow for the placing of voluminous sources in front of the vertically oriented detector, the off-line reduction of this integral count by the CR veto condition is only about 18%. Up to a factor of two might be gained if the veto detector were to be positioned at the closest possible distance over the BGe detector. This configuration requires some changes of the lead shield including introducing a sliding lead lid. Such a new shielding and veto configuration would be additionally reduce gamma-ray background up to the same factor that corresponds to factor of reduction expected for cosmic rays.

We do not insist on the lowering of statistical errors which depend on background levels solely and are difficult to reduce further with available means, but rather emphasize its stability due to the low and controlled radon concentration in the laboratory. This is essential, especially in NORM measurements, and makes our system virtually free of systematic errors as compared to systems which operate in environments where radon is not controlled. In that systems the reduction of post-radon background activities is achieved by flushing the detector cavity with liquid nitrogen vapor, where the transient regimes during sample changes and possible deposition of radon progenies may introduce systematic uncertainties which are difficult to estimate.

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На основу члана 82. Закона о научноистраживачкој делатности ("Службени гласник Републике Србије", број 110/2005, 50/2006 - испр., 18/2010 и 112/2015), члана 33. тачка 5. Статута Института за физику и захтева који је поднео

НИКОЛА ВЕСЕЛИНОВИЋ
на седници Научног већа Института за физику одржаној 07.06.2016. године, донета је

ОДЛУКА
О СТИЦАЊУ ИСТРАЖИВАЧКОГ ЗВАЊА

НИКОЛА ВЕСЕЛИНОВИЋ
стиче истраживачко звање
Истраживач сарадник
Р е и з б о р

ОБРАЗЛОЖЕЊЕ

Никола Веселиновић је 13.04.2016. године поднео захтев за реизбор у истраживачко звање истраживач сарадник. Научно веће Института за физику је на седници одржаној 15.04.2016. године образовало Комисију за спровођење поступка у саставу др Александар Драгић, виши научни сарадник, Институт за физику, др Димитрије Малетић, виши научни сарадник, Институт за физику и др Предраг Ујић, виши научни сарадник, Институт за нуклеарне науке ВИНЧА. Научно веће је на седници од 07.06.2016. године утврдило да именовани испуњава услове из члана 70. став 3. Закона о научноистраживачкој делатности за реизбор у звање **истраживач сарадник,** па је одлучило као у изреци ове одлуке.

Одлуку доставити подносиоцу, архиви Института за физику, кадровској служби Института за физику и рачуноводственој служби Института за физику.

Председник Научног већа
др Марија Радмиловић Рађеновић

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УНИВЕРЗИТЕТ У БЕОГРАДУ
ФИЗИЧКИ ФАКУЛТЕТ
Бр. 36/10
29.6. 2018 год.
БЕОГРАД СТУДЕНТСКИ ТРГ 12-16
П. ФАХ 44

На основу члана 161 Закона о општем управном поступку («Службени Лист СРЈ» број 33/97 и 31/01), и члана 120 Статута Универзитета у Београду - Физичког факултета, по захтеву НИКОЛЕ ВЕСЕЛИНОВИЋА, дипломираног физичара, издаје се следеће

УВЕРЕЊЕ

НИКОЛА ВЕСЕЛИНОВИЋ, дипломирани физичар, дана 29. јуна 2018. године, одбранио је докторску дисертацију под називом

"РЕАЛИЗАЦИЈА ДЕТЕКТОРСКОГ СИСТЕМА У ПОДЗЕМНОЈ ЛАБОРАТОРИЈИ ЗА ИЗУЧАВАЊЕ СОЛАРНЕ МОДУЛАЦИЈЕ КОСМИЧКОГ ЗРАЧЕЊА У ХЕЛИОСФЕРИ"

пред Комисијом Универзитета у Београду - Физичког факултета, и тиме испунио све услове за промоцију у ДОКТОРА НАУКА – ФИЗИЧКЕ НАУКЕ.

Уверење се издаје на лични захтев, а служи ради регулисања права из радног односа и важи до промоције, односно добијања докторске дипломе.

Уверење је ослобођено плаћања таксе.

ДЕКАН ФИЗИЧКОГ ФАКУЛТЕТА

Проф. др Јаблан Дојчиловић