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Measurements of muon flux in the Pyhäsalmi underground laboratory

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Abstract

The cosmic-ray induced muon flux was measured at several depths in the Pyhäsalmi mine (Finland) using a plastic scintillator telescope mounted on a trailer. The flux was determined at four different depths underground at 400 m (980 m.w.e), at 660 m (1900 m.w.e), at 990 m (2810 m.w.e) and at 1390 m (3960 m.w.e) with the trailer, and also at the ground surface. In addition, previously measured fluxes from depths of 90 m (210 m.w.e) and 210 m (420 m.w.e) are shown. A relation was obtained for the underground muon flux as a function of the depth. The measured flux follows well the general behaviour and is consistent with results determined in other underground laboratories.
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1. Introduction

Existing and future experiments on searching for proton decay or dark matter, or on low-energy neutrino detection need a deep underground location and low-background environment. The cosmic-ray muon flux can be reduced several order of magnitudes by shielding experiments with rock overburden.

Muons, however, are usually not the dominant background in underground experiments as they can be identified and distinguished by relatively simple way. Much more problematic contribution on the background comes from high-energy neutrons generated by muons in the interactions

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with the surrounding rock or with the detector material. The energy of these neutrons may even extend up to the GeV region [1]. This is, for example, the factor limiting the current experiments on dark matter searches [2].

Precise knowledge of the muon flux is thus important in order to estimate, or calculate by Monte Carlo codes, the absolute underground neutron flux. In the present work, the underground cosmic-ray muon flux was systematically investigated by measuring it at several depths in the Pyhäsalmi mine.

The Pyhäsalmi mine (owned by Inmet Mining Corporation, Canada) is an active zinc, copper and pyrite mine in central Finland. It is the oldest and the deepest operational base-metal mine in Europe, extending down to about 1440 m (corresponding about 4100 m.w.e.). The site provides excellent opportunities for the research of underground physics by offering very stable bedrock, modern infrastructure, and good traffic conditions all around a year. CUPP (Centre for Underground Physics in Pyhäsalmi) is establishing an international underground laboratory into the connection with the mine.

2. Experimental details

The experimental setup consisted in total of 12 plastic scintillation counters of type NE102A, having maximum light output at wavelength of 423 nm. The size of a scintillation plate is 50 cm × 50 cm × 5 cm. Each counter was attached with Hamamatsu head-on type R329-02 photomultiplier tube (PMT) using fishtail-shaped acrylic light guide and BC-630 as an optical connector. The sensitivity range of the PMT is 300–600 nm.

Each scintillation plate and PMT was mounted on a water- and light-tight stainless-steel box with size of 1.55 m × 0.65 m × 0.15 m, and the total weight of about 60 kg. The boxes were arranged in a geometry covering a sensitive area of $1.5 \, m^2$, and were installed on a movable trailer together with the data acquisition system (DAQ). The vertical distance (of the mid-planes) of two scintillation plates was 15 cm.

Two boxes were overlaid, as shown in Fig. 1, in order to get a coincidence signals and reduce noise

signals. The DAQ consisted of two separate and identical systems, each one connected into six scintillators. Standard NIM electronics with discriminators and coincidence units were used together with 8-bit ADC & Scaler units. Detection threshold was set such that noise signals or Cherenkov radiation in the PMTs is not measured. All signals above the threshold were accepted to the coincidence determination. The procedure of the threshold setting is described more detailed in Ref. [3]. UPS system was used to ensure secure data collection in the case of (probable) electrical break-down.

The scintillators were tested before the installation on the trailer. The efficiency measurement was done by piling-up three detectors (stainless-steel boxes), and the one to be tested was placed in the middle. The trigger was taken from a coincidence unit which verified that muon had passed all the counters. The efficiency of $(97 \pm 3)\%$ was obtained as the average result of the test measurements, and this value was used for all detectors. The uncertainty was determined from the standard deviation.

3. Measurements

The muon-flux measurements were performed with the trailer at the ground surface and at 4
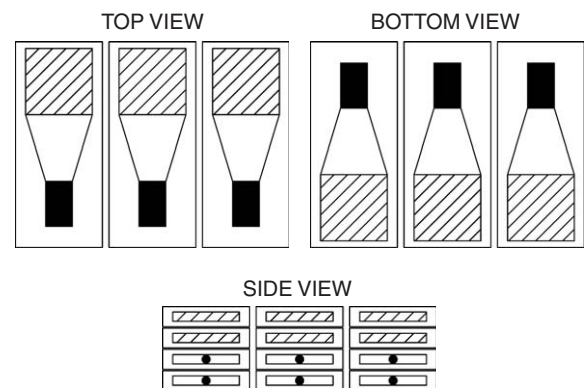

Fig. 1. Schematic drawing of the experimental arrangement. The shaded areas illustrate plastic scintillator plates and black areas photomultiplier tubes, and they are connected by light guides. The frame around a plate, light guide and PMT combination illustrates a stainless steel box.

different depths underground, which were two positions at 400 m (corresponding 980 m.w.e), 660 m (1900 m.w.e), 990 m (2810 m.w.e), and 1390 m (3960 m.w.e). In addition, data are shown for the depths of 90 and 210 m which have been measured earlier with similar (but stationary) detector telescope. Their corresponding depths are 210 m.w.e and 420 m.w.e, respectively.

The measurement durations were chosen such that the statistical uncertainty would be small (about 2% or less). The measurement took about two weeks in 400 and 660 levels each, about two months at 990 levels, and about four months at 1390 level. Details of the measurements are shown in Table 1.

4. Data analysis and results

The composition of the rock in the mine is well known [4], and the average rock density of $2.85\,\text{g/cm}^3$ was used to convert the depths in the m.w.e-units (metre water equivalent). The muon flux was obtained by dividing the measured counts by the measurement time (see Table 1) and the detector area ($1.5\,\text{m}^2$). In the analysis vertical muons were not distinguished from non-vertical muons.

The measurement positions of underground levels of 210 and 400 m situate directly under the open pit mine which is nearly 100 m depth, and contains also some loose rocks and sand. The metre-water-equivalent values of these two depth were taken as effective depth determined by simulation [5]. Their depth (as m.w.e) corresponds to flat surface geometry giving the same reduction in the flux.

The open pit mine has no (significant) effect on other measurement positions since they are not directly below it, and mostly lie deeper. For these levels the metre-water-equivalent depth was determined from the vertical distance to the surface, taking into account possible underground caverns.

The number of muons were obtained from the energy-loss spectrum by counting the events. The statistical uncertainty was taken as square root of the number of events. Fig. 2 shows, as an example, the total muon energy-loss spectrum measured at 660 m underground.

The collected number of muons were corrected for the detector efficiencies (being about $(97\%)^2$), and by the amount of muon events below the energy threshold which was estimated in the test measurement to be $(5 \pm 2)\%$ [3]. Signals from neutrons induced by the rock activity or muons were not corrected for.

The geometrical uncertainty, i.e. that the two scintillation plates were not fully overlapping, was estimated as 4%. The uncertainty in the depth was taken as about 5 m corresponding to about 20 m.w.e including also the variation in the average rock density.

The detector acceptance was taken into account by determining the effective area of the scintillation pair at each depth using two different zenith angle distribution (Miyake model and

Table 1
Parameters of the measurements of the present work

Depth (m) (m.w.e)	Duration (h)	Coordinates (x, y)	Counts	Flux density $(\text{m}^{-2}\,\text{s}^{-1})$
0	12	(8308,2680)	7600000	180 ± 20
400 (980)	192	(8535,2635)	13232	
400 (980)	132	(8580,2657)	10510	$(2.1 \pm 0.2) \times 10^{-2}$
660 (1900)	325	(8390,2425)	3850	$(3.2 \pm 0.3) \times 10^{-3}$
990 (2810)	1368	(8400,2392)	3282	$(6.2 \pm 0.6) \times 10^{-4}$
1390 (3960)	2748	(8225,2460)	1206	$(1.1 \pm 0.1) \times 10^{-4}$

In the first column the nominal depth and corresponding equivalent depth are given. Coordinates are those used by the mine and they describe the position of the trailer. The 'Counts' means the uncorrected number of muons collected. In the last column the deduced muon flux of the corresponding level is shown. The average is given for the depth of 400 m.
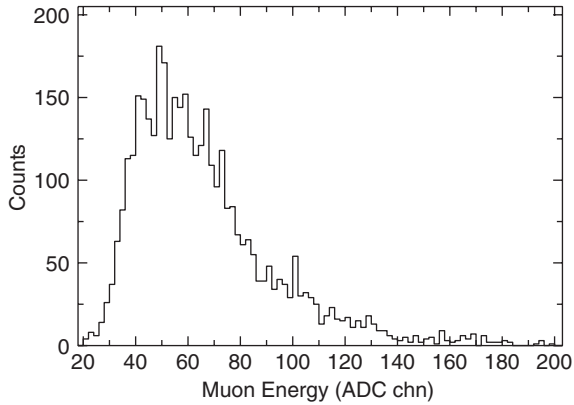
Fig. 2. The total energy-loss spectra, in ADC-channels, collected at 660 m underground. The bin size is two channels.

Intermediate-depth model) of cosmic-ray muons. The distributions were taken from Ref. [6], and they resulted the same effective area for 210-level and deeper. For the surface and 90-level the Miyake distribution was used. The acceptance correction decreases for deeper depths; for the surface the acceptance was corrected by a factor of 1.42 and for the 1390-level by a factor of 1.23. The uncertainty of the correction was assumed to be better than 10%.

The results of the muon fluxes measured in the present work are shown in Fig. 3 as full circles. The flux at 400 level is an average of the two measurement. In addition, Fig. 3 shows fluxes from 90- and 210-levels, which have been measured earlier with similar but stationary detector system [3], as full squares. The reduction factor of the muon flux compared with the surface flux is shown in parentheses for each level. Open symbols show the results of other muon-flux measurements in some underground laboratories for comparison.

The behaviour of the total muon flux underground as a function of the depth was extracted from the data using six data points (full symbols in Fig. 3 except the surface flux) by fitting a function of the form [7]

$$F(x) = A \cdot (x_0/x)^{\eta} \cdot \exp(-x/x_0), \qquad (1)$$

where F is the flux as $\mathrm{m}^{-2}\,\mathrm{s}^{-1}$ and x the depth as m.w.e. The following values were obtained for the
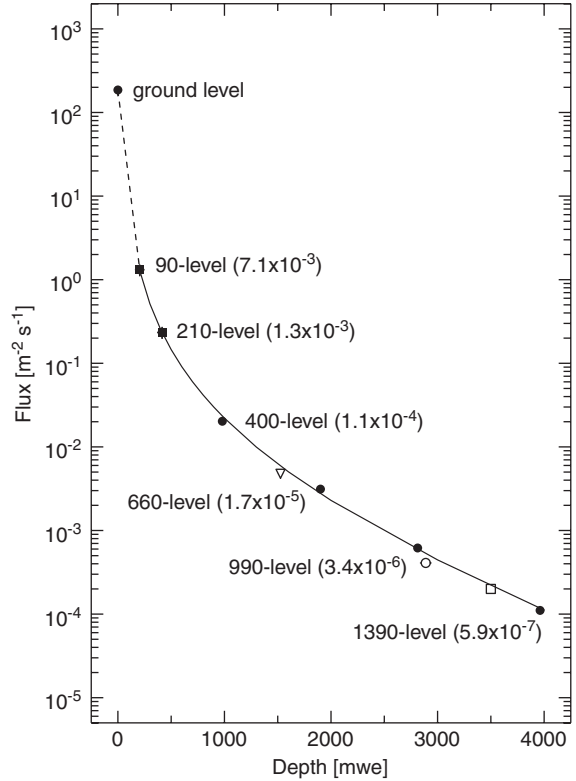

Fig. 3. Full symbols present the fluxes measured in the Pyhäsalmi mine: full circles are the result of the present work, full squares have been measured earlier with similar detector system. In parentheses the corresponding reduction of the flux compared with the flux at the surface is given. Open symbols are shown in comparison with other measurements: open circle from Ref. [1], open square from Ref. [8], open triangle from Ref. [9]. If not shown, the uncertainty is smaller than the size of a symbol. The solid line is the result of the fit of Eq. (1), and the dashed line is just a straight line to guide the eye.

fit parameters (with $\chi^2 \approx 0.007$):

$A = (0.025 \pm 0.004)\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}$,

$\eta = 2.18 \pm 0.12$,

$x_0 = (1330 \pm 140)\ \mathrm{m.w.e.}$

The fit function (Eq. 1) is plotted in Fig. 3 with the above parametres as the solid line.

5. Discussion

The flux measured in the present work is consistent with results obtained in other underground

laboratories at specific depths (Fig. 3). The data agrees very well with the measurements done at Gran Sasso and WIPP (Refs. [8,9]), and reasonably well also with the result measured at Boulby [1]. The deviation with the Boulby value at this specific depth is some 30%.

The best fit plotted in Fig. 3 as the solid line describes well the decrease of the flux as a function of the depth, and it can be used to estimate the muon flux at an arbitrary depth with a good accuracy. The values of η and x_0 are also relatively close to the values of other similar fit-results obtained for the behaviour of the vertical muon intensity as a function of the depth ($\eta = 1.93^{+0.20}_{-0.12}, x_0 = (1155^{+60}_{-30})$ m.w.e) [7].

6. Conclusion

Cosmic-ray induced muon flux has been systematically measured at several depths in the Pyhä-salmi mine. The data appear to be the most comprehensive one of this type, and at specific points consistent with results determined in other underground laboratories. A relation obtained for the underground muon flux as a function on the depth is also consistent with previous investigations. However, since the measurements were done with the same detector at the different depths, the systematical uncertainty between the depths should be negligible. The muon-flux measurements will continue.

The fast neutron background is going to be measured in the Pyhäsalmi underground laboratory during the next two years. The measured muon flux of the present work offers already a good way to estimate the magnitude of the muon-produced neutron flux. The results of the present work are also valuable in evaluating the suitability of the Pyhäsalmi site as a underground laboratory hosting future experiments requiring effective cosmic-ray shielding.

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