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The Muon Decay and Muon Capture Detection with LVD

N. Agafonova[d], M.Aglietta[a], P.Antonioli[b], G.Bari[b], V.Boyarkin[d], G.Bruno[a], C.Castagnoli[a†], E.Dobrynina[d], W.Fulgione[a], P.Galeotti[a], M.Garbini[b], P.L.Ghia[a], P.Giusti[b], F. E.Kemp[c], V.Kuznetsov[d], A.S.Malguin[d], H.Menghetti[b], A.Porta[a], A.Pesci[b], I.A.Pless[e], V.G.Ryasny[d], O.G.Ryazhskaya[d], O.Saavedra[a], G.Sartorelli[b], M.Selvi[b], C.Vigorito[a], L.Votano[f], V.F.Yakushev[d], G.T.Zatsepin[d] and A.Zichichi[b] (for LVD collaboration)

(a) IFSI-CNR,Torino, University of Torino and INFN-Torino, Italy
(b) University of Bologna and INFN-Bologna, Italy
(c) University of Campinas, Campinas, Brazil
(d) Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia
(e) Massachusetts Institute of Technology, Cambridge, USA
(f) INFN-LNF, Frascati, Italy
[†]deceased
Presenter: O. Ryazhskaya (ryazhskaya@vaxmw.tower.ras.ru), rus-ryazhskaya-O-abs1-he11-oral

The purpose of the measurement is the evaluation of the charge composition of primary cosmic rays at energy higher than 10 *TeV* using the μ^+ / μ^- ratio for muon flux underground. The method of the muon capture detection with LVD is used and preliminary results are presented.

1. Introduction

The study of the charge composition of primary cosmic rays (PCR) using the ratio of N_{μ^+}/N_{μ^-} in the muon flux deep underground is the only possible method for PCR energies higher than 1 *TeV*. The depth of LVD location (3650 m.w.e.) provides an opportunity for such experiment.

2. Detection Method

LVD [1] is situated at the depth of 3650 m.w.e. under the Gran Sasso mountain in Italy. It is a scintillation-tracking detector with iron-carbohydrate target. The iron mass is 50.7 % of total detector one (2130 *tons*). Scintillator and iron are uniformly distributed in the volume of apparatus, making a cell orthogonal structure. The number of cells is 912. They are placed in three towers consisting of 8 layers. The tower has dimensions of 13 x 6 x 10 m^3. The cell is a scintillation counter with a volume of 100 x 150 x 100 cm^3 surrounded by iron (the mean thickness of it is 3.54 *cm*). 8 counters are integrated into the module. Two planes of tracking system with a total area of 21 m^2 are attached to the bottom and lateral sides of the module. The structure permits the detection of the products of nuclear interactions in iron using scintillation counters.

The iron mass is equal to 45% of total mass in the inner part of a tower. So the ratio of muons stopping in scintillator to muons stopping in iron is $N_{st}^{sc} / N_{st}^{Fe} = 1.22$.

The information from the tracking system and scintillation counters is taken from each tower quarter by quarter.

Stopping μ^+ undergo only decay with known positron energy spectrum and time distribution:

$$\mu^+ \to e^+\nu_e\tilde{\nu}_\mu, \quad \tau_d = 2{,}2\ \mu s, \quad E_{e^+}^{\max} = 52{,}8\ MeV, \quad E_{e^+}^{prob} = 37\ MeV. \tag{1}$$

These positrons are detected in the scintillation counters, together with gamma from electromagnetic cascades (if muon decay takes place in iron) and gamma from electron-positron annihilation. The observed energy spectrum and detection efficiency for μ^+-decay in scintillator differ essentially from the corresponding values for μ^+-decay in iron.

Stopping μ^- may either decay or be captured by iron and carbon nuclei.

The decay of negative muons has essentially the same time and energy features as the positive ones.

The probability Λ_c of μ^--capture by the nucleus rapidly grows with the increasing atomic number Z. For Z ~ 11 Λ_c is approximately equal to the muon decay probability $\Lambda_d = 1/\tau_0$, (τ_0=2,2 μs). For nuclei with Z>11 the Λ_c value follows a Z^4 low. So in case of stop in iron μ^- are mainly captured by iron nuclei (90.9% of all μ^--stop in iron), and in case of stop in scintillator they decay (94.4% of all μ^--stop in scintillator). The probability of μ^--capture by a free proton is 200 times smaller than the probability of $\mu^{-\,12}C$-capture. So this process wasn't taken into account.

The $\mu^- - Fe$ *capture* is accompanied by gamma emission (0.32 gammas per capture) with energies of 3 – 10 *MeV* [2] and also emission of ~1.13 neutron [3]. The time distribution of gamma pulses is described with a μ^- lifetime in iron: $\tau_{Fe} = 1/\left(\Lambda_c^- + \Lambda_d^+\right) = 0.206\ \mu s$ ($\Lambda_c^- = 44.0\cdot 10^{-5} s^{-1}$). The same exponent corresponds to the time distribution of μ^--decay in iron. Neutrons from $\mu^- - Fe$ capture coming into scintillator are slowed down, diffuse and are captured both in scintillator and iron wall with a mean time ~ 120 – 150 μs. In case of neutron capture by proton of scintillator one 2.23 *MeV* gamma is emitted ($np \to D\gamma$). In case of *n-Fe* capture the mean number of gammas with the energies in the range 0.2 – 10.2 *MeV* is 1.8. $\mu^- Fe$ -events can be identified using either gamma or neutrons produced in muon capture.

Absorption of μ^- by ^{12}C nucleus is accompanied by the reactions:

$$\mu^{-\,12}C \to \begin{cases} ^{12}B\nu_\mu, {}^{12}B \to {}^{12}Ce^-\tilde{\nu}_e, \tau = 39ms, E_e^{\max} = 13.37MeV & (2) \\ ^{11}B(n)\nu_\mu & (3) \\ ^{10}B(2n)\nu_\mu & (4) \\ ^{12}B^*\nu_\mu, {}^{12}B^* \to {}^{12}B\gamma & (5) \end{cases}$$

Reaction (5) with the production of the ^{12}B excited nucleus makes up 10% of all captures by carbon. Reaction (2) dominates among reactions (2, 3, 4). The probability of electron detection in this reaction is low, 0.025. Taking into account the portion of μ^- -captures in scintillator

$$P_c\left(^{12}C\right) = \frac{\Lambda_c(^{12}C)}{\Lambda_c(^{12}C) + \Lambda_d(\mu^-)} = \frac{0.37\cdot 10^5}{0.37\cdot 10^5 + 4.52\cdot 10^5} = 0.076.$$

We can conclude that the fraction of detected muon stopping in scintillator is negligible (~0.1%). Thus, $\mu^{-\,12}C$ -captures do not contribute to the final result.

The charge composition of the muon flux can be obtained using the fraction of negative or positive muons in the total number of the muon stoppings. The properties of LVD experiment allow establishing:

a) the number of $\mu^{\pm}$-decays in scintillator;
b) the number of μ^{+}-decays in iron;
c) the number of μ^{-}-captures by iron.

The value of *a)* is determined using scintillation counters crossed by the muon, i.e. placed along the muon track. If a single muon passes through the scintillation counter its energy losses are from 5 MeV to 500 MeV. The energy losses of 3 – 80 *MeV* in time window 1 – 10 *μs* are regarded as $\mu^{\pm}$ -decay candidates. The beginning of the time interval is specified by a counter dead time $t_d = 1.0 \;\mu s$ after muon ionization loss pulse.

The values of *b)* and *c)* can be obtained by using the data of the counters outside the muon track. These counters are triggered at the moment of muon entering into a given tower quarter (the time accuracy is ± 70 *ns*, TDC discreteness is 12.5 *ns*). The pulses in the same energy and time intervals as *a)* are considered as candidates for $\mu^{\pm}$-decay in iron. The pulses with energy of 3 – 15 *MeV* in time range of 0.25-1.00 *μs* are regarded as $\mu^{-}Fe$-captures. The time interval of 0 – 0.25 *μs* is excluded because it contains a muon electromagnetic accompaniment which can distort the muon track up to 10% .

3. Results

The preliminary analysis of stopping muons is performed using data of the 1st tower, containing 39843 single muons with reconstructed tracks and 8887 tracks without reconstruction. Trigger conditions were: response of all 4 quarters of the tower and presence of muon pulses with $E \geq 40$ *MeV* in at least two counters. The energy resolution for the energy release in one counter is ~20% for 5 – 100 *MeV* energy range. 47 of 72 inner counters of 2nd, 3rd and 4th levels of the tower were used for the analysis. They were selected according to time characteristics and stability. To exclude a significant background in 1-10 *μs* range all muon events were divided into 2 groups: through-going and stopping. The muon was regarded as through-going if it produces a pulse with energy higher than 10 *MeV* in 0 – 0.25 *μs* time interval in the 1st level counter. 36108 events are rated as through-going ones. The remaining 12622 events are regarded as stopping ones. Obviously, the fraction of muons that really stopped in the detector is negligible. The first group allows to determine the PMT afterpulses background as well as muon-induced background (electromagnetic and neutron accompaniment).

The presence of the dead time ($t_d = 1.0 \;\mu s$), the PMT delay scattering for muon pulses 0.25 *μs* and the electromagnetic accompaniment lead to a decreasing of the detection efficiency of muon captures and decays. The resulting efficiencies are:

- for $\mu^{\pm}$-decays in scintillator ~60% (1.0 – 10.0 *μs*);
- for μ^{+}-decays in iron ~20% (1.0 – 10.0 *μs*);
- for μ^{-}-captures by iron ~10% (0.25 – 1.0 *μs*);.

μ^{+} / μ^{-} - ratio turned out to be $1.2^{+0.4}_{-0.3}$.

This value is preliminary. It will be more accurate on the basis of the full statistics of $3.5 \cdot 10^{6}$ muon events.

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