High-energy hadrons produced by cosmic-ray muons in the earth as a source of background in proton-decay experiments

A. S. Mal'gin, O. G. Ryazhskaya, V. G. Ryasnyĭ, and F. F. Khal'chukov
Institute of Nuclear Research, Academy of Sciences of the USSR

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The flux density of neutrons with energies of 20–80 MeV produced by muons underground at a depth of 550 meters water equivalent has been measured. The flux density of hadrons with energies above 0.7 GeV is estimated for various depths. The hadron background is important in experiments on the decay of the proton at depths down to 8000 meters water equivalent.

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The experimental search for the decay of the nucleon has recently focused attention on the question of the background from cosmic-ray muons and neutrinos. One background source which has not received adequate study is the flux of hadrons with energies above 0.7 GeV. It was shown[1,2] back in 1965–66 that the primary mechanism for the production of hadrons deep underground is a nuclear cascade process which results from an inelastic interaction of cosmic-ray muons with nuclei of the earth.

Some recent experiments[4,5] have confirmed the calculations of Refs. 1 and 2 and have revealed that the average number of neutrons produced in the nuclear cascades increases with the muon energy, in proportion to $E_\mu^{0.75 \pm 0.05}$. The neutron flux densities per muon at various depths depend on the average muon energy at the depth in the same way.[3]

Figure 1 shows curves of the energy dependence of the neutron contribution on the energy transferred in the interaction for various depths.

With increasing depth (with increasing average muon energy $\overline{E}_\mu$), more neutrons are produced per passing muon in high-energy nuclear cascades. Shown along with the curve for a depth of 550 m.w.e. (meters water equivalent) are experimental points obtained with the 100-(metric ton) scintillation detector of the Institute of Nuclear Research.[4–7] The good agreement between the experimental results and the calculated curve at high energies raises the hope that the calculations for great depths are reliable.

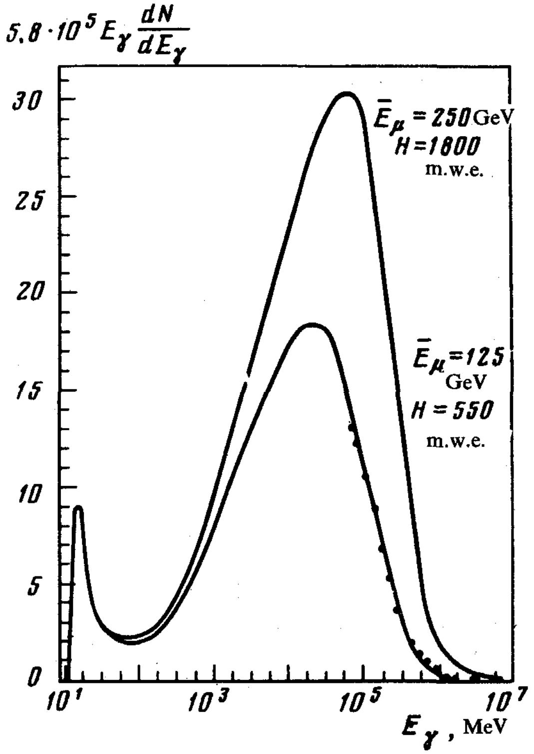

FIG. 1. Contribution of the neutrons produced in the inelastic interaction of muons vs the energy transferred in the interaction (E_γ).

In addition to studying the depencence of the total number of neutrons on the energy transferred in the interaction, we have measured the flux density of neutrons with energies of 20–80 MeV emerging from rock. This flux density was found by studying the delayed coincidences of pulses from recoil protons in a liquid scintillator and from γ rays resulting from the capture of slow neutrons in hydrogen. The result is 2.3×10^{-4} neutron/(s·m^2). In finding this value we took into account the simulation of true events by the simultaneous incidence on the detector of charged particles or γ rays and of the genetically related slow neutrons. This effect amounts to less than 20% of the value given. Calculations show that neutrons with energies of 20–80 MeV enter largely through the lateral surface. They are uncorrelated with the muons that intersect the detector.

To calculate the neutron flux densities at great depths, we work from the basis that essentially all the neutrons with 20 MeV$\leqslant E_n \leqslant$80 MeV are produced in nuclear cascades. Their flux density at an arbitrary depth, $I_n(H)$, is then

$$I_n(H) = \int_{20\,\mathrm{MeV}}^{80\,\mathrm{MeV}} I_n(H)dE_n = \frac{\int_{20\,\mathrm{MeV}}^{80\,\mathrm{MeV}} I_n(E_n, 550)dE_n}{I_\mu(550)\bar{E}_\mu^{0,75}(550)} \quad I_\mu(H)\bar{E}_\mu^{0,75}(H).$$

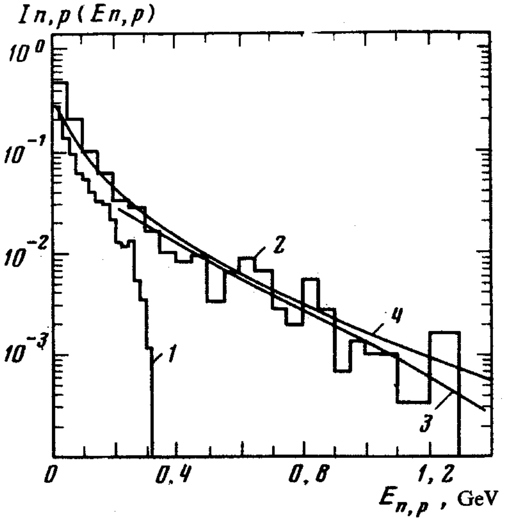

FIG. 2. 1—Energy spectrum of the neutrons produced in the reaction $\pi^{-27}\mathrm{Al} \rightarrow nX$ at $E_{\pi^-} = 0.4$ GeV, $0 \leqslant \theta \leqslant 180°$ (Ref. 9); 2—the same, for $E_{\pi^-} = 1.87$ GeV (Ref. 9); 3—energy spectrum of the protons from the reaction $\gamma\,^{12}\mathrm{C} \rightarrow pX$ at $E_\gamma = 4.5$ GeV, $25° \leqslant \theta \leqslant 180°$ (Ref. 8); 4—energy spectrum of the protons from the reaction $p\,^{27}\mathrm{Al} \rightarrow pX$, $E_p = 1.84$ GeV (Ref. 10).

In determining the flux density of neutrons with energies above E_n we can use the production spectrum for protons and neutrons from Refs. 8–11 (Fig. 2). Curve 3 was found by integrating the spectra of protons measured at various angles from 25° to 180°. We assume that the spectrum of neutrons produced at energies above 20 MeV corresponds to the proton spectrum. It should be noted that the production spectrum shown here depends on neither the nature of the incident particle nor its energy, provided that this energy is above 2 GeV (Refs. 12 and 13).

Below 2 GeV, the high-energy part of the nucleon spectrum begins to be cut off, according to Fig. 2. Accordingly, an important consideration in the calculation of the flux density of nucleons with $E_n > 0.7$ GeV is the number (N_h) of particles in the nuclear cascade which have energies above 2 GeV. This number depends on the initial energy of the cascade or, equivalently, the average energy of the muons at the depth. The ratio $K = N_h(>2\ \mathrm{GeV})/N_h(<2\ \mathrm{GeV})$ ranges from 1/5 at a depth of 550 m.w.e. to 1/2 at depths greater than 4000 m.w.e. The final expression for the nucleon flux density at depth H is

$$\int_{700\,\mathrm{MeV}}^{\infty} I_n(E_n, H)\,dE_n = \frac{I_n(H)\int_{700\,\mathrm{MeV}}^{\infty} N_n(E_n)\,dE_n}{\int_{20\,\mathrm{MeV}}^{80\,\mathrm{MeV}} N_n(E_n)\,dE_n}\,K,$$

where $N_n(E_n)$ is the neutron production spectrum.

Table I shows the flux densities of neutrons with $E_n > 0.7$ GeV which are not correlated with muons passing through the apparatus for depths of 550, 850, 1500, 5300, and 7600 m.w.e., expressed as the numbers of neutrons per 100 m^2 of the lateral

TABLE I.

H (m.w.e.)	550	850	1500	5300	7600
I_n (n/yr per 100 m^2)	2×10^{-4}	10^4	1.5×10^3	15	1.5

surface area per year. The flux densities of the protons at these energies and also the flux densities of π mesons are of the same order of magnitude.

In interactions with nuclei, hadrons with energies ~ 1 GeV form an average of two three-prong stars. The averge emission angle of the secondary particles is $\bar{\theta}_N = 65°$ or $\bar{\theta}_\pi = 82°$ for nucleons and pions, respectively. The stars produced by hadrons may have their nucleation points anywhere in the detector, since the absorption mean free path of a hadron is[10,14] $\lambda = 100$–120 g/cm^2. The charged particles (protons or π mesons) incident on the detector can be eliminated by an anticoincidence system. For the neutron component, the anticoincidence shielding must be very thick, since the neutron flux density falls off as $e^{-x/\lambda}$. The neutron component is thus the most dangerous part of the background in the detection of the decay of nucleons. In order to extract the effect of interest from the background, it is necessary to measure both the energy spectrum of the events and their distributions along the coordinates. For an apparatus with large linear dimensions, $L \gg \lambda$, the events resulting from the neutron background will be distributed along the periphery. As can be seen from Fig. 2, the energy spectrum of the neutrons is a decreasing spectrum. For such a spectrum, however, the threshold effect may give rise to a maximum in the distribution in the region under study, especially if there is a multiple coincidence circuit. Low thresholds must apparently be used in the apparatus for this reason.

It should be noted that these estimates are accurate within about a factor of two, but they indicate that the hadron background is appreciable at any of the depths which have been used to date.

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