Depth-intensity curve of nuclear events induced by muons

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Abstract. Different processes leading to nuclear reactions induced by muons were considered. It was found that the main yield was given by photonuclear interactions and that nuclear cascades produced in high energy photonuclear interactions played a significant role. The depth-intensity curve of nuclear events can be approximated by the formula:

$$I_n(x) = AI_\mu(x)\,\overline{E_\mu(x)}^{0\cdot 7}$$

where A is a constant dependent on the type of nuclear process, $I_\mu(x)$ is the muon intensity and $\overline{E_\mu(x)}$ is the average energy of muons at the depth x.

Recently, the interest in the processes induced by muons, particularly processes of the photonuclear type has increased. The correct consideration of nuclear interactions connected with fast muons turns out to be important for the estimation of the value of the false background in the detection of the neutrino flux from the Sun when radiochemical methods are used. As a result of the calculations it was found that for different nuclear reactions the dependence of the frequency of the events is almost the same function of depth. In particular, our calculations give the generation of neutrons underground. Apparently these may be detected by the most simple methods. The neutrons produced by muons arise from three processes: the first is the direct interaction of the electromagnetic field of the muon with nuclei, the second is the photonuclear interaction of real photons generated in the electron-photon cascade associated with δ electrons, e^- e^+ pairs and photons of the bremsstrahlung. The third process, i.e. the capture of stationary negative muons by nuclei which gives a significant contribution only in neutron generation at small depth, was not considered here. Following von Weizsacker (1934) and Williams (1935) the energy spectrum of the virtual photons is given by:

$$f\gamma(E\gamma, E_\mu)dE\gamma = \frac{2}{137\pi}\,\frac{dE\gamma}{E\gamma}\,\ln\left(\frac{2}{3}\,\frac{E_\mu}{E\gamma}\right) \qquad (1)$$

where $E\gamma < 2/3\ E_\mu$.

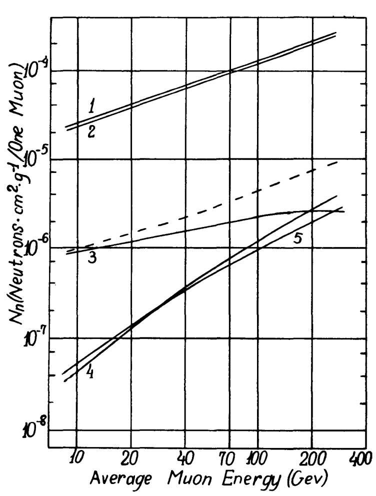

Fig. 1.

Following Kessler and Kessler (1956) the spectrum of the photons must be written

$$f\gamma(E\gamma, E_\mu)dE\gamma = \frac{2}{137\pi}\,\frac{dE\gamma}{E\gamma}\left(\ln\frac{E_\mu}{m} - \tfrac{1}{2}\right) \qquad (2)$$

where $E\gamma < E_\mu$, $E\gamma$ is the photon energy, E_μ is the muon energy and m is the muon mass in energy units. The flux of virtual photons accompanying the muons at different depths was found by integrating (1) and (2) over the corresponding muon spectra. The number of neutrons produced by one muon per g cm^{-2} of matter with atomic number A was calculated by multiplying the flux of virtual photons by the expression

$$\sigma_n\,(E\gamma)\nu(E\gamma)\,\frac{N_0}{A}$$

and by integrating over $E\gamma$. $\sigma_n(E\gamma)$ is the effective cross section of the photonuclear interaction in units of cm^2 per atom, $\nu(E\gamma)$ is the multiplicity of neutrons and N_0 is Avogadro's number. The values of $\sigma(E\gamma)\nu(E\gamma)$ for $10 \leqslant E\gamma \leqslant 320$ MeV and $A \sim 27$ was taken from Jones and Terwilliger (1953). Following Higashi et al. (1963) for $E\gamma > 320$ MeV, $\frac{\sigma_n}{A}$ was taken to be 1.4×10^{-28} cm^2 per nucleon for the treatment of von Weizsacker and Williams and it was taken to be 2.1×10^{-29} cm^2 per nucleon for the Kessler and Kessler expression. The multiplicity $\nu(E\gamma)$ for $E > 320$ MeV was found by taking into account the development of nuclear cascades produced in high energy photonuclear interactions. The variation of the number of neutrons with average muon energy for the von Weizsacker and Williams expression is shown in figure 1 (curve 2). The number of neutrons produced by one muon per g cm^{-2} increases with the average muon energy approximately as $\overline{E}_\mu^{0\cdot 7}$. The calculations for the Kessler and Kessler expression give us an increase of the type $\overline{E}_\mu^{0\cdot 8}$. For small depths

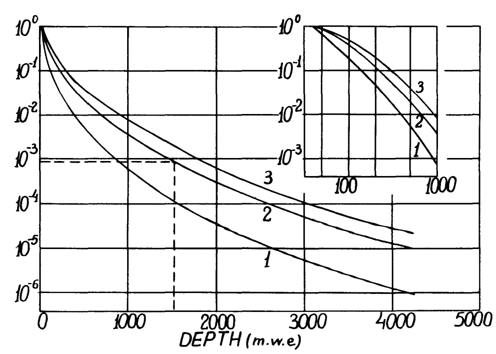

Fig. 2.

(25 m w.e.) where $\overline{E}_\mu \sim 10$ GeV the number of neutrons arising in nuclear cascades is comparable with the number of neutrons associated with photons of low energy. At a depth of more than 250 m w.e. ($\overline{E}_\mu > 50$ GeV) neutrons are generated mainly in nuclear cascades. The total energy of protons generated in nuclear cascades increases with $\overline{E}_\mu$ (for $\overline{E}_\mu > 50$ GeV) approximately as $\overline{E}_\mu^{0.75}$. These dependences are not sensitive to the model of the development of the nuclear cascades and are similar. Such calculations give the dependence on $\overline{E}_\mu$ to good accuracy, but absolute values are accurate only in the order of magnitude. The number of neutrons associated with real photons was calculated in the same way.

The spectra of photons from cascades associated with δ electrons, $e^+ e^-$ pairs and photons of the bremsstrahlung were calculated on the basis of the electromagnetic cascade theory by averaging over the muon spectra. As the differential spectra of real photons are proportional to dE_γ/E_γ^2 in a significant region of energies the greater part of the neutrons is generated by photons of low energy. The variation of the number of neutrons produced by one muon per g cm^{-2} of the ground in all processes with the average muon energy for different depths is shown in figure 1. Curves 3, 4 and 5 correspond to neutrons from showers associated with δ electrons, pairs and photons of the bremsstrahlung respectively. The broken curve shows us the total number of neutrons generated by photons from electromagnetic showers. Curve 1 is the number of neutrons produced in all the processes. The number of neutrons produced by one fast muon per g cm^{-2} of the ground increases with $\overline{E}_\mu$ approximately as $\overline{E}_\mu^{0.7}$.

In figure 2 the dependence on depth of the global muon intensity (curve 1), the intensity of the generation of neutrons in all the processes except muon capture (curve 2) and the muon energy flux normalized to a point 25 m w.e. underground (curve 3) are shown. One can see that the generation of neutrons by fast muons decreases only a little more quickly than the muon energy flux.

All the calculations in this work were made for $Z/A \simeq 0.482$ and $Z^2/A \simeq 6.27$. For lower values of Z^2/A the curve must fall more slowly because of the slower absorption of muons at greater depths. As the frequency of different nuclear reactions depends on the average muon energy in almost the same way curve 2 must also describe correctly the intensity of the production of ^{37}Ar from ^{37}Cl associated with muons. Therefore, using the results of Davis (1964) and Bahcall and Frautschi (1964) it is possible to find from curve 2 that at a depth of 1500 m w.e. the effect of the generation of ^{37}Ar by cosmic rays should be equal to the effect of the production of ^{37}Ar in the reaction ^{37}Cl (ν, e^-)^{37}Ar.

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Discussion

A. W. WOLFENDALE. Some years ago Meyer et al. studied neutrons produced by muons in a local absorber at Durham. Very roughly, the product of neutron multiplicity and cross section was found to vary as $\overline{E}_\mu^{0.6}$ for $1 < E_\mu < 100$ GeV.

G. T. ZATSEPIN. I think that the small disagreement between our calculations and your experimental results (exponent 0.7 instead of 0.6) is because we integrated the production of neutrons over all distances from the photonuclear interaction points, and your results are related to small distances from the interaction.

A. M. SHORT. Your calculated rates of neutron production by knock-ons and pairs appear to be the same at muon energies of about 20 GeV.

G. T. ZATSEPIN. No, our calculations show that neutron production by knock-on electrons is higher than by pairs up to muon energies of about 200 GeV.