Is there an excees of electron neutrinos in the flux in the atmosphere?

O. G. Ryazhskaya
Institute of Nuclear Research, Russian Academy of Sciences, 117312 Moscow, Russia

(Submitted 11 October 1994)
Pis'ma Zh. Eksp. Teor. Fiz. **60**, No. 9, 609–612 (10 November 1994)

The background caused in Čerenkov detectors by isolated neutrons during the detection of neutrinos in the atmosphere is discussed. The neutrons are generated in nuclear showers initiated by muons in the earth around the detectors. Incorporating events associated with the detection of π^0 mesons which are produced in $nA \rightarrow \pi^0 X$ reactions and which simulate the detection of ν_e leads to a measured ratio $I(\nu_\mu)/I(\nu_e)$ which is close to that expected for the energy range 0.2–5 GeV. © *1994 American Institute of Physics.*

Recent studies,[1–3] carried out primarily with Čerenkov detectors, have called attention to the circumstance that the ratio of the number of muon-like events to the number of electron-like events is small in comparison with that which would be expected on the basis of Monte Carlo calculations. The ratio $R = (\mu/e)_{\rm data}/(\mu/e)_{\rm MC}$ increases with the depth,[4–6] approaching one at depths $H > 4000$ meters water equivalent. This result suggests that in experiments carried out to measure electron neutrinos there is an additional source of background, which decreases with depth. Since all detectors have highly effective anticoincidence shielding, this background source could consist only of neutral particles, specifically, neutrons.

In some previous studies we examined the depth behavior of the neutron component associated with cosmic-ray muons, and we measured the fluxes and spectra of isolated neutrons at kinetic energies of 18–92 MeV (Refs. 7–13). The Monte Carlo calculations carried out in those papers and also by other authors[14] show that the energy distributions of the nuclear-active particles with energies of 0.02–5 GeV outside the central region of the nuclear shower, especially of the particles moving in a direction perpendicular to the shower axis, are essentially independent of the energy of the primary particle at $E > 20$ GeV. Figure 1 shows some calculated energy spectra of neutrons and $\pi^\pm$ mesons behind a layer of shielding with a thickness of 250 g/cm^2 thick, on which a flux of neutrons with a spectrum dT_n/T_n ($T_n \leqslant 200$ MeV) or dT_n/T_n^2 ($T_n > 200$ MeV) is incident. This is the spectrum of neutron generation in showers; T is the kinetic energy of the particles. Note that the shape of the spectrum depends only weakly on the angle of incidence of the neutrons and on the thickness of the shielding in the range 100–500 g/cm^2 (Ref. 14). Knowing the neutron flux in the range 18–92 MeV measured at a depth of 570 meters water equivalent, i.e., $N_n(570)$; allowing for the dependence of N_n on the depth and on the average muon energy at this depth, $\bar{E}_\mu(H)$, i.e.,

$$N_n(H) = \frac{I_\mu(H)}{I_\mu(570)} \left(\frac{\bar{E}_\mu(H)}{\bar{E}_\mu(570)} \right)^{0.75} N_n(570);$$

© 1994 American Institute of Physics

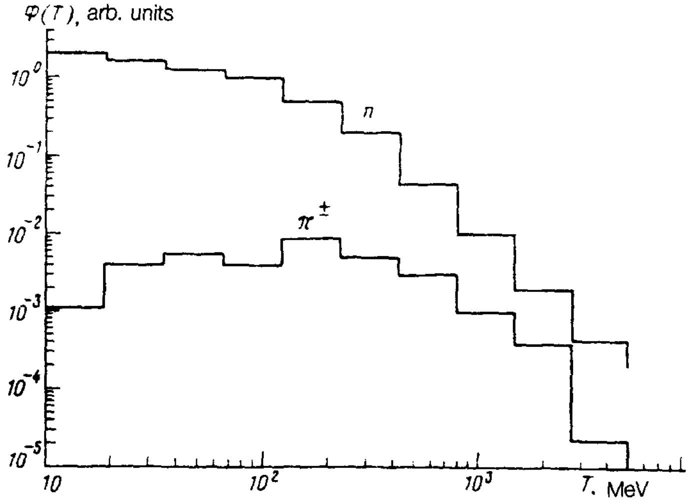

FIG. 1.

and also using the spectra in Fig. 1, we can calculate the fluxes of neutrinos incident on the surface of a detector at any depth, and we can do so quite accurately. Here are the results of such calculations, for various fluxes of isolated neutrons with energies $T_n > 200$ MeV incident per year per square meter of the lateral surface of the detector (mwe stands for "meters water equivalent"):

H, mwe:	1570	2700	3300	4000	5300
N_n, $m^{-2}\cdot yr^{-1}$:	230	65	25	7	3

At energies $T_n < 1$ GeV, and for light nuclei, the average pion multiplicity is[15] $\bar{N}_\pi < 1$, and the pion energy spectrum in Fig. 1 is very nearly the same as the spectrum of events in the detector. In most cases, $\pi^{\pm}$ mesons interacting with O^{16} lose energy to a value below the threshold for detection of Čerenkov radiation. Estimates show that at 200 MeV$< T_\pi <$1.5 GeV no more than 8–10% of the $\pi^{\pm}$ mesons may look like muon-like events. Their apparent energy release is less than 500 MeV. The π^0 mesons which decay into two γ rays simulate electron-like events in more than 30% of the cases. Since the minimum γ-ray separation angle decreases with the energy ($\sin\psi_{\min}/2 = m_{\pi 0}/E_{\pi 0}$), the percentage of simulations of electron-like events increases with the π^0 energy or, equivalently, with the apparent energy. In the case of a $\pi^{\pm}$ meson, the probability for the simulation of a muon-like event with an apparent energy of more than 1 GeV is negligible. It follows that the reactions $nA \rightarrow \pi^0 X$ are an additional mechanism for electron-like events and constitute a background in the detection of electron neutrinos at energies up to ~5 GeV.

In examining the spatial distribution of false events we should bear in mind that the angular distributions of pions with $T_\pi < 1$ GeV which are produced in nA reactions with $T_\pi / T_n < 0.5$ are approximately isotropic.[15,16] Accordingly, a substantial fraction of the γ rays generated in π^0 decays near the boundary of the working volume will contribute

TABLE I.

			Detector			
	IMB		Kamiokande ($E<1.33$ GeV)		Kamiokande ($E>1.33$ GeV)	
Type of event	experimental	background	experimental	background	experimental	background
Isolated:						
total	610	~ 250	389	~ 54	195	
shower (e-like)	378	210	191	46	98	40
shower (μ-like)	232	<40	198	<8	31	
$(\mu/e)_{\text{data}}$ without background	0.61		1.04		0.32	
with background	~ 1.1		~ 1.4		0.53	
$(\mu/e)_{\text{MC}}$ (Refs. 1–3)	1.10		1.60		0.57	

signals in the anticoincidence shielding. True internal events are those which are formed by pions in the central part of the detector, at a distance of more than ~ 1.5 m from the boundary of the working volume; for those produced near the boundary, the true events are those in which the γ rays move into the detector.

Table I shows calculations of background events within the working volume, the results of IMB experiments (the exposure here was 7.7 kton·yr), and the data from Kaniokande experiments (6.18 kton·yr for $E<1.33$ GeV and 8.2 kton·yr for $E>1.33$ GeV), along with theoretical and experimental values of the ratio of the number of μ -like events to the number of e-like events.

The calculations were carried out within an error of 30%, but they show that the background is significant in the measurements of the electron-like events. The incorporation of this background leads to a value of $R=(\mu/e)_{\text{data}}/(\mu/e)_{\text{MC}}$ close to one. With regard to the angular distribution of background events with $E>1.3$ GeV, we could say that it is approximately the same as the angular distribution of the incident neutrons.[15] Since the probability for an isolated neutron moving nearly along the vertical to enter the working volume is exceedingly small, there should be no background events in this direction.

We wish to thank R. Barliuto, G. T. Zatsepin, A. S. Mal'gin, S. P. Mikheev, V. G. Ryasnyĭ, P. Monacelli, L. R. Sulak, M. Spinetti, O. Saavedra, and J. Fiorentini for useful discussions.

[1] K. S. Hirata *et al.*, Phys. Lett. B **280**, 146 (1992).
[2] R. Becker-Szendi *et al.*, Phys. Rev. D **46**, 3720 (1992).
[3] M. Nakahata, Report to 27 ICHEP, Glasgow (1994).
[4] M. Aglietta *et al.*, Europhys. Lett. **8**, 611 (1989).
[5] Ch. Berger *et al.*, Phys. Lett. B **245**, 305 (1990).
[6] M. Goodman, Talk at the Atmosphere Neutrino Workshop, Louisiana (1993).
[7] G. T. Zatsepin and O. G. Ryazhskaya, Izv. Akad. Nauk SSSR, Ser. Fiz. **29**, 1946 (1965).

[8] A. S. Mal'gin *et al.*, JETP Lett. **36**, 376 (1982).
[9] F. F. Khalchykov *et al.*, Nuovo Cim. C **6**, 320 (1983).
[10] F. F. Khalchukov *et al.*, Proc. 20 ICRC (Moscow, 1987), Vol. 5, p. 266.
[11] L. B. Bezrukov *et al.*, Yad. Fiz. **17**, 98 (1973) [Sov. J. Nucl. Phys. **17**, 51 (1973)].
[12] R. I. Enikeev *et al.*, Yad. Fiz. **46**, 1492 (1987) [Sov. J. Nucl. Phys. **46**, 883 (1987)].
[13] M. Aglietta *et al.*, Nuovo Cim. C **12**, 467 (1989).
[14] A. N. Kalinovskiĭ *et al.*, *Passage of High-Energy Particles through Matter* [in Russian] (Energoatomizdat, Moscow, 1985).
[15] V. S. Barashenkov *et al.*, *Interaction of High-Energy Particles and Nuclei with Nuclei* (Atomizdat, Moscow, 1972).
[16] S. Hayakawa, *Cosmic Ray Physics* (Wiley, New York, 1969).

Translated by D. Parsons