COSMIC-RAY BACKGROUNDS IN NEUTRINO EXPERIMENTS

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ABSTRACT

Cosmic-ray backgrounds in neutrino experiments are considered. In spark-chamber and counter experiments the time resolution permits effective vetoing of cosmic-ray events. Cosmic-ray backgrounds are not negligible in the 25-ft bubble chamber because of its long sensitive time and large volume. The muon flux with an estimated 5-msec sensitive time should be about 17 per picture. These tracks will not interfere with scanning and will serve to check the chamber sensitivity and illumination. Cosmic-ray neutrons, however, will simulate many of the neutrino-induced reactions. Analysis of the elastic reactions $\bar{\nu} + p \to \mu^+ + n$ followed by $n + p \to n + p$ and $\nu + n \to \mu^- + p$ shows that kinematic fitting can eliminate the fake cosmic-ray events in these experiments, but the labor of the analysis would be greatly reduced and the cleanness of the data enhanced by shielding out cosmic-ray neutrons. This would also be advantageous for the study of inelastic neutrino reactions. It is concluded that a hadron shielding roof, while not absolutely necessary, is desirable. A roof of 6 ft of earth or 2 ft of iron is recommended.

I. COSMIC-RAY MUON BACKGROUND

Cosmic-ray backgrounds can only be discussed intelligently in the context of specific experiments. Experience with spark-chamber neutrino experiments has shown that use of anticoincidence counters gated on the rf structure of the fast spill almost completely eliminates cosmic-ray backgrounds. In possible future spark-chamber experiments using long spills, fast coincidence timing will serve the same purpose. But the long sensitive time of a bubble chamber makes it vulnerable to cosmic-ray backgrounds.

We consider the 25-foot hydrogen bubble chamber, as described in the proposal BNL-12400 dated March 1969. The sensitive time is expected (W. B. Fowler, private communication) to be about 7.5 msec, the delay from onset of sensitivity to flashing of the light. To be conservative we shall use 5 msec as the sensitive time for photographed tracks. In order to arrive at an opinion as to whether any roof shielding is necessary, we assume initially that there is none. The material between the liquid hydrogen and the atmosphere is then one inch of stainless steel (20 g cm^{-2}, which stops muons of less than 125 MeV/c). [This may be an overly conservative estimate, as the 7-foot chamber has 1-7/8 in. stainless steel (37 g cm^{-2}, stopping muons of less than 165 MeV/c)]. In addition there is about 6 g cm^{-2} of hydrogen between the chamber top and the region that is usefully photographed, corresponding to an additional 17 g cm^{-2} iron. The photographed region can be approximated by a right circular cylinder with axis along the (horizontal) beam line, of length 6.9 m and diameter 3.7 m, of volume 72 m^3. The area of the horizontal section containing the beam line is 6.9 m × 3.3 m = 23.0 m^2.

Rates

Cosmic-ray rates can be calculated precisely for the muonic component and for fast protons and neutrons. Low-energy hadron and electron-photon fluxes are very sensitive to small amounts of material and are therefore poorly known. We do, however, know from experience with smaller chambers of about 3 msec sensitive time and varying amounts of overhead cover that the density of cosmic-ray tracks and events is so small as to be essentially negligible. A mere scaling-up in size of the chamber will not produce appreciable background clutter, as the scanner will examine one part of the picture at a time.

From Rossi[1] we infer that the vertical intensity of the hard component (muons of momentum > 320 MeV/c) at the atmospheric depth of Batavia (1006 g cm^{-2}) is 0.86×10^{-2} cm^{-2}sec^{-1}sr^{-1}; the angular distribution with respect to the vertical follows a $\cos^2\theta$ law. The flux through unit horizontal area is $J_1 = 1.32 \times 10^{-2}$ cm^{-2}sec^{-1}; that through a sphere of unit cross sectional area is $J_2 = 1.74 \times 10^{-2}$ cm^{-2}sec^{-1}. The near-equality of J_1 and J_2 results from the concentration of the cosmic rays around the vertical.

For a volume of arbitrary shape, the number of tracks entering it per unit time is

$$\int_S \int_\Omega dS \cos(\vec{n},\vec{s}) \cdot d\Omega \cdot I(\vec{s}),$$

where $\vec{n}$ is the inward normal to the surface element of area dS, $\vec{s}$ is the particle direction, $d\Omega$ is the element of solid angle, and $I(\vec{s})$ is the directional intensity of flux per unit solid angle per unit area normal to $\vec{s}$. Integrating over the surface we obtain

$$\int_\Omega d\Omega \quad I(\vec{s}) \times (\text{cross sectional area} \perp \vec{s}).$$

If the sensitive volume is a horizontal slab of area A_h, this integral is simply $A_h J_1$.

If it is a sphere of cross sectional area A_s, the integral is $A_s J_2$. For the cylindrical shape involved here we take (area of horizontal section at beam line) $\times J_1 + J_2/2 = 23.0 \times 10^4 \text{cm}^2 \times 1.5 \times 10^{-2} \text{cm}^{-2} \text{sec}^{-1} = 34.5 \times 10^2 \text{sec}^{-1}$ or 17 fast muons per picture (5 msec sensitive time). These will be nearly vertical and thus essentially parallel to the chamber magnetic field and camera axes. Three-quarters of them have momentum > 0.88 GeV/c, one-half have momentum > 1.9 GeV/c, one-quarter have momentum > 4.5 GeV/c. The overwhelming majority will screw through the photographed volume. They will not intefere with scanning, and will, on the other hand, provide a useful control of the chamber sensitivity and illumination. A roof-shield of 5 ft of heavy concrete as suggested by Peoples[1] would cut the flux by only 29%, not by a factor of three as claimed. To obtain a factor of three attenuation would require a roof shield stopping 3.3 GeV/c muons (8.2 ft iron, or 18.3 ft heavy concrete, or 53 ft water).

Stopping Muons

Stopping muons, even if not recognized by bubble density increase, will be tagged by the 40 MeV (average) decay electron. Their intensity[3] is 0.62×10^{-5} $(\text{g } H_2O)^{-1} \text{sec}^{-1} \text{sr}^{-1}$, with an approximate $\cos^2 \theta$ distribution about the vertical. This gives an omni-directional flux of stopping muons of $(2\pi/3) \times 0.62 \times 10^{-5} = 1.3 \times 10^{-5}$ $(\text{g } H_2O)^{-1} \text{sec}^{-1}$. The number stopping in the photographed volume is $1.3 \times 10^{-5} \times$ (mass of hydrogen in g) $\times$ (stopping power of H_2: stopping power of H_2O) $= 1.3 \times 10^{-5} \times (0.06 \times 72 \times 10^6) \times (4.13/2.03) = 114$ stopping μsec^{-1} or 0.6 stopping μ per picture (5 msec sensitive time).

The "geomagnetic cut-off" due to the chamber's dipole field will have little effect because the axis of the dipole is vertical.

II. COSMIC-RAY NUCLEON BACKGROUND

At sea level the differential momentum spectrum of cosmic-ray protons[4] falls as $p^{-2.8}$; at 1 GeV/c its value is $0.9 \times 10^{-4} \text{cm}^{-2} \text{sec}^{-1} \text{sr}^{-1} (\text{GeV/c})^{-1}$. Thus the flux of protons of momentum > 1 GeV/c is $0.5 \times 10^{-4} \text{cm}^{-2} \text{sec}^{-1} \text{sr}^{-1}$. If the directional distribution of protons is more isotropic than that of muons, say $\sim\cos \theta$ rather than $\cos^2\theta$, then $J_1 = 1.05 \times 10^{-4} \text{cm}^{-2} \text{sec}^{-1}$ and $J_2 = 1.57 \times 10^{-4} \text{cm}^{-2} \text{sec}^{-1}$. The number of fast protons per picture is then 0.15 fast protons per picture (5 msec sensitive time). The rate of inelastic interactions (cross section σ per nucleon) is

$$\rho N_0 \sigma \times \text{sensitive volume} \times J_2 = 26 \times 10^{29} \sigma J_2 = 4.1 \times 10^{26} \sigma \text{ sec}^{-1}.$$

With $\sigma = 26$ mb, there are 10 interactions sec^{-1}, or 0.05 fast-proton-produced nuclear interactions per picture (5 msec sensitive time). In deuterium the interaction rate is essentially doubled.

The cosmic-ray neutron momentum spectrum is essentially equal to that of protons at high momentum. As the momentum diminishes toward values characteristic of "star" prongs (~200 MeV/c) a large neutron excess develops. An empirical expression[4] for the neutron/proton ratio above ~200 MeV/c is

$$N/p = \frac{p^2 + M^2}{p^2}$$

which has the value 1.88 at 1 GeV/c, 1.22 at 2 GeV/c. Say that there are 1.5× as many neutrons as protons above 1 GeV/c. Then there are 0.23 fast neutrons per picture (5 msec sensitive time). The inelastic interaction cross section is about the same as for fast protons, so there are 0.075 fast-neutron-produced nuclear interactions per picture (5 msec sensitive time).

The flux of neutrons of 100-400 MeV/c is roughly about 10 times that of the fast neutrons. They produce single elastic recoil protons in the liquid hydrogen, with a cross section in the range 1.5-0.1 b. Thus each of these neutrons is almost certain to produce at least one recoil proton in the sensitive volume. We estimate 5 recoil protons per picture (5 msec sensitive time).

The absorption length of the nucleons is about twice the nuclear interaction length. Should it prove necessary to attenuate the cosmic-ray neutrons, a roof cover of about 5 nuclear interaction lengths would attenuate about 10×. This amounts to about 6 ft of earth, 5 ft of heavy concrete, or 2 ft of iron (watch out for magnetic stresses!).

III. BACKGROUNDS IN EXPERIMENTS

Let us now consider the effects of these backgrounds on specific neutrino experiments in the 25-ft chamber.

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n. \tag{1}$$

In doing this experiment in the 25-ft chamber, one will attempt to measure the polarization of the recoiling neutron by observing its elastic scatter on a proton in the photographed volume (Fig. 1). The momenta of the recoil proton and the muon are measured, and the directions of the neutrino and neutron are also known. There are five unknowns: E_ν, E_n, and the three momentum components of the scattered neutron. There are eight constraints: conservation of four-momentum at two vertices. Thus a 3c fit can be made. Kinematic fitting will eliminate both spurious muon production events and spurious proton recoil events. The latter could be simulated by fast neutron reactions, such as

$$\begin{aligned} n + p &\rightarrow n + n + \pi^+ \\ &\rightarrow n + p + \pi^o \\ &\rightarrow n + n + \pi^+ + \pi^o. \end{aligned}$$

Cosmic-ray events of this type will occur in about one-third of the fast-neutron-produced interactions, giving 0.025 per picture (5 msec sensitive time). The charged prong will be predominantly downward, and there will be more such events in the upper than in the lower half of the chamber (the nuclear interaction length in liquid hydrogen is 4.4 m). Some of the pions will be distinguishable from muons by their secondary interactions in the liquid. Most of the slow ones (< 1.5 BeV/c) will be trapped and tagged by the $\pi \rightarrow \mu \rightarrow e$ decay. The proton recoil could be caused by elastic scatters of slow (100-400 MeV/c) cosmic-ray neutrons. We have estimated that there will be about 5 such events per picture (5 msec sensitive time). The probability of a coincidence of these unrelated cosmic-ray events is then 0.125, or one every eighth picture (5 msec sensitive time). With a bubble growth time of 2.5 msec, the frequency would be reduced to 0.031 (1:32) per picture.

The primary elastic event is expected to occur once in eight pictures.[5] The probability of a useable n-p scatter[6] is about 1/8, so that there will be a genuine event of the required topology once every 64 pictures.

Experiments in which only a fraction of the measured events turn out to be the reaction of interest are the rule in bubble-chamber physics. This experiment could be done without a hadron-stopping roof. But the data would be much cleaner, and the labor of analysis reduced by an order of magnitude if a roof of, say, 6 ft of earth were placed over the chamber.

$$\nu_\mu + n \rightarrow \mu^- + p \qquad (2)$$

In this deuterium experiment, there is a 3c fit at the vertex if the spectator proton is measurable and a 0c fit it it is not. In the latter case one can use known properties of the deuteron wave function to make a quasi-3c fit. The event is expected[5] to occur once in four pictures without spectator, once in 20 pictures with.

Cosmic-ray neutron events such as

$$n + n \rightarrow n + p + \pi^-$$

can simulate this reaction. Assuming that 1/4 of the fast-neutron-produced interactions fake the required topology (fast π^- indistinguishable from μ^-), their frequency will be about 0.019 (1:53) per picture (5 msec sensitive time). It will be possible to eliminate the cosmic-ray events in the fitting, without excessive labor. The data sample of non-spectator events will not, however, be clean enough to permit study of the few cases where there is large momentum transfer.

A second stage of the experiment will involve measurement of the recoil proton polarization, say by scattering in carbon plates.[6] The probability of a useable scattering per primary event would be about $1/5 \times 1/20 \times 1/2 = 1/200$, giving one useable scattering event in 800 pictures. The probability of a cosmic-ray particle passing through the vertex in the liquid is essentially zero. No cosmic-ray shielding is required for this phase of the neutrino experiment.

<u>Inelastic Neutrino Interactions</u>

Typical reactions are

$$\nu_\mu + p \rightarrow \mu^- + N^{*++}$$
$$\qquad\qquad\quad \hookrightarrow p + \pi^+$$
$$\qquad\qquad\quad \hookrightarrow p + \pi^+ + \pi^o$$

or

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Sigma^- + \pi^+$$

or

$$\nu_\mu + p \rightarrow \mu^- + p + W^+ \qquad \text{(W search)}$$
$$\qquad\qquad\qquad \hookrightarrow \mu^+ + \nu$$

These can be simulated by cosmic-ray fast neutron interactions which occur about once every twenty pictures. While the latter can be recognized statistically, the experiments would be much cleaner if they were not present. In identifying rare events, every constraint helps!

IV. CONCLUSIONS

For 25-ft bubble-chamber neutrino experiments,

1. It is not necessary to shield out cosmic-ray muons.

2. An overhead shield to stop cosmic-ray neutrons would reduce the analysis time by a large factor and permit unambiguous identification of rare neutrino events, such as those involving large momentum transfer. A roof thickness of 6 ft of earth, 5 ft of heavy concrete, or 2 ft of iron should be sufficient.

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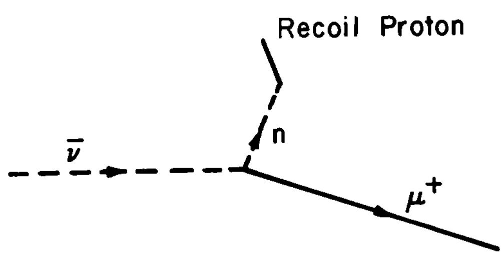

Fig. 1. Elastic event $\bar{\nu} + p \to \mu^+ + n$, followed by elastic scatter of recoil neutron.