SEARCH FOR NEUTRINO-INDUCED REACTIONS*

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The object of this experiment was to see if an upper limit could be placed on the value of the cross section for the reaction

$$\bar{\nu}_\mu + p \to \mu^+ + n.$$

Two observations, reported by Cowan in experiments with cosmic-ray neutrinos, may be used to estimate this cross section.[1] A diurnal effect is reported in the counting rate, suggesting that the earth is acting as an absorber for the neutrino flux. This would demand a cross section per bound proton of $\sim 10^{-33}$ cm^2. A value of $\sim 10^{-28}$ cm^2 is given by an attenuation measurement in which the rate at the surface of the earth is compared with the rate a known distance below. If there exists such an enhancement over the normal order of magnitude of the cross section for neutrino-induced events, it could be evidence for the appearance of the resonance postulated by Kinoshita[2] from the intermediate-boson hypothesis of Tanikawa and Watanabe.[3] Preliminary results from the experiment of Cowan suggested the possibility of such a resonance at incoming neutrino energies of ~200 MeV.

The 184-inch cyclotron should be a reasonable source of 200-MeV neutrinos (decay of a 350-MeV pion gives a 204-MeV neutrino in the forward direction). A rough estimate of the neutrino flux indicates that limits as high as 10^{-28} cm^2 for the cross section for neutrino-induced events can readily be checked with a manageable block of detector placed in the meson cave.

In the present experiment the detector was a 7- by 7- by 3-in. sodium iodide crystal. The signature for the reaction under investigation was the appearance in the detector of a muon which registered through a delayed coincidence with its decay electron. The position of the crystal in the meson cave is shown in Fig. 1. In addition to the usual shielding in the cave, three feet of steel was placed between the machine and the crystal, which was surrounded on the other five sides by a 1-ft layer of steel. At first no anticoincidence counter was used to veto events due to cosmic rays, since, in a preliminary run away from the machine, the delayed coincidence rate from cosmic-ray muons stopping in the crystal was about one per minute. It was believed that by using the machine on

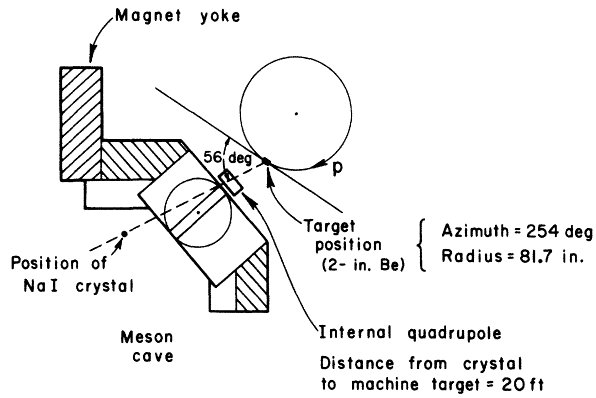

FIG. 1. Geometrical arrangements of sodium iodide crystal with respect to the 184-inch cyclotron target.

pulsed operation (64 beam pulses per sec, each ~300 μsec in width) and gating the detector, a factor of ~50 could be gained over the cosmic-ray background. However, the rate of accidentals proved to be so great that we had to abandon this method of approach and use the auxiliary dee to improve the duty cycle. Under these conditions, some 50% of the intensity appears in a "beam spike" (~300 μsec), but the remaining intensity is spread out uniformly in time over a "beam stretch" (~10 msec). There is a second but comparatively weak "beam spike" at the end of the "beam stretch."

The sodium iodide crystal was viewed by nine (6655) phototubes. Essentially, if two pulses occur in the crystal within 5 μsec, then an event is registered and their time separation is measured from a photograph of the oscilloscope trace. The trace shows two electron pulses separated by a fixed delay (~6 μsec) with the muon pulse between them. A plot of the accumulated data from cosmic rays is shown in Fig. 2(a), illustrating the capability of the apparatus to detect muons. It should be noted that π^+ mesons would be registered as muons.

During the experiment an anticoincidence counter was placed over the sodium iodide crystal in an effort to reduce the cosmic-ray background. However, because of the arrangement of the heavy steel shielding, it could not be placed in an optimum position, but some reduction in rate was observed.

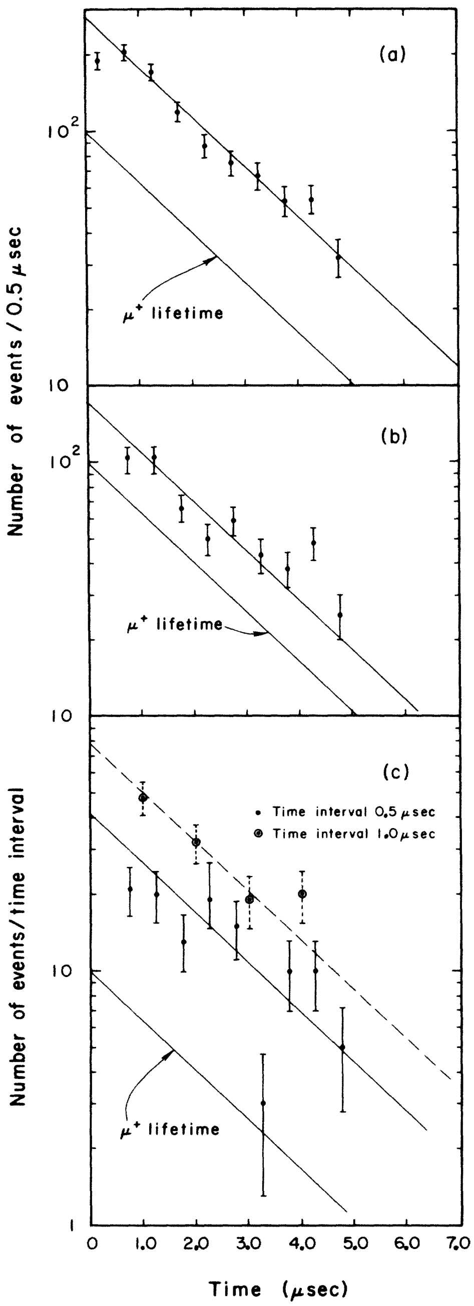

FIG. 2. Time distributions of events in the sodium iodide crystal. (a) Cosmic-ray muon data; (b) machine on, no cosmic-ray anticoincidence; (c) machine on, cosmic-ray anticoincidence.

The experimental results are given in Table I and the time distributions of the delayed coincidences are shown in Figs. 2(b) and 2(c). It is evident that the distributions have lifetimes very close to that of the positive muon, but the rate of events is really consistent with that of cosmic rays viewed with the duty cycle of the cyclotron. The gate width was reduced from 10 to 8 msec to avoid the second "spike" in the intensity distribution of the stretched beam. The errors quoted in all cases are from counting statistics only and are therefore somewhat optimistic.

Suppose we assume that some events are produced by the machine with a rate equal to $(0.2 - 0.15) = 0.05 \pm 0.02$/min. These events could be accidentals, π^+ mesons produced by neutrons, or muons produced by neutrinos. The flux of neutrons in the sodium iodide crystal has not been estimated, but estimates of the accidental rate and the neutrino flux are given below.

A run was made with a 0.5-msec gate on the beam "spike" and the events rate found to be 0.74 ± 0.07/min. The calculated cosmic-ray background for these conditions was only ~0.03 events/min, so the accidental rate was ~0.7 events/min. If we assume that the intensity of the beam in the "spike" roughly equals that in the "stretch," then in going from a 0.5-msec gate on the "spike" to an 8-msec gate on the "stretch," the accidental rate should be reduced by a factor of $(16)^2$, giving 0.003 event/min.

The complicated geometry of the internal target of the cyclotron and the effects of the fringe field make a simple estimate of the flux of neutrinos difficult. The approach used finally was to take the known flux of high-energy π^- mesons in the meson cave and assume the following:

(a) The transmission efficiency of the magnet system after the internal quadrupole was unity, i.e., the flux in the cave gave the number of pions of a given energy entering a known solid angle (60% of the aperture of the internal quadrupole).

(b) The percentage contamination of muons in the beam was used to give a measure of the fraction of pions that would give neutrinos into an acceptable solid angle.

The π^- fluxes and muon contaminations used in this work are 310 MeV, 4.5% muons[4]; 374, 417, and 454 MeV, 5% muons[5]; and 250 MeV, 8% muons.[6] The estimated flux of neutrinos with energy greater than 180 MeV entering the solid angle of the sodium iodide crystal is ~4 $\times 10^3$/sec. This estimate is believed to be accurate to about a factor of 2, and is purposely conservative since the conditions for accepting neutrinos are not as stringent as those for muons, where the momentum requirements of the beam must be satisfied.

Table I. Experimental results.

Experimental conditions	Events rate (per min)
No anticoincidence counter	
10-msec gate on the stretched beam	0.56 ± 0.05
Cosmic rays (beam off)	0.85 ± 0.03
8-msec gate on the stretched beam	0.38 ± 0.04
Calculated background rate due to cosmic-ray events during the machine runs with a 10-msec gate = $64\times10^{-2}\times0.85$	0.54 ± 0.02
Calculated background rate from cosmic-ray events during runs with an 8-msec gate	0.43 ± 0.01
Cosmic-ray anticoincidence counter	
8-msec gate on stretched beam	0.20 ± 0.02
Cosmic rays (beam off)	0.30 ± 0.02
Calculated background rate from cosmic-ray events	0.15 ± 0.01

The result of the present experiment may be interpreted in terms of an upper limit on the value of the cross section for neutrino-induced events, or a lower limit on the mass of the intermediate boson. If we assume that the events rate of 0.05 ± 0.02/min is different from zero and due to neutrino-induced events, then we can estimate these limits.

The number of events expected in the 3-in. thick sodium iodide crystal is

$$[4.3\times10^{23}\times(\text{flux/sec})\times\sigma] \text{ per min.}$$

No attempt has been made to correct for inefficiencies in the detection system (for instance, a 5-μsec gate was used to look for decaying muons), since these errors are negligible compared with that introduced in the neutrino flux. The experiment suggests that σ is less than 4×10^{-32} cm^2 per bound proton.

The limit on the boson mass may be placed by a method of analysis like that used by Kinoshita. Because of the motion of the protons in the nucleus, neutrinos with a broad band of energies can react with the resonant cross section for a given boson mass. Therefore the effective cross section, σ_e, is given by the cross section at resonance, σ_R, reduced by a factor $\Gamma_R/\Delta E$, where Γ_R is the width of the resonance, and ΔE the width of the band of neutrino energies.

Figure 3 shows a plot of the expected events

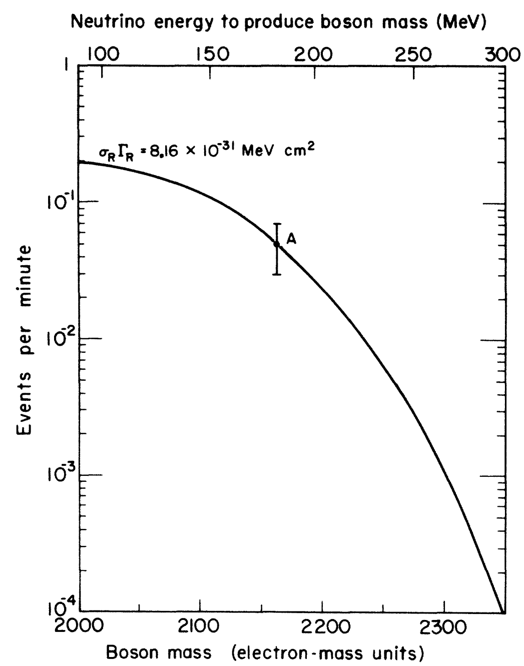

FIG. 3. Expected events rate in sodium iodide crystal for different values of the intermediate boson mass. Here $A(0.05\pm0.02)$ is the point from the present experiment if (beam minus cosmic-ray background) gives the neutrino-induced events. Errors are from counting statistics only.

rate for different masses of the intermediate boson. The end point of the neutrino spectrum from the 184-in. cyclotron is ~250 MeV, and neutrinos with this energy in collision with a stationary proton would produce a boson of mass equal to $2270\,m_e$. However, with the momentum distribution in the nucleus, higher boson masses may be attained, but only a small fraction of the protons can participate, so the rate of events falls off rapidly.

Because of the low energy of the neutrinos produced at the 184-in. cyclotron, only a rather conservative limit of $2130\,m_e$ can be placed on the mass of the intermediate boson.

We would like to thank Professor Luis Alvarez for suggesting this measurement and showing a keen interest in its progress, and also Professor Clyde Cowan for communicating his results before their publication. Our thanks are due Mr. Howard Goldberg, Professor Robert Kenney, and Mr. James Vale and the crew of the cyclotron, without whose full cooperation the run would not have been possible. We are also grateful to Mr. Philip Beilin, Mr. Ned Dairiki, and Mr. Robert Shafer for their help in running the experiment.

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[1]Clyde L. Cowan, Bull. Am. Phys. Soc. 8, 383 (1963); and (private communication).

[2]Toichino Kinoshita, Phys. Rev. Letters 4, 378 (1960).

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[5]Richard J. Kurz, Lawrence Radiation Laboratory Report UCRL-10564, 15 November 1962 (unpublished).

[6]Howard Goldberg (private communication).

GRAVITATIONAL FIELD OF A SPINNING MASS AS AN EXAMPLE OF ALGEBRAICALLY SPECIAL METRICS

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Goldberg and Sachs[1] have proved that the algebraically special solutions of Einstein's empty-space field equations are characterized by the existence of a geodesic and shear-free ray congruence, k_μ. Among these spaces are the plane-fronted waves and the Robinson-Trautman metrics[2] for which the congruence has nonvanishing divergence, but is hypersurface orthogonal.

In this note we shall present the class of solutions for which the congruence is diverging, and is not necessarily hypersurface orthogonal. The only previously known example of the general case is the Newman, Unti, and Tamburino metrics,[3] which is of Petrov Type D, and possesses a four-dimensional group of isometries.

If we introduce a complex null tetrad (t^* is the complex conjugate of t), with

$$ds^2 = 2tt^* + 2mk,$$

then the coordinate system may be chosen so that

$$t = P(r + i\Delta)d\zeta,$$

$$k = du + 2\,\mathrm{Re}(\Omega d\zeta),$$

$$m = dr - 2\,\mathrm{Re}\{[(r - i\Delta)\dot{\Omega} + iD\Delta]d\zeta\} + \Big\{r\dot{P}/P + \mathrm{Re}[P^{-2}D(D^*\ln P + \dot{\Omega}^*)] + \frac{m_1 r - m_2\Delta}{r^2 + \Delta^2}\Big\}k; \qquad (1)$$

where ζ is a complex coordinate, a dot denotes differentiation with respect to u, and the operator D is defined by

$$D = \partial/\partial\zeta - \Omega\partial/\partial u.$$

P is real, whereas Ω and m (which is defined to be $m_1 + im_2$) are complex. They are all independent of the coordinate r. Δ is defined by

$$\Delta = \mathrm{Im}(P^{-2}D^*\Omega).$$

There are two natural choices that can be made for the coordinate system. Either (A) P can be chosen to be unity, in which case Ω is complex, or (B) Ω can be taken pure imaginary, with P different from unity. In case (A), the field equations are

$$(m - D^*D^*D\Omega) = |\partial_u D\Omega|^2, \qquad (2)$$

$$\mathrm{Im}(m - D^*D^*D\Omega) = 0, \qquad (3)$$

$$D^*m = 3m\dot{\Omega}. \qquad (4)$$

The second coordinate system is probably better, but it gives more complicated field equations.

It will be observed that if m is zero then the field equations are integrable. These spaces correspond to the Type-III and null spaces with