SEARCH FOR INTERMEDIATE BOSONS IN HIGH-ENERGY NEUTRINO INTERACTIONS*

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This Letter reports on a continuation of the search for intermediate-boson production[1] via the high-energy neutrino reactions

$$\nu_\mu + Z \to \mu^- + W^+ + Z' \tag{1}$$

and

$$\bar{\nu}_\mu + Z \to \mu^+ + W^- + Z'. \tag{2}$$

We have observed no evidence for the existence of the W, and so interpret our results in terms of a lower limit on the mass of the W, if indeed such a particle were to exist. This is in agreement with a result recently published by the CERN group.[2] In order that the limit be reasonably firm, particular care must be taken with the various factors which contribute to the sensitivity. These factors are (i) the expected production cross section as a function of neutrino energy, (ii) the neutrino flux, and (iii) the efficiency of the detector for the adopted signature. Since this depends on a set of selection criteria, the efficiency may possibly be a sensitive function of production dynamics, e.g., polarization of the W, as well as decay kinematics. In addition, we are faced with certain unknowns, the influence of which must be considered: the magnetic moment of the W and the branching ratio into the selected decay mode. Since we have observed no events, considerations of backgrounds are only relevant to future extensions of this work.

The search was carried out in a new high-energy neutrino arrangement based on an external proton beam at the AGS. This arrangement is shown in Fig. 1. Neutrinos are generated by the decay-in-flight of pions and kaons produced in a 1.5-cm-diameter × 30-cm Be target by 30-BeV/c protons near zero degrees. No focusing device was employed. The 22-m flight path was followed by a 27-m iron shield which permitted about one muon per five pulses to pass into the detector. This was an aluminum spark chamber composed of 184 plates, each 6 ft × 6 ft × $\frac{1}{4}$ in. and weighing a total of 12 tons. This "production chamber" was followed by

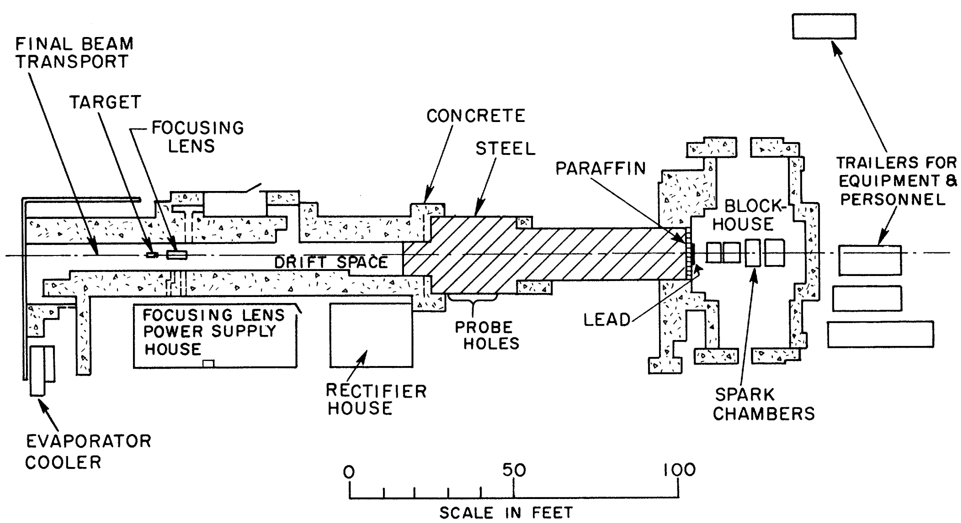

FIG. 1. General layout.

a "range chamber" consisting of 90 plates, each 8 ft×8 ft×1 in. thick, with interspersed steel plates designed to measure the range of muons up to about 2 BeV.

The chambers were triggered after every pulse in order to avoid bias due to counting efficiency. The spark chambers were designed to integrate over the 2.5-μsec spill and maintain multitrack efficiency for this duration. In this mode of operation, the clearing field was pulsed off (to <1 V) just before the sensitive time. In addition, it was found necessary to purify continuously the Ne-He gas mixture by circulation through a liquid-N_2-cooled charcoal trap.

The data reported here come from about 300 hours of exposure amounting to 1.2×10^{17} protons on target. This run yielded about 800 events with a muon of visible momentum greater than 400 MeV/c in a fiducial volume of 24 tons. For the W analysis only the production chamber was used.

Among the many well-known properties of this (still hypothetical) particle are the decay modes

$$W \to e + \nu \quad (3)$$

$$\to \mu + \nu \quad (4)$$

$$\to \text{pions, kaons,} \quad (5)$$

with a lifetime $\lesssim 10^{-17}$ sec. Our approach was to design the search around decay mode (3). This was guided essentially by the relative freedom from backgrounds and relative insensitivity to calibration problems which beset Reactions (4) and (5).

Thus, the over-all signature is a neutrino-event vertex out of which appears a muon track and an electron track. This track configuration can be simulated by events of the following type:

$$\left.\begin{array}{l} \nu_\mu + Z \to \mu^- + \pi^0 + Z' \\ \pi^0 \to e^+ + e^- + \gamma \end{array}\right\}, \quad (6)$$

$$\left.\begin{array}{l} \nu_e + Z \to e^- + \pi^+ + Z' \\ \pi^+ \to \mu^+ + \nu_\mu \end{array}\right\}, \quad (7)$$

$$\nu_\mu + Z \to \mu^- + e^+ + \nu_e + Z'. \quad (8)$$

Reaction (6) is "naturally" suppressed by the small probability of π^0 production in our neutrino interactions. Reaction (7) is suppressed by the small ν_e component (~3%) and the requirement that the track associated with the electron not interact. Reaction (8) has been calculated theoretically[3] to contribute 5×10^{-4} of the total elastic neutrino yield.

The production chamber was designed to have good discrimination between electrons and photons. This was verified in calibration runs with electron beams of 500 to 2000 MeV. The main point is that an electron maintains single-track integrity for many gaps before developing a shower. We selected events in which the "muon" had a visible momentum of more than 200 MeV/c and the "electron" at least four clear sparks before shower development. The calibration runs dictated a minimum electron energy of 500 MeV for reliable detection efficiency, and this was also imposed. To establish the geometric efficiency a fiducial volume of 8 tons was defined and only projected angles of less than 45° with respect to the neutrino direction were accepted. These criteria influence the efficiency. To estimate this, we took the case of minimum momentum transfer and 100%-polarized W's, i.e., the case of minimum efficiency. For this case the efficiency within our cone, and including the requirement of no shower for four plates, is >60%.

A numerical calculation has been carried out by Wu et al.[4] for the production of W via (1) and (2) for boson masses up to 1.5 BeV (see also Bell and Veltmann[5] and Überall[6]). This has recently been extended to 2.8 BeV.[7] This calculation is parametrized by the unknown magnetic moment of the W. The results for zero anomalous moment are presented in Fig. 2. The calculation was done using the theory of Lee and Yang[8] in which the reaction proceeds via virtual Coulomb scattering of the outgoing muon or W. Two production modes are calculated, a coherent mode ($\sim Z^2\alpha^2$) and an incoherent mode ($\sim Z\alpha^2\sigma_{\nu p} + N\alpha^2\sigma_{\nu n}$). In our experiment the incoherent mode dominates, and this gives rise to some additional complications: (1) The nuclear motion contributes energy to the reaction having the effect of a shift in the neutrino spectrum to higher energies,[9] (2) the Pauli principle involves consideration of nuclear structure details.[5] This latter effect is crudely included in Wu et al. We have made an estimate of the effect of nuclear motion, using the results of a study of high-momentum tail via $\bar{p}$ production.[10] It contributes less than 20%.

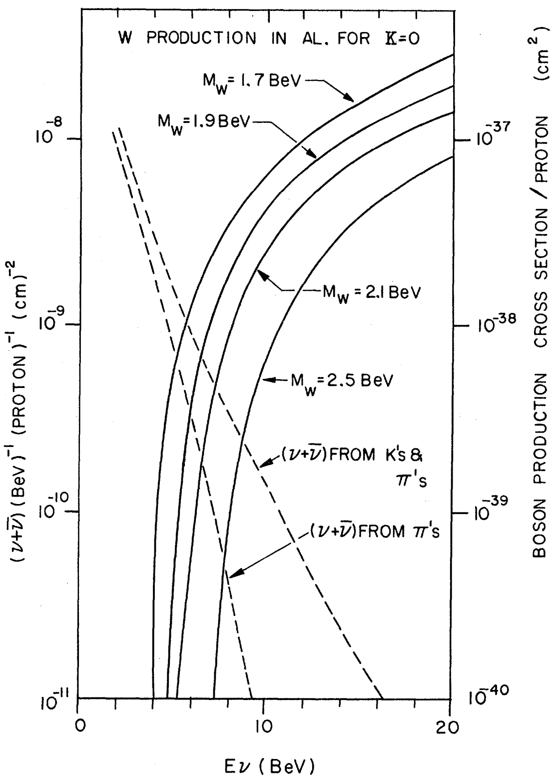

FIG. 2. Calculated W-production cross sections for various W masses. The neutrino flux is also shown.

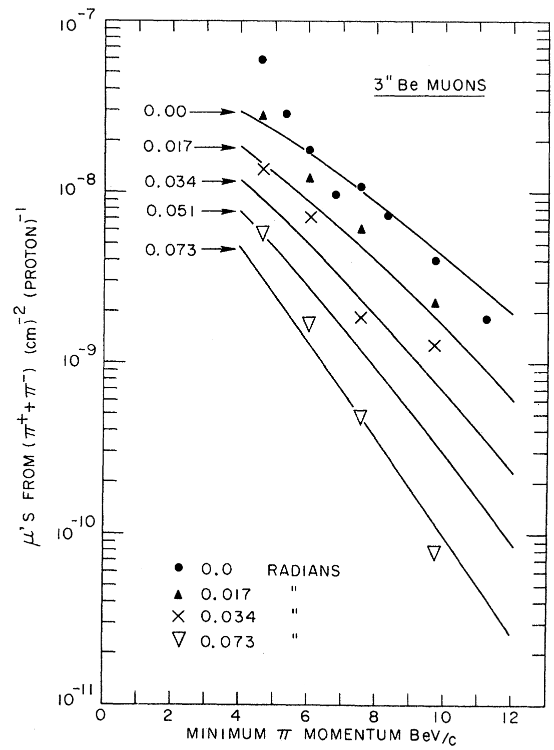

FIG. 3. Emulsion data compared to the muon spectra calculated from beam survey data for 30-BeV/c protons. The data shown are normalized on a plane 100 ft from a 3-in. Be target.

To use these calculations, we must know the neutrino spectrum and its absolute normalization. The philosophy of neutrino flux determination here is that a knowledge of the differential muon flux $d^2N/d\Omega dp_\mu$ leads directly to the parent pion flux from which the pion-neutrino yield may be calculated.[11] The important kaon-neutrino contribution is then obtained from K to π ratios which are very well measured in beam surveys.

Probe holes 3 in.×3 in. were built into the steel shield every two feet and extending transversely from +12 ft to −1 ft relative to the beam center line. In these holes, we inserted 100μ emulsions, exposed simultaneously with foils which monitored the protons on target via radiochemical analysis. The emulsions thus sampled the integral range spectrum and angular distribution of muons. Strongly interacting particles did not contribute since the first emulsions were shielded by 8 ft of steel. Multiple scattering corrections are negligible. The exposure was made with a thin target (3-in. Be) and with no target to subtract production in the air and shield. These results are given in Fig. 3 along with the muon spectra calculated from beam survey data.[11] The agreement gave us confidence in our interpretation of these data. A 12-in. Be exposure was then made to account for the thick target effects. The resulting neutrino flux is given in Fig. 2 for $E_\nu > 1$ BeV. It is difficult for us to see how uncertainties in the K to π ratios used here can introduce errors much more than ~20-30%. Since radiochemical foil monitoring was used throughout the run, an absolute normalization is also obtained.

We have observed no events satisfying our criteria for a boson decay via Reaction (3). One "candidate" was produced in the 2-in.-thick first plate. In another event, the track accompanying the shower scatters through >15°. These were the sole candidates. A folding of the detection efficiency, neutrino spectrum, and production curves of Wu et al. leads to the prediction of the number of W events leading to e-ν signatures given in Table I. This assumes a branching ratio of $\frac{1}{4}$ for this mode. If we include the possibility of a plausible mag-

Table I. Number of W mesons as a function of boson mass/1.2×10^{17} protons/8 tons. Branching ratio $(W\to e\nu)/(W\to \text{all})$ of $\frac{1}{4}$ is assumed. Detection efficiency of 60% for $e\nu$ mode is also included in this calculation.

m_W (in BeV)	Expected number of W mesons
1.5	9
1.8	4
2.0	2
2.2	1

netic-moment contribution ($\pm e/2M_W$) and allow for some of the theoretical uncertainties as well as the neutrino flux uncertainty, a boson mass of $2m_p$ would predict 3 ± 1.2 events where we see none. The result, on the basis of $\geq 90\%$ confidence level, is then

$$m_W > 2m_p.$$

This conclusion re-enforces a similar one recently obtained by the CERN group.[12] A study of the backgrounds (6), (7), and (8) leads us to believe that this limit may be extended to about 2.5 BeV using the technique described here.

We would like to thank Professor S. Taylor and the group at Stevens Institute of Technology for scanning the emulsions, and J. Hudis for assistance with the radiochemistry. The cooperation of the AGS group was essential, especially in the extraction[13] of the external beam by Green, Raka, and Forsythe. Finally, we would like to thank Professor J. Steinberger for his collaboration during the early stages of this investigation.

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ELASTIC SCATTERING OF PROTONS, ANTIPROTONS,* NEGATIVE PIONS, AND NEGATIVE KAONS AT HIGH ENERGIES

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This Letter reports the extension to higher energy of our previous measurements[1-3] of the differential cross section for elastic p-p, π^--p, $\bar{p}$-p, and K^--p scattering in the region $|t| = 0.2$ to 1.0 $(\text{BeV}/c)^2$, where t is the negative square of the four-momentum transfer. The region of incident momentum covered was 15 to 26 BeV/c for π^--p and p-p and 12 to 16 BeV/c for K^--p and $\bar{p}$-p scattering, the main purpose being to investigate further the energy dependence of the differential cross sections. Above 15 BeV/c incident momentum, the p-p differential cross sections continue to shrink with increasing energy while the π^--p differ-