Observation of Single-Pion Production by a Weak Neutral Current*

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In exposures of the Argonne National Laboratory 12-ft bubble chamber filled with hydrogen and deuterium to a neutrino beam, we have observed events consisting of (1) a single π^+ meson originating in the liquid, and (2) a proton with an e^+e^- pair pointing to it. Only a small fraction of these events can be ascribed to known reactions such as $np \to nn\pi^+$ and $np \to np\pi^0$. The remaining events, which correspond to a signal of about 4.5 standard deviations, we ascribe to the reactions $\nu p \to \nu n\pi^+$ and $\nu p\pi^0$.

In the conventional current-current theory of the weak interaction, only charge-changing lepton bilinear combinations $(\nu_\mu\mu^-)$, etc., are used and, although the theory is not renormalizable, it accounts in a quantitative way for almost all experimental facts. Direct evidence for neutral-current combinations such as (ν, ν) is difficult to obtain, and it is only recently that experiments searching for the existence of the inclusive reactions $\nu N \to \nu +$anything and $\bar{\nu}N \to \bar{\nu} +$anything have reported positive results.[1] In strangeness-changing decays, no evidence has been seen for neutral currents and very stringent limits have been set. Formulations of weak interaction theory that are renormalizable have been proposed[2] and require the existence of neutral currents or heavy leptons. Thus, the question of the existence and properties of the neutral-current interaction is of paramount importance.

Our experiment measures single-pion production through the reactions[3]

$$\nu_\mu p \to \nu_\mu n\pi^+, \tag{1}$$

$$\nu_\mu p \to \nu_\mu p\pi^0. \tag{2}$$

Three separate exposures of the Argonne National Laboratory 12-ft bubble chamber were used: the first with a hydrogen filling and the other two with deuterium fillings. Each exposure consisted of about 300 000 pictures and had about 4×10^{17} protons incident on the primary production target. An analysis of single-pion production in the charged-current reaction

$$\nu p \to \mu^- p\pi^+ \tag{3}$$

and a brief description of the experimental arrangement have been published.[4]

The signal for Reaction (1) is a single π^+ meson originating in the chamber fiducial volume of 11.1 m^3. Ten events were uniquely identified as π^+ mesons because the single positive track stopped in the chamber and decayed via the chain $\pi^+ \to \mu^+ \to e^+$. Four events were identified because the track scattered giving a unique kinematic fit to π^+p elastic scattering. In addition, four leaving π^+ tracks were uniquely identified on the basis of energy loss. If interpreted as protons, they were overstopped by 5 or more standard deviations, and they are inconsistent with incoming π^-.[5]

The signal for Reaction (2) is a proton track originating in the chamber fiducial volume with a converted γ ray (e^+e^- pair) pointing to the origin of the proton track. We find thirteen events of this topology which we refer to as one-prong $+\gamma$. Because our experiment is done near threshold, 99% of the protons from the $\nu p \to \mu^- p\pi^+$ events have the azimuth and dip of the proton track within 60° of the neutrino beam direction, and we apply this selection to the proton track of the one-prong $+\gamma$ events. In addition, 88% of protons from Reaction (3) have momentum <1 GeV/c, so we apply this cut. Eight one-prong $+\gamma$ events satisfy these criteria.

Since the Reactions (1) and (2) are not constrained, we cannot prove that any individual event originates from these reactions and not from such processes as

$$np \to nn\pi^+, \qquad (4)$$

$$np \to np\pi^0. \qquad (5)$$

We measure the neutron background using events of the reaction[6]

$$np \to pp\pi^-, \qquad (6)$$

which are observed as three-prong events and are identified by a one-constraint kinematic fit. Since the final states $nn\pi^+(\pi^0)$ and $pp\pi^-(\pi^0)$ are charge symmetric, the number of events fitting the $pp\pi^-$ hypothesis is a direct measure of the number of π^+ mesons coming from the $nn\pi^+$ final state.[6]

In order to scale our observed number of $np \to pp\pi^-$ events to measure the background from Reactions (4) and (5) within our selection criteria, a number of correction factors are necessary. These corrections were measured in a separate experiment in which the bubble chamber was exposed to a 0- to 3-GeV/c neutron beam. This exposure well simulates the neutron background we observe in the neutrino exposure.

Figure 1 shows the pion momentum spectrum for (a) the single-π^+ meson sample, (b) the $\mu^-p\pi^+$ events, (c) the $pp\pi^-$ events in the ν film, and (d) the $pp\pi^-$ events observed in the auxiliary neutron experiment. As seen in Fig. 1(b), only 12% of the charged-current events have pion momentum ≥ 400 MeV/c; in addition, our detection efficiency for single π^+ is low above this momentum so we select as a neutral-current signal π^+ mesons with momentum below 400 MeV/c. Furthermore, we find that 90% of the background neutrons which give rise to Reaction (6) enter through the top of the chamber (where the shielding is weakest because of the camera ports), and produce a π^- which also goes downwards. Hence, we choose events with the pion traveling upwards in the chamber. These selections give a neutron-induced background from Reaction (4) of 0.55 ± 0.55 events.

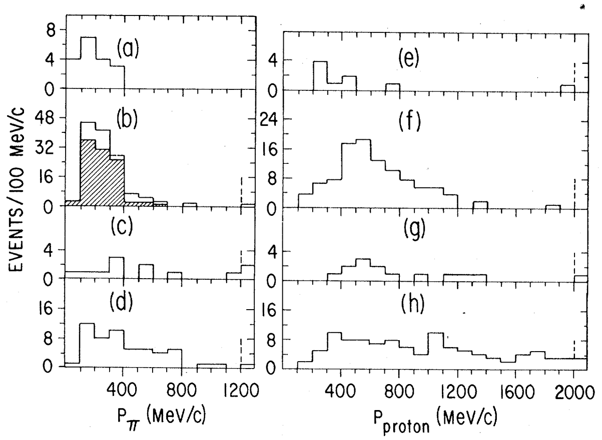

FIG. 1. Pion momentum spectrum for (a) the single-π^+-meson sample, eighteen events; (b) $\nu p \to \mu^- p\pi^+$, 133 events; (c) $np \to pp\pi^-$ in the neutrino film, twelve events; and (d) $np \to pp\pi^-$ in the neutron film, 51 events. The shaded events in (b) represent the $\nu p \to \mu^- p\pi^+$ events after applying our detection efficiency on the single π^+ sample. Proton momentum spectrum for (e) the one-prong$+\gamma$ sample, nine events; (f) $\nu p \to \mu^- p\pi^+$, 102 events; (g) $np \to pp\pi^-$ in the neutrino film, fourteen entries; and (h) $np \to pp\pi^-$ in the neutron film, 102 entries.

In order to measure the background from photoproduced mesons $\gamma p \to n\pi^+$, etc., we use the e^+e^- pairs found in a scan of 55 000 pictures. Almost all of these pairs are close to cosmic-ray tracks as the photon has been produced by bremsstrahlung in the magnet iron above the chamber. By rejecting all events having the vertex within 20 cm of any cosmic ray, we drastically reduce this background.[5] After this selection, the measured photoproduced background to Reaction (1) is 0.33 ± 0.10 events.

For those events where the π^+ leaves the chamber, a possible background is $\bar{\nu}p \to \mu^+ n$. Using our $\bar{\nu}$ beam contamination, we calculate a background of 0.04 ± 0.04 events from this reaction. Finally, K_L^0-induced background from, for example, $K_L^0 \to \Lambda\pi^+$ has been measured and is found to be negligible.

We now discuss the background contributions to the one-prong$+\gamma$ events. Figure 1(e) shows the proton momentum distribution for these after the angle selections discussed previously. Figures 1(f)-1(h) show the proton momentum spectrum from the $\nu p \to \mu^- p\pi^+$ events and the $np \to pp\pi^-$ events from the ν film and the neutron film, respectively. Applying the same selections to the $pp\pi^-$ events as to the one-prong$+\gamma$ events, we are left with five $pp\pi^-$ events. We have measured the empirical ratio of one-prong$+\gamma$ events to $pp\pi^-$ events to be 0.19 ± 0.04 in our neutron experiment, so after some small corrections, the neutron background to Reaction (2) is 0.92 ± 0.40 events.

The photoproduced background $\gamma p \to p\pi^0$ was measured as described above and is only 0.02 ± 0.01 events. The probability of a converted γ

ray accidentally pointing to a one-prong event was determined to be 0.11 ± 0.11 events. The K_L^0-induced background was again found to be negligible. Finally, for the one-prong $+\gamma$ events, there is a background source consisting of an incoming π^- that undergoes charge exchange with the subsequent conversion of one γ ray from the π^0. We have measured this background by analyzing $\pi^- p \to \pi^- p$ scatters of all π^- that enter the chamber and whose tracks could not be distinguished from a leaving proton. By scaling from the known elastic and charge-exchange cross sections, this background was measured to be 0.52 ± 0.23 events.

Table I gives a summary of the events found. With the selections mentioned, we observe with no other corrections seven single-π^+ events and seven one-prong $+\gamma$ events with a total measured background of 2.49 ± 0.73 events. Folding the Poisson-distributed fluctuations of the background with the uncertainty of 0.73 in the measured background level, the probability of seeing fourteen or more events when 2.49 are expected is 1.2×10^{-5} which corresponds to a 4.3 standard deviation effect. We conclude then that neutral currents exist and are responsible for the exclusive reactions (1) and (2).

In order to compare to the measured cross section for $\nu p \to \mu^- p \pi^+$, we must treat the π^+ and proton tracks in the $\mu^- p \pi^+$ events in the same way as the neutral-current candidates and know the overall detection efficiencies for the $\nu n \pi^+$ and $\nu p \pi^0$ final states. These are 75% and 6%, respectively. The number of $\mu^- p \pi^+$ events on the sample of film is about 100. Applying the corrections, we obtain the ratios[7]

$$R_0 = \frac{\sigma(\nu p \to \nu p \pi^0)}{\sigma(\nu p \to \mu^- p \pi^+)} = 0.51 \pm 0.25, \quad p_p < 1 \text{ GeV}/c,$$

and

$$R_+ = \frac{\sigma(\nu p \to \nu n \pi^+)}{\sigma(\nu p \to \mu^- p \pi^+)} = 0.17 \pm 0.08,$$

$$p_{\pi^+} < 400 \text{ MeV}/c,$$

with $R_0 + R_+ = 0.68 \pm 0.28$. The value of $R_0 + R_+$ is somewhat larger than, but not inconsistent with, the value predicted in the Salam-Weinberg theory,[8] which gives $0.15 < R_0 + R_+ < 0.44$ for our spectrum. Our measured ratio

$$\frac{\nu p \to \nu p \pi^0}{\nu p \to \nu n \pi^+} = 3.1 \pm 2.1$$

suggests isospin-$\frac{3}{2}$ dominance of the final state, which does not support the suggestion of Sakurai[9] that the neutral current may be an isoscalar, but the errors on this ratio are too large to rule this out.

Finally, we note that all other experiments on neutral currents have problems of muon identification and/or neutron background that must be estimated using a Monte Carlo calculation. The events of the present experiment consist of a single positive track and so the absence of a μ^- particle is evident. In addition, we make direct measurements of all background contributions.

We wish to thank the staff of the zero-gradient synchrotron and the bubble chamber operators for fine cooperation in obtaining the pictures. Our scanners, under Hope Chafee, have responded well to a difficult and tedious job. J. Campbell, R. Engelmann, A. Mann, U. Mehtani, and B. Musgrave gave help in the earlier stages of the experiment.

TABLE I. Event and background summary. For the H_2 exposure, all three π^+ modes have been analyzed; for the D_2 exposure, somewhat different fractions of the film have been processed for the three modes.

Events	H_2	D_2	Sum	Cosmic cut	π^+ dip cut
π^+ Events					
Stop	2	8	10	7	6
Scatter	3	1	4	3	1
Leave	3	1	4	3	0
One-prong $+\gamma$ events	3	5	8	7	7
Total			26	20	14

Background	π^+	One-prong $+\gamma$
Neutron	0.55 ± 0.55	0.92 ± 0.40
γ induced	0.33 ± 0.10	0.02 ± 0.01
$\nu p \to \mu^+ n$	0.04 ± 0.04	...
$\pi^- p \to \pi^0 n$	...	0.52 ± 0.23
Accidental γ pointing	...	0.11 ± 0.11
Totals	0.92 ± 0.56	1.57 ± 0.47
Total background	2.49 ± 0.73	

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[1] F. Hasert *et al.*, Phys. Lett. 46B, 138 (1973); A. Benvenuti *et al.*, Phys. Rev. Lett. 32, 800 (1974); B. Aubert *et al.*, Phys. Rev. Lett. 32, 1454 (1974).

[2] A. Salam and J. C. Ward, Phys. Lett. 13, 168 (1964); S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967).

[3] We are really measuring the sum of the cross sections $\nu p \to \nu n \pi^+ l \pi^0$ and $\nu p \to \nu p \pi^0 l \pi^0$, $l \geq 0$, but since our neutrino spectrum peaks at 500 MeV/c and is down by an order of magnitude by 1500 MeV/c, we expect the contribution of the final states with additional π^0's to be very small.

[4] J. Campbell *et al.*, Phys. Rev. Lett. 30, 335 (1973).

[5] More details of the experiment are given by S. J. Barish, Argonne National Laboratory Report No. ANL/HEP 7418 (unpublished).

[6] Y. Cho *et al.*, in Proceedings of the Sixteenth International Conference on High Energy Physics, The University of Chicago and National Accelerator Laboratory, 1972 (unpublished), paper 473.

[7] In doing this we are implicitly assuming that the characteristics of our neutral- and charged-current events are the same. This is true on the Salam-Weinberg model but may not be true in general. For the charged-current events, we measure the ratio $N(\nu p \to \mu^- p \pi^+ \pi^0)/N(\nu p \to \mu^- p \pi^+) = 0.1 \pm 0.05$ and, therefore, we reduce the observed $\nu N\pi/\mu^- p \pi^+$ ratios by 10%. In addition, for the one-prong + γ events, a small contribution from the reaction $\nu d \to \nu n \pi^0 (p_s)$ has been subtracted.

[8] S. Adler, private communication.

[9] J. Sakurai, Phys. Rev. D 9, 250 (1974).

Hierarchy of Interactions in Unified Gauge Theories*

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We present a general formalism for calculating the renormalization effects which make strong interactions strong in simple gauge theories of strong, electromagnetic, and weak interactions. In an SU(5) model the superheavy gauge bosons arising in the spontaneous breakdown to observed interactions have mass perhaps as large as 10^{17} GeV, almost the Planck mass. Mixing-angle predictions are substantially modified.

The scaling observed in deep inelastic electron scattering suggests that what are usually called the strong interactions are not so strong at high energies. Asymptotically free gauge theories of the strong interactions[1] provide a possible explanation: The gluon coupling constant $g(\mu)$ (defined as the value of a three-gluon or gluon-fermion-fermion vertex with momenta characterized by a mass μ) is small when μ is several GeV or larger, but becomes large when μ is small, through the piling up of the logarithms encountered in perturbation theory. In one recent calculation[2] a fit was found for a gauge coupling [in a color SU(3) model][3] with $g^2(\mu)/4\pi \simeq 0.1$ when $\mu \simeq 2$ GeV.

If $g(\mu)$ is small when μ is large, then perhaps the strong gauge coupling at some large fundamental mass is of the same order as the couplings in gauge theories of the weak and electromagnetic interactions.[4] Georgi and Glashow[5] have recently gone one step farther, and proposed a model based on the *simple* gauge group SU(5), in which there naturally appears only one free gauge coupling. In their model, SU(5) suffers a spontaneous breakdown to the gauge subgroups SU(3) and SU(2)⊗U(1), which are associated respectively with the strong[3] and the weak and electromagnetic[6] interactions. In order to suppress unobserved interactions, Georgi and Glashow made the necessary assumption[7] that some vector bosons are superheavy.

We find the notion of a simple gauge group uniting strong, weak, and electromagnetic interactions extraordinarily attractive. However, as emphasized by Georgi and Glashow, the success of any such scheme hinges on an understanding of the effects which produce the obvious disparity in strength between the strong and the weak and electromagnetic interactions at ordinary energies. We therefore wish to present in this paper a general formalism for the calculation of such effects. This will lead us to an estimate of the mass of the superheavy gauge bosons. Where a specific model of the gauge groups of the observed interactions is needed as an example, we shall assume that the strong and the weak and electromagnetic interactions are described by color SU(3)[3] and by SU(2)⊗U(1), respectively, and where a specific example of a unifying simple gauge group is needed, we shall use SU(5).

If we neglect all renormalization effects, the embedding of the gauge groups G_i of the observed interactions in a larger simple group G imposes a relation among their coupling constants. We