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Schematic Experiment to Search for Neutral Weak Currents*

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A schematic experiment is described to search, via the reaction $\nu_\mu + p \to \nu_\mu + n + \pi^+$, for a neutral hadronic weak current, either isovector or isotensor, coupled to a neutral leptonic weak current. The analysis of the experiment makes use of the equality of the cross sections for $n + p \to n + n + \pi^+$ and $n + p \to p + p + \pi^-$, dictated by charge symmetry, and is capable of obtaining, at least in principle, an upper limit of less than 1% on the ratio

$$\sigma(\nu_\mu + p \to \nu_\mu + n + \pi^+)/\sigma(\nu_\mu + p \to \mu^- + p + \pi^+).$$

We outline a schematic experiment designed to search for a strangeness-preserving neutral hadronic weak current coupled to a neutral leptonic weak current, *viz.*:

$$\begin{aligned}
\{\mathcal{H}(x)\}_{\text{inter}} &= \left(\frac{G_{\text{neut}}}{\sqrt{2}}\right)[l_\alpha^\dagger(x)h_\alpha(x) + h_\alpha^\dagger(x)l_\alpha(x)], \\
h_\alpha(x) &= v_\alpha(x) + a_\alpha(x), \qquad\qquad (1)\\
l_\alpha(x) &= \sum_{\xi=\nu_\mu,\mu^-,\nu_e,e^-} (\bar\psi_\xi(x)\gamma_\alpha(1+\gamma_5)\psi_\xi(x)),
\end{aligned}$$

where, as indicated by our notation, we take both $h_\alpha(x)$ and $l_\alpha(x)$ to have $V-A$ space-time transformation properties. It is of particular interest that $h_\alpha(x)$ may be isoscalar, or isovector, or isotensor, or, more generally, a linear combination of isoscalar, isovector, and isotensor, and we discuss means of distinguishing among these possibilities.

Suppose that a beam of high-energy muon neutrinos is available and that this beam, accompanied by a certain number of fast neutrons in equilibrium with it, is incident on a hydrogen-filled bubble chamber. The fast neutrons originate in the reactions:

$$\nu_\mu + \{Z,A\}_0 \to \mu^- + n + \{Z+1, A-1\}_j$$

which take place when the neutrinos strike nuclei in their ground states ($\{Z,A\}_0$) located in the walls of the chamber and in other material surrounding the chamber.[1] The average number of such incident fast neutrons per incident neutrino is[2]

$$\begin{aligned}
\frac{\mathfrak{N}_{\text{incid}}(n)}{\mathfrak{N}_{\text{incid}}(\nu_\mu)} &\approx \frac{\sigma(\nu_\mu + \{Z,A\}_0 \to \mu^- + n + \sum_{\text{all } j}\{Z+1,A-1\}_j)}{\sigma(n + \{Z,A\}_0 \to n + \sum_{\text{all } j}\{Z,A\}_j)} \\
&\approx [10^{-2}(A\times 10^{-38})/(A^{2/3}\times 5\times 10^{-26})] \\
&\cong 10^{-14}. \qquad\qquad (2)
\end{aligned}$$

The following zero-pion and one-pion reactions may take place in the hydrogen-filled chamber:

$$\nu_\mu + p \to \mu^- + p + \pi^+, \qquad (3)$$
$$\nu_\mu + p \to \nu_\mu + p, \qquad (4)$$
$$\nu_\mu + p \to \nu_\mu + p + \pi^0, \qquad (5)$$
$$\nu_\mu + p \to \nu_\mu + n + \pi^+, \qquad (6)$$
$$n + p \to n + p, \qquad (7)$$
$$n + p \to n + p + \pi^0, \qquad (8)$$
$$n + p \to n + n + \pi^+, \qquad (9)$$
$$n + p \to p + p + \pi^-. \qquad (10)$$

We emphasize that only the final μ^-, π^+, π^-, and p are readily observable which makes it difficult to distinguish between reactions (6) and (9) or among reactions (4), (5), (7), and (8). We note also that the relative number of ν_μ-induced and n-induced events in the chamber is [using Eq. (2)]

$$\begin{aligned}
\frac{[\mathfrak{N}_{\text{incid}}(\nu_\mu)]\sigma(\nu_\mu + p \to \text{all})}{[\mathfrak{N}_{\text{incid}}(n)]\sigma(n+p\to\text{all})} &\approx \frac{\sigma(n + \{Z,A\}_0 \to n + \sum_{\text{all } j}\{A,Z\}_j)\sigma(\nu_\mu + p\to \text{all})}{\sigma(\nu_\mu + \{Z,A\}_0 \to \mu^- + n + \sum_{\text{all } j}\{Z+1,A-1\}_j)\sigma(n+p\to\text{all})}, \qquad (11)\\
\sigma(\nu_\mu + p \to \text{all}) &\equiv \sigma(\nu_\mu + p \to \mu^- + p + \pi^+) + \sigma(\nu_\mu + p \to \nu_\mu + p) + \sigma(\nu_\mu + p \to \nu_\mu + p + \pi^0) + \sigma(\nu_\mu + p \to \nu_\mu + n + \pi^+) + \cdots, \\
\sigma(n+p\to\text{all}) &\equiv \sigma(n+p\to n+p) + \sigma(n+p\to n+p+\pi^0) + \sigma(n+p\to n+n+\pi^+) + \sigma(n+p\to p+p+\pi^-) + \cdots
\end{aligned}$$

and this quantity is of order 10–100 for $0 \leq G_{\text{neut}} \lesssim G$.

We now make the crucial comment that, on the basis of the *charge symmetry* of the strong interactions, and apart from the effect of electromagnetic corrections ($\lesssim$ few percent), the cross section of reaction (9) must equal the cross section of reaction (10)[3]:

$$\sigma(n+p\to n+n+\pi^+)=\sigma(n+p\to p+p+\pi^-). \qquad (12)$$

Thus, the observation of *any statistically significant difference* in the number of π^+ events $N(\pi^+)$ (without an accompanying μ^-) and the number of π^- events $N(\pi^-)$ (also without an accompanying μ^-) *must* be ascribed to reaction (6):

$$\nu_\mu+p\to\nu_\mu+n+\pi^+ \;.$$

In terms of observed quantities, one has to a good approximation

$$\frac{\sigma(\nu_\mu+p\to\nu_\mu+n+\pi^+)}{\sigma(\nu_\mu+p\to\mu^-+p+\pi^+)}=2\frac{(\text{obs. No. of } pp\pi^- \text{ events})}{(\text{obs. No. of } \mu^-p\pi^+ \text{ events})}\times\frac{N(\pi^+)-N(\pi^-)}{N(\pi^+)+N(\pi^-)}\,. \qquad (13)$$

It is noteworthy that Eq. (13) requires no explicit independent knowledge of beam intensities or partial cross sections, and that the event types to be counted for the purpose of normalization, $n+p\to p+p+\pi^-$ and $\nu_\mu+p\to\mu^-+p+\pi^+$, are identifiable as 1-constraint and 3-constraint fits, respectively. Furthermore, the normalization factor on the right-hand side is actually an enhancement factor since (obs. No. of $pp\pi^-$ events)/(obs. No. of $\mu^-p\pi^+$ events) <1. Thus, in the recent neutrino exposure of the ANL 12-foot hydrogen bubble chamber, the value of this last ratio was $\approx\frac{1}{20}$ with no selection criteria imposed.[4] An experiment based on Eq. (13) is therefore capable of yielding an experimental upper limit on the cross section ratio

$$\sigma(\nu_\mu+p\to\nu_\mu+n+\pi^+)/\sigma(\nu_\mu+p\to\mu^-+p+\pi^+)$$

of less than 10^{-2} for any value of

$$[N(\pi^+)-N(\pi^-)]/[N(\pi^+)+N(\pi^-)]$$

less than 0.1. The primary experimental difficulty appears to lie in making adequate selection of the π^+ (from $n+p\to n+n+\pi^+$ and $\nu_\mu+p\to\nu_\mu+n+\pi^+$) from the large background of protons (from $n+p\to n+p$ and $n+p\to n+p+\pi^0$).[5]

In a hydrogen bubble chamber of sufficient volume, a large fraction of the final-state neutrons from reactions (6) and (9) will be identified by the recoil protons they produce in the chamber. Hence, for these events, as well as for the events of reaction (10), the effective masses of the $n\pi^+$ and $p\pi^-$ systems can be determined experimentally. These mass distributions will decide whether or not reactions (6), (9), and (10) are predominantly $\nu_\mu+p\to\nu_\mu+\Delta^+$, $n+p\to n+\Delta^+$, and $n+p\to p+\Delta^0$, where the nucleon isobar

$$\Delta\equiv\{1236\text{ MeV},\; J^{(P)}=\tfrac{3}{2}^+,\; I=\tfrac{3}{2}\}.$$

As an illustration of a possible outcome of the experiment under discussion, suppose that a statistically significant excess of π^+ events is observed and that the $n\pi^+$ and $p\pi^-$ effective mass distributions indicate strong Δ production; further, suppose that the corresponding value of $\sigma(\nu_\mu+p\to\nu_\mu+n+\pi^+)$ is appreciably greater than that expected on the basis of the predicted[6] electromagnetic form factor of the neutrino [i.e., $\gg(10^{-42}\text{–}10^{-43})\,\text{cm}^2$]. The existence of an isovector or an isotensor h_α is then demonstrated. The distinction between these two possibilities requires a measurement of the "allowedness" or "forbiddenness" of the process $\nu_\mu+p\to\nu_\mu+p$. Thus, observation of $\nu_\mu+p\to\nu_\mu+p$, again with a cross section significantly greater than that expected on the basis of the above-mentioned predicted electromagnetic form factor of the neutrino (i.e., $\gg10^{-42}$ cm^2), would rule out a predominantly isotensor h_α but would admit a predominantly isovector h_α or a linear combination in roughly equal proportion of an isotensor h_α and an isoscalar h_α. However, because of the absence of any constraint from charge symmetry, it does not seem likely that a search for the $\nu_\mu p$ final state can be made in a hydrogen bubble chamber with a sensitivity comparable to that of the search for the $\nu_\mu\Delta^+$ final state, and consequently a different experimental technique is required for an unambiguous identification of $\nu_\mu+p\to\nu_\mu+p$.

As an illustration of a second possible outcome of the experiment, suppose that no statistically significant difference is observed between $N(\pi^+)$ and $N(\pi^-)$, so that no evidence is found for the existence of the process $\nu_\mu+p\to\nu_\mu+n+\pi^+$ [Eq. (6)]. Apart from an accidental destructive interference between the contributions of an isovector h_α and an isotensor h_α to the process in question, this would leave only the possiblity of an isoscalar h_α which, if present, would manifest itself in a nonvanishing value of $\sigma(\nu_\mu+p\to\nu_\mu+p)$.

We conclude with four comments relating to event identification and background: (i) The presence of one or more additional π^0 on the right-hand side of Eqs. (3)–(10) will not upset the previous argument since, again by *charge symmetry,*

$$\sigma(np\to nn\pi^+)+\sigma(np\to nn\pi^+\pi^0)+\sigma(np\to nn\pi^+\pi^0\pi^0)+\cdots$$
$$=\sigma(np\to pp\pi^-)+\sigma(np\to pp\pi^-\pi^0)+\sigma(np\to pp\pi^-\pi^0\pi^0)+\cdots, \qquad (14)$$

so that in this case also the difference $N(\pi^+) - (N(\pi^-)$ can arise only from ν_μ-induced events. (ii) The presence of additional charged pions in one or another of the reactions, which must occur in appropriate pairs, is immediately visible. Further, for ν_μ and n of not too high energy, the relative number of final states with two or more pions is small. (iii) Background from a small contamination of $\bar{\nu}_\mu$ in the incident beam leading to $\bar{\nu}_\mu + p \rightarrow \mu^+ + p + \pi^-$ should be negligible for a muon detection efficiency of reasonable value ($\lesssim 1\%$). Finally, (iv) a list of reactions analogous to (3)–(10) with a bound neutron in deuterium as target shows that no π^+ events (unaccompanied by μ^-) are expected at all from ν_μ-induced reactions and no simple manipulation of numbers of events serves to isolate events induced by ν_μ from those induced by n. This occurs because neutrons incident on neutrons do not produce states which are charge symmetric to those produced by neutrons incident on protons (compare, e.g., $\nu_\mu + n \rightarrow \nu_\mu + p + \pi^-$ vs $\nu_\mu + p \rightarrow \nu_\mu + n + \pi^+$ and $n + n \rightarrow n + p + \pi^-$ vs $n + p \rightarrow p + p + \pi^-$). Thus the experiment described here must be done in hydrogen.

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[1]Some γ rays also originate in these reactions but the overwhelming proportion of these γ rays have too low an energy to produce a pion and so to simulate the processes of Eq. (5) or Eq. (6).

[2]The factor of 10^{-2} in Eq. (2) arises from the circumstance that the basic ν_μ reactions are $\nu_\mu + p_{\text{bound}} \rightarrow \mu^- + p + \pi^+$ and $\nu_\mu + n_{\text{bound}} \rightarrow \mu^- + p$. Hence to obtain a fast neutron, one must have a collision of the type $p + n_{\text{bound}} \rightarrow n + p$ either in the original or in a neighboring nucleus.

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