NAL PROPOSAL No. 294

Scientific Spokesman:

B. Roe
Department of Physics
University of Michigan
Ann Arbor, Michigan 48104

Phone: (313) 764-4441
Home : (313) 665-7042

Experimental Proposal to NAL

Anti-Neutrino Interactions in Deuterium in the NAL 15-ft. Bubble Chamber

C.T. Coffin, R. N. Diamond, B. Roe, A. Seidl,
J. Vander Velde

University of Michigan
Ann Arbor, Michigan

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Abstract

A study of anti-neutrino interactions in the 15-ft. bubble chamber filled with deuterium is proposed. We request a flux of about 5 x 10^{18} interacting protons (500K pictures with 10^{13} p/pulse interacting) at the highest available energy.

Our experiment, together with one or another of the proposed νd experiments, will allow the complete matrix of cross-sections νp, νn, $\bar{\nu}$p, $\bar{\nu}$n to be measured. As we will discuss, this should be a great help in separating out W_1, W_2, W_3 for νp, $\bar{\nu}$p.

It will also be possible to check several assumptions forming an important part of the basis of present theories. For example, we will be able to check whether the weak current is consistant with coupling to the I-spin current, as is now believed. For this test, we compare $d\sigma(\bar{\nu}n)$ with the cross-section we will measure in our approved hydrogen run, $d\sigma(\nu p)$. We feel it will be an advantage to have the same group analyze both processes since it will be easy to employ the same cuts and criteria. This will greatly facilitate comparisons.

We will also be able to examine various specific channels unanalyzable in hydrogen and search for new $\Delta S/\Delta Q$ violation channels.

Finally, this run will add to the statistics of $\bar{\nu}$p runs. This is important since the $\bar{\nu}$ cross-section is lower than the ν cross-section and for equal running times we will have less $\bar{\nu}$ than ν events.

Contents

I. Neutrino Energy Determination and Muon Indentification

The first question that should be addressed is how, in deuterium, we can hope to measure $\frac{d\sigma}{dq^2 d\nu}$, i.e., how we can estimate the energy of the incident neutrino.

G. Myatt[1] has recently proposed a method which shows great promise. An assumption must, of course, be made but it is one which can be tested by the data. It is assumed that the hadronic energy comes out in a jet and within the jet the transverse momenta distributions relative to the total jet momentum are typical hadronic values (i.e. around 0.3 GeV/c). This can be tested by examining the visible hadronic particles and is consistent with current Gargamelle data.

If this proves to be true, then we can estimate the anti-neutrino energy in the following way. Measure the vector sum of the momenta of the visible hadronic particles. Assume the direction of this vector is the direction of the jet (visible plus invisible particles). This direction plus the energy and direction of the muon is sufficient to determine the energy of the anti-neutrino. Monte-Carlo tests indicate an r.m.s. error of around 10% in the incident neutrino energy.

If this proves unfeasible, then many significant comparisons similar to those below can still be made[2] but they will, of necessity, be more qualitative.

It is necessary also to identify the muon. For anti-neutrino reactions considerably more than 50% of the anti-neutrino energy goes to the muon on the average and we would assume the highest energy positive particle is the muon. If the EMI proves usuable, it would certainly improve muon identification here and we would wish to use it.

If the hadronic energy comes out in a jet as assumed above, then various angle cuts based essentially on the muon and hadron jet having equal and opposite transverse momenta relative to the neutrino direction can be devised to help sort out the muon for the fraction of events in which the muon is not the most energetic particle.

It may be premature to detail such tests further, until we see what nature in fact does, but we will estimate crudely the fraction of events, which we might expect would need such treatment. This fraction is expected to be worse for the present experiment than for neutrino experiments. For anti-neutrino interactions, the muon carries off more energy, but the number of charged prongs needed to have a particle of the same charge as the muon is smaller.

Barish[3] has stated that the NAL narrow band neutrino experiments at about 50 GeV are consistent with a $\frac{d\sigma\bar{\nu}}{dy} \propto (1-y)^2$, where $y=E\mu/E\nu$. This implies $\langle y\rangle=7/12$. The first inelastic channels with a positively charged hadron are; $\bar{\nu}n \to \mu^+ p\pi^-\pi^-$ or $\mu^+ n\pi^+\pi^-\pi^-$

$$\bar{\nu}p \to \mu^+ p\pi^- \quad \text{or} \quad \mu^+ n\pi^+\pi^-$$

If we take as a typical case, an even division of hadronic momentum, then for the case of 2 hadrons ($\bar{\nu}p$ case), the dividing point is $E\mu = 1/3\ E\nu$, and for 3 hadrons ($\bar{\nu}n$ case), $E\mu=1/4\ E\nu$.

With this, we estimate that for two final state hadrons, we would be correct 85% and for three final state hadrons over 90% of the time without <u>any</u> angle tests. For higher numbers of hadrons, we would do still better on the average. If the jets are present, then further angle tests should reduce the confusion area to a very small fraction of the events even without an EMI.

For gamma rays, we would expect to have about a 15% detection efficiency in an average 7 foot path length. For neutrons, we distinquish low and high energy. For a low energy distribution of neutrons similar to that expected from elastic events, we calculate about 40% to be visible. We might find these hard to distinquish if there is a background of other low energy neutrons in the chamber. For higher energy neutrons we estimate about 50% will interact and give visible stars in a 7 foot length.

For spectator protons, the rule of thumb in practice has been that about 1/3 are visible in small bubble chambers. Since here, the expected resolution is worse for the 15' chamber, than for the small chambers, we expect an even smaller fraction, perhaps 1/6 to be visible.

The measurement and monitoring of the neutrino spectrum was discussed in Proposal 45A[4].

II. Inclusive Reactions

The inclusive cross-section can be written:

$$\frac{d^2\sigma}{dq^2 d\nu} \simeq \frac{G^2 E'}{2M^2 \pi E} \left[2W_1 \sin^2 \frac{\theta}{2} + W_2 \cos^2 \frac{\theta}{2} \mp W_3 \sin^2 \frac{\theta}{2} \left(\frac{E+E'}{M} \right) \right]$$

Where: θ = laboratory angle of muon
E = neutrino energy
E' = muon energy
M = mass of nucleon

W_1, W_2, W_3 are form factors which are functions of the invariant of momentum transfer squared, $q^2 = (p_\nu - p_\mu)^2$ and $\nu = E - E'$. The sign $\mp$ is for incident $\left\{ \begin{matrix} \text{neutrinos} \\ \text{anti-neutrinos} \end{matrix} \right.$

If scaling holds, then in the scaling region

$$W_1 \ (q^2, \ \nu) \to F_1 \ (\omega = \frac{2M\nu}{q^2})$$

$$\nu \ W_{2,3} \to MF_{2,3} \ (\omega)$$

If the weak current couples to I-Spin then, $F_i(\bar{\nu}n) = F_i(\nu p)$. (Note that in spite of this equality, the q^2 dependence is quite different since the ∓ sign for the V-A interference term is outside the F_i). This relation ignores the strangeness changing events ($\propto \sin^2\theta$) but they are a small correction. We should be able to check this result.

If this seems correct, than by taking sums and differences of νp, $\bar{\nu}n$, we should have a fairly good way of separating F_1, F_2, from F_3 terms. Having these two runs done by the same group should greatly facilitate comparisons.

We will be interested in comparing $\bar{\nu}p$ and $\bar{\nu}n$ cross-sections. Since we will do this in the same experiment we hope to eliminate many flux biases. These comparisons can also be done in neutrino deuteron experiments. In practice, if the current does couple to I-spin as indicated above, the two experiments together can yield far better tests than either individually, i.e.

$$d\sigma_{\nu n} \pm d\sigma_{\bar{\nu}p} \quad \text{isolates} \left\{ \begin{matrix} F_1, & F_2, & \nu n \\ F_3 & & \end{matrix} \right.$$

$$d\sigma_{\nu p} \pm d\sigma_{\bar{\nu}n} \quad \text{isolates} \left\{ \begin{matrix} F_1, & F_2, & \nu p \\ F_3 & & \end{matrix} \right.$$

Some predictions are[5]:

$$F_2^{ep}(\omega) + F_2^{en}(\omega) \geq 5/9\ (F_2(\omega)^{\nu n} + F_2(\omega)^{\nu p}) = 5/9\ (F_2(\omega)^{\bar{\nu}p} + F_2(\omega)^{\bar{\nu}n})$$

$$F_2^{ep} - F_2^{en} = 1/3\ (F_2^{\nu n} - F_2^{\nu p}) = 1/3\ (F_2^{\bar{\nu}p} - F_2^{\bar{\nu}n})$$

$$\frac{F_2^{\nu n}}{F_2^{\nu p}} = 2 \text{ in the limit of exact SU (6) symmetry}$$

$(F_2^{\nu n} + F_2^{\nu p}) / 3\, F_2^{ep} = 1$ for all ω, if SU(6) exact → 3/4 as $1/\omega$ → 1 in a particular SU(6) breaking model[6]

$$\frac{F^{\nu p}}{F^{\nu n}} = \frac{F^{\bar{\nu} n}}{F^{\bar{\nu} p}} \rightarrow 0 \text{ as } 1/\omega \rightarrow 0$$ (Feynman prediction)[6]

Current experiments indicate F_3 to be about as large as possible and σ_{tot} $(\bar{\nu}N) \sim 1/3$ σ_{tot} (νN).[8] The CERN results [10] have indicated that for neutrinos the neutron cross-section is close to two times the proton cross-section (1.8± .3). This then implies that only n quarks interact and that the anti-neutrino proton cross-section is twice the anti-neutrino neutron cross-section.

The total event rate (n and p) is given in Table II. We have assumed $\sigma_{total\ nucleon}$ $\bar{\nu} = (.8 \times 10^{-38} E_\nu)/3$ (i.e. 1/3 σ_{total} (ν-nucleon)), 5×10^{18} interacting protons at 350 GeV/c and the anti-neutrino spectrum using 2 horns which we used in proposal 180.[9]

At very high energies we will be able to examine the Adler relations.[11]

$$\frac{d\sigma}{dq^2}(\bar{\nu}p) - \frac{d\sigma}{dq^2}(\nu p)\Big|_{E\rightarrow\infty} = \frac{G^2}{\pi}\left(\cos^2\theta_c + 2\sin^2\theta_c\right)$$

$$\frac{d\sigma}{dq^2}(\nu n) - \frac{d\sigma}{dq^2}(\bar{\nu}n)\Big|_{E\rightarrow\infty} = \frac{G^2}{\pi}\left(\cos^2\theta_c - \sin^2\theta_c\right)$$

Again in the first of these relations the fact that the same group will have νp and $\bar{\nu}p$ will greatly facilitate this examination.

Finally we hope to examine the semi inclusive channels with either single or associated pairs of strange particles. As discussed in proposal E180 we might expect that as in hadronic interactions perhaps 15% of the cross-section has associated pairs. Comparisons between νn, νp, $\bar{\nu}n$, $\bar{\nu}p$ would be quite interesting.

III. Exclusive channels

The comparison with νp also will be quite interesting here. There are several channels that can be reached in $\bar{\nu}n$ that are quite difficult to detect for the charge symmetric νp reaction.

$\bar{\nu} n \to \mu^+ \pi^- \pi^- p$	$(\nu p \to \mu^- \pi^+ \pi^+ n)$
$\to \mu^+ \pi^+ \pi^- \pi^- \pi^- p$	$\to \mu^- \pi^- \pi^+ \pi^+ \pi^+ n)$
$\to \mu^+ K^\circ \Sigma^-$	$\to \mu^+ K^+ \Sigma^+$
	(or Y^{*-} $I = 1$)
	(the K^+ is hard to identify)

Let us look at the channel: $\bar{\nu} N \to \mu^+ \Delta$

From the $\Delta I = 1$ rule we can predict that:[12]

$$\sigma\ (\bar{\nu} + n \to \mu^+ + \Delta^-) = 3\sigma\ (\bar{\nu} + p \to \mu^+ + \Delta^\circ)$$

For the Δ°, 1/3 of the decays are by the analyzable channel $p\pi^-$. There are several models predicting specific cross-sections in the range of a few times 10^{-39} cm^2.[12] We would have about 1200 events for a 3×10^{-39} cm^2 cross-section. For all events including non-Δ events in these channels we have only the inequality

$$\frac{\sigma(\bar{\nu} n \to \mu^+ n \pi^-)}{\sigma(\bar{\nu} p \to \mu^+ n \pi^\circ) + \sigma\ (\bar{\nu} p \to \mu^+ p \pi^-)} \leq 3$$

This in fact may be somewhat difficult to check. The $\Delta^\circ \to p\pi^-$ channel will be detectable but the $\Delta^- \to n\pi^-$ is OC and thus requires that we see a neutron star to make it a 2C case. As discussed in Section I, we will see some sort of interaction about 50% of the time but only experience will tell us how easy it will be to distinquish from background in the chamber.

There are additional interesting channels, isobar and vector meson searches possible as discussed in our proposal E180.[9]

For strangeness changing channels we will look for

$\bar{\nu}n \rightarrow \mu^+\Sigma^-$

$\mu^+\Omega^-$ Forbidden $\Delta S = 3$

$\mu^+\Xi^-$ Forbidden $\Delta S = 2$

$\mu^+\Omega^-\bar{K}^\circ$ Forbidden $\Delta S = 4$ (or 2 if K° not $\bar{K}^\circ$)

The first reaction above can be compared with $\bar{\nu}p \rightarrow \mu^+\Sigma^\circ \rightarrow \Lambda^\circ\gamma$.

The $\Delta I = 1/2$ rule predicts $\frac{\mu^+ \Sigma^-}{\mu^+ \Sigma^\circ} = 2$

The neutron reaction ($\mu^+\Sigma^-$) is easier to identify than the proton reaction. If we can identify both we can test $\Delta I = 1/2$ at high energy. If we cannot, we can use the rule to help sort out the $\bar{\nu}p$ results with their Σ°, Λ° ambiguities.

If there are sufficient events with K° mesons, a test for $\Delta S/\Delta Q$ sensitive to the amplitude of the violation can be made.[13]

There are, of course, a great many more allowed and non-allowed strangeness changing channels with several final state particles. Some of these are catalogued in our proposal E180, and we will be looking at all of them.

As indicated in proposal E180, we will search for T-odd correlation in 2 body channels, especially strangeness changing ones in which the hyperon decay analyzes the polarization for us automatically.

IV. Neutral Currents: Search for New Particles

If neutral currents exist and are plentiful, we can examine whole new classes of events:

$$\bar{\nu}n \rightarrow \bar{\nu}\pi^- p$$
$$\rightarrow \bar{\nu}\,\Lambda^\circ$$
$$\rightarrow \bar{\nu}\,\bar{K}^\circ\pi^- p$$

Again, we would compare νn, $\bar{\nu}p$, $\bar{\nu}n$

If the currents are small the searches for neutral currents would be similar to those outlined in our proposal E180. For these searches, neon would seem to have some advantages over deuterium. These searches are made more difficult by the falling neutrino energy spectrum. If the CERN Gargonelle results are correct, then the neutral current events[14] have a y distribution similar to the charged current. This implies that the neutrino is given about one-half the energy in a typical neutral current event and the visible energy is only one-half E_ν. Hence, it will be compared with charged current events of lower energy. Because of the steeply falling spectrum, this makes the background considerably worse.

We would search for intermediate bosons, heavy leptons, and quarks of all flavors. Again, this is outlined in our neon proposal E180 and would be very similar here, although neon would be more effective for many of these searches.

V. $\bar{\nu}p$ Interactions

We would considerably increase the world store of $\bar{\nu}p$ interactions. Since $\bar{\nu}p$ cross-sections are smaller than νp, these results are harder to collect and this will be a significant addition. The kinds of things that can be done are discussed in our proposal E180, and also in the $\bar{\nu}p$ proposal of ANL-Carnegie Mellon.[15]

VI. Capabilities and Commitments of our Group.

We have been active in preparing monitoring and measuring equipment to determine and monitor the neutrino spectrum in these experiments.

We have other neutrino experiments requested at NAL, but since they all use the same bubble chamber, they will have to occur more or less serially. Neutrino exposures for the most part are characterized by lots of film and few events. (The neon run should have more events, but is divided between 4 laboratories). Given the range of commitments of the chamber and reasonable estimates for the fraction of time it can expect to be up and be a major part user it does not appear that our facilities will be strained by this additional experiment. We feel that, in fact, we will be quite experienced in neutrino events by the time we obtain this film and will be able to do a very rapid efficient analysis.

References

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5. F.E. Close Partons and Quarks. Daresbury Lecture Note Series No. 12 (1973).

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15. NAL Proposal 31A, Proposal to Investigate Anti Neutrino Interactions in Hydrogen at NAL, ANL, Carnegie-Mellon.

TABLE I

Number of Anti-neutrino Events for 5 x 10^{18} Interacting Protons

Energy Interval (GeV)	D_2 V=20 M^3	V=11M^3
0-10	3000	1700
10-20	10000	5700
20-30	10000	5700
30-40	7400	4200
40-50	3800	2200
50-60	1800	1000
60-70	800	400
70-80	420	240
80-90	230	130
90-100	160	90
100-110	130	70
110-120	100	60
120-130	90	50
130-140	70	40
140-150	50	30
150-160	30	20
160-170	20	13
170-180	13	7
180-220	13	7
Total Number	39000	22000

Addenda to Fermilab Proposal E294
($\bar{\nu}$ in 15-ft. deuterium chamber)

I. We wish to expand the groups involved in the experiment. The experiment is now proposed to be performed jointly by

University of Michigan: C.T. Coffin, R.N. Diamond, B.P. Roe, A.A. Seidl, J.C. Vander Velde

University of California, Berkeley - Lawrence Radiation Laboratory: A. Barbero-Galtieri, G.R. Lynch, J. Marriner, L.M. Stevenson

University of Hawaii: R.J. Cence, F.A. Harris, M.W. Peters, S.I. Parker, V.Z. Peterson, V.J. Stenger.

The spokesmanship will rotate between:

B.P. Roe

L.M. Stevenson

V.Z. Peterson

in the order given above at six month intervals starting at the date of approval of the experiment.

II. Further Physics Discussion

An EMI is an important element in the present proposal. The cross section for $\bar{\nu}n$ is expected to be the smallest of the neutrino nucleon cross sections. In the simplest quark model one expects $\sigma(\nu n) = 2\ \sigma(\nu p) = 3\ \sigma(\bar{\nu}p) = 6\ \sigma(\bar{\nu}n)$. The EMI will be exceedingly useful in separating out the background events due to neutrinos which get through the horn system; an especially important effect at high energies.

The laboratories involved in this proposal have now had some initial experience analyzing neutrino film. We realize that the scanning load is quite large and will require considerable effort from our combined facilities. We note, however, that because of the small cross-section large exposures are required. In a 20 m^3 (large) fiducial volume we expect 39,000 events of which only 13,000 would be $\bar{\nu}n$. If we wish the secondaries to have a large probability of traversing the EMI we may have to reduce this

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fiducial volume considerably.

Finally, we wish to point out that the laboratories represented here are all involved in the νp experiment E45. Most of the comparisons for sum rules that one wishes to make require comparing $\sigma(\nu p)$ with $\sigma(\bar{\nu} n)$. In order to minimize relative biases and keep the myriad of small factors that can create systematic corrections uniform, it is a great advantage to have an overlap in the groups analyzing the two sets of data.