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ANTINEUTRINO INTERACTIONS IN THE DEUTERIUM FILLED 15 FOOT BUBBLE CHAMBER

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One Page Summary
For FNAL Proposal No. ______

ANTINEUTRINO INTERACTIONS IN THE DEUTERIUM FILLED 15-FOOT BUBBLE CHAMBER

Purdue University, Carnegie-Mellon University
and Argonne National Laboratory

It is proposed to study the interactions of antineutrinos in deuterium. The initial request is for 300,000 pictures out of a total of one million pictures using the two-horn broad band system with 10^{13} protons (300 GeV) per pulse. We plan to use the external muon identifier.

The physics motivation includes the following:

1) Search for charmed mesons.

2) Study of elastic and inelastic hyperon production. Only in antineutrino interactions can we study the $\Delta S = 1$ charged current in quasi two-body interactions at energies and momentum transfers higher than that available in decays.

3) Study of the quasi elastic and pion production reactions. These data will be combined with the $\bar{\nu}p$ data of our experiment (E-31).

4) Inclusive study of charged current interactions off neutrons and protons.

5) We will study the structure of the neutral current interaction. We will check the absence of $\Delta S = 1$ neutral currents.

6) We will also look for di-muon events using the EMI.

7) We are interested in the possibility of inserting a three-radiation length metal plate in the bubble chamber to serve as a gamma converter and an electron detector.

Summary prepared by
A. F. Garfinkel, April 1975

SUMMARY OF REQUEST

We propose to make a one-million picture exposure of the deuterium-filled 15-foot bubble chamber to the broad band antineutrino beam. We will measure and analyze all events inside a 20 m^3 fiducial volume. This will allow us to make the first measurements of antineutrino neutron reactions and to directly compare them to antineutrino proton reactions. The proton data from this exposure (two-thirds of the charged current events) will be added to our data from E-31 to improve the statistics on all reactions and particularly those proportional to $\sin^2\theta_c$. It is requested that there be initial approval of at least 300,000 pictures. This will permit a significant study of the antineutrino neutron interaction ($\sim$ 6000 $\bar{\nu}n$ events).

The antineutrino flux calculation (Figure 1) assumes the use of two horns. The event rates are based on 10^{13} protons per pulse at 300 GeV on the neutrino target, and assume 300,000 pictures unless stated otherwise. A substantially larger proton flux would of course be very welcome, as would higher incident proton energy.

We anticipate that the E.M.I. will be available for usage as a laboratory facility and we are committed to make whatever efforts are required in preparing to utilize it efficiently.

INTRODUCTION

The study of antineutrino interactions in deuterium is interesting for several reasons. It is the only way that one can study the interaction of antineutrinos with quasi-free neutrons, one of the basic interactions in nature. It allows one to make the simplest and most direct comparison of antineutrino neutron and antineutrino proton scattering from which can be deduced the scattering on the basic quarks. The antineutrinos are an excellent tool in a search for charmed mesons. They are unique since one can probe the quasi two-body $\Delta S = 1$ reactions and test the Cabibbo theory in new domains of energy and momentum transfer. The simplicity of the study of the production and decay of strange particles is a major asset of hydrogen and deuterium bubble chambers. It is considerably more difficult in heavy liquid bubble chambers due to the loss of resolution from multiple scattering and the problem of secondary interactions inside the target nucleus.

In a study of inclusive reactions we will not only study the final state muon distribution of the charged current reactions, but distributions in final state hadrons as well. Having the measured momenta of all charged particles, one can make detailed studies of the hadronic system that are inaccessible to the electronic experiments. The fact that the deuteron is an isoscalar particle permits interesting tests as will be discussed.

It is clear that much of the interesting neutrino physics that the bubble chamber can contribute centers around a comparison between the results of νn, νp, $\bar{\nu}n$ and $\bar{\nu}p$ reactions. Since we are presently analyzing the $\bar{\nu}p$ exposure (E-31), if the present proposal were approved we would make the $\bar{\nu}n$ and $\bar{\nu}p$ comparisons directly.

The physicists submitting this proposal have had considerable experience in analyzing neutrino experiments in large bubble chambers. We are able to scan and measure the film promptly and accurately and should have physics results in the shortest possible time. For the $\bar{\nu}$, ν comparison we propose to have the ANL, CMU and Purdue groups collaborate with the groups analyzing the neutrino film. We feel that a decoupling of the basic ν, $\bar{\nu}$ analyses (scanning, measuring, etc.) will lead to a more efficient production of the physics data.

I. PRODUCTION OF CHARMED PARTICLES

The observation[(I-1)] of neutral currents in the strangeness-nonchanging interactions and not in the strangeness-changing interactions requires explanation. Perhaps the most elegant solution proposed to date[(I-2)] requires the existence of a fourth charmed quark. The discovery of the new mesons[(I-3)] with masses 3.1, 3.7 as well as the enhancement at 4.2 GeV has been interpreted as support for this hypothesis. However, direct observation of charmed hadrons is the crucial test. The possible observation of one such event has been reported[(I-4)] by the BNL group. It has been interpreted as the production of a doubly charged charmed baryon in a neutrino proton collision at 13.5 GeV. Possible additional evidence for the production of charmed states has been obtained[(I-5)] in the observation of di-muon events and in the observation of an excess of events at large y in $\bar{\nu}N$ interactions at high energies.

Production of Charmed Mesons by Antineutrinos

The production of charmed mesons by antineutrinos can occur without Cabibbo angle suppression through the following lepton quark reactions involving $s\bar{s}$ or $c\bar{c}$ pairs in the nucleon. We use the notation u, d, s, c for the four quarks.

$$\bar{\nu}\bar{s} \rightarrow \mu^+\bar{c} \qquad \text{I-(1)}$$

$$\bar{\nu}c \rightarrow \mu^+ s \qquad \text{I-(2)}$$

While these reactions require the presence of strange quarks or charmed quarks in the nucleon at some level, their amplitudes are proportional to the cosine of the Cabibbo angle. M. K. Gaillard has estimated[(I-6)] that a 10% level of $\bar{s}$ quarks in the nucleon would give rise to a 33% enhancement in the total $\bar{\nu}$ cross section.

One can produce the physical charmed mesons $F^- = \bar{c}s$, $D^- = \bar{c}d$ and $\bar{D}^o = \bar{c}p$ through the following reactions:

$$\bar{\nu}p \rightarrow \mu^+F^-p \qquad \text{I-(3)}$$

$$\bar{\nu}n \rightarrow \mu^+F^-n \qquad \text{I-(4)}$$

$$\hookrightarrow K^{*-}K^o + \text{pions} \qquad \text{I-(4a)}$$

$$\bar{\nu}p \rightarrow \mu^+\bar{D}^o(\Lambda,\Sigma^o,Y^{*o}) \qquad \text{I-(5)}$$

$$\bar{\nu}n \rightarrow \mu^+\bar{D}^o(Y^{*-},\Sigma^-) \qquad \text{I-(6)}$$

$$\hookrightarrow K^+ + \text{pions} \qquad \text{I-(6a)}$$

$$\bar{\nu}p \rightarrow \mu^+D^-(\Sigma^+,Y^{*+}) \qquad \text{I-(7)}$$

$$\bar{\nu}n \rightarrow \mu^+D^-(\Lambda^o,\Sigma^o,Y^{*o}) \qquad \text{I-(8)}$$

$$\hookrightarrow K^o + \text{pions.} \qquad \text{I-(8a)}$$

Since the F mesons probably decay primarily to $K\bar{K}$ plus pions, while the D mesons probably decay primarily to single kaons plus pions and are produced in conjunction with S = -1 hyperons, one signature for charmed meson production is an apparent associated production of strange particles. In addition, lepton decays may be detected with the aid of the EMI.

Finally, the bubble chamber has a major advantage in being able to detect multiparticle decays of charmed hadrons.

II. EXCLUSIVE CHARGED CURRENT REACTIONS

1. Elastic hyperon production

Wolfenstein in a recent paper(II-1) suggested "It is possible that we cannot understand the absence of $|\Delta S| = 1$ neutral currents until we have a better understanding of $\Delta S = 1$ charged currents, which occur in the Weinberg theory and most other theories by the arbitrary introduction of the Cabibbo mixing angle."

In antineutrino reactions one can study the strangeness-changing part of the weak interactions over a wide range of energy and momentum transfer. The reaction rates are expected to be small. On the basis of Cabibbo's description(II-2) (based on strange particle decays) and experiments in freon(II-3), they should occur at the few per cent level.

The basic quark reaction in the production of hyperons is proportional

$$\bar{\nu}u \rightarrow \mu^+ s \qquad \text{II-(1)}$$

to $\sin^2\theta_c$ and gives rise to the observable reactions:

$$\bar{\nu}p \rightarrow \mu^+(\Lambda^o \text{ or } \Sigma^o) \qquad \text{II-(2)}$$

$$\bar{\nu}n \rightarrow \mu^+\Sigma^- . \qquad \text{II-(3)}$$

Since the probability of conversion of the gamma from Σ^o decay is only about five per cent, one must consider reaction II-(2) to measure the sum of Λ^o and Σ^o production. The ratios of the rates for reactions II-(2) and II-(3) can be measured and compared to Cabibbo's theory.

Based on Cabibbo's theory we expect to detect approximately 37 Λ^o events, 10 Σ^o events and 29 Σ^- events.

2. Inelastic hyperon production

With the same quark reactions as for elastic production we obtain the following observable reactions for decuplet production:

$$\bar{\nu}n \to \mu^+\Sigma^*(1385)^- \qquad \text{II-(4)}$$
$$\hookrightarrow \Lambda^\circ\pi^-.$$

This could be compared to

$$\bar{\nu}p \to \mu^+\Delta^\circ \qquad \text{II-(5)}$$
$$\hookrightarrow p\pi^-$$

serving as a high energy test of the Cabibbo theory.

This comparison is experimentally simpler than for the quasi elastic case and may be simpler within the theory since no F/D ratio needs to be determined.

The $\Delta I = 1$ rule predicts that reaction II-(5) will have a rate one-third of that for

$$\nu p \to \mu^-\Delta^{++}. \qquad \text{II-(6)}$$

We measured this cross section at ANL to be $\sigma = 0.68 \pm .13 \times 10^{-38}$ cm^2 and so expect a total of 350 events for reaction II-(5) of which one-third will decay as indicated.

3. Quasi elastic scattering

The reaction

$$\bar{\nu}p \to \mu^+ n \qquad \text{II-(7)}$$

measures the weak form factors of the nucleon. Measurements have been made by our group at ANL(II-4) at moderate q^2. We will be able to extend them to higher values. Data from this experiment will be added to that of E-31 in a measurement of the form factor.

In addition, since

$$\frac{d\sigma}{dq^2} = \left(\frac{G}{2\pi}\right)^2\left\{|g_V|^2 + |g_A|^2\right\} \qquad \text{II-(8)}$$

at low q^2 is independent of neutrino energy, this reaction can serve as a check on flux determinations.

We have measured the total elastic cross section $0.8 \pm 0.3 \times 10^{-38}$ cm^2 leading to a total of 1150 events. Estimating a neutron detection efficiency of 20% from secondary scattering, we will obtain 250 useful events.

4. Pion production reactions

We can test the $\Delta I = 1$ rule at high energy by comparing the rate for $\mu^+ \Delta^o$ production (reaction II-(5)) to the rate for

$$\nu n \rightarrow \mu^+ \Delta^- \quad \hookrightarrow n\pi^- . \qquad \text{II-(9)}$$

Finally, other constrained reactions such as $\bar{\nu} n \rightarrow \mu^+ p \pi^- \pi^-$ and $\bar{\nu} p \rightarrow \mu^+ p \pi^- \pi^+ \pi^+$ will also be studied.

III. CHARGED CURRENT INCLUSIVE REACTIONS

1. Total cross sections

The measurement of the total charged current cross section on nucleons

$$\sigma_T(\bar{\nu}p \rightarrow \mu^+ + X) \qquad \text{III-(1)}$$

and

$$\sigma_T(\nu n \rightarrow \mu^+ + X) \qquad \text{III-(2)}$$

can be made and compared, subject to the limitations imposed on our knowledge of the antineutrino energy by the presence of undetected π^0's. Various models of the hadronic system can be used to deduce a value for the total energy. For example, if one assumes that the charged hadrons accurately define the direction of the total hadronic system, then one can solve for the antineutrino energy using it, the antineutrino direction and the μ^+ momentum. Monte Carlo estimates show that one can measure E_ν and q^2 to approximately 10% (see Figure 2).

One expects these cross sections to increase linearly with energy until nonlocal effects such as the W boson propagator come into play. In a naive quark model[III-1] one expects $\sigma(\bar{\nu}p) = 2\sigma(\bar{\nu}n)$.

In a similar way a measurement of the total charged current cross section on the deuteron $\sigma_T(\bar{\nu}d \rightarrow \mu^+ + X)$ can be made. The naive quark model predicts the ratios of this cross section to the total cross section by neutrinos on deuterons $\sigma_T(\nu d \rightarrow \mu^+)$ to be

$$R = \sigma_T(\bar{\nu}d)/\sigma_T(\nu d) = 1/3. \qquad \text{III-(3)}$$

2. Differential cross sections and scaling

We use the usual scaling variables

$$x = -q^2/2(pq) = -q^2/2\nu \qquad \text{III-(4)}$$

$$y = (pq)/(pk) = (E - E')/E \qquad \text{III-(5)}$$

where k, p, and q are the incident neutrino momentum, target momentum and leptonic momentum transfer respectively, E and E' are the incident and final lepton energies, and $\nu = M_n(E - E')$.

In terms of these variables the deep inelastic electroproduction on protons is

$$d^2\sigma(ep)/dx\,dy = e^4 q^{-4} mE\pi^{-1} F_2(ep)[1 + (1-y)^2] \qquad \text{III-(6)}$$

where

$$F_2(ep) = x\left(\frac{4}{9}u + \frac{1}{9}d\right) \qquad \text{III-(7)}$$

and u(x) and d(x) are the probability densities for finding a given quark with fraction x of the proton's longitudinal momentum. Denoting by $\Sigma(\nu p)$ and $\Sigma(\bar{\nu}p)$ the charged current cross sections for ν and $\bar{\nu}$ on protons in units of G^2mE/π the naive quark model gives

$$d^2\Sigma(\nu p)/dx\,dy \equiv (\pi/G^2mE)[d^2\sigma(\nu p)/dx\,dy] = 2xd \qquad \text{III-(8)}$$

$$d^2\Sigma(\bar{\nu}p)/dx\,dy \equiv 2xu(1 - y)^2 \qquad \text{III-(9)}$$

$$d^2\Sigma(\nu n)/dx\,dy = 2xu \qquad \text{III-(10)}$$

$$d^2\Sigma(\bar{\nu}n)/dx\,dy = 2xd(1 - y)^2. \qquad \text{III-(11)}$$

The u and d functions may be determined from electroproduction data[III-2] and the resulting predictions compared to the measured neutrino distributions. Some such comparisons have been made[III-3] and the agreement has generally been good at low energies. At high energies an anomaly has been found in the antineutrino y distribution[III-4] which is of considerable interest. We will attempt to confirm it and study its origin in specific channels.

Strong tests can be obtained in terms of the variable

$$xy = -q^2/2mE \cong q_\perp{}^2/2mE' \qquad \text{III-(12)}$$

which only requires measurement of the muon momentum. Comparisons have been made[III-5] to electroproduction which indicate deviations from the expected distributions.

3. Single-particle inclusive reactions for hadrons

The bubble chamber technique will allow us to measure single-particle inclusive reactions of the form

$$\bar{\nu}n \rightarrow h^{\circ} + \mu^{+} + X \qquad \text{III-(13)}$$

where h° is a neutral hadron such as Λ°, $\bar{K}^{\circ}$ or π°. The π° is detectable at the 5% level from pair production in the liquid. The insertion of a high Z plate would enhance the π° detection substantially.

Similarly charged current reactions of the form

$$\bar{\nu}n \rightarrow h^{\pm} + \mu^{+} + X \qquad \text{III-(14)}$$

can be measured and the results compared to those from electroproduction.

4. Semi-inclusive reactions for hadrons

Semi-inclusive reactions of the form

$$\bar{\nu}n \rightarrow h^{*} + \mu^{+} + X \qquad \text{III-(15)}$$

where h^{*} is either a meson or a baryon resonance such as ρ°, $\bar{K}^{*}$, or Δ° can be measured. Such reactions are likely to be inaccessible to electronic detectors.

IV. NEUTRAL CURRENT REACTIONS

The problem of understanding the structure of the neutral current presents one of the most exciting problems in particle physics. This experiment will compare the neutral current interactions of antineutrinos with neutrons and protons in an isospin zero target which has certain special advantages.

A. Antineutrino Hadron Neutral Current Interactions

1. Identification of neutral current events

We can often say that no muon is present if no charged particle balances the $p_{\perp}$ of the hadronic matter. Furthermore, at least in a restricted fiducial volume the EMI is an efficient muon identifier.

2. Measurement of isovector neutral currents

The use of an isoscalar target leads to various simplifications in an analysis of inclusive neutral current reactions. Thus having a deuteron as target is a substantial advantage.

Following Wolfenstein(II-1) one may consider neglecting isoscalar terms (v_o, a_o) in the neutral current. They would be proportional to $\sin^4\theta_w$ in the Weinberg theory. Then the effective neutrino-hadron interaction is

$$\frac{G}{\sqrt{2}} \nu\gamma_\lambda(1 + \gamma_5)\nu \left[g_V V_\lambda^3 + g_A A_\lambda^3\right] \qquad \text{IV-(1)}$$

where for Weinberg's theory

$$g_V = 1 - 2\sin^2\theta_w, \; g_A = 1. \qquad \text{IV-(2)}$$

Wolfenstein defines the following inclusive cross sections for charged currents:

$$\sigma_- \equiv \sigma(\nu + d \rightarrow \mu^- + X) = A + V + I \qquad \text{IV-(3)}$$

$$\sigma_+ \equiv \sigma(\bar{\nu} + d \rightarrow \mu^+ + X) = A + V - I \qquad \text{IV-(4)}$$

where X is some set of final state hadrons (summed over charges) and A, V, and I are the axial, vector, and AV interference contributions. For neutral current inclusive interactions he defines

$$\sigma_o \equiv \sigma(\nu + d \rightarrow \nu + X) = \tfrac{1}{2}(g_A{}^2 A + g_V{}^2 V + g_A g_V I) \qquad \text{IV-(5)}$$

$$\bar{\sigma}_o \equiv \sigma(\bar{\nu} + d \rightarrow \bar{\nu} + X) = \tfrac{1}{2}(g_A{}^2 A + g_V{}^2 V - g_A g_V I). \qquad \text{IV-(6)}$$

He also defines $R \equiv \sigma_o/\sigma_-$, $\bar{R} \equiv \bar{\sigma}_o/\sigma_+$ and $r = \sigma_+/\sigma_-$. Measurement of these quantities and a theoretical value for A/V allow a determination of both g_A and g_V. This experiment along with an experiment of ν on deuterium allow a measurement of the three ratios (R, $\bar{R}$ and r). If Wolfenstein's conjecture (based on the parton model) that A = V is correct, then

$$R = \frac{1}{8}\left[(g_A + g_V)^2 + r(g_A - g_V)^2\right] \qquad \text{IV-(7)}$$

$$\bar{R} = \frac{1}{8}\left[(g_A + g_V)^2 + r^{-1}(g_A - g_V)^2\right] \qquad \text{IV-(8)}$$

and since $r \approx$ one-third the antineutrino ratio, $\bar{R}$ is then particularly sensitive to $(g_A - g_V)$.

3. <u>Measurement of isoscalar neutral currents</u>

At present there is no good experimental evidence indicating the relative importance of isovector and isoscalar neutral currents. As pointed out by Albright et al.[(IV-1)] a study of charge asymmetry in inclusive pion production off an isoscalar target is a sensitive test for isoscalar isovector interference. We will be able to compare the reactions

$$\bar{\nu}d \rightarrow \bar{\nu} + \pi^+ + X \qquad \text{IV-(9)}$$

$$\bar{\nu}d \rightarrow \bar{\nu} + \pi^- + X \qquad \text{IV-(10)}$$

where X is any set of final states summed over charges.

Another reaction which clearly measures the isoscalar neutral current is

$$\bar{\nu}d \rightarrow \bar{\nu}d \qquad \text{IV-(11)}$$

which in principle is measurable in this experiment. While this reaction is extremely interesting, it will certainly be difficult to measure due to neutron background problems.

4. Are strangeness-changing neutral currents really absent?

If charmed particles turn out not to exist the absence of $|\Delta S| = 1$ neutral currents is a serious problem for the Weinberg theory. Wolfenstein points out that the measured decays of strange particles do not rule out an axial vector A_6 term. We will be able to place an upper limit on such a term by looking for reactions of the type

$$\bar{\nu} + p \rightarrow \bar{\nu}\Sigma^{+} \qquad \text{IV-(12)}$$

or

$$\bar{\nu} + n \rightarrow \bar{\nu}\Lambda^{o} \qquad \text{IV-(13)}$$

and for the inclusive reactions

$$\bar{\nu} + p \rightarrow \bar{\nu}\Sigma^{+} + X \qquad \text{IV-(14)}$$

$$\bar{\nu} + n \rightarrow \bar{\nu}\Lambda^{o} + X \qquad \text{IV-(15)}$$

where X represents all nonstrange hadrons. We note that reactions IV-(12) and IV-(14) are easier to measure than IV-(13) and IV-(15).

5. Associated production by neutral currents

We have observed associated production by neutral currents at Argonne energies[IV-2] and have found an indication that the fractional rate for associated production is larger than in charged current reactions. We propose to extend this study to higher energies.

6. If heavy leptons (M) exist, the neutral member can be produced in the reaction

$$\bar{\nu} + N \rightarrow \overline{M}^{o} + \text{hadrons}. \qquad \text{IV-(16)}$$

If the $\overline{M}^{o}$ decays via $\overline{M}^{o} \rightarrow \bar{\nu}\mu^{+}\mu^{-}$, we can identify di-muon events with the EMI and set limits on the M mass.

B. Antineutrino Electron Elastic Scattering

The basic lepton-lepton elastic scattering process is the simplest neutral current process.

$$\bar{\nu}e^{-} \rightarrow \bar{\nu}e^{-} \qquad \text{IV-(17)}$$

The angular distribution can in principle be used to test whether the neutral current is of the Weinberg type (V and A) and if so, to measure the Weinberg angle, since

$$\frac{d\sigma}{d\Omega}(\bar{\nu}e \rightarrow \bar{\nu}e) = \frac{G^{2}s}{(2\pi)^{2}}\left[C_{-}^{2} + C_{+}^{2}\cos^{4}\frac{\theta}{2}\right] \qquad \text{IV-(18)}$$

where θ is the C.M. scattering angle.

In the Weinberg theory

$$C_{+} = -1/2 + \sin^{2}\theta_{w}$$
$$C_{-} = \sin^{2}\theta_{w}. \qquad \text{IV-(18a)}$$

Further very important (but stastically limited) information can be obtained from the electron energy spectrum alone. Since $E_{e} \sim 1 + \cos\theta$, equation IV-18 can be written

$$\frac{d\sigma}{dE_e}\,(\bar{\nu}e \rightarrow \bar{\nu}e) \sim \left[C_-^2 + C_+^2\left(1 - \frac{E_e}{E_\nu}\right)^2\right] . \qquad \text{IV-19}$$

The predicted electron energy spectrum is then obtained by folding in the $\bar{\nu}$ flux and provides another test of the Weinberg theory. We would expect somewhere between 7 and 100 events based on the Weinberg theory. It is also interesting to note that if the distribution is an increasing function of θ, then the weak interaction can not be any combination of V and A[(IV-3)].

Experimentally one would look for a single negative track starting in the liquid. It would be distinguished from a μ^- by being totally absorbed before it hit the EMI if within the EMI acceptance. If it is a low-energy electron it may be resolved by multiple scattering, energy loss shape, δ ray production or bremsstrahlung. The situation is more favorable than with neutrinos since there are relatively few neutrinos in the antineutrino beam and hence the μ^- background is smaller. If this reaction appears feasible after the initial exposure, we would consider adding a downstream plate of about three radiation lenghts which would also be useful in gamma detection in other reactions.

C. Neutron Background to Neutral Current Reactions

The most difficult background to the neutral current events comes from neutron interactions. By shielding improvements one will be able to reduce them until only those neutrons in equilibrium with the beam will be incident on the bubble chamber. Since the neutral current to charged current ratio is ~ two times larger for $\bar{\nu}d$ than νd, the ultimate neutron background will be less in the $\bar{\nu}$ exposure than for a ν beam.

The results from the ongoing analysis of H_2 and Neon exposures should be used in a sustematic study of this important background. Our experience with the low-energy experiment in the 12' chamber may help in this respect.

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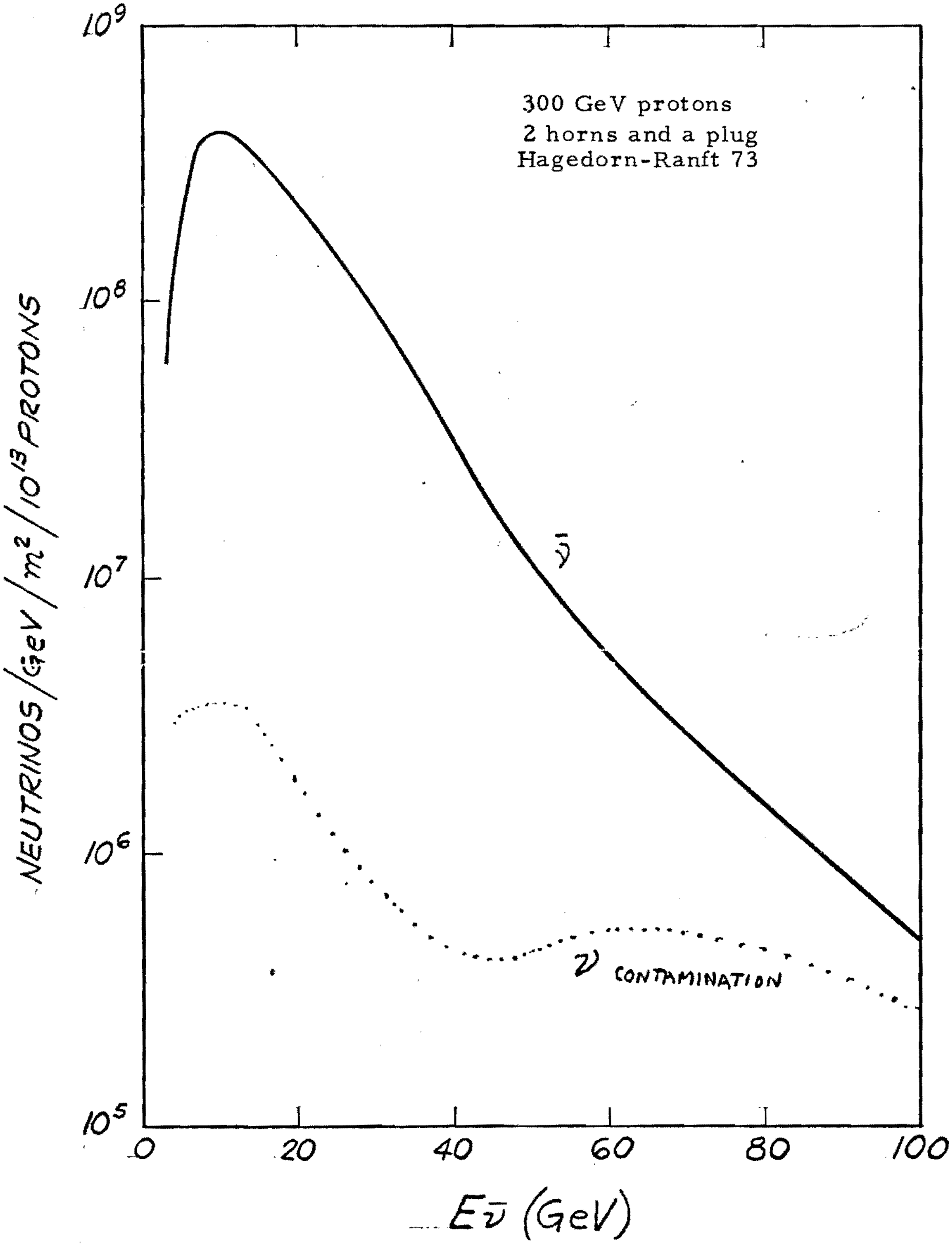
300 GeV protons
2 horns and a plug
Hagedorn-Ranft 73
$\bar{\nu}$
ν CONTAMINATION
NEUTRINOS / GeV / m^2 / 10^{13} PROTONS
10^9
10^8
10^7
10^6
10^5
0
20
40
60
80
100
$E_{\bar{\nu}}$ (GeV)

Fig. 1

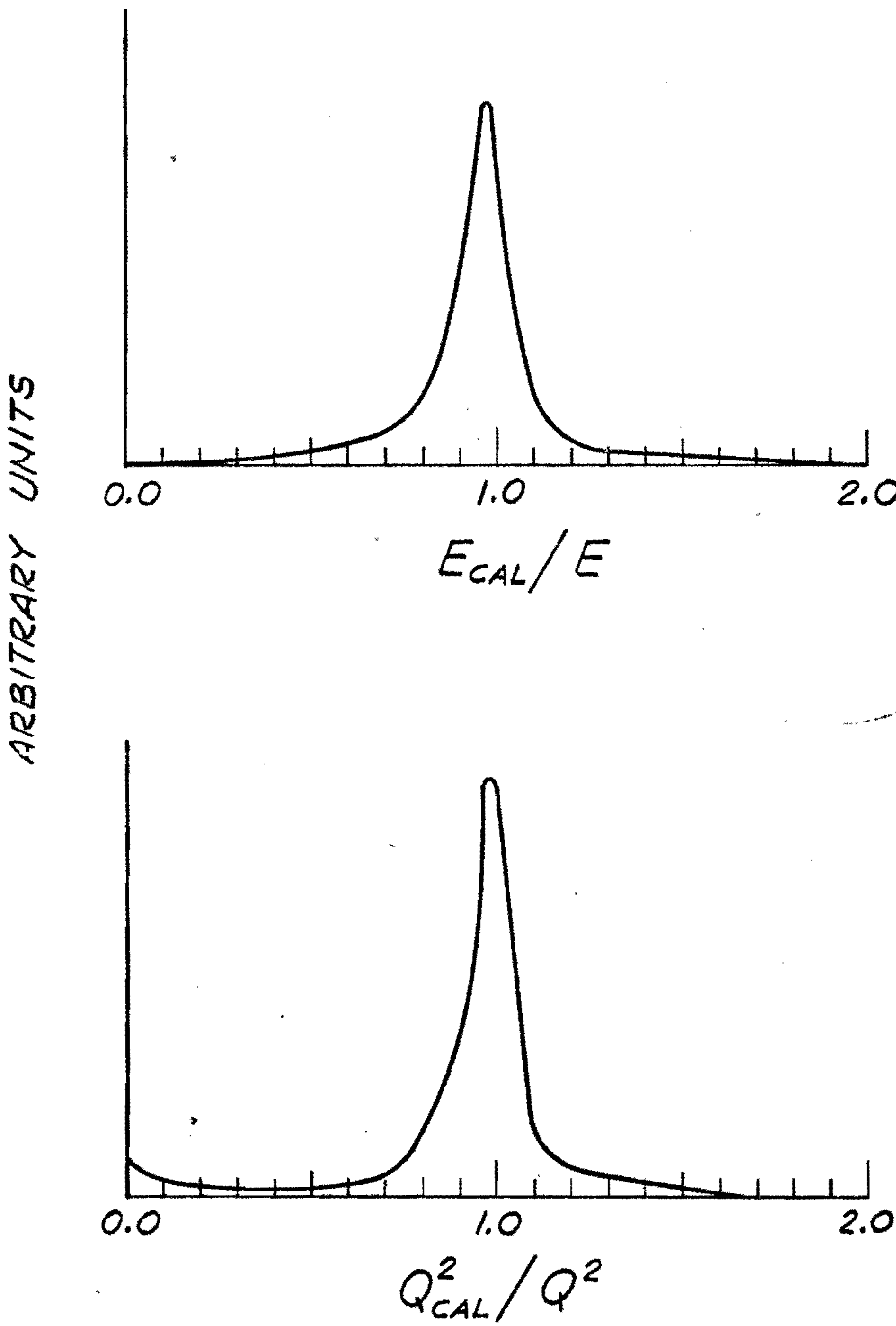

Fig. 2