NAL PROPOSAL No. 151

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PRELIMINARY PROPOSAL TO STUDY NEUTRINO INTERACTIONS WITH NEUTRONS AND PROTONS USING THE 15-FOOT BUBBLE CHAMBER AT NAL FILLED WITH DEUTERIUM

G. A. Snow, U. of Md.

R. A. Burnstein, IIT

July 15, 1971

Preliminary Proposal to Study Neutrino Interactions with Neutrons and Protons Using the 15-Foot Bubble Chamber at NAL Filled with Deuterium

ABSTRACT

We propose an investigation of neutrino interactions in the deuterium filled 15-foot bubble chamber at NAL. A 250,000 picture run with 200 GeV protons should yield very interesting physics even with a "bare" deuterium chamber.

Correspondents: G. A. Snow, U. of Md.

R. A. Burnstein, IIT

Date: July 15, 1971

In response to the letter of June 10, 1971 circulated by Dr. R. R. Wilson, the High Energy Physics Groups at the Illinois Institute of Technology and at the U. of Maryland are submitting this preliminary proposal on neutrino physics in the 15-foot bubble chamber. Both of our groups are already fully committed in FY72 so that we cannot contribute to the development of downstream equipment in connection with the 15-foot chamber. On the other hand we are convinced that a great deal of interesting physics can be done with neutrinos and a "bare" bubble chamber. This document is being submitted now in order that our interest be on record for a neutrino run in deuterium in 1973. Further details will be submitted in the future -we anticipate another request for ν proposals in Summer 1972 analogous to the "bare" bubble chamber proposals on strong interactions in the 15-foot alluded to in the letter of June 10, 1971.

As an initial exposure we request a 250,000 picture run with 200 GeV protons (assuming $\sim 10^{13}$ interacting protons/pulse and a horn focusing efficiency of 50%) and the 15-foot chamber filled with deuterium. A rough estimate indicates that such a run will yield about 25,000 inelastic νn events, a comparable number of νp events and most important for flux calibration as well as for form factor studies, a few thousand "elastic" $\nu + n \rightarrow p + \mu^-$ events.

We anticipate that substantial hydrogen running will precede any deuterium filling, and that the W will already have been found if it is there to find. On the other hand deuterium provides the best source of target neutrons. Numerous excellent summaries of what can be effectively studied in such experiments have been given. (See for example L. Clavelli and R. Engelmann, p. 255, NAL Summer Study 1970.) In particular with a ν run in deuterium as proposed here, one can

(1) Study Elastic $\nu + n \rightarrow p + \mu^-$ form factors and calibrate ν fluxes. (See M. M. Block's proposal #20.)

(2) Compare (ν,n) and (ν,p) inelastic corss sections directly in one run. (See also E. A. Paschos, p. 366, NAL Summer Study 1970, for a discussion of such comparisons.)

(3) Accumulate data for Adler test of PCAC, (for example by a comparison of $\sigma(\nu + n \rightarrow \mu^- + p + \pi^+ + \pi^-)$ with $\sigma(\pi^+ + n \rightarrow p + \pi^+ + \pi^-)$. Note that the (3,3) resonance production that dominates the low energy hadronic excitations in (ν,p) interactions and confuses the Adler test is no longer dominant in (ν,n) collisions.

(4) Search for $\Delta S = -\Delta Q$ transitions at high momentum transfer via reactions such as $\nu + n \rightarrow \begin{cases} \Sigma^+ + \mu^- \\ \Lambda^0 + \mu^+ + \mu^- \end{cases}$.

(5) Look for new particles and unexpected things. [e.g. the reaction $\nu + n \rightarrow p + \ell^-$ where ℓ^- is a new, heavy lepton.] Kinematic measurements of such a reaction in a bare bubble chamber could be used to determine the mass of an ℓ^- with reasonable accuracy if the ℓ^- mass is in the multi BeV range.

(6) Analyze deep inelastic events assuming the energetic negative track is a μ^- and estimating the π^0 contributions to the total energy of each large multiplicity event statistically from the measured energies of the charged particles.

At the present time, the physicists interested in working on this experiment in 1973 include:

IIT: R. Burnstein, C. Fu, D. Petersen, and H. A. Rubin,

U. of Md.: C. Y. Chang, R. G. Glasser, B. Kehoe, B. Sechi-Zorn, G. A. Snow and G. B. Yodh.

In addition, we expect that several graduate students will be involved in this experiment.

NAL Proposal 151-A

Addendum to Proposal Number 151

A Study of Neutrino Interactions with Neutrons and Protons Using the 15-Foot Bubble Chamber at NAL Filled with Deuterium

ABSTRACT

An investigation of neutrino interactions in the deuterium filled bubble chamber at NAL is proposed. A 300,000 picture run with neutrinos from 200 GeV protons in a "bare" deuterium chamber should yield very interesting physics.

Correspondents: G. A. Snow, U. of Md.

R. A. Burnstein, IIT

Date: November 1, 1971

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I. Introduction

This proposal is a supplement to a preliminary proposal submitted by the high energy physics groups at the Illinois Institute of Technology and the University of Maryland for a neutrino physics experiment in the 15-foot bubble chamber.

We request as an initial exposure a 300,000 picture run with 200 GeV protons (assuming 10^{13} interacting protons/pulse and a horn focusing efficiency of 50%)[1] and the 15-foot chamber filled with deuterium. Such an experiment will yield about 25,000 inelastic (ν,n) events, a comparable number of (ν,p) events, and most important for flux calibration as well as for form factor studies, a few thousand "elastic" $\nu + n \rightarrow p + \mu^-$ events (see Table I).

We anticipate that substantial hydrogen running will precede any deuterium filling, and that the W will already have been found if it is there to find. On the other hand, deuterium provides the best source of target neutrons. Numerous excellent summaries of what can be effectively studied in such experiments have been given. (See for example, L. Clavelli and R. Engelmann, NAL Summer Study 1970 and C. L. Smith, SLAC-PUB- 958, May 1971.) We are willing to use tagging devices downstream to the bubble chamber if they are in existance by the time a deuterium run is scheduled and are willing to collaborate with other groups for their use. This proposal is written without reference to any such apparatus since we are convinced that a great deal of interesting physics can be done with a "bare" bubble chamber run in deuterium.

II. Physics Justification

There are a wide range of physics problems for which the deuterium filled bubble chamber is particularly well suited.

1. <u>Comparison of $\sigma(\nu,p)$ and $\sigma(\nu,n)$ Directly in one Experiment.</u>

A comparison of (ν,p) and (ν,n) total cross sections furnishes a sensitive test for the predictions of various theoretical models of neutrino nucleon scattering. In particular, using Table I from a recent thesis of Budny[2] we can see the wide range of variation in the ratio of $\frac{\sigma(\nu,n)}{\sigma(\nu,p)}$ for fifteen published theoretical models. These predictions are derived from more general relations among $\frac{d\sigma}{dq^2}$ so that the predictions can be tested at even more fundamental levels.

TABLE I

Several predictions of published models. X means model cannot predict.

Predictions \ Models	A (B)	B (YD)	C (GLS)	D (G)	E (PS)	F (H)	G (LS)	H (BP)	I (L)	J (IKN)	K (KY)	L (LP)	M (P)	N (LP)	O (G)
$\frac{\sigma(\nu n)}{\sigma(\nu p)}$	2	1	1.8	1	1	1	X	X		1.7	1.5	2	X	1.8	1.9 1.73
$\frac{\sigma(\bar{\nu})}{\sigma(\nu)} = \frac{\frac{1}{2}\sigma(\bar{\nu}n+\bar{\nu}p)}{\frac{1}{2}\sigma(\nu n+\nu p)}$	1/3	1/3	0.44	1	1	1	X	0.6	1	0.52	0.61	1/3	X	0.49	0.64 0.38

A = Budny

B = Yan and Drell

C = Gross and Llwellyn Smith

D = Griffith

E = Pikety and Stvdulsky

F = Harari

G = Llwellyn Smith

H = Bjorken

I = Landshoff

J = Iizaka, Kobayashi and Nitto

K = Kitani and Yoshi

L = Landshoff and Polkinghorne (1970)

M = Pagels

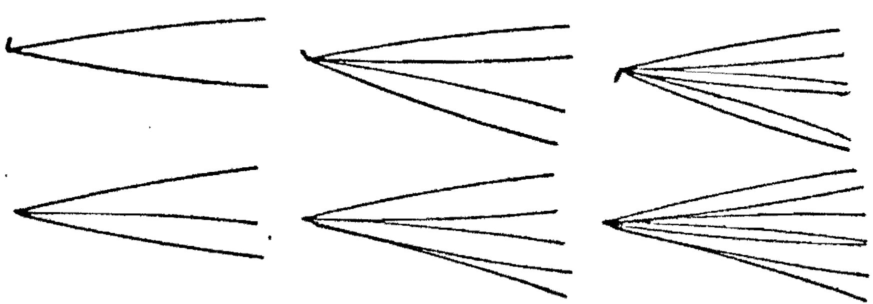
N = Landsdorff and Polkinghorne (1971)

O = Gourdin

For the comparison of neutron and proton cross-sections, problems of neutrino flux determinations become minimal in deuterium, since the incident flux is identical pulse by pulse on neutrons and protons. In addition the absolute flux can be determined from a study of the elastic channel events, $\nu + n \rightarrow \mu^- + p$ (discussed in Section 3). Finally, the broad reasonably flat neutrino energy spectrum between 5 and 30 GeV will allow fairly accurate variations of the cross section with energy to be made for (ν,n) as well as (ν,p) collisions.

Table I also lists the predictions of the various theoretical models for the ratio $\frac{\langle\sigma(\bar{\nu})\rangle}{\langle\sigma(\nu)\rangle} = \frac{\frac{1}{2}\sigma(\bar{\nu},n+\bar{\nu},p)}{\frac{1}{2}\sigma(\nu,n+\nu,p)}$. However, it will be difficult to accuratel determine anti-neutrino cross sections because of problems in determining the absolute flux and purity of anti-neutrino beams. Using the assumptions of isotopic spin symmetry and no second class currents, one obtains the relations among $\sigma(\bar{\nu},p)$ & $\sigma(\nu,n)$ and $\sigma(\bar{\nu},n)$ & $\sigma(\nu,p)$.

The method for separating (ν,n) from (ν,p) events involves a simple prong counting procedure. Excluding recoil protons, events with an



even no. of prongs
(ν,n) interactions

odd no. of prongs
(ν,p) interactions

even number of prongs are (ν,n) interactions and events with an odd number of prongs are (ν,p) interactions. The low energy short recoil protons from (ν,n) interactions which are not tabulated in the above prong count, are frequently visible and, furnish an additional calibration. The probability that a (ν,p) collision produce a slow recoil in the laboratory is small and can be corrected for by comparison with (ν,p) collisions from H_2 exposures.

This separation technique works well as long as the probability for charge exchange scattering of the secondary hadrons on the spectator nucleon is small. This is a reasonable approximation in deuterium[3-7] but clearly would be a poor approximation in heavier targets such as neon.

Converting an observed cross section for neutrinos on neutrons in deuterium to a cross section for neutrinos on free neutrons is straightforward with small numerical corrections except for the low q^2 region of reactions in which the Pauli principle is important.[8] Such reactions will comprise a rather small fraction (<10%) of the total cross section at NAL neutrino energies.

2. Elastic Neutrino Interactions - Form Factor and Flux Determinations.

The axial vector form factor (g_A), as has been pointed out by Block and others[8,9], can be determined from measurements of neutrino elastic scattering $\nu+n \rightarrow \mu^-+p$. For the first generation experiments, one will want to test predictions of simplified theories. For example, assuming T invariance, $|\Delta I| = 1$, CVC, and neglecting lepton mass effects, the total elastic scattering cross section approaches the limit (in the notation of Pais[10]),

$$\lim_{\varepsilon\to\infty} \frac{d\sigma}{dq^2} = \frac{G^2}{2\pi} W_2$$

where $$W_2 = |g_A|^2 + |g_v - 2Mf_v|^2 + q^2|f_v|^2$$

$$g_v = [f_Q(q^2) + (\mu_p - \mu_N) f_M(q^2)] \cos\theta_c$$

$$f_v = \frac{1}{2M}(\mu_p - \mu_N) f_M(q^2) \cos\theta_c$$

g_A = axial vector form factor

g_V = vector form factor

f_V = weak vector form factor

θ_c = Cabibbo angle

μ = magnetic moment

The quantities g_V and f_V can be evaluated assuming $f_Q(q^2)$ and $f_M(q^2)$ (the isovector electric and magnetic form factors) are determined from electron scattering and this yields an expression and the q^2 dependence of g_A can be evaluated,

$$\lim_{\varepsilon\to\infty} \frac{d\sigma}{dq^2} = f(g_A(q^2))$$

Because of the higher q^2 available, (ν,n) experiments at NAL energies will serve as an important check of elastic form factor fits made at ZGS and AGS energies from similar (ν,d) runs. Additional experiments will be required to test theory with fewer restrictive assumptions and also determine additional form factors from the data.

In the limit that $q^2 \to 0$ there is the particularly simple and important result that the neutrino elastic cross section is a constant since

$$\frac{d\sigma}{dq^2}(q^2 \to 0) = \frac{G^2}{2\pi}\left(|g_A(0)|^2 + |f_Q(0)|^2\right) = \text{const} \cong 2\text{x}10^{-38}\left(\frac{\text{cm}}{\text{BeV/c}}\right)^2.$$

This expression can be used to directly determine the absolute value of the mean neutrino flux, since if the cross section is predicted to be constant, and the number and energy dependence of the elastic scatters at low q^2 is known, then the absolute number of neutrinos and their energy spectrum can be determined. If one selects elastic scattering events with $q^2 < 0.10$, we expect about 500 events in a 300,000 picture exposure. The Pauli principle correction must be applied to these events. Theoretical uncertainties of $\sim$20% in the Pauli principle correction plus uncertainties in the axial vector form factors have the effect of introducing an overall uncertainty of ∼5-10% in the absolute flux determination. The slope of the predicted spectrum can also be independently checked, but with limited statistical accuracy. This method is to be compared against the ± 15% error associated with the CERN neutrino experiment which involved measurements of the continuously monitored muon range spectrun in the shielding. Undoubtedly there will be improvements in the muon monitoring techniques but great efforts and expense will be required. The method discussed of determining the absolute neutrino flux in deuterium is a unique property of the deuterium target. A neutrino run in deuterium will thus serve as an independent check of the absolute value of the neutrino flux determined by combining muon measurements, K/π production ratios, instrument calibrations, interpolating theoretical calculations, etc. The credibility of all other absolute cross section measurements will be greatly enhanced if the two methods are in agreement.

3. Inelastic Neutrino Interactions - Energy Dependence of Cross Sections, Multiplicity, and Deep-Inelastic Scattering.

The energy dependence of the total inelastic cross section can be studied. The quantity determined in a "bare" bubble chamber experiment is σ vs. E(visible) which can be related to E_ν on a statistical basis (as was done in the CERN neutrino experiments) by estimating the average energy carried away by neutral pions and a possible neutron. The neutral pions will have $\lesssim$ 1/3 of E_{Hadron} or $\lesssim$ 15% of E (assuming ∼ 50% of the energy is E_μ). Since the γ-ray conversion efficiency is ∼ 15% in deuterium, one can expect to determine this 15% correction factor statistically with at least a twenty per cent accuracy in the course of the experiment. Similarly, one can statistically estimate the energy carried away by neutrons since they interact in the chamber with a probability of ~40%. One should, overall, be able to determine the slope of the cross section with some accuracy up to $E \gtrsim 25$ GeV and obtain some crude cross section measurements at much higher energies. The reduced neutrino flux for energies over ~25 GeV coupled with the steep energy dependence of the neutrino flux makes σ_ν (total) difficult to measure since uncertainties in E_ν and in the shape of the neutrino spectrum are also present. On the other hand, the neutrino flux for an NAL experiment such as ours has a much less steep energy dependence than the neutrino flux for a CERN, BNL, or ANL experiment (as can be deduced from Fig. 1).

The particle multiplicity as a function of neutrino energy can be tested against predictions of a log E or $\sqrt{E}$ c.m. dependence. Again in this case one relates the visible energy of the interaction products to the actual neutrino energy on a statistical basis using γ-ray conversions and neutron recoils in the liquid to estimate the energy and multiplicity of neutrals. Any unusual features of the inelastic channels such as anomolously large or small strange particle or anti-particle production will be more easily verified if one has available hadron targets with charges of 0 and 1 (e.g. $\nu + n \rightarrow \mu^- + p + \bar{p} + p$).

In order to study structure functions of the nucleon in the deeply inelastic region, one needs to determine the quantities E_ν, E_μ, and θ_μ which appear in expressions for the inelastic differential scatterings such as[11]

$$\frac{\partial^2\sigma}{dq^2\partial\nu} = \frac{G^2 E_\mu}{2\pi M E_\nu}\left[W_2(q^2,\nu)\cos^2\frac{\theta_\mu}{2} + 2W_1(q^2,\nu)\sin^2\frac{\theta_\mu}{2} + \frac{E+E_\mu}{M}W_3(q^2,\nu)\sin^2\frac{\theta_\mu}{2}\right].$$

Most (>95%) of the inelastic neutrino events will occur with neutrino energies below 50 GeV ($\langle E_\nu \rangle \sim 20$ GeV). From this one can guess an expected mean number of charged prongs $\sim$ 5-6 from existing experimental data for (γ,p) and (π,p) collisions.[12] For the low multiplicity events - the two charged prong (ν,n) interactions and the three charged prong (ν,p) interactions E_μ and θ_μ are unambiguous since the μ is the only negative track.[13] For these two and three prong events E_ν can be determined from $E_{visible}$ (many of these topologies can be fitted). In the case of higher multiplicity reactions, there is frequently more than one negative prong.

In more than 50% of all reactions the μ^- will carry with it the major fraction of the incident neutrino's energy (in the discussion we are ignoring W meson production events). For these cases (the 50%), it will be a rigorously correct assumption that the most energetic negative track is in fact the μ^-. When one considers events in which $E_\mu < 1/2E_\nu$, it will still be true in a majority of cases that the μ^- will be the most energetic negative track in the laboratory since fragmentation pions will clearly be slow in the laboratory, and as $\nu = E_\nu - E_\mu$ increases, the hadron multiplicity will also increase, so that the average energy of a secondary π^- will be of the order of $\frac{E_\nu - E_\mu}{n}$ where n is the multiplicity.

Since the π^- has a mean free path of $\sim$4 meters in deuterium, a π^- has about a 40% chance of interacting in half a chamber diameter. Using the 40% subsample of events where one of the two negatives interacts (this fixes the non-interacting track as the μ^-), then the analysis of deep inelastic scattering can be extended unambiguously to include these four and five prong (ν,n) and (ν,p) interactions. This data will also allow a test of the hypothesis that the μ^- is the most energetic negative track in four and five prong events. For higher multiplicities similar analyses of negative track interactions will provide estimates of the error made in the μ^- assignment, as well as a smaller sample of pure unambiguous events.

This analysis procedure is applicable to a bare hydrogen bubble chamber exposure as well. The advantage of a deuterium exposure is that one can obtain information about the neutron structure functions and compare the structure functions for neutrons and protons directly in one experiment without flux normalization problems.

4. Physics of Special Channels.

The three body reactions include single pion production N^* and Y^* production and associated production processes. In the case of N^* production there is a simple test of the $|\Delta I| = 1$ selection rule (discussed in Section 6).

Another interesting test is the Adler test[14] of PCAC involving for example a comparison of distributions energy, angle, and number at small θ_μ for the reaction $\nu + {}^{n}_{p} \rightarrow \mu^- + {}^{p}_{n} + \pi^+ + \pi^-$ with distributions for the reaction $\pi^+ + {}^{n}_{p} \rightarrow {}^{p}_{n} + \pi^+ + \pi^-$. The Adler test is much simpler in this case for neutron than for proton — neutrino interactions since all the final state reaction products are charged.

5. Search for Violations of the $\Delta S/\Delta Q$ Selection Rule at Large q^2.

The following reactions are forbidden by the $\Delta S = \Delta Q$ selection rule and are easily detected in the bubble chamber.

$$\nu + n \rightarrow \mu^- + \Sigma^+$$

$$\nu + p \rightarrow \mu^- + \Sigma^+ + \pi^+$$

$$\nu + n \rightarrow \mu^- + \Sigma^\circ + \pi^+$$

$$\nu + n \rightarrow \mu^- + \Lambda + \pi^+$$

For events with high momentum transfer, these searches would furnish tests in a new kinematic region of a selection rule established from particle decays.

6. Test of the $|\Delta I| = 1$ Selection Rule and Search for $|\Delta I| = 2$ Weak Currents.

The branching ratios for the following reactions can be determined

$$\nu + p \rightarrow N^{*++} + \mu^- \qquad N^{*++} \rightarrow p + \pi^+ \qquad \text{(A)}$$

$$\nu + n \rightarrow N^{*+} + \mu^- \qquad N^{*+} \rightarrow n + \pi^+ \text{ or } p + \pi^\circ \qquad \text{(B)}$$

The $|\Delta I| = 1$ rule predicts (A)/(B) = 3/1. Hence these events in deuterium will provide a simple and unique test of this weak interaction rule in a new energy and q^2 regime.

7. Search for New Particles and Unexpected Phenomena.

The detection of some types of heavy leptons is easier in deuterium than in hydrogen. The two body reactions from neutrinos allows both final particles to be charged, e.g.,

$$\nu + n \rightarrow p + \ell^-$$

If such a heavy lepton would exist with a lifetime longer than $\sim 10^{-11}$ sec. then it would be detected and some of its properties determined in a straightforward way. Even if its lifetime is too short to leave a visible track, it might still be detected by decay modes such as $\pi^- + \nu$ or $e + \nu + \nu'$.

In deuterium, just as in hydrogen, one can also search for W bosons, and other rare leptonic events. This type of investigation would be most rewarding after such phenomena had been discovered using more massive neutrino detectors. The hydrogen and deuterium bubble chambers could then provide an excellent source of data about production and decay properties of W's, neutral bosons, etc. The bare bubble chamber because of its size is a rather good discriminator of electrons and positrons relative to pions due to the appreciable energy loss caused by radiation.

III. Personnel

The physicists interested in working on this experiment include:

IIT: R. A. Burnstein, C. Fu, D. Petersen, and H. A. Rubin

U. of Md.: C. Y. Chang, R. G. Glasser, B. Kehoe, B. Sechi-Zorn, G. A. Snow, and G. B. Yodh.

In addition, we expect that several graduate students will be involved in this experiment.

IV. Experiment Preparation and Data Analysis

Both of our groups are already fully committed in FY'72 so that we cannot contribute to the development of equipment in that period. Where and how we can make our most important contribution to the development of bubble chamber neutrino physics at NAL in FY'73 and '74 is difficult to anticipate at this time. Such contributions could relate to the improvements and monitoring of the neutrino beam, improvements in reconstruction programs for the chamber itself, downstream particle identification apparatus, etc.

We have a great deal of experience in experiments requiring very careful scanning of bubble chamber pictures, which should help considerably in the rapid analysis of the proposed neutrino run in deuterium.

V. Footnotes

1. The flux estimates and neutrino flux spectrum are consistent with NAL TM-265 (August 1970).
2. R. V. Budny, Ph.D. Thesis, Univ. of Maryland (1971), unpublished.
3. Z. Bar-Yam, J. dePragter, M. M. Hoenig, and W. Kern et al., PRL 19, 40 (1967).
4. P. Heide, U. Kotz, R. A. Lewis, P. Schmüster et al., PRL 21, 248 (1968).
5. A. M. Boyarski, R. Diebold, S. D. Ecklund, G. E. Fischer et al., PRL 25, 695 (1970).
6. H. G. Hilpert, P. Lauscher, M. Matziolis, H. Schnackers et al., Nuc. Phys. B8, 535 (1970).
7. D. D. Davies, Ph.D. Thesis, UCRL Report No. 19263 (July 1969) and references therein.
8. M. M. Block, NAL Summer STudy Report B. 1-68-42 (1968) and NAL Proposal No. 20 (1970).
9. See, for example, N. Cabibbo and R. Gatto, Nuovo Cimento 15, 304 (1960).
10. A. Pais. Proc. of Intern. Conf. on Expectations for Part. Reactions at the New Accel. (April 1970).
11. B. Bjorken and E. Paschos, Phy. Rev., D1, 3141 (1970).
12. M. Danier, I. Derade, D. Prichez, D. Fries et al., Phys. Rev. D1, 790 (1970).
13. The anti-neutrino contamination is estimated to be only a few per cent.
14. S. L. Adler, Phys. Rev. 140B, 736 (1965).

TABLE I. APPROXIMATE NUMBER OF EXPECTED EVENTS IN DEUTERIUM FOR 300,000 PICTURES AT 200 GeV

Interval in E_ν (BeV)	(ν,n) Number Elastic Events	$(\nu,n) + (\nu,p)$ Number Inelastic Events
0-5	150	1,400
5-10	470	7,350
10-15	510	12,250
15-20	355	12,000
20-30	260	10,000
30-40	112	4,280
40-50	16	1,350
50-60	6	500
60-75	3	410
75-100	2	310
100-125	1	170
125-150		35
TOTAL	1,875	50,000

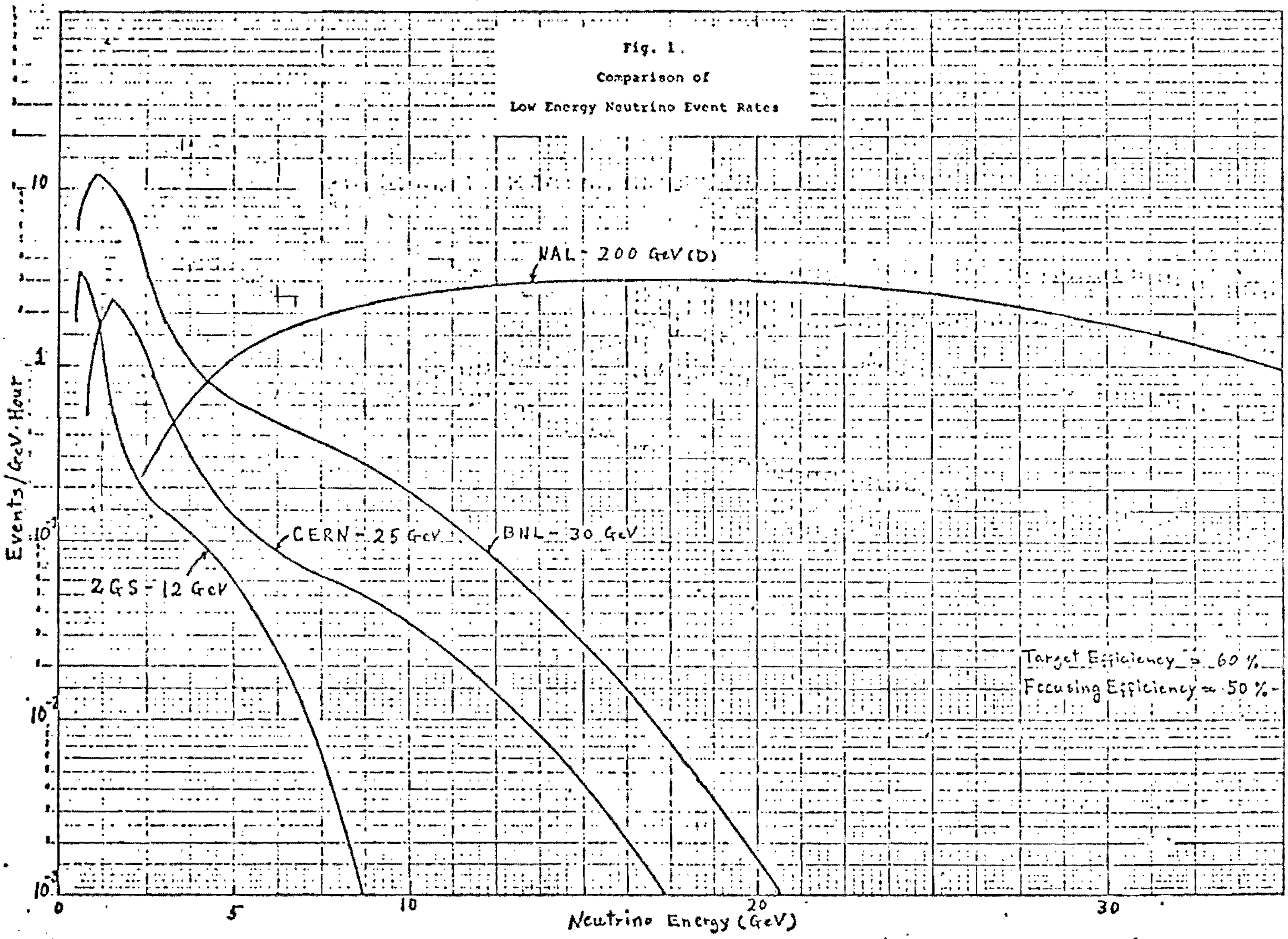


Fig. 1.
Comparison of
Low Energy Neutrino Event Rates
NAL - 200 GeV (D)
CERN - 25 GeV
BNL - 30 GeV
ZGS - 12 GeV
Target Efficiency ≈ 60 %
Focusing Efficiency ≈ 50 %
Events/GeV·Hour
10
1
10⁻¹
10⁻²
10⁻³
0
5
10
20
30
Neutrino Energy (GeV)

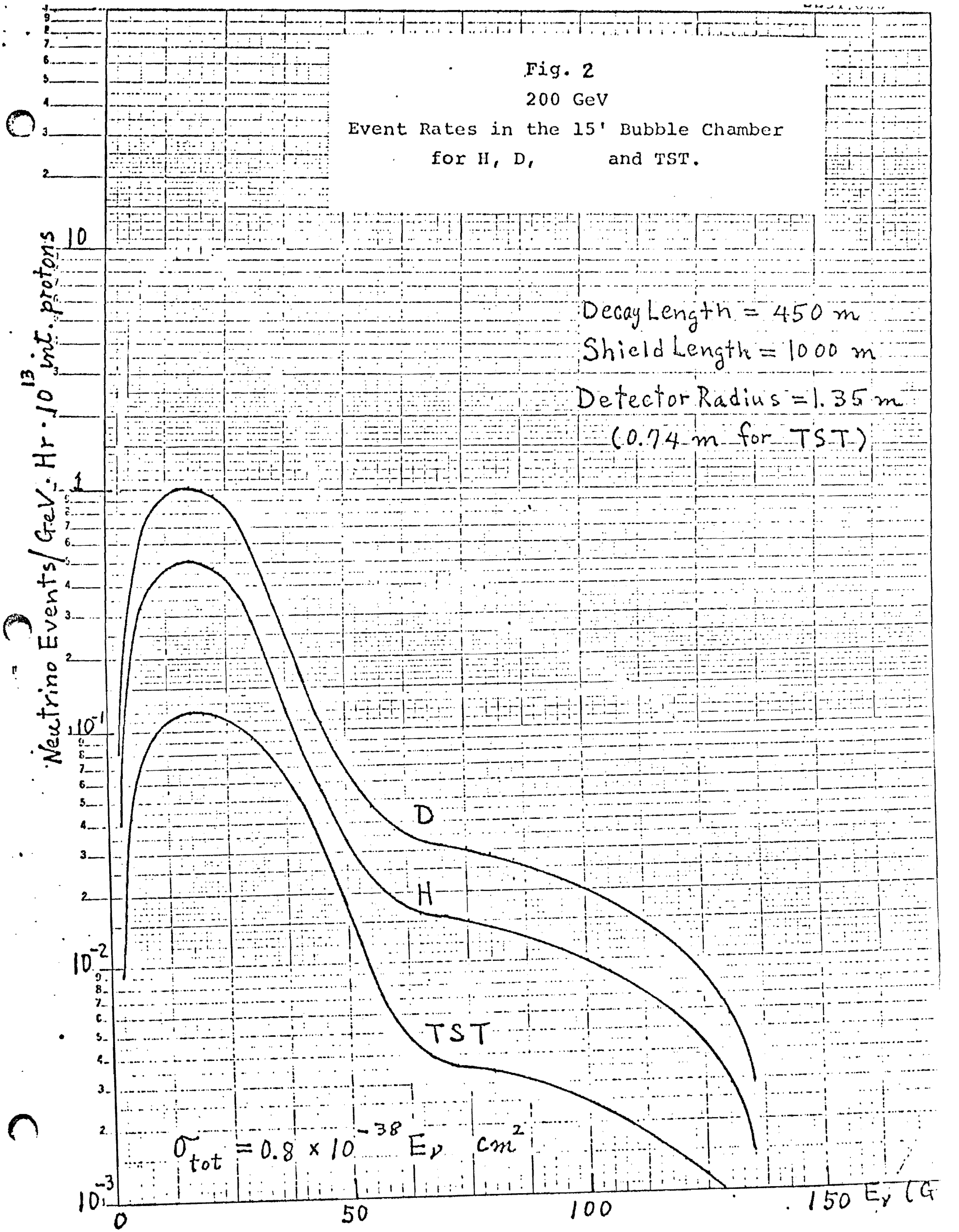


Fig. 2
200 GeV
Event Rates in the 15' Bubble Chamber
for H, D, and TST.

NAL Proposal 151-B
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College Park, Maryland

Addendum to Proposal Number 151-A

A STUDY OF NEUTRINO INTERACTIONS WITH NEUTRONS AND PROTONS USING THE 15' BUBBLE CHAMBER AT NAL FILLED WITH DEUTERIUM

ABSTRACT

This addendum extends the physics discussion in the original proposal to the search for charm particles, and the study of neutral currents. A (ν_μ, d) bubble chamber exposure with $E_p \approx 200 - 300$ GeV is the most promising experiment that can be done to search for the type of charm particles that are essential to Gauge theories of weak and electromagnetic interactions.

May 1974

Proposal 151-B

I. Charm Particles

The theoretical success of Gauge theories plus the discovery of neutral currents have given great impetus to the search for charm particles. [Charm denotes the new quantum number carried by the fourth quark p' needed to reduce the $\Delta s \neq 0$ neutral current contributions to experimental magnitudes, as pointed out by Glashow, Iliopoulos, and Maiani.][1] Charmed baryons (or mesons) are extremely difficult to discover in strong or electromagnetic interactions if their masses are $\gtrsim 2.0$ GeV ($\gtrsim 1.0$ GeV) since they are made in pairs and have many possible decay modes.[2]

On the other hand the predicted production and decay properties of charm particles suggest that the most promising experiments in which to search for charm particles are neutrino experiments[1,2,3] at NAL.

Following the Weinberg-Salam model (with extensions to colour if desired), one predicts[1,3] reactions at the quark level of the type

$$\nu_\mu + n \to \mu^- + p' \qquad \text{of strength } G_F \sin\theta_c \tag{1}$$

At the nucleon level then

$$\nu_\mu + N \to \mu^- + B_c \quad \left\{ \begin{array}{l} \sim G_F \sin\theta_c, \end{array} \right. \tag{2}$$

$$\nu_\mu + P \to \mu^- + B_c^{++} \quad \left\{ \begin{array}{l} \text{above the charmed} \\ \text{baryon threshold} \end{array} \right. \tag{3}$$

For E_ν well above the threshold for B_c production, this charmed baryon cross section will be $\sim 5\%$ of the total $\sigma_\nu(E_\nu)$ cross section, since $\sin^2\theta_c \cong 5\%$.

Proposal 151-B

The key to detection is that the $(p'\lambda)$ quark current has strength $\cos\theta_c$ while the $(p'n)$ current is $\sim\sin\theta_c$, that is, the $\Delta S = \Delta C$ weak transitions dominate over the $\Delta C \neq \Delta S$ transitions. Hence, a given hadronic state carrying charm will cascade via the strong interaction to the lightest charm state and then that state will decay into a hyperon, plus pions (or, an unknown fraction of the time, $e\nu$ or $\mu\nu$).[2,3] We therefor expect reactions of the type

$$\nu_\mu + N \to \mu^- + B_c^+ \quad (+\pi's)$$
$$\to \Lambda^o + \pi^+$$
$$\to \Lambda^o + \pi^+ + \pi^o, \text{ etc.}$$
$$\to \Sigma^+ + \pi^+ + \pi^-, \ldots$$

with a frequency at the few percent level.[3] Recall that $S = -1$ baryonic states can only be produced by $\bar{\nu}_\mu$, not by ν_μ, if charm particles do not exist, hence the production of such states by ν_μ (an apparent violation of the $\Delta S = \Delta Q$ rule) is the key to deducing the presence of charm particle production. As one accumulates such events one can search for a sharp mass state, the mass of B_c, among the final $(Y + n\pi)$ products. [τ (B_c) is expected to be $\sim 10^{-14}$ - 10^{-16} sec., hence $\Gamma(B_c)$ << experimental error in invariant mass.]

The principle background arises from associated production events in which the strangeness +1 meson is not identified. Hadronic interactions indicate that the total YK production should be $\sim$3 - 5% of the total neutrino cross section, i.e. the same order of magnitude as the predicted charm particle production. (If λ and $\bar{\lambda}$ quarks are in the nucleon, YK production can be much larger.)[3] This background can be controlled statistically by a study of events

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in which both the hyperon and a K meson are identified. It is this associated production event background that may preclude using the increased statistics available in a ν - Ne run for the charm particle search via their strange particle decay. The problem is that the secondary interactions of neutrino produced pions in the Neon nucleus will increase the associated production background significantly. (In addition hyperons are identified with much more difficulty in heavy liquid bubble chamber, and the sharp mass of the charm particle will be smeared out by experimental errors.)

In the simplest quark model for a neutron and a proton, (N = (nnp), P = (ppn)), a(ν_μ, d) exposure would produce three times as many charm particles as a(ν_μ, p) exposure of the same intensity since only the neutron quark is coupled to the charmed quark. (i.e. One expects $\sigma(\nu N \rightarrow B_c + \mu^-) \approx 2\sigma(\nu P \rightarrow B_c + \mu^-)$]. The exposure requested in this proposal (300,000 pictures with proton energy in the 200 - 300 GeV region) could produce a few hundred identified charm particle events if $M(B_c) \lesssim 5 - 7$ GeV. <u>A negative result in such a search would put current Gauge model theories in great jeopardy.</u>

II. <u>Neutral Current Events</u>

It is important to compare the number of neutral current events on neutrons and protons. It is not clear in advance that this can be carried out in the exposure proposed here. The largest uncertainty relates to the number of neutron induced background events at NAL as a function of energy. Even without an EMI, neutral current events can be isolated on a statistical basis by analyzing the energy distributions of positive and negative tracks. In addition there will be a subset of "clean" events in which there are no μ^-

candidates. One can expect several hundred such clean events. If the neutron background is not overwhelming, one can apply the track counting method described in the main proposal 151-A, to determine the neutron/proton neutral current event ratio. With an effective EMI, this ratio can be determined with a sample of events in the thousands. The feasibility of isolating particular channel events such as

$$\nu + d \to \nu + d$$

$$\nu + d \to \nu + p + n$$

$$\nu + d \to \nu + p + p + \pi^-$$

etc.

will be made. The background events from (n,d) collisions may have different characteristics from ν events or if not, may be subtracted statistically, in special channels.

III. References

[1] S. L. Glashow, J. Iliopoulos, L. Maiani, Phys. Rev. D2, 1285 (1970).

[2] G. A. Snow, Nucl Phys. B55, 445 (1973), and Proceedings of the Conference of Moriond at Meribel-les-alles, France (1973).

[3] M. K. Gaillard, "Notes on Charmed Particle Searches in Neutrino Experiments", FN-259, 2000 (April 1974).

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Addendum to Proposal Number 151

PROPOSAL TO STUDY NEUTRINO INTERACTIONS WITH NEUTRONS AND PROTONS USING THE FERMILAB 15' BUBBLE CHAMBER FILLED WITH DEUTERIUM

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SUMMARY

This addendum updates and summarizes Proposal 151. We propose a 300,000 picture run of the 15' bubble chamber filled with deuterium exposed to a wide band, 2 horn, neutrino beam from protons of energy $E_p \geq 300$ GeV. The analysis will be based primarily on the bare bubble chamber data but will also use the EMI wherever useful.

The physics purposes of the experiment include

- Extensive search for charmed baryons and mesons
- Determination of the ratio of the total charged current cross sections $\sigma(\nu,n)/\sigma(\nu,p)$.
- Determination of $\frac{d^2\sigma^{C.C.}}{dxdy}$ for (ν,n) and (ν,p) interactions separately
- Study of (ν,n) and (ν,p) neutral current interactions
- Physics of Special Channels in charged current and neutral current events

I. Introduction

The purpose of this addendum to Proposal 151 (A and B) is to highlight the most important contributions that the 15' bubble chamber filled with D_2 exposed to a wide band neutrino beam can make, and to summarize the contents of the earlier proposal and addenda.

We request 300,000 pictures with the two horn system from accelerated protons in the 300-400 GeV range. As discussed in the 1974 Neutrino Mini Summer Study Report at FermiLab, the maximum event rate is obtained with protons in the 300-400 GeV energy range. Figure 1 shows the ν-flux estimates in this energy range.[1]

In order to maximize the physics that can be obtained from a ν-D_2 run, we emphasize our wish to collaborate with the developers of the downstream tagging device (EMI) behind the bubble chamber. We anticipate that if our proposal is approved we will be able to enlist a subset of the physicists who built and have used the EMI to join us in this experiment.[2] Where appropriate we will therefore not hesitate to make use of the information that the EMI can provide in the discussion that follows.

Using the most recent calculations by Nezrick[1] of charged current (ν,p) event rates per 10^{13} p on target with two horns in a 20 m^3 fiducial volume, we list in Table I the expected number of charged current events in 100,000 D_2 pictures as a function of neutrino energy for proton energies, E_p = 300 GeV and E_p = 350 GeV. We have assumed that the density is 0.14 gr/cm^3, the ν-flux is given by Figure 1, and that $\sigma(\nu_\mu n)/\sigma(\nu_\mu p)$ is 1.7 (current experimental results range from 2.1 to 1.4 for this ratio).

We propose an extensive search for charm particles, a study of charged current reactions on neutrons and protons separately, and (to the extent possible) a study of neutral current reactions. The analysis will primarily be based on the bare bubble chamber data but will use EMI wherever useful.

We emphasize that the advantages of deuterium over other bubble chamber liquids are

- a three time larger event rate than liquid hydrogen at the same ν flux
- better quality momenta and angles, and hence better invariant masses than a H_2 - Ne or D_2 - Ne mixture
- a direct comparison between (ν,p) and (ν,n) interactions in the same film
- a direct determination of ν flux from the two reactions: $\nu n \rightarrow \mu^- p$ and $\nu p \rightarrow \mu^- p \pi^+$

II. Physics Justification

A. Charm Particles

The discussion that we presented in 151 B on charm particles is more pertinent than ever today. Only additional comments are made below.

i) Charmed Baryons

The apparent $\Delta S = -\Delta Q$ event, interpreted as $\nu_\mu + p \rightarrow \mu^- + \Lambda^o + \pi^+ + \pi^+ + \pi^+ + \pi^-$, reported by BNL at the Paris Neutrino Conference last month, is, most probably, the first example of charmed baryon production by neutrinos. If this interpretation is correct it implies that the lightest charmed baryon has a mass less than 2.43 GeV. Consequently neutrinos at the peak of the Fermilab spectrum and above should make such particles easily with a probability close to the theoretical value of $\sin^2 \theta_c \cong 5\%$. Neutrinos in deuterium are probably the ideal combination for charmed baryon spectroscopy studies, provided enough events can be obtained, since

- there is no background of single hyperon production from ordinary $\Delta S = +\Delta Q$ events, as there is for antineutrinos
- the cross section for charmed baryon production on deuterons is expected to be about three times as large as charmed baryon production on protons since the n quark but not the p quark can be converted to a p′ (or charmed) quark by the charged current.
- the D_2 filling allows, just as for H_2, accurate identification of hyperons and accurate measurements of the momenta of all visible particles.
- the background of hyperon production from associated production in charged current events is expected to be of the same order (∿ 5% of all CC events) as the charmed particle production, not a factor of 10^2 to 10^4 larger as in strong interaction experiments.

ii) Charmed Mesons

The literature is now full of theoretical discussions of charmed mesons, lead by the review article of M. K. Gaillard, B. W. Lee and J. Rosner.[3] These theoretical ideas will not be repeated here. Experimentally the dimuon events seen in high energy ν_μ and $\bar{\nu}_\mu$ collisions by the Harvard-Penn-Wisconsin experiment[4] at FermiLab and confirmed by the CalTech-FermiLab experiment,[5] strongly suggest that charmed mesons are in fact being produced. Furthermore, the fact that the transverse momenta of the slower muon, in the 32 dimuon events reported by HPW at the Paris Neutrino Conference (1975), were all $\lesssim$ 1.2 GeV/c, suggest that the mass of the parent particles (i.e. the charmed mesons) is $\lesssim$ 2.4 GeV. HPW also report that the product of the relative probability of production of these particles multiplied by their muonic branching ratio is about 1% (within a factor of 2 or 3). This fact probably implies that the production probability is as high as 5-10%. The HPW dimuon events were observed to occur only for neutrino energies $\gtrsim$ 40 GeV, but this rather sharp energy threshold could be related at least in part to the increasing dimuon detection efficiency of their apparatus with increasing energy of the particle that decays into the second muon. If indeed the observed second muons come from the decays of charmed mesons with mass $\lesssim$ 2.4 GeV, then such particles could easily be made by neutrinos with energies ($\sim$ 20 GeV) near the peak of the wide band spectrum.

Some further experimental evidence for the existence of not too heavy charmed mesons was provided by the one event reported in Paris by the Gargamelle bubble chamber group, namely ν_μ + Freon $\rightarrow e^+ + V^o + \mu^- + X$, where the V^o was most probably a $K^o \rightarrow \pi^+ \pi^-$ decay. This could be the first dilepton event associated with charmed meson production observed in a bubble chamber.

In the D_2 exposure proposed here, dilepton events associated with strange particles can be detected, since the muons can be picked up with the EMI and the positrons can be detected quite often using trapping and bremsstrahlung signatures (Detection efficiency for an e^+ is $\sim$ 100% for $E_{e^+} \lesssim$ 1 GeV, falling smoothly to $\sim$ 15% at 10 GeV). Since one expects the non-leptonic modes of the charmed mesons to dominate the decay process, many more events of this type should be available than dilepton events. A significant fraction of these could then be used for the study of charmed meson spectroscopy with good mass resolution.

In conclusion, the evidence cited above strongly indicates that the total charm particle production is at least 5% of all (ν_μ, D_2) events for energies above 15-20 GeV (see Table I).

B. Determination of the Ratio of the Total Charged Current Cross Sections $\sigma(\nu,n)/\sigma(\nu,p)$

This very simple experimental method has already been discussed in some detail in Proposal 151A, pgs. 2, 3, and will not be repeated here. An accuracy $\sim$10% should be achievable, in several different energy bins.

C. Determination of $\frac{d^2\sigma^{C.C.}}{dxdy}$ for (νn) and (νp) Interactions Separately

The discussion presented in Proposal 151A (pgs. 3-8) on this subject can be sharpened and improved in several respects. The neutrino flux can be measured directly in the bubble chamber by counting the number of $\nu n \rightarrow \mu^- p$ and $\nu p \rightarrow \mu^- \Delta^{++}$ events at small q^2. (We expect $\sim$ 500 events with $q^2 < 0.1$ for each type in 300,000 pictures.) Again the EMI should help in this flux determination at lower energies, by eliminating almost all neutron background events of the type: $n + n \rightarrow p + \pi^- + n$ and $n + p \rightarrow p + \pi^+ + \pi^- + n$.

The C.C. inelastic events can be analyzed much more completely than had been discussed in Proposal 151A. Of course for modest values of y ($\lesssim$ 0.7) the outgoing μ^- has a large fraction of the incoming energy E_ν and is clearly singled out even without an EMI. The EMI can give the μ^- identification in a larger fraction of the cases and also eliminate NC and neutron induced events from the C.C. sample. Using momentum and energy conservation, a series of papers by Myatt,[6] Burmeister and Cundy,[7] and Nezrick[8] have pointed out that the negative track with the highest $p_\perp$ can be identified as μ^- if $p_\perp^{ch}$ of the remaining charged hadrons projected on the ν-μ plane lies on the "opposite" side of the ν direction from $p_\perp^{\mu-}$. Figure 2 shows the configuration of a charged current event. Based on this method they pointed out that a 94% pure C.C. event sample in H_2 can be obtained using bare bubble chamber information alone. Furthermore if one assumes that the direction of the total momentum of the charged hadrons approximates the total momentum of all hadrons (charged + neutral), then E_ν, x and y can be evaluated from the following expressions:

$$E_\nu = p_\mu \cos\theta_\mu + p_\mu \frac{\sin\theta_\mu}{\tan\theta_q}$$

$$= p_{\mu /\!/} + p^{ch}_{/\!/} \frac{p^\mu_\perp}{p^{ch}_\perp}$$

$$x = q^2/2ME_\nu$$

and $y = E_H/E_\nu = (E_\nu - E_\mu)/E_\nu$.

Hence a fairly complete analysis of the deep inelastic C.C. events can be carried out in terms of the q^2, x and y variables, separately for neutron and proton collisions. The approximation that assumes that the direction of $(\Sigma\, \vec{p}_{\text{charged hadrons}}) = (\Sigma\, \vec{p}_{\text{all hadrons}})$ can be tested in special cases where the neutral particles convert in the chamber and are detected.

D. Neutral Currents

Very little is known in detail about the neutral currents. Different experiments at different energies and using different techniques yield ratios of $\sigma^{\nu n}_{N.C.}/\sigma^{\nu n}_{C.C.}$ that vary from 0.11 to 0.3. The spatial form of the interaction, the isotopic spin dependence, and the amount of parity non-conservation all are poorly determined or completely unknown at present. Clearly a clean sample of $\nu + D \rightarrow \nu + x$ events could add much to our present information. How well this can be done depends on the magnitude of the neutron background problem. Using kinematics, Nezrick[8] described how a 75% pure sample of N.C. events can be extracted from a mixture of N.C. and C.C. events. Adding in EMI information can eliminate a large fraction of these C.C. contaminants. However the EMI is of no assistance in distinguishing real neutrino N.C. events from neutron background events. Almost certainly a pure sample of N.C. events can be extracted at high enough E_ν and y, since the neutron events are expected to fall off rapidly with energy. Other indicators, such as dip angle distribution, can be used to study the neutron background, and attempt to isolate a fairly clean N.C. sample. Much can be done with such a sample. One can

- determine the ratio $\sigma_{N.C.}(\nu n)/\sigma_{N.C.}(\nu p)$ by prong counting. (The importance of this kind of information has been recently stressed by M. Gourdin at the Paris Neutrino Conference and Par/LPTHE 75,3)
- determine the ratio of (N.C./C.C.)
- look for parity violating evidence in specific channels such as $\nu p \rightarrow \Lambda K^+ \nu$ or $\nu n \rightarrow \nu \Lambda^o K^o$, or by using a triple scalar product in reactions such as $\nu p \rightarrow \nu p \pi^+ \pi^-$
- study I spin dependence of N.C. by, for example, determining the ratio $\frac{\nu + D \rightarrow \nu + \pi^+ + x}{\nu + D \rightarrow \nu + \pi^- + x}$. Exploiting the deuterium I = 0 target, this ratio must equal 1 if N.C. is pure I = 1 or pure I = 0. It is different from 1 when both terms are present. Other specific reactions can also yield I spin information
- compare hadron multiplicities and resonance production cross sections by N.C. as compared to C.C.

Clearly, if the neutron background can be controlled much can be learned about neutral currents in this experiment.

E. Physics of Special Channels in Charged Current Events

- Production cross sections of baryon and meson resonances by neutrinos
- Test of $|\Delta I| = 1$ rule, pg. 9 of 151A.
- Adler test of PCAC, pg. 8 of 151A.

III. Personnel

The physicists who would like to work on this experiment include: IIT: R. Burnstein, C. Fu, D. Petersen and H. A. Rubin; U. of Md.: C. Y. Chang, R. G. Glasser, D. G. Hill, M. Kazuno, G. McClellan, B. Sechi-Zorn, G. A. Snow and G. B. Yodh. As mentioned in the introduction, we expect to add to this collaboration a few more physicists who are familiar with the hardware and software of the EMI.

IV. Experiment Preparation and Data Analysis

Both groups contain programming experts who have done experiments in the ANL 12' chamber. The Md. group plans to collaborate on a 15' hadron experiment in the immediate future so that we will get our machines and programs in condition to handle the 15' chamber film. IIT has a working analysis system for the ANL 12' chamber that can be immediately used for the 15' chamber. The two groups can deploy many scanning and measuring machines plus a PEPR machine. We have also had a great deal of experience in experiments requiring careful scanning of bubble chamber pictures, an important part of a neutrino experiment in D_2. Finally we have just completed a low energy experiment on K^+ meson interactions in D_2, so we are familiar with the idiosyncrasies of working with that liquid.

FOOTNOTES AND REFERENCES

[1]Frank A. Nezrick, FNAL Internal Note E45-1007, Oct. 3, 1974

[2]R. Cence et al., FNAL 15' EMI Test #155. See also F. Harris et al., NALREP pp 1-11, December 1974.

[3]M. K. Gaillard et al., FNAL-pub-74/86-Thy (1974), to be published in Rev. of Mod. Phys. (1975).

[4]A Benvenuti, et al., Phys. Rev. Lett. 34, 419 (1975), and report presented at the Paris Neutrino Conference March 1975.

[5]B. C. Barish et al. Report presented at ANL Neutrino Conference (1975) also at Paris Neutrino Conference, March 1975.

[6]G. Myatt - The use of transverse momentum balance as a means of estimating the energy of interacting neutrinos, ECFA 300 GeV Working Group, Vol. II, p 117.

[7]H. Burmeister and D. C. Cundy, CERN Internal Report, TC-L/Int. 75-1, January 6, 1975.

[8]Frank A. Nezrick FNAL Internal Note E45-1016, March 17, 1975.

FIGURE CAPTIONS

Figure 1 Neutrino Flux Estimates for 300 and 350 GeV protons on target (from Frank A. Nezrick, FNAL Internal Note E45-1007).

Figure 2 Typical Configuration of a Charged current event.

Table I. Number of events vs E_ν in 10^5 pix in D_2 (10^{18} protons on target)

	Ep = 300 GeV	Ep = 350 GeV
E_ν (GeV)	No. of Events	No. of Events
5	103	90
10	1276	1394
15	2031	2293
20	2134	2468
25	1900	2430
30	1722	2252
35	1313	1828
40	986	1385
45	702	1039
50	524	770
55	383	577
60	290	433
65	209	324
70	168	262
75	143	224
80	115	196
85	109	175
90	106	168
100	374	577
120	349	487
140	215	368
160	115	231
180	56	131
200	22	68
TOTAL	15345	20170

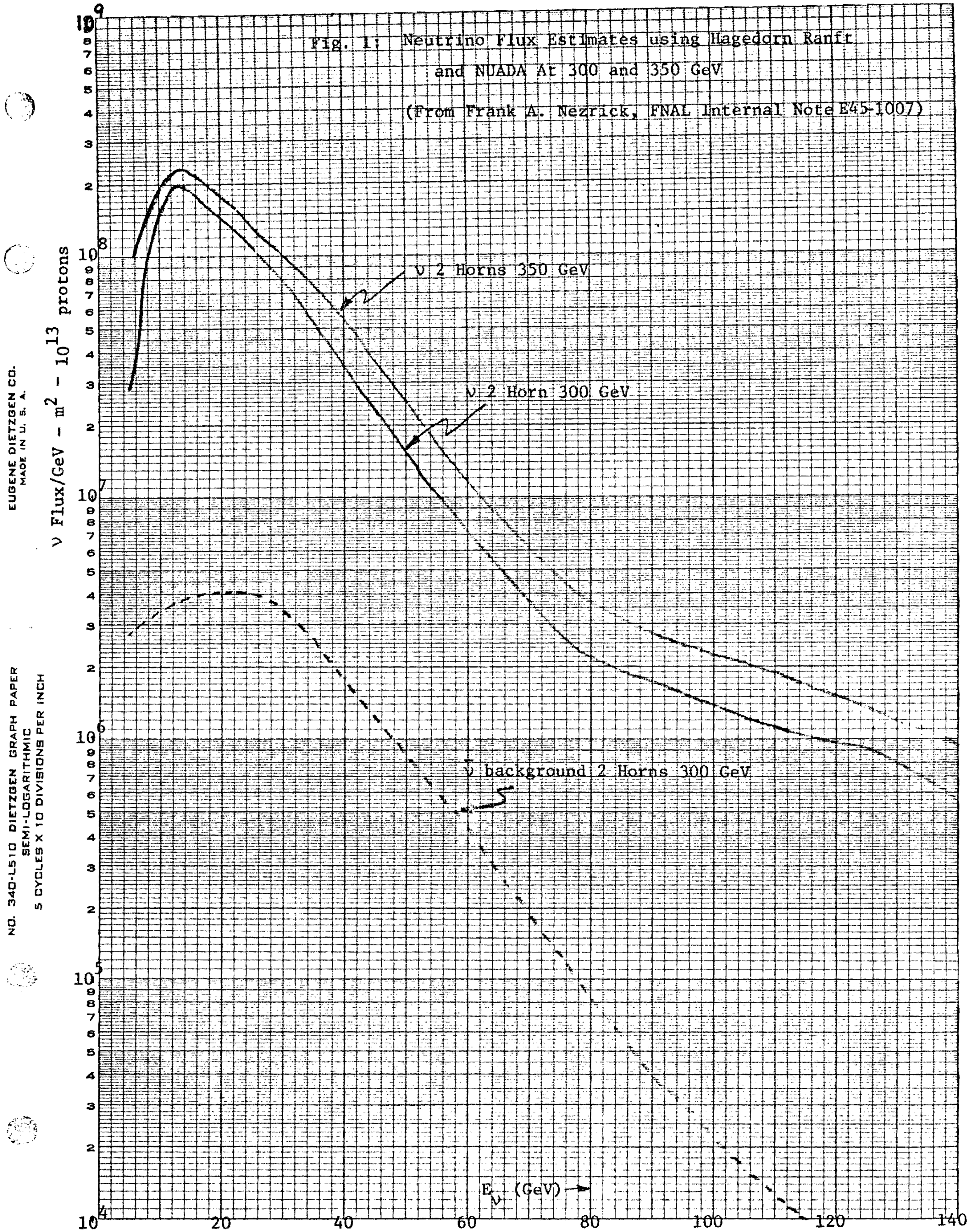

Fig. 1: Neutrino Flux Estimates using Hagedorn Ranft and NUADA At 300 and 350 GeV

(From Frank A. Nezrick, FNAL Internal Note E45-1007)

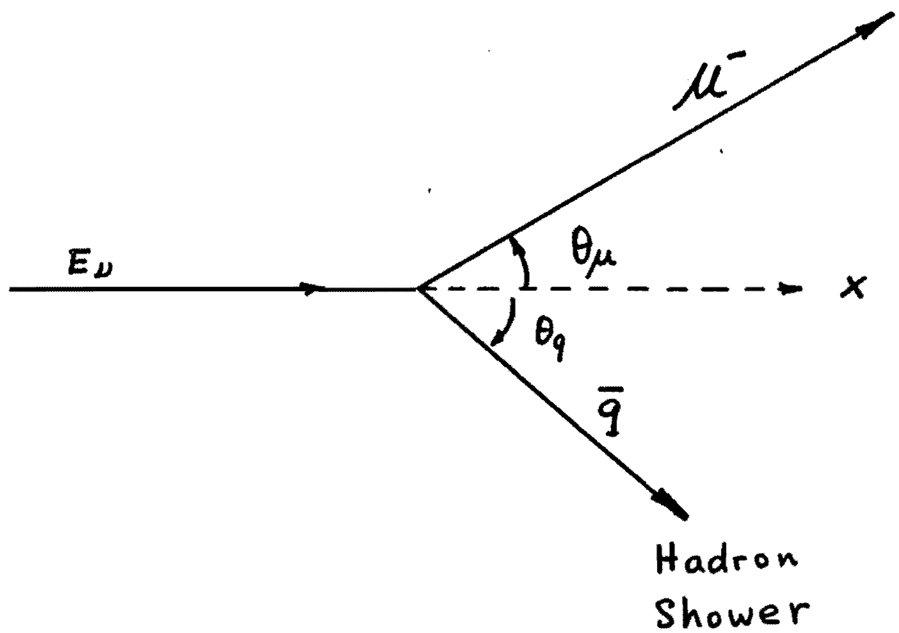

Fig. 2