NAL PROPOSAL No. 45

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PROPOSAL TO STUDY NEUTRINO INTERACTIONS WITH PROTONS USING THE 14-FOOT BUBBLE CHAMBER AT NAL

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ABSTRACT

We propose a detailed study of the individual channels produced in neutrino-proton interactions, as well as an exploration for new particles and phenomena. To accomplish this study we request an exposure in hydrogen yielding at least 50,000 events resulting from the targeting of at least 200 BeV protons. Using current flux estimates from a double horn focusing system and assuming 10^{13} interacting protons per pulse, this exposure length would be 200,000 pictures.

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I. Introduction

The operation of the NAL accelerator opens a new era in the study of neutrino physics which should lead to a deeper understanding of the weak interaction. Neutrino interactions in the bubble chamber will for the first time be studied with statistics comparable to present day hadron experiments in bubble chambers.

High intensity neutrino beams and large bubble chambers will exist in 1973 at BNL, CERN, NAL, Serpukhov and ANL. A comparison of the neutrino event rates on free protons expected at each accelerator in 1973 has been calculated[1] and is presented in Fig. 1. The detailed parameters of the detectors and beams used for these calculations are given in Table 1. Neutrino interactions in the energy range below 5 BeV are available at nearly all of the accelerators and those from 10 BeV to 30 BeV in principle are accessible at both Serpukhov and NAL. However, in this energy range the Serpukhov event rate is less than 5% of the NAL event rate even when an optimistic proton intensity is used for Serpukhov. It is clear then that the region of neutrino physics unique in practice to NAL is the energy region above about 5 BeV.

In present neutrino experiments the muon takes approximately one-half of the neutrino energy. Bjorken[2] estimates $\frac{\langle E_\mu \rangle}{E_\nu} = 0.62 \pm 0.12$ at high energies from an extrapolation of present data. Hence, for hadronic energy transfers of more than around 3.5 BeV, NAL is effectively unique and even in the region 2-3.5 BeV, NAL has a distinct advantage over Serpukhov. It is worth noting that within this range of hadronic energies the bubble chamber has proven itself exceedingly valuable in the study of strong interactions. The energies are large enough to produce interesting resonances but not so large that a great many channels are opened with only a few events per channel.

We intend to study in detail the individual channels produced by neutrino interactions on protons. The proposed exposure of neutrinos to the hydrogen chamber would produce about 50,000 events which would yield quantitative and qualitative results. The qualitative studies include a search for new particles (intermediate vector bosons, heavy leptons, shadows particles, monopoles, quarks, etc.), a search for neutral current induced events and tests of the $\Delta S/\Delta Q$ law. We will also be able to make qualitative studies of the structure of the inelastic interaction. Quantitative studies can be made of all interactions involving only charged final state particles such as N^{*++} production. Tests can be made of locality by studying the four-fermion interaction, of the Cabbibo theory via Y^* production, of strange particle associated production, and of locality and V-A interference from the single pion analysis.

This exposure is viewed as a candidate for the first major run of the 14-foot bubble chamber, focusing system and muon monitoring system since this is the simplest possible bubble chamber configuration for efficient neutrino operation.

2. Event Rate

The neutrino spectrum incident on the bubble chamber has been calculated and is shown in Fig. 2. The beam parameters and assumptions used are given in Table 2 for accelerator operations of 200 BeV and 500 BeV. The most critical assumption in this calculation is the particle production model which predicts the meson spectra. We have chosen the Hagedorn-Ranft[3] model which was fit[4] to the 70 BeV Serpukhov data.[5]

Using 10^{13} 200 BeV protons per pulse interacting in the neutrino target, a two-horn focusing system and a bubble chamber fiducial volume of $20m^3$ of hydrogen, we calculate a yield of approximately 50,000 events in a 200,000 picture exposure. The energy distribution of these events is given in Table 3. It has been assumed that the total neutrino-nucleon cross section rises linearly with neutrino energy. This is known to be true experimentally[6] to approximately 10 BeV and should be true theoretically if scale invariance holds and there is no intermediate boson or cut-off in the weak interaction.[7] If the cross section saturates at 20 BeV, then the total number of events expected is reduced by about 13%.

3. Expected Physics Results

The purpose of this exposure is a detailed study of the individual channels produced in neutrino-proton interactions. However, some of the most exciting prospects are the possibilities of finding new particles or different phenomena. What particles are produced by the weak interactions at high energy and high q^2? Nature might produce whole sets of new particles which may even interact strongly among themselves but may be coupled only weakly to other strong particles[8] (a "shadow world"). We only know that unless selection rules operate, these particles would have to have a mass larger than 250 MeV or K mesons could decay into them. These could be seen directly from interactions in the chamber or we might see long-lived particles which were produced in the shield and decayed in the chamber. Heavy leptons might be produced at the lepton vertex and decay by $\mu^* \rightarrow \mu\gamma$[9] or by weak decays.[10] If the average path length of a gamma ray is taken as 7 feet (0.18 conversion lengths), then about 20% of the decay gammas from $\mu^* \rightarrow \mu\gamma$ should convert and be seen. The effective mass of the μ^* could then be measured. As discussed by Kraemer and Derrick,[11] the error in the μ^* mass should be comparable with present day mass errors, i.e., about 25 MeV or less. The gamma ray will have a shorter track length than their example, but the measurement accuracy obtainable seems considerably better[12] than the 500μ used there. Quarks, monopoles[13] or even more exotic particles may be produced. Surely there must be some surprises awaiting us in the study of neutrino interactions.

We may ask what is expected to happen at the hadronic vertex. The total cross section is believed to be proportional to the neutrino energy. The elastic cross section experimentally[14] and theoretically[15] flattens out above about 1 BeV as does the one pion $N^*_{\frac{3}{2}\frac{3}{2}}$ (1238) cross section.[16] What then happens to form the bulk of the cross section in the 10-20 BeV region? Calculations[17,18] of ρ and A_1 production, although quite crude, predict only a small number of events and again flat cross sections using vector dominance type models. It will be very interesting to see if these channels are small experimentally and if so which channels dominate. A separation can be made using events with no π^o's and events with π^o's where one or more gamma rays have converted since the gamma conversion probability is about 20%. It is possible, for instance, that the inelastic cross sections are dominated by production of higher N^* resonances. The present CERN results are consistent with this[19] although the multiplicities of high energy events seem high. If this is true, then a side result of these experiments might be the strong decay branching fractions of the higher N^* $(I = \frac{3}{2})$ resonances as well as their β decay coupling and weak form factors. Cross sections for $\rho + N^*$ etc. are as yet uncalculated. The specific channels that dominate will have a great impact on the various theories of deep inelastic scattering. As an example, in the theory of Drell, Levy, and Yan[20] at low $q^2/2m\nu$ the nucleon should generally carry a large part of the longitudinal momentum transferred to the hadronic system. If this qualitative check can be made (for instance, by measuring δ-rays to find out what fraction of the time the fast particle is a proton) then even with large uncertainties in σ_{total} or $d\sigma/dq^2$, significant limits can be placed on various deep inelastic theories.

A study of the four-fermion interaction $\nu_\mu + e^- \rightarrow \nu_e + \mu^-$ seems feasible.[21] The theoretically expected event rate assuming the standard point interaction is about 100 events at 200 BeV. The backgrounds are discussed in Ref. 21, and it would appear that the real interactions can be separated out. The study of this four-fermion interaction leads directly to a test of locality of the weak interaction since no form factors are involved.

Associated production of strange particles should occur. There is essentially no experimental information on this at present, but if associated production occurs 5-10% of the time as it does in strong interactions, we would have 2500-5000 events. In many of the channels we will be able to obtain well constrained fits as well as see Λ^O, K^O, $\Sigma^\pm$ etc. For example, possible reactions are $\nu P \rightarrow \mu^-\Sigma^+K^+$, $\nu P \rightarrow \mu^-Y^{*+}K^+$ followed by Y^{*+} (1385) $\rightarrow \Lambda^O\pi^+$ ($\sim$90%b.r.) and $\nu P \rightarrow \mu^-\Xi^O K^+K^+$ followed by $\Xi^O \rightarrow \Lambda^O\pi^O$. The first two reactions are 3C at the main vertex, the latter is a 2C fit although one constraint is somewhat weak. It will be very interesting to make SU_3 tests among different modes here.

Several $\Delta S/\Delta Q$ searches can be made. $\nu P \to \mu^- \pi^+ \Sigma^+$ etc. should not occur. Limits on these can be set and when compared with results from $\bar{\nu}$ experiments will give us $\Delta S/\Delta Q$ results. If $\nu P \to \mu^- K^o P \pi^+$ has an appreciable cross section, an even more sensitive test can be made[22] since the K^o can have a small $\bar{K}^o$ component. Even a crude measurement of K^o_1/K^o_2 decays (by observing K^o_2 interactions) can give a sensitive $\Delta S/\Delta Q$ test since a measurement of relative amplitudes rather than amplitudes squared is being made. If the K^o_2 path length is 7 feet and if its $\sigma_{tot} \simeq 20$ mb then 14% of the K^o_2 should interact in the chamber. The observation of $\nu P \to \mu^- K^o P \pi^+$ and similar channels is interesting in its own right because positive strangeness kaons are the only kind of single strange particle that neutrinos are allowed to produce if the $\Delta S/\Delta Q$ law holds. The observation of this reaction gives us some information on the strength of the strangeness changing current at high energy and high q^2. It will also be quite interesting to find the percentages of N^* and especially K^* in the above reactions. This is the strangeness changing equivalent of ρ production.

An intermediate vector boson search via $\nu P \to \mu^- P W^+$ followed by $W \to e\nu$ can be made in this experiment. The branching ratio for this decay should be the same as for $\mu\nu$. In a 7-foot path in hydrogen, an electron should lose, on the average, about 23% of its energy by radiation. For a high energy particle this is far greater than the ionization loss; hence, electrons should be identifiable by measuring momentum at the beginning and end of the track. For all reasonable energies, measurement errors of momentum should be far less than this value.[23] The muon produced at the incoming neutrino-muon vertex tends to be of low energy in the lab (about 50% are below 2 BeV)[24] and the signature for this event becomes a low energy μ^- and a high energy e^+. The background can be estimated by looking for high energy e^- since most forms of background give equal numbers of e^- as e^+ (or pure e^-). The mass which produces 100 intermediate vector boson decays in this experiment is about 8 BeV and 12.5 BeV respectively for 200,000 pictures at 200 BeV and 500 BeV operation.

We have studied the information contained in the measurement of only the muon direction and energy summed over all neutrino energies. As an example, we have assumed the parameters and formulas given in reference 25, and various value for an intermediate boson mass. If an over-all normalization constant is removed, it is found that the muon energy spectrum is sensitive only if $M_W < 5$ BeV, but the muon angular distribution is more sensitive. This can be understood immediately since a virtual intermediate boson introduces a factor $\frac{M_W{}^2}{q^2 + M_W{}^2}$ into the cross-section formula and hence has the effect of suppressing high q^2 (and hence high angle) events. If one defines R to be the ratio of those events with E_μ between 10 and 30 BeV with $\theta_{\mu\nu} > 0.1$ to those events with $\theta_{\mu\nu} < .05$, we find the results given in Table 4. If the systematic error (not individual measurement error) in $\theta_{\mu\nu}$ is 2mr, then $\frac{\Delta R}{R} = .09$. The statistical error is small since both numerator and denominator have about 2000 events or more. The presence or absence of a W_3 form factor can also widen or narrow the angular distribution. The uniqueness of the interpretation of this data depends on the inelastic parameters being known. These parameters are to be studied at lower energies at CERN and BNL within the next few years. However, in any case, the proposed experiment will certainly put a limitation on the set of allowable parameters.

A neutral current search can be performed on the events without muon candidates. These events must be distinguished from events caused by neutrino induced neutrons interacting in the chamber. We expect approximately 0.5 neutrino induced neutron interactions per pulse. These background events would have two nucleons rather than one in the final state and the total momentum would be in the neutrino direction, while a neutral current event would have a total hadronic momentum not in the beam direction. Because of the problem of unseen neutrals, it is not clear how well this test could be performed. However, there exists no high energy or high q^2 information on neutral currents, and any limits that can be set are useful.

Even with incomplete reconstruction of events, tests of locality, V-A interference, etc., are quite possible as has been pointed out especially by Pais.[26]

In conclusion, we feel these are very exciting experiments, with many results definitely obtainable. As with so many exploratory bubble chamber experiments in the past, however, there is an excellent chance that the most interesting results will not be those emphasized above but will be new and as yet unexpected phenomena.

II. Experimental Arrangement

The layout of the proposed experiment consists of a thick target and meson focusing system to maximize the neutrino flux below about 50 BeV, a 600-meter long decay region one meter in diameter, a 300-meter long iron shield and the 14-ft. bubble chamber.

1. Target

A thick target of high Z material has been shown[27] to optimize the lower energy meson yield from the target via hadronic cascading, thereby optimizing the lower energy neutrino flux, i.e., $E_\nu \lesssim 20$ BeV. The target, for example, could be of Cu two interaction lengths long and 4 mm in diameter. The choice of target material may well be a compromise between optimizing the neutrino flux and obtaining adequate cooling.

2. Focusing System

A high efficiency broad-energy band meson focusing system is proposed to maximize the information content per photograph and minimize the exposure length of the experiment. The neutrino energy range of interest in this experiment is primarily between 10 BeV and about 50 BeV. The pulsed horn-type focusing system has a focusing efficiency of about 50% over this entire region. The pulsed horn-type focusing system is the only focusing system which has been successfully used in previous neutrino experiments.

Successful operation of pulsed horns have been achieved at ANL, BNL and CERN. New focusing systems may be developed, but at the present time there is no proven competition to the pulsed horn for high efficiency broad band focusing. For comparison, a "broad band" adiabatic quadrupole focusing system[28] optimized at about 10 BeV has an integrated efficiency of about 25% with respect to the horns in the energy range above 5 BeV. If the adiabotic quadrupole channel were used, then for the same statistics our exposure request would be for 800,000 photographs, rather than for 200,000, if the other parameters remain the same. We therefore propose the two-horn system whose preliminary parameters are given in Table 5. This focusing system is under detailed study by the NAL staff.

3. Meson Decay Region

The meson decay region is a pipe approximately one meter in diameter and approximately 600 meters long. Since the meson interaction length in air is 540 m, we recommend that the decay region be evacuated to a pressure of about 1/10 atm.

4. Shielding

The amount of shielding between the meson decay region and the bubble chamber is assumed to be sufficient to shield the chamber from all beam induced particles to the level of a few per pulse, except for neutrinos and neutrino induced secondaries for an accelerator operation of at least 200 BeV. The request that the shielding be adequate to the highest machine energies is important and obvious. We request the exposure at the highest accelerator energy compatible with an acceptable background in the bubble chamber.

5. Neutrino Spectrum Monitoring

The neutrino spectrum incident on the bubble chamber can, in principle, be determined in at least two ways. If the pion and kaon angle and momentum spectra are known at the target, then the mesons can be followed mathematically through the focusing system, allowed to decay, and the energy spectrum of the neutrinos passing through the chamber determined. Uncertainty in the shape of the neutrino spectrum results from not knowing accurately the meson spectra from the thick target used in the experiment in the full momentum and angle range needed ($10 \frac{BeV}{c} < P < 140 \frac{BeV}{c}$ and $0 < \theta < 60$ mrad). The uncertainty in the absolute normalization of the neutrino flux results from the uncertainty in the proton intensity on the target. Also, absorption and mesonic cascading in the focusing system and vacuum windows are difficult to include in the flux calculations.

The second method of determining the neutrino spectrum is to measure the muon flux distribution in radius and depth in the muon shield, and via the meson decay kinematics unfold the parent meson distribution in the decay tunnel and thus predict the neutrino flux. This method gives directly a normalized neutrino spectrum with the above mentioned uncertainties removed. We propose using both methods to determine the neutrino spectrum.

6. Detector

The bubble chamber considered is the 14-foot chamber which has a total volume of $30m^3$. The useful fiducial volume for neutrino interaction has been taken at $20m^3$. The chamber filling requested is hydrogen. The magnetic field requested is at least 20 kG but we desire the highest field available.

7. Exposure

This proposal requests 50,000 events of neutrinos on protons. Using the present flux predictions, these 50,000 events can be obtained in 200,000 accelerator pulses, with 1×10^{13} protons per pulse interacting in the neutrino target. For an accelerator cycle of four seconds, this exposure could be obtained in 220 hours, or using a total experimental arrangement efficiency of 30%, the exposure time would be about one month.

Several of the experiments described above require the full number of events requested. For 200 BeV operation of the accelerator about 100 events are estimated for the four-Fermion interaction. This gives a statistical error of about 10% on the event rate which is comparable to our other normalization errors. With 100 events we can also obtain a rough energy distribution of the muons. The clearly identifiable strangeness changing channel in this experiment is $\nu p \to \mu^- K^o \pi^+ p^+$ plus possible neutrals where only 1/3 of the K^o decay by $K_1^o \to \pi^+\pi^-$. Therefore to obtain any sort of information on the production mechanism, at least the full exposure length would be required. Since this is also the channel for an amplitude test of $\Delta S = \Delta Q$, one again wants as many events as possible. In the search for an intermediate boson by means of $W \to e\nu$, one also becomes event limited for higher boson masses.

III. Apparatus

We wish to indicate here some of the technical reasons why we believe the presently proposed experiment should be considered for the initial neutrino experiment in the 14-foot bubble chamber.

This experiment is viewed as a first major run of the 14-foot bubble chamber and neutrino focusing and monitoring system, all of which are being designed by the authors of this proposal. Since hydrogen is by far the cheapest chamber filling, it is highly probable that the initial operation of the chamber will be with hydrogen rather than with mixes of neon and hydrogen or with deuterium.

An early neutrino exposure has several operational and technical advantages over an early antineutrino exposure. In the first place, the flux of neutrinos is 2.5-4 times that of antineutrinos. An equivalent statistics antineutrino experiment will consume more running time than a neutrino experiment. Also, the beam purity (percentage of wrong kind of neutrinos) is considerably better for neutrinos than antineutrinos.

In νP interactions the final state hadronic system is left doubly charged resulting in fewer neutral particles than the $\bar{\nu}P$ interactions in which the hadronic system is neutral. Furthermore, since muon identification may be difficult in the first experiments, there will be fewer μ-π ambiguities for ν than $\bar{\nu}$ since there will be fewer π^- from ν interactions than π^+ from $\bar{\nu}$ interactions. We would not be happy with a beam focusing system that did not separate ν and $\bar{\nu}$ since having both interactions in the chamber would greatly compound our muon identification problems.

Analysis of these experiments will be dominated by scanning time. It is probable that every event will be examined by a physicist. This seems quite feasible with the present group. The measurement load is modest by today's standards especially when divided between our two groups. This is true even assuming that one might measure double the actual numbers of events eliminating fake events with the aid of track reconstruction information. The University of Michigan and NAL are currently building POLLY devices and the measurement load is easily managed. We anticipate having initial results within a year of the time the pictures are taken.

We require:

1. Neutrino focusing system.
2. Neutrino flux monitoring system.
3. 14-foot bubble chamber filled with hydrogen.

These pieces of equipment which are to be built by the people involved in this proposal are to be available as NAL facilities.

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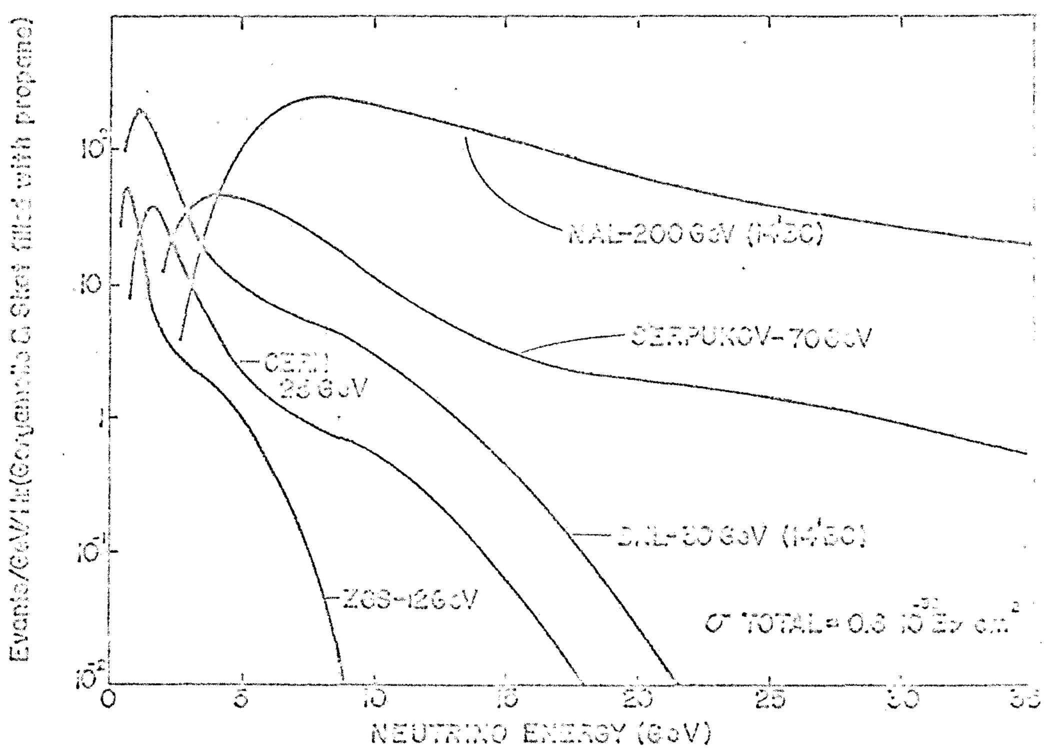

Fig. 1

Neutrino event rates possible at high energy accelerators in 1973.

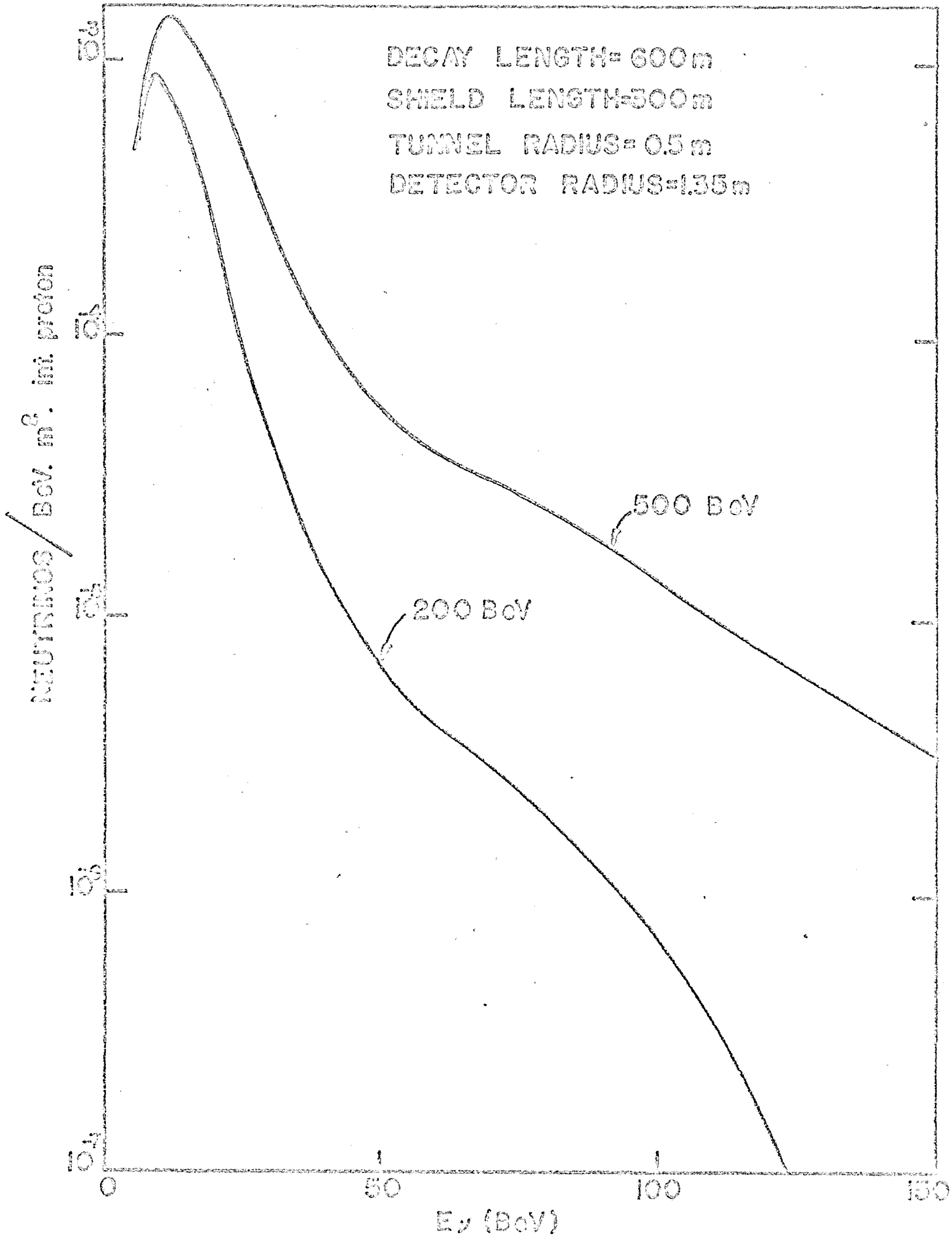

Fig. 2

200 BeV and 500 BeV neutrino energy distributions for NAL

(Perfect Focusing)

TABLE I

Neutrino Beam Parameters

	NAL	Serpukhov	BNL	CERN	ZGS
Energy (GeV)	200	70	30	25	12
Beam Intensity at Present (10^{12} protons/sec.)	-	0.2	1.5	0.7	1.3
Beam Intensity in 1973 (10^{12} protons/sec.)	15	10	20	6	10
Decay Distance (m)	600	150	62	72	33
Shielding Length (m)	150	50	30	23	9
Tunnel Radius (m)	0.75	1.0	1.20	1.8	1.6
Recess (m)	22.5	5.0	5.4	1.5	4.2
Particle Production Model	Hagedorn-Ranft	Hagedorn-Ranft	Sanford-Wang	Sanford-Wang	Sanford-Wang
Maximum Angle Acceptance by focusing element	3.4°	11.5°	17.2°	20°	30°
Accepted pion multiplicity	1.8	1.8	1.2	0.92	0.54
Accepted Kaon multiplicity	0.37	0.24	0.14	0.10	0.051
Bubble Chamber	14'	SKAT (heavy liquid)	14'	Gargamelle heavy liquid	12'
Radius (m)	1.4	0.6	1.4	0.9	1.5
Visible volume (m^3)	24	4	24	10	20
Length	4	4	4	3.9	2.8

TABLE 2

NAL Neutrino Beam Parameters and Assumptions

Meson decay length	600 m
Muon shield length	300 m
Recess between shield and detector	22.5 m
Decay tunnel diameter	1.0 m
Detector diameter	2.7 m
Target materials	Copper
Particle production model	Hagedorn-Ranft
Focusing efficiency	Perfect (100%)
Maximum meson angle focused	60 mr

TABLE 3

Distribution of 50,000 Events From a 200 BeV Exposure

Neutrino Energy Interval (BeV)	No. of Events
0 - 10	12,200
10 - 20	21,700
20 - 30	7,900
30 - 40	2,900
40 - 50	1,400
50 - 75	2,200
75 - 100	1,210
100 - 150	500

TABLE 4

Dependence of R on the Intermediate Boson Mass

M_W (BeV)	R
5	1.3
10	2.0
15	2.2
20	2.2
25	2.3
∞	2.4

TABLE 5

Preliminary Parameters of a Two-Horn Focusing System

Horn Parameters	Horn 1	Horn 2
Length (m)	9.5	4.5
Distance from target (m)	0	29.5
Outside diameter (m)	0.8	0.8
Minimum inside diameter (cm)	1.0	6.0
Wall thickness (mm of aluminum)	2-3	2-3
Peak current (10^5 amps)	3-5	3-5
Peak voltage (10^3 volts)	12	12
Inductance (10^{-6} H)	3.0	0.6
Stored energy (10^3 J)	133-370	43-120
Total power required (KVA)	200-500	
(e.g. at 480V 3 phase)		

national accelerator laboratory

July 15, 1971

Dear Don,

We wish to replace our proposal NAL No. 45 with the enclosed proposal which we want numbered NAL No. 45A.

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NAL PROPOSAL No. 45- A

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PROPOSAL TO STUDY NEUTRINO INTERACTIONS WITH PROTONS USING THE 14-FOOT BUBBLE CHAMBER AT NAL

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F. A. Nezrick and W. Smart

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July 15, 1971

Proposal to Study Neutrino Interactions with Protons

Using the 15-Ft Bubble Chamber at NAL

Abstract:

We propose a detailed study of the individual channels produced in neutrino-proton interactions, as well as an exploration for new particles and phenomena. To accomplish this study we request an exposure in hydrogen yielding about 50,000 events resulting from the targeting of 350 BeV protons. Using current flux estimates from a double horn focusing system and assuming 10^{13} incident protons per pulse on the target, we estimate the exposure length to be about 500,000 pictures. We have been and will continue to be active in the design and construction of the neutrino beam and detector components needed for this experiment, e.g. the meson focusing system, the neutrino monitoring system, and the 15-ft bubble chamber.

We intend to measure and analyze nearly every event, squeezing the maximum possible information out of the film. It will be the major physics occupation of both groups. We would hope generally to have preliminary results available within one year. In searching for new particles such as quarks or monopoles, identifiable in an initial scan, we hope to have initial results much sooner.

Among the topics we intend to examine are intermediate boson production, single pion production, multiple pion production, and deep inelastic scattering, associated production and strangeness changing reactions, four fermion interactions, conservation laws, ν_e interactions, and a neutral current search.

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I. INTRODUCTION

The operation of the NAL accelerator opens a new era in the study of neutrino physics which should lead to a deeper understanding of the weak interaction. Neutrino interactions in the bubble chamber will for the first time be studied with statistics comparable to present day hadron experiments in bubble chamber.

High intensity neutrino beams and large bubble chambers will exist in 1973 at BNL, CERN, NAL and ANL. It is also possible that a neutrino facility will exist at Serpukhov in 1973. A comparison of the neutrino event rates on free protons expected at each accelerator in 1973 has been calculated[1] and is presented in Fig. 1. The detailed parameters of the detectors and beams used for these calculations are given in Table I. Neutrino interactions in the energy range below 7 BeV are available at nearly all of the accelerators. Neutrino interactions from 10 BeV to 30 BeV in principle are accessible at both Serpukhov with the heavy liquid bubble chamber and NAL with the 15-ft hydrogen bubble chamber. However, in this energy range the Serpukhov event rate is about 12% of the NAL event rate even when an optimistic proton intensity is used for Serpukhov. If the Serpukhov proton intensity stays at its present intensity then NAL will have a superior event rate above about 4 GeV. It is clear then that the region of neutrino physics unique in practice to NAL is the energy region above about 7 BeV.

In neutrino interactions below 5 GeV, the muon takes approximately one-half of the neutrino energy.[2] Bjorken[3] estimates $\frac{\langle E_\mu \rangle}{E_\nu} = 0.62 \pm 0.12$

at high energies from an extrapolation of present data. Hence, for hadronic energy transfers of more than around 3.5 BeV, NAL is effectively unique. It is worth noting that within this range of hadronic energies the bubble chamber has proven itself exceedingly valuable in the study of strong interactions. The energies are large enough to produce interesting resonances but not so large that a great many channels are opened with only a few events per channel.

We intend to study in detail the individual channels produced by neutrino interactions on protons. The proposed exposure of neutrinos to the hydrogen chamber would produce about 50,000 events which would yield quantitative and qualitative results. The qualitative studies include a search for new particles (intermediate vector bosons, heavy leptons, shadows particles, monopoles, quarks, etc.), a search for neutral current induced events and tests of the $\Delta S/\Delta Q$ law. We will also be able to make qualitative studies of the structure of the inelastic interaction. Quantitative studies can be made of all interactions involving only charged final state particles such as N^{*++} production. Tests can be made of locality by studying the four-fermion interaction, of strange particle associated production and of locality and V-A interference from the single pion analysis. In Section II we elaborate on each of these physics objectives. In Section III we point out the regions of neutrino physics which should have already been studied in bubble chamber experiments at ANL, BNL and CERN and with the counter experiments at NAL by the time this experiment could be performed.

This exposure is viewed as a candidate for the first major run of the 15-ft bubble chamber, focusing system and muon monitoring system since this is the simplest possible bubble chamber configuration for efficient neutrino operation. In Section IV we discuss in detail the experimental arrangement required. In Section V we point out the contributions that this group have made and will continue to make toward developing the equipment necessary to perform this experiment. In Section VI we conclude the proposal and commit ourselves to the construction of specific equipment.

If an external muon identifier (EMI) of the type described by M. L. Stevenson et al. in the NAL proposal No. 9 were available, it would be used in this experiment. However the objectives of this experiment would not be seriously impaired if the EMI did not exist. We insert comments in the discussion of the physics objectives for those objectives where the use of an EMI is an important consideration. For many reactions there is no muon ambiguity since there is only one negative track. For reactions with more than one negative track, we use the fact that since the muon takes about 60% of the neutrino energy on the average, a good first order decision as to which negative particle is the muon can be made by taking the fast negative particle as the muon.

II. PHYSICS CONTENT OF THE EXPOSURE

The purpose of this exposure is a detailed study of the individual channels produced in neutrino-proton interactions and a search for new particles and unexpected phenomena.

Following is an enumeration of the physics content of this experiment based on the neutrino spectrum given in Fig. 2. The beam parameters and assumptions used to calculate this neutrino spectrum are given in Table II. The neutrino spectrum was calculated using the NAL neutrino flux program NUADA. The most critical assumption in this calculation is the particle production model which predicts the meson spectra. We have chosen the Hagedorn-Ranft[4] model which was fitted[5] to the 70 BeV Serpukhov data.[6]

Using 10^{13} 350 BeV protons per pulse incident on a one interaction length target, a two-horn focusing system and a bubble chamber fiducial volume of 20 m^3 of hydrogen, we calculate a yield of approximately 50,000 events in a 500,000 picture exposure. The energy distribution of these events is given in Table III. It has been assumed that the total neutrino-nucleon cross section rises linearly with neutrino energy $\sigma_{total} = 0.8\ E_\nu \times 10^{-38}\ cm^2$. This is known to be true experimentally[2] to approximately 10 BeV and should be true theoretically if scale invariance holds and there is no intermediate boson or cutoff in the weak interaction.[7] If the cross section saturates at 30 BeV, then the total number of events expected is reduced by about 18%.

1. <u>New Particle Search</u>

$\nu + p \rightarrow$	heavy leptons + anything	(1)
$\rightarrow$	quarks + anything	(2)
$\rightarrow$	magnetic monopoles + anything	(3)
$\rightarrow$	shadow particles + anything	(4)
$\rightarrow$	unexpected + anything	(5)

What particles are produced by the weak interactions at high energy and high q^2? Searches for heavy leptons, quarks, magnetic monopoles and shadow particles can be accomplished in this experiment and will be discussed below.

Heavy leptons might be produced at the lepton vertex and decay by $\mu^* \to \mu\gamma$[8] or by weak decays.[9] If the average potential path length of a gamma ray is taken as 7 feet (0.18 conversion lengths), then about 20% of the decay gammas from $\mu^* \to \mu\gamma$ should convert and be seen. The effective mass of the μ^* could then be measured. As discussed by Kraemer and Derrick,[10] the error in the μ^* mass should be comparable with present day mass errors, i.e. about 25 MeV or less. The gamma ray will have a shorter track length than their example, but the measurement accuracy obtainable seems considerably better[11] than the 500μ used there.

If $\mu^* \to \mu\nu\nu^*$, then for a sufficiently heavy μ^* (well above 1 BeV) ionization would indicate the event for those μ^* which are slow in the lab. For masses around 1 BeV or slightly lower, decay in flight may indicate the μ^* if the coupling is similar to ordinary muon decay. This latter method would probably only work over a narrow region since $\tau \propto 1/m_\mu^5$. For these events, it would be desirable for the identity of the muon to be confirmed by an EMI.

Quark production in the bubble chamber can appear dramatically as charge non-conserved events if the bubble chamber is not sensitive to charge 1/3 tracks via reactions such as $\nu p \to \mu^- \pi^+ q_{2/3}^+ q_{2/3}^+ q_{1/3}^-$. If the bubble chamber is sensitive to charge 1/3 tracks then there will be apparent charge non-conservation in reactions such as $\nu p \to \mu^- p\, q_{2/3}^+ q_{1/3}^+$. Quark tracks can always be tested by measuring their energy loss in traversing the bubble chamber. Also quark tracks should be distinguishable in the chamber since a relative ionization loss of nine-to-one should be distinguishable in the bubble chamber.

A search for magnetic monopoles will be similar to the recent analysis[12] of the 1967 CERN neutrino bubble chamber film. A magnetic monopole because of its high dE/dx stops rapidly[13] (< 1 mm) in the bubble chamber and because of the viscous drag of the hydrogen drifts along a magnetic field line. Since the magnetic field lines flair out at the ends of the chamber, this signature is unique, i.e. a stray cosmic ray track cannot be mistaken for a monopole.

Nature might also produce whole sets of new particles which may even interact strongly among themselves but may be coupled only weakly to other strong particles[14] (a "shadow world"). We only know that unless selection rules operate, these particles would have to have a mass larger than 250 MeV or K mesons could decay into them. These could be seen directly from interactions in the chamber or we might see long-lived particles which were produced in the shield and decayed in the chamber.

2. Intermediate Vector Boson

$$\nu p \to \mu^- p\, w^+, \qquad w^+ \to \begin{cases} e^+ \nu \\ \text{hadrons} \\ \mu^+ \nu \end{cases} \tag{6}$$

An intermediate vector boson (IVB) search via Reaction (6) followed by positron decay of the W can be made in this experiment. The branching ratio for this decay should be the same as for $\mu\nu$. In a 7-ft path in hydrogen, an electron should lose, on the average, about 23% of its energy by radiation. For a high energy particle this is far greater than the ionization loss; hence, electrons should be identifiable by measuring momentum at the beginning and end of the track. For all reasonable energies, measurement errors of momentum should be far less than this value.[10] The muon produced at the incoming neutrino-muon vertex tends to be of low energy in the lab (about 50% are below 2 BeV)[15] and the signature for the IVB event becomes a low energy μ^- and a high energy e^+. The background can be estimated by looking for high energy e^- since most forms of background give equal numbers of e^- as e^+ (or pure e^-). If the mass is 8 BeV or less about 100 IVB decays would occur in this experiment. The expected yield of intermediate vector bosons as a function of the IVB mass is given in Fig. 3 where the cross sections of Brown et al.[16] have been used. The IVB events tend to be concentrated at much higher energies than the inelastic events, see Fig. 4. The signature of a low energy muon in a high energy event might well be sufficient to enable us to search using all modes of W decay not just $e\nu$. However, we have even a further handle on the W events. The calculations[15] of Smith and Brown show that the muon is produced at quite small angles in spite of its low energy. This puts intermediate boson events in one very small part of the available phase space plotted as a function of $\frac{q^2}{2M(E_\nu - E_\mu)}$

and $\frac{(E_\nu - E_\mu)}{E_\nu}$. Using present crude experimental estimates of the inelastic cross section[17] one does not expect the density of normal inelastic events to vary by more than a factor of three or so over most of this plot. In fact it should be low for low energy forward muons (low q^2 and low E_μ) and there should not be sharp peaks. Hence these events should stand out quite clearly from the background (remember $\frac{E_\mu}{E_\nu}$ is around 0.62). Furthermore if E_ν is badly measured (by say 20%) this will not strongly effect q^2 and will leave $\frac{E_\nu - E_\mu}{E_\nu}$ still close to one. This means that one may use many decay modes including the hadronic decay modes in searching for a boson in this experiment. We will simply use an estimate based on observed electron pairs for the average fraction of energy in neutrals.

There is of course a background here due to events with two negative particles when it is not clear which is the muon. However, the fact that for W events the slow muon is very forward ($\cos\theta > 0.98$ in most cases for $E_\nu \gtrsim 50$ GeV) will help considerably. Slow pions will almost surely not have a sharp forward peak.

Furthermore if a boson is found we can get some information on decay mode frequences using the above peculiar production kinematics to signal the bosons, and can probably get a rather precise mass determination (around 20 MeV) from some of the hadronic modes. This will thus enable us to answer the very important question of whether there is one boson or perhaps a whole set of bosons or indeed no boson of well defined mass. If the boson mass is sufficiently low, we can get a preliminary indication of its existence by looking at the ratio of $\frac{\mu^+}{\mu^-}$ from muons entering the bubble chamber from neutrino interactions in the shield and bubble chamber coils.

3. Four Fermion Interaction

$$\nu_\mu e^- \rightarrow \nu_e \mu^- \qquad (7)$$

$$\nu_e e^- \rightarrow e^- \nu_e \qquad (8)$$

$$\nu_\mu e^- \rightarrow e^- \nu_\mu \qquad (9)$$

A study of the four-fermion interaction via Reaction (7) seems feasible[18] in this experiment. The theoretically expected event yield assuming the standard point interaction is about 70 events. The backgrounds are discussed in Ref. 18, and it would appear that the real interactions can be separated out. The study of this four-fermion interaction leads directly to a test of locality of the weak interaction since no form factors are involved. Reaction (9) is forbidden with normal first order weak interaction theory but would be allowed by higher order weak interactions, by neutral currents, or if lepton quantum numbers were multiplicative, not additive.[19] Again we can identify the electron by the approximately 20% radiative energy loss within the chamber. A background to Reaction (9) comes from electron-neutrino elastic scattering Reaction (8). The ν_e flux is estimated to be about 0.2% of the ν_μ flux[20]. If the cross section for Reaction (8) is anomalously large[21] this would contribute to the events. Hence a limit on $\frac{(\nu + e \rightarrow \nu + e)}{(\nu + e \rightarrow \nu + \mu)}$ will be a very useful test. A background to this process comes from gamma rays converting in the chamber with one member of the pair taking most of the energy. However, for Reaction (8) the electron should be predominantly in the beam direction and will generally take a large fraction of the neutrino energy. Hence some separation should be possible.

4. Single-Pion Production

$$\nu + p \rightarrow \mu^- N^{*++}_{3/2\ 3/2}\ (1238) \tag{10}$$

$$\rightarrow \mu^- N^{*++}_{3/2\ 1/2}\ (1640) \tag{11}$$

$$\rightarrow \mu^- N^{*++}_{3/2\ 7/2}\ (1950) \tag{12}$$

$$\rightarrow \mu^- \text{ Higher } N^* \text{ States} \tag{13}$$

$$\rightarrow \mu^- p \pi^+ \tag{14}$$

Single pion production in the neutrino interaction as in electropion and photopion production can proceed through N^* resonances, pion exchange or nucleon exchange. At neutrino energies of a few GeV single pion production is dominated by $N^*(1238)$ resonances,[22] Reaction (10). The cross section for the $N^*(1238)$ has been calculated using dispersion relations,[23] isobar models,[24] CVC models,[25] SU(6) models[26] and quark models.[26] The values of cross section using the different models do agree. It will be important to test these models at high q^2 since most models introduce a correction factor[27] to better fit electroproduction data for $|q^2| < 0.6\ cm^2$. Using a cross section of $1.13 \times 10^{-38}\ cm^3$ for Reaction (10), about 1800 events are expected in this experiment with an energy distribution shown in Table III.

As the neutrino energy and momentum transfer increases, higher spin states of the N^* should be produced[28] such as Reactions (11) and (12). The strong decay branching fractions of these higher $N^*(I = 3/2)$ states as well as their β decay coupling and weak form factors may also be determined. The production cross sections for the higher N^* states have not yet been calculated.

The non-resonant single pion production, Reaction (14), has been calculated using dispersion relations[23] and can be tested. By treating all single pion events in a quasi-elastic approximation,[29] a test of locality can be made because locality of the leptonic action gives $\frac{d^2\sigma}{dq^2\,d\nu}$ which at most is a quadratic function of the neutrino energy.[29]

As has been pointed out,[29] more information can be extracted from Reaction (14) by analyzing the events in terms of the angle ϕ between the normals to the hadron plane and the lepton plane as well as other parameters (γ, q^2, Δ^2, K^2). Locality can then be tested from the ϕ dependence alone. Also from the ϕ dependence the presence of a hadronic V-A interference can be tested.

5. Vector Meson Production and Multiple Pion Production

$$\nu p \rightarrow \mu^- \, p \, \rho^+ \quad (\rho^+ \rightarrow \pi^+ \pi^o) \tag{15}$$

$$\rightarrow \mu^- \, p \, A_1^+ \quad (A_1^+ \rightarrow \pi^+ \pi^+ \pi^-) \tag{16}$$

$$\rightarrow \mu^- \, N^{*++} \, \omega^o \quad (\omega^o \rightarrow \pi^+ \pi^- \pi^o) \tag{17}$$

$$\rightarrow \mu^- \, N^{*++} \, \rho^o \quad (\rho^o \rightarrow \pi^+ \pi^-) \tag{18}$$

$$\rightarrow \mu^- \, N^{*+} \, \rho^+ \quad (N^{*+} \rightarrow p\pi^o, \; n\pi^+; \;\; \rho^+ \rightarrow \pi^+ \pi^o) \tag{19}$$

$$\rightarrow \mu^- \, (\pi^+\text{'s}) \, (\pi^-\text{'s}) \, (\pi^o\text{'s}) \, (p\text{'s}) \, (n\text{'s}) \tag{20}$$

The total cross section is believed to be proportional to the neutrino energy. The quasi-elastic cross section experimentally[30] and theoretically[31] flattens out above about 1 BeV as does the one pion $N^*_{3/2\ 3/2}$ (1238) cross section.[22] What then happens to form the bulk of the cross section in the 10-20 BeV region? Calculations[32, 33] of ρ and A_1 production and calculations[34] of $N^{*++}\ \omega^o$, $N^{*++}\ \rho^o$ and $N^{*+}\ \rho^+$ production predict only a small number of events and again flat cross sections using vector dominance type models. Firmer predictions should soon be available based on electroproduction results. It will be very interesting to see if these channels are small experimentally, and if so, which channels dominate. It will be hard to do better than set a limit on ρ production since Reaction (15) involves a π^o. A partial separation of Reaction (15) and single-pion production events can be made using events with no π^o's and events with π^o's where one or more gamma rays have converted since the gamma conversion probability is about 20%. However, A_1, 3π and $N^{*++}\ \rho^o$ production are quite accessible in this experiment because of the all-charged final state.

The specific channels that dominate the multi-pion events will have a great impact on the various theories of deep inelastic scattering. We can also make many other qualitative tests of deep inelastic scattering theories. As an example, in the theory of Drell, Levy, and Yan[35] at low $q^2/2m\nu$ the nucleon should generally carry a large part of the longitudinal momentum transferred to the hadronic system. This qualitative check can be made for instance by measuring δ-rays to find out what fraction of the time the fast particle is a proton. Bjorken[36] conjectures that the transverse momenta of the hadrons will tend to lie in a plane. This can be checked for multiple pion events even without seeing the missing π^o's. Thus even with large uncertainties in σ_{total} and $\frac{d\sigma}{dq^2}$, significant limits can be placed on various deep inelastic theories.

We have studied the information contained in the measurements of only the muon direction and energy summed over all neutrino energies. We find the angular distribution is more sensitive than the meson spectrum. The angular distribution is sensitive to the presence of virtual intermediate boson states and to the presence or absence of a W_3 form factor. The uniqueness of the interpretation of the angular distribution depends on the inelastic parameters being known. These parameters are to be studied at lower energies at CERN and BNL within the next few years. However, in any case, the proposed experiment will certainly put a limitation on the set of allowable parameters.

6. Associated Production and Strangeness Changing Reactions

$$\nu p \rightarrow \mu^- K^+ \Sigma^+ \qquad (21)$$

$$\rightarrow \mu^- K^+ Y^{*+} \qquad (22)$$
$$\quad\quad \hookrightarrow \Lambda^o \pi^+$$

$$\rightarrow \mu^- K^+ K^+ \Xi^o \qquad (23)$$
$$\quad\quad \hookrightarrow \Lambda^o \pi^o$$

$$\rightarrow \mu^- p \pi^+ K^o \qquad (24)$$

Associated production of strange particles should occur. There is essentially no experimental information on this at present, but if associated production occurs 10% of the time as it does in strong interactions,[37] we should obtain about 5000 events. In many of the channels we will be able to obtain well constrained fits as well as see Λ^o, K^o, $\Sigma^{\pm}$, etc. For example, Reactions (21), (22) and (23) are possible. Reactions (21) and (22) are 3C at the main vertex, and Reaction (23) is a 2C fit although one constraint is somewhat weak.

The observation of Reaction (24) and similar channels is interesting in its own right because positive strangeness kaons are the only kind of single strange particle that neutrinos are allowed to produce if the $\Delta S/\Delta Q = 1$ law holds. The observation of this reaction gives us some information on the strength of the strangeness changing current at high energy and high q^2. It will also be quite interesting to find the percentages of N^* and especially K^* in the above reactions. This is the strangeness changing equivalent of ρ production.

7. Conservation Laws

a) $\Delta S/\Delta Q$ Laws

$$\nu p \rightarrow \mu^- \pi^+ \Sigma^+ \qquad (25)$$

$$\rightarrow \mu^- p \pi^+ K^o \qquad (26)$$

Several $\Delta S/\Delta Q$ searches can be made. For example Reaction (25) should not occur. A cross section for Reaction (25) can be set and will give us a $\Delta S/\Delta Q$ test when compared with $\bar{\nu} p \rightarrow \mu^+ \pi^- \Sigma^+$ from an $\bar{\nu}$ experiment.

If Reactions (26) has an appreciable cross section, an even more sensitive test can be made[38] since the K^o can have a small $\overline{K}^o$ component. Even a crude measurement of K_S^o/K_L^o decays (by observing K_L^o interactions) can give a sensitive $\Delta S/\Delta Q$ test since a measurement of relative amplitudes rather than amplitudes squared is being made. If the K_L^o path length is 7 feet and if its $\sigma_{tot} \simeq 20$ mb then 14% of the K_L^o should interact in the chamber. The time dependence of e^-/e^+ in K_{e3}^o decay modes for Reaction (26) also provides an amplitude dependent test of $\Delta S/\Delta Q$. The present test involves almost the same matrix element but at different (higher) energy and q^2. The present test also has the advantage of a more straightforward measurement (i.e., ratio of K_L^o to K_S^o). Further, if the amplitude is parameterized as $A_+ + \epsilon A_-$, then the ratio of K_L^o to K_S^o is approximately $1 + 4\epsilon$.

For the present class of tests, an EMI which would detect the K_L^o and hence increase its detection efficiency well past 14% would enhance our ability to perform this test.

b) $\Delta S = 2$ Test

$$\nu p \rightarrow \mu^- \pi^+ \overline{K}^o \Sigma^+ \qquad (27)$$

It is questioned[29] whether low energy weak interaction selection rules hold in the high energy region. It is important to test, for example, if $\Delta S = 2$ or $\Delta S/\Delta Q = -1$ violation occurs. Such a test can be made by searching for Reaction (27).

c) T Invariance Test

A T invariance test can be made by measuring the hyperon polarization in Reaction (21). This important measurement only requires the study of $\overline{\sigma}_{\Sigma} \cdot (\overline{P}_{\mu} \times \overline{P}_{\nu})$ and does not require a detailed knowledge of the neutrino spectrum.

8. Other Tests of Basic Theories

As was pointed out in Section III. 4 locality can be tested using the single pion events. Similar tests of locality can be made using other inelastic channels.[29] The single pion events at high q^2 also provide a test of hadronic V-A interferences. It may also be possible from the single pion events to test Regge pole dominance since the consequences of a dominating Pomeranchuk trajectory has been pointed out,[29] in particular ω and ϕ production should be suppressed relative to ρ production.

Using the inelastic neutrino interactions Adler[39] has proposed tests of CVC and PCAC. It will be important to make these tests at high q^2?

Therefore tests of locality, V-A interference, and T violation are quite possible using the single pion and inelastic events.

9. ν_e Interactions with Protons

$$\nu_e + p \rightarrow e^- p \pi^+ \qquad (28)$$

$$\rightarrow e^- \pi^+ \pi^+ n \qquad (29)$$

etc.

$$\overline{\nu}_e + p \rightarrow e^+ + \text{anything} \qquad (30)$$

The electron-neutrino flux was estimated from K_{e3}^+ and μ^+ decays using a procedure previously reported.[20] The dominant contribution to the ν_e flux, because of the beam geometry, comes from the K_{e3}^+ decays. Assuming the Hagedorn-Ranft particle production model and ν_μ-ν_e universality for the total cross section ($\sigma_{tot} \mp 0.8 \times 10^{-38} E_\nu \, cm^2$), about 200 ν_e events are expected. This yeild is strongly dependent on the kaon to pion ratio at 350 GeV for $p_{meson}/p_{max} \sim 0.3$.

The μ-e universality and additive lepton number conservation laws can be tested using Reactions (28), (29) and (30).

If the lepton number conservation law is multiplicative then $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ and $\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu$ producing on $\bar{\nu}_e$ flux. Also $\nu_e \rightleftharpoons \bar{\nu}_e$ oscillations[40] can produce on $\bar{\nu}_e$ flux. Approximately 20 events of Reaction (30) can be expected if the μ^+ decays equally into ν_e and $\bar{\nu}_e$. Although the yield is low a measurement of e^+/e^- events is a sensitive test of the multiplicative law.

10. Neutral Current Search

$$\nu + p \rightarrow \nu + p \qquad (31)$$

A neutral current search can be performed on the events without lepton candidates for example Reaction (31). These events must be distinguished from events caused by neutrino induced neutrons interacting in the chamber. We expect approximately 0.5 neutrino induced neutron interactions per pulse. These background events would be of lower average energy than neutrino events, would have two nucleons rather than one in the final state. The total momentum of the nucleon in the background event would be in the neutrino direction, while a neutral current event would have a total hadronic momentum not in the beam direction. Because of the problem of unseen neutrals, it is not clear how well this test could be performed. However, there exists no high energy or high q^2 information on neutral currents,[41] and any limits that can set are useful.

An EMI to provide better detection of muons and to distinguish the approximately 1% of $\bar{\nu}$ events with μ^+ but no μ^- candidates would enhance our ability to perform this test.

III. THE RELATION OF THIS EXPERIMENT TO OTHER EXPERIMENTS IN PREPARATION

Assuming that this experiment will start in January of 1973, it is reasonable to ask what areas of neutrino physics will have been studied by then in other experiments. The other experiments fall into two classes: bubble chamber neutrino experiments at other accelerators and counter neutrino experiments at NAL.

Bubble chamber experiments are presently in progress or in preparation at ANL using the 12-ft bubble chamber, at BNL using the 7-ft bubble chamber and at CERN using Gargamelle. The ANL and BNL experiments plan to study neutrino interactions in hydrogen and deuterium while CERN plans to study neutrino and anti-neutrino interactions in a heavy liquid. Table IV gives a brief summary of these experiments, their event rates and major topics of investigation. As the neutrino energy increases from 0.25 GeV to about 5 GeV the physics emphasis in the analysis changes from form factor studies of the elastic and N^* channels to studies of the more inelastic channels. The fact that CERN has a large heavy liquid bubble chamber encourages them to study the more general properties of neutrino interactions (e.g. the total cross sections and deep inelastic scattering) since individual channels are difficult to identify in a heavy liquid chamber due to nuclear effects and final state interactions.

In the proposed experiment most of the events occur in the energy region from 5 GeV to 80 GeV. Therefore, only a small overlap in neutrino energy exists between this experiment and the Gargamelle experiment. Our events will however be free of the heavy liquid bubble chamber problems thereby allowing us to study the individual reaction channels.

The counter neutrino experiments in preparation at NAL will study several physics topics extensively where the bubble chamber experiments can made few additional contributions unless the bubble chamber is instrumented to also be a "counter experiment". These nearly exclusive regions of study of the counter experiments are:

1. Deep inelastic neutrino and anti-neutrino scattering,

   $\nu + p \rightarrow \mu +$ (anything).

2. Total neutrino and anti-neutrino cross section as a function of energy.

3. Intermediate vector boson search via $w \rightarrow \mu\nu$.

4. Lepton pair production in a coulomb field.

The proposed experiment does not overlap the counter experiments but will compliment them. For example, by searching for the intermediate vector boson via $w \rightarrow e\nu$ or $w \rightarrow$ hadrons. Also by looking at the evolution of the individual channels into the deep inelastic region.

This experiment of neutrinos on hydrogen we feel does not duplicate other neutrino experiments in preparation. It does however open up a new and complimentary region of study in our pursuit to understand the nature of the weak interaction.

IV. EXPERIMENTAL ARRANGEMENT

The layout of the proposed experiment consists of a one interaction length aluminum target, a meson focusing system which maximizes the neutrino flux below about 70 BeV, a 390 m long decay region 0.88 m in diameter, a 910 m long iron shield and the 15-ft bubble chamber.

1. Target

A thick target of high Z material has been shown[42] to optimize the lower energy meson yield from the target via hadronic cascading, thereby optimizing the lower energy neutrino flux; i.e. $E_\nu \lesssim 20$ BeV. Too thick a target, however, drastically reduces the neutrino flux above about 50 GeV. We therefore propose a target of aluminum one interaction length long and 4 mm in diameter. The final choice of target material and size may well be a compromise between optimizing the neutrino flux and obtaining adequate cooling of the target.

2. Focusing System

A high efficiency broad-energy band meson focusing system is proposed to maximize the information content per photograph and minimize the exposure length of the experiment. The neutrino energy range of interest in this experiment is primarily between 5 BeV and about 70 BeV. The pulsed horn-type focusing system has a focusing efficiency of about 50% over this entire region.

Successful operation of pulsed horns have been achieved at ANL, BNL and CERN. New focusing systems may be developed, but at the present time, there is no proven competition to the pulsed horn for high efficiency broad band focusing. For comparison, a "broad band" adiabatic quadrupole focusing system[43] optimized at about 10 BeV has an integrated efficiency of about 25% with respect to the horns in the energy range above 5 BeV. If the adiabatic quadrupole channel were used, then for the same statistics our exposure request would be for two million photographs, rather than for one-half million photographs, if the other parameters remain the same. We therefore propose the two-horn system whose preliminary parameters are given in Table V. This focusing system is presently under engineering design by the NAL staff.

3. Meson Decay Region

The meson decay region is a pipe 0.88 m in diameter and 390 m long. Since the meson interaction length in air is 540 m, we recommend that the decay region be evacuated to a pressure of about 1/10 atm.

4. Muon Shielding

The amount of shielding between the meson decay region and the bubble chamber is assumed to be sufficient to shield the chamber from all beam induced particles to the level of a few per pulse, except for neutrinos and neutrino induced secondaries, for an accelerator operation of about 350 BeV. We request the exposure at the highest accelerator energy compatible with an acceptable background in the bubble chamber. We have anticipated that this energy is 350 GeV.

5. Neutrino Spectrum Monitoring

The neutrino spectrum incident on the bubble chamber can, in principle, be determined in two ways. First, if the pion and kaon angle and momentum spectra are known at the target, then the mesons can be followed mathematically through the focusing system, allowed to decay, and the energy spectrum of the neutrinos passing through the chamber determined.[44] Uncertainty in the shape of the neutrino spectrum results primarily from not knowing accurately the meson spectra from the thick target used in the experiment in the full momentum and angle range needed (12 BeV/c $< P <$ 220 BeV/c and $0 < \theta < 20$ mrad). Also, meson absorption and mesonic cascading in the focusing system and vacuum windows introduce uncertainties in the shape of the neutrino spectrum. The uncertainty in the absolute normalization of the neutrino flux results from the uncertainty in the proton intensity interacting in the target.

The second method of determining the neutrino spectrum is to measure the transverse and longitudinal muon flux distribution in the muon shield and via the meson decay kinematics unfold the parent meson distribution in the decay tunnel and thus produce the neutrino flux.[45] This method should give directly a normalized neutrino spectrum with the above mentioned uncertainties removed. However, the large number of inhomogeneities in the NAL muon shield introduce uncertainties in this method which were not encountered at CERN where this method was used.[45]

Because of the uncertainties involved in both methods, a monitoring procedure has been devised[46] which uses both methods in a cross-checking manner to determine the neutrino spectrum. The procedure follows.

A. No Meson Focusing System Installed

1) Measure the π and K yields from the actual neutrino target.

We propose using the neutrino area to measure the absolute π and K yields from a one interaction length target in the ranges:

$$12 < p_\pi < 80 \text{ GeV} \qquad 0 < \theta_\pi < 20 \text{ mrad}$$

$$20 < p_K < 200 \text{ GeV} \qquad 0 < \theta_K < 20 \text{ mrad}$$

A bending magnet after the target bends the appropriate pθ trajectories into the 30-inch bubble chamber hadron-beam channel. This channel with a Cerenkov counter installed will serve as our spectrometer. Muon monitors in the front end of the shield will test the vertical symmetry of the beam (since the bending magnet deflects in the horizontal plane) allowing corrections to be made in the vertical steering of the proton beam onto the target.

2) Check muon flux programs.

By removing the deflection magnet after the target, a conventional wide-band non-focused neutrino beam is produced. The muon distribution is measured throughout the shield and compared with the calculated muon distribution in the shield. This allows the muon flux (and hence neutrino flux) programs to be tested and corrected for an easily calculated geometry. These measurements could be made during the wide-band non-focusing exposure of Experiment 1A.

B. Meson Focusing System Installed

1) Measure meson spectrum in the 30-inch channel.

By measuring the meson momentum distribution in the 30-inch hadron channel with the focusing system operating and by using the information from A. 1 and A. 2, a cross check can be made on the meson tracjectory program. Specifically, the meson tracing routines through the focusing system can be tested.

2) The muon distribution is measured in the shield.

If the above tests and corrections have been made, then when the focusing system is operated, the muon flux program should predict a muon distribution consistent with the measured distribution in the shield. This is a final test of the meson focusing and muon following programs and therefore the neutrino flux program.

C. Neutrino Spectrum Determination

1) Spectrum shape.

The shape of the neutrino spectrum is given by the neutrino flux program on the basis of the experimental data from A. 1.

2) Spectrum shape changes during experiment.

A continuous monitor of the neutrino spectrum shape during the experiment is obtained by sampling the muon spectrum shape via the muon monitors in the shield.

3) Absolute normalization.

The absolute normalization of the neutrino spectrum is obtained in two ways. First by monitoring the total number of protons interacting in the neutrino target. Second by integrating the muon monitors in the front end of the muon shield over the entire neutrino experiment.

D. Neutrino Spectrum Cross Checks

As described in our NAL Proposal No. 44, independent determinations of the neutrino spectrum can be made in two ways. First from the low q^2 neutrino-neutron pseudo-elastic scattering event energy distribution. Second from the neutrino-neon pseudo-elastic scattering events. In addition, by making specific assumptions on the total neutrino cross section, the neutrino spectrum can be determined from NAL Experiment 1A.

6. Detector

The bubble chamber considered is the 15-ft chamber which has a total volume of 30 m^3. The useful fiducial volume for neutrino interaction has been taken at 20 m. The chamber filling requested is hydrogen. The magnetic field requested is at least 20 kG but we desire the highest field available.

7. Exposure

This proposal requests 50,000 events of neutrinos on protons. Using the present flux predictions with the two-horn focusing system, these 50,000 events can be obtained in 500,000 accelerator pulses at 350 GeV with 1×10^{13} protons per pulse incident on the neutrino target.

Several of the experiments described above require the full number of events requested. For 350 BeV operation of the accelerator, about 60 events are estimated for the four fermion interaction. This gives a statistical error of about 10% on the event rate which is comparable to our other normalization errors. With 60 events we can also obtain a rough energy distribution of the muons. The clearly identifiable strangeness changing channel in this experiment is $\nu p \rightarrow \mu^- K^o \pi^+ p^+$ plus possible neutrals where only 1/3 of the K^o decay by $K_1^o \rightarrow \pi^+\pi^-$. An antineutrino exposure to a similar flux results in about 400 events per calculable strangeness changing channel. There are no estimates available for the present channel (which includes an extra prong) but it probably would not be greater than 400 (133 with visible K^o decay). Therefore to obtain any sort of information on the production mechanism, at least the full exposure length would be required. This is also the channel for an amplitude test of $\Delta S = \Delta Q$, which will also be strongly event-rate limited. In the search for an intermediate boson by means of $W \to e\nu$, one also becomes event limited for higher boson masses. It is important that this exposure be at the highest proton bombarding energy possible consistent with background in the chamber. We have taken this energy to be about 350 GeV. However we would consider operating at a lower energy (down to about 200 GeV) if it were necessary for other considerations.

V. THE GROUP ACTIVITIES RELATED TO NEUTRINO EXPERIMENTS

The activities and contributions of the NAL members of the group as regards the construction of NAL neutrino facilities (bubble chamber, track sensitive target, neutrino horn) are well known and we shall not mention them further. Here we would like to point out some work which the Michigan group has undertaken in collaboration with NAL to measure and monitor the neutrino spectrum.

We have written a Monte-Carlo program which has in it parameters for the production of pions and kaons, the focusing and absorbtion of the horn, the length and width of the decay tunnel, the structure and density of the muon shield, etc. We use this program to calculate the flux of muons throughout the shield. The parameters of the program are then adjusted to produce results in agreement with muon flux measurements taken during the running of the experiment and these adjusted parameters are used to calculate the neutrino spectrum in the bubble chamber.

We hope soon to begin measuring muon fluxes in the shield, running parasitically with E21 (NAL-Cal Tech. Neutrino Experiment). We thus hope to check many features of our Monte-Carlo program, specifically those which have to do with energy loss and multiple scattering in the shield.

VI. CONCLUSION

We wish to indicate here some of the technical reasons why we believe the presently proposed experiment should be considered for the initial neutrino experiment in the 15-ft bubble chamber.

This experiment is viewed as a first major run of the 15-ft bubble chamber and neutrino focusing and monitoring system, all of which are being designed by the authors of this proposal. Since hydrogen is by far the cheapest chamber filling, it is highly probable that the initial operation of the chamber will be with hydrogen rather than with mixes of neon and hydrogen or with deuterium.

An early neutrino exposure has several operational and technical advantages over an early antineutrino exposure. In the first place, the flux of antineutrinos is comparable to the flux of neutrinos. The antineutrino event rate will be about three times lower because of the lower cross section. An equivalent statistics antineutrino experiment will consume more running time than a neutrino experiment. Also, the beam purity (percentage of wrong kind of neutrinos) is considerably better for neutrinos than antineutrinos.

In νp interactions the final state hadronic system is left doubly charged resulting in fewer neutral particles than the $\bar{\nu}p$ interactions in which the hadronic system is neutral. Furthermore, since muon identification may be difficult in the first experiments, there will be fewer μ-π ambiguities for ν than $\bar{\nu}$ since there will be fewer π^- from ν interactions than π^+ from $\bar{\nu}$ interactions. We would not be happy with a beam focusing system that did not separate ν and $\bar{\nu}$ since having both interactions in the chamber would greatly compound our muon identification problems.

Analysis of these experiments will be dominated by scannint time. It is probable that every event will be examined by a physicist. This seems quite feasible with the present group. The measurement load is modest by today's standards especially when divided between our two groups. This is true even assuming that one might measure double the actual numbers of events eliminating fake events with the aid of track reconstruction information. The University of Michigan and NAL are currently building POLLY devices and the measurement load is easily managed. We anticipate having initial results within a year of the time the pictures are taken.

We require:

1) Neutrino focusing system.

2) Neutrino flux monitoring system.

3) 15-ft bubble chamber filled with hydrogen.

These pieces of equipment which are to be built by the people involved in this proposal are to be available as NAL facilities.

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TABLE I

Neutrino Beam Parameters

	NAL	Serpukhov	BNL	CERN	ZGS
Energy (GeV)	350	70	30	25	12
Beam Intensity at Present (10^{12} protons/sec)	-	0.2	1.5	0.7	1.3
Beam Intensity in 1973 (10^{12} protons/sec)	15	10	20	6	10
Decay Distance (m)	390	150	62	72	33
Shielding Length (m)	910	50	30	23	9
Tunnel Radius (m)	0.44	1.0	1.20	1.8	1.6
Recess (m)	86	5.0	5.4	1.5	4.2
Particle Production Model	Hagedorn-Ranft	Hagedorn-Ranft	Sanford-Wang	Sanford-Wang	Sanford-Wang
Maximum Angle Acceptance by focusing element	1.8^{o}	11.5^{o}	17.2^{o}	20^{o}	30^{o}
Accepted pion multiplicity	1.9	1.8	1.2	0.92	0.54
Accepted kaon multiplicity	0.45	0.24	0.14	0.10	0.051
Bubble Chamber	15-ft	SKAT (heavy liquid)	7-ft	Gargamelle heavy liquid	12-ft
Radius (m)	1.35	0.6	0.7	0.9	1.5
Visible volume (m^3)	20	4	6	10	20
Length	3.5	4	3.9	3.9	2.8

TABLE II

NAL Neutrino Beam Parameters and Assumptions

Meson Decay Length	390.0 m
Muon Shield Length	910 m
Recess Between Shield and Detector	86 m
Decay Tunnel Diameter	0.88 m
Detector Diameter	2.7 m
Target Materials	Aluminum
Particle Production Model	Hagedorn-Ranft
Focusing System	Two Horn, Real
Maximum Meson Angle Focused	1.80°

TABLE III

Distributions of 50,000 Events from a 350 GeV Exposure

Neutrino Energy (BeV)	Flux/GeV $-m^2$ 10^5 Int. Protons	Total Events	One-Pion Prod.	Assoc. Prod.	Four-Fermion Events
5	0.77	470	80	45	
10	3.5	3290	290	330	0.3
15	4.35	6140	360	615	7.3
20	3.7	6960	310	695	13.6
25	2.87	6750	240	675	16.3
30	2.03	5730	170	575	15.6
35	1.3	4280	110	430	12.6
40	0.86	3250	70	325	10.1
45	0.54	2290	50	230	7.4
50	0.39	1830	30	185	6.1
55	0.25	1290	20	130	4.4
60	0.19	1030	20	105	3.7
65	0.13	800	10	80	2.8
70	0.10	670	8	65	2.4
75	0.088	620	7	60	2.3
80	0.065	490	5	50	1.8
85	0.052	420	4	40	1.6
90	0.043	370	4	35	1.4
95	0.041	370	3	35	1.4
100	0.038	360	3	35	2.7
110	0.028	640		65	2.6
120	0.022	610		60	2.5
130	0.016	560		55	2.1
140	0.012	450		45	1.7
150	0.0079	350		35	1.3
160	0.0053	260		25	1.0
170	0.0034	200		20	0.7
180	0.0021	140		15	0.5
190	0.0014	100		10	0.3
200	0.0009	70		5	0.2
TOTAL		50,790	1,794	5,075	63.0

TABLE IV

Bubble Chamber Experiment in Progress or In Preparation

	ANL	BNL	CERN	
Bubble Chamber	12-ft	7-ft	Gargamelle	
Exposure	10^6 ν + Hydrogen 1/2 · 10^6 ν + Deuterium	10^6 ν + Deuterium	propane freon mixture with 10^6 ν	10^6 $\bar{\nu}$
Event Yield				
Elastic	1200	500	3000	150
N^{*++}	500	1000	2500	200
Inelastic	200	600	6000	900
Total	1900	2100	11,500	1250
Energy Range	0.25 - 1.5 GeV	1 - 3 GeV	1 - 5 GeV	
Main Topics of Study	1) Form factor study for elastic and N^{*++} events for $q^2 \lesssim 3$ GeV^2	1) Form factor study for elastic and N^{*++} events for $q^2 <$ GeV^2 2) Preliminary look at higher N^* states and deep inelastic scattering.	1) Measure total ν and $\bar{\nu}$ cross section to about 15 GeV. 2) Deep inelastic scattering 3) Look at higher N^{*++} states.	

TABLE V

Parameters of the Two-Horn Focusing System

Horn Parameters	Horn 1	Horn 2
Length (m)	4.0	5.5
Distance from Target (m)	3.0	39.5
Outside Diameter (m).	0.15	0.4
Minimum Inside Diameter (cm)	1.4	6.0
Wall Thickness (mm of aluminum)	2-3	2-3
Peak Current (10^5 amps).	1.4	1.4
Peak Voltage (10^3 volts)	15	15
Inductance (10^{-6} H)	1.2	1.3
Stored Energy (10^3 J).	23	25
Total Power Required (kVA) . . . . (e.g. at 480 V 3 phase)		70

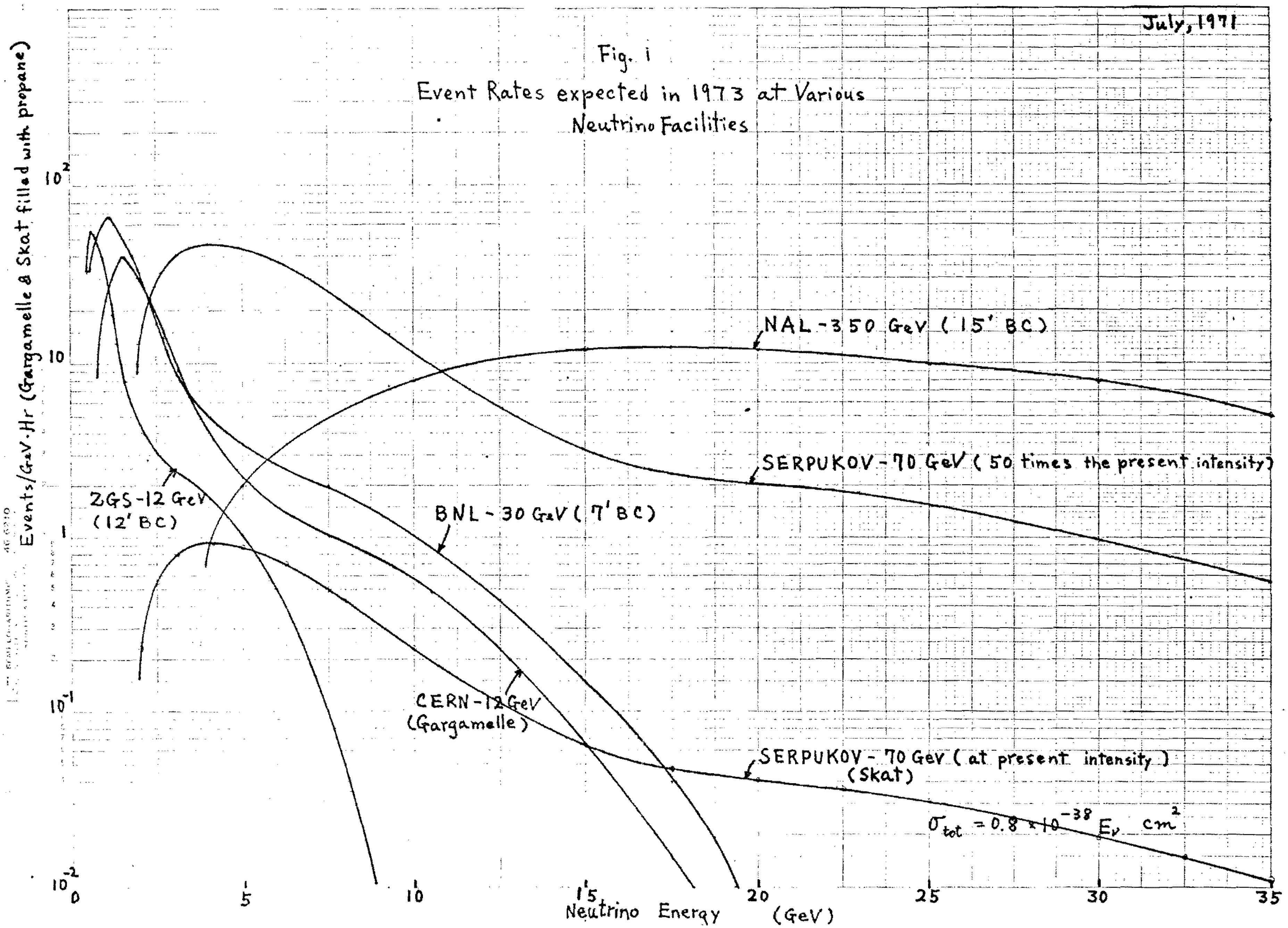
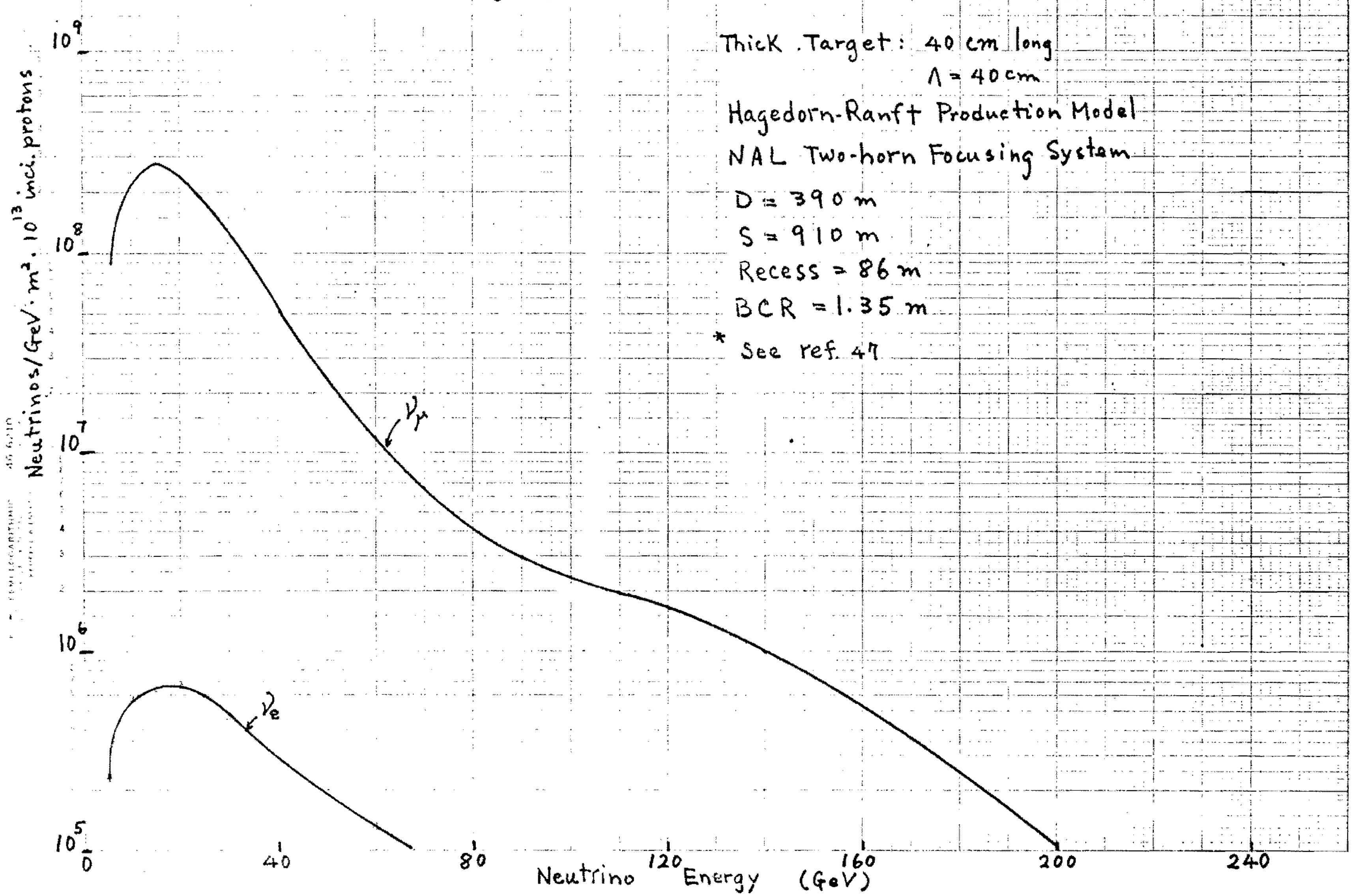

July, 1971
Fig. 1
Event Rates expected in 1973 at Various Neutrino Facilities
Events/GeV·Hr (Gargamelle & Skat filled with propane)
NAL - 350 GeV (15' BC)
SERPUKOV - 70 GeV (50 times the present intensity)
ZGS - 12 GeV (12' BC)
BNL - 30 GeV (7' BC)
CERN - 12 GeV (Gargamelle)
SERPUKOV - 70 GeV (at present intensity) (Skat)
$\sigma_{tot} = 0.8 \times 10^{-38} E_\nu \ cm^2$
Neutrino Energy (GeV)
10^{-2}
10^{-1}
1
10
10^2
0
5
10
15
20
25
30
35

Fig. 2

350 GeV

Neutrino Energy Spectrum expected for This Experiment*



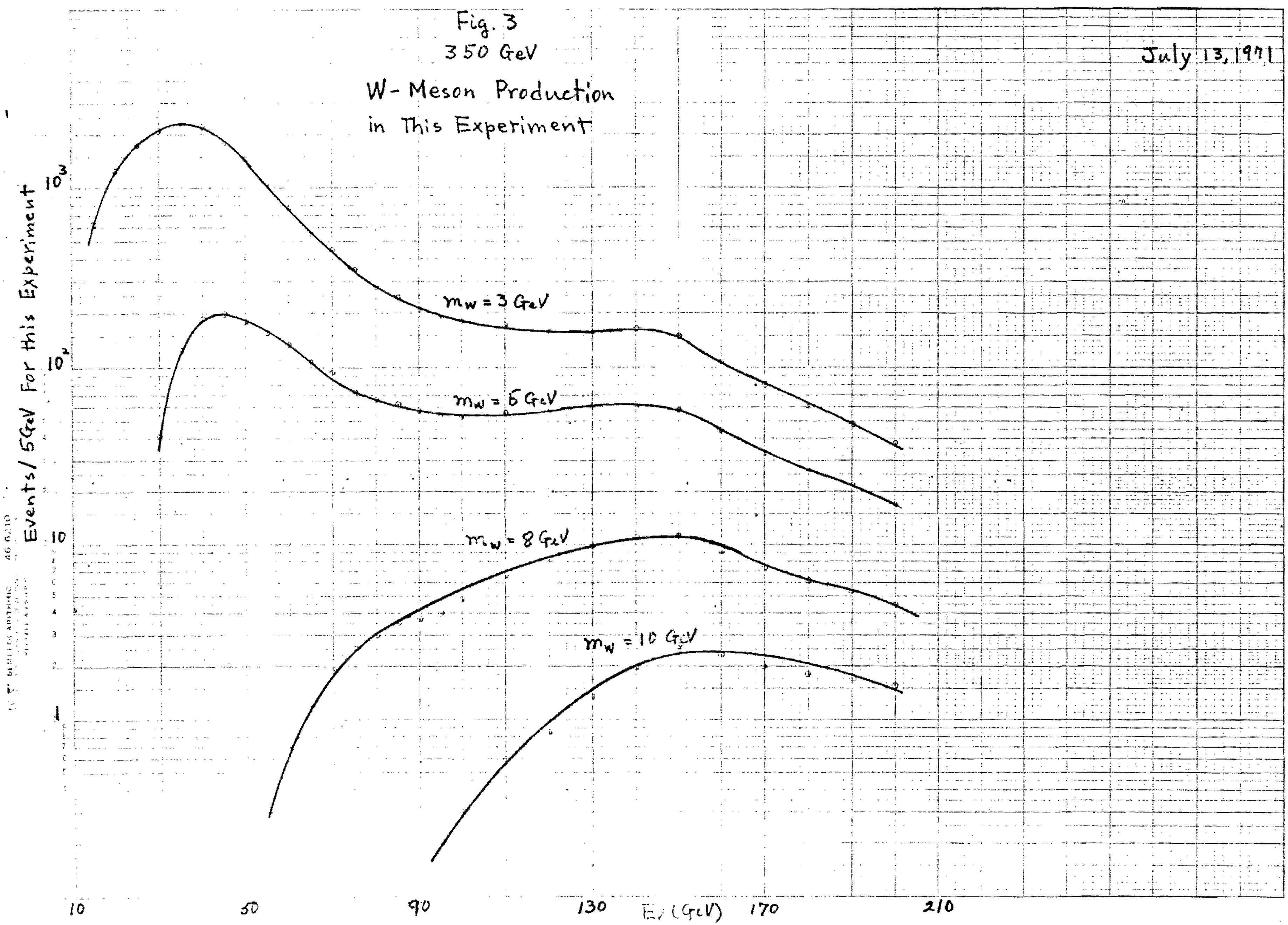


Fig. 3
350 GeV
W-Meson Production
in This Experiment
July 13, 1971
$m_W = 3$ GeV
$m_W = 6$ GeV
$m_W = 8$ GeV
$m_W = 10$ GeV
Events/5GeV For this Experiment
10^3
10^2
10
1
10
50
90
130
170
210
E_ν (GeV)

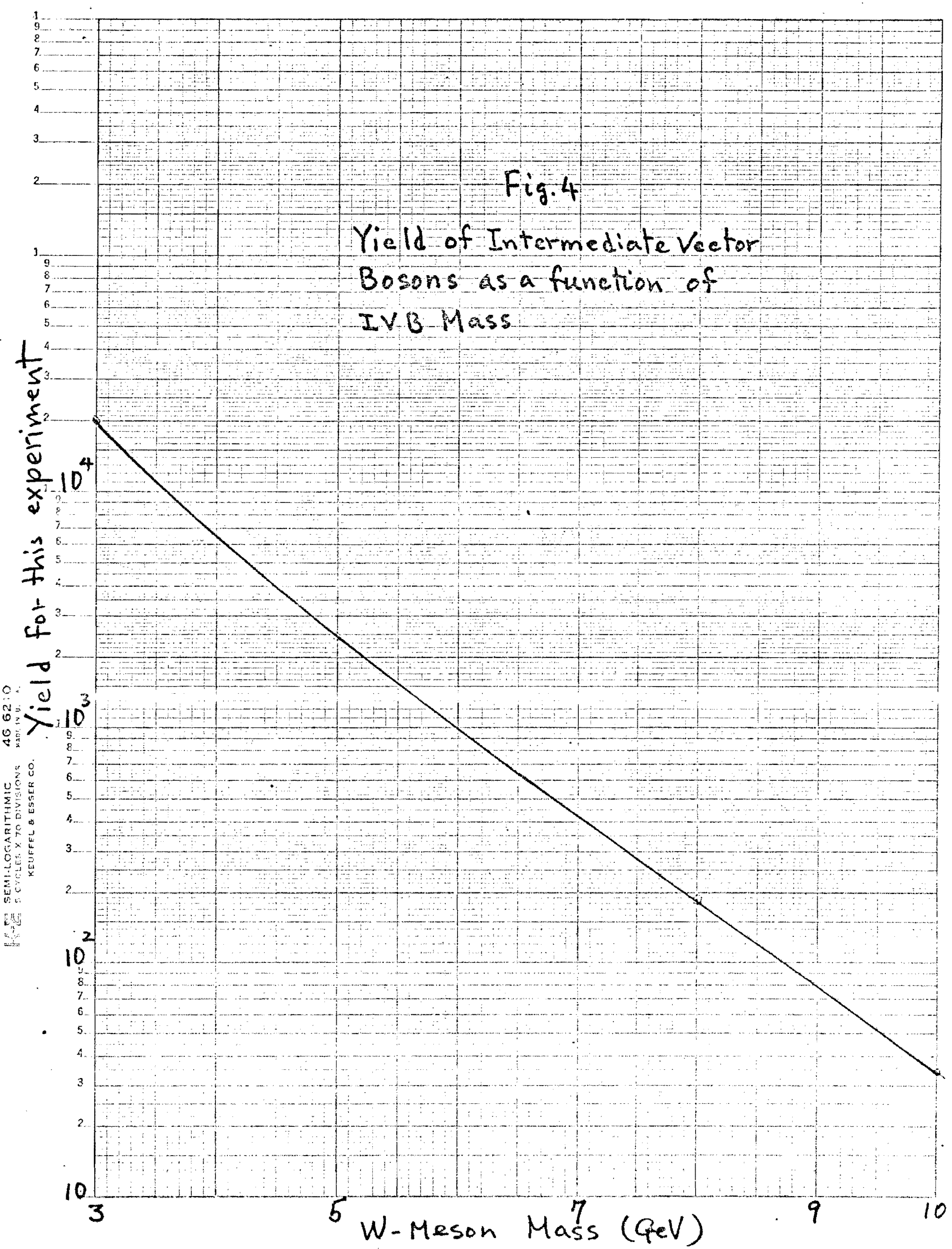


Fig. 4
Yield of Intermediate Vector Bosons as a function of IVB Mass
Yield for this experiment
10^4
10^3
10^2
10
3
5
7
9
10
W-Meson Mass (GeV)
SEMI-LOGARITHMIC
5 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO.
46 6210
MADE IN U.S.A.