NAL PROPOSAL No. 31

Correspondent: M. Derrick
Argonne National Lab
9700 So. Cass Ave.
Argonne, Ill. 60439

FTS/Commercial 312-739-4075

Proposal to Investigate $\bar{\nu}_\mu$ Interactions in Hydrogen at NAL

Bubble Chamber Groups from Argonne National Laboratory

and

Carnegie-Mellon University

John Campbell
Gordon Charlton
Yanglai Cho
Alan Cooper
Malcolm Derrick
Roderick Engelmann
Tom Fields
Tom Groves
Lloyd Hyman
Brian Musgrave
Gale Pewitt
Lou Voyvodic
Tom Wangler
John Wong
Haru Yuta

June, 1970

Proposal to Investigate $\bar{\nu}_\mu$ Interactions in Hydrogen at NAL

Bubble Chamber Groups from Argonne National Laboratory

and

Carnegie-Mellon University

Spokesman: M. Derrick

INTRODUCTION

We propose to investigate high energy $\bar{\nu}_\mu$ interactions on H_2 in the 15' bubble chamber at NAL. Some of the topics that can be studied are listed below.

1. $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ — elastic scattering

2. $\bar{\nu}_\mu + p \rightarrow \begin{cases} \mu^+ + \Lambda \\ \mu^+ + \Sigma^o \\ \mu^+ + Y^{*o} \end{cases}$ — hyperon production

3. $\bar{\nu}_\mu + p \rightarrow \mu^+ + N^{*o}$ — isobar formation

4. $\bar{\nu}_\mu + p \rightarrow \begin{cases} \mu^+ + \Xi^o \\ \mu^+ + \Sigma^+ + K^- \end{cases}$ — possible $\Delta S = 2$ reactions

5. Polarization of recoil baryons

6. Total cross section

7. Study of specific inelastic channels

8. Miscellaneous

We have throughout this paper used the notation given by Pais.[(1)] This notation is reviewed in the appendix.

DISCUSSION

A. Beam and Detector

For purposes of estimating rates we assume the bubble chamber has a fiducial volume containing 1.0 ton of hydrogen. The ν flux estimates we used were made by F. Nezrick and co-workers at NAL.[(2)]

The ν flux is shown in Fig. 1. We have assumed the $\bar{\nu}$ flux is 1/3 the ν value.[*] The $\bar{\nu}$ spectrum, of course, will differ from the ν spectrum, particularly at high energies. The rates quoted in this letter are based on an exposure of 10^{19} interacting protons on the horn target, i.e., 10^6 pictures at 10^{13} protons/pulse.

[*]We have not included any additional factors to account for the fact that the spectrum computed is for the ideal focus case.

B. Reactions

1. Elastic Scattering: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$

The elastic cross section is expected to be flat as a function of antineutrino energy with $\sigma \approx 6 \times 10^{-39}\ \mathrm{cm}^2$. The exposure will give 20,000 elastic events; however, it is likely that only those events can be used in which the neutron scatters in the chamber to give a visible recoil. Fig. 2 illustrates the expected neutron spectrum. This spectrum was found by using

$$f_Q = f_M = \frac{1}{\left[1 + \frac{q^2}{(0.84)^2}\right]^2}, \qquad g_A = \frac{g_A(0)}{\left[1 + \frac{q^2}{(1.0)^2}\right]^2}$$

with $f_A = h_V = h_A = 0$.

Using an average path length of 1.5 meters we will have a neutron detection efficiency of $\sim 25\%$. Thus, this exposure will yield 5000 useful events. Kinematic studies have shown that these 3 C events are well separated from the background.(3) The cross section at $q^2 = 0$ is given by

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

and so is independent of energy. The number of events at $q^2 = 0$, then is a measure of the $\bar{\nu}$ flux. This can be used to measure other cross sections.

Alternatively, once the flux is measured independently, one can test the above relation, which is a general result of weak interaction theory as presently formulated.

$$2. \quad \text{Hyperon Production:} \quad \bar{\nu}_\mu + p \rightarrow \begin{array}{ll} \mu^+ + \Lambda^o & \text{(a)} \\ \mu^+ + \Sigma^o & \text{(b)} \\ \mu^+ + Y_1^{*o} & \text{(c)} \\ \mu^+ + Y_0^{*o} & \text{(d)} \end{array}$$

Cabibbo and Chilton[4] have calculated various hyperon cross sections based on the SU(3) model. Using a form factor mass of ~ 1.0 GeV, the $\mu^+ + \Lambda$ cross section is $\sim 0.5 \times 10^{-39}$ cm^2. (This estimate is likely to be optimistic by a factor of ~ 3 according to Pais.) The $\Sigma^o + \mu^+$ cross section is the same order in this model. From reaction (a) we would expect ~ 1300 events with a visible Λ. A measurement of the cross sections would test the Cabibbo theory in a new range of momentum transfer. This can range up to ~ 20 (GeV/c)^2 although it is expected the cross section would fall as e^{-4q2} so one expects very few events at large q^2. At present there is no experimental information available on these channels.

The Y_1^{*o} cross sections are estimated by Liu and Albright[5] at $\sim 0.06 \times 10^{-39}$ cm^2. The $Y_1^*(1385)$ decay rate into $\Sigma^\pm \pi^\mp$ is 10%, thus this exposure will yield approximately 20 events in this topology. For the $\Lambda\pi^o$ decays, the events are 0 C but the background is not overwhelming, mostly coming from $\Sigma^o\mu^+$. The transverse momentum unbalance will separate $\Sigma^o\mu^+$ from

$\Lambda^o \mu^+$ events. In about 1/4 of the cases one of the two γ rays from the π^o will convert in the hydrogen to an electron pair. The events then become 1 C and can be kinematically analyzed. This gives about 50 events of $\Lambda\pi^o$ with 1 γ ray converting.

If other Y^*'s are produced with comparable cross sections, then we would expect several hundred $Y^*(1405)$ and $Y^*(1520)$ decaying into $K^- p$ and $\Sigma^{\pm}\pi^{\mp}$.

3. Nonstrange Isobar Formation: $\bar{\nu}_\mu + p \rightarrow \mu^+ + N^{*o}$

Calculations[6] indicate a relatively flat cross section of $\sim 2 \times 10^{-39}\,\mathrm{cm}^2$ although the CERN experiment on N^* production by ν yielded a cross section twice as large as this.[7] For $\bar{\nu}_\mu + p \rightarrow \mu^+ + N^{*o}(1236)$, 1/3 of the decays are $p\pi^-$, so we expect 6000 events.

It would be interesting at a later time to follow up with an antineutrino exposure in deuterium to measure $\bar{\nu} + n \rightarrow \mu^+ + N^{*-}$ as the $\Delta I = 1$ rule predicts this cross section to be three times larger than the cross section for $\bar{\nu} + p \rightarrow \mu^+ + N^{*o}$ discussed above. The strange particle production by $\bar{\nu}$ on neutrons via the reaction $\bar{\nu}n \rightarrow \mu^+\Sigma^-$ could also be used to test the $\Delta I = 1/2$ rule by comparison with $\bar{\nu}p \rightarrow \mu^+\Sigma^o$.

4. Search for $\Delta S = 2$ transitions: $\bar{\nu}_\mu + p \rightarrow \begin{cases} \mu^+ + \Xi^o \\ \mu^+ + \Sigma^+ + K^- \end{cases}$

The $\mu^+ \Sigma^+ K^-$ is 3 C fit and is easily identified. The $\Xi^o \rightarrow \Lambda^o \pi^o$ decay is a 0 C fit with two solutions, but the $\Lambda^o \pi^o$ mass can be plotted for both solutions. Also, some fraction of the time the Λ^o will not point to the vertex but close to it. If we use a Ξ^o momentum distribution similar to the neutron momentum distribution from elastic events, we find 80% of the Λ's will not point to the production vertex. Thus, the detection of Ξ^o is kinematically possible.

5. Polarization of Recoil Baryons

Polarization measurements give additional information about the form factors. In the high energy limit, the muon polarization is either proportional to the muon mass or inversely proportional to the neutrino energy; on the other hand, the baryon polarization is independent of energy. Thus a measurement of baryon polarization is superior to a measurement of the muon polarization at high energy. [1]

5(a). Orthogonal Polarization

The component of baryon polarization orthogonal to the production plane, P_Z, is of prime interest. This polarization is due to either the presence of the "wrong G-parity" second class currents ($f_A \neq 0$) or to complex form factors (or both). Thus, finite orthogonal polarization implies time reversal violation. Furthermore if CVC holds good, the only terms contributing to the orthogonal polarization are due to second class currents.

Fig. 3(a) shows the orthogonal polarization as a function of q^2 under the following assumptions:

1. CVC
2. Second class currents f_A has the same magnitude as g_A.
3. f_A is pure imaginary (as implied by $|\Delta I| = 1$).

In case there are no second class currents but g_V and f_V are out of phase by $\pi/2$ (CVC broken), then the expected orthogonal polarization is the same as shown in Fig. 3(a). Fig. 3(b) shows the product of polarization and $d\sigma/dq^2$. It should be noted that the orthogonal-polarization formalism mentioned here holds for all two-body reactions considered in this proposal.

5(b). Perpendicular Polarization

At high energy the component of baryon polarization in the production plane perpendicular to the baryon direction of motion is proportional to the real part of $(g_E^* g_A - \frac{q^2}{2M} g_V^* f_A)$. If $|\Delta I| = 1$, f_A is pure imaginary and only the $g_E^* g_A$ term survives. If we further set $f_M = 0$, then $P_X \sim 1$ for all q^2. If $f_M = f_Q$ (CVC), P_X drops to ~ 0.4 at $q^2 \sim 0.5$.

The number of events useful for the polarization measurements are

$\bar{\nu} + p \to \mu^+ + n;\ n + p \to n + p$	5000 events
$\bar{\nu} + p \to \mu^+ + \Lambda^o (\Sigma^o);\ \Lambda^o \to \pi^- + p$	1400 events

A study[8] of np scattering shows that the average analyzing power of np scattering in this experiment is ~ 0.25. Although the Λ yield is ~ 4 times smaller than that of elastic scattering, the Λ decay is a better analyzer of the Λ polarization. Using the above two reactions we expect to measure P_Z and P_X with a precision of $\sim 0.05 - 0.1$.

6. Total Cross Section

This is a very exciting topic as the ν total cross section seems to increase linearly with energy as $\sigma = (0.8 \pm 0.2)E_\nu \; 10^{-38} \text{cm}^2$ up to $E_\nu \sim 10$ GeV. There is no information on the $\bar{\nu}$ total cross section. The idea of scaling will be tested. About 1/3 of the energy deposited in the hadron system will not be detected in the hydrogen bubble chamber (based on experience with the CERN propane bubble chamber). To do a definitive job will probably require ancillary equipment to detect the neutral hadronic components, and to identify the muon. However, one must remember that the only information available at present comes from a small heavy liquid bubble chamber. One will be able to do an experiment of similar quality using the hydrogen chamber alone, and so get the first evidence on how the total cross section varies up to ~ 100 GeV.

A followup in a second generation experiment with a hydrogen target in a neon filling and auxilliary detectors will be needed. Such an experiment could best be designed based on the results of an experiment in pure hydrogen. If the cross section really continues to increase linearly with energy, there will be a very large number of inelastic events ($\sim$ 100 K) which will provide a rich field of study. The intermediate boson may show up in a form-factor-dampening of the linear rise of the cross section. A 10 GeV W would decrease the total cross section by 33% from the linear prediction $\sigma = (0.8)\, E_\nu$ at $E_\nu = 80$ GeV.

7. $\bar{\nu}_\mu + p \rightarrow \mu^+ + p + \pi^-$, etc.

Cases in which a specific three body final state is singled out can be studied. Theoretical expectations[9] lead to various tests concerning the dependence of the cross section on the angle between the lepton plane and the hadron plane. These events can be used to test locality.

The above events can also be used for the Adler test of PCAC comparing the $\bar{\nu}$ reaction $\bar{\nu} + p \rightarrow \mu^+ + \beta$ with the pion reaction $\pi^- + p \rightarrow \beta$ in the limit $\cos\theta_{\mu_\nu} = 1$.

8. Miscellaneous

The W can be produced in the reaction $\bar{\nu} + p \rightarrow \mu^+ + W^- + p$. The μ^+ will have low momentum (the μ^+ distribution peaks at several hundred MeV/c). The proton will also have low momentum and should be easily recognized as a proton. The W will carry off the bulk of the energy and decay into hadrons such as $\pi^- \pi^o$, $K^- K^o$ etc. or leptons $\mu^- + \bar{\nu}_\mu$ and $e^- + \bar{\nu}_e$. We would expect 40 events* for $M_W = 7$ GeV.

REMARKS

We think the experiment outlined here will be one very important first step in the NAL neutrino program in the 15' bubble chamber. We would like to see the program implemented at the earliest possible data and we wish to contribute significant help at NAL to get the program started. From conversations with several NAL persons, we see (1) focusing devices, and (2) flux measurement and monitoring, as two major areas we could usefully contribute to.

We are willing to take complete responsibility for the flux measurement and monitoring for both ν and $\bar{\nu}$ operation of the facility. The planning and execution of this work would go on in close collaboration with all relevant NAL people as the flux determinations interact with the accelerator, the focusing devices, the shield, and the bubble chamber. We would anticipate spending large blocks of time at NAL and in fact are prepared to commit two full-time people in residence at NAL to work on the problem of the flux measurement and monitoring in preparation for the run. They would be available to contribute to other aspects of the program as necessary.

---

*The high energy end of the $\bar{\nu}$ spectrum could easily be off by a large factor which of course affects the number by a similar factor.

There will be fourteen physicists from the Argonne group and eight from the Carnegie-Mellon group involved in this experiment. In addition, it is expected that several graduate students will participate. The numbers of technicians and programmers, and the scanning, measuring and computing facilities at the two laboratories are sufficient to provide an intensive analysis effort once the film is obtained.

Many of the subjects discussed in this note can probably be studied using the deuteron as a proton-containing target. However, there are a number of reasons for believing that a hydrogen $\bar{\nu}$ run should precede a deuterium $\bar{\nu}$ run. Among these are the earlier time at which the chamber can be expected to operate with a hydrogen filling, the increased discrimination against various kinds of background which may be achieved (as well as the enhanced ability to identify very unusual or unexpected kinds of events), the complications of using secondary n-d scattering for elastic event identification, and the significantly decreased power of kinematic fitting which will result from the $\sim$ 100 MeV/c of (invisible) spectator transverse momentum. While most of the problems will be manageable in a deuterium exposure aimed at using a neutron target, the results from a prior hydrogen exposure will be essential in sorting out many of the details, including Glauber corrections. The hydrogen provides an unambiguous measurement of polarization.

In conclusion we feel this modest proposal will provide very exciting physics results and is well matched to the difficulties associated with bringing on a new bubble chamber in a new beam. Many of us will have experience from the 12' HBC work at the ZGS, which will aid us in contributing to the NAL bubble chamber neutrino facilities.

REFERENCES

1. A. Pais, Proc. of the Intl. Conf. on Expectations for Particle Reactions at the New Accelerators, April 1970.
2. F. A. Nezrick, Private Communication.
3. M. Derrick and R. Kraemer, NAL Summer Study, Vol. 1 (1968).
4. N. Cabibbo and F. Chilton, Phys. Rev. 137B, 1628 (1965).
5. C. H. Albright and L. S. Liu, Phys. Rev. 140B, 748 (1965).
6. S. L. Adler, Ann. Phys. 50, 189 (1968); Ph. Salin, Nuovo Cimento 48, 506 (1967); G. Altarelli et al., Nuovo Cimento 37, 1817 (1965).
7. I. Budagov et al., Phys. Lett. 29B, 524 (1969).
8. A. Ray, Thesis, Carnegie-Mellon University (1968).
9. A. Pais and S. B. Treiman, Phys. Rev. D1, 907 (1970).

APPENDIX

Notation

Following the notation of Pais, the hadronic current J_λ is written

$$J_\lambda = \frac{iG}{\sqrt{2}} \left[\gamma_\lambda (g_V + g_A \gamma_5) + iP_\lambda (f_V + f_A \gamma_5) - iq_\lambda (h_V + h_A \gamma_5) \right] \qquad (1)$$

where P is the total four momentum of the initial state, q is the four momentum transfer, and the six form factors $g_V \, . \, . \, h_A$ are generally functions of q^2. We also define

$$g_E = g_V - 2M f_V \left(1 + \frac{q^2}{4M^2}\right)$$

$$g_V = \left[f_Q + (\mu_p - \mu_n) f_M \right] \left[1 + \frac{q^2}{MW^2} \right]^{-1} \cos\theta_c$$

under CVC

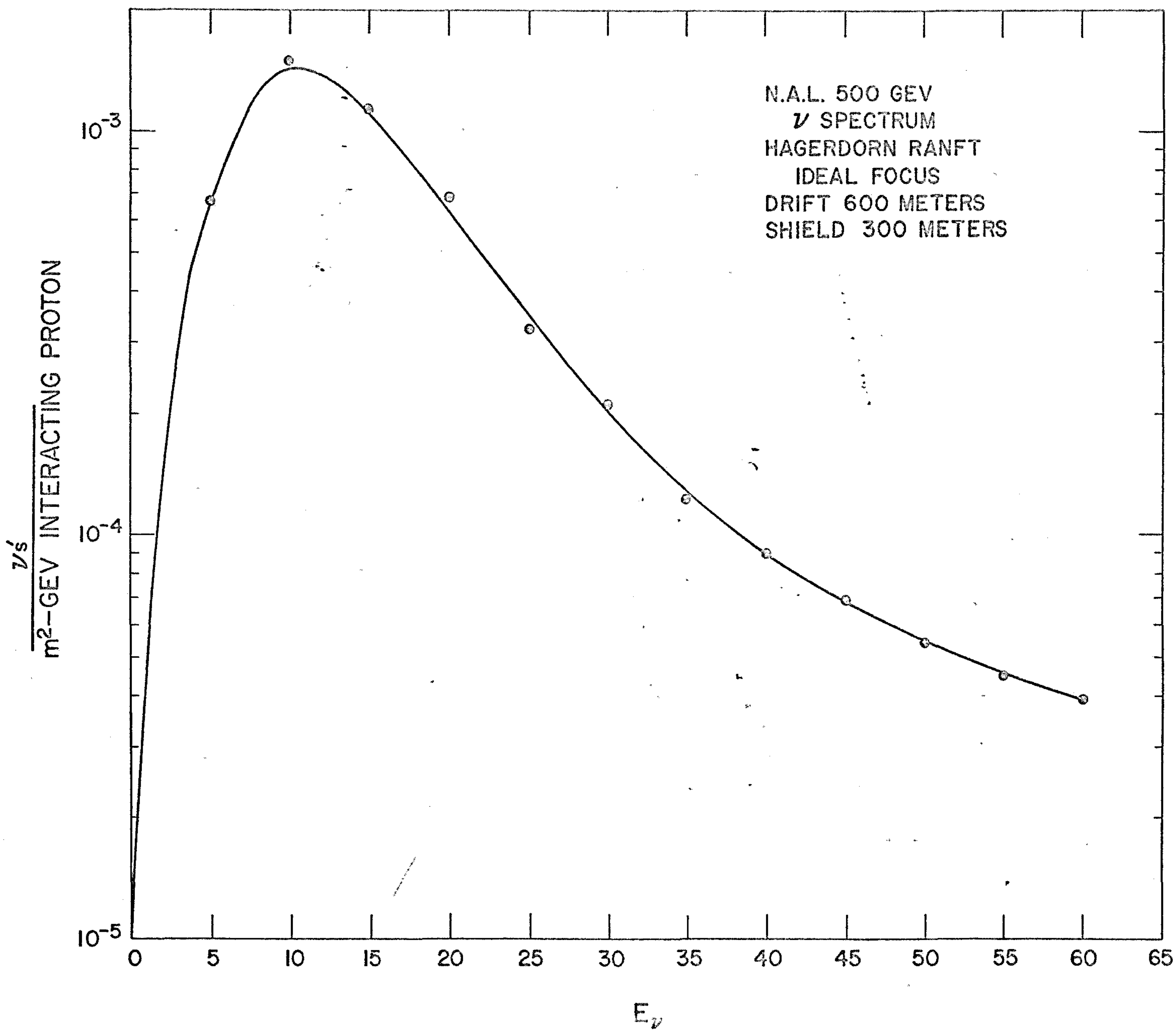
$$f_V = \left[\frac{1}{2M} (\mu_p - \mu_n) f_M \right] \left[1 + \frac{q^2}{MW^2} \right]^{-1} \cos\theta_c$$

where f_Q', f_M' are isovector electric and magnetic form factors respectively, and μ_p and μ_n are the magnetic moments of proton and neutron. These form factors are normalized to:

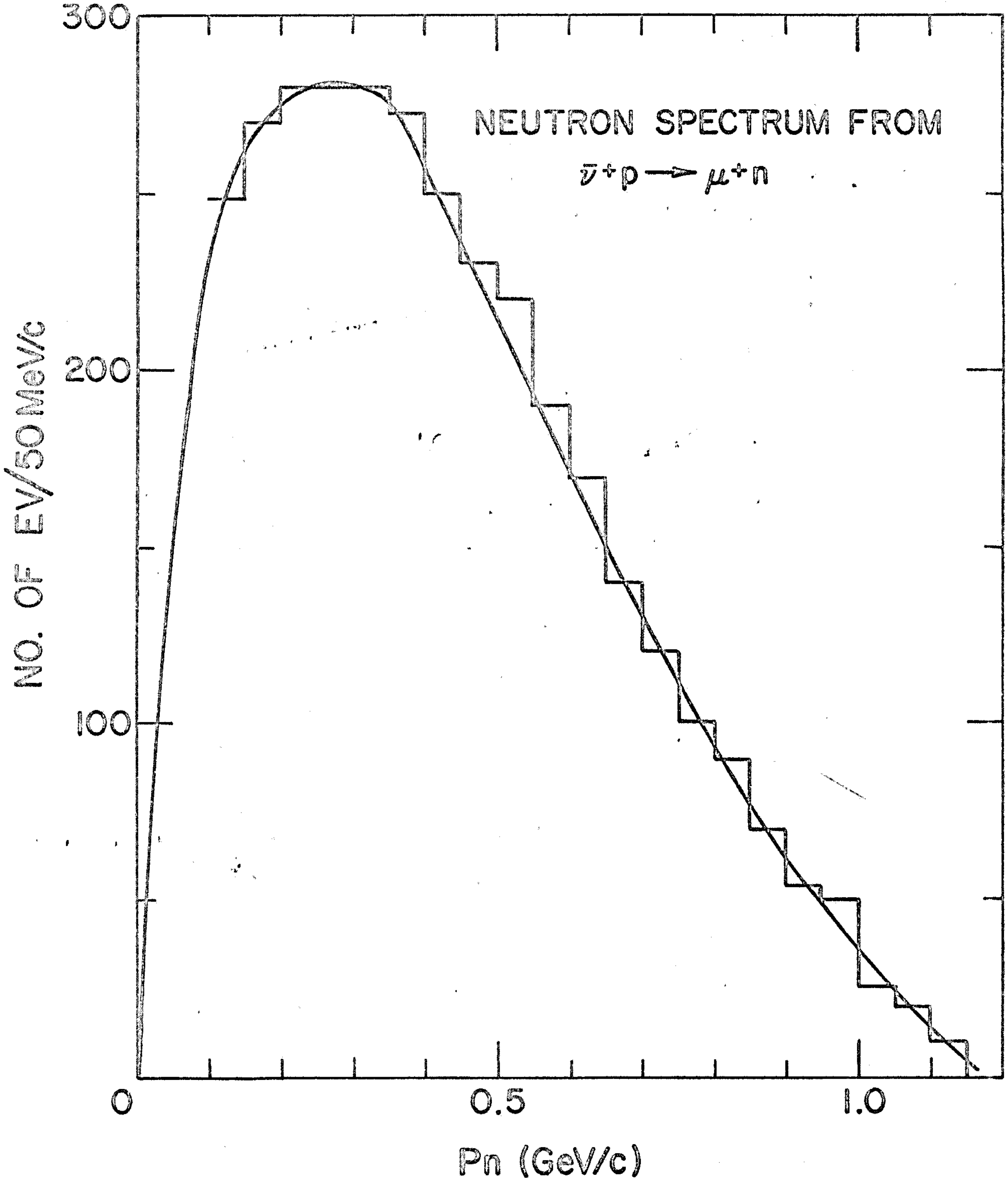
$$f_Q(0) = f_M(0) = 1$$

$$g_E(0) = \cos\theta_c$$

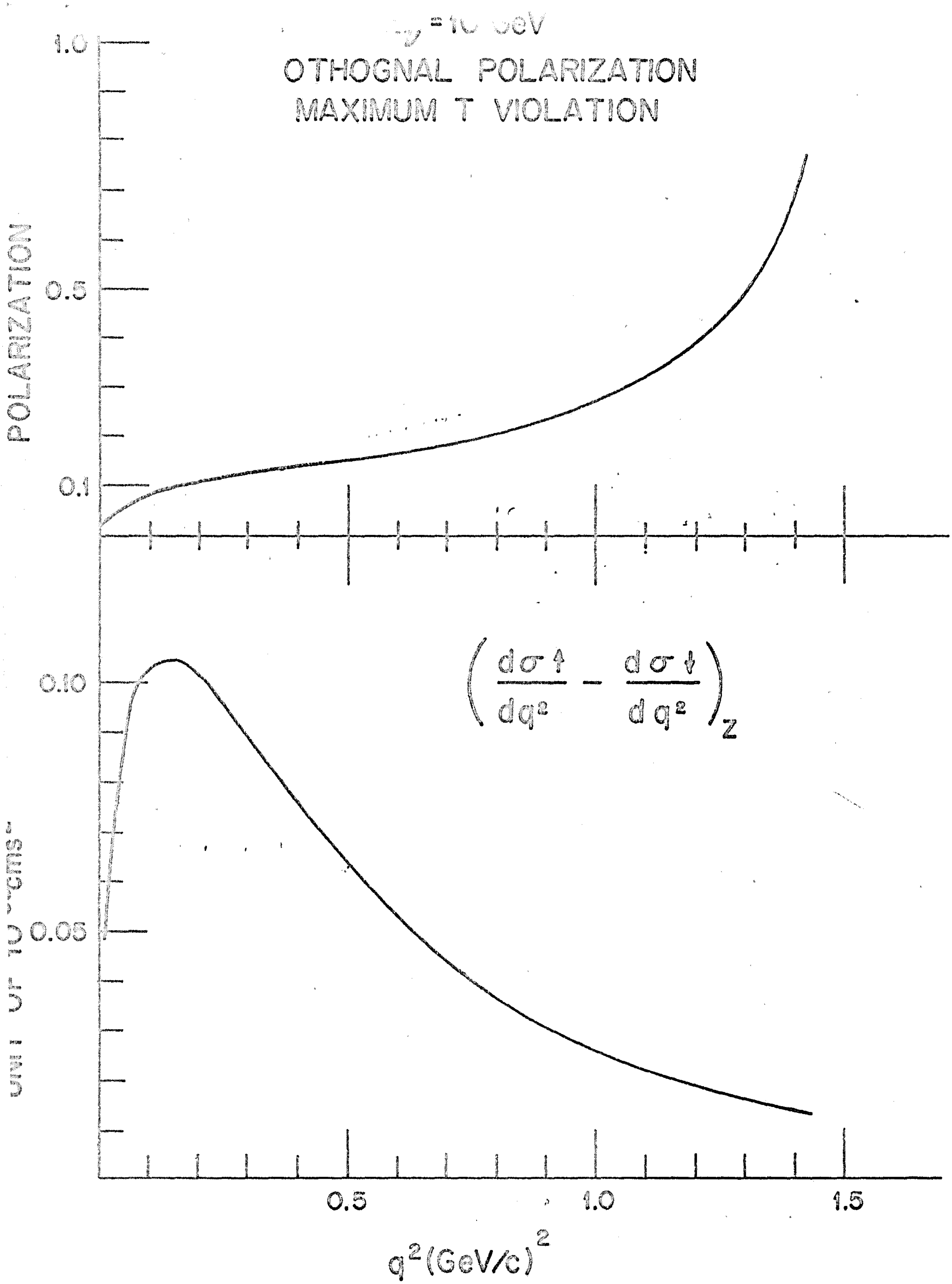
$$g_A(0) = -1.2 \cos\theta_c \quad .$$



N.A.L. 500 GEV
ν SPECTRUM
HAGERDORN RANFT
IDEAL FOCUS
DRIFT 600 METERS
SHIELD 300 METERS
ν's / m²-GEV INTERACTING PROTON
10⁻³
10⁻⁴
10⁻⁵
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Eν



NEUTRON SPECTRUM FROM
$\bar{\nu}+p \longrightarrow \mu^{+}n$
300
200
100
0
0.5
1.0
NO. OF EV/50 MeV/c
Pn (GeV/c)



OTHOGNAL POLARIZATION
MAXIMUM T VIOLATION
POLARIZATION
1.0
0.5
0.1
0.10
0.05
$\left(\frac{d\sigma\uparrow}{dq^2} - \frac{d\sigma\downarrow}{dq^2}\right)_Z$
0.5
1.0
1.5
$q^2(GeV/c)^2$

NAL PROPOSAL No. 31

Correspondent: M. Derrick
Argonne National Lab
9700 So. Cass Ave.
Argonne, Ill. 60439

FTS/Commercial 312-739-4075

Proposal to Investigate $\bar{\nu}_{\mu}$ Interactions in Hydrogen at NAL

Bubble Chamber Groups from Argonne National Laboratory

and

Carnegie-Mellon University

John Campbell
Gordon Charlton
Yanglai Cho
Alan Cooper
Malcolm Derrick
Roderick Engelmann
Tom Fields
Tom Groves
Lloyd Hyman
Brian Musgrave
Gale Pewitt
Lou Voyvodic
Tom Wangler
John Wong
Haru Yuta

July 16, 1971

PROPOSAL TO INVESTIGATE $\bar{\nu}_\mu$ INTERACTIONS IN HYDROGEN AT NAL

Bubble Chamber Groups from Argonne National Laboratory

and

Carnegie-Mellon University

Spokesman: M. Derrick

July 16, 1971

Introduction

We propose to investigate high energy $\bar{\nu}_\mu$ interactions on H_2 in the 15' bubble chamber at NAL. The purpose of the experiment is to do a study of two-body and quasi-two-body reactions, to measure the total $\bar{\nu}_\mu p$ cross section and to study gross features of the inelastic channels. An exposure of 10^{19} interacting protons on the horn target would be reasonable, i.e., 10^6 pictures at 10^{13} protons/pulse.

As a first stage of this experiment, we propose to obtain 2×10^5 pictures. These will be analyzed quickly to verify the rates and the backgrounds for various channels we intend to study. This initial run can also be used to investigate the utility of an external muon detector.

We have throughout this paper used the notation given by Pais[1]. This notation is reviewed in the Appendix.

A. Beam and Detector

For purposes of estimating rates, we assumed the bubble chamber has a fiducial volume containing 1.0 ton of hydrogen. The $\bar{\nu}$ flux estimates shown in Fig. 1 were made by F. Nezrick[2] and co-workers at NAL.

The yields quoted in this proposal are based on the full exposure of 10^{19} interacting protons on the horn target.

B. Two-Body and Quasi-Two-Body Reactions

These reactions which are the inverse β-decays of baryons can be used to test the formal structure of the weak currents. For example, the reaction $\bar{\nu}p \to \Lambda\mu^+$ will extend the results on Λ-β decay to higher momentum transfer and the study of N^* production and Y^* production (which may be small) is analogous to the study of Ω^--β decay in terms of the SU(3) scheme.

These reactions also check the weak interaction selection rules such as $\Delta I = 1$, $\Delta I = 1/2$, etc. These selection rules which describe decay reactions are not fully tested. For example, the $\Delta I = 2$ transition in the $\Delta S = 0$ reactions cannot be tested in decays because no such final states are available.

Events belonging to this category are kinematically over-constrained and we do not anticipate any difficulty with the selection of events. Some of the topics that can be studied are discussed in detail below.

1. Elastic Scattering: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$

The elastic cross section is expected to be flat as a function of antineutrino energy with $\sigma \approx 6 \times 10^{-39}\ \mathrm{cm}^2$. The exposure will give 6,000 elastic interactions; however, it is likely that only those events can be used in which the neutron scatters in the chamber to give a visible recoil. Fig. 2 illustrates the expected neutron spectrum. This spectrum was found by using

$$f_Q = f_M = \frac{1}{\left[1 + \frac{q^2}{(0.84)^2}\right]^2} \quad , \quad g_A = \frac{g_A(0)}{\left[1 + \frac{q^2}{(1.0)^2}\right]^2}$$

with $f_A = h_V = h_A = 0$.

Using an average path length of 1.5 meters, we will have a neutron detection efficiency of $\sim 25\%$. Thus, this exposure will yield 1500 useful events. Kinematic studies have shown that these 3C events are well separated from the background[3]. The cross section at $q^2 = 0$ is given by

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

and so is independent of energy. The number of events at $q^2 = 0$ is a measure of the $\bar{\nu}$ flux and can be used in turn to measure other cross sections. Alternatively, if the flux is measured independently, one can test the above relation, which is a general result of weak interaction theory as presently formulated.

2. Hyperon Production: $\bar{\nu}_\mu + p \rightarrow \begin{matrix} \mu^+ + \Lambda^o & \text{(a)} \\ \mu^+ + \Sigma^o & \text{(b)} \end{matrix}$

Cabibbo and Chilton[4] have calculated various hyperon cross sections based on the SU(3) model. Using a form factor mass of $\sim$ 1.0 GeV, the $\mu^+ + \Lambda$ cross section is $\sim 0.5 \times 10^{-39}$ cm^2. The $\Sigma^o + \mu^+$ cross section is of the same order in this model. From reaction (a) we would expect $\sim$ 360 events with a visible Λ. A measurement of the cross sections would test the Cabibbo theory in a new range of momentum transfer. This can range up to $\sim$ 20 (GeV/c)^2 although it is expected the cross section would fall as e^{-4q2} so one expects very few events at large q^2. At present there is no experimental information available on these channels.

3. Non-strange Isobar Formation: $\bar{\nu}_\mu + p \rightarrow \mu^+ + \Delta^o$

Several authors have calculated the Δ production cross sections[5], and the CERN experiment on Δ^{++} production by ν yield a cross section section $\sim 1.2 \times 10^{-38}$ cm^2.[6] The $\Delta I = 1$ rule predicts that the Δ^o production by the $\bar{\nu}_\mu$ p reaction is 1/3 of the Δ^{++} production by the ν_μ p reaction. Of the Δ^o productions, 1/3 of the decays are in the π^-p mode, so we expect to observe 1200 events.

It would be interesting to compare the Δ^o productions from this exposure and the Δ^{++} productions from the ν_μ p exposure to test the $\Delta I = 1$ rule. If there is the $\Delta I = 2$ transition, we can write the isobar production amplitudes:

$$A(\nu_\mu p \rightarrow \Delta^{++}\mu^-) = a_1 - \sqrt{1/5}\, a_2 \quad ,$$

$$A(\bar{\nu}_\mu p \rightarrow \Delta^{o}\mu^+) = \sqrt{1/3}\, a_1 - \sqrt{3/5}\, a_2 \quad ,$$

where a_1 and a_2 are the amplitudes of $\Delta I = 1$ and $\Delta I = 2$ transitions, respectively.

4. Polarization of Recoil Baryons

Polarization measurements give additional information about the form factors. In the high energy limit, the muon polarization is either proportional to the muon mass or inversely proportional to the neutrino energy; on the other hand, the baryon polarization is independent of energy. Thus a measurement of baryon polarization is superior to a measurement of the muon polarization at high energy.[(1)]

(a) Orthogonal Polarization

The component of baryon polarization P_Z, orthogonal to the production plane, is of prime interest. This polarization is due to either the presence of the "wrong G-parity" (second class currents) ($f_A \neq 0$) or to complex form factors (or both). Thus, finite orthogonal polarization implies time reversal violation. Furthermore, if CVC holds good, the only terms contributing to the orthogonal polarization are due to second class currents.

Fig. 3(a) shows the orthogonal polarization as a function of q^2 under the following assumptions:

1. CVC

2. Second class currents f_A has the same magnitude as g_A.

3. f_A is pure imaginary (as implied by $|\Delta I| = 1$).

In case there are no second class currents but g_V and f_V are out of phase by $\pi/2$ (CVC broken), then the expected orthogonal polarization is the same as shown in Fig. 3(a). Fig. 3(b) shows the product of polarization and $d\sigma/dq^2$. It should be noted that the orthogonal-polarization formalism mentioned here holds for all two-body reactions considered in this proposal.

(b) Perpendicular Polarization

At high energy the component of baryon polarization in the production plane perpendicular to the baryon direction of motion is proportional to the real part of $(g_E^* g_A - \frac{q^2}{2M} g_V^* f_A)$. If $|\Delta I| = 1$, f_A is pure imaginary and only the $g_E^* g_A$ term survives. If we further set $f_M = 0$, then $P_X \sim 1$ for all q^2. If $f_M = f_Q$(CVC), P_X drops to ~ 0.4 at $q^2 \sim 0.5$.

The number of events useful for the polarization measurements are

$\bar{\nu} + p \rightarrow \mu^+ + n;\ n + p \rightarrow n + p$ 1200 events

$\bar{\nu} + p \rightarrow \mu^+ + \Lambda^o(\Sigma^o);\ \Lambda^o \rightarrow \pi^- + p$ 600 events .

The average analyzing power of np scattering in this experiment will be ~ 0.25.[7] Although the Λ yield is ~ 2 times smaller than that of elastic scattering, the Λ decay is a better analyzer of the Λ polarization. Using the above two reactions we expect to measure P_Z and P_X with a precision of $\sim 0.1 - 0.2$.

(c) Polarization of Δ

The polarization of Δ will be used to study the time-reversal violation. Since the magnitude of symmetry breaking is expected to be proportional to the mass difference between the initial and final hadrons, the study of this reaction was emphasized by Primakoff and Oakes.[8] Furthermore, this reaction is the transition between two different multiplets, it is also expected larger symmetry breaking contribution.[8] Aside from the final state interactions, the effect of symmetry breaking will manifest itself in the decay distribution of Δ.

C. Total Cross Section and Inelastic Processes

Two important questions which we hope to settle during the first stage of the experiment are:

a. Comparison of $\sigma(\bar{\nu} p)$ and $\sigma(\nu p)$

The predicted ratio of two cross section depends strongly to various theoretical models. While the diffractive scattering model predicts $\sigma(\nu p) = \sigma(\bar{\nu} p)$, the model by Drell, Levy and Yan predicts $\sigma(\nu p) = 3\sigma(\bar{\nu} p)$.

b. Linear Rise of the Total Cross Section

The existing data is consistent with the ν total cross section increasing as $\sigma = 0.8\ E \times 10^{-38}\ cm^2$ up to $E_\nu \sim 10$ GeV. There is no information on the $\bar{\nu}$ totaled cross section. Assuming this relation holds for $\bar{\nu}$, we expect $\sim 10^5$ interactions in our proposed experiment.

Given the $\bar{\nu}$ spectrum, we can clearly obtain a good estimate of $\sigma(\bar{\nu}p)$ from the number of observed interactions. The energy dependence of the total cross section can be crudely estimated from the total hadron energy measured in the chamber. (Based on experience with the CERN propane bubble chamber, $\sim 1/3$ of the energy deposited in the hadron system will not be detected in the hydrogen bubble chamber.) A more refined method of estimating the energy dependence of the total cross section based on the kinematically well-constrained events is discussed later.

To do a definitive job on the inelastic scattering will probably require ancillary equipment to detect the neutral hadronic components and to identify the muon.(9) Such an experiment could best be designed based on the results of an experiment such as the one proposed here.

c. Kinematically Well-Constrained Events

Most of the inelastic events will be final states of the type $\mu^+ Nn\pi$. We estimate that approximately 10^4 events will have a proton and charged pions only, i. e., these events will be of the 3-C variety. For these events, the energy of $\bar{\nu}$ can be determined, and they are particularly useful in studying the $\sigma_{tot}(E_\nu)$, the mulitplicity of the final states, and the details of the inelastic reactions such as ρ^o, A_1 production, etc.

Various theoretical models predict strikingly different muon energy distributions as shown in Fig. 4. These distributions were obtained by a Monte Carlo study of 1000 events at $E_\nu = 20$ GeV using the W_2 (R = 0 solution) from the SLAC e-p experiment and:

(A) $W_1/W_2 = (1+\frac{\nu^2}{q^2})$, $W_3 = 0$ (Diffractive Model)

(B) $W_1/W_2 = \frac{\omega\nu}{2M}$, $W_3/W_2 = \omega$, $\omega = \frac{2M\nu}{q^2}$ (Drell) .

It is clear from these figures that if we assign the fast positive track with $E > .7\, E_\nu$ as the muon, then we should be able to distinguish the models. The effects of a wrong assignment or ambiguities caused by fast positive tracks will be studied using, for example, a statistical model of the hadron vertex. Experimentally studying negative tracks which cannot be muons (except for small ν contamination) will pin down the problems associated with correctly identifying the μ^+.

D. <u>Search for New Phenomena</u>

Any neutrino exposure in a hydrogen bubble chamber represents a search in a completely new territory. Although many of the phenomena to be studied can be listed based on our present knowledge of the weak interaction, one must expect quite new phenomena to appear in the kind of experiment proposed here. Any such phenomena cannot be specifically listed since by definition they are unknown, but they may very well provide the most exciting results from such an experiment.

Remarks

We think the experiment outlined here will be one important first step in the NAL neutrino program in the 15' bubble chamber. We would like to see the program implemented at the earliest possible date.

There will be fourteen physicists from the Argonne group and eight from the Carnegie-Mellon group involved in this experiment. In addition, it is expected that several graduate students will participate. The numbers of technicians and programmers, and the scanning, measuring and computing facilities at the two laboratories are sufficient to provide an intensive analysis effort once the film is obtained.

We are willing to take responsibility for the determination of optical constants of the chamber. In addition, we can develop the geometrical reconstruction program. The planning and execution of this work would go on in close collaboration with all relevant NAL people. We believe that we can contribute to the development of the 15' bubble chamber program on these matters by utilizing our experience with the 12' bubble chamber.

In conclusion we feel this modest proposal will provide very exciting physics results and is well matched to the difficulties associated with bringing on a new bubble chamber in a new beam. Many of us will have experience from the 12' HBC work at the ZGS, which will aid us in contributing to the NAL bubble chamber neutrino facilities.

References

1. A. Pais, Proc. of the Intl. Conf. on Expectations for Particle Reactions at the New Accelerators, April 1970.

2. F. A. Nezrick, Private Communication.

3. M. Derrick and R. Kraemer, NAL Summer Study, Vol. 1 (1968).

4. N. Cabibbo and F. Chilton, Phys. Rev. 137B, 1628 (1965).

5. S. L. Adler, Ann. Phys. 50, 189 (1968); Ph. Salin, Nuovo Cimento 48, 506 (1967); G. Altarelli et al., Nuovo Cimento 37, 1817 (1965).

6. I. Budagov et al., Phys. Lett. 29B, 524 (1969).

7. A. Ray, Thesis, Carnegie-Mellon University (1968).

8. H. Primakoff, Talk given at Weak Interaction Workshop at ANL (1971); R. Oakes, Talk given at Weak Interaction Workshop at ANL (1971).

9. M. L. Stevenson, Presented at the 15' BC Workshop (March 1971).

APPENDIX

Notation

Following the notation of Pais, the hadronic current J_λ is written

$$J_\lambda = \frac{iG}{\sqrt{2}} \left[\gamma_\lambda (g_V + g_A \gamma_5) + iP_\lambda (f_V + f_A \gamma_5) - iq_\lambda (h_V + h_A \gamma_5)\right] \tag{1}$$

where P is the total four momentum of the initial state, q is the four momentum transfer, and the six form factors $g_V \, . \, . \, h_A$ are generally functions of q^2. We also define

$$g_E = g_V - 2M f_V \left(1 + \frac{q^2}{4M^2}\right)$$

$$g_V = \left[f_Q + (\mu_p - \mu_n) f_M \right] \left[1 + \frac{q^2}{MW^2} \right]^{-1} \cos\theta_c$$

under CVC

$$f_V = \left[\frac{1}{2M} (\mu_p - \mu_n) f_M \right] \left[1 + \frac{q^2}{MW^2} \right]^{-1} \cos\theta_c$$

where f_Q, f_M are isovector electric and magnetic form factors respectively, and μ_p and μ_n are the magnetic moments of proton and neutron. These form factors are normalized to:

$$f_Q(0) = f_M(0) = 1$$

$$g_E(0) = \cos\theta_c$$

$$g_A(0) = -1.2 \cos\theta_c \quad .$$

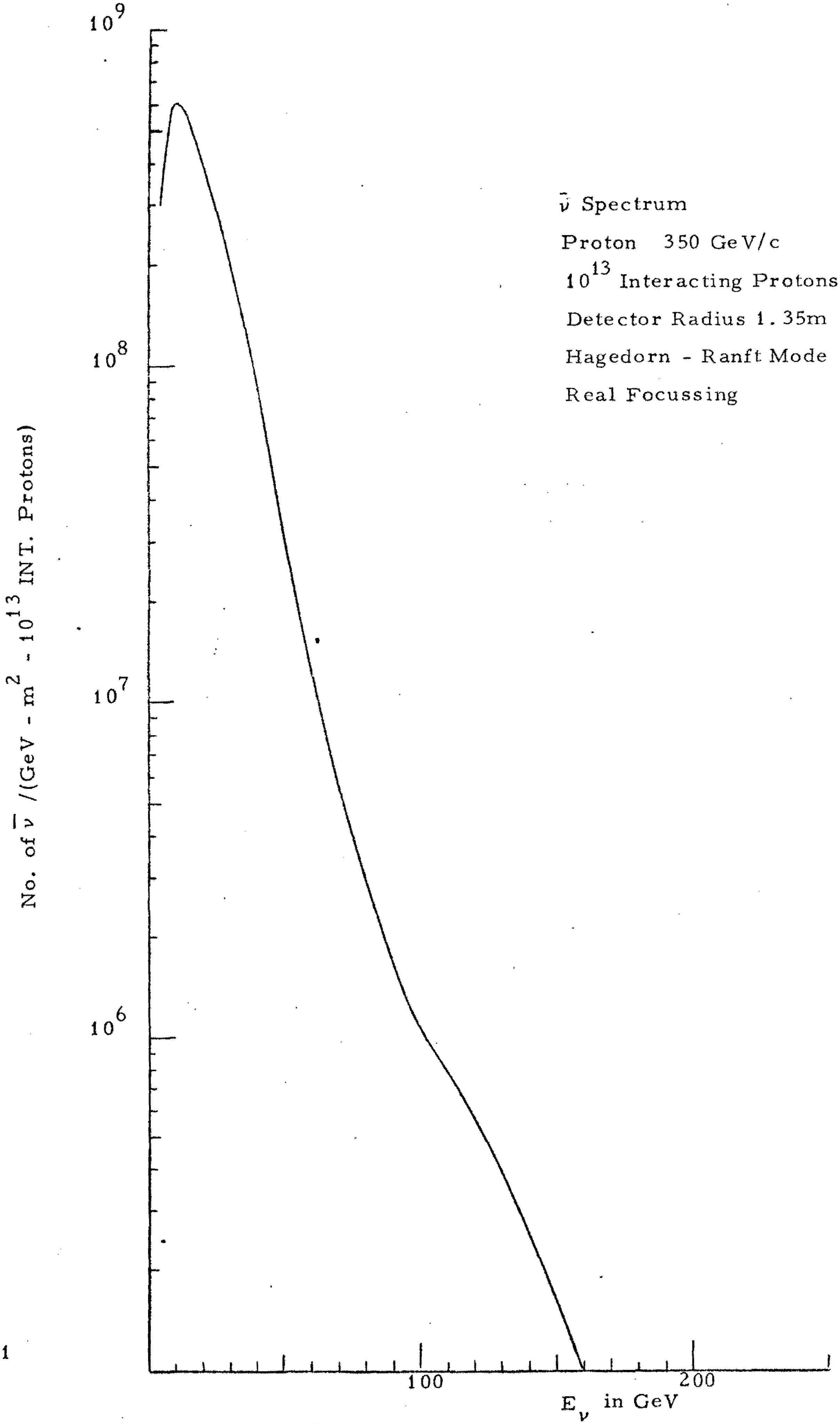

$\bar{\nu}$ Spectrum
Proton 350 GeV/c
10^{13} Interacting Protons
Detector Radius 1.35m
Hagedorn - Ranft Mode
Real Focussing
No. of $\bar{\nu}$ /(GeV - m^2 - 10^{13} INT. Protons)
10^9
10^8
10^7
10^6
100
200
E_ν in GeV

Figure 1

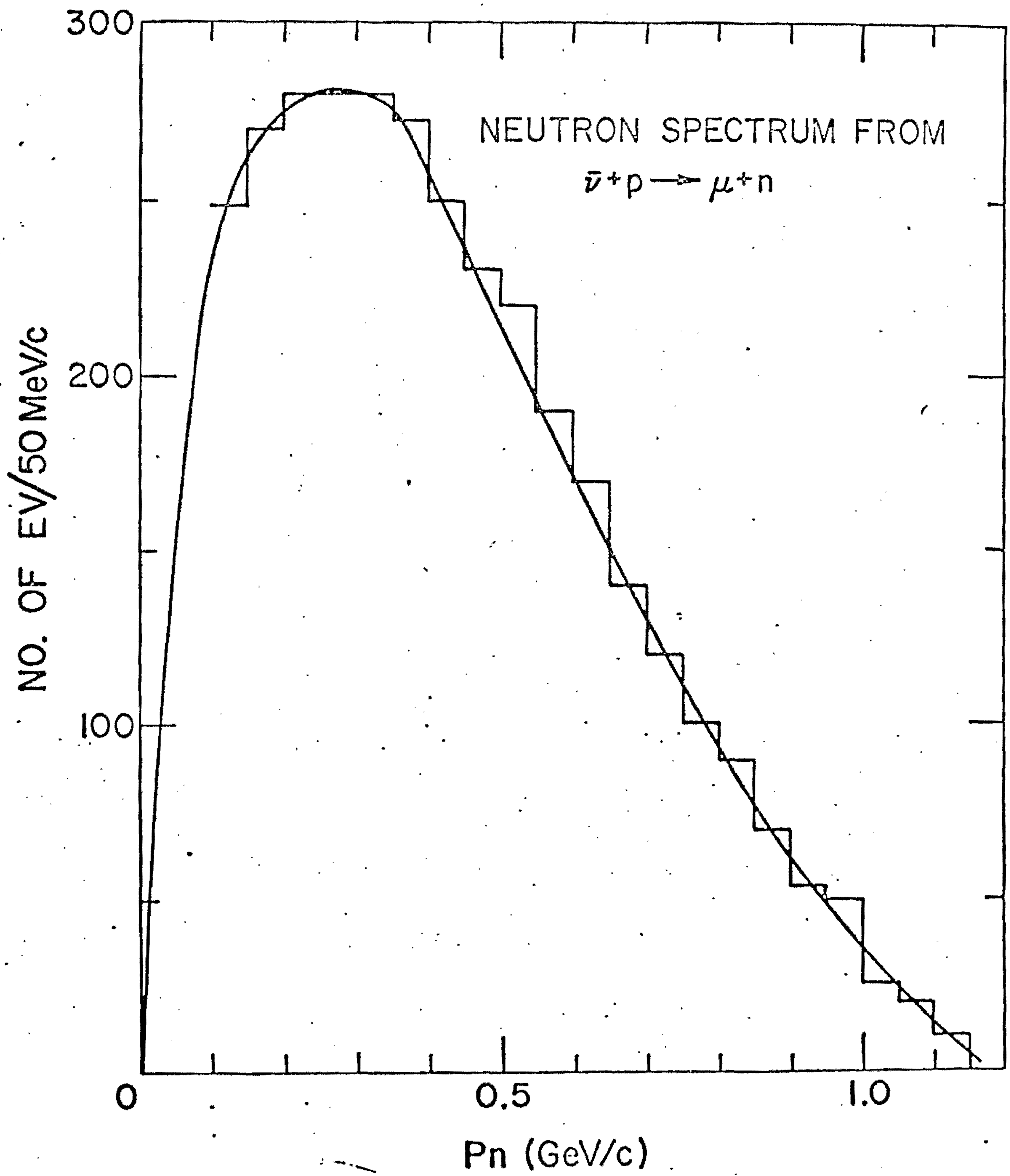

NEUTRON SPECTRUM FROM
$\bar{\nu}+p \rightarrow \mu^{+}n$
300
200
100
0
0.5
1.0
NO. OF EV/50 MeV/c
Pn (GeV/c)

Fig. 2

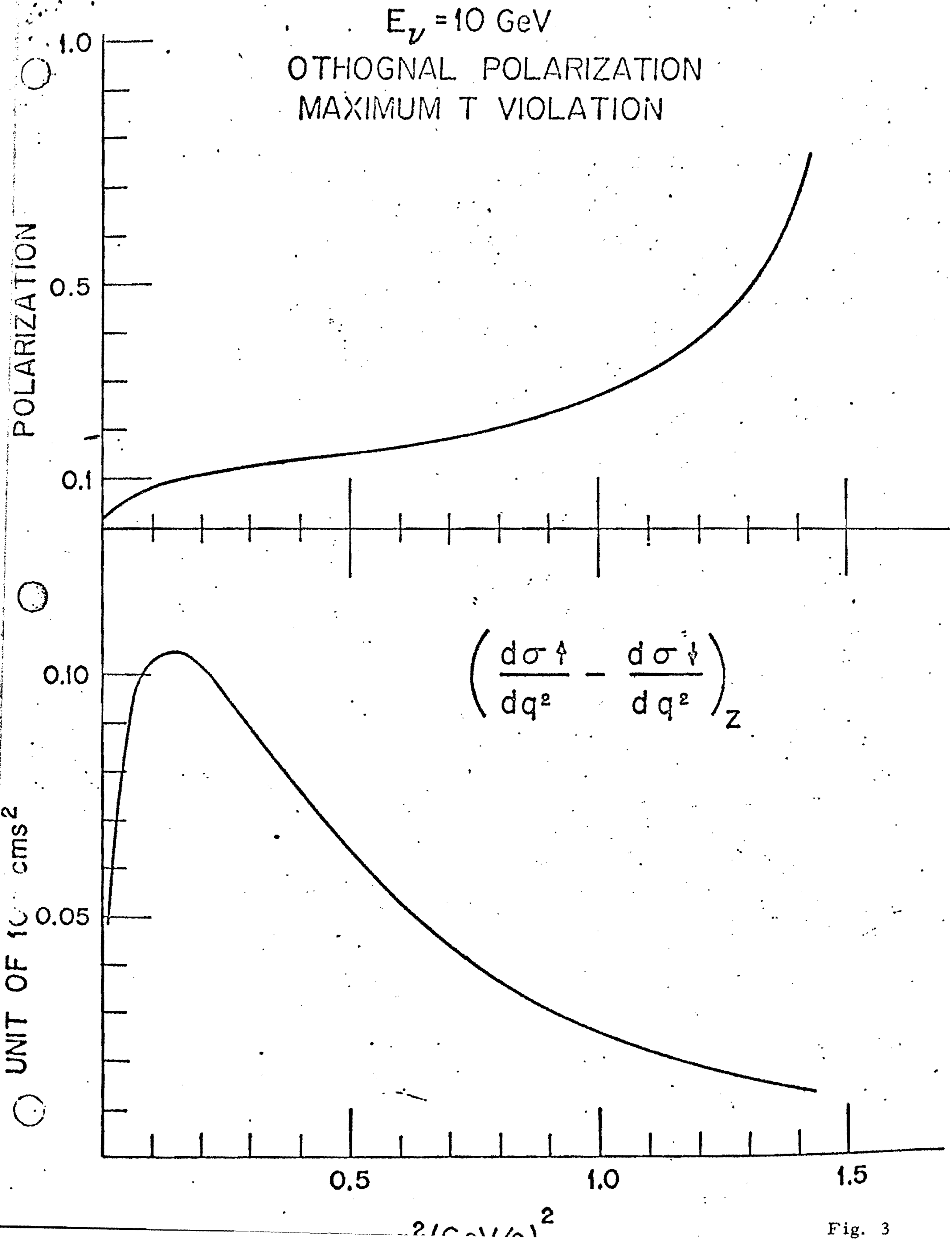

$E_\nu = 10$ GeV
OTHOGNAL POLARIZATION
MAXIMUM T VIOLATION
POLARIZATION
1.0
0.5
0.1
$\left(\frac{d\sigma\uparrow}{dq^2} - \frac{d\sigma\downarrow}{dq^2}\right)_Z$
0.10
0.05
UNIT OF 10 cms^2
0.5
1.0
1.5

Fig. 3

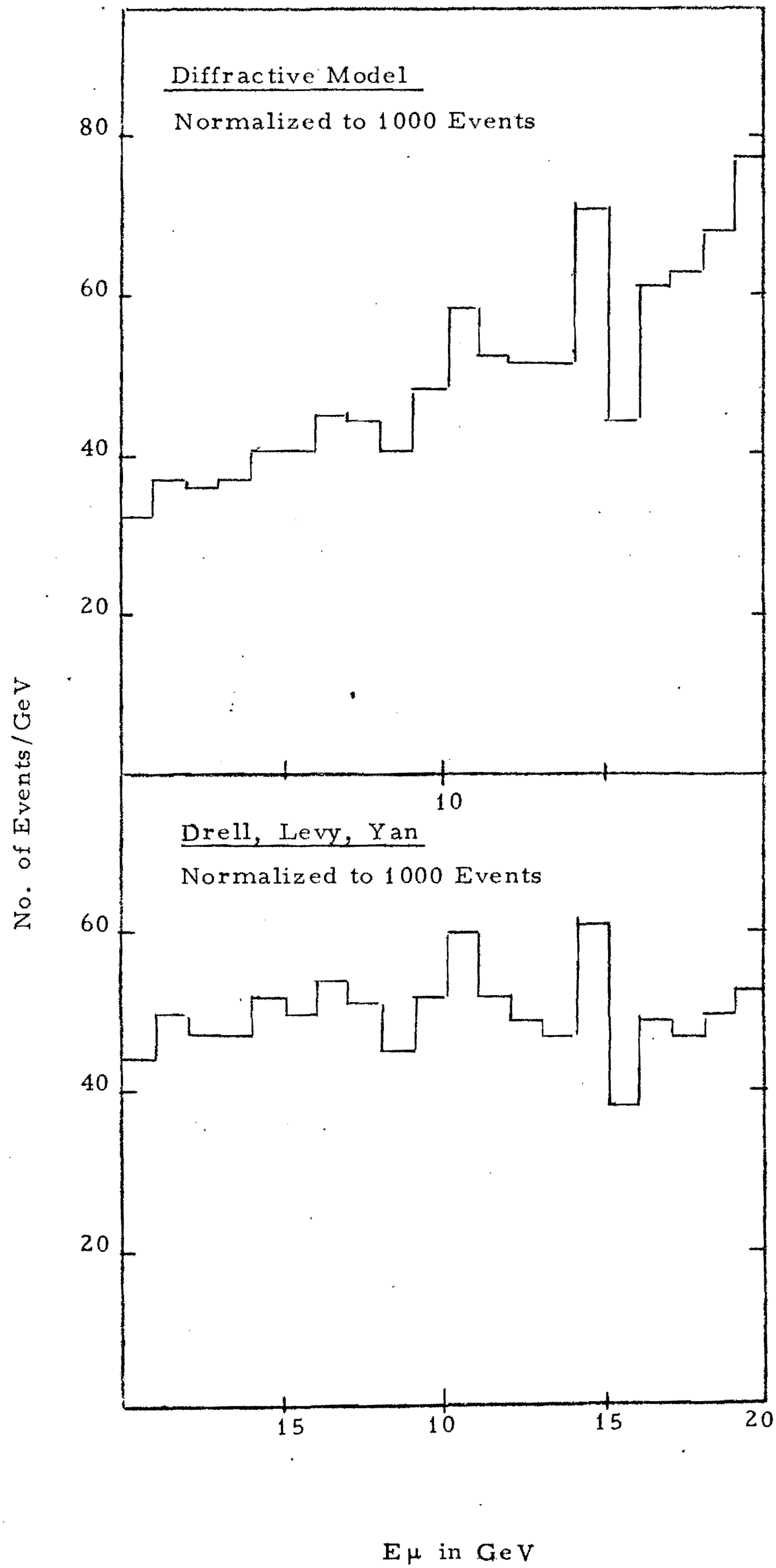

Diffractive Model
Normalized to 1000 Events
80
60
40
20
10
Drell, Levy, Yan
Normalized to 1000 Events
60
40
20
15
10
15
20
No. of Events/GeV
Eμ in GeV

Fig. 4