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A STUDY OF ANTINEUTRINO INTERACTIONS IN THE NAL 15-FT BUBBLE CHAMBER, FILLED WITH HYDROGEN AND NEON

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ABSTRACT

A study of antineutrino interactions in the 15-ft bubble chamber filled with a neon-hydrogen mixture is proposed. This mixture provides good detection efficiency for a neutral component and lepton identification. We request a total flux of $\sim 10^{19}$ interacting protons at the highest available energy for the proposed program.

Our program includes the measurement of total cross sections of antineutrino interactions, inclusive and exclusive reactions, which can be described by either charged or neutral currents, pure lepton interactions and searches for new particles and new phenomena.

As a first step, we ask for 200,000 photographs at the earliest possible date with a mixture of the order of 30 atomic percent neon in the bubble chamber.

We propose performing this experiment as a joint effort of groups from the USSR and USA: Institute of High Energy Physics, Serpukhov; Institute of Theoretical and Experimental Physics, Moscow; National Accelerator Laboratory, Batavia; and University of Michigan, Ann Arbor.

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I. INTRODUCTION

We propose the study of interactions of high energy antineutrinos in the 15-ft bubble chamber filled with a neon-hydrogen mixture.

The addition of neon to the hydrogen in the chamber is very useful for a search and survey experiment:

1) The target mass is increased and we have a target consisting of both neutrons and protons.
2) γ-rays can be detected with high efficiency.
3) Detection of neutrons is enhanced over pure hydrogen.
4) Positive muon and electron identification are much higher than in hydrogen.

We emphasize in this proposal the following problems: lepton interactions, dependence of $\bar{\nu}$ total cross sections on energy, deep inelastic processes, weak semi-leptonic currents (especially with strange particle production) and searches for new particles and processes. To attack some of these problems a Ne-H_2 mixture is uniquely necessary and for others it will give data complementary to other neutrino experiments. We estimate that 15-30 atomic percent of neon is a desirable range. We may wish to revise this figure for some parts of the exposure.

For the present proposal we have used 30 atomic percent of neon for quantitative calculations. For the experiment we request a run corresponding to 10^{19} interacting protons at the highest available energy. As a first step towards this goal we request an initial exposure of 200,000 pictures at the highest proton intensity available. If we have only 10^{12}

protons/pulse we would obtain 3,000 events for a 350 GeV exposure and 1,500 events for a 200 GeV exposure of 200,000 pictures. This calculation assumes a conservative 11 m^3 fiducial volume (R = 1.35 m, L = 2 m) which is considerably smaller than the 20 m^3 usually considered. Event rates for both fiducial volumes are given in Table II. The antineutrino flux assumed in this proposal and presented on Fig. 1 is based on the standard beam layout and the Hagedorn-Ranft production model.

II. CHOICE OF A NEON-HYDROGEN MIXTURE

The choice of a particular mixture of Ne-H_2 involves several factors. We need enough neon to have high stopping power and high efficiency for γ-rays and neutrons (see Figs. 2a and 2b). In this sense the more neon we have the better results we get. On the other hand too dense a mixture brings the problem that we will have only a short length over which we can measure tracks before they scatter. Our knowledge of an event is determined by the worst measured track. If for instance we have six outgoing tracks, then 50% of the time at least one track will scatter in a length less that 0.12 of the interaction length of the mixture. Neutron detection also involves a balance since for too dense a mixture we do not see the recoils well.

Putting all these factors together we estimate 15-30 atomic percent of neon to be a desirable compromise.

For a 30% mixture, the precision of angular measurements for muons and other charged particles is still reasonably good (Fig. 3). The average precision in momentum measurements is ~5% (Fig. 4).

Detection efficiency of the neutral component (Figs. 2a, 2b) is sufficient to detect 80% of the γ-rays and 50% of the neutrons. If one assumes that ~30% of the energy goes to neutral hadrons, then in the average the part which is lost is ~5%. Thus E_ν, q^2 and ν (= $E_\nu - E_\mu$) can be measured with reasonable accuracy.

Muon identification can be made using the following criteria:

1) positive electric charge

2) absence of interactions or decays on a track (L coll = 250 cm, and average length of a track $\simeq$ 170 cm)

3) the muon must be in general an energetic particle (from the CERN experiments $\overline{E_\mu} \geq \frac{E_\nu}{2}$)

4) for some classes of events the muon has a high transverse momentum.

We believe that the use of all of the above mentioned criteria will enable us to identify muons with high confidence.*

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*This does not exclude, however, the use of the external muon identifier[1] if it is ready by the time of the experiment.

III. INCLUSIVE REACTIONS

1. Total Cross Sections

Energy dependence of antineutrino total cross sections is a very important problem in weak interactions. Today data on it exists only up to about 8 GeV. The problem includes also the determination of $R = \sigma(\bar{\nu}N)/\sigma(\nu N)$. The predicted ratio depends on theoretical models which give values within limits $1/3 \leq R \leq 1$, though the latest experimental data from CERN[2] suggests the lower limit. Expected numbers of events in our experiment are given in Table II, where it was assumed that $3\,\sigma(\bar{\nu}N) = \sigma(\nu N) = 0.8 \times 10^{-38}\,E_\nu$.

To measure a total cross section, one should know the antineutrino spectrum and the antineutrino energy for each event. With a neon-hydrogen mixture, it is possible to measure the hadronic part of the energy with reasonably good precision because neutral particle detection efficiency is high (Fig. 2).

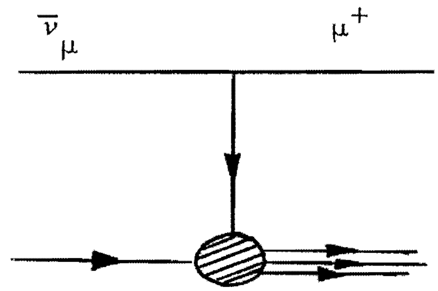
We do not discuss the measurement of neutrino spectrum and how to monitor the beam, as it was already discussed in Proposal #45-A.[3]

2. Deep Inelastic Interactions

It is natural to suppose that most events will be inelastic interactions, produced by antineutrinos

$$\bar{\nu}_\mu + N \rightarrow \mu^+ + \text{hadrons}.$$

A process of this type can be described by the diagram:



The differential cross section is usually parameterized in the following way:

$$\frac{d^2\sigma^{(\nu,\overline{\nu})}}{dq^2\,d\nu} = \frac{G^2}{8\pi M^2}\left[W_2^{(\nu,\overline{\nu})}\left(1 - \frac{2\,M\nu}{S - M^2} + \frac{q^2 M^2}{(S - M^2)^2}\right)\right.$$

$$\left. - W_1^{(\nu,\overline{\nu})}\frac{2q^2 M^2}{(S - M^2)^2} \pm W_3^{(\nu,\overline{\nu})}\frac{q^2}{2\,(S - M^2)}\left(1 - \frac{M\nu}{S - M^2}\right)\right] \qquad (1)$$

where $q^2 = 4E_\nu E_\mu \sin^2\frac{\theta_{\mu\nu}}{2}$, $\nu = E_\nu - E_\mu$, W_1, W_2, W_3 - structural functions depending on q^2 and ν.

An analysis of inelastic events can be split into two parts:

a) Distributions of events according to parameters, depending only on 4-momentum of leptons

b) Distributions depending on the hadronic part of the events (multiplicity, transverse momenta, etc.).

From a detailed analysis one can extract the structure functions W_{1-3}. It is worth emphasizing that W_3 for transitions with $\Delta S = 0$ can be determined from a simple comparison of ν and $\overline{\nu}$ cross section on neon

$$\frac{d^2\sigma\ (\nu\,Ne)}{dq^2\ d\nu} - \frac{d^2\sigma\ (\bar{\nu}\,Ne)}{dq^2\ d\nu} \sim 2W_3 \qquad (2)$$

This occurs because Ne nuclei have I = 0 and weak currents with S = 0 are assumed to belong to the same isotopic multiplet. Even measurement of the difference of total cross sections would give information on the magnitude of a certain integral from W_3.

The current CERN Gargamelle experiment[2] gives results indicating that at low energy $\sigma_{\bar{\nu}N} \simeq 1/3\ \sigma_{\nu N}$. Furthermore the momentum transfer dependence for $\sigma(\nu N)$ is flat while for $\sigma(\bar{\nu}N)$ it falls down. Thus W_3 would appear to be almost of maximal size and hence V-A interference maximal. This means that neutrino interactions will give us qualitatively different information than electroproduction experiments.

As we shall have events at very high energies it will be possible to check the Adler relations:[4]

$$\left.\frac{d\sigma\ (\bar{\nu}p)}{dq^2} - \frac{d\sigma\ (\nu p)}{dq^2}\right/ E_\nu \to \infty = \frac{G^2}{\pi}\ (\cos^2\theta_c + 2\sin^2\theta_c) \qquad (3)$$

$$\left.\frac{d\sigma\ (\nu n)}{dq^2} - \frac{d\sigma\ (\bar{\nu}n)}{dq^2}\right/ E_\nu \to \infty = \frac{G^2}{\pi}\ (\cos^2\theta_c - \sin^2\theta_c) \qquad (4)$$

where θ_c is the Cabibbo angle. According to the Bjorken and Tuan[5] estimations the integral form of relations (3,4) does not fit experimental data. If this disagreement is real some interesting possibilities arise[5] for weak interactions at high energy and our experiment might be crucial to decide whether these possibilities do realize.

3. Strange Particle Production

All neutrino experiments have been done so far at relatively low energies, where strange particle production is low and experimental data is poor. If we assume that the yield of strange particles in strong and weak interactions is not drastically different we can use for a rough estimate the πp data. For instance, at 25 GeV, in πp collisions[6] the cross section for strange particle production is equal to ~ 0.15 of σ_{tot} and does not change much in this energy region. This estimate does not contradict data from νN-interactions at lower energies.[7] If the same is true for higher energies, then for the total exposure of 10^{19} protons we shall get ~20,000 events with production of strange particles.

The following problems can be studied:

1) specific channels with strange particles in $\bar{\nu}p$ and $\bar{\nu}n$ interactions

2) associated production of strange particles ($\Delta S = 0$).

A certain number of Ξ^o and Ξ^- can be produced, but the event numbers are 50 to 100 times less than Λ and Σ^-.

IV. WEAK SEMI-LEPTON INTERACTIONS

1. Neutral Currents

The problem of neutral currents is of great importance for the theory of weak interactions.

In the proposed experiment, we can continue to search for a process:

$$\bar{\nu}_\mu + p \rightarrow \bar{\nu}_\mu + p \qquad (5)$$

At present, one cannot exclude this process with a cross section of the order $0.1\,\sigma(\nu n \rightarrow \mu^- p)$. The background for reaction (5) is mainly due to neutrons produced in the outside material. The large size of the bubble chamber gives us the possibility of following the exponential absorption of these neutrons and of separating neutrino produced events which should be distributed in the chamber uniformly. Moreover in a neutron induced event, there is some probability that the neutron suffers a second scattering and is detected. We hope that the limit measured at CERN[8] would be lowered at least by a factor of 10.

This improvement would be of great importance, as many theories today predict existence of neutral currents on the level of charged currents. For instance, in the model of Glashow, Illiopulis and Maiani[9] $\sigma_{\nu p \rightarrow \nu p}$ is roughly equal to 1/4 of $\sigma_{\nu n \rightarrow \mu p}$.

2. $\Delta S = 0, \; \Delta T = 1$

We wish to study several exclusive reactions with $\Delta S = 0$.

a) Quasielastic scattering:

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n \qquad (6)$$

gives information on nucleon form factors. Since many of the neutrons from reaction (6) will scatter inside the chamber, these events will have

2c-configuration and so can be separated from inelastic channels. High efficiency for γ-ray conversion will help us get rid of events with π^o mesons. The expected number of events for reaction (6) is included in Table III. From Monte-Carlo calculations our precision for the value of axial form factor should be of the order of 10%.

b) Isobars also will be produced in antineutrino interactions via reactions

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Delta^o \qquad (7)$$

$$\bar{\nu}_\mu + n \rightarrow \mu^+ + \Delta^- \qquad (8)$$

In 1/3 of cases Δ^o decays into $p + \pi^-$ which gives a complete identification of the event. Comparison of cross sections for the reactions (7) and (8) gives us a check on the $\Delta T = 1$ rule

$$\sigma(\bar{\nu}_\mu + p \rightarrow \mu^+ + \Delta^o) : \sigma(\bar{\nu}_\mu + n \rightarrow \mu^+ + \Delta^-) = 1:3 \qquad (9)$$

The expected number of events is presented in Table III.

c) Vector meson and isobar production

$$\bar{\nu}p \rightarrow \mu^+ \rho^o n \rightarrow \mu^+ \pi^+ \pi^- n \qquad (10)$$

$$\rightarrow \mu^+ \rho^- p \rightarrow \mu^+ \pi^- \pi^o p \qquad (11)$$

Estimates[10, 11] of cross sections for reaction 11 are quite small ($1\text{-}10 \times 10^{-41}$ cm^2) and for 10 even smaller. We can hope only to set limits on these processes if they are indeed that small.

There are many other yet unestimated processes which may well be larger than (10, 11). The channels calculated so far do not account for the bulk of the cross section. Some interesting examples follow:

$$\bar{\nu}p \rightarrow \mu^+ \rho^o \Delta^o \rightarrow \mu^+ \pi^+ \pi^- \pi^- p \qquad (12)$$
$$\mu^+ \pi^+ \pi^- \pi^o n$$

$$\bar{\nu}p \rightarrow \mu^+ \rho^- \Delta^+ \rightarrow \mu^+ \pi^- \pi^+ n\pi^o \qquad (13)$$
$$\mu^+ \pi^- p\pi^o \pi^o$$

$$\bar{\nu}p \rightarrow \mu^+ \omega^o n \rightarrow (\mu^+ \pi^+ \pi^- n\pi^o) \qquad (14)$$

$$\bar{\nu}p \rightarrow \mu^+ \omega^o \Delta^o \rightarrow (\mu^+ \pi^+ \pi^- \pi^- p\pi^o) \qquad (15)$$

$$\bar{\nu}p \rightarrow \mu^+ \eta^o n \rightarrow \mu^+ \pi^+ \pi^- n\pi^o \qquad (16)$$
$$\mu^+ n\gamma\gamma$$

$$\bar{\nu}p \rightarrow \mu^+ \eta^o \Delta^o \rightarrow \mu^+ \pi^+ \pi^- \pi^- p\pi^o \qquad (17)$$
$$\mu^+ \pi^- p\gamma\gamma$$

$$\bar{\nu}p \rightarrow \mu^+ \phi^o n \rightarrow (\mu^+ K^+ K^- n) \qquad (18)$$

$$\bar{\nu}p \rightarrow \mu^+ \phi^o \Delta^o \rightarrow \mu^+ K^+ K^- \pi^- p \qquad (19)$$
$$\mu^+ K^+ K^- n\pi^o$$

Channels which have $2\pi^o$ or $1\pi^o$ and 1 neutron will be difficult but perhaps not impossible. As can be seen above several channels involve only a neutron or a π^o and we certainly should be able to handle these. Channels similar to the above produced from bound neutrons in the neon will also be interesting.

d) The coherent process

$$\bar{\nu} + Ne^{20} \rightarrow \mu^{+} + F^{20} \qquad (20)$$

should occur. If we take over the calculation for the similar process in carbon^{12} we obtain ~200 events. The signature is one positive high energy muon. We note that the similar process for neutrinos has the same signature as the four-fermion process, $\nu_{\mu}\, e^{-} \rightarrow \nu_{e}\, \mu^{-}$. It is hard to sort these out in neon. For $\bar{\nu}$ we do not have this problem. This cross section (expected to be flat with energy) will help give a crude shape of the neutrino spectrum. We will also be able to calibrate the size of this effect as a background to the four-fermion process in the neutrino-neon experiment.

3. $\Delta S = 1$ and $\Delta T = 1/2$

A single hyperon production is possible in an antineutrino beam via the reactions:

$$\bar{\nu}_{\mu} + p \rightarrow \mu^{+} + \Lambda^{o} \qquad (21)$$

$$\bar{\nu}_{\mu} + p \rightarrow \mu^{+} + \Sigma^{o} \qquad (22)$$

$$\bar{\nu}_{\mu} + n \rightarrow \mu^{+} + \Sigma^{-} \qquad (23)$$

and other reactions with pions in the final state.

Due to our high efficiency for the conversion γ-rays, we can separate events with Λ^{o} from those with Σ^{o}. A comparison of cross sections for the reactions mentioned above gives a check on the $\Delta T = 1/2$ rule, which demands:

$$\sigma(\bar{\nu}_\mu + p \rightarrow \mu^+ + \Sigma^o) : \sigma(\bar{\nu}_\mu + n \rightarrow \mu^+ + \Sigma^-) = 1:2 \qquad (24)$$

$$\sigma(\bar{\nu}_\mu + p \rightarrow \mu^+ + Y^{*o}) : \sigma(\bar{\nu}_\mu + n \rightarrow \mu^+ + Y^{*-}) = 1:2 \qquad (25)$$

The study of hyperon production is more difficult in neon than in hydrogen because of the effects of absorption, scattering and charge exchange inside the Ne nuclei. To minimize these effects, one should select events with high energy hyperons, where they are small.[13] (At P_Λ = 500 MeV/c, $\sigma_{int} \simeq$ 20 to 40 mbn, while at P_Λ = 100 MeV/c, $\sigma_{int} \simeq$ 200 to 400 mbn.) The data on this subject is presented in Table IV.

4. $\Delta Q = \Delta S$

To check this rule, we want to look for reactions forbidden by it. Examples of such forbidden reactions are

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n + \pi^+ + K^- \qquad (26)$$

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

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n + K^o \qquad (28)$$

$$\bar{\nu}_\mu + n \rightarrow \mu^+ + n + \pi^- + K^o \qquad (29)$$

If reactions 27, 28, 29 are sufficiently frequent we can perform a test for $\Delta S/\Delta Q$ sensitive to the amplitude of the violation.[14]

As was the case for hyperon production, the main difficulties come from interactions inside nuclei, but the K^o cross sections are not large: $\sigma\,(K^- + p \rightarrow \bar{K}^o + n) \sim 6$ mbn at $P_K \sim 500$ MeV/c.

Reactions allowed by $\Delta Q = \Delta S$ rule are:

$$\bar{\nu}_\mu + n \rightarrow \mu^+ + \Sigma^- \quad (30)$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + \pi^- + \Sigma^+ \quad (31)$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + \pi^+ + \Sigma^- \quad (32)$$

Complementary reactions in a neutrino beam, forbidden by the $\Delta Q = \Delta S$ rule, are:

$$\nu_\mu + n \rightarrow \mu^- + \Sigma^+ \quad (33)$$

$$\nu_\mu + p \rightarrow \mu^- + \pi^+ + \Sigma^+ \quad (34)$$

Comparison of both allowed and forbidden reactions gives a check on the validity of the rule.

5. Search for Processes with $\Delta S = 2$

In an antineutrino beam, we can look for reactions with $\Delta S = 2$. A list of some possible $\Delta S = 2$ reactions is given below.

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + K^- + \Sigma^+ \quad (35)$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + \bar{K}^o + \Lambda^o \quad (36)$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + \bar{K}^o + \Sigma^o \quad (37)$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + \pi^+ + \Xi^- \quad (38)$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Xi^o \quad (39)$$

$$\bar{\nu}_\mu + n \rightarrow \mu^+ + \Lambda^o + K^- \quad (40)$$

$$\bar{\nu}_\mu + n \rightarrow \mu^+ + \Sigma^o + K^- \quad (41)$$

$$\bar{\nu}_\mu + n \rightarrow \mu^+ + \Sigma^- + \bar{K}^o \quad (42)$$

$$\bar{\nu}_\mu + n \rightarrow \mu^+ + \Xi^- \quad (43)$$

If reactions 36, 37, or 42 afford sufficient events, a test of $\Delta S = 2$ sensitive to the amplitude of $\Delta S = 2$ violation can be made.

6. T-Invariance

Antineutrino interactions with Ne-H mixture open unique possibilities to look for T-odd correlations which have not yet been found in the decay of polarized neutrons[15] and in the decay of F^{19}.[16]

In an antineutrino experiment, we can look for this effect in a wide range of momenta transferred and in a number of channels, for instance:

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n \tag{44}$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Delta^o \tag{45}$$

$$\bar{\nu}_\mu + n \rightarrow \mu^+ + \Delta^- \tag{46}$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda^o \tag{47}$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Sigma^o \tag{48}$$

$$\bar{\nu}_\mu + n \rightarrow \mu^+ + \Sigma^- \tag{49}$$

Analogs of reactions 44-46 can be studied in the neutrino exposures, the rest can be studied only in antineutrino exposures. (Provided $\Delta Q = \Delta S$ holds.)

If T-invariance is violated, hadronic current constants become complex. This leads to polarization of the hadrons normal to the reaction plane. In Fig. 5 one can find results of expected polarization in the reactions mentioned above according to a model where T-invariance is violated by a tensor term. Values of $|f_T|$ and $\mathrm{Im}\, f_T$ are taken from Ref. 17.

The graph shows that the polarization slowly varies with q^2 and its value is ~30%. This polarization can be tested with the expected number of events given in Table III.

V. LEPTONIC INTERACTIONS

1. Neutral Currents

A search for the scattering of muon antineutrinos on electrons

$$\overline{\nu}_\mu + e^- \rightarrow \overline{\nu}_\mu + e^- \tag{50}$$

will be made.

Reaction (50) is an example of the so-called diagonal processes where the breaking of the classical theory by Feynman and Gell-Mann is the most plausible according to the current theoretical expectations.[18,19] The cross section of (50) is expected to grow linearly with the neutrino energy in the lab system. For this reason, the NAL facilities are unique for a search for $\overline{\nu}_\mu$ e scattering.

According to the renormalized theory of weak interactions proposed by Weinberg[19] the cross section of the reaction (50) lies within the limits

$$0.06\ \sigma^{V-A}_{\nu_e e} \lesssim \sigma(\overline{\nu}_\mu e^- \rightarrow \overline{\nu}_\mu e^-) \lesssim 1.08\ \sigma^{V-A}_{\nu_e e} \tag{51}$$

where $\sigma^{V-A}_{\nu_e e}$ stands for the cross section $\nu_e e$ scattering in the standard V-A theory. A similar relation holds for the cross section of $\nu_\mu e^-$ scattering

$$0.06\ \sigma^{V-A}_{\nu_e e} \lesssim \sigma(\nu_\mu e^- \rightarrow \nu_\mu e^-) \lesssim 0.58\ \sigma^{V-A}_{\nu_e e} \tag{52}$$

Measurements of either of the cross sections would fix the only free parameter of the theory (which is related to the W-boson mass) and would allow one to predict the other cross section. Thus both runs of the neutrino and antineutrino experiments seem desirable.

For the 30% Ne + 70% H mixture the number of events corresponding to (51) is

$$50 \leqslant N \leqslant 900 \tag{53}$$

Proposed experiment may serve as a crucial test of the Weinberg theory.

Identification of the recoil electron is not difficult in the bubble chamber with a neon-hydrogen mixture.

If there were no background events and no ν_μ e scattering the upper limit on the cross section would be

$$\frac{\sigma(\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-)}{\sigma^{V-A}_{\nu_e e}} \lesssim 2.5 \times 10^{-3} \tag{54}$$

However, there are two obvious sources of background. Firstly, the γ-rays produced by neutrinos in the shielding and magnet coils can convert into $e^+ e^-$ pairs with the e^+ having a low energy and escaping detection in some cases. Secondly, the single electron events may come from the reactions

$$\nu_e (\bar{\nu}_e) + e^- \rightarrow \nu_e (\bar{\nu}_e) + e^- \tag{55}$$

$$\nu_e + n \rightarrow e^- + p \tag{56}$$

with the proton not detected in the case of (56).

The number of events (55, 56) is expected to be small, ~ 2. The number of γ-induced events is not easy to calculate. We have made a rough estimate which indicates that the number of these events may be made very small by introducing appropriate energy and angle cuts. Moreover, the numbers of apparent e^+ and e^- produced should be equal to each other and this also may be helpful in getting rid of the background events.

Thus we hope that the upper bound given in equation (54) can be achieved.

This experiment with neon-hydrogen filling has advantages over an experiment with pure hydrogen. Firstly, the statistics are ~ 3.5 times higher. Secondly, the identification of the recoil electron is more reliable.

It may be worth mentioning that if copious production of single electrons is indeed discovered, some additional efforts may be needed to clarify the production mechanism. A comparison of neutrino and antineutrino data can check consistency of Weinberg's theory. To elucidate the nature of other possible mechanisms, it might be necessary to have some other exposures (e.g. without focusing the charged particles by the horn). However, the possibilities opened would be so exciting that the additional efforts would be quite justified.

2. Multiplicative Conservation Law of Lepton Number

The proposed experiment will enable us to look for the reaction

$$\bar{\nu}_\mu e^- \rightarrow \mu^- \bar{\nu}_e \qquad (57)$$

which is allowed by the multiplicative form of the lepton conservation law and is forbidden if the lepton number is additive.

Reaction (57) can be separated from background by searching for the emission of a single negative muon with large energy at a small angle with respect to the beam direction.

The cross section for reaction (57) is

$$\sigma = \frac{G_M^2}{3\pi} \cdot \frac{(S - M^2)\ (S + M^2/2)}{S^2} \tag{58}$$

where S is c.m. energy squared and G_M is the interaction constant violating the conservation of the additive lepton number. If $G_M = G$, we will observe ~140 events of reaction (57). Again, the high energy neutrino beam available at NAL gives us much more discrimination in this search than with facilities of other laboratories. This particular check of the multiplicative conservation law for the leptonic interaction is possible only in antineutrino experiments because for a neutrino beam, the only reaction of the same kind

$$\nu_\mu e^- \rightarrow \mu^- \nu_e$$

allowed by conservation of the electric charge does not distinguish between different schemes of conservation of leptonic number.

The background events may come from the reaction

$$\nu_\mu n \rightarrow \mu^- p \tag{59}$$

if the recoil proton has a too low energy to be detected. The amount of the neutrino admixture in the antineutrino beam depends on the efficiency of the focusing system. We hope with special techniques we can limit this background to about 1%. If the admixture of the neutrinos is ~1%, the number of the background events of reaction (59) is expected to be around 10. The background from $\nu_\mu e^- \to \mu^- \nu_e$ is negligible.

3. Limits on Charged Currents

The production of muon pairs in the Coulomb field is possible via the charged currents interaction

$$\bar{\nu}_\mu + Z \to \bar{\nu}_\mu + \mu^- + \mu^+ + Z \tag{60}$$

$$\bar{\nu}_\mu + Z \to \bar{\nu}_e + e^- + \mu^+ + Z \tag{61}$$

The expected number of events is 4 and 10, respectively, the background being hard to estimate at present.

Experimentally the scattering of electron antineutrinos on electrons

$$\bar{\nu}_e e^- \to \bar{\nu}_e e^- \tag{62}$$

cannot be discriminated from the scattering of muon antineutrinos. The muon antineutrino scattering will dominate if the cross sections are comparable since there are many more muon antineutrinos than electron antineutrinos. If the neutral current interaction is suppressed $\bar{\nu}_e e^-$ scattering will be in principle observable. However, in this experiment, the number of events is expected to be small.

Clearly, if these reactions occur near their calculated value, we will only be able to get limits on them, but we would be able to see them if they are anomalously high.

VI. SEARCH FOR NEW PARTICLES AND INTERACTIONS

One may hope that the experiment proposed will reveal some new and unexpected phenomena. Just to illustrate how things may go, we consider a few exotic processes.

1. Heavy Leptons

The possible existence of heavy leptons was suggested by several authors.[20] Below we list some theoretical possibilities.

a) Heavy leptons that have the same quantum numbers as muons or electrons. Such leptons could be produced by antineutrinos

$$\bar{\nu}_\mu + N \rightarrow \bar{\mu}' + N \tag{63}$$

and decay e.g. in the following way

$$\begin{aligned} &\bar{\mu}' \rightarrow \mu^+ + \gamma; \ \bar{\mu}' \rightarrow \pi^+ + \pi^o + \bar{\nu}_\mu; \\ &\bar{\mu}' \rightarrow \mu^+ + \pi^o; \ \bar{\mu}' \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \end{aligned} \tag{64}$$

b) Charged leptons with helicities opposite to the helicities of the known leptons. Such leptons would be produced with opposite charge as compared with the usual case, e.g.

$$\bar{\nu}_\mu + n \rightarrow \mu^{1-} + p \tag{65}$$

$$\mu^{1-} \rightarrow \begin{cases} \mu^- + \bar{\nu}_\mu + \bar{\nu}_\mu \\ e^- + \bar{\nu}_e + \bar{\nu}_\mu \\ \pi^- + \bar{\nu}_\mu \end{cases}$$

c) Heavy leptons with new lepton numbers. Such particles could be produced in the Coulomb field of the nuclei via the $(\nu_\mu \mu) \cdot (\nu_\lambda \lambda)$ interaction or in decays of W-bosons if they exist.

A search for decays $\mu' \rightarrow \mu^+ + \gamma$, $\mu^+ + \pi^o$, etc. could be made by searching for an effective mass peak in final state particles. The decays with no final charged lepton would simulate neutral current events. Similarly events with $e^\pm$ or μ^- in a final state could be generated in anomalous electron neutrino interactions or through neutrino oscillations. However, any of these possibilities look exciting. With no observed event we can put upper limits on these reactions.

2. W-Bosons

The search for the negative W-bosons in the antineutrino experiment supplements the search for the positive W-bosons in the neutrino experiments. The expected number of W-bosons produced is presented in Fig. 6 as a function of the boson mass. In the neon-hydrogen mixture the electron decay of the W can be clearly identified.

The spin 0 intermediate boson, W_o, which has been introduced[18] to remove divergence difficulties in renormalization can be detected via its all hadronic decay mode.[21] With the Ne-H_2 mixture an effective mass search for the W_o is possible.

If the initial protons have energy up to 350 GeV, detection of W-bosons with mass up to 9-10 GeV seems quite reasonable.

3. Multifermion Interactions

Our present knowledge of weak interactions of baryons and leptons is confined to the four-fermion interaction. This may be a basic feature of weak interactions. But this might also be just due to the fact that we have dealt with low energy processes exclusively. A multifermion interaction,[22] even if it exists with large coupling constant would not manifest itself in decays just because of the smallness of the phase space.

Neutrino interactions at high energy provide a unique possibility for observing multifermion processes because the cross section is expected to grow rapidly with energy (if they exist at all). For six- and eight-fermion interactions, we have cross sections[22]

$$\sigma_6 \cong 10^{-7}\, G_6^{\,2} \times S^3 \tag{66}$$

$$\sigma_8 \cong 10^{-15}\, G_8^{\,2} \times S^7 \tag{67}$$

where $S = 2\,M_p\,E_\nu$.

Multifermion interactions in our exposure would result in production of lepton showers

$$\bar{\nu} + p \rightarrow n\,\mu^+\,\mu^+\,\mu^-;\quad \bar{\nu} + p \rightarrow n\,\mu^+\,\mu^+\,\mu^-\,\nu_\mu\,\bar{\nu}_\mu \tag{68}$$

and so on with final leptons having large transverse momentum.

Existing limits on the constants G_6, G_8 introduced above are quite poor and do not rule out the possibility of large cross sections. Thus, the number of six-fermion interactions could be as large as about 10^4 in the experiment proposed.

4. Weak Electromagnetic Interactions

Our present knowledge of weak electromagnetic interactions is so poor that the possibility of a rapidly growing cross section for reaction

$$\bar{\nu}_\mu + N \rightarrow \mu + \gamma + \text{Hadrons} \tag{69}$$

cannot be ruled out. Such a possibility was proposed by B. A. Arbuzov within his scheme of weak interactions.

To estimate the number of events one may use a simplified version of his model:

$$L_{int} = \frac{eG}{m^2} \bar{\mu} \quad \gamma_\alpha (1 + \gamma_5) \nu_\mu \bar{p} \quad \gamma_\beta (1 + \gamma_5) n \, F^{\alpha\beta} \tag{70}$$

where $F_{\alpha\beta}$ is the electromagnetic field strength tensor. Then we come to the following expression for the cross section

$$\sigma_t \approx \frac{S^3}{M_p^2 m^4} \cdot 4 \cdot 10^{-43} \text{ cm}^2 \tag{71}$$

where m is an intrinsic mass. According to (71), the cross section for (69) grows faster with energy than the cross section for nonradiative processes. The radiative and nonradiative cross sections become equal to each other for m = M at $E_{\bar{\nu}} \cong 40$ GeV (see also Fig. 6).

VII. CONCLUSIONS

We propose to undertake the study of antineutrino interactions in a Ne-H_2 mixture by a joint effort of American and Soviet physicists.

Our program consists of traditional items in neutrino physics and those special problems which can be solved in the particular combination of a $\bar{\nu}$-beam and a Ne-H_2 mixture. Some exotic processes are also considered.

A neon concentration of 15 to 30 atomic percent would be suitable for this experiment.

As a first phase of this experiment, we ask for 200,000 photos (out of a total exposure of the order of 10^6) at the highest available proton energy with an intensity of about 10^{13} interacting protons per pulse. A neutrino horn focusing system is considered essential.

A lower proton intensity ($\gtrsim 10^{12}$ p/p) would be sufficient to start the experiment. Some thousands of events obtained in this preliminary run already would be sufficient to produce some new and important results:

- to estimate the total cross section of the antineutrino-nucleon interaction and its dependence on energy
- to study the structure functions of the deep inelastic interactions
- to improve the existing limit on neutral current interactions
- to perform a search for heavy leptons (with the mass up to 2-3 GeV) and for the intermediate $\overline{W^o}$-boson (with the mass up to 4-5 GeV)

- to set limits on multifermion and weak-electromagnetic interactions.

Participants of this experiment will take part in the preparation of the neutrino beam and the NAL 15-ft bubble chamber facility as well as the data taking phase and analysis of this experiment.

Each of the participating groups has an adequate scanning and measuring capacity to successfully handle this experiment and will consider it to be a major effort and a major commitment. Furthermore, by carrying out the already approved neutrino-hydrogen experiment 45A, we will have obtained invaluable experience to enable us to handle this exposure efficiently.

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TABLE I.

Main Parameters of Neon-Hydrogen Mixture

C_{Ne}(MOL %)	C_{Ne}(AT.%)	ρ(G/cm^3)	λRAD.(cm)	λ COLL.(cm)	No. of Nucleons (rel. units)
0	0	0.06	970	710	1
35	21	0.3	110	300	4.9
46	30	0.4	80	250	6.7
70	53.7	0.7	42.5	150	11.2
100	100	1.2	24	94	20

TABLE II

Number of Antineutrino Events for 10^{19} Interacting Protons

Energy Interval (GeV)	100% H_2		10% Ne		30% Ne		100 % Ne	
	$V=20M^3$	$V=11M^3$	$V=20M^3$	$V=11M^3$	$V=20M^3$	$V=11M^3$	$V=20M^3$	$V=11M^3$
0-10	3000	1700	8700	5000	20000	11000	60000	33000
10-20	10000	5700	31000	17000	67000	40000	207000	116000
20-30	10000	5700	30000	17000	67000	40000	200000	110000
30-40	7400	4200	21000	12000	49000	28000	147000	83000
40-50	3800	2200	11000	6300	26000	15000	77000	43000
50-60	1800	1000	5000	2900	12000	6700	35000	20000
60-70	800	460	2300	1300	5300	3000	16000	9000
70-80	420	240	1200	700	2800	1000	8400	4700
80-90	230	130	700	390	1600	900	4700	2700
90-100	160	90	470	270	1100	600	3200	1800
100-110	130	70	330	200	870	470	2500	1440
110-120	100	60	300	170	670	400	2100	1200
120-130	90	50	240	140	550	330	1700	970
130-140	70	40	200	120	450	270	1300	770
140-150	50	30	140	80	330	190	1000	550
150-160	30	20	100	55	230	130	670	400
160-170	20	13	70	37	140	84	440	260
170-180	13	7	40	24	90	53	270	150
180-220	13	7	40	24	90	53	270	150
Total Number	39000	22000	112000	64000	260000	150000	770000	440000

TABLE III

Number of Events per 10^{19} Interacting Protons

Process	$\sigma (cm^2)$	N_p	N_{tot}	N_{DET}	Notes
$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$	$6 \cdot 10^{-39}$	2000	10000	4000	
$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Delta^\circ$	$4 \cdot 10^{-39}$	1400	7000	2200	Only $\pi^- p$ Decay Mode
$\bar{\nu}_\mu + n \rightarrow \mu^+ + \Delta^-$	$12 \cdot 10^{-39}$	-	16500	6000	
$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda^\circ$	$0.34 \cdot 10^{-39}$	120	600	400	Only $\pi^- p$ Decay Mode
$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Sigma^\circ$	$0.12 \cdot 10^{-39}$	40	200	130	Only $\pi^- p$ Decay Mode
$\bar{\nu}_\mu + n \rightarrow \mu^+ + \Sigma^-$	$0.24 \cdot 10^{-39}$	-	350	150	
$\bar{\nu}_\mu + p \rightarrow \mu^+ + Y^{\circ *}$	$0.10 \cdot 10^{-39}$	34	170	110	Only $\Lambda \rightarrow \pi^- p$
$\bar{\nu}_\mu + n \rightarrow \mu^+ + Y^{-*}$	$0.20 \cdot 10^{-39}$	-	300	200	Only $\Lambda \rightarrow \pi^- p$

N_p ---- Free Proton Events

N_{tot} ---- Total Number of Events

N_{DET} ---- Number of Detected Events

TABLE IV

NUCLEAR EFFECTS

P_Y (MeV/c)	Absorption of Λ	$\Lambda p \to \Lambda p$	$\Sigma^- p \to \Sigma^- p$	$\Sigma^- p \to \Lambda n$	$\Sigma^- p \to \Sigma^\circ n$
100	> 70%	48%	24%	20%	45%
500	~ 40%	3%	-	3%	4%
1000	~ 10%	-	1%	-	-

FIGURE CAPTIONS

Fig. 1 Muonic antineutrino spectrum. $E_p = 350$ GeV.

Fig. 2 Efficiency of interaction for secondaries in the bubble chamber:

a) averaged over the whole bubble chamber volume,

b) averaged over the "target" volume ($r = 1.35$ m, $L = 2.0$ m).

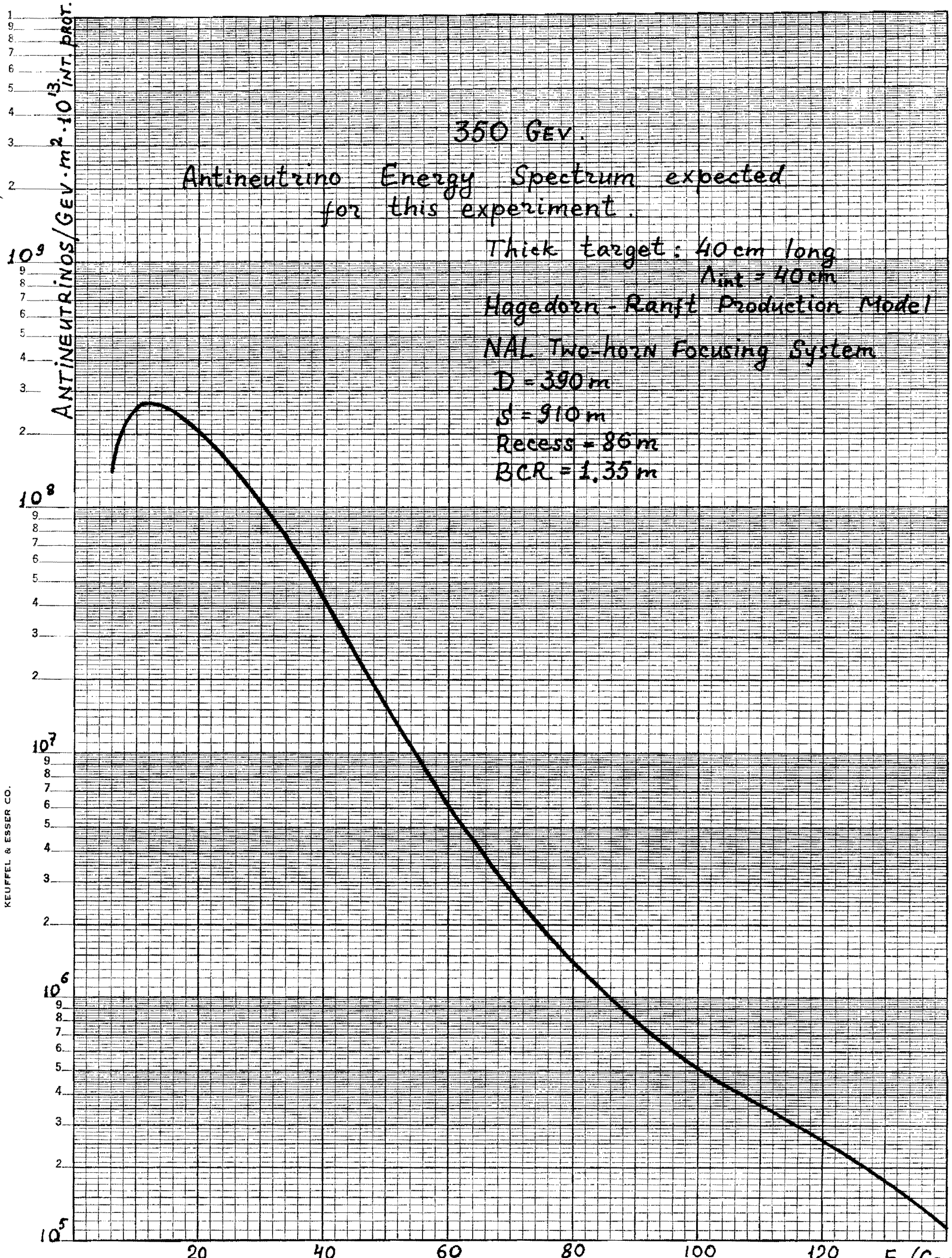
Fig. 3 Accuracy of the angle measurements for various track lengths and neon concentrations (ϕ is the azimuthal angle and λ is the depth angle).

Fig. 4 Precision in momentum measurements for various neon concentrations.

Fig. 5 q^2-dependence of the hadron polarization perpendicular to the plane of interaction.

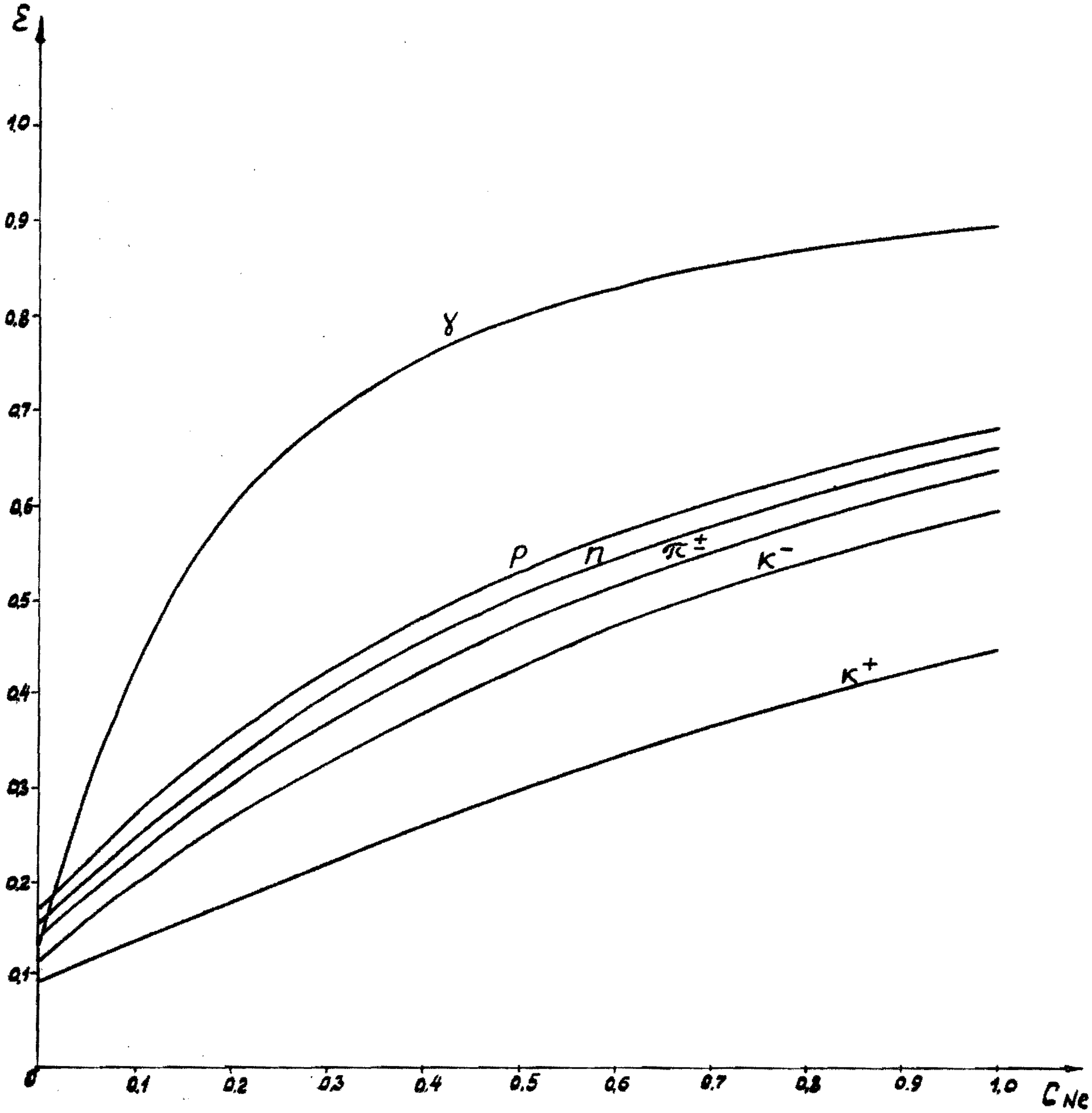
Fig. 6 Expected number of W^--bosons produced as a function of the boson mass.

Fig. 7 Comparison of total weak and weak-electromagnetic cross sections.



350 GEV.
Antineutrino Energy Spectrum expected for this experiment.
Thick target: 40 cm long
Λint = 40 cm
Hagedorn - Ranft Production Model
NAL Two-horn Focusing System
D = 390 m
S = 910 m
Recess = 86 m
BCR = 1.35 m
ANTINEUTRINOS/GEV·m²·10¹³ INT. PROT.
20
40
60
80
100
120
Eν (GEV)
SEMI-LOGARITHMIC
5 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO.
46 6210
MADE IN U.S.A.

Fig. 1



ε
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
C_{Ne}
γ
p
n
π±
K⁻
K⁺

Fig. 2a.

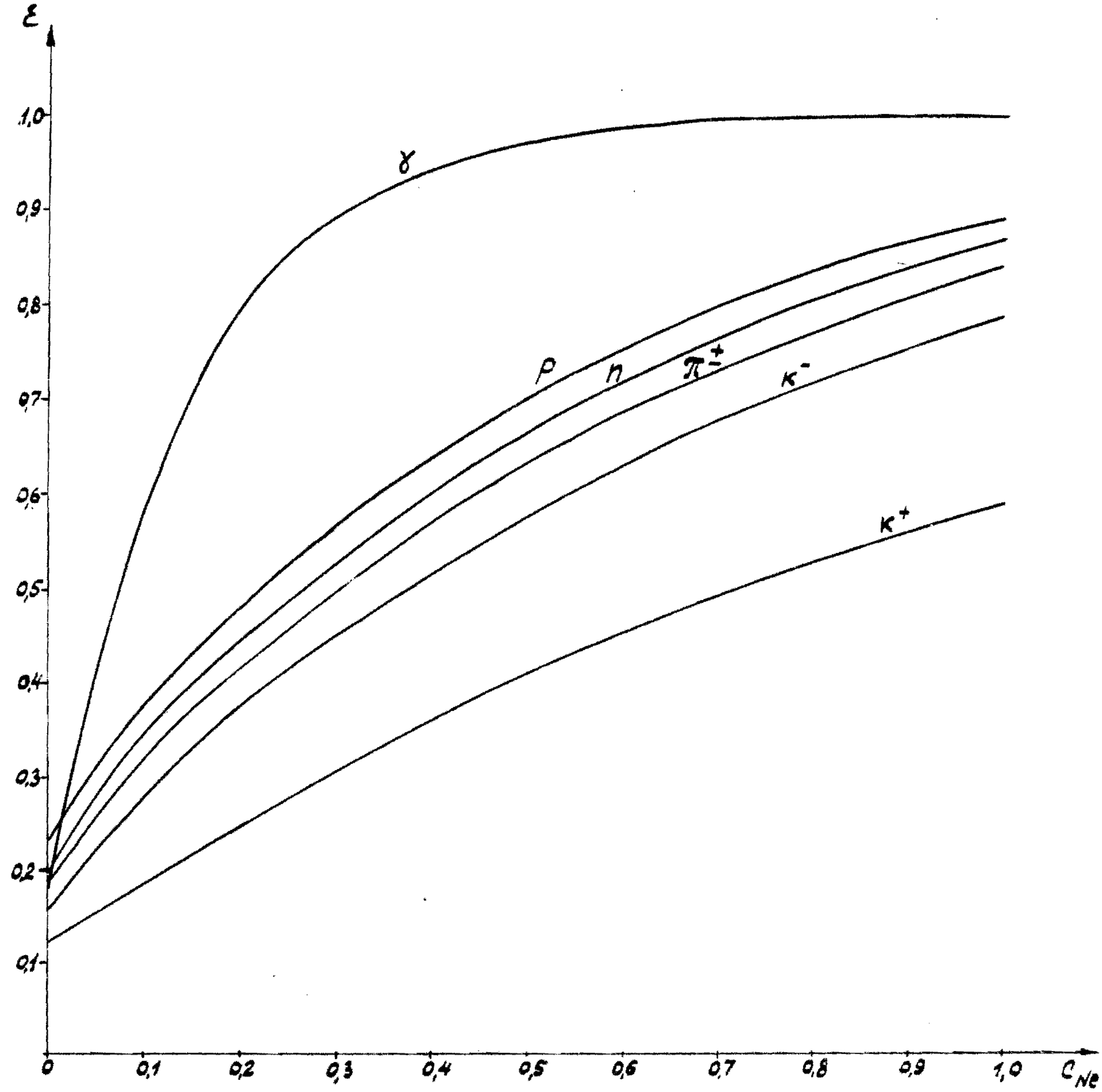
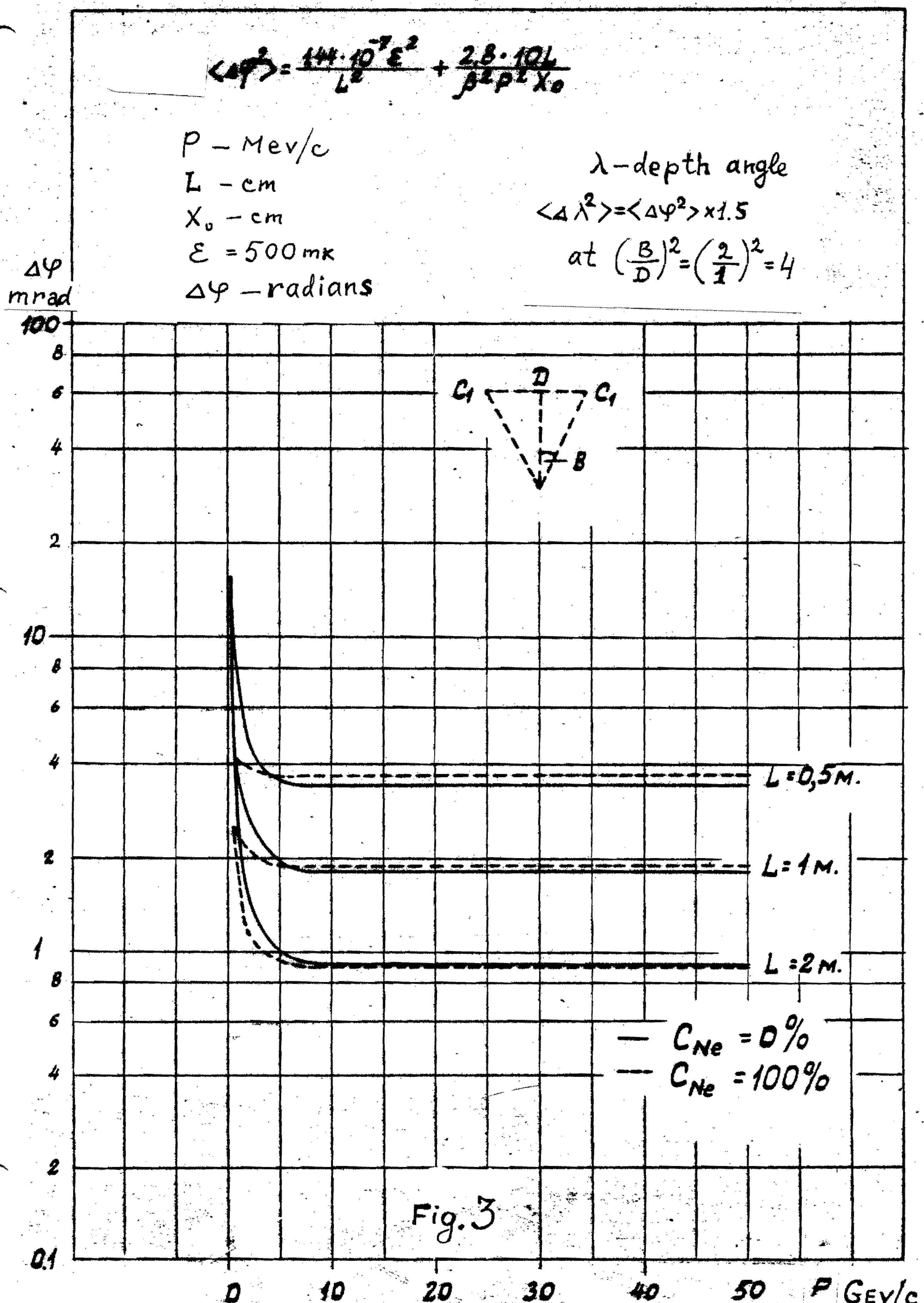
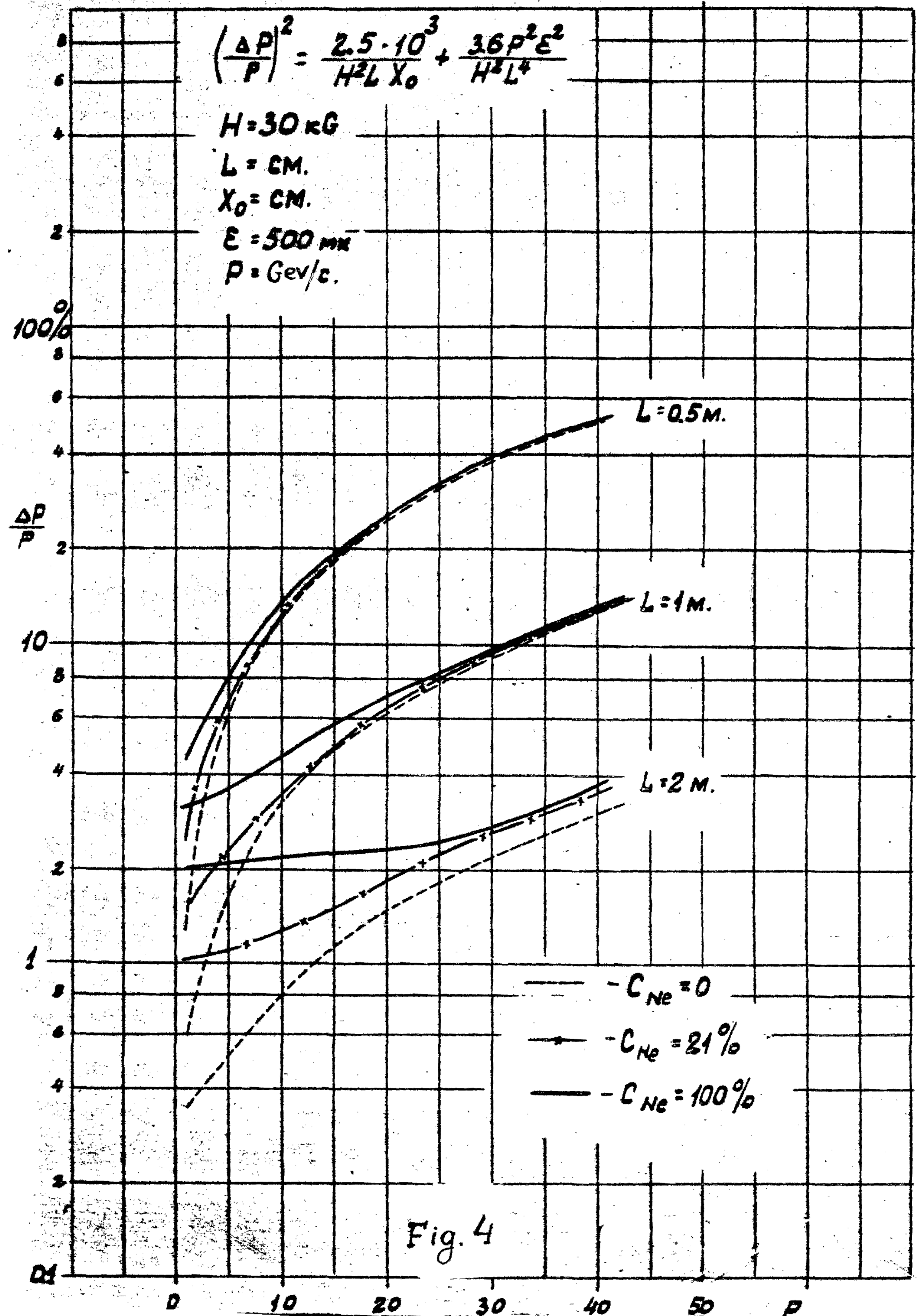

ε
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
C_{Ne}
γ
p
n
π±
κ⁻
κ⁺

Fig. 2b.



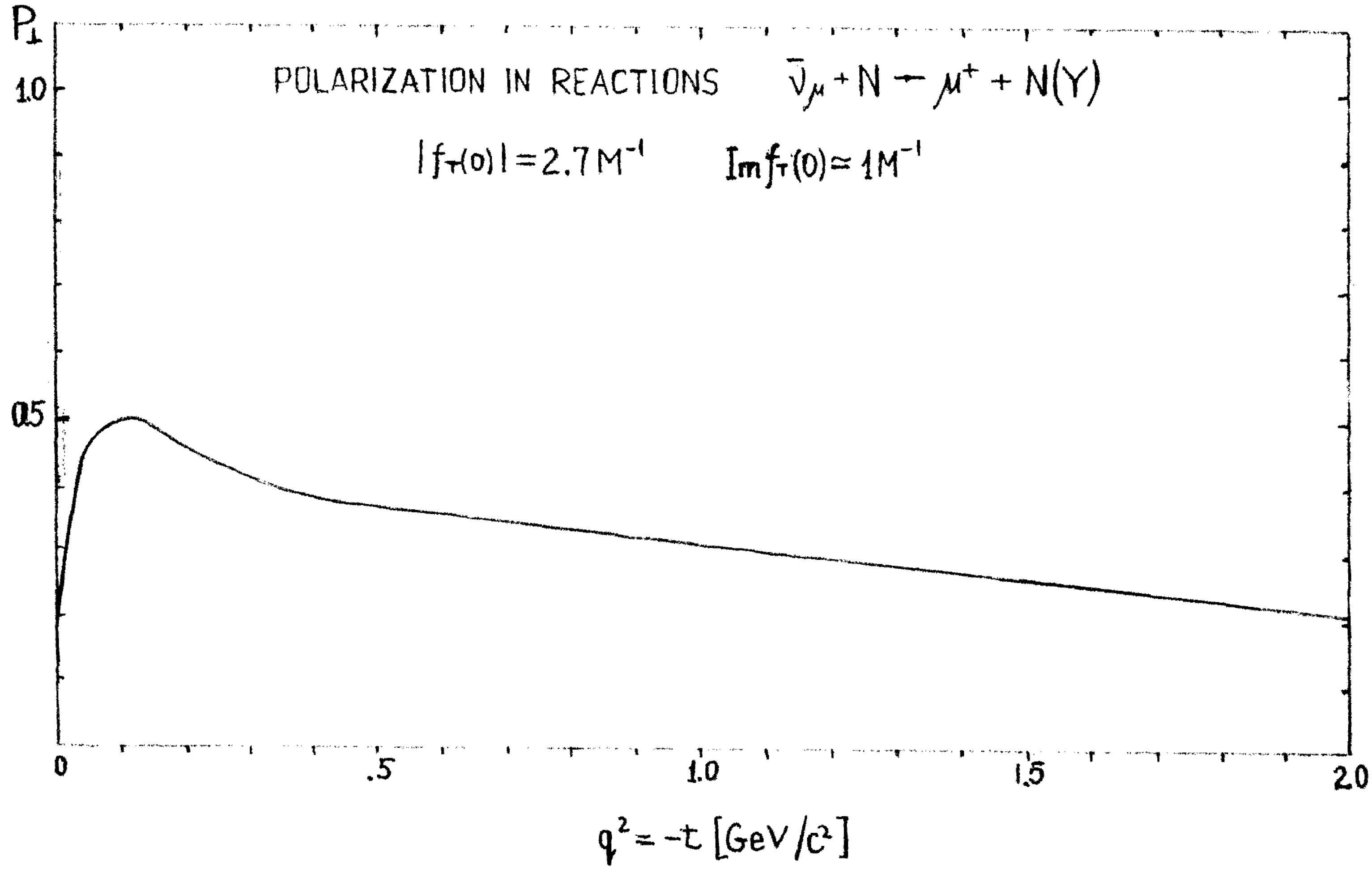
$\langle\Delta\varphi^2\rangle = \frac{1.44\cdot10^{-7}\varepsilon^2}{L^2} + \frac{2.8\cdot10L}{\beta^2 P^2 X_0}$
P – Mev/c
L – cm
X_0 – cm
ε = 500 mk
Δφ – radians
λ – depth angle
$\langle\Delta\lambda^2\rangle = \langle\Delta\varphi^2\rangle \times 1.5$
at $\left(\frac{B}{D}\right)^2 = \left(\frac{2}{1}\right)^2 = 4$
Δφ
mrad
100
8
6
4
2
10
8
6
4
2
1
8
6
4
2
0.1
C_1
D
C_1
B
L = 0,5 м.
L = 1 м.
L = 2 м.
— C_{Ne} = 0%
– – C_{Ne} = 100%
0
10
20
30
40
50
P Gev/c

Fig. 3



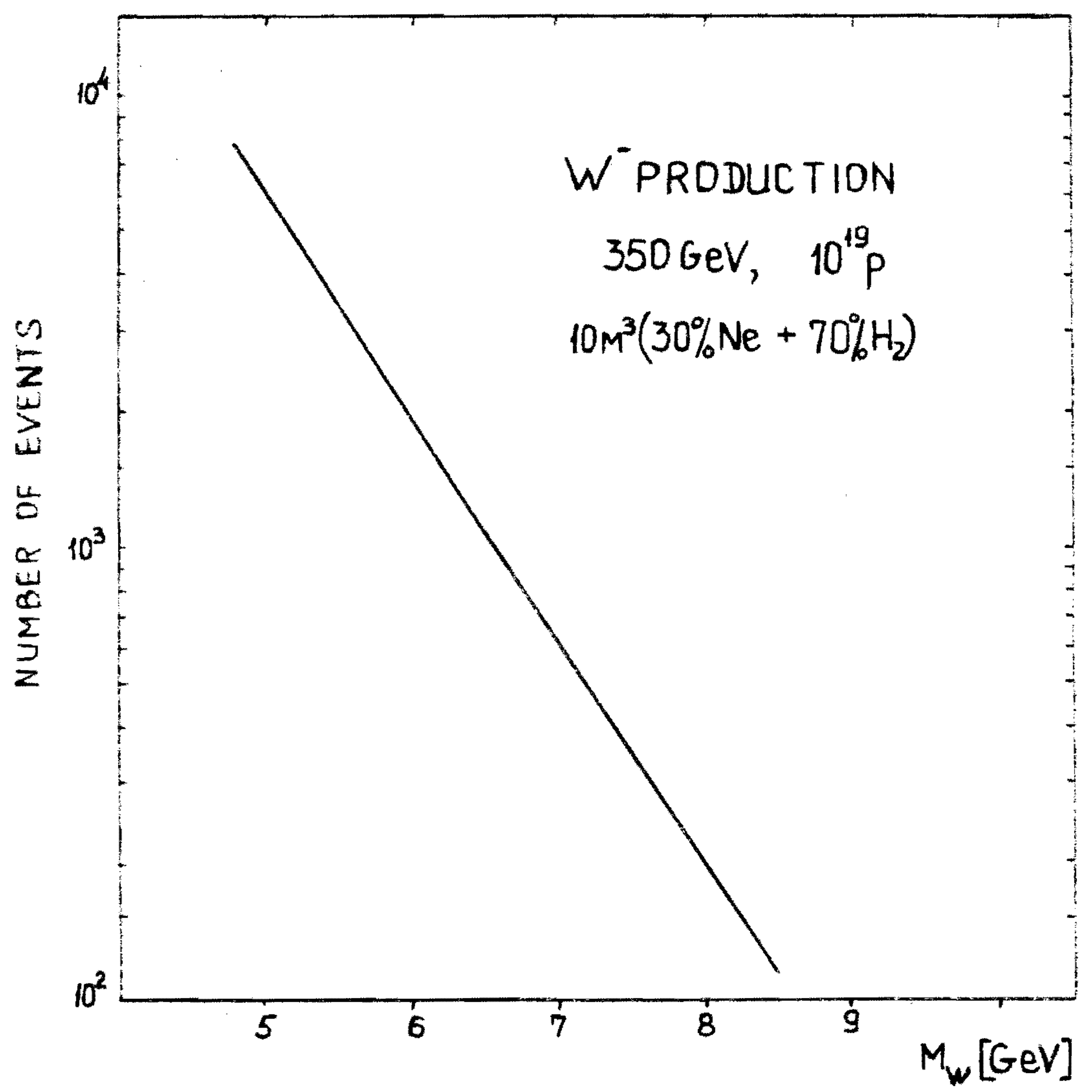
$\left(\frac{\Delta P}{P}\right)^2 = \frac{2.5\cdot10^3}{H^2 L X_0} + \frac{36 P^2 \varepsilon^2}{H^2 L^4}$
H = 30 кG
L = CM.
X_0 = CM.
ε = 500 мк
P = Gev/c.
$\frac{\Delta P}{P}$
100%
10
1
0.1
L = 0.5 м.
L = 1 м.
L = 2 м.
$- C_{Ne} = 0$
$- C_{Ne} = 21\%$
$- C_{Ne} = 100\%$
0
10
20
30
40
50
P

Fig. 4



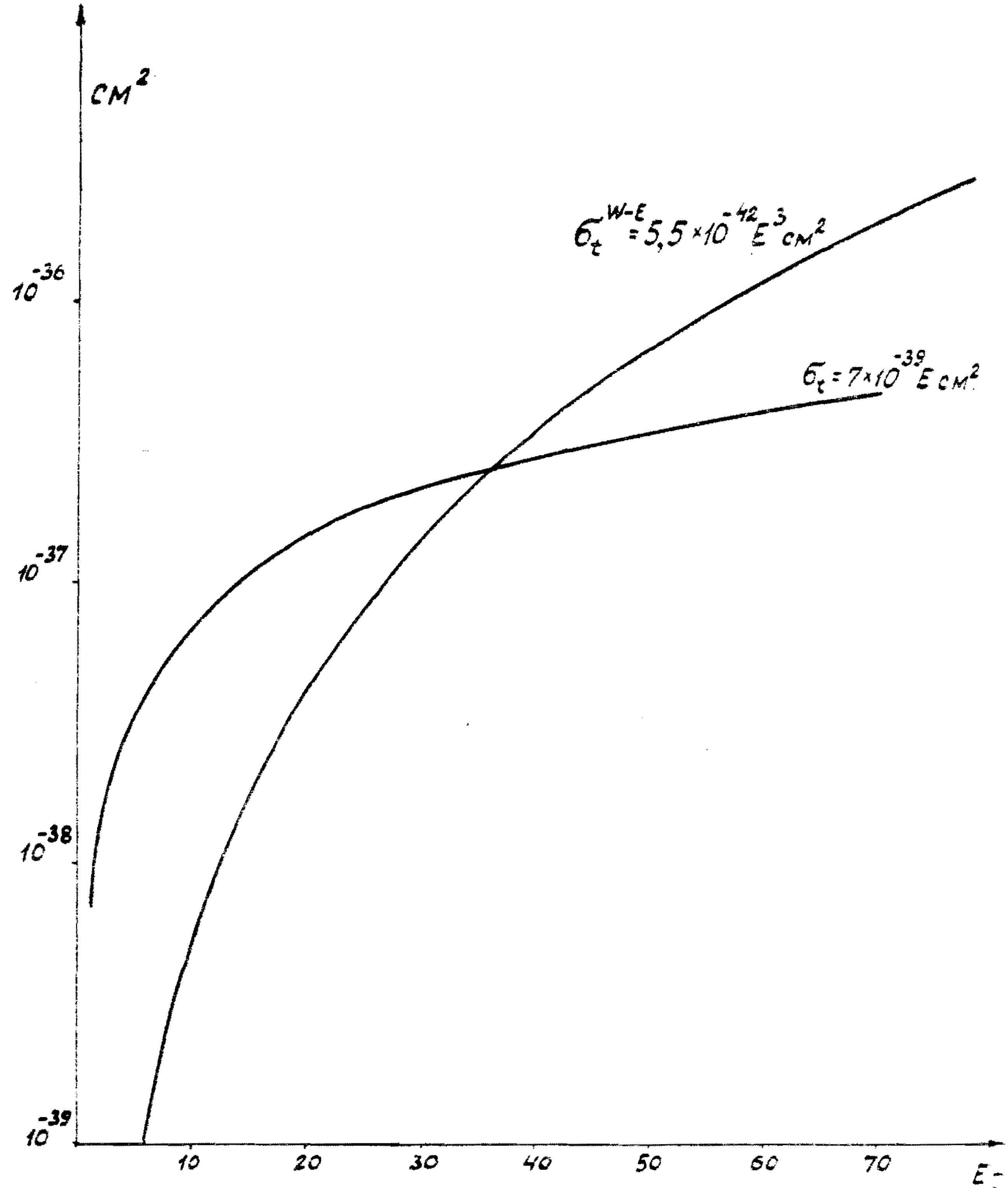
$P_\perp$
1.0
0.5
POLARIZATION IN REACTIONS $\bar{\nu}_\mu + N \to \mu^+ + N(Y)$
$|f_T(0)| = 2.7 M^{-1}$ $\mathrm{Im} f_T(0) \simeq 1 M^{-1}$
0
.5
1.0
1.5
2.0
$q^2 = -t$ [GeV/c²]

Fig. 5



W⁻ PRODUCTION
350 GeV, 10^{19} p
$10 M^3 (30\% Ne + 70\% H_2)$
NUMBER OF EVENTS
10^4
10^3
10^2
5
6
7
8
9
M_W [GeV]

Fig.6



cm^2
$\sigma_t^{W-E} = 5,5 \times 10^{-42} E^3 cm^2$
$\sigma_t = 7 \times 10^{-39} E\ cm^2$
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10
20
30
40
50
60
70
E

Fig. 7