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for

NEUTRINO PHYSICS
AT THE PULSED SPALLATION NEUTRON SOURCE SNS

by

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NEUTRINO PHYSICS AT THE PULSED SPALLATION NEUTRON SOURCE SNS

Abstract

An experimental facility for neutrino physics at the Spallation Neutron Source SNS at the Rutherford Appleton Laboratories in Chilton, England is described. Neutrinos ν_μ, ν_e and $\bar{\nu}_\mu$ will be produced by the SNS with energies of 0 - 53 MeV for $\bar{\nu}_\mu$ and ν_e and 30 MeV for ν_μ. Time and energy structure of the different neutrino spectra allow the observation of various neutrino induced reactions simultaneously with a suitable detector system. Thorough investigations on the background - accelerator associated as well as from cosmic rays - led to the requirement of a separated neutrino cave 22 m below the SNS target to perform such experiments. A multipurpose detector is proposed consisting of a 50 ton segmented organic scintillator detector and another 50 ton wide gap liquid argon detector. For this system feasibility studies are presented for experiments on elastic neutrino electron scattering, inelastic scattering of neutrinos from carbon nuclei and inverse β-decay processes on carbon and hydrogen nuclei. Experimental sensitivities are investigated in detail for neutrino oscillation experiments and purely leptonic weak interaction processes i.e. electron neutrino scattering. The proposed experiments will be feasible with good statistics and small systematic errors.

NEUTRINOPHYSIK AN DER GEPULSTEN SPALLATIONSNEUTRONENQUELLE SNS

Zusammenfassung

Es wird eine Einrichtung für Experimente mit Neutrinos aus der gepulsten Spallationsneutronenquelle SNS des Rutherford Appleton Laboratoriums in Chilton, England vorgestellt. Die Spallationsquelle erzeugt Neutrinos mit Energien zwischen 0 - 53 MeV für ν_e und $\bar{\nu}_\mu$ und von 30 MeV für ν_μ. Mit einem geeigneten Detektor lassen sich aufgrund der Zeit- und Energiestruktur der unterschiedlichen Neutrinospektren verschiedene Neutrino-induzierte Reaktionen gleichzeitig beobachten. Die Untergrundstrahlung, die sowohl vom Beschleuniger als auch von der Höhenstrahlung herrührt, wurde eingehend untersucht. Daraus ergab sich die Forderung nach einem separaten Neutrino Bunker 22 m unterhalb des SNS Targets, um die geplanten Experimente durchführen zu können.
Als Detektorsystem wird ein 50 t segmentierter organischer Szintillationsdetektor und ein 50 t Flüssig-Argon-Detektor vorgeschlagen. Mit diesem System können Experimente zur elastischen Neutrino-Elektronstreuung, der inelastischen Neutrino-Kernstreuung sowie zum inversen β-Zerfall an Kohlenstoff- und Wasserstoffkernen durchgeführt werden. Speziell für Neutrino-Oszillationsexperimente sowie dem rein leptonischen schwachen Wechselwirkungsprozeß der Neutrino-Elektronstreuung wurde die experimentelle Empfindlichkeit im Detail untersucht. Mit der beschriebenen experimentellen Einrichtung für Neutrinophysik an der SNS sind die vorgeschlagenen Experimente mit guter Statistik und kleinen systematischen Fehlern durchführbar.

PROPOSAL SUMMARY

We are proposing the development and construction of a versatile neutrino detector system for experiments using the beam stop neutrinos from high intensity pulsed proton accelerators. The detector system would be developed and constructed at the Kernforschungszentrum Karlsruhe. It is further proposed that installation of the system in a neutrino cave at the Spallation Neutron Source (SNS) of the Rutherford Appleton Laboratories in Chilton, England be completed in 1986.

We have studied in detail both accelerator associated and cosmic backgrounds in a neutrino cave located in the chalk between 11 and 22 m below the spallation neutron target. The conclusion is that both backgrounds can be kept sufficiently low by shielding the source with an additional 3 m of iron and by making use of the very low duty cycle of the accelerator.

A 50 ton segmented organic scintillation detector system was taken as a reference detector for the feasibility calculations. But at least for neutrino electron scattering experiments much better resolution in energy and space is expected from new developments of liquid Argon chambers using the time projection method. For simultaneous measurements of reactions having quite complicated signatures, a high degree of 'intelligence' in the detector system is needed.

The SNS will produce equal numbers of neutrinos, ν_μ,ν_e and $\bar{\nu}_\mu$ with an average source strength of about 10^{14}/sec each, the peak intensities being even higher by a factor of 10^5. The proposed neutrino facility will be unique because of its high flux of ν_e (0-53 MeV) and its high peak flux of monoenergetic ν_μ (30 MeV). The ν_μ can be well separated from the ν_e and $\bar{\nu}_\mu$ by time measurement.

With this system, the SNS could be used for many types of interesting experiments conducted simultaneously. Feasibility studies are presented for the following examples:

1. Elastic lepton scattering:

   $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ and $\nu_e + e^- \rightarrow \nu_e + e^-$ used for the study of weak charged and neutral current interaction and test of μ-e universality.

2. Inelastic scattering of ν_μ from carbon nuclei:
   e.g. $\nu_\mu + {}^{12}C \rightarrow \nu_\mu' + {}^{12}C^*$ (15.1) used for observation of neutral current excitation of the nucleus and determination of the isovector axial coupling constant.

3. Inverse ß-decay:
   e.g. $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$ and $\bar{\nu}_e + p \rightarrow e^+ + n$ used for the detection of appearance of ν_e and (or) $\bar{\nu}_e$ in search of neutrino oscillations.

It has not been possible to study the reactions $\nu_e + e^- \rightarrow \nu_e + e^-$, $\nu_\mu + {}^{12}C \rightarrow \nu_\mu' + {}^{12}C^*$ and $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$ with existing accelerators.

Our calculations show that the proposed experiments will be feasible with good statistics and small systematic errors. The experiments can be performed in a separated underground neutrino cave without any distortion of the neutron scattering experiments at the SNS.

More detailed proposals on the detector system will follow after completion of the development of prototypes for the scintillator as well as for the liquid Argon detector by the end of 1983.

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I. INTRODUCTION

The high intensity pulsed proton accelerators under construction at the Rutherford Laboratory and at LAMPF (PSR) will offer exciting new possibilities for experiments in low and medium energy neutrino physics. We propose a versatile neutrino facility using the beamstop neutrinos ($\nu_\mu, \nu_e, \bar{\nu}_\mu$) near the Spallation Neutron Source (SNS) of the Rutherford Laboratory at Chilton, England.

The SNS is based on an 800 MeV rapid cycling proton synchrotron. The machine will produce pulse pairs separated in time by 230 nsec and with each pulse 100 nsec long, extracted with a repetition rate of 50 Hz. Each pulse will contain $1.3 \cdot 10^{13}$ protons giving $1.3 \cdot 10^{15}$ protons per sec or an averaged current of 200 μA.

The protons do not only give rise to the production of neutrons in the spallation target. At the same time large numbers of pions are produced which emit neutrinos while decaying. Therefore, the SNS will be a source of neutrinos (ν_μ, ν_e and $\bar{\nu}_\mu$) with an average strength of the order of 10^{14} ν/sec for each kind. In addition the usual difficulty with continuous background, from cosmic rays etc. is considerably reduced by the accelerator's very small duty factor of 10^{-5}.

The neutrino detector system can be installed in a separate cave in the chalk under the SNS target without any distortion of the neutron scattering experiments.

The proposed common neutrino facility will allow many experiments on fundamental properties of the neutrinos and the study of other interesting problems of modern weak interaction physics simultaneously. Several examples are discussed in this proposal for a reference detector system of 50 tons of a segmented organic scintillator. The detector system proposed here will consist of a 50 to organic scintillator part and a 50 to liquid Argon chamber. The use of two types of detectors would allow better optimization for the simultaneous measurement of different neutrino reactions. Another possibility still under discussion is the use of only one common organic scintillation detector with high granularity. The final decisions on the type of detector system will be made until the end of 1982. First test modules of the scintillation as well as the liquid Argon detectors are under construction.

The development of prototypes for the scintillator system will be performed until the end of 1982; that of a prototype for the liquid Argon chamber is expected to continue through the end of 1983. The detector system will be developed and constructed at the Kernforschungszentrum Karlsruhe. Installation at SNS should be finished in early 1986 when the full beam intensity is expected.

II. PHYSICS MOTIVATION

In recent years interest in the physics of neutrinos has grown substantially. Especially in the context of the successful application of gauge theories and quark models the new weak interaction theories have led to new questions concerning the elementary properties of the neutrinos. The interest in possible 'anomalous' properties of the neutrinos has been further stimulated by the discrepancy existing between the measured and the calculated numbers of neutrinos from the sun.

An explanation of the deficit of solar neutrinos may be possible by assuming that the neutrinos have a small but finite mass. It is plausible to further assume, that this mass differs for the different kinds of neutrino: $(\nu_e, \nu_\mu, \nu_\tau)$. However, this opens up the possibility that neutrinos transform into each other. In principle, this transformation could be either a reversible process by so-called oscillations or by decay /1/.

If the interaction violates muon number conservation and if the neutrinos of the electron and of the muon have different masses, this leads e.g. to the oscillation: $\nu_e \leftrightarrow \nu_\mu$ and to the decay $\nu_\mu \rightarrow \nu_e + \gamma$ (assuming $m_{\nu_\mu} > m_{\nu_e}$). But the lifetime for the decay can be estimated to $\tau > 5 \cdot 10^{11}$ years /1/. Therefore, the decay of neutrinos cannot be observed in the laboratory. According to their helicity the leptons are combined into a doublet and a singlet each:

For example:

$$L = \begin{pmatrix} \nu_L \\ e^-_L \end{pmatrix}; \quad R = e^-_R$$

(L = left handed; R = right handed).

In total, this gives the following doublets:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} ; \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} ; \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

$$\begin{pmatrix} \bar{\nu}_e \\ e^+ \end{pmatrix} ; \quad \begin{pmatrix} \bar{\nu}_\mu \\ \mu^+ \end{pmatrix} ; \quad \begin{pmatrix} \bar{\nu}_\tau \\ \tau^+ \end{pmatrix} \qquad (0)$$

$\nu_\tau(\bar{\nu}_\tau)$ have not yet been unambiguously detected experimentally. Moreover, the mass of the τ-particle of 1.8 GeV/c^2 lies beyond the range of energies accessible at the spallation neutron source. Therefore, only the particles of the first four doublets will be considered in this proposal.

For zero-mass particles mixing of different states of helicity and different doublet assignments (lepton flavours) is not possible. Also, in addition to the conservation of lepton number, there is the separate conservation of muon number. In the weak interactions, in vertical direction in (0) e.g. for the ν_e-e^- coupling, exchange of the so-called $W^{\pm}$ boson is assumed to take place. However, because of its great mass, this boson has not yet been detected in experiment. The proof of interactions by 'neutral currents' (e.g. ν_μ-e^--coupling) has been one of the great discoveries in the past years. As a consequence, the existence of a (likewise very heavy) electrically neutral exchange particle Z_0 is predicted. Experiments aiming at the direct proof of the existence of $W^{\pm}$ and Z_0 can be performed only in high energy physics. However, a large number of fundamental questions can be studied particularly well by means of the very high neutrino fluxes to be generated at the high intensity spallation neutron sources.

In this context the interactions in the horizontal direction of (0) will be of special interest. One class of transitions are the flavour oscillations $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$, but also the particle - antiparticle oscillations: $\nu_e \leftrightarrow \bar{\nu}_e$ and $\nu_\mu \leftrightarrow \bar{\nu}_\mu$ cannot be excluded by the theory.

As will be shown in the next chapter the SNS is unique because of the very high source strength of ν_μ, ν_e and $\bar{\nu}_\mu$. Using inverse ß-decay of Hydrogen and Carbon respectively as a selective detector reaction we can search for the appearance or disappearance of ν_e's and (or) $\bar{\nu}_e$'s from $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_e \rightarrow \nu_\mu$.

The theoretical description was given by Pontecorvo /1/. If the physical neutrinos ν_μ and ν_e are formed by superposition of two fundamental neutrinos ν_1 and ν_2 having defined masses m_1 and m_2, oscillations $\nu_\mu \leftrightarrow \nu_e$ can occur. ν_μ and ν_e in this case are no longer stationary states, nor do they have defined masses.

The mixture is described by:

$$\nu_e = \nu_1 \cdot \cos\Theta + \nu_2 \cdot \sin\Theta$$

$$\nu_\mu = -\nu_1 \cdot \sin\Theta + \nu_2 \cdot \cos\Theta$$

where Θ is the still unknown mixing angle. If at the time $t = 0$ a pure beam $|\nu_e>$ or $|\nu_\mu>$ starts, a combination of both kinds of neutrino will be found at the time $t = t$. In this case, the probability of transition in terms of quantum mechanics can be calculated as usual. For a constant energy, conversion from time dependence into flight path dependence yields for the probability of $\nu_\mu(\nu_e)$ starting at the source to appear at distance x as $\nu_e(\nu_\mu)$:

$$P(x) = \sin^2 2\Theta \cdot \sin^2\left(\frac{\pi \cdot \delta m^2}{2.48 \cdot E_\nu} \cdot x\right) \qquad (1)$$

where Θ = mixing angle, $\delta m^2 = |m_1 - m_2|^2$ in eV^2, E_ν = neutrino energy in MeV, and x = distance from the source in m.

One way to measure the mass difference and (or) the mixing angle will be the detection of the appearance of ν_e's as a function of x and E_ν. This example is discussed in more detail in chapter VI. Equation 1 is of course also valid for other types of oscillation. Studies of the appearance and disappearance of different neutrino types could provide valuable information about mass differences and (or) violations of number conservation.

Measurements on neutrino coupling to other leptons continue to be important for the test of weak interaction theory. A particularly interesting process with beam stop neutrinos is the elastic scattering of electron neutrinos from electrons: $\nu_e + e^- \rightarrow \nu_e + e^-$. There the presence of neutral current (NC) as well as charged current (CC) interaction allows the observation of NC-CC interference. Because of the lack of sufficiently intense beams of ν_e's at high energies this reaction could not be studied until now.

In addition the measurement of $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ is still interesting for the study of the neutral current interaction at low energies.

The cross section for neutrino electron elastic scattering is calculated using the Lagrangian /2/:

$$L = \frac{G}{\sqrt{2}} \bar{\Psi}_\nu \gamma_\mu (1+\gamma_5) \Psi_\nu \bar{\Psi}_e \gamma_\mu (g_V + g_A \gamma_5) \Psi_e$$

In the Weinberg theory we have for the leptonic neutral coupling constants:

$$\text{for } \nu_e + e^-: \quad g_V^e = \frac{1}{2} + 2\frac{e^2}{g^2}; \quad g_A^e = \frac{1}{2} \tag{2}$$

$$\text{for } \nu_\mu + e^-: \quad g_V^\mu = -\frac{1}{2} + 2\frac{e^2}{g^2}; \quad g_A^\mu = -\frac{1}{2} \tag{3}$$

$$\frac{e^2}{g^2} \equiv \sin^2\Theta_W \tag{4}$$

This includes μ,e universality:

$$g_V^e = g_V^\mu + 1 \;\; ; \;\; g_A^e = g_A^\mu + 1 \tag{5}$$

The elastic differential cross section for (ν_e,e) is then given by:

$$\frac{d\sigma}{dE_e} = \frac{G^2 \cdot m_e}{2\pi E_\nu^2} \left[E_\nu^2 (g_V^e + g_A^e)^2 + (E_\nu - E_e)^2 (g_V^e - g_A^e)^2 + m_e E_e ({g_A^e}^2 - {g_V^e}^2) \right] \tag{6}$$

Inserting (5) into (6) and neglecting the third term in (6) gives:

$$\frac{d\sigma}{dE_e} = \frac{G^2 \cdot m_e}{2\pi} \Big[\underbrace{(g_V^\mu + g_A^\mu)^2 + \left(1 - \frac{E_e}{E_\nu}\right)^2 (g_V^\mu - g_A^\mu)^2}_{NC} + \underbrace{4}_{CC} + \underbrace{4(g_V^\mu + g_A^\mu)}_{IF} \Big] \tag{6a}$$

corresponding to neutral current, charged current and the interference term respectively.

Using equations (2) - (4) and integrating (6a) gives the total cross sections:

$$\sigma(\nu_e + e) \approx \frac{\sigma_o \cdot E_\nu}{m_e} \left(\frac{1}{4} + x + \frac{4}{3} x^2\right) \qquad (7)$$

$$\sigma(\nu_\mu + e) \approx \frac{\sigma_o \cdot E_\nu}{m_e} \left(\frac{1}{4} - x + \frac{4}{3} x^2\right) \qquad (8)$$

with $x \equiv \sin^2\Theta_W$; $\sigma_o \equiv \frac{2}{\pi} G^2 \cdot m_e^2 = 8.805 \cdot 10^{-45}$ cm^2.

The experimental results from all cross sections of purely leptonic neutral current reactions measured so far /3/ appear as ellipses in the (g_V^μ, g_A^μ) plane of fig.1.

Measuring $\sigma(\nu_e + e^-)$ would be interesting for three reasons /4/:

1. Assuming μ,e universality to be valid the Weinberg angle can be determined for electron neutrinos and at low energies using eq. (7).

2. In addition the measurement defines an ellipse in the g_V^e, g_A^e plane from the integral of eq. (6). Using eq. (6a) this can be transformed into an ellipse in the g_V^μ, g_A^μ plane with the center as for $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$ but with the major and minor axes interchanged (see fig.1). The displacement of the ellipse for $\nu_e + e^-$ away from the origin in the g_V^μ, g_A^μ plane is a measurement of the relative sign between the neutral and charged current amplitudes. This sign is given in the Weinberg-Salam-Glashow theory by the +1 in relation (5). Comparison with precise results from pure neutral current interactions (e.g. $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$) is, therefore a check of μ-e universality.

3. Measurement of the differential cross section (6) would give information on $|g_V^e|$ and $|g_A^e|$ separately.

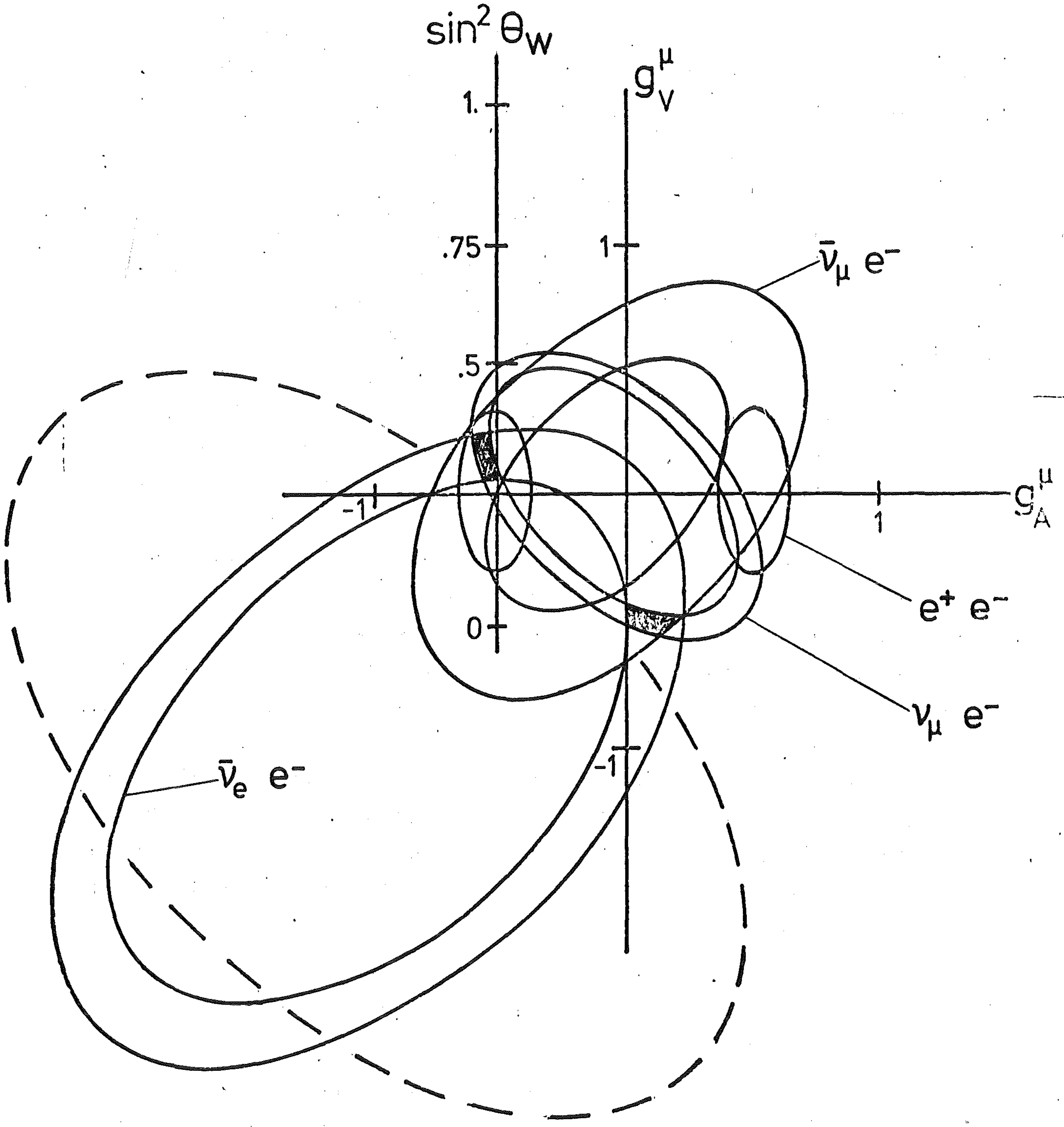

Fig.1: Experimental results from all cross section measurements of purely leptonic neutral current reactions

Using $\sin^2\Theta_W = 0.23$ a total counting rate of 350/fbyear$^+$ is expected in the 50 to organic scintillator reference detector at 16 m distance from the source.

In addition to the study of neutrino interaction with other leptons, coupling to hadrons is of interest. Coupling constants and form factors both for charged and neutral interactions could be derived from suitable experiments /5,6/. An interesting field of activities not covered so far by experiments is the excitation of nuclear levels by neutrino scattering. The nucleus is used as a microscopic laboratory having a defined spin-isospin, with a view to determine coupling constants in a selective way which is largely model independent. The excitation by mu-neutrinos would be particularly interesting. The reason is that this interaction excites nuclei only by neutral current coupling. The combination of the results of such measurements from β-decay, electron scattering and γ-decay of energy levels of nuclei would allow detailed testing of the unified theory of electromagnetic and weak interactions. A number of articles and proposals have been published in recent years about this field of 'nuclear physics involving neutral currents'. A comprehensive description has been presented by T.W.Donnelly and R.D.Peccei /7/. An interesting example would be the inelastic excitation of the $(1^+,1)$ 15.11 MeV level in ^{12}C by mu-neutrinos:

$$^{12}C(\nu_\mu,\nu_\mu')^{12}C^* \; (0^+0 \rightarrow 1^+1,\ 15.11\ \text{MeV})$$

Since the level in ^{12}C decays into the ground state with 95% probability the 15.11 MeV γ-ray constitutes a clear signature for the excitation of a nucleus by neutral current coupling. Since the spin and the isospin are defined, measurement of the

$^+$fbyear means one year of full beam intensity at SNS. This is expected to be two years of actual time.

total cross section for this reaction would already be appropriate for the selective determination of the isovector part of the neutral current. The integral cross section at neutrino energies below approximately 100 MeV is obtained as /7/:

$$\sigma_{\nu\nu'} = \text{const.}\,|< 1;1||L||0;0>|^2\ (E_\nu - 15.11)^2\ C_Q^2 \quad (9)$$

where E_ν is the neutrino energy in MeV. The reduced matrix element is the same as that occurring in the calculation of the β-decay rate (see p.47 of /7/):

$$\omega_{\beta^\pm} = \frac{4}{3\pi^2}\, G^2\, f^\pm \,.\, |< 1;1||L||0;0>|^2 \quad (10)$$

Introducing (10) into (9) and use of the measured β-decay rates gives independent of the nuclear model:

$$\sigma_{\nu\nu'} = 1.08\cdot 10^{-38}\ \frac{(E_\nu - 15.11)^2}{M_N^2}\cdot C_Q^2 \quad \text{cm}^2 \quad (11)$$

where C_Q^2 is a coupling constant for isovector axial coupling. Very different values are obtained for this cross section for different gauge theories /7/.

Supposing that the WSGIM-model is correct, we have $C_Q^2=1$. With this assumption, an integral inelastic scattering cross section of $\sigma(\nu_\mu, \nu_\mu') = 2.5\cdot 10^{-42}$ cm^2 is obtained for the mu-neutrinos from the spallation neutron source (E_{ν_μ} = 30 MeV).

Since the measurement can be confined to the beam-on time of only 100 ns per pulse the background suppression is expected to be very good. The counting rate in the 50 to organic scintillator reference detector would be about 500/fbyear.

Inverse β-decay with electron neutrinos would produce the highest counting rates of all neutrino induced reactions. Measurements of the cross sections can be valuable as another check of weak interaction theory in nuclei at neutrino energies up to 50 MeV. But their main importance may lie in their use as detector reactions for the appearance or disappearance of electron neutrinos in oscillation experiments. An example in our 50 to reference detector is the reaction:

$$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N - 17.8\ \text{MeV}$$

$$\downarrow 11\ \text{msec}$$

$$e^+ + {}^{12}C + 16.8\ \text{MeV}$$

The expected counting rate at 16 m distance is approximately 3000/fbyear.

The desired extension of the unified theories of interactions might lead to the postulation of light scalar gauge bosons /8,11/. Because of the small duty cycle investigations including such particles could be performed at SNS in parallel with neutrino physics using similar or the same detectors.

The importance of neutrino experiments at high-intensity proton accelerators at medium energies has been discussed intensively by several authors in recent years; see /6,7,12/. During the past months, detailed proposals have been submitted for experiments to be performed at LAMPF /13,14,15,16,17/.

III. NEUTRINOS FROM THE SPALLATION NEUTRON SOURCE

1. Intensity and energy distribution of beam stop neutrinos

The protons do not only give rise to the production of neutrons in the spallation target. At the same time large numbers of pions are produced which emit neutrinos while decaying. Fig.2 shows the calculated number of π^+ particles produced per stopped proton for different target materials as a function of the proton injection energy /18/. The result of the calculation for the SNS with E_p = 800 MeV and a mixture of Uranium and heavy water as target material /19/ is $N_{\pi^+}/N_p = 0.07$.

The pions are very quickly stopped (10^{-10}s) still in the target zone so that only a small fraction of about 10^{-3} decay while in flight. Whilst the negative pions, when at rest, are captured by nuclei and finally absorbed, the positive pions, with a lifetime τ = 26 ns, decay into a positive muon and a muon neutrino. This means that only the positive pions and the positive muons play a role at the spallation neutron source. The muon with a lifetime τ = 2.2 μs subsequently decays into a positron and into an electron neutrino and a muon antineutrino. Thus, we have

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \tau = 26.03\times10^{-9}\ \mathrm{s} \qquad (12)$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \qquad \tau = 2.197\times10^{-6}\ \mathrm{s} \qquad (13)$$

Since the pion at rest decays into two particles only, the muon neutrinos from (12) have a constant energy E_{ν_μ} = 29.79 MeV.

By contrast, continuous distributions with an end energy of 52.83 MeV are obtained for the neutrinos produced by the three-particle decay (13). The energy distribution of the ν_e and $\bar{\nu}_\mu$ respectively are given by:

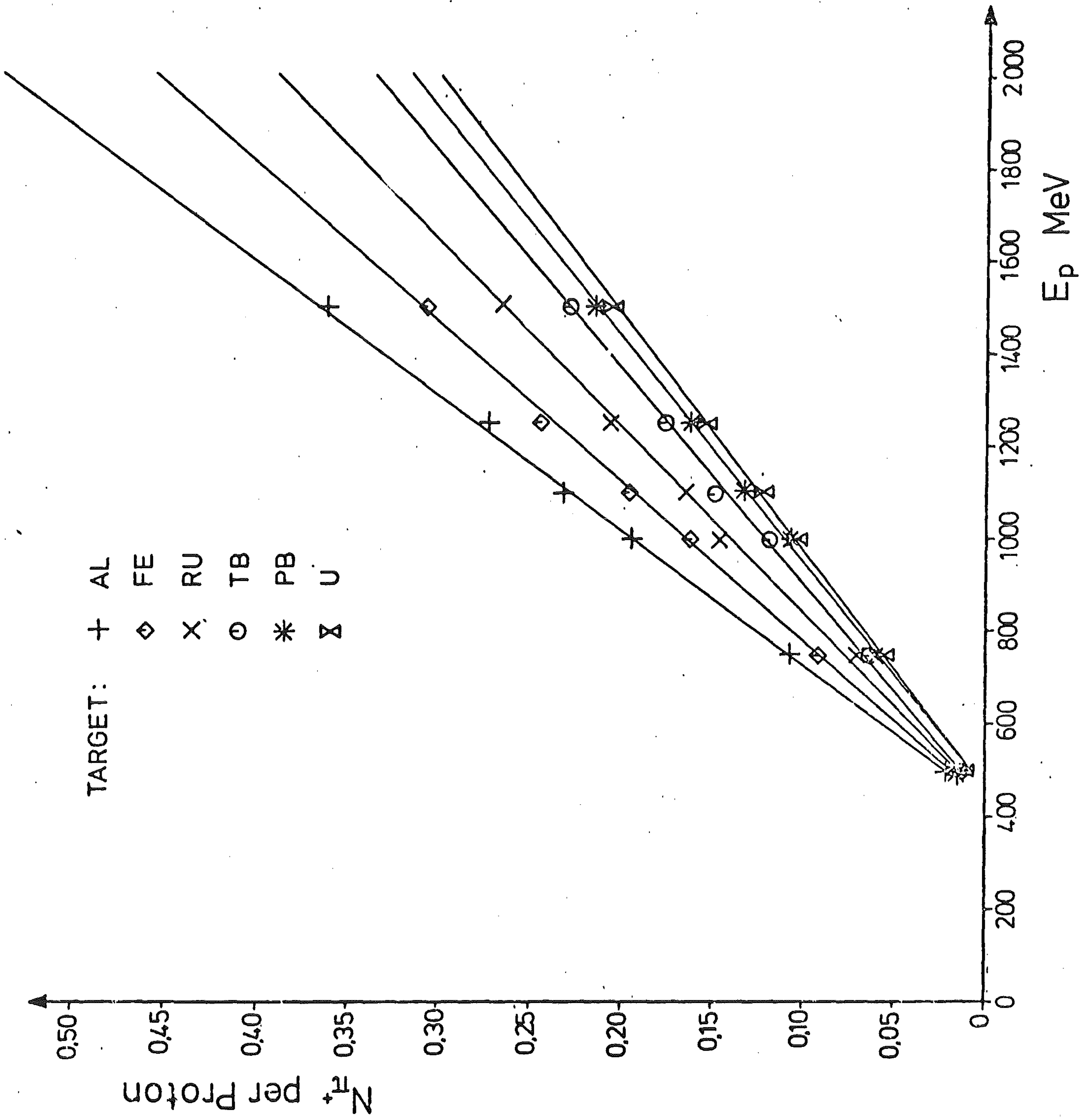

Fig.2: Yields of pions (π^+) per stopped proton for different target materials

$$N(\varepsilon)\,d\varepsilon = 4\varepsilon^2 \left[3(1-\varepsilon)+\tfrac{2}{3}\rho(4\varepsilon-3)\right]d\varepsilon \qquad (14)$$

$$\varepsilon \equiv \frac{E_\nu}{E_{max}}\ ;\ E_{max} = 52.83\ \text{MeV}$$

$$\rho \equiv \begin{cases} \frac{3}{4} & \text{for } \bar{\nu}_\mu \\ 0 & \text{for } \nu_e \end{cases}$$

The spectra expected at the SNS are shown in fig.3.

This source can be utilized for distances from about 12 m on, where it will appear practically as a point source yielding (for each type of neutrino ν_μ, ν_e and $\bar{\nu}_\mu$) a flux of:

$$\phi_\nu = \frac{Q_\nu}{4\pi r^2} \qquad (16)$$

$$\phi_\nu = \frac{7.0\times10^8}{r^2}\ \text{cm}^{-2}\ \text{s}^{-1} \qquad (17)$$

r in m; flux for $\bar{I}_p$ = 200 μA at SNS

However, in future experiments involving neutrinos not only a high average flux but likewise a suitable time structure and the highest possible peak flux will play a role. There are three main reasons for this requirement:

Many of the experiments of interest after 1985 need separation of the different kinds of neutrino. For this purpose, the very different lifetimes of pion- and muon decay can be used. This will be treated more comprehensively in the next chapter.

Because of the very small cross sections in neutrino experiments, the number of background events originating from continuous sources (cosmic rays, detector noise, etc.) must be kept extremely low. Therefore, the smallest possible effective duty cycle of the beam should be sought.

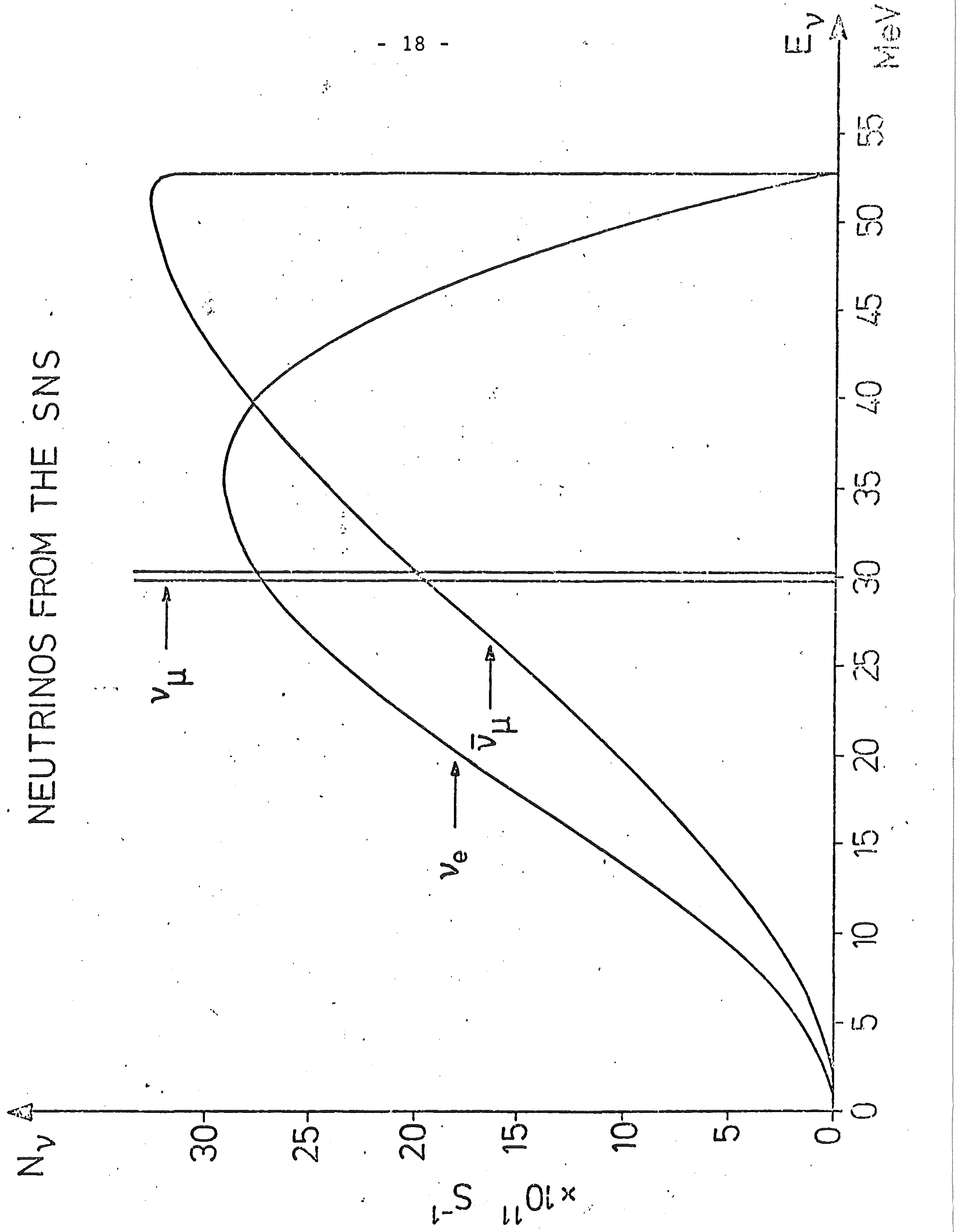

Fig.3: Energy distributions of the neutrinos generated at the SNS spallation neutron source (beamstop). The total numbers of all three kinds of neutrino are equal. The indicated source strengths apply to 200 µA averaged proton current for E_p=800 MeV

Background events from the source reaching the detector even through the very thick shielding are produced mainly by neutrons. The slow part of the spectrum of neutrons can be eliminated by time of flight measurements.

2. Time Dependence of the Neutrino Flux

For a rectangular pulse of the proton beam with the pulse duration t_p the time dependence of the neutrino source strengths given by the expressions (18) to (21) are obtained in accordance with the different lifetimes τ_π and τ_μ of the pions and muons generated:

For the source flux of the mu-neutrinos ν_μ from the π^+-decay one gets:

$$\phi_{\nu_\mu} = Q_0 \left(1 - e^{-\frac{t}{\tau_\pi}}\right) \qquad t \leq t_p \qquad (18)$$

$$\phi_{\nu_\mu} = Q_0 \left(e^{\frac{t_p}{\tau_\pi}} - 1\right) e^{-\frac{t}{\tau_\pi}} \qquad t \geq t_p \qquad (19)$$

For the source flux of the electron neutrinos ϕ_{ν_e} (identical with that of mu-antineutrinos $\phi_{\bar{\nu}_\mu}$) we obtain in good approximation ($\tau_\mu >> \tau_\pi$):

$$\phi_{\nu_e} = Q_0 \frac{t_p}{(t_p+\tau_\pi)\tau_\mu} \cdot t \cdot e^{-\frac{t}{\tau_\mu}} \qquad t \leq t_p + \tau_\pi \qquad (20)$$

$$\phi_{\nu_e} = Q_0 \frac{t_p}{\tau_\mu} e^{-\frac{t}{\tau_\mu}} \qquad t \geq t_p + \tau_\pi \qquad (21)$$

where

$$Q_0 = 0.07 \, \frac{6.24\text{x}10^{15}}{f \cdot t_p} \, mA^{-1} \, s^{-1} \qquad (22)$$

f = pulse frequency in Hz

t_p= pulse length of the protons in s.

The double proton pulse structure (2 pulses of 100 nsec length each, separated by 230 nsec) leads to the time dependence of the neutrino fluxes shown in fig.4. The repetition frequency of this structure is f = 50 Hz. As can be easily seen the use of time windows of 100 nsec will separate the ν_μ from the ν_e and $\bar{\nu}_\mu$. The ratio to the rest of ν_e and $\bar{\nu}_\mu$ under the short ν_μ pulses can be calculated with high precision.

Using this time structure in combination with corresponding selective detector reactions leads to very stringent signatures for measurements with ν_μ,ν_e and (oscillated) $\bar{\nu}_e$.

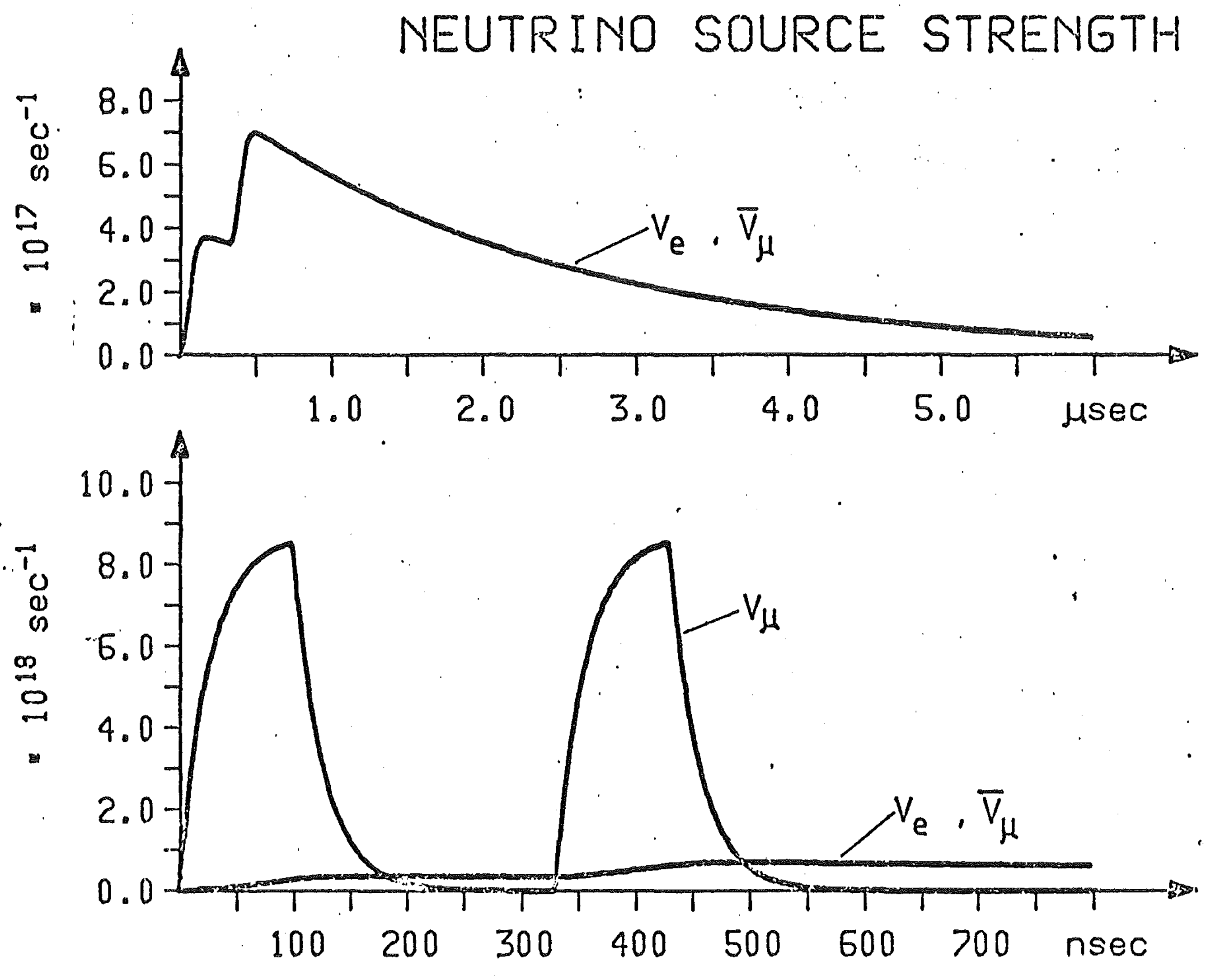

Fig. 4: Time dependence of the neutrino source strengths at the SNS spallation neutron source (t_p = 100 nsec; Δt_p = 330 nsec; $\bar{I}_p$ = 200 μA; f = 50 Hz)

IV. PROPOSED FACILITY AT SNS

Neutrino experiments are difficult mainly for the reason that the probability of detecting strong or electromagnetic interacting background radiation is higher by 10 to 20 orders of magnitude than it is for neutrinos governed by the weak interaction. In table 1 realistic counting rates for different neutrino reactions in a 50 ton organic scintillator detector are listed for various distances from the neutrino source. These numbers have to be compared with those from background reactions of neutrons and gammas correlated to the SNS as well as from cosmic rays. As this background must not exceed the true event rate a facility in which neutrino experiments are to be performed has to be shielded heavily both against the source and cosmic rays. The small duty factor of 10^{-5} strongly suppresses all sources of continuous residual background radiation. In addition this background can be measured on-line in the pulse pause of the SNS. Nevertheless shielding has to provide a reduction of background in the detector to about 1 day^{-1}. Therefore, detailed calculations were carried out to find the optimum location and shielding requirements for a neutrino area at the SNS:

1. Background from the Spallation Neutron Source

Presently there is only 2 m of iron and 1 meter of concrete below the target station. The concrete base is followed by chalk ($CaCO_3$) with density of 2.1 g/cm^3. To reduce the number of neutrons and gammas entering the detector to a level in the order of 1 day^{-1} will require an underground cave, the top of which is located 9 meters below floor level (see fig.7). Even then an additional shielding of 3 m of iron above the detector will be required.

Table 1: Counting rates for various neutrino reactions for a 50 ton organic scintillator reference detector with neutrinos from the Spallation Neutron Source SNS

Reaction	Counting Rate $(\text{fbyear})^{-1}$ at 12m	16m	18m	mean cross section
$\nu_e + e^- \rightarrow \nu_e + e^-$ (*)	624	351	277	$\bar{\sigma} = 3.1\times10^{-43}$ cm^2
$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ (*)	93	52	41	$\bar{\sigma} = 4.7\times10^{-44}$ cm^2
$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$ (*)	98	55	44	$\bar{\sigma} = 4.9\times10^{-44}$ cm^2
$\nu_\mu + {}^{12}C \rightarrow \nu_\mu + {}^{12}C^*(15.11)$ $\downarrow$ ${}^{12}C + \gamma$	881	495	392	$\sigma = 2.5\times10^{-42}$ cm^2
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N - 17.8$ MeV $\downarrow$ ${}^{12}C + e^+ + 16.8$MeV	5146	2894	2287	$\bar{\sigma} = 1.4\times10^{-41}$ cm^2

fbyear means one year (24 h x 365 d) of full beam intensity ; expected to be two years of actual time

SNS parameters: $E_p = 800$ MeV; $\pi^+/p = 0.07$; $\bar{I}_p = 200$ μA

$\phi^o_\nu(12m) = 4.83\times10^6$ cm^{-2} sec^{-1}

Detector parameters: Organic scintillator $CH_{1.1}$; $\rho = 1.032$ g cm^{-3}

$N_{^{12}C} = 4.78\times10^{22}$cm^{-3}; $N_p = 5.28\times10^{22}$cm^{-3}

$N_{e^-} = 3.39\times10^{23}$ cm^{-3}

* ν-spectra folded in; energy cut $E_e > 5$ MeV, $\sin^2\Theta_W = 0.23$

The time dependent neutron flux for different energy regions entering the top of the detector is shown in fig.5 together with the associated γ-flux. Fig.6 shows the energy spectra of neutrons and gammas entering the top of the reference detector. Taking into account only neutrons and gammas with energies above 1 MeV, 0.3 day^{-1} of each will enter the detector.

Although the massive amounts of iron and concrete on top of the cave can shadow shield many neutrons and gamma rays approaching the detector, those which enter the side of the cave have also to be taken into account.This is due to the fact that the shielding of neutrons by chalk is less effective compared to iron. For example, the ratio of the attenuation of iron, heavy concrete and chalk goes like 300:100:10. Neutrons which come down the side of the cave through the chalk can scatter into the detector room. The calculations showed that even at 12.5 meter below floor level walls with thickness of at least 1 m of heavy concrete ($\rho \geq 3.5$ g/cm^3) are required to reduce the number of neutrons entering the detector to about 1 day^{-1}. As these neutrons enter mostly within the top 50 cm of the detector room it is necessary that the access tunnel enter the neutrino area at the bottom of the cave.

2. Cosmic background

The high energy muon component of cosmic rays is much more penetrating. Therefore, this is another source of background to be considered. From earlier very conservative calculations /18/ for a 50 to detector below 3.3 m of iron and 2 m of concrete we got an event rate due to cosmic background of about $5\text{x}10^6$/day $^+$. As at the SNS much more iron is located above the detector this value will be reduced by at least a factor of two. The low effective duty factor of 10^{-4} (10^{-5} for ν_μ's) thus reduces the cosmic ray background to about 100 day^{-1}. An active antishield with a suppressionfactor of only 10^{-2} to 10^{-3} will reduce this background to a neglible quantity. An active shield

$^+$see fig.6a

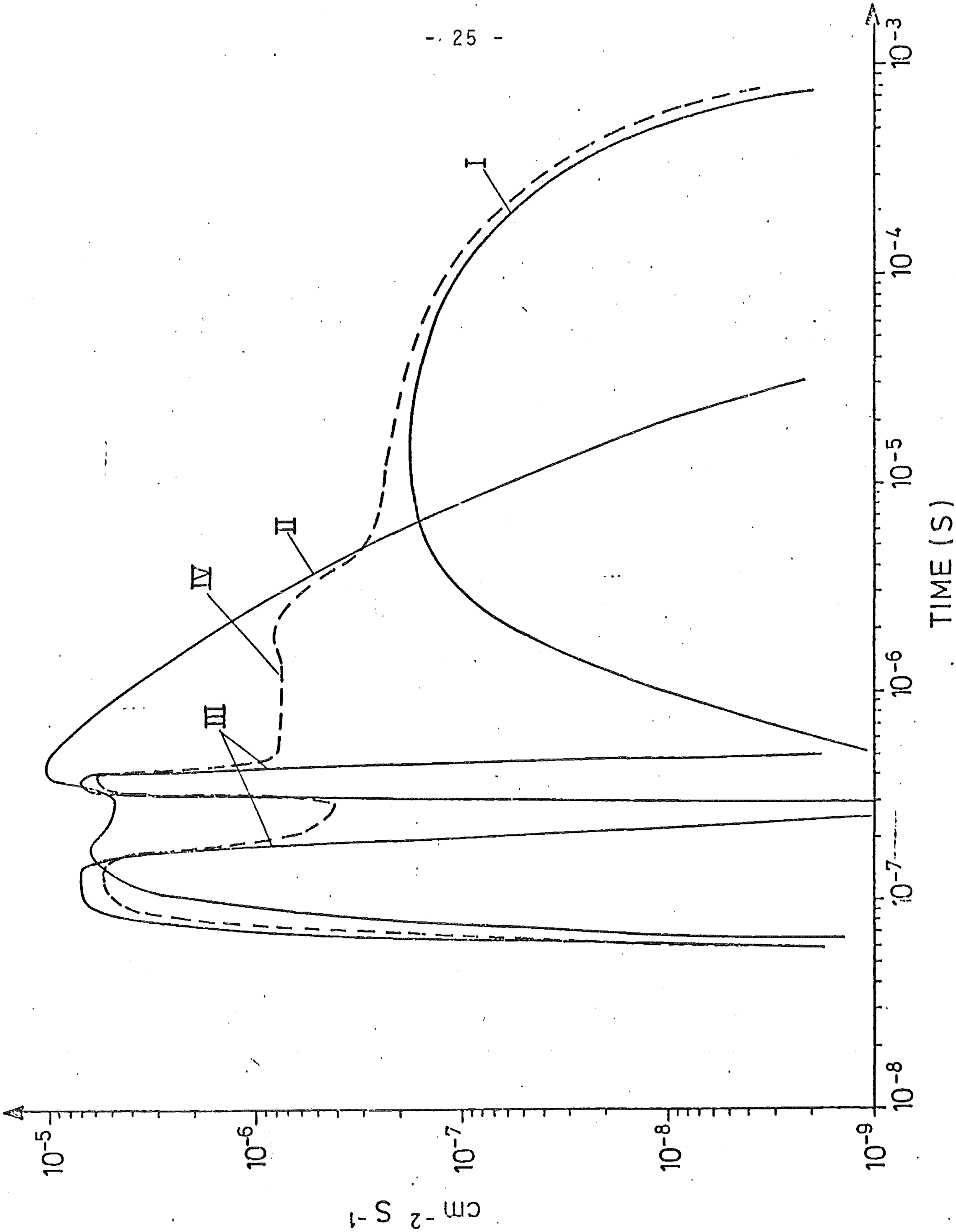

Fig.5: Time dependence of the neutron and gamma ray flux at the front edge of the detector in the neutrino facility at SNS; E_p = 800 MeV, $\bar{I}_p$ = 200 µA
I thermal neutrons
II low energy neutrons; 0.4 MeV < E_n < 1 MeV
III fast neutrons; E_n > 1 MeV
IV gamma rays

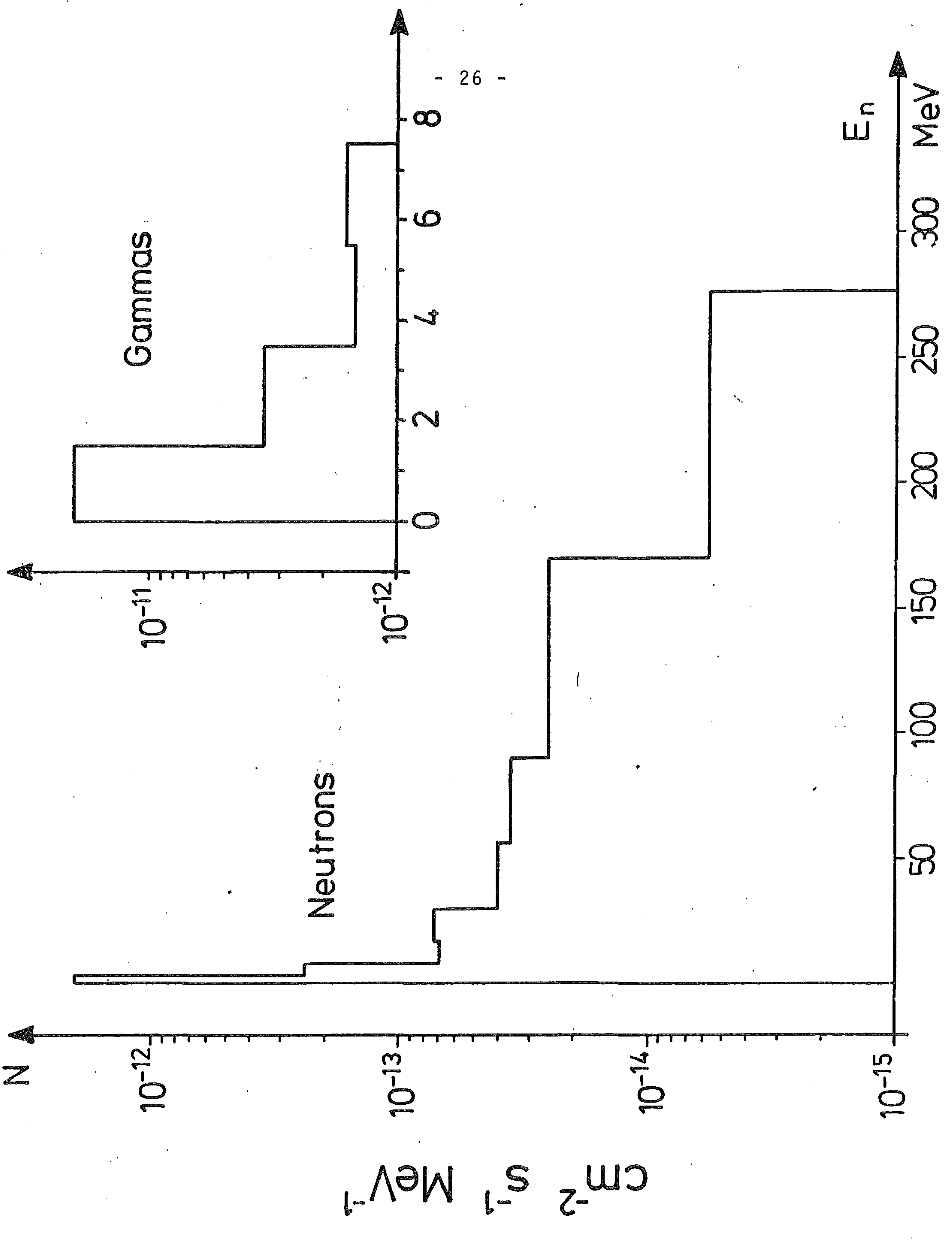

Fig.6 : Energy dependence of the neutron and gamma ray background entering the neutrino cave at SNS

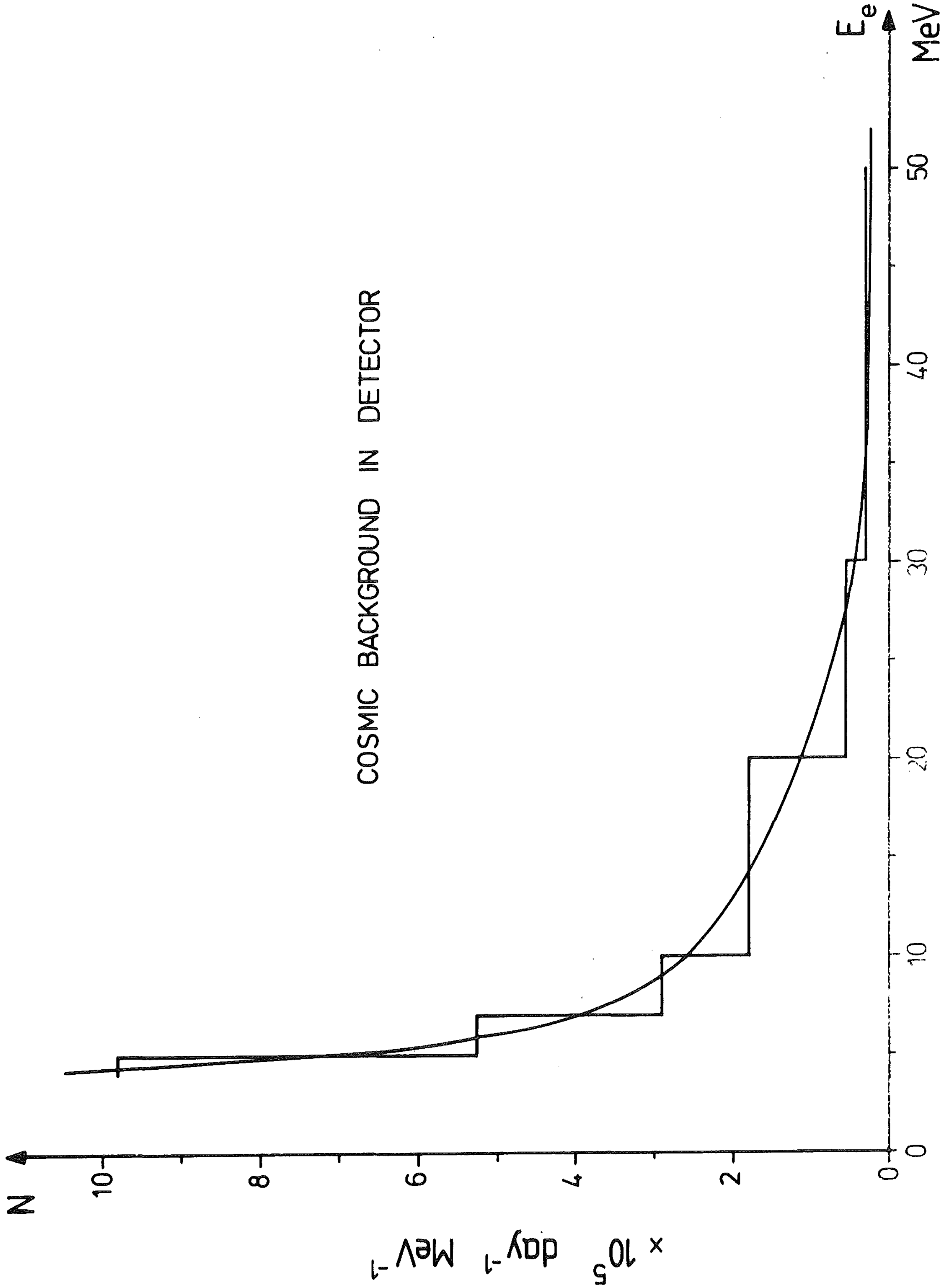

Fig.6a: Energy dependence of the cosmic background measured in the detector

may even be dispensable when the outer layer of the detector will be regarded as an anticounter. In addition this background will be measured between the beam pulses of the spallation source.

The above considerations led to the proposal of a neutrino facility at the SNS as shown in fig.7. A 25 m long access tunnel from outside the experimental hall reaches the bottom of the neutrino cave directly below the spallation target at 20 m below floor level. The inner cave measures 6 m width x 7 m length x 7 m height which is a volume of 294 m^3. The walls of the cave are of heavy concrete with a thickness of 1 meter. The roof consists of 3 meters of iron. The feasibility of elevating the iron roof has been investigated and does not cause serious technical problems. Anticounters may be placed between the support of the roof and the iron to reduce gamma background from bremsstrahlung from muons and electrons, mainly produced in the last layer of the shielding towards the detector. The detector has to be brought into the cave through the access tunnel in suitable parts and will be mounted together there. The shielding properties and the size of this neutrino cave will allow a 50 to organic scintillator detector together with a 50 to liquid Argon detector to measure various neutrino reactions.

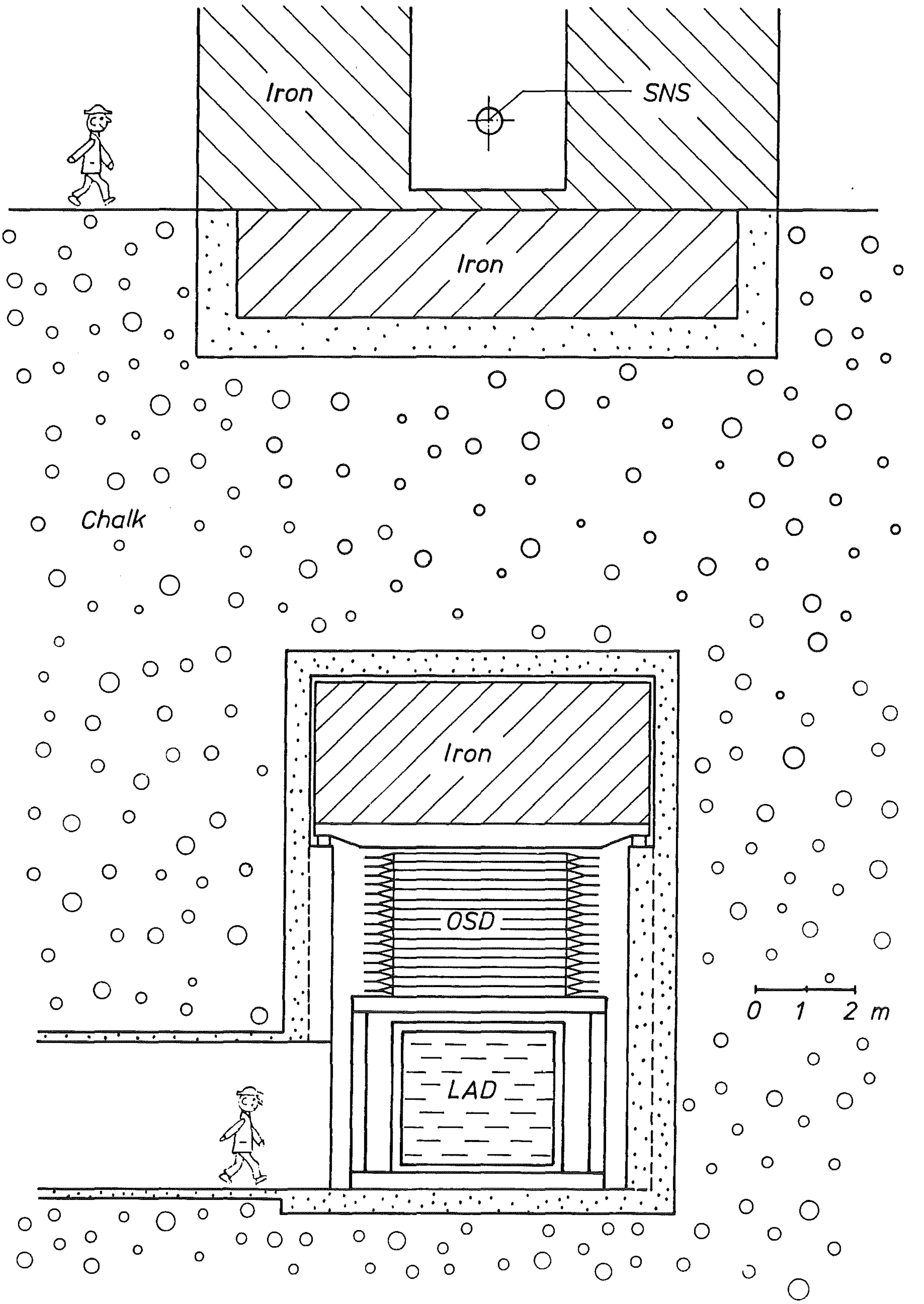

Fig.7: Schematic view of the proposed neutrino cave in the chalk below the Spallation Neutron Source SNS.(see also fig. 7a)

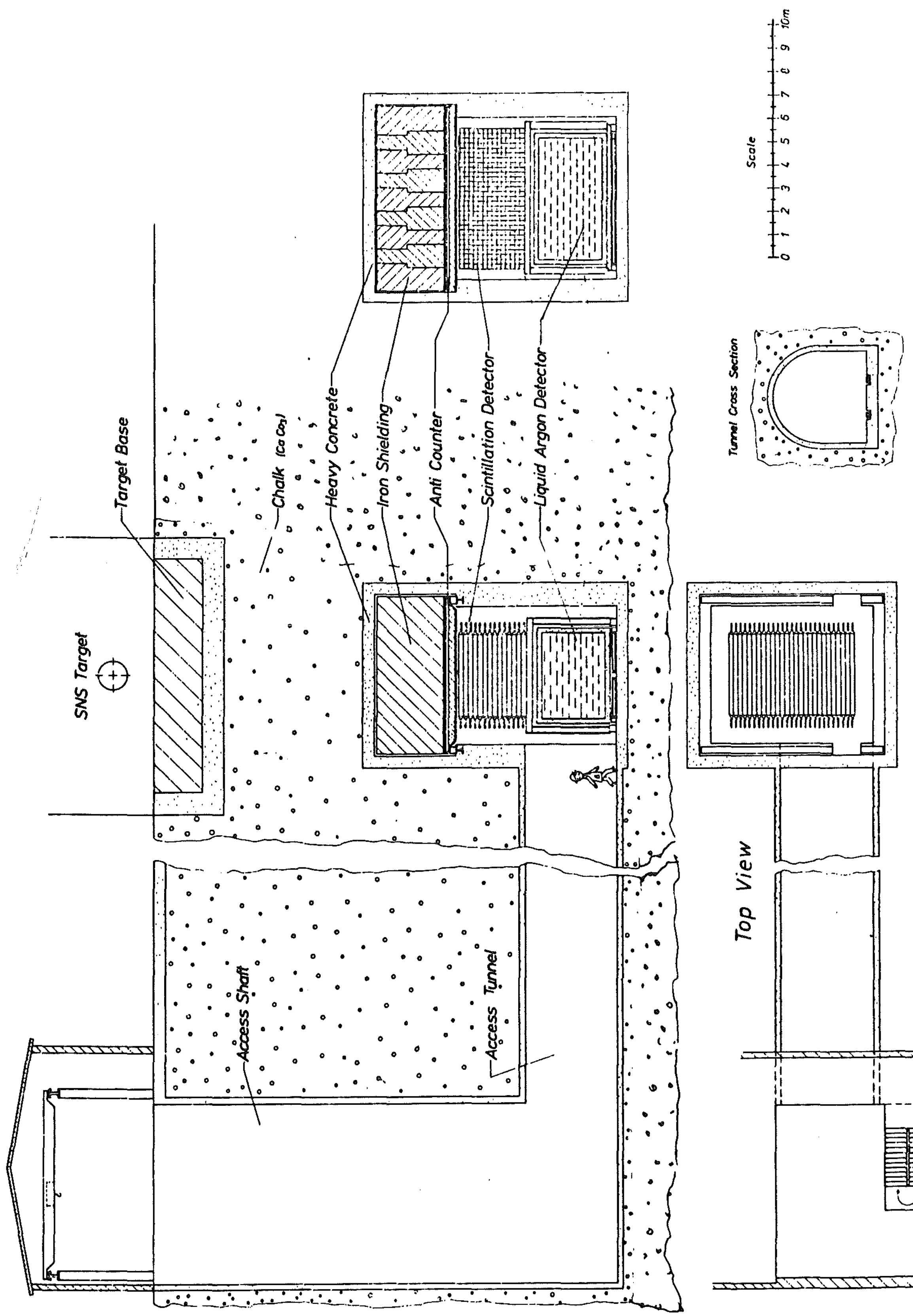

Fig. 7a: Side view and top view of the proposed neutrino facility at the Spallation Neutron Source SNS .

V. DETECTOR SYSTEM

The design of the detector system is determined by the requirements to allow observation of the various neutrino induced reactions quoted in chapter II, i.e.:

i. elastic neutrino electron scattering

$$\nu + e^- \rightarrow \nu + e^-$$

ii. inelastic neutrino-^{12}C scattering

$$\nu + {}^{12}C \rightarrow \nu' + {}^{12}C^* \text{ (15.11 MeV)}$$

$$\xrightarrow{95\%} {}^{12}C + \gamma$$

iii. inverse ß-decay of ^{12}C

$$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N \quad - 17.8 \text{ MeV}$$

$$\xrightarrow{11 \text{msec}} {}^{12}C + e^+ + \nu_e + 16.8 \text{ MeV}$$

iiii. inverse ß-decay of ^{1}H

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Thus a multipurpose detector is necessary which simultaneously serves as electron, carbon and proton target. In order to be able to measure the above reactions with sufficient statistics within a reasonable time of about two years (see table 1) the detector should have a fiducial mass of at least 50 to. It has to supply an unambigous signature with quantitative information for each of the different reactions.

Such a detector generally should have good energy- and spatial resolution as well as good timing properties. For such a big detector it is normally impossible to give all three properties maximum performance. Therefore, for each reaction type one has to decide which of these are crucial, having in mind the energy and time spectra of the different types of neutrinos.

We propose a combined detector system consisting of a large Liquid Argon Ionisation Detector (LAD) of 50 tons fiducial mass and an organic scintillation detector (OSD) with a total mass of another 50 tons as shown schematically in fig.7.

$\nu + e^-$ scattering

The differential cross section $\frac{d\sigma}{dE_e}(E_e)$ of neutrino electron elastic scattering is shown in fig.8. The counting rate per MeV and year is plotted versus the energy of the recoil electrons in a 50 ton liquid Argon detector at 18 m distance from the SNS ν-source. The different ν-spectra are already folded in. To measure this quantity the detector should provide good energy resolution for electrons in the energy range from 10 MeV to 50 MeV.

Due to the ν-e scattering kinematics shown in fig. 9 an energy cut at 10 MeV restricts the direction of the recoil electrons within a cone of $\pm 15^o$. The mean range of these electrons is of the order of 10 - 20 g/cm^2. Although the multiple scattering angle for electrons in this energy range is of the order of 5^o a fine granularity would allow one to at least roughly determine the scattering angle. This would substantially improve the event signature. Time resolution of the order of 30 to 50 nsec would allow to separate ν_e-e^- and $\bar{\nu}_\mu$-e^- from ν_μ-e^- scattering.

A detector system with these properties can be realized by a large liquid Argon ionization chamber. The unique energy resolution of a liquid ionization detector due to the statistics of charged particles per deposited energy should be preserved in the specific detector design. Two different prototypes will be investigated more thoroughly during the next two years. One is a small gap (10 mm) ionization chamber with low capacitance anode strips, a technique well proved at our laboratory. The other is a wide gap (70 mm) time projection drift chamber with additional grid electrods. In both cases for 10 - 50 MeV electrons an energy

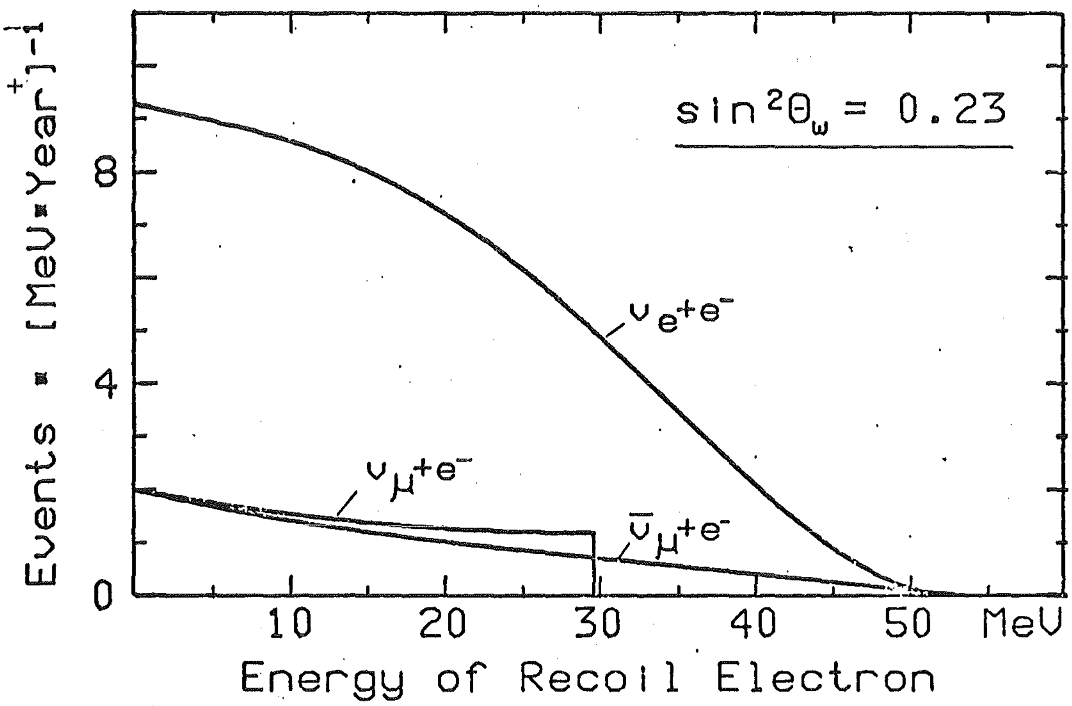

Fig.8: Energy dependent countrate for ν-e^--scattering expected in a 50 ton liquid Argon detector at 18 m distance from the ν-source.
The differential cross section using the Weinberg-Salam model with $x = \sin^2\Theta_W = 0.23$ has been folded with the neutrino spectra for ν_e, ν_μ and $\bar{\nu}_\mu$ from the SNS

$^+$fbyear

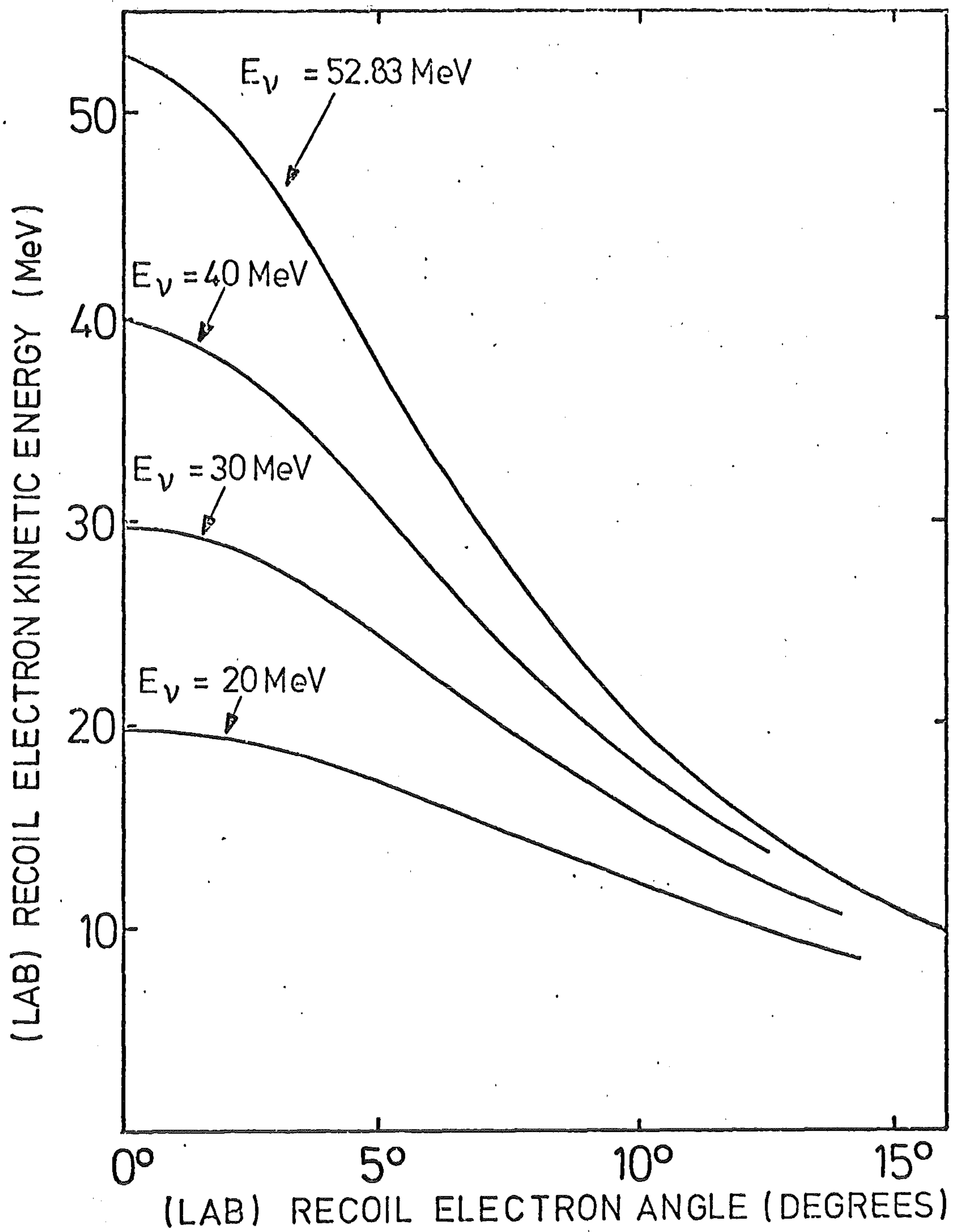

Fig. 9 : Angular dependence of the energy of the recoil electrons from ν-e^- elastic scattering for various neutrino energies

resolution of better than 10% and a granularity of 5-10 mm is expected where the wide gap solution provides the more promising features. Reasonable timing of about 50 nsec will be achievable from charge collection only. Better time resolution may be provided by the scintillation light from LAr which would permit the identification of ν_μ-e^- scattering.
A report containing some more detailed considerations of a LAr-detector is in preparation /20/.

The observation of ν_e-e^- scattering in a LAr detector may be distorted by the reaction $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K$. There are no published calculations on the cross section of this reaction. First results of corresponding calculations were reported by S.Furui /22/. The mean total cross section is expected to be of the order of $1.3 \cdot 10^{-40}$ cm^2,the angular distrubition of the electrons being approximately isotropic. On the other hand the cross section of ν_e-e^- scattering is concentrated at angles smaller than $\Theta_e \approx 15^o$. Thus a reliable extrapolation and subtraction of the ν_e-Ar cross section is possible. Depending on the actual energy and angular resolution of the LAD the uncertainty of the ν_e-e^- cross section is expected to be smaller than $\pm$ 10%. More detailed considerations need the knowledge of the properties of the LAD prototype.

ν-^{12}C- and ν-p reactions

For detection of the ν-^{12}C-reactions a 50 ton organic scintillator detector (OSD) is proposed consisting of 350 cm long rectangular segments of organic scintillator with cross section of about 20 cm x 20 cm and photo tubes at each end. The coincidence requirement between the two photomultipliers allows for noise suppression whereas a time difference measurement provides a spatial resolution of about 10 cm.

The excellent timing properties of an OSD permit full use of the time structure and low duty cycle of the SNS. Thus the inelastic scattering process $\nu_\mu + {}^{12}C \rightarrow \nu_\mu' + {}^{12}C^*$ (15.1 MeV) will be observed only during the first 100 nsec. This together with an energy resolution of about 15% for gammas and of $\leq$ 10% for electrons, which has been calculated for a 50 ton reference detector with a light and energy transport code /14/ will give a clear signature for such events. Inelastic scattering of ν_e and $\bar{\nu}_\mu$ on ^{12}C will be observed during the next 0.5 - 5 μsec looking for a 15 MeV energy signal.

The inverse beta decay process

$$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N \xrightarrow{11\ msec} {}^{12}C + e^+$$

will be identified by delayed coincidence between the e^- and the e^+ signal with the e^+ having an end point energy of 16.3 MeV. In addition although the granularity does not allow the exact definition of a vertex, the spatial resolution of about 10 cm is sufficient to decide whether the coincidence has the same local origin.

Looking for these events in the first 100 nsec will yield information about $\nu_\mu \rightarrow \nu_e$ oscillations (see chapter I. and VI.).

For a measurement of the cross section of ν-e scattering in the OSD a much higher granularity would be desirable to at least roughly define the direction of the recoil electrons. This is also true for the observation of the $\bar{\nu}_e + p \rightarrow e^+ + n$ reaction. There the e^+ emerge mainly in the backward direction carrying roughly the $\bar{\nu}_e$-energy. The neutrons, going forward, can be detected by coincidence in another scintillation layer. The signature would be even more stringent if wire chambers would be used between the scintillator layers which would only be triggered by charged particles /14/.

However, first estimates from our reference detector calculation /18/ indicate decreasing energy resolution in a sandwich design of scintillator slabs and position sensitive proportional drift chambers in between. The deterioration of energy resolution arises from worse scintillation light statistics in each slab, energy sampling uncertainties and energy straggling within inactive material. This will be investigated more thoroughly in the prototype developement.

In our proposed detector system the OSD contains 50 tons of organic scintillator at a mean distance of R_1 = 16.5 meters from the ν-source. In case of a mineral oil liquid scintillator

Table 2: Counting Rates for various neutrino reactions for the proposed scintillation and liquid Argon detector system at the SNS

Reaction	Counting Rate $(\text{fbyear})^{-1}$ OSD	LAD	TOTAL	mean cross section
$\nu_e + e^- \rightarrow \nu_e + e^-$ (*)	330	186	516	$\bar{\sigma} = 3.1\text{x}10^{-43}$ cm^2
$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ (*)	49	28	77	$\sigma = 4.7\text{x}10^{-44}$ cm^2
$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$ (*)	52	30	82	$\bar{\sigma} = 4.9\text{x}10^{-44}$ cm^2
$\nu_\mu + {}^{12}C \rightarrow \nu_\mu' + {}^{12}C^*(15.11)$	465			$\sigma = 2.5\text{x}10^{-42}$ cm^2
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$ ↓ ${}^{12}C + e^+$	2721			$\bar{\sigma} = 1.4\text{x}10^{-41}$ cm^2
$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$		4500		$\bar{\sigma} \approx 1.3\text{x}10^{-40}$ cm^2
$\bar{\nu}_e + p \rightarrow e^+ + n$ (+)	2722			$\bar{\sigma} = 1.2\text{x}10^{-40}$ cm^2

fbyear means one year (24 h x 365 d) of full beam intensity at SNS with $\bar{I}_p = 200\ \mu A$

Detector parameters:

OSD: averaged distance $R_1 = 16.5$ m, $\bar{\phi}_o = 2.55\text{x}10^6$ cm^{-2} sec^{-1},
mass = 50 to

LAD: averaged distance $R_3 = 20$ m, $\phi_o = 1.74\text{x}10^6$ cm^{-2} sec^{-1},
mass = 50 to, $N_e = 1.36\text{x}10^{31}$

* ν-spectra folded in; energy cut $E_e > 5$ MeV; $\sin^2\Theta_W = 0.23$

(+) $\bar{\nu}_e$ from hypothetical oscillation $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$: assuming $\delta m^2 = 1$ eV^2; $\sin^2 2\Theta = 0.4$ would result in $N_{\bar{\nu}_e} = 11\%\ N_{\bar{\nu}_\mu}$ at 16.5 m.

it could be contained in rectangular extruded acrylic pipes or in large vessels with suitable segmentation by totally reflecting lucite sheets.

The LAD is proposed to have a fiducial Argon mass of another 50 ton. For the wide gap solution with 70 mm drift space the collection electrodes are segmented into pads of about 10 mm x 10 mm. Suitable connection in parallel of different pads will keep the electronic channels to be read out at about 15000.

In table 2 the counting rates for the different ν-reactions are given for this specific detector design at the SNS.

The final decision on the detector design will be made after thorough experimental investigations on prototypes for the scintillation detector as well as for the liquid Argon detector.

VI. EXPERIMENTAL SENSITIVITIES

1. Neutrino Oscillation Experiments

There are several possibilities in detecting the appearance or disappearance of a certain kind of neutrino. In the following we will discuss a typical example in somewhat more detail. We want to observe $\nu_\mu \leftrightarrow \nu_e$ oscillations using the unique time structure of SNS:

a) All ν_e events (detected in the OSD by the $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$ reaction) are stored together with the information of their time of appearance relative to the proton pulses.

b) We compare the number of ν_e events during beam-on times with the number detected after beam-on time.

Without oscillation only a very small number of ν_e's reach the detector during the two 100 nsec beam-on times.

In addition this number is reduced by a cut at approximately 25 MeV in the continuous E_{ν_e} spectrum.

But with oscillation $\nu_\mu \rightarrow \nu_e$ as a function of distance a line of 30 MeV ν_e's will appear (during beam on times only).

After beam on time (0.5 - 5 μsec) we will detect the disappearance of ν_e's as a function of distance.

Since we are measuring both numbers simultaneously we can define an asymmetry which is a sensitive and flux independent measurement of the $\nu_\mu \leftrightarrow \nu_e$ oscillation:
The transition probability is (see equ.1) given by:

$$P(x) = \sin^2 2\Theta \sin^2 \left(\frac{\pi \ \delta m^2}{2.48 \cdot E_\nu} \cdot x\right) \text{for } \nu_\mu \rightarrow \nu_e \qquad (23)$$

where Θ = mixing angle, $\delta m^2 = (m_1 - m_2)^2$ in eV^2
x = distance from the source in m

Without oscillation (P(x)=0) the event rate detected at distance x is:

$$N^0_{\nu_e}(x) = \frac{1}{x^2} \frac{Q_{\nu_e} \cdot \sigma_{\nu_e} \cdot N(^{12}C)}{4\pi \cdot 100^2} \qquad (24)$$

x in m; σ_{ν_e} for $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$

With oscillation $\nu_\mu \leftrightarrow \nu_e$ we expect the event rate:

$$N_{\nu_e}(x) = N^0_{\nu_e}(x) \cdot (1 - P(x)) + N^0_{\nu_\mu}(x) \cdot P(x) \qquad (25)$$

where $N^0_{\nu_\mu}(x)$ would be the event rate for total transformation $\nu_\mu \to \nu_e$ $(P(x) \equiv 1)$.

We now make a distinction between the counting rate during beam-on and after beam-on time. For the integral counting rate during beam-on time (2x100 nsec proton pulses) the index < is used. For the neutrinos generated after this time interval (0.5 - 5.5 μsec) we mark the counting rate with the index >.

Inserting numerical values for the organic scintillation reference detector at 16 m from the source yields the numbers: $N^<_{\nu_e}$ shown in fig.10 and $N^>_{\nu_e}$ shown in fig.11.

The different energy dependence of the neutrinos and a cut in electron energy at 10 MeV was taken into account. The counting rates are for one year of measuring time with full beam intensity. The error bars were calculated for 1 background event per day equally distributed within the 5.5 μsec interval open for measurement.

Comparison of fig.10 and fig.11 shows that the ν_e appearance experiment from $\nu_\mu \to \nu_e$ is much more sensitive to the mass difference δm^2 and to the mixing angle Θ than the disappearance measurement.

For a combination of both we define the asymmetry:

$$R(x) = \frac{N^<_{\nu_e} - N^>_{\nu_e}}{N^<_{\nu_e} + N^>_{\nu_e}} \qquad (26)$$

This ratio is shown for x = 16 m in fig.12. It is largely independent of systematic errors.The error bars are calculated for one year of measuring time at SNS with full beam intensity and for 1 background event per day in the 5 μsec time window.

In order to simulate an experimental result we choose a value of R(x) which would be consistent with the most probable result from the two reactor measurements $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$ of Mößbauer et al. and Reines et al. /21/: $\delta m^2 = 1\ eV^2$; $\sin^2 2\Theta = 0.4$.

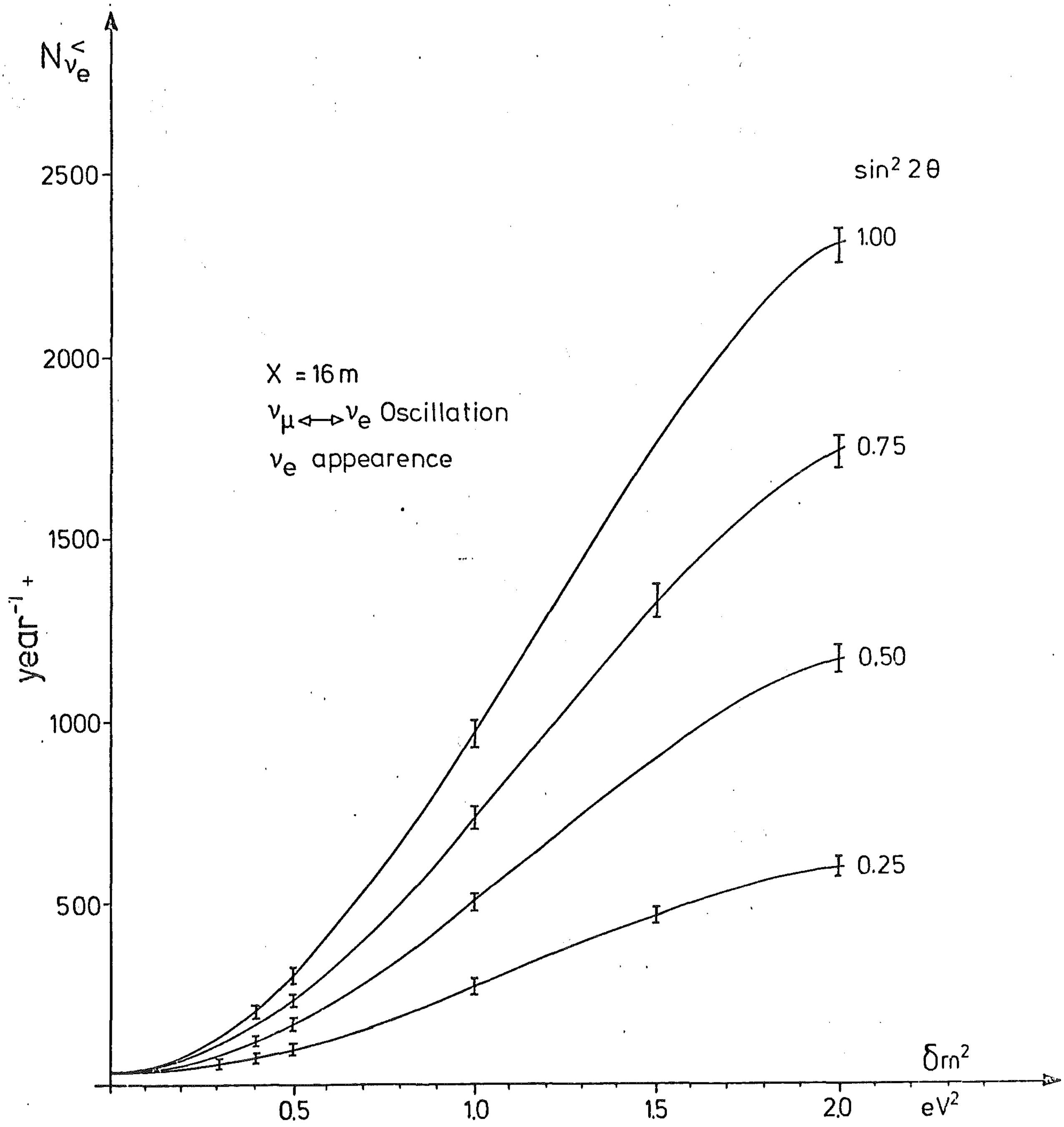

Fig.10: Expected counting rates from electron neutrinos during beam on time

+ one year of full beam intensity at SNS

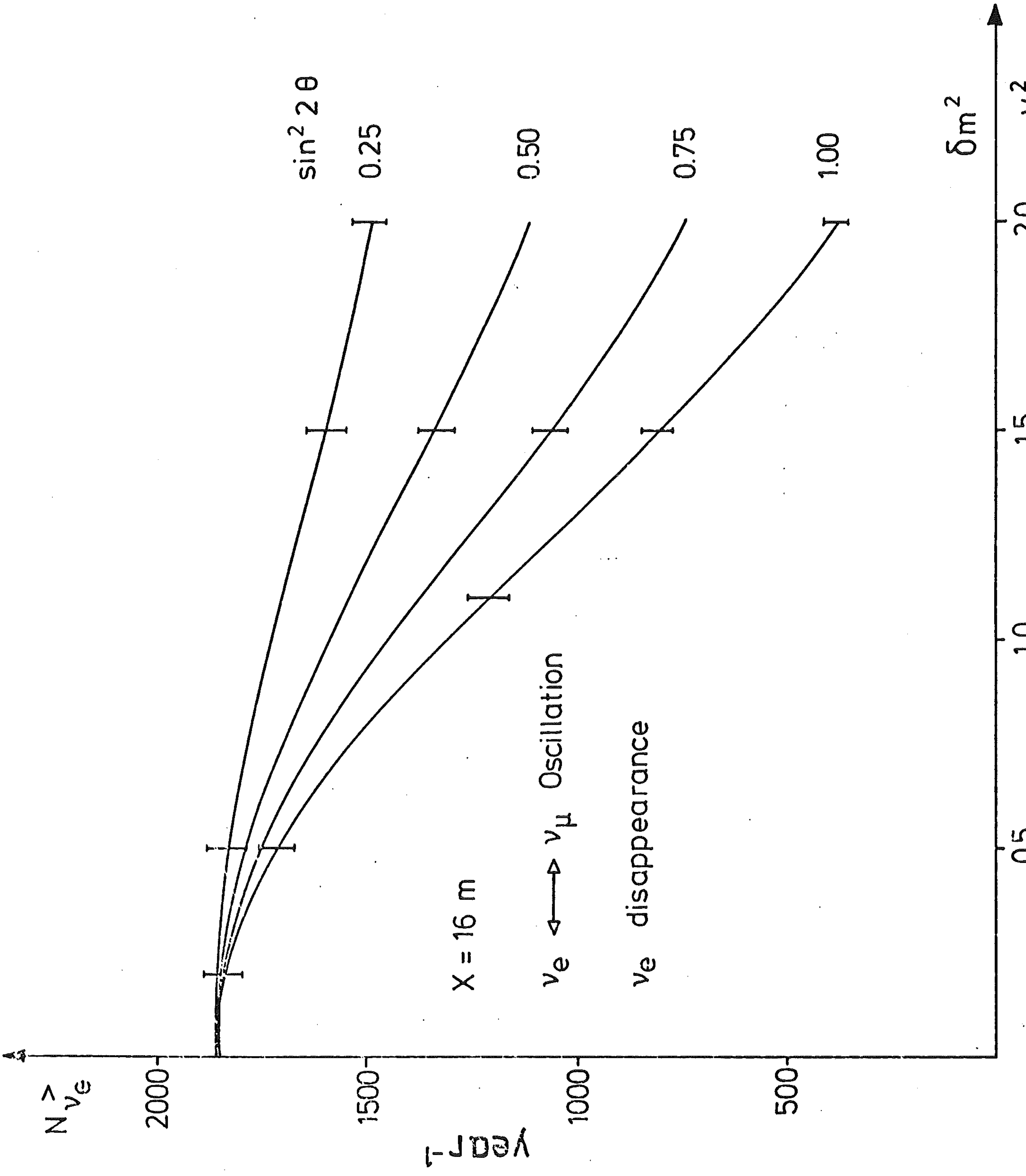

Fig.11: Expected counting rates from electron neutrinos after beam on time

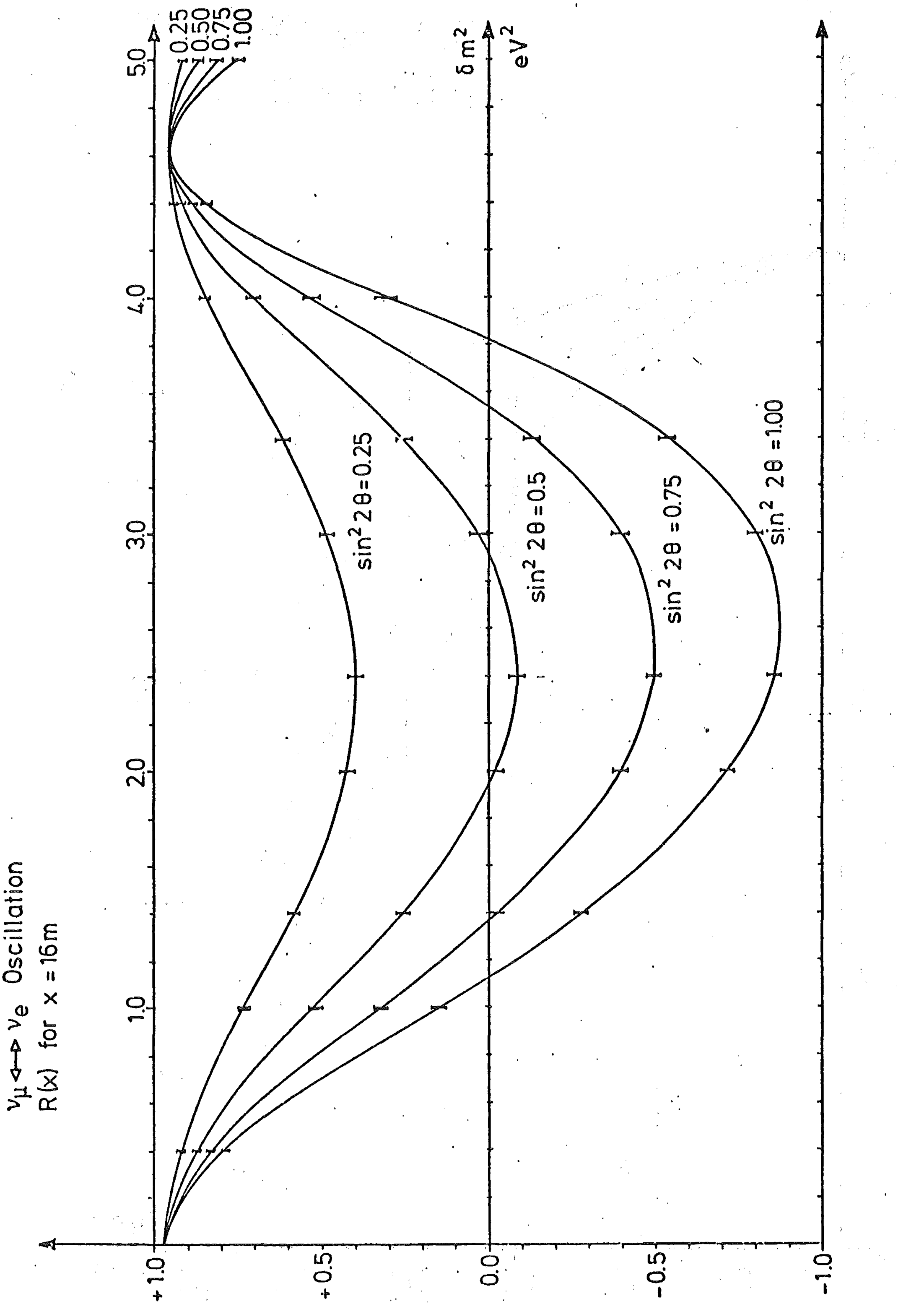

Fig.12: Asymmetry of counting rates during and after beam on time

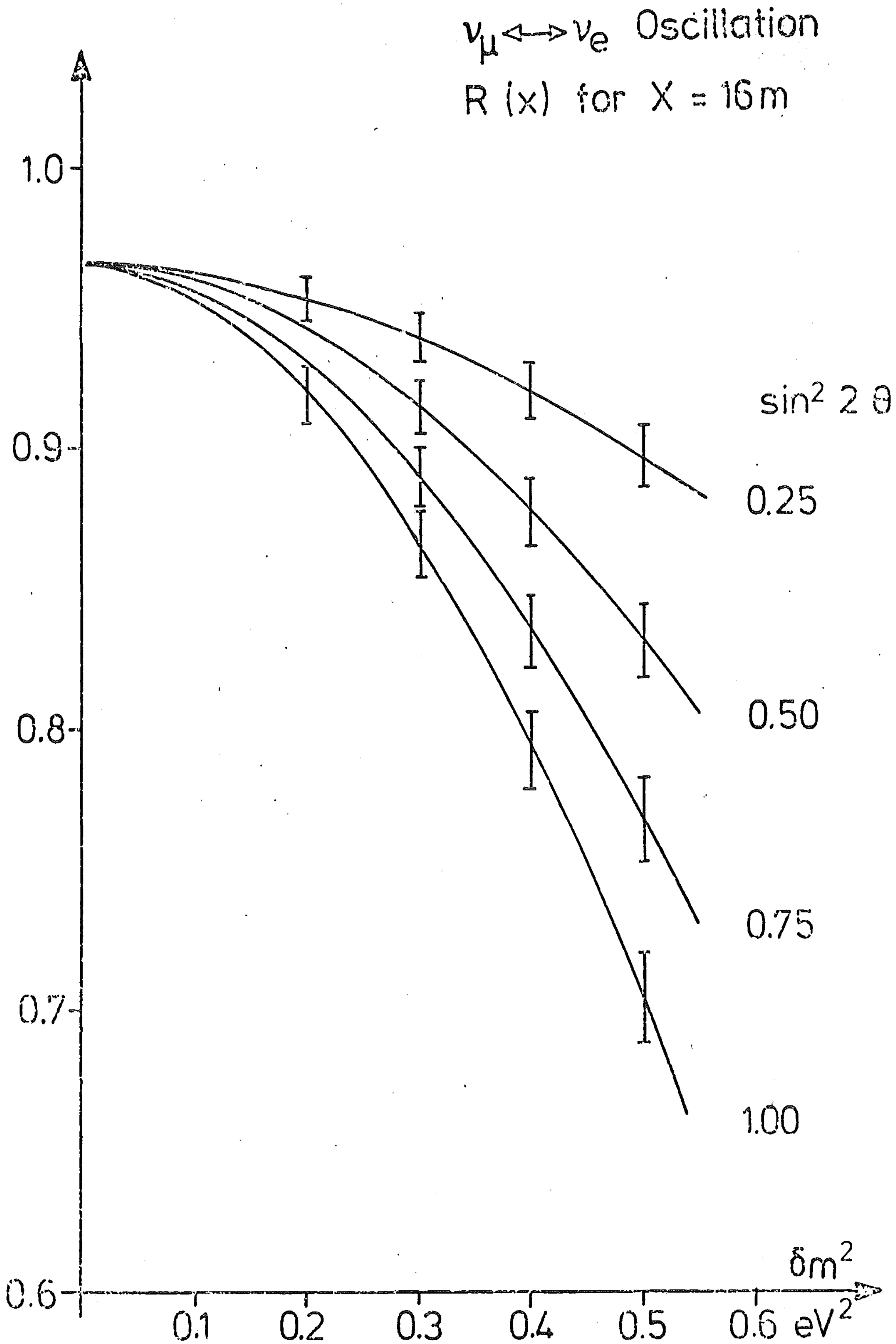

Fig.12a: Asymmetry of counting rates during and after beam on time

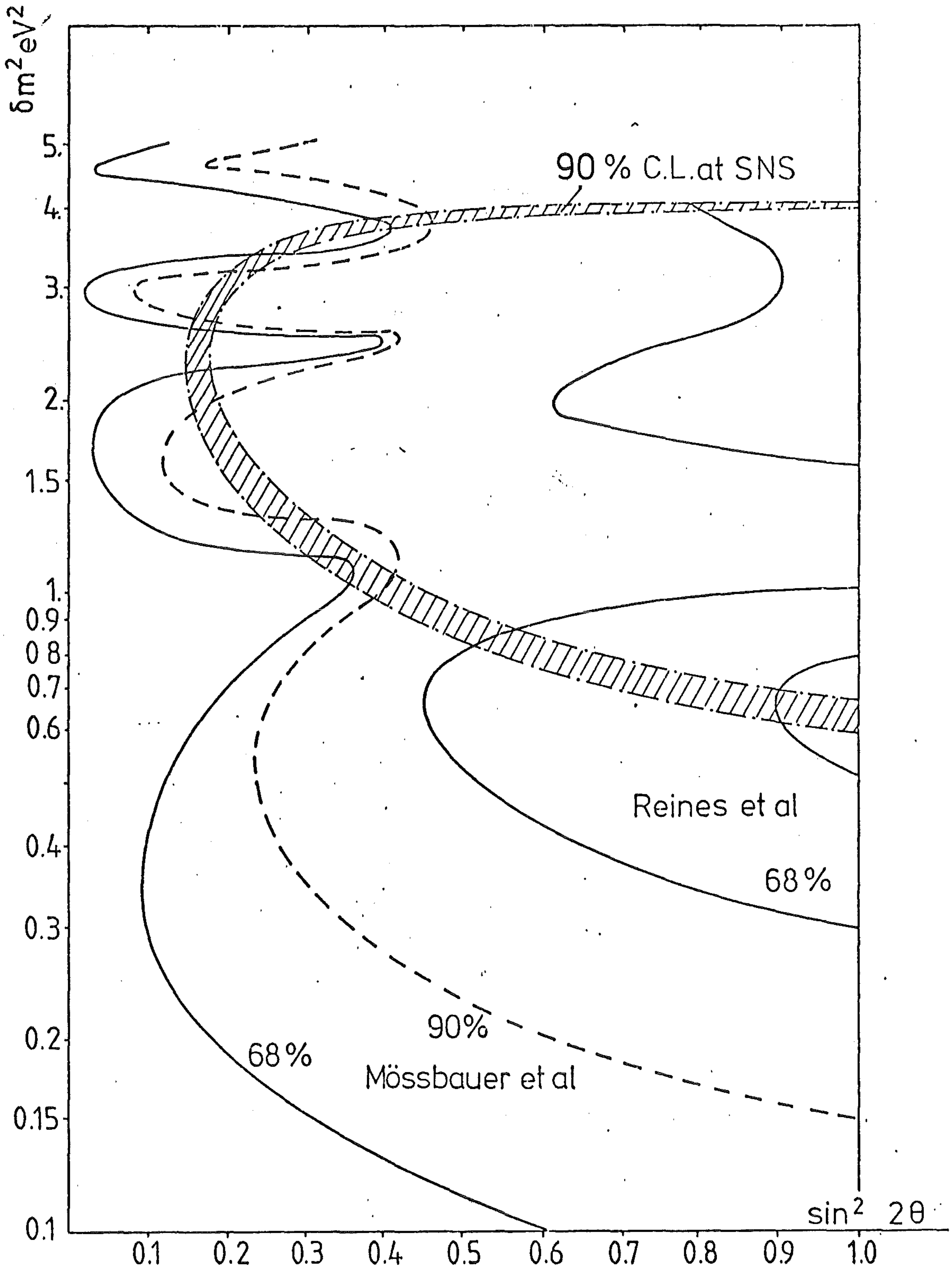

Fig. 13: Expected 90% confidence limits after one year of full beam intensity at SNS consistent with the hypothetical assumption $\delta m^2 = 1$ eV^2, $\sin^2 2\Theta = 0.4$, compared with the results from reactor neutrinos /21/.

This hypothetical experimental result would give the 90% confidence limits in the δm^2 - $\sin^2 2\Theta$ diagram shown in fig. 13.

The calculations show that we can expect high sensitivity for the mass difference δm^2 and the mixing angle Θ from the appearance experiment $\nu_\mu \to \nu_e$. The same statement is true for the appearance of $\bar{\nu}_e$ from $\bar{\nu}_\mu \to \bar{\nu}_e$ where the selective detector reaction is $\bar{\nu}_e + p \to e^+ + n$.

For both oscillations the lowest value of δm^2 which could be detected at all at the distance of 16 m with the reference detector would be about 0.05 eV^2 (for maximal mixing and four years of measuring time). But for $\delta m^2 > 0.3\ eV^2$ the method is quite sensitive even for very small mixing angles.

2. ν-e^- scattering

In the proposed neutrino experiment both the total and the differential cross section for ν-e scattering will be measured. From folding the differential cross section using the Weinberg model (equ. 6) and the neutrino spectra (equ. 14) one gets the differential probability of finding an electron in the energy range between E_e and $E_e + dE_e$ for the different kinds of neutrinos:

$$\frac{dN}{dE_e}(\nu_e) = \frac{\sigma_o \phi_o}{4\ m_e}[(1-4\varepsilon^3+3\varepsilon^4)\ (g_V^e+g_A^e)^2 + + (1-4\varepsilon+6\varepsilon^2-4\varepsilon^3+\varepsilon^4)\ (g_V^e-g_A^e)^2] \quad (27)$$

$$\frac{dN}{dE_e}(\bar{\nu}_\mu) = \frac{\sigma_o \phi_o}{4\ m_e}[(1-2\varepsilon^3+\varepsilon^4)\ (g_V^\mu-g_A^\mu)^2 + + (1-\frac{10}{3}\varepsilon+4\varepsilon^2-2\varepsilon^3+\frac{1}{3}\varepsilon^4)\ (g_V^\mu+g_A^\mu)^2] \quad (28)$$

$$\frac{dN}{dE_e}(\nu_\mu) = \frac{\sigma_o \phi_o}{4\ m_e}[(g_V^\mu+g_A^\mu)^2 + (1-\eta)^2\ (g_V^\mu-g_A^\mu)^2] \quad (29)$$

$\varepsilon = \frac{E_e}{W}$; $W = 52.83$ MeV; $\eta = \frac{E_e}{E_o}$, $E_o = 29.79$ MeV

$\sigma_o = \frac{2G^2 m_e^2}{\pi} = 8.805 \times 10^{-45}$ cm^2

$g_V^\mu = -\frac{1}{2} + 2 \sin^2\Theta_W$, $g_A^\mu = -\frac{1}{2}$

assuming unversality i.e. $g_V^e = g_V^\mu + 1$; $g_A^e = g_A^\mu + 1$

$g_V^e = \frac{1}{2} + 2 \sin^2\Theta_W$, $g_A^e = \frac{1}{2}$

These energy spectra of the recoil electrons are plotted in fig.14 as counting rates fcr a 50 ton liquid Argon detector. The total number of events using different energy cuts can easily be obtained by integrating equ. 27-29 which yields

$$N(\nu_e) = N_e \frac{\sigma_o \phi_o W}{4\, m_e} \Big[\left| \varepsilon - \varepsilon^4 + \tfrac{3}{5}\varepsilon^5 \right|_{\varepsilon_o}^{1} (g_V^e + g_A^e)^2 + \\ + \left| \varepsilon - 2\varepsilon^2 + 2\,\varepsilon^3 - \varepsilon^4 + \tfrac{1}{5}\varepsilon^5 \right|_{\varepsilon_o}^{1} (g_V^e - g_A^e)^2 \Big] \qquad (30)$$

$$N(\bar{\nu}_\mu) = N_e \frac{\sigma_o \phi_o W}{4\, m_e} \Big[\left| \varepsilon - \tfrac{1}{2}\varepsilon^4 + \tfrac{1}{5}\varepsilon^5 \right|_{\varepsilon_o}^{1} (g_V^\mu - g_A^\mu)^2 + \\ + \left| \varepsilon - \tfrac{5}{3}\varepsilon^2 + \tfrac{4}{3}\varepsilon^3 - \tfrac{1}{2}\varepsilon^4 + \tfrac{1}{15}\varepsilon^5 \right|_{\varepsilon_o}^{1} (g_V^\mu + g_A^\mu)^2 \Big] \qquad (31)$$

$$N(\nu_\mu) = N_e \frac{\sigma_o \phi_o E_o}{4\, m_e} \Big[\left| \eta \right|_{\eta_o}^{1} (g_V^\mu + g_A^\mu)^2 + \left| \eta - \eta^2 + \tfrac{1}{3}\eta^3 \right|_{\eta_o}^{1} (g_V^\mu - g_A^\mu)^2 \Big] \qquad (32)$$

Measuring the total cross section in this way makes it possible to deduce another value of the Weinberg angle from pure leptonic interactions at an energy of about 35 MeV where up to now this value has not been determined. Based on an expected sum of 216 true events for

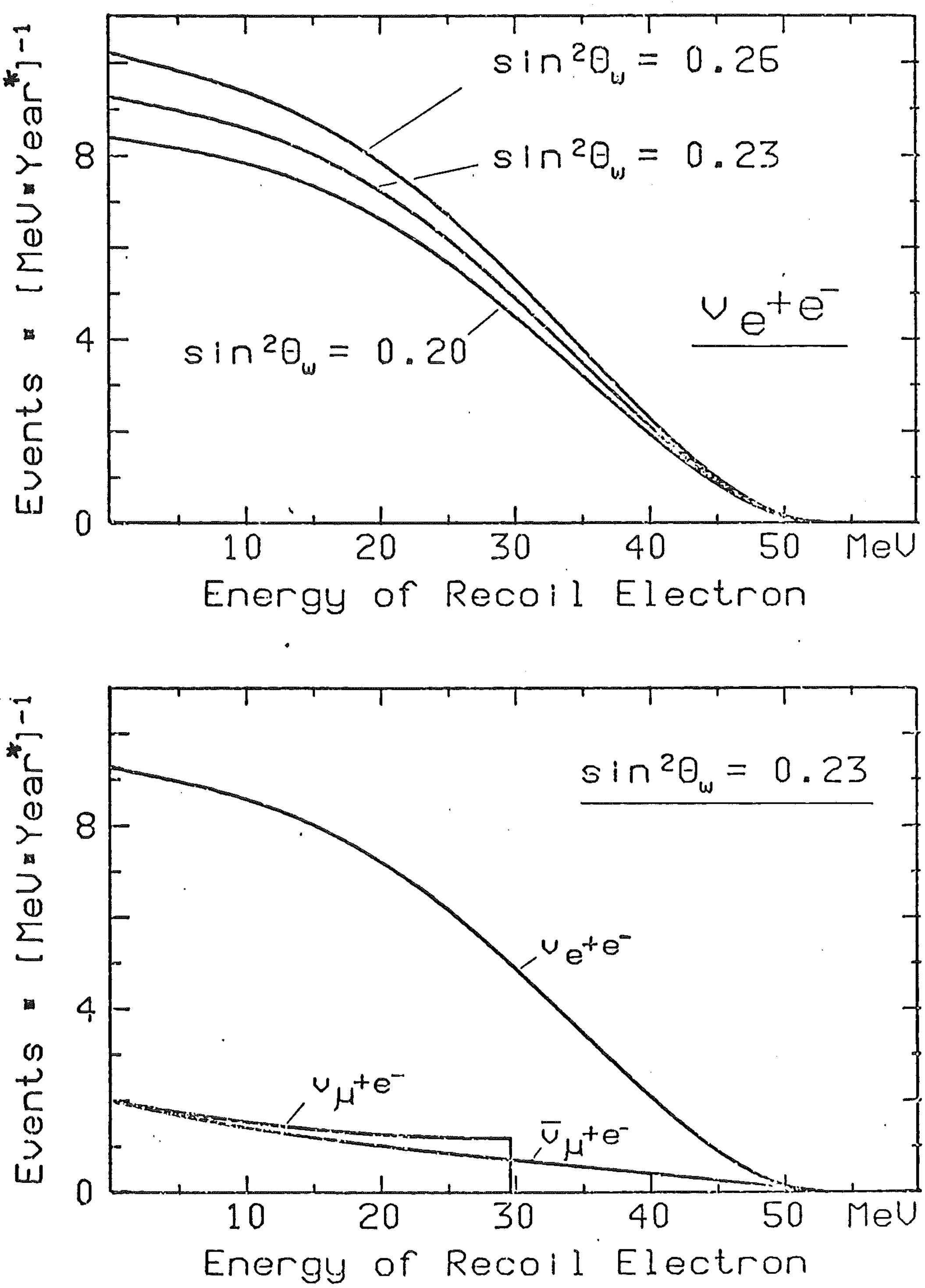

Fig.14: Energy dependent countrate for ν-e-scattering expected in a 50 ton liquid Argon detector at 18 m distance from the ν-source

*fbyear

ν_e and $\bar{\nu}_\mu$ scattering collected in the LAD detector (at 20 m) within one fbyear with an estimated total background[+] of 150 events, the data would determine the Weinberg angle with an accuracy of $\Delta \sin^2\Theta_W = \pm 0.03$. The expected result for the total cross section is also shown in fig. 15 as an ellipse in the g_V^μ/g_A^μ plane, having assumed $\sin^2\Theta_W = 0.23$, together with the results from high energy and reactor neutrino experiments. The concentric ellipses indicate the 68% confidence level which for the expected result at SNS is due to statistics only. Uncertainties in the absolute value of the neutrino flux of about 5% would only slightly broaden the 68% confidence level ring.

The reaction $\nu_e + e^- \rightarrow \nu_e + e^-$ has the highest cross section of all beam dump neutrinos (see fig.14). Here neutral current (NC) as well as charge current (CC) interaction is present. This gives rise to the possibility of interference. With an ansatz $g_V^e = g_V^\mu + z$ and $g_A^e = g_A^\mu + z$ equation (27) and (30) may be rewritten as

$$\frac{dN(\nu_e)}{dE_e} = \text{const}\left[a_1^e(\varepsilon)((g_V^\mu+g_A^\mu)^2+4z^2+4z(g_V^\mu+g_A^\mu))+a_2^e(\varepsilon)(g_V^\mu-g_A^\mu)^2\right] \qquad (33)$$

$$N(\nu_e) = \text{const } W\left[b_1^e(\varepsilon_0)((g_V^\mu+g_A^\mu)^2+4z^2+4z(g_V^\mu+g_A^\mu))+b_2^e(\varepsilon_0)(g_V^\mu-g_A^\mu)^2\right] \qquad (34)$$

With the terms $(g_V^\mu+g_A^\mu)^2$ and $(g_V^\mu-g_A^\mu)^2$, $4z^2$ and $4z(g_V^\mu+g_A^\mu)$ the ν_e-e^- cross section explicitely contains the NC, the CC, and the interference terms respectively. From the standard Weinberg Salam model assuming universality i.e. z=+1, this interference is predicted to be negative i.e.

$$(g_V^\mu+g_A^\mu)^2+4+4(g_V^\mu+g_A^\mu) = (1-2\sin^2\Theta_W)^2+4\underline{-4(1-2\sin^2\Theta_W)} \qquad (35)$$

[+]neutrino induced background included

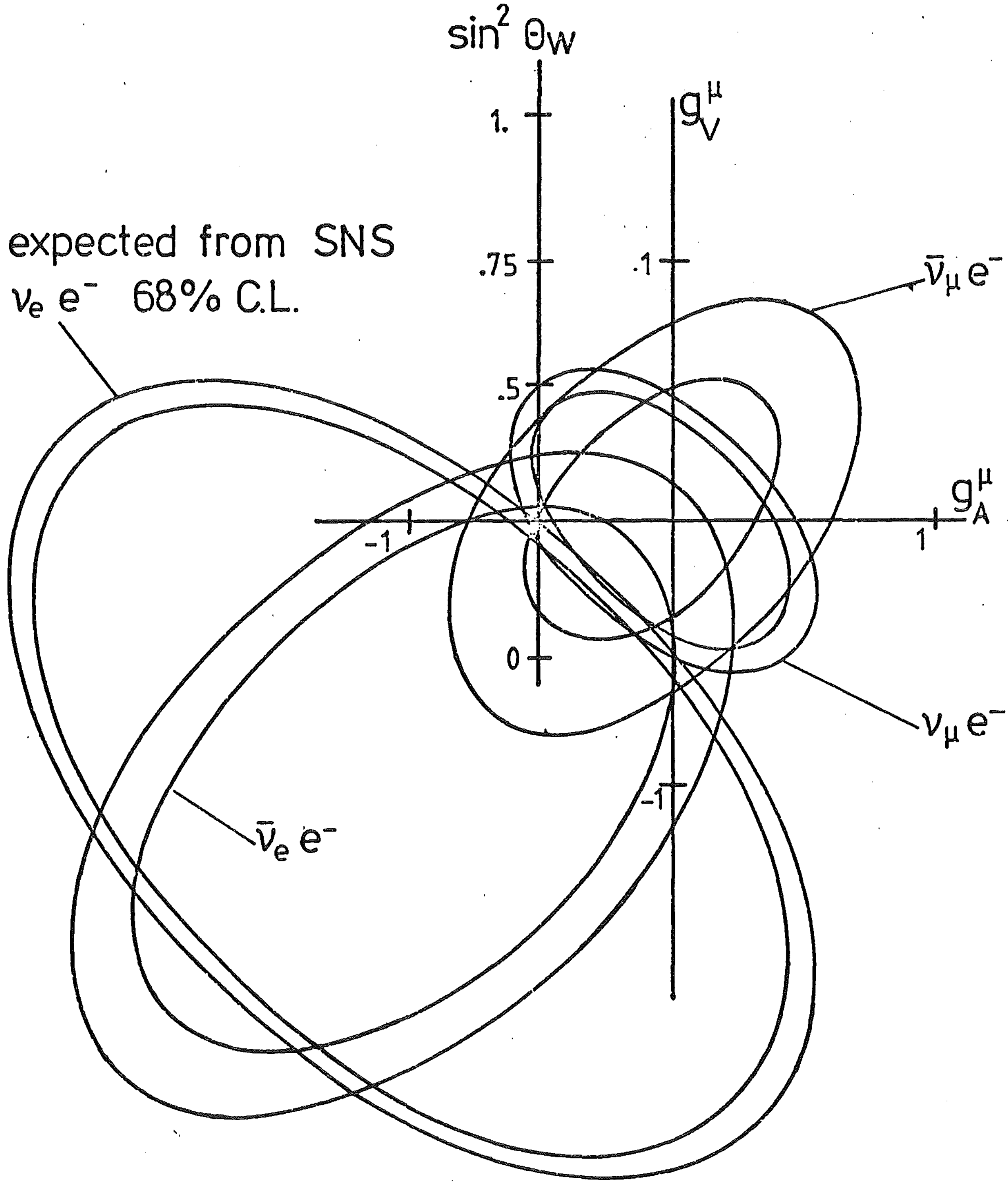

Fig.15: Expected 68% confidence ellipses in the g_V^μ/g_A^μ plane for the proposed ν_e-e^- total cross section measurement at SNS, together with results from other ν-e scattering experiments

Using $\sin^2 \Theta_W = 0.23$ gives for the sum of ν_e and $\bar{\nu}_\mu$ scattering 216 events in the LAD at 20 m for one full beam year at SNS. With an estimated total background of 150 events and an uncertainty in the absolute neutrino flux of about 5% the total cross section is determined with an error of 10%. On the other hand assuming that there is no interference at all the event rate would increase by 80%. Thus the accuracy of the proposed experiment within approximately two years of real measuring time with the LAD at 20 m average distance is sufficient for the determination of the NC-CC interference term.

The expected energy and angular resolution at the LAD would allow also to measure the differential cross sections. This could be used for the determination of g_V and g_A separately from a fit to equ.27. Reliable estimates of the errors would need the knowledge of the properties of the LAD.

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