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Abstract

The advantages which the new high intensity neutron spallation sources will offer for neutrino physics are discussed. The experimental area planned for neutrino measurements at the SNQ (Spallations-Neutronen-Quelle) is presented. An experiment to search for neutrino oscillations $\nu_\mu \leftrightarrow \nu_e$ is proposed.

NEUTRONENPHYSIK AN DER SPALLATIONS-NEUTRONEN-QUELLE

Zusammenfassung

Die Vorteile, welche die neuen hochintensiven Spallationsneutronenquellen für die Neutrinophysik bieten können werden diskutiert. Der geplante Experimentierbereich für Neutrinomessungen an der SNQ (Spallations-Neutronen-Quelle) wird vorgestellt. Ein Experiment zur Suche nach Neutrinooszillationen $\nu_\mu \leftrightarrow \nu_e$ wird vorgeschlagen.

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I. INTRODUCTION

During the last years interest in the physics of neutrinos has substantially grown. Especially in the context of 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. The second assumption is then plausible 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 $m_{\nu_\mu} > m_{\nu_e}$). The lifetime can be estimated to $\tau > 5 \cdot 10^{11}$ years /1/. Therefore, the decay of neutrinos cannot be observed in the laboratory.

The oscillation of particles to particles (and antiparticles to antiparticles, respectively) has been recently termed also "flavour oscillation". The reason is that in the unified theory of weak and electromagnetic interactions lepton flavours have been introduced by analogy with quark flavours. According to their helicity the leptons are combined into a doublet and a singlet each:

For example:

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

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

In total, this gives the following doublets:

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

$$\begin{pmatrix} \bar{\nu} \\ e^+ \end{pmatrix} \quad \begin{pmatrix} \bar{\nu}_\mu \\ \mu^+ \end{pmatrix} \quad \begin{pmatrix} \bar{\nu}_\tau \\ \tau^+ \end{pmatrix} \qquad (1)$$

$\nu_\tau(\bar{\nu}_\tau)$ has not yet been unambiguously detected in the experiment, 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 paper.

For zero-mass particles mixing of different states of helicity and different doublet assignments (lepton flavours) is not possible. Also, besides the conservation of the lepton number, there is a separate conservation of the muon number. In the weak interactions in vertical direction in (1) 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 could 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, quite a number of very fundamental questions can be studied particularly well by means of the very high neutrino fluxes to be generated at the planned SNQ spallation neutron source.

In this context the interactions in the horizontal direction in (1) will be of special interest. The interest at the time being concentrates on studies of the transitions $\nu_e \leftrightarrow \nu_\mu$; $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$ (flavour oscillations) but also on possible particle-antiparticle oscillations: $\nu_e \leftrightarrow \bar{\nu}_e$; $\nu_\mu \leftrightarrow \bar{\nu}_\mu$; $\nu_e \leftrightarrow \bar{\nu}_\mu$ etc..

Such studies could provide information about possible mass differences and violations of the conservation numbers. But more accurate measurements on neutrino coupling to other leptons continue to be equally important. For instance, measurements with good statistics of elastic neutrino scattering from electrons may serve this purpose, viz. $\nu + e \rightarrow \nu + e$. A particularly interesting process is the elastic scattering of mu-neutrinos from electrons: $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ or $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$. Studying this fundamental reaction yields clear information about the weak neutral coupling of the electron. The results allow to make comparisons with theory in a very direct manner, e.g., the determination of the Weinberg angle /3,4,5,6/. The existence of $\nu_e + e \rightarrow \nu_e + e$ could not be even proven until now.

Besides the study of neutrino interaction with other leptons, coupling to hadrons offers some interest. Coupling constants and form factors both for charged and neutral interactions could be derived from suitable experiments /7,8/. An interesting field of activities not covered so far by experiments is the defined excitation of nuclear levels by neutrino scattering. Firstly, the nucleus is used as a microscopic laboratory with a defined spin-isospin with a view to determine coupling constants in a selective way and largely model independent. Secondly, nuclear matrix elements can be measured for light nuclei. The excitation by mu-neutrinos would offer particular interest. The reason is that this interaction allows to excite the nuclei merely by neutral current coupling. The combination of the results of such measurements with corresponding (in most cases already known) numerical values 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. If, however, this theory is supposed to be valid, the nuclear matrix elements are obtained practically independent of the model. A number of articles and proposals have been published during recent years about this field of "nuclear physics involving neutral currents". A comprehensive description has been furnished by T.W.Donnelly and R.D.Peccei /9/. The new high-intensity accelerators with a time structure suitable for separation of the mu-neutrinos will enable us for the first time to perform such experiments. 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 by 95%, the 15.11 MeV γ-ray constitutes a clear signature for excitation of a nucleus by neutral current. Since the spin and the isospin are defined, measurement of the integral 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 /9/:

$$\sigma'_{\nu\nu} = \text{const.} \ |<1;1 \ ||L||0;0>|^2 \ (E_\nu-15.11)^2 C_Q^2 \qquad (2)$$

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 /9/):

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

Introducing (3) into (2) and use of the measured ß-decay rates gives independent of the nuclear model:

$$\sigma'_{\nu\nu} = 1.08 \cdot 10^{-38} \frac{(E_\nu - 15.11)^2}{M_N^2} \cdot C_Q^2 \ \mathrm{cm}^2 \qquad (4)$$

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. This is demonstrated in Fig.1.

Supposing that the WSGIM-model is correct, we have $C_Q^2 = 1 (C_Q^2 = \frac{1}{4}$ for the b-quark model). 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 SNQ spallation neutron source (beam stop E_ν = 30 MeV). With adequate shielding and a suitable time structure this extremely small cross section could be measured within one week of measuring time at the proposed SNQ spallation neutron source, the statistical accuracy being better than ± 10% (for 1 mA averaged proton current).

The desired extension of the unified theories of interaction might lead to the postulation that light scalar gauge bosons exist /10,11/. In the meantime, H.Faissner has reported about first experimental indications of the existence of such semiweak interacting spin-zero particles having a mass m_a = (300 ± 50)KeV /12,13/. Given an adequate time structure, investigations including such particles could be performed at a high-intensity spallation neutron source in parallel with neutrino physics investigations and in the same experimental hall, using similar or the same detectors /2/.

The importance of neutrino experiments at high-intensity proton accelerators at medium energies have been discussed intensively by several authors in recent years; see /8,9,14/. During the past months, detailed proposals have been submitted for experiments to be performed at LAMPF /6,15,16,17/.

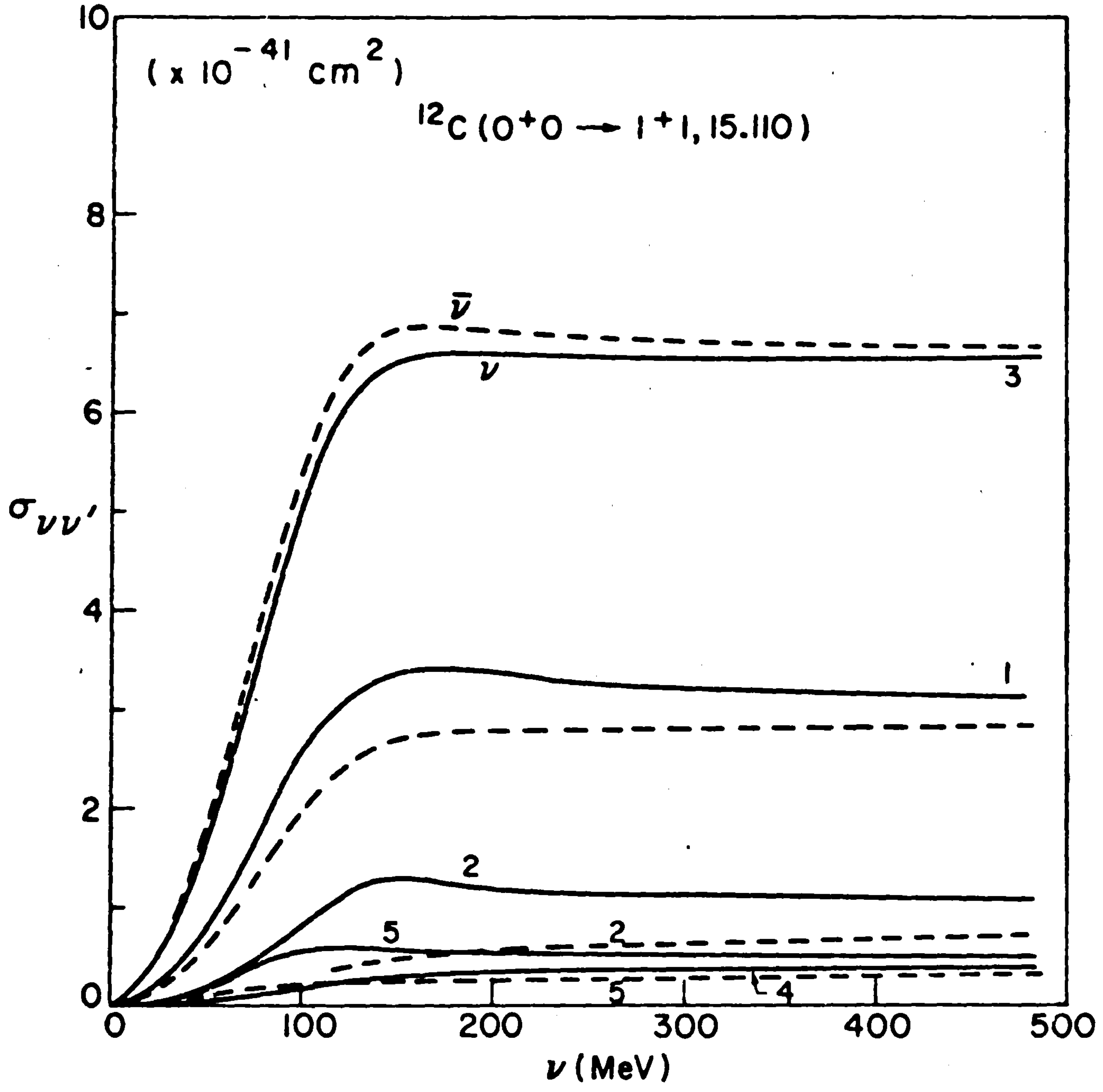

Fig.1: Cross sections for inelastic neutrino scattering from ^{12}C (15.1 MeV) for different quark models 1 - 5 (taken from /9/). 1: WSGIM; 2: b-quark

It is evident from all these publications that this type of neutrino physics is on the way to become a field of research for several working groups. Thanks to the extremely high neutrino fluxes to be generated at the high-intensity proton accelerators already under construction and planned, respectively, work on the weak neutral currents nowadays considered as rather exotic could develop into a standard discipline of modern nuclear and particle physics.

The great advantages which the facility proposed in this study would offer for neutrino physics, will be explained by way of example in the following chapters. The computations required in this context, part of them very extensive, were carried out as a collaboration of the Karlsruhe Nuclear Research Center and the Oak Ridge National Laboratory by T.Gabriel (ORNL) and J.Wilczynski (KfK). A comprehensive presentation of the methods and results will be published soon /18/.

II. NEUTRINOS FROM THE SPALLATION NEUTRON SOURCE
(Beamstop Neutrinos)

The protons do not only give rise to the production of neutrons in the spallation target. At the same time a considerable number of pions π^+ (and π^-) is 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/. It can be noted that in our case with E_p = 1100 MeV and lead as the target material: $N_{\pi^+}/N_p = 0.13(3)$.

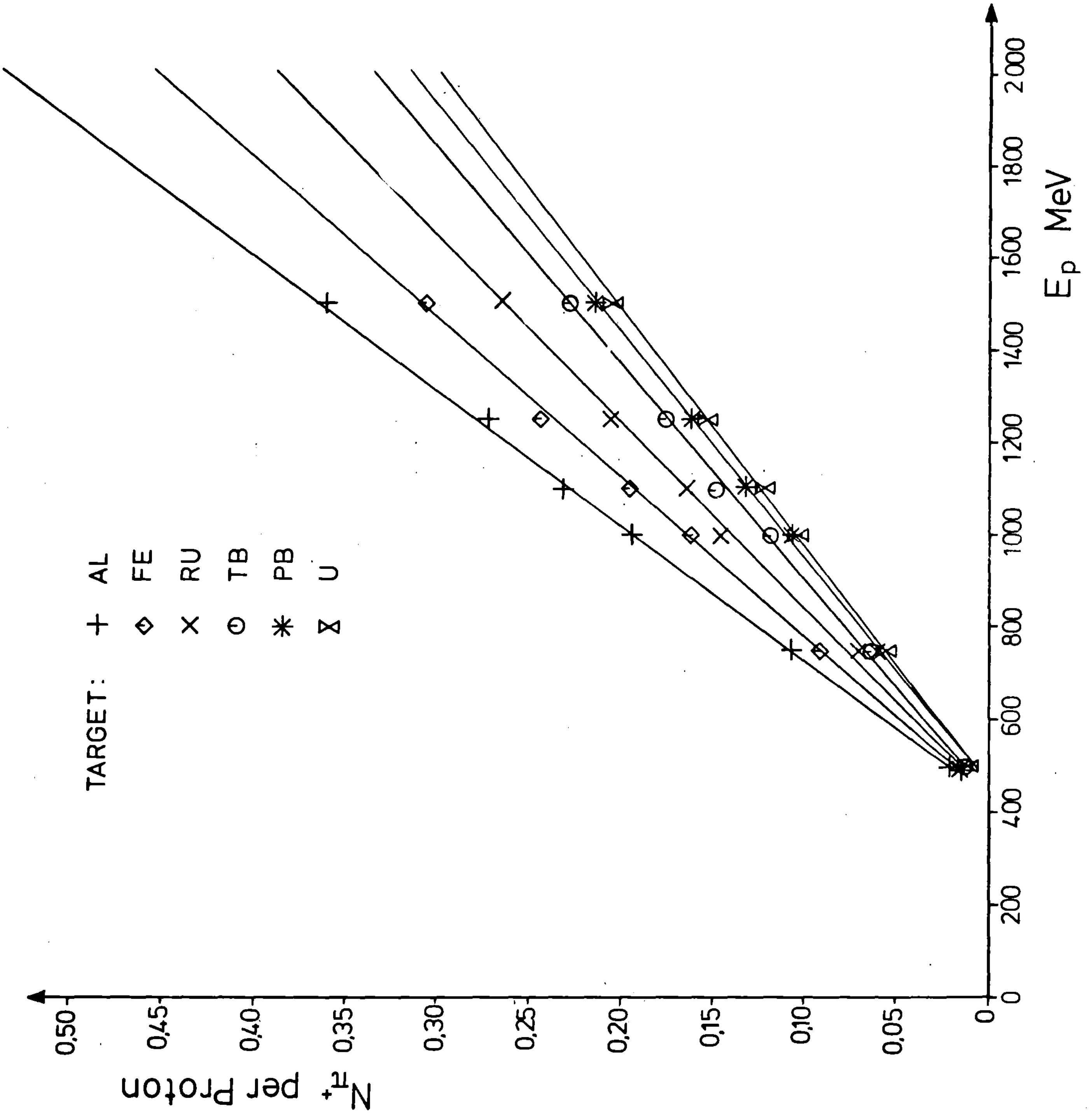

Fig.2: Yields of pions (π^+) per stopped proton for different target materials

The pions are very quickly stopped (10^{-10} s) still in the target zone so that only a small fraction of about $5 \cdot 10^{-3}$ decay while on flight. Whilst the negative pions, when at rest, are captured by nuclei and finally absorbed, the positive pions, with a life time $\tau = 26$ ns, decay into a positive muon and a muon neutrino. This means that, practically, only the positive pions and the positive muons play a role at the SNQ spallation neutron source. The muon with a life time $\tau = 2.2$ µs subsequently decays into a positron and (because of conservation of the lepton and muon numbers) into an electron neutrino and a muon antineutrino. Thus, we have

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \tau = 26.03 \times 10^{-9}\ \text{s} \qquad (5)$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \qquad \tau = 2.197 \times 10^{-6}\ \text{s} \qquad (6)$$

Since the pion at rest decays into two particles, the muon neutrinos from (5) have a constant energy $E_{\nu_\mu} = 29.79$ MeV. By contrast, continuous distributions with an end energy of 52.83 MeV are obtained for the neutrinos produced by the three-particle decay (6). Fig.3 shows the respective energy distributions. Since the decays take place with the particles at rest, the intensities of all three kinds of neutrino are equal and isotropic in space. The source strengths given in Fig.3 were calculated for an averaged proton current $\bar{I}_p = 1$ mA. For each kind of neutrino and the desired parameters of the spallation neutron source $E_p = 1100$ MeV and $\bar{I}_p = 5$ mA an averaged source strength is obtained of

$$\bar{Q}_\nu = 3 \times 4.1 \times 10^{15}/\text{s}. \qquad (7)$$

This means that the facility would be the most powerful source for the three kinds of neutrino $\nu_\mu, \nu_e, \bar{\nu}_\mu$.

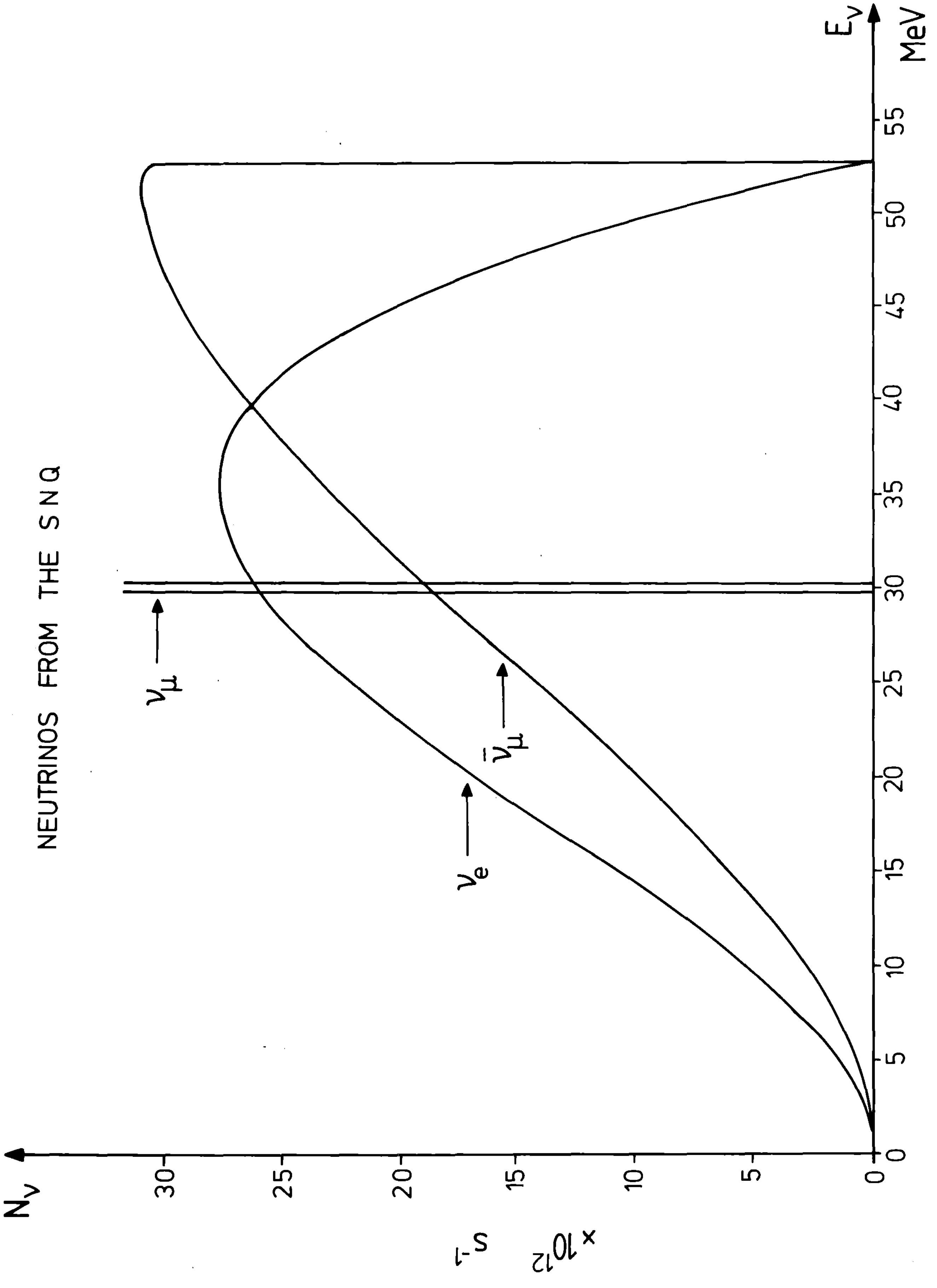

Fig.3: Energy distributions of the neutrinos generated at the SNQ spallation neutron source (beamstop). The total numbers of all three kinds of neutrino are equal. The indicated source strengths apply to 1 mA averaged proton current for E_p=1100 MeV

This source can be utilized for distances from about 6 m on, where it will appear practically as a point source yielding a flux of

$$\varphi_\nu = \frac{Q_\nu}{4\pi r^2} \tag{8}$$

$$\varphi_\nu = 3 \times \frac{3.2 \times 10^{10}}{r^2} \text{ cm}^{-2} \text{ s}^{-1} \tag{9}$$

(r in m).

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:

1. Most of the experiments which will be of interest also after some years need separation of the different kinds of neutrino. For this purpose, the very different lifetimes of pion and muon decay can be utilized provided a suitable time structure of the beam. This problem will be treated more comprehensively later in this paper.

2. On account 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 duty cycle of the beam should be aimed at.

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

II.1 Dependence on Time of the Neutrino Flux

For a rectangular pulse of the proton beam with the pulse duration t_p the time dependencies of the neutrino source strengths indicated by the expressions (10) to (13) are obtained

in accordance with the different lifetimes τ_π and τ_μ of the pions and muons generated (cf. also /19/):
For the source flux of the mu-neutrinos ν_μ from the π^+-decay:

$$\varphi_{\nu_\mu} = Q_0 \, (1-e^{-\frac{t}{\tau_\pi}}) \qquad t \leq t_p \qquad (10)$$

$$\varphi_{\nu_\mu} = Q_0 \, (e^{\frac{t_p}{\tau_\pi}} -1) \, e^{-\frac{t}{\tau_\pi}} \qquad t \geq t_p \qquad (11)$$

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

$$\varphi_{\nu_e} = Q_0 \, \frac{t_p}{(t_p+\tau_\pi) \, \tau_\mu} \cdot t \cdot e^{-\frac{t}{\tau_\mu}} \qquad t \leq t_p+\tau_\pi \qquad (12)$$

$$\varphi_{\nu_e} = Q_0 \, \frac{t_p}{\tau_\mu} \, e^{-\frac{t}{\tau_\mu}} \qquad t \geq t_p+\tau_\pi \qquad (13)$$

where

$$Q_0 = 0.133 \, \frac{6.24 \times 10^{15}}{f \cdot t_p} \, mA^{-1} \, s^{-1} \qquad (14)$$

f = pulse frequency in Hz

t_p = pulse length of the protons in s.

Fig.4 shows this time dependence of the neutrino source fluxes for the practical example of a proton pulse length of t_p = 200 ns with a repetition frequency of 100 Hz, i.e. for $Q_0 = 4.15 \times 10^{19}$ mA^{-1} s^{-1}. (The unit mA relates to the averaged proton current).

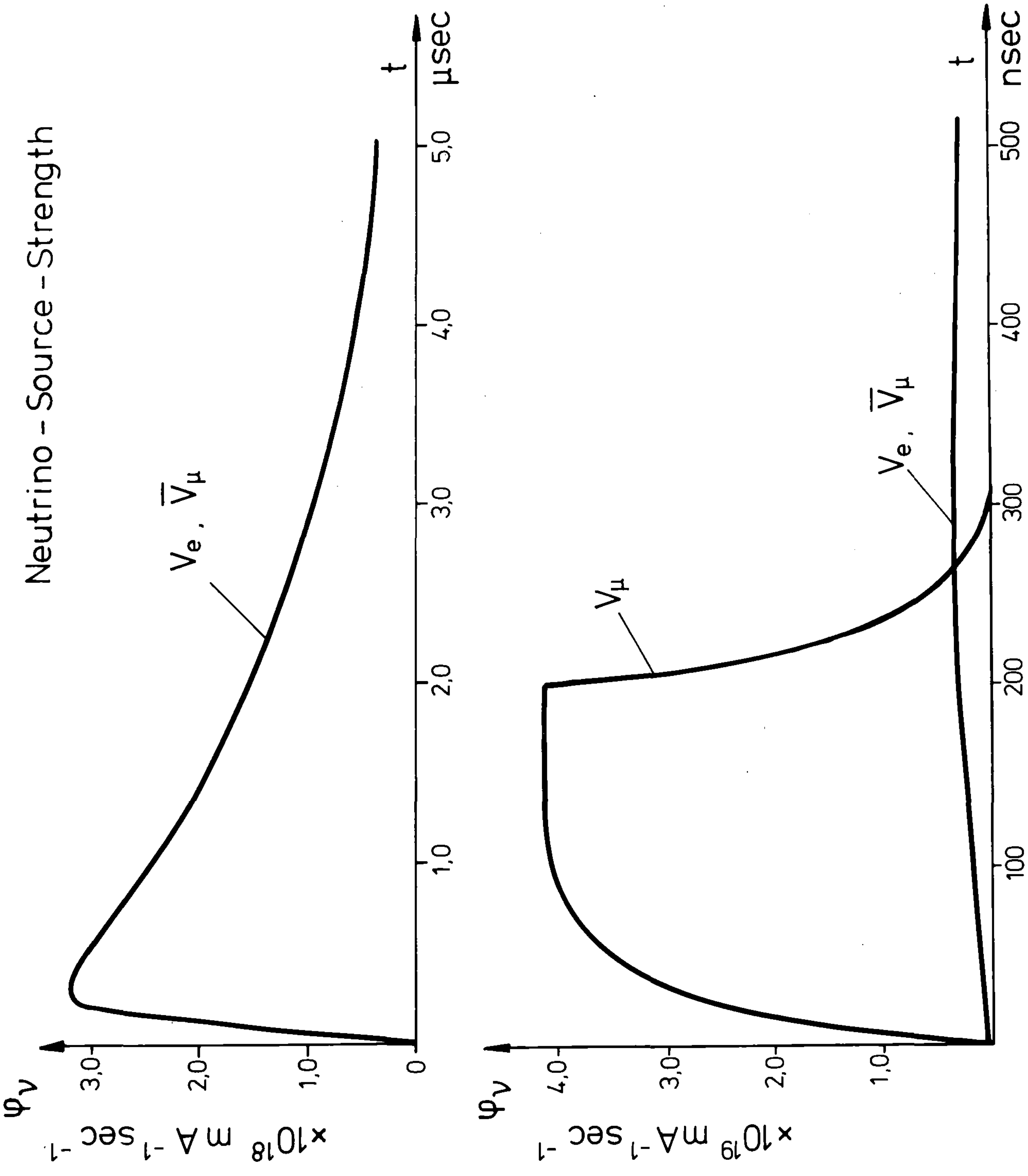

Fig.4: Time dependence of the neutrino source fluxes at the SNQ spallation neutron source (t_p = 200 ns, $\bar{I}_p$ = 1 mA, f = 100 Hz)

As has been expected, saturation of the mu-neutrino source strength φ_{ν_μ} is attained already after about t = 100 ns. Since the muons have a much longer lifetime, the fluxes of the electron- and muonantineutrinos φ_{ν_e} and $\varphi_{\bar{\nu}_\mu}$ are still much smaller at that time. Thus, the optimum pulse length for the separation in terms of time of ν_μ is about 50 ns. However, for most of the experiments the total intensity attainable is equally important as the degree of separation. The ideal case of a pulse length t_p = 50 ns with the averaged proton current of 5 mA maintained at the same time (at f = 100 Hz), would require a peak current of 1000 A. However, since this would probably exceed the existing technical and financial limits (see chapter dealing with the storage rings), compromises must be made. A closer study of the conditions prevailing in some interesting experiments shows (see example of neutrino oscillation, chapter IV) that a pulse length of about 200 ns with an averaged current of about 1 mA would still be a good compromise. The source has to be compared with the facilities planned for construction in the next years at the Rutherford Laboratory in the United Kingdom and at LAMPF in the USA.

Since the proton energies of these competing accelerators lie at about 800 MeV, the neutrino intensities in these facilities will be lower by the factor 1.9 for the same current level (see Fig.2). On the whole, it can be supposed that an accelerator with an energy of E_p = 1100 MeV, a time structure of about $t_p < 200$ ns for f = 100 Hz and, at the same time, I_p = 1 to 5 mA, will be an extremely interesting source of neutrinos ν_μ,ν_e and $\bar{\nu}_\mu$, even in about ten years. Since the high peak intensity will be of major importance, it can be assumed that such a facility would be unrivaled for a long period of time.

The desired time structure with the simultaneous conservation of the mean intensity can be attained only by bunching with a storage ring. Therefore, a storage ring would be of particular interest for neutrino physics.

In case a storage ring will not be available in the initial phase, the required time structure of the beam could be achieved in the meantime by a compromise associated with loss in intensity. One could, e.g., think of a prepulse group ahead of the main pulse, as shown in Fig.5. Depending on the purpose of the experiment, the pulse length t_p could be varied from the ion source of the accelerator. The minimum interval between two beam pulses is about 10 μs because of the necessary reduction in the number of μ-decays. With a good time structure (useful pulse: $t_p = 200$ ns, pulse interval $t = 10$ μs) and a peak current of 100 mA ($\bar{I}_p = 5$ mA for $t_p = 0.5$ ms) this would yield an averaged current $\bar{I}_p = 100$ μA which could still be utilized for neutrino physics. Consequently, the facility would just be competitive with the planned facility at the Rutherford Laboratory as regards its mean neutrino flux. The accelerator at the Rutherford Laboratory will produce double pulses at a frequency of 50 Hz. The duration of each single pulse will only be 100 ns. However, the second pulse arrives as early as 250 ns after the first. The averaged current will be $\bar{I}_p = 200$ μA at an energy of 800 MeV. This means that the mean intensity which can be used for neutrino physics will attain roughly the same level in both accelerators, even without a storage ring. However, the duty cycle, which is very important in suppressing the continuous cosmic background, is less favourable in the proposed interim solution. For the experiments with muneutrinos to be performed at the Rutherford accelerator this duty cycle will be $2\cdot10^{-5}$ as compared with $1\cdot10^{-3}$ in our interim solution. In experiments involving electron and muon antineutrinos a duty cycle of about $1\cdot10^{-3}$ could be expected as compared with $5\cdot10^{-2}$ in our facility.

Here the advantages are evident which would be derived from installation of a storage ring. The values of the duty cycle of the Rutherford accelerator, i.e., $2\cdot10^{-5}$ and $1\cdot10^{-3}$, respectively, could also be attained in our facility if the storage ring were used. At the same time, the neutrino intensities would be higher by nearly a factor 50.

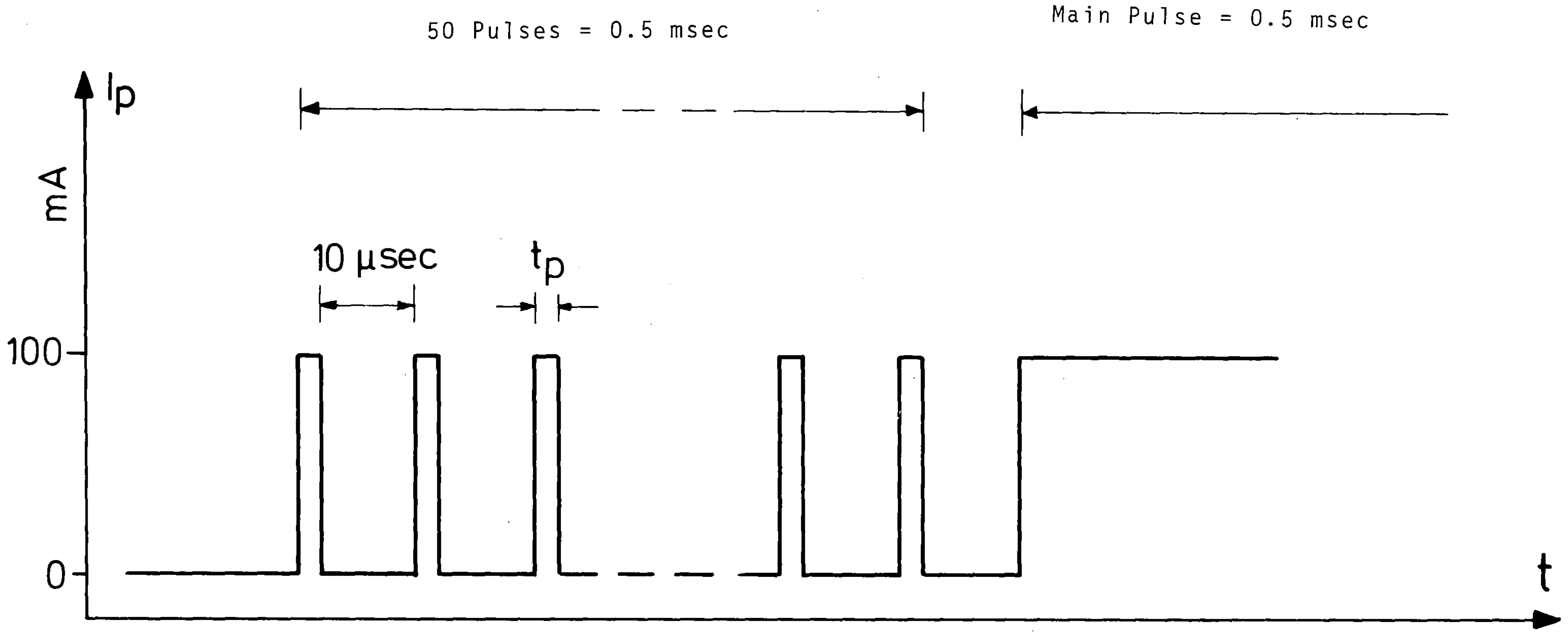
Preceding Pulse Group

Fig.5: Time structure of the beam for a preceding neutrino pulse group. Interim solution before a storage ring has been provided

Obviously, a comparison of the interim solution proposed by us with the proton storage ring (PSR) planned to be built at Los Alamos in 1985 will lead to less favorable results. At Los Alamos an averaged proton current I_p = 100 μA is to be achieved for a duty cycle of $3 \cdot 10^{-6}$. The proton energy will be 800 MeV. This means that the mean neutrino intensity in our facility would be higher by a factor 2 already if the interim solution were adopted. However, a disadvantage is that the duty cycle would be poorer by a factor 1000 for mu-neutrino experiments (500 for ν_e and $\bar{\nu}_\mu$ experiments).

Another accelerator for planned neutrino physics experiments is already under construction in Moscow. It is intended to provide also a proton storage ring at some later date which will deliver an averaged current of about 500 μA, although at 600 MeV only. A comparison of our interim solution with the facility in Moscow also shows that we would just be competitive as regards the mean neutrino intensity, but not as regards the duty cycle.

For a number of neutrino experiments still of some interest, a larger duty cycle could be compensated initially by better shielding and by extra expenditure for the neutrino detectors. However, experiments on neutrino-electron scattering would become very difficult. With respect to all experiments the storage ring would result in an additional considerable improvement of the quality of results. This will be demonstrated in more detail in chapter IV by the example of measurement of $\nu_\mu \leftrightarrow \nu_e$ oscillations.

The utilization of neutrinos generated during flight while the pions decay has not been discussed here because this would require an expensive decay channel provided at an external beam. However, if such a beam was available for other purposes, above all those experiments could be performed which require higher neutrino energies. They include neutrino disappearance experiments involving muons, e.g., $\nu_\mu + {}^{12}C \rightarrow \mu^- + {}^{12}N$ etc. /8,15,16/. The cross sections for inelastic neutrino scattering continue to grow by the square of neutrino energy up to about 100 MeV (see Fig.1). However, the extent of practical utilization of this advantage depends on many details of equipment and operation of the facility.

The great advantage offered by the utilization of the pions stopped in the spallation source is that they are available anyway so that the neutrino experiments can be performed simultaneously over extended periods of time and without noticeably impairing the solid state physics experiments.

III. PROPOSAL FOR AN EXPERIMENTAL AREA IN WHICH NEUTRINO MEASUREMENTS COULD BE PERFORMED AT THE SNQ SPALLATION NEUTRON SOURCE

Neutrino experiments are difficult mainly for the reason that the probability of detecting strong or electromagnetic interacting background radiations are higher by 10 to 20 orders of magnitude than they are for neutrinos characterized by weak interaction. The total cross sections listed in Table 1, which are typical of beamstop neutrinos, have to be compared with the total cross sections for capturing thermalized background neutrons from the source or also with that of muons originating in cosmic rays. Therefore, a facility in which neutrino experiments are to be performed, must be very well shielded both against the source and against cosmic rays. In addition, all sources of continuous residual background radiation (cosmic rays, natural radioactivity, noise, etc.) must be suppressed as much as possible by a small duty cycle accompanied by a high peak intensity of the neutrino source. The requirements on the time structure have

Table 1: Cross Sections and Counting Rates Typical for Neutrinos at the SNQ Spallation Neutron Source

Reaction	Mean Energy MeV	σ_{tot} (cm^2)	Counting Rate* $(day, mA, to)^{-1}$	Remarks
$\nu_e + d \rightarrow p + p + e^-$	37	$5 \cdot 10^{-41}$	29	
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N 11ms$	37	$1.5 \cdot 10^{-41}$	2.9	WSGIM theory
$\nu_e + e^- \rightarrow \nu_e + e^-$	37	$6 \cdot 10^{-43}$	0.74	V-A theory
$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$	30	$5 \cdot 10^{-44}$	0.062	
$\nu_\mu + {}^{12}C \rightarrow \nu_\mu' + {}^{12}C^*(15.1)$	30	$2.5 \cdot 10^{-42}$	0.48	WSGIM theory
$\nu_\mu + {}^{6}Li \rightarrow \nu_\mu' + {}^{6}Li^*(3.56)$	30	$1.5 \cdot 10^{-41}$	5.7	

*Counting rates at 12 m distance from the neutron source. Target electrons per ton of organic scintillator.

already been discussed in the preceding chapters. To achieve also a sufficient separation in time, a beam pulse length of less than about 200 ns must be realized with at least about 10 μs intervals between the pulses (see Fig.4).

In order to be able to measure the extremely small cross sections listed in Table 1 within a reasonable period of time, we need a correspondingly great target. The target nuclei or target electrons should, if possible, also be part of the detector for the respective signature of the neutrino reaction. Depending on the problem, different types of detector will be necessary in order to comply with these requirements. The large detectors currently used today in elementary particle physics cannot be simply taken over. The main reason is that the energy available as a signature for beam stop neutrinos is much lower than the energy in neutrino experiments at high-enery accelerators. Related to electrons in the detector the energies for interesting cases lie below about 20 MeV, for the major part of nuclear physics signatures (γ-transitions and β^- (β^+) emissions) even well below 10 MeV. On the other hand, the background both from the source and from cosmic rays increases roughly exponentially towards the smaller energies. For these reasons neutrino experiments at the beam stop have been performed until now only for energies between 25 and 50 MeV /20,21/. Only going down to energies between 3 and 20 MeV offers the possibility of nuclear physics signatures. This would allow for the first time to perform a great number of interesting experiments which could employ over a long period two to three research groups.

The calculations of shielding and background already mentioned above resulted in the proposal of the two detector regions shown in Fig.6. It can be easily seen that the shielding conditions are most favourable for the detector region I (ring bunker below the spallation source).

The calculated total background in that region is lower by a factor of five than in the detector region II. Therefore,

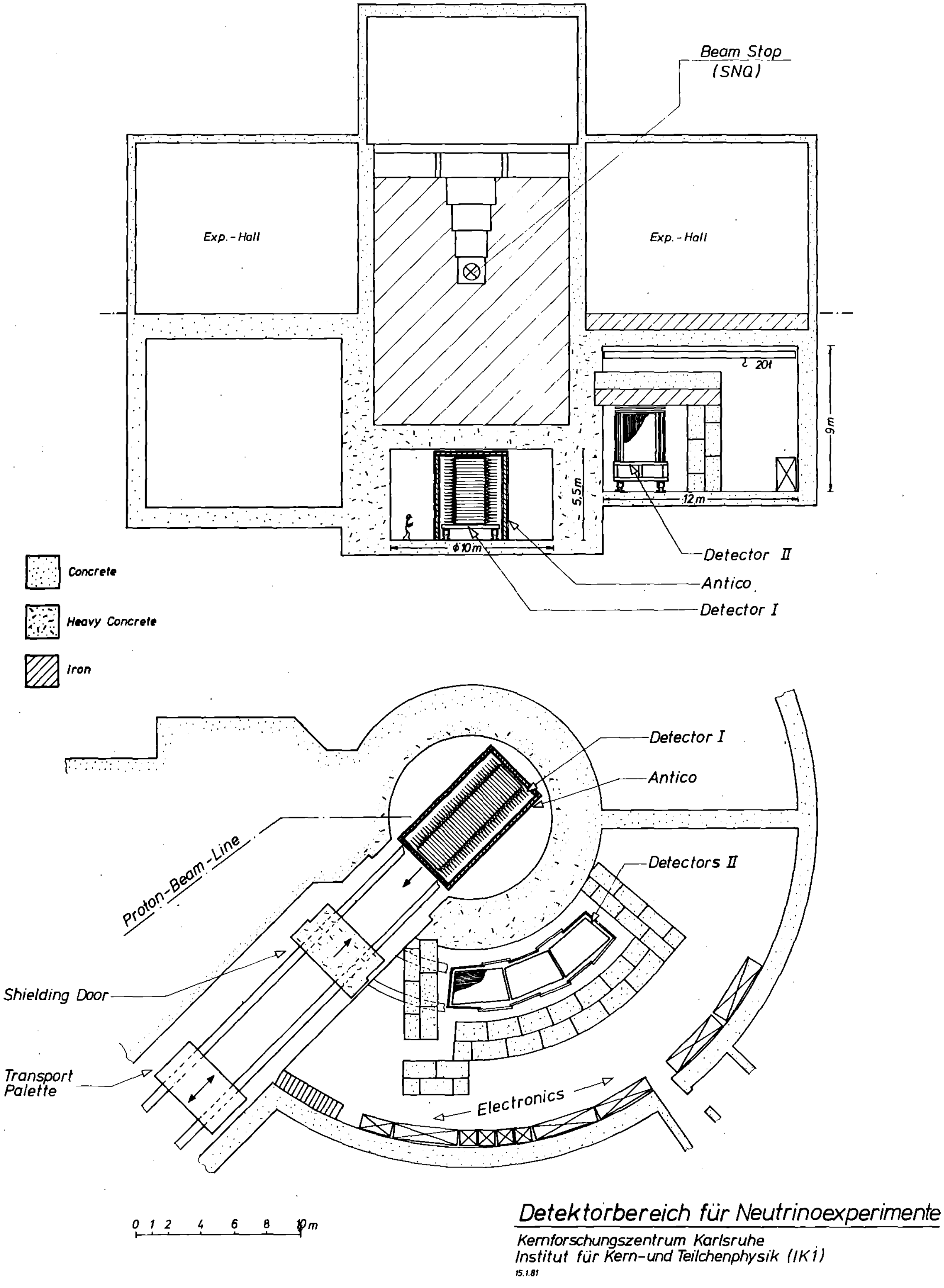

Fig.6: Proposal for the neutrino facility at the spallation source

it is particularly well suited for measurements with low γ- or electron energies. To be able to study the situation in quantitative terms we have selected a practical example of a detector placed in the region I. The target is formed by the ^{12}C nuclei in an organic scintillator. The scintillator is divided into segments consisting of elements of 1.5 m length each with a square cross section of 20 x 20 cm. Each element is supplied with one photomultiplier on both ends. This permits local resolution of about 10 cm along the element. Moreover, the requirement of coincidence of the two photomultipliers acts as an additional noise suppression. To obtain reasonable measuring time, about 50 tons of detector material are necessary.

With these requirements fulfilled, the following numbers of events are expected per mA of averaged current (see also Table 1):

$\nu_\mu + {}^{12}C \rightarrow \nu'_\mu + {}^{12}C^*(15.1$ MeV): 24 events/day

$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N - 18$ MeV: 145 events/day

$$\begin{tikzcd} {}^{12}N \arrow[d] \\ e^+ + {}^{12}C + 18 \text{ MeV} \end{tikzcd}$$

$\nu_e + e^- \rightarrow \nu_e + e^-$: 35 events/day

$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$: 3 events/day

Thus, if one wishes to study mu-neutrino-electron scattering, the total background in an interval of about 10 to 25 MeV must not exceed about one event/day. As shown by the computations, this requirement can be fulfilled with a suitabele time structure at the SNQ spallation neutron source:

1. Background from the spallation neutron source

   The background from the SNQ spallation neutron source at the location of the detector I after having passed through 8 m iron and 1 m borated high-density concrete is shown in Figs. 7 to 9. Details will be presented in /18/. Within the interesting range between approximately 10 - 25 MeV (related to electron energies in the scintillator) a flux in the detector due to background events caused by fast neutrons of about $2 \cdot 10^{-12}/(cm^2 s\ mA)$ is obtained at the SNQ spallation neutron source. For our 50 ton scintillator this means 0.02 event per day per mA. Consequently, the background of the SNQ spallation neutron source can be reduced to negligible values through shielding.

2. The high-energy muon component of cosmic rays is much more penetrating. It can be sufficiently reduced only by combination of a passive with an active shielding. Therefore, in the detector region I, two separate anticoincidence counters will be provided in addition to a passive detector shielding consisting of 20 cm thick iron plates (or a similar lead shielding). After a muon (or electron) has passed through these counters, the whole detector is switched to be insensitive for about 25 μs. In addition it can be made insensitive by the topmost segment layer and by about 10 cm surface layer at the ends of the segments.

More detailed investigations /18/ have shown that a suppression factor of about 10^{-5} by anticoincidence should be possible. In the proposal for an experiment at LAMPF, submitted by T.Y.Ling et al. /16/, even a value of $3 \cdot 10^{-6}$ is assumed for a similar anticoincidence shielding. Disturbing background from cosmic rays is mainly produced by the bremsstrahlung of the muons (or the electrons following them) near the detector shielding. The neutral radiation (true neutrals) still passing through the detector shielding (20 cm iron) is less intense by a factor 10^5 than the bremsstrahlung generated there by muons. Therefore, further

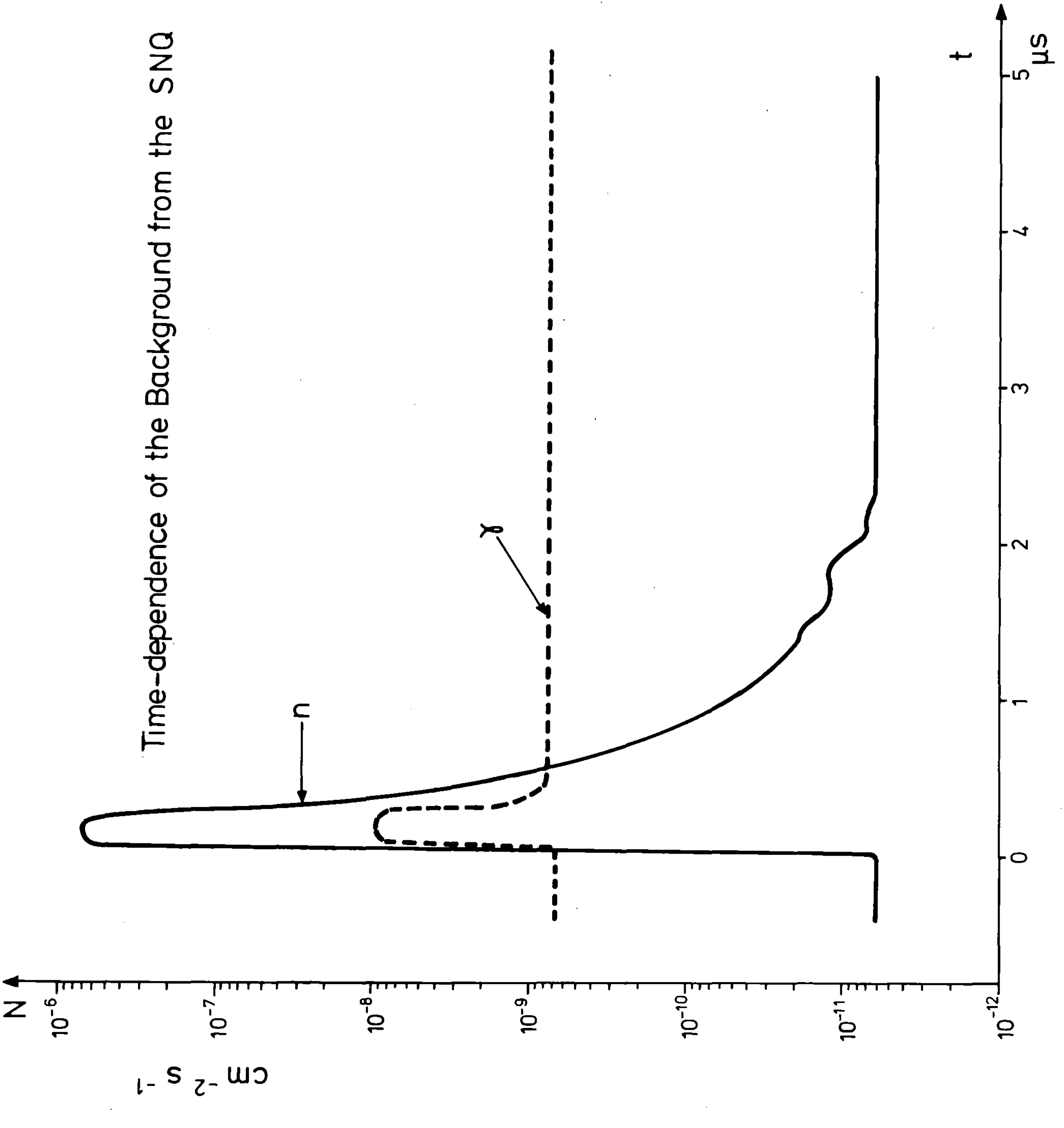

Fig.7: Time dependence of the background from the SNQ spallation neutron source (gammas, neutrons) for $\bar{I}_p$ = 1 mA

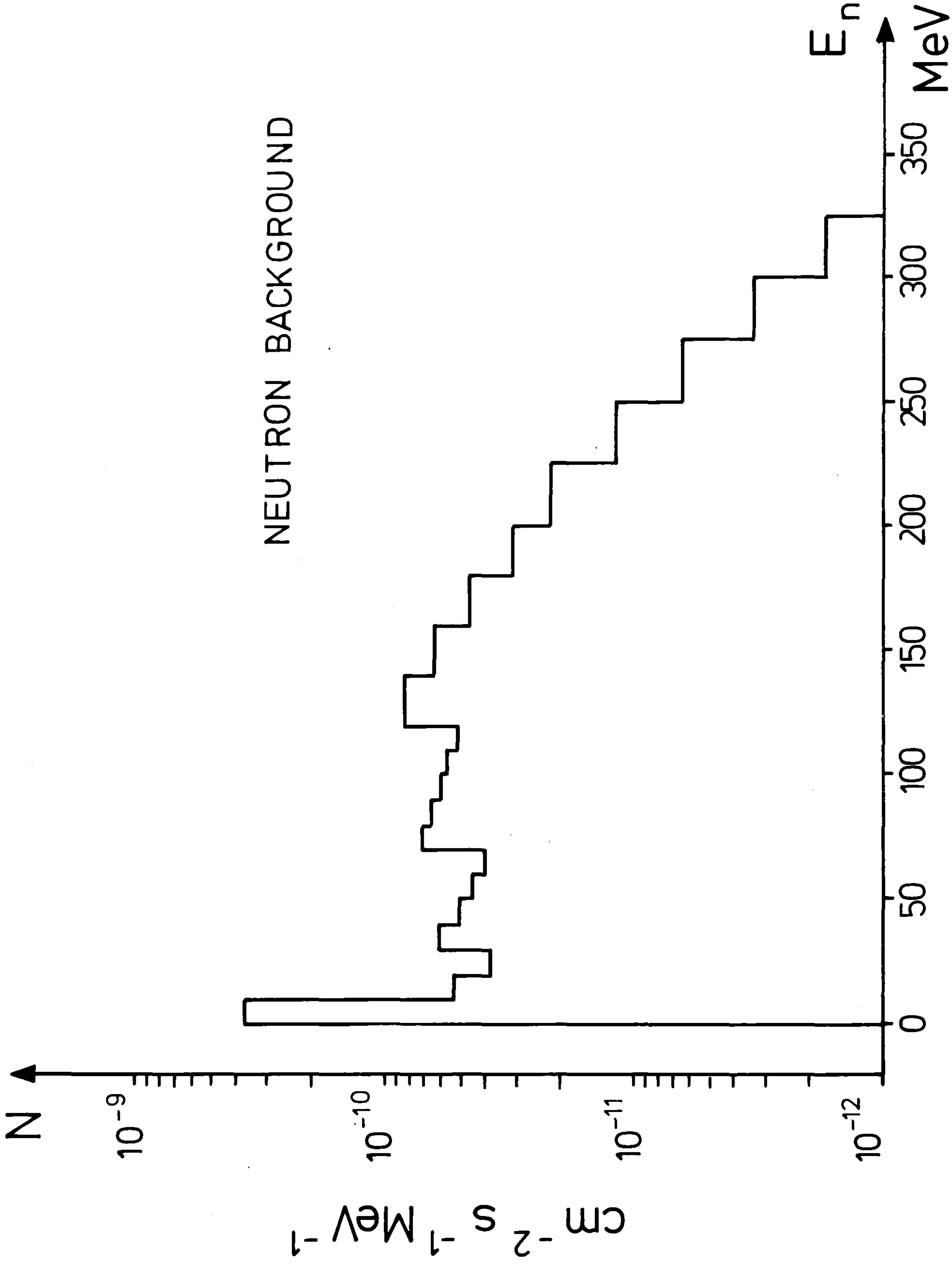

Fig.8: Energy dependence of the neutron background from the SNQ spallation neutron source for $\bar{I}_p = 1$ mA

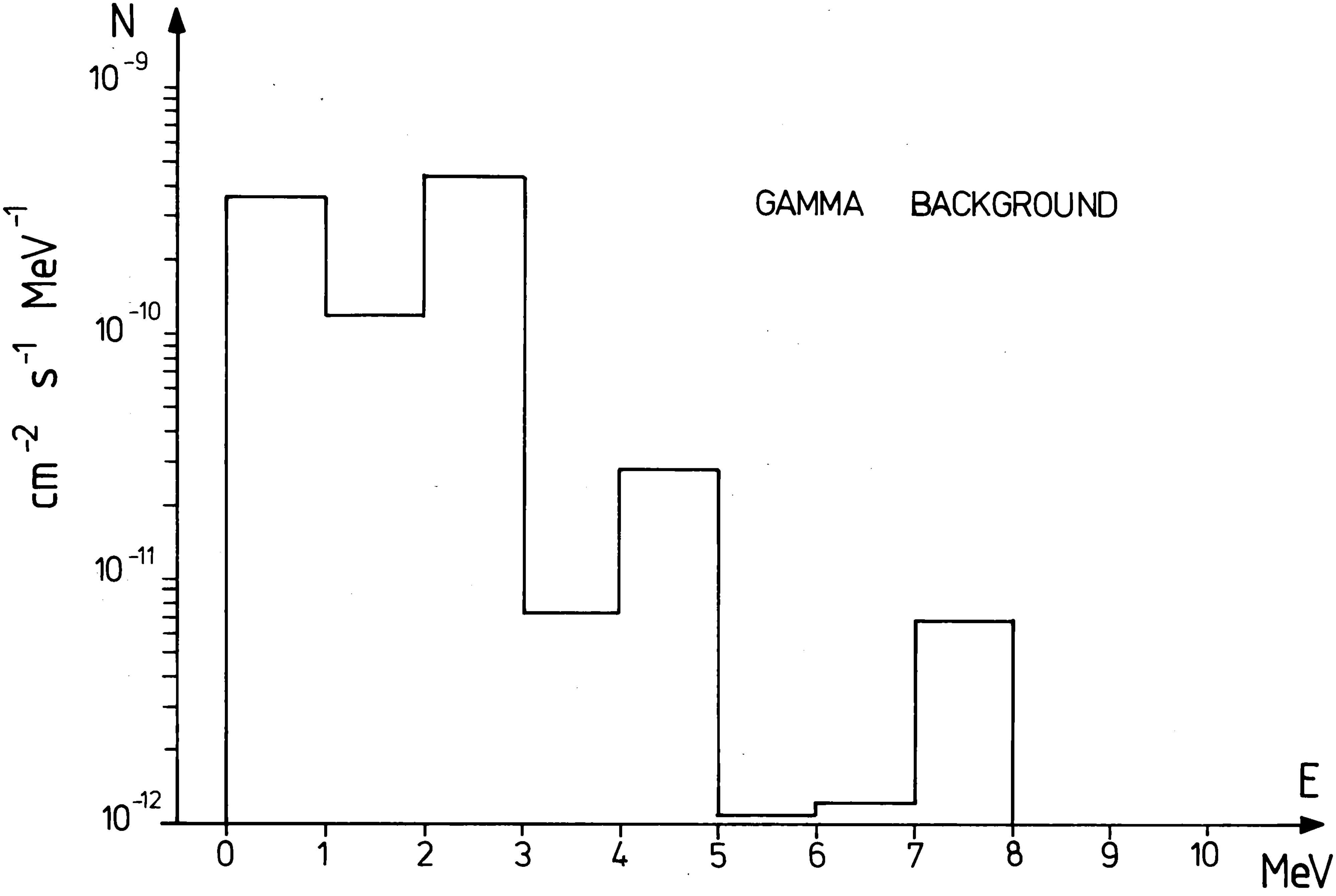

Fig.9: Energy dependence of the gamma background from the SNQ spllation neutron source for $\bar{I}_p = 1$ mA

optimization of the geometry of the passive and active detector shieldings might be rewarding.

Fig.10 shows the bremsstrahlung background in the detector I converted into electron energies in the scintillator, plotted versus the energy. The individual components are discussed in /18/. The background intensities are higher by approximately the factor three for the detector region II.

For our range of energies of 10 - 25 MeV the cosmic background yields $N_U = 1.5 \cdot 10^6$ events per day, leaving out of consideration the anticoincidence and the duty cycle. With an anticoincidence suppression factor of 10^{-5} we, therefore, expect $N_U = 15 \cdot DF$ per day (DF = duty factor). Consequently, even for the proposed interim solution ($DF = 5 \cdot 10^{-2}$) a background rate of less than 1 event per day can still be expected.

This would be comparable with the rate for neutrino-electron scattering: From Table 1 a rate of 3.7/day is calculated for $\nu_e + e^- \to \nu_e + e^-$ and 0.3/day for $\nu_\mu + e^- < \nu_\mu + e^-$ (based on the averaged current 100 μA attained in the proposed interim solution). In the presence of a storage ring the expected counting rates would be higher by a factor 50 while the background would still be strongly reduced. It is worth mentioning in this context that so far not even the existence of the reaction $\nu_e + e^- \to \nu_e + e^-$ has been proved.

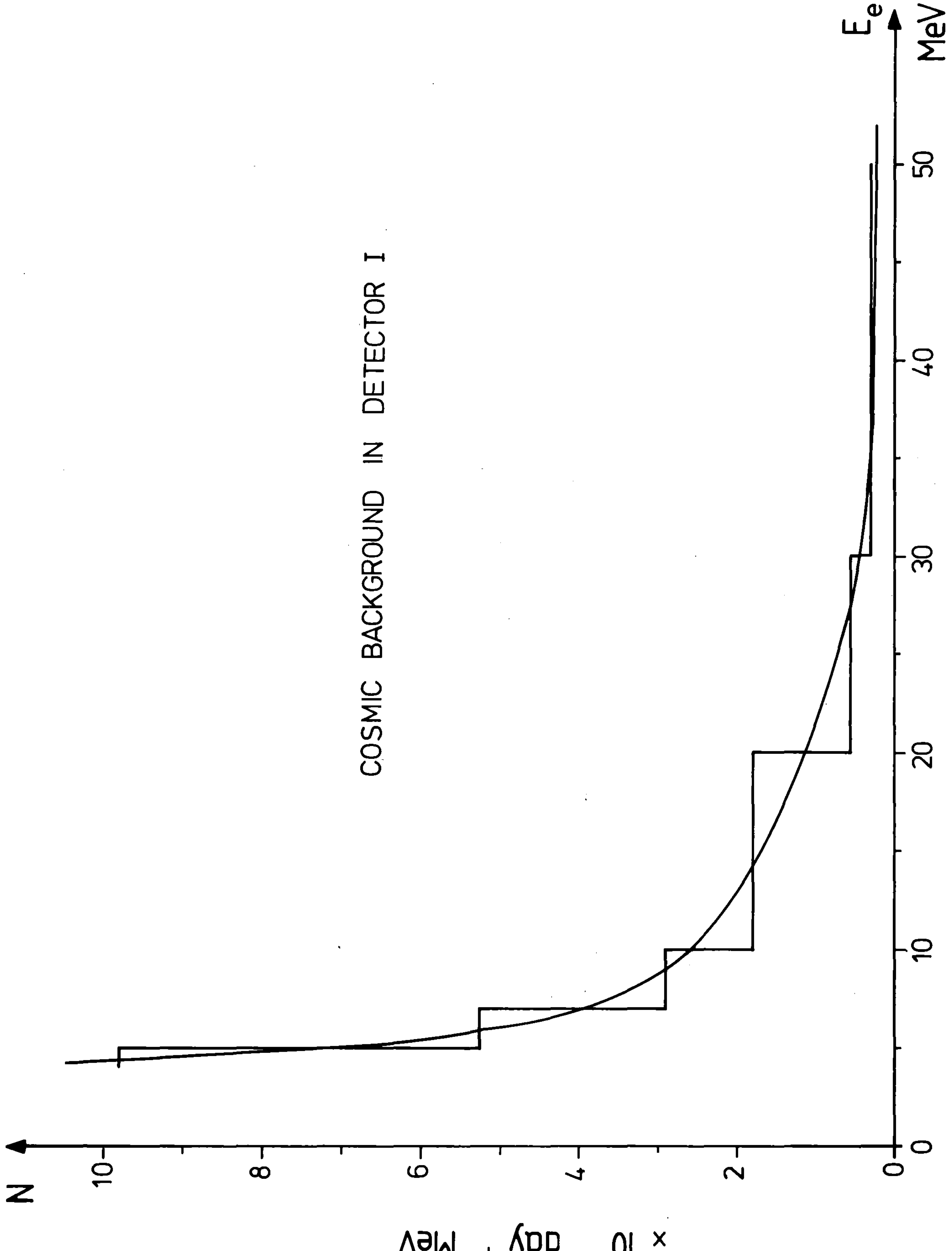

Fig.10: Energy dependence of the cosmic background measured in the detector I

IV. PROPOSAL FOR AN EXPERIMENT TO SEARCH NEUTRINO OSCILLATIONS $\nu_\mu \leftrightarrow \nu_e$ AT THE SPALLATION NEUTRON SOURCE

To demonstrate the extraordinary possibilities for neutrino physics at a high-intensity spallation neutron source associated with a good time structure an experiment will be proposed below for observation of neutrino oscillations $\nu_\mu \leftrightarrow \nu_e$.

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 /1/. 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 mixing angle still unknown. 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 /1/. For a constant energy, conversion is possible from time dependence into flight path dependence. This gives for the transition probability:

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

$$P'(x) = 1 - P(x) \quad \text{for } \nu_e \rightarrow \nu_\mu \qquad (15)$$

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

We now assume a source pulsed according to Fig.4 i.e., a pulse length of $t_p = 200$ ns. As shown by Eqs.(10) to (13), the number of muon neutrinos at the source is much greater in the range < 200 ns than the number of electron neutrinos, whilst in the range > 200 ns we find almost exclusively electron neutrinos (except for the muon antineutrinos). This fact can be utilized to define a ratio of measurable counting rates which reacts very sensitively to the oscillation $\nu_\mu \leftrightarrow \nu_e$ but which, on the other hand, is insensitive to instabilities and other systematic errors.

We firstly set up the following counting rates applicable to the reactions with the ^{12}C nuclei in the detector I (50 t scintillator):

$$N_\nu(1) = \frac{\varphi_\nu \cdot N(^{12}C)}{4\pi \cdot 100^2}$$

$$N(^{12}C) = 2.51 \cdot 10^{30} \text{ (target nuclei in the detector)}$$

The expected counting rates at the distance x in meters from the source will then be:

$$N_{\nu_\mu}(x) = \frac{\sigma_{\nu_\mu}}{x^2}(N_{\nu_\mu}(1) \cdot (1-P(x)) + N_{\nu_e}(1) \cdot P(x))$$

$$N_{\nu_e}(x) = \frac{\sigma_{\nu_e}}{x^2}(N_{\nu_e}(1) \cdot (1-P(x)) + N_{\nu_\mu}(1) \cdot P(x)) \tag{16}$$

For simplification the energy of the mu-neutrinos and of the electron neutrinos will be assumed to be $\langle E_\nu \rangle = 30$ MeV, σ_{ν_μ} and σ_{ν_e} are the total cross sections:

σ_{ν_μ} for $\nu_\mu + {}^{12}C \rightarrow \nu_\mu' + {}^{12}C^+(15.1)$; σ_{ν_e} for $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$

Assuming a proton pulse duration of $t_p = 200$ ns we now make a distinction between two counting rates each. For the time interval between $t = 0$ and $t = t_p = 200$ ns we mark the counting rates from (16) with the index <. For the neutrinos generated after this time interval (200 ns to 8 μs) the index > is used. Inserting numerical values yields:

$$N^{<}_{\nu_\mu}(x) = \frac{1}{x^2}\,(3346(1-P(x))+345\cdot P(x))$$

$$N^{>}_{\nu_\mu}(x) = \frac{1}{x^2}\,(175(1-P(x))+3146\cdot P(x))$$

$$N^{<}_{\nu_e}(x) = \frac{1}{x^2}\,(2067(1-P(x))+20074\cdot P(x)) \qquad (17)$$

$$N^{>}_{\nu_e}(x) = \frac{1}{x^2}\,(18875(1-P(x))+1049\cdot P(x))$$

The numerical values relate to 1 mA averaged current over a period of one day (24 hours) and with 50 to of ^{12}C in the target.

For $\langle E_\nu \rangle = 30$ MeV it follows from Eq. (15):

$$P(x) = \sin^2 2\Theta\cdot\sin^2(0.042\cdot\delta m^2\cdot x) \qquad (18)$$

and assuming maximum mixing ($\sin^2 2\Theta = 1$):

$$P(x) = \sin^2 (0.042\cdot\delta m^2\cdot x) \qquad (19)$$

From equation (19) follows that for $\delta m^2\cdot x \leq 1$ (e.g. $\delta m^2 = 0.1\ \mathrm{eV}^2$; x=10 m)the transition probability gets proportional to $\delta m^4\cdot x^2$. Thus, the number of converted neutrinos at the distance x ist approximately:

$$N \sim \frac{1}{x^2}\cdot\delta m^4\cdot x^2 = \delta m^4 = \text{constant.}$$

Using the counting rates in (17), the following ratio can be defined:

$$R(x) = \frac{N^{<}_{\nu_\mu}(x) - N^{<}_{\nu_e}(x) + N^{>}_{\nu_e}(x)}{N^{<}_{\nu_e}(x) + N^{>}_{\nu_e}(x)} \qquad (20)$$

The number $N^{>}_{\nu_\mu}(x)$ was not used because it is difficult to measure. Introducing (17) into (20) gives:

$$R(x) = \frac{20154 - 39883 \cdot P(x)}{20942 + 181 \cdot P(x)} \qquad (21)$$

It can be noticed that the denominator is practically independent of x. Therefore, it can be determined with the smallest possible statistical error for a small distance. If one introduces in addition (19) into (21), one obtains:

$$R(x) = 0.962 - 1.904 \sin^2 (0.042 \cdot \delta m^2 \cdot x) \qquad (22)$$

Since $1 - \sin^2\alpha = \cos 2\alpha$, the following expression applies approximately:

$$R(x) \approx \cos (0.084 \cdot \delta m^2 \cdot x) \qquad (23)$$

The expression (23) reflects the fact that $\tau_\pi << \tau_\mu$. If the number of mu-neutrinos abruptly became zero after the time interval t_p, (23) would apply exactly.

Since in one detector the counting rates in (20) can be measured simultanesously for the same number of target nuclei, the ratio R(x) is relatively insensitive to systematic errors. The statistical error of R(x) can be estimated by:

$$\Delta R(x) \approx \pm \frac{1}{N(x)} \sqrt{R(x) \cdot N(x) + N_U} \qquad (24)$$

where N(x) is the denominator of (21) which can be determined with a small error and N_U is the (cosmic) background rate which can be measured conveniently during the beam intervals. As has been shown in chapter III, $N_U \approx 1$/day can be expected.

Fig.11 is a plot of R(x) (x = 12 m, 60 m and 120 m) versus the square of the mass difference. The error bars represent statistical errors to be expected for an averaged current of 1 mA and a duration of measurement period of one year (300 days). A widely used reference variable is the smallest still measureable mass difference for a maximum mixture. This minimum mass difference can be read from Fig.12.

It appears that for an averaged current of 5 mA the lower limit of the still measureable mass difference of neutrinos lies at $\delta m^2(\min) = 0.03$ eV^2. However, this extremely small value can be attained only in the presence of a storage ring. The minimum values roughly depend on the square root of the averaged proton current at the spallation neutron source. One obtains e.g. $\delta m^2(\min) = 0.06$; 0.2 eV^2 for $\bar{I}_p = 1$; 0.1 mA.

These numbers must be compared with the limit of $\delta m^2 \approx 1$ eV^2 obtained from very lengthy and difficult high-energy and reactor experiments /15,22,23/. Even with the proposed interim solution with $\bar{I}_p = 100$ µA, this value could be measured at the spallation neutron source within about ten days of measurement time with an error of only about $\pm$ 0.25 eV^2.

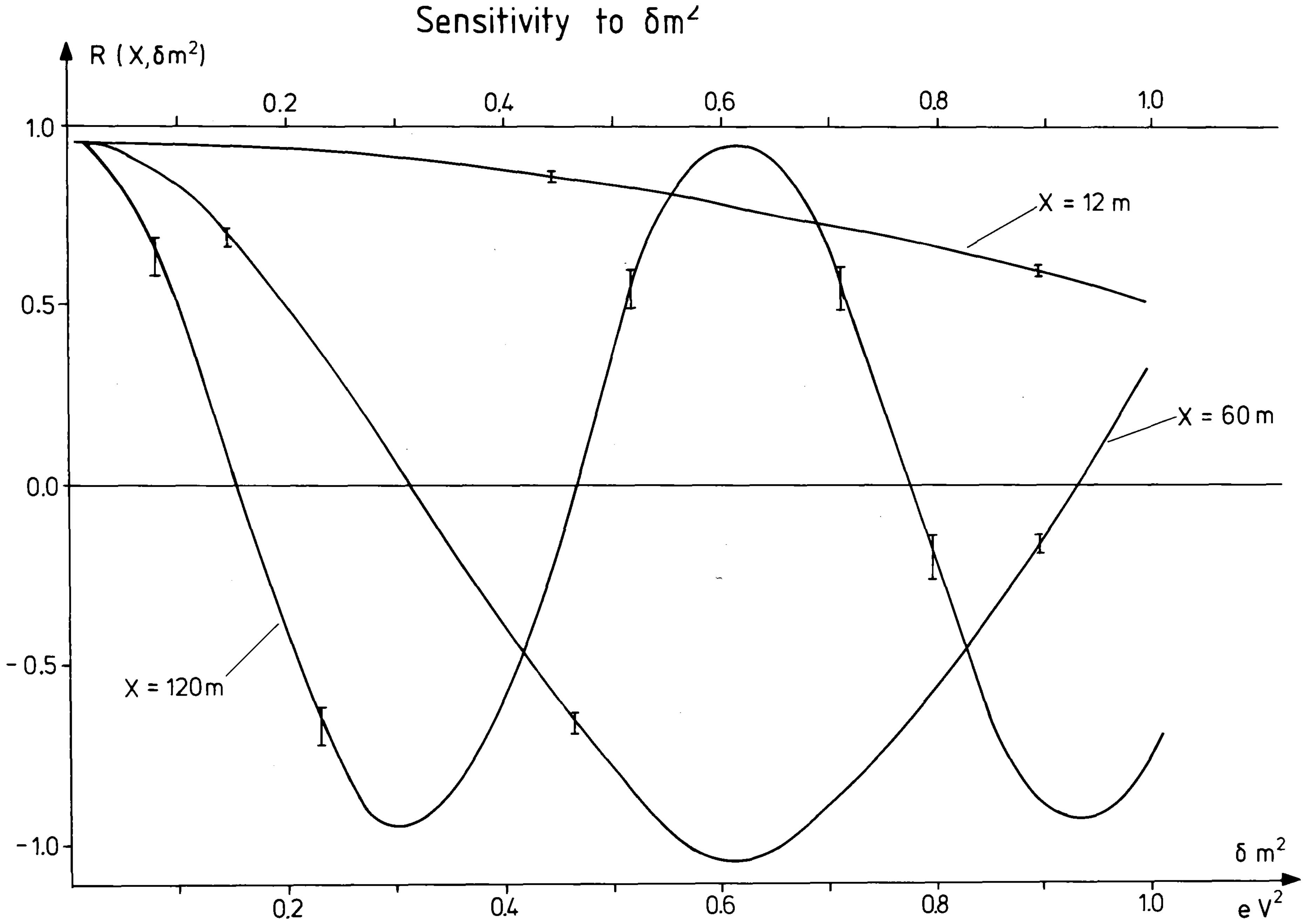

Fig.11: Dependence of the ratio R(x) on the mass difference of the neutrinos for different distances from the source. The error bars apply to a period of measurement of one year at 1 mA proton current

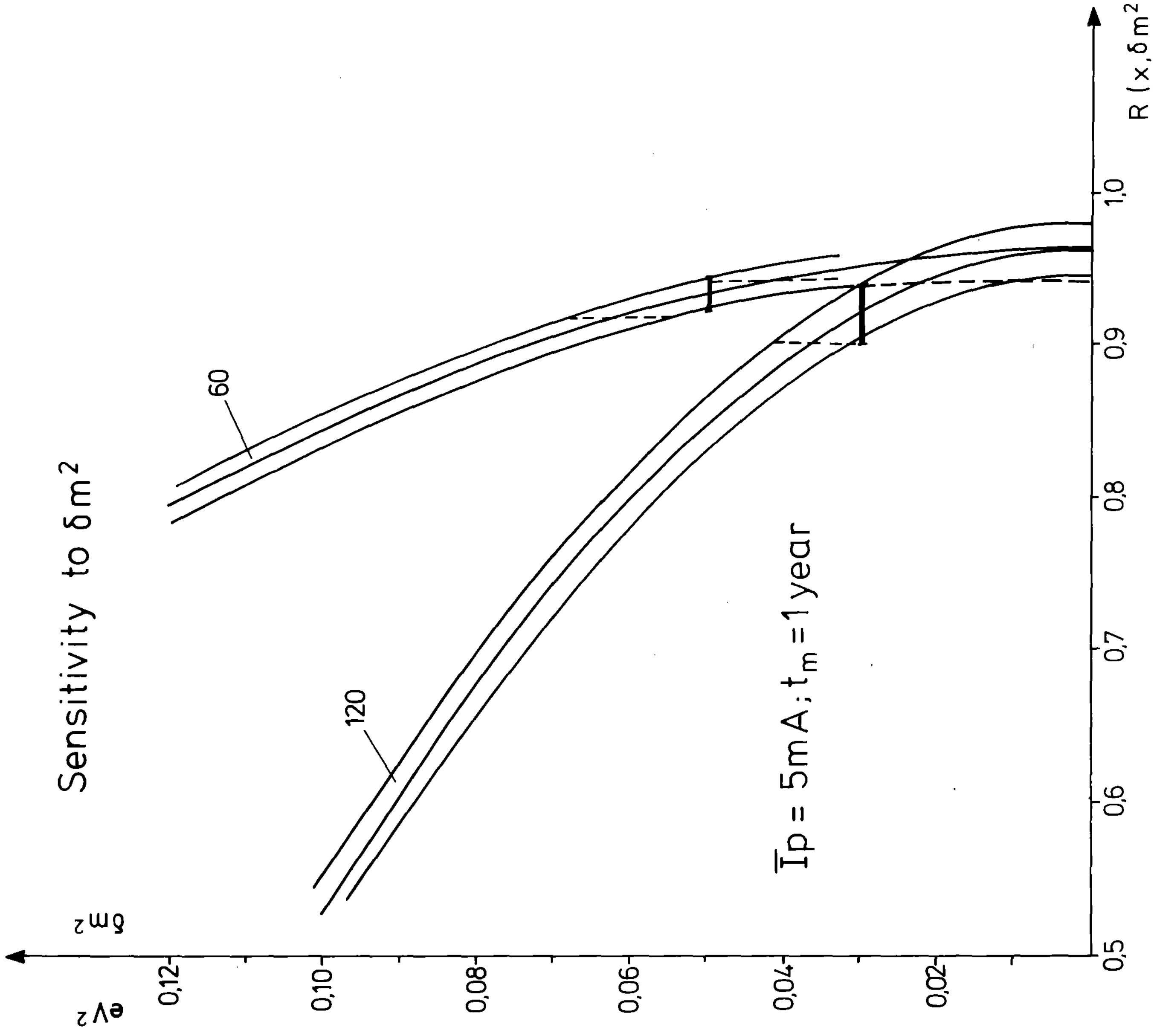

Fig.12: Sensitivity of the ratio R(x) to δm^2 for the distance 120 and 60 m for a period of measurement of one year at 5 mA averaged current.

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