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Low energy neutrino scattering measurements at future Spallation Source facilities

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Abstract.

In the future several Spallation Source facilities will be available worldwide. Spallation Sources produce large amount of neutrinos from decay-at-rest muons and thus can be well adapted to accommodate state-of-the-art neutrino experiments.

In this paper low energy neutrino scattering experiments that can be performed at such facilities are reviewed. Estimation of expected event rates are given for several nuclei, electrons and protons at a detector located close to the source. A neutrino program at Spallation Sources comprises neutrino-nucleus cross section measurements relevant for neutrino and core-collapse supernova physics, electroweak tests and lepton-flavor violation searches.

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1. Introduction

Spallation sources can be well adapted to accommodate innovative neutrino experiments.

Large amounts of neutrinos are produced at such facilities, from the decay of pions $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and the subsequent decay of muons $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$. On the other hand,

very few

electron anti-neutrinos are emitted via π^- decay

(typically at the level of 10^{-5}),

due to the strong π^- absorption in the spallation target.

Spallation sources have already been used to perform a very interesting neutrino physics program in the past.

In particular, crucial results on neutrino oscillations have been obtained by the LSND [1, 2, 3] and KARMEN [4] collaborations

at LANSCE in Los Alamos and ISIS at Rutherford Appleton Laboratory respectively.

These experiments have used a 167 (LSND) and 65 (KARMEN) tons scintillator detector located at about 17 meters from the source.

The same experimental setups have also been exploited to perform measurements of neutrino scattering on ^{12}C [5, 6, 7, 8, 9, 10, 11, 12], ^{13}C and ^{56}Fe [13] as well as electroweak tests (lepton flavor universality [11], V-A structure in muon decay [14], Weinberg angle [15]) and lepton-flavor violation searches [16].

New spallation sources are being constructed, planned or under study. These include the Spallation Neutron Source (SNS) facility at Oak Ridge [17], the European Spallation Source (ESS) facility in Lund, the Japanese Spallation Neutron Source (JSNS) at JPARC [18] and the SPL at CERN [19].

Table 1 presents a comparison of some key characteristics of these sources.

Although their physics program is focussed on neutron and material science, these facilities will be ideal locations to

host a low energy neutrino physics program of interest for particle physics[‡], neutrino astrophysics and nuclear physics.

The only technical alternative to produce controlled neutrino fluxes in the 100 MeV energy range is a low energy beta-beam facility [21]. This

is based on the novel method of the beta-beams [22] that exploits the beta-decay of boosted radioactive ions. Detailed investigations of the low energy beta-beam physics potential have pointed out[§] a variety of interesting

applications in nuclear physics, in the study of fundamental interactions and core-collapse supernova physics (for a review of beta-beams see [23]).

[‡] Note that in [20] a new idea for the search of CP violation in the lepton sector is proposed, using spallation sources.

[§] The main goal of the standard beta-beam is the search of CP violation in the lepton sector [22].

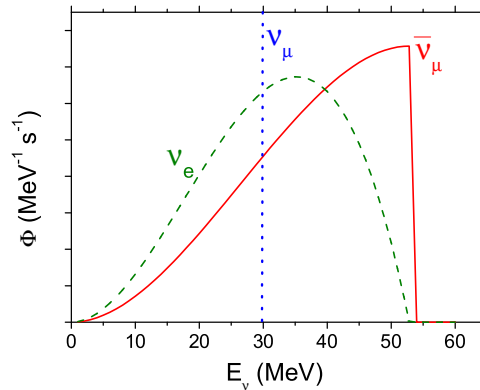


Figure 1. Neutrino fluxes from muon and pion decay-at-rest at a spallation source.

Beta-beams have two main advantages compared to spallation sources: i) they produce collimated beams of both ν_e and $\bar{\nu}_e$; ii) the average energy of the neutrino beams can be varied. On the other hand, spallation sources will reach significantly larger neutrino production rates.

The determination of neutrino cross sections in a broad range of energies (several hundred MeV to multi-GeV range) is currently the focus of many experiments such as Minerva [24] and Sciboone [25].

The MiniBOONE experiment is also providing interesting cross section measurements, like the quasi-elastic differential neutrino-carbon one [26].

Note that the MiniBOONE results have revealed an excess of the electron-like events for the several hundred MeV neutrino energy range [27].

Neutrino scattering experiments at Spallation Sources are complementary to such experiments since the neutrino fluxes are in the 50 MeV energy range (Figure 1).

Neutrino-nucleus cross section measurements with low energy neutrinos have timely applications, that go from

the precise calibration of neutrino detectors to constraining neutrino-less double beta decay calculations.

Neutrino detectors based on nuclei are used for the observation of neutrinos from a future core-collapse supernova explosion, or from past explosions (the diffuse supernova neutrino background).

Indeed neutrino-nucleus scattering is necessary for the identification of the electron neutrinos; while

electron anti-neutrinos can be detected through proton scattering in water Cherenkov and scintillator detectors.

For example,

a lead-based supernova observatory – the HALO project – is now planned at SNOLAB. The measurement of neutrino-scattering on lead in coincidence with 1 or 2 neutrons would be necessary since this observable has an interesting sensitivity upon the third neutrino mixing angle [28].

Large-size detectors are currently under study (GLACIER, MEMPHYS/UNO/Hyper-K and LENA) [29]. In these observatories the ν_e

from a core-collapse supernova or of the diffuse supernova neutrino background can be measured through scattering on argon [30], on oxygen and on carbon [31]. Concerning the observation of supernova neutrinos from past explosions in our galaxy,

an original strategy is based on the geochemical measurement of ^{97}Tc produced by the interaction of electron neutrinos in ^{98}Mo ore [32].

To extract unambiguously such a contribution the ν - ^{98}Mo and ν - ^{97}Tc cross sections need to be precisely known, as pointed out in [33]. Neutrino-nucleus cross sections on stable and radioactive nuclei are also necessary to understand stellar nucleosynthesis and, in particular, to unravel the site of the r-process (see e.g. [34, 35]), one of the major open questions in nuclear astrophysics (see e.g. [36]).

Finally a precise knowledge of the nuclear response to neutrinos is also crucial in order to calibrate some ingredients of the microscopic approaches currently used to predict neutrinoless double-beta decay (e.g. forbidden multipole contribution to the half-lives and their possible quenching) [37, 38].

The observation of this lepton-flavour violating process represents a major discovery.

Key information on the CP Majorana phases, on the electron neutrino effective mass and mass hierarchy can be extracted if this rare process is observed [39, 40].

However this requires

reducing the current discrepancies among the half-life predictions.

In this respect a step forward can be made through neutrino-nucleus measurements, combined with other measurements on the candidate emitters (beta-decay, muon capture, charge-exchange reactions and the two-neutrino double beta decay) [41].

The theoretical description of neutrino-nucleus cross sections in the low energy range benefits from a variety of sophisticated models, including Effective Field Theories [42, 43], the Continuum Random-Phase-Approximation (CRPA) [44, 45], the Quasi-particle RPA (QRPA) [46] and projected QRPA [47], relativistic RPA [49], the Shell Model (SM) [46, 48] and the Shell Model in the complex energy plane [50]. Regardless the high degree of sophistication achieved, important discrepancies remain between the predicted neutrino-nucleus cross sections. For example, in [47] it is shown that the calculations of the energy dependent cross section on ^{56}Fe differ as much as by factor 3-4 at a given energy, whereas

the convoluted neutrino cross sections turn to be in agreement with the

Facility	Power	Proton energy	Time structure	Repetition rate
LANSCE (USA)	56 kW	0.8 GeV	Continuous	N/A
ISIS (UK)	160 kW	0.8 GeV	200 ns	50 Hz
SNS (USA)	> 1 MW	1 GeV	380 ns	60 Hz
JSNS (Japan)	1 MW	3 GeV	1 μ s	25 Hz
SPL (CERN)	4 MW	3.5 GeV	0.76 ms	50 Hz
ESS (Sweden)	5 MW	1.3 GeV	2 ms (1.4 μ s)	17 Hz (50 Hz)

Table 1. Comparison of characteristics of the past, present, and future Spallation Source Facilities in different regions of the world.

experimental data|| [13]. In [49] the comparison of the flux-averaged neutrino-lead cross sections, associated to supernova neutrinos, show very similar discrepancies.

The realization of precise measurements of the neutrino scattering cross sections for an ensemble of nuclei would help to pin down differences among the models, enabling accurate and reliable description of

the isospin and spin-isospin nuclear response.

Coherent neutrino-nucleus scattering has never been measured as well.

Such an experiment is a useful test of the Standard Model and to establish the feasibility of supernova neutrino detectors and dark matter searches based on this process. The corresponding cross section in the 50 MeV energy range can be as large as 10^{-39}cm^2 . Its measurement is now planned at SNS (the CLEAR experiment) [51, 52]. Finally let us mention the neutrino capture on radioactive nuclei that might open a completely new window on the Universe. This process could indeed be used to observe the cosmological neutrino background. This exciting possibility as pointed out in [53] and further investigated in [54].

Note that one can calibrate the corresponding cross sections using the inverse process, namely the beta-decay of the nuclei of interest, since the impinging neutrino energy is extremely low (the neutrino background has a temperature of 1.96 K).

The physics scope of spallation source facilities covers neutrino physics, neutrino astrophysics and tests of the Standard Model. Detailed investigations can be found in the literature (see e.g. [55]).

Ref. [17] is a proposal made for the SNS facility presenting also an in-depth study of possible backgrounds and of detectors' design. In this paper, we present new predictions for neutrino-nucleus, neutrino-proton and electron scattering rates, motivated by the recently approved European Spallation Source facility. We emphasize general aspects, relevant for the cross section measurements and for low energy tests of the Standard Model. In particular we focus on a Weinberg angle measurement and Lepton-Flavour Violation (LFV) searches.

|| Note that the experimental uncertainties are in this case at the level of 50%. [13]

	10	20	50	ρ (g/cm ³)	$\langle \sigma \rangle_{DAR}$
¹² C (in C ₁₆ H ₁₈)	1470	384	63	0.992	≈ 0.14 [13, 10]
¹⁶ O (in water)	998	261	43	1.	0.131 [56]
⁴⁰ Ar	8860	2310	380	1.43	2.56 [44]
⁵⁶ Fe	9100	2330	377	7.87	3.53 [56]
¹⁰⁰ Mo	17300	4420	716	10.28	11.95 [56]
²⁰⁸ Pb	34500	8820	1430	11.34	49.6 [56]
²⁰⁸ Pb + 1n	1630	4180	677		23.5 [28]
²⁰⁸ Pb + 2n	9420	1140	390		13.5 [28]

Table 2. Results on the number of events at a neutrino experiment based at a spallation source facility.

The events are calculated assuming 10^{15} ν_e /s, in a year ($3 \cdot 10^7$ s), with a fully efficient 1 ton cubic detector. The columns correspond to the considered targets (first column), the rates at different distances d (meters) from the source, the material density (fourth column) and the flux-averaged cross sections in units 10^{-40} cm² (last column).

2. Results on expected rates

We assume here a neutrino flux at the source of $n_\nu = 10^{15}$ ν_e /s and a fully efficient 1 ton cubic detector.

At this early stage, we present only very general estimates for the expected neutrino event rates, neglecting statistical and systematic errors coming from possible backgrounds. Therefore,

our numbers of events can be easily scaled, for any neutrino production rate and experiment running time.

Nuclear excitations: Neutrino-nucleus charged-current event rates

are given in Table 2, assuming different target nuclei. The detector location is varied, its front being set

at distance $d = 10, 20$ and 50 meters from the source. It is obvious that the detector should be placed as close

as possible to the source in order to increase the rates, since the neutrino flux decreases as the inverse distance squared.

At such short distances

the detector finite size also impacts the number of events. To demonstrate this effect

we present in Figure 2 the ratio of the neutrino flux averaged over the detector volume V , i.e. $\langle \phi \rangle_{det} = \int_V dV \phi(E_\nu) dE_\nu / V$ over the neutrino flux at the detectors front side ($n_\nu / 4\pi d^2$), as a function of the distance from the source.

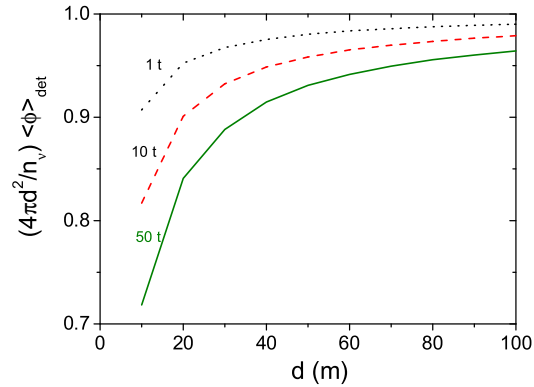


Figure 2. Effect of the finite size of a fully efficient cubic water Cherenkov detector: the curves show the ratio of the neutrino flux averaged over the detector volume $\langle \phi \rangle_{det}$, normalized by the flux $n_\nu/(4\pi d^2)$ at distance d , as a function of the distance from the spallation source (see text). The quantity n_ν is the number of electron neutrinos per unit time at the source. The curves correspond to a 1 ton, a 10 ton and a 50 ton detector.

We see that the bigger is the detector the larger is its finite size effect which disappears only at distances as far as about 60 meters from the source.

We present rates for nuclei that can be found in detectors based on various technologies, namely carbon (detectors made of liquid scintillators, e.g. $C_{16}H_{18}$), oxygen (for water Cherenkov), argon, iron, molybdenum and lead.

The corresponding neutrino-nucleus cross sections, averaged over the decay-at-rest (DAR) muon flux (Michel spectrum, Figure 1), are chosen as follows. We take the experimental flux-averaged cross sections

for ^{12}C [13, 10]. Our

QRPA calculations with the Skyrme interaction are used for ^{16}O , ^{56}Fe , ^{100}Mo and ^{208}Pb from Ref. [56].

The ^{208}Pb cross sections with neutron(s) emission are from Ref. [56]. CRPA calculations

of the ^{40}Ar cross sections are taken from [44].

As can be seen from Table 2 convolved DAR cross sections as well as the event rates are lowest for

carbon and oxygen

nuclei. This is mainly due to the high reaction threshold but, for oxygen, also due to the closed shell structure.

The most interesting event rates are obviously from detectors based on heavy nuclei.

In order to understand the nuclear structure response, involved in the DAR flux-averaged

${}^A\text{X}$	0^+	1^+	2^+	3^+	0^-	1^-	2^-	3^-
${}^{16}\text{O}$	0.23	1.38	0.70	0.74	0.79	42.3	53.7	0.1
${}^{56}\text{Fe}$	13.0	66.7	1.09	1.12	0.24	9.45	8.27	0.06
${}^{100}\text{Mo}$	16.7	53.3	2.12	2.08	0.30	12.2	12.6	0.29
${}^{208}\text{Pb}$	12.9	43.3	4.95	4.76	.317	14.1	17.1	1.14

Table 3. Fraction (in %) of the flux-averaged cross section associated to states of a given multipolarity, with respect to the total flux-averaged cross section, i.e. $\langle\sigma\rangle_{J\pi}$

$\langle\sigma\rangle_{tot}$. Results are given for

all positive and negative states, having total angular momentum J between 0 and 3. The first column gives the considered nucleus [56].

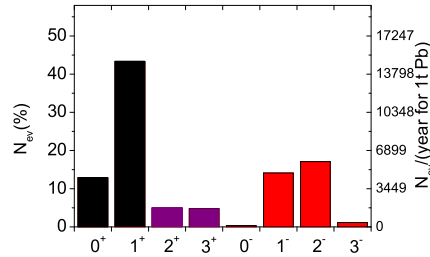


Figure 3. Contributions of the positive and negative parity states, in percentage, to the number of events for oxygen (left) and lead (right figure) nuclei, as examples.

	10	20	50	ρ (g/cm ³)	$\langle\sigma\rangle_{DAR}$
ν_e -e	230 (223)	60 (58)	10	1.0 (0.992)	$2.99\cdot 10^{-3}$
ν_μ -e	35 (34)	9.15 (9.0)	1.52 (1.5)	1.0 (0.992)	$4.58\cdot 10^{-4}$
$\bar{\nu}_\mu$ -e	38 (37)	9.9 (9.6)	1.6 (1.5)	1.0 (0.992)	$4.93\cdot 10^{-4}$

Table 4. Same as Table 2 (anti)neutrino scattering on electrons in water. The values given in parenthesis correspond to the results for electrons in $\text{C}_{16}\text{H}_{18}$ as another example.

cross sections, it is necessary to identify the different multipole contributions.

Note that a precise knowledge of the nuclear transition matrix elements of states of high multipolarity is crucial

to better constrain neutrino-less double beta-decay predictions [38].

The forbidden contributions are usually located at higher energies and can be best studied when one can vary the

average energy of the impinging neutrinos.

In this respect low energy beta-beams constitute a powerful tool since the average neutrino energy can be increased by accelerating the ions at different boost factors.

On the other hand DAR neutrino fluxes from Spallation Sources have much higher intensities than the ones that will be achieved by low energy beta-beams.

In [58] a comparative analysis of the multipole contributions to the neutrino-lead cross section at spallation sources and low energy beta-beams is made, showing that measurements at these facilities are complementary. Ref.[59] has first investigated neutrino-nucleus cross section measurements at a low energy beta-beam facility while the multipole decomposition of the corresponding flux-averaged cross sections are given in [56].

In Figure 3 and Table 3 we show the decomposition of the total cross section over the states of different multipolarity, that contribute to the cross sections.

For a closed shell nucleus as oxygen, the forbidden 1^- , 2^- excitations dominate the cross section.

The case of oxygen is exceptional: the allowed (Gamow-Teller and Fermi) transitions

accounts for less than 2% of the total cross section. In most cases allowed excitations are

the dominant contribution; while the forbidden one can be significant. For example it is at the level

of 30% for ^{100}Mo and ^{208}Pb .

A Weinberg angle measurement: Neutrino detectors can also be used to study neutrino-electron scattering.

The expected number for $\nu_{e,\mu}$ -e and $\bar{\nu}_{\mu}$ -e scattering are given in Table 4. Although the ν -e cross section is much weaker compared to those on nuclei, such events can be separated in the detector by

considering forward scattering.

If the systematic errors are kept sufficiently low, one can use this measurement to extract

non-standard contributions to the weak interaction (e.g. flavor-changing neutral currents effects)

and perform a precise measurement of the Weinberg angle at low momentum transfer.

The current best value for $\nu_e - e$ scattering is $\sigma = 10.1 \pm 1.1(stat) \pm 1.0(sys) E_{\nu_e} \times 10^{-45} \text{cm}^2$ [15]. Note that a possible measurement with low energy beta-beams can

determine the Weinberg angle with a precision of 10 % if the systematic errors are kept below 10% [60].

The time-structure of the beam pulse can be crucial for the accurate determination

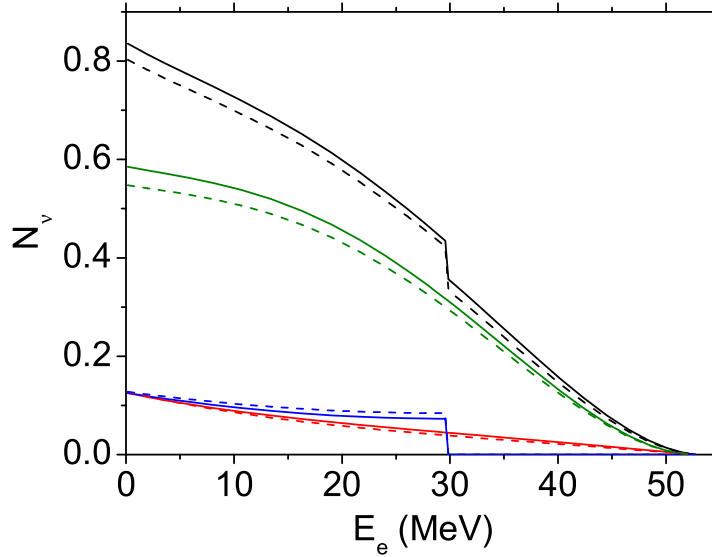


Figure 4. Energy distributions of the ν -e events, in relative units, for a Weinberg angle $\sin^2\theta_W = 0.21$ (dashed), 0.23 (full lines). The upper (two) curves represent the total number of electron events, the next lines correspond to: the ν_e -e events, followed by the ν_μ -e and the $\bar{\nu}_\mu$ -e ones.

of the Weinberg angle at spallation sources. Indeed, positive pion (π^+) decay produce neutrinos of $\bar{\nu}_\mu$,

ν_e and ν_μ flavors, whose scattering on electrons have a very different reaction cross section

dependence on the Weinberg angle, as can be seen in Figure 4. The ν_e -e and $\bar{\nu}_\mu$ -e cross sections increase for an increasing value of the Weinberg angle, while ν_μ -e cross section decreases.

Let us define the quantity :

$$S = -\frac{dN(\sin^2\theta_W)}{d\sin^2\theta_W} \frac{1}{\frac{\sin^2\theta_W}{N(\sin^2\theta_W)}}, \quad (1)$$

that we will call the sensitivity, where N stands for the experimental observable to be used in determining the Weinberg angle $\sin^2\theta_W$.

It turns out that the measurement of the total number of neutrino-electron events has a sensitivity of $S = 0.5$ only.

If the pulse length is made much shorter than the muon life-time, the ν_μ -e events can be separated

from $\bar{\nu}_\mu$ -e and ν_e -e ones. This enables one to study the quantity – as proposed for the SNS facility

in [55, 17] –

$$O = N(\nu_\mu - e) \frac{1}{N(\bar{\nu}_\mu - e) + N(\nu_e - e)}, \quad (2)$$

whose sensitivity to the Weinberg angle is as much as $S = 1.68$.

If however one disposes of a detector with a decent energy resolution the determination of the Weinberg angle can be

improved even in the case of long pulses.

To this aim one has to determine the size of the jump in the electron energy window at $E_e = 29.7$ MeV, the end point of the ν_μ -e events.

In practice, this method can be realized by counting the number of events and fitting the electron energy distributions in two separate windows[¶] .:

one containing electron energies below 29.7 MeV, and the other comprising the events whose energies exceed 29.7 MeV.

Although such a procedure increases the statistical error in each window by roughly a factor of 2, compared to the total cross section measurement,

the jump height turns out to have a sensitivity to the Weinberg angle as large as $S = 2$.

Therefore the impact of the increased statistical error in determining the Weinberg angle

is reduced by a factor of 4 compared to an experiment measuring the total cross section,

due to the significant improvement of S .

A similar conclusion can be drawn on

the effect of the systematic errors,

related e.g. to the finite energy resolution of the detector.

[¶] In general, there are almost 4-times more events in the energy window below $E_e = 29.7$ MeV than in the above window. However in practice an important part of the low energy events are cut out due to backgrounds and to the detector sensitivity.

	10	20	50	ρ (g/cm ³)	$\langle \sigma \rangle_{DAR}$ (10 ⁴⁰ cm ²)
$\bar{\nu}$ -H (water)	11300	2950	490	1.0	0.738 [57]
$\bar{\nu}$ -H (C ₁₆ H ₁₈)	8720	2280	374	0.992	0.738 [57]

Table 5. Same as Table 2 but for electron anti-neutrino scattering on protons.

The measurement made by the LSND collaboration have identified about 200 events as ν -e scattering using 167 tons of liquid scintillator at 17 meters from the target.

If a 5 ton scintillator detector can be placed as close as 10 meters from the ESS source for example, one can expect in a running time of 1 year almost 5 times more events (Table 4).

Lepton-Flavour-Violation: Finally let us discuss the case of $\bar{\nu}_e$ scattering. If the amount of anti-neutrinos

is as low as expected at the SNS facility, namely 10^{-5} , one could use this very pure source of neutrinos to search for rare processes

such as the Lepton-Flavour-Violating decay $\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu$.

This search has been performed, e.g. by the KARMEN Collaboration using 65 tons of scintillator at 17 meters from the source which has given the current best limit for the branching ratio of 0.9×10^{-3} [16].

This experiment requires a precise identification of the associated events, measuring the neutron through

neutron capture on Gadolinium or on protons as done in [16].

Table 5 gives the expected $\bar{\nu}_e$ -p scattering rates assuming that as many $\bar{\nu}_e$ as $10^{15} \bar{\nu}_e/s$ are produced,

these numbers must be scaled according to the suppression factor, that depends on the specific spallation source considered. The electron anti-neutrino-proton cross section has been calculated using the exact formula, valid to all orders in the anti-neutrino energy (E_ν/m_p) expansion, as derived by Ya. I. Azimov and V. M. Shekhter [57].

3. Conclusions

New Spallation Source facilities are under construction, planned or under study. They will produce an intense flux of neutrinos.

If these facilities are designed to accommodate a neutrino detector(s) close to the source, they will offer an unique

opportunity to perform low energy neutrino scattering experiments.

Neutrino detectors with different active material can be used to perform neutrino nucleus cross section measurements that have a variety of innovative and timely applications going from nuclear physics to neutrino astrophysics.

Neutrino-nucleus scattering data would create conditions for the breakthrough of the theoretical models, permitting to pin down some of their phenomenological ingredients. Besides,

physics beyond the standard model can be tested through the searches for non-standard contributions to neutrino electron scattering; while

the identification of electron anti-neutrino scattering on protons can be used to improve established limits on rare lepton

flavor violating decays, in particular

$\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$. We have presented new predictions for these processes and emphasized some general aspects, hoping one day

such measurements to be realized.

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