Simulated analysis of low-flux solar neutrinos and their terrestrial detection

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Abstract. The energy spectra of hep and pep solar neutrinos produced by pp-chain and those produced from the CNO-cycle reactions are analyzed for various nuclear detectors in current terrestrial experiments. We intend to investigate the differential and total cross section of the coherent scattering of neutrinos off nuclear isotopes like \textsuperscript{28}Si. In such experiments the relevant quantity to measure is the kinetic energy distribution of the recoiling nucleus. This type of experiment has been proposed in order to observe the coherent elastic neutrino-nuclear scattering. We focus on the differential cross section \( \frac{d\sigma}{dT} \) as a function of the kinetic energy \( T \) of the promising nuclear isotope \textsuperscript{28}Si.

1. Introduction
More than forty years ago, neutrinos were conceived as a way to test the validity of the standard solar model which tells that stars are powered by nuclear fusion reactions. The first experiment built to detect solar neutrinos was performed by Raymond Davis in the late 60s in the Homestake mine in South Dakota and detected only one third of the expected flux, deficit known as the Solar Neutrino Problem. Different experiments were built in order to understand the origin of this discrepancy. Now we know that neutrinos undergo oscillations, i.e. they change flavor travelling from the core of the Sun to the terrestrial detectors [1].

\textbf{Figure 1.} Neutrino energy spectrum as predicted by the Solar Standard Model (SSM).
Recently SNO has finished its final phase as a solar neutrino detector, and has accumulated over neutrino data covering the energy range from approximately $5 - 20$ MeV. Almost all the observed neutrinos are due to the $^8B$ reaction in the Sun. Neutrinos produced through the hep process, $^3He + p \rightarrow ^4He + e^+ + \nu_e$, also in the Sun, has not yet been observed. The hep neutrino energy endpoint extends above the $^8B$ spectrum. The most recent data analysis by SNO has also lowered the threshold for the detection of $^8B$ solar neutrinos using neutral and charged-current reactions of neutrinos on deuterium while recent results from the Borexino experiment measured the rate of $^7Be$ solar neutrinos that are in lower energy than $^8B$ solar neutrinos (see Fig.1) [2].

Several future solar neutrino experiments have been proposed. Measurements of the pep and CNO solar neutrinos are a goal of the SNO+ experiment [3]. The flux of pep solar neutrinos is calculated to 1.5% uncertainty in the Standard Solar Model [4].

In the elastic neutral current (NC) neutrino-nucleus scattering, a neutrino scatters off a nucleus at low momentum transfer $Q$ such that the nucleon wavefunction amplitudes are in phase and add coherently. For these reactions is very useful to calculate the differential cross section as a function of recoil nucleus kinetic energy ($T$), instead of scattering angle ($\Phi$) while many of the neutrino detectors have no directional sensitivity. The maximum recoil kinetic energy is directly related to the energy ($E$) of the incoming solar neutrino.

Since the coherent neutrino-nucleus scattering has not been experimentally proven, the development of new detectors (cryogenic, etc.) are planned for future applications in low energy neutrino physics. Such studies could be probed in conjunction with Cold Dark Matter (e.g. CRESST) and double beta decay experiments (e.g. those using $^{150}$Nd and $^{116}$Cd absorbers).

In the present work, we study coherent neutrino-nucleus elastic scattering from a theory point of view. We currently concentrate on calculations for reaction cross sections of the form $d\sigma/dT$ (see Sect. 2) for coherent neutrino-nucleus processes. Such processes could be, furthermore, used in the future to search for new physics like neutrino magnetic moment, non-standard neutral current interactions, etc.

### 2. Coherent Neutrino-Nucleus Scattering

Coherent neutrino scattering on a nucleus $(A,Z)$,

$$\nu + (A, Z) \rightarrow \nu + (A, Z)'$$

is a neutral current interaction (i.e. sensitive to all active neutrino flavors) and should occur for processes with small momentum transfer ($A$ represents the mass number and $Z$ the atomic number, $A=N+Z$ with $N$ the neutron number). In these reactions the nuclear wavefunction remains unchanged i.e. we have $gs \rightarrow gs$ transition. Only the nucleus experiences a recoil as a whole.

The maximum recoil kinetic energy in neutrino-nucleus coherent scattering is

$$T_{max} = \frac{2E^2}{M + 2E},$$

where $E$ is the incident neutrino energy, and $M$ is the mass of the target nucleus [5].

The four-momentum transfer is related to the recoil kinetic energy by $Q^2 = 2MT$, and the three-momentum transfer $q$ is approximately $\sqrt{2MT}$. For neutrino energies below 20 MeV and nuclear targets such as $^{28}Si$ and $^{32}S$, the maximum recoil kinetic energy is approximately around 30 keV, and therefore the maximum possible $q$ is quite small, $< 1 fm^{-1}$.

The dependence of the cross section on the scattering angle means that solar neutrino elastic scattering events will, in principle, point back to the Sun. However, many of neutrino detectors do not have directional sensitivity, and so it is most useful to calculate event rates as a function of recoil nucleus kinetic energy [6]. The scattering angle and the recoil kinetic energy are related
via 2- body kinematics and the cross section can be expressed in terms of the kinetic energy $T$ of the recoiling nucleus as

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi} \left[ 1 + \left(1 - \frac{E}{E_T}\right)^2 - \frac{MT}{E^2} \right] Q_w^2 F^2(Q^2)$$

(3)

In the latter expression, $G_F$ denotes the Fermi constant, $G_F^2 M / 2\pi = 5.14 \times 10^{-41} \text{cm}^2 / \text{MeV}$ and $Q_w$ which is given by

$$Q_w = N - Z (1 - 4 \sin^2 \theta_w)$$

(4)

is the weak charge ($\sin^2 \theta_w \approx 0.231$) with $\theta_w$ the Weinberg angle. The quantity $Q^2$ is the squared momentum transfer

$$Q^2 = \frac{2E^2TM}{(E^2 - ET)}$$

(5)

and $F(Q^2)$ is the nuclear form factor. Denoting the neutron and proton densities as $\varrho_{n,p}(r)$ the form factor is

$$F(Q^2) = \frac{1}{Q_w} \int \left[ \varrho_n(r) - (1 - 4 \sin^2 \theta_w) \varrho_p(r) \right] \frac{\sin(Qr)r^2}{Qr} dr$$

(6)

From Eq.(6) we see that, since $(1 - 4/\sin^2 \theta_w)$ is small, a neutrino scattered elastically off a spin-zero nucleus couples mostly to the neutron distribution. A measurement of the cross section for this process would, at some level, provide a determination of the neutron form factor. This would be complementary to the parity violating experiment with lead because it would provide additional data, obtained at different energy ranges and with different nuclei that could be used to calibrate nuclear structure calculations [7].

In the present work we are treating the proton and neutron distributions separately, as in Eq.(6). The form factor we use is

$$F(Q^2) = \frac{1}{Q_w} \left[ NF_n(Q^2) - Z (1 - 4 \sin^2 \theta_w) F_p(Q^2) \right]$$

(7)

where $F_n(Q^2)$ and $F_p(Q^2)$ are the nuclear neutron and proton (electromagnetic) form factors, respectively.

### Table 1

| $Q$ ($fm^{-1}$) | $F(Q)$ | $T$ (MeV) | $\frac{d\sigma}{dT} \times 10^{-39} \text{cm}^2 \text{MeV}^{-1}$ |
|-----------------|--------|-----------|-------------------------------------------------------------|
| 0.14            | 0.9705 | 6.4216 $\times 10^{-5}$ | 4.050                                                        |
| 0.15            | 0.9662 | 2.7547 $\times 10^{-4}$ | 4.013                                                        |
| 0.16            | 0.9616 | 0.0018     | 3.967                                                        |
| 0.17            | 0.9667 | 0.0050     | 3.912                                                        |
| 0.18            | 0.9516 | 0.010      | 3.846                                                        |
| 0.19            | 0.9462 | 0.017      | 3.768                                                        |
| 0.20            | 0.9405 | 0.027      | 3.677                                                        |
| 0.21            | 0.9346 | 0.040      | 3.573                                                        |
| 0.22            | 0.9284 | 0.056      | 3.453                                                        |
| 0.23            | 0.9220 | 0.075      | 3.319                                                        |
In the case of \(^{28}\text{Si}\) and \(^{32}\text{S}\) we have performed explicit calculations for \(d\sigma/dT\) and received preliminary results in the following cases:

- We employ experimental nuclear form factors obtained from electron scattering experiments [8].
- We utilized the theoretical nuclear form factors obtained in the frame note of the deformed BCS calculations for a set of light nuclei in Ref. [9].

The results for the nuclear isotope \(^{28}\text{Si}\) are listed in Table 1. The values of \(d\sigma/dT\) in Table 1 are in agreement with similar calculations performed by Vergados et al. (Ref. [5]) where examined the coherent contribution of all neutrons in neutrino nucleus scattering due to the neutral current considering the boron solar neutrinos which could potentially become a source of background in the future dark matter searches.

### 3. Summary and Conclusions

Current proposed and ongoing solar neutrino experiments like BOREXINO and SNO+, expect to observe low-rate solar neutrinos as pep and CNO neutrinos significant to study solar physics. Neutrinos will help in understanding the metallicity in the solar core that appears to contrast with recent interpretations of solar surface chemical abundances.

Furthermore, other type of experiments (cryogenic, etc.) are designed with the aim to study coherent neutral-current scattering of neutrinos on nuclei. Such experiments may provide a potential to detect low-energy neutrinos with an excellent energy resolution. Neutrino-induced recoil events may constitute a background to detect dark matter searches.

Our aim in this work, is to provide the theoretical background of such searches by evaluating differential cross sections \(d\sigma/dT\) as functions of the kinetic energy \(T\) for promising nuclear detectors. We presented results for the \(^{28}\text{Si}\) isotope (one of the best choices for coherent neutrino-nucleus studies) and we are currently working in evaluating event rates for a set of nuclear isotopes in the area of \(^{28}\text{Si}\) and \(^{32}\text{S}\) isotopes.

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