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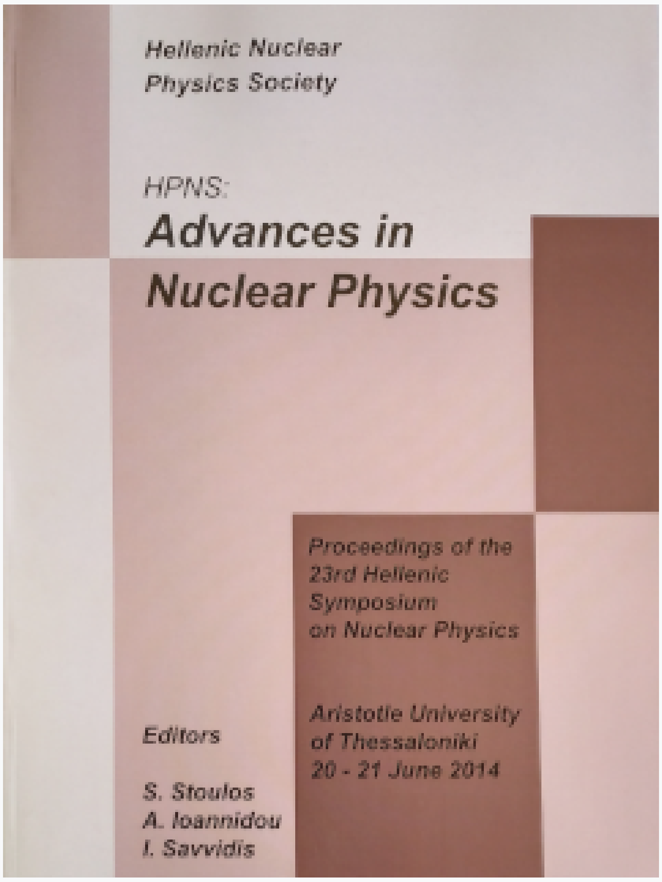

Nuclear study of the exotic neutrino interactions

D. K. Papoulias, T. S. Kosmas

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D.K. Papoulias and T.S. Kosmas

Division of Theoretical Physics, University of Ioannina, GR 45100 Ioannina, Greece

Abstract

Open neutrino physics issues require precision studies, both theoretical and experimental ones, and towards this aim coherent neutral current neutrino-nucleus scattering events are expected to be observed soon. In this work, we explore ν-nucleus processes from a nuclear theory point of view and obtain results with high confidence level based on accurate nuclear structure cross sections calculations. The present study explores the differential event rates as well as the total number of events expected to be measured by nuclear detectors, indicating measurable rates. We concentrate on the possibility of detecting supernova neutrinos by using massive detectors like those of the GERDA and SuperCDMS dark matter experiments and at spallation neutron source facilities (at Oak Ridge National Lab) by the COHERENT experiment.

Introduction

Coherent scattering of neutrinos on complex nuclei was proposed long ago [1] as a prominent probe to study neutral-current (NC) ν-nucleus processes, but up to now no events have been experimentally measured. Neutrino detection, constitutes an excellent probe to search for a plethora of conventional neutrino physics applications and new-physics open issues [2]. In principle, low-energy astrophysical and laboratory neutrino searches provide crucial information towards understanding the underling physics of the fundamental electroweak interactions within and beyond the SM. Well-known neutrino sources include (i) supernova neutrinos (with energies up to 60-100 MeV) and (ii) laboratory neutrinos (with energies up to 52.8 MeV) emerging from stopped-pion and muon decays at muon factories (Fermilab, PSI, JPARC, etc.) and at the spallation neutron source (SNS) at Oak Ridge National Lab. Recently, it became feasible [3] to detect neutrinos by exploiting the neutral current interactions and measuring the nuclear recoil signals through the use of very low threshold-energy detectors. To this purpose, great experimental effort has been put and new experiments have been proposed to be performed at facilities with stopped-pion neutrino beams, based on promising nuclear detectors like those of the COHERENT experiment [4] and others. The nuclear ν-detectors adopted by the relevant experiments include liquid noble gases, such as ^{20}Ne, ^{40}Ar, ^{132}Xe as well as, ^{76}Ge and CsI[Na] detection materials.

On the theoretical side, the ν-signals of low-energy neutrinos, expected to be recorded in sensitive nuclear detectors, could be simulated through nuclear calculations of ν-nucleus scattering cross sections [5]. Such results may provide useful information relevant for the evolution of distant stars, the core collapse supernovae, explosive nucleosynthesis and other phenomena. In fact, coherent neutral current ν-nucleus scattering events are expected to be observed by using nuclear targets for which recoil energies are of the order of a few to tens of keV, and therefore appropriate for detection of WIMPs [6]. Such detectors are e.g. the SuperCDMS [7], GERDA [8] and other multi-purpose detectors [9,10,11]. For low-energies, the dominant vector components of NC interactions lead to a coherent contribution of all nucleons (actually all neutrons) in the target nucleus.

One of our main purposes in this paper, which is an extension of our previous study [12], is to comprehensively study the above issues by performing nuclear structure calculations for a set of experimentally interesting nuclei. By exploiting our accurate original cross sections, we obtain the total number of events expected to be recorded over the energy-threshold for the studied nuclear targets. We stress that, we have devoted special effort to obtain results of high accuracy by constructing the nuclear ground state within the context of the quasi-particle random phase approximation (QRPA), i.e. by solving iteratively the BCS equations for realistic pairing interactions (the Bonn C-D potential) [13], and achieving high reproducibility of the available experimental data [14]. In addition, we made comparisons with the results of other methods evaluating the nuclear form factors that enter the coherent rate as the one which employs fractional occupation probabilities (FOP) of the states (on the basis of analytic expressions) [15], and other well-known methods [16].

Brief Description of the Formalism

The effective (quark-level) SM ν-nucleus interaction Lagrangian, $\mathcal{L}_{\rm SM}$ at low and intermediate neutrino energies, is written as [12]

$$\mathcal{L}_{\rm SM} = -2\sqrt{2}G_F \sum_{u,d}^{\alpha=e,\mu,\tau} g_P^f \left[\bar{\nu}_\alpha \gamma_\rho L \nu_\alpha\right]\left[\bar{f}\gamma^\rho P f\right], \tag{1}$$

where $g_L^u = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W$ and $g_R^u = -\frac{2}{3}\sin^2\theta_W$ are the left- and right-handed couplings of the u-quark to the Z-boson and $g_L^d = -\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$ and $g_R^d = \frac{1}{3}\sin^2\theta_W$ are the corresponding couplings of the d-quark (θ_W is the Weinberg mixing angle). For coherent ν-nucleus scattering, the SM angle-differential cross section reads [5]

$$\frac{d\sigma_{\rm SM,\nu_\alpha}}{d\cos\theta} = \frac{G_F^2}{2\pi} E_\nu^2 \left(1+\cos\theta\right) \left|\langle gs \| \hat{\mathcal{M}}_0(q) \| gs\rangle\right|^2 . \tag{2}$$

The operator $\hat{\mathcal{M}}_0$ in the nuclear matrix element of the latter equation is the Coulomb operator which is equal to the product of the zero-order spherical Bessel function times the zero-order spherical harmonic [13]. This matrix element can be cast in the form

$$\left|M_{V,\nu_\alpha}^{\rm SM}\right|^2 \equiv \left|\langle gs \| \hat{\mathcal{M}}_0(q) \| gs\rangle\right|^2 = \left[g_V^p Z F_Z(q^2) + g_V^n N F_N(q^2)\right]^2, \tag{3}$$

where, the polar-vector couplings of protons g_V^p and neutrons g_V^n with the Z boson, are written as $g_V^p = 2(g_L^u + g_R^u) + (g_L^d + g_R^d) = \frac{1}{2} - 2\sin^2\theta_W$ and $g_V^n = (g_L^u + g_R^u) + 2(g_L^d + g_R^d) = -\frac{1}{2}$, respectively. The nuclear form factors are computed within the context of the QRPA, which takes into account realistic strong nuclear forces. As can be easily seen, the vector contribution of all protons is very small ($g_V^p \sim 0.04$), hence the coherence in Eq. (3) essentially refers to all neutrons only of the studied nucleus. After some straightforward elaboration the differential cross section with respect to the nuclear recoil energy, T_N, takes the form [5]

$$\frac{d\sigma_{\rm SM,\nu_\alpha}}{dT_N} = \frac{G_F^2\, M}{\pi}\left(1 - \frac{M\, T_N}{2E_\nu^2}\right) \left|\langle gs \| \hat{\mathcal{M}}_0(q) \| gs\rangle\right|^2 . \tag{4}$$

From experimental physics perspectives, predictions for the differential event rate, Y_{ν_α}, of a ν-detector are crucial. The usual expression for computing the yield in events is based on the neutrino flux, and is defined as [12]

$$Y_{\nu_\alpha}(T_N) = \frac{dN}{T_N} = K \sum_{\nu_\alpha} \Phi_{\nu_\alpha} \int \eta_{\nu_\alpha}^{\rm SN}\, dE_\nu \int \frac{d\sigma_{\nu_\alpha}}{d\cos\theta}\, \delta\!\left(T_N - \frac{q^2}{2M}\right) d\cos\theta, \tag{5}$$

where $K = N_{targ.} t_{tot.}$ accounts for the total number of nuclei (atoms) in the detector material $N_{targ.}$ times the total time of exposure t_{tot}. Using the latter equation, one concludes that, the lower the energy recoil, the larger the potentially detected number of events (see Fig. 1 and Fig. 2). In principle, in order to maximize the potential detection of a rare event process like the ν-nucleus scattering, detector materials with very low energy-recoil threshold and low-background are required. For the case of supernova neutrinos, the total neutrino flux, $\Phi(E_\nu)$, arriving at a terrestrial detector as a function of the SN neutrino energy E_ν, the number of emitted (anti)neutrinos N_{ν_α} at a distance d from the source (here we consider $d = 10\,\text{kpc}$), reads [12]

$$\Phi(E_\nu) = \sum_{\nu_\alpha} \Phi_{\nu_\alpha} \eta_{\nu_\alpha}^{\rm SN}(E_\nu) = \sum_{\nu_\alpha} \frac{N_{\nu_\alpha}}{4\pi d^2} \eta_{\nu_\alpha}^{\rm SN}(E_\nu). \tag{6}$$

In the latter expression, $\alpha = e, \mu, \tau$ is the (anti)neutrino flavour and $\eta^{\mathrm{SN}}_{\nu_\alpha}$ denotes the energy distribution. The emitted SN-neutrino energy spectra $\eta^{\mathrm{SN}}_{\nu_\alpha}(E_\nu)$ may be parametrised by Maxwell-Boltzmann distributions that depend only on the temperature T_{ν_α} of the (anti)neutrino flavour ν_α or $\tilde{\nu}_\alpha$ (the chemical potential is ignored) we have [12]

$$\eta^{\mathrm{SN}}_{\nu_\alpha}(E_\nu) = \frac{E_\nu^2}{2T_{\nu_\alpha}^3} e^{-E_\nu/T_{\nu_\alpha}} , \tag{7}$$

($T_{\nu_e} = 3.5\mathrm{MeV}$, $T_{\tilde{\nu}_e} = 5.0\mathrm{MeV}$, $T_{\nu_x,\tilde{\nu}_x} = 8.0\mathrm{MeV}$, $x = \mu, \tau$. For each flavour, the total number of emitted neutrinos N_{ν_α} is obtained from the mean neutrino energy [12]

$$\langle E_{\nu_\alpha} \rangle = 3T_{\nu_\alpha} \tag{8}$$

and the total energy released from a SN explosion, $U = 3\times10^{53}\mathrm{erg}$.

Results and Discussion:

Initially, in this paper the evaluation of the required nuclear matrix element, related to Standard Model ν-nucleus processes is formulated, and realistic nuclear structure calculations of ν-nucleus cross sections for a set of interesting nuclear targets are performed. The first stage involved cross sections calculations for the dominant coherent channel in the range of incoming neutrino-energies $0 \le E_\nu \le 150$ MeV, including ν-energies of stopped pion-muon neutrino decay sources, supernova neutrinos, etc.

Additionally, new results for the total number of events expected to be observed in one ton of various ν-detector materials are provided and the potentiality of detecting neutrino-nucleus events is in detail explored. The calculations are concentrated on interesting nuclei, like $^{20}\mathrm{Ne}$, $^{40}\mathrm{Ar}$, $^{76}\mathrm{Ge}$ and $^{132}\mathrm{Xe}$ which are important detector materials for several rare event experiments, like the COHERENT at Oak Ridge National Laboratory, and also experiments searching for dark matter events as the GERDA, SuperCDMS, XENON 100, CLEAN, etc. By comparing our results with those of other methods, we see that the nuclear physics aspects (reflecting the accuracy of the required ν-nucleus cross sections), appreciably affect the coherent $gs \to gs$ transition rate, a result especially useful for supernova ν-detection probes.

In the present work, the QRPA method that considers realistic nuclear forces has been adopted in evaluating the nuclear form factors. Moreover, a comparison with other simpler methods as (i) effective methods and (ii) the method of fractional occupation probabilities, which improves over the simple Shell-Model and gives higher reproducibility of the available experimental data, is presented and discussed. We conclude that among all the adopted methods the agreement is quite good, especially for light and medium nuclear isotopes. However, we remark that since coherent neutrino-nucleus scattering can probe the neutron nuclear form factors, methods like the BCS provide more reliable results.

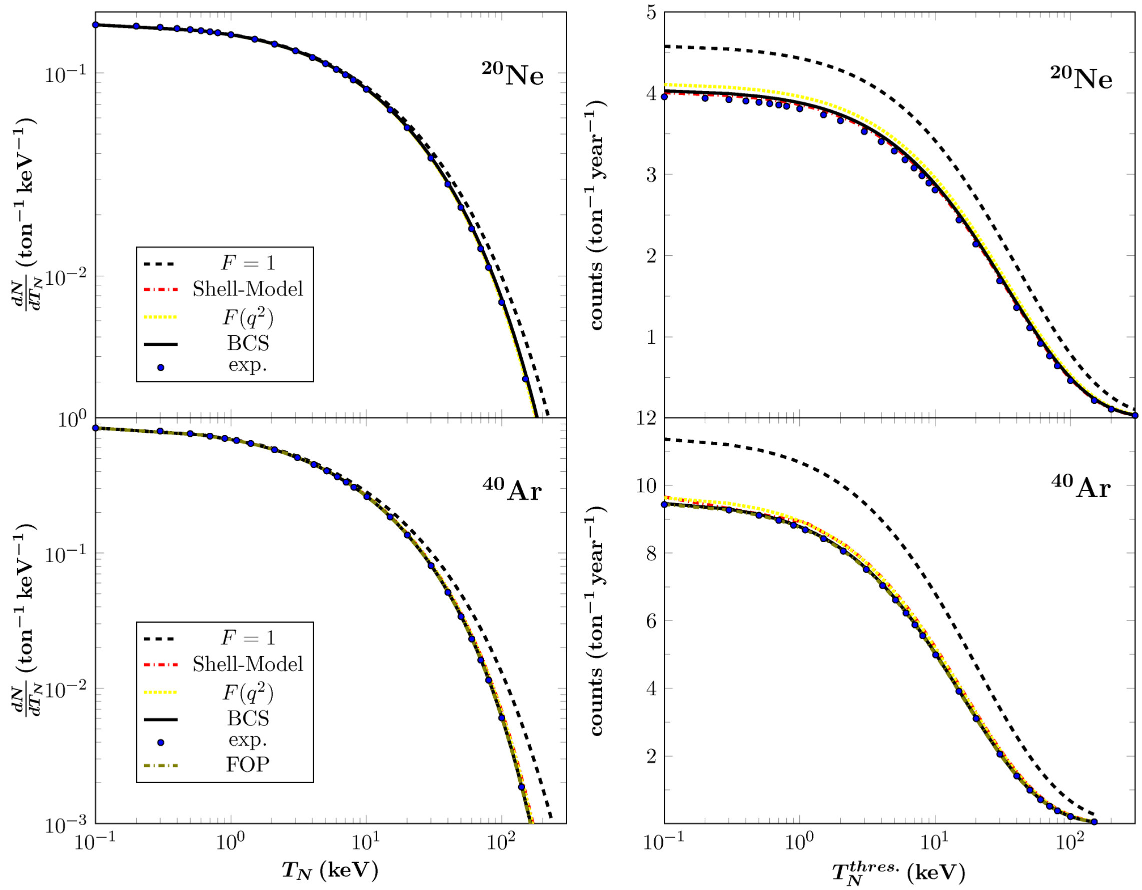

Figure 1: Yield in events (left) and total number of events over nuclear recoil threshold $T_N^{thres.}$ (right), for supernova neutrinos at $d = 10\,\mathrm{kpc}$. Here, 1 ton of perfectly efficient ^{20}Ne and ^{40}Ar detectors have been considered and also possible neutrino oscillation in propagation effects are neglected. For heavier nuclear targets the differences become rather significant. For more details see the text.

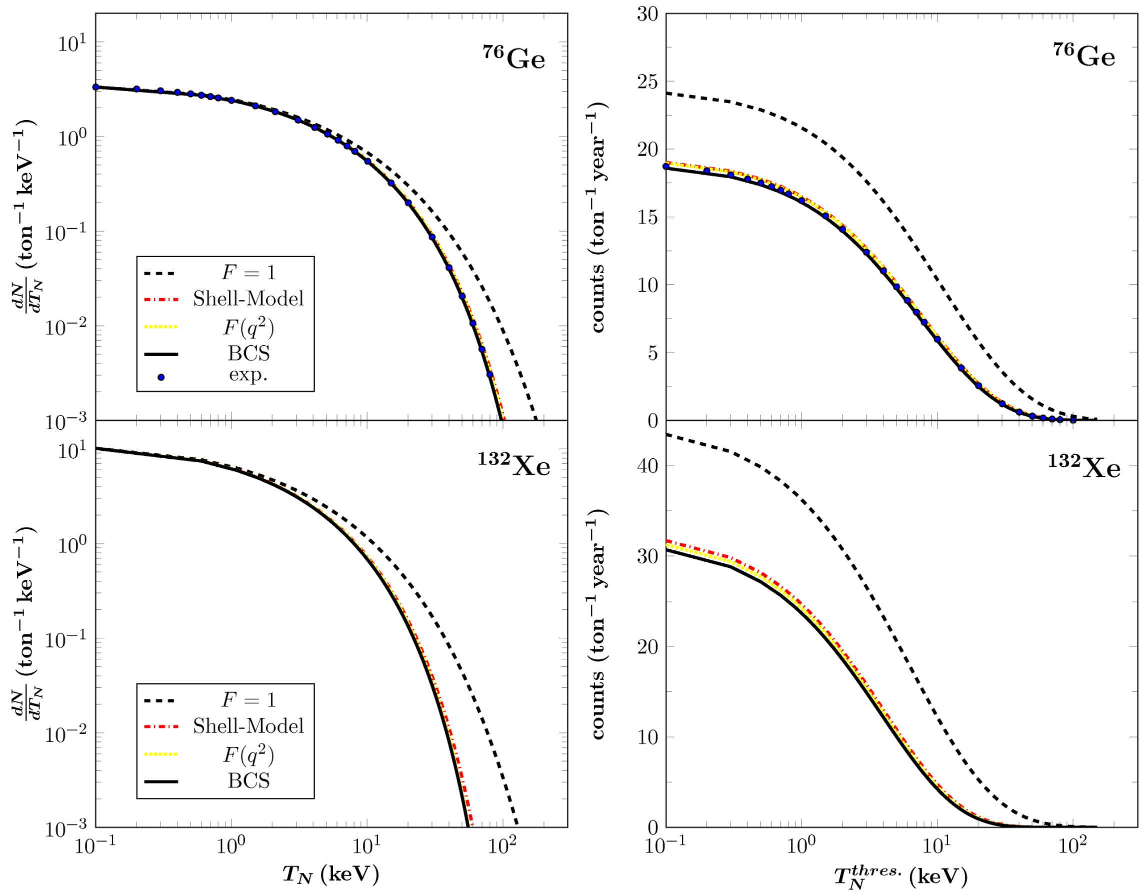

Figure 2: Same as Fig. \ref{fig.5} but for ^{76}Ge and ^{132}Xe.

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