Coherency in Low Energy Neutrino Nucleus Elastic Scattering

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Neutrino-nucleus elastic scattering provides a unique laboratory to study the quantum mechanical coherency effects in electroweak interactions, towards which several experimental programs are being actively pursued. We report results of our quantitative studies on the transitions towards decoherency.

1. Introduction

The coherent elastic neutrino-nucleus scattering (CENNS) is a fundamental electroweak neutral current interaction which is well defined in the standard model of particle physics. It has not been yet observed experimentally [1-2]. The study of CENNS is useful to understand the irreducible background for dark matter search experiments and to constrain the sensitivities for physics beyond the standard model [3-5]. CENNS may play an important role in astrophysical processes. The differential cross-section for this process is in terms of three momentum transfer $q \equiv |\bar{\mathbf{q}}|$ is shown in Fig. 1 and written as:

$$\left(\frac{d\sigma_\nu A_{el}}{dq^2}\right)^{Coh}_{SM} = \frac{1}{2}\frac{G_F^2}{4\pi}\left[1-\frac{q^2}{4E_\nu^2}\right]\left[\varepsilon Z F_Z(q^2) - N F_N(q^2)\right]^2 \quad (1)$$

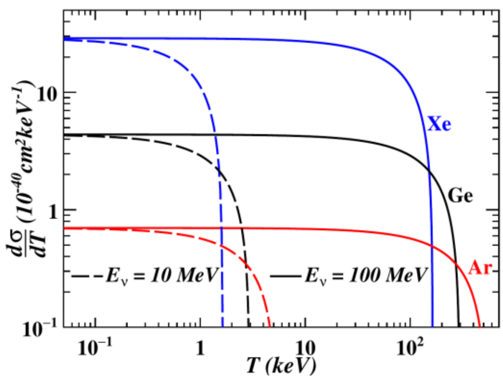

FIG. 1: Differential cross-section for Xenon, Germanium and Argon with respect to recoil energy (T) for E_ν = 10, 100 MeV.

The total cross-section is given by the integral over three momentum transfer of the nuclei:

$$\sigma_\nu A_{el} = \int_{q^2_{\min}}^{q^2_{\max}} \left[\frac{d\sigma_\nu A_{el}}{dq^2}(q^2, E_\nu)\right] dq^2 \quad (2)$$

given that $q^2 = 2MT + T^2 \cong 2MT$ where, G_F is fermi constant and E_ν is incident neutrino energy. While M, Z and N are mass, atomic number and neutron number of target nuclei and $F(q^2)$ is nuclear form factor. Minimum and maximum limit for momentum transfer is $q^2_{\min} = 2MT_{\min}$ and $q^2_{\max} = 4E_\nu^2 \cdot M/(M + 2E_\nu) = 4E_\nu^2$. In our calculations, effective nuclear form-factor for neutron and proton is given in Ref. [6]: $F_N(q^2) = - F_Z(q^2) \equiv F(q^2) \in [1, 0]$, where the nuclear form-factor for different nuclei is shown in Fig. 2 and given by:

$$F(q^2) = \left[\frac{3}{qR_0}\right] J_1(qR_0) \exp\left[-\frac{1}{2}q^2 s^2\right]. \quad (3)$$

Where, J_1 is the first-order spherical Bessel function. The target nuclei dependence is introduced through $R_0^2 = R^2 - 5s^2$, s=0.5 fm and $R = 1.2A^{1/3}$fm. Several nuclei with experimental interest and having different mass ranges, at Z = (0, 18, 32, 54), are selected for studies. The nuclear form factors $F(q^2)$ as a function of T, the differential cross sections at fixed E_ν= (10, 100) MeV is depicted in Fig. 2.

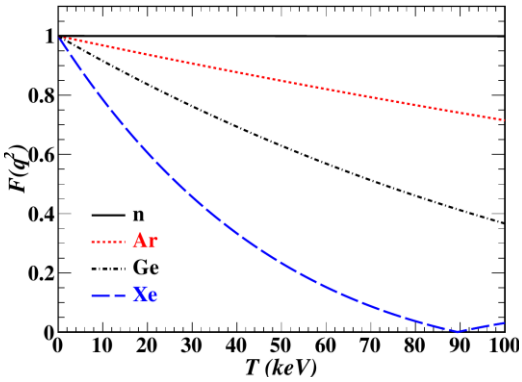

FIG. 2: Nuclear Form Factor for Xe, Ge and Ar approaches to 1 with lower nuclear recoil and three momentum transfer (q^2).

2. Formulation and Estimation of Coherency

The coherency in pion production with accelerator neutrino is due to the coupling of a virtual meson with the nucleus producing a physical pion [7], and hence is a strong interaction effect which varies as A^2. While in neutrino nucleus interactions is due to the coupling of a virtual Z-boson with the nucleus and hence is an electroweak process. We estimated the coherency for different target nuclei at different incident neutrino energy and consider FWHM of product of $\sigma_\nu A_{el}$ and neutrino flux Φ_ν at T_{min}=0 as shown in Fig. 3.

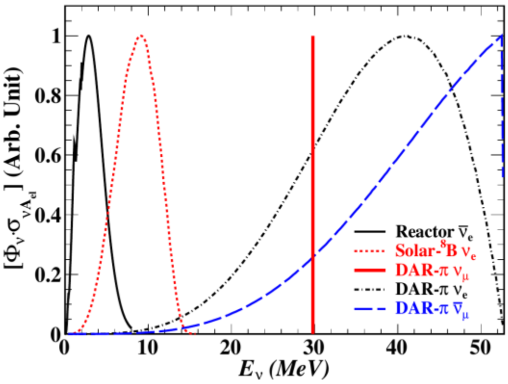

FIG. 3: Product of neutrino flux from different source with total cross-section of CENNS.

The decoherency effect in CENNS can be described as deviation from $[\epsilon Z-N]^2$ scaling as increase in q^2 [8]. The addition of phase angle between amplitude of different nucleons gives a relative finite phase instead of being perfectly aligned. This affect as an average misalignment angle $<\phi> \in [0, \pi/2]$ can be parameterize degree of coherency as $\alpha \equiv \cos <\phi> \in [0, 1]$. Accordingly, the cross-section ratio between A (Z, N) and neutron (0,1) can be expressed as:

$$\frac{\sigma_\nu A_{el}(Z,N)}{\sigma_\nu A_{el}(0,1)} = Z\varepsilon^2[1+\alpha(z-1)] + N[1+\alpha(N-1)] - 2\alpha\varepsilon ZN. \quad (4)$$

The limiting conditions are: (a) α = 1 implies complete coherency, while (b) α = 0 brings total decoherency effect. As an alternative, the partial coherency effect can be characterized by the relative change in cross-section:

$$\xi \equiv \frac{\sigma_\nu A_{el}(\alpha)}{\sigma_\nu A_{el}(\alpha=1)} = \alpha + (1-\alpha)\frac{(\varepsilon^2 Z + N)}{(\varepsilon Z - N)^2}. \quad (5)$$

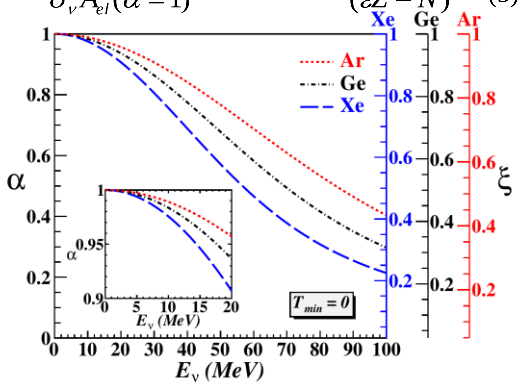

FIG. 4: Variation of α and ξ with incident neutrino energy E_ν.

The variation in α and ξ with respect to incident neutrino energy with zero recoil threshold is shown in Fig. 4. At very low energy both α and ξ approaches to unity, which indicates the better coherency probing region for threshold less experiment and for neutrino source like reactor, solar, supernova and stopped pion decay at rest (DAR). The contour for α for different nuclei (neutron number) with zero thresholds is also estimated in Fig. 5. Three bands indicate different isotopes range and FWHM of $\sigma_\nu A_{el} \Phi_\nu$ for different neutrino sources.

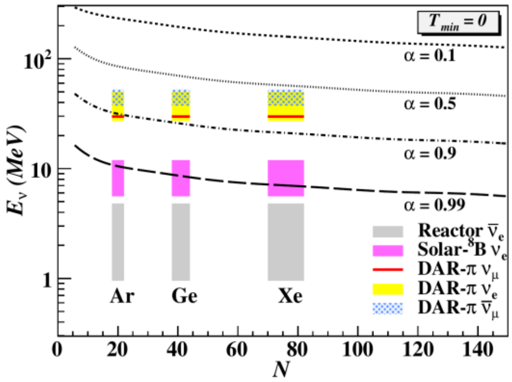

FIG. 5: The α-contour on N-E_ν plane with zero recoil thresholds with three Bands for FWHM of $\sigma_\nu A_{el} \Phi_\nu$ for different neutrino sources with three target nuclei isotopes.

3. Conclusion

The low energy neutrino from solar and reactor are more promising to probe unseen regime of elastic neutrino-nucleus scattering with coherency $\alpha \in [0.95, 1.0]$. While DAR source seems to deviate from coherency as target mass and threshold of detector get higher. Higher mass nuclei are better in terms of large recoil threshold but for threshold less experiment, lighter nuclei detectors are a better option.

4. Acknowledgement

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