Probing the Neutrino Nucleus Elastic Scattering at Reactors and its Quantum Mechanical Coherency Effects

V. Sharma[1*] and H. T. Wong[1]
[1]*Institute of Physics, Academia Sinica, Taipei - 11529, Taiwan*

Introduction

The neutrino nulceus elastic scattering (νA_{el}) is a well understood process of the Standard Model[1]. It opens a new window to study the physics beyond the Standard Model (BSM), astrophysical, and supernova process. It offers a unique laboratory for the study of the quantum mechanical coherency effects in electroweak interactions and neutron density distributions. It also has importance in the irreducible neutrino floor background in dark matter experiments originated due to solar and atmospheric neutrinos[2–4].

Recently, the first positive measurement of νA_{el} was achieved by COHERENT experiment with CsI(Na) detector[5], followed by measurements with a liquid Ar detector[6]. The neutrino flux for this detection was from decay-at-rest stopped pions (DAR-π) provided by spallation neutron source. There are several active experimental programs are ongoing to observe the νA_{el} with reactors[2]. The future dark matter experiments will also be sensitive to νA_{el} from solar neutrinos.

Formulation

The differential cross-section of νA_{el} scattering at three-momentum transfer q($\equiv |\vec{q}|$) and indcient neutrino energy E_ν can be expressed as

$$\frac{d\sigma_{\nu A_{el}}}{dq^2}(q^2, E_\nu) = \frac{1}{2}\frac{G_F^2}{4\pi}\left[1 - \frac{q^2}{4E_\nu^2}\right]\cdot\Gamma(q^2), \quad (1)$$

where $\Gamma(q^2)$ describes the contribution of many-body physics of target nuclei. It can have complimentary formulation on the basis of different physics aspects. The general description of $\Gamma(q^2)$ came from nuclear physics, given by $\Gamma(q^2) \equiv \Gamma_{NP}(q^2) = [\epsilon Z F_Z(q^2) - N F_N(q^2)]^2$, where $F_Z(q^2)$ and $F_N(q^2)$ are the are the form-factors of proton and neutron of target nucleus respectively. G_F is the Fermi coupling constant and $\epsilon = 1 - 4sin^2\theta_W = 0.045$ indicates the dominant contributions from neutrons. The merit of this description is to connect νA_{el} to the nuclear physics.

Coherency in νA_{el}

The coherency in neutrino-nucleus scattering evolves due to coherent addition of scattering amplitudes of nucleons which gives a relative phase angle [3]. This relative phase angle is finite rather than perfectly aligned. This misalignment $\Phi \in [0, \pi/2]$ can be parameterized as a measure of degree of coherency (α). The expression for degree of coherency can be derived with the help of scattering amplitude, which comprises both coupling strength and phase of each nucleon. The expression of degree of coherency as described in [3] is

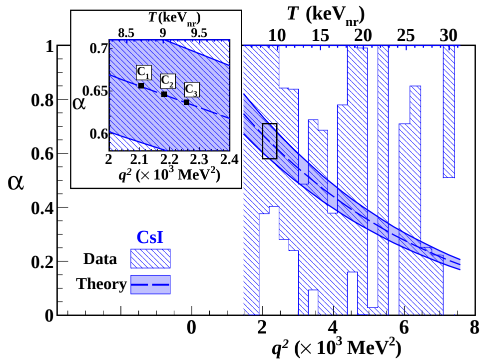
$$\frac{d\sigma_{\nu A_{el}}[Z,N]/dq^2}{d\sigma_{\nu A_{el}}[0,1]/dq^2} = Z\epsilon^2[1+\alpha(Z-1)] + N[1+\alpha(N-1)] - 2\alpha\epsilon ZN. \quad (2)$$

The formalism of α in eq. 2 leads to a define $\Gamma(q^2)$ in terms of QM coherency as [4]

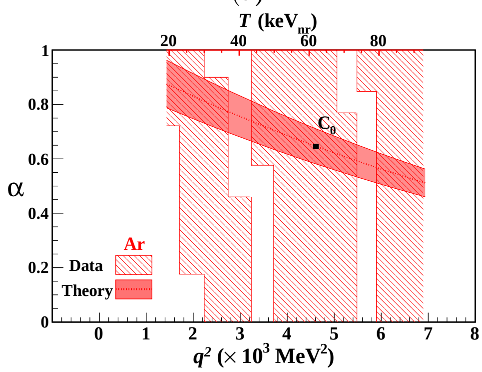
$$\Gamma(q^2) \equiv \Gamma_{QM}(q^2) = (\epsilon Z - N^2)\cdot\alpha(q^2) + (\epsilon^2 Z + N).[1-\alpha(q^2)]. \quad (3)$$

This formulation leads to the limiting behavior at the complete coherency ($\alpha = 1$ at $q^2 \sim 0$) and complete decoherency ($\alpha = 0$ at $q^2 \geq [\pi/R]^2$) states, corresponding to $(d\sigma/dq^2) \propto [\epsilon Z - N]^2$ and $(d\sigma/dq^2) \propto [\epsilon^2 Z + N]$, respectively.

*Electronic address: vsharma.phys@gmail.com



(a)



(b)

FIG. 1: Measurements on α[4] from COHERENT (a) CsI(Na), and (b) LAr data with DAR-π neutrinos[5, 6]. The stripe-shaded areas are the 1σ allowed regions derived from the reduction in cross section relative to the complete coherency conditions independent of nuclear physics input. The dark-shaded regions are the theoretical expectations adopting the nuclear form factor[4] with a $\pm\sigma$ uncertainty of 10%.

There is an alternative measurement-driven description for coherency which is denoted by $\xi(q^2)$. It represents the cross-section reduction relative to that of the complete coherency condition, where

$$\Gamma(q^2) \equiv \Gamma_{Data}(q^2) = [\epsilon Z - N]^2 \cdot \xi(q^2). \quad (4)$$

The experimentally measurable cross-section suppression $\xi(q^2)$ can be related to the QM coherency and nuclear form factor as

$$\xi(q^2) = \alpha(q^2) + [1 + \alpha(q^2)] \left[\frac{(\epsilon^2 Z + N)}{(\epsilon Z - N)^2} \right], \textit{ and}$$

$$\xi(q^2) = \frac{[\epsilon Z F_Z(q^2) - N F_N(q^2)]^2}{(\epsilon Z - N)^2}$$

Although the first-generation discovery measurements cannot be expected to provide severe constraints on $\alpha(q^2)$, it is instructive to check its significance for the specific cases of $\alpha = 1(0)$ equivalently, $\Phi = 0(\pi/2)$ which is depicted in Fig. 1. The most stringent bounds within the stated region of interest for complete QM coherency are α <0.57 (Φ <0.61[$\pi/2$]) with p = 0.004 at q^2 = 3.1×10^3 MeV^2 and for comeplete decoherency are α >0.30 (Φ >0.80[$\pi/2$]) with p = 0.016 at q^2 = 2.3×10^3 MeV^2. These results verify that both QM superpositions among the nucleonic scattering centers and nuclear many-body effects contribute to the νA_{el} scattering.

Conclusion

The νA_{el} process involves the concepts of elastic kinematics and QM coherency. The kinematics of scattering is well known, but the QM coherency aspect in binary state may have the unintended consequences of missing the complexities of the process, and it suppress the potential richness of its physics content. This newly derived universal quantitative description of coherency facilitate studies of QM effects in νA_{el} under which the fundamental parameters are experimentally accessible.

References

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