Studies of Coherency Effects in Neutrino-Nucleus Elastic Scattering at Reactors

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Neutrino nucleus elastic scattering is an electroweak interaction of the Standard Model of particle physics. We formulate a quantitative and universal parametrization of the quantum mechanical coherency effects in the neutrino nucleus elastic scattering, under which the experimentally accessible misalignment phase angle between nonidentical nucleonic scattering centers can be studied. We relate it to the conventional description of nuclear many-body physics through form factor and data-driven cross-section reduction fraction. We present the limits on first observation from CsI and LAr data from COHERENT collaboration along with prospects of observing the neutrino nucleus elastic scattering process from the reactor and solar neutrinos with a variety of nuclear targets at the sub-keV threshold.

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1. Introduction and Formulation

The elastic scattering of neutrino ($E_{\nu}<100\text{MeV}$) with nucleus ($\nu A_{el}$) has a large scattering cross-section due to the coherent addition of nuclear wavefunctions [1, 2]. The study of $\nu A_{el}$ process provides the probes to physics beyond the Standard Model (BSM) [3] and certain astrophysical processes [2]. It offers the prospects to understand the coherence effects in electroweak interactions and neutron density distributions [4]. Furthermore, it plays important role in the detection of supernova neutrinos [5], and provides compact and transportable neutrino detectors for real-time monitoring of nuclear reactors [6].

The $\nu A_{el}$ process was first experimentally observed for stopped-pions decay-at-rest neutrinos (DAR-$\pi - \nu$) [7] and various other experimental programs are being pursued with reactors [8–13]. The differential cross-section of $\nu A_{el}$ scattering at three momentum transfer $q (\equiv |\vec{q}|)$ and incident neutrino energy $E_{\nu}$ on a target nuclei of mass $M$, can be expressed as [14]

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

where $G_F$ is fermi constant and term $\Gamma(q^2)$ introduce the coherence effects in the cross-section [14]. The three momentum transfer ($q (\equiv |\vec{q}|)$) serves as a universal kinematic parameter, which relates to the experimental observable nuclear recoil ($T$) via $q^2=2MT+\xi^2 \approx 2MT$. The commonly adopted description of $\Gamma(q^2)$ comes from the nuclear physics aspect as

$$\Gamma(q^2) \equiv \Gamma_{Np}(q^2) = \left[\varepsilon Z F_Z(q^2) - NF_N(q^2)\right]^2, \tag{2}$$

where $F_Z(q^2) \in [0,1]$ and $F_N(q^2) \in [0,1]$ are respectively, the proton and neutron form-factors, while $\varepsilon \equiv (1-4\sin^2\theta_W)=0.045$, gives the $N^2$ enhancement to the cross-section. This description connects the $\nu A_{el}$ to nuclear physics. The experimental data for proton form factor $F_Z(q^2)$ is provided by electron nucleus scattering [15], while the $\nu A_{el}$ provides the probe to $F_N(q^2)$ through the weak process along with the experiments using polarized electrons parity-violation scattering.

In the kinematics regime $q^2 R^2 \ll \pi^2$, nucleons can be taken as structureless point-like particles. At $q^2 \to 0$, the scattering amplitude vectors of individual nucleons align perfectly in the target nucleus which gives complete coherence in $\nu A_{el}$ [16]. As $q^2$ increases, the coherency decreases and leads to the reduction in cross-section. The degree of coherency can be quantified by a universal parameter $\alpha=\cos \phi \in [0,1]$, where $\phi(q^2) \in [0,\pi/2]$ is the average phase misalignment angle between nonidentical nucleonic scattering centers. This leads to a formulation of $\Gamma(q^2)$ in terms of quantum mechanical (QM) superpositions as

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

The limiting behavior of this description at complete coherency state ($\alpha = 1$ at $q^2 \sim 0$) gives $(d\sigma/dq^2) \propto [\varepsilon Z - N]^2$ and decoherency state ($\alpha = 0$ at $q^2 \gtrsim [\pi R]^2$) gives $(d\sigma/dq^2) \propto [\varepsilon^2 Z + N]$. Another alternative description of the $\Gamma(q^2)$ is given by the cross-section reduction in measurement relative to the complete coherency condition, denoted by $\xi(q^2)$ [16], where

$$\Gamma(q^2) \equiv \Gamma_{Data}(q^2) = (\varepsilon Z - N)^2 \cdot \xi(q^2). \tag{4}$$
The experimentally measurable cross-section reduction fraction is related to the QM coherence and nuclear form factors via, respectively,

\[ \xi(q^2) = \alpha(q^2) + [1 - \alpha(q^2)] \left( \frac{\varepsilon^2 Z + N}{\varepsilon Z - N} \right) \quad \text{and} \quad \xi(q^2) = \frac{\varepsilon Z F_Z(q^2) - NF_N(q^2)}{(\varepsilon Z - N)^2}. \]  

(5)

whereas, the physics descriptions are connected by,

\[ \left[ \varepsilon Z F_Z(q^2) - NF_N(q^2) \right]^2 = (\varepsilon Z - N)^2 \cdot \alpha(q^2) + (\varepsilon^2 Z + N) \cdot [1 - \alpha(q^2)]. \]  

(6)

The behavior of complementary descriptions of the νAei interactions with functions ΓNP, ΓQM, and ΓData are summarized in Table 1. The frequently adopted approach of form factor considers \( F_N(q^2) = F_Z(q^2) = F_A(q^2) \). Using this approach, the expression for the cross-section reduction from Eq. 5 becomes \( \xi(q^2) = |F_A(q^2)|^2 \). One can adopt the specific formulation of this form factor for the phenomenological studies. The Helm form factor is widely used in the νAei studies, where

\[ F_A(q^2) = \left| \frac{3}{q R_0^2} \right| j_1(q R_0) e^{-q^2 R_0^2}. \quad \text{with} \quad j_1(x) = [\sin x / x^2 - \cos x / x]. \]  

(7)

Here \( R_0^2 = R^2 - 5s^2, R = 1.2A^{1/3} \) fm and \( s = 0.5 \) fm is the surface thickness of the nuclei.

**Table 1:** The summary of the three formulations of \( \Gamma(q^2) \) with limiting cases of complete coherency and decoherency in νAei scattering.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Complete Coherency</th>
<th>Complete Decoherency</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q^2 \rightarrow 0 )</td>
<td>( 0 )</td>
<td>( \geq \frac{1}{R^2} )</td>
</tr>
<tr>
<td>( q^2 )</td>
<td>( 1 )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>( \Gamma_N(q^2) )</td>
<td>( \Gamma_P(q^2) )</td>
<td>( (\varepsilon Z - N)^2 )</td>
</tr>
<tr>
<td>( (\varepsilon^2 Z + N) )</td>
<td>( (\varepsilon Z - N)^2 )</td>
<td></td>
</tr>
<tr>
<td>( \phi(q^2) )</td>
<td>( 0 )</td>
<td>( \pi / 2 )</td>
</tr>
<tr>
<td>( \alpha(q^2) )</td>
<td>( 1 )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>( \Gamma_Q(q^2) )</td>
<td>( \Gamma_D(q^2) )</td>
<td>( \varepsilon(q^2) )</td>
</tr>
<tr>
<td>( (\varepsilon Z - N) )</td>
<td>( \xi(q^2) )</td>
<td>( [\frac{\varepsilon^2 Z + N}{(\varepsilon Z - N)^2]} )</td>
</tr>
<tr>
<td>( \frac{d\alpha}{dq^2}(q^2) )</td>
<td>( \xi(q^2) )</td>
<td>( \propto (\varepsilon Z - N)^2 )</td>
</tr>
<tr>
<td>( \alpha(q^2) )</td>
<td>( \propto (\varepsilon^2 Z + N) )</td>
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</tr>
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2. Measurement from Experimental Data

The COHERENT CsI(Na) and Ar experiments at the Oak Ridge National Laboratory have provided the first positive measurements on νAei with DAR neutrinos [7, 17, 18]. This measurement cannot be expected to provide severe constraints on \( \alpha(q^2) \). The allowed regions are derived from the reduction in cross-section relative to the complete coherency conditions independent of nuclear physics input. This region is depicted by stripe-shaded areas in Fig. 1. The most stringent bounds.
within the region of interest [7], excluding complete QM coherency and decoherency at 90% confidence levels with specified $p$-values are, respectively, $\alpha < 0.57$, $\phi < 0.61\pi/2$, $p = 0.004$ at $q^2 = 3.1\times 10^3$ MeV$^2$ and $\alpha < 0.30$, $\phi < 0.80\pi/2$, $p = 0.016$ at $q^2 = 2.3\times 10^3$ MeV$^2$. It can be seen that the data are consistent with the general predictions of Eq. 7. Whereas future measurements with high accuracies are expected to probe the QM coherency within

$$\begin{align*}
\text{CsI/Xe @ DAR-}\nu & : \alpha \in [0.72; 0.14] \quad \text{for} \quad T \in [6.6; 36] \text{keV}_{nr}
\text{Ar @ DAR-}\nu & : \alpha \in [0.88; 0.51] \quad \text{for} \quad T \in [19; 93] \text{keV}_{nr}
\text{Ge @ Reactor (Projected)} & : \alpha \in [1.0; 0.96] \quad \text{for} \quad T \in [0; 1.9] \text{keV}_{nr}.
\end{align*}$$

(8)

following the nuclear recoil range from Fig. 1 and full energy range for Ge in the reactor experiment. It can be seen that the diverse ranges of QM coherency indicate the complementarity of $\nu A_{el}$ measurements among DAR-\nu and reactor neutrinos. While, the solar $\nu A_{el}$ with multiton detectors would probe the QM coherency in similar range as of the reactor neutrinos. The expected differential event rates derived from the reactor and solar neutrinos and three targets showing their variations with $\alpha$ are displayed in Fig. 2.

3. Summary

The $\nu A_{el}$ interaction involves two distinct concepts: elastic kinematics and QM coherency. The QM coherency aspect in electroweak interaction should be characterized by distributions with dependence on $A(Z,N)$ and $q^2$. The descriptions of QM coherency as a binary state or having them both coupled together may have the unintended consequences of missing complexities in the $\nu A_{el}$ and suppressing the potential richness of its physics content. One such consequence arises in weakly interacting massive particles (WIMPs) dark matter searches, where at a detection threshold of 1 keV$_{nr}$, with WIMP mass of 1 TeV and an (Ar;Ge;Xe) target, 90% of the elastic

![Figure 1: Measurements on $\alpha$ from COHERENT (left) CsI [17] and (right) Ar [18] data with DAR-\nu. The stripe-shaded region are the 1-$\sigma$ allowed regions derived from the reduction in cross-section. The dark-shaded regions are the theoretical expectations adopting the nuclear form factor formulation of Eq. 7 with a $\pm 1\sigma$ uncertainty of 10%. The configurations C$_{0,1,2,3}$ illustrate the cases where $a_0 < a_1$, $a_0 = a_2$, and $a_0 > a_3$ despite of having $F_A = \xi(q^2)$ and $\xi_0 > \xi_{1,2,3}$ in all cases[14].](image)
scattering events have kinematics ranges correspond to $\alpha$ as low as $(0.49; 0.22; 0.14)$. This region is far from the complete coherency. Accordingly, the description “the neutrino floor originates from coherent neutrino-nucleus scattering” is not applicable to WIMPs at TeV or higher mass scales. Understanding and applications of such topics are beyond the scope of this work. Furthermore, the formulation of coherency as a quantitative and universal parametrization may serve as natural entry points to some BSM studies. One of the BSM signatures is that $\nu_{A\text{el}}$ cross-section (Eq. 1) no longer varies as $(\varepsilon Z - N)^2$ even in the high coherency regime ($\alpha \approx 1$). Such deviations can open the window to new physics couplings.

The $\alpha(q^2)$ parameter qualifies on QM coherency to each measurement. It can facilitate comprehensive bookkeeping of the expanding array of data from diverse configurations. Although the first positive measurements on $\nu_{A\text{el}}$ provide only weak constraints to $\alpha(q^2)$, data with $O(10\%)$ accuracy would have a deep understanding of the coherency transitions. New measurements on $\nu_{A\text{el}}$ from a variety of neutrino sources and nuclear targets can be expected in the near future [11–13, 19–21] to give the sensitivity constraints on both coherent and decoherent channels.

References


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