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Studies of Quantum Mechanical Coherency Effects in Neutrino-Nucleus Elastic Scattering

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Low energy neutrinos play important role in nuclear and astrophysical processes. Such neutrinos with energy below ~100 MeV are able to scatter off the nucleus via elastic scattering. Neutrino-nucleus elastic scattering (νA_{el}) provides a unique laboratory to study the quantum mechanical coherency effects in electroweak interactions. We present the detailed study and formulation of coherency effects, relate this to nuclear form factors and experimental cross-section ratios. The parameters chosen to quantify the coherency are universally applicable to different neutrino sources and target nuclei. We characterize how the energy dependence of the coherence factor leads to complementary among measurements at various neutrino sources with different targets. We also provide the constraints on coherency for the first generation discovery measurements of νA_{el} with CsI target and theoretical expectations from Argon and Germanium target.

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1. Introduction and Formulation

Neutrino-nucleus elastic scattering (νA_{el}) is a well defined process in Standard Model (SM) of particle physics [1, 2] towards which several experimental programs are being pursued[3–8]. The νA_{el} is a flavor-blind process which is mediated by the exchange of Z boson. This makes the process a probe for the study of weak current in SM. The differential cross-section of νA_{el} scattering at three momentum transfer q ($\equiv |\vec{q}|$) and incident neutrino energy E_ν on a target nuclei of mass M, can be expressed as[9]

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

where G_F is fermi constant and term $\Gamma(q^2)$ describes the contribution of many-body physics of the target nuclei, since νA_{el} scattering involves collective contribution of individual nucleons in the nucleus.

The kinematics constraints on squared three momentum transfer ($q^2 \simeq 2MT$) is $q^2_{max} = 4E_\nu^2[M/(M + 2E_\nu)] \simeq 4E_\nu^2$ and $q^2_{min} \simeq 2MT_{min}$, where T is the experimentally observable nuclear recoil energy expressed in keV$_{nr}$ unit.

The formulation of $\Gamma(q^2)$ in eq. 1 depends on different aspects of physics probe. The usual description is based on nuclear physics given as

$$\Gamma(q^2) \equiv \Gamma_{NP}(q^2) = [\varepsilon Z F_Z(q^2) - N F_N(q^2)], \tag{2}$$

where $F_Z(q^2)$ ∈[0,1] and $F_N(q^2)$ ∈[0,1] are respectively, the proton and neutron form-factors, while $\varepsilon \equiv(1\text{-}4 \sin^2\theta_W)$=0.045, gives the N^2 enhancement to the cross-section. This description connects the νA_{el} scattering to nuclear physics. The proton form-factor gets contribution from electron nucleus scattering data, while neutron form-factor would require a probe from weak processes. Various formulation for nuclear form-factor are discussed in [10–12].

Another description of $\Gamma(q^2)$ comes from quantum mechanical coherency effects[13] given by

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

where $\alpha(q^2) \equiv \cos\phi \in [0, 1]$ is the degree of coherency given that ϕ is the misalignment phase angle. This description leads the limitation behavior of complete coherency state ($\alpha = 1$ at $q^2 \sim 0$) with $(d\sigma/dq^2) \propto [\varepsilon Z - N]^2$ and decoherency state ($\alpha = 0$ at $q^2 \gtrsim [\pi/R]^2$) with $(d\sigma/dq^2) \propto [\varepsilon^2 Z + N]$.

An alternative measurement driven description is given by the cross-section reduction relative to complete coherency condition[13] as

$$\Gamma(q^2) \equiv \Gamma_{DATA}(q^2) = (\varepsilon Z - N)^2 \cdot \xi(q^2), \tag{4}$$

where the limiting behavior leads to complete coherency state at $\xi(q^2) = 1$ and decoherency state at $\xi(q^2) = \left[\frac{(\varepsilon^2 Z+N)}{(\varepsilon Z-N)^2}\right]$. The experimentally measurable cross-section suppression ($\xi(q^2)$) is related to the quantum mechanical coherence and nuclear physics via, respectively,

$$\xi(q^2) = \alpha(q^2) + [1 - \alpha(q^2)]\left[\frac{(\varepsilon^2 Z + N)}{(\varepsilon Z - N)^2}\right] \quad \text{and} \quad \xi(q^2) = \frac{[\varepsilon Z F_Z(q^2) - N F_N(q^2)]^2}{(\varepsilon Z - N)^2}. \tag{5}$$

while both of these are connected by

$$\left[\varepsilon Z F_Z(q^2) - N F_N(q^2)\right]^2 = (\varepsilon Z - N)^2 \cdot \alpha(q^2) + (\varepsilon^2 Z + N) \cdot [1 - \alpha(q^2)]. \tag{6}$$

The functions $\Gamma_{NP}(q^2)$, $\Gamma_{QM}(q^2)$ and $\Gamma_{DATA}(q^2)$ can be directly measured from νA_{el} data. Prior to actual measurements, specific formulations of the nuclear form factors have to be adopted for phenomenological studies. One of the general description of the identical nuclear form factor for both proton and neutron ($F_Z(q^2) = F_N(q^2) \equiv F_A(q^2)$) is given by Helm model, which can be expressed as[11, 13]:

$$F_A(q^2) = \Big[\frac{3}{qR_0}\Big] j_1(qR_0) \exp\Big[-\frac{1}{2}q^2 s^2\Big], \tag{7}$$

where $j_1(x)$ is the first order spherical Bessel function and the target nuclei dependence is introduced through $R_0^2 = R^2 - 5s^2$, where $s = 0.5$ fm and $R = 1.2A^{1/3}$. In this formulation the squared form-factor is equal to the cross-section suppression: $[F_A(q^2)]^2 = \xi(q^2)$.

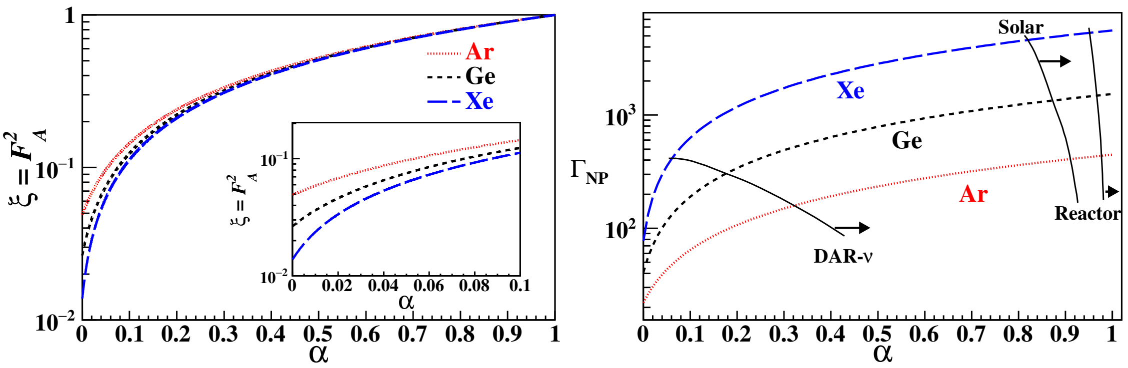

Figure 1: The variation of cross-section ratios [ξ] (left) and many-body nuclear physics term [Γ_{NP}] (right) with α for three target nuclei, independent of underlying nuclear physics.

The relation between ξ and Γ_{NP} with α is shown in Fig. 1 left & right for three representative nuclei. Contours of maximum-q^2 for different neutrino sources are marked in Fig. 1 right. The limiting domains corresponding to complete coherency and decoherency for Γ_{NP}, α and ξ are summarized in Table 1. The relation $\Gamma_{NP} = (\varepsilon^2 Z + N)$ for complete decoherency, is a result that emerges by relating Γ_{NP} and Γ_{QM} in Eq. 6, and could not be derived by considerations of nuclear form factor of Eq. 2 alone.

2. Experimental Projection

The $\Gamma(q^2)$ functions are directly measurable from νA_{el} data without the underlying physics input. Although, we need to choose the specific formulation of the nuclear form-factor for the phenomenological studies. Therefore, we used the frequently adopted nuclear form-factor formulation of Eq. 7. We studied the νA_{el} processes on several nuclei of experimental interest and at different mass ranges (Ar;Ge;Xe) with Z=(18;32;54) The first measurement of νA_{el} was done by CsI, having Z = 55 and 53, respectively [14, 15]. CsI is approximated as Xe (Z=54) in this discussion.

Table 1: The limiting cases of complete coherency and decoherency are described for three formulations of many-body physics in νA_{el} scattering.

Conditions	Complete Coherency	Complete Decoherency
q^2	$\rightarrow 0$	$\gtrsim [\frac{\pi}{R}]^2$
(I) $\Gamma_{NP}(q^2) = [\varepsilon Z F_Z(q^2) - N F_N(q^2)]^2$		
$F_Z(q^2)$	1	-
$F_N(q^2)$	1	-
$\Gamma_{NP}(q^2)$	$(\varepsilon Z - N)^2$	$(\varepsilon^2 Z + N)$
(II) $\Gamma_{QM}(q^2) = (\varepsilon Z - N)^2 \alpha(q^2) + (\varepsilon^2 Z + N)[1 - \alpha(q^2)]$		
$\phi(q^2)$	0	$\pi/2$
$\alpha(q^2)$	1	0
(III) $\Gamma_{DATA}(q^2) = (\varepsilon Z - N)^2 \xi(q^2)$		
$\xi(q^2)$	1	$\left[\frac{(\varepsilon^2 Z + N)}{(\varepsilon Z - N)^2}\right]$
$\left[\frac{d\sigma}{dq^2}\right](q^2)$	$\propto (\varepsilon Z - N)^2$	$\propto (\varepsilon^2 Z + N)$

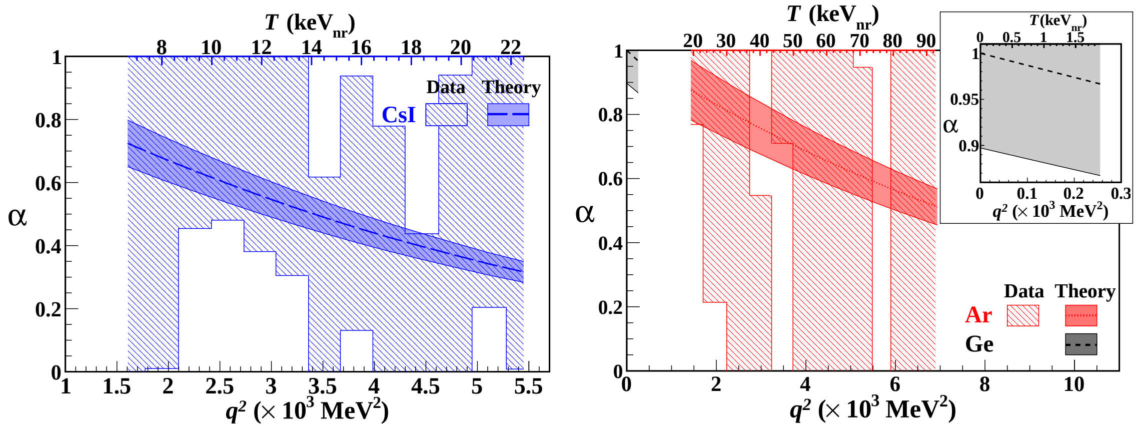

Figure 2: Measurements on α from COHERENT (left) CsI [15] and (right) Ar [16] data with DAR-ν. The stripe-shaded areas are the 1-σ allowed regions derived from the reduction in cross-section relative to the complete coherency conditions independent of nuclear physics input. The dark-shaded regions are the theoretical expectations adopting the nuclear form factor formulation of Eq. 9 with a $\pm 1\sigma$ uncertainty of 10%. The same projection applies to reactor-ν on Ge in (b) with q^2 range specified by FWHM in $[\Phi_\nu \cdot \sigma_{\nu A_{el}}]$. The $\sigma(q^2)$ values for different nuclei can be consistently compared[9].

The bin-wise $\xi(q^2)$ cross-section suppression relative to the complete coherency condition was provided by measurements. The allowed 1-σ ranges in $\alpha(q^2)$ are evaluated according to Eq. 7 and depicted as stripe-shaded region in Fig. 2. The results are data-driven without invoking nuclear physics input. The theoretical expectations adopting the nuclear form factor formulation of Eq. 9 with a $\pm 1\sigma$ uncertainty of 10% are superimposed as dark-shaded bands, showing the cases with CsI (equivalently, Xe) and Ar at DAR-π, and with Ge at reactors.

The significance in terms of p-values of the CsI data in probing the specific cases of complete coherency and decoherency are excluded with p=0.023 at $q^2 = 3.5 \times 10^3$ MeV^2 and with p=0.013

at $q^2 = 2.6 \times 10^3$ MeV^2, respectively. The 90% confidence levels of these bounds are α (ϕ) < 0.73 (0.48π/2) and α (ϕ) > 0.37 (0.76π/2), respectively.

These diverse ranges of α-sensitivity indicate the complementarity of νA_{el} measurements among reactor and DAR-π-neutrinos. Future measurements of solar νA_{el} with multi-ton detectors would probe a similar range of α as reactor neutrinos. Xenon detectors with scale O(100)ton would be required to probe the weakly coherent region at α<0.2 with atmospheric neutrinos.

3. Summary

Elastic scattering of neutrino with nucleus provides a probe to study the quantum mechanical coherence effects in electroweak interactions. This interpretation of the process is complementary to the language of the nuclear form factors. We relate these approaches and provide constraints on degree of coherency $\alpha(q^2)$ on positive measurements of νA_{el}. Current positive measurements on νA_{el} provide only weak constraints to $\alpha(q^2)$ and equivalently misalignment phase-angle $\phi(q^2)$. Data with O10% accuracy would allow the studies of coherency transitions.

We note that the interaction νA_{el} of Eq. 1 involves two distinct concepts: elastic kinematics and quantum mechanical coherency. The coherency aspect should be characterized by distributions with dependence on $A(Z, N)$ and q^2. Descriptions of coherency as a binary state or having both concepts bundled together may have the unintended consequences of missing the complexities of the process and suppressing the potential richness of its physics content.

The TEXONO experiment [17–20] is working on reactor νA_{el} with Germanium detector technology. The high energy resolution and low threshold germanium detectors have been used to study neutrino magnetic moment, neutrino millicharge and χN interactions[17, 21, 22]. The near future observation of νA_{el} with reactor neutrinos, can probe the mostly complete (α>95%) coherency region of νA_{el} scattering (inset of Fig. 2 right). Future measurements of solar νA_{el} with multi-ton detectors would probe a similar range of α as reactor neutrinos.

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