Coherency Effects in Elastic Neutrino Nucleus Scattering

V. Sharma[1],* H. T. Wong[2], S. Karmakar[2,3], L. Singh[4], and V. Singh[4]
[1]*Department of Physics, H. N. B. Garhwal University, Srinagar, Uttarakhand-246174, India*
[2]*Institute of Physics, Academia Sinica, Taipei-11529, Taiwan*
[3]*Department of Physics, GLA University, Mathura-281406, India and*
[4]*Physics Department, School of Physical & Chemical Sciences, Central University of South Bihar, Gaya-824236, India*

Introduction

The elastic neutrino-nucleus scattering (νA_{el}) cross-section [1] was first experimentally measured with CsI(Na) and LAr scintillator detectors[2]. The measurement was done with >10 MeV stopped pions decay-at-rest neutrinos (DAR-ν) from Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. The energy region of DAR-ν has partial coherence whereas the complete coherency effects can be observed for reactor and solar neutrinos[3, 5].

Formulation

The differential cross-section of νA_{el} process in terms of incident neutrino energy E_ν and of three momentum transfer(q $\equiv |\vec{q}|$), for a nucleus of can be written as

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

where, G_F is the Fermi constant and $\Gamma(q^2)$ is the many-body term describing the collective contribution of individual nucleons in the target nuclei. The universal kinematic variable q^2 is related to the experimentally observable nuclear recoil energy (T) and nuclear mass (M) via $q^2 = 2MT + T^2 \simeq 2MT$. Whereas, the kinematically allowed maximum nuclear recoil energy is given by $T_{max} = 2E_\nu^2/(2E_\nu + M) \simeq 2E_\nu^2/M$, while the least observable recoil energy depends on the detector threshold.

The formulation of $\Gamma(q^2)$ term have complimentary formulations based on different physics aspects[3]. The commonly adopted description is based on nuclear physics given by,

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

where, $F_Z(q^2) \in [0,1]$ and $F_N(q^2) \in [0,1]$, are the respectively, the proton and neutron nuclear form factors, while $\varepsilon \equiv (1 - 4\sin^2\theta_W) = 0.045$ is responsible for neutron dominant contribution. In this description, the proton form factor, $F_Z(q^2)$ is determined by the electron-nucleus scattering experiments, while neutron form factor $F_N(q^2)$, require weak processes to probe.

Another description of $\Gamma(q^2)$ arises from the region where $q^2 \to 0$, where nucleons can be taken as structureless pointlike particles. This gives a perfect alignment of the scattering amplitude vectors of individual nucleons in the target nucleus and the interactions becomes completely coherent. As q^2 increases, the cross-section reduces due to deviation from the complete coherence. This leads to a formulation of QM coherency effects by a parameter $\alpha(q^2) \equiv \cos\phi \in [0,1]$. Thus, the QM formulation of $\Gamma(q^2)$ [5] becomes

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

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

Other than NP and QM descriptions, $\Gamma(q^2)$ can be defined by a measurement driven description. This description is based on cross-section reduction denoted by $\xi(q^2)$, relative to

*Electronic address: `vsharma.phys@hnbgu.ac.in`

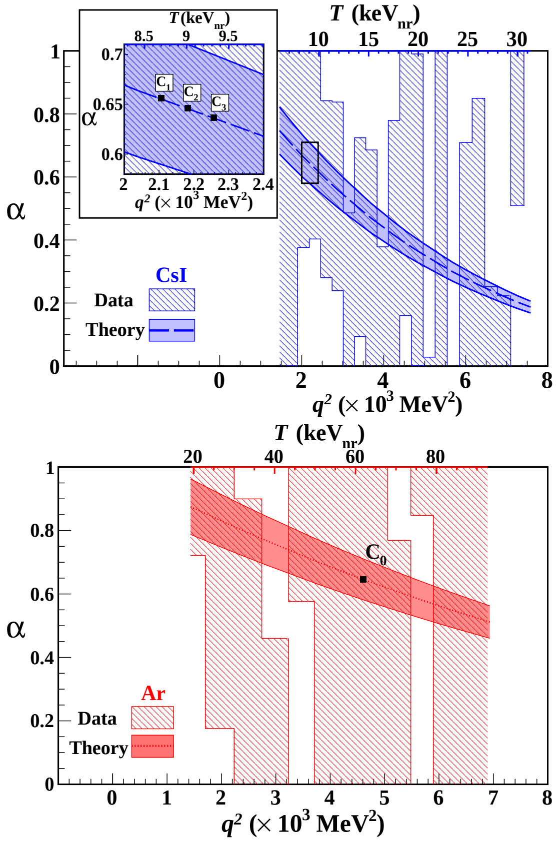

FIG. 1: Measurement on α with COHERENT CsI and Ar data. The stripe-shaded areas are the 1σ allowed regions derived from the reduction in cross section. The dark-shaded regions are the theoretical $\pm 1\sigma$ uncertainty of 10%..

that of the complete coherency, where

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

These three formulations of $\Gamma(q^2)$ are complementary descriptions of the νA_{el} interaction, and are related via

$$\xi(q^2) = \alpha(q^2) + [1 - \alpha(q^2)] \frac{[\varepsilon^2 Z + N]}{[\varepsilon Z - N]^2},$$

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

and

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

Limits on Data and Conclusions

The first-generation positive measurements on νA_{el} is provided by the COHERENT experiment [2]. The energy of DAR-π neutrinos goes upto $\sim$53 MeV for which the three momentum transfer is $\sim 11 \times 10^3$ MeV^2. The coherency $\alpha(q^2)$ and their uncertainties were extracted from the cross-section reduction ($\xi(q^2)$). The allowed ranges derived in $\alpha(q^2)$ from measurements and the theoretical expectations adopting the nuclear form factor with a 1σ uncertainty of 10% are depicted (Fig. 1). The most stringent bounds within the stated region of interest for CsI at 90% confidence level, excluding complete QM coherency is $\alpha < 0.57$ with p=0.004 at $q^2 = 3.1 \times 10^3$ MeV^2, and complete decoherency is $\alpha > 0.30$ with p=0.016 at $q^2 = 2.3 \times 10^3$ MeV^2. Future measurements on νA_{el} from a variety of low energy neutrino sources and nuclear targets will probe high QM coherency regions[3, 4]. Detailed quantitative studies on coherency also have the potential to provide the entry points to different BSM models[6]. Understanding and applications of coherency effects from nuclear to nucleons level with Γ_{NP} description are the possible topics of future research.

References

[1] D. Z. Freedman, Phys. Rev. D **9**, 1389 (1974).

[2] D. Akimov et al., Science **10.1126** aao0990 (2017); D. Akimov et al., Phys. Rev. Lett. **126**, 012002 (2021).

[3] V. Sharma et al., Phys. Rev. D **103**, 092002 (2021).

[4] V. Sharma et al. Indian J. of Phys., 92(9), 1145 (2018); V. Sharma et al., J. Phys.: Conf. Ser. 1468 012149 (2020).

[5] S. Kerman, Phys. Rev. D **93**, 113006 (2016).

[6] L.M. Krauss, Phys. Lett. B269, **407** (1991), K. Scholberg, Phys. Rev. D **73**, 033005 (2006).