Coherency in Neutrino-Nucleus Elastic Scattering

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Abstract. Elastic scattering of neutrino with nucleus ($\nu A_{el}$) is the well defined weak interaction processes in the Standard Model. The TEXONO collaboration adopt electro-cooled point contact Germanium detector technology with sub-keV sensitivities for the detection of $\nu A_{el}$ with reactor neutrinos. The detection of $\nu A_{el}$ cross-section is beneficial in studies of irreducible background in dark matter experiments, study of Solar and Supernova processes, etc. It also provides the probe the quantum mechanical coherence effects in electroweak interactions. We defined a parameter $\alpha$ to measure degree of coherency in $\nu A_{el}$. Reactor neutrinos are found to be one of the best candidates to probe $\nu A_{el}$ with high coherency. The divergence from full coherence leads to the study of neutron density distribution and to constrain the sensitivities in probing physics beyond the Standard Model.

1. Introduction
Neutrinos play a significant role in nuclear processes. The small interaction rate of $\nu A_{el}$ with sub-keV nuclear recoil gave the technical hurdle to observe this process from decades. The study of $\nu A_{el}$ can provide the tool for realtime monitoring of reactor and astrophysical processes. It also has importance in the study of core-collapse supernova. The Standard Model cross-section for $\nu A_{el}$ interaction can be written as [1, 2, 3]

$$\frac{d\sigma_{\nu A_{el}}}{dT} = \frac{G_F^2 M}{4\pi} \left[ 1 - \frac{MT}{2E_\nu} \right] [\varepsilon Z - N]^2 F(q^2),$$

where $G_F$ is the fermi constant, $E_\nu$ and $T$ are incident neutrino energy and nuclear recoil, respectively. $Z, N$ and $M$ are atomic number, neutron number and mass of target nucleus and $F(q^2)$ is nuclear form factor respectively. Due to small value of $\varepsilon \equiv (1 - 4 \sin^2 \theta_W) = 0.045$, the cross-section have N$^2$ enhancement. This makes $\nu A_{el}$ scattering very appealing for target with large mass number. This cross-section is valid for small three momentum transfer such that $q^2 R^2 < 1$, where $q^2 \ll M^2$ and $q^2 = 2MT + T^2 \simeq 2MT$. The kinematic constraint on nuclear recoil is given by

$$T_{max} = \frac{2E_\nu}{2E_\nu + M} \simeq \frac{2E_\nu}{M}.$$  

For the detector threshold $T_{min}$, the total cross-section $\sigma(E_\nu,T_{min}; M, N, Z)$ of $\nu A_{el}$ can be restrained as

$$\sigma_{\nu A_{el}} = \int_{T_{min}}^{T_{max}} \left[ \frac{d\sigma_{\nu A_{el}}(T, E_\nu)}{dT} \right] dT = \int_{q_{min}^2}^{q_{max}^2} \left[ \frac{d\sigma_{\nu A_{el}}(q^2, E_\nu)}{dq^2} \right] dq^2.$$  


Total cross-section as a function of incident neutrino energy $E_\nu$ is shown in Fig. 1. The nuclear form factor can be calculated using different nuclear models and parameters [4]. One of the effective nuclear form-factor is given by

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

(4)

where $J_1(x)$ 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, where $R$ and $s$ being the radius and surface thickness parameters of the nucleus, respectively.

2. Neutrino Sources for $\nu A_{el}$

Neutrinos below 50 MeV are capable to elastically scatter off the nucleus. The small cross-section of $\nu A_{el}$ process requires high neutrino flux to see significant signal of nuclear recoil in a low threshold detector. The three primary neutrino-source candidates for $\nu A_{el}$ are; Nuclear Reactor, Sun and Stopped Pion Accelerator facility. The stopped pion neutrinos provide the maximum energy flux up to $\sim 53$ MeV with three flavors of neutrinos ($\nu_e$, $\bar{\nu}_\mu$ and $\nu_\mu$) [3]. The maximum intensity of delayed neutrino energy is at $\sim 35$ MeV for $\nu_e$ and $\sim 53$ MeV for $\bar{\nu}_\mu$, while $\nu_\mu$ is monoenergetic with energy of 29.8 MeV. The maximum nuclear recoil for the Germanium target with $\sim 53$ MeV neutrinos is 83 keV.

The largest natural neutrinos flux on earth is provided by the Sun, in which the maximum energy neutrinos are provided by its $^8$B and hep reactions. The highest flux of $^8$B Solar neutrinos is at $\sim 7$ MeV with flux goes up to $\sim 17$ MeV. The maximum nuclear recoil with the Germanium target for $^8$B solar neutrino flux is 8.5 keV.

Among the artificial neutrino source, Nuclear reactors are one of the clean single flavored neutrino source with energy upto $\sim 8$ MeV. Nuclear reactors produce neutrinos via $\beta$-decay process in active fission. Nuclear reactor produces an average energy of about 200 MeV per fission with $\sim 6$ neutrinos from the $\beta$-decay chain of the fission products. The reactor neutrino spectrum has its highest intensity at $\sim 0.3$ MeV. The maximum nuclear recoil from reactor neutrinos in the Germanium target is $< 2$ keV, which comprises the high coherency in $\nu A_{el}$ interaction. The normalized neutrino flux are shown in Fig. 2.

3. Coherency in $\nu A_{el}$

Coherency in $\nu A_{el}$ comes to play when neutrino scatter-off simultaneously all of the nucleons in a nucleus in a phase with small three-momentum($q^2$) transfer. In this interaction, a virtual
Z-boson couples with the nucleus of size smaller or equal to the de-Broglie wavelength associated with the incident neutrino. The amplitude vectors of the different nucleons add with a finite relative phase angle $\langle \phi \rangle$ rather than being perfectly aligned. The cosine of relative phase angle $\langle \phi \rangle$ is quantified as degree of coherency ($\alpha$). The degree of coherency in terms of ratio of cross-section ratio between $A(Z, N)$ and neutron $(0, 1)$, is given by [5]

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

(5)

For $\alpha = 0$, the above equation approaches as $\sigma_{\nu A_{el}}(Z, N) \propto \varepsilon^2 Z + N$, which leads the condition of total incoherence while for $\alpha = 1$, it approaches to full coherence as $\sigma_{\nu A_{el}}(Z, N) \propto (\varepsilon Z - N)^2$. The departure from the $(\varepsilon Z - N)^2$ scaling as increase in $q^2$ is characterised as deviation from coherency. The relative change in cross section is an alternative parameter to characterize partial coherency,

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

(6)

It readily follows that $\xi$ varies linearly with $\alpha$, and both are unity at full coherency.

**Figure 3.** Expected degree of coherency versus detector threshold for Germanium target with different neutrino sources.

**Figure 4.** Integral interaction rate versus detector threshold and degree of coherency with different target nuclei for reactor neutrino (10$^{13}$ $\nu_e$ cm$^{-2}$ s$^{-1}$).

The nuclear reactors are the most competent artificial neutrino source to probe $\nu A_{el}$ with the highest degree of coherency >96% with Germanium target, whereas for stopped pion neutrinos coherency is below 87% at $T_{\text{min}} = 0$ (Fig. 3). The degree of coherency approaches to $\sim$100% at $T_{\text{min}} = 0$ keV, with all nuclear targets for reactor neutrinos (Fig. 4).

**4. Status of $\nu A_{el}$ at KSNL**

The TEXONO collaboration is using state-of-the-art point-contact Germanium (PCGe) detector technology to probe $\nu A_{el}$ [6]. The ability to distinguish single-sited interactions with high sensitivity and with only one electrode increases the appealing of PCGe detector. The recent development in PCGe detector is the addition of low noise pulse tube cooling mechanism by replacing the liquid nitrogen dewar system. This technology used pressure wave mechanism for cooling of the Germanium crystal and capable in self tuning to adapt changes of system’s vibration characteristics over time.

We have achieved a threshold of 300 eV$_{ee}$ with liquid nitrogen dewar detectors. The detector threshold is further improved by 100 eV$_{ee}$ with new electro-cooled PCGe detectors with upgraded electronics. This advancement is important as $\nu A_{el}$ interaction rate rapidly increase by lowering...
the detector threshold. In order to compare the $\nu A_{el}$ nuclear recoil spectrum to PCGe data, we use the quenching factor calculated with TRIM software [6]. The typical $\nu A_{el}$ interaction rate with PCGe detector at Kuo-Sheng Neutrino Laboratory (KSNL) is given in Table 1 (Fig. 5).

Table 1. Differential and integral $\nu A_{el}$ scattering rates in typical Germanium detector at KSNL.

| Threshold | 300 eV$_{ee}$ | 200 eV$_{ee}$ | 150 eV$_{ee}$ | 100 eV$_{ee}$ |
|-----------|---------------|---------------|---------------|---------------|
| Differential (Counts kg$^{-1}$ keV$^{-1}$ day$^{-1}$) | 0.54 | 6.4 | 21.8 | 75.6 |
| Integral (Counts kg$^{-1}$ day$^{-1}$) | 0.04 | 0.47 | 1.6 | 6.4 |

The main advantage of using reactor neutrinos for $\nu A_{el}$ study is having both source-ON and source-OFF data. Despite of short reactor OFF period, the subtracted ON-OFF spectrum can give high discovery potential for reactor neutrino properties. The realistic scenario for discovery potential of $\nu A_{el}$ with different reactor ON/OFF statistics is shown in Fig. 6.

Figure 5. Expected $\nu A_{el}$ integral rate at KSNL with both quenched and unquenched scales. The current achieved threshold with PCGe is 200 eV$_{ee}$

Figure 6. Experiment potential to get sensitive for $\nu A_{el}$ is shown w.r.t ambient background. Three scenarios are shown for 150 eV$_{ee}$ threshold with different reactor ON/OFF statistics and only reactor ON case.

5. Conclusion

PCGe detectors have been used to study neutrino magnetic moment, neutrino milicharge and Dark Matter interactions [7]. The current achieved threshold is 200 eV$_{ee}$ which hope to be further reduced by 100 eV$_{ee}$ with more detector R&D. Sub-keV sensitivities of electrocooled PCGe detectors are promising to probe $\nu A_{el}$ interaction with high Confidence Level. It will allow the detailed study of quantum mechanical coherence effects and as a probe to beyond Standard Model physics. Intensive simulations and data taking are being pursued for the understanding and suppression of sub-keV background and advanced detector hardware configurations.

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