Coherency in Neutrino-Nucleus Elastic Scattering

S. Kerman, V. Sharma, M. Deniz, H. T. Wong†, J.-W. Chen,
H. B. Li, S. T. Lin, C.-P. Liu and Q. Yue
(TEXONO Collaboration)
Institute of Physics, Academia Sinica, Taipei, Taiwan

4^{th} International Workshop on Dark Matter, Dark Energy and Matter-Antimatter Asymmetry
December 29-31, 2016, NTHU, Hsinchu, Taiwan

* **Coherency in Neutrino-Nucleus Elastic Scattering, Phys. Rev. D 93, 113006 (2016)**

Outline

Introduction

Motivation

- νA_{el} process: A convenient channel to study ***the quantum mechanical coherency effects in electroweak interactions***.
- The generic scale for coherency is: $E_\nu < 50\ MeV$.
- We focesed on ***quantitative studies on the transitions towards decoherency***. Our theme's ***objective is to quantify this transition—the first such investigation in the literature***.
- ***The degree of coherency is described by a measurable parameter*** (α) ***and the dependency of*** α ***parameter to the incoming neutrino energy, detector threshold, and target nucleus*** are examined.

Formalism

$$\nu A_{el} : \nu + A(Z,N) \rightarrow \nu + A(Z,N).$$

The SM differential cross section of νA_{el} scattering:

$$\frac{d\sigma_{\nu A_{el}}}{dq^2}(q^2, E_\nu) = \frac{1}{2}\left[\frac{G_F^2}{4\pi}\right]\left[1 - \frac{q^2}{4E_\nu^2}\right] \times \left[\varepsilon Z F_Z(q^2) - N F_N(q^2)\right]^2, \quad (1)$$

$q^2 = 2MT + T^2 \simeq 2MT$. The total cross section:

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

For nuclear form factors the effective method is adapted,

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

with parameters: $R_0^2 = R^2 - 5s^2$ and $s = 0.5\ fm$.

Neutron and several different nuclei (n, Ar, Ge, Xe), compatible with exp. interest, are selected for studies $\{Z = (0, 18, 32, 54)\}$.

Fig. 1.(a) Nuclear form factor $F(q^2)$ as a function of T:

Fig. 1.(b) Total cross section ($\sigma_{\nu A_{el}}$) at $T_{min} = 0$ as a function of E_ν:

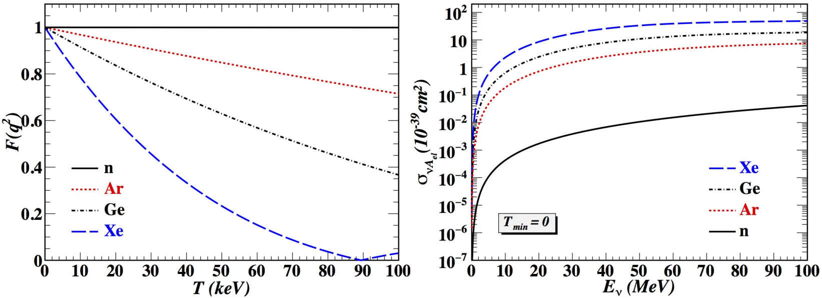

Figure 1: (a) Nuclear form factor $F(q^2)$ as a function of T, related by $q^2 = 2MT$; (b)Total cross section ($\sigma_{\nu A_{el}}$) at $T_{min} = 0$ as a function of E_ν. (n, Ar, Ge, Xe) nuclei are selected for illustrations.

Decoherency

Decoherency for $\sigma_{\nu A_{el}}$ is characterized by deviations from the $[\varepsilon Z - N]^2$ scaling as q^2 increases.

The scattering amplitude of individual nucleons adds with a finite relative phase angle to contribute to the cross section. The combined amplitude $\mathcal{A}$:

$$\mathcal{A} = \sum_{j=1}^{Z} e^{i\theta_j}\mathcal{X}_j + \sum_{k=1}^{N} e^{i\theta_k}\mathcal{Y}_k, \quad (4)$$

$(\mathcal{X}_j, \mathcal{Y}_k) = (-\varepsilon, 1)$: the coupling strengths for protons and neutrons;
$e^{i\theta_j}$ $\left(e^{i\theta_k}\right)$: the phase for protons (neutrons).

$$
\begin{aligned}
\sigma_{\nu A_{el}} \propto \mathcal{A}\mathcal{A}^{\dagger} &= \sum_{j=1}^{Z} \mathcal{X}_j^2 + \sum_{k=1}^{N} \mathcal{Y}_k^2 \\
&+ \sum_{j=l+1}^{Z} \sum_{l=1}^{Z-1} \left[e^{i(\theta_j - \theta_l)} + e^{-i(\theta_j - \theta_l)} \right] \mathcal{X}_j \mathcal{X}_l \\
&+ \sum_{k=m+1}^{N} \sum_{m=1}^{N-1} \left[e^{i(\theta_k - \theta_m)} + e^{-i(\theta_k - \theta_m)} \right] \mathcal{Y}_k \mathcal{Y}_m \\
&+ \sum_{j=1}^{Z} \sum_{k=1}^{N} \left[e^{i(\theta_j - \theta_k)} + e^{-i(\theta_j - \theta_k)} \right] \mathcal{X}_j \mathcal{Y}_k . \qquad (5)
\end{aligned}
$$

The decoherence effects between any nucleon pairs is described by the average phase misalignment angle $\langle\phi\rangle \in [0, \pi/2]$:

$$
\left[e^{i(\theta_j - \theta_k)} + e^{-i(\theta_j - \theta_k)} \right] = 2cos(\theta_j - \theta_k) = 2cos\langle\phi\rangle . \qquad (6)
$$

The degree of coherency can therefore be quantified by a measurable parameter $\alpha \equiv cos\langle\phi\rangle \in [0, 1]$.

The cross-section ratio between A and neutron is:

$$\begin{aligned} \frac{\sigma_{\nu A_{el}}(Z,N)}{\sigma_{\nu A_{el}}(0,1)} &= \{\varepsilon^2 Z + N + \varepsilon^2 Z(Z-1)\alpha \\ &+ N(N-1)\alpha - 2\varepsilon ZN\alpha\} \\ &= \{Z\varepsilon^2[1+\alpha(Z-1)] + N[1+\alpha(N-1)] \\ &- 2\alpha ZN\}. \end{aligned} \tag{7}$$

The limiting conditions:
Full coherency: $\alpha = 1$; $\sigma_{\nu A_{el}} \propto [\varepsilon Z - N]^2$
Total decoherency: $\alpha = 0$; $\sigma_{\nu A_{el}} \propto [\varepsilon^2 Z + N]$.
Partial coherency, the relative change in cross section, ξ:

$$\xi \equiv \frac{\sigma_{\nu A_{el}}(\alpha)}{\sigma_{\nu A_{el}}(\alpha=1)} = \alpha + (1-\alpha)\left[\frac{(\varepsilon^2 Z + N)}{(\varepsilon Z - N)^2}\right], \tag{8}$$

which varies linearly with α, and both are unity at full coherency.

Numerical Results and Discussion

Numerical Analysis

The α contours on the $(N,\ E_\nu)$ plane at $T_{min} = 0$:

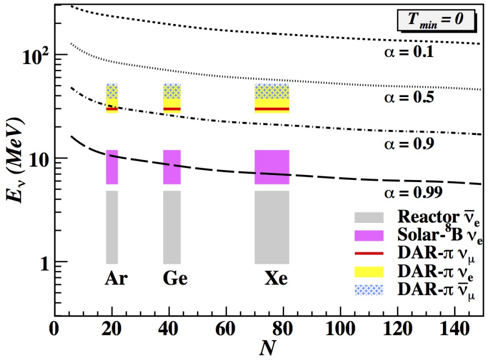

Figure 2: The α contours on the $(N,\ E_\nu)$ plane at $T_{min} = 0$, with bands of realistic neutrino sources and target nuclei superimposed.

Variations of α and ξ as functions of (a) E_ν at $T_{min} = 0$; (b) T_{min} at $E_\nu = 50\ MeV$:

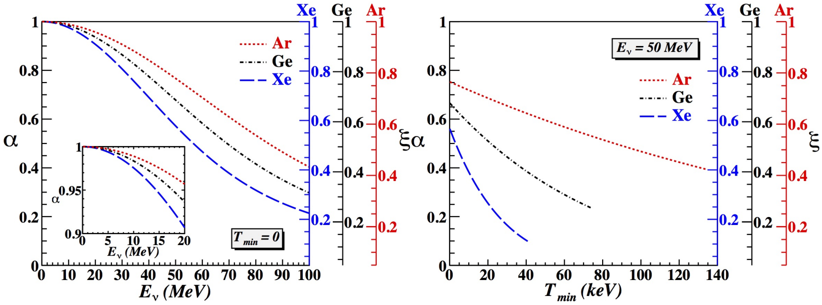

Figure 3: Variations of α and ξ for Ar, Ge, Xe as functions of (a) E_ν at $T_{min} = 0$, and (b) T_{min} at $E_\nu = 50\ MeV$ where the end points correspond to maximum recoil energies.

Experimental studies of coherency would be performed with realistic neutrino sources.

The current projects: reactor $\overline{\nu}_e$, $DAR-\pi$ $(\nu_\mu, \nu_e, \overline{\nu}_\mu)$ & the high energy solar-^8B ν_e.

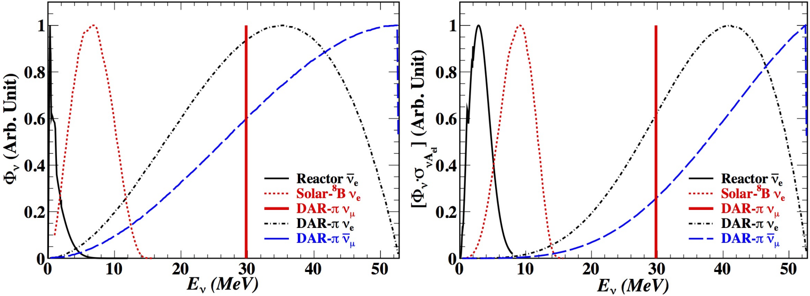

Figure 4: Neutrino spectra (Φ_ν) from reactor $\overline{\nu}_e$, $DAR-\pi$ $(\nu_\mu, \nu_e, \overline{\nu}_\mu)$, and solar-$^8B$ ν_e, normilized by their maxima. (b)Distributions of $\left[\Phi_\nu \cdot \sigma_{\nu A_{el}}\right]$ at $T_{min} = 0$, which are the weights in the averaging of $(\alpha,\ \xi)$ to provide measurements of $(\langle\alpha\rangle, \langle\xi\rangle)$.

The values of $\langle\alpha\rangle$ at $T_{min} = 0$:

ν	Half maxima of $[\Phi_\nu \cdot \sigma_{\nu A_{el}}]$	$\langle\alpha\rangle$ with		
source	in E_ν (MeV)	Ar	Ge	Xe
Reactor $\overline{\nu}_e$	$0.96 - 4.82$	1.00	1.00	1.00
solar-^8B ν_e	$5.6 - 11.9$	0.99	0.99	0.98
$DAR - \pi\nu_\mu$	29.8	0.91	0.86	0.80
$DAR - \pi\nu_e$	$27.3 - 49.8$	0.89	0.83	0.76
$DAR - \pi\overline{\nu}_e$	$37.5 - 52.6$	0.85	0.79	0.71

Table 1: The half maxima in the distributions of $\left[\Phi_\nu \cdot \sigma_{\nu A_{el}}\right]$ at $T_{min} = 0$ for the different neutrino sources, and the values of $\langle\alpha\rangle$ probed by the selected target nuclei.

For *Ge* variations of $(\langle\alpha\rangle, \langle\xi\rangle)$ with T_{min} with different ν sources :

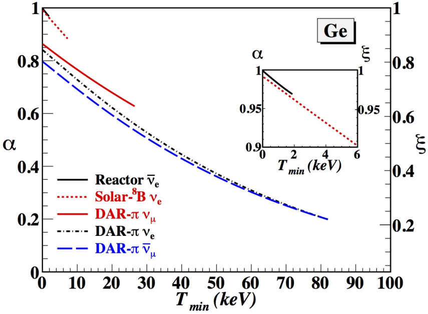

Figure 5: Variations of $(\langle\alpha\rangle, \langle\xi\rangle)$ as a function of T_{min} with reactor $\overline{\nu}_e$, solar-^8B ν_e and $DAR - \pi$ $(\nu_\mu, \nu_e, \overline{\nu}_\mu)$ for *Ge*. The end points correspond to maximum recoil energies allowed by kinematics.

The low energy reactor $\overline{\nu}_e$ and solar-^8B ν_e probe the full coherency region $(\alpha > 0.9)$, while $DAR - \pi\nu$'s allow measurements in the transition regions $(0.9 > \alpha > 0.1)$.

THANK YOU