

Proceeding Paper

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# Coherent Neutrino Scattering and Quenching Factor Measurement

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# Coherent Neutrino Scattering and Quenching Factor Measurement <sup>†</sup>

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**Abstract:** The latest direct measurements of the germanium quenching factor deviate significantly from the standard Lindhard model for nuclear recoil energies at the sub keV region. Here, we show that the recently measured coherent elastic neutrino–nucleus scattering (CE $\nu$ NS) data from reactor antineutrinos can be used to probe the quenching factor model, and a  $2\sigma$  improvement can be achieved in the fit to the measured CE $\nu$ NS data if the quenching factor is described by a modified Lindhard model with a negative value of  $q$ , which is also consistent with the direct quenching factor measurement. Constraints on the parameter space of a light vector or scalar mediator that couples to neutrinos and quarks, and on a neutrino magnetic moment, are also placed by using the measured CE $\nu$ NS data, and we find that they are quite sensitive to the quenching factor model at low recoil energies.

**Keywords:** CE $\nu$ NS; quenching factor; light mediator

## 1. Introduction

The study of nuclear recoils plays an important role in both dark matter direct detection experiments and Coherent elastic neutrino–nucleus scattering (CE $\nu$ NS) experiments. CE $\nu$ NS is a process in which low-energy neutrinos scatter off a nucleus as an entire entity via neutral current interactions [1]. This process was first observed by the COHERENT collaboration [2] by using a pion-decay-at-rest ( $\pi$ DAR) neutrino source with a cesium-iodide detector. The COHERENT collaboration also confirmed the existence of CE $\nu$ NS with an argon detector at a confidence level (CL) of more than  $3\sigma$  using the same source [3]. The observation of CE $\nu$ NS opens a new window to probe neutrino and nuclear physics at low energies; for a recent review, see Ref. [4] and references therein.

Due to the abundant neutrino fluxes produced by nuclear power reactors, reactor antineutrinos also serve as an ideal source for the measurement of CE $\nu$ NS. However, the observation of CE $\nu$ NS from reactor antineutrinos is much more difficult than from the  $\pi$ DAR source due to the lower energies of reactor antineutrinos. Thus, a detector with a very low threshold is required to detect CE $\nu$ NS from reactor antineutrinos. Currently, CONNIE [5] and CONUS [6] experiments have placed constraints on CE $\nu$ NS with reactor antineutrinos with a silicon and germanium detector, respectively. Colaresi et al. have also used a germanium detector to measure CE $\nu$ NS at the Dresden-II power reactor [7], and they found the first hint of CE $\nu$ NS from reactor antineutrinos in a recent measurement made with the NCC-1701 germanium detector [8]. In addition, the latest direct measurements of the germanium quenching factor show a significant deviation from the standard Lindhard model for nuclear recoil energies in the sub keV region [9]. In this work, we use the recently measured CE $\nu$ NS spectrum to probe the germanium quenching factor model.



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## 2. CE $\nu$ NS

Here we show the calculation of the CE $\nu$ NS spectrum from reactor antineutrinos in details. The differential CE $\nu$ NS event rate with respect to the nuclear recoil energy  $E_R$  is given by

$$\frac{dR}{dE_R} = N_T \int \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_R} dE_\nu, \quad (1)$$

where  $N_T$  is the number of nuclei in the detector, and  $\frac{d\Phi}{dE_\nu}$  is the reactor antineutrino flux. The differential CE $\nu$ NS cross section in the standard model (SM) is given by [1]

$$\frac{d\sigma_{SM}}{dE_R} = \frac{G_F^2 M}{4\pi} q_W^2 \left(1 - \frac{M E_R}{2 E_\nu^2}\right) F^2(q), \quad (2)$$

where  $M$  is the nuclear mass,  $G_F$  is the Fermi coupling constant,  $q_W = N - (1 - 4 \sin^2 \theta_W) Z$  with  $\theta_W$  the weak mixing angle, and  $F(q)$  is the Klein–Nystrand form factor [10]. Due to the low momentum transfer in CE $\nu$ NS with reactor antineutrinos, the calculated signal is not sensitive to the specific choice of the form factors and its uncertainties [11].

The measured CE $\nu$ NS spectrum is strongly dependent on the germanium quenching factor  $Q$ , which is defined as the ratio of the observable ionization energy  $E_I$  to the nuclear recoil energy  $E_R$ , i.e.,  $Q \equiv E_I/E_R$ . Therefore, the differential event rate with respect to  $E_I$  is

$$\frac{dR}{dE_I} = \frac{dR}{dE_R} \left( \frac{1}{Q} - \frac{E_I}{Q^2} \frac{dQ}{dE_I} \right). \quad (3)$$

Currently, experimental measurements of the quenching factor are well described by the standard Lindhard model [12] for  $E_R \gtrsim 1 \text{ keV}_{\text{nr}}$ , which can be clearly seen from Figure 3 in Appendix II of Ref. [13]. In the Lindhard model, the quenching factor is given by

$$Q(E_R) = \frac{k g(\epsilon)}{1 + k g(\epsilon)}, \quad (4)$$

where  $g(\epsilon)$  is well fitted by  $g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon$  with  $\epsilon = 11.5 Z^{-\frac{7}{3}} \left(\frac{E_R}{\text{keV}}\right)$  [14], and  $k = 0.133 Z^{\frac{2}{3}} A^{-\frac{1}{2}} = 0.157$  for germanium in the standard Lindhard model.

However, for sub-keV nuclear recoils, the quenching factors are not well modeled by the Lindhard model due to uncertainties in nuclear scattering and stopping at low energies [15,16]. A recent measurement of the germanium quenching factor shows a departure from the Lindhard model for nuclear recoil energies below  $\sim 1 \text{ keV}_{\text{nr}}$  [9], and the overall shape of the quenching factor can be parameterized by a modified Lindhard model [16,17],

$$Q(E_R) = \frac{k g(\epsilon)}{1 + k g(\epsilon)} - \frac{q}{\epsilon}, \quad (5)$$

where the parameter  $q$  can be negative (positive) if the energy given to electrons is enhanced (cutoff). After taking into account of the energy resolution, the differential event rate with respect to the measured energy  $E_M$  is

$$\frac{dR}{dE_M} = \frac{\int_0^\infty G(E_M, E_I, \sigma^2) \frac{dR}{dE_I} dE_I}{\int_0^\infty G(E_M, E_I, \sigma^2) dE_I}. \quad (6)$$

where

$$G(E_M, E_I, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp \left[ -\frac{(E_M - E_I)^2}{2\sigma^2} \right], \quad (7)$$

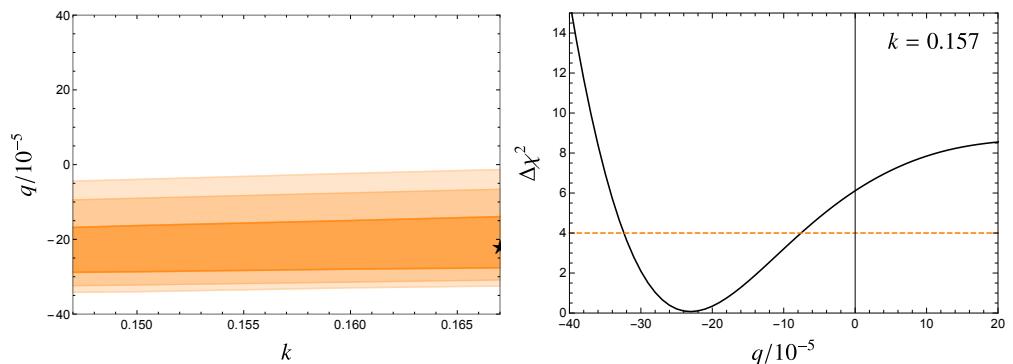
and  $\sigma^2 = \sigma_n^2 + E_I \eta F$  with  $\sigma_n = 68.5$  eV the intrinsic electronic noise,  $\eta = 2.96$  eV the average energy to produce an electron–hole pair in germanium, and  $F \approx 0.105$  the Fano factor taken from Ref. [8].

### 3. Results and Discussion

We first use the measured CEvNS data [8] to probe the quenching factor model. The CEvNS data are measured by a low-noise 3 kg germanium detector with a distance of  $\sim 10$  m from the 2.96 GW Dresden-II power reactor for a 96.4 day exposure. We analyze the spectrum of residual counts in Figure 5 of Ref. [8] and fit 20 bins in  $E_M$  from 0.2 to 0.4 keV<sub>ee</sub>. We use the following  $\chi^2$  to evaluate the statistical significance of a theoretical model, i.e.,

$$\chi^2 = \sum_i \left[ \frac{N_{\text{exp}}^i - N_{\text{th}}^i(1 + \alpha)}{\sigma_i} \right]^2 + \left( \frac{\alpha}{\sigma_\alpha} \right)^2, \quad (8)$$

where  $N_{\text{exp}}^i$  ( $N_{\text{th}}^i$ ) is the measured (predicted) number of residual counts per bin and  $\sigma_i$  is the corresponding uncertainty with  $\sigma_\alpha = 5\%$  being the percent uncertainty in the reactor neutrino flux normalization. The minimum of  $\chi^2$  is obtained by marginalizing over the auxiliary parameter  $\alpha$ . We get  $\chi^2_{\text{min}} = 14.3$  for the SM with the standard Lindhard model for the quenching factor. Moreover, we find that a modified Lindhard model can improve the fit. In order to be compatible with quenching factor measurements at high recoil energies [13], we only consider  $k$  values in the range of [0.147, 0.167]. The  $1\sigma$ , 90% CL, and  $2\sigma$  allowed regions in the  $(k, q)$  space are shown in Figure 1. The best-fit point is located at  $k = 0.167$  and  $q = -22.2 \times 10^{-5}$ , with  $\chi^2_{\text{min}} = 8.14$ . We can see that it is a substantial improvement over the standard Lindhard model. Furthermore, we notice that this best-fit point is consistent with the direct quenching factor measurements of Ref. [9], which can be parametrized by a negative  $q$ , as shown in Ref. [17]. Hence, the measured NCC-1701 data provide an independent probe of the quenching factor. From the left panel of Figure 1, we see that the data are not sensitive to  $k$ , and negative values of  $q$  are preferred. We also plot  $\Delta\chi^2 \equiv \chi^2(q) - \chi^2_{\text{min}}$  for  $k = 0.157$  in the right panel of Figure 1. We can see that the measured data prefer  $q < 0$  at  $2.5\sigma$  CL.



**Figure 1.** Left panel: The  $1\sigma$ , 90% CL, and  $2\sigma$  allowed regions in the  $(k, q)$  plane for the modified quenching factor model. The best fit point is marked by a star. Right panel:  $\Delta\chi^2 \equiv \chi^2(q) - \chi^2_{\text{min}}$  for a fixed  $k = 0.157$  [18].

We also use the measured CEvNS spectrum to place constraints on three simple new physics scenarios in the neutrino sector: a light  $Z'$  or scalar that couples to neutrinos and quarks universally, and a large neutrino magnetic moment. The differential cross sections of the three new physics scenarios are given in Ref. [18], and we use the same  $\chi^2$  in Equation (8) for our analysis. In order to place constraints on the new physics parameter space, we scan over possible values of the coupling and mediator mass for the light  $Z'$  and scalar cases. We also consider two different treatments of the quenching factor: (i) we fix the quenching factor as the standard Lindhard model, and (ii) we reduce the dependence on the quenching

factor model by marginalizing over  $k$  and  $q$  in the modified Lindhard model. The best fit points and  $\chi^2_{\min}/\text{dof}$  values are listed in Table 1. We see that if the standard Lindhard model is assumed for the quenching factor, the data show a mild preference for the new physics scenarios compared to the SM. Furthermore, we find that the constraints are qualitatively affected by the quenching factor model due to its dependence on  $q$  [18]. The best-fit value of the neutrino magnetic moment, and the corresponding  $\chi^2_{\min}$  are also provided in Table 1. We find that the 90% CL bound from NCC-1701 data is  $\mu_\nu < 4.0 \times 10^{-10} \mu_B$ , which is an order of magnitude weaker than the current bound on the electron neutrino magnetic moment by the GEMMA experiment,  $\mu_\nu < 2.9 \times 10^{-11} \mu_B$  [19].

**Table 1.** Values of  $\chi^2_{\min}/\text{dof}$  for the SM and new physics scenarios with various quenching factor model from the NCC-1701 data.

Scenarios	$k$	$q/10^{-5}$	$\chi^2_{\min}/\text{dof}$
SM w/standard Lindhard	0.157	0	14.34/19
SM w/modified Lindhard w/fixed $k$	0.157	-23.8	8.28/18
SM w/modified Lindhard w/ $0.147 \leq k \leq 0.167$	0.167	-22.2	8.14/17
light $Z'$ w/ $m_{Z'} = 63.1 \text{ MeV}$ , $g_{Z'} = 1.4 \times 10^{-4}$	0.157	0	9.09/17
light scalar w/ $m_\phi = 25.1 \text{ MeV}$ , $g_\phi = 1.6 \times 10^{-5}$	0.157	0	7.77/17
neutrino magnetic moment w/ $\mu_\nu = 2.5 \times 10^{-10} \mu_B$	0.157	0	11.71/18

#### 4. Conclusions

Recent direct measurement of germanium quenching factor indicates a departure from the standard Lindhard model at low energies, and this deviation can be parameterized by a negative  $q$  in the modified Lindhard model. The recently measured CE $\nu$ NS data can be also used to provide an independent probe of the quenching factor models. We show that the latest measured NCC-1701 data prefer negative values of  $q$  in the modified Lindhard model, and the best-fit point is consistent with the direct quenching factor measurements. A precise measurement of the quenching factor is essential to detect new physics at CE $\nu$ NS. If the germanium quenching factor is described by the standard Lindhard model correctly, then the NCC-1701 data may indicate the presence of a light vector or scalar or a large neutrino magnetic moment.

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