Atomic ionization by neutrinos at low energies

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Abstract.
It is well-known that neutrino-electron scattering at low recoil energies provides sensitivity gain in constraining neutrinos’ magnetic moments and their possible milli-charges. However, in detectors with sub-keV thresholds, the binding effects of electrons become significant. In this talk, we present our recent works of applying ab initio calculations to germanium ionization by neutrinos at low energies. Compared with the conventional differential cross section formulae that were used to derive current experimental bounds, our results with less theoretical uncertainties set a more reliable bound on the neutrino magnetic moment and a more stringent bound on the neutrino milli-charge with current reactor antineutrino data taken from germanium detectors.

1. Introduction
The electromagnetic (EM) moments of neutrinos are interesting topics for they not only are basic properties of elementary particles, but also point to potential new physics and have important implications for astrophysics and cosmology. (For review, see e.g. [1]. Also, the talks in this conference by A. I. Studenikin, H.-B. Li, and K. A. Kouzakov have similar themes.) In the Standard Model (SM) of particle physics, neutrinos are neutral, and EM moments like neutrino magnetic moments (NMM) and neutrino charge radius (NCR) arise through radiative corrections, which are extremely tiny. Therefore, a large NMM or NCR above the SM prediction, or the existence of a nonzero neutrino milli-charge (NmQ) would imply physics beyond the SM.

Experimental searches of these EM moments have been going on for many years, and the current limits are: (i) NMM $< 2.9 \times 10^{-11} \mu_B$ [2] (GEMMA, Ge detector) and $< 7.4 \times 10^{-11} \mu_B$ [3] (TEXONO, Ge detector), where $\mu_B$ is the Bohr magneton, (ii) NmQ $< 1.5 \times 10^{-12} e$ [4] (data from GEMMA) and $< 3.7 \times 10^{-12} e$ [5] (data from TEXONO), where $e$ is the fundamental charge unit, and (iii) NCR $< (3.3 \times 10^{-32} \text{ cm}^2)^{1/2}$ [6] (TEXONO, CsI detector). More stringent bounds can be extracted indirectly from astrophysical and cosmological observations, however, they are more or less model dependent.

The basic idea of direct measurements of neutrino EM moments is to look for the scattering events in detectors resulting from such additional EM interactions other than the standard interactions including neutral and charged weak forces. For solar and reactor neutrinos, the primary reaction channel is neutrino-impact atomic ionization

$$\nu + A \rightarrow \nu + A^+ + e^-,$$

and the recoil electron triggers the detector signal (the nuclear recoil is below the current detector thresholds.)
To further improve the direct search limits, in addition to having more intense neutrino beams, larger detector masses, longer data-taking periods, and smaller backgrounds, lowering detector thresholds can be a quite efficient way. From scattering of a neutrino and a free electron, one learns that the differential cross section $d\sigma/dT$, where $T$ is the energy that the neutrino loses, scales as $T^0$, $T^{-1}$, and $T^{-2}$, for the weak (also NCR), NMM, and NmQ interaction, respectively (see, e.g. [7, 5]). As a result, detectors have enhanced sensitivities to NMM and NmQ at low energies.

However, this low-threshold sensitivity gain comes with a price to pay, that is, the detector responses at low energies inevitably involve many-body physics to be understood. The current best limits on NMM and NmQ were deduced from data taken by germanium detectors with thresholds at about a few keV. Motivated by the fact that this energy scale already overlaps with typical atomic scales, and the status that sub-keV germanium detectors are fast developing and emerging, we carried out a series of study on atomic ionization of germanium in the energy range $100\text{ eV} \leq T \leq 10\text{ keV}$, and provided our limits on NMM and NmQ using a few available data sets [8, 9, 10]. In this talk, I will briefly summarize the theoretical part of our recent works and highlight the noteworthy points. (The experimental part has been covered in the talk by H.-B. Li.)

### 2. Theory Approaches

The main theoretical challenge in calculation of $d\sigma/dT$ is the transition matrix elements which involve many-body initial and final states. Two approximation schemes: (i) free electron approximation (FEA), and (ii) equivalent photon approximation (EPA), are particularly attractive, and in fact widely employed by high energy communities, because many-body problems are circumvented.

In the FEA,

$$\left.\frac{d\sigma}{dT}\right|_{\text{FEA}} = \sum_{i=1}^{Z} \theta(T - B_i) \frac{d\sigma^{(0)}}{dT},$$

one simply counts the number of electrons (out of the total number $Z$) that can be ionized by an energy deposition $T$ (so there is the step function $\theta$ enforcing the conditions that the binding energy $B_i$ of the $i$th electron must be smaller than $T$), with each ionized electron acting like a free electron and whose differential cross section $d\sigma^{(0)}/dT$ is well-known. Hence, the only atomic knowledge needed is $B_i$’s, which can be extracted from atomic photoabsorption data. Differential cross section formulae built on this approximation have been used extensively, including extractions of those limits on neutrino EM moments listed in the last section. Also, their validity in weak and NMM scattering were discussed in several recent papers [11, 12, 13].

In the EPA,

$$\left.\frac{d\sigma}{dT}\right|_{\text{EPA}} = N_\gamma(T)\sigma_\gamma(T),$$

where the exchanged virtual photon approaches the real limit, one only has to multiply the experimentally measurable photoabsorption cross section $\sigma_\gamma(T)$ with the equivalent photon spectrum, which can be easily determined by the kinematics of the ionization process. Although this approximation was applied to NMM scattering unsuccessfully [14], as argued in [11, 15], we will demonstrate later on that it indeed works in certain kinematic regimes of NmQ scattering.

While the FEA or EPA may have its own applicable cases, but it is not always obvious to judge \textit{a priori} when it should or should not work. Therefore, one’d better rely on well-benchmarked atomic calculations for definitive answers. Many-body studies on neutrino-impact atomic ionization started with the Hartree-Fock (HF) scheme with local density approximation [16, 17, 18, 19], and our approach is the multiconfiguration relativistic random phase approximation (MCRRPA). The MCRRPA improves the previous HF scheme not only
by treating the exchange potential exactly, more importantly, it integrates several refinements which are crucial for divalent open-shell atoms such as germanium, in both ground and excited states: First, a divalent atom typically has more than one valence configuration. For Ge (with total angular momentum \( J = 0 \)), there should be two: \( 4p^{2}_{3/2} \) and \( 4p^{2}_{1/2} \). Second, the relativistic correction is not negligible for medium mass atoms. For Ge, \( Z \alpha \sim 1/4 \). Third, atomic ionization involves continuum states, and it is well-known that two-body correlations have important effects on such bound-to-free transitions. Applying random phase approximation to the mean-field equations effectively includes a large part of these residual correlations. For details on the method, we refer to [10] and references therein.

3. Results and Discussion

As the first step, we carefully benchmarked our MCRRPA calculations with known properties of germanium. For the ground state, the binding energies of all occupied shells are given in TABLE I of Ref. [10]. The percentages of the \( 4p^{2}_{3/2} \) and \( 4p^{2}_{1/2} \) configurations are 72.15% and 27.85%, respectively. This yields a first ionization energy 7.899 eV which is in excellent agreement with the experimental result 7.856 eV, this tells the importance of a multiconfiguration reference state and relativistic corrections.

For transition matrix elements to ionized germanium states, we computed the photoabsorption cross sections and compared with experiments. As shown in Fig. 1a, our results have good agreement, generally in 5%, with data for \( T \geq 80 \text{ eV} \), which justifies the full capability of MCRRPA. The discrepancy in the \( T < 80 \text{ eV} \) region is mainly due to the fact that our atomic calculations did not properly take into account the solid-state band structure, which modifies the wave functions of outer-shell electrons significantly. To ensure reliability, we limit the applicable range of MCRRPA in germanium detectors, which are solid-state based, with a theoretical threshold at \( T = 100 \text{ eV} \), which is still lower than the current detector thresholds.

Getting confidence from the above benchmark calculations, we went on to compute the differential cross sections of neutrino-impact atomic ionization of germanium by the weak, NMM, and NuQ interactions (the NCR interaction can be effectively included in the weak interaction).

Fig. 1b shows the results of both weak and NMM (set to be the current limit: \( 2.9 \times 10^{-11} \text{ \mu_B} \)) scattering with a \( E_{\nu} = 1 \text{ MeV} \) reactor antineutrino. As \( T \) gets smaller, the weak cross section decreases only slightly, and the NMM one does increase. This agrees qualitatively with the previous scaling rules based on scattering with free electrons. However, while the FEA works pretty good in the \( T > 1 \text{ keV} \) region, it overestimates in both weak and NMM scattering at lower energies, i.e., the binding effects suppress the cross sections.

On the other hand, for NuQ scattering, the situation changes rather dramatically as shown by Fig. 1c, where \( E_{\nu} = 1 \text{ MeV} \) and NuQ is set to be \( 1 \times 10^{-12} e \): At low energies, the FEA underestimates the results by order of magnitude; in other words, the binding effects enhance the NuQ cross section so that the sensitivity gain is even bigger than what is predicted by the free electron picture. Another interesting thing to point out is the EPA becomes a reasonably good approximation for low-energy NuQ scattering. The sharp contrast between NMM and NuQ scattering can be traced back to the scattering kinematics and the relative importance between atomic longitudinal and transverse response functions, we refer to [15] for more detailed discussion.

One more thing worth mentioning is the phase space of final states. In the FEA, as there are only two bodies in the final state, the energy momentum conservation limits the maximum energy that a neutrino can deposit to the detector. In the massless limit of neutrinos, this energy is the same as the Compton edge. But for a realistic neutrino-impact atomic ionization, there are three bodies in the final state, so there is no limit on the maximum energy transfer, other than the incident neutrino energy. Fig. 1d shows an example with \( E_{\nu} = 10 \text{ keV} \): the FEA is cut off at \( T \sim 0.4 \text{ keV} \), so the kinematically allowed region by the FEA is very restricted compared
Figure 1: (a) Photoabsorption cross section of atomic germanium by MCRRPA (solid) vs solid-state germanium from experimental data (red circle). (b) Differential cross sections of $\bar{\nu}$-Ge weak and NMM ($2.9 \times 10^{-11} \mu_B$) scattering with $E_{\nu} = 1$ MeV. (c) Differential cross sections of $\bar{\nu}$-Ge weak and NmQ ($1 \times 10^{-12} e$) scattering with $E_{\nu} = 1$ MeV. (d) Same as (b) with $E_{\nu} = 10$ keV.

to the realistic situation for extremely low energy neutrino sources.

4. Summary
By using a well-benchmarked many-body approach, the multiconfiguration random phase approximation, we demonstrate that atomic physic is relevant for sub-keV detectors, and the theoretical uncertainty in evaluating the differential cross section formulae can be substantially reduced. Compared with the conventional free electron approximation (or stepping approximation in some literature), our results set a more reliable bound on the neutrino magnetic moment and a more stringent bound on the neutrino milli-charge with current reactor antineutrino data taken from germanium detectors, and their impact on future fully-functional sub-keV detectors will be even more significant.
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