Constraints on Millicharged Neutrinos via Analysis of Data from Atomic Ionizations with Germanium Detectors at sub-keV Sensitivities

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With the advent of detectors with sub-keV sensitivities, atomic ionization has been identified as a promising avenue to probe possible neutrino electromagnetic properties. The interaction cross-sections induced by millicharged neutrinos are evaluated with the ab-initio multi-configuration relativistic random-phase approximation. There is significant enhancement at atomic binding energies compared to that when the electrons are taken as free particles. Positive signals would distinctly manifest as peaks at specific energies with known intensity ratios. Selected reactor neutrino data are observed, and a combined limit on the neutrino charge fraction of $|\delta Q| < 1.0 \times 10^{-12}$ at 90% confidence level is derived.

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The physical origin and experimental consequences of finite neutrino masses and mixings [1] are not fully understood. Investigations on anomalous neutrino properties and interactions [2] are crucial to address these fundamental questions and may provide hints or constraints to new physics beyond the Standard Model (SM). An avenue is on the studies of possible neutrino electromagnetic interactions [2-4] which, in addition, offer the potentials to differentiate between Majorana and Dirac neutrinos. The neutrino electromagnetic form factors in C, P and T-conserving theories can be formulated as:

$$\Gamma_{\text{em}}^\nu = F_1 \cdot \gamma^\mu + F_2 \cdot \sigma^{\mu \nu} \cdot q_\nu,$$

with

$$F_1 = \delta Q \cdot e_0 + \frac{1}{6} \cdot q^2 \cdot \langle r^2 \rangle, \quad \text{and} \quad F_2 = (-i) \cdot \frac{\mu_{\nu}}{2 \cdot m_\nu},$$

where $\gamma^\mu$ and $\sigma^{\mu \nu}$ are the standard QED matrices, $e_0$ and $m_\nu$ are the electron charge and mass, respectively, $q = (q_\nu, \bar{q})$ is the four-momentum transfer, while the neutrino properties are parametrized by the neutrino fractional charge relative to the electron ($\delta Q$ — commonly referred to as “neutrino millicharge” in the literature), the neutrino charge radius ($\langle r^2 \rangle$), and the anomalous neutrino magnetic moment ($\mu_{\nu}$) [2-4] in units of the Bohr magneton $\mu_B$. The $F_1$ and $F_2$ terms characterize neutrino interactions without and with a change of the helicity states, respectively. The studies of $\delta Q$ and $\langle r^2 \rangle$ should in general be coupled to those due to SM-electroweak interactions to account for the possible interference effects among them. For completeness, we note that two additional form factors are possible [4]: the electric dipole moments in theories violating both P- and T-symmetries, and the anapole moments in P-violating theories.

The theme of this article is to report a new direct laboratory limit on $|\delta Q|$. The searches are based on $\bar{\nu}_e$ emitted from the nuclear power reactor via atomic ionization [5], an interaction channel considered for the first time in this process. The cross-section is derived using the Multi-Configuration Relativistic Random-Phase Approximation (MCRRPA) theory [6-7]. As will be demonstrated in Figure 1, the bounds on event rates from $\delta Q$-induced atomic interactions $[\bar{\nu}_e - A(\delta Q)]:$

$$\bar{\nu}_e + A \rightarrow \bar{\nu}_e + A^+ + e^-$$

to be probed in this work ($\sim 1$ count kg$^{-1}$keV$^{-1}$day$^{-1}$ at an energy transfer of $T \sim 0.1 - 10$ keV) far exceed those due to SM interactions as well as $\langle r^2 \rangle$-induced processes at its current limits [8], such that these effects and their interference can be neglected in our analysis.

The origin of electric charge quantization and whether it is exact is one of Nature’s profound mysteries. Many theories [9], such as extra dimensions, magnetic monopoles, and grand unified theories, provide elegant solutions, but they remain speculative. Electric charges are quantized in SM due to $U(1)$ gauge invariance and anomaly cancellation [10-11], implying $\delta Q = 0$. However, charge quantization is no longer ensured in many extensions of SM [11-12]. For example, in theories with right-handed neutrinos and Dirac mass terms, electric charge is no longer quantized and $\delta Q$ can assume an arbitrary value due to a hidden $U(1)$ symmetry whose conserved

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that break the additional conditions such as Majorana mass terms. The charge is the difference of baryon and lepton numbers or $B - L$. Charge quantization can be restored by introducing additional conditions such as Majorana mass terms that break the $U(1)$ symmetry. Neutrinos with finite charge will necessarily imply they are Dirac particles.

Model-dependent astrophysics bounds [2, 13] ranging at $|\delta_Q| < 10^{-13}$ to $10^{-15}$ are derived from stellar luminosity and cooling, as well as the absence of anomalous timing dispersion of the neutrino events in SN 1987A. The most stringent indirect limit is $|\delta_Q| < 3 \times 10^{-23}$ [13], inferred from constraints on the neutrality of the hydrogen atoms and the neutrons [14], and assuming charge conservation in neutron beta-decay. Earlier efforts with direct laboratory experiments placed constraints $|\delta_Q| < 10^{-12}$ [15, 16] through the extrapolations of the $\mu$-$\nu$-results from reactor $\bar{\nu}_e$ experiments [17, 18] using simplistic scaling relationships and neglecting atomic effects.

The conventional way of evaluating the effects due to $\Gamma_{em}$ is with the Free Electron Approximation (FEA). The corresponding differential cross-section for $\delta_Q$-induced neutrino-electron scattering [13, 16] due to an incoming neutrino of energy $E_\nu$ at $T \ll E_\nu$ is:

$$\left( \frac{d\sigma_{em}}{dT} \right)_{FEA} = \delta_Q^2 \left[ \frac{2\pi \alpha_m^2}{m} \right] \left[ \frac{1}{T^2} \right],$$

where $\alpha_m$ is the fine structure constant. The $(1/T^2)$-dependence is different from that of $(1/T)$ for $\mu$. With the advent of low-energy detectors sensitive to the energy range of atomic transitions and binding energies ($T < 10$ keV), FEA is no longer adequate and atomic ionization effects have to be taken into account [5]. Cross-sections of $\mu$-induced $\nu$ scattering have been formulated [21, 19, 20] by various authors.

The cross-section $\bar{\nu}_e-\nu_e(\delta_Q)$ is analogous to that induced by relativistic charged leptons, and can be described at atomic energies by the Equivalent Photon Approximation (EPA) [21]:

$$\left( \frac{d\sigma_{em}}{dT} \right)_{EPA} = \delta_Q^2 \left[ \frac{2\alpha_m}{\pi} \right] \left[ \frac{\sigma_\gamma(T)}{T} \right] \log \left[ \frac{E_\nu}{m_\nu} \right],$$

where $m_\nu$ is the neutrino and $\sigma_\gamma(T)$ is the photo-electric cross-section by a real photon of energy $T$. The divergence at $m_\nu \rightarrow 0$ is expected in Coulomb scattering and some cutoff schemes are necessary. The Debye length for solid-Ge (0.68 $\mu$m or 0.29 eV), which characterizes the scale of screen Coulomb interaction, is chosen. This may introduce an uncertainty of ~20% to the normalization if $m_\nu$ would be replaced by other values related to neutrino mass bounds. The EPA method neglects the contributions from the longitudinal polarization of the virtual photons and hence would deviate from the correct results as $T$ increases. It fails to describe ionizations by $\mu$, $<\sigma_\nu >$ or electro-weak interactions [24].

We adopted the MCRRPA theory [6] as an ab-initio approach [7] to provide an improved description of the atomic many-body effects. This becomes relevant for data from Ge detectors at sub-keV sensitivities. The MCRRPA theory is a generalization of relativistic random-phase approximation (RRPA) by the use of a multi-configuration wave function as the reference state. It has been successfully applied to photoexcitation, photo-ionization and $\mu$-induced ionization of dvalent or quasi-divalent atomic systems [6, 7]. There are various aspects where MCRRPA improves over the time-dependent HartreeFock (HF) approximation in describing the structures and transitions of Ge — (i) The Ge atom has two valence 4p electrons. Its ground state,
Table I: Summary of experimental limits on millicharged neutrino at 90% CL with selected reactor neutrino data. “This Work” compares data with results from FEA and MCRRPA calculations via a complete analysis, while “Previous Analysis” is based on extrapolations from $\mu_e$-results using simplistic scaling relations to the FEA spectra. The projected sensitivity of measurements at the specified experimental parameters is also shown.

| Data Set                  | Reactor-$\nu_e$ Flux ($\times 10^{13}$ cm$^{-2}$s$^{-1}$) | Data Strength Reactor ON/OFF (kg-days) | Analysis Threshold (keV) | $|\delta_Q|$ 90% CL Limits (< $\times 10^{-12}$) Previous Analysis | This Work MCRRPA |
|--------------------------|----------------------------------------------------------|--------------------------------------|--------------------------|---------------------------------------------------------------|------------------|
| TEXONO 1 kg Ge $^{17}$   | 0.64                                                     | 570.7/127.8                         | 12                       | 3.7 $^{15}$                                                   | 14               |
| GEMMA 1.5 kg Ge $^{18}$   | 2.7                                                      | 1133.4/280.4                        | 2.8                      | 1.5 $^{16}$                                                   | 2.1              |
| TEXONO Point-Contact Ge $^{24}$ | 0.64                                             | 124.2/70.3                          | 0.3                      | –                                                            | –                |
| Projected Point-Contact Ge | 2.7                                                    | 800/200                             | 0.1                      | –                                                            | –                |

Figure 2: Germanium photo-ionization cross section. The solid curve corresponds to the results of MCRRPA calculation. The dotted line is a fit to experimental data taken from Ref. $^{22}$. The relative differences (excess of MCRRPA results over data relative to the measurements) are shown in the lower panel.

a $^3P_0$ state, can be formed by either a $4p_1^2$ or a $4p_2^2$ valence configuration. This entails the necessity of a multi-configuration reference state. (ii) With an atomic number of $Z=32$, the relativistic corrections, in power of $Z\alpha_{em} \sim 1/4$, can no longer be ignored. By solving a relativistic wave equation, the leading relativistic effects are included non-perturbatively from the onset. (iii) The two-body correlation beyond HF is generally important in building excited states. The RRPA is an established method in accounting for two-body correlation, having nice features such as treating the reference and excited states on the same footing and preserving gauge invariance. In combination with the multi-configuration reference state, configuration mixing due to two-body correlation is also taken into account.

The MCRRPA results of this work are benchmarked by the measured photo-absorption cross section of solid Ge from real photons $^{7, 22}$. As demonstrated in Figure 2, the calculations successfully reproduce the data to an accuracy of within 5% at energy transfer larger than 100 eV, where the inner-shell electrons of Ge (3p and below) provide the dominant contributions. The deviations originate from the small contributions of the outer-shell electrons. At lower energy, the solid state effects start to play a role, since Ge is fabricated as semiconductor crystals in ionization detectors.

The derived differential cross-section for $\bar{\nu}_e$-$A(\delta_Q)$ on Ge under various schemes are depicted in Figure 1 with a mono-chromatic incident neutrino at $E_{\nu} = 1$ MeV, a typical range for reactor-$\bar{\nu}_e$. The FEA scheme is expected to provide good descriptions at energy transfer larger than the atomic binding energy scale, while EPA at $q^2 \rightarrow 0$. The MCRRPA results converge to these benchmarks: $T > 50$ keV for FEA and $T < 1$ keV for EPA, confirming the method covers a wide range of validity. Two features are particularly note-worthy: (i) There is an order-of-magnitude enhancement in the MCRRPA or EPA cross-section over FEA at low energy when atomic effects are taken into account. This behaviour is opposite to that for $\mu_e$-induced interactions $^{7, 19}$ where the cross-section is suppressed, the origin of which is discussed in Ref. $^{20}$. (ii) There exists a unique “smoking gun” signature for $\bar{\nu}_e$-$A(\delta_Q)$, through the observation of K- and L-shell peaks at the specific binding energies and with known intensity ratios. Both features favor the use of detectors with low threshold at sub-keV energy, and yet possess good resolution to resolve peaks and other structures at such energy.

To be comparable with experimental data, the differential cross-sections are convoluted with the neutrino spectrum $d\phi/dE_{\nu}$ to provide the observable spectrum of event rates ($R$) as function of $T$:}

$$\frac{dR}{dT} = \rho_e \int_{E_{\nu}} \left( \frac{d\sigma}{dT} \right) \left( \frac{d\phi}{dE_{\nu}} \right) dE_{\nu}, \quad (7)$$

where, $\rho_e$ is the electron number density per unit target mass. The MCRRPA spectrum for $|\bar{\nu}_e$-$A(\delta_Q)|$ with Ge at a typical reactor neutrino flux of $\phi(\bar{\nu}_e) = 10^{13}$ cm$^{-1}$s$^{-1}$ is depicted in Figure 1b, and is compared with those of $\mu_e$-induced and SM $\nu_e$-$e$ and $\bar{\nu}_e$-nucleus coherent scatterings $^{29}$. It can be seen that low threshold detectors can
greatly enhance the sensitivities in most of the channels.

The previous analysis \cite{15} with FEA are repeated using full spectral data via standard statistical procedures. Comparisons of the results listed in Table I can be statistically combined. The overall limit from these reactor neutrino data is
\[ |\delta_Q| \times 10^{-12} < 1.0 \times 10^{-12} \]  

at 90% CL. The projected sensitivity for a measurement at an achieved flux and data strength \cite{18} together with 100 eV detector threshold targeted for next generation of experiments \cite{23} would be \[ |\delta_Q| \sim 6 \times 10^{-14} \].

The MCRRPA theory improves descriptions on neutrino electromagnetic effects at atomic energy scales over previous techniques. Possible charge-induced interactions show enhancement at atomic binding energies, and would manifest as peaks with known intensity ratios. Novel Ge-detectors with sub-keV sensitivities and superb energy resolution are ideal to study these effects. We plan to extend our studies to neutrinos at different kinematics regimes, as well as to possible electromagnetic interactions with WIMPs as non-relativistic particles.

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