

Test of electric charge conservation in dark matter direct detection experiments

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Electric charge conservation (ECC) is typically taken as an axiom in the standard model. Searching for small violations with high-performance experiments could lead us to new physics. In this work, we tested “invisible” electric charge nonconservation events with 1.16 ton · yr electron recoil data from the XENONnT experiment. There was no statistically significant signal, and the limit was updated to $\tau(e^- \rightarrow \nu_e + \bar{\nu}_e + \nu_e) > 8.0 \times 10^{27}$ yr (90% confidence level). This work increases the limit by 2 orders of magnitude and shows that dark matter direct detection experiments have great potential for further ECC testing.

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I. INTRODUCTION

In 1957, Wu *et al.* reported that parity is not conserved in weak interactions in β decay experiments [1]. In 1964, Christenson *et al.* discovered the violation of charge-parity invariance [2]. These findings greatly shocked the community. Since then, new experiments have been conducted to examine fundamental laws, such as electric charge conservation (ECC).

ECC arises from the local $U(1)$ symmetry gauge invariance of the electric field [3]. The experimental evidence for ECC is that a photon has an extremely small upper limit on its rest mass [4]. However, electric charge nonconservation (ECNC) is allowed in some theoretical frameworks beyond the standard model [5–8]. If ECNC is confirmed, then new physics will emerge. However, to date, no definite signal of ECNC has been found. In previous tests of ECC, the limits on the mean lifetime τ have gradually become increasingly stringent. The most recent result of $\tau(e^- \rightarrow \nu_e + \bar{\nu}_e + \nu_e) > 2.8 \times 10^{25}$ yr was from the MAJORANA DEMONSTRATOR with a 37.5 kg · yr exposure [9].

The MAJORANA experiment pursues neutrinoless double-beta decay via a high-purity germanium (HPGe) array with an ultralow background [10]. Dark matter direct detection experiments, such as XENON [11] and PandaX [12], also have an ultralow background, can carry out the search for the other ultrarare physical events while searching for dark matter [13]. The event rate is approximately 8×10^3 counts/keV/ton/yr at 11 keV in the MAJORANA DEMONSTRATOR experiment [9], and approximately 12 counts/keV/ton/yr at 5 keV in the XENONnT experiment [14]. HPGe detector usually has an excellent energy resolution of $\sigma \sim 80$ eV at 5 keV [10,15]. Although the energy resolution of XENONnT ($\sigma \sim 0.7$ keV at 5 keV) cannot match that of the MAJORANA DEMONSTRATOR, XENONnT has a lower event rate, which allows it to obtain better results. In this work, we tested the ECC with 1.16 ton · yr 0–50 keV exposure data from the XENONnT experiment and updated the most stringent limit.

II. EXPECTED SIGNAL

ECNC occurs when an electron decays into neutral particles. Since electrons are the lightest charged lepton, if it ever decays, it can only decay to chargeless particles. There are two main types of experiments on ECNC in electron decay:

- (I) “visible,” $e^- \rightarrow \nu_e + \gamma$. This process splits the energy of the electrons equally, giving them 256 keV each. The photon can be picked up by

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TABLE I. Electron binding energies of the xenon atom [18,19].

Shell	Energy (keV)	Electron number
$K\ 1s$	34.6	2
$L_1\ 2s$	5.45	2
$L_2\ 2p_{1/2}$	5.11	2
$L_3\ 2p_{3/2}$	4.79	4
$M_1\ 3s$	1.15	2
$M_2\ 3p_{1/2}$	1.00	2
$M_3\ 3p_{3/2}$	0.94	4
$M_4\ 3d_{3/2}$	0.69	4
$M_5\ 3d_{5/2}$	0.68	6
Others	<0.3	26

the detector, so this process is “visible.” BOREXINO is a typical example of this type of experiment [16,17] and reached the limit of $\tau(e^- \rightarrow \nu_e + \gamma) > 6.6 \times 10^{28}$ yr.

- (II) “invisible,” $e^- \rightarrow \nu_e + \bar{\nu}_e + \nu_e$. This process produces neutrinos instead of photons, so it is called an “invisible” decay of the electron. When one of the inner electrons of an atom is lost by invisible decay, the outer electron fills the electron vacancy, and x-rays are emitted. The atomic levels of xenon are listed in Table I [18,19]. For example, when an electron in the K shell undergoes invisible decay in a Xe atom, x-rays of 34.6 keV are detected. Xenon atoms can also achieve relaxation by emitting Auger electrons [20], but this is not discussed in detail here. Theoretically, the angular momentum of this process is balanced, and the lepton number is conserved [9]. Moreover, numerically, the previous limits are far more relaxed than those in the “visible” process [21]. Thus, we choose this most favorable mode to test ECC and search for ECNC in this work.

Considering the energy resolution of the detector and the total efficiency $\eta_{\text{eff}}(E)$ of the experiment, the ECNC signal S in the experiment can be described by Eq. (1). For the sake of expression, we define the signal that does not take η_{eff} into account as a physical signal P , and the signal that takes η_{eff} into account as a detected signal S . Rather than a pure Gaussian, a skew-Gaussian smearing function is used to model the energy resolution of the XENONnT detector [14,22],

$$\begin{aligned}
 S &= P \cdot \eta_{\text{eff}}, \\
 P &= \sum_i \frac{I_i}{\sqrt{2\pi}\omega_i} e^{-\frac{(E-\xi_i)^2}{2\omega_i^2}} \cdot \left[1 + \text{erf}\left(\frac{\alpha(E-\xi_i)}{\sqrt{2}\omega_i}\right) \right], \\
 \omega(\text{keV}) &= 0.3842 \cdot \sqrt{E} + 0.00477 \cdot E, \\
 \alpha &= 1.72 \cdot E^{-1.169}, \\
 \Delta E(\text{keV}) &= 0.02 \cdot \arctan(0.017E) \cdot E,
 \end{aligned} \tag{1}$$

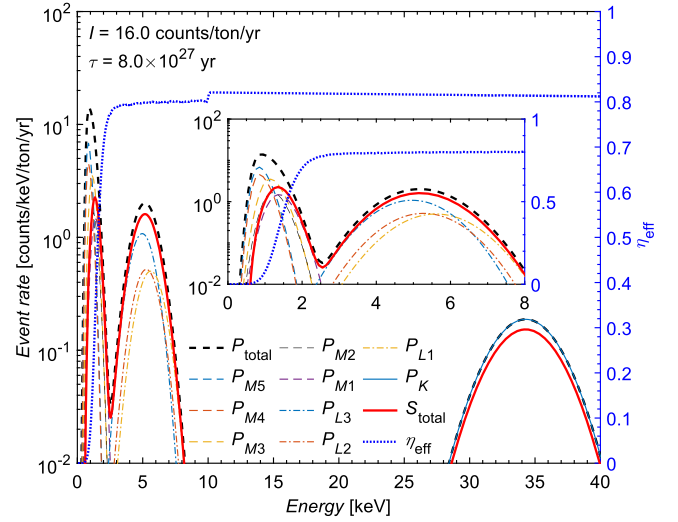


FIG. 1. Expected signal of the “invisible” ECNC in the XENONnT detector. The physical (P) and detected (S) signals are respectively plotted as black dashed and red solid lines. The three large peaks (thick lines) of the physical signal contain nine smaller peaks (thin lines). The total intensity of ECNC is 16.0 counts/ton/yr; for more details, see the text. The total efficiency η_{eff} of XENONnT detector [22] is plotted on the right y axis.

where, I_i , ξ_i , and ω_i are the intensity, the position and the width of the i th peak, respectively; α and ΔE represent the skewness of the distribution and the energy bias; and E is in the unit of keV.

In the example shown in Fig. 1, the total intensity of ECNC is $I \equiv \sum I_i = 16.0$ counts/ton/yr, and the value is discussed later. We distribute the total intensity to the peaks in proportion to the number of electrons as listed in Table I, $I_1(0.68 \text{ keV}) : I_2(0.69 \text{ keV}) : I_3(0.94 \text{ keV}) : I_4(1.00 \text{ keV}) : I_5(1.15 \text{ keV}) : I_6(4.79 \text{ keV}) : I_7(5.11 \text{ keV}) : I_8(5.45 \text{ keV}) : I_9(34.6 \text{ keV}) = 6:4:4:2:2:4:2:2:2$. Owing to η_{eff} , the physical signal represented by the black dashed line moves down to the expected signal in the xenon detector represented by the red solid line. The other 26 electrons from higher shells are neglected because they fall below the energy threshold of 1 keV [14,22]. The three large peaks (thick lines) of the physical signal contain nine smaller peaks (thin lines). The total efficiency η_{eff} [22] is plotted on the right y axis of Fig. 1.

III. RESULTS AND DISCUSSION

The expected energy spectrum consists of the detected signal (S) and the background (B). The expected spectrum ($S + B$) and the measured spectrum n were compared via minimum- χ^2 analysis:

$$\chi^2 = \sum_j \frac{[n_j - (S_j + B_j)]^2}{\Delta_j^2}, \tag{2}$$

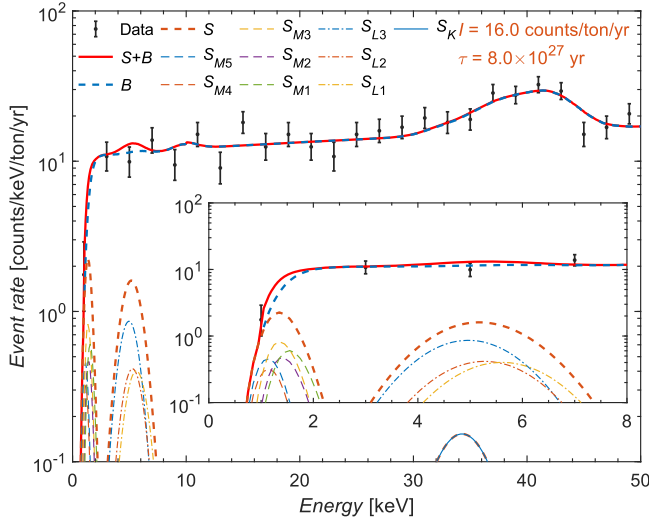


FIG. 2. Matching between the experimental and expected energy spectra. The data points with error bars represent the electron recoil spectrum in the XENONnT experiment, extracted from Fig. 5 in Ref. [22]. The B (blue dashed line) is the background B_0 in Ref. [22]. Three peaks attributed to the eight L -shell electrons are plotted with thin solid lines.

where n_j and Δ_j denote the measured data and standard deviation with statistical and systematic components at the j th energy bin extracted from Fig. 4 in Ref. [22], respectively; S_j denotes the ECNC event rate at the j th energy bin; and B_j denotes the background contribution at the j th energy bin in Ref. [22]. We found that the no-signal hypothesis yielded a $\chi^2_0 = 20.47$. The one-sided 90% confidence level (CL) limit was estimated with $\chi^2 = \chi^2_0 + \Delta\chi^2 = 23.18$, based on Feldman-Cousins unified approach [23].

By Eq. (3), the event intensity I can be converted into the mean lifetime τ :

$$\tau = \frac{n_e \cdot N}{I}, \quad (3)$$

where $N = 4.58 \times 10^{27} \text{ ton}^{-1}$ is the number of Xe atoms per ton, and n_e is the number of tested electrons in an atom.

There was no statistically significant signal in the experimental spectrum [22], as shown by the data points

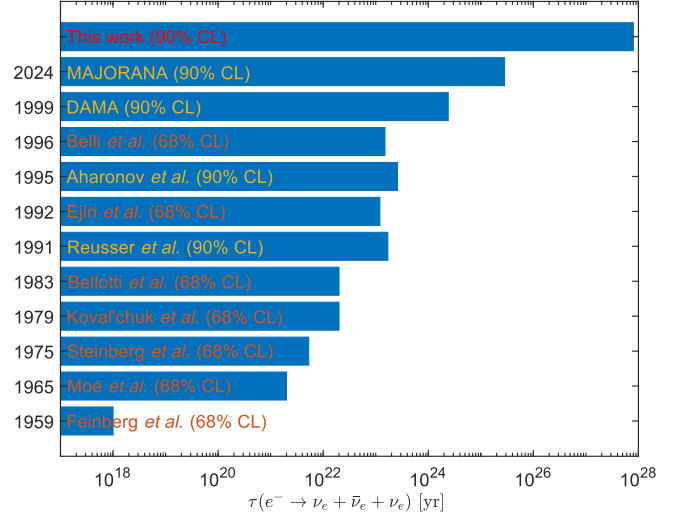


FIG. 3. The lower limits on the mean lifetime of ECNC in electron decay $e^- \rightarrow \nu_e + \bar{\nu}_e + \nu_e$. The previous results are from Refs. [9,24–33].

with error bars in Fig. 2. When $I \geq 16.0$ counts/ton/yr, $\chi^2 \geq 23.18$, as shown by the thick red line in Fig. 2. Thus, we can set a 90% CL limit of ECNC in “invisible” electron decay: $\tau(e^- \rightarrow \nu_e + \bar{\nu}_e + \nu_e) > 8.0 \times 10^{27} \text{ yr}$ for the (K, L, M) -shell electrons.

As shown in Fig. 3, starting in 1959, researchers and collaborations have continually pushed the lower limit. The pace of updating results was relatively slow in the 1990s until the DAMA experiment in 1999 gave significantly stronger limits. After more than 20 yrs of silence, MAJORANA again significantly refreshed the limits. Finally, this work has rapidly increased the limit by 2 orders of magnitude with XENONnT’s 1.16 ton · yr electron recoil data.

This work, together with the DAMA and MAJORANA’s explorations, reveals the advantages of dark matter detection experiments to examine ECC and search for ECNC cases, although more uncertainties need to be further analyzed and discussed. Experiments such as XENON and MAJORANA, which have ultralow background and excellent energy resolution, have great potential for further ECC testing and searching for ECNC with their greater exposure.

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