PHYSICAL REVIEW C **89**, 014608 (2014)

Measuring double-electron capture with liquid xenon experiments

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(Received 7 October 2013; published 9 January 2014)

We investigate the possibilities of observing the decay mode for ^{124}Xe in which two electrons are captured, two neutrinos are emitted, and the final daughter nucleus is in its ground state, using dark matter experiments with liquid xenon. The first upper limit of the decay half-life is calculated to be 1.66×10^{21} years at a 90% confidence level (C.L.) obtained with the published background data from the XENON100 experiment. Employing a known background model from the large underground xenon (LUX) experiment, we predict that the detection of double-electron capture of ^{124}Xe to the ground state of ^{124}Te with LUX will have approximately 115 events, assuming a half-life of 2.9×10^{21} years. We conclude that measuring ^{124}Xe 2ν double-electron capture to the ground state of ^{124}Te can be performed more precisely with the proposed LUX-Zeplin (LZ) experiment.

DOI: 10.1103/PhysRevC.89.014608　　PACS number(s): 07.05.Tp, 23.40.−s, 29.40.Wk

I. INTRODUCTION

The decay mode of an atomic nucleus in which two of the orbital electrons are captured by two protons and two neutrinos are emitted in the process is called two neutrinos double-electron capture (2νDEC) [1–3]. Equation (1) shows the decay process:

$$2e^- + (Z,A) \rightarrow (Z-2,A) + 2\nu_e, \tag{1}$$

where Z is the atomic number, and A is the atomic mass number for a given nucleus. The positive results were reported by a geochemical experiment [4] for ^{130}Ba with a half-life of $(2.2 \pm 0.5) \times 10^{21}$ years and a noble gas experiment [5] for ^{78}Kr with a half-life of $(9.2^{+5.5}_{-2.6}(\text{stat}) \pm 1.3(\text{syst})) \times 10^{21}$ years. The 2νDEC process is allowed by the standard model of particle physics and no conservation laws (including lepton number conservation) are violated.

If two electrons are captured by two protons in the nucleus, and neutrinos are *not* emitted, the process is called neutrinoless double-electron capture (0νDEC) [6] in which the lepton number is *not* conserved, and the neutrino is its own antiparticle, a Majorana particle. If observed, this mode of decay described in Eq. (2) would require new particle physics beyond the standard model:

$$2e^- + (Z,A) \rightarrow (Z-2,A). \tag{2}$$

The experimental study of this process is very challenging due to its extremely long lifetime. This is because the decay process is expected to be accompanied by an internal Bremsstrahlung gamma quantum and the final nucleus is in an excited state, which strongly suppresses the allowed decay phase space [7,8]. In contrast to neutrinoless double-β decay, a rare process used as a powerful tool to test neutrino properties and lepton number violation with several on-going experiments [19–25], neutrinoless double-electron capture appears to be extremely slow as pointed out by Vergados [7] and discussed in detail by Doi and Kotani [8]. However, a possible resonant 0νDEC process in which the close degeneracy of the initial and final (excited) atomic states can enhance the decay rate by a factor as large as 10^6 [9], which might occur, has been studied by many authors [9–18]. The 0νDEC might be realized as a resonant decay [9,10,12–17] or as a radiative process with or without a resonance condition [18]. Figure 1 shows an example of 0νDEC with ^{124}Xe.

Nonetheless, the 2νDEC process is a standard nuclear process and it should be detected experimentally by measuring its half-life, as expressed below:

$$\left(T_{\frac{1}{2},2\nu}\right)^{-1} = \frac{a_{2\nu} F_{2\nu} |M_{2\nu}|^2}{\ln(2)}, \tag{3}$$

where $a_{2\nu} \sim 2 \times 10^{-22}$ y^{-1} is the dimensional factor, $F_{2\nu}$ is the phase-space factor (proportional to Q^5), and $M_{2\nu}$ is the nuclear matrix element (NME).

The measurement of the two x-ray energies and the half-life of the 2νDEC decay ($T_{\frac{1}{2},2\nu}$) to the ground state is of great interest to nuclear physics. Of particular interest is, how the double K vacancy refills after the capture of two electrons by two protons in the nucleus occurred. Measuring the total energy from x rays can shed some light on the precise mechanism of this atomic decay process. Moreover, if the mass difference between the initial and final states is greater than twice the mass of electron (1.022 MeV), the reaction Q value is enough to initiate another mode of decay, which would be electron capture and positron emission. This decay mode occurs in competition with double-electron capture and their branching ratio depends on nuclear properties, which is of great interest. Furthermore, when the mass difference is greater than four electron masses (2.044 MeV), the third mode—double-positron decay—can occur as well. However, only six naturally occurring nuclides can decay via these three modes simultaneously [26]. ^{124}Xe, discussed below, is one of them. Therefore, measuring the decay modes of ^{124}Xe has particular meaning in nuclear physics. In addition, the model predictions for 0νDEC half-life require the evaluation of nuclear matrix elements. These calculations are complicated and have large

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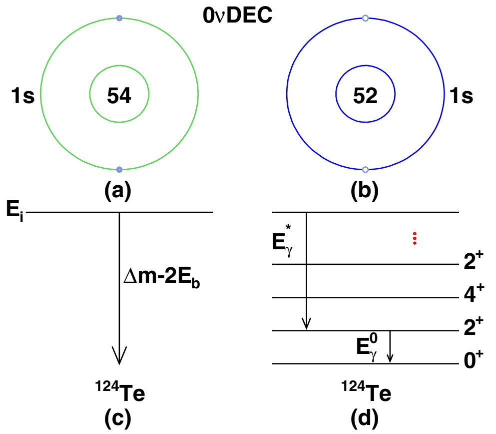

FIG. 1. (Color online) The schematic diagram for the ^{124}Xe 0νDEC process. (a) ^{124}Xe has 54 electrons (two electrons in the 1s shell) and 54 protons. (b) ^{124}Te has 52 electrons (two holes in the 1s shell) and 52 protons in an excited state. Both can emit electromagnetic radiation through de-excitation. The atomic de-excitation is shown in (c). (d) shows the nuclear de-excitation. E_γ^* is the γ ray which will signal double electron capture originating from a state with energy $\Delta m - 2b$ which has tiny admixtures of 0^+, 2^+, 4^+, etc.

uncertainties. They are different from those required for 2νDEC. However, within the same model framework, some constraints on the 0νDEC NME0ν can be derived using knowledge of the 2νDEC NME2ν [13,27]. Also, the NME2ν, which is extracted from the measurement of the half-life of 2νDEC, can be directly compared with the NME2ν from predictions [7]. A good agreement would indicate that the reaction mechanisms and the nuclear structure aspects that are involved in 2νDEC are well understood.

2νDEC has large Q values, but the decay to ground state in the final nucleus releases only x rays and Auger electrons, making its detection difficult. At their energy range ($\sim$1 to $\sim$100 keV), the background is usually high. Thus, the experimental detection of double electron capture with 2ν emission is more difficult than 2ν double-β decay, which has been observed for a variety of nuclei [21,28–35]. Nevertheless, experiments directly searching for dark matter require ultra-low background events in the low energy region (down to $\sim$1 to $\sim$100 keV). This lays the foundation to experimentally measure 2νDEC process for the first time. In this paper, we discuss the detection of 2νDEC with ^{124}Xe in the dark matter experiments with natural xenon as targets, such as XENON100 [36], LUX [37], and LUX-Zeplin (LZ) [38].

Natural xenon possesses ^{124}Xe at an abundance of 0.1% [39,40]. The process for 2νDEC of ^{124}Xe is

$$^{124}\mathrm{Xe} + 2e^- \rightarrow {}^{124}\mathrm{Te} + 2\nu_e. \tag{4}$$

The reaction Q value is 2864 keV. For the ground state of ^{124}Xe to the ground state of ^{124}Te, the detectable x rays are 31.8 keV from ^{124}Te, for a one-step process in which the two K-shell electrons are captured simultaneously by two protons in the nucleus. The nuclear recoil energy of ^{124}Xe allocated in the decay process is on the order of $\sim$30 eV, which is negligible. The predicted half-life for 2νDEC is 2.9×10^{21} years [41] for a ground state to ground state process.

Since the reaction Q value in Eq. (4) is 2864 keV, the two other decay modes, electron capture with positron (2$\nu\beta^+$EC) emission and double positron decay (2$\nu\beta^+\beta^+$), can simultaneously occur with double electron capture. The available energies are shown below:

$$\begin{cases} Q_{\mathrm{DEC}} = M(A,Z) - M(A,Z-2), \\ Q_{\beta^+EC} = M(A,Z) - M(A,Z-2) - 2mc^2, \\ Q_{\beta^+\beta^+} = M(A,Z) - M(A,Z-2) - 4mc^2. \end{cases} \tag{5}$$

However, the 2νDEC rate is much faster than 2$\nu\beta^+$EC and 2$\nu\beta^+\beta^+$ as discussed in Refs. [10,41].

It is worth mentioning that ^{126}Xe has also a natural abundance of 0.09% and can only undergo a 2νDEC or a 0νDEC decay, ^{126}Xe → ^{126}Te, with ^{126}Te at its ground state and the total decay Q value of 896 keV. Because this decay Q value, 896 keV, is a factor of 3.2 smaller than the Q value, 2864 keV, from ^{124}Xe decays, the ^{126}Xe 2νDEC is much slower than ^{124}Xe 2νDEC decay. Therefore, we will not discuss ^{126}Xe 2νDEC in this paper.

II. THE FIRST UPPER LIMIT OF HALF-LIFE FROM XENON-124

The average upper limit in an experiment with background can be obtained using the unified approach proposed by Feldman and Cousins [42]. For a detector with ^{124}Xe target, the upper limit of the half-life can be derived using the following equations [43]:

$$T_{1/2}(0^+ \rightarrow \mathrm{g.s.}) \geqslant \frac{\ln(2) f_k \epsilon a \frac{MN_A}{A} \Delta T}{\mu_{\mathrm{up}}}, \tag{6}$$

$$\mu_{\mathrm{up}} \cong \alpha\sqrt{B}, \tag{7}$$

$$B = b\Delta T \Delta E, \tag{8}$$

where f_k is the fraction of 2K captures accompanied by the emission of two K x rays, ϵ is the efficiency of the detection at a full energy peak, a is the isotopic abundance of ^{124}Xe, and M is the total mass of the target. N_A is the Avogadro constant,

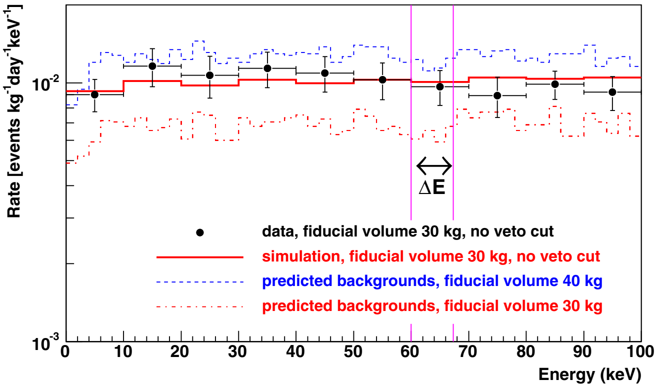

FIG. 2. (Color online) Shown is a digitized background spectrum from the published XENON100 data [45]. The region of interest, 63.6 ± ΔE keV, is labeled.

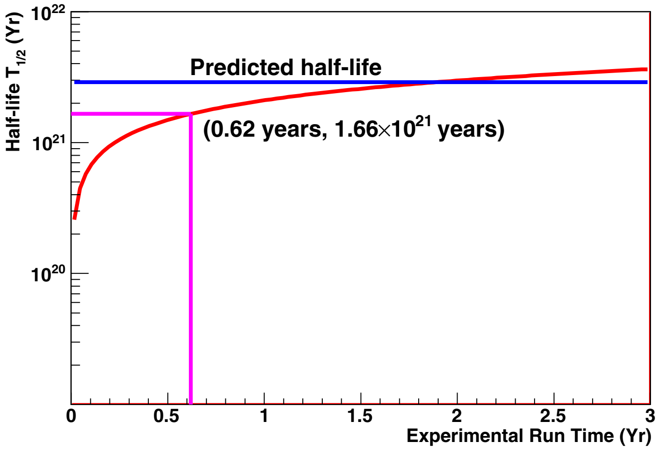

FIG. 3. (Color online) Above is the half-life limit of the ^{124}Xe 2νDEC process to the ground state of ^{124}Te.

A is the atomic mass number of ^{124}Xe, ΔT is the live time of measurements in days, α is a constant that equals to 1.64 at 90% confidence level (C.L.), b is the background rate per unit energy, and ΔE is the energy window around the peak position.

A. Results and analysis from XENON100

The XENON100 dark matter experiment reported their dark matter analysis with a 34 kg active target of liquid xenon [44]. The electromagnetic background events in the region of interest was reported as 5.3×10^{-3} events/(kg day keV). We analyzed the XENON100 electromagnetic background data with a digitized spectrum, as shown in Fig. 2, from the published background spectra (Figs. 3 and 12 in Ref. [45]) between 0 to 100 keV. A peak-searching algorithm, wavelet transform [47], was applied in searching for peaks and no peak was found in the region of interest as shown in Fig. 2.

Consequently, an average background rate, 5.3×10^{-3} events/(kg day keV), was used in the calculation of the background index, events/(keV day), in Table I. The width of the region of interest, $\Delta E = 7.94$ keV, is determined using $\alpha \times \sigma$, where α equals 1.64 at 90% C.L. and $\frac{\sigma}{E} = 0.009 + 0.485/\sqrt{E(\text{keV})}$ [45] is energy resolution, E is the sum of the expected two x rays (2×31.8 keV) from ^{124}Te. In addition, Gavrilyuk *et al.* reported that the energy released in the refilling of a double K vacancy is not equal to the sum of two single vacancies [5]. Therefore, a possible reduction of the total energy release (2×31.8 keV) was taken into account, using an energy window of 7.94 keV, in our analysis. This possible energy reduction is from fluorescence yield, which might not be detectable in liquid xenon, induced by the emission of Auger electrons. Because the position resolution is less than 3 mm [45], the detection efficiency for two x rays can be 90% since the the mean free path of x rays with energy of 31.8 keV in liquid xenon is about 0.5 mm. The determined analysis parameters are summarized in Table I.

TABLE I. The experimental parameters and values.

Mass of liquid xenon, kg	34
Isotope abundance, %	0.1
Live time, days	225
Background index, events/(keV day)	0.18
K-shell fluorescence yields (ω_k)	0.875 [46]
$f_k = \omega_k^2$	0.766
Efficiency at 63.6 keV	0.9
Energy resolution ($\frac{\sigma}{E}$) at 63.6 keV, %	7.0
The region of interest ΔE, keV	7.94
Reaction Q value, keV	2864

TABLE II. Radioactivity level of the LUX 8778 PMT [37]. Units are in mBq/PMT.

^{238}U	^{232}Th	^{60}Co	^{40}K
9.8 ± 0.7	2.3 ± 0.5	2.2 ± 0.4	65 ± 2

Using Eqs. (6)–(8) and the values given in Table I, the half-life limit of ^{124}Xe 2νDEC to its ground state is determined to be 1.66×10^{21} years with a 90% C.L. (1.64σ), as shown in Fig. 3.

B. Predicted results from LUX-like and LZ-like experiments

The LUX dark matter experiment has been constructed at Sanford Underground Research Facility (SURF) [37] and is currently taking data. The LUX detector contains 360 kg of xenon with an assumed fiducial volume of 100 kg. We calculated the detectable events, for ^{124}Xe to the ground state of ^{124}Te, to be approximately 115 per year, assuming the predicted half-life is 2.9×10^{21} years. From a background model published with a Monte Carlo simulation [48] for the LUX detector, we know the dominant background is from the PMT sphere, which has radioactivity contents shown in Table II. Using the radioactivity levels in Table II, a simple Monte Carlo simulation was performed to predict the signal events from ^{124}Xe DEC process together with several

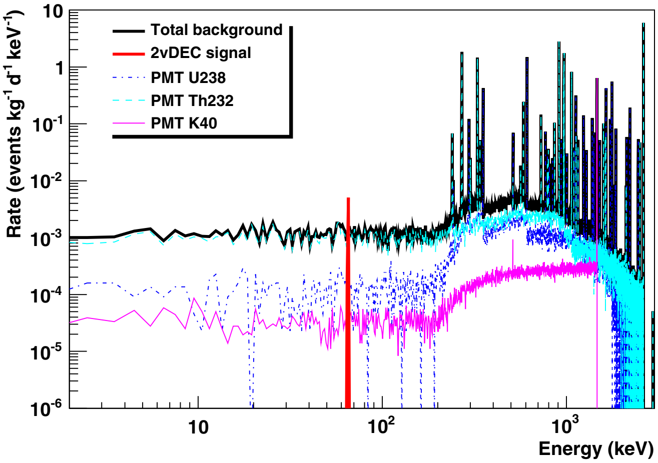

FIG. 4. (Color online) Simulated signal events for ^{124}Xe 2νDEC to the ground state of ^{124}Te in the LUX detector with a known background model.

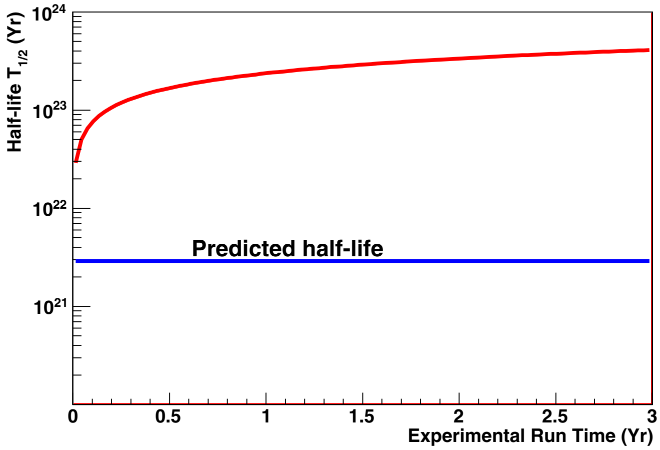

FIG. 5. (Color online) The sensitivity of the half-life limit for ^{124}Xe 2νDEC to the ground state of ^{124}Te, utilizing the LZ experiment.

significant sources of background from PMTs, Figure 4 shows the predicted results.

The proposed LUX-Zeplin (LZ) experiment will contain 7 tons of liquid xenon [38]. Although the mass of xenon in LZ is only 20 times greater than in LUX [37], the expected sensitivity of LZ will exceed that of LUX by over two orders of magnitude. The additional sensitivity, which is greater than a simple scaling of xenon mass, is due primarily to improved background suppression. This, in turn, enables a longer running time for the LZ experiment and allows a larger effective fiducial mass fraction after the projected analysis cuts. Figure 5 shows a sensitivity plot for measuring 2νDEC using the LZ detector, assuming a background rate of 1.8×10^{-4}/(kg keV day) at the region of interest.

III. CONCLUSION

We have derived the first upper limit of the two neutrino double-electron capture process for ^{124}Xe to the ground state of ^{124}Te using published XENON100 experimental data. The obtained upper limit of 1.66×10^{21} years was compared to the predicted half-life of 2.9×10^{21} years, which can be measurable from the XENON100 experiment in three more years. Utilizing the published LUX background model, we predicted approximately 115 events per year in the LUX detector, assuming a half-life of 2.9×10^{21} years. These 115 events are measurable with the LUX background model. By comparing our predicted events from the LUX detector to the more sensitive and larger LZ detector, we should be able to confidently measure this process.

ACKNOWLEDGMENTS

The authors wish to thank Christina Keller for a careful reading of this manuscript. In particular, the authors would like to thank D′Ann Barker for useful discussions and the members of the LZ collaboration for their many invaluable suggestions in preparing this paper. This work was supported in part by NSF PHY-0758120, NSF PHY-0919278, NSF PHY-1242640, DOE Grant No. DE-FG02-10ER46709, the Office of Research at the University of South Dakota, and a 2010 research center supported by the state of South Dakota.

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