Measuring Double-Electron Capture with Liquid Xenon Experiments

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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 $1.66 \times 10^{21}$ 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 $2.9 \times 10^{21}$ years. We conclude that measuring $^{124}$Xe $2\nu$ double-electron capture to the ground state of $^{124}$Te can be performed more precisely with the proposed LUX-Zeplin (LZ) experiment.

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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.

$$2e^- + (Z, A) \rightarrow (Z - 2, A) + 2\nu_e,$$

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 $^{76}$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 equation (2) would require new particle physics beyond the Standard Model.

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

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-beta 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, J.D. [7] and discussed in detail by Doi, M. and Kotani, T. [8].

However, a possible resonant 0ν-DEC 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 0ν-DEC 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 0ν-DEC with $^{124}$Xe.

![Diagram of 0ν-DEC process](image)

FIG. 1: (Color online) The schematic diagram for the $^{124}$Xe 0ν-DEC 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. $E_{\gamma}^*$ is the $\gamma$-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.

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Nonetheless, the 2νDEC process is a standard nuclear
However, within the same model framework, some con- 
quire the evaluation of nuclear matrix elements. These 
ecular recoil 
measuring the two X-rays and the half-life of the $2\nu$DEC decay ($T_{1/2,\nu}^{2\nu}$) 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 6 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 $0\nu$DEC half-life require the evaluation of nuclear matrix elements. These calculations are complicated and have large uncertainties. They are different from those required for $2\nu$DEC. However, within the same model framework, some constraints on the $0\nu$DEC NME$^{\nu\nu}$ can be derived using knowledge of the $2\nu$DEC NME$^{2\nu}$ [13] [27]. Also, the NME$^{2\nu}$, which is extracted from the measurement of the half-life of $2\nu$DEC, can be directly compared with the NME$^{2\nu}$ from predictions [7]. A good agreement would indicate that the reaction mechanisms and the nuclear structure aspects that are involved in $2\nu$DEC are well understood.

$2\nu$DEC 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 $2\nu$ emission is more difficult than $2\nu$ double beta decay, which has been observed for a variety of nuclei [21] [25] [55]. 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 $2\nu$DEC process for the first time. In this paper, we discuss the detection of $2\nu$DEC 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 $2\nu$DEC of $^{124}$Xe is:

$$^{124}\text{Xe} + 2e^- \rightarrow ^{124}\text{Te} + 2\nu_e. \quad (4)$$

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 $2\nu$DEC is $2.9\times 10^{21}$ years [11] for a ground state to ground state process.

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

$$\begin{align*}
Q_{\text{DEC}} &= M(A,Z) - M(A,Z-2), \\
Q_{\beta^+\text{EC}} &= M(A,Z) - M(A,Z-2) - 2mc^2, \\
Q_{\beta^+\beta^+} &= M(A,Z) - M(A,Z-2) - 4mc^2.
\end{align*} \quad (5)$$

However, the $2\nu$DEC rate is much faster than $2\nu\beta^+\text{EC}$ and $2\nu\beta^+\beta^+$ as discussed in Refs [10] [11].

It is worth mentioning that $^{126}$Xe has also a natural abundance of 0.09% and can only undergo a $2\nu$DEC or a $0\nu$DEC decay, $^{126}$Xe$\rightarrow ^{126}$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 $2\nu$DEC is much slower than $^{124}$Xe $2\nu$DEC decay. Therefore, we will not discuss $^{126}$Xe $2\nu$DEC 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 G. Feldman and R. Cousins [42]. For a detector with $^{124}$Xe target, the upper limit of the half-life can be derived using the following equations [43]:

$$T_{1/2}(0^+ \rightarrow \text{g.s.}) \geq \frac{ln(2) \cdot f_k \cdot c \cdot a \cdot M \cdot N_A \cdot \Delta T}{\mu_{up}}, \quad (6)$$

$$\mu_{up} \cong a \cdot \sqrt{B}, \quad (7)$$

$$B = b \cdot \Delta T \cdot \Delta E, \quad (8)$$

where $f_k$ is the fraction of $2K$ captures accompanied by the emission of two K X rays, $c$ 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 Avogadro constant, A is the atomic mass number of $^{124}$Xe, $\Delta T$ is the live time of measurements in days, $\alpha$ is a constant that equals to 1.64 at 90% confidence level (C.L.), $b$ is the background rate per unit energy, and $\Delta E$ 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 $5.3 \times 10^{-3}$ events/(kg day keV). We analyzed the XENON100 electromagnetic background data with a digitized spectrum, as shown in Figure 2 from the published background spectra (Figure 3 and Figure 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 Figure 2.

Consequently, an average background rate, $5.3 \times 10^{-3}$ 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 $\alpha$ equals 1.64 at 90% C.L. and $\sigma = 0.009+0.485/\sqrt{E}$ [45] is energy resolution, $E$ is the sum of the expected two X-rays ($2 \times 31.8$ 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 ($2 \times 31.8$ 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 mean free path of X-rays with energy of 31.8 keV is about 0.5 mm. The determined analysis parameters are summarized in Table I.

![FIG. 2: (Color online) Shown is a digitized background spectrum from the published XENON100 data [45]. The region of interest, $63.6 \pm \Delta E$ keV, is labelled.](image)

Using equations (6-8) and the values given in Table I, the half-life limit of $^{124}$Xe $2\nu$DEC to its ground state is determined to be $1.66 \times 10^{21}$ years with a 90% C.L. ($1.64 \alpha$), as shown in Figure 3.

![FIG. 3: (Color online) Above is the half-life limit of the $^{124}$Xe $2\nu$DEC process to the ground state of $^{124}$Te.](image)

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 $2.9 \times 10^{21}$ 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

![TABLE II: Radioactivity level of the LUX 8778 PMT [37]. Units are in mBq/PMT.](table)

Monte Carlo simulation was performed to predict the signal events from $^{124}$Xe DEC process together with several significant sources of background from PMTs, Figure 4 shows the predicted results.

The proposed LUX-Zeplin (LZ) experiment will con-
tain 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 4 shows a sensitivity plot for measuring 2νDEC using the LZ detector, assuming a background rate of $1.8 \times 10^{-4}$/kg keV day) at the region of interest.

FIG. 5: (Color online) The sensitivity of the half-life limit for $^{124}\text{Xe}$ 2νDEC to the ground state of $^{124}\text{Te}$ using published XENON100 experimental data. The obtained upper limit of $1.66 \times 10^{21}$ years was compared to the predicted half-life of $2.9 \times 10^{21}$ years, which can be measured 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 $2.9 \times 10^{21}$ 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.

III. CONCLUSION

We have derived the first upper limit of the two neutrino double-electron capture process for $^{124}\text{Xe}$ to the ground state of $^{124}\text{Te}$ using published XENON100 experimental data. The obtained upper limit of $1.66 \times 10^{21}$ years was compared to the predicted half-life of $2.9 \times 10^{21}$ years, which can be measured 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 $2.9 \times 10^{21}$ 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.

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