Charged current neutrino cross section for solar neutrinos, and background to $\beta\beta(0\nu)$ experiments

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Solar neutrinos can interact with the source isotope in neutrinoless double-β-decay experiments through charged-current and neutral-current interactions. The charged-current product nucleus will then β decay with a Q value larger than the double-β-decay Q value. As a result, this process can populate the region of interest and be a background to the double-β-decay signal. We estimate the solar neutrino capture rates on three commonly used double-β-decay isotopes, ^{76}Ge, ^{130}Te, and ^{136}Xe. We then use the decay scheme of each product nucleus to estimate the possible background rates in those materials. As half-life sensitivities in future experiments approach 1×10^{28} yr, this background will have to be considered although its rate will depend on detector design in addition to nuclear structure.

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I. INTRODUCTION

Neutrinoless double-β-decay [$\beta\beta(0\nu)$] experiments provide a unique opportunity to search for the Majorana neutrino masses, the lepton sector charge conjugation parity symmetry (CP) phases, and other physics quantities beyond the electroweak standard model. The scientific motivation for $\beta\beta(0\nu)$ has been well discussed in the literature. In addition, many reviews summarize the present status and plans for the future experimental program. References [1–10] provide a comprehensive overview of $\beta\beta(0\nu)$.

Experiments searching for $\beta\beta(0\nu)$ are reaching ever greater sensitivity. This improvement in sensitivity arises from both an increase in the mass of the source isotope and a decrease in background. The next generation of experiments aims to cover the inverted hierarchy region of the Majorana neutrino mass (15–50 meV). To meet this goal requires that experiments be capable of measuring half-lives greater than 1×10^{27} yr and have backgrounds better than 1 count/(ton yr) in the region of interest (ROI) about the $\beta\beta$ Q value. Such an experiment would require 1–10 tons of isotope. In a future generation of experiments that may try to reach the normal mass hierarchy region (<5 meV), a sensitivity greater than $\sim 1 \times 10^{29}$ yr will be required. Depending on the $\beta\beta(0\nu)$ nuclear matrix elements and the weak coupling constants, the size of these experiments may be an order of magnitude or more larger. Experiments at this scale will have to consider background due to solar-ν charge-current (CC) interactions with the $\beta\beta$ isotope. Background due to neutral-current (NC) interactions are much less than those due to CC interactions, as discussed later.

In Ref. [2] the possibility of solar-ν CC interactions giving rise to background for $\beta\beta(0\nu)$ experiments was discussed. In particular the case of ^{136}Xe was of interest because such background could not be eliminated by the detection of the ^{136}Ba daughter. However, at the time of that publication, the level structure and transition strengths for ^{136}Cs were not well-enough known to estimate the size of this background. With the recent measurements of the pertinent nuclear physics input (see Refs. [10,11] for a review), an estimate can now be made. In this article, we calculate the rate for this important isotope and others of frequent use in $\beta\beta(0\nu)$ experiments. Specifically we discuss this CC capture background for ^{76}Ge, ^{130}Te, and ^{136}Xe and discuss possible background rates in general at the $\beta\beta(0\nu)$ ROI. The important case of ^{100}Mo is considered in detail elsewhere [12] and so we do not include it here. It should be mentioned, however, that the solar-ν capture rate is high enough for this isotope that it is also considered for use as a detector for that purpose. The $\beta\beta$ isotopes ^{116}Cd [13] and ^{150}Nd [14] have been considered as targets for solar neutrino detection. Reference [13] also estimates the ^{7}Be solar-ν capture rate for ^{130}Te and finds a larger value than reported here. The possibility of the elastic scattering of solar neutrinos with electrons in the detector material was considered previously [2,15].

The present article aims at reporting solar neutrino capture rates on the current $\beta\beta$ isotopes and possible background rates to help design future multiton-scale experiments with sensitivities of an order of 1×10^{28}–1×10^{29} yr. We show that the actual background rates do depend on the detector energy resolution and configuration as well as the nuclear structure, and then we discuss how they can be reduced by various techniques. We then present estimated background rates depending on the energy resolution, but we do not consider experimental techniques beyond energy resolution that may reduce this background further because it is not practical to simulate all possible future experimental configurations. We discuss such techniques below and emphasize that they may have a significant impact on the residual background faced by future experiments. We anticipate that experimentalists will use our solar neutrino rate estimates as part of the simulations used to better understand a detector's response and the resulting mitigation of these backgrounds. However, as experiments extend their sensitivity beyond 1×10^{28} yr, mitigation strategies for these backgrounds will be required.

II. $\beta\beta(0\nu)$ AND BACKGROUND FROM SOLAR-ν CHARGED-CURRENT INTERACTIONS

Figure 1 depicts the various processes under consideration in this article. The $\beta\beta(0\nu)$ of ^{Z-1}A to ^{Z+1}A shows a peak

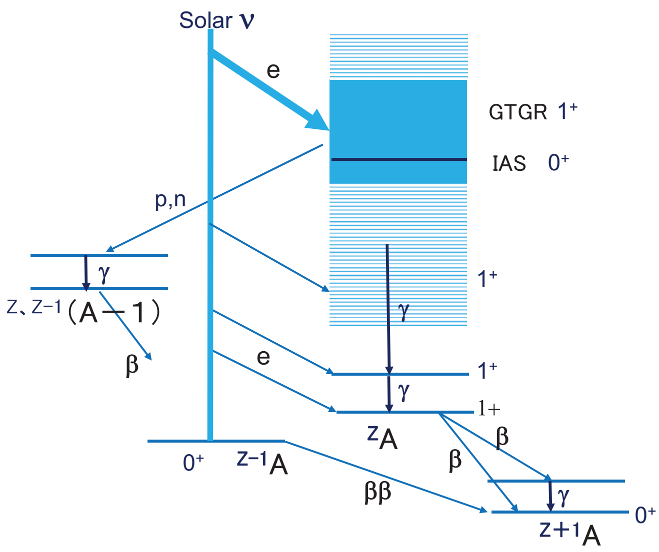

FIG. 1. (Color online) A generic energy level diagram showing the double-β decay of an isotope ${}^{Z-1}A$ to isotope ${}^{Z+1}A$ with the indicated solar neutrino capture on isotope ${}^{Z-1}A$ producing isotope ${}^{Z}A$. The resulting γ decay of the excited states in ${}^{Z}A$ followed by the β decay to isotope ${}^{Z+1}A$ is indicated. The possible particle decays of the excited states in ${}^{Z,Z-1}A$ are also shown.

at the decay Q value in the $\beta\beta$ energy sum spectrum. The intermediate states in ${}^{Z}A$ are necessarily higher in energy than the initial state ${}^{Z-1}A$ in most $\beta\beta$ nuclei, and therefore the successive single-β decays of ${}^{Z-1}A$ to ${}^{Z}A$ to ${}^{Z+1}A$ are energetically forbidden. The solar-ν CC interaction with the initial nucleus ${}^{Z-1}A$ excites Gamow-Teller (GT) 1^+ states and the isobaric analog state (IAS) 0^+ in the intermediate nucleus ${}^{Z}A$, while emitting an electron (e^-). If the product nucleus is in an excited state below the particle separation threshold, it will decay to the ground state of ${}^{Z}A$, emitting some number of γ rays. This is followed by the β decay of ${}^{Z}A$ to ${}^{Z+1}A$. In many cases this β decay is to excited states and γ rays are emitted also. Alternatively, if the product nucleus is produced in an excited state above the particle separation threshold, it will decay by emitting a proton or neutron to a neighboring nucleus indicated by ${}^{Z-1}(A-1)$ or ${}^{Z}(A-1)$, as shown in the figure.

The production rate and energy of the particles produced by solar ν reactions may be comparable to those of the sought $\beta\beta(0\nu)$ signal. Accordingly these processes may contribute as a background within the $\beta\beta(0\nu)$ ROI.

Charge exchange reaction (CER) experiments on $\beta\beta$ nuclei were carried out at the Research Center for Nuclear Physics, Osaka, to study GT 1^+ states involved in $\beta\beta$ matrix elements [12,16–22]. In fact, it was shown that the solar ν signal could be well measured by a ^{100}Mo $\beta\beta$ experiment on the basis of the observed GT strengths for the solar-ν CC interaction [12]. In general, there are several 1^+ states in the low excitation region and one 0^+ IAS and one broad GT 1^+ giant resonance (GR) in the high excitation region in the intermediate nucleus. It is these states that are excited by solar-ν CC interactions with $\beta\beta$ nuclei.

The half-lives of ${}^{Z}A$ for the cases considered here are long enough that the ν capture and the β-decay events are separated in time. Therefore, we consider three separate processes that may lead to background.

(1) *The solar-ν CC capture* will produce ${}^{Z}A$ in either its ground state or one of a number of excited states. This capture produces an e^- and, if the nucleus is in an excited state below the particle emission threshold, a number of γ rays as it relaxes to its ground state. The sum of the e^- and γ-ray energies will produce a spectrum that surpasses the $\beta\beta(0\nu)$ Q value and therefore is a potential background.

(2) *The capture to states above the particle emission threshold* may result in the emission of a p or n plus additional radiations from the resultant nucleus. The broad GT 1^+ GR and the 0^+ IAS are strongly excited by ^{8}B solar-ν CC interaction. The upper part of the GT GR and the IAS are above the particle threshold energy and decay because they emit a neutron or proton to low-lying states in a neighboring nucleus [indicated by ${}^{Z}(A-1)$ and ${}^{Z-1}(A-1)$ in Fig. 1]. These low-lying excited states decay by emitting γ rays to the respective ground state, which decays by emitting a β ray if it is β unstable. The sum of the e^-, p/n, and γ rays, also produces a spectrum that may populate the $\beta\beta(0\nu)$ ROI.

(3) *The β decay of ${}^{Z}A$* will emit a β ray and some number of γ rays as it decays to the excited state of ${}^{Z+1}A$. The Q value of this decay is greater than the $\beta\beta(0\nu)$ Q value and therefore it may also populate the $\beta\beta(0\nu)$ ROI.

All three of these processes have continuum spectra extending beyond the $\beta\beta(0\nu)$ ROI. Consequently, they may contribute to the background at the ROI in future $\beta\beta$ experiments with a large mass of isotope. There are also time and spatial relationships between these processes. Hence, the contributions depend not only on the nuclear structure of the isotopes, but also on the experimental design. Here we summarize some key points to be considered in designing future experiments.

(a) Low-lying 1^+ states located well below the pp or ^{7}Be ν spectral end point values of 420 and 860 keV are strongly excited by those neutrinos.

(b) The broad GT 1^+ GR and the 0^+ IAS are strongly excited by ^{8}B-ν CC interactions. The strengths are around $B(GT) \sim 1.5(N-Z)$ and $B(F) \sim (N-Z)$ with N and Z being the neutron and proton numbers of the $\beta\beta$ nucleus. The lower part of the GR, which is below the particle emission threshold energy, decays by emitting γ rays to the ground state of ${}^{Z}A$, which in turn decays by emitting β and γ rays to the ground state of ${}^{Z+1}A$.

(c) Since the e^--γ, e^--p/n-γ, and β-γ sum energy spectra are continua, their contributions to the $\beta\beta(0\nu)$ ROI are proportional to the energy width of the ROI, that is, to the experimental energy resolution.

(d) In ^{100}Mo and ^{116}Cd nuclei, the intermediate 1^+ ground state in ${}^{Z}A$ is strongly excited by pp and/or ^{7}Be neutrinos. This state decays predominantly to the ground state of the final nucleus ${}^{Z+1}A$. Since the e^- and

β rays are not followed by γ rays, an analysis rejecting events with multiple-site energy (MSE) deposits is not possible. If the initial capture e^- and subsequent β decay can be correlated, the events may be rejected [4].

(e) In other $\beta\beta$ nuclei, low-lying 1^+ excited states in the intermediate nucleus ^{Z}A are excited by the solar-ν CC interaction. The ground state in ^{Z}A decays to the excited state in the final nucleus ^{Z+1}A. Consequently, e^- and β decays are followed by γ rays from the excited states in ^{Z}A and ^{Z+1}A, respectively. These γ rays can be used to reduce the possible background by a MSE deposit analysis [4].

(f) The e^--γ rays produced in the initial interaction producing ^{Z}A and the β-γ rays in the final nucleus ^{Z+1}A are separated in time by the half-life ($\tau_{1/2}$) of ^{Z}A. Therefore, they can be correlated effectively by a single site time correlation (SSTC) analysis [4]. In this way they can be rejected as background. To avoid reduction of the $\beta\beta(0\nu)$ signal efficiency due to accidental coincidences, $\tau_{1/2}$ must be much shorter than the average background interval of $1/R_b$. Here R_b is the rate of the total background above the detector threshold per volume cell (V_c) of the $\beta\beta$ detector, and the cell volume is defined in terms of the position resolution of the experiment. In the case of a typical high-purity $\beta\beta$ detector with background rates below 10 mBq/ton, a V_c of 125 mm^3, and a density of 4 g/cm^3, one finds a maximum possible half-life of $\tau_{1/2} \ll$ 0.8 yr. Hence, SSTC can be applied for most high-radiopurity $\beta\beta$ detectors with a small V_c.

(g) The e^- and β rays associated with the solar-ν CC interaction are lone particles from a single point in space but from different points in time, whereas $\beta\beta(0\nu)$ events are two β rays from one point in both space and time. Thus, measurements of the two β tracks are very powerful for selecting the $\beta\beta(0\nu)$ signal and rejecting these solar ν single β rays.

III. SOLAR NEUTRINO CAPTURE RATES

The prescription for calculating the cross section is summarized in Ref. [11] and we only summarize it here. The cross section (σ_k) for a neutrino (ν) interacting with a target nucleus (^{Z-1}A) to produce the kth excited state in a final nucleus ($^{Z}A_k$),

$$\nu + ^{Z-1}A \rightarrow e^- + ^{Z}A_k, \tag{1}$$

is given by the expression

$$\begin{aligned}\sigma_k &= \frac{G_F^2 \cos^2\theta_c}{\pi} p_e E_e F(Z,E_e)\left[B(F)_k + \left(\frac{g_A}{g_V}\right)^2 B(GT)_k\right] \\ &= (1.597\times 10^{-44}\ \text{cm}^2) p_e E_e F(Z,E_e) \\ &\quad \times\left[B(F)_k + \left(\frac{g_A}{g_V}\right)^2 B(GT)_k\right],\end{aligned} \tag{2}$$

where G_F is the weak coupling constant, θ_c is the Cabibo angle, p_e (E_e) is the outgoing electron momentum (total energy), $F(Z,E_e)$ is the Fermi function, and $B(F)_k$ [$B(GT)_k$] is the Fermi (Gamow-Teller) response. The constant is applicable for energies and momenta in MeV. Z (A) is the atomic number (mass number) of the product. The ratio of the axial vector (g_A) and vector (g_V) coupling constants is taken to be 1.267 [23]. We used the tabulated values of $F(Z,E_e)$ from Ref. [24]. The $B(GT)$ values for the states k are derived from the recent series of charge exchange measurements. The $B(F)$ values are taken to be 0, except for the IAS, where it is taken to be $(N-Z)$.

TABLE I. The reaction rates in SNU for the various sources of solar neutrinos.

Isotope	pp	pep	^{7}Be	^{8}B	^{13}N	^{15}O	Total
^{76}Ge	0	1.4	0	13.4	0.1	0.8	15.6
^{100}Mo	695	16	234	16	12	16	989
^{130}Te	0	5.9	43.2	15.9	2.4	4.6	71.9
^{136}Xe	0	11.7	94.8	25.8	4.3	9.1	145.6

The solar neutrino reaction rate is then determined by integrating the product of the solar neutrino flux and the cross section given by Eq. (2) and finally summing over the product nucleus states. Hence, the rate (R) is given by

$$R = \sum_k \int \sigma_k \frac{d\phi_\nu}{dE_\nu} dE_\nu, \tag{3}$$

where $\frac{d\phi_\nu}{dE_\nu}$ is the neutrino flux as a function of neutrino energy (E_ν). We use fluxes from BP05(OP) [25] and express R in units of SNU (1×10^{-36} interactions per target atom per second).

For the isotopes of interest in this article, the rates are summarized in Table I. We used the charge-exchange-measurement data for ^{76}Ge [16], ^{100}Mo [17], ^{130}Te [20], and ^{136}Xe [22] to obtain the $B(GT)_k$ and $B(F)$ for the IAS for the indicated isotopes. We estimate the uncertainty in our calculations to be less than 10%, except for that due to the solar ^{8}B neutrinos, which agrees to about 10–20 %. Given the uncertainties in the $B(GT)$ values, which increase with excited-state energy, this precision suffices.

The oscillation of solar neutrinos will reduce the CC interaction rate. We approximated that effect by imposing an energy-dependent survival probability (P_{ee}) for electron neutrinos exiting the sun. We parametrized that probability with the following approximate functional form:

$$P_{ee} = 0.336 + 0.117 e^{\frac{-E_\nu - 0.1}{4.82}} + 0.119 e^{\frac{-E_\nu - 0.1}{4.88}}. \tag{4}$$

To compare the solar-ν CC reaction event rate to that of $\beta\beta(0\nu)$, Eq. (5), taken from Ref. [25], provides a quick reference. The rate ($R_{\beta\beta}$) of $\beta\beta(0\nu)$ events can be written, assuming 100% for the signal selection efficiency,

$$R_{\beta\beta} = \frac{1}{M}\frac{dN}{dt} = \frac{\lambda N}{M} \approx \frac{420}{W}\left(\frac{10^{27}}{T_{1/2}^{0\nu}}\right)/(\text{ton yr}), \tag{5}$$

where the constant is calculated for the molecular weight (W) in grams of molecule containing the $\beta\beta$ isotope, the $\beta\beta(0\nu)$ half-life ($T_{1/2}^{0\nu}$) in years, and the mass (M) of the $\beta\beta(0\nu)$ material in tons.

IV. THE INITIAL SOLAR-ν CAPTURE

The initial solar-ν CC capture emits an electron e^- that will have a continuum of energy up to the ^{8}B end point minus the Q value for the interaction. The other solar neutrino energies are too low to produce background in the ROI. Here we give a rough estimate of this background so that its impact can be compared to that of the decay of ^ZA.

For ^{76}Ge, most of the capture is due to the ^{8}B neutrinos. The energy sum of the e^- and γ rays are a continuum spectrum extending up to around 14 MeV. The energy sum spectrum for the β-γ rays from the decay of ^ZA extends up to $Q_\beta \approx 3$ MeV. Taking into account the reaction Q value, the fraction of the ^{8}B spectrum that falls within the ΔE window of 4 keV at the ^{76}Ge $\beta\beta$ end point is about 3×10^{-4}. The fraction of the β-γ spectrum from the decay of ^ZA that falls in this window is 2×10^{-3} (see Sec. VI A). Hence, the ratio is about 15%, indicating that the initial ν CC capture contributes only a fraction to the background. This estimate is for ^{8}B ν and the case of ^{76}Ge. The ratio is much smaller in other $\beta\beta$ nuclei since other ν sources are major contributors (see Sec. VI).

V. SOLAR-ν CC CAPTURE TO STATES ABOVE THE PARTICLE SEPARATION ENERGY

Only the highest energy ^{8}B neutrinos can populate those states in ^ZA that are beyond the particle separation threshold. That contribution to the CC interaction rate is a fraction of the total ^{8}B ν capture rate. Table II gives the capture rates for states below the particle separation energy. If we include that contribution, the ^{8}B CC rate would increase by 0.9 SNU for ^{76}Ge, and 5.4 SNU for ^{100}Mo as the IAS is in the middle of the ^{8}B spectrum. In contrast, it results in small changes for ^{130}Te and ^{136}Xe because the IAS is near the ^{8}B end point. The process will produce a set of particles including e^- and γ rays, along with protons or neutrons. The total energy emitted will again be a continuum up to the ^{8}B end point. Hence, this rate will be a subset of the contribution from the initial solar-ν CC capture rate and is also small compared to the β decay of ^ZA. Note that the residual nuclei of $^{Z,Z-1}(A-1)$ in the present cases of ^{76}Ge, ^{130}Te, and ^{136}Xe are a stable nucleus and unstable nuclei with $Q_\beta < Q_{\beta\beta}$. Thus, they do not contribute to the ROI.

VI. THE β DECAY OF ^ZA

Of the background processes considered in this article, this is the most significant and we focus on it for each isotope of interest.

TABLE II. Same as Table I but for oscillated solar neutrino fluxes.

Isotope	pp	pep	^{7}Be	^{8}B	^{13}N	^{15}O	Total
^{76}Ge	0	0.7	0	5.0	0.06	0.4	6.2
^{100}Mo	390	8.2	126	6.0	6.7	8.3	545
^{130}Te	0	3.0	23.2	6.1	1.3	2.4	35.9
^{136}Xe	0	6.0	50.9	9.8	2.3	4.7	73.4

A. Germanium-76

A solar neutrino that interacts with ^{76}Ge through a CC interaction can produce excited states of ^{76}As. Our estimate of this rate is ∼6.2 SNU. Any produced excited state transitions to the ^{76}As ground state, which decays with a 1.08-d half-life by β decay to the ground and excited states in ^{76}Se. The long half-life of ^{76}As complicates the use of the solar neutrino event as a tag to remove the As decays on an event-by-event basis but a SSTC might be effective in Ge detectors with a background level less than 100 mBq/ton and cell volume $V_c = 3$ cm^3.

Typical Ge $\beta\beta(0\nu)$ experiments have energy resolution near 0.2% full width at half maximum (FWHM) or ∼4 keV. The Q value for the β transition is 2962 keV and when the sum energy of the β and γ rays falls between 2037 and 2041 keV, it will be a $\beta\beta(0\nu)$ background. We estimated the fraction of decays that will populate this region by considering the three β decay transitions with the largest branching ratios. These three include the 51% branch to the ground state, the 35.2% branch to the 559-keV level, and the 7.5% branch to the 1216-keV level. Hence, we considered 93.7% of the total β decay strength and ignored the large number of small branching ratio transitions. This approximation does not significantly alter our result.

For the β spectrum we used the approximate functional form

$$\frac{dN}{dE} \sim (E_0 - E_e)^2 E_e p_e F(Z,E_e), \quad (6)$$

where E_0 is the β end point energy. The calculation indicates that about 0.2% of the decays will populate the ROI for a resolution of 0.2% FWHM. Figure 2 shows the energy deposited from the β and γ emissions assuming all the γ energy is deposited within the detector. The spectrum was convolved with a resolution function corresponding to 2% FWHM. For a resolution of 0.5% FWHM, the fraction within the ROI is 0.5%, and for 2% FWHM it is 1.9%.

For Ge enriched to 100% in ^{76}Ge, Eq. (5) predicts about 5.5 $\beta\beta(0\nu)$ events per year per ton for $T^{0\nu}_{1/2} = 10^{27}$ yr. There are

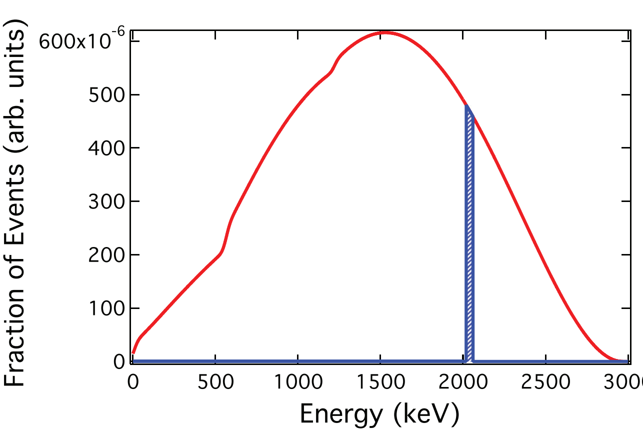

FIG. 2. (Color online) The approximate β-γ-ray energy spectrum from the decay of ^{76}As. The shaded region shows the part of the spectrum that will populate the ROI for a resolution of 2% FWHM.

7.9×10^{27} atoms/ton in ^{76}Ge, therefore we expect about 1.5 solar neutrino events/(ton yr) for the 6.2-SNU rate calculated for Ge. Approximately 0.2% of these, or 0.003 events, will be in the ROI. Different experiments will have different efficiencies for selecting the $\beta\beta(0\nu)$ signal events and for rejecting MSE-deposit $\beta + \gamma$ events and therefore removing this background. With no such MSE rejection, the sensitivity floor of a Ge experiment would be about $T_{1/2}^{0\nu} = 1.8 \times 10^{30}$ yr.

B. Tellurium-130

A solar neutrino that interacts with ^{130}Te through a CC interaction can produce excited states of ^{130}I. Our estimate of this rate is ~36 SNU. Any produced excited state transitions to the ^{130}I ground state, which decays with a 12.36-h half-life by β decay to excited states in ^{130}Xe. The long half-life of ^{130}I complicates the use of the solar neutrino event as a tag to remove the I decays on an event-by-event basis, but a SSTC analysis might be effective in an ultrapure Te detector with radioactive impurities less than 2 mBq/ton within a detector cell around 1 kg.

Because the β decay is to a highly excited state that decays quickly emitting accompanying γ rays, the fraction of the decays that populate an energy region near the end point for the $\beta\beta(0\nu)$ decay of ^{130}I is relatively large. The various Te $\beta\beta(0\nu)$ experiments have widely varying energy resolutions. The Q value for the β transition is 2949 keV, whereas the $\beta\beta(0\nu)$ Q value is 2528 keV. We estimated the fraction of decays that will populate this region by considering the two β-decay transitions with the largest branching ratios. These two include the 48% branch to the 1944-keV level, and the 46.7% branch to the 2362-keV level. Hence, we considered 94.7% of the total β-decay strength.

The β-spectrum calculation indicates that about 9.8% of the decays will populate the ROI for a resolution of 2% FWHM. Figure 3 shows the energy deposited from the β and γ emissions. The spectrum was convolved with a resolution function corresponding to 2% FWHM. For a resolution of 0.5% FWHM, the fraction within the ROI drops to 2.5%, and for 0.2% FWHM it is 1%.

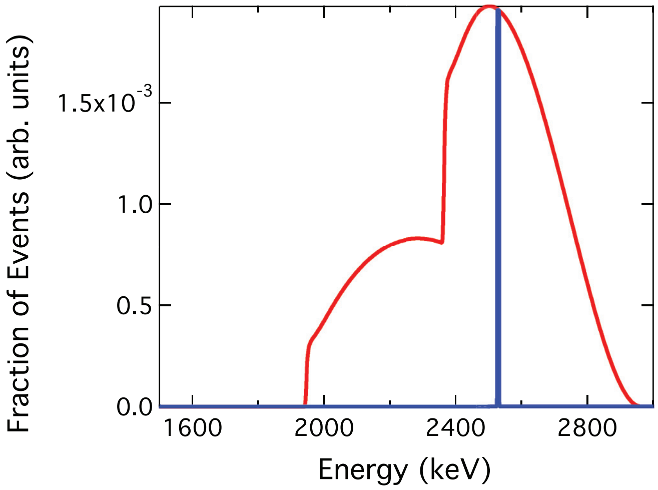

FIG. 3. (Color online) The approximate β-γ-ray energy spectrum from the decay of ^{130}I. The shaded region shows the part of the spectrum that will populate the ROI for a resolution of 2% FWHM.

For pure ^{130}Te, Eq. (5) predicts about 3.2 $\beta\beta(0\nu)$ events per year per ton for $T_{1/2}^{0\nu} = 1 \times 10^{27}$ yr. There are 4.6×10^{27} atoms/ton in ^{130}Te; therefore, we expect about 5.2 solar neutrino events/(ton yr) for the 36-SNU rate calculated for Te. Approximately 9.8% (1%), or 0.51 (0.05) events for a resolution of 2% (0.2%), of these will be in the ROI. Different experiments will have different efficiencies for rejecting MSE-deposit $\beta + \gamma$ events and therefore for removing this background. With no such MSE rejection, the sensitivity floor of a Te experiment would be about $T_{1/2}^{0\nu} = 6.3 \times 10^{27}$ yr (6.3×10^{28} yr) for the 2% (0.2%) resolution.

C. Xenon-136

A solar neutrino that interacts with ^{136}Xe through a CC interaction can produce excited states of ^{136}Cs. Our estimate of this rate is ~74 SNU. Any produced excited state transitions to the ^{136}Cs ground state, which decays with a 13.16-d half-life by β decay to excited states in ^{136}Ba. The long half-life of ^{136}Cs prevents the use of the solar neutrino event as a tag to remove the Cs decays on an event-by-event basis, but it might permit the implementation of a purification step to remove Cs from the Xe. A SSTC analysis might be effective in liquid Xe detectors with a background level less than 10 mBq/ton and $V_c = 3$ cm^3. One must consider, however, whether the Cs ion will remain localized for the required time scales within a gaseous or liquid detector medium. As discussed in Sec. II, identification of $\beta\beta$ tracks and also MSE analyses are quite effective to reject these solar-ν backgrounds.

Because the β decay is to a highly excited state that decays quickly emitting accompanying γ rays, the fraction of the decays that populate an energy region near the end point for the $\beta\beta(0\nu)$ decay of ^{136}Xe is relatively large. Future possible Xe $\beta\beta(0\nu)$ experiments may have an energy resolution near 2% FWHM or ~50 keV. The Q value for the β transition is 2548 keV and the Q value for $\beta\beta(0\nu)$ is 2458 keV. We estimated the fraction of decays that will populate the ROI by considering the four β-decay transitions with the largest branching ratios. These four include the 70.3% branch to the 2207-keV level, the 13% branch to the 1867-keV level, the 10.5% branch to the 2140-keV level, and the 4.7% branch to the 2053-keV level. Hence, we considered 98.5% of the total β-decay strength.

The β-spectrum calculation indicates that about 5.7% of the decays will populate the ROI for a resolution of 2% FWHM. Figure 4 shows the energy deposited from the β and γ emissions. The spectrum was convolved with a resolution function corresponding to 2% FWHM. For a resolution of 0.5% FWHM, the fraction within the ROI drops to 1.4%, and for 0.2% FWHM it is 0.5%.

For pure ^{136}Xe, Eq. (5) predicts about 3.1 $\beta\beta(0\nu)$ events per year per ton for $T_{1/2}^{0\nu} = 1 \times 10^{27}$ yr. There are 4.4×10^{27} atoms/ton in ^{136}Xe; therefore, we expect about 10.3 solar neutrino events/(ton yr) for the 74-SNU rate calculated for Xe. Approximately 5.7%, or 0.59 events, of these will be in the ROI. With no MSE rejection, the sensitivity floor of a Xe

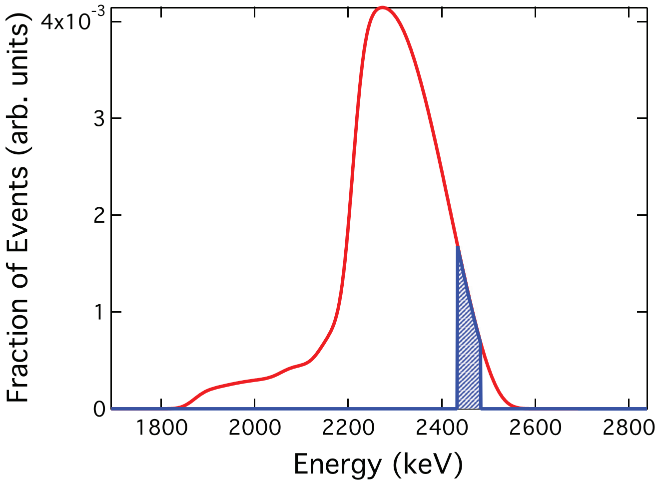

FIG. 4. (Color online) The approximate β-γ-ray energy spectrum from the decay of ^{136}Cs. The shaded region shows the part of the spectrum that will populate the ROI for a resolution of 2% FWHM.

experiment would be about $T_{1/2}^{0\nu} = 5.3 \times 10^{27}$ yr. It is very important to notice that this background produces a ^{136}Ba ion and hence will not be rejected by Ba tagging [26].

VII. DISCUSSION

Here we considered solar-ν CC interactions and the subsequent β-γ decays that might contribute to background within the $\beta\beta(0\nu)$ ROI. We neglected the smaller background contributions from electrons (inverse β rays) associated with solar-ν CC interactions, the solar-ν CC interactions that excite the product nucleus above proton- or neutron-emission threshold, and solar-ν NC interactions. Such interactions could add an additional 15% or more to the total solar-ν capture rate, depending on the nucleus. We did not consider in detail the various possible proton- or neutron-emission decay channels and how they might produce $\beta\beta(0\nu)$ background. We did not consider NC interactions because their contribution to the ROI is at most 15% of the major β-γ background contribution. This article focused on the solar-ν CC interactions with $\beta\beta$ isotopes in detectors, but not on interactions with other nuclei. They may not be ignored in detectors where the $\beta\beta$ isotopes are only a fraction of the active detector medium.

We estimated the solar-ν CC capture rate on ^{76}Ge, ^{130}Te, and ^{136}Xe using recently measured Gamow-Teller strengths in charge exchange reactions. We then used those production rates and the known decay schemes of the product nuclei to estimate the potential for background in double-β-decay experiments using these isotopes. In the cases of Te and Xe, the product nucleus decays to highly excited states resulting in a sizable fraction of the decays depositing energy in the region of interest for double-β-decay. These decays, however, will produce MSE deposits by coincident interaction of β and γ rays, which suggests that position resolution would be effective at reducing this background by MSE analyses. Tracking detectors are also effective at reducing single β-e^- and β-γ backgrounds. We also note that these background

TABLE III. The background rates in the ROI as a function of resolution given in % FWHM. These are the raw rates based only on energy-resolution considerations and make no allowance for detector capability to reject events based on time and space correlations, which may result in a significant decrease in the residual background.

	Background rate [events/(ton yr)]	
Isotope	2%	0.2%
^{76}Ge	0.03	0.003
^{130}Te	0.51	0.05
^{136}Xe	0.59	0.06

β-γ rays from ^{Z}A are correlated in time with the electron and γ rays from the excited states in ^{Z}A, and thus they may be reduced by SSTC analyses in case of high purity detectors with good position resolution. Regardless, as experimental half-life sensitivities begin to surpass 5×10^{27} yr, this background will need to be considered. The background rates within the ROI are approximately proportional to the energy resolution. Table III summarizes the results. The energy resolution is indeed very important to reduce background from the solar-ν CC interactions as well as those from the $\beta\beta(2\nu)$. It is noted, however, that the solar-ν event rate at the ROI may be reduced much by appropriate spatial and time correlation analyses even though one may not avoid the solar-ν CC interactions with energy resolution as one might for $\beta\beta(2\nu)$.

In short, the solar-ν CC interaction rates are of the same order as anticipated $\beta\beta(0\nu)$ rates in the future $\beta\beta(0\nu)$ experiments searching for an effective Majorana neutrino mass in the inverted to normal hierarchy region (<50 meV). The present analysis addresses only the detector (half-life) sensitivity (the mass sensitivity depends on the phase-space factor and the matrix element as well). The background event rate due to solar-ν CC interactions depends strongly on the $B(GT)$ strengths of the low-lying states in the intermediate nuclei as well as the signal selection analysis techniques based on the topology of the event in energy, time, and position. We did not try to incorporate a rejection factor due to this final point in our analysis as it is not possible to simulate future experiments. We note that such rejection factors can be large and may significantly reduce these backgrounds. Our analysis does indicate that such rejection techniques may be required for future experiments sensitive to half-lives greater than 1×10^{28} yr.

We note the similar situation occurs also for multiton-scale dark matter experiments to search for weakly interacting massive particles in the 1×10^{-10}–1×10^{-11} pb region [27].

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