

## Research Article

# Nuclear and Detector Sensitivities for Neutrinoless Double Beta-Decay Experiments

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Neutrinoless double beta-decay (DBD) is of current interest in high-sensitivity frontiers of particle physics. The decay is very sensitive to Majorana neutrino masses, neutrino CP phases, right-handed weak interactions, and others, which are beyond the standard electroweak model. DBDs are actually ultrarare events, and thus, DBD experiments with ultrahigh sensitivity are required. Critical discussions are presented on nuclear and detector sensitivities for high-sensitivity DBD experiments to study the neutrino masses in the normal and inverted mass hierarchies.

## 1. Introduction

Neutrinoless double beta-decay (DBD) is of current interest in sensitivity frontiers of particle physics. The decay violates the lepton number conservation law, and thus, DBD is beyond the standard electroweak model. DBD is very sensitive to the Majorana nature (neutrino=antineutrino) of neutrino, the absolute neutrino mass scale and the neutrino mass hierarchy, the neutrino CP phases, the possible right-handed weak interactions, and others, which are beyond the standard model. Accordingly, it has been used to study these fundamental questions on the neutrino and the weak interaction for decades. Recent experimental and theoretical DBD works are discussed in the review articles and references therein [1–5].

In fact, neutrinoless DBDs are due to various modes such as the light neutrino mass mode, the right-handed weak current mode, and the SUSY particle exchange mode, which are all beyond the standard model [1, 4]. In the present work, we discuss mainly the neutrinoless DBD due to the light neutrino mass mode, which is of current interest.

DBD, however, is a very low-energy and ultrarare decay. The energy is of the order of  $E_{\beta\beta} \approx 10^{-3}$  GeV, and the decay rate is in the range of  $T_r^{0\nu} \approx 10^{-27}$ – $10^{-30}$  per year (y), depending on the neutrino mass and the nuclear matrix element

(NME). The neutrino mass to be studied is around  $m = 3$  meV and 30 meV in cases of the normal mass hierarchy (NH) and the inverted mass hierarchy, respectively. Then, low-background high-sensitivity DBD detectors are required to search for such low-energy and ultrarare DBD signals [1, 4].

Many experimental groups are working hard for high-sensitivity DBD experiments to search for the small Majorana neutrino mass and others beyond the standard model. Current lower limits on the DBD half-lives are of the order of  $10^{26}$  y for both  $^{76}\text{Ge}$  and  $^{136}\text{Xe}$ . The neutrino mass limits are, respectively, 600 meV/ $M(76)$  and 230 meV/ $M(136)$  with  $M(76)$  and  $M(136)$  being the nuclear matrix elements (NMEs) for  $^{76}\text{Ge}$  and  $^{136}\text{Xe}$ , respectively. So, they are in the range of 300–100 meV if NMEs are around 2 (see Section 4 for discussions on DBD experiments). Then, one needs to improve the sensitivity by factors 5 and 50 to access the IH and NH mass regions, respectively. In fact, the DBD sensitivity to the neutrino mass depends much on NME.

DBD with a light neutrino mass mode is considered a neutrino exchange process, where a light Majorana neutrino is exchanged between two neutrons in the DBD nucleus. Here, the nucleus acts as a high-luminosity microcollider of two neutrons, as shown in Figure 1. The neutrino exchange cross-section for the IH neutrino is as small as  $\sigma \approx 10^{-83}$  cm<sup>2</sup> because of the second-order weak process and the small

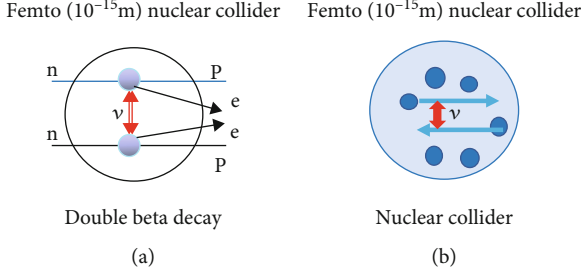


FIGURE 1: Schematic views of neutrinoless double  $\beta$ -decay with Majorana neutrino exchange (a) and nuclear collider (b).

neutrino mass [4, 6, 7]. The luminosity of one nucleus is as high as  $L \approx 10^{48} \text{ cm}^{-2} \text{ s}^{-1}$  because of the very small (a few fm) distance between the two neutrons in the nucleus. The summed luminosity for 1 ton DBD nuclei is  $L \approx 10^{76} \text{ cm}^{-2} \text{ s}^{-1}$ . Thus, one gets 2-3 DBD signals per year for the IH neutrino exchange by using a large DBD detector with 1 ton DBD isotopes.

The DBD neutrino mass sensitivity to search for the small neutrino mass is defined as the minimum neutrino mass  $m_m$  to be measured by the DBD experiment. It is given by a product of a nuclear sensitivity and a detector sensitivity. The nuclear sensitivity depends on nuclear parameters such as the nuclear phase space and the NME, while the detector sensitivity depends on the detector parameters such as the total number of the DBD isotopes, the enrichment, the exposure time, the detection efficiency, and the backgrounds. The minimum neutrino mass to be measured and the nuclear and detector sensitivities are discussed in the review articles [1, 4, 7].

The present report is aimed at critically discussing the nuclear and detector sensitivities to search for the ultra-rare DBD events associated with very small IH and NH masses. Critical discussions on DBD NMEs are presented elsewhere [8].

## 2. Neutrino Mass Sensitivity for DBD Experiment

The neutrinoless DBD transition rate is expressed in terms of the axial-vector weak coupling  $g_A = 1.27$  in units of the vector coupling of  $g_V$  as [1, 4]

$$T_r^{0\nu} = g_A^4 G^{0\nu} |M^{0\nu} f(\nu)|^2, \quad (1)$$

where  $G^{0\nu}$  is the phase space volume,  $M^{0\nu}$  is the NME, and  $f(\nu)$  stands for the effective neutrino mass and the other neutrino and weak interaction parameters beyond the standard model. These three quantities are associated with the kinematic factor, the nuclear physics factor, and the particle physics factor, respectively.

In case of the light neutrino mass process,  $f(\nu)$  is given by the effective neutrino mass of  $m = \sum |U_i|^2 m_i e^{i\alpha_i}$  with  $m_i$ ,  $U_i$ , and  $\alpha_i$  being the  $i$ th neutrino mass, the mixing coefficient, and the phase, respectively. In case of the right-handed weak-boson process,  $f(\nu)$  includes the term  $k(M_W^L/M_W^R)^2$

with  $M_W^L$  and  $M_W^R$  being the left-handed and right-handed weak-boson masses, respectively [1, 4].

The DBD NME for the light neutrino mass mode is expressed in terms of the Gamow-Teller (GT), the Fermi (F), and the tensor (T) NMEs as [1, 4, 7]

$$M^{0\nu} = \left(\frac{g_A^{\text{eff}}}{g_A}\right)^2 \left[ M(\text{GT}) + \left(\frac{g_V^{\text{eff}}}{g_A^{\text{eff}}}\right)^2 M(\text{F}) + M(\text{T}) \right], \quad (2)$$

where  $g_A^{\text{eff}}$  and  $g_V^{\text{eff}}$  are, respectively, the effective axial-vector and vector couplings and  $g_A$  and  $g_V$  are the axial-vector and vector couplings for a free nucleon.  $M(\text{GT})$ ,  $M(\text{F})$ , and  $M(\text{T})$  are, respectively, the model NMEs for Gamow-Teller, Fermi, and tensor transition operators.

The GT and T NMEs are very sensitive to nucleonic and nonnucleonic correlations and nuclear medium effects, and thus, the ratios  $g_A^{\text{eff}}/g_A$  and  $g_V^{\text{eff}}/g_V$  stand for the renormalization coefficients due to such correlations and nuclear medium effects that are not explicitly included in the nuclear model. Thus, they depend on the models and the transition operators. Since the axial-vector NMEs are strongly modified by the strong isobar (quark spin-isospin excitation) and other nonnucleonic correlations, we usually consider explicitly the renormalization coefficient  $g_A^{\text{eff}}$ , but the renormalization coefficient  $g_V^{\text{eff}}$  for the vector coupling should be well considered unless the models include all correlations and the medium effect [6–8]. The DBD NMEs are discussed in review articles on neutrino nuclear responses [6–8]. Theoretical works on DBD NMEs are discussed in reviews [9–11].

The DBD rate  $T_r^{0\nu}$  per year (y) and per ton (t) of the DBD isotope-mass is expressed by using a neutrino mass unit  $m_0$  as [1, 4, 7, 8]

$$T_r^{0\nu} = \left(\frac{m}{m_0}\right)^2, \quad m_0 = \frac{m'_0}{M^{0\nu}}, \quad (3)$$

$$m'_0 = 7.8 \text{ meV} \frac{A^{1/2}}{g_A^2 (G^{0\nu})^{1/2}},$$

where  $A$  is the mass number of the DBD nucleus,  $G^{0\nu}$  is the phase space factor in a unit of  $10^{-14}/\text{y}$ , and  $m_0$  is the neutrino mass that gives the DBD rate  $T_r^{0\nu} = 1$  per t y. We define  $m_0$  as the nuclear sensitivity of the DBD nucleus, being inversely proportional to  $(G^{0\nu})^{1/2} M^{0\nu}$ . Here, high sensitivity to the neutrino mass means high capability of measuring a small neutrino mass.  $m'_0$  is the neutrino mass  $m_0$  in case of  $M^{0\nu} = 1$ .

The values  $m'_0$  for typical DBD nuclei of  $^{82}\text{Se}$ ,  $^{100}\text{Mo}$ ,  $^{116}\text{Cd}$ , and  $^{130}\text{Te}$ , which are of current interest, are all around 40 meV, which are close to the upper bound of the IH neutrino mass. The values for  $^{76}\text{Ge}$  and  $^{150}\text{Nd}$  are, respectively, larger and smaller by a factor 2 than the value of 40 meV because of the smaller and larger phase space volumes.

In order to study the neutrino mass, the number of the DBD signals is required to be larger than the fluctuation

$\delta$  of the number of the background signals. Then, it is expressed as [1, 7, 8]

$$T_r^{0\nu} \eta \epsilon N T \geq \delta, \quad \delta = \delta_0 \times (BNT)^{1/2}, \quad (4)$$

where  $N$  is the total DBD isotope-mass in units of t,  $T$  is the exposure in units of y,  $\delta_0$  is around 2,  $B$  is the number of the backgrounds per  $N=1$  ton per  $T=1$  year,  $\eta$  is the enrichment coefficient of the DBD isotope, and  $\epsilon$  is the DBD signal detection efficiency. Note that the actual DBD isotope-mass is  $\eta N$  ton, the signal yield is  $T_r^{0\nu} \eta \epsilon N T$ , and the BG yield is  $BNT$ .

Then, the minimum effective neutrino mass to be measured with a 90% confidence level is expressed in terms of the nuclear sensitivity  $m_0$  and the detector sensitivity  $d$  as

$$m_m = m_0 \times d, \quad d = d_0 \times \eta^{-1/2} \epsilon^{-1/2} \left( \frac{NT}{B} \right)^{-1/4}, \quad (5)$$

where  $d_0$  is around 1.4. The neutrino mass to be measured is  $m_m = 2m_0'/M^{0\nu}$  in a typical case of the DBD detector exposure of  $NT = 1$  ty, the BG rate of  $B = 1/t$  y,  $\epsilon = 0.55$ , and  $\eta = 0.9$ .

On the basis of the simple expression of the mass sensitivity  $m_m$  as given in equation (5), key points for high-sensitivity DBD experiments are as follows.

- (1) The neutrino mass to be measured is proportional to  $1/M^{0\nu}$  and  $(B/NT)^{1/4}$ . Therefore, the DBD nucleus with larger  $M^{0\nu}$  by a factor 2 is equivalent to the DBD isotope-mass ( $N$ ) larger by a factor 16. Then, the detector volume gets more than an order of magnitude larger if  $M^{0\nu}$  gets smaller by 40%
- (2) The minimum mass to be measured depends on the ratio of  $(B/N)^{1/4}$ . Then, the neutrino mass sensitivity is improved by a factor 2 by increasing the DBD isotope-mass ( $N$ ) by a factor 16, or by decreasing the BG rate by a factor 16, or by increasing the DBD isotope-mass by a factor 4 and decreasing the BG rate by a factor 4
- (3) The effective neutrino mass depends on the neutrino mixing phases and is in the regions of  $m \approx 17$ -45 meV and  $m \approx 1.5$ -4 meV, respectively, in cases of IH and NH. Assuming a typical NME of  $M^{0\nu} = 2$ , one needs the DBD detectors with the mass sensitivities around the nuclear sensitivity of  $m_0 \approx 20$  meV and one-tenth of that, respectively, in cases of IH and NH. Then, one needs DBD detectors with  $N \approx 1$  t and  $B \approx 1/t$  y and  $N \approx 100$  t and  $B \approx 0.01/t$  y, respectively, to measure the IH and NH neutrino masses
- (4) DBD isotope enrichment is very effective. Enrichment by a factor 3 is equivalent to the increase of DBD isotope-mass by a factor 10. Accordingly, it is effective to use ton scale 80-90% enriched DBD isotopes

### 3. DBD Nuclear and Detector Sensitivities

In this section, we discuss DBD nuclear and detector sensitivities as given in equation (5) for DBD experiments to access the IH and NH neutrino masses.

**3.1. Nuclear Sensitivity.** The nuclear sensitivity  $m_0$  is a ratio of the unit mass  $m_0'$  and the NME  $M^{0\nu}$ . In fact,  $M^{0\nu}$  is so sensitive to the details of the nuclear structures that accurate evaluation for  $M^{0\nu}$  is very hard. So, we discuss in the present work mainly  $m_0'$  and assume that  $M^{0\nu}$  is in the region of 1-3 (see the recent review on DBD NMEs [7] and references therein for detailed discussions on  $M^{0\nu}$ ).

The unit mass  $m_0'$  is proportional to  $A^{1/2}(G^{0\nu})^{-1/2}$ . The phase space factor  $G^{0\nu}$  increases with the increase of the DBD  $Q$  value. Thus, double  $\beta^-$  nuclei with the large  $Q$  around 3 MeV are used. The large  $Q$  is also effective to reduce much BGs from  $^{208}\text{Tl}$  and  $^{214}\text{Bi}$ , which are two major BGs. The mass number  $A$  dependence reflects the number of the DBD nuclei per ton of the total DBD isotope-mass. The mass sensitivities for a typical DBD nucleus with  $m_0' = 40$  meV are plotted as a function of the exposure  $NT$  in Figure 2. In order to access the IH mass of 20 meV, one needs a DBD exposure  $NT$  of around 16 ty, i.e.,  $N \approx 5$  ton DBD isotopes and  $T \approx 3$  y measurement in case of a typical NME of  $M^{0\nu} = 2$  and BG rate of  $B = 1/t$  y. On the other hand, one needs  $NT$  of around 3 ty, i.e.,  $N \approx 1$  ton DBD isotopes and  $T \approx 3$  y measurement in case of  $M^{0\nu} = 3$ , and  $NT$  of around 250 ty, i.e.,  $N \approx 60$  ton DBD isotopes and  $T \approx 4$  y measurement, in case of  $M^{0\nu} = 1$ . So, it is very crucial to know the NME even for designing the DBD detector.

The mass sensitivities for the enrichment factors of  $\eta = 10$ , 50, and 100% are plotted as a function of the total DBD isotope-mass  $N$  in Figure 3.

In order to access the IH mass of 20 meV, one needs  $N = 3.4$  t and 4.1 t of the total DBD isotopes, respectively, in case of  $\eta = 100\%$  and 90%, while it is  $N = 14$  t in case of  $\eta = 50\%$  ( $\eta N = 7$  t), and  $N = 340$  t in case of  $\eta = 10\%$  ( $\eta N = 34$  t). Therefore, enrichment around  $\eta \geq 80\%$  is very effective. The 1-ton DBD total isotope-mass with  $\eta \approx 90\%$  is equivalent to the  $N \approx 10$  ton of the total DBD isotope-mass with  $\eta \approx 30\%$ .

**3.2. DBD Detector Sensitivity and Backgrounds.** The DBD experiment requires an ultra-low-BG detector since the DBD signal is very low in energy and the event rate is very rare. The neutrino mass sensitivity for a typical exposure time of  $T = 5$  y and  $\eta = 0.9$ ,  $\epsilon = 0.55$ , and  $d_0 = 1.4$  is rewritten in terms of the ratio of the DBD isotope-mass  $N$  and the BG rate  $B$  as

$$m_m \approx 1.35 \frac{m_0'}{M^{0\nu}(N/B)^{1/4}}. \quad (6)$$

The mass sensitivities for the  $m_0' = 40$  meV with typical NMEs of  $M^{0\nu} = 2$  and  $M^{0\nu} = 3$  are simply given as  $m_m \approx 27$  meV/( $N/B$ )<sup>1/4</sup> and  $m_m \approx 18$  meV/( $N/B$ )<sup>1/4</sup>. They are shown as a function of  $N/B$  in Figure 4. So, in the case of  $M^{0\nu} \approx 2$ , DBD detectors to search for the IH mass of 20-30 meV and

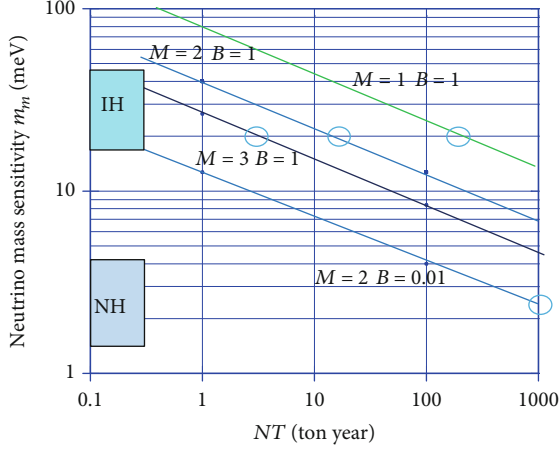


FIGURE 2: Neutrino mass sensitivities  $m_m$  as a function of the exposure  $NT$ .  $M$  and  $B$  are the NME and the BG rate per ty.  $d_0 = 1.4$ ,  $\varepsilon = 0.55$ , and  $\eta = 0.9$  (see equation (5)).

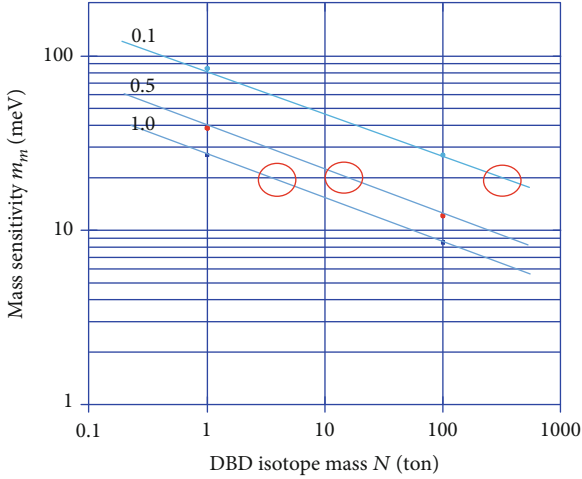


FIGURE 3: Neutrino mass sensitivities  $m_m$  for  $\eta = 1.0, 0.5$ , and  $0.1$  as a function of the total isotope-mass  $N$ . The exposure time is  $T = 5$  y, and the nuclear sensitivity of  $m_0 = 20$  meV,  $\varepsilon = 0.55$ ,  $d_0 = 1.4$ , and  $B = 1/t$  y.

the NH mass of 2-3 meV are required to be large isotope-mass and low-BG detectors with  $N/B \approx 1$  and  $N/B \approx 10^4$ , respectively.

Let us see how the mass sensitivity changes if one gets a BG-free ( $B = 0$ ) detector. In this case, the mass sensitivity is derived by requiring the signal yield  $\geq 2.3$  as [4]

$$m_m = 1.5 \times m_0 \varepsilon^{-1/2} \eta^{-1/2} (NT)^{-1/2}. \quad (7)$$

The mass sensitivities for three BG cases of  $B = 1, 0.01$ , and  $0$  are compared in Figure 5. Then, the DBD isotope-mass  $N$  required to access the IH mass of 20 meV is 1 t, while the DBD isotope-mass to access the NH mass of 2 meV is 100 t. They are a factor 3 smaller than those for the detectors with  $B = 1$  and  $0.01$ . Thus, one needs 1-ton scale and 100-ton scale DBD isotope-masses to access the IH and NH neutrino masses even by using the BG-free detectors.

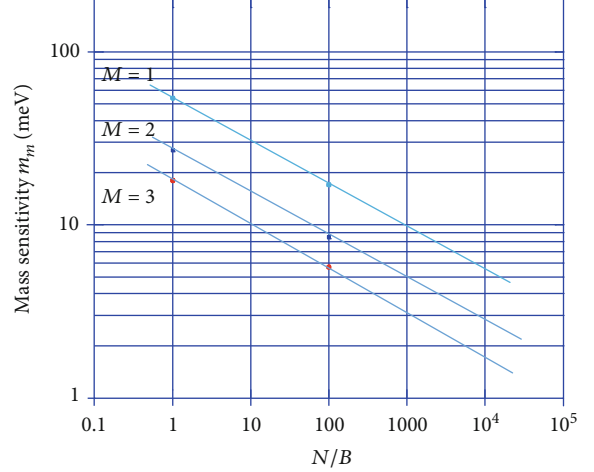


FIGURE 4: Neutrino mass sensitivities  $m_m$  for  $\eta = 0.9$ ,  $\varepsilon = 0.55$ , and  $d_0 = 1.4$  as a function of the ratio of the total isotope-mass  $N$  to the BG rate  $B$ . The exposure time is  $T = 5$  y, and the unit mass  $m'_0 = 40$  meV.

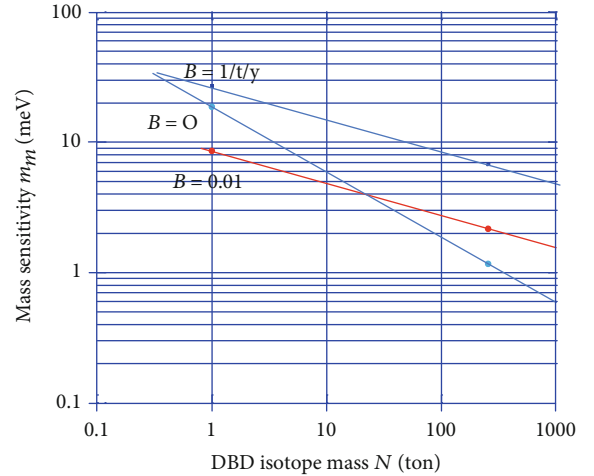


FIGURE 5: Neutrino mass sensitivities  $m_m$  as a function of the DBD isotope-mass  $N$  in cases of  $B = 1, 0.01$ , and  $0$ . The exposure time is  $T = 5$  y. The unit mass  $m'_0 = 40$  meV and  $M^{0v} = 2$ ,  $\varepsilon = 0.55$ , and  $\eta = 0.9$ .

The DBD signal is expected to appear as a sharp peak at the energy of  $E = Q$  in the energy spectrum. The peak width is around the FWHM (full width half maximum) of the detector. Thus, one usually sets the energy window of  $\Delta E = 2$  FWHM as the region of interest (ROI).

BGs in ROI are mostly due to  $\beta$ -rays and Compton-scattered  $\gamma$ -rays, which are continuum spectra. Backgrounds due to the solar neutrino interaction, which gets serious in the NH mass search, are also continuum [12, 13]. Then, the BG rate at the energy window of ROI is proportional to FWHM. Since the mass sensitivity is proportional to  $(B/N)^{1/4}$ , improvement of the energy resolution by an order of magnitude is equivalent to an increase of the DBD isotope-mass by the same order of magnitude.

The mass sensitivity depends on the detection efficiency as  $m_m = k\varepsilon^{-1/2}$ . The efficiency includes all efficiencies associated with the energy and PSA windows/cuts and analyses to select the DBD signals and to reject BG ones. It is around  $\varepsilon \approx 0.5$ -0.6. Severe cuts to reject BGs reduce both the efficiency  $\varepsilon$  and the BG rate  $B$ . The decrease of  $\varepsilon$  by 20% is compensated if  $B$  gets smaller by 40%.

#### 4. Remarks and Discussions on DBD Detectors

There are many high-sensitivity DBD experiments and future plans to access the IH mass around 20 meV and the NH mass around 2 meV. The detailed reports on the present status of individual experiments and plans are given in their reports, and detailed discussions on them are given in the reviews [1, 4, 5, 7] and references therein and also in the recent Neutrino 2020 conference proceedings. The present and future DBD experiments are discussed there (see, for example, Ref. [14]). So, we give in this section a few comments on some (not all) possible DBD experiments from viewpoints of the DBD mass sensitivity, i.e., the nuclear and detector sensitivities as given in equation (5).

The DBD isotopes of  $^{82}\text{Se}$ ,  $^{100}\text{Mo}$ , and  $^{136}\text{Xe}$  are very useful isotopes because of the small  $m'_0 \approx 40$  meV due to the large phase space  $G^{0\nu}$  and the large  $Q$  value and multiton scale enriched isotopes with  $N \approx 10$  and  $\eta \approx 90\%$  are available by centrifugal separation.

Cryogenic  $^{82}\text{Se}$ - and  $^{100}\text{Mo}$ - bolometers with both thermal and scintillation signals are promising detectors with high-energy resolution and low-BG rate (see Refs. [15–18]).  $^{116}\text{Cd}$  with  $m'_0 \approx 40$  meV is also interesting (see Refs. [19, 20]).

$^{136}\text{Xe}$  can be easily enriched to get a 10 t scale isotope-mass and thus is possible to access the IH and NH masses. Various kinds of  $^{136}\text{Xe}$  detectors are in progress (see Refs. [21–27]).

$^{76}\text{Ge}$  with  $Q = 2.039$  MeV has the unit mass of  $m'_0 = 80$  meV, a factor 2 larger than the others given above. Ton scale enriched DBD isotopes are possible by centrifugal separation, and the energy resolution of  $10^{-3}$  in FWHM is very good. Accordingly, the Ge BG rate is almost an order of magnitude smaller than others to get the neutrino mass sensitivity comparable with other detectors (see Refs. [28–32]).

The natural abundance of  $^{130}\text{Te}$  is 34%, and thus, multiton scale natural Te isotopes may be used although the mass sensitivity  $m_m$  gets larger by a factor 1.6 than the mass sensitivity with enriched  $^{130}\text{Te}$ -isotope detectors (see Refs. [18, 33]).

$^{150}\text{Nd}$  has a large phase space factor because of the large  $Q$  value of 3.4 MeV and the large  $Z$  number of 60. Thus,  $m'_0 = 18$  meV is half of the others [7, 8]. The natural abundance, however, is only 5.6%, and enrichment is not easy (see Ref. [34]).

Tracking detectors have been used to study DBDs on  $^{100}\text{Mo}$ ,  $^{116}\text{Cd}$ ,  $^{82}\text{Se}$ , and many other DBD nuclei as discussed in review articles and references therein [1, 2, 4, 5]. They measure individual two  $\beta$ -rays to identify the DBD signals and to reject single- $\beta$  background signals. The measured energy and angular correlations are used to differentiate the

DBD processes due to the left-handed and right-handed weak currents (see Refs. [35–37]).

Finally, it should be remarked that the NME is one of the key ingredients for the DBD mass sensitivity, and thus, selection of DBD isotopes with a large NME is very crucial for getting high-sensitivity DBD experiments [6, 7]. It is however very hard to evaluate accurately the DBD NMEs. So, various experiments are in progress to provide nuclear parameters, the effective axial-vector weak couplings, and nuclear structures to help theoretical evaluations of the neutrinoless DBD NMEs. These are discussed in recent articles [8, 38].

#### Data Availability

There are no experimental data for this work because this is based on theoretical analyses and calculations.

#### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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