Fast-neutron-induced potential background near the Q value of neutrinoless double-β decay of ^{76}Ge

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Fast neutron-induced potential background near the Q-value of neutrinoless double-beta decay of ^{76}Ge

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The ^{76}Ge(n,p)^{76}Ga reaction and the subsequent β decay of ^{76}Ga to ^{76}Ge has been used to excite the 3951.89 keV state of ^{76}Ge, which decays by emission of a 2040.70 keV γ ray. Using HPGe detectors, the associated pulse-height signal may be undistinguishable from the potential signal produced in neutrinoless double-beta decay of ^{76}Ge with its Q-value of 2039.0 keV. At 20 MeV neutron energy the production cross section of the 2040.70 keV γ ray is approximately 0.1 mb.

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According to current knowledge, neutrinoless double-beta ($0\nu\beta\beta$) decay, if realized in nature, is the only mechanism that would provide unambiguous information on the Majorana nature of the neutrino. In addition, it would result in lepton number violation, provide a measure of the effective neutrino mass $< m_{\beta\beta} >$ and may offer an explanation for the matter-antimatter asymmetry in the universe. Therefore, it is not surprising that strong efforts are underway in the nuclear and particle physics communities to search for this elusive decay mode as a venue to new physics not contained in the current Standard Model of particle physics.

As a second order weak interaction process, the expected half-life time for $0\nu\beta\beta$ decay is $T_{1/2}>10^{25}$ yr. The present limit published by the GERDA collaboration for ^{76}Ge is $T_{1/2}>2.1 \times 10^{25}$ yr (90% C.L.) [1]. The EXO-200 and KamLAND-Zen collaborations reported lower limits for ^{136}Xe of 1.1×10^{25} yr [2] and 2.6×10^{25} yr (90% C.L.) [3], respectively. Future large-scale experiments aim at the so-called inverted neutrino mass hierarchy regime ($m_{\beta\beta}>\sim 20$ meV), which corresponds to $T_{1/2}>\sim 5 \times 10^{26}$ yr.

Reaching this goal rests on the assumption that background events in the measured electron energy spectrum in the region of interest (ROI), which is centered at the Q-value for $0\nu\beta\beta$ decay, are extremely small and well understood. In experiments where the $0\nu\beta\beta$ candidate isotope is a large fraction of the detector medium, for example in enriched ^{76}Ge HPGe detectors, enriched ^{136}Xe based time projection chambers or bolometers using natural Te, typical requirements call for background event rates not to exceed 1 count per 1 tonne of the isotope of interest per keV in the ROI during 1 year of counting. This requirement mandates the use of unprecedented radio-pure materials in the detector construction, and sophisticated measures to eliminate the effect of external radiation, which could mimic the signal of interest. Here, neutron induced reactions in the detector material itself or its surrounding shielding are the major concern. To mitigate the influence of neutrons produced by cosmic-ray muons, $0\nu\beta\beta$ decay searches must be performed deep underground in mines with overburden of at least a few kilometer-water-equivalent. But even at large depth and using sophisticated veto detectors, the fast neutron flux at the location of the detector is a concern, unless it is known that neutrons cannot produce a signal in the ROI.

In the following, we will focus on fast ($E_n>10$ MeV) neutron induced background processes in ^{76}Ge $0\nu\beta\beta$ decay searches performed with enriched (86% ^{76}Ge and 14% ^{74}Ge) HPGe detectors. In this case the ROI is centered at 2039.0 keV, with width of ± 2.5 to ± 3 keV. It has already been shown [4] that thermal neutron capture on ^{76}Ge produces a delayed γ ray (from the decay of the ^{77}Ge ground and isomeric state) of energy 2037.87 keV, which potentially could interfere with the signal of interest. Very recently, neutron-capture cross-section data on ^{76}Ge and ^{74}Ge were reported by Megha Bhike *et al.* [5] for neutron energies up to approximately 10 MeV, filling the gap between thermal and fast neutron capture cross-section data. However, the amount of background caused by neutron scattering and reaction processes involving ^{76}Ge and ^{74}Ge at energies $E_n>10$ MeV is still poorly known. Recently, the Geel group [6] performed a ^{76}Ge(n,n$'\gamma$)^{76}Ge experiment to investigate the importance of the 69^{th} [7, 8] excited state of ^{76}Ge at 3951.89 keV, that decays with an 8% branching ratio to the 5^{th} excited state in ^{76}Ge (located at 1911.07 keV) by emitting a 2040.70 keV γ ray, which could potentially mimic the $0\nu\beta\beta$ signal of interest. A partial level scheme of ^{76}Ge is shown in Fig. 1, indicating the decay of the 3951.89 keV state with its associated branching ratios. The work of the Geel group [6] was done with a white neutron beam focusing on neutron energies up to approximately 13 MeV. None of the decay γ rays of the 3951.89 keV state were positively identified, but upper limits of the cross section for the 2040.70 keV transition were given, ranging between approximately 1 and 5 mb. Even more recently, the Kentucky group performed ^{76}Ge(n,n$'\gamma$)^{76}Ge experiments in the 2 to 5 MeV neutron energy range [9]. Again, the 2040.70 keV γ-ray was not observed, but the 3951.70, 3388.75 and 2843.50 keV transitions were positively identified.

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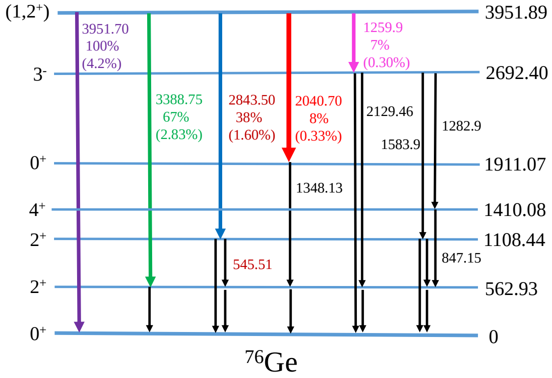

FIG. 1: (Color online). Partial level scheme of ^{76}Ge [7]. The transitions of interest with their branching ratios are given by bold arrows. The branching ratios given in parenthesis refer to the decay of ^{76}Ga. Energies are in keV.

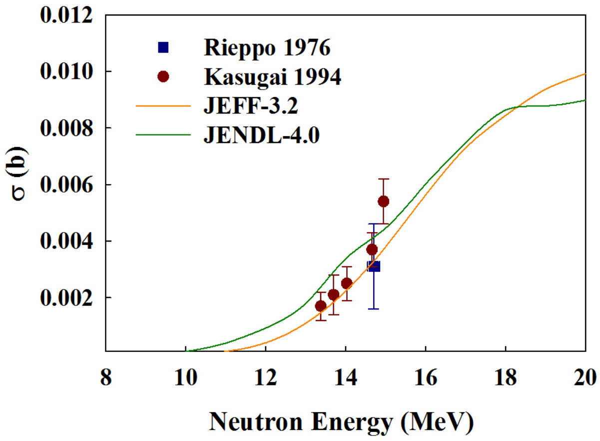

FIG. 2: (Color online). Data and evaluation for the ^{76}Ge(n,p)^{76}Ga cross section [7].

The level scheme and the associated branching ratios shown in Fig. 1 are based on the work of Camp and Foster [10], who studied the ^{76}Ge(n,p)^{76}Ga reaction with 14 MeV neutrons. The γ-ray decay scheme and energy levels of ^{76}Ge were deduced from measurements of 107 γ-ray transitions following the β decay of ^{76}Ga back to ^{76}Ge with $T_{1/2}$=32.6 s.

Difficulties in understanding our own results obtained at TUNL during the past eight years in measurements of γ-ray spectra of the ^{74,76}Ge(n,n$'\gamma$)^{74,76}Ge reactions with 5, 8, and 12 MeV neutrons [11], especially the observation of many new γ-ray transitions, including one at 2036.8 keV, prompted us to revisit the ^{76}Ge(n,p)^{76}Ga reaction with focus on the decay of the 3951.89 keV state and its emission of a 2040.70 keV γ ray.

In the following we briefly describe our experimental procedure, present our result, and discuss its consequences for large-scale $0\nu\beta\beta$ searches using enriched (in ^{76}Ge) HPGe detectors.

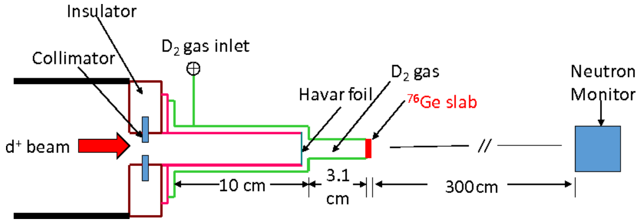

FIG. 3: (Color online). Deuterium gas cell with 10 mm × 10 mm × 6 mm ^{76}Ge slab attached to.

The ^{76}Ge(n,p)^{76}Ga reaction has a threshold of 6215.4 keV. Its evaluated cross section (see Fig. 2) [7] has a value of approximately 10 mb at 20 MeV neutron energy. The short decay time of ^{76}Ga necessitates a high neutron flux in order to produce a sufficiently large ^{76}Ga activity for subsequent γ-ray counting. Therefore, with limited neutron source strength available at TUNL, we used the ^{2}H(d,n)^{3}He reaction to produce 19 MeV neutrons rather than 14 MeV neutrons and the ^{3}H(d,n)^{4}He reaction as employed in Ref. [10]. The former not only produces 19 MeV neutrons, but also provides a copious supply of neutrons with energies below 12.5 MeV (so-called deuteron breakup neutrons) for initiating the ^{76}Ge(n,p)^{76}Ga reaction. A neutron energy spectrum obtained with a 16.6 MeV deuteron beam striking a 3 cm long gas cell (see Fig. 3) pressurized to 6 atm of deuterium gas is shown in Fig. 4, indicating that about 25% of the neutrons have energies of 19 MeV. Of the breakup neutrons only those with energies above 6.2 MeV (the other 75%) will contribute to the ^{76}Ge(n,p)^{76}Ga reaction. The energy spectrum of Fig. 4 was deduced from a neutron time-of-flight measurement using a pulsed deuteron beam and taking into account the energy dependence of the neutron detector efficiency.

A germanium slab of size 10 × 10 × 6 mm^{3}, mass of approximately 3.2 g, and isotopic composition of 86% ^{76}Ge and 14% ^{74}Ge was attached to the end of the deuterium gas cell (see Fig. 3) and irradiated for 120 s with neutrons produced by a 1.7 μA deuteron beam (unpulsed). After irradiation, the slab was removed and positioned in front of a 60% relative efficiency HPGe detector located outside of the irradiation room. Typically, the time between the end of irradiation and the beginning of γ-ray counting was approximately 30 s, resulting in a factor of two loss of the initial activity. The germanium slab was counted for a total of 120 s in 30 s increments using the Canberra Multiport II hardware and the associated GENIE software [13]. The total yield in the 3951.70 keV line was approximately 150 counts and more than a factor of 10 lower for the 2040.70 keV γ-ray line. The HPGe detector was shielded against environmental radiation by a lead enclosure. It was energy calibrated and monitored with ^{56}Co and ^{60}Co γ-ray test sources and its background spectrum is well known. In order to accumulate statistics, after a typically 10 minute break, the same sample was irradiated again, following the proce-

TABLE I: Predicted and measured intensity ratios for γ-ray transitions involving the 3951.89 keV state in ^{76}Ge obtained from the ^{76}Ge(n,p)^{76}Ga reaction.

E_x keV/3951.70 keV	predicted	measured	corrected
E_x=3388.75	0.674 ± 0.081	0.528 ± 0.008	0.573 ± 0.098
E_x=2843.50	0.381 ± 0.043	0.311 ± 0.006	0.356 ± 0.060
E_x=2040.70	0.079 ± 0.013	0.089 ± 0.014	0.071 ± 0.012

dure outlined above. After typically seven of such irradiations the germanium sample was replaced by a fresh one, because it was noticed that the peak-to-background ratio in the γ-ray spectrum of interest deteriorated slightly with increasing neutron exposure of the sample. A total of 110 individual irradiations were performed. The resulting spectra were added to form three subsets and one sum spectrum, after making sure no gain changes occurred during the course of the measurements. The γ-ray energy region containing the 2843.50 keV, 3388.75 keV, and 3951.70 keV transitions is shown in panel (a) of Fig. 5, while panel (b) focuses on the 2040.70 keV energy region. These spectra represent the sum spectrum. In addition to the energies quoted by Camp and Foster [10] and adopted in the evaluation of [7], we provide in parenthesis the energy values found in the present work. Due to the smaller branching ratio of the 2040.70 keV transition, the peak-to-background ratio in Fig. 5 (b) is considerably smaller than that of the more intense γ-ray lines shown in Fig. 5 (a). Small corrections were applied to the raw data to account for γ-ray summing effects. Determining the yield ratios with the 3951.70 keV yield normalized to 100 and taking into account the energy dependent efficiency of the HPGe detector, we obtain the intensity ratios given in Table I, in good agreement with the original work of Camp and Foster. The energy dependent efficiency of the HPGe detector was measured with a ^{56}Co and a mixed source containing 13 γ-ray emitters ranging from ^{241}Am to ^{88}Y.

Zooming in on the energy region of the γ-ray line at 2040.70 keV (see Fig. 5 (b)), we notice that the centroid of this line is not located at 2040.70 keV, but at 2039.4 keV, much closer to the Q-value of $0\nu\beta\beta$ decay of ^{76}Ge at 2039.0 keV. In addition, the line appears to be broader than expected from a single γ ray. However, due to the high background and poor statistics, an unbiased and consistent fit to this γ-ray line using one or two gaussians could not be achieved. Figure 6 shows the energy region of interest for our three subsets of data (bottom three panels) and the sum spectrum (top panel, a zoomed-in view of Fig. 5(b)), where the vertical lines indicate the energy of interest (2040.70 keV) and that of the ^{76}Ge(n,γ)^{77}Ge capture γ-ray at 2037.87 keV. Due to our inability of fitting the peak of interest, we attempted a different approach: Inspecting the adjacent 2073.75 keV and 2129.46 keV γ-ray lines resulting from the ^{76}Ge(n,p)^{76}Ga reaction with its known intensity values [4] of 4.24% and 2.20%, respectively, we observe reasonably good agreement between the predicted and measured intensity ratios of (1.93 ± 0.15) and (1.72 ±0.24), respectively. Here, the latter ratio is obtained from 25873 ± 2370 counts for the 2073.75 keV line and 14680 ± 1511 counts for the 2129.46 keV transition. Subsequently, the associated yields and the predicted [10] branching ratio of the 2040.70 keV transition were used to calculate the predicted yield for this transition, resulting in 1843 ± 482 counts (after applying a small HPGe detector efficiency correction), in comparison to the measured yield of 2506 ± 214. The yields for the sum spectrum and its three subsets are given in Table II. Within the quoted uncertainties, these yields are consistently lower than the measured yields.

In order to find out whether the neutron capture γ-ray of 2037.87 keV referred to above is responsible for the larger than expected yield, the broader width and the lower centroid energy, the yields of the 714.37 keV,

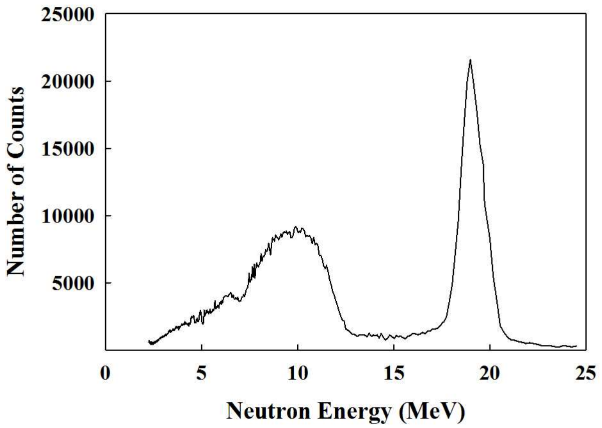

FIG. 4: Neutron energy spectrum used in the present experiment. The peak centered at 19 MeV is from the ^{2}H(d,n)^{3}He reaction with 16.6 MeV deuterons incident on a deuterium filled gas cell. The broad structure centered at approximately 9 MeV is due to the reactions ^{2}H(d,np)d and ^{2}H(d,nnnp), and the deuteron breakup on the structural materials of the gas cell.

TABLE II: Yield for the 2040.70 keV transition in ^{76}Ge deduced from the published intensities of this transition and that of the 2073.75 keV and 2129.46 keV transitions obtained from the present ^{76}Ge(n,p)^{76}Ga measurements for the individual subsets and the associated sum spectrum. The 3rd row represents the average of the yields.

γ-ray transition used	Subset#1	Subset#2	Subset#3	Sum Spectrum
2073.75 keV	424 ± 126	604 ± 179	701 ± 208	1738 ± 514
2129.46 keV	485 ± 137	650 ± 183	742 ± 209	1948 ± 549
Average	455 ± 119	627 ± 164	721 ± 189	1843 ± 482

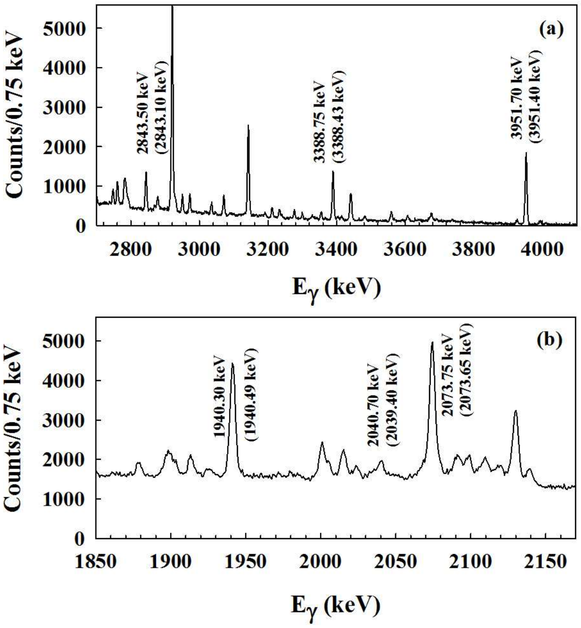

FIG. 5: Gamma-ray energy spectrum obtained from the reaction ^{76}Ge(n,p)^{76}Ga following γ-decay of ^{76}Ga (a) containing 3951.70 keV, 3388.75 keV and 2843.50 keV transitions (b) containing the 2040.70 keV transition. The energy assignments given in parenthesis are from the present work. Note the good agreement seen in (b) between the literature values for the (1940.3 ± 0.14)keV and (2073.75 ± 0.07)keV lines [10] and those found in the present work of (1940.49 ± 0.15)keV and (2073.65 ± 0.15)keV, providing confidence in our energy assignment near 2040 keV.

1085.23 keV and 2341.74 keV γ-ray lines were determined (see Table III). These transitions originate from the decay of the ^{77}Ge ground and/or isomeric state after neutron capture on ^{76}Ge and seem to be free of interference effects from other γ-ray lines. From the known intensity ratios $I_\gamma(2037.87)/I_\gamma(714.37) = 0.009 \pm 0.001$, $I_\gamma(2037.87)/I_\gamma(1085.23) = 0.010 \pm 0.001$, and $I_\gamma(2037.87)/I_\gamma(2341.74) = 0.130 \pm 0.011$ [4] the expected yields for the 2037.87 keV line in the sum spectrum were calculated, providing a mean value of 514 ± 38, after taking into account the energy dependent detector efficiency. The yields for the individual subsets are given in Table III.

Subsequently, the predicted yield for the 2037.87 keV transition was added to the predicted yield determined above for the 2040.70 keV transition, resulting in 2357 ± 483 counts, in excellent agreement with the measured yield of 2506 ± 214 counts determined from the sum spectrum. Finally, subtracting the predicted yield for the 2037.87 keV transition from the measured yield (2506 ± 214) used in Table I, provides the true yield of 1992 ± 217 for the 2040.70 keV transition, and the new ratio of 0.071 ± 0.012 (labelled corrected in Table I) was obtained. As can be seen, this value is now in slightly better agreement with the branching-ratio result reported by Camp and Foster for the 2040.70 keV transition.

TABLE III: Yield for the 2037.87 keV transition in ^{76}Ge deduced from the published [4] intensity of this transition and that of the 714.37 keV, 1085.23 keV and 2341.74 keV transitions obtained from the present ^{76}Ge(n,γ)^{77}Ge measurements for the individual subsets and the associated sum spectrum.

γ-ray transition used	Subset#1	Subset#2	Subset#3	Sum Spectrum
714.37 keV	83 ± 13	167 ± 26	254 ± 40	522 ± 78
1085.23 keV	72 ± 11	148 ± 23	223 ± 35	443 ± 69
2341.74 keV	120 ± 20	181 ± 32	279 ± 48	577 ± 89
Average	91 ± 7	166 ± 13	252 ± 20	514 ± 38

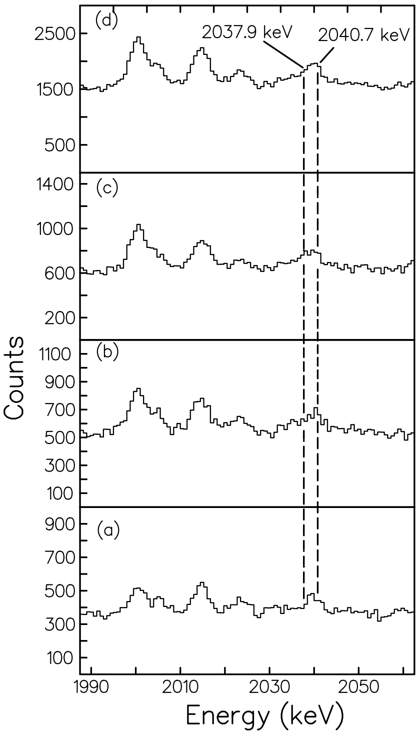

FIG. 6: Zoomed-in views of the region of interest for our three subsets of data (a), (b), and (c), and their sum (d), indicating the predicted position of the ^{76}Ge(n,γ)^{77}Ge capture γ-ray transition at 2037.87 keV and the 2040.70 keV transition from the deexcitation of ^{76}Ge following β-decay of ^{76}Ga produced in the ^{76}Ge(n,p)^{76}Ga reaction.

Of course, the question arises whether or not the probability for producing the 2040.70 keV γ ray is large enough to be relevant to $0\nu\beta\beta$ searches using ^{76}Ge. To answer this question, the neutron flux and energy distribution at the location of the HPGe detectors, the production cross section of the 2040.70 keV γ ray, and characteristics of the HPGe detector must be known.

The first and third points depend on the specifics of the underground location where the $0\nu\beta\beta$ decay search takes place, and on details of the HPGe detector assembly and associated shielding, respectively. The discussion of these issues is beyond the scope of the present work. The second point can be addressed easily, though. Using the predicted cross section for the ^{76}Ge(n,p)^{76}Ga reaction of approximately 10 mb at E_n=20 MeV (see Fig. 1) [7] and the known probability of 9.6% [7] for exciting the 3951.70 keV state after β decay of ^{76}Ga, results in a cross section of approximately 1 mb. Taking the 8% branching ratio for its decay via the emission of a 2040.70 keV γ ray into account, provides a production cross section of (0.08 ± 0.02) mb at 20 MeV.

In addition to the ^{76}Ge(n,p)^{76}Ga reaction focused on in the present work, inelastic neutron scattering, i.e., the ^{76}Ge(n,n$'\gamma$)^{76}Ge reaction is expected to produce the 2040.70 keV γ-ray line as well. Using their measured yields for the 3951.70, 3388.75 and 2843.50 keV and the known branching ratios, the Kentucky group deduced a production cross section for the unobserved 2040.70 γ-ray transition of $\sim$ 0.1 mb [9] below 5 MeV incident neutron energy. Furthermore, the 2037.5±0.3 keV γ-ray from the reaction ^{76}Ge(n,n$'\gamma$)^{76}Ge reported in [9] for neutron energies below 5 MeV and observed already in the work of Esterline *et al.* [11] with energy assignment of 2036.8±0.5 keV, is even more important due to its larger production cross section of a few mb. Adding the 2037.87 keV γ-ray line from neutron capture on ^{76}Ge, we note that $0\nu\beta\beta$ decay searches involving ^{76}Ge are susceptible to background γ-ray events produced by three different neutron-induced reactions on ^{76}Ge, with two of them involving fast neutrons.

Returning to the question raised above about the significance of the 2040.70 keV line with respect to $0\nu\beta\beta$ searches involving enriched ^{76}Ge based HPGe detectors, we note that detailed neutron production and transport calculations are required to estimate the implications for a given setup at a given underground location. In addition, γ-ray tracking calculations are needed for the specific HPGe detector arrangement used, because after all, the 2040.70 keV γ ray is only a problem, if the subsequent 1348.13 keV and 562.93 keV γ rays escape their detection. As has been stated already above, answering this question is beyond the scope of present work. However, incorporating our findings into background model of the GERDA collaboration should provide useful information.

A quick answer could be obtained by checking whether the 3951.70 keV γ-ray line is present in the spectra obtained by the GERDA collaboration. If not, then it is probably safe to conclude that the 2040.70 keV γ ray will most likely not cause any problems for the present generation of $0\nu\beta\beta$ searches with enriched HPGe detectors. However, for future detectors with active mass of 1 ton and beyond, the neutron-induced background discussed in the present work may turn out to be a major obstacle, potentially limiting $0\nu\beta\beta$ searches with enriched HPGe detectors from successfully probing the entire region of the inverted neutrino mass hierarchy.

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