9-2015

Inelastic Neutron Scattering Cross Sections for ^{76}Ge Relevant to Background in Neutrinoless Double-β Decay Experiments

Benjamin P. Crider
University of Kentucky, bpscrider@gmail.com

Erin Elizabeth Peters
University of Kentucky, eepeters26@gmail.com

J. M. Allmond
Oak Ridge National Laboratory

Marcus T. McEllistrem
University of Kentucky, marcusmcellistrem@uky.edu

Francisco M. Prados-Estévez
University of Kentucky, francisco.prados-estevez@uky.edu

See next page for additional authors

Inelastic neutron scattering cross sections for ^{76}Ge relevant to background in neutrinoless double-β decay experiments

B. P. Crider,[1] E. E. Peters,[2] J. M. Allmond,[3] M. T. McEllistrem,[1] F. M. Prados-Estévez,[1,2] T. J. Ross,[1,2] J. R. Vanhoy,[4] and S. W. Yates[1,2]

[1]*Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[2]*Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506-0055, USA*
[3]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[4]*Department of Physics, United States Naval Academy, Annapolis, Maryland 21402, USA*

(Received 5 May 2015; published 11 September 2015)

The experimental signature in searches for the neutrinoless double-β decay of ^{76}Ge is a peak near 2039 keV in the spectrum. Given the low probability of the process, it is important that the background in this region be well understood. Inelastic scattering reactions with neutrons from muon-induced interactions and (α,n) reactions in the surrounding materials or in the detector can provide contributions to the background. We have measured the production cross sections for γ rays from the ^{76}Ge$(n,n'\gamma)$ reaction in the 2039-keV region at incident neutron energies up to 4.9 MeV. In addition to determining that the cross sections of a previously known 2040.7-keV γ ray from the 3952-keV level in ^{76}Ge are rather small, we find that a larger contribution arises from a 2037.5-keV γ ray which is attributed to a newly identified level at 3147 keV in ^{76}Ge. A third contribution is also possible from another new level at 3577 keV. These results indicate that the 2039-keV region in ^{76}Ge neutrinoless double-β decay searches is more complex than was previously thought.

DOI: 10.1103/PhysRevC.92.034310 PACS number(s): 21.10.Tg, 25.40.Fq, 27.50.+e, 23.40.−s

I. INTRODUCTION

Neutrinoless double-β ($0\nu\beta\beta$) decay is a lepton-number-violating process whose observation would identify the neutrino as a massive Majorana fermion. This rare decay process is speculated to occur in a handful of nuclei with predicted half-lives around 10^{25} years or greater [1]. Neutrino oscillation experiments indicate that neutrino flavors mix and that neutrinos have mass, yet such experiments only yield information about $(\Delta m)^2$ between the flavors themselves. If neutrinos are Majorana particles, the process of $0\nu\beta\beta$ decay offers a means of determining both the neutrino mass hierarchy and the absolute mass scale of the three flavors of neutrinos [2].

A favorable nucleus for the observation of $0\nu\beta\beta$ decay is ^{76}Ge, where the decay leads to ^{76}Se. In addition, ^{76}Ge is of considerable interest due to its capabilities as a high-resolution detector for $0\nu\beta\beta$ decay. To date, ^{76}Ge is also the only nuclide with a reported $0\nu\beta\beta$ decay half-life [3]; however, this report has come under heavy criticism, and is thus the focus of large-scale, multinational collaborations such as MAJORANA [4] and GERDA [5]. In these experiments, the summed β energies at the Q value of the reaction will be detected. Testing of their initial phases and publication of results, detector tests, and models for operation are in progress [6–9]. Recent results from the GERDA Collaboration yield a limit on the $0\nu\beta\beta$ decay half-life [10] that is in disagreement with the previous work of Ref. [3].

Observation of $0\nu\beta\beta$ decay requires sensitivity to a signal from a decay with a half-life greater than 10^{25} years, which in turn, requires precise knowledge of contributions to background at the Q value for the reaction, a region of interest (ROI) at 2039 keV for ^{76}Ge. Contributions to the background must be eliminated to the level of a single event per year per tonne. To this end, Mei and Hime [11] recognized that γ rays produced from the inelastic scattering of cosmic-ray produced neutrons are important for backgrounds in tonne-scale experiments and later assessed background contributions to the continuum from both $^{\mathrm{nat}}$Ge$(n,n'\gamma)$ and $^{\mathrm{nat}}$Pb$(n,n'\gamma)$ and identified a few particularly troublesome γ rays, e.g., 2041 keV in ^{206}Pb and a double-escape peak from a 3062-keV γ ray from ^{207}Pb$(n,n'\gamma)$ [12]. Subsequently, Guiseppe *et al.* [13] performed an investigation of the γ rays produced by several Pb isotopes, which can be found in a Pb-shielded $0\nu\beta\beta$ decay experiment and measured their cross sections as a function of energy across the range of neutron energies likely to be encountered in the tonne-scale ^{76}Ge experiments. Inelastic neutron scattering studies at GELINA were also carried out to assess background interferences from materials typically found in experimental setups near the $0\nu\beta\beta$ decay experimental signatures of ^{76}Ge and ^{130}Te [14] and, more specifically, on potential background contributors from Ge isotopes [15]. In this latter study, the authors focused on characterizing the contribution to background near 2039 keV from the 3951.89-keV level in ^{76}Ge; the present work elaborates on this level and on other contributors to the 2039-keV ROI.

Camp and Foster [16] first established the existence of the 3951.89-keV level by producing ^{76}Ga with the ^{76}Ge$(n,p)^{76}$Ga reaction and observing the population of ^{76}Ge following the β^- decay of ^{76}Ga ($T_{1/2} = 32.6$ s; $J^\pi = (2^+,3^+)$, $Q_\beta = 7.0$ MeV). As shown in Fig. 1, they reported that the 3951.89-keV level has five deexciting γ rays. Of particular concern is the 2040.70-keV γ ray, which lies very near the ^{76}Ge ROI for $0\nu\beta\beta$ decay observation. The 3951.89-keV level is the 69th known level of ^{76}Ge and the 2040.70-keV γ ray is a $<4\%$ branch, so its intensity is expected to be low. As such, Rouki *et al.* [15] were unable to directly observe the γ rays from this level and instead placed limits on the cross sections. The aim of our work was to identify and measure γ-ray

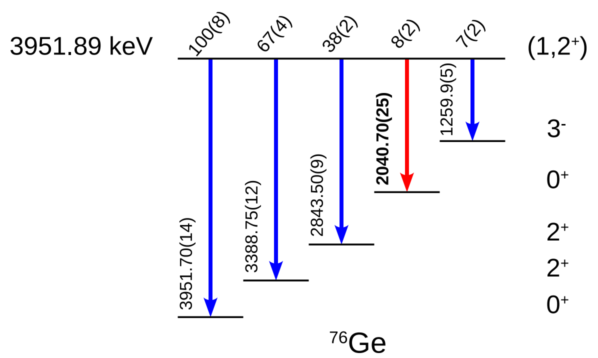

FIG. 1. (Color online) Partial level scheme of γ rays deexciting the 3951.89-keV level in ^{76}Ge [16,17]. The 2040.70-keV γ ray is near the Q value for the double-β decay of ^{76}Ge to ^{76}Se.

production cross sections for this and any other potential interferences to the $0\nu\beta\beta$ decay experimental signature within the ROI.

II. EXPERIMENTAL DETAILS AND DATA ANALYSIS

The ^{76}Ge$(n,n'\gamma)$ experiments were performed in two separate runs at the University of Kentucky Accelerator Laboratory (UKAL). In both experiments, protons from the 7-MV Van de Graaff accelerator were used to create nearly monoenergetic, fast neutrons via the ^{3}H$(p,n)^3$He reaction which then impinged upon an enriched ^{76}Ge scattering sample. The inelastic neutron scattering (INS) reaction nonselectively populates low-spin nuclear states up to the neutron energy, allowing the determination of the cross section of a particular level. The first data run consisted of two days of beam time using an elemental ^{76}Ge powder with mass = 11.13 g, radius = 1.1 cm, thickness = 0.8 cm, and enriched to 84.12(23)% in ^{76}Ge in a polyethylene vial. The majority of the other data runs were performed using a scattering sample of ^{76}GeO$_2$ powder with mass = 41.84 g, radius = 1.25 cm, height = 4.8 cm, enriched to 85% in ^{76}Ge and contained within a polyethylene vial. At the end of the first experiment, a 12-hour run was taken using an elemental $^{\text{nat}}$G*e* sample with mass = 106.55 g, radius = 1.3 cm, height = 3.7 cm, which was used for intensity comparisons between the Ge isotopes. A single high-purity germanium detector with an annular ring of bismuth germanate (BGO) used for Compton suppression was employed to detect the emitted γ rays. All samples were suspended by string so little mass, particularly of lighter elements, was near the scattering samples. No contributions from neutron capture by the samples were observed in the γ-ray spectra.

The first experiment utilized an incident neutron energy of 4.5 MeV at angles of 50°, 90 °, and 133° for the ^{76}GeO$_2$ and 90° only for both the ^{76}Ge powder and $^{\text{nat}}$Ge scattering samples. The second experiment utilized incident neutron energies of 4.3, 4.5, 4.7, and 4.9 MeV at 125°, as well as additional angles of 65°, 147 °, and a short 90° measurement for normalization with respect to the first run in an effort to extract angular distribution information. Apart from this last 90° measurement, each data run was performed with 24 hours of beam on target in order to populate the 3951.89-keV level. Each data run was accompanied with a ^{56}Fe$(n,n'\gamma)$ measurement using a 59.23 g $^{\text{nat}}$Fe sample of radius = 0.95 cm, height = 2.54 cm, which was used for normalization of the ^{76}Ge cross sections with respect to those for ^{56}Fe. For the first data run, this ^{56}Fe measurement was taken at 90° at an incident neutron energy of 4.5 MeV. During the second data run, the ^{56}Fe measurement was taken at 125° for each of 4.3-, 4.5-, 4.7-, and 4.9-MeV incident neutron energies. Additionally, a long counter was used to determine the relative neutron fluences when comparing the ^{76}Ge$(n,n'\gamma)$ and ^{56}Fe$(n,n'\gamma)$ reactions.

Finally, separate excitation function measurements for further identification of relevant γ rays were performed using a scattering sample of ^{76}GeO$_2$ powder, enriched to 85% in ^{76}Ge, with mass = 19.56 g, radius = 1.1 cm, and height = 4.7 cm. The incident neutron energies ranged from 1.6 to 3.7 MeV in 0.1-MeV steps.

Energy calibrations and detector efficiencies were determined using a ^{226}Ra source. Since some of the γ rays of interest have energies that lie outside of the range of relatively intense ^{226}Ra γ rays, extrapolations of the efficiency and energy nonlinearity curves were performed. This extrapolation procedure is particularly relevant for the efficiency, and doing so warrants an increase in the uncertainty, which has been included in the final results. In addition to energy and efficiency calibrations, other effects such as incident neutron attenuation, multiple neutron scattering, absorption of γ rays, as well as angular distribution effects were considered. All were taken into account using well-established procedures.

A lifetime analysis was performed using the Doppler-shift attenuation method (DSAM) [18]. The energy of a Doppler-shifted γ ray as a function of detection angle with respect to the direction of the incident neutrons is given by

$$E_\gamma(\theta) = E_0\left[1 + F(\tau)\frac{v_{c.m.}}{c}\cos\theta\right] \tag{1}$$

where E_0 is the energy of the γ ray emitted by the nucleus at rest, $v_{c.m.}$ is the recoil velocity of the center of mass, and c is the speed of light. The experimental attenuation factor, $F(\tau)$, describes the slowing down of the recoiling nucleus within the target material. The Winterbon formalism for describing the electronic and nuclear stopping powers for the sample material [19] was employed to extract the lifetime, τ, from $F(\tau)$. The measured $F(\tau)$ values and resulting lifetimes must agree for all γ rays from a given level. Disagreements between these values are indicative of a multiplet or misplaced γ ray.

III. RESULTS AND DISCUSSION

A. Proposed new levels and γ rays that impact the 2039-keV ROI

A new result from this work is the observation of a ^{76}Ge γ ray at 2037.5(3) keV. It has been assigned to ^{76}Ge due to the relative intensities with which it is seen in both the $^{\text{nat}}$Ge and ^{76}GeO$_2$ samples for the first experiment. The ratio between the intensities (normalized to the total number of neutrons) is nearly within the uncertainty of the ratio of the mass of ^{76}Ge in each of the samples, while the same ratio comparison is

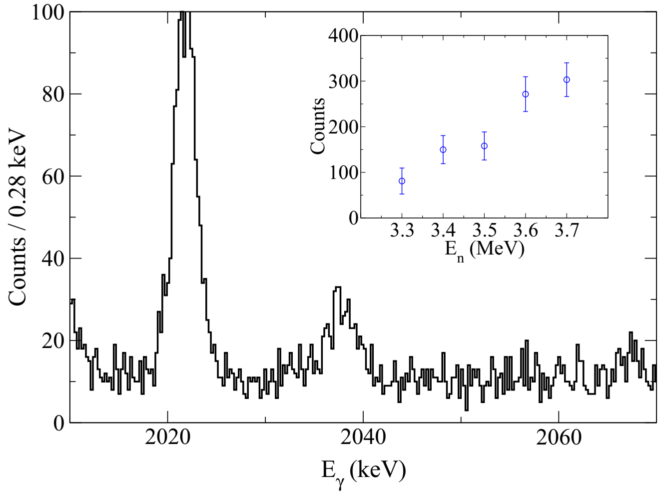

FIG. 2. (Color online) Gamma-ray spectrum from the ^{76}Ge$(n,n'\gamma)$ reaction taken at an incident neutron energy of 3.7 MeV and a detection angle of 90° showing a new 2037.5(3)-keV γ ray. The inset shows the yield of this γ ray from the $(n,n'\gamma)$ excitation function data with incident neutron energies of 3.3 to 3.7 MeV.

discrepant to at least an order of magnitude for all other Ge isotopes.

Placement of the new 2037.5(3)-keV γ ray is supported by its appearance in ^{76}Ge$(n,n'\gamma)$ excitation function measurements made with incident neutron energies ranging from 1.6 to 3.7 MeV. The new γ ray is first observed at $E_n = 3.3$ MeV and the yield increases with neutron energy. The γ-ray spectrum and excitation function are shown in Fig. 2. As the threshold is between incident neutron energies of 3.1 and 3.3 MeV, the only candidate level for this new γ ray to populate is the 1108.44-keV 2_2^+ level in ^{76}Ge. This would suggest a new

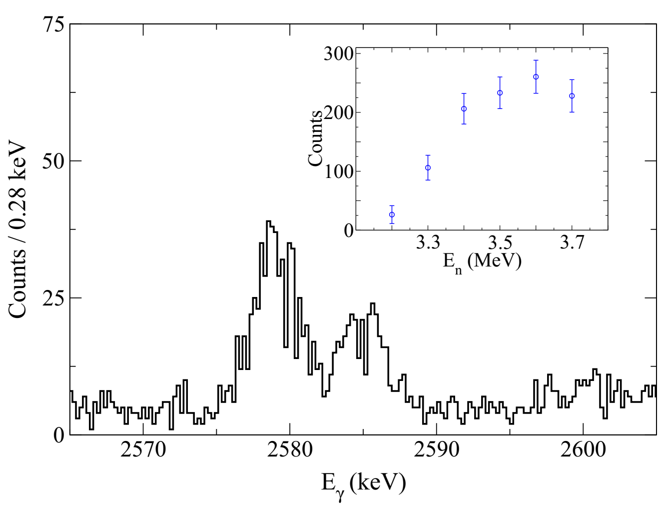

FIG. 3. (Color online) Gamma-ray spectrum from the ^{76}Ge$(n,n'\gamma)$ reaction taken at an incident neutron energy of 3.7 MeV and a detection angle of 90° showing a new 2584.7(2)-keV γ ray. The inset shows the yield of this γ ray from the $(n,n'\gamma)$ excitation function data with incident neutron energies of 3.2 to 3.7 MeV.

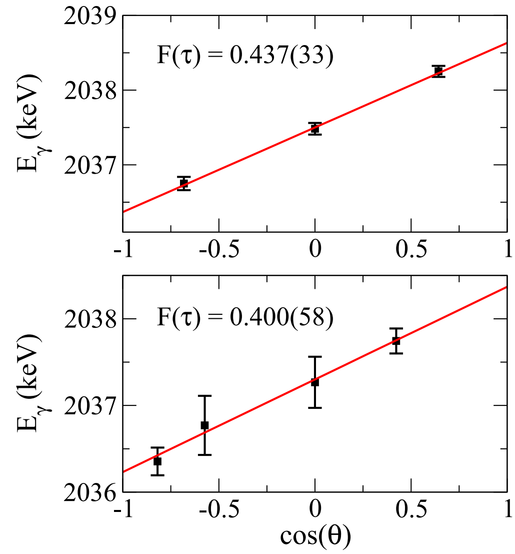

FIG. 4. (Color online) Experimental attenuation factor $F(\tau)$ for the newly observed 3147-keV level as measured from the 2037.5-keV γ ray. The top plot is from the first data run while the bottom plot is from the second data run.

level near 3147 keV. Further examination of the excitation function spectra indicates another γ ray at 2584.7(3) keV with a threshold between $E_n = 3.1$ and 3.2 MeV. This is likely a γ ray to the 562.93-keV 2_1^+ state from the same 3147-keV level. Figure 3 shows the γ-ray spectrum at $E_n = 3.7$ MeV and the excitation function from 3.2 to 3.7 MeV. The γ ray to the left that forms a doublet is the known 2578.55-keV γ ray to the 2_1^+ state from the 3141.51-keV level. The 3141.51-keV level has a known lifetime of 90^{+100}_{-60} fs [17].

Doppler shifts from the two data runs for the 2037.5(3)-keV and 2584.7(2)-keV γ rays were observed and are shown in Figs. 4 and 5, respectively. While the attenuation factors for these γ rays differ, our excitation function data indicates that these γ rays have the same threshold. The lack of evidence for new low-lying levels in ^{76}Ge from our excitation function data indicates that these γ rays must arise from the same 3147-keV level. Further confidence in the accuracy of the new lifetime measurements is supplied through good agreement for previously known level lifetimes (see Table I).

Another new γ ray listed in Table I has an energy of 3014.0(3) keV. This γ ray appears only at 3.6 and 3.7 MeV in the excitation function data (which extends to $E_n = 3.7$ MeV).

TABLE I. Experimental attentuation factors $[F(\tau)]$ and level lifetimes derived from the Doppler shifts of various γ rays (τ_{exp}) and comparison with those found in Ref. [17] ($\tau_{ref.}$) for ^{76}Ge.

E_{level} (keV)	E_γ (keV)	$F(\tau)$	τ_{exp} (fs)	$\tau_{ref.}$ (fs)
3007.8	3007.0(3)	0.711(45)	37^{+8}_{-7}	38^{+40}_{-19}
3141.51	2578.7(3)	0.325(24)	172^{+19}_{-17}	90^{+100}_{-60}
3147	2037.5(3)	0.428(29)	120^{+14}_{-12}	
3147	2584.7(2)	0.238(35)	236^{+52}_{-39}	
3577	3014.0(3)	0.669(43)	44^{+8}_{-7}	

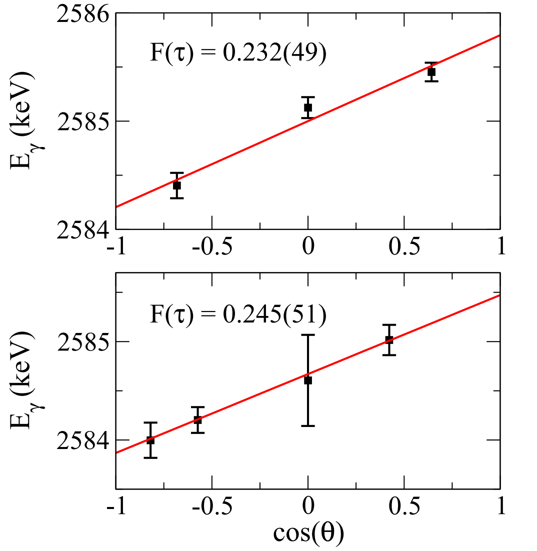

FIG. 5. (Color online) Experimental attenuation factor $F(\tau)$ for the newly observed 3147-keV level as measured from the 2584.7-keV γ ray for the first and second experiments.

Thus, it must be a newly observed γ ray to the 562.93-keV 2_1^+ level in ^{76}Ge. This result means that there exists another new level at 3577 keV. This level is mentioned only because of its speculative possibilities. If this new 3577-keV level has a transition to the 1539.46(6)-keV $3_1^{(+)}$ level, there would be another γ ray near 2037.5 keV.

In this work, using incident neutron energies from 4.3 to 4.9 MeV, the peak near 2039 keV is observed to be abnormally broad. Across all angles and incident neutron energies, the peak has a width nearly 1 keV greater than nearby peaks. Typically, this observation indicates a doublet, though no firm doublet assignment can be made. Figure 6 shows the width of the 2037.5(3)-keV peak as fit in the excitation function spectrum shown in Fig. 2. Indeed, the width appears to increase

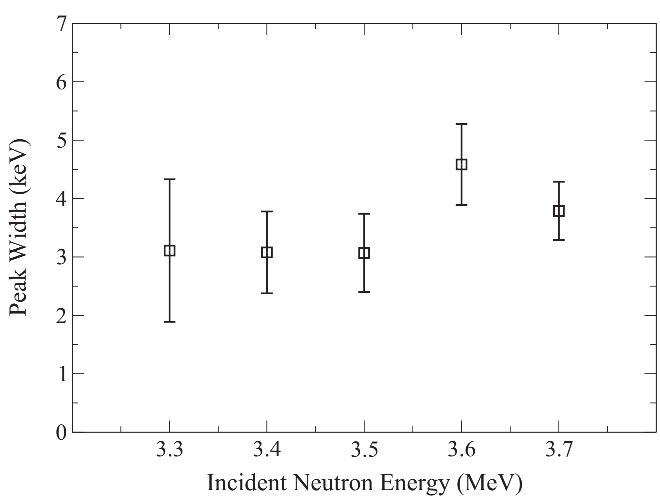

FIG. 6. Widths of the 2037.5(5)-keV peak. The increase in width at 3.6 MeV likely corresponds to an unresolved doublet due to another γ ray from the 3577-keV level.

TABLE II. ^{76}Ge photopeak cross section near the 2039-keV ROI. The contributors are the 2037.5(5)-keV γ ray from the 3147-keV level and, most probably to a lesser extent, the 2037.5(5)-keV γ ray from the 3577-keV level, as well as the previously known 2040.70-keV γ ray from the 3951.89-keV level.

E_n	σ (mb)	%(^{56}Fe $2_1^+\gamma$)
4.3	7.12(72)	0.501(20)
4.5	5.80(60)	0.406(18)
4.7	5.51(57)	0.385(18)
4.9	4.84(70)	0.334(38)

at $E_n = 3.6$ MeV and likely explains the sudden increase in the excitation function yield shown in the inset of Fig. 2. Furthermore, such a doublet could explain the differences in level lifetimes for the 3147-keV level as deduced from the 2037.5(5)- and 2584.7(3)-keV γ rays. Indeed, if the 3577-keV level lifetime is nearly 44 fs as measured by the 3014.0(3)-keV γ ray, a weak contaminant that shifts more in energy than the dominant peak across varying detection angles would alter the lifetime such that it appears shorter than it should due to the resultant centroid shifts. While not definitive, this work suggests the presence of a 2037.5-keV transition from the 3577-keV level to the 1539.46(6)-keV $3_1^{(+)}$ level.

While we were unable to completely resolve any potential multiplets in the spectral region near 2039 keV, the total $(n,n'\gamma)$ cross section of γ rays in this ROI was determined. The cross sections from all observed γ rays with incident neutron energies from 4.3 to 4.9 MeV are shown in Table II. Since the angular distribution corrections for the sample were shown to agree each time, the data presented in Table II is from the 125° data taken from the second data run using the $^{76}GeO_2$ target. The cross sections given are again normalized to the γ-ray cross section of the ^{56}Fe 846.76-keV γ ray [20].

B. Cross sections, lifetime, and angular distribution of the 3951.89-keV level in ^{76}Ge

From the data, we were able to observe only the three most intense γ rays (2843.50-, 3388.75-, and 3951.70-keV) from the 3951.89-keV level in ^{76}Ge, as shown in Fig. 7. There is at least one other γ ray in the spectra near 2040.70 keV, so this branch could not be directly determined. This new γ ray is of considerable interest and was discussed in Sec. III A. The weakest transition from the 3951.89-keV level (1259.9 keV) was also found to be obscured by the relatively strong 1259.1-keV γ ray from the 2669.2-keV level, which is not found in the Nuclear Data Sheets [17] but was recently placed by Toh *et al.* [21], and is confirmed by this work. The 2843.50-keV γ ray lies in a region of the spectrum where there are several additional peaks. While it is observed above background, the statistics are quite poor and it was not included in any of the final cross sections reported.

The averaged level cross sections for the 3951.89-keV level from 4.3 to 4.9 MeV incident neutron energy are shown in Fig. 8, where the values given are normalized to the γ-ray cross section of the ^{56}Fe 846.76-keV γ ray presented in Ref. [20]. It is important to note that each calculated level cross section was

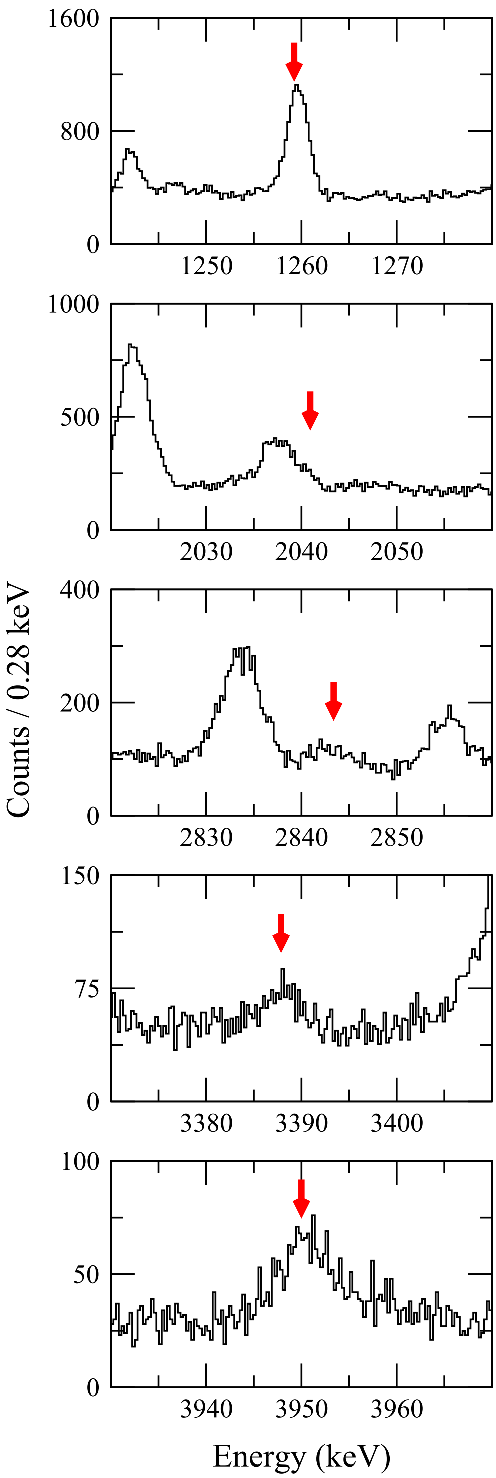

FIG. 7. (Color online) Gamma-ray spectra from the ^{76}Ge$(n,n'\gamma)$ reaction at an incident neutron energy of 4.5 MeV and a detection angle of 125°. The regions shown are centered around energies of γ rays deexciting the 3951.89-keV level in ^{76}Ge.

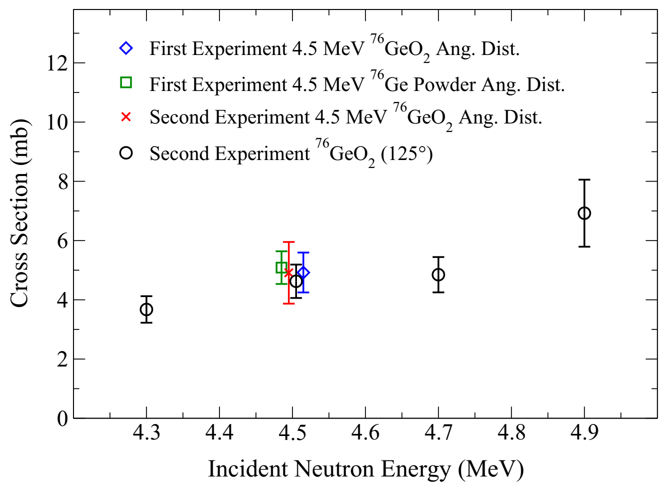

FIG. 8. (Color online) Inelastic neutron scattering cross section for the 3951.89-keV level in ^{76}Ge determined from the 3388.75-keV and 3951.70-keV γ-ray yields and branching ratios from Camp and Foster [16].

made using the branching ratios for the 3951.89-keV level in ^{76}Ge determined by Camp and Foster [16]. Using that branching ratio, we deduced INS cross sections for the 2040.70-keV γ ray [16]. These values can be found in Table III and are shown graphically in Fig. 9.

Despite the lack of observation of the proposed γ rays from the 3951.89-keV level, the relative intensity of the 3389.75-keV γ ray to that of the 3951.70-keV γ ray was determined from the 125° data from the second experiment and is shown in Table IV. Intensity ratios were measured at 125°, because at this angle $a_2\cos(\theta) \sim 0$. In general, our results agree well with the Camp and Foster [16] value of 67(4), albeit with larger uncertainties.

In addition to the cross sections, the lifetime of the 3951.89-keV level was measured using the Doppler-shift attenuation method mentioned in Sec. II. Figure 10 shows the measured experimental attenuation factor, $F(\tau)$, for the three most intense γ rays at an incident neutron energy of 4.5 MeV. The $F(\tau)$ values agree within uncertainty for each of the γ rays, which supports the conclusion that all of the γ rays deexcite the same level and that they are not multiplets. When determining an average lifetime from the two experiments, the most intense γ rays were used. Table V summarizes the

TABLE III. Cross sections for the 2040.70-keV γ ray from the 3951.89-keV level in ^{76}Ge, as well as for the level itself. The values presented here are based on the γ-ray branching ratios of Camp and Foster [16].

Target	E_n (MeV)	Angle	σ (mb) 2040.70 -keV γ-ray	σ (mb) 3951.89 -keV Level
^{76}GeO$_2$	4.3	125°	0.134(38)	3.67(45)
^{76}GeO$_2$	4.5	125°	0.168(47)	4.63(56)
^{76}GeO$_2$	4.5	50°, 90°, 133°	0.179(52)	4.92(67)
^{76}GeO$_2$	4.5	65°, 125°, 147°	0.179(59)	4.91(110)
^{76}Ge powder	4.5	90°	0.185(51)	5.09(55)
^{76}GeO$_2$	4.7	125°	0.176(50)	4.85(60)
^{76}GeO$_2$	4.9	125°	0.252(76)	6.92(129)

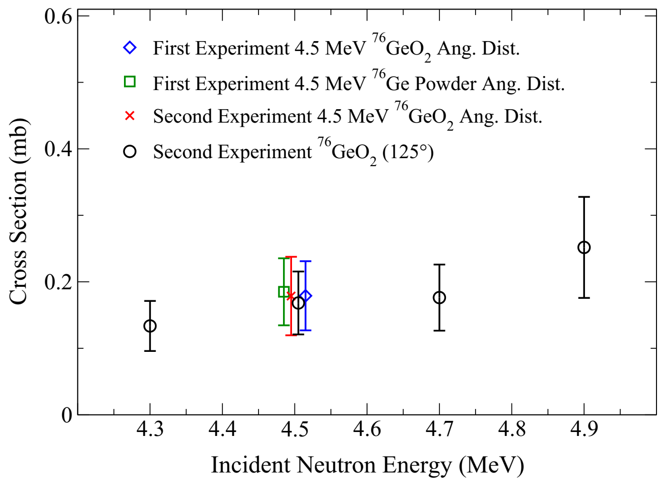

FIG. 9. (Color online) Inelastic neutron scattering cross section for the 2040.70-keV γ ray based on the branching ratios found by Camp and Foster [16].

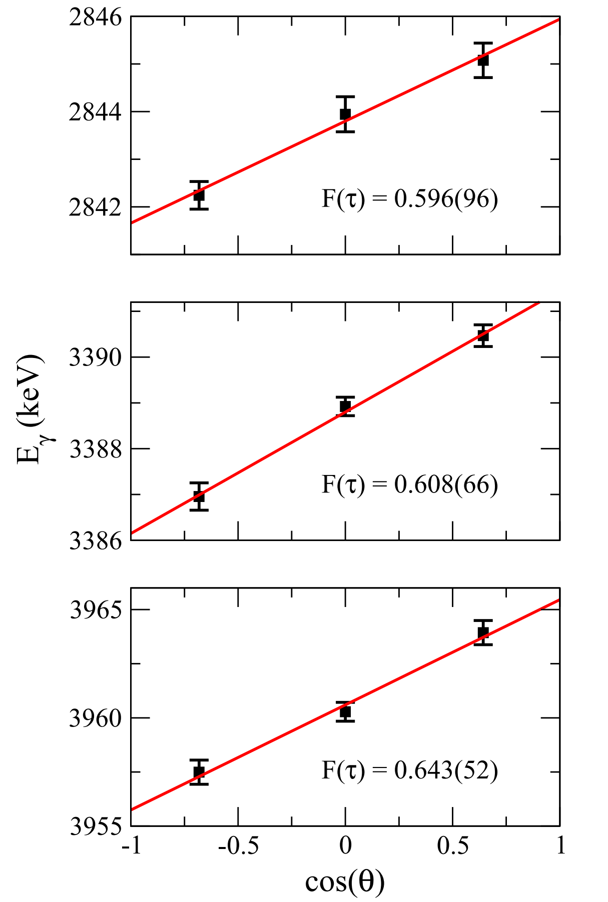

FIG. 10. (Color online) Experimental attenuation factor $F(\tau)$ for the 3951.89-keV level as measured from the 2843.50-, 3388.75-, and 3951.70-keV γ rays. The plots shown are from the 4.5-MeV data taken during the first data run.

lifetime results, where the accepted value is derived from a weighted average of the $F(\tau)$ values.

Much effort was put into extracting angular distribution information for the γ rays from the 3951.89-keV level in order to make a firm spin assignment beyond the previous $(1,2^+)$ assignment by combining the measurements at various angles from the two data runs. Unfortunately, due to poor statistics, contaminants from other γ rays, and the resultant large uncertainties, no firm conclusions could be drawn.

IV. SUMMARY

Inelastic neutron scattering on ^{76}Ge was performed at incident neutron energies up to 4.9 MeV with the goal of identifying potential backgrounds for ^{76}Ge $0\nu\beta\beta$ decay searches. New in this work is the firm identification of a level at 3147 keV. This new level decays via γ rays to the 2_1^+ and 2_2^+ levels with energies of 2584.7(2) and 2037.5(3) keV, respectively. The attenuation factors measured for these two γ rays are not in agreement, however. This disagreement is most likely attributable to a γ ray from another newly observed level at 3577 keV. This level, whose identification was based on an observed 3014.0(3)-keV transition to the 2_1^+ level at a threshold of 3.6 MeV from the excitation function data, could also have a branch to the 1539.46(6)-keV $3_1^{(+)}$ level. Analysis of the excitation function data of the 2037.5(3)-keV γ ray indicates sudden increases in both intensity and width at 3.6 MeV, supporting the existence of this second 2037.5-keV transition. The γ-ray cross section in the 2039-keV ROI was measured to be between 5 and 7 mb across the range of incident neutron energies studied.

The cross section for the 2040.70-keV γ ray that originates from the 3951.89-keV level, which was previously identified as the 69th level in ^{76}Ge, was also determined. While unambiguous observation of this γ ray was not possible, the three most intense γ rays from this level were observed. Using the branching ratios from Camp and Foster [16], we obtained level cross sections. Once again, using the previously determined [16] branching ratio to obtain the cross section, the 2040.70-keV γ-ray cross section is measured to be nearly

TABLE IV. Relative intensities of the 3389.75-keV γ ray with respect to the 3951.70-keV γ ray for various incident neutron energies at a detection angle of 125 °.

E_n	$\frac{I_\gamma(3389.75)}{I_\gamma(3951.70)}$
4.3	62(12)
4.5	47(8)
4.7	80(14)
4.9	65(18)

TABLE V. Lifetime of the 3951.89-keV level in ^{76}Ge.

Experiment	$F(\tau)$	τ (fs)
First	0.643(52)	42^{+10}_{-8}
Second	0.724(76)	30^{+12}_{-10}
Accepted	0.669(43)	40(7)

0.2 mb across the range of neutron energies measured in this work and is much smaller than the cross sections of the newly identified potential background γ rays. The deduced cross section of the 2040.70-keV γ ray from this work is consistent with the limit of 3.0 mb from Rouki *et al.* [15], yet the larger cross section measured in the 2039-keV region further suggests greater complexity than just the 2040.70-keV γ ray, which was the only previously identified γ ray in the 2039-keV ROI. A lifetime for the 3951.89-keV level was determined to be $\tau = 40(7)$ fs and, although an effort was made, no convincing γ-ray angular distribution information could be extracted to determine the spin and parity of the level.

Overall, the results from this work further emphasize the importance for sufficient neutron shielding and good position resolution of the detector [15] as important considerations for extracting a reliable ^{76}Ge $0\nu\beta\beta$ decay rate, if indeed such a process is to be observed. While a γ ray in the 2039-keV ROI resulting from a ^{76}Ge$(n,n'\gamma)$ reaction would likely result in multiple interactions within the Ge detectors of the large-scale experiments and thus be vetoed, there is a small chance that the γ ray would deposit its full energy in a single site such that it would not be vetoed. This contribution would need to be simulated, where the cross sections presented in this work provide critical input.

Finally, it is worth mentioning that the structure of these new levels is important with regards to the reactions that may populate these levels strongly (recalling that the $(n,n'\gamma)$ reaction is nonselective). While no additional information about the structure was obtained in this work, other experiments performed at UKAL will yield such information.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of H.E. Baber in maintaining the University of Kentucky Accelerator. This material is based upon work supported by the U.S. National Science Foundation under Grant No. PHY-1305801.

[1] F. T. Avignone, S. R. Elliott, and J. Engel, Rev. Mod. Phys. **80**, 481 (2008).

[2] S. Elliott and J. Engel, J. Phys. G **30**, R183 (2004).

[3] H. V. Klapdor-Kleingrothaus, I. V. Krivosheina, A. Dietz, and O. Chkvorets, Phys. Lett. B **586**, 198 (2004).

[4] N. Abgrall, E. Aguayo, F. T. Avignone III, A. S. Barabash, F. E. Bertrand, M. Boswell, V. Brudanin, M. Busch, A. S. Caldwell, Y.-D. Chan *et al.* (MAJORANA Collaboration), Adv. High Energy Phys. **2014**, 365432 (2014).

[5] K.-H. Ackermann, M. Agostini, M. Allardt, M. Altmann, E. Andreotti, A. M. Bakalyarov, M. Balata, I. Barabanov, M. B. Heider, N. Barros *et al.* (GERDA Collaboration), Eur. Phys. J. C **73**, 1 (2013).

[6] M. Agostini, M. Allardt, E. Andreotti, A. M. Bakalyarov, M. Balata, I. Barabanov, M. B. Heider, N. Barros, L. Baudis, C. Bauer *et al.* (GERDA Collaboration), Eur. Phys. J. C **74**, 1 (2014).

[7] M. Agostini, M. Allardt, E. Andreotti, A. M. Bakalyarov, M. Balata, I. Barabanov, M. B. Heider, N. Barros, L. Baudis, C. Bauer *et al.* (GERDA Collaboration), J. Phys. G: Nucl. Part. Phys. **40**, 035110 (2013).

[8] W. Xu, N. Abgrall, E. Aguayo, F. T. Avignone III, A. S. Barabash, F. E. Bertrand, M. Boswell, V. Brudanin, M. Busch, D. Byram *et al.* (MAJORANA Collaboration), Phys. Procedia **61**, 807 (2015).

[9] C. Cuesta, N. Abgrall, E. Aguayo, F. T. Avignone III, A. S. Barabash, F. E. Bertrand, M. Boswell, V. Brudanin, M. Busch, D. Byram *et al.* (MAJORANA Collaboration), Phys. Procedia **61**, 821 (2015).

[10] M. Agostini, M. Allardt, E. Andreotti, A. Bakalyarov, M. Balata, I. Barabanov, M. Barnabé Heider, N. Barros, L. Baudis, C. Bauer *et al.* (GERDA Collaboration), Phys. Rev. Lett. **111**, 122503 (2013).

[11] D.-M. Mei and A. Hime, Phys. Rev. D **73**, 053004 (2006).

[12] D.-M. Mei, S. R. Elliott, A. Hime, V. Gehman, and K. Kazkaz, Phys. Rev. C **77**, 054614 (2008).

[13] V. E. Guiseppe, M. Devlin, S. R. Elliott, N. Fotiades, A. Hime, D.-M. Mei, R. O. Nelson, and D. V. Perepelitsa, Phys. Rev. C **79**, 054604 (2009).

[14] A. Negret, C. Borcea, and A. J. M. Plompen, Phys. Rev. C **88**, 027601 (2013).

[15] C. Rouki, A. R. Domula, J. C. Drohé, A. J. Koning, A. J. M. Plompen, and K. Zuber, Phys. Rev. C **88**, 054613 (2013).

[16] D. C. Camp and B. P. Foster, Nucl. Phys. A **177**, 401 (1971).

[17] B. Singh, Nucl. Data Sheets **74**, 63 (1995).

[18] T. Belgya, G. Molnár, and S. W. Yates, Nucl. Phys. A **607**, 43 (1996).

[19] K. B. Winterbon, Nucl. Phys. A **246**, 293 (1975).

[20] R. Beyer, R. Schwenger, R. Hannaske, A. R. Junghans, R. Massarczyk, M. Anders, D. Bemmerer, A. Ferrari, A. Hartmann, T. Kögler *et al.*, Nucl. Phys. A **927**, 41 (2014).

[21] Y. Toh, C. J. Chiara, E. A. McCutchan, W. B. Walters, R. V. F. Janssens, M. P. Carpenter, S. Zhu, R. Broda, B. Fornal, B. P. Kay *et al.*, Phys. Rev. C **87**, 041304 (2013).