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Inelastic neutron scattering studies of ^{76}Ge and ^{76}Se: relevance to neutrinoless double-β decay

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Abstract. Inelastic neutron scattering measurements were performed at the University of Kentucky Accelerator Laboratory on enriched ^{76}Ge and ^{76}Se scattering samples. From measurements at incident neutron energies from 2.0 to 4.0 MeV, many new levels were identified and characterized in each nucleus; level lifetimes, transition probabilities, multipole mixing ratios, and other properties were determined. In addition, γ-ray cross sections for the ^{76}Ge(n,n′γ) reaction were measured at neutron energies up to 5.0 MeV, with the goal of determining the cross sections of γ rays in 2040-keV region, which corresponds to the region of interest in the neutrinoless double β decay of ^{76}Ge. Gamma rays from the three strongest branches from the 3952-keV level were observed, but the previously reported 2041-keV γ ray was not. Population cross sections across the range of incident neutron energies were determined for the 3952-keV level, resulting in a cross section of ~0.1 mb for the 2041-keV branch using the previously determined branching ratios. Beyond this, the data from these experiments indicate that previously unreported γ rays from levels in ^{76}Ge can be found in the 2039-keV region.

1 Introduction

1.1 Nuclear structure of the stable A = 76 nuclei

The ^{76}Ge and ^{76}Se nuclei lie between the magic numbers of 28 and 50, and shape coexistence plays a prominent role in their structure [1]. Recently, it was proposed by Toh *et al.* [2] that ^{76}Ge may be a rare example of a nucleus exhibiting rigid triaxial deformation in its low-lying states, *i.e.*, it follows the rigid triaxial model of Davydov and Filipov [3] with a well-defined potential minimum at a non-zero value of γ. The defining feature on which this claim is based is the energy staggering in the γ band. Motivated by this experimental result, Nikšić and coworkers [4] performed calculations within the framework of nuclear density functional theory for the $^{72-82}$Ge isotopes. Their analysis did not confirm the evidence for rigid triaxial deformation at low energy in ^{76}Ge; in fact, they arrived at the conclusion that the mean-field potential of ^{76}Ge is γ soft, more in keeping with the γ-unstable rotor model of Wilets and Jean [5]. For these reasons, a detailed study of the nuclear structure of this nucleus is easily justified. At the same time, measurements which lead to a characterization of the low-lying level schemes of ^{76}Ge and ^{76}Se can also supply structural information relevant to the calculation of the nuclear matrix elements for the neutrinoless double-β decay (0νββ) rate.

1.2 Neutrinoless double-β decay

The observation of neutrino oscillations has revealed that neutrino flavors mix and neutrinos have mass; however, oscillation experiments yield only information on $(\Delta m)^2$, and thus the absolute mass scale remains unknown [6]. Double-β decay with the emission of two β^- particles and two electron antineutrinos is among the rarest forms of radioactive decay and has been observed for only a handful of nuclei. Neutrinoless double-β decay, 0νββ, a lepton-number-violating nuclear process that has not yet been observed, will occur only if the neutrinos have mass and are Majorana particles, *i.e.,* they are their own antiparticles. The observation of 0νββ provides the best method for obtaining the mass of the neutrino, and it is the only practical way to establish if neutrinos are Majorana particles. The rate of 0νββ, if driven by the exchange of light Majorana neutrinos, is approximately

$$(T_{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta},Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2 \quad , \qquad (1)$$

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where $G_{0\nu}(Q_{\beta\beta},Z)$ is the known phase-space factor for the emission of the two electrons, $\langle m_{\beta\beta}\rangle$ is the effective Majorana mass of the electron neutrino, and $M_{0\nu}$ is a nuclear matrix element which must be calculated from nuclear structure models. A focus of many of our recent measurements has been to provide the detailed nuclear structure data for guiding these model calculations.

The approaches employed most frequently during the past two decades to calculate $M_{0\nu}$'s for both νvββ and 0vββ decay are derivatives of the shell model (*e.g.*, Ref. [7]) or the quasi-particle random-phase approximation (QRPA) [8]. Recently, calculations within the framework of the interacting boson model (IBM-2) have been introduced [9, 10].

For a variety of reasons, several 0vββ searches focus on the decay of ^{76}Ge. The use of ^{76}Ge as both the source of the radiation and the detector, for which the technology is well developed, serves to maximize detection sensitivity for the expected rare events. Moreover, ^{76}Ge is the only nuclide with a reported, although widely criticized, 0vββ half-life, 1.19 x 10^{25} years [11]. Recent measurements by the GERDA collaboration [12] yield a limit for the half-life that does not support the earlier work of Ref. [11]. Limits on the neutrino mass established from the EXO-200 experiment [13, 14] also contradict the reported half-life for 0vββ of ^{76}Ge [11].

Nuclear structure calculations are crucial to our understanding of 0vββ (if it is observed) and in determining the mass of the neutrino. Data constraining the nuclear model calculations for double-β decay become of particular importance as experimental searches for 0vββ, *e.g.*, the MAJORANA and GERDA collaborations, are coming online or are pushing to increasing sensitivities. With colleagues from Yale University, Triangle Universities Nuclear Laboratory (TUNL), the Technische Universität Darmstadt, and the Australian National University, the University of Kentucky group has initiated a diverse program for obtaining detailed spectroscopic data relevant to 0vββ decay of ^{76}Ge.

1.3 Background Issues in double-β decay

The "signal" of ^{76}Ge 0vββ is a single peak at $Q_{\beta\beta}$, 2039.06 ± 0.01 keV [15], in the spectrum of the ^{76}Ge-enriched HPGe detectors (see Figure 1 [16]). As even weak background γ rays occurring near $Q_{\beta\beta}$ can complicate the analysis of 0vββ experiments, it is important to assess, quantify, and eliminate these possible obstacles [6]. A 2040.70 ± 0.25 keV γ ray has been placed as de-exciting the 3952-keV level in ^{76}Ge [17]. Camp and Foster [17] first established the existence of the 3952-keV level by observing its population in ^{76}Ge following the subsequent β decay from ^{76}Ga ($T_{½}$ = 32.6 s, J^{π} = (2^+, 3^+), Q_β = 7.0 MeV). As shown in Fig. 2, the 3952-keV level is reported to have five de-exciting γ rays. Of course, of particular concern is the 2041-keV γ ray, which lies very near the ^{76}Ge region of interest for 0vββ observation. Admittedly, the 3952-keV level is approximately the 70th excited level of ^{76}Ge and the 2041-keV ray is a 4% branch, so its intensity is expected to be low. In the tonne-scale experiments envisioned, however, this level could be excited by inelastic scattering of fast neutrons produced by the (α,n) reaction on light elements, where α particles arise from natural radioactivity in the surroundings, or from cosmic-ray muon-induced neutrons. Also, ^{76}Ga can be produced by the ^{76}Ge(n,p) reaction, but higher-energy neutrons, E_n > 6.2 MeV, are required. In view of the expected long half-life of 0vββ, a small contribution of a γ ray of this energy could be problematic.

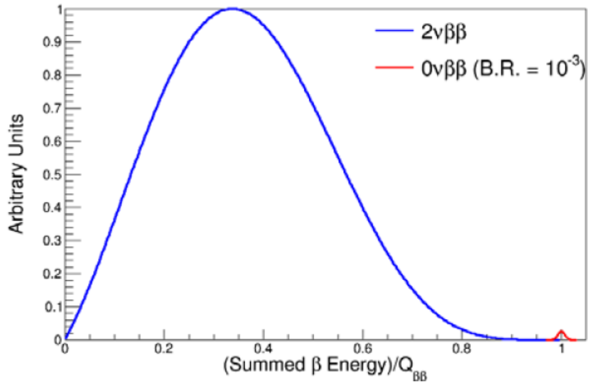

Figure 1. Hypothetical two-neutrino (blue) and neutrinoless (red) double-β decay energy spectrum. The resolution and ratio of decay rates (assumed to be 10^{-3} in the plot above) affect the potential overlap of the blue and red curves in the region around $Q_{\beta\beta}$ [16].

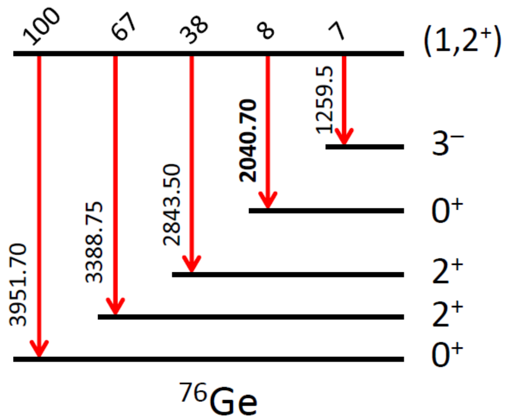

Figure 2. Decays of the 3951.9-keV level of ^{76}Ge. The branchings shown are those obtained by Camp and Foster from the β^- decay of ^{76}Ga [17].

Mei and Hime [18] recognized γ rays produced from inelastic scattering of cosmic-ray produced neutrons become important for backgrounds in tonne-scale experiments and later assessed background contributions to the continuum from both Ge(n,n′) and Pb(n,n′) and identified a few particularly pernicious γ rays (2041 keV in ^{206}Pb and a double-escape peak from a 3062-keV transition) from ^{207}Pb(n,n′)[19]. Subsequently, Guiseppe *et al.* [20] performed an investigation of the γ rays produced by several Pb isotopes, which can be found in a Pb-shielded 0vββ experiment, and measured their cross sections as a function of energy across the range of neutron energies likely to be encountered in the ^{76}Ge experiments. Inelastic neutron scattering studies at GELINA were also carried out to assess background interferences from many materials typically found in experimental setups near the 0νββ experimental signatures of ^{76}Ge and ^{130}Te [21] and, more specifically, on potential background contributors from Ge isotopes [22]. In this latter study, the authors spent a great deal of effort characterizing the contributions to background near 2039 keV from the 3952-keV level in ^{76}Ge. Rouki *et al.* [23] were unable to directly observe the transitions from the 3952-keV level and instead placed limits of a few millibarns. The present measurements address the same questions.

The primary goal of our work was to measure (n,n′γ) cross sections for the 3952-keV level over a neutron energy range of 4 to 5 MeV and to establish cross sections for any potential interferences to the 0νββ experimental signature within this neutron energy range.

2 Neutron scattering measurements

2.1 Nuclear structure measurements

With the inelastic neutron scattering reaction, nuclear levels can be non-selectively populated up to the incident neutron energy, and lifetimes in the femtosecond regime can be determined. Most low-spin excited states can be observed and transition probabilities can be extracted.

At the University of Kentucky Accelerator Laboratory (UKAL), we have studied the nuclear structure of ^{76}Ge and ^{76}Se, the double-β decay daughter, with the (n,n′γ) reaction. Our contributions include an expansion of the low-lying level schemes of these nuclei, measurements of level lifetimes from which transition probabilities can be deduced and compared with model predictions, and the observation of experimental quantities which may affect the actual 0νββ searches. Complementary photon scattering experiments were conducted on these nuclei with high-intensity bremsstrahlung at the TU Darmstadt and with linearly polarized photons at the High Intensity Gamma Source (HIγS) at the Duke Free Electron Laser Facility at TUNL. Filling in the gaps in our knowledge of the low-lying levels of these nuclei with new spectroscopic data provides valuable constraints on model descriptions, permitting credible calculations of $M_{0\nu}$'s. In addition to yielding information relevant to 0νββ, these measurements led to new structural insights into ^{76}Se and ^{76}Ge, which exhibit intriguing band-like structures and shape coexistence [24].

2.2 Cross section measurements

As noted earlier, the (n,n′γ) reaction has been identified as an important potential source of background interference in the observation of 0νββ. Given the rarity with which 0νββ is predicted to occur, knowledge of all interferences in the region of interest is critical. Of particular concern is the aforementioned 3952-keV level in ^{76}Ge [17], with a small (~4%) 2041-keV γ-ray branch that is unlikely to be completely resolved from the 0νββ experimental signature. Recent studies to measure the cross section of this γ ray resulted in an upper limit of 3 mb, but the 2041-keV γ ray was not directly observed [23].

Inelastic neutron scattering experiments on enriched samples of ^{76}Ge were performed during two separate runs at 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 a scattering sample. Two days of beam time during the first data run were devoted to scattering from an elemental ^{76}Ge disc of mass 11.13 g, radius = 1.1 cm, and enriched to 84.12(23)% in ^{76}Ge. For the remainder of the data runs, the scattering sample was 41.84 g of $^{76}GeO_2$ powder with radius = 1.25 cm, height = 4.8 cm, enriched to 85% in ^{76}Ge and contained within a polyethylene vial. Emitted γ rays were detected using a single HPGe detector with an annular BGO shield for Compton suppression.

In the first data run, spectra were accumulated at an incident neutron energy of 4.5 MeV at angles of 50^o, 90^o, and 133^o for the enriched oxide sample and 90^o only for the ^{76}Ge disk. During the second run, data were taken at 125^o for incident neutron energies of 4.3, 4.5, 4.7, and 4.9 MeV, as well as additional angles of 65^o, 147^o, and a short 90^o measurement performed for normalization with the first run in an effort to extract angular distribution information. Apart from this last 90^o measurement, each data measurement was performed for 24 hours in order to obtain sufficient population of the 3952-keV level, which has a low cross section. At each incident neutron energy, a 57.00 g cylindrical sample of natural iron with a radius of 0.95 cm and a height of 2.54 cm was employed for normalization of the ^{76}Ge cross sections with ^{56}Fe, which is considered a cross section standard. During the first data run, this ^{56}Fe measurement was performed at 90^o at an incident neutron energy of 4.5 MeV. A long counter was used to determine the relative neutron fluences when comparing the ^{76}Ge and ^{56}Fe reactions.

3 Data analysis

We searched for the production of γ rays through the (n,n′γ) reaction with monoenergetic accelerator-produced neutrons of 4.0 to 4.9 MeV. The three most intense γ rays from the 3952-keV level, approximately the 70th excited state, were observed; however, the 2041-keV branch was not observed with certainty (see Fig. 3 and discussion). From the data obtained and the accepted branching ratios [17], we were able to determine the γ-ray production cross section at several incident neutron energies, even though the 2041-keV γ was below our detection sensitivity. The 3952-keV state has also been excited through the (γ,γ′) reaction at the TU Darmstadt and at HIγS. At HIγS, excitation with monoenergetic photons often permits a measurement in the absence of interfering backgrounds; however, the 2041-keV branch was below the sensitivity limits.

For the relevant peaks from the 3952-keV level in ^{76}Ge, only the three most intense γ rays at 2843.50, 3388.75, and 3951.70 keV could be fit. There exists at least one additional γ ray in the spectra near 2041 keV, so this branch cannot be directly determined. This new γ ray is of considerable interest and will be revisited later. The weakest transition from the 3952-keV level (1259.5 keV) was also found to be obscured by the relatively strong 1259-keV γ ray from the 2669-keV level, which is not found in the Nuclear Data Sheets [25] but was recently placed by Toh *et al.* [2]. The 2844-keV γ ray also lies in a region of the spectrum where there are several additional peaks. While it is observed above background, the statistics are meager.

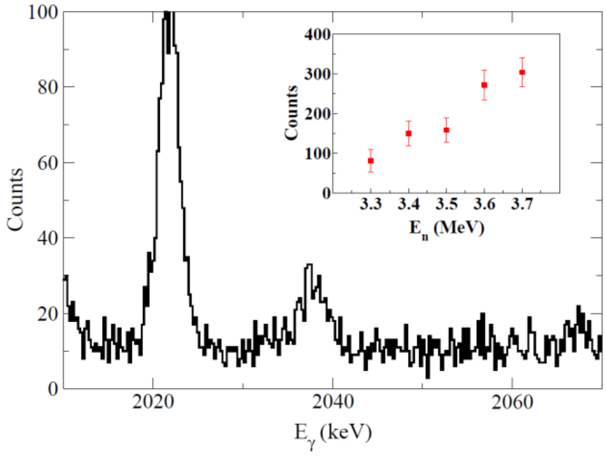

Figure 3. The 2040-keV region of the γ-ray spectrum from the ^{76}Ge(n,n′γ) reaction performed at the University of Kentucky Accelerator Laboratory with 3.7 MeV neutrons at a detector angle of 90°. The excitation function for the 2038-keV γ ray is shown in the inset.

Energy and detector efficiency calibrations were performed using a ^{226}Ra source. Since the γ rays of interest have energies that lie outside of the range of relatively intense ^{226}Ra γ rays, extrapolations of the efficiencies and energy nonlinearities were necessary. This procedure is particularly relevant for the efficiency and making this extrapolation warrants an increase in the uncertainties. In addition to energy and efficiency calibrations, other considerations such as incident neutron attenuation, absorption and multiple scattering of γ rays, and angular distribution effects where necessary; all were taken into account.

4 Results and discussion

From (n,n′γ) measurements on ^{76}Ge and ^{76}Se, a wealth of new spectroscopic information has been obtained, and many new levels were identified and characterized in each nucleus. These data, including level lifetimes, transition probabilities, multipole mixing ratios, and other properties will be provided in a forthcoming publication [24].

In addition, γ-ray cross sections for the ^{76}Ge(n,n′γ) reaction were determined at neutron energies up to 5.0 MeV, with the goal of determining the cross section of γ rays in the 2040-keV region, which corresponds to the region of interest in the neutrinoless double-β decay of ^{76}Ge. Gamma rays from the three strongest branches from the 3952-keV level were observed, but the previously reported 2041-keV γ ray was not. Population cross sections of 4 to 7 mb across the range of incident neutron energies were assigned to the 3952-keV level, resulting in a cross section of ~0.1 mb for the 2041-keV branch using the previously determined branching ratios [17]. Beyond this, the data from these experiments indicate that previously unreported γ rays occur in the 2039-keV region.

A new result from this work is the observation of a ^{76}Ge γ ray at 2037.5 ± 0.3 keV, which complicates any direct assessment of the previously assigned 2041-keV transition from the 3952-keV level. This new γ ray has been assigned to ^{76}Ge from the relative intensities with which it is seen in both the ^{nat}Ge and $^{76}GeO_2$ samples, where the ratio between the intensities (normalized to the total number of neutrons) is nearly within uncertainty to the ratio of the mass of ^{76}Ge in each of the samples. The same ratio comparison disagrees by at least an order of magnitude for all other Ge isotopes.

This new γ ray is much more intense in our spectra than the 20401-keV γ ray from the 3952-keV level. Placement of the new 2038-keV γ ray is supported by its appearance in the ^{76}Ge(n,n′γ) excitation function measurements. Unobserved at neutron energies less than 3.1 MeV, the new γ ray appears at 3.3 MeV and becomes more intense as the neutron energy increases (see Figure 3). As the threshold is between incident neutron energies of 3.1 and 3.3 MeV, the level to which this new γ ray decays must be the 1108-keV 2^+ level in ^{76}Ge. This placement would suggest a new level near 3147 keV. Further examination of the excitation function spectra indicates another γ ray at 2584.7 ± 0.3 keV that appears at neutron energies between 3.1 and 3.2 MeV. This γ ray likely populates the 563-keV 2^+ first excited state from the same 3147-keV level. Figure 4 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 in the doublet is the known 2578.55-keV γ ray to the first excited state from the 3141.51-keV level.

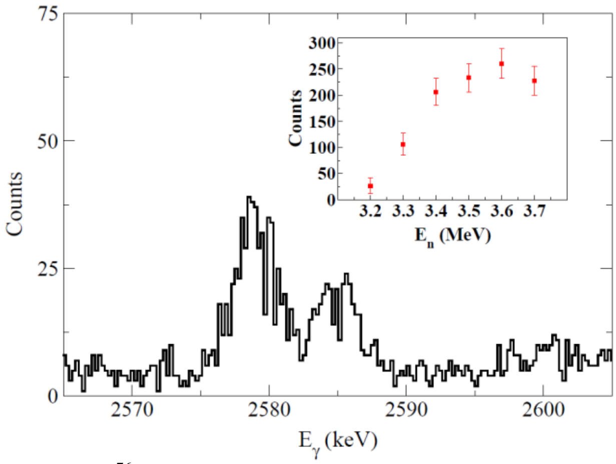

Figure 4. ^{76}Ge(n,n′γ) spectrum taken at an incident neutron energy of 3.7 MeV and a detection angle of 90° showing a new 2584.7 ± 0.3 keV γ ray. The inset shows the yield of this γ ray at incident neutron energies of 3.2 to 3.7 MeV.

If these two new γ rays do indeed establish a new level, the lifetimes measured through the Doppler shifts must be similar. From the two data runs for the 2038-keV and 2585-keV γ rays, the resultant lifetimes, while not exactly the same, are similar. Unless there are missing low-lying levels in ^{76}Ge (a possibility that is not supported by our excitation function data), these two γ rays must arise from the same 3147-keV level. The fact that the measured lifetimes are close provides some confirmation of the above. The measurements on the previously known transitions show good agreement, which provides further confidence in the present measurements.

The 2041-keV γ ray, which was reported to de-excite the 3952-keV level in ^{76}Ge, was not observed in our measurements. As its cross section was once thought crucial for understanding the background in neutrinoless double-β decay searches, a detailed study of the β^- decay of ^{76}Ga would prove worthwhile.

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