Relevance of the Nuclear Structure of the Stable Ge Isotopes to the Neutrinoless Double-Beta Decay of ^{76}Ge

S. W. Yates[1,*], E. E. Peters[1], B. P. Crider[1,2], S. Mukhopadhyay[1], and A. P. D. Ramirez[1]

[1]Departments of Chemistry and Physics & Astronomy, University of Kentucky, Lexington, KY 40506-0055 USA
[2]Department of Physics and Astronomy, Mississippi State University, Mississippi State, MS 39762 USA

Abstract. Gamma-ray detection following the inelastic neutron scattering reaction on isotopically enriched material was used to study the nuclear structure of ^{74}Ge. From these measurements, low-lying, low-spin excited states were characterized, new states and their decays were identified, level lifetimes were measured with the Doppler-shift attenuation method (DSAM), multipole mixing ratios were established, and transition probabilities were determined. New structural features in ^{74}Ge were identified, and the reanalysis of older ^{76}Ge data led to the placement of the 2^+ member of the intruder band. In addition, a number of previously placed states in ^{74}Ge were shown not to exist. A procedure for future work, which will lead to meaningful data for constraining calculations of the neutrinoless double-beta decay matrix element, is suggested.

1 Introduction

Double-beta decay with the emission of two β^- particles and two antineutrinos ($2\nu\beta\beta$) has been observed in a handful of nuclei [1]; however, the neutrinoless double-beta decay process without the emission of antineutrinos ($0\nu\beta\beta$) remains unobserved, although several large-scale international searches are in progress. $0\nu\beta\beta$, a lepton-number-violating nuclear process, will only occur if the neutrinos have mass, which has now been established from several sources, and if they are Majorana particles, i.e., they are their own antiparticles. In addition to being the only practical way to establish if neutrinos are Majorana particles, the observation of $0\nu\beta\beta$ promises to provide perhaps the best method for obtaining the mass of the neutrino.

The rate of $0\nu\beta\beta$ is approximately the product of three quantities [2], the phase space factor for the emission of two electrons, $G_{0\nu}$, the effective Majorana mass of the electron neutrino, $m_{\beta\beta}$, squared, and the nuclear matrix element (NME), $M_{0\nu}$, squared:

$$[T_{1/2}]^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2 m_{\beta\beta}^2.$$

The rate of $0\nu\beta\beta$ will be obtained with the first experimental observation of this process, and the mass of the neutrino will then become available, if the NME is known. The NMEs cannot be determined experimentally but must be calculated from nuclear structure models (see Ref. [2] for a recent review of the status and progress in calculating NMEs). Unfortunately, there is significant disagreement between the various theoretical approaches used in calculating the NMEs, with values differing by factors of two and greater (and the NMEs are squared in the rate equation). As the NMEs are obtained from nuclear structure calculations, a focus of many of our recent measurements at the University of Kentucky Accelerator Laboratory (UKAL) has been on providing detailed nuclear structure data to guide and constrain these model calculations.

At UKAL, we have performed γ-ray spectroscopic studies following inelastic neutron scattering from ^{76}Ge [3], which is widely regarded as one of the best candidates for the observation of $0\nu\beta\beta$ and is the focus of two large-scale searches [4, 5], and ^{76}Se, its double-beta decay daughter [6]. Configuration interaction shell-model calculations in the $jj44$ model space (see the Appendix of Ref. [3]) were performed with the shell-model code NUSHELLX for both the parent and daughter, i.e., ^{76}Ge and ^{76}Se. While the calculations explained the low-energy nuclear structure of ^{76}Ge quite well, they were not as successful for ^{76}Se. A notable problem is that the first 3^+ excited state in ^{76}Se is calculated to occur more than an MeV higher than it is observed experimentally, thus making it difficult to explain the experimentally observed "γ band".

As meaningful nuclear structure calculations should be able to explain the structure of a region of nuclei rather than just an isolated nucleus, we have initiated studies of other nuclei in the A = 76 region (see Fig. 1). The structure of this region is not simple, as previous work has provided evidence of shape transitions, shape coexistence, and triaxiality [7–12]. In the case of ^{74}Ge, the first additional nucleus in the region we have chosen to study, a great deal of information is available from other studies [13–18]; however, some of these works are very dated and there is need for improvement.

*e-mail: yates@uky.edu

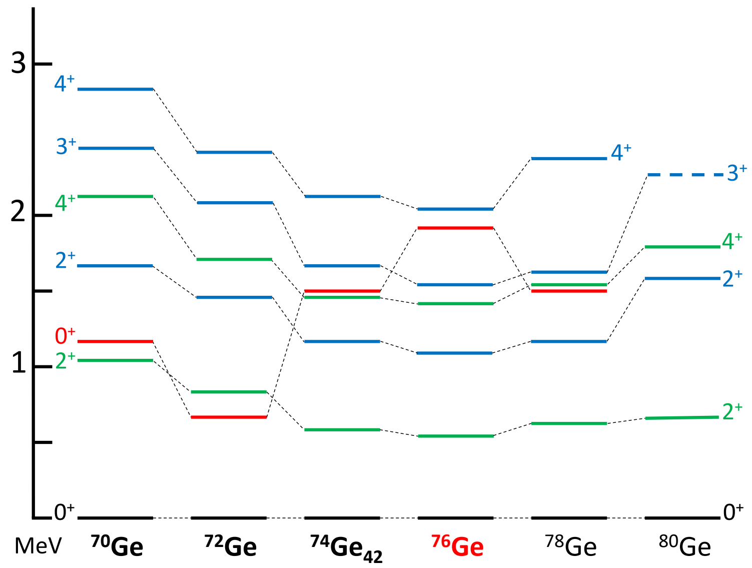

Figure 1. Low-lying excitations in ^{76}Ge and surrounding nuclei. Except for the lowest excited 0^+ states, which are generally attributed to shape coexistence, the level properties appear to be slowly varying. Data extracted from the National Nuclear Data Center's ENSDF database, www.nndc.bnl.gov/ensdf.

2 Experimental

The methods used in our $(n, n'\gamma)$ studies of ^{74}Ge are similar to those described in detail in our studies of ^{76}Ge [3] and ^{76}Se [6]; however, some comments are in order about the inelastic neutron scattering reaction as employed in our laboratory. As neutrons do not experience a Coulomb barrier, by varying the incident neutron energy the nucleus can be selectively excited to any energy. The detection of γ rays with HPGe detectors assures excellent energy resolution, although the incident neutrons typically have energy spreads of 50 to 100 keV. The reaction is statistical in nature and thus nonselective of the nuclear structure of the excited levels; it is limited to low-spins as the neutrons do not lead to large transfers of angular momentum. Large multigram scattering samples are usually employed; this restriction is not because the cross sections are small but because the neutron fluxes are limited in these secondary reactions. The neutrons are produced typically by the ^{3}He(p, n) reaction or the ^{2}H(d, n) reaction. The quality of the data is improved by employing isotopically enriched scattering samples, which are generally leased from the National Isotope Development Center at Oak Ridge National Laboratory.

The scattering samples for the present measurements were approximately 20 g of elemental Ge powder enriched to 98.90% in ^{74}Ge, and two types of measurements were performed. Excitation functions were obtained by increasing the incident neutron energy, while keeping the angle of measurement constant, and can be used to construct the level scheme from the observed γ-ray thresholds. Angular distributions were measured at a constant neutron energy, while the angle of detection is varied. Figure 2 illustrates a spectrum obtained from the ^{74}Ge$(n, n'\gamma)$ reaction.

3 New Structural Features

In addition to the known ground-state and γ bands, the 2^+ mixed-symmetry state in ^{74}Ge was identified at 2833 keV and is characterized by a $B(M1; 2^+_{ms} \to 2^+_1)$ of $(0.181 \pm 0.007)\,\mu_{N^2}$. A similar excitation was observed in ^{76}Ge at 2767 keV [3]. Moreover, the 2^+ and 4^+ members of the "band" built on the lowest excited 0^+ state at 1483 keV, usually described as an intruder or shape-coexisting structure, was observed. The 2^+ state at 2198 keV decays with a $B(E2; 2^+ \to 0^+)$ of (20 ± 3) W.u. and the 4^+ state at 3049 keV decays with a $B(E2; 4^+ \to 2^+)$ of (13 ± 4) W.u. The intruder band in ^{74}Ge is now the best characterized of any shape-coexisting structure of the even-A Ge nuclei.

With the identification of the shape-coexisting structure in ^{74}Ge and the determination of the $B(E2)$s within this band, a search for corresponding structures in ^{76}Ge was initiated from the data taken by Mukhopadhyay et al. [3] in our laboratory. Assuming that the band-head of this structure is the lowest 0^+ state at 1911 keV in ^{76}Ge, the next 2^+ state in the reported level scheme is at 2504 keV, which was observed to de-excite to the ground band and the γ band, but a γ ray to the 1911 keV state was not reported. From the summed spectra of all angles in the 3.0 MeV angular distribution, a γ ray at 593 keV was evident. This placement was verified from the excitation function, which showed a threshold near 2.5 MeV, and the branch to the 1911 keV 0^+ state was determined to be (6 ± 1) %. When these new results were combined with the measured lifetime for the 2504 keV state, a $B(E2)$ of (21 ± 10) W.u. was obtained.

4 Conclusions

From inelastic neutron scattering with γ-ray detection, we are able to establish the level scheme, determine γ-ray

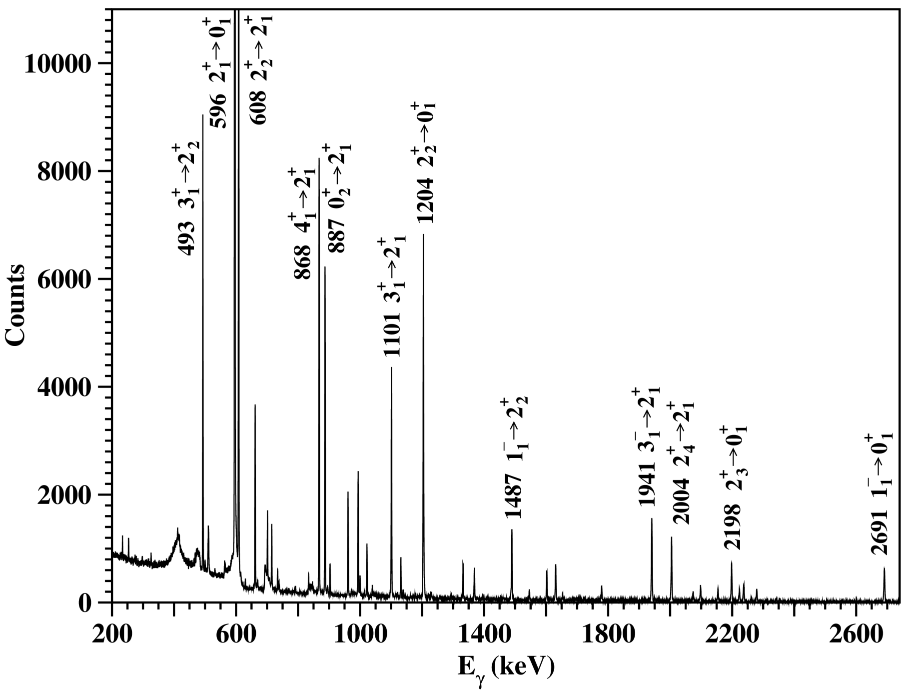

Figure 2. ^{74}Ge (n , n′γ) spectrum obtained with 3.0 MeV incident neutrons at a detection angle of 90°. γ rays of interest are labeled.

branching ratios, transition multipolarities, multipole mixing ratios, and level lifetimes. Ultimately, we also determine γ-ray reduced transition probabilities, which can be compared with nuclear structure calculations.

To date, experimental nuclear structure work has been a rather haphazard procedure, with nuclear spectroscopists studying a nucleus in detail with a particular reaction, publishing their data and interpretation, and moving on to the next project. Rarely is a systematic study performed for a mass region. To provide a more holistic approach to nuclear structure studies providing data for comparison with NME calculations, we suggest a different procedure.

First, we recommend that effort be directed at identifying **all** of the excited states up to some energy (e.g., 3 MeV) in as many nuclei in the region of interest as possible, but certainly those near the nuclei of interest, i.e., the parent and daughter of the neutrinoless double-beta decay. As most reactions have some selection rules associated with them, this requirement will not be possible in many cases; however, it is important to characterize, as fully as possible, those nuclear states that are observed. We suggest that considerable effort be directed at characterizing **all** of these states **completely**. This requirement is a significant challenge. Finally, it is important to compare these data with theoretical model calculations and establish some criteria for "success", i.e., benchmarking. Through this rigorous procedure (and the eventual experimental identification of $0\nu\beta\beta$), the mass of the neutrino can be determined with small uncertainties.

After laying out this demanding procedure, it is important to assess how successful our study of ^{74}Ge was in meeting the criteria outlined. By necessity, the details will be presented in a future, larger publication [19], so only a summary is given here. We remain cognizant of previous work and these contributions to our knowledge of the nuclear structure of ^{74}Ge [13–18].

We feel that we have identified all levels in ^{74}Ge up to 2.5 MeV in excitation and that we have correctly assigned spins and parities to these levels. The lifetime of one level (the first 3^+ excited state) below 2.8 MeV remains undetermined because it is too long lived for a DSAM lifetime determination. Nonetheless, we have established an upper limit on its lifetime. Similarly, there remains one level below 2.8 MeV that cannot be assigned a definite spin-parity. Obtaining this degree of clarity of the level scheme of ^{74}Ge also required the elimination of several states which appear in the data compilations. The necessity of eliminating these spurious levels has been discussed previously [20].

What is the status of additional studies like the one described here? The other stable Ge and Se are clear candidates for detailed nuclear structure studies with the (n , n′γ) reaction, and the experimental observation of $0\nu\beta\beta$ would hasten the process.

5 Acknowledgments

We sincerely thank H.E. Baber for his many contributions to these measurements. We also thank W.B. Walters for his interest in this work and for providing unpublished data for our use. The enriched isotope used in this research was supplied by the United States Department of Energy Office of Science by the Isotope Program in the Office of Nuclear Physics. This material is based upon work supported by the U.S. National Science Foundation under Grant no. PHY-1913028.

References

[1] F. T. Avignone, S. R. Elliott, J. Engel, Rev. Mod. Phys. **80**, 481 (2008).
[2] J. Engel, J. Menéndez, Rep. Prog. Phys. **80**, 046301 (2017).
[3] S. Mukhopadhyay, B. P. Crider, B. A. Brown, *et al.*, Phys. Rev. C **95**, 014327 (2017).
[4] S. I. Alvis, I. J. Arnquist, F. T. Avignone, *et al.* (Majorana Collaboration), Phys. Rev. C **100**, 025501 (2019).
[5] M. Agostini, A. M. Bakalyarov, M. Balata, *et al.*, Science **365**, 1445 (2019).
[6] S. Mukhopadhyay, B. P. Crider, B. A. Brown, *et al.*, Phys. Rev. C **99**, 014313 (2019).
[7] K. Heyde, J. L. Wood, Rev. Mod. Phys. **83**, 1467 (2011).
[8] J. B. Gupta, J. H. Hamilton, Nucl. Phys. A **983**, 20 (2019).
[9] A. D. Ayangeakaa, R. V. F. Janssens, C. Y. Wu, *et al.*, Phys. Lett. B **754**, 254 (2016).
[10] Y. Toh, C. J. Chiara, E. A. McCutchan, *et al.*, Phys. Rev. C **87**, 041304 (2013).
[11] A. M. Forney, W. B. Walters, C. J. Chiara, *et al.*, Phys. Rev. Lett. **120**, 212501 (2018).
[12] M. Lettmann, V. Werner, N. Pietralla, *et al.*, Phys. Rev. C **96**, 011301 (2017).
[13] J. J. Sun, Z. Shi, X. Q. Li, *et al.*, Phys. Lett. B **734**, 308 (2014).
[14] Y. G. Kosyak, L. V. Chekushina, A. S. Ermatov, Bull. Russ. Acad. Sci **67**, 151 (2003).
[15] R. Massarczyk, R. Schwengner, L. A. Bernstein, *et al.*, Phys. Rev. C **92**, 044309 (2015).
[16] D. Negi, M. Wiedeking, E. G. Lanza, *et al.*, Phys. Rev. C **94**, 024332 (2016).
[17] C. Hofmeyr, C. Franklyn, G. Barreau, *et al.*, Private communication to the Nuclear Data Sheets (1985).
[18] W. B. Walters, Private communication (2017).
[19] E. E. Peters, *et al.*, to be published (2020).
[20] S. W. Yates, *et al.*, Proceedings of the International Nuclear Physics Conference, Glasgow 2019 (2020).