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Probing the nuclear structure of candidates for neutrinoless double-beta decay with fast neutrons

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Abstract. The low-lying, low-spin levels of several nuclei which are either the possible parent or daughter for neutrinoless double-beta decay have been studied with the (n,n'γ) reaction. From these measurements, level spins, level lifetimes, γ-ray intensities, and multipole mixing ratios were determined; however, considerable effort must be expended in elaborating the level schemes before comparisons of the level characteristics with large-scale shell model calculations are meaningful.

1. Introduction

Double-β decay with the emission of two β^- particles and two electron antineutrinos (2νββ) is among the rarest forms of radioactive decay and has been attributed to only a handful of nuclei [1]. Neutrinoless double-β decay (0νββ) has not been observed but is being sought in several large-scale experiments. 0νββ, a lepton-number-violating nuclear process, will occur only if the neutrinos have mass and are Majorana particles, *i.e.*, they are their own antiparticles. The observation of neutrino oscillations has revealed that neutrino flavors mix and that neutrinos have mass; however, these experiments yield information only on $(\Delta m)^2$, and thus the absolute mass scale remains unknown. The observation of 0νββ would provide perhaps 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 is approximately the product of three factors: the known phase-space factor for the emission of the two electrons, the effective Majorana mass of the electron neutrino, and a nuclear matrix element (NME) squared. The NMEs cannot be determined experimentally and, therefore, must be calculated from nuclear structure models. A focus of many of our recent measurements has been on providing detailed nuclear structure data to constrain these model calculations.

At the University of Kentucky Accelerator Laboratory (UKAL), we have performed γ-ray spectroscopic studies following inelastic neutron scattering from several candidates for 0νββ with our most recent measurements focusing on ^{76}Ge [2], ^{76}Se [3], ^{136}Xe [4], and other nuclei in these regions, such as ^{74}Ge, ^{130}Xe [5], ^{132}Xe [5,6], and ^{134}Xe [7]. The experiments, from which a variety of spectroscopic quantities were extracted, employed solid isotopically enriched scattering samples, and the methods have been described previously [8]. From these measurements, low-lying excited states in these nuclei were characterized, new excited 0^+ states and their decays were identified, level lifetimes were measured with the Doppler-shift attenuation method, multipole mixing ratios were established, and transition probabilities were determined. However, for the nuclear structure determinations to be most

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meaningful, the level schemes of the parent and daughter of the 0νββ candidates must be firmly understood. One aim of this contribution is to show that the required level of detail is not easily obtained and that the results from a variety of nuclear structure investigations will be required.

2. Nuclear structure in the Ge region

The Ge nuclei exhibit a number of interesting structural features including shape coexistence [9], shape transitions [10], and possible triaxiality [11-14], but renewed interest in these nuclei has been motivated by the possibility that ^{76}Ge has emerged as one of the best candidates for 0νββ [1].

A focus of our recent measurements has been on providing detailed nuclear structure data to constrain the model calculations necessary for determining the NME; however, our recent studies of ^{76}Ge [2] and ^{76}Se [3] with the (n,n'γ) reaction have made it clear that additional information about other nuclei in the region will be useful in guiding these model calculations. To better characterize this transitional region, studies of the lighter stable Ge nuclei have been initiated; the study of ^{74}Ge with the (n,n'γ) reaction is the first of these additional studies and has yielded a wealth of new spectroscopic information, including level spins and parities, level lifetimes, multipole mixing ratios, and transition probabilities for a large number of states.

3. Experimental details and data analysis

The (n,n'γ) measurements were performed at the UKAL using methods which have been described in detail [8]. Fast neutrons produced via the ^{3}H(p,n)^{3}He reaction with a tritium gas target and a time-bunched proton beam impinged on a scattering sample, which typically consisted of 10 to 20 grams of enriched isotopic material. Promptly emitted γ rays were detected with a high-purity germanium (HPGe) detector of 50% relative efficiency and energy resolution of 2.0 keV (FWHM) at 1332 keV surrounded by a bismuth germanate (BGO) annulus, which functioned as a Compton suppressor and active shield.

Gamma-ray excitation functions were measured as the incident neutron energy was increased in 100 keV increments, and the placements of the γ rays were obtained from their energy thresholds. In addition, relative experimental level cross sections were compared with cross sections computed with the statistical model code CINDY to infer spins of the levels.

At several incident neutron energies, γ-ray spectra were measured at angles from 40^{o} to 150^{o} relative to the beam axis. The yield of a γ ray can be fit with a least-squares Legendre polynomial expansion in which only the even-order terms contribute and the angular distribution coefficients, a_2 and a_4, depend on the level spins, multipolarities, and mixing ratios. These spectra can also be used to determine level lifetimes with the Doppler-shift attenuation method. The spectroscopic results from the present measurements are summarized in other publications [2,3,15]. As one of the goals of this work is a comprehensive image of the low-lying states in these nuclei, we focus on newly identified levels, previously suggested levels whose existence is refuted, and levels for which the spin-parity assignments were revised.

4. Shell model calculations

As in our recent studies of ^{76}Ge [2], ^{76}Se [3], and ^{74}Ge [15] configuration interaction (CI) calculations in the jj44 model space, consisting of the $0f_{7/2}$, $1p_{3/2}$, $1p_{1/2}$, $0g_{9/2}$ orbitals for protons and neutrons, were performed with the shell model code NUSHELLX with the JUN45 and jj44b Hamiltonians. Calculated B(E2) values for transitions between low-lying states were compared with experimental values, when they were available. The overall agreement between experiment and theory is rewarding.

5. Constructing comprehensive level schemes

Comprehensive level schemes are necessary if detailed descriptions of the structure of these nuclei are to be obtained. Figure 1 illustrates the data available at the beginning of our study of ^{76}Ge. Levels indicated by black lines had well-known spins and parities listed in the Evaluated Nuclear Structure Data File (ENSDF) by the National Nuclear Data Center (NNDC) [16]. Those represented by red lines were listed in ENSDF but were shown in our study to be placed in error, *i.e.*, we refuted their existence. Levels shown with green lines were known levels, but their spins and/or parities were uncertain or were shown to be incorrect through our work. Data for ^{76}Se and ^{74}Ge using the same color-coding system are shown in figures 2 and 3. In each case, low-lying levels were revised or removed. From these figures, it is clear that considerable effort must be directed at resolving ambiguities in the level schemes before detailed comparisons with nuclear models are meaningful. Figure 4 further highlights this important point.

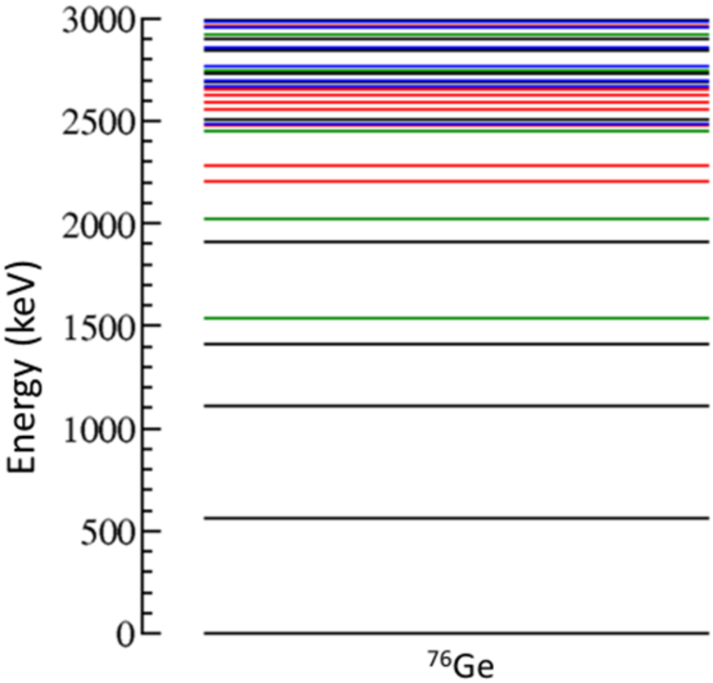

Figure 1. Data available for ^{76}Ge. Levels indicated by black lines had well-known spins and parities in ENSDF. Those represented by red lines were listed in ENSDF but were shown in our study to be placed in error, *i.e.*, we refuted their existence. Levels shown with green lines were known levels, but their spins and/or parities were uncertain or were shown to be incorrect through our work and were revised. Levels shown as blue lines are new from our work.

6. Conclusions

In the examples presented above, it is shown that considerable effort must be expended in determining level properties (spins and parities) prior to comparison of nuclear data with theoretical calculations. In the cases presented, a minority of the energy levels observed in previous work are shown to have the correct placements or spins and parities thus making comparisons with theoretical calculations difficult to assess.

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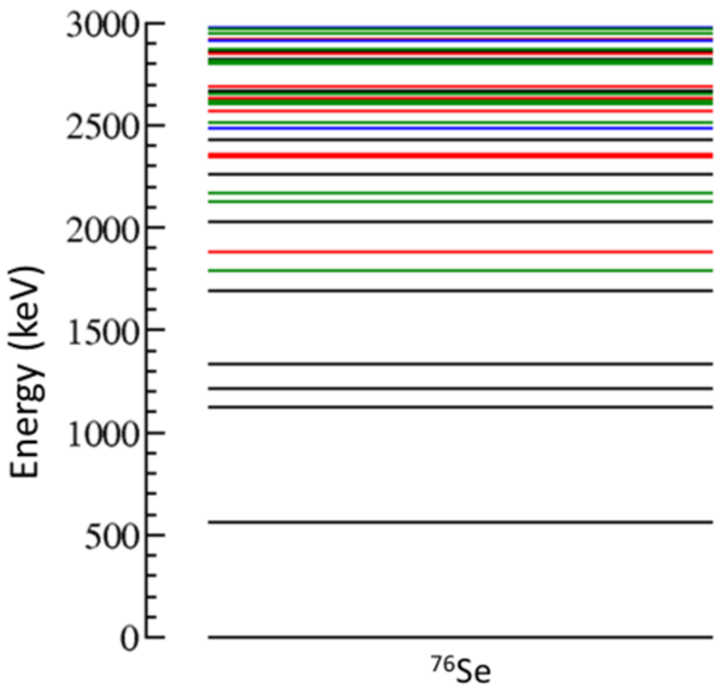

Figure 2. See the caption for figure 1.

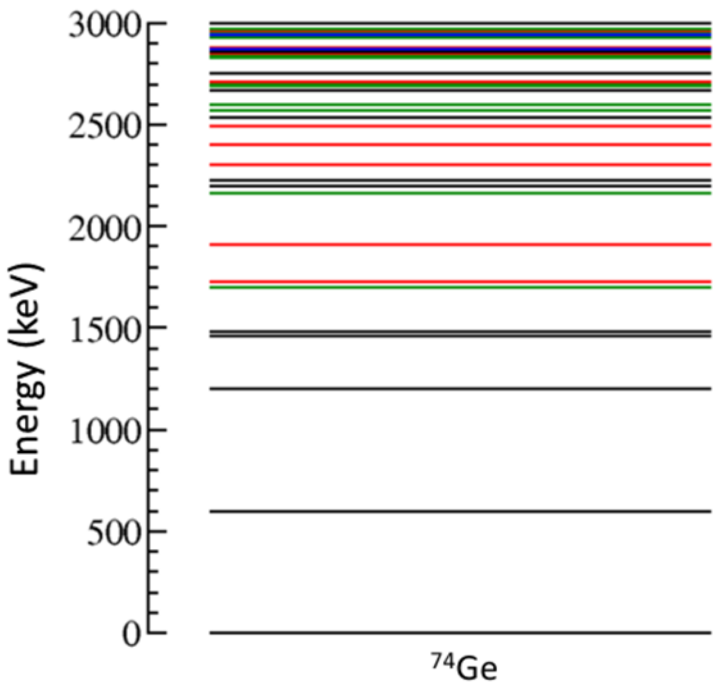

Figure 3. See the caption for figure 1.

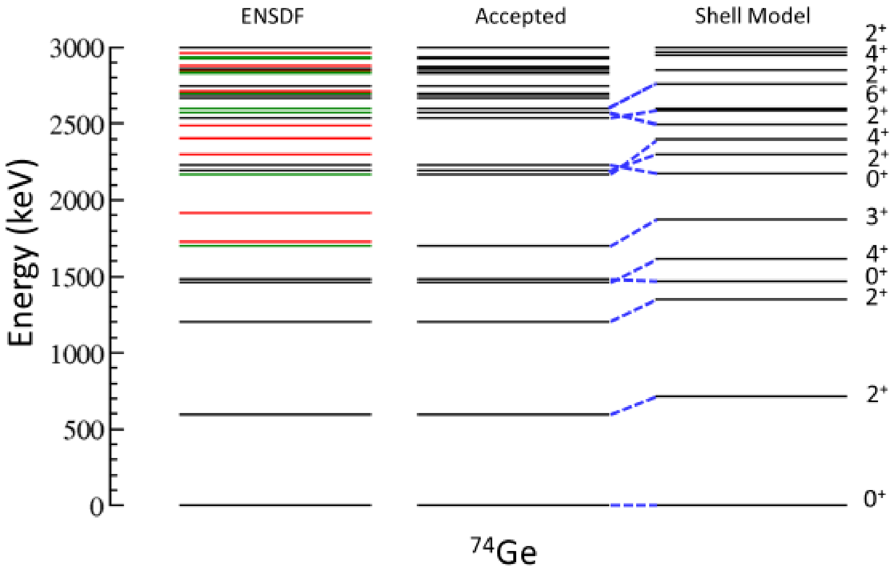

Figure 4. Comparison of accepted (center) low-lying levels in ^{74}Ge with the ENSDF compilation (left) [16] and a shell model calculation (right) [15]. See the caption of figure 1 for color-coding details.

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