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The Nuclear Structure of ^{74}Ge from Inelastic Neutron Scattering

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Abstract. The low-lying structure of ^{74}Ge has been studied with γ-ray detection following inelastic neutron scattering. From excitation function and angular distribution data, the levels and transitions have been characterized including level spins and lifetimes, branching ratios, and multipole mixing ratios. In addition, a number of levels found in the literature for ^{74}Ge appear to be erroneously placed. Upon removal of these states from the level scheme, excellent agreement with large-scale shell-model calculations was obtained.

1 Introduction

The germanium nuclei have been of recent interest for several reasons. First, ^{76}Ge is one of the leading candidates for the observation of neutrinoless double-beta decay. The structure of both the parent and daughter are important for calculating the nuclear matrix element for the process, which cannot be experimentally determined. Moreover, the deformation of the parent and daughter have an impact on the magnitude of the matrix element; similar deformations would lead to a larger matrix element, and thus a shorter lifetime for the decay. Thus, understanding the nuclear structure of these nuclei becomes important. The Ge nuclei are also interesting from a structural perspective. Open questions of triaxiality among these isotopes remain a topic of investigation. In order to better understand the structures of the Ge nuclei, we have undertaken studies of $^{76;74;72;70}$Ge using inelastic neutron scattering. A number of new structural features have been identified and characterized in each nucleus, but ^{74}Ge will be the focus of this work.

Inelastic neutron scattering (INS) provides non-selective or statistical population of low-lying, low-spin ($J \leq 6$) states. As such, the reaction populates all of these levels including non-yrast states allowing a determination of a comprehensive level scheme. In addition, the Doppler-shift attenuation method following INS can be utilized to measure level lifetimes in the femtosecond regime. Overall, the method allows the extraction of gamma-ray energies, level energies, level lifetimes, a_2 and a_4 angular distribution coefficients, branching ratios, and multipole mixing ratios. These data can then be used to calculate reduced transition probabilities, which are a sensitive test of the nuclear structure and can be compared to theoretical calculations to further our understanding.

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A recent focus of work has been to develop a comprehensive approach to studying the nucleus of interest. We strive to

1. Identify all of the excited states up to some energy (e.g., 3 MeV) in as many nuclei in the region as possible, but certainly those near the nucleus of interest.
2. Remove the "erroneous" states from the level scheme.
3. Characterize all of the remaining states.
4. Compare these data with theoretical model calculations.

2 Experiments

Inelastic neutron scattering experiments were conducted at the University of Kentucky Accelerator Laboratory using 19.3406 g of 98.9% enriched elemental ^{74}Ge powder in a cylindrical polyethylene vial 2.28 cm in diameter and 3.58 cm in height. Neutrons were produced by the ^{3}H$(p, n)^3$He reaction using protons generated by our 7 MV Van de Graaff accelerator and a target cell of $^3H_2$ gas at approximately 1 atm of pressure. The γ rays were detected by an $\approx$50% efficient HPGe detector which was Compton-suppressed by an annual BGO shield. The pulsed beam timing allowed for collection of both prompt and background spectra.

Excitation functions were measured for neutron energies between 1.6 and 3.8 MeV in 100 keV increments at an angle of 125° relative to the incident beam direction in order to minimize the effect of the a_2 coefficient. Angular distributions were obtained at neutron energies of 2.0, 2.6, 3.0, 3.4, and 3.8 MeV at incident angles from 40° to 150°. Energy and efficiency calibrations were obtained using ^{137}Cs, ^{24}Na, ^{56}Co, and ^{226}Ra radioactive sources.

3 Data analysis and results

Spins of the levels were determined by the comparison of both the γ-ray angular distributions and excitation functions with statistical model calculations from the code CINDY [1]. For the excitation functions, the level cross sections were compared with the calculated ones for a variety of spins and parities. For the angular distributions, the Legendre polynomial fits to the data yielded a_2 and a_4 coefficients which were compared with the calculations for a variety of initial spins for the transitions. The fit with the lowest χ^2 value was taken to indicate the initial spin and should agree with the excitation function cross section as well. Multipole mixing ratios were also obtained in this manner for the lowest χ^2 fit to the angular distribution coefficients. Level lifetimes were obtained using the Doppler-shift attenuation method [2] for values in the femtosecond regime. Placements of γ rays in the level scheme are a result of the neutron energy threshold from the excitation function, and consistent data for the lifetime, spin, and excitation function shape for decays originating from the same level.

3.1 Search for erroneous states

As an additional part of our data analysis, we seek to remove the "erroneous states" from the level scheme in the literature. We begin by analyzing our own spectra and developing a level scheme, then compare it with that found in the literature, such as the Nuclear Data Sheets and Evaluated Nuclear Structure Data File (ENSDF). In some cases, we find no evidence of the existence of a level. For ^{74}Ge, a number of states in the literature appear to be erroneous and will be discussed presenting detailed evidence. Table I gives a list of the first ten excited states in ^{74}Ge in the ENSDF [3] for reference.

The sixth excited state is reported as a 1724.954 keV (0^+) state [3]. However, no evidence of the depopulating γ ray is found. Figure 1 shows the relevant portion of the spectrum at an incident neutron energy of 3.0 MeV, well above the threshold, but no 520.7 keV γ ray is seen. Figure 2 demonstrates the calculated cross section via CINDY if the level were to exist. As can be seen, the cross section is significant, thus the level would be populated in our measurements and the deexciting γ ray would be observed. Therefore, the existence of the level is refuted.

For the tenth reported excited state, the 2403.5 keV spin-1 state [3], the situation is more complex. The 2403.5 keV γ ray was reported from nuclear resonance fluorescence [4] as a ground-state transition. However, it is not evident in our spectra until an incident neutron energy of 3.1 MeV as shown in Fig. 3. If the level does exist as a spin-1 state, the calculated cross section is shown in Fig. 4. At an incident neutron energy of 2.6 MeV, the calculated cross section would result in approximately 10400 counts in the peak accounting for the detector efficiency and other corrections, and thus would be observed. Another γ ray with an energy of 2999.1 keV is apparent with the same threshold, indicating it is a ground-state transition. It also has the same excitation function shape, as shown in Fig. 3. Moreover, the 2403.5 keV and 2999.1 keV γ rays have similar lifetimes, as shown in Figs. 5 and 6. Both angular distributions indicate that the spin of the initial level is 2^+ (see Figs. 7, 8, and 9). For the ground-state transition, the positive a_2 coefficient indicates a quadrupole transition and thus the level must have an initial spin-parity of 2^+. The a_2 and a_4 coefficients for the 2403.5 keV transi-

Table 1. First 10 levels with previously observed γ ray decays in ^{74}Ge found in ENSDF [3]. The level energies, spins and parities, and γ ray energies are included.

E_{level} (keV)	J^π	E_γ (keV)
595.850(6)	2^+	595.847(6)
1204.205(7)	2^+	608.353(5)
		1204.208(12)
1463.759(8)	4^+	867.898(6)
1482.81(4)	0^+	887.19(7)
1697.140(8)	(3^+)	233.395(12)
		492.936(6)
		1101.267(12)
1724.954(14)	(0^+)	520.744(12)
2165.259(8)	$(3,4)^+$	468.11(3)
		701.487(6)
		961.055(10)
2197.933(24)	2^+	715.17(3)
		734.17(4)
		993.67(6)
		1602.0(2)
		2197.95(8)
2227.77(10)	0^+	1021.9(1)
		1631.89(12)
2403.5(4)	1	2403.5(4)

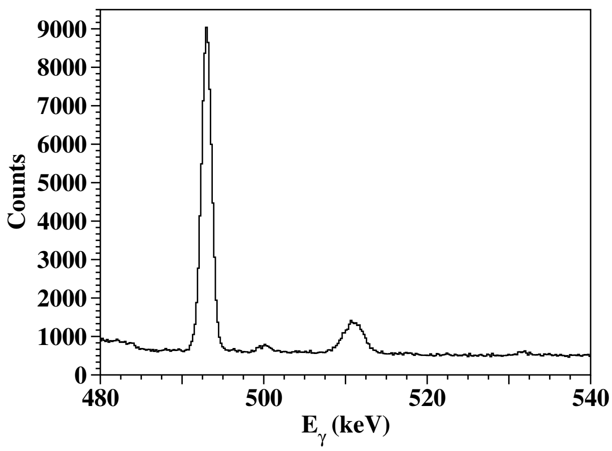

Figure 1. Portion of the spectrum showing γ rays produced by inelastic neutron scattering on ^{74}Ge at an incident neutron energy of 3.0 MeV and detection angle of 90°. Note the clear absence of a peak at 520.7 keV.

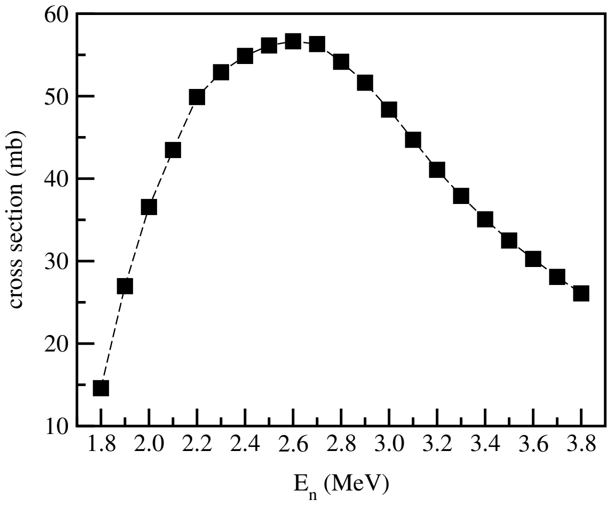

Figure 2. Calculated inelastic neutron scattering cross section for the purported 1724.954 keV (0^+) level assuming a 0^+ spin-parity.

tion when compared with theoretical values from CINDY calculations have a lowest χ^2 fit for a $2^+ \rightarrow 2^+$ transition. These data provide a consistent picture of a new 2^+ level at 2999.1 keV with branches to the ground and first excited states, rather than a 2403.5 keV level with a γ ray of the same energy emanating from it. We, therefore, refute the existence of the 2403.5 keV spin-1 state in the literature and propose a new 2999.1 keV 2^+ state.

4 Discussion

Inelastic neutron scattering provides detailed spectroscopic data that enable the development of a comprehensive level scheme. In some cases, sufficient evidence is obtained to refute the existence of certain levels in the literature. Two examples are given in the previous section for the 1725.0 and 2403.5 keV states in ^{74}Ge. Both levels would have a significant cross section and would thus be populated and their decays observable in the presented experiments. However, the 520.7 keV γ ray purportedly from the 1725.0 keV state is not seen at all, and the 2403.5 keV γ ray is shown to be misplaced in the level scheme. Thus, two of the first ten states in ^{74}Ge reported in ENSDF [3] are shown to be erroneous.

It is important to establish an accurate level scheme for the correct interpretation of the structure and the comparison with theoretical calculations. Otherwise, it appears that there are low-lying levels missing in the calculations which negatively affects their credibility. The calculations for Ge isotopes have additional implications for neutrinoless double beta decay matrix elements and thus have further-reaching impacts.

For ^{74}Ge, shell-model calculations were performed with NuShellX [5] using the *jj*44 model space and the *JUN*45 Hamiltonian [6]; the comparison with the literature and present level schemes are shown in Fig. 10. After the erroneous states have been removed, there is remarkable agreement between the calculations and experimental

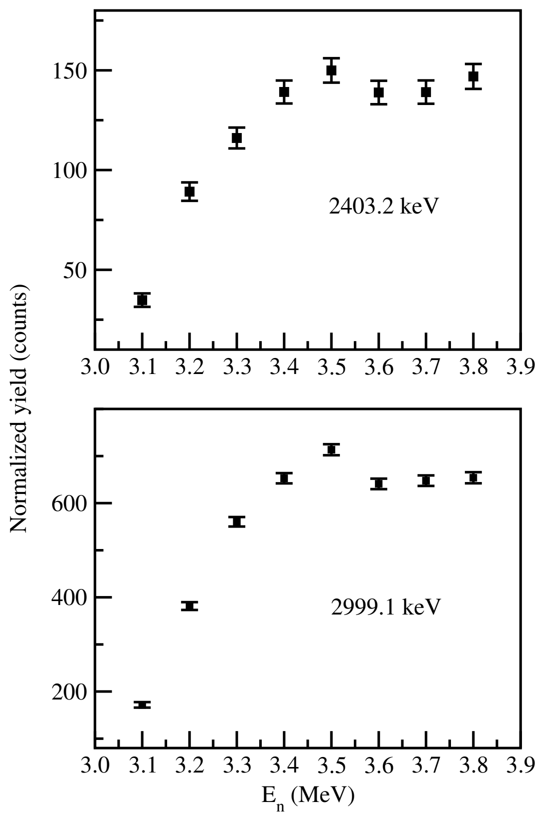

Figure 3. Excitation functions for the 2403.5 and 2999.1 keV γ rays.

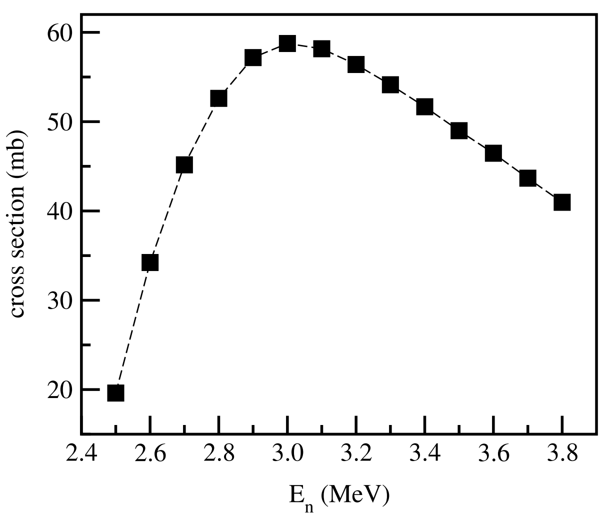

Figure 4. Calculated inelastic neutron scattering cross section for the purported 2403.5 keV spin-1 level assuming a 1^+ spin-parity. The cross section for a 1^- state would be similar.

data, including a one-to-one correspondence of theoretical and experimental levels up to 2.8 MeV.

5 Conclusion

The low-lying nuclear structure of ^{74}Ge has been examined with inelastic neutron scattering and detailed spectroscopic data have been obtained which allow the devel-

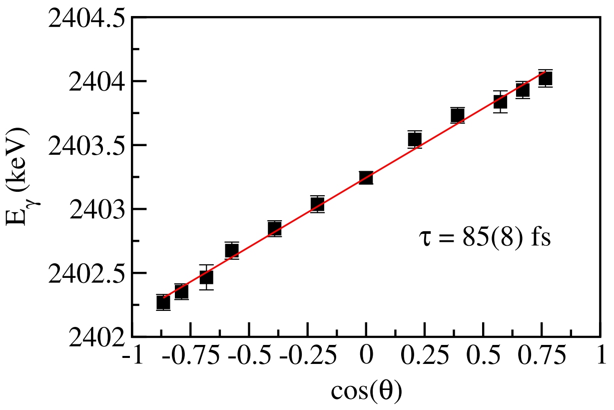

Figure 5. Extraction of the lifetime of the 2403.5 keV γ ray using the Doppler-shift attenuation method following inelastic scattering of 3.4 MeV incident neutrons.

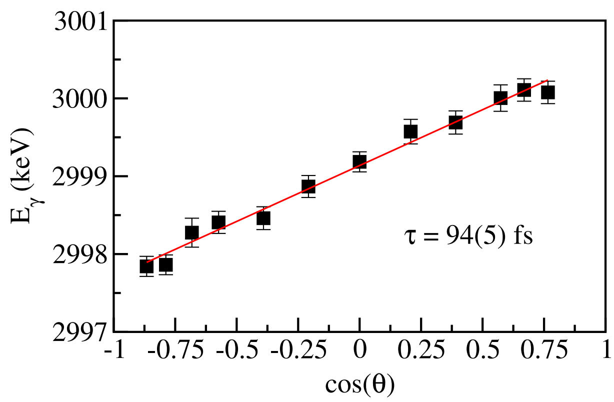

Figure 6. Extraction of the lifetime of the 2999.1 keV γ ray using the Doppler-shift attenuation method following inelastic scattering of 3.4 MeV incident neutrons.

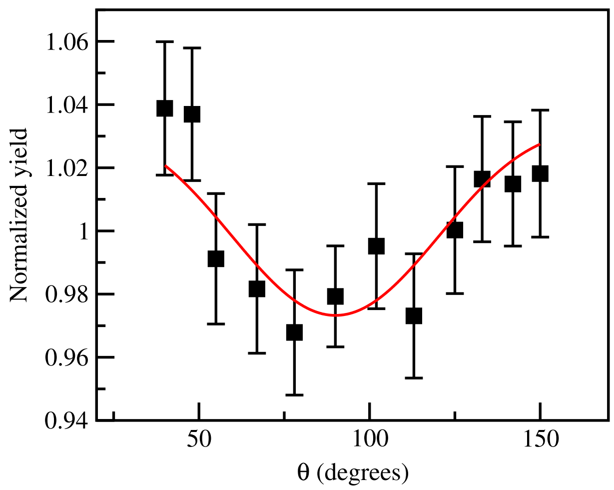

Figure 7. Angular distribution of the 2403.5 keV γ ray at an incident neutron energy of 3.4 MeV.

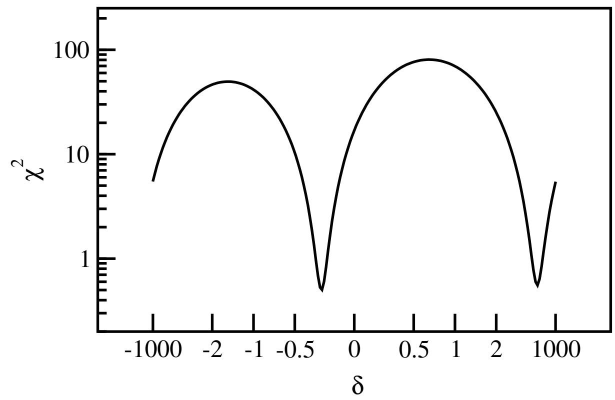

Figure 8. Mixing ratio as derived from the comparison of the a_2 and a_4 coefficients with the theoretical values from CINDY calculations. The lowest χ^2 value is that for a $2^+ \to 2^+$ transition and is the only one shown.

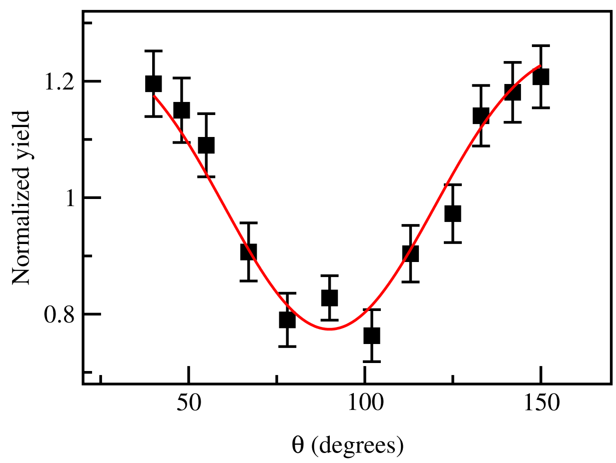

Figure 9. Angular distribution of the 2999.1 keV γ ray at an incident neutron energy of 3.4 MeV. The positive a_2 coefficient dictates that the initial spin-parity is 2^+ for a ground-state transition.

opment of a comprehensive level scheme. Revisions to the level scheme including removal of two of the reported first ten excited states have been proposed. The revisions create an excellent agreement with large-scale shell-model calculations up to 2.8 MeV in excitation energy.

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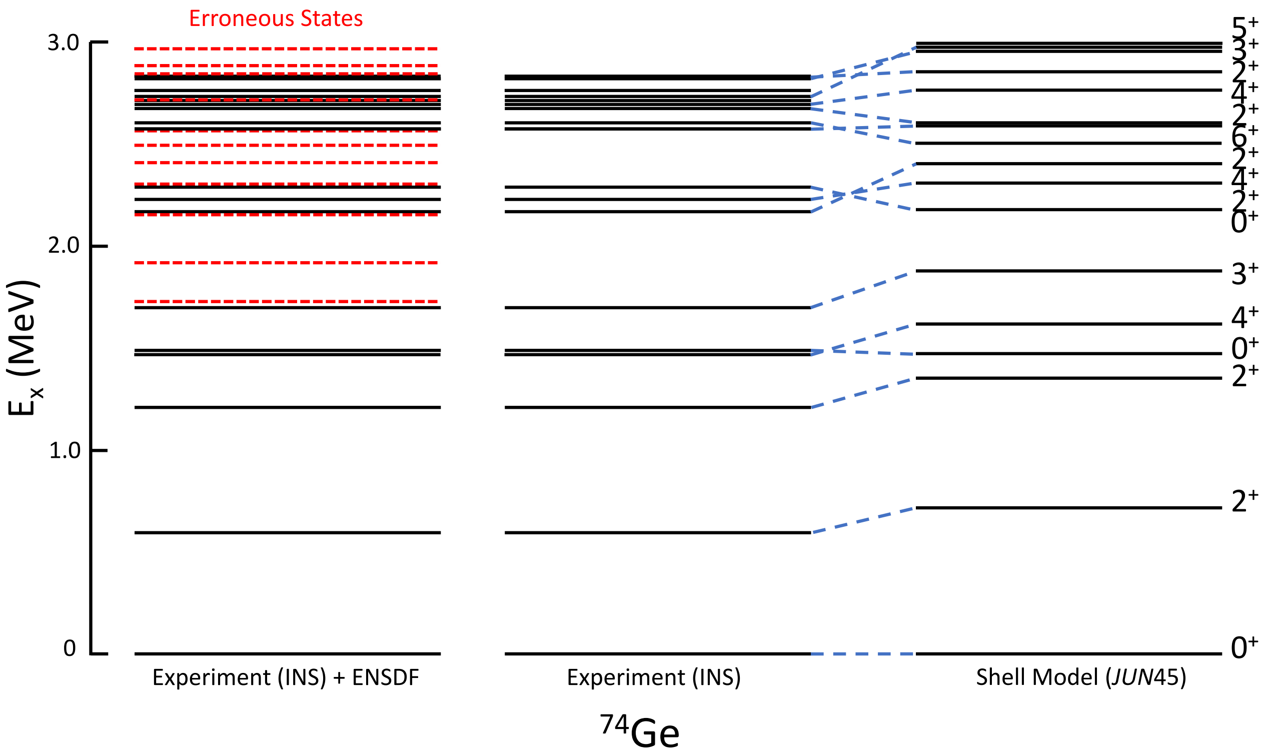

Figure 10. Comparison of the literature, proposed revised, and theoretical level schemes for ^{74}Ge.

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