Using Fast Neutrons to Probe the Structure of Candidates for Neutrinoless Double-Beta Decay

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Introduction

Double-β decay with the emission of two β^- particles and two electron antineutrinos is among the rarest forms of radioactive decay and is seen in only a few nuclei [1]; however, 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 only information on $(\Delta m)^2$, and thus the absolute mass scale remains unknown. The observation of 0νββ provides 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 guide these model calculations.

Experiments

At the University of Kentucky Accelerator Laboratory (UKAL), we have recently completed γ-ray spectroscopic studies following inelastic neutron scattering from the "stable" mass-76 nuclei, ^{76}Ge and ^{76}Se. These experiments, from which a variety of spectroscopic quantities were extracted, employed solid isotopically enriched scattering samples, and the methods have been described previously [2]. 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.

Nuclear Structure of the Ge Region

Two recent large-scale 0νββ searches have focused on the decay of ^{76}Ge [3,4]. 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. Nuclear structure observables constraining the model calculations for 0νββ become of particular importance as the aforementioned searches are pushing to increasing sensitivities and the Large Enriched Germanium Experiment for Neutrinoless ββ Decay (LEGEND), a combined US-European effort, is in the offing.

Our work in this area includes nuclear structure studies of ^{76}Ge and ^{76}Se, the parent and daughter of A = 76 double-β decay [5,6]. We have also published neutron scattering cross section data, which provides an assessment of the background contributions in the ongoing and proposed neutrinoless double-β decay searches [7]. The nuclear structure in this mass region has also received considerable attention for its many fascinating features. It was proposed that ^{76}Ge may be a rare example of a nucleus exhibiting rigid triaxial deformation in its low-lying states, *i.e.*, that it follows the rigid triaxial model of Davydov and Filipov with a well-defined potential minimum at a non-zero value of γ [8]. The defining feature on which this claim was based is the energy staggering in the γ band. Other calculations within the framework of nuclear density functional theory for the $^{72\text{-}82}$Ge isotopes do not confirm the evidence for rigid triaxial deformation at low energy in ^{76}Ge; in fact, they lead to the conclusion that the mean-field potential of ^{76}Ge is γ soft, more in keeping with the γ-unstable rotor model [9].

Our nuclear structure studies of ^{76}Ge and ^{76}Se have exposed the complexity of the nuclei this region, which offers many interesting structural features. The low-lying 0^+ states in the Ge nuclei have long been interpreted as evidence for shape coexistence and was recently extended to ^{80}Ge [10]. Letterman *et al*. [11] observed the low-lying states of ^{84,86,88}Ge by means of in-flight γ-ray spectroscopy and interpreted their data as indicating that these heavy Ge nuclei are triaxial. Moreover, Forney *et al.* [12] recently interpreted an observed $\Delta J = 1$ sequence of levels in ^{78}Ge as possible evidence of triaxiality.

Interacting boson model calculations with microscopic input from an energy density functional have recently been performed for a large range of Ge and Se nuclei [13] and indicate the coexistence of prolate and oblate, as well as spherical and γ-soft, shapes in the nuclei of this region. In this survey, detailed level properties are given for ^{76}Se, and a comparison between the available experimental data and these predictions, which include coexistence between spherical and γ-soft minima. The low energy of the γ band and the large $B(E2;2_2^+\rightarrow 2_1^+)$ suggest γ softness, and the small energy spacing of the 3_γ^+ and 4_γ^+ states is reminiscent of the γ-unstable rotor. Further, the prediction that the ground state of ^{76}Se is predominantly based on the deformed intruder configuration appears to be borne out by the larger energy spacings and smaller collectivity of the band built on the 0_2^+ excitation.

In the case of ^{76}Ge, shell-model calculations performed with no adjustable parameters are in remarkable agreement with our spectroscopic data [5]. The level scheme of ^{76}Se is surprisingly more complex, and the calculations have proven less satisfying [6]. In fact, a serious unresolved issue is the excitation energy of the lowest 3^+ state of ^{76}Se, which is calculated to be more than 1 MeV above its experimental energy. In addition, a low-lying, possibly oblate 0^+ intruder band was identified in ^{76}Se.

From the above observations, it is clear that a coherent picture of the structure of the Ge and Se nuclei has yet to emerge. It is also evident that the detailed information from our (n,n'γ) studies—*i.e.*, level lifetimes, multipole mixing ratios, and reduced transition probabilities—provide valuable information in assessing the various suggested structural possibilities.

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