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Inelastic neutron scattering studies of ^{132,134}Xe: Elucidating structure in a transitional region and possible interferences for $0\nu\beta\beta$ searches

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Abstract. Highly enriched (> 99.9%) ^{132}Xe and ^{134}Xe gases were converted to solid ^{132}XeF$_2$ and ^{134}XeF$_2$ and were used as scattering samples for inelastic neutron scattering measurements at the University of Kentucky Accelerator Laboratory (UKAL). Lifetimes of levels up to 3.5 MeV in excitation energy in these xenon isotopes were measured using the Doppler-shift attenuation method, allowing the determination of reduced transition probabilities. Gamma rays corresponding to new transitions and levels have been observed. In particular, tentative new excited 0^+ states and associated decays have been examined in an effort to elucidate the structure of these nuclei in a transitional region, and comparisons have been drawn with models which seek to describe such nuclei, e.g., the E(5) critical-point symmetry of the IBM. Newly identified potential interferences for neutrinoless double-beta decay searches involving ^{136}Xe are also discussed.

1 Introduction

1.1 Transitional nuclei

In contrast to the transition from spherical vibrators to axially symmetric rotors, little is understood about the transition from spherical vibrators to gamma-soft nuclei. Several theories exist concerning the nature of this transition. For example, Iachello [1] proposed that a critical point in this transition, similar to a critical point in a phase change of matter, exists between the U(5) vibrational limit and the SO(6) γ-soft rotor limit to which the designation E(5) was given. The first proposed example of an E(5) nucleus was ^{134}Ba [2] and remains the only reification to date.

The stable isotopes of xenon span a region which exhibits such an evolution of nuclear structure, and in a literature search for other E(5) candidates, Clark et al., proposed ^{128}Xe as the best prospect [3]. This conclusion was based on several criteria: the ratio $E(4_1^+)/E(2_1^+) \sim 2.2$, the ratio $B(E2; 4_1^+ \rightarrow 2_1^+)/B(E2; 2_1^+ \rightarrow 0_1^+) \sim 1.5$, and the presence of two excited 0^+ states where $E(0^+)/E(2_1^+) \sim 3-4$ and the phonon-like 0_3^+ state decays only to the 2_2^+ state and the 0_2^+ state decays only to the 2_1^+ level, as dictated by the E(5) selection rules.

Following this supposition, the structure of ^{128}Xe was investigated using Coulomb excitation [4]. These measurements revealed that the order of the excited 0^+ states was reversed compared to the E(5) expectation, i.e., the 0_2^+ state decays only to the 2_2^+ state and the 0_3^+ state decays only to the 2_1^+ state, in direct contradiction to the E(5) selection rules. It was thus concluded that ^{128}Xe does not represent an E(5) nucleus.

As the excited 0^+ states were yet be identified in ^{132,134}Xe, these nuclei were excluded by Clark et al. [3] from the list of potential candidates. If these states and their decays were to be identified, comparisons could be drawn to determine if one of these nuclei may be classified as a representation of the E(5) critical-point symmetry.

1.2 Relevance to $0\nu\beta\beta$ searches

The search for neutrinoless double-beta decay ($0\nu\beta\beta$) is currently the focus of significant research efforts. Observation of this process would determine that the neutrino is a Majorana particle, i.e., its own antiparticle, and would establish the neutrino mass. The experimental signature of $0\nu\beta\beta$ is a distinct feature present at the energy of the Q value for the decay, as opposed to the broad distribution detected in the $2\nu\beta\beta$ process.

The nuclear structure of ^{134}Xe is of relevance for $0\nu\beta\beta$ experiments, specifically those searching for the decay of ^{136}Xe to ^{136}Ba. For example, the detector constructed by the EXO collaboration utilizes liquid xenon as the source and detector and is enriched to approximately 80% in ^{136}Xe, while the remaining 20% is ^{134}Xe [5]. Because the $0\nu\beta\beta$ process is very rare, if it occurs at all, a detailed understanding of the backgrounds in the measurement is of utmost importance. One potential source of background is inelastic neutron scattering. As neutrons may be produced by incident muons or natural radionuclides present in the

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surroundings, excited states in either isotope may be populated by inelastic neutron scattering. Therefore, γ rays emitted upon de-excitation of ^{134}Xe which have energies near the $0\nu\beta\beta$ Q value, 2457.8 keV, may obscure the observation of this rare decay. Also of note, the resolution of such scintillation detectors is rather poor, ~100 keV at the Q value [5]. Thus, it is important to identify any potential interferences from $(n, n'\gamma)$ reactions in this energy region.

2 Experiments

Inelastic neutron scattering, $(n, n'\gamma)$, measurements were carried out at the University of Kentucky Accelerator Laboratory (UKAL). Nearly monoenergetic neutrons were produced by the reaction of tritium gas with accelerated protons from a 7-MV single-stage Van de Graaff accelerator. The resulting neutrons were scattered from approximately 10 g each of highly enriched (> 99.9%) solid ^{132}XeF$_2$ and ^{134}XeF$_2$ contained in polytetrafluoroethylene vials. The emitted γ rays were detected by a ~50% HPGe detector surrounded by an annular BGO for active Compton suppression. The pulsed and bunched proton beam (~1-ns pulse every 533 ns) allowed time-of-flight gating for further background reduction.

For ^{132}Xe, an excitation function measurement was performed from E_n = 1.8 – 3.4 MeV, and for ^{134}Xe from E_n = 2.0 – 3.5 MeV at a detection angle of 90°. Angular distribution measurements were obtained for ^{132}Xe at E_n = 2.2, 2.7, and 3.4 MeV and for ^{134}Xe at E_n = 2.2, 2.7, and 3.5 MeV at detection angles between 40° and 150°.

3 Results and discussion

3.1 Structure of ^{132,134}Xe

The excitation function data yielded thresholds which aided in the placement of new γ rays and were also compared with statistical model calculations, which assisted in the determination of the spin of the initial level. From the angular distribution data, level lifetimes (or limits) were obtained using the Doppler-shift attenuation method, multipole mixing ratios were extracted, and further information about the spins and parities of the levels was obtained. This information allowed the determination of B(E2) values (or limits) for many transitions. Also, new tentative excited 0^+ states and their decays were identified. Previously published results on ^{128}Xe compared the decays of the excited 0^+ states with those predicted in the E(5) critical-point symmetry in order to definitively conclude ^{128}Xe does not exhibit E(5) behavior. Such comparisons can now be drawn for ^{132,134}Xe.

3.1.1 ^{132}Xe

The E(5) prediction for ^{132}Xe yields excited 0^+ states at 2023 and 2397 keV. The newly identified tentative 0^+ states were found at 1948 and 2169 keV. While the level energies are not in poor agreement with the theoretical prediction, the decays of the states are. Both states were observed to decay only to the 2^+_1 state, which is contradictory to the E(5) selection rules. Figure 1 demonstrates the predicted decays with B(E2) values in the E(5) description compared with the experimentally deserved decays and B(E2)s.

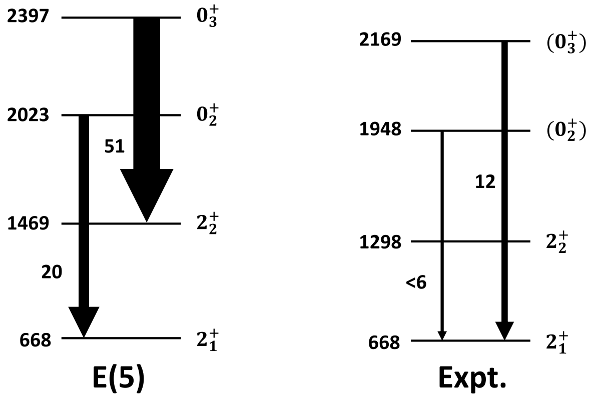

Figure 1. The E(5) predicted decays of the excited 0^+ states in ^{132}Xe (left) compared with the experimentally observed decays (right). The B(E2)s are also shown and the width of the arrows are proportional to those values.

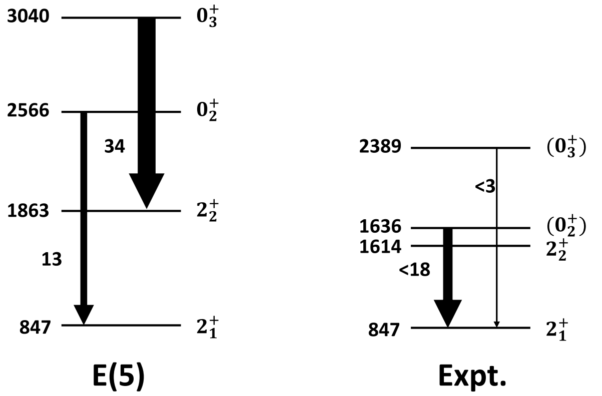

Figure 2. The E(5) predicted decays of the excited 0^+ states in ^{134}Xe (left) compared with the experimentally observed decays (right). The B(E2)s are also shown and the width of the arrows are proportional to those values.

3.1.2 ^{134}Xe

The E(5) prediction for ^{134}Xe yields excited 0^+ states at 2566 and 3040 keV. Tentative 0^+ states were observed at 1636 and 2389 keV, significantly lower than the theoretical prediction. The decays of the states are also in contradiction with the theory; as in ^{132}Xe, both states were observed to decay only to the 2^+_1 state. Figure 2 displays the E(5) prediction for the decays of the excited 0^+ states and B(E2) values compared with the experimental determinations.

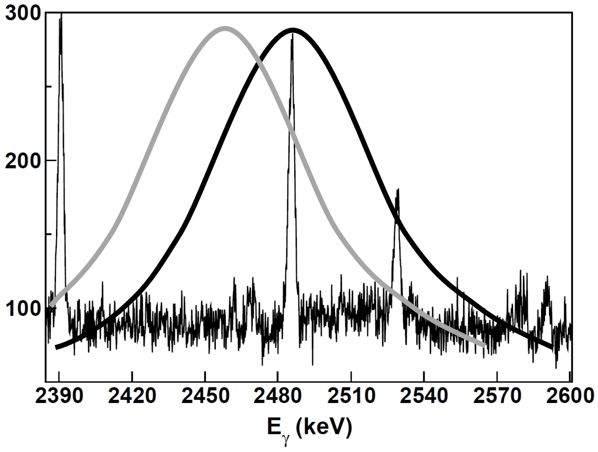

Figure 3. A portion of the γ-ray spectrum as observed in the present measurements at an incident neutron energy of 2.7 MeV. Schematic Gaussian distributions are also shown with 100-keV resolution for both the observed 2485.7-keV γ ray (black) and what would be the $0\nu\beta\beta$ signature (gray). Other peaks in the spectrum are background γ rays.

3.2 Possible interferences for $0\nu\beta\beta$ searches

A new γ ray corresponding to a transition in ^{134}Xe has been observed in the energy region near the $0\nu\beta\beta$ endpoint energy, within the ~100-keV resolution of the EXO detector [5]. A new level in ^{134}Xe was identified at 2485.7-keV with a 20% branch to the ground state exhibiting a quadrupole angular distribution allowing a spin assignment of $J^\pi = 2^+$. The γ-ray production cross section was also measured for this branch relative to ^{56}Fe and was found to be ~10 mb for incident neutron energies of 2.5–4.5 MeV. As this γ ray lies well within the resolution of the EXO detector for a $0\nu\beta\beta$ event at the Q-value of 2457.8-keV, this γ ray may produce an interference for the unambiguous identification of a $0\nu\beta\beta$ signature. Figure 3 shows the observed spectrum, and in a schematic way, the γ rays as they would be observed by the EXO collaboration based on a 100-keV resolution at the Q value.

4 Conclusions

New information about the structure of ^{132,134}Xe was obtained using the $(n, n'\gamma)$ reaction. Specifically, new tentative 0^+ states were identified, lifetimes (or limits) were measured, and B(E2) values were determined. Based on the decays of the tentative second and third excited 0^+ states, ^{132,134}Xe do not represent the E(5) critical-point symmetry. In both nuclei, the predicted decay of the phonon-like 0_3^+ state to the 2_2^+ state is not observed. Instead, the 0_3^+ state decays to the 2_1^+ state, which is a forbidden transition in the E(5) description. These transitional nuclei appear to be neither definitively vibrational nor rotational and continue to be difficult to interpret in terms of model descriptions.

A new γ ray produced by inelastic neutron scattering from ^{134}Xe was observed, which will produce background in the region of a potential $0\nu\beta\beta$ signal in the decay of ^{136}Xe to ^{136}Ba for searches which employ a mixture of ^{134,136}Xe. The production cross section for the 2485.7-keV γ ray was measured to be ~10 mb for neutron energies between 2.5 and 4.5 MeV. This γ ray is an important new consideration for modeling backgrounds in such experiments as that of the EXO collaboration.

Acknowledgments

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