Probing nuclear structure through isomers

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Isomers provide a unique way to probe nuclear structure on account of their well-defined wavefunctions and the plethora of information on single-particle energies, pair gaps, residual interactions and transition probabilities which can be gleaned from their study. Recent results on spin isomers in the vicinity of the doubly-magic ^{208}Pb and K isomers in $A \approx 130$ and 170 nuclei will be presented along with their implications for a detailed understanding of nuclear structure in these regions.

Introduction

The understanding of various facets of the structure of the many-body, strongly-interacting nuclear system is usually complicated by the fact that the vast majority of excited states have wavefunctions resulting from the superposition of multiple contributions. However, the situation is different for a small class of states which are typically metastable and referred to as nuclear isomers. Such states have relatively pure wavefunctions in comparison to those of neighboring levels; their study can therefore provide a more direct insight into the nature of the interactions between nucleons. Metastable states are broadly classified as spin, shape, K and seniority isomers; here, K denotes the projection of the intrinsic angular momentum of an unpaired nucleon along the symmetry axis of a deformed nucleus.

The talk will summarize recent results of this group on spin isomers around the doubly-magic ^{208}Pb, and K isomers in the $A \approx 170$-180 and $A \approx 130$ regions. The experiments have been performed at various laboratories in India and the US, and the reaction mechanisms used range from fusion-evaporation with ^{4}He, ^{7}Li, ^{32}S, ^{50}Ti beams, and inelastic excitation and multi-nucleon transfer with ^{207}Pb and ^{209}Bi projectiles. Beam sweeping, with periods ranging from microseconds through milliseconds and up to seconds, with data collected in the beam-off periods, was utilized to allow for the identification of long-lived states. Gamma rays from the decay of excited states in the product nuclei were recorded in multi-fold coincidence using large Compton-suppressed high-purity germanium (HPGe) detector arrays like the Indian National Gamma Array (INGA) and the Gammasphere. The centroid shift method was employed to ascertain $T_{1/2}$ = 1-10 ns. About twenty isomers with half-lives ranging from a few nanoseconds up to several milliseconds, along with detailed level schemes of the corresponding nuclei, have been established [1-11]. These discoveries have been instrumental in obtaining noteworthy insights into nuclear interactions across the chart of nuclides.

Spin isomers in the $A \approx 200$ region

Isotopes of Pb (Z = 82) and Bi (Z = 83), specifically ^{204}Pb and ^{205,206}Bi, have been found to exhibit the three longest-lived states across the nuclear chart (with $T_{1/2}$ = 220 μs, 8 ms and 27 μs, respectively) at high excitation (E_x > 7 MeV) [1, 2]. These states result from the occupation of proton and neutron orbitals both below and above the Z = 82 and N = 126 shell closures, respectively, following excitations of the ^{208}Pb core. While the discovery of such long-lived states is experimentally challenging owing to their quite limited population, these have set distinctive benchmarks for predictions of excitation energies, wavefunctions and transition probabilities, thus providing the means to validate effective interactions which are employed in large-scale shell model calculations.

Along the chain of Tl (Z = 81) isotopes, isomers with one proton hole and multi-neutron hole configurations can be realized. In ^{203}Tl, five isomers with 3- and 5-quasiparticle (qp) configurations, and half-lives from 1.9 ns to 6.6 μs have been identified [3]. In ^{202}Tl, a 4-qp isomer with $T_{1/2}$ = 215 μs has been established [5], while in ^{201}Tl, one 3-qp and two 5-qp ones have been located [9]. In ^{200}Tl, a 6-qp isomer with $T_{1/2}$ = 57 ns has been placed above E_x = 6 MeV [7]. Consequently, the knowledge of residual interactions involving orbitals near ^{208}Pb has been significantly expanded.

In the case of Hg (Z = 80) and Pt (Z = 78) isotopes, moderate deformation is evident due to the presence of multiple valence nucleons. The bandheads of 2-qp semi-decoupled and decoupled states are found to be isomeric, and their study contributes to a detailed understanding of the mechanisms driving collectivity in these nuclei. Two isomers have been established in ^{202}Hg and one in ^{200}Hg; their half-lives range from 1.0 ns to 10.4 ns [4]. An interesting observation is the enhancement in collectivity for the 2-qp states in the Hg isotopes with an increase in neutron number from N = 114 to N = 118 in marked contrast to the decrease around the ground state nearing the N = 126 shell closure [4]. Isomers with nanosecond half-lives have been identified in ^{193,195,196}Pt [8, 11]. The collectivity of the decoupled states with 2-qp configurations in even Pt isotopes is found to abruptly decrease at N = 120 [11].

K isomers in A ≈ 130 and 170 nuclei

High-*j* neutron orbitals in deformed nuclei with $A \approx 130$ are responsible for the realization of *K* isomers. In ^{134}Sm (Z = 62), a new *K* isomer with a two-quasineutron character has been identified; only six levels in the ground-state band had previously been reported.

The presence of two isomeric states with 3-quasiparticle configurations has been determined in the odd-even nucleus ^{173}W (Z = 74). An unusually high number of decay branches is evident with degrees of hindrance ranging from ν = 1-10 indicating the role of gamma tunneling in these isomeric decays. The band structures built on the high-*K* states have been established, and their configurations have been unambiguously identified from the associated $M1/E2$ branching ratios.

In $^{172\text{-}178}$Hf, existing *K* isomers have been verified, and non-yrast high-*K* states have been populated in proton-rich isotopes. The population and study of the reduced hindrances as a function of excitation energy above the yrast line for the decay of several isomers along the Hf isotopic chain from a single dataset is of particular interest.

In ^{180}Hf, 2- and 4-qp states with half-lives ranging from a few nanoseconds up to a microsecond were identified [10]. For almost all isomeric decays, the reduced hindrances were found to be quite high attesting to the robustness of the *K* quantum number.

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