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Shape Coexistence At The Outer Edges Of Stability

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Abstract. A major program of Gammasphere when coupled with the Fragment Mass Analyzer (FMA) has been to study excited states in nuclei beyond the proton drip line. We have recently performed in-beam experiments using Gammasphere + FMA to measure excited states in proton rich Au, Hg, Tl and Pb isotopes. These studies have allowed us to characterize the evolution of nuclear shapes as one approaches the proton drip line. In two of the isotopes studied, namely ^{175}Au and ^{179}Hg, structures built on three distinct shapes have been found to coexist at low excitation energy.

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INTRODUCTION

Above N=82, the proton dripline follows closely the outer edge of the well deformed rare-earth region, and the ground states of nuclei lying close to the dripline are expected to have spherical or weakly deformed prolate shapes. Our recent experimental studies have concentrated in the upper portion of this region, namely the study of excited states in Pt (Z=78) through Pb (Z=82) isotopes located in the vicinity of the proton dripline. One of our principle motivations has been to characterize the evolution of shape from the well studied deformed region to the near spherical ground states deduced for the proton emitters.

In-beam γ-ray studies of such heavy systems far from stability are hampered by the large fission cross sections associated with the heavy-ion fusion reactions used to produce these proton-rich nuclides. However, the use of recoil separators allows one to easily distinguish fusion-evaporation residues from fission products. In addition, all nuclides in this region which lie at the dripline or beyond, decay via charge particle radioactivity. As a result, the recoil decay tagging (RDT) technique can be utilized allowing for in-beam γ-ray studies of nuclides produced with sub-μb cross-sections. By coupling the Fragment Mass Analyzer (FMA) with Gammasphere, the high-spin structure of a number of nuclides in this Pt-Pb region has been investigated. In addition, complimentary decay studies of these same nuclides have allowed, in several instances, spin/parity and excitation energy assignments for all observed states. These studies have allowed us to characterize the evolution of nuclear shapes as one approaches the proton dripline. In several isotopes, structures built on three distinct shapes at low excitation energy have been observed.

EXPERIMENTAL TECHNIQUE

One of the principle applications of Gammasphere when sited at the ATLAS accelerator at Argonne National Laboratory is to couple the device with the Fragment Mass Analyzer (FMA) in order to study nuclei lying far from stability. The FMA is a high resolution mass spectrometer which transports reaction products produced at the target position and disperses them by their mass/charge (M/q) ratio at the focal plane, 8.8 meters away.

The coupling of the FMA to Gammasphere allows for mass identification of γ rays produced at the target. However, this is usually not sufficient to identify γ rays emitted from the most proton-rich isotopes due to the fact that proton evaporation dominates over neutron evaporation when proton-rich nuclei are created in heavy-ion induced fusions evaporation reactions. Since the evaporation of neutrons produces systems that lie furthest from stability, γ rays emitted from nuclides with the largest proton excess can become completely obscured by the γ rays from the other isotopes produced in these reactions. Consequently, isotopic identification may become necessary for isolating γ transitions in these nuclei.

With the FMA, this is achieved by placing ancillary detectors behind the focal plane. For light and medium mass nuclei (Z<50), it is possible to obtain isotopic selection by using an ionization chamber. In heavy nuclei (Z>50) which lie near the proton drip line, isotopic identification of γ rays can be made by correlating the characteristic charged-particle radioactivity of an ion implanted in a pixel of a double-sided silicon strip detector (DSSD) with a previously implanted recoil. This technique is referred to as Recoil Decay Tagging (RDT) [1].

Fig. 1 demonstrates the power of the FMA to isolate specific reaction channels utilizing RDT. The data come from an experiment using the reaction ^{84}Sr + ^{92}Mo to produce Au nuclei which are proton unbound. The top panel shows the γ-ray spectrum in coincidence with mass 175 residues while the middle panel shows the spectrum correlated with the α decay of ^{175}Au. The γ rays in the ^{175}Au spectrum are barely observable in the mass gated spectrum illustrating the need for isotopic selectivity. The bottom panel is a sum of gates obtained from a γ-ray coincidence matrix correlated with the α decay of ^{175}Au. This last panel illustrates the power of Gammasphere to allow for a proper γ-γ analysis even when requiring an RDT gate which in turn allows the level structure of these very proton rich nuclei to be extended to spins in excess of 10ħ. Using Gammasphere, excited states have been identified in nuclei produced with cross-sections as low as 50 nanobarns, a sensitivity unrivaled by other forms of selectivity utilized for in-beam γ-ray spectroscopy studies.

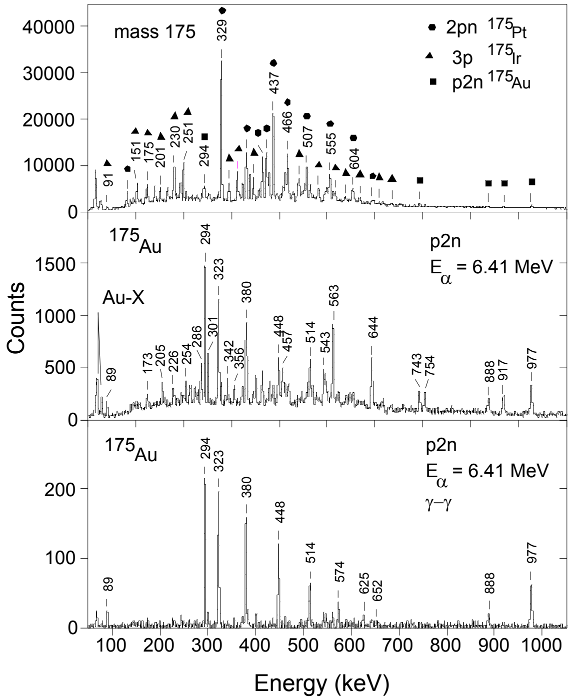

FIGURE 1. *Top Panel*: Gamma-ray spectrum in coincidence with mass 175 residues. *Middle Panel*: Gamma-ray spectrum correlated with the α decay of ^{175}Au. *Bottom Panel*: Summed, background-subtracted γ-ray coincidence spectra from the *α–γ–γ* matrix produced by gating on the E_α = 6.41 MeV (^{175}Au) α line. The γ-ray gating transitions are the 294, 323, 380, 448, 514 and 574 keV lines.

SPECTROSCOPY OF PROTON UNBOUND ^{173,175,177}Au

It has been shown that proton decay rates, which depend on the tunneling probability through the Coulomb and centrifugal barriers, are sensitive not only to the quantum numbers and the intrinsic configurations of the parent and daughter nuclei, but also to other important structural effects, most notably deformation [2]. In the region near the Z=82 shell closure, effects of deformation on the properties of proton emitters should be expected because of the shape coexistence mentioned above and the ensuing interaction between configurations associated with the different shapes. However, the experimental situation is unclear because the degree to which this coexistence persists in drip line nuclei is poorly known. Proton emitters in ^{171}Au [3] and ^{177}Tl [4] were interpreted as resulting from the coupling of the $\pi h_{11/2}$ orbital to the *near-spherical* ground state of the even-even core. The proton decay rate in ^{185}Bi [5] was also reproduced satisfactorily with a configuration consisting of a $s_{1/2}$ proton coupled to the $\pi(h_{9/2})^2$ core, although the influence of the *oblate* shape associated with this intruder configuration was not explicitly considered in the calculations.

In order to better characterize the evolution of shape towards the proton dripline, we have recently observed in a Gammasphere + FMA experiment excited structures in the ^{173}Au (*N=94*), ^{175}Au (*N=96*) and ^{177}Au (N=98) isotopes. These nuclei provide the opportunity to elucidate the shape driving properties of proton excitations based on the important $h_{9/2}$, $f_{7/2}$ and $i_{13/2}$ proton orbitals in a region where they have not been investigated much before, *e.g.* below mid-shell. All three Au isotopes are energetically unbound to the emission of protons [6], but their decay via α emission is favored by the associated Q values and barrier heights.

Excited states in ^{173}Au, ^{175}Au, and ^{177}Au were populated via the *p2n* channels in fusion reactions of

^{84}Sr ions with ^{92,94,96}Mo, respectively. Gamma-rays in these isotopes were identified by the RDT technique. Figure 2 shows partial level structures deduced from this work for the three isotopes. The yrast structures of ^{175}Au and ^{177}Au are found to be the result of the coupling of an intruder $i_{13/2}$ proton to the prolate deformed Pt and Hg cores. Remarkably, no sign of collectivity is observed in the lightest isotope, ^{173}Au.

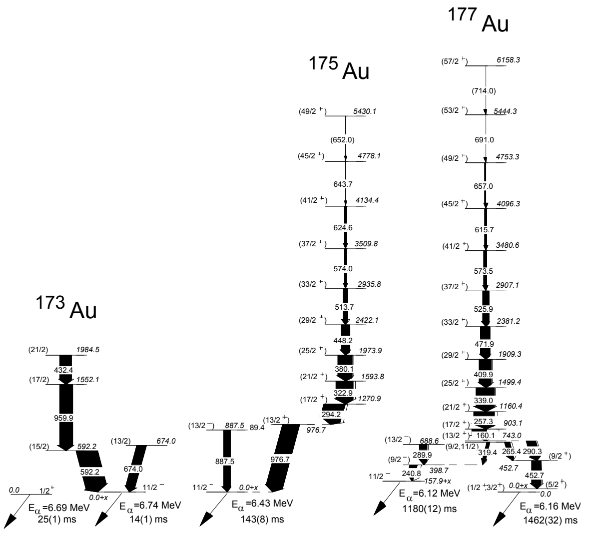

Figure 2. Partial level schemes for ^{173,175,177}Au.

With regards to shape coexistence, it is worth noting that structures associated with three different shapes compete for yrast status in ^{175}Au. A near-spherical ground state (I^π=11/2$^-$) is followed by the (13/2$^+$) oblate level while the prolate band dominates at higher spins. The energy separation between the observed states can be associated with the energy difference between these minima, although the excitation energy of the prolate well is more subtle since the $i_{13/2}$ prolate band is not observed down to its bandhead, presumably due to effects associated with deformation and Coriolis mixing. A paper reporting the results of this experiment has recently been published [6].

SPECTROSCOPY OF ^{179}Hg

Neutron-deficient, even-even Hg (Z=80) isotopes with N≤110 exhibit a co-existence at low spin between two shapes: a weakly deformed *oblate* ground state and a more deformed, excited, *prolate* band. The energy difference between the two minima exhibits a parabolic trend as a function of neutron number and minimizes around mid-shell at ^{180}Hg (N=102). In contrast, the ground states of the odd-mass, ^{181,183,185}Hg (N=101,103,105) isotopes are associated with a prolate shape with rotational bands built on the ground state. In addition, a weakly-deformed, oblate high-spin (J^π=13/2$^+$) isomer has been identified in each of the three odd-mass Hg isotopes, however, the excitation energies have not been established. The mechanism responsible for this preferred prolate shape at low spin in the odd-mass isotopes is still not understood. Interestingly, the ^{186}Pb [7] and ^{175}Au [6] (see above) isotopes have recently been observed to form three minima at low spin, associated with near-spherical, oblate, and prolate shapes. A similar trifecta of shapes has been found in ^{188}Pb through the identification of a suite of multi-quasiparticle isomers [8].

In order to clarify how shapes in the odd-A Hg isotopes evolve below mid-shell, we have performed two experiments to study the nuclear structure of ^{179}Hg (N =99). The first was an in-beam measurement using Gammasphere coupled to the FMA [9], and the second was performed at RITU to measure in detail the α decay of ^{183}Pb into ^{179}Hg [10].

For the in-beam study, excited states in ^{179}Hg were populated with the ^{90}Zr(^{90}Zr,n) reaction using 369 and 380 MeV beams delivered by the ATLAS superconducting linear accelerator at Argonne National Laboratory. Gamma rays associated with ^{179}Hg were identified by the RDT technique using Gammasphere coupled to the FMA. The level structure deduced from this work is shown in Figure 3.

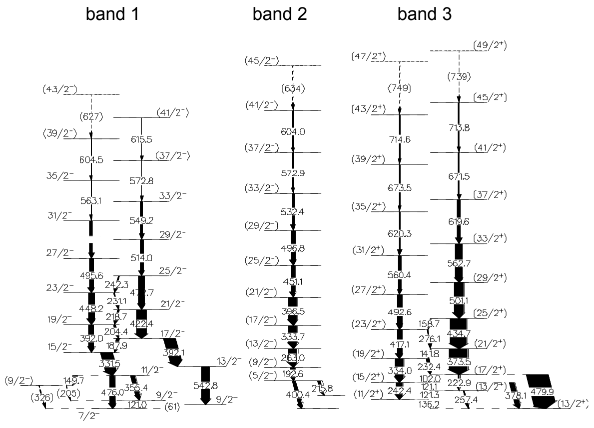

Figure 3. Partial level scheme for ^{179}Hg

Based on the deduced α-decay reduced widths, which are sensitive to changes in the angular momenta between initial and final states, and on the known experimental information about the daughter (^{175}Pt) and grand-daughter (^{171}Os) nuclei, the ground state of ^{179}Hg is firmly assigned J^π=7/2$^-$. In contrast, the heavier isotopes ^{181,183,185}Hg have a 1/2$^-$ ground state. Three collective bands have been placed in the level scheme shown in Figure 3 and are associated with a well deformed prolate deformation. This change in the ground state spin can only be understood if the ground state in ^{179}Hg is weakly deformed or possibly spherical.

Of particular interest to this discussion is band 3 which consists of two rotational cascades linked by $\Delta J=1$ transitions. The spins and parity of the in-band levels follow from the measured angular correlations and from the assumption that the band decays into a $(13/2^+)$ isomeric state originating from the oblate $i_{13/2}$ configuration, as suggested for the heavier odd-A Hg isotopes. From this work, it was concluded that the isomeric state must have a significant γ-ray decay branch since the γ rays that precede the isomer were found to be correlated with the α decay of the ground state. Consequentially, ^{179}Hg marks another example where three shapes are found to coexist at low-spin and excitation energy. More details concerning this study can be found in ref. [9].

In the decay experiment performed at the Cyclotron Facility at the University of Jyväskylä, excited levels in ^{179}Hg were populated after the α decay of ^{183}Pb produced in the ^{42}Ca + ^{144}Sm reaction at 200 MeV. Fusion-evaporation residues were separated from scattered beam and fission products using the RITU gas-filled separator. The fusion products were implanted in an 80 mm x 35 mm silicon strip detector at the focal plane. The subsequent α decay of these residues was recorded in the strip detector.

By analyzing the α–γ coincidences following the decay of ^{183}Pb, the excitation energy and half-life of the $13/2^+$ isomer in ^{179}Hg was determined (172 keV and 6.4 msec). In addition, support for the assignment of $7/2^-$ to the ground state was obtained based on the hindrance factors deduced from the α decay. More details concerning this study can be found in ref. [10].

ALPHA DECAY OF ^{181}Pb

One of our most recent experiments with Gammasphere at the FMA involved the study of ^{181}Pb and ^{181}Tl with the setup described above. Excited states in both ^{181}Tl and ^{181}Pb were populated in the reaction ^{90}Zr + ^{92}Mo at 385 MeV. In this measurement, new data on the α decay of ^{181}Pb was obtained. Figure 4 summarizes the results of this study. An α decay from the ground state of ^{181}Pb to an excited $9/2^-$ state in ^{177}Hg was observed followed by the decay to the ground state via a 78 keV transition. The spin and parity of the $9/2^-$ level was established in a recent study by Melerangi *et al.* [11]. This observation leads to an assignment of $9/2^-$ to the ground state of ^{181}Pb. This is in contrast to the heavier odd-A Pb isotopes (A=183-199) whose ground states are $3/2^-$. This change in the ground state spins results from the complete emptying of the $i_{13/2}$ and $p_{3/2}$ states lying above the N=100 sub-shell closure and the creation of a hole state in the $h_{9/2}$ orbital lying below the N=100 gap. In addition, a γ transition with a lifetime of ~ 10 msec is observed to feed the ^{181}Pb ground state. This level has been given a tentative assignment of $(13/2^+)$ and could represent the excitation into the $i_{13/2}$ orbital.

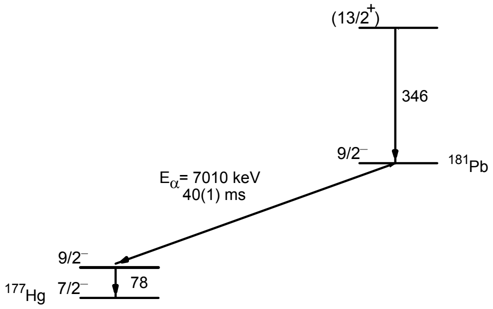

Figure 4: Decay scheme showing the α decay from ^{181}Pb into ^{177}Hg.

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