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Studies of neutron-deficient nuclei near the $Z = 82$ shell closure via cold fusion reactions

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Abstract

We have recently performed in-beam experiments using Gammasphere + FMA to measure excited states in proton-rich Au, Hg, Tl and Pb isotopes. In these studies, the use of the FMA is essential in order to differentiate evaporation residues from the large fission background which dominates the reaction cross-section. In addition, we have found that using near-symmetric reactions at bombarding energies near the Coulomb barrier is beneficial in performing these studies. By keeping the bombarding energy low, fission is minimized and the reaction products are concentrated in only a few channels. New results have recently been obtained using the ^{90}Zr+^{92}Mo reaction to study ^{181}Tl and ^{181}Pb via the 1p and 1n channels, respectively.

1. 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 be characterized by spherical or weakly deformed prolate shapes. Our recent experimental studies have concentrated on the upper portion of this region and have focused on 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 main motivations has been to characterize the evolution in 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, nearly all the nuclides of interest in this region 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. Finally, we have found that the use of near-symmetric reactions at bombarding energies near the Coulomb barrier is beneficial in performing these studies. Due to the large negative Q-values associated with these reactions, fusion at the

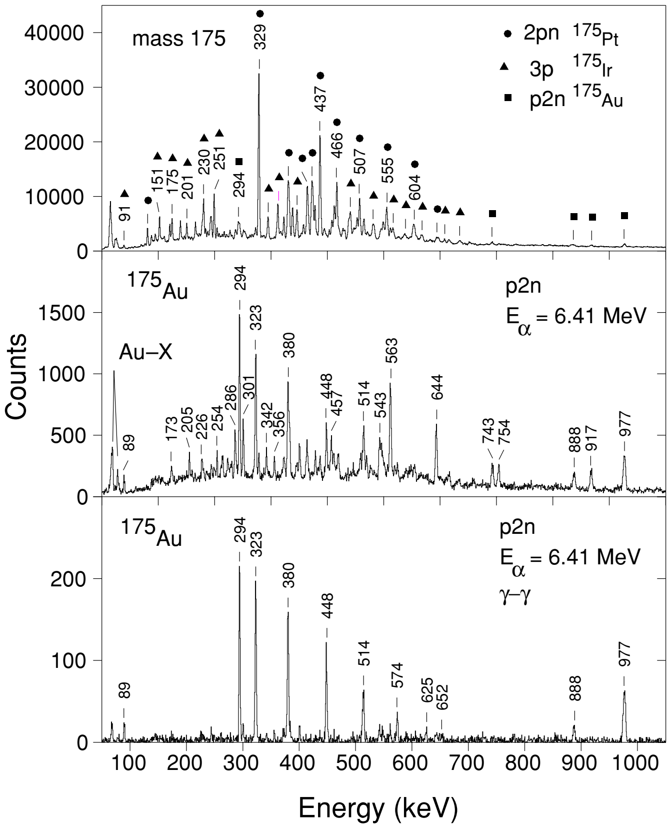

Figure 1. Top panel: gamma-ray spectrum in coincidence with mass 175 residues. Middle panel: gamma-ray spectrum correlated with the α decay of ^{175}Au. Bottom panel: summed, background-subtracted γ-ray coincidence spectra from the $\gamma - \gamma$ matrix produced by gating on the $E_\alpha =$ 6.41 MeV (^{175}Au) line.

Coulomb barrier results in low excitation energy of the compound which minimizes both fission and particle evaporation. As a result, higher beam currents can be utilized which yield larger production rates for the most proton-rich nuclides of interest.

2. Experimental technique

One of the principal applications of Gammasphere when sited at the ATLAS accelerator at Argonne National Laboratory consists in coupling the device with the fragment mass analyser (FMA) in order to study nuclei 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 m away.

Figure 1 demonstrates the power of the FMA to isolate specific reaction channels utilizing both mass gating and RDT. The data come from an experiment using the reaction ^{84}Sr + ^{92}Mo to produce proton unbound Au nuclei [1]. The top panel shows the γ-ray spectrum in coincidence with mass 175 residues to be compared with the middle panel where the spectrum correlated with the α decay of ^{175}Au is given. 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

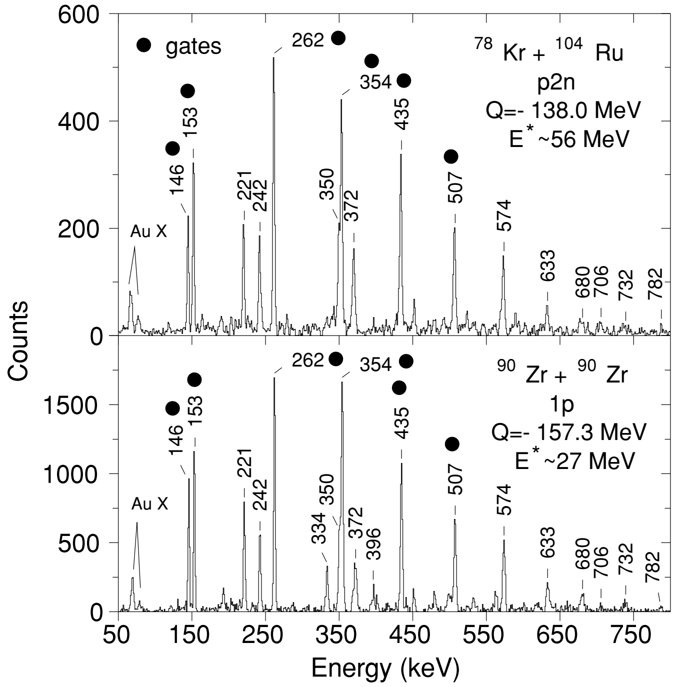

Figure 2. Top panel: summed, background-subtracted γ-ray coincidence spectrum from data taken with the ^{78}Kr+^{104}Ru reaction. The gates used are marked in the figure. Bottom panel: same as top panel, but with data taken from the ^{90}Zr+^{90}Zr reaction.

sum of gates obtained from a γ-ray coincidence matrix correlated with the α decay of ^{175}Au. The coincidence information allows for the level structure of these very proton-rich nuclei to be extended to spins in excess of $20\hbar$. Utilizing RDT with Gammasphere, excited states have been identified in nuclei produced with cross-sections as low as 50 nanobarns, a sensitivity unrivalled by other forms of selectivity applied to in-beam γ-ray spectroscopy studies.

In addition, the use of symmetric reactions with bombarding energies near the Coulomb barrier offers experimental advantages in the study of neutron-deficient nuclei in this region. Due to the large, negative Q-value one finds for these reactions, the compound system is left with relatively low excitation energy once fusion takes place. An illustrative example is given in figure 2, where γ-ray spectra are shown for ^{179}Au produced in two different reactions, ^{104}Rh(^{78}Kr, p2n)^{179}Au and ^{90}Zr(^{90}Zr, p)^{179}Au. The excitation energy of the compound nucleus differs by a factor of 2 for these two reactions (56 MeV and 27 MeV, respectively), and statistical model calculations indicate that the fission cross-section is an order of magnitude greater for the Kr-induced reaction. Even though the excitation energies differ by a factor of 2, the two spectra are quite similar with regards to the relative intensities of each γ transition, indicating that both reactions have similar spin distributions. The Zr-induced data have nearly three times the statistics of the Kr-induced spectrum, even though both reactions were run for nearly the same time. The reasons for this are twofold. Firstly, by minimizing both fission and the number of evaporated particles, one is able to run with significantly more beam on target for the Zr-induced reaction due to a reduced counting rate in the Gammasphere detectors per pnA of beam. Secondly, for the Kr-induced reaction, a large part of the production cross-section

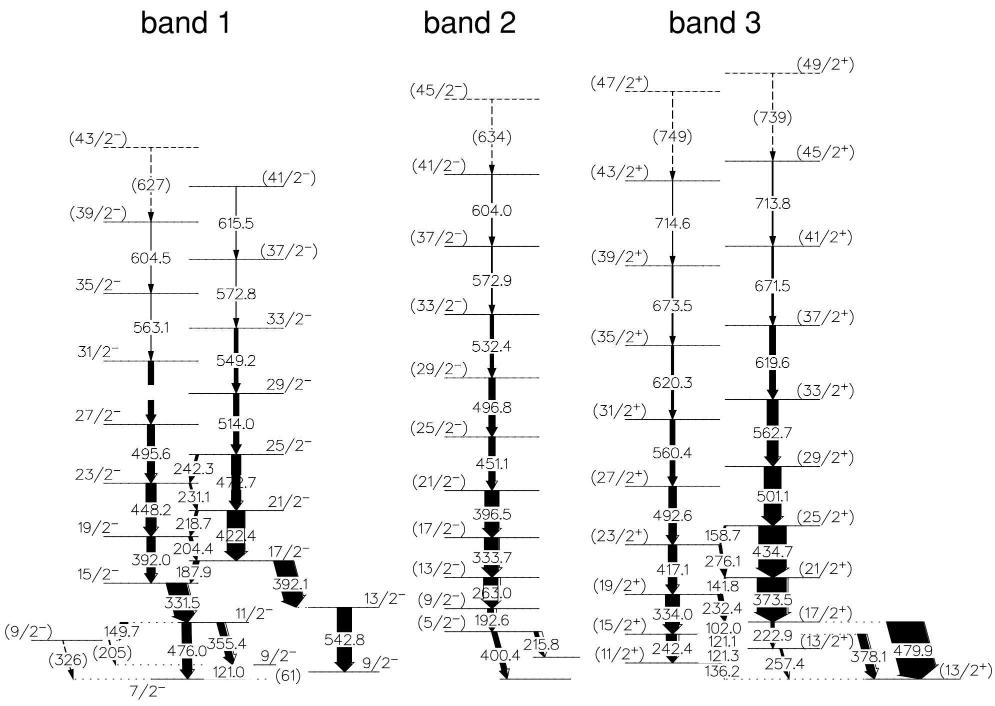

Figure 3. Partial level scheme for ^{179}Hg.

for A = 179 is in the 2p,n(^{179}Pt) and 3p(^{179}Ir) channels while for the Zr-induced reaction, the 1p channel dominates for A = 179.

3. Spectroscopy of ^{179}Hg

In the Kr-induced reaction, the 3n channel leading to ^{179}Hg was quite small and did not allow for a proper coincidence analysis to be performed. This was not the case for the ^{90}Zr+^{90}Zr reaction where ^{179}Hg was populated via the 1n channel. Before our study, no information on excited states in ^{179}Hg was available. Figure 3 shows the extensive level scheme constructed from this data set for ^{179}Hg [2].

The neutron deficient Hg isotopes are of interest due to the fact that below $N = 110$, the Hg isotopes exhibit a co-existence at low spin between two different shapes. For the even-A isotopes, a weakly deformed oblate ground state coexists with a more deformed, excited prolate band. The energy difference between the two 0^+ states associated with these shapes exhibits a parabolic trend as a function of neutron number, minimizing in energy around mid-shell at ^{182}Hg ($N = 102$). Experiments performed by our group on ^{176,178}Hg were able to establish the excitation energy of the prolate band beyond the mid-shell [3]. 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 ($J = 13/2^+$) isomer has been identified in each of the three odd-mass Hg isotopes. The mechanism responsible for this preferred prolate shape at low spin in the odd-mass isotopes is still not fully understood.

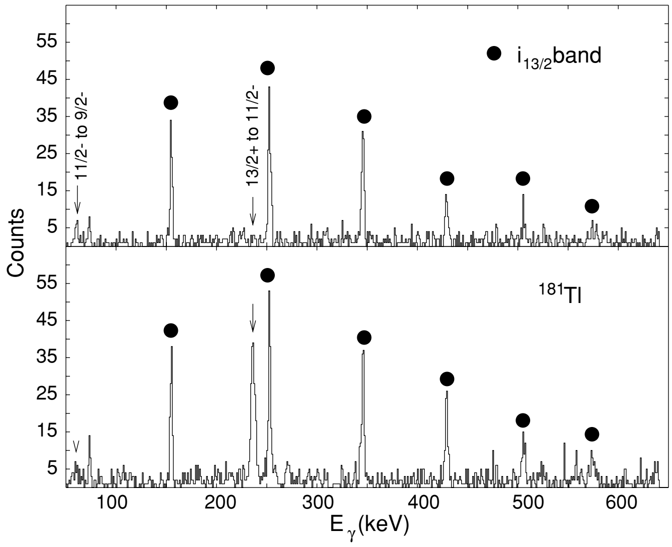

Figure 4. Representative γ-ray spectra for ^{181}Tl. Top panel: sum of double gates with members of the $i_{13/2}$ rotational band (indicated by filled circles) and the 236 keV $(13/2^+ - 11/2^-)$ transition. Bottom panel: sum of double gated spectra using all possible combinations of γ rays in the $i_{13/2}$ rotational band.

Our new data on ^{179}Hg [2] help clarify how shapes in the odd-A Hg isotopes evolve below mid-shell. From an analysis of the α decay of ^{179}Hg into ^{175}Pt, the ground state of ^{179}Hg was firmly assigned $J^+ = 7/2^-$. 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 shape. This change in the ground state spin can only be understood if the ground state in ^{179}Hg is weakly deformed or possibly spherical. In addition, band 3 decays into a $13/2^+$ isomeric state. This state is not part of the rotational band but rather it originates from an oblate $i_{13/2}$ configuration as observed for the heavier odd-A Hg isotopes. Consequently, ^{179}Hg is an example of three coexisting shapes at low-spin and excitation energy. Some of the other recent examples of triple shape co-existence are ^{186}Pb [4], ^{188}Pb [5] and ^{175}Au [1]. More details concerning this study can be found in [2].

4. Spectroscopy of ^{181}Pb and ^{181}Tl

One of our most recent experiments with Gammasphere at the FMA involved the study of ^{181}Pb and ^{181}Tl with the set-up described above. ^{181}Pb is the lightest odd-A Pb isotope identified thus far and ^{181}Tl is proton unbound. However, Q-values are not favourable for proton emission in this case. Excited states in both ^{181}Tl and ^{181}Pb were populated in the reaction ^{90}Zr+^{92}Mo at 385 MeV.

From this measurement, new information on the α decay of ^{181}Pb was obtained. An α decay from the ground state of ^{181}Pb to an excited $9/2^-$ state in ^{177}Hg was observed. The spin and parity of the $9/2^-$ level in ^{177}Hg was established in a recent study by Melerangi *et al* [6]. 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 where $3/2^-$ ground states have been found. This change in the ground state spin 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 this gap. In addition, a γ transition with a lifetime of $\sim$10 μs is observed to feed the ^{181}Pb ground state. This level has been given a tentative assignment of $(13/2^+)$ and could represent an excitation into the $i_{13/2}$ orbital.

Figure 4 shows double gated spectra for the $i_{13/2}$ rotational band identified in ^{181}Tl taken from an $A = 181$ gated coincidence cube. The top spectrum is a sum of gates where a 236 keV transition is combined with members of the rotational band marked by closed circles. The 236 keV transition represents the decay from the $13/2^+$ level of the rotational band to the $11/2^-$ spherical state. A 61 keV transition is observed and assigned to the decay from the $11/2^-$ spherical state to a $9/2^-$ oblate state. The $9/2^-$ state is isomeric ($t_{1/2} \sim 1$ ms) with a small α-decay branch directly feeding a $9/2^-$ state in ^{177}Au. The bottom panel is a sum of double coincidence gates using all possible double gate combinations of transitions assigned to the rotational band. The assigned $13/2^+$ to $11/2^-$ transition exhibits a γ-ray peak whose FWHM is wider than the γ-ray peaks assigned to the rotational band, indicating a lifetime of a few nanoseconds. This observation is consistent with an E1 transition connecting a deformed state to a spherical state. As is the case in the heavier odd-A Tl isotopes (^{183,185,187}Tl), ^{181}Tl exhibits triple shape coexistence as well [7].

Acknowledgments

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