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Isomers and seniority in the trans-Pb nuclei

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Abstract

Low-energy excited states of ^{210}Ra and ^{208}Ra were investigated at the Wright Nuclear Structure Laboratory of Yale University. Fusion evaporation recoils were selected using the gas-filled spectrometer, SASSYER. Delayed γ-rays, following isomeric decays, were detected at the focal plane of SASSYER with a small array of HPGe detectors. Transitions following the proposed $J^\pi = 8^+$ isomers were observed, and the half-lives measured. The experiments are discussed and results compared to expectations from the seniority scheme.

1. Introduction

The heavy nuclei ($Z \geqslant 82$) with $N \leqslant 126$ exhibit many interesting features, one of which is a wealth of isomerism. For example, the singly magic ^{214}Ra isotope has five isomers below 5 MeV with half-lives longer than 100 ns [1]. As the neutron number decreases, the isomer density decreases. However, the $(\pi h_{9/2})^2 8^+$ isomers persist at low excitation energies until $N \sim 118$. The presence of the $(\pi h_{9/2})^2 8^+$ isomers alludes to the dominance of proton excitations for a low-spin, low-energy structure near $N = 126$. This suggests that the seniority concept can be successfully used to describe the observed structure and transition probabilities.

However, little experimental data are available in the $Z > 82$, $N < 126$ mass region. Population of the excited states is typically performed using heavy-ion fusion evaporation

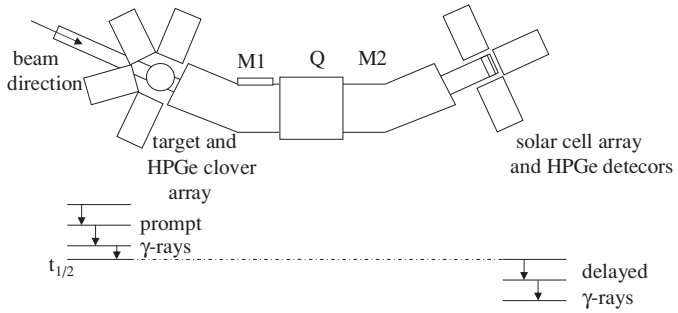

Figure 1. A typical set-up for a SASSYER experiment.

reactions. As Z increases from 82 and/or N decreases from 126, survival probabilities for heavy compound nuclei decrease steeply and fission dominates over the formation of evaporation residues. To successfully study these isotopes, the fission detection needs to be suppressed. Gas-filled separators, such as RITU [2] at the University of Jyväskylä and SASSYER [3] at Yale University, have proven to be invaluable tools to study heavy-mass nuclei.

The SASSYER spectrometer originated from Berkeley National Laboratory where it was employed in the heavy element research of Ghiorso *et al* [4, 5]. The three magnets, two magnetic dipoles surrounding a single quadrupole, were brought to the Wright Nuclear Structure Laboratory in hopes of expanding the function of the separator to a broad range of studies.

Using the 'new' spectrometer, a physics program studying the structure of $Z > 82$, $N < 126$ nuclei has been implemented. An early study was the refinement of low-energy excited states in the even–even ^{210}Ra [6] and ^{208}Ra [7] nuclei. Prior to this work, half-lives for the proposed $(\pi h_{9/2})^2 8^+$ isomers were reported [8], although transitions and excitation energies were not explicitly provided.

2. Experiments and results

The ^{208}Ra and ^{210}Ra isotopes were studied separately, using similar detector configurations. A schematic for experiments involving SASSYER is shown in figure 1.

A low pressure (0.8 Torr), constantly circulating He gas, is utilized in the system. The gas enters at the second dipole of SASSYER and is removed ∼1.5 m prior to the first dipole. The use of the gas equilibrates charges for slow-moving ions, such as those produced in fusion–evaporation reactions while not appreciably affecting the high-velocity beam particles and fission fragments.

The target position is surrounded by HPGe clover detectors, of 150% relative efficiency each. Typical experiments employ four clover detectors at 90° and four at 140° relative to the beam axis. In this configuration, the detection efficiency for a 1.3 MeV γ-ray is ∼2.4%.

Reaction products and remaining beam particles enter the first magnet, where an applied field is chosen such that fusion recoils pass through the central trajectory. Particles with low rigidity, such as fission fragments and unreacted beam particles, are bent into a lead-lined dump box within the first dipole.

Selected recoils passing through SASSYER are deposited in a 30 element Si solar cell array. The dimension of each cell is 1 cm^2; the entire array is 10 cm wide and 3 cm high. Surrounding the array are HPGe detectors to record delayed γ-emissions. Isomeric half-lives

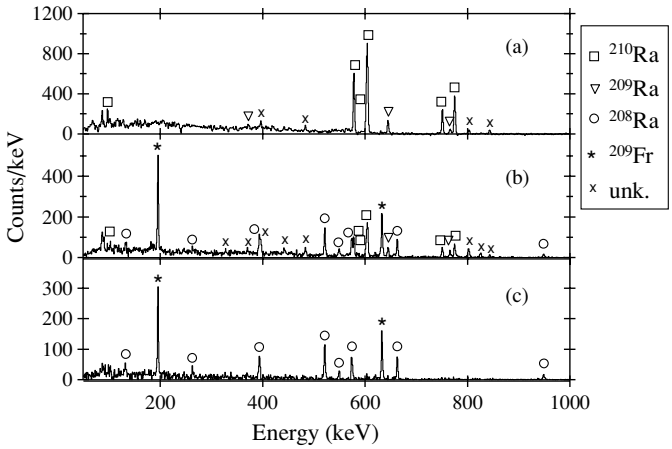

Figure 2. Delayed γ-rays observed in the (a) ^{210}Ra and (b), (c) ^{208}Ra experiments. In (a), all transitions within 6 μs after a recoil implantation in the solar cell array are shown. In (b), the time window is 3 μs. For (c), a time subtraction shows only short-lived isomers.

are determined by noting the time between a recoil implantation in the solar cell array and a subsequent γ-decay.

For the ^{210}Ra study, a beam of 148 MeV ^{30}Si ions bombarded two stacked, isotopically pure ^{184}W targets of 200 μg cm^{-2} thickness each. Prompt γ-rays produced directly following the reaction were detected by eight HPGe clover detectors surrounding the target station. Five smaller HPGe detectors (25% relative efficiency each) were used near the solar cell array at the exit of SASSYER. A total of 5.0×10^6 recoils and 8.7×10^4 recoil-γ_{delayed} events were observed.

Delayed γ-rays observed within 6 μs after a recoil are shown in figure 2(a). The spectrum is dominated by ^{210}Ra, produced in the ^{184}W(^{30}Si,4n) reaction channel. Less intense transitions arising from isomers in ^{209}Ra are also observed, as well as a number of unassigned peaks. These are most likely from the Fr isotopes, where very little data are available.

For the ^{208}Ra study, an enriched $^{182}WO_3$ target of 460 μg cm^{-2} was used. The isotopic enrichment of ^{182}W was 94.32%; contaminant masses were ^{183}W (2.54%), ^{184}W (2.32%), ^{186}W (0.82%) and ^{180}W (<0.05%). Due to the low yield of ^{208}Ra fusion recoils, the HPGe detectors at the target station were removed and three clovers were placed around the solar cell array. A total of 1.8×10^6 recoils and 2.8×10^4 recoil-γ_{delayed} coincidences were observed.

Delayed γ-rays observed within 3 μs after a recoil are shown in figure 2(b). Numerous transitions are observed, many of which can be attributed to longer lived components produced from the target contaminants. To clarify the short-lived decays, transitions detected within 1–2.5 μs were subtracted from the transitions within 0–800 ns after a recoil. This subtracted spectrum, showing only ^{208}Ra and ^{209}Fr is displayed in figure 2(c).

Half-lives for the isomers were determined by weighted least-squares fits to the time difference between recoil implantation and γ-ray identification. Time spectra for both ^{210}Ra and ^{208}Ra are shown in figure 3. For ^{210}Ra, a half-life of 2.2(1) μs was determined; this is in excellent agreement with the previous measurement of 2.24 μs of [8]. For ^{208}Ra, the half-life was determined from the time spectra of the 520, 548, 661 and 948 keV transitions. Remaining transitions were not used due to insufficient resolution from contaminant energies. A half-life of 250(30) ns was measured for the the ^{208}Ra isomer.

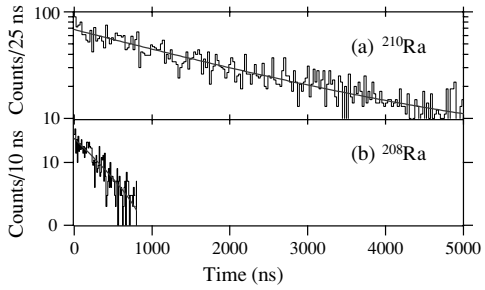

Figure 3. Time between a recoil implantation and delayed γ-ray for (a) ^{210}Ra and (b) ^{208}Ra. From a weighted least-squares fit to these data, half-lives of 2.1(1) μs and 0.25(3) μs were determined for ^{210}Ra and ^{208}Ra, respectively.

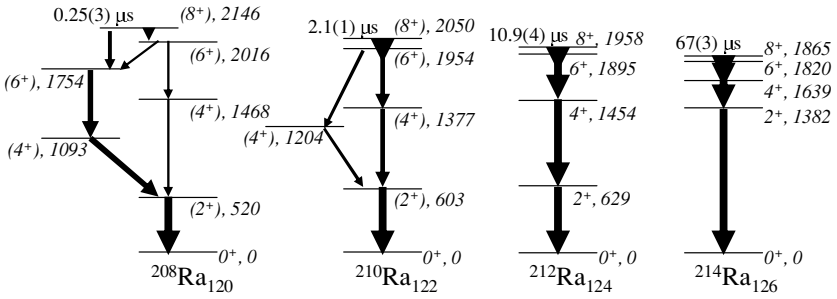

Figure 4. Energy level schemes, relative transition intensities and isomeric half-lives for even–even $^{208–214}$Ra. Decay intensities are proportional to the arrow width. Data for ^{208,210}Ra were derived from the experiments here; data for ^{212}Ra and ^{214}Ra were adopted from [11, 1], respectively.

Level schemes below the isomers in ^{210}Ra and ^{208}Ra were built from recoil-γ–γ coincidences measured with the isomer detectors. Energy level diagrams are shown in figure 4, where the arrow width is proportional to the decay intensity, normalized to the $2^+ \rightarrow 0^+$ transition for each isotope. Assigned spins and parities were derived from intensity balances and comparisons to neighbouring nuclei.

3. Discussion

An increasing complexity in the level schemes for the Ra isotopes as the neutron number decreases below $N = 126$ is evident. Similar structures are observed in the Rn and Po isotones, and can probably be attributed to neutron degrees of freedom and a softening of the nucleus towards collective excitations.

Using the decay half-lives, energies and theoretical conversion coefficients [9], quadrupole reduced transition probabilities for the isomeric decays were determined. For ^{210}Ra, the $B(E2; 8^+ \rightarrow 6^+) = 0.035(2)$ Wu, for ^{208}Ra, $B\left(E2; 8^+ \rightarrow 6^+_1\right) = 0.0014(3)$ Wu, and $B\left(E2; 8^+ \rightarrow 6^+_2\right) = 0.11(3)$ Wu.

The ^{210}Ra isotones ^{208}Rn and ^{206}Po have transition probabilities of $BE(E2; 8^+ \rightarrow 6^+) = 0.187(7)$ Wu and $BE(E2; 8^+ \rightarrow 6^+) = 2.49(17)$ Wu, respectively. Therefore, a general trend of decreasing $B(E2)$ values is observed as the proton number increases from $Z = 82$. A similar trend is observed for the $N = 124$ and $N = 126$ isotones of Po, Rn and Ra.

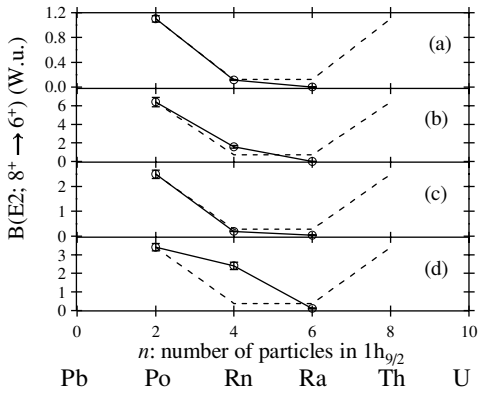

Figure 5. Comparison of experimental data and predictions of the simple seniority scheme for (a) $N = 126$, (b) $N = 124$, (c) $N = 122$ and (d) $N = 120$. Calculated $B(E2)$ values are normalized to the Po experimental data. The scheme reproduces the observed transition probabilities for $N = 126$, $N = 124$ and $N = 122$ well, but has much less agreement with $N = 120$.

This lowering of $B(E2)$ values away from a shell closure for $J > 2$ spins is a natural result of the seniority scheme. The concept of seniority simplifies calculations; for a state of the angular momentum J comprising n particles in an orbital j ($j^n = J$), seniority (ν) is the minimum number of unpaired particles needed to produce J ($j^\nu = J$). For the 0^+ ground states $\nu = 0$, while for $2 \leqslant J \leqslant 2j - 1$, $\nu = 2$. For even-tensor, one-body transitions (i.e., $E2$ decays) between states of the same seniority, the matrix element for n particles in a j orbital can be rewritten in terms of seniority by

$$\langle j^n \nu J || O_p^{\text{even}} || j^n \nu J' \rangle = \frac{(2j + 1 - 2n)}{(2j + 1 - 2\nu)} \langle j^\nu \nu J || O_p^{\text{even}} || j^\nu \nu J' \rangle.$$

If it is assumed that the wavefunctions for the final and initial states involved in the decay vary little between the isotones, it is expected that $B(E2; \Delta\nu = 0)$ values for the Po–Rn–Ra follow the trend determined by the square of the pre-factor above.

Comparisons between experimental $B(E2; 8^+ \rightarrow 6^+)$ values and those predicted by the seniority scheme are plotted in figure 5. The calculated $B(E2)$ values are determined for protons filling the $1h_{9/2}$ ($j = 9/2$) shell model orbital. For Po, with two protons in the $1h_{9/2}$ orbital, $n = 2$, while for Rn and Ra $n = 4$ and 6, respectively.

For the $N = 122$ isotones, there is good agreement with the simple seniority prediction. This suggests that good seniority persists four neutrons away from the $N = 126$ shell closure. This can be attributed to the low number of valence particles, as well as weak interactions between the valence protons and neutrons [10]. While protons are assumed to be filling the $1h_{9/2}$ orbital, neutrons are largely $3p_{1/2}$–$2f_{5/2}$–$3p_{3/2}$ in character.

For the $N = 120$ isotones, the experimental values deviate from expectations. This suggests that seniority is no longer a good quantum number six neutrons away from $N = 126$. This result is not surprising since collective effects are expected to become increasingly important away from the shell closure.

4. Conclusions

In conclusion, half-lives and decay transitions of the (8^+) isomers in ^{210}Ra and ^{208}Ra have been measured. Transition probabilities for the $(8^+ \rightarrow 6^+)$ decays have been determined

and compared to predictions of the seniority scheme. For the $N = 122$ isotones, measured $B(E2; 8^+ \rightarrow 6^+)$ values agree well with the simple calculations. For the $N = 120$ isotones, the addition of two more neutron holes causes the agreement to be poorer and the seniority model is no longer useful.

Acknowledgments

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