Spectroscopy Of Reflection-Asymmetric Nuclei Using Multinucleon Transfer Reactions

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Abstract

The heavy-ion collisions of $^{56}$Fe + $^{232}$Th, $^{86}$Kr + $^{232}$Th and $^{136}$Xe + $^{232}$Th with beam energies 15-20% above the Coulomb barrier were used to populate nuclei in the light-actinide region. Yield distributions of the binary reaction products stopped in thick targets were obtained by measuring $\gamma$-$\gamma$ coincidence intensities. The $^{136}$Xe + $^{232}$Th reaction was repeated at Lawrence Berkeley National Laboratory using a recent implementation of the GAMMASPHERE array. Many interesting discoveries concerning the high-spin structure of octupole-deformed light-actinide nuclei have been made.

Nuclei with Z$\approx$88 and N$\approx$134 have their neutron and proton Fermi levels in close proximity to the octupole-driving $\nu$(j_{15/2} and g_{9/2}) and $\pi$(i_{13/2} and f_{7/2}) orbitals. Thus these light-actinide nuclei are susceptible to octupole deformation [1], [2]. Nuclei in this region can be studied using fusion-evaporation reactions but low production cross-sections (Smillibarns) and large fission cross-sections [3] make these nuclei difficult to study by these means. This
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population mechanism is limited further by a lack of suitable projectiles and stable targets above $^{209}$Bi. Virtually no information exists concerning the excited states in $^{222}$Ra and the octupole-deformed Rn isotopes with $A \geq 218$. We have used multinucleon transfer reactions to populate this region of nuclei. Three experiments were carried out in which thick $^{232}$Th targets were bombarded by different heavy ions at energies between 15% and 20% above the Coulomb barrier. The details of these experiments are summarised in Table 1.

For each system, measurements of the yield of the populated nuclei were produced using quantitative in-beam and out-of-beam $\gamma$-$\gamma$ coincidence analyses, where the intensities were corrected for efficiency and internal conversion [4]. Figure 1 shows the target-like product yields for the reactions $^{56}$Fe + $^{232}$Th, $^{86}$Kr + $^{232}$Th and $^{136}$Xe + $^{232}$Th. The yields were normalised by matching the yield of the Coulomb-excited $2^+$ state in $^{232}$Th. The least neutron-rich of the projectiles, $^{56}$Fe, picks up most neutrons from the target and shifts the distribution of heavy products into the region which is already accessible by compound-nucleus reactions. The $^{86}$Kr and $^{136}$Xe projectiles populate the region which cannot be accessed by presently-

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Target (mg/cm$^2$)</th>
<th>Beam Species</th>
<th>Beam Energy (MeV)</th>
<th>%above CB</th>
<th>Germanium Detector Array</th>
<th>Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$^{232}$Th (30)</td>
<td>$^{56}$Fe</td>
<td>362</td>
<td>20</td>
<td>12 TESSA-type</td>
<td>K-130 cyclotron, JYFL, Jyväskylä</td>
</tr>
<tr>
<td>II</td>
<td>$^{232}$Th (30)</td>
<td>$^{86}$Kr</td>
<td>511</td>
<td>16</td>
<td>TESSA3 frame: 12 detectors + 50-element multiplicity filter</td>
<td>K-130 cyclotron, JYFL, Jyväskylä</td>
</tr>
<tr>
<td>III</td>
<td>$^{232}$Th (40)</td>
<td>$^{136}$Xe</td>
<td>830</td>
<td>15</td>
<td>Argonne–Notre Dame: 12 25%-efficiency detectors + 50-element BGO ball</td>
<td>ATLAS, Argonne National Laboratory</td>
</tr>
</tbody>
</table>

Table 1: Summary of experimental details. The Coulomb barrier energy is defined as
\[ E_{CB} = \frac{1.44(A_p^{1/3} + A_t^{1/3})Z_pZ_t}{1.16(A_p^{1/3} + A_t^{1/3})} \]
where $A_p$, $Z_p$, $A_t$ and $Z_t$ are the mass and proton numbers of the projectile and target respectively.
available fusion-evaporation reactions. The $^{136}$Xe projectile, with the largest neutron-to-proton ratio, populates octupole-deformed Rn and Ra isotopes in the light-actinide region with the greatest intensity.

The $^{136}$Xe + $^{232}$Th reaction was repeated at Lawrence Berkeley National Laboratory using the high-efficiency GAMMASPHERE array. The array consisted of 73 large-volume ($\sim$75% relative efficiency) Compton-suppressed germanium detectors [5], [6], 27 of which were segmented [7]. After 54 hours of collecting gamma-ray events of fold 3 or higher, subsequent unpacking of events revealed a total of $1.1 \times 10^{10}$ triple and $6.7 \times 10^9$ fourfold Compton-suppressed gamma-ray coincidences. The typical spectra shown in figure 2 serve to illustrate the quality of these data. Figure 2(a) is a threefold gamma-ray spectrum which shows transitions in $^{218}$Rn. The spectrum was produced by double-gating on transitions in the ground state rotational band in $^{218}$Rn in a $\gamma$-$\gamma$-$\gamma$-correlation matrix. Figure 2(b) is a fourfold spectrum showing transitions in $^{224}$Ra. This spectrum was produced by double-gating on transitions in the ground state rotational band in $^{224}$Ra in a gated $\gamma$-$\gamma$-$\gamma$-correlation matrix. The initial

Figure 1: A comparison of the yields of target-like nuclei produced in the $^{56}$Fe + $^{232}$Th, $^{86}$Kr + $^{232}$Th and $^{136}$Xe + $^{232}$Th reactions.
Figure 2: (a) Threefold gamma-ray spectrum showing transitions in $^{218}$Rn. (b) Gamma-ray spectrum showing transitions above and including the 6$^+$ to 4$^+$ transition in $^{224}$Ra. This spectrum is from unpacked fourfold coincidence events where one of the gamma rays has the same energy as the 4$^+$ to 2$^+$ transition in $^{224}$Ra.

High-spin states in many light-actinide nuclei have been observed. The level schemes of $^{218}$Rn, $^{220}$Rn and $^{222}$Rn are shown in figure 3. Previous to the present work, only the 5 lowest-lying states in each nucleus were known [8], [9]. In the present work, alignment effects for the positive parity states in $^{218}$Rn and $^{220}$Rn have been observed at $\hbar \omega \approx 0.22$ MeV. Cranked shell model calculations predict a strong alignment of a pair of $i_{13/2}$ protons close to this rotational frequency in these two nuclei.

The level schemes of $^{222}$Ra, $^{224}$Ra and $^{226}$Ra are shown in figure 4. Previous knowledge of these nuclei can be found in references [10], [11], [12] and [13]. The level schemes of $^{222}$Ra, $^{224}$Ra and $^{226}$Ra have been considerably extended in the present work and interleaving positive- and negative-parity states have been observed for the first time in $^{222}$Ra.
Figure 3: Level scheme of $^{218}$Rn, $^{220}$Rn and $^{222}$Rn, produced using energy sums and intensity balance arguments. The transition energies have errors which range from 0.2 keV for low-lying transitions in the positive parity bands to 0.5 keV for 5$^{-}$ to 3$^{-}$ and 7$^{-}$ to 5$^{-}$ transitions and transitions between the highest spin states observed.

Figure 4: Level scheme of $^{222}$Ra, $^{224}$Ra and $^{226}$Ra, produced using energy sums and intensity balance arguments. The transition energies have errors which range from 0.2 keV for low-lying transitions in the positive parity bands to 0.5 keV for 5$^{-}$ to 3$^{-}$ and 7$^{-}$ to 5$^{-}$ transitions and transitions between the highest spin states observed.
For each state that is depopulated by both E1 and E2 transitions in the six nuclei, intrinsic electric dipole-to-quadrupole ($Q_0$) ratios were extracted from branching ratios. Upper limits were obtained for high-spin states in $^{224}$Ra. The $Q_0$ values were constant within each nucleus. Using weighted mean values of $Q_0$ and published values of $Q_0$, a measure of the intrinsic electric dipole moment, $D_0$, was determined for the Rn and Ra isotopes. The intrinsic electric dipole moment measured for $^{224}$Ra, $0.030(1)$ e.fm, is much lower than those for $^{222}$Ra, $0.27(4)$ e.fm, and $^{226}$Ra, $0.18(2)$ e.fm. The anomalously low dipole moment in $^{224}$Ra persists to high spins ($<0.09$ in the spin range $I=12-23\hbar$). At low spin, the calculations of Butler and Nazarewicz [15] reproduced an anomalously low $D_0$ for $^{224}$Ra by treating the intrinsic electric dipole moment as the sum of a macroscopic (liquid drop) component and a microscopic (shell correction) term. These two components cancel for $^{224}$Ra but the addition of the two contributions results in large intrinsic electric dipole moments for $^{222}$Ra and $^{226}$Ra. Good agreement between the experimental and theoretical $D_0$ values for the Rn isotopes was observed.

References