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Spectroscopy Of Reflection-Asymmetric Nuclei Using Multinucleon Transfer Reactions

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J.F.C.Cocks[1], P.A.Butler[1], K.J.Cann[1], P.T.Greenlees[1], G.D.Jones[1], R.Broda[3], B.Fornal[3], P.M.Jones[2], R.Julin[2], S.Juutinen[2], D.Müller[2], M.Piiparinen[2], A.Savelius[2], J.F.Smith[6], I.Ahmad[4], S. Asztalos[5], P.Bhattacharyya[7], D.J.Blumenthal[4], M.P.Carpenter[4], R.M.Clark[5], B.Crowell[4], M.A.Delaplanque[5], R.M.Diamond[5], P.Fallon[5], R.V.F.Janssens[4], T.L.Khoo[4], T.Lauritsen[4], I.Y.Lee[5], A.O.Macchiavelli[5], R.W.MacLeod[5], D.Nisius[4], F.S.Stephens[5], C.T.Zhang[7]

(1) Oliver Lodge Laboratory, University of Liverpool, Liverpool. L69 3BX U.K.

(2) Accelerator Laboratory, University of Jyväskylä, FIN-40351, Jyväskylä, Finland

(3) Institute of Nuclear Physics, Radzikowskiego 152, PL-31-342, Kraków, Poland

(4) Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA

(5) Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA

(6) State University of New York, Stony Brook, New York, NY11794-3800, USA

(7) Chemistry Department, Purdue University, West Lafayette, Indiana 47907, USA

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 γ-γ 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$\simeq$88 and N$\simeq$134 have their neutron and proton Fermi levels in close proximity to the octupole-driving ν($j_{15/2}$ and $g_{9/2}$) and π($i_{13/2}$ 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 ($\leq$millibarns) and large fission cross-sections [3] make these nuclei difficult to study by these means. This

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Reaction	Target (mg/cm^2)	Beam			Germanium Detector Array	Facility
		Species	Energy (MeV)	%above CB		
I	^{232}Th (30)	^{56}Fe	362	20	12 TESSA-type (23% efficiency) detectors	K-130 cyclotron, JYFL, Jyväskylä
II	^{232}Th (30)	^{86}Kr	511	16	TESSA3 frame: 12 detectors + 50-element multiplicity filter	K-130 cyclotron, JYFL, Jyväskylä
III	^{232}Th (40)	^{136}Xe	830	15	Argonne–Notre Dame: 12 25%-efficiency detectors + 50-element BGO ball	ATLAS, Argonne National Laboratory

Table 1: Summary of experimental details. The Coulomb barrier energy is defined as $E_{CB} = \frac{1.44(\frac{A_p}{A_t}+1)Z_pZ_t}{1.16(A_p^{1/3}+A_t^{1/3}+2)}$ where A_p, Z_p, A_t and Z_t are the mass and proton numbers of the projectile and target respectively.

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 γ-γ 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-

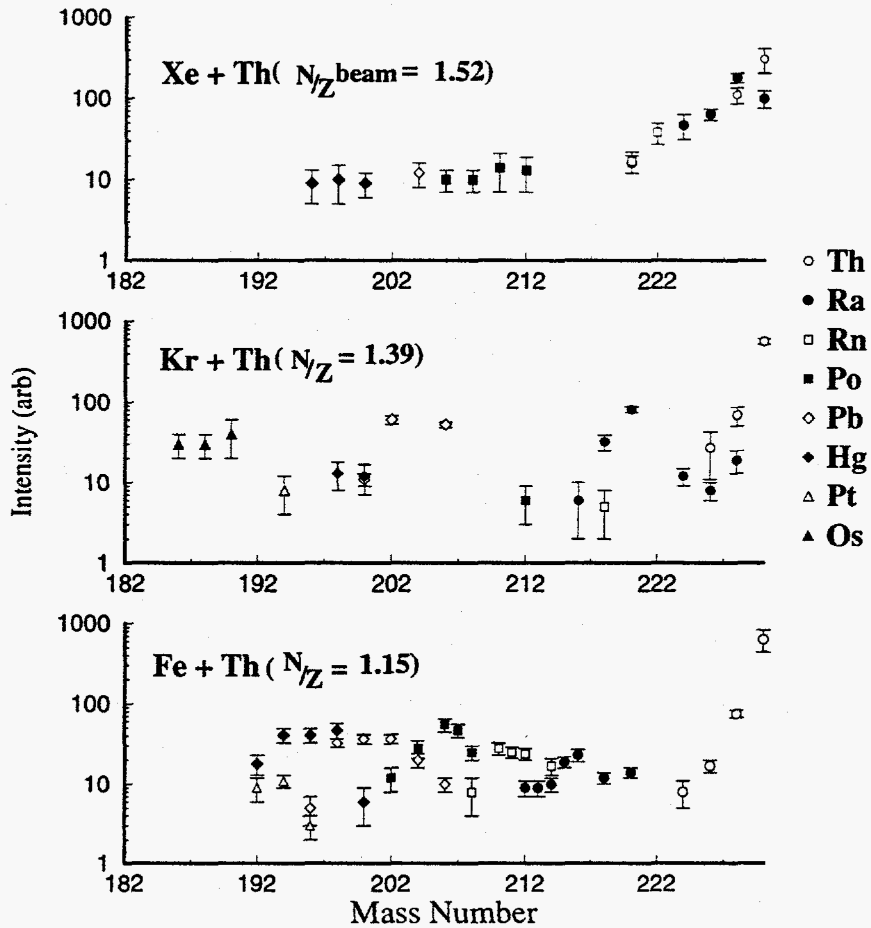

Figure 1: A comparison of the yields of target-like nuclei produced in the ^{56}Fe + ^{232}Th, ^{86}Kr + ^{232}Th and ^{136}Xe + ^{232}Th reactions.

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 (~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 1.1×10^{10} triple and 6.7×10^{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 γ-γ-γ-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 γ-γ-γ-correlation matrix. The initial

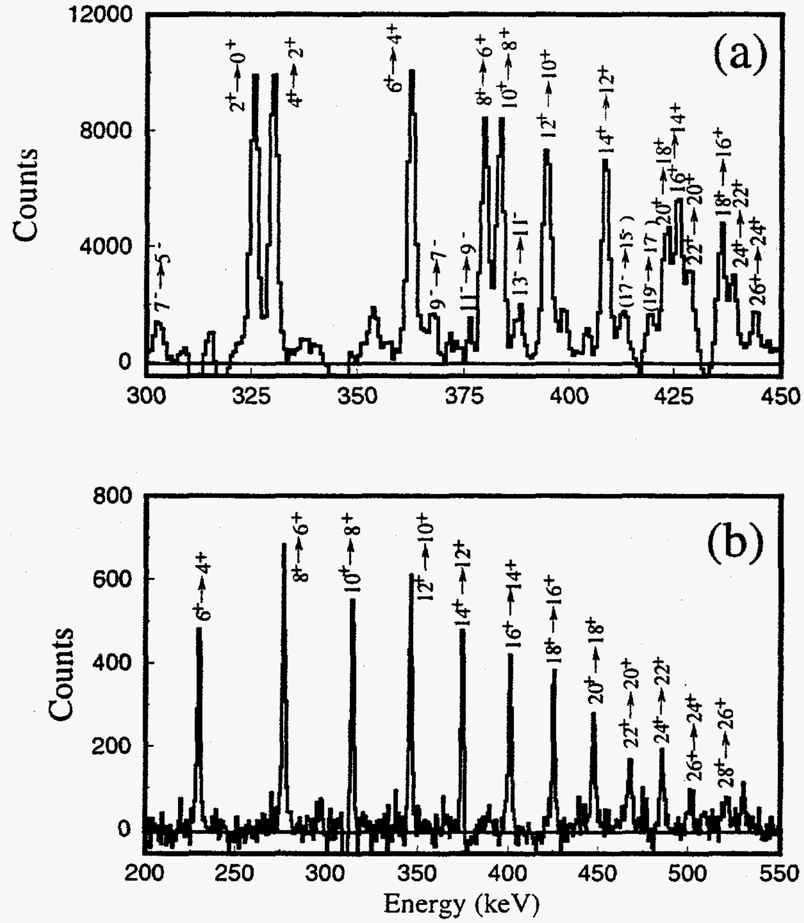

Figure 2: (a) Threefold gamma-ray spectrum showing transitions in ^{218}Rn. (b) Gamma-ray spectrum showing transitions above and including the 6^+ to 4^+ transition in ^{224}Ra. This spectrum is from unpacked fourfold coincidence events where one of the gamma rays has the same energy as the 4^+ to 2^+ transition in ^{224}Ra.

gate was set on 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 $i_{13/2}$ 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.

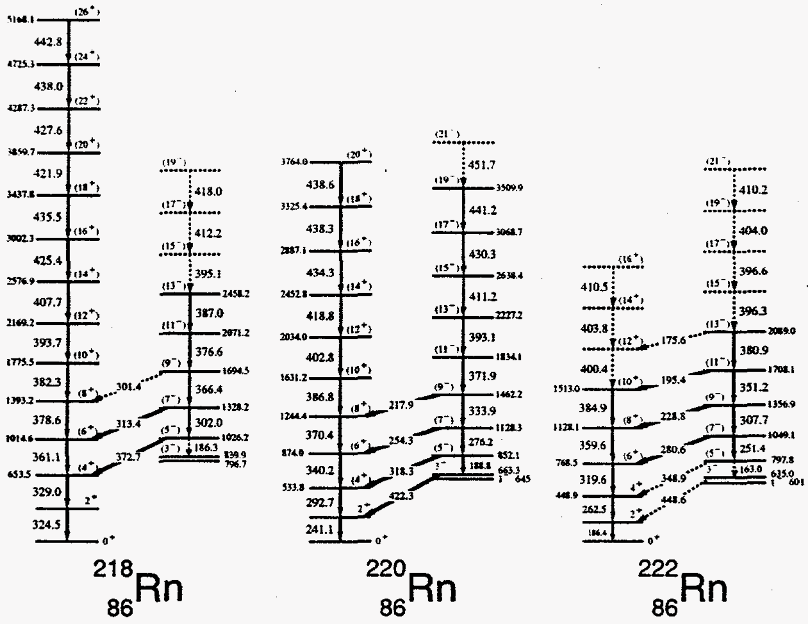

Figure 3: Level scheme of ^{218}Rn, ^{220}Rn and ^{222}Rn, produced using energy sums and intensity balance arguments. The transition energies have errors which range from 0.2 keV for low-lying transitions in the positive parity bands to 0.5 keV for 5^- to 3^- and 7^- to 5^- transitions and transitions between the highest spin states observed.

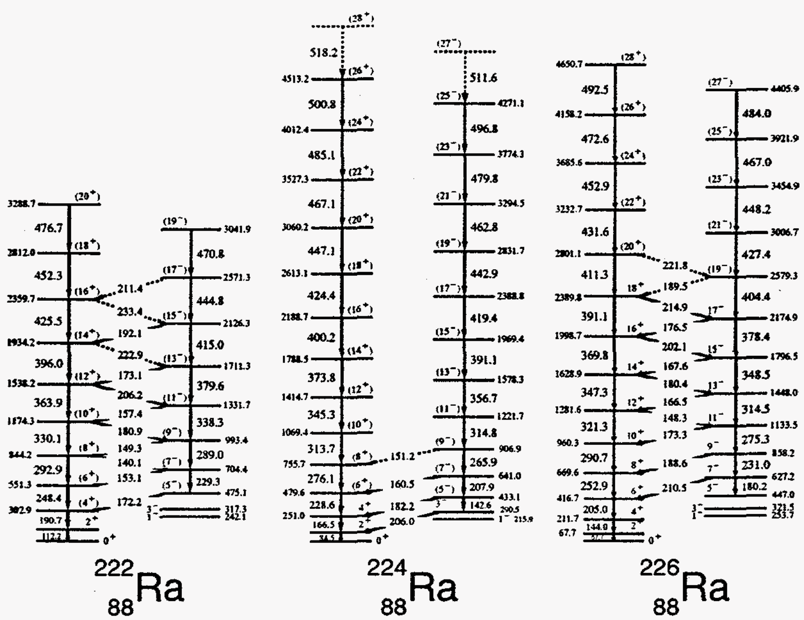

Figure 4: Level scheme of ^{222}Ra, ^{224}Ra and ^{226}Ra, produced using energy sums and intensity balance arguments. The transition energies have errors which range from 0.2 keV for low-lying transitions in the positive parity bands to 0.5 keV for 5^- to 3^- and 7^- to 5^- transitions and transitions 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 ($\frac{D_0}{Q_0}$) ratios were extracted from $\frac{B(E1)}{B(E2)}$ branching ratios. Upper limits were obtained for high-spin states in ^{224}Ra. The $\frac{D_0}{Q_0}$ values were constant within each nucleus. Using weighted mean values of $\frac{D_0}{Q_0}$ and published values of Q_0 [14], 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.

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