Vol. 30 (1999) *ACTA PHYSICA POLONICA B* No 5

PEAR-SHAPED NUCLEI IN THE RADIUM PLAYGROUND*

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(Received August 4, 1998)

The current knowledge of octupole phenomena in radium isotopes is reviewed. The systematic behaviour of the low-lying structure of these heavy nuclei will be discussed, with emphasis on their energy levels and electromagnetic moments. Prospects for developing new probes of asymmetric charge and mass distributions will also be discussed.

PACS numbers: 21.10.Re, 23.20.Lv, 25.70.Gh, 27.90.+b

1. Introduction

The large volume of evidence for the existence of rotating reflection-asymmetric, or *pear-shaped*, nuclei is well illustrated by the behaviour of the radium isotopes. I will discuss experimental data on Ra isotopes with mass numbers ranging from 218 to 230 which demonstrate not only this phenomenon but also how differently the nuclear system responds as a function of neutron number or angular momentum. This is largely a historical review which tries to illustrate the differing experimental techniques which have been employed in the last fifteen years or so to measure the properties of these rather inaccessible nuclei. It is appropriate in this conference celebrating the discovery of polonium and radium that the naturally occuring isotopes of radium, ^{223}Ra (Actinium X), ^{224}Ra (Thorium X), ^{226}Ra (Radium) and ^{228}Ra (Mesothorium 1) which were isolated in the early years of this century have concealed gold nuggets of spectroscopic information which have, in the most part, only recently been extracted. One exception is of course the observation [1], nearly 50 years ago, of a low-lying 1^- state in ^{224}Ra populated by α-decay. This led almost immediately to the suggestion (see [2] for reference) that "this state may have the same intrinsic structure

* Presented at the International Conference "Nuclear Physics Close to the Barrier", Warszawa, Poland, June 30–July 4, 1998.

as the ground state and represents a collective distortion in which the nucleus is pear-shaped." The energy of this 1^- state, while being the lowest observed of all nuclei, lies higher than that of the 2^+ member of the ground state rotational band. Experiments to extend both positive and negative parity bands to higher spins using nuclear reactions were carried out much later (see Section 4).

2. ^{218}Ra and ^{220}Ra

The characteristic fingerprint of a rotating pear-shaped nucleus is a sequence of states having alternating positive and negative parity. The first observation in heavy nuclei of such a sequence was made by Fernández-Niello *et al.* [3] who employed the reaction ^{208}Pb(^{13}C,3n) to populate states up to 17^- in ^{218}Ra. To populate higher spin states, Schulz *et al.* [4] made use of a radioactive ^{14}C beam which had become available at a few selective accelerator facilities. These new studies revealed, in addition to sidebands having unnatural parity, an irregular sequence of states at higher spins up to 31^-, expected for such a nucleus where the quadrupole deformation is smaller than the expected octupole deformation.

To obtain information on high spin states in ^{220}Ra, the lack of suitable targets forces more exotic methods to be used. Barrier threshold reactions such as (^{14}C, 2n) are limited in angular momentum input. The reaction ^{208}Pb(^{18}O,α 2n) brings in more angular momentum, and initially this was used [5] with a modest array of Ge detectors in which the small evaporation channel ($\approx 100\mu$barn) was isolated using a parallel plate avalanche recoil detector - an early example of "exotic" nuclei studies. Ten years later the power of the large escape suppressed Ge array EUROGAM I allowed this weak channel be selected by gating on γ-ray transitions alone. In this experiment, high spin sequences, up to 29^-, of alternating positive and negative parity were observed in ^{220}Ra, while its isotone ^{222}Th exhibits a sudden drop in population intensity at spin 24^+ [6]. This behaviour has been interpreted [7] as a reversion to reflection symmetry caused by the alignment of both $i_{13/2}$ protons and $j_{15/2}$ neutrons to the rotation axis.

3. ^{226}Ra

The fabrication of ^{226}Ra targets ($T_{1/2} = 1600$ a) by the Munich hot-lab opened up the possibility of studies of this nucleus by Coulomb excitation, which were performed at Munich and GSI using a variety of projectiles [8]. A striking feature of the spectrum of γ-ray emission following Coulex is the relatively strong decays from members of the octupole band, which can only arise from E3 excitation of the negative parity states. This implies that careful analysis of the measured yields following the pure electromagnetic process will yield information on the E3 matrix elements, and such analysis was indeed carried out using the GOSIA code developed by Tomasz Czosnyka, Douglas Cline and C.Y. Wu. This development was crucially important in the understanding of pear-shaped nuclei, as the E3 moment can be regarded as a straightforward measure of odd order mass deformations as it is predominantly isoscalar, very collective and in first order independent of quadrupole deformation. Although dynamic charge distortions strictly cannot be distinguished from static deformation, the description of the E3 moments connecting the ground state positive parity and lowest negative parity band in ^{226}Ra (see figure 1) in terms of a rotating static octupole moment is a very attractive one.

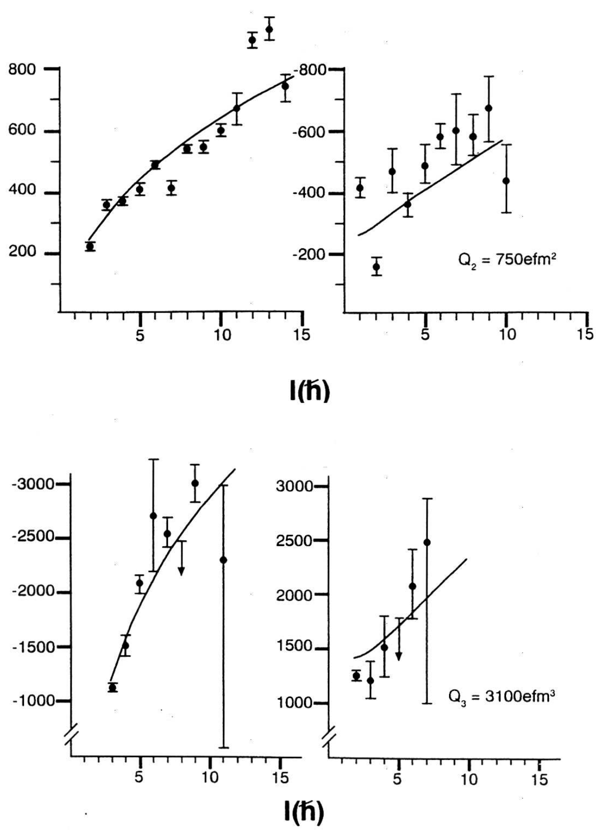

Fig. 1. Plot of E2 (upper figure) and E3 (lower figure) matrix elements (in units of e fm$^\lambda$) versus spin I deduced from Coulomb-excitation measurements [8] for ^{226}Ra. The left hand figures give values of $\langle I||E\lambda||I-\lambda\rangle$, the right hand figures values of $\langle I||E\lambda||I+2-\lambda\rangle$. Solid lines join points calculated assuming a constant electric quadrupole or octupole moment.

4. ^{224}Ra

Important information on E1 modes in Ra isotopes was obtained also with the help of ^{226}Ra targets. Poynter *et al.* [9] employed the rather exotic transfer reaction ^{226}Ra(^{58}Ni, ^{60}Ni)^{224}Ra to show that the E1 strength in ^{224}Ra is much weaker than in its even–even neighbouring isotopes. This result was soon confirmed by Marten-Tölle *et al.* [10] who used the ^{226}Ra(α,α' 2n) reaction. It is a graphic illustration of cancellation effects to which the electric dipole is susceptible to, and rather convincingly endorsed the theoretical models which were able to predict this behaviour (see Section 7).

5. ^{222}Ra,^{228}Ra,^{230}Ra

New developments in spectroscopic techniques were necessary in order to obtain high spin information on other Ra isotopes. The arrival of the third generation Ge arrays such as EUROGAM, GAMMASPHERE, and EUROBALL allows γ^n selection of weak channels and was used effectively in the studies of ^{220}Ra (see Section 2). Another major development was the realisation by Rafal Broda and his collaborators that the new arrays are capable of identifying the weak channels populated by multi-nucleon transfer reactions. In the case of mass region near $Z = 88$, experiments carried at Jyväskylä and at Argonne showed that heavy ion transfer reactions using a ^{232}Th target are effective in populating a wide range of Rn, Ra and Th isotopes. In the case of ^{222,224,226,228,230}Ra existing information was greatly expanded following measurements made using GAMMASPHERE following the reaction ^{136}Xe + ^{232}Th at 833 MeV [11,12].

6. Systematics of energy levels

Perhaps the most important indicator of whether a nucleus is pear-shaped or not is the behaviour of the energy levels themselves. Alternating negative and positive parity states can arise in two ways from instability in the octupole degree of freedom. One limit is that the nucleus has permanent octupole deformation, in which case the component of angular momentum aligned to the rotation axis of a state having positive parity, i_x^+, or negative parity, i_x^-, is equal to the rotational angular momentum, R. In this case the *difference* in aligned angular momentum, $\Delta i_x = i_x^- - i_x^+$, at the same rotational frequency ω, is equal to zero. The other limit is that the negative parity band arises from octupole vibrations of the rotating (quadrupole) deformed system. Here the negative parity states are formed by coupling R to the angular momentum of the octupole phonon ($3\hbar$). If the phonon angular momentum is *aligned* with respect to the rotational angular momentum then $\Delta i_x = 3\hbar$ for a given value of ω. If the lowest negative parity band has $K = 0$ (and this seems to provide the most favourable situation for alignment of the phonon) then the resulting spectrum can give rise to an alternating sequence of negative and positive parity states. Values of Δi_x are plotted against $\hbar\omega$ in figure 2 for nuclei in the radium isotopes. It can be seen that there are several Ra isotopes, ^{222,224,226}Ra, where the value of Δi_x tends to zero at high rotational frequencies, whereas the behaviour of ^{228}Ra is typical of that of an octupole vibrator.

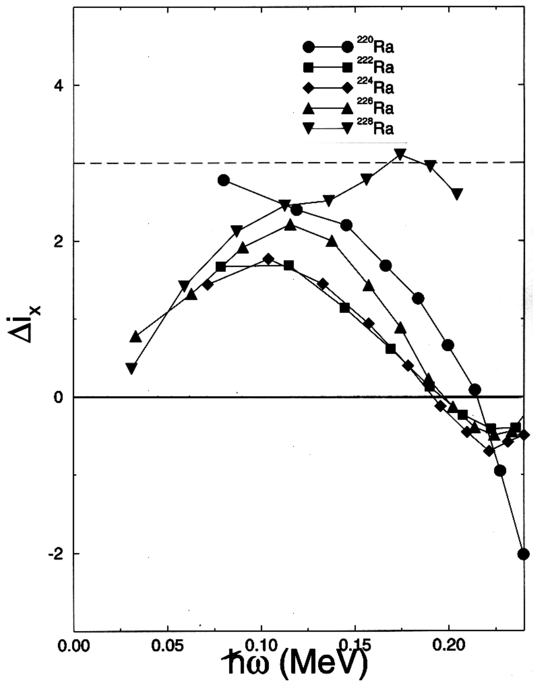

Fig. 2. Plot of the difference in angular momentum, $\Delta i_x = i_x^- - i_x^+$ (in units of $\hbar$), at a given rotational frequency ω, for Ra isotopes. The value of Δi_x was calculated by subtracting from the value of i_x^- an interpolated value of i_x^+ at the same value of $\hbar\omega$. The solid and dashed lines are respectively the octupole deformed and vibrational limits as described in the text.

7. Electric dipole moments

An important experimental observable of pear-shaped nuclei is the intrinsic E1 moment which is induced by the separation of centre-of-mass and centre-of-charge. Calculations of this quantity have been made using both microscopic-macroscopic (liquid-drop with shell correction) and microscopic (Hartree–Fock) approaches (see [13] for references). An early success of the former method was the prediction [14] of a near-zero value of the E1 moment for Ra isotopes with $N \approx 136$, which was verified experimentally shortly afterwards (see Section 4). The calculations show that there is a cancellation of the liquid droplet contribution and the shell correction term which occurs for ^{224}Ra, while the sign of the E1 moment in ^{226}Ra is opposite to that for ^{222}Ra. The measured [11,12] variation of the ratio of the electric dipole moment (D_0) to electric quadrupole moment (Q_0) as a function of angular momentum is shown in figure 3 for a series of radium isotopes. The D_0/Q_0 values measured for the excited states in ^{224}Ra are much lower than those in ^{222}Ra and ^{226}Ra, and the figure shows that the cancellation effect described above persists to high angular momenta in ^{224}Ra. For all Ra isotopes the D_0/Q_0 values are constant over the full range of spin measured, which suggests that the asymmetric charge and mass distribution in these nuclei does not change with increasing spin.

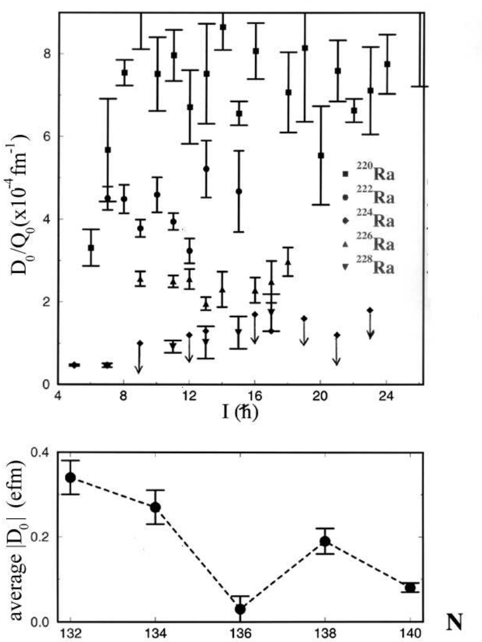

Fig. 3. (Upper figure) Plot of the experimental ratio of the absolute magnitude of the intrinsic electric dipole and quadrupole moments ($|D_0/Q_0|$) as a function of spin for transitions de-exciting states of spin I in even-even Ra isotopes [11,12]. (Lower figure) Plot of $|D_0|$ averaged over all values at different angular momenta for the Ra isotopes.

8. Magnetic dipole moments: ^{223}Ra

The energy spectra of odd mass pear-shaped nuclei will consist of parity doubled rotational bands. The $M1$ transitions within the positive parity and negative parity bands will have a transition probability which is proportional to the square of the difference of the odd particle g-factor, g_K, and the core g-factor, g_R. The value of g_K should be the same for the positive and the negative parity bands if both arise from the laboratory projection of the same intrinsic structure. In the mass region around $Z = 88$, $N = 134$, there are very few systematic data on the the behaviour of this quantity. Recently, $\alpha - \gamma$ and $\alpha - e_{K,L,M}$ measurements for ^{223}Ra, populated by the α-decay of ^{227}Th, have revealed [15] that the values of $(g_K - g_R)/Q_0$ for several transitions in the $K^\pi = 5/2^+$ band are similar to those in the neighbouring $K^\pi = 5/2^-$ band in this nucleus (see figure 4). This is consistent with the interpretation (Section 6) that the radium isotopes with A $\approx$ 224 are reflection asymmetric.

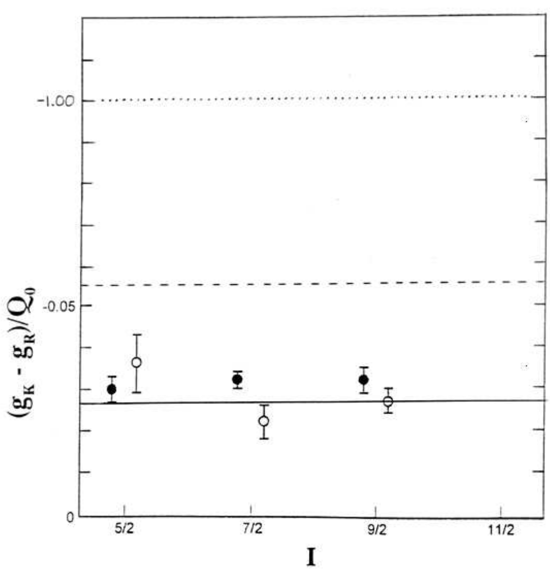

Fig. 4. Measured values of $(g_K - g_R)/Q_0)$ for the positive parity (closed circles) and negative parity (open circles) $K = 3/2$ bands in ^{223}Ra, taken from Ref. [15]. The dashed line and dotted lines represent the calculated value [15] assuming that the odd neutron occupies pure intrinsic parity ($\beta_3 = 0$) positive and negative parity orbitals respectively. The solid line assumes that the parity is mixed with $\beta_3 = 0.05$.

9. Outlook

The study of pear-shaped nuclei has been a challenge both theoretically and experimentally but slowly our knowledge of these reflection-asymmetric systems is becoming more comprehensive. For the future it is worth commenting that several interesting phenomena have been predicted but as yet not yet experimentally confirmed, and these remain challenges for the enterprising experimentalist. Two examples are given here. The first concerns the predicted change of sign of the intrinsic electric dipole moment between that of ^{222}Ra and ^{226}Ra. While a measurement of this quantity is impossible, it is in principle possible to measure the sign of the E1 moment relative to the E3 moment for a mixed nuclear transition. This can be achieved by exploiting Coulomb excitation in which the relative amounts of E1 and E3 excitation become comparable at optimal values of the distance of closest approach of the projectile and target (see figure 5).

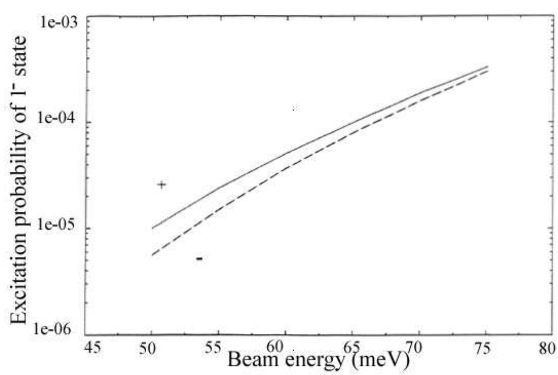

Fig. 5. Excitation probability of the lowest 1^- state in ^{226}Ra calculated using the Coulomb excitation code GOSIA for ^{40}Ar ions scattered at $\theta_{\rm lab} = 142°$. The two curves are calculated with different phases for the E1 and E3 matrix elements.

The second example concerns exotic nuclear shapes predicted to exist for heavy nuclei, the hyper-quadrupole, super-octupole configurations whose excitation energy is predicted [16] to lie quite low, ≈ 5 MeV, in heavy Ra nuclei such as ^{230}Ra. Provided that they remain stable against fission, the super-octupole bands should de-excite predominantly by E1 transitions [17], giving rise to a high multiplicity cascade of low-energy photons.

Some of the work described here was supported by grants from the U.K. Engineering and Physical Sciences Research Council and its predecessors.

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