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INTRINSIC REFLECTION ASYMMETRY IN NUCLEI*

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The evidence for intrinsic reflection asymmetry in atomic nuclei, with examples from recent experiment work, is reviewed.

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1. Introduction

The manifestation of reflection asymmetry in quantum systems can be observed in molecules such as HCl or CH_3Cl where the rotational bands consist of a sequence of alternating positive and negative parity bands which arise from the projection in the laboratory frame of a parity-mixed intrinsic system. Features analogous to the behaviour of reflection asymmetric *nuclei* can be found in the spectra of the ammonia molecule, in which the nitrogen atom tunnels through the plane containing the hydrogen atoms between the right-handed and left-handed configuration. The tunneling through the mass-asymmetry barrier gives rise to deviations from that expected for a rigid system, for example the energies levels of the parity doublet states for $K \neq 0$ bands are no longer degenerate.

Examples of reflection asymmetry in nuclear systems can be found in the quasi-molecules which are formed following nuclear reactions. There are resonances in the intermediate compound system which arise from reflection-asymmetric configurations. Such a sequence of states has been observed [1] in the ^{28}Si(α,α') reaction which corresponds to the rotation of an asymmetric system. For *bound* systems the situation is less clear. The increase in stability of a nuclei with asymmetric deformation in the most favourable cases is still not sufficient for the shape to be considered rigid (at least in the ground state), so that the energy spectra are intermediate between static and dynamic asymmetric deformation.

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The occurrence of low lying negative parity states has been explained in the framework of many nuclear models (for review, see [2]), for example algebraic models where they arise from couplings of p and f bosons to s and d bosons (both odd ℓ bosons appear to be necessary to simultaneously describe energy levels and transition moments), and cluster models in which the nucleus assumes a molecular-like configuration. At the microscopic level, nuclear reflection asymmetry has its origin in the proximity of the high spin intruder orbital from the $(N+1)$ shell to the opposite parity orbitals in the N shell. In mean field theories, the mass asymmetry naturally arises from the *octupole* interaction which allows scattering between these states. Both macroscopic-microscopic (shell correction using the Strutinsky prescription) and self-consistent microscopic (Hartree-Fock) calculations have been used very successively to predict regions of octupole instability and calculate transition moments. Fig. 1 shows an example of the application of the Strutinsky method [3] which uses a deformed Woods-Saxon potential to analyse octupole instability in medium and heavy-mass nuclei. It predicts that Ra, Th and U isotopes with $N \approx 134$ should exhibit the features of nuclei having static octupole deformation. It has been the goal of recent experiments to test these predictions.

2. Experimental evidence for reflection asymmetry

The observation [4], nearly 50 years ago, of a low-lying 1^- state in ^{224}Ra populated by α-decay led almost immediately to the suggestion (see [5] for reference) that "this state may have the same intrinsic structure 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 (see Fig. 2). Experiments to extend both positive and negative parity bands to higher spins using nuclear reactions were carried out much later. The pioneering experiments of Bonin *et al.* [6] and Ward *et al.* [7] who studied the low-lying collective structure of ^{222}Th, revealed that the negative parity states became interleaved with the positive parity states, a necessary requirement for static reflection asymmetry. A similar structure was observed in ^{224}Ra by Poynter *et al.* [8] and Marten-Tölle *et al.* [9] who employed radioactive ^{226}Ra targets, and more recently by Cocks *et al.* [10] (see Fig. 2) who exploited multi-nucleon transfer from ^{232}Th. The highest spin sequences, up to 29^-, of alternating positive and negative parity have been observed in ^{220}Ra, while its isotone ^{222}Th exhibits a sudden drop in population intensity at spin 24^+ [11]. This behaviour has been interpreted [12] as a reversion to reflection symmetry caused by the alignment of both $\mathrm{i}_{\frac{13}{2}}$ protons and $\mathrm{j}_{\frac{15}{2}}$ neutrons to the rotation axis. For odd mass nuclei, the

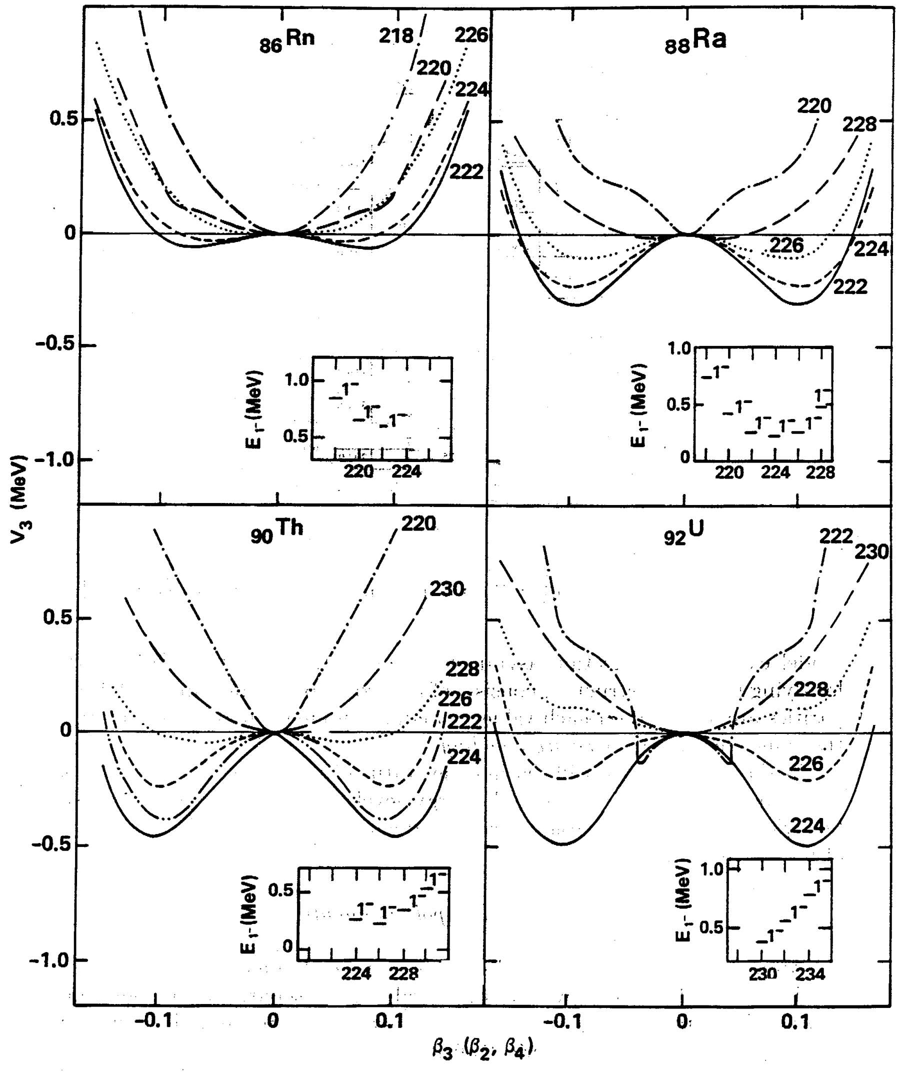


Fig. 1. Octupole deformation energy curves for even-even isotopes of Rn, Ra, Th and U obtained in the shell-correction + Woods-Saxon model [3]. Insets show experimental energies of the lowest negative-parity states in these isotopes.

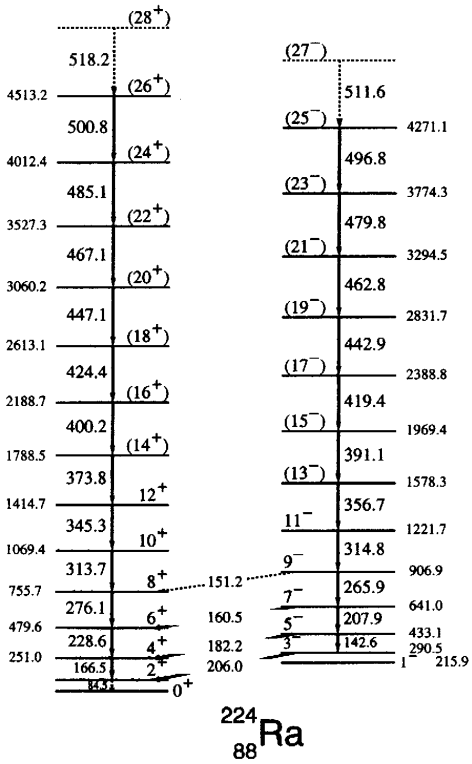


Fig. 2. Energy level scheme of ^{224}Ra, taken from the work of Cocks *et al.* [10].

model example of reflection asymmetry remains that of ^{223}Th [13] whose low-lying rotational structure consists of four rotational bands in which both parities are observed for each value of angular momentum at approximately the same energy, called *parity doubling*.

In the following, we will discuss the status of recent experimental work on both transition moments and energy levels. We will review how the behaviour of these observables is reconciled with their interpretation in terms of nuclear reflection asymmetry.

2.1. Electric dipole moments

An important experimental observable of reflection asymmetric nuclei is the intrinsic $E1$ moment which is induced by the separation of centre-of-mass and centre-of-charge. Almost as an accident of nature, the resulting intensity of the electromagnetic transition between opposite parity states becomes comparable to that of the in-band $E2$ intensity. Calculations of this quantity have been made using both microscopic-macroscopic (liquid-drop with shell correction) and microscopic (Hartree-Fock) approaches (see

[2] 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 [8] shortly afterwards. The results of the most refined calculations using the microscopic-macroscopic method [15] for Ra and Th isotopes are shown in Fig. 3. This figure shows that there is a cancellation of the liquid droplet contribution and the shell correction term

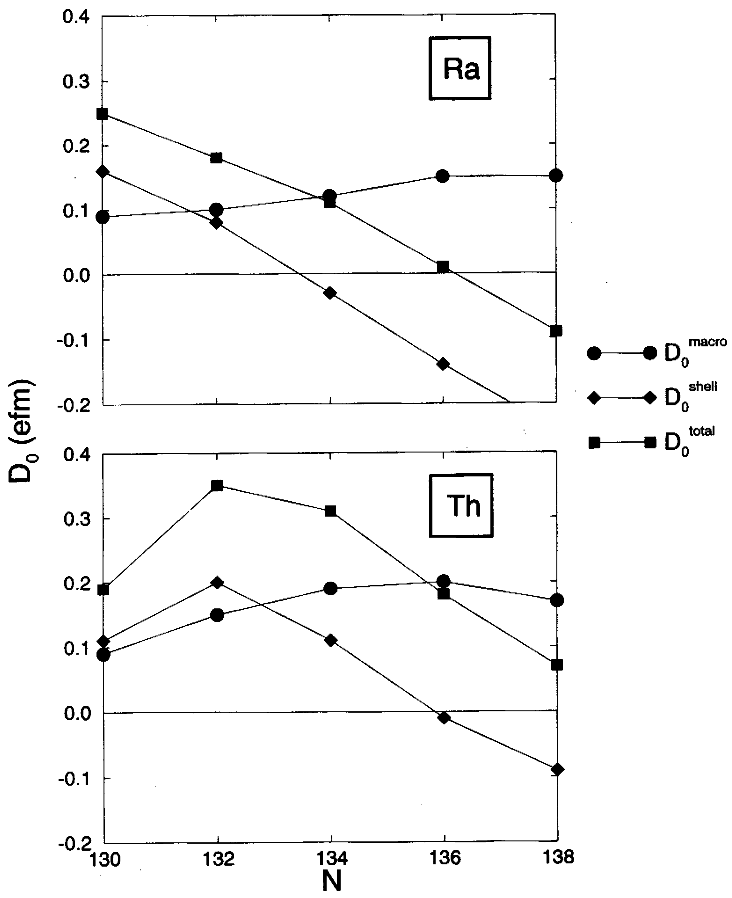


Fig. 3. Calculated [15] macroscopic contribution (using the droplet model), D_0^{macro}, shell-correction contribution, D_0^{shell}, and total value of the intrinsic electric dipole moment, D_0^{total}, for Ra and Th isotopes.

which occurs for ^{224}Ra, while the sign of the $E1$ moment in ^{226}Ra is opposite to that for ^{222}Ra. The measured [10] 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 Fig. 4 for a series of radium isotopes. The

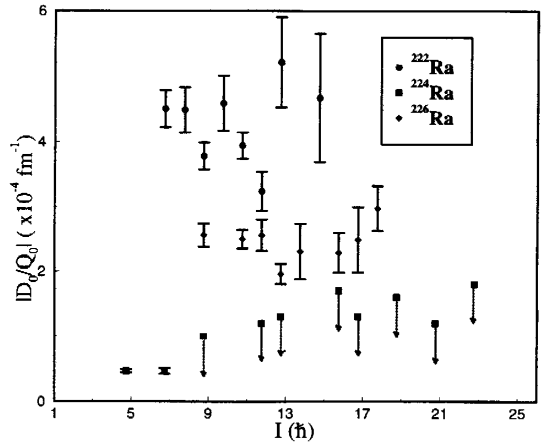


Fig. 4. Plot of the experimental ratio of the absolute magnitude of the intrinsic electric dipole and quadrupole moments ($|D_0/Q_0|$) as a function of spin for transitions de-exciting states of spin I in ^{222}Ra, ^{224}Ra and ^{226}Ra [10].

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 ^{222}Ra and ^{226}Ra 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 all three isotopes does not change with increasing spin.

2.2. Electric octupole moments

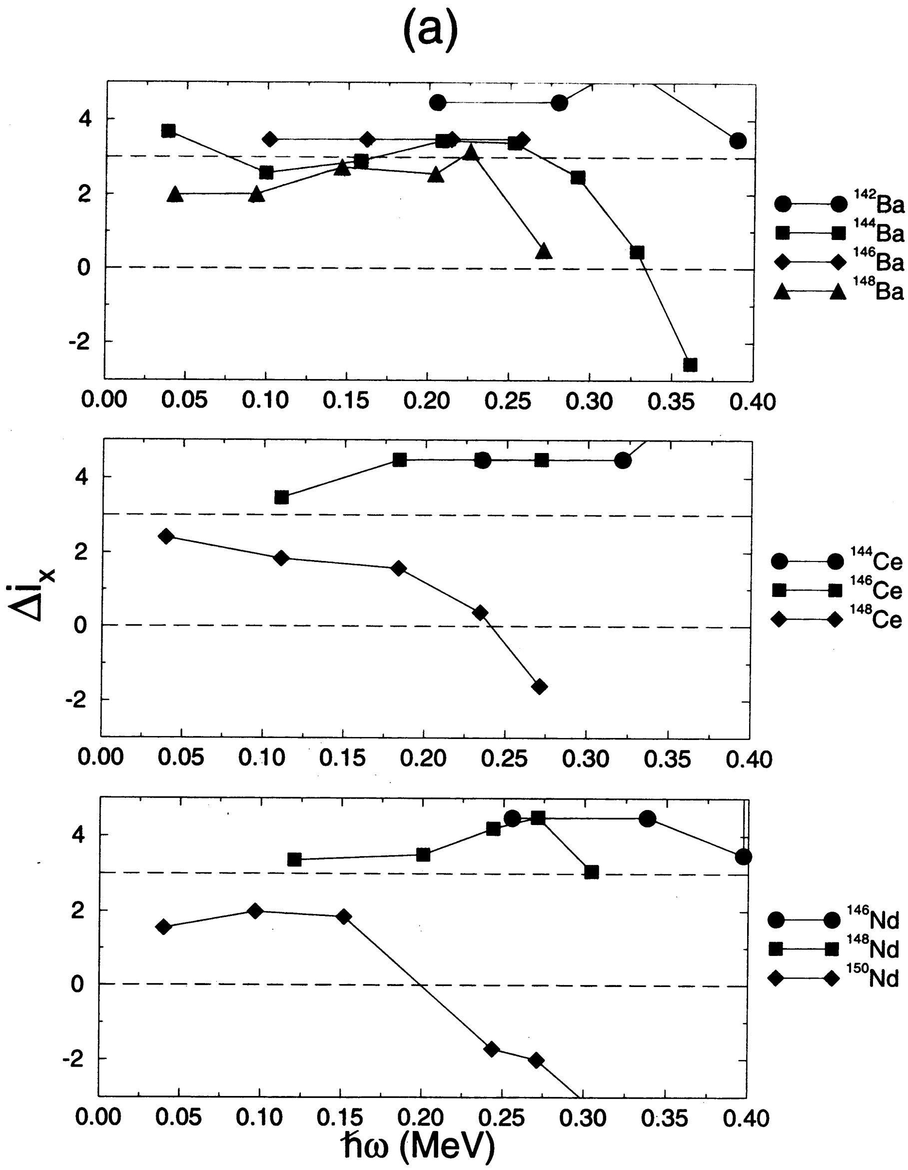
The $E3$ moment can be regarded as a more straightforward measure of odd order mass deformations as it is predominantly isoscalar, very collective and in first order independent of quadrupole deformation. Although dynamic charge distortions strictly cannot be distinguished from static deformation, the description of the $E3$ moments connecting the ground state positive parity and lowest negative parity band in ^{226}Ra [16] in terms of a rotating static octupole moment is a very attractive one. In contrast, large fluctuations are observed in ^{148}Nd [17-19] which can be approximately accounted [18] by a model of a one-phonon octupole vibration coupled to the quadrupole ground band. A large coupling of the negative parity band to the $K^\pi = 0_2^+$ band is also observed [18,19], whose origin is not fully understood at this time.

2.3. Magnetic dipole moments

The energy spectra of odd mass pear-shaped nuclei, as discussed earlier, 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 both the positive and the negative parity bands if both arise from the laboratory projection of the same intrinsic (reflection-asymmetric) 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 $\alpha - \mathrm{e}_{\mathrm{K,L,M}}$ measurements for ^{223}Ra, populated by the α-decay of ^{227}Th, have revealed [20] 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. This is consistent with the interpretation (see next section) that the radium isotopes with A = 220-226 are reflection asymmetric.

2.4. Energy levels

Perhaps the most important indicator of whether a nucleus is reflection-asymmetric 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 Fig. 5 for nuclei in the $Z \approx 58$, $N \approx 88$, and $Z \approx 88$, $N \approx 134$ mass regions. As can be seen, there are no good examples of permanent octupole deformation in the lighter mass region. Indeed most of these nuclei behave as octupole vibrators. In contrast, there are several examples of the heavy nuclei, such as ^{222,224,226}Ra [10] and ^{224,226}Th where the value of Δi_x tends to zero at high rotational frequencies. The Rn isotopes, on the other hand, are almost perfect octupole vibrators [10].


(a)
142Ba
144Ba
146Ba
148Ba
144Ce
146Ce
148Ce
146Nd
148Nd
150Nd
Δi_x
ħω (MeV)

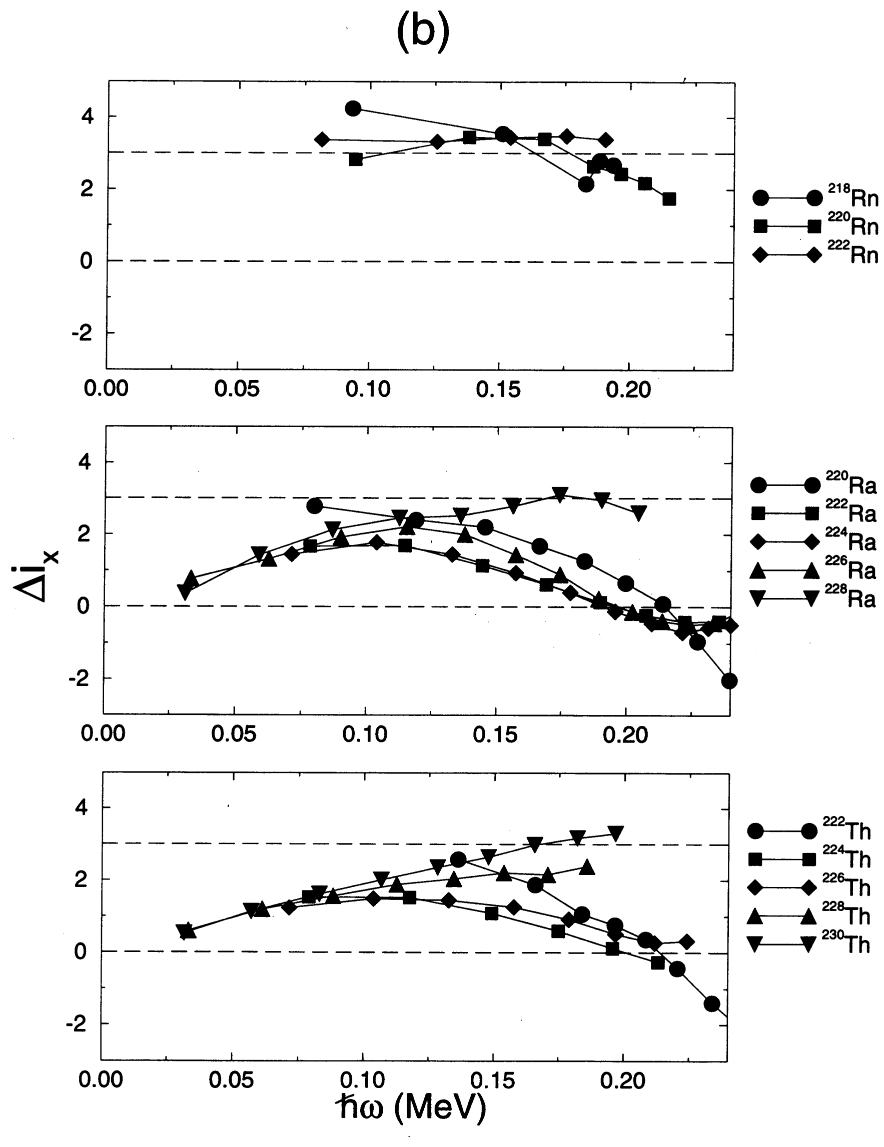


Fig. 5. Plot of the difference in angular momentum, $\Delta i_x = i_x^- - i_x^+$ (in units of $\hbar$), at a given rotational frequency ω, for: (a) Ba, Ce and Nd isotopes with $N \approx 88$, and (b) Rn, Ra and Th isotopes with $N \approx 134$. The value of Δi_x was calculated by subtracting from the value of i_x^- an interpolated value of i_x^+ at the same value of $\hbar\omega$. The dashed lines at $\Delta i_x = 0$ and $3\hbar$ are respectively the octupole deformed and vibrational limits as described in the text.

2.5. Study of octupole U nuclei

The nuclei predicted to have the deepest minimum in potential energy at a non-zero value of octupole deformation are uranium isotopes with $N \approx 134$. These fissile nuclei are accessible via compound nucleus reactions but the survival cross sections are very small [21]. Our preliminary level scheme [22] of ^{226}U reveals an alternating parity structure whose value of Δi_x tends to zero for values of $\hbar\omega > 0.15$MeV. In addition to the behaviour of the energy levels, the large average value of the electric dipole moment for several transitions (≈ 0.5efm) is consistent with ^{226}U being another example of a reflection asymmetric nucleus.

3. Summary and outlook

We have established that there are several nuclei in the $Z = 88$, $N = 134$ mass region - $^{220-226}$Ra, $^{222-226}$Th and ^{226}U - whose behaviour is consistent with reflection asymmetry in their intrinsic frame. This is in contrast to Rn isotopes with similar neutron numbers and nuclei with $Z \approx 58$, $N \approx 88$ which are octupole vibrational in nature. There is a number of open questions, some of which can be addressed with the aid of new experimental developments. The prediction that the sign of the D_0 moment changes sign at $N = 136$ for the Ra isotopes needs to be tested. Since the Coulomb excitation process is sensitive to the *relative* phase of $E1$ and $E3$ matrix elements this quantity can in principle be measured for the long-lived isotope ^{226}Ra. Another goal is to study the nucleus ^{224}U, predicted [3] to have the deepest octupole minimum, and which is now experimentally accessible using modern spectrometry. Finally, the most exotic nuclear shapes accessible in heavy nuclei are the hyper-quadrupole, super-octupole configurations whose excitation energy is predicted [23] to lie quite low, ≈ 3 MeV, in $^{230-236}$U and is comparable to that of the superdeformed (quadrupole) minima in these nuclei. Provided that they remain stable against fission, the super-octupole bands should de-excite predominantly by $E1$ transitions [24], giving rise to a high multiplicity cascade of low-energy photons.

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