HIGH-SPIN SPECTROSCOPY OF REFLECTION ASYMMETRIC NUCLEI

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Abstract

The band structure observed in high-spin spectroscopy is illustrated through typical examples. The question whether observed alternating parity bands within a nucleus originate from a single intrinsic orbital is considered. Future directions in the experimental exploration of octupole deformed nuclei are suggested.

1. INTRODUCTION

High-spin spectroscopy, as well as alpha- or beta-decay studies, yield evidence for octupole deformation or octupole instability of nuclei in several region of the nuclear chart. In order to describe these effects, it is convenient to consider the standard parametrization of the nuclear surface

$$R(\theta,\varphi) = R_0\ c(\alpha) \left[1 + \sum_{\lambda} \sum_{\mu=-\lambda}^{\lambda} \alpha^*_{\lambda\mu} Y_{\lambda\mu}(\theta,\varphi)\right] \tag{1}$$

In the beginning of this talk, only axially symmetric nuclei ($\mu = 0$) will be considered. The shape of a reflection symmetric nucleus is described only by even multipolarities : $\lambda = 2,\ 4 \ldots$. The intrinsic Hamiltonian of this nucleus is invariant with respect to both $\mathcal{R}$, a rotation of 180° about an axis perpendicular to its symmetry axis, and the space inversion $\mathcal{P}$. Therefore the ground-state band of an

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even-even nucleus is characterized by spin-parity states 0^+, $2^+ \ldots$. But if the amplitude of the spherical harmonic Y_{30} has a non-zero value, the nucleus will have a pear-like shape and for such a nucleus, the intrinsic Hamiltonian is no longer invariant with respect to $\mathcal{R}$, nor to $\mathcal{P}$. However it is invariant to the combined operation $\mathcal{S} = \mathcal{P}\,\mathcal{R}^{-1}$, which represents a reflection in a plane containing the symmetry axis. The eigenvalue s associated to the $\mathcal{S}$ operator, called the simplex quantum number, is related to the angular momentum I through $p = s\, e^{i\pi I}$, where p is the external parity. Thus for an even particle number

$$
\begin{array}{lll}
s = +1 & \text{for} \quad I^p & = 0^+, 1^-, 2^+, 3^- \ldots \\
s = -\,1 & \text{for} \quad I^p & = 0^-, 1^+, 2^-, 3^+ \ldots
\end{array}
$$

while for an odd number of nucleons

$$
\begin{array}{lll}
s = +i & \text{for} \quad I^p & = 1/2^+, 3/2^-, 5/2^+ \ldots \\
s = -\,i & \text{for} \quad I^p & = 1/2^-, 3/2^+, 5/2^- \ldots
\end{array}
$$

The rotational properties of an axially symmetric octupole deformed nucleus are governed by this simplex symmetry. For example for an even-even nucleus, the positive parity ground-state band and the low-lying negative parity band will form a simple band characterized by $s = +1$.

The origin of octupole deformation can be seen in the near degneracy of a pair of $\Delta N = 1$, $\Delta \ell = \Delta j = 3$ orbitals. So for the light actinide nuclei the octupole Y_{30} term couples strongly the $j_{15/2}$ and $g_{9/2}$ neutron orbitals on one side and the $i_{13/2}$ and $f_{7/2}$ proton orbitals on the other. Other combinations appear in the level sequence of the shell model: for example the $\pi(d_{5/2} - h_{11/2})$ and $\nu(f_{7/2} - i_{13/2})$ configurations which correspond to heavy Ba isotopes, where manifestation of octupole deformation have effectively been observed [1].

2. EXPERIMENTAL ASPECTS

Most of the high-spin data arise from γ-ray spectroscopy following fusion-evaporation reactions. The first example of a high-spin spectroscopy of an octupole deformed nucleus dates back to 1982 and concerns ^{218}Ra[2] : with conventional equipment the ground-state band could be observed up to spin 17. Over the past few years, the strongest impact on the experimental data results from the advent of gamma multicounter arrays such as the Château de Cristal in Strasbourg or the Crystal Ball in Heidelberg. The improvement arised not only from the increase of the γ-ray detection efficiency and from the Compton suppressed Ge-detectors, but also from the multiplicity and energy filter associated to the Ge counters. The selectivity of such a filter for different reaction channels is shown in fig.1. The jump which resulted from the use of a multicounter device may be illustrated by the level scheme of ^{218}Ra for which the ground state band extends now to I = 34 (fig.2). Level schemes, like the one shown here, are built with the help of D.C.O. ratios extracted from the experimental data (fig.3). The nature of the dipole transitions may be obtained by using intensity balance, a common technique in the light actinide region where internal conversion coefficients may be large. Alternatively, it may be deduced from conversion electron measurements.

A typical aspect of the high-spin γ-ray spectra in the actinide region is the presence of doublets. For ^{218}Ra for example (fig.2), 28 % of the γ transitions form doublets, i.e. both transitions differ by less than 1 keV. This is not surprising since almost all of the γ rays are squeezed into an energy range of 500 keV.

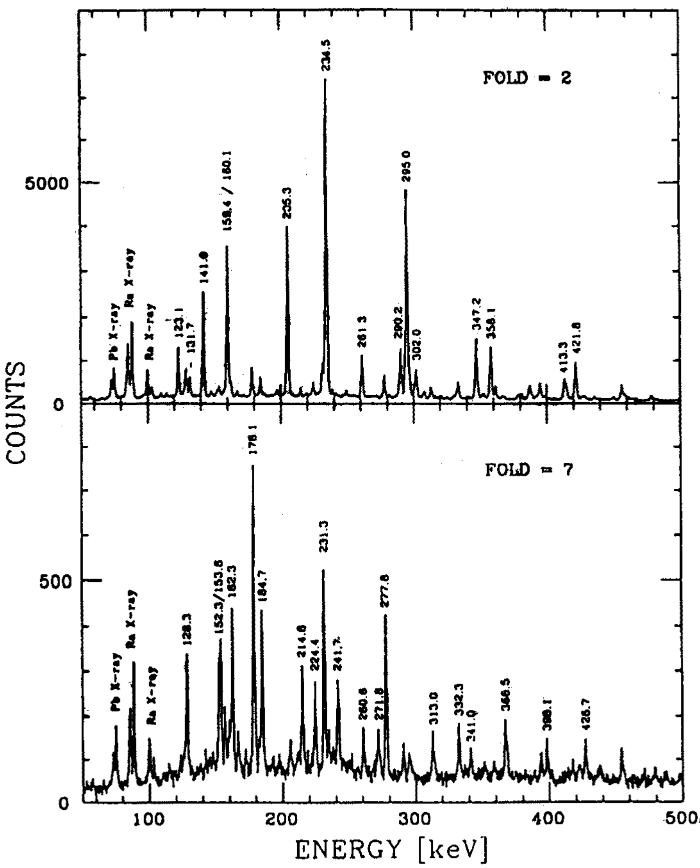

Fig.1 *Emphasis of either ^{219}Ra or ^{220}Ra γ- transitions with two choices for the fold condition in the Château de Cristal. The Ra isotopes were produced in the ^{208}Pb + ^{14}C reaction [8].*

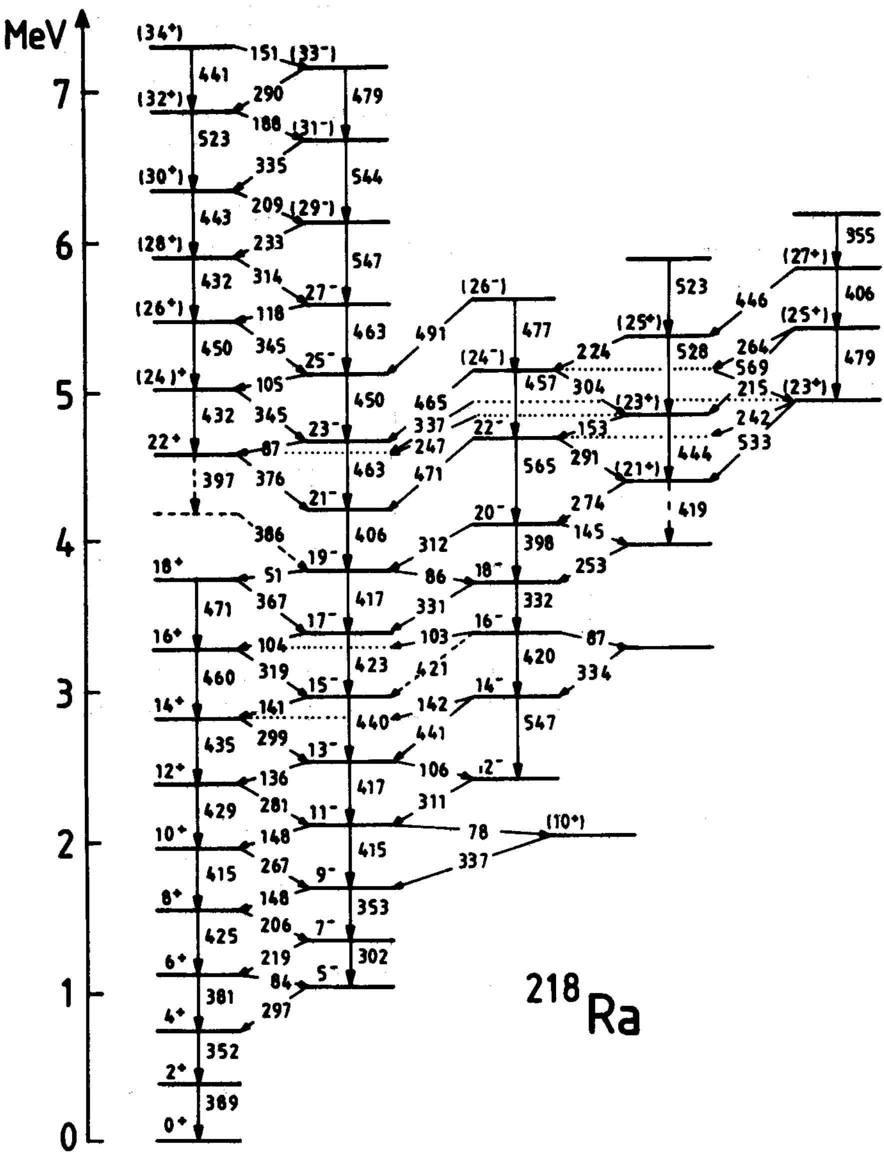

Fig.2 *Level scheme of* ^{218}Ra *[4]*

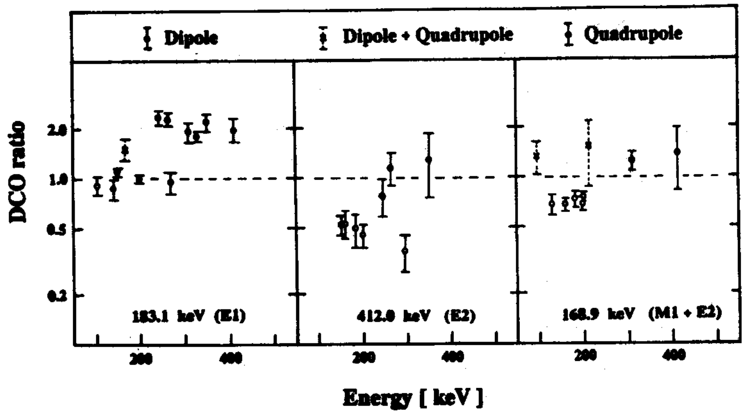

Fig.3 *Examples of D.C.O. ratios R obtained in the $^{209}Bi(^{14}C,3n)^{220}Ac$ reaction [5]. In the present case $R = \gamma_1(90^\circ) \cdot \gamma_2(30^\circ/150^\circ)/[\gamma_1(30^\circ/150^\circ) \cdot \gamma_2(90^\circ)]$, where γ_1 refers to the transition indicated at the bottom of each example.*

3. BAND STRUCTURE

The alternating parity structure which results from the hybridization of the ground-state band and the low-lying opposite parity state band reflects the breaking of the reflection symmetry in the considered nucleus. In the actinide region, the earliest manifestations are observed in the N = 129 isotones : ^{216}Fr [6] ^{217}Ra[7] and ^{218}Ac[8]. An almost equidistant level spacing is observed (see for example the ^{218}Ra level scheme, fig.2) in the lightest nuclei which are only weakly deformed. Moreover in ^{218}Ra[9], which has four neutrons outside the N = 126 shell, it has been shown that the octupole effects dominate over those due to a quadrupole deformation. The same observation can be made in the lanthanide region for ^{148}Sm[10], which has like ^{218}Ra 4 valence neutrons. In heavier nuclei appears a more regular structure where E2 transition energies steadily increase with spin.

a) Odd-mass nuclei

One of the fingerprints of octupole deformation in odd-A nuclei is the appearance of parity doublets and even of rotational bands composed of parity doublets. (The first observation in high-spin spectroscopic studies of two bands which could be simplex partners has been made in the ^{219}Ac nucleus [11]). The doublets consist of two levels that are almost degenerate in energy, having the same angular momenta and opposite parity, and corresponding to a single parity-mixed intrinsic orbital.

But parity doubling is not a proof by itself for octupole deformations, since in the deformed shell model for reflection *symmetric* shapes, there happen to be many closely spaced but unrelated Nilsson orbitals.

Among the odd-mass nuclei which are believed to be octupole deformed, a number of nuclei exhibit at least two alternating parity bands (even three in the case of ^{219}Ra [3]). Are these bands simplex partners or do they arise from different orbitals? Rather than trying to give a general answer, a detailed analysis of a single case, ^{221}Ac, will be made.

^{221}Ac (see its level scheme in fig.4) was produced [12] by the ^{209}Bi(^{14}C,2n) reaction and the γ-rays were detected with the Château de Cristal. The target thickness was such that the beam energy was degraded below the Coulomb barrier in the target. Only $\simeq$ 15 % of the integrated cross-section corresponds to ^{221}Ac. The contribution of ^{220}Ac in the bidimensional $\gamma-\gamma$ matrices constructed off-line was reduced by setting conditions on fold and sum energy. Drastic cuts could however not be done, since they would have reduced too much the number of coincidences to be analysed. Therefore gates had to be set on complex spectra where the background is not well defined and this hampered the extraction of D.C.O. ratios as could be done in similar experiments. Gamma-ray multipolarities for some transitions could be determined using the data of a conversion electron-gamma coincidence experiment performed in Orsay[13]. Although having low statistics, this experiment was also of great help for finding the links between the two alternating parity bands, since the connecting transitions are highly converted M1 transitions. An example of the contribution of the $e^- - \gamma$ experiment is given by the 140 keV line : the $\gamma - \gamma$ data indicates that it corresponds to two lines in coincidence, whereas the e^--γ data is able to place the second member of the doublet in the decay scheme and at the same time to state its M1 character (fig.5).

The spin of the ^{221}Ac ground-state is not determined experimentally but calculations using the reflection-asymmetric mean field approach [14] predict a $3/2^-$ ground-state and a $5/2^-$ excited state at 8 keV. Such spin assignments for the ground-state and the state observed at 9 keV would fit with the data (whereas $5/2^-$ for the g.s. and $3/2^-$ for the excited state would not) and they were adopted subsequently for the sake of simplicity.

According to calculations the two alternating parity bands displayed in fig.4 correspond to different orbitals, but which lesson can be drawn from the sole experiment ? Are there arguments in favor or against the interpretation of the two bands being simplex partners ? Generally speaking, the evidences for parity doublets (in the sense that they originate from intrinsic reflection-asymmetry) are related to the fact that they both can be described as the projection from a single parity-mixed intrinsic state. Therefore they should have especially:

- similar magnetic moments

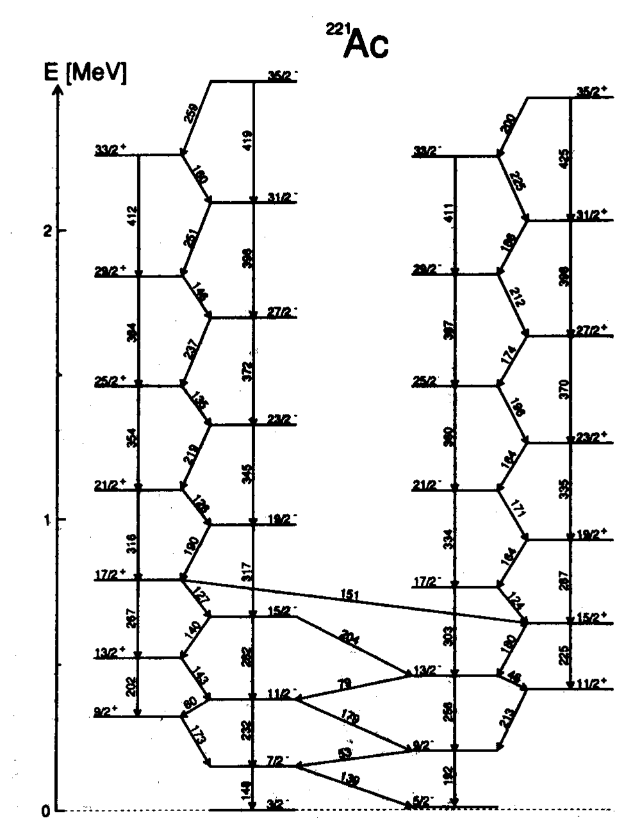

Fig.4 *Level scheme of* ^{221}*Ac. The spin-parity assignments is made under the assumption of* $3/2^-$ *spin parity for the ground-state (see text).*

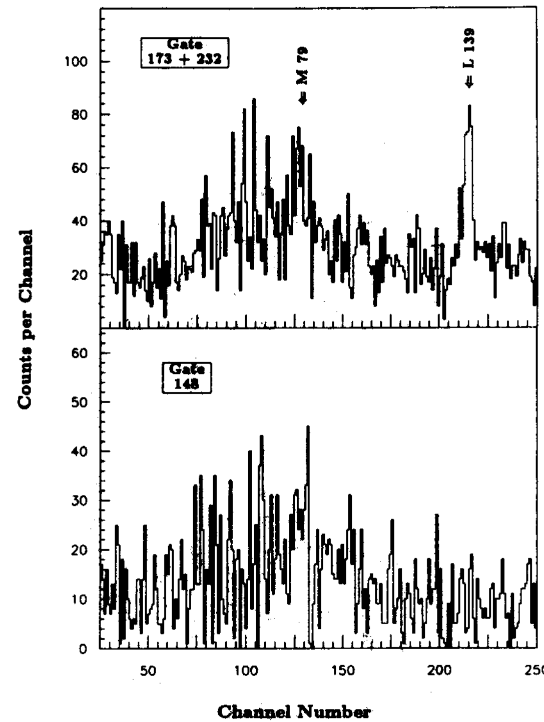

Fig.5 *Gamma gated electron spectra. The strong peak corresponding to the L line of the 139 keV transition in the sum of the spectra gated by the 173 and 232 keV* γ*-transitions and its absence in the spectrum gated by the 148 keV line indicate the placing of 139 keV transition and its M1 character.*

- decoupling factors of equal magnitude, but opposite sign
- similar hindrance factors for α-transitions to both P.D.states.

The last mentioned condition does not refer to high-spin states.

⋆ Magnetic moments

Usually no information on magnetic moments are available from high spin state physics. However (g_K-g_R) values may be extracted from mixed M1/E2 transitions or from M1/E2 branching ratios. This process isn't possible for ^{221}Ac, nor for most of the light actinide nuclei, due to the high internal conversion of the M1 transitions. There is one exception which concerns ^{223}Th, a nucleus whose level scheme displays two alternating parity bands with $5/2^+$ and $5/2^-$ band heads [15].These bands could be simplex partners. The E2 admixture in M1 transitions could be derived from internal conversion coefficients measurements. The deduced (g_K-g_R) values differ from the one calculated in the strong coupling limit and assuming an octupole deformation. However other models, like the rigid reflection-asymmetric rotor model [16] lead to partially hybridized magnetic moments, i.e. that the magnetic moments for parity doublets differ, but less than in a reflection symmetric picture of the nucleus.

Another experimental example arises from the lanthanid region: the magnetic moments for the $5/2^+$ and $5/2^-$ band heads of ^{151}Pm are inferred from branching ratios [17] and their values are close to the values predicted for a reflection-symmetric nucleus. However the measured (and not inferred) value for the magnetic moment of the $5/2^+$ ground-state is close to the hybridized value ($\sim 2.0\mu_N$) for the $K^\pi = 5/2^\pm$ bands [18] and is therefore in favor of a reflection asymmetric shape for ^{151}Pm.

⋆ Intrinsic dipole moments

Another fingerprint of octupole deformation is the presence of E1 transitions which are *generally* enhanced by two orders of magnitude compared to the El in the neighbouring reflection symmetric nuclei. Consequently the intrinsic dipole moments D_0 in octupole deformed nuclei are usually large. They may be extracted from the reduced transition B(E1) rates via the rotational model formula. But since in most cases absolute values of B(E1) aren't available, D_0 has to be extracted from measured B(E1)/B(E2) branching ratios using the formula

$$D_0(efm) = Q_0\sqrt{\frac{5}{8}\frac{B(E1)}{B(E2)}\frac{(I+K-1)(I-K-1)}{(2I-1)(I-1)}} \tag{2}$$

where the value of the intrinsic quadrupole moment is taken as the arithmetic average of the adjacent even-even nuclei and its value is assumed to be independant of the angular momentum values.

Applying this to ^{221}Ac, one obtains average values of $|D_0|$: 0.40(2) efm and 0.35(1) efm for the assumed $K^\pi = 3/2^-$ and $K^\pi = 5/2^-$ bands respectively, whereas for ^{219}Ac one obtains similar values for both bands (see Table 1). Note that for each band an average value of D_0 is calculated only after stabilization of the values to an almost constant value.

May the similarity for the two bands in ^{219}Ac be taken as a proof that the two bands are simplex partner ? Recently the intrinsic dipole moments in the Ra-Th and Ba-Sm regions have been analyzed within the shell correction method based on a reflection-asymmetric model [21]. Whereas a pronounced configuration dependence on D_0 is obtained in some cases, like for ^{227}Th, in other cases single particle levels with different Ω values yield the same D_0 value (see table 2). This happens in particular for ^{223}Th, and therefore the fact that the two K=5/2 bands have similar intrinsic dipole moments can't be used as an argument to state their common origin.

Table 1 : *Experimental intrinsic dipole moments*

Nuclei	K^π a)	$\|D_0\|_{exp.}$ (efm)
^{219}Ac b)	$5/2^+$	0.33(2)
	$5/2^-$	0.33(2)
^{221}Ac	$3/2^-$	0.40(2)
	$5/2^-$	0.35(1)
	$(3/2^+)$	0.36(1)
^{219}Ra	$1/2^-$	0.29(1)
	$3/2^-$	0.22(1)
^{223}Th	$5/2^+$	0.33(6)c (both bands)
	$5/2^-$	
^{225}Th d)	$3/2^+$	0.38(3)
	$3/2^-$	0.46(4)

a) Assumed values
b) Ref.19
c) *"D_0 does not seem to depend on the simplex quantum number"* [15]
d) Ref.20

★ Quasiparticle routhians

A comparison of experiment and theory may be achieved by inspecting routhians.

Table 2 : *Theoretical intrinsic dipole moments[21]*

Nuclei	Ω	D_0 (efm)
^{219}Ra	1/2	0.18
	3/2	0.16
^{223}Th	5/2	0.29
	1/2	0.29
^{227}Th	5/2	0.05
	1/2	0.12

Such comparisons have been made for neutron quasiparticle routhians in the case of ^{223}Th [15] and ^{225}Th[20]. The values deduced from experiment for ^{221}Ac are displayed in fig.6. They may be compared to theoretical values based on cranked Woods-Saxon-Bogolyubov calculations incorporating an octupole degree of freedom for Z = 90 (see fig.8 for $\beta_3 = 0.10$ in ref.22). Whereas the gross features are similar, such as the slopes of the curves which are a measure of

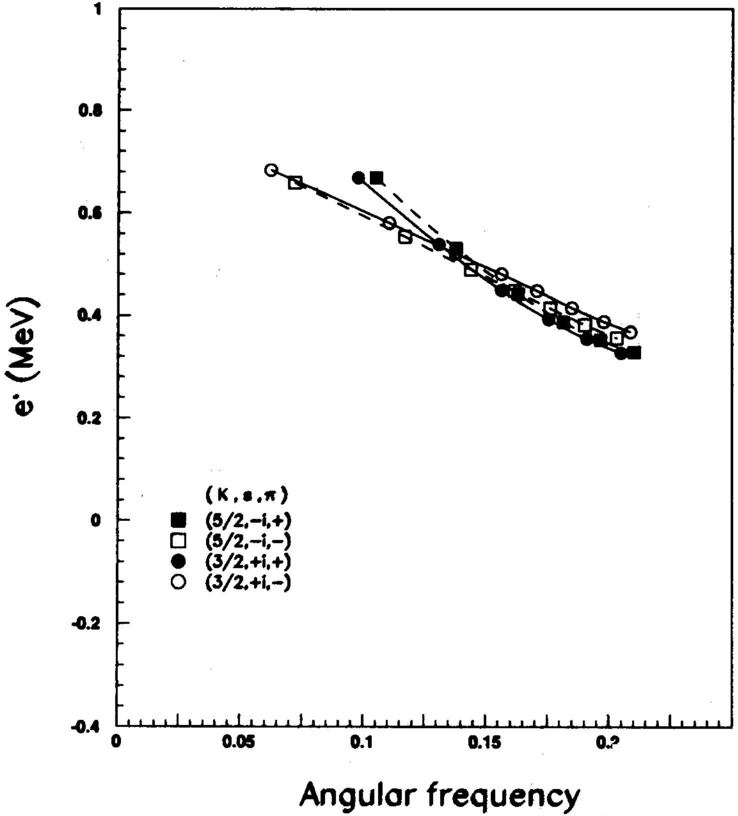

Fig.6 *Experimental values of the single-particle routhians versus rotational frequency for ^{221}Ac.*

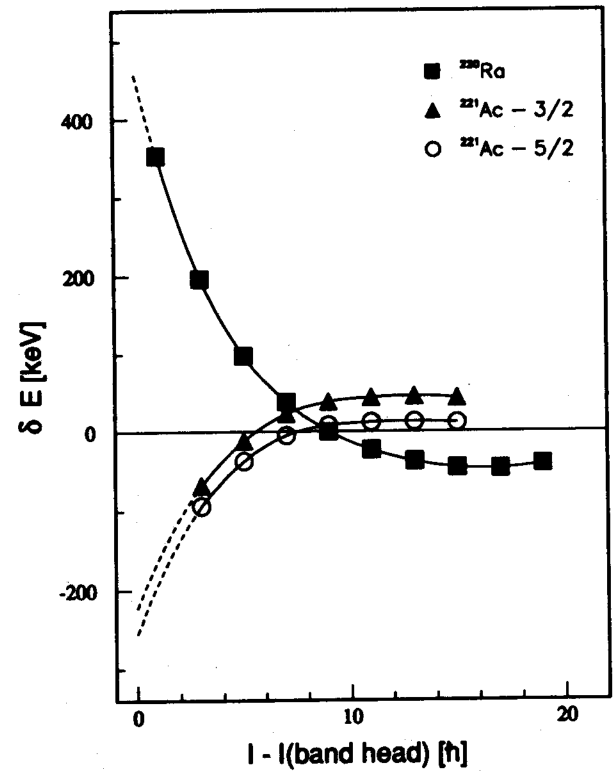

Fig.7 *The displacement of the energy between the negative and positive parity bands (see formula 4) as a function of the angular momentum difference I-$I_{b.h.}$, where $I_{b.h.}$ is the angular momentum of the considered band head.*

the alignment, the experiment doesn't reproduce the details of the theoretical calculations, like the variations with simplex or orbitals.

⋆ Parity splitting

The parity splitting, in other words the energy differences between parity doublets, is given in the strong coupling limit by the formula

$$E_K^{-*} - E_K^{+*} = < K|\hat{\pi}|K > E(0^-) \tag{3}$$

where $< \hat{\pi} >$ is the parity content of the single-particle orbital $|K>$ and E(0^-) the parity splitting of the even-even core. Since the absolute value of $< \hat{\pi} >$ is smaller than unity, the formula explains the reduction of parity splitting for odd-mass nuclei, compared to even-even nuclei. Table 3 compares the information obtained from experiment with the results of a recent calculation [14] using the reflection asymmetric mean field approach: the appearance of parity doublet bands and orbitals with parity content close to zero go hand in hand.

Table 3 : *Simplex partner bands and parity content. The theoretical values on the right are from ref.14*

Nuclei	Simplex partner bands ?	Ω	E(keV)	$< \hat{\pi} >$
^{219}Ra	doubtful	1/2	0	+ 0.66
		3/2	161	+ 0.27
		5/2	202	+ 0.24
^{221}Ra	probable	5/2	0	+ 0.17
^{219}Ac	probable	5/2	0	- 0.19
^{221}Ac	doubtful	3/2	0	- 0.44
		5/2	8	- 0.50
^{221}Th	single band observed	1/2	0	+ 0.65
^{223}Th	probable	5/2	0	+ 0.11
^{225}Th	doubtful	3/2	0	+ 0.78
		5/2	34	+ 0.07

The displacement energy δE, which is defined as

$$\delta E = E_{I^-} - (2I+1)^{-1} \cdot \left[(I+1) \cdot E_{(I-1)^+} + I \cdot E_{(I+1)^+}\right], \qquad (4)$$

is plotted in figure 7 for the two bands in ^{221}Ac and for the alternating parity band in the core nucleus ^{220}Ra. The parity splitting for each band is obtained by extrapolating δE to the band-head spin, and using relation (3) experimental values of $< \hat{\pi} >$ are obtained : - 0.49 and - 0.56, which are to be compared to the theoretical values - 0.44 (Ω = 3/2) and - 0.50 (Ω = 5/2). The agreement with theory yields some confidence in the tentative spin assignment in the ^{221}Ac nucleus.

b) Odd-odd nuclei

Study of odd-odd nuclei started only recently in the actinide region. High-spin spectroscopic investigations of ^{216}Fr[6], ^{218}Ac[8] and ^{220}Ac[5] were carried on, and meanwhile the level structures following alpha decay were studied in ^{220}Fr [23] and ^{224}Ac[24].

The level scheme of ^{220}Ac (see fig.8) is characterized by three alternating parity bands, one being shifted up in energy by roughly 200 keV compared to the two other bands. The states of the latter bands may form parity doublets: the bands have almost identical E1 sequences and the B(E1)/B(E2) ratios appear to be simplex independant. In such a nucleus one anticipates an additional reduction of the parity splitting due to the combined effect of valence neutron and valence proton. Comparing ^{220}Ac to ^{219}Ac, it appears [5] that this further reduction, if present, isn't pronounced. The additional reduction should arise from the odd neutron, however no parity doublets have been observed in ^{219}Ra [3] which seems to indicate a large parity content associated to the ground state band. This is corroborated by calculations which predict a value $< \hat{\pi} >$ = 0.66 for the Ω = 1/2 orbital in ^{219}Ra [14].

c) Even-even nuclei

In even-even nuclei too, one may expect to find bands which are simplex partners. There is however a restriction for axially symmetric nuclei: the simplex eigenvalues of the ground-state band (K=0) are restricted to s=+1.

In two even-even nuclei, ^{218}Ra [4] and ^{148}Sm [10], a second alternating parity band has been observed and in both cases s = - 1. Energetically, the members of the second alternating parity band in each nucleus seem to form parity doublets with the yrast states. Is this an indication that the considered nuclei aren't axially symmetric? This question deserves at least another and deeper experimental investigation of both nuclei.

These two nuclei where a second alternating parity band has been observed are transitional nuclei. Therefore an attempt has been made to observe an s =-1 band in a more deformed nucleus, ^{220}Ra. The analysis is in progress [25].

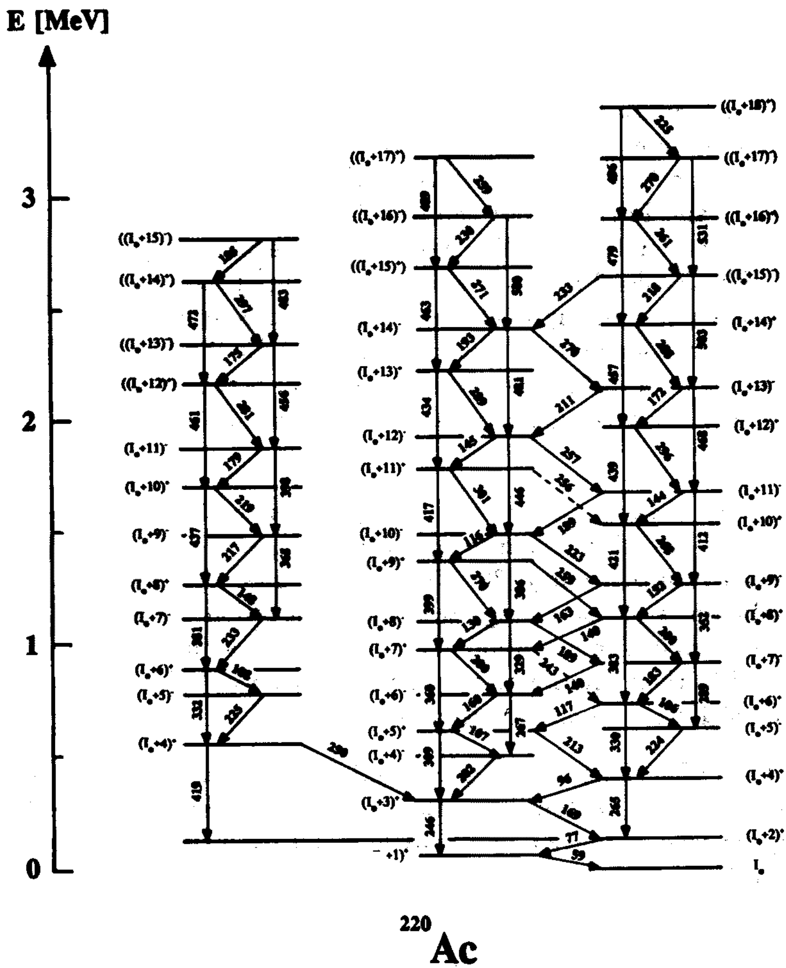

Fig.8 *Level scheme of ^{220}Ac. The spin of the lowest observed level is labelled I_0.*

4. A GLANCE AT THE FUTURE

The advent of γ-ray multicounter arrays of the second generation, such as Eurogam, GASP or Gammasphere, will allow a better insight into the structure of some octupole deformed nuclei. It would certainly be of interest to study nuclei having *exotic* octupole shapes, in other words for which the nuclear shapes are described by spherical harmonics $Y_{3\mu\neq0}$. There have been some investigations in that field : Chasman and Ahmad [26] search the actinide nuclei for which triaxial deformation effects are most likely to be found in conjunction with octupole deformation; Piepenbring and Leandri [27] notice that some bands in $^{124,126}Ba$ are better reproduced in a microscopic treatment if at least an α_{31} contribution is added to the α_{30} octupole force. Other transitional nuclei are expected to show non axial octupole shape efffects : the light Ge isotopes and the heavy Zr isotopes [28]. Recently Dudek and Li [29] performed calculations of the microscopic-macroscopic type taking into account all the $Y_{3\mu}$-type of deformations. In particular they found out that for the translead region the nonaxial octupole components play a significant role. Moreover, in many nuclei one exotic degree of freedom dominates over all others. This predominance is illustrated in fig.9 for the ^{218}Ra nucleus.

Investigations on hitherto unexplored aspects of octupole deformation in nuclei could benefit in the future from radioactive beam facilities. Let's mention a few of them:

i) There were always attemps to reach the heavier Ra-Th isotopes and they include the use of radioactive beams (^{14}C) or radioactive targets (^{210}Pb) or even both simultaneously [30]. It would be specially interesting to check if, as predicted, a shape change towards a reflection symmetric shape occurs at higher angular momentum for these nuclei which are already octupole deformed in their ground state. Such a study would benefit from the use of neutron-rich Carbon and Oxygen beams.

ii) The study of very neutron rich Ra and Th isotopes could also be an opportunity to observe for the first time the manifestations of a collective $\Delta\ell = 5$ mode; the reflection asymmetry would result from the simultaneous coupling between the $\pi j_{15/2} - \pi d_{5/2}$ orbitals on one side and the $\nu i_{13/2} - \nu p_{3/2}$ orbitals on the other.

iii) The B(E3) transition probability may be linked to the octupole deformation parameter β_3 if a stable octupole deformation is assumed in the intrinsic frame of the nucleus. The only way to measure B(E3) values is by Coulomb excitation. The heavy Zr isotopes, for which both theory [28] and experiment [31] suggest the presence of octupole correlations, present the unique opportunity to study the evolution of β_3 in the spin versus neutron number plane by using (in the future) radioactive Zr beams.

Acknowledgments

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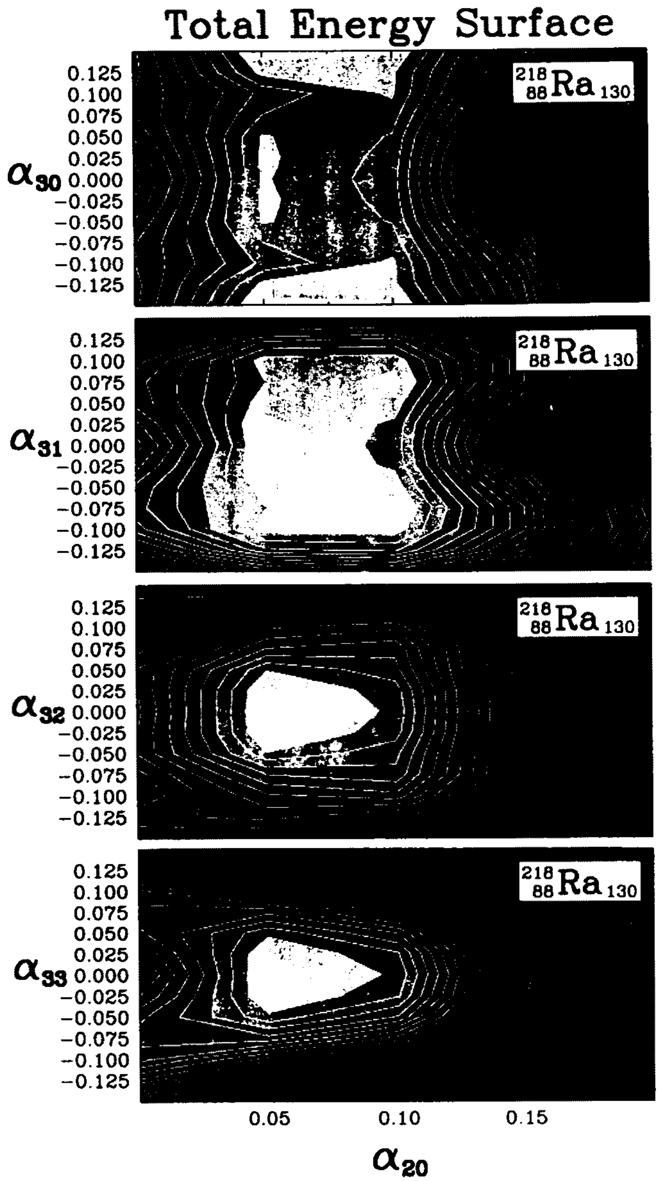

Fig.9 *The total energy surface for the* ^{218}*Ra nucleus in function of the quadrupole,* α_{20}*, and the four octupole deformations,* $\alpha_{3\mu}(\mu = 0,1,2,3)$*. Note the existence of minimum structures for* $\alpha_{20} = 0.10$ *and* $\alpha_{31} = \pm\ 0.075$*.*

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