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PROPOSAL TO THE ISOLDE COMMITTEE

OCTUPOLE DEFORMED NUCLEI IN THE ACTINIDE REGION

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Summary

The aim of the proposed study is to investigate the limits of the "island" of octupole deformation in the mass region A ≈ 225. To this end, the present proposal focuses on the nuclei ^{231}Ra and ^{227}Fr, and on the odd-A Rn isotopes, ^{219,221,223}Rn.
Previous experiments have demonstrated clear evidence for stable octupole deformation in several Ra and Fr nuclei. It is of particular importance to demonstrate experimentally the sudden disappearance of the octupole deformation in the presence of a well developed quadrupole field. This transition effect should be more clearly observed in the high mass region than in the low mass one due to a more stable quadrupole field. The present cases, ^{231}Ra and ^{237}Fr are at the predicted upper border line. In the case of Rn isotopes there are not enough data to draw conclusions concerning possible octupole deformations. In order to enable meaningful comparison with the theoretical model over the whole octupole region detailed spectroscopic studies are required. Therefore, to establish the upper border and to follow the effect of octupole deformation through the odd-A Rn isotopes, 48 shifts of beam time are requested.

1. Introduction

In recent years numerous experimental and theoretical discoveries have provided new indications of reflection–asymmetric octupole deformation in the nuclei around A=225 (see recent reviews[1,2]). These nuclei exhibit features familiar from molecular physics[3]. The region where stable octupole deformation is expected to occur is relatively small. The close lying $g_{9/2}$ and $j_{15/2}$ neutron orbitals and the $f_{7/2}$ and $i_{13/2}$ proton orbitals, in the proximity of the Fermi surface for nuclei around A=225, form the basis for the existence of octupole deformation. The theoretical calculations[4–7] predict about 30 nuclei in the region between At and U to have this property. These nuclei also belong to the region where the relatively large deviations between calculated and experimental masses are reduced when octupole correlations are taken into account[8,9]. The experimental study of isotonic and isotopic sequences of nuclei around A=225 is feasible at ISOLDE[10–25] whilst many of the nuclei are inaccessible to in–beam spectroscopy.

The study of the excited levels in $^{224,226,228,230}Ra$, performed at the ISOLDE facility, was focused on the signatures of an octupole shape. One signature of such a reflection–asymmetric shape in the ground state of the even–even nuclei is the presence of particularly low $K,J^{\pi} = 0,1^-$ states. The very low hindrance factors (HF) of the α–transitions feeding the $K,J^{\pi} = 0,1^-$ states are consistent with this interpretation. The concept of a ground state octupole deformation is closely related to the non–observation of the harmonic two–photon octupole vibrations in nuclei like $^{224,226}Ra$. The even isotopes $^{224,226}Ra$ have features of the octupole–deformed nuclei[10], while for ^{228}Ra this mode of deformation (if any) is less pronounced[12], and the nucleus ^{230}Ra (ref.[17]) appears to be outside the limited region of nuclei with stable octupole deformation, see fig.1.

An important signature for static octupole deformation in odd–A nuclei is the observation of parity doublets, i.e. close–lying bands with the same K–value but opposite parity. Parity doublets are identify by their similar magnetic moments, similar decoupling parameter with opposite signs for the $K^{\pi} = 1/2^{\pm}$ bands, similar α–hindrance factors (HF), and enhanced E1 transitions connecting these bands[7]. Among the odd Ra isotopes, ^{225}Ra exhibits octupole deformation. This conclusion arises from the nuclear structure of ^{225}Ra established in a model–independent way[13,14,20] (see fig.2 and table 1). For ^{227}Ra there is indication for octupole deformation[11,18]. Octupole effects persist at least up to ^{229}Ra, its level structure is similar to the one in the lighter Ra–isotopes[23] conctradicting the theoretical predictions[5,6].

Additional signature of an octupole shape was found in laser spectroscopy measurements[25]. An inverted staggering – i.e. larger mean square charge radius of the odd–N isotopes compared to their even–N neighbours – observed for $^{220-228}Ra$ is related to a ground–state octupole deformation in these nuclei.

2. Proposed studies and experimental methods

We propose to extend the search for octupole signatures in odd–A nuclei to ^{231}Ra, ^{227}Fr and $^{219,221,223}Rn$. Our aims are to investigate the limits of the island of octupole deformation in the A=225 mass region, and to clarify the situation for the Rn isotopes where the laser spectroscopic data[25] are in disagreement with the theoretical predictions[5,6].

The excited–state spectroscopy of odd–A nuclei will provide information on the effect of single–particle orbitals on the octupole component of the mean field deformation. The quasiparticle excitations induce a strong octupole shape–polarization effect on the core. One may thus expect that ground state deformation and the size of octupole barrier in odd–A system would vary depending on what single–particle orbital is occupied by the odd particle[1].

Presently, proposed experiments could be done at the ISOLDE facility only, because availability of the high intensity mass separated radioactive beams.

2.1. SEARCH FOR OCTUPOLE SIGNATURES IN ^{231}Ra

For radium isotopes, the transitional nucleus ^{219}Ra appears to lie at the beginning of the light actinide region where stable octupole deformation is predicted to occur[5,6]. Two side bands in ^{219}Ra, recently investigated in heavy–ion reaction[26], have vibrational–like patterns similar to the ground state band[27]. The presence of parity doublets as well as enhanced E1 transitions in ^{221}Ra (ref.[28]) and ^{223}Ra (ref.[29]) suggests a reflection–asymmetric shape for these nuclei.

Our study of the heavy radium isotopes performed at the ISOLDE facility indicated that octupole effects persist at least up to ^{229}Ra (see sec.1). The decoupling parameter of the [631↓]-like band seems to be positive in ^{229}Ra as in the other Ra-isotopes (see table 1), which may be taken as signature of octupole deformation in this nucleus in contradiction to theoretical calculations[5,6]. In a reflection-asymmetric rotor model[5], as well as according to the recent calculations[6] the nucleus ^{229}Ra is outside of the mass region where static octupole deformation occurs (see fig.3). Because ^{229}Ra, somewhat unexpectedly, showed significant influence of the octupole correlation, we propose to extend the study to the neighbouring nucleus ^{231}Ra. The half-lives of ^{231}Ra and the parent nucleus ^{231}Fr have been determined as 103(3)s and 17.5(8)s, respectively[15]. No information is available concerning the excited states of ^{231}Ra. We propose to search for the signatures of stable octupole deformation in ^{231}Ra, especially for the decoupling parameter of the lowest K=1/2 band.

2.2. SEARCH FOR K = 1/2 BANDS IN ^{227}Fr

Among the francium isotopes, ^{219}Fr is at the edge of the region of reflection asymmetry[30], while the level structure of ^{221}Fr has been interpreted[31,32] in terms of parity doublet bands. Our data for ^{223}Fr (ref.[24]) gave evidence for octupole shape of this nucleus. Low-excited states of ^{223}Fr were assigned to the $K^{\pi} = 3/2^{\pm}$ and $1/2^{\pm}$ parity doublet bands, and a second $K^{\pi} = 3/2^{\pm}$ parity doublet. The electric dipole moment value of Q_1= 0.24(4) e.fm for ^{223}Fr, deduced from the B(E1)/B(E2) branching ratio[24], is typical for nuclei in a ground-state octupole deformation region[7]. On the other hand, spectroscopic data for ^{225}Fr (ref.[19]) do not allow us to draw any firm conclusions about the presence of parity doublets. The nucleus ^{225}Fr is predicted[6] to be very octupole-soft. According to the calculations the nucleus ^{227}Fr is reflection-symmetric. Calculated octupole barriers for the Ω= 1/2, 1/2 and 3/2 proton orbitals in ^{227}Fr are very low (see fig.4). The ground-state spins of J = 1/2 and 5/2 for the nucleus ^{227}Fr (ref.[33]) and the parent nucleus ^{227}Rn (ref.[34]), respectively, were measured with fast-beam high-resolution laser spectroscopy. The half-life of the parent nucleus ^{227}Rn has been determined as 23(1)s (ref.[16]). No information is available concerning the excited states of ^{227}Fr ($T_{1/2}$ = 2.47(3)min). According to ref.[6] three one-quasiparticle states with Ω=1/2, 1/2 and 3/2 appear close to the Fermi level in nucleus ^{227}Fr, predicting a reflection symmetric shape for this nucleus. Experimentally we can characterize this shape by studying the K = 1/2 band.

2.3. SEARCH FOR STABLE OCTUPOLE DEFORMATION IN ^{219,221,223}Rn

In order to experimentally test the behaviour of the potential surface in the actinide region, it is important to know how the octupole deformation varies as a function of N and Z. For the even isotopes ^{218,220,222}Rn a reflection–asymmetric shape is predicted[6], while ^{224}Rn is predicted to be reflection–symmetric (fig.4). Calculations indicate that the odd isotopes ^{219,221,223}Rn have an octupole deformation, with the highest asymmetry energy of 0.76 MeV for ^{219}Rn (see table 2 and fig.4), while the nucleus ^{225}Rn is predicted to be at the border of octupole deformation region. The Rn isotopes are expected to be softer than the isotones of Ra.

Ground–state properties (spins and electromagnetic moments) of the $^{219-227}$Rn were measured with fast–beam high–resolution laser spectroscopy[25,30] (see table 3). The normal odd–even staggering restored for ^{223}Rn and ^{225}Rn indicates ground-state reflection–symmetric shapes of these nuclei and gives $\beta_3 = 0$ only for ^{219}Rn and ^{221}Rn. However, the observed ground–state properties could be explained with the reflection–asymmetric rotor model[5] taking the same octupole deformation parameter $\beta_3 = 0.1$ for ^{219,221}Rn and ^{223,225}Rn (table 3). Excited–state spectroscopy is needed to establish any specific configurations. We propose detailed investigations of the decay properties of the parent neutron–rich ^{219,221,223}At nuclei with the aim to search for the "finger–prints" of reflection–asymmetric shapes, i.e. parity doublets, enhanced E1 transitions, sign–reversal of decoupling parameters in the odd–A radon nuclei, ^{219,221,223}Rn.

2.4. EXPERIMENTAL PROCEDURE

In agreement with the programme outline above we plan to start with the ^{227}Rn decay, followed by ^{231}Fr and ^{219,221,223}At decays. The experimental methods will be γ–ray spectroscopy, conversion electron spectroscopy with a mini–orange spectrometer in front of a Si(Li) detector, $\beta\gamma$– and γe– coincidence measurements (fig.5a). The $\gamma\gamma$ measurements will be performed using an array containing 8 Compton–suppressed germanium detectors (fig.5b). Simultaneous collection of data at multiple angles with many detectors greatly enhances the efficiency of $\gamma\gamma$ angular correlation measurements. In the second part of the study (with known level schemes of the nuclei investigated) the lifetime measurements to reach for anhanced E1 transitions, will be performed using BaF_2 and germanium detectors.

2.5. TARGETS

A yield of 1.10^3 atoms/s.μA is expected for chemically pure sources of ^{231}Fr from UC target with W–surface ionization ion–source.

The ^{227}Rn nuclei are easily obtained, with the yield of $1.3 \cdot 10^4$ atoms / s$\cdot\mu$A, as chemically pure sources from a ThC_2 target with a cold transfer line and a plasma-discharge ion–source.

Attempts to construct a target system providing satisfactory intensity with high chemical purity beams of At have still not been successful. The negative surface ionizer gives pure At beams from targets of ThO_2 or a mixture of Th foils and Ta foils[22)], but the intensities are down by two orders of magnitude compared to what could be expected. The reason for this is that the LaB_6 surface is very sensitive to contaminations. A target of thorium carbide equipped with a hot plasma ion–source gives high yields of At isotopes (estimated to 8 x 10^5, 1 x 10^5 and 2 x 10^3 atoms/s of ^{219}At, ^{221}At and ^{223}At, respectively), but with poor chemical separation. The yields of contaminating isobaric activities from the thorium carbide target may be three orders of magnitude higher than At yields. However, at mass number 219 the undesired isobars have shorter half–lives that ^{219}At, and, the conditions are therefore not as bad as the three orders of magnitude may indicate, provided that the sources are allowed to "cool" between collection and detection. Measurements should be feasible with the unselective ThC target with a hot plasma ion–source.

Although the ^{219}At source seems pure enough for coincidences, singles measurements should also be performed with a chemically selective ThO_2 target with negative surface ionizer, to avoid erroneous assignments of γ–transitions due to cross contamination from other masses or molecular side bands.

At the mass–numbers 221 and 223 the conditions for At are much less favourable with a chemically unselective target. For these nuclides, measurements with a thorium carbide target equipped with a plasma discharge ionizer do not seem feasible, and the coincidence measurements must also be performed with a target with a negative surface ionizer.

BEAM TIME REQUEST

Beam	Min.intensity	Target material	Ion source	Shifts
^{227}Rn	$1 * 10^4$	ThC_2	plasma discharge with cooled transfer line	6
^{231}Fr	$1 * 10^3$	UC	W–surface ionization	9
^{219}At	$4 * 10^5$	ThC	hot plasma	6
^{219}At	$1 * 10^3$	e.g. ThO_2	negative surface ionizer	3
^{221}At	$5 * 10^2$	e.g. ThO_2	negative surface ionizer	9
^{223}At	$2 * 10^2$	e.g. ThO_2	negative surface ionizer	15

Totally, it is thus estimated that **48 shifts** are needed for the entire programme.

REFERENCES

1. S.Aberg et al., Ann.Rev.Nucl.Part.Sci.**40**(1990)439
2. A.K.Jain et al., Rev.Mod.Phys.**62**(1990)393
3. E.Merzbacher, Quantum mechanics (Wiley, NY 1961) ch.5
4. W.Nazarewicz et al., Nucl.Phys. **A429**(1984)269
5. G.A.Leander and Y.S.Chen, Phys.Rev. **C37**(1988)2744
6. S.Ćwiok and W.Nazarewicz, Nucl.Phys. **A529**(1991)95.
7. P.A.Butler and W.Nazarewicz, Nucl.Phys.**A533**(1991)249
8. P.Møller and J.R.Nix, Nucl.Phys.**A361**(1981)117
9. P.Møller et al., Nucl.Phys.**A536**(1992)61
10. W.Kurcewicz et al., Nucl.Phys. **A356**(1981)15
11. T.von Egidy et al., Nucl.Phys. **A365**(1981)26
12. E.Ruchowska et al., Nucl.Phys. **A383**(1982)1
13. K.Nybø et al., Nucl.Phys.**A408**(1983)127
14. R.K.Sheline et al., Phys.Lett.**B133**(1983)13
15. P.Hill et al., Z.Phys. **A320**(1985)531
16. M.J.G.Borge et al., Z.Phys. **A325**(1986)429

17. W.Kurcewicz et al., Nucl.Phys. **A464**(1987)1
18. M.J.G.Borge et al., Nucl.Phys. **A464**(1987)189
19. D.G.Burke et al., AIP Conf. Proc. **164** (AIP, New York, 1988) ed. Jan S.Towner, p.553
20. E.Andersen et al., Nucl.Phys. **A491**(1989)290
21. M.J.G.Borge et al., Z.Phys. **A333**(1989)109
22. D.G.Burke et al., Z.Phys. **A333**(1989)131
23. M.J.G.Borge et al., Nucl.Phys.**A539**(1992)249
24. W.Kurcewicz et al., Nucl.Phys.**A539**(1992)451
25. R.Neugart et al., AIP Conf. Proc. **164** (AIP, New York, 1988) ed. Jan S.Towner, p.126 (and references quoted therein)
26. M.Wieland et al., Phys.Rev.**C45**(1992)1035
27. C.F.Liang et al., Z.Phys.**A341**(1992)401
28. J.Fernandez–Niello et al., Nucl.Phys.**A531**(1991)164
29. Ch.Briancon et ai., J.Phys.**G16**(1990)1735
30. C.F.Liang et al., Phys.Rev. **C44**(1991)676
31. R.K.Sheline, Phys.Lett. **B205**(1988)11
32. C.F.Liang et al., Mod.Phys.Lett. **A16**(1990)1243
33. A.Coc et al., Nucl.Phys.**A468**(1987)1
34. W.Borchers, Thesis, Univ.Mainz 1989

Table 1

Experimental decoupling parameters (a) for the K = $1/2^{\pm}$ bands in ^{225}Ra compared with those from pure Nilsson configurations for $\delta = 0.15$ (taken from ref.[14]) .

Parity mixed configuration	Experimental decoupling parameter	Pure Nilsson configuration	Theoretical decoupling parameter
$K = 1/2^+$	+1.534	$1/2^+[631\downarrow]$	–0.68
		$1/2^+[640\uparrow]$	–4.5
$K = 1/2^-$	-2.594	$1/2^-[770\uparrow]$	-7.79

Table 2

Calculated excitation energies E, equilibrium deformations $\beta_2 - \beta_7$, asymmetry energies E_{om} and parity contents $<\pi>$ of low–lying 1qp excitations in $^{219-225}$Rn. Orbitals are labelled by means of Ω and n_Ω quantum numbers. The asterisk indicates the cases where the spurious interaction between states with identical Ω quantum number was removed (taken from ref.[6]) .

N (A)	Ω	n_Ω	E (keV)	β_2	β_3	β_4	β_5	β_6	β_7	E_{om} (MeV)	$\langle\hat{\pi}\rangle$
133 (219)	$\frac{1}{2}$	24	0	0.088	0.098	0.061	0.044	0.021	0.032	0.49	+0.63
	$\frac{5}{2}$	12	9	0.091	0.100	0.063	0.044	0.022	0.032	0.76	+0.27
	$\frac{3}{2}$	18	296	0.094	0.082	0.065	0.036	0.023	0.030	0.40	+0.93
	$\frac{3}{2}$	17	386	0.085	0.055	0.061	0.018	0.030	0.021	0.07	−0.34
135 (221)	$\frac{5}{2}$	12	0	0.110	0.087	0.072	0.035	0.024	0.026	0.65	+0.21
	$\frac{3}{2}$	18	30	0.111	0.091	0.071	0.036	0.021	0.025	0.41	+0.86
	$\frac{1}{2}$	25	190	0.114	0.060	0.079	0.022	0.034	0.019	0.21	−0.06
	$\frac{1}{2}$	24	296	0.096	0.110	0.058	0.042	0.014	0.026	0.41	+0.67
137 (223)	$\frac{1}{2}$	25	0	0.129	0.081	0.078	0.024	0.023	0.015	0.26	−0.22
	$\frac{3}{2}$	18	19	0.126	0.085	0.077	0.025	0.023	0.016	0.06	+0.72
	$\frac{5}{2}$	12	66	0.130	0.083	0.078	0.024	0.023	0.015	0.14	+0.13
	$\frac{3}{2}$	19	74	0.131	0	0.087	0	0.034	0	0	+1
	$\frac{7}{2}$	8	212	0.120	0.115	0.066	0.032	0.015	0.016	0.51	+0.18
139 (225)	$\frac{5}{2}$	12*	0	0.150	0.027	0.089	0.004	0.026	0.005	0.06	+0.20
	$\frac{3}{2}$	19	7	0.152	0.038	0.089	0.006	0.026	0.005	0.04	+0.59
	$\frac{5}{2}$	13*	33	0.152	0	0.090	0	0.027	0	0	+1
	$\frac{3}{2}$	18	189	0.142	0	0.083	0	0.023	0	0	−1
	$\frac{1}{2}$	25	245	0.142	0.080	0.076	0.020	0.015	0.011	0.26	−0.19
	$\frac{7}{2}$	8	343	0.145	0.094	0.076	0.015	0.017	0.005	0.40	+0.05

Table 3
Experimental versus calculated ground-state spins, parities, spectroscopic magnetic dipole moments, and electric quadrupole moments for $^{219-227}$Rn.

Nucleus	Experiment[34]			Theory[5]		
	I	μ [n.m.]	Q_s [b]	I^{π}	μ [n.m.]	Q_s [b]
^{219}Rn	5/2	-0.442(15)	1.416(9)	$5/2^+$	-0.44	1.30
^{221}Rn	7/2	-0.020(8)	-0.581(4)	$7/2^+$	0.62	-0.47
^{223}Rn	7/2	-0.7761(11)	1.216(8)	$7/2^-$[a]	-0.74[a]	1.01[a]
^{225}Rn	7/2	-0.6952(25)	1.272(9)	$7/2^-$[a]	-0.74[a]	1.12[a]
^{227}Rn	5/2	-0.0817(9)	2.593(17)	-	-	-

[a] Lowest calculated negative-parity state, located 8 keV above the lowest calculated positive-parity state in ^{223}Rn and 26 keV above in ^{225}Rn.

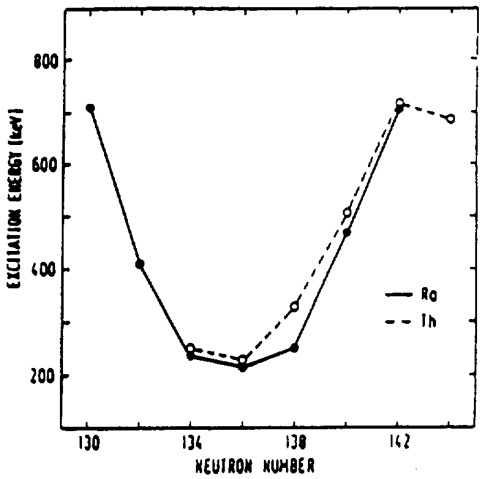

Fig.1. Excitation energy of the K,J^{π} = 0,1^- states in radium and thorium nuclei (taken from ref.[17]).

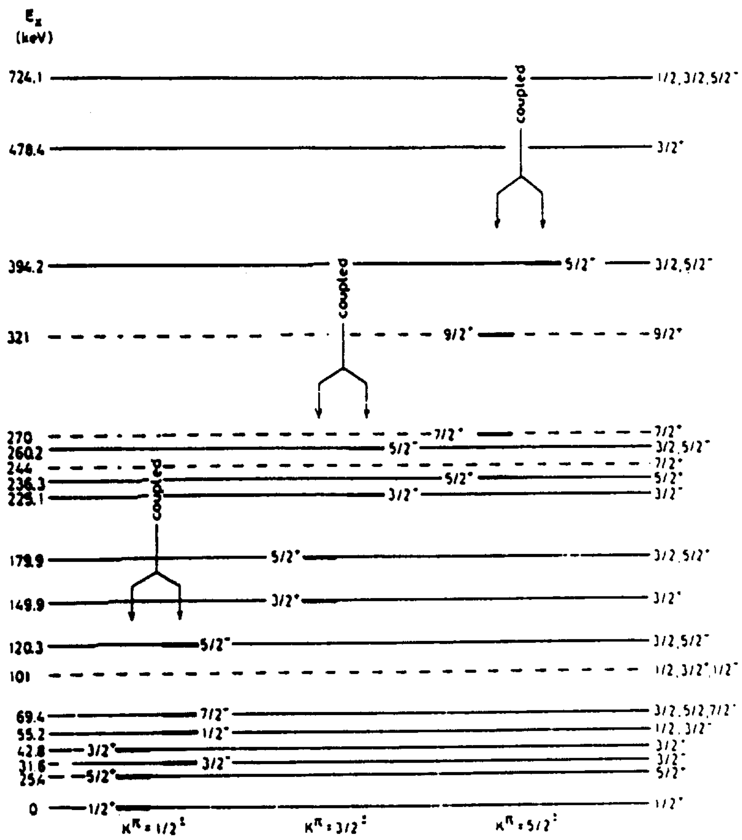

Fig.2. Partial level diagram for ^{225}Ra (taken from refs.[13,14,20]).

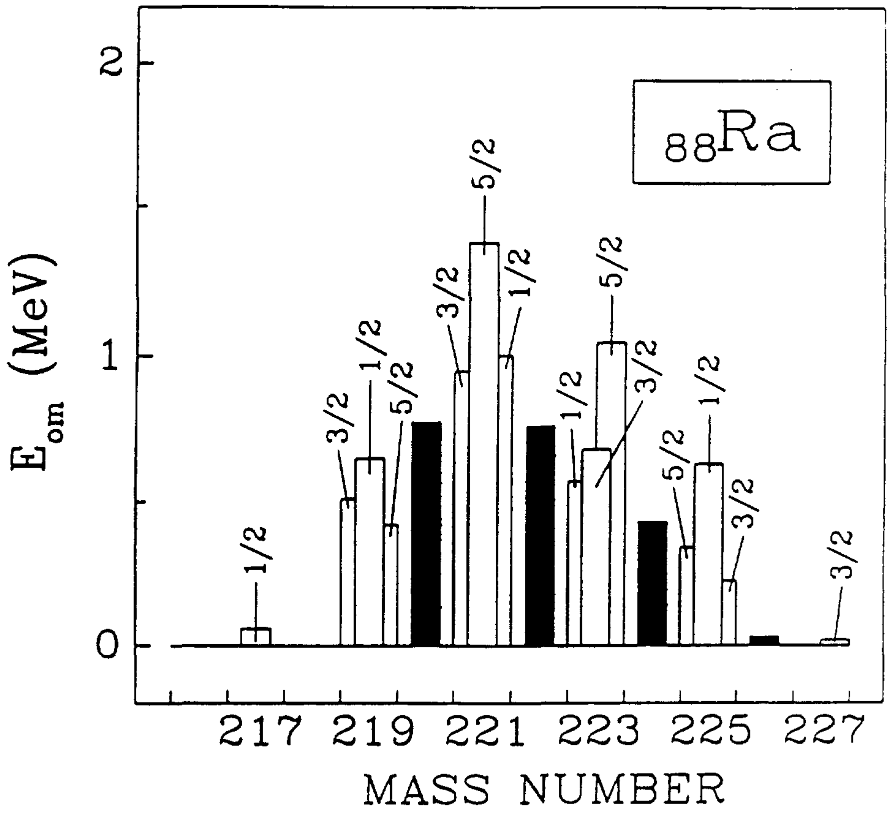

Fig.3. Calculated asymmetry energies (octupole barriers), E_{om}, for the three lowest states in the odd-A Ra isotopes.
The asymmetry energies for neighbouring even–even Ra isotopes are also shown for comparison (taken from ref.[6]) .

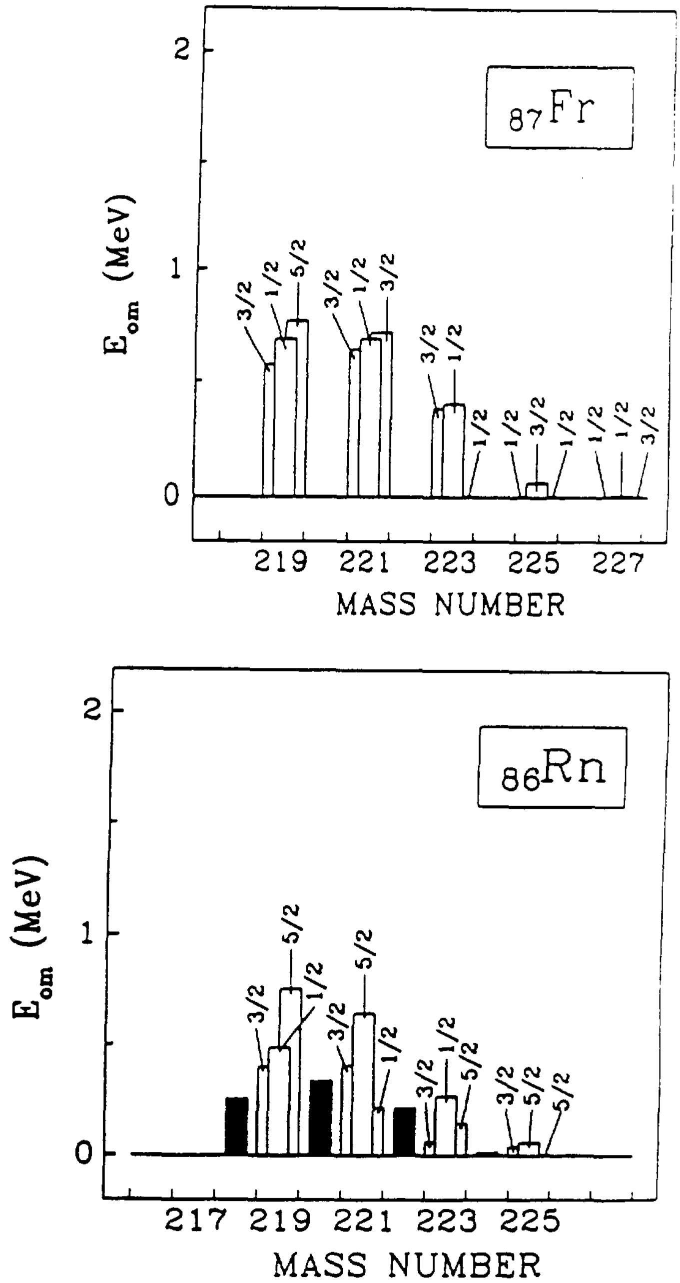

Fig.4. Calculated asymmetry energies (octupole barriers), E_{om}, for the three lowest states in the odd-A Fr and Rn isotopes. The asymmetry energies for neighbouring even-even Rn isotopes are also shown for comparison (taken from ref.[6]) .

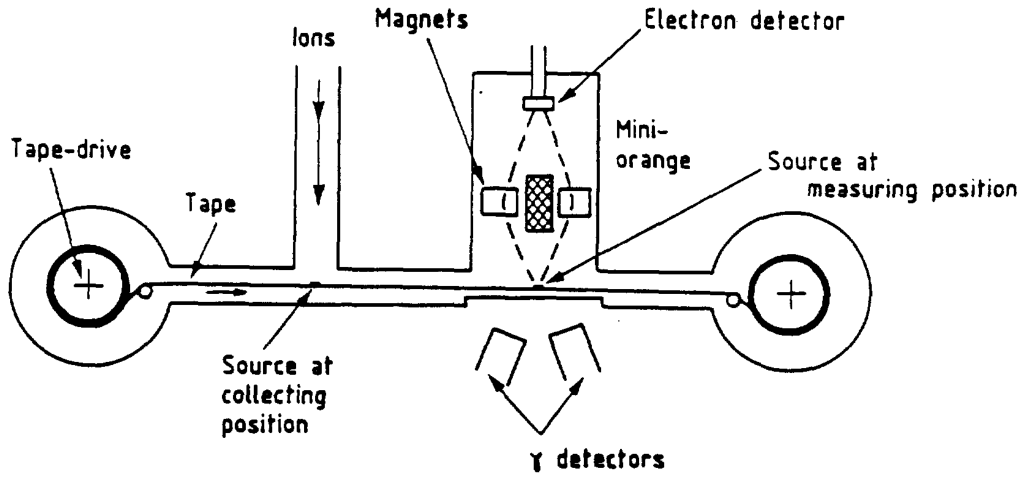

Fig.5a. Arrangement of the experimental set-up for eγ and eX coincidences, showing the tape-transport system, the mini-orange electron spectrometer, and the gamma detectors. The tape system moves the radioactivity in front of the detectors.

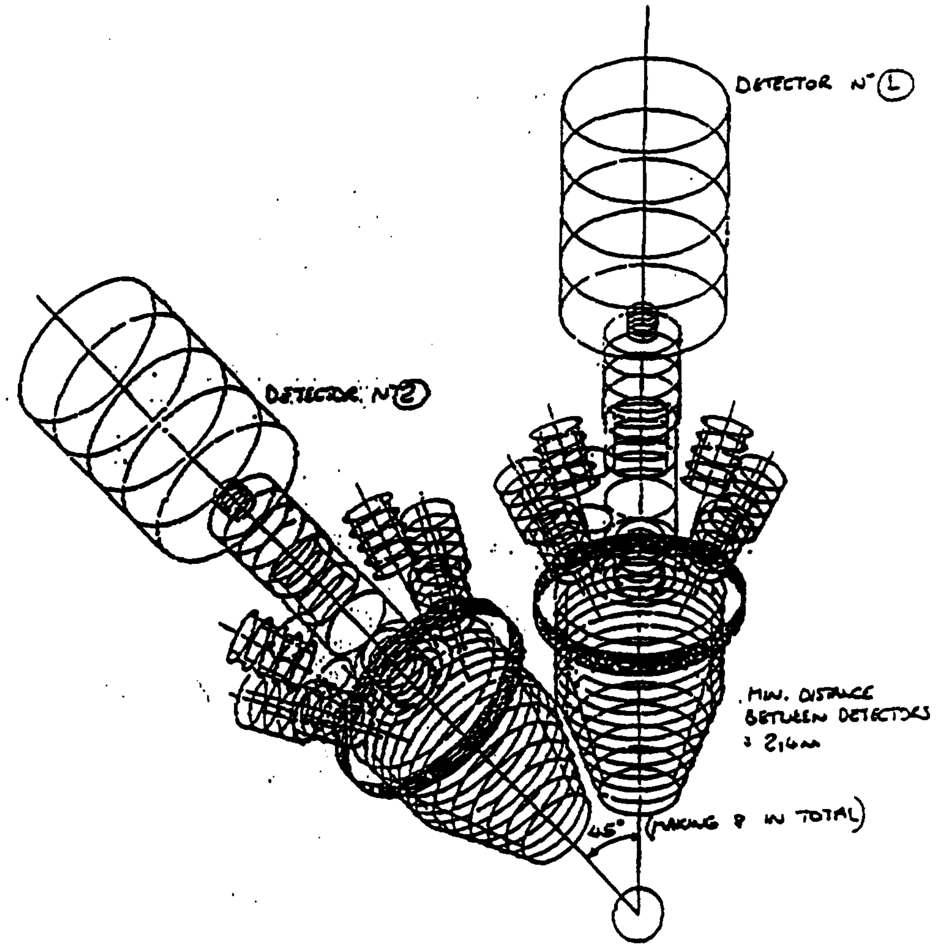

Fig.5b. Attempt at installing eight (two shown) Compton-suppressed germanium detectors for γγ angular correlation measurements.