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COLLECTIVE STATES IN ^{230}Ra FED BY β^- -DECAY OF ^{230}Fr

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Abstract: The γ -rays following the β^- -decay of ^{230}Fr have been investigated by means of γ -ray singles including multispectrum analysis and $\gamma\gamma$ coincidence measurements using Ge(Li) detectors. The half-life of ^{230}Fr was measured to be 19.1 ± 0.5 s. Most of the observed transitions could be placed in a level scheme comprising 23 new excited states of ^{230}Ra , ten of them grouped into the $K^\pi = 0^+$ ground-state band, the $K^\pi = 0^-$ band with its 1^- state at 710.9 keV and a $K^\pi = 2^+$ γ -vibrational band with its head at 734.8 keV. It is concluded that ^{230}Ra is a better rotator than the lighter radium isotopes, and has no ground-state octupole deformation.

RADIOACTIVITY ^{230}Fr [from $^{238}\text{U}(p,6p3n)$, mass separation]; measured E_γ , I_γ , $\gamma\gamma$ coin., $T_{1/2}$. ^{230}Ra deduced levels, J , π . Ge(Li) detectors.

1. Introduction

Experimental studies of the collective $K^\pi = 0^-$ excitations in $^{224,226}\text{Ra}$ have established that these states are not adiabatic octupole vibrations but are related to ground-state octupole deformation¹⁾. These nuclei belong to the region where the relatively large deviations between calculated and experimental masses are reduced if octupole correlations are taken into account²⁾.

Recently, a number of experimental and theoretical investigations have produced evidence for stable octupole deformation in nuclei with neutron numbers around $N=136$ (see e.g. refs.^{3,4)} and references quoted therein).

In order to extend the knowledge on collective states in even radium isotopes^{1,5,6)} we have undertaken a study of the β^- -decay of ^{230}Fr into levels of ^{230}Ra . No information on excited states in ^{230}Ra was available prior to this investigation; preliminary results have been published in ref.⁷⁾.

2. Experimental techniques and results

Francium activities were produced in spallation reactions of ^{238}U induced by 600 MeV protons from the CERN Synchro-cyclotron. The nuclide ^{230}Fr was obtained as a mass-separated beam from the ISOLDE II on-line separator^{8,9)}. The beam was collimated in order to reduce contaminations from adjacent masses and then deflected onto a movable tape that was operated in a start-stop mode to carry the activity into the counting position, which was equipped with a small plastic scintillator and two Ge(Li) detectors (active volumes: 32 and 180 cm³, energy resolution at 1332 keV: 1.75 and 1.8 keV, respectively).

For background reduction the γ -rays were gated by the signals from the plastic scintillator used as a β -ray detector. The β -gated γ -ray spectrum of ^{230}Fr for energies below 1300 keV is shown in fig. 1.

A rather strong contamination from 13-s ^{211}Ra and its daughter products was observed. The radium activity was able to pass the mass separator as an ionized $^{211}\text{Ra}^{19}\text{F}$ -molecule.

A half-life of 19.1 ± 0.5 s for ^{230}Fr has been obtained by means of multi-spectra analysis using cycles of 20 s collection time followed by 6×7 s measuring time.

For energy calibration the ^{230}Fr activity was measured simultaneously with a set of γ -ray standard sources (^{57}Co , ^{60}Co , ^{85}Sr , ^{88}Y , ^{109}Cd , ^{113}Sn , ^{137}Cs , ^{139}Ce , and ^{203}Hg). Precisely known energies of γ -lines from natural background and from ^{211}Ra descendants¹⁰⁾ were also used as internal standards. The efficiency calibration of the γ -ray detectors was performed with the absolutely calibrated set of activities mentioned above. The energies and intensities including their uncertainties of all γ -ray transitions assigned to the decay of ^{230}Fr have already been reported⁷⁾. The $\gamma\gamma$ coincidence experiments have been performed simultaneously with the singles γ -ray measurements.

3. Decay scheme

Most of the observed γ transitions following the β^- -decay of ^{230}Fr were placed in a decay scheme based on coincidence results and energy balances. Fig. 2 shows only the excited levels which were confirmed by coincidence data. From a comparison with the lighter isotopes $^{224,226,228}\text{Ra}$ (refs.^{1,6)}), one may suggest the spin-parity assignments given in fig. 2 for the excited states in ^{230}Ra .

Total transition intensities were determined from γ -ray intensities⁷⁾ using theoretical conversion coefficients¹¹⁾. The β -branching to the individual levels results from intensity balances under the assumption of no β -feeding of the ^{230}Ra ground state. The β -feeding of 6 and 19% to the 57.4 ($J^\pi = 2^+$) and 186.5 keV ($J^\pi = 4^+$) excited states, respectively, suggests spin $J = 3$ for the ground state of ^{230}Fr . A factor of 0.107 has been used to convert the relative intensities (given in fig. 2) to absolute intensities. An upper limit of 22% is obtained for the absolute intensity of transitions observed in the γ -ray spectrum but not placed in the level scheme of ^{230}Ra .

4. Discussion

4.1. EVEN-PARITY STATES

The even parity levels presented in fig. 3 are associated with the $K^\pi = 0^+$ ground-state and $K^\pi = 2^+$ γ -vibrational bands with moment-of-inertia parameters A of 9.57 and 8.50 keV, respectively. The ground-state band is identified up to the $J^\pi = 6^+$ member, while the γ -band is observed up to the 5^+ state.

An attempt to confirm the assignments to the ground-state- and γ -band levels was performed via the analysis of reduced branching ratios. A comparison of the experimental $B(E2)$ -ratios with those given by the Alaga rule¹²⁾ (see table 1) shows deviations. An adjustment of one parameter $a = 0.014^{+0.007}_{-0.008}$ (ref.¹³⁾), obtained from the branching ratio of the transitions de-exciting the 734.8 keV level of the γ -band, provides agreement between the calculated (column 8) and experimental ratios.

The $E(4^+)/E(2^+)$ energy ratio of 3.25 calculated for the members of the ground-state band in ^{230}Ra is close to the value of 3.28 for the isotone

^{232}Th and is higher than the values of 3.13 and 3.21 calculated for ^{226}Ra and ^{228}Ra , respectively. The value of 3.25 for ^{230}Ra should also be compared with the value of 3.33 characteristic of rotational nuclei and it may be concluded that ^{230}Ra is a better rotator than the lighter Ra isotopes.

4.2. ODD-PARITY STATES

The odd-parity states of ^{230}Ra are interpreted (fig. 3) as members of the $K^\pi = 0^-$ octupole band with a parameter $A = 5.75$ keV. The experimental $B(E1)$ -ratios given in column 6 of table 1 show large deviations in comparison with the Alaga rule¹²⁾. These discrepancies are attributed to the Coriolis interaction of the $K^\pi = 0^-$ band with the in this study unobserved $K^\pi = 1^-$ band. The theoretical branching ratios of E1 transitions between the $K^\pi = 0^-$ band and the $K^\pi = 0^+$ ground-state band listed in column 9 of table 1 are calculated using the same procedure as described in ref.⁶⁾. Good agreement with the experimental values is obtained for the free parameter $S = M_{01}/M_{00}$ of $-0.99^{+0.47}_{-0.63}$, where M_{00} and M_{01} are intrinsic matrix elements¹⁴⁾.

In fig. 4 a systematic of the excitation energy of the $K, J^\pi = 0, 1^-$ states in radium and thorium nuclei is presented. The changes are large when increasing the neutron number from 130 to 142. The energy splitting between the virtual $K, J^\pi = 0, 0^-$ band head and the ground state ($K, J^\pi = 0, 0^+$), which is suggested to be correlated with octupole deformation^{1,3)}, is in ^{230}Ra where it amounts to 699.4 keV much higher than in the $^{224,226}\text{Ra}$ nuclei with ground-state octupole deformation. Therefore, ^{230}Ra with neutron number $N = 142$ is obviously outside a limited region of nuclei with stable octupole deformation.

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Figure Captions

Fig. 1: The β -gated γ -ray spectrum of ^{230}Fr below 1300 keV measured with a 180 cm^3 Ge(Li) detector. Measuring cycle: 40 s collection and 20 s counting time. The peaks assigned to ^{211}Ra and its descendants and to the background are also shown.

Fig. 2: Decay scheme of ^{230}Fr . Transitions which have been confirmed by coincidence measurements are marked by dots, the other transitions have been placed on the basis of energy balances. The relative intensities are given in parentheses. Corrections for internal conversion are included for transitions linking levels with indicated spin and parity values.

Fig. 3: Interpretation of the excited states in ^{230}Ra observed below 1000 keV.

Fig. 4: Excitation energy of known $K, J^\pi = 0, 1^-$ states in radium and thorium nuclei.

Table 1

Reduced branching ratios of E2 transitions de-exciting the $K^\pi = 2^+$ band
and of E1 transitions de-exciting the $K^\pi = 0^-$ band

Initial level energy (keV)	Initial level $J_i^\pi K_i$	Final level		Transition energy (keV)	Reduced branching ratios		
		energy (keV)	$J_f^\pi K_f$		experiment	a)	b) theory c)
734.8	2^+2	0	0^+0	734.9	1	1	1
		57.4	2^+0	677.4	1.70 ± 0.17	1.43	1.70
		186.5	4^+0	548.0	0.24 ± 0.03	0.07	$0.12^{+0.04}_{-0.03}$
785.8	3^+2	57.4	2^+0	728.4	1	1	1
		186.5	4^+0	599.3	0.70 ± 0.06	0.40	$0.59^{+0.13}_{-0.12}$
849.8	4^+2	57.4	2^+0	792.4	1	1	1
		186.5	4^+0	663.2	3.93 ± 0.39	2.95	$4.54^{+1.42}_{-1.04}$
932.1	5^+2	186.5	4^+0	745.4	1	1	1
		379.0	6^+0	553.2	1.32 ± 0.23	0.57	$1.05^{+0.40}_{-0.31}$
710.9	1^-0	0	0^+0	711.0	1	1	1
		57.4	2^+0	653.4	1.21 ± 0.32	2.0	1.21
768.4	3^-0	57.4	2^+0	711.0	1	1	1
		186.5	4^+0	581.9	0.24 ± 0.03	1.33	$0.43^{+0.31}_{-0.23}$
879.8	5^-0	186.5	4^+0	693.3	1	1	1
		379.0	6^+0	500.8	<0.14	1.20	$0.42^{+0.65}_{-0.31}$

Table 1 (cont.)

- a) According to the Alaga rule¹²⁾.
- b) According to the Mihailov formula¹³⁾ which applied to the investigated cases may be written:
- $$B(E2; J_i \rightarrow J_f) = [J_i K_i 2\Delta K J_f K_f]^2 \cdot M^2 \cdot \{1 + [J_f(J_f+1) - J_i(J_i+1)] \cdot a\}^2,$$
- where M and a are parameters of the theory. For a = 0 this formula is identical with that given by Alaga et al.¹²⁾.
- c) According to the Kocbach and Vogel formula¹⁴⁾.

Fig.1

Fig.2

379.0 — 6^+

186.5 — 4^+

57.4 — 2^+

0 — 0^+
 $K\pi = 0^+$

100% 25R

Fig. 3

Fig. 4