COLLECTIVE EXCITATIONS IN THE TRANSITIONAL NUCLEI $^{224,226,228,230}Ra$

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Abstract

The γ-rays following the β^-decay of $^{224,226,228,230}Fr$ have been investigated by means of γ-ray singles (including multi-spectrum analysis) and γγ coincidence measurements using Ge(Li) spectrometers. The study of the excited levels in $^{224,226,228,230}Ra$ was focused on the properties of collective states. The analysis of the results leads one to the conclusion that a ground-state octupole deformation is the most likely explanation for the special features of the collective excitations in Ra and some neighbouring nuclei in the N=136 region.

1. Introduction

In the even isotopes of radium and thorium with neutron numbers from 134 to 138 the $K,J^\pi=0,1^-$ states occur at an unusually low excitation energy. These states can be interpreted as rotational states of a permanently octupole deformed nucleus. This has been discussed in previous studies[1] of the γ-rays following the α-decay of the corresponding precursors. The moment-of-inertia parameter A ($\hbar^2/2\mathcal{J}$) should then be the same for the $K^\pi=0^+$ ground-state and $K^\pi=0^-$ bands, but experimentally they are found to be different. However, this difference can be explained by assuming a strong Coriolis interaction of the $K^\pi=0^-$ band with the experimentally unobserved $K^\pi=1^-$ band. In the present study we have undertaken a search for these $K^\pi=1^-$ bands in $^{224,226}Ra$ by investigating the β^- decay schemes of $^{224,226}Fr$. In order to extend the evidence for the $K^\pi=0^-$ excitations, we have also undertaken a study of $^{228}Fr\rightarrow^{228}Ra$ decay and initiated a search for the $^{230}Fr\rightarrow^{230}Ra$ decay. Our study of the excited states of $^{224,226,228,230}Ra$ was focused on the properties of collective states.

The analysis of the results obtained leads one to the conclusion that the ground-states of radium isotopes and some neighbouring nuclei from the N=136 region possess a non-zero octupole deformation.

2. Experimental techniques

Sources of francium isotopes were produced in a spallation reaction of ^{238}U induced by 600 MeV protons from the CERN Synchrocyclotron. The targets were of the UC_2-graphite cloth type[2] and contained about 20 g of uranium. The nuclides were obtained as mass-separated ion beams from the ISOLDE II on-line separator[3]. A selected beam was collimated in order to reduce contamination from adjacent masses, and deflected onto a movable tape system, working in a start-stop mode, to carry the activity away from the collection point to the detectors.

The γ-ray singles and coincidence measurements were performed simultaneously with two Ge(Li) detectors of 32 and 74 cm^3 active volume and an energy resolution (FWHM) of 1.8 and 2.1 keV at 1332 keV, respectively. In addition, multispectrum analysis experiments were performed in order to determine the half-life of the stronger γ-lines. Additional experimental details have been described elsewhere[4,5].

3. Experimental results and the individual decays

Most of the transitions observed in our investigations were placed in the individual decay schemes based on the results of the coincidence experiments and on energy fits. Since complete data on the decay of $^{224,226}Fr$ has recently been made available[4,5], only the construction of the ^{228}Fr decay scheme is presented here.

Total transition intensities were determined from γ-ray intensities and theoretical conversion coefficients[6]. The β-branches resulted from intensity balances based on the assumption that the ground-state of ^{228}Ra is not fed in β decay of ^{228}Fr. The log ft values were determined using the half-life of 39± 1 s, ref.[7], the "f"-tables of ref.[8] and Q_β value of 3480 ± 660 keV. This Q_β value results from the difference of the mass excess values of ^{228}Fr, ref.[9], and ^{228}Ra, ref.[10].

3.1. The ^{224}Fr→^{224}Ra and ^{226}Fr→^{226}Ra decays

The decay schemes of ^{224,226}Fr were published elsewhere[4,5] and will be reviewed here only briefly. The interpretations of the low-energy levels in ^{224}Ra and ^{226}Ra nuclei are presented in figs. 1 and 2, respectively.

Besides the known ground-state $K^{\pi}=0^{+}$ band, the $K^{\pi}=0^{-}$ band and a second $K^{\pi}=0^{+}$ band, the $K^{\pi}=1^{-}$ states have been identified in ^{224}Ra and ^{226}Ra at 1052.9 and 1048.6 keV, respectively.

3.2. The ^{228}Fr→^{228}Ra decay

Most of the transitions observed in the ^{228}Fr decay could be placed into a level scheme of ^{228}Ra comprising 36 excited states. Of those only the first state ($I^{\pi}=2^{+}$) was known previously[11]. Eleven of these states are grouped into the ground-state band, the $K^{\pi}=0^{-}$ band with its head at 474.1 keV and two excited $K^{\pi}=0^{+}$ bands with heads at 721.1 and 1041.9 keV. The partial decay scheme of ^{228}Fr is shown in fig. 3. The complete data will be published elsewhere[12].

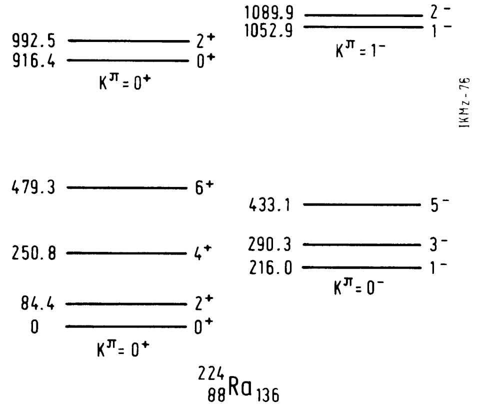

Fig.1 Collective excitations in ^{224}Ra

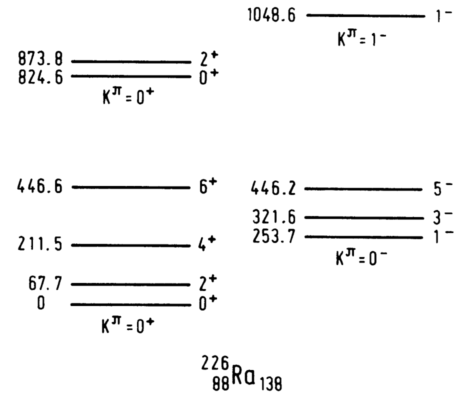

Fig.2 Collective excitations in ^{226}Ra

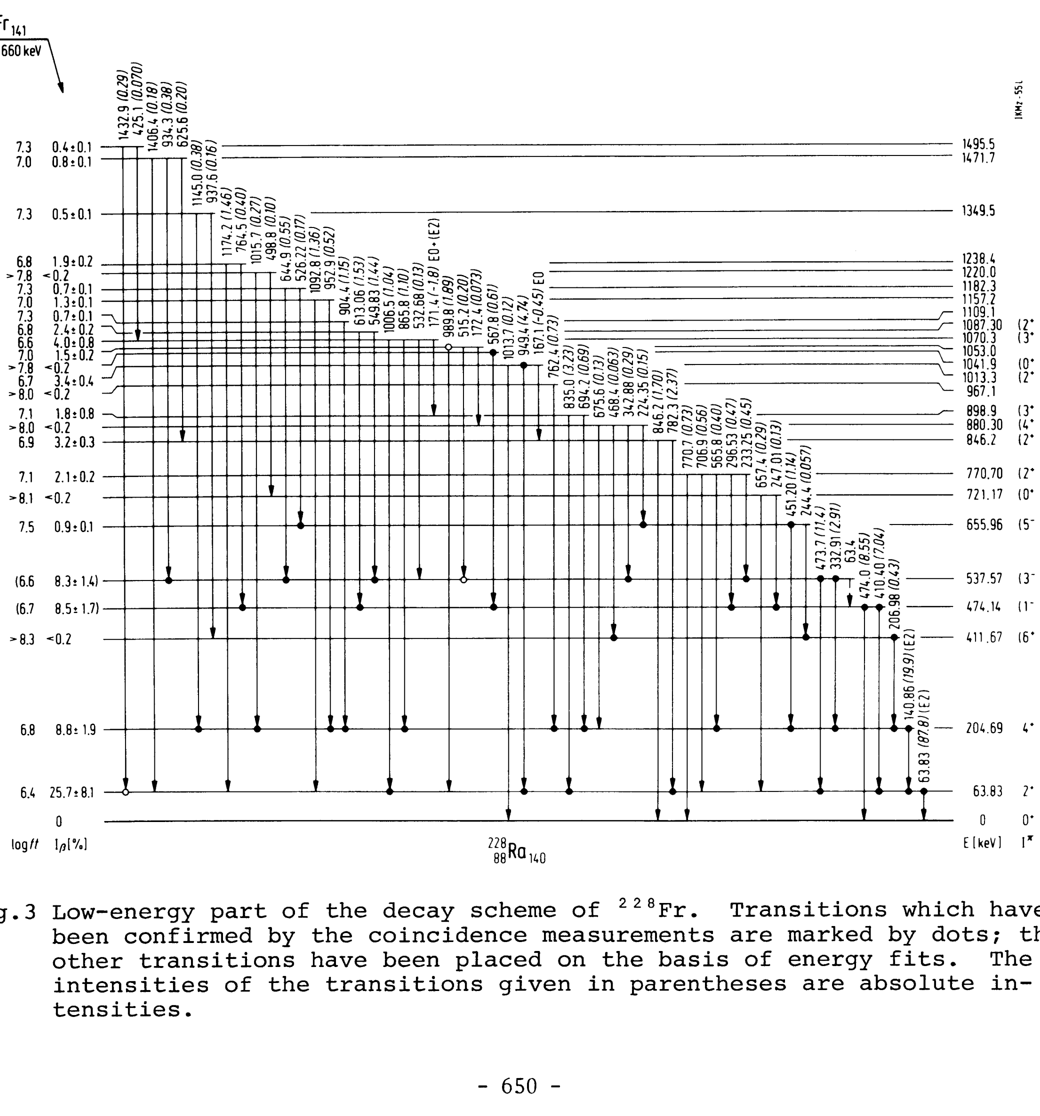

Fig.3 Low-energy part of the decay scheme of ^{228}Fr. Transitions which have been confirmed by the coincidence measurements are marked by dots; the other transitions have been placed on the basis of energy fits. The intensities of the transitions given in parentheses are absolute intensities.

3.3 The $^{230}Fr \rightarrow ^{230}Ra$ decay

Based on results from the multispectrum analysis experiment, the γ-transitions of 57.4 ± 0.1, 129.0 ± 0.1, 192.4 ± 0.1 and 710.5 ± 0.5 keV have been assigned to mass 230. The time-decay curves of these γ-rays are shown in fig.4. The half-life of $T_{1/2}$ = 20 ± 1 s obtained for ^{230}Fr in this way is somewhat shorter than the value of 30 s predicted by the gross theory of beta decay[13]. The observation of the Ra KX-rays which confirms the Z-assignment, and γ-lines at 129 and 192 keV in the coincidence spectra, enabled us to introduce new levels in ^{230}Ra at 57.4, 186.4 and 378.8 keV. These are interpreted as the 2^+, 4^+ and 6^+ levels, respectively.

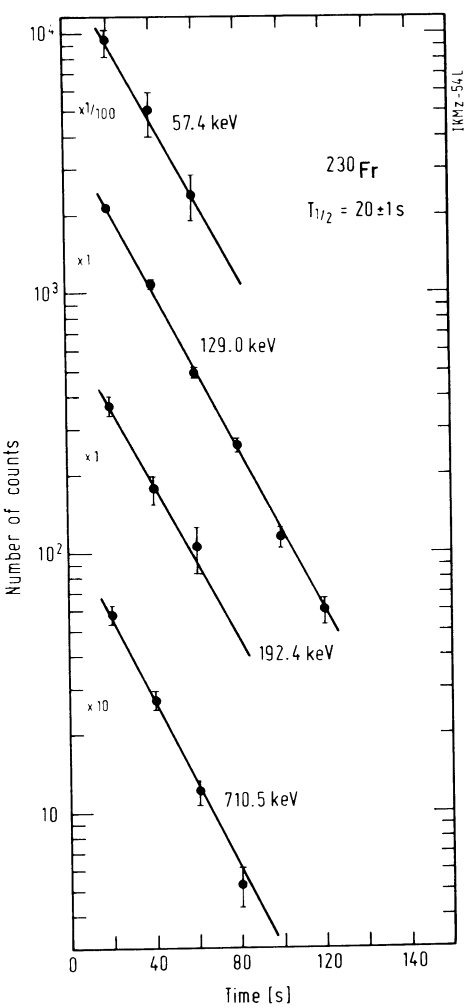

Fig.4 Decay curves for selected γ-rays of ^{230}Fr.

4. Discussion

It is known (see fig.5) that the $K,J^{\pi}=0,1^-$ states in Ra, Th and U nuclei from the N=136 region occur at an unusually low-excitation energy. The new excited state in ^{228}Ra at 474.1 keV extends this systematics. On the basis of the experimental results, a non-zero ground-state octupole deformation has been considered[1] to explain the special features of nuclei in this region. According to this interpretation the moment-of-inertia parameter A for the $K^{\pi}=0^+$ ground-state and $K^{\pi}=0^-$ bands should be the same, but this is remarkably different from what is experimentally observed. This difference can, however, be explained by a strong Coriolis interaction of the $K^{\pi}=0^-$ with the $K^{\pi}=1^-$ bands unobserved prior to the present study. The experimental results concerning ^{224,226}Fr decays[4,5] provide the possibility for checking the above assumption.

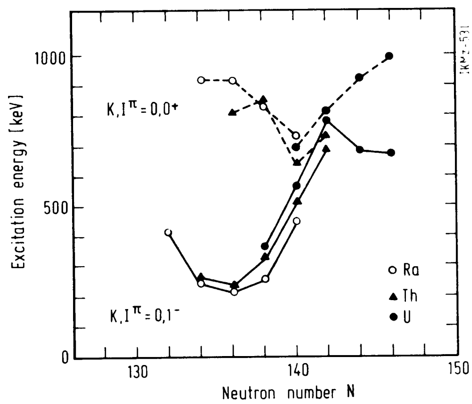

Fig.5 Excitation energies of known $K,J^{\pi}=0,1^-$ (solid lines) and $K,J^{\pi}=0,0^+$ (dashed lines) states in Ra, Th and U nuclei (data are from this work; see also ref.1)).

If the A-parameter of 7.43 keV for the $K^{\pi}=0^-$band (compared to 14.06 keV for the ground-state band) in ^{224}Ra (fig.1) is due to Coriolis interaction with the $K^{\pi}=1^-$ band with its band head at 1052.9 keV, then the experimental coupling matrix element would have an absolute value of 77 $[I\ (I+1)]^{1/2}$ keV. By assuming that the energies of the 1^- levels of the $K^{\pi}=0^-$ and $K^{\pi}=1^-$ bands in ^{226}Ra at 253.7 and 1048.6 keV (fig.2), respectively, are perturbed by this interaction, an experimental coupling matrix element of 61 $[I\ (I+1)]^{1/2}$ keV results. These values can be compared with the theoretical values[14] of $\langle H' \rangle = -69\ [I\ (I+1)]^{1/2}$ keV for ^{224}Ra and $\langle H' \rangle = -55\ [I\ (I+1)]^{1/2}$keV for ^{226}Ra. The calculations were performed under the assumption that the A-parameters for two unperturbed octupole bands are both equal to that of the ground-state band. The experimental coupling matrix elements are in qualitative agreement with the theoretical values. As emphasized in ref.[14], this theoretical estimate is not expected to have a quantitative validity. These data favour the interpretation of the $K^{\pi}=0^+$ ground-state and $K^{\pi}=0^-$ bands in ^{224,226}Ra as being connected with a non-zero ground-state octupole deformation.

In conclusion, a brief summary of the experimental results which support the concept of non-zero ground-state octupole deformation in Ra, Th and U nuclei in the N=136 region is presented:

(i) The energy splitting of of $K^{\pi}=0^{+}$ ground-state and $K^{\pi}=0^{-}$bands is small (the ammonia molecule can be used as simple model).

(ii) The rotational states in the $K^{\pi}=0^{+}$ ground-state and $K^{\pi}=0^{-}$ bands can be described by the same moment-of-inertia parameter A.

(iii) The energy ratios of the excited 0^{+} and 0^{-} states are much higher than 2.0 expected for harmonic two-phonon octupole vibrational states and even higher than the value of 2.7 for an infinite square-well potential.

In addition, it is probable that the very low HF (hindrance factors) of the α-transitions feeding the $K,J^{\pi}=0,1^{-}$ states[1] are connected with this interpretation.

Recently, a stable octupole deformation has been obtained for nuclei in the Ra and Th region in theoretical calculations[15].

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