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MEASUREMENTS OF MULTIPOLARITIES IN ^{225}Ra

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Abstract: Multipolarities of 45 transitions in ^{225}Ra have been established by investigating the radiations associated with the β^- decay of ^{225}Fr . The study includes β^- , e^- and γ -singles spectra, $e^- \gamma$ - and $\gamma\gamma$ -coincidence measurements. The conversion electrons were measured with a mini-orange electron spectrometer, and the γ -spectra with Ge detectors. The multipolarities obtained from the measured conversion coefficients support the assignments of spin parity doublets thus giving evidence for a stable octupole deformation of this nucleus. The negative parity of the 394.2 keV level established in the present work indicates that this level is a candidate for the parity-doublet partner of the $5/2^+$ state at 236.3 keV.

RADIOACTIVITY ^{225}Fr (β^-) [from Th,U (p, spallation)]; measured E_e , $I(\text{ce})$, $\gamma\gamma$ -, $e\gamma$ -coincidences. ^{225}Ra deduced levels, ICC, multipolarities, I^π . UC_2 and ThC_2 targets. On-line mass separation. Ge, Si(Li) detectors, mini-orange spectrometer.

1. Introduction

Searches for reflection-asymmetric shaped nuclei have been of increasing interest during recent years. Both experimental and theoretical evidence has been found for the existence of an extended region of stable octupole deformation around $A=225$. One of the first nuclei studied, whose properties can be explained by assuming stable octupole deformation to be present in the ground state^{1,2)}, is ^{225}Ra .

The utmost importance of establishing the level scheme, including spin-parity assignments as well as the possible band structure in a model-independent way, led to further measurements by several groups using different techniques. Up to now ^{225}Ra is the most thoroughly studied nucleus in this region. Recent studies include the β -decay¹⁾ of ^{225}Fr , the α -decay⁽³⁻⁷⁾ of ^{229}Th as well as the charged particle (d,t) , $(\bar{d},t)$ and (t,α) -reactions^{1,8)}, all contributing to a more model-independent interpretation of the level scheme. The ground state spin has been measured with fast-beam collinear laser spectroscopy⁹⁾. The half-lives of some excited states were determined⁶⁾ finding evidence for enhanced E1 transitions between parity doublets. Parity doublets, i.e. close-lying energy levels which have the same spin, but opposite parity, and which are connected by enhanced E1 transitions, are an important signature of intrinsic reflection-asymmetry in odd-mass nuclei.

In the present study we have measured internal conversion coefficients of transitions in ^{225}Ra following the β^- decay of ^{225}Fr using a mini-orange electron spectrometer and Ge γ -detectors. The establishment of multipolarities for the different transitions narrows the limits of possible spin-parity values of the energy levels, thus providing a safer experimental basis for the interpretation of the level scheme, particularly concerning parity doublets.

2. Experimental procedure

The ^{225}Fr activity, produced by spallation reactions induced by the bombardment of UC_2 and ThC_2 targets with 600 MeV protons from the CERN Synchro-cyclotron, was obtained as a mass separated beam in the ISOLDE-2 isotope separator and deposited on the tape of a tape transport system. This system was operated in a start-stop mode where, after a collection time of 80 s, the activity was transported to the source position of the mini-orange spectrometer and measured for 200 s. Details of the experimental set-up and procedures are given in ref.¹⁰⁾. Singles spectra of conversion electrons and γ -rays as well as event by event recording of $e^-\gamma$ and $\gamma\gamma$ coincidences have been measured. A singles electron spectrum from the decay of ^{225}Fr is shown in fig. 1. The spectrum was recorded during a period of ~ 4 hours. The overall energy resolution was ~ 2.0 keV FWHM. As an example of the resulting $e^-\gamma$ coincidence spectra an electron spectrum gated with the 75.1 keV γ -transition is shown in fig. 2.

3. Internal conversion coefficients

The previously reported level scheme¹⁾ has been confirmed by the $\gamma\gamma$ and γe^- data obtained in the present experiment. The main object for this experiment was, however, the extraction of internal conversion coefficients. These were obtained from the singles electron and gamma spectra where possible, and from coincidence data in cases where the electron groups were not resolved. The coincidence method used is described in ref.¹⁰⁾. The measured conversion coefficients are listed in table 1, together with theoretical values¹¹⁾ for E1, E2 and M1 transitions and the dominant multipolarities assigned to the transitions. Experimental values of the conversion coefficients from ref.⁷⁾ are also included in table 1.

It has not been possible to determine the amount of multipole mixing which certainly is present in several transitions. This is due to insufficient energy resolution in the electron detector, and to poor statistics for weak transitions.

For the 37.8 keV transition it is not possible to distinguish between E2 and M1 multipolarity on the basis of the α_L or α_M value (see table 1). However, the ratios $L_3:\bar{L}M$ are on the average 1.7 ± 1.0 , which

compared to the theoretical¹¹⁾ ratios of 1.8 for E2 and 0.03 for M1 indicates that the dominant multipolarity is E2. Previously this transition was given a tentative E2 assignment by Tretyakov et al.³⁾.

4. The ^{225}Ra level scheme

The ground state spin $I = 1/2$ has been measured with fast-beam collinear laser spectroscopy⁹⁾, and from the angular distributions of cross sections and analysing powers¹⁾ the ground state has been assigned to $I^\pi = 1/2^+$. The $5/2^+$ assignment to the 236.3 keV level is established by favoured α -transition from ^{229}Th which has ground state spin-parity $I^\pi = 5/2^+$ (ref.¹⁴⁾). The E2 multipolarity of the 236.4 keV transition (236.3, $5/2^+ \rightarrow \text{g.s.}$) is furthermore confirmed by Helmer et al.⁷⁾ using the K-line intensities of Tretyakov³⁾ and the γ -ray intensities from their work. The spins and parities of all other levels discussed in the present work have been established relative to the 236.3 keV, $5/2^+$ and the ground state, $1/2^+$ levels.

The level scheme shown in fig. 3 is consistent with the level scheme reported by Nybø et al.¹⁾. Only the gamma transitions for which multipolarities were obtained in this work are shown. The properties of the levels are summarised in table 2, where the column labelled "model-independent level interpretation" shows the restrictions which are placed on the spin-parity values, using all available information.

Both Shelton et al.²⁾ and Helmer et al.⁷⁾ have assigned the 69 keV level as the $7/2^-$ member of the $K^\pi = 1/2^-$ band which starts with its $3/2^-$ member at 31 keV. The 69.4 keV level decays by an E1 transition to the 25.4 keV level ($5/2^+$), thereby limiting the spin of the 69.4 keV level to $3/2, 5/2, 7/2$ with negative parity. This is consistent with the E2-multipolarity assigned to the 37.8 keV transition between the 69.4 keV level and the $3/2^-$ state at 31.6 keV.

An important result from the present work is that the 394 keV level is found to have negative parity. This result comes from the determination of the multipolarity of the 169.0 keV transition ($394.2 \rightarrow 225.1, 3/2^-$) which is unambiguously found to be M1 from several $e^- \gamma$ -coincidences.

The reported⁷⁾ M1 multipolarity of the 158 keV transition ($394.2 \rightarrow$

236.3, $5/2^+$) is in contradiction with the results of the present work. With the present statistics a M1 multipolarity for the 158 keV transition would produce a significant peak in the $e^- \gamma$ -coincidence spectra, but no such group has been observed. From the upper limit for the unobserved peak in the electron spectrum, and the observed negative parity of the 394.2 keV level it is concluded that the 158 keV transition has E1 multipolarity. The 394.2 keV level consequently has spin-parity assignment $3/2^-$ or $5/2^-$. The possibility then arises that the 394.2 keV level and the $5/2^+$ level at 236.3 keV form a parity-doublet as suggested by Helmer et al.⁷⁾. The $7/2$ members of the $K^\pi = 5/2^+$ and the proposed $K^\pi = 5/2^-$ bands are not populated directly by β -decay from ^{225}Fr , which has^{12,13)} a $3/2^-$ ground state.

From the measured multipolarities of several transitions depopulating the 478.4 keV level, the spin-parity of this level is found to be $I^\pi = 3/2^+$.

The 724.1 keV level is the highest lying level for which it has been possible to comment on spin and parity. It is found to have negative parity and a possible spin value $1/2$, $3/2$ or $5/2$.

5. Log ft-values

The continuous β -spectrum from the decay of ^{225}Fr was measured in the mini-orange spectrometer simultaneously with the conversion electrons. Since the silicon detector (3 mm thick) in the mini-orange spectrometer stops electrons up to energies of only about 1530 keV, and the β -decay Q-value to the ground state of ^{225}Ra is¹⁵⁾ 1852 ± 90 keV, the high energy part of the β -spectrum was not measured. However, the Kurie-plot constructed has a long straight-line segment corresponding to a β -group with an end-point energy of about 1600 keV, which indicates that the main β -feeding goes to levels at excitation energies of about 150 to 350 keV.

The intensity balance for the 225.1 keV level, calculated using the γ -intensities from Table 2 of ref.¹⁾ and theoretical conversion coefficients¹¹⁾ showed that 96 % of the population of this level comes from β -feeding. This is the strongest of the β -groups, and its log ft-value was obtained in the following manner. The β -spectrum was reconstructed by extrapolating the Kurie plot up to 1600 keV. The

total β -intensity obtained in this way was compared with that of the L-conversion electrons for the 169.9 keV transition in the same spectrum. Since the 169.9 keV transition depopulates the 225.1 keV level, this information could be used to find that 24 % of the β -intensity feeds this level. Using the half-life¹⁾ of ^{225}Fr , $T_{1/2}$ 4.0 $\pm$ 0.2 min., the partial half-life for β -decay to the 225.1 keV level is 16.7 $\pm$ 1.6 min., corresponding to a log ft value of 6.2 $\pm$ 0.1. The β -intensities of the levels from 120.3 keV to 724.1 keV were then calculated relative to that of the 225.1 keV level from the intensity balance in the level scheme. The log ft values obtained are given in Table 3. The uncertainties listed in Table 3 have been increased by 0.2 in the positive direction to reflect the largest possible intensity which could have been present but not observed for β -groups with higher end-point energies feeding the ground state or low-lying levels.

The log ft-values range from 6.2 to 7.7, and are thus in the regions of allowed transitions ($\Delta I = \Delta K = 0$ or 1; no) and first-forbidden transitions ($\Delta I = \Delta K = 0$ or 1; yes).

The lowest log ft-value measured is for the transition to the 225.1 keV level, $\log ft = 6.2 \pm \begin{smallmatrix} 0.3 \\ 0.1 \end{smallmatrix}$. If this level is predominantly $3/2^-$ [761], which is the most likely negative-parity $K = 3/2$ orbital in the Nilsson model, and the ^{225}Fr ground state is $3/2^-$ [532] as recently suggested¹⁶⁾, the β -transition would have $\Delta N = 2$. Such violation of the selection rule in the principal quantum number N is usually connected with log ft-values higher than 7, and thus the relatively low log ft-value of 6.2 might possibly favour a different assignment for the ^{225}Fr ground state. Another possible explanation is that if octupole deformation existed, the Nilsson orbitals indicated above might be merely dominant components in more complicated configurations, and thus the selection rules would no longer be appropriate.

In the event of permanent octupole deformation the log ft-values are expected to have the same value for members of a spin parity doublet. This is also the case, within error limits, for the proposed $K^\pi = 3/2^\pm$ bands. In the case of $K^\pi = 5/2^\pm$ the log ft-values differ by 10% which is outside the error limits, and thus might indicate soft octupole deformation.

A definite conclusion about the nature of the octupole deformation cannot be drawn from these observations, however.

6. Summary

Multipolarities for 45 transitions were determined in the present work. The measured multipolarities confirm the assignments for the levels previously made in ref. ¹⁾, and are consistent with the suggested ²⁾ $K^\pi = 1/2^\pm$ and $K^\pi = 3/2^\pm$ parity doublets. (See fig. 3).

The present assignment $3/2^-$, $5/2^-$ made for the 394.2 keV level, together with the α -hindrance factor (≈ 23) observed in ref. ⁷⁾, constitute plausible evidence that the 394.2 keV level is the missing $K^\pi = 5/2^-$ parity doublet state which has as its other member the $K^\pi = 5/2^+$ state at 236.3 keV. This observation gives further evidence for the presence of a reflection-asymmetric shape for ²²⁵Ra.

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Figure captions

Fig. 1. Electron spectrum from the decay of ^{225}Fr . Peaks are labelled with internal conversion lines which contribute to their intensities.

Fig. 2. Electron spectrum in coincidence with the 75.1 keV γ -transition.

Fig. 3. Partial level scheme for ^{225}Ra . Only transitions for which multipolarities have been determined in this work are shown. The dashed energy levels were observed only in particle transfer studies¹⁾. In the right part of the figure

three sets of coupled bands having negative and positive parity components are shown, each of which may be treated as a band. They are labeled only as $K^\pi = 1/2^\pm$, $K^\pi = 3/2^\pm$ and $K = 5/2^\pm$ because the usual Nilsson assignments are invalidated by the octupole deformation. At the right hand side of the figure the model independent spin parity assignments are given (see table 2).

TABLE 1

Internal conversion coefficients for ^{225}Ra transitions

Transition energy (keV)	Parent level ^{a)} (keV)	Conversion shell	Previous ⁷⁾	Internal conversion coefficients					Dominant multi-polarity
				Experiment	Theoretical ¹¹⁾				
					E1	E2	M1		
31.7	31.6	ΣM		< 0.6	0.45	400	18	E1	
37.8	69.4	L_2 ΣM		b)	0.50	360	0.27	E2	
				58 ± 22 34 ± 24	0.30	200	10		
42.8	42.8	ΣL		13.3 ± 3.1	0.72	320	28	M1	
44.0	69.4	ΣL		0.60 ± 0.12	0.80	300	27	E1	
45.2	225.2	ΣL		2.0 ± 0.5	0.70	300	24	E1	
50.8	120.3	ΣL		7.3 ± 1.8	0.50	120	18	M1	
55.1	55.2	ΣL		< 1.9	0.40	95	13	E1	
56.3	236.3	ΣL	21 ± 3 ¹⁾	9.6 ± 2.7	0.33	120	12	M1	
75.1	225.1	ΣL ΣM		0.12 ± 0.03	0.16	24	5.5	E1	
				0.02 ± 0.01	0.04	6.0	1.2		
77.5	120.3	ΣL		< 0.3	0.16	22	5.2	E1	
80.3	260.2	ΣL		< 0.9	0.14	20	5.0	E1	
86.7	236.3	ΣL ΣM		b)	0.11	14	3.6	M1	
				5.0 ± 1.9 1.2 ± 0.2	0.029	3.9	0.8		
95.0	120.3	ΣL		< 0.12	0.09	8.8	3.0	E1	
95.0	149.9	ΣL		< 0.04	0.09	8.8	3.0	E1	
107.1	149.9	ΣL ΣM	0.76 ± 0.08 ¹⁾	b)	0.08	6.0	2.0	M1	
				0.71 ± 0.20 0.37 ± 0.07	0.017	1.2	0.42		

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Internal conversion coefficients for ^{225}Ra transitions

Transition energy (keV)	Parent level ^{a)} (keV)	Conversion shell	Previous ⁷⁾	Internal conversion coefficients				Dominant multi-polarity
				Experiment	Theoretical ¹¹⁾			
					E1	E2	M1	
110.3	260.2	ΣL		0.07 ± 0.04 b)	0.065	4.0	1.9	E1
124.5	149.9	K ΣL	0.93 ± 0.09 ¹⁾	7.3 ± 1.5 1.3 ± 0.4	0.26 0.046	0.32 2.3	7.0 1.3	M1
137.0	179.9	K ΣL	5.1 ± 0.5 1.0 ± 0.1	1.6 ± 0.3 b) 1.0 ± 0.1	0.17 0.036	0.30 1.6	5.6 1.0	M1
139.8	260.2	K ΣL ΣM		3.3 ± 0.3 b) 1.7 ± 0.3 b) < 0.4	0.17 0.035 0.007	0.28 1.5 0.3	5.0 1.0 0.2	M1
148.4	179.9	K ΣL	~0.02	< 0.2 < 1.0 a)	0.15 0.03	0.27 1.1	4.4 0.28	E1
149.9	149.9	K	≥0.62	9.6 ± 1.4	0.15	0.26	4.0	M1
154.4	179.9	K	3.6 ± 0.4	7.6 ± 1.5 b)	0.13	0.24	3.8	M1
157.9	394.2	K	4.3 ± 2.1	< 0.6 a)	0.12	0.23	3.3	E1
169.0	394.2	K ΣL		2.8 ± 0.7 b) 0.4 ± 0.1 b)	0.11 0.02	0.20 0.65	3.0 0.46	M1
169.9	225.1	K ΣL ΣM		2.3 ± 0.8 b) 0.46 ± 0.05 0.16 ± 0.02	0.11 0.018 0.005	0.20 0.42 0.13	3.0 0.54 0.12	M1
179.9	179.9	K		0.32 ± 0.11	0.09	0.19	2.2	E2
182.3	225.1	K ΣL		0.062± 0.008 0.0089±0.0011	0.09 0.018	0.19 0.46	2.4 0.43	E1
190.8	260.2	K ΣL ΣM		3.1 ± 0.3 b) 0.56 ± 0.10 a) < 0.096	0.08 0.015 0.0036	0.18 0.36 0.07	2.0 0.39 0.072	M1

TABLE 1
Internal conversion coefficients for ^{225}Ra transitions

Transition energy (keV)	Parent level ^{a)} (keV)	Conversion shell	Previous ⁷⁾	Internal conversion coefficients				Dominant multi-polarity
				Experiment	Theoretical ¹¹⁾			
					E1	E2	M1	
193.5	225.1	K ΣL ΣM		1.6 ± 0.2 0.36 ± 0.02 0.08 ± 0.01	0.08 0.015 0.032	0.17 0.40 0.080	1.95 0.35 0.080	M1
193.5	236.1	K	2.0 ± 0.2	2.9 ± 1.0	0.08	0.17	1.95	M1
199.7	225.1	K ΣL ΣM		0.041± 0.005 0.016± 0.002 ^{c)} < 0.06	0.070 0.014 0.0032	0.16 0.32 0.070	1.8 0.35 0.070	E1
204.9	236.3	K		0.10 ± 0.06 ^{b)}	0.07	0.15	1.6	E1
210.9	236.3	K ΣL	2.0 ± 0.2 0.38 ± 0.04	1.0 ± 0.3 0.25 ± 0.05	0.06 0.012	0.16 0.30	1.60 0.30	M1
217.5	260.2	K ΣL		< 0.3 ^{c)} < 0.03 ^{c)}	0.068 0.011	0.14 0.32	1.6 0.28	E1
225.1	225.1	K ΣL ΣM		< 0.06 ^{b)} < 0.02 ^{c)} < 0.004 ^{c)}	0.052 0.01 0.0023	0.13 0.20 0.052	1.3 0.23 0.040	E1
228.6	260.2	K ΣL		0.90 ± 0.05 0.17 ± 0.02	0.050 0.020	0.12 0.19	1.2 0.23	M1
234.8	260.2	K		< 0.06 ^{b)}	0.05	0.12	1.12	E1
242.1	478.4	K		1.3 ± 0.2	0.05	0.11	1.1	M1
328.6	478.4	K		0.74 ± 0.12	0.022	0.05	0.50	M1
435.6	478.4	K ΣL		0.16 ± 0.03 0.046± 0.015	0.013 [*] 0.002	0.033 0.015	0.24 0.042	M1

TABLE 1
Internal conversion coefficients for ^{225}Ra transitions

Transition energy (keV)	Parent level ^{a)} (keV)	Conversion shell	Previous ⁷⁾	Internal conversion coefficients					Dominant multi-polarity
				Experiment	Theoretical ¹¹⁾				
					E1	E2	M1		
453.0	478.4	K		0.29 ± 0.06	0.020	0.032	0.22	M1	
464.1	724.1	K		0.13 ± 0.06	0.012	0.028	0.21	M1	
478.3	478.4	K		0.13 ± 0.03	0.010	0.027	0.18	M1	
		ΣL	0.04 ± 0.01	0.0019	0.011	0.032			
499.0	724.1	K		0.11 ± 0.01	0.009	0.025	0.16	M1	
		ΣL	0.03 ± 0.01	0.0016	0.01	0.028			
574.1	724.1	K		< 0.06 ^{a)}	0.007	0.20	0.12	E1	

¹⁾ L_1

- a) Value obtained from the upper limit for the intensity of the unobserved peak in the electron spectrum.
- b) Value from coincidence measurements.
- c) This upper limit was obtained by assuming that the total intensity in the unresolved multiplet in the electron spectrum was due to this transition.

TABLE 2
LEVELS IN ^{225}Ra

Level energy (keV)	Model independent level interpretation I^π
0	$1/2^+$, $j=1+1/2^a)$
25.4	$5/2^+$, $(j=1+1/2)^a)$
31.6	$3/2^-$
42.8	$3/2^+$, $j=1-1/2^a)$
55.2	$1/2^-$, $3/2^-$
69.4	$3/2^-$, $5/2^-$, $7/2^-$
101	$1/2^+$, $3/2^+$, $1/2^-$, $(j=1\pm 1/2)^a)$
120.3	$3/2^-$, $5/2^-$
149.9	$3/2^+$, $(j=1-1/2)^a)$
179.9	$3/2^+$, $5/2^+$
225.1	$3/2^-$
236.3	$5/2^+$
244	$7/2^+$, $j=1-1/2^a)$
260.2	$3/2^-$, $5/2^-$
270	$7/2^+$, $j=1-1/2^a)$
321	$9/2^+$, $j=1+1/2^a)$
394.2	$3/2^-$, $5/2^-$
478.4	$3/2^+$
724.1	$1/2^-$, $3/2^-$, $5/2^-$

a) The j -value has been determined from the signs of the $(\bar{d}, t)$ analysing powers.

TABLE 3
Log ft-values for the beta-decay of ^{225}Fr

Level keV	Log ft
724.1	7.3 +0.3 -0.1
478.4	7.1 +0.3 -0.1
394.2	7.3 +0.3 -0.1
260.2	6.4 +0.3 -0.1
236.3	6.7 +0.3 -0.1
225.1	6.2 +0.3 -0.1
179.9	6.8 +0.3 -0.1
149.9	6.6 +0.3 -0.1
120.3	7.7 +0.3 -0.1

Fig. 1

Fig. 2

Fig. 3.