**MEASUREMENTS OF MULTIPOLARITIES IN ^{227}Ra AS
TESTS OF EVIDENCE FOR STABLE OCTUPOLE DEFORMATION**

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ABSTRACT

Multipolarities of ~ 30 transitions in ^{227}Ra have been established by measuring conversion electrons following the β^- decay of ^{227}Fr . For this purpose a 'mini-orange'-type electron spectrometer has been constructed. The ^{227}Fr isotopes were produced by the ISOLDE on-line separator at the CERN Synchro-cyclotron. Internal conversion coefficients were obtained from singles spectra and also from simultaneous γ - e^- and γ - γ coincidence measurements. The new results support the placement of levels and transitions in the earlier level scheme but require changes in the previously assigned parities for four of the levels. Also, one E0 transition was identified. The results are consistent with previous interpretations for most of the levels that have been used to argue in favour of a small permanent octupole deformation for ^{227}Ra .

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RADIOACTIVITY $^{227}\text{Fr}(\beta^-)$ [from U(p, spallation)]; measured E_e , I_e , $\gamma\gamma$ -, $e\gamma$ -coinc. ^{227}Ra deduced levels, ICC, multipolarities. Uranium carbide target. On-line mass separation. Ge, Si(Li) detectors, 'mini-orange' spectrometer.

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1. INTRODUCTION

There has recently been a great deal of interest in the possibility that stable reflection-asymmetric shapes may exist for nuclei in the actinide region near $A \sim 225$. The available experimental evidence indicates¹⁻⁶⁾ a strong probability that such shapes exist in $^{223,225,227}\text{Ra}$, but the level schemes for most odd- A nuclides in this region are not well established. In many cases the assignments of spins, parities, and other quantum numbers to the levels have been made on the basis of systematics in neighbouring nuclides, or by arguments which are strongly model-dependent. Therefore it is important to test the experimental foundation on which the claims for observed octupole deformations are based. One expected feature of an octupole-deformed nucleus is that it should have parity-doublers^{4,7)}, i.e. close-lying bands with the same K -value but opposite parity, and there should be enhanced $E1$ and $E3$ transitions connecting these bands. It is therefore important to establish the parities of levels and the multipolarities of transitions in nuclides of the $A \sim 225$ region.

For this purpose, a mini-orange-type electron spectrometer has been constructed and used to study conversion electrons and γ - e^- coincidences following the β -decays of neutron-rich francium and radon isotopes. The present report describes briefly the spectrometer system, and presents results obtained for the structure of ^{227}Ra .

In an earlier work⁸⁾ on ^{227}Ra , (n,γ) , (d,p) , and (t,d) , measurements were combined with a study of γ - γ coincidences following the β^- decay of ^{227}Fr . A level scheme was constructed but it was not possible to establish spins and parities uniquely in a model-independent manner. Therefore, tentative assignments of I^π values and of levels to rotational bands were proposed, but these were made more on the basis of model expectations than on experimental data. Because these tentative assignments have since been cited⁴⁾ as experimental evidence supporting the existence of a stable octupole deformation, it is important to make additional tests of their accuracy. The internal conversion coefficients measured in the present work, combined with the recently measured ground-state spins^{5,9,10)} for ^{227}Ra and ^{227}Fr , provide much support for the previous tentative assignments, but also require some changes to be made.

2. EXPERIMENTAL DETAILS AND RESULTS

Francium isotopes were produced in a UC_2 target by spallation reactions induced by 600 MeV protons from the CERN Synchro-cyclotron. The ^{227}Fr activity was isolated as a mass-separated beam from the ISOLDE on-line isotope separator¹¹⁾ and deposited on the aluminium-coated Mylar tape of a tape transport system. This system was operated in a start-stop mode to collect the ^{227}Fr activity for a period of 50 s and then transport it to the source position of the mini-orange electron spectrometer for a 200 s counting period. The physical arrangement of the apparatus is shown in Fig. 1. The detector in the electron spectrometer was a 300 mm^2 $\text{Si}(\text{Li})$ crystal with a thickness of 2 mm, cooled to liquid-nitrogen temperature by means of a copper cold finger. An absorber block placed between the source and detector shields the latter from direct X-rays and γ -rays. A set of permanent magnets positioned around the spectrometer axis deflect electrons from the source to the detector with efficiencies depending on the electron energy and the magnet configuration. The vacuum chamber of the electron spectrometer had a thin Kapton window to minimize absorption of low-energy photons which were detected by gamma counters placed as shown in Fig. 1.

Several different magnet types were tested. The efficiencies at various energies for each type and configuration were determined by placing radioactive samples at the source position and recording conversion electron spectra in the normal mode, and also with the magnets and absorber block

removed. Ratios of count rates in corresponding peaks of these spectra were combined with the known geometrical solid angle of the detector when used without magnets to determine the efficiency of the system. For the measurements without magnets the electrons approach the detector at or near normal incidence, and the probability of an electron producing a count in the full energy peak was estimated from the results of Damkjaer¹²⁾. This probability is typically about 85%, and varies by only a few percent over the energy range used in the present experiments.

The first magnets used were carefully shaped according to the design of van Klinken and Wisshak¹³⁾. Although a relatively high efficiency of $\sim 1.8\%$ of 4π was obtained over a fairly small energy range, the set finally chosen for general survey studies had a lower, but more uniform, efficiency ($\sim 0.5\%$) over a broad range of energies. This set consisted of three equally spaced flat rectangular magnets $5\text{ cm} \times 2\text{ cm} \times 0.5\text{ cm}$, with the long dimension oriented radially. Measurements with different magnet and detector positions showed that the optimum situation was with the detector a distance of $\sim 15\text{ cm}$ from the source and with the magnets located approximately midway between the source and detector. The measured efficiency as a function of energy for these conditions is shown in Fig. 2.

A singles electron spectrum from ^{227}Fr recorded during a period of ~ 6 hours is shown in Fig. 3. The overall energy resolution was $\sim 2.0\text{ keV}$ full width at half-maximum (FWHM). Energy calibration was established using known lines¹⁴⁾ from ^{152}Eu and ^{207}Bi sources.

Two high-purity Ge photon detectors were also placed near the source position of the spectrometer, as shown in Fig. 1, permitting γ - e^- and γ - γ coincidences to be recorded simultaneously. These detectors had active volumes of 68 cm^3 and 88 cm^3 , and typical resolutions (FWHM) of 0.8 keV at 122 keV and 1.8 keV at 1.3 MeV . The smaller detector had a thin entrance window to minimize absorption of low-energy photons. Energy and efficiency calibrations for these detectors were performed with ^{133}Ba , ^{152}Eu , ^{207}Bi , and ^{241}Am sources, and also with a commercially obtained, absolutely-calibrated reference source of different radionuclides. Coincident events between any pair of the three detectors were selected by standard hardware circuitry, with the information from the time-to-amplitude and analog-to-digital converters being stored on magnetic tape in event-recorded mode. During a data-collection time of ~ 17 hours, approximately 0.8×10^6 photon-electron coincidences and 1.3×10^6 photon-photon coincidences were obtained. The taped information was sorted to extract spectra in coincidence with windows set on specific peaks and with similar windows on the neighbouring continuum. The electron spectrum in coincidence with the 90 keV γ -ray is shown in Fig. 4.

3. INTERNAL CONVERSION COEFFICIENTS

An examination of all the γ - γ and γ - e^- data from the present study confirms the placement of transitions shown in the previously reported level scheme⁸⁾. However, in the present measurements important new information in the form of conversion coefficients was obtained. These were extracted from the singles electron spectra in many cases, but for some lines which were not resolved in the singles spectra the coincidence results were used.

In practice, the procedure used to extract conversion coefficients from the singles data was to obtain first a value for the K-line of the 585.8 keV transition and then determine other values relative to this one, using electron intensities from the spectrum of Fig. 3 and relative gamma-ray intensities from the work of von Egidy et al.⁸⁾. The average value α_K for the 585.8 keV line, averaged from measurements taken on two separate occasions, is 0.095 ± 0.010 . This is consistent with the theoretical value¹⁵⁾ of 0.10 for a pure M1 transition, but a small E2 admixture may also be present.

The conversion coefficients obtained are listed in Table 1, where theoretical values for E1, E2, and M1 transitions are also shown. The dominant multiplicities as determined from the conversion coefficients are listed in column 8. It is noted that there are many cases where lines in the electron spectrum were not resolved, but for which it was possible to establish upper limits on the conversion coefficients, using the total intensity of the unresolved multiplet. For several important cases these upper limits have served to establish E1 character for the transitions.

Several of the conversion coefficients in Table 1 are designated as being obtained from coincidence data. These are cases for which the line was not resolved in the singles electron spectrum. Although a number of different approaches exist for using the coincidence results, one of the simplest is as follows. If transitions 1 and 2 are in cascade, and can be observed by gamma detectors A and B and electron detector E, it can easily be shown that the conversion coefficient for transition 1 is

$$\alpha_1 = [N(E_1 A_2)/N(B_1 A_2)] [\epsilon(B_1)/\epsilon(E_1)] ,$$

where $N(E_1 A_2)$ is the rate for electrons from transition 1 in coincidence with gammas in detector A for transition 2. Also $\epsilon(B_1)$ is the efficiency of detector B for transition 1, and so on. This result is independent of other modes of feeding or branching of any of the levels but has ignored possible angular correlation effects. However, since the electron spectrometer averages over a fairly large range of angles, relative to each gamma detector, it is estimated that angular correlations should not affect the conversion coefficients obtained in this work by more than $\sim 15\%$. This method was checked by using it for lines which were resolved in the singles spectrum and comparing the conversion coefficients obtained in the two different manners. Although the agreement was within 15% for some of the strongest lines there were also several cases for which the values from the coincidence method were smaller than those from singles by factors as large as 1.5. However, even with this large an uncertainty the results obtained can be very useful in determining multiplicities.

One interesting observation is that the 379.2 keV transition linking the 675.9 and 296.6 keV levels has a value of α_K that is much larger than expected for an E1, E2, E3, or M1 transition. Since it competes with several E1 and M1 transitions in the decay of the 675.9 keV level, a higher-order multipolarity is unlikely. Therefore the 379.2 keV transition is assumed to have an E0 component. The high value of α_K for this line is also confirmed by coincidence data with the 175.9 keV line.

4. THE ^{227}Ra LEVEL SCHEME

The present results are consistent with the placement of levels and transitions reported by von Egidy et al.,⁸⁾ and therefore the level scheme shown in Fig. 5 is based on the one established in that work. The main difference is that Fig. 5 shows only the gamma transitions for which multiplicities were obtained in the present study. The properties of the levels are summarized in Table 2. The column labelled 'Model-independent' interpretation shows the restrictions that can be placed on the I^π values using all the available data. The ground-state spin $I = 3/2$ has been measured with fast-beam collinear laser spectroscopy^{5,9)}. Several levels are known to have $I = 1/2$ or $3/2$ because they are populated by primary transitions in the (n,γ) process⁸⁾. For some others the signs of the $(\vec{t},d)$ analysing powers⁸⁾ were sufficiently distinctive to establish whether the j-value for the neutron transfer was $\ell + 1/2$ or $\ell - 1/2$.

The log ft values in the beta decay of ^{227}Ra provide arguments¹⁶⁾ that the ground-state neutron of ^{227}Ra is in the $3/2^+ [651]$ orbital and thus has positive parity. This model-dependent parity value

has been adopted for the ground state. The parities given in Table 2 for the other levels have been established relative to this ground state value from the multipolarities of the present work. The parities for the levels at 384.3 keV, 438.8 keV, 475.0 keV, and 731.6 keV differ from those proposed by von Egidy et al.⁸⁾

The first two of these levels decay by M1 transitions to the ground state or other low-lying positive-parity levels and therefore must have positive parity. The 178.5 keV and 449.3 keV transitions which depopulate the 475.0 keV level have E1 character and M1 character, respectively, which contradict the assignment⁸⁾ of negative parity for this level. The conversion electron data are also more readily explained if the 475.0 keV ground-state transition is M1, again consistent with positive parity.

The 731.6 keV level decays to the 384.4 keV state by a 347.2 keV transition which is M1. Therefore, the 731.6 keV level has positive parity and cannot be a rotational member based on the 675.9 keV state as assigned by von Egidy et al.⁸⁾. These changes do not affect any of the levels used in the arguments⁴⁾ for a stable octupole deformation for ²²⁷Ra.

In addition to the level information established above, two model-dependent assumptions were made by von Egidy et al.⁸⁾ in order to arrive at tentative spins and parities for the levels. The first is that the low log ft value of ~ 5.5 for the beta decay to the 675.9 keV level of ²²⁷Ra can be attributed to a $1/2^+ [400]$ single-proton ground state of ²²⁷Fr decaying to a $1/2^- [501]$ single-neutron configuration. The second is that the levels at 25.8 keV and 64.1 keV can be assigned on the basis of the $I(I+1)$ rule to be spin $5/2$ and $7/2$ members of a $K = 3/2$ ground-state band. In addition, the 1.7 keV and 84 keV levels were assigned as the $5/2$ and $9/2$ members of the $5/2^+ [633]$ band by analogy with levels in the isotone ²²⁹Th.

The first of these assumptions has received support from recent laser spectroscopy measurements¹⁰⁾ which have found the ground-state spin of ²²⁷Fr to be $1/2$ and the magnetic moment to be $+1.50 \pm 0.03$ nm. The only $K = 1/2$ Nilsson states expected in this region are the $1/2^+ [400]$, $1/2^+ [660]$, and $1/2^- [530]$ orbitals. It is unlikely that the pure $1/2^+ [660]$ orbital forms the ²²⁷Fr ground state because it has a large theoretical decoupling parameter, $a \sim 6.7$, and the $5/2$ or $9/2$ member of the band would have the lowest energy. This is indeed found to be the case in other nuclides in which this band is observed. The magnetic moment for the bandhead is calculated to be 2.5 nm using the wavefunctions of Chi¹⁷⁾ with $g_s = g_s^{\text{free}}$, or 2.1 nm with $g_s = 0.6g_s^{\text{free}}$.

The $1/2^- [530]$ orbital is also an unlikely candidate for the ²²⁷Fr ground state because the calculated magnetic moment for the $I = 1/2$ bandhead is -1.1 nm for $g_s = g_s^{\text{free}}$, or -0.7 nm for $g_s = 0.6g_s^{\text{free}}$. Furthermore, the negative decoupling parameter, $a \sim -3$, would cause the $I = 3/2$ member to have the lowest energy, as is observed^{18,19)} for this orbital in the ground-state bands of ²³¹Pa and ²³³Pa.

The $1/2^+ [400]$ orbital is a likely candidate for the ground state of ²²⁷Fr. It has a theoretical magnetic moment of $+1.5$ nm with $g_s = g_s^{\text{free}}$ or $+0.94$ nm with $g_s = 0.6g_s^{\text{free}}$, in agreement with the measured value. It is found from (t, α) experiments²⁰⁾ that the $1/2^+ [400]$ orbital occurs at low excitation energies in this mass region, and that it forms the ground states of ²³¹Ac and ²³⁷Pa. Of course it is unlikely that the observed levels can be represented by pure Nilsson states because $\Delta N = 2$ and Coriolis effects would cause mixing among the positive-parity bands, and possible octupole deformations would mix states of opposite parities. Calculations of Nazarewicz²¹⁾ suggest that the most likely configuration for the ²²⁷Fr ground state is a mixture of the $1/2^+ [660]$ and $1/2^+ [400]$ orbitals, with the former component dominant. This calculated configuration has a

decoupling parameter small enough for the $I = 1/2$ member to have the lowest energy, and a magnetic moment of 1.78 nm, near to the experimental value. Therefore the available experimental data can be explained by the ^{227}Fr ground state being either a $1/2^+ [400]$ proton, or a mixed configuration as predicted by Nazarewicz, both with $\epsilon_3 \sim 0$.

This supports the interpretation of von Egidy et al.⁸⁾, which attributed the low log ft value to a transition between the $1/2^+ [400]$ and $1/2^- [501]$ states. The tentative $1/2^- [501]$ assignment⁸⁾ for the 675.9 keV level in ^{227}Ra is therefore reasonable, but cannot yet be considered as firmly established. In neighbouring actinide nuclei, log ft values as low as 5.5 are found between states that do not have such good overlap in the asymptotic quantum numbers as those considered above, and also for $\Delta I = 1$, $\Delta\pi = \text{no transitions}$. Therefore, although the available evidence favours the $1/2^- [501]$ assignment for the 675.9 keV level in ^{227}Ra , it would be desirable to have this spin value confirmed in a model-independent manner. The 731.6 keV level, which was suggested earlier⁸⁾ as the $3/2^-$ member of this rotational band, is shown by the present measurements to have positive parity.

The acceptance of the $1/2^- [501]$ assignment for the 675.9 keV level of ^{227}Ra leads to an unambiguous $1/2^-$ assignment for the 296.6 keV level owing to the E0 component in the 379.2 keV transition. For other connected levels, similar unambiguous assignments cannot be made. The last column of Table 2 shows the model-dependent assignments one obtains by accepting the value of $I^\pi = 1/2^-$ for the 675.9 keV level, as well as the 'reasonable' $3/2^- [761]$ and $1/2^+ [631]$ tentative assignments. The value of $I^\pi = 9/2^+$ for the 84 keV level which is strongly populated in the $(\bar{t}, d)$ reaction⁸⁾ is supported by the measured angular distributions of cross-sections and analysing powers. It is, however, not connected to any other levels by transitions observed in the present study. With these arguments the suggested I^π values given in Table 2 for the levels are obtained.

Next, it is necessary to consider the assumption of von Egidy et al.⁸⁾ that the 25.8 keV and 64.1 keV levels are the spin $5/2$ and $7/2$ members of the $K = 3/2$ ground-state rotational band. If this were so, the $9/2$ and $11/2$ members would be expected at energies near 112 keV and 170 keV, respectively, on the basis of the $I(I+1)$ rule. These two members are important because the positive-parity neutron Nilsson orbitals in this region originate from $g_{9/2}$ and $i_{11/2}$ shell model states, and therefore most of the spectroscopic strength for single-neutron transfer reactions to positive-parity bands is for the spin $9/2$ and $11/2$ members. The wave functions calculated by Chasman²²⁾ show that this remains true even in the presence of an octupole deformation. In single-neutron transfer studies²³⁻²⁶⁾ of neighbouring deformed actinide nuclei the $3/2^+ [631]$ band is always found to have a strongly populated $I = 9/2$ member. [The spin $11/2$ member is more difficult to observe experimentally with (d, p) , (d, t) , and (t, d) reactions because the $\ell = 6$ transfer has small cross-sections]. Thus, the absence of a strongly populated $9/2^+$ level near 112 keV in the $^{226}\text{Ra}(\bar{t}, d)$ or $^{226}\text{Ra}(d, p)$ reactions poses problems for the assignment of a well-behaved rotational band based on a $3/2^+ [631]$ ground state.

Since a strongly populated level at 84 keV has been assigned⁸⁾ as the $9/2^+$ member of the $5/2^+ [633]$ band, one might suggest that Coriolis mixing could have transferred much of the $IK^\pi[Nn_2\Lambda] = 9/2^+ 3/2^+ [631]$ strength to this level. However, this also implies mixing of other band members as well, and distortion of the $I(I+1)$ spacing. This could therefore destroy the basis on which the $5/2$ and $7/2$ assignments of the 25.8 and 64.1 keV levels were made.

Although the strength calculated by von Egidy et al.⁸⁾ for the $9/2^+ 3/2^+ [631]$ state is relatively small, examination shows that this is because the Nilsson calculation of that work used a value of $\mu = 0.30$, which causes the $3/2^+ [631]$ orbital to be mostly $i_{11/2}$ in nature. This parametrization is

therefore not consistent with the experimental results in neighbouring nuclei²³⁻²⁶, which show large $9/2^+$ strengths for this orbital. In general, the (d,p) strengths in ^{227}Ra are not in very good agreement with the model predictions⁸, but there are no obvious simple parameter changes which can reconcile all the differences. One should therefore regard the tentative Nilsson assignments with some caution.

As mentioned above, the 1.7 keV and 84 keV levels were assigned⁸ to the $5/2^+$ [633] band on the basis of analogy with ^{229}Th . Although at first sight the low-lying positive-parity level structure of ^{227}Ra appears similar to that of the isotone ^{229}Th , there are significant differences in the single-neutron transfer strengths. In ^{229}Th the proposed $9/2^{5/2^+}$ [633] level at 97 keV is not reported as being populated in the (d,t) reaction, whereas the $9/2^{3/2^+}$ [631] level at 125 keV is²⁶. The lowest $9/2^+$ level is therefore presumably weakly populated, contrary to the situation in ^{227}Ra , where the lowest $9/2^+$ level at 84 keV is responsible for the largest peak in the (d,p) and (t,d) spectra. This difference cannot be ascribed to the natures of the reaction processes, because pairing and Coriolis mixing effects are known to make the (d,p) populations of the lowest bands in odd-neutron nuclei similar to the (d,t) ones. This suggests that the structures in ^{227}Ra differ from those in ^{229}Th , and therefore it is unsafe to make assignments in ^{227}Ra on the basis of analogy with its ^{229}Th isotone.

An interesting possibility is that the ground state may actually be the $3/2^+$ member of the $1/2^+$ [631] orbital (for which the theoretical decoupling parameter is about -0.9), and the 1.7 keV and 84 keV levels may belong to the ground-state band. This could also provide an alternate explanation for the somewhat anomalous magnetic moment of the ^{227}Ra ground state ($-0.385 \text{ nm} \pm 5\%$). However, with this description there is difficulty in arranging all the positive parity levels up to 90 keV into one well-behaved decoupled band. In order to decide which of the various possible structures actually exists in ^{227}Ra , it is necessary to have experimental determinations of the spins for more of the levels involved.

5. CONCLUDING REMARKS

In the present experiment, multipolarities were determined for ~ 30 transitions connecting low-lying levels in ^{227}Ra . These levels are important for the discussion of the possibility of a stable octupole shape in this nucleus. All the new data are consistent with the earlier suggested assignments for low-lying bands that have been used to argue for the presence of an octupole deformation. To this extent the results support the existence of such a deformation. The results of this study have shown that the parities previously proposed for four levels in ^{227}Ra were incorrect.

However, even with the availability of the new multipolarity information, combined with the recently measured ground-state spins of ^{227}Fr and ^{227}Ra , it is still not possible to establish I^π values for any of the excited states in a model-independent manner. One of the reasons for this is that the spin of the ^{227}Fr parent is only $1/2$, so that very few rotational members of any band in ^{227}Ra are populated by β decay. This makes it difficult to assign levels into bands.

One promising aspect of this feature, however, is that it should simplify the execution and analysis of a γ - γ angular correlation experiment which could provide unambiguous model-independent determinations of spins for a number of the important levels. This is probably the most useful type of experiment which could be performed with existing techniques to test further the tentative assignments in ^{227}Ra which have been used as evidence for an octupole deformation.

Table 1
Internal conversion coefficients for ^{227}Ra transitions

Transition energy (keV)	Parent level ^{a)} (keV)	Conversion shell	Internal conversion coefficient				Dominant multipolarity
			Experiment ^{b)}	Theoretical ^{c)}			
				E1	E2	M1	
37.9	101.9	ΣM	≤ 1.5 ^{d)}	0.27	~ 200	~ 10	E1
64.3	90.0	L ₁ + L ₂	≤ 0.20 ^{d)}	0.19	32	8.8	} E1
		L ₃	≤ 0.10 ^{d)}	0.090	25	0.054	
		M ₁ + M ₂ + M ₃	≈ 0.06 ^{d)}	0.061	15	2.1	
76.1	101.9	L ₁ + L ₂	≤ 13 ^{d)}	0.125	15	5.5	
		L ₃	≤ 4.8 ^{d)}	0.049	12	0.033	
90.0	90.0	L ₁ + L ₂	≤ 0.09 ^{d)}	0.082	6.8	3.3	} E1
		L ₃	≤ 0.03 ^{d)}	0.028	4.8	0.020	
		ΣM	0.026 ± 0.005	0.027	3.1	0.80	
100.1	101.9	ΣL	≤ 0.08 ^{e)}	0.083	7.0	2.5	E1
101.9	101.9	ΣL	≤ 0.07 ^{e)}	0.080	6.6	2.4	E1
107.3	284.3	ΣL	≤ 0.35 ^{e)}	0.070	5.0	2.0	E1
120.7	120.7	ΣL	1.0 ± 0.3 ^{f)}	0.050	3.0	1.5	M1
135.3	161.1	ΣL	0.3 ± 0.1 ^{g)}	0.038	1.7	1.05	} One of these is E1
135.5	296.6						
161.1	161.1	K	≤ 4.5 ^{d)}	0.12	0.23	3.4	
		ΣL	≤ 0.65 ^{d)}	0.024	0.80	0.63	
163.6	284.3	K	≤ 0.5 ^{d)}	0.12	0.23	3.2	} E1
		ΣL	≤ 0.04 ^{d)}	0.023	0.75	0.61	
175.2	177.0	K	≤ 5.6 ^{d)}	0.10	0.21	2.7	
		ΣL	≤ 0.4 ^{d)}	0.020	0.56	0.50	
		ΣM	≤ 0.13 ^{d)}	0.0047	0.15	0.11	
175.9	296.6	K	≤ 2.6 ^{d)}	0.10	0.21	2.7	} E1
		ΣL	≈ 0.18 ^{d)}	0.020	0.56	0.50	
		ΣM	≤ 0.06 ^{d)}	0.0047	0.15	0.11	

Table 1 (Cont.)

Internal conversion coefficients for ^{227}Ra transitions

Transition energy (keV)	Parent level ^{a)} (keV)	Conversion shell	Internal conversion coefficient				Dominant multipolarity
			Experiment ^{b)}	Theoretical ^{c)}			
				E1	E2	M1	
178.5	475.0	ΣL	≤ 0.28 ^{d)}	0.019	0.50	0.48	E1
182.4	284.3	K	1.8 ± 0.4	0.090	0.19	2.4	M1 + E2
		ΣL	0.52 ± 0.10	0.018	0.46	0.45	
194.3	284.3	K	≤ 3.3 ^{d)}	0.077	0.17	2.0	
		ΣL	≤ 0.7 ^{d)}	0.015	0.36	0.38	
204.3	675.9	K	1.5 ± 0.3 ^{g)}	0.069	0.16	1.7	} M1
		ΣL	0.34 ± 0.04	0.013	0.29	0.32	
		ΣM	0.076 ± 0.01	0.0032	0.081	0.072	
284.3	284.3	K	≤ 0.5 ^{e)}	0.033	0.080	0.69	(E1) ^{h)}
291.6	675.9	K	≤ 0.18 ^{d)}	0.031	0.076	0.65	E1 or E2, (E1) ^{h)}
294.5	471.6	K	≤ 0.06 ^{e)}	0.030	0.074	0.63	E1 or E2, (E1) ^{h)}
321.8	475.0	K	0.6 ± 0.2	0.024	0.062	0.50	M1
347.3	731.6	K	0.46 ± 0.08	0.021	0.052	0.40	M1
362.9	523.9	K	≤ 0.07 ^{e)}	0.019	0.048	0.36	E1 or E2, (E1) ^{h)}
369.7	471.6	K	0.34 ± 0.02	0.018	0.046	0.34	} M1
		ΣL	0.056 ± 0.006	0.0032	0.028	0.060	
379.2	675.9	K	2.4 ± 0.8	0.017	0.044	0.32	} M1 + E0
		K	1.8 ± 0.8 ^{g)}				
381.6	471.6	K	0.36 ± 0.05	0.017	0.043	0.31	} M1
		ΣL	0.067 ± 0.010	0.0030	0.025	0.057	
384.3	384.3	K	0.24 ± 0.04	0.017	0.042	0.30	M1
		ΣL	≤ 0.08 ^{d)}	0.0029	0.024	0.055	
391.6	675.9	K	0.29 ± 0.03	0.016	0.040	0.29	M1
		ΣL	≤ 0.08 ^{d)}	0.0028	0.023	0.053	

Table 1 (Cont.)

Internal conversion coefficients for ^{227}Ra transitions

Transition energy (keV)	Parent level ^{a)} (keV)	Conversion shell	Internal conversion coefficient				Dominant multipolarity
			Experiment ^{b)}	Theoretical ^{c)}			
				E1	E2	M1	
403.2	523.9	K	$\leq 0.02^e)$	0.015	0.038	0.27	E1
413.0	438.8	K	0.29 ± 0.05	0.014	0.037	0.25	M1
433.8	523.9	K	0.22 ± 0.02	0.013	0.033	0.22	} M1
		ΣL	0.037 ± 0.006	0.0022	0.016	0.041	
		ΣM	0.012 ± 0.003	0.00054	0.0042	0.010	
437.0 438.8	438.8 438.8	} K	$0.21 \pm 0.05^i)$	0.013	0.033	0.22	(M1) ^{j)}
449.3	475.0						
475.0	475.0	K	$\sim 0.15^j)$	0.011	0.028	0.17	(M1) ^{j)}
514.8	675.9	K	$\leq 0.010^e)$	0.0092	0.024	0.14	E1
555.2	675.9	K	≤ 0.007	0.0080	0.021	0.11	E1
573.8	675.9	K	≤ 0.025	0.0073	0.020	0.10	E1 or E2, (E2) ^{h)}
585.8	675.9	K	0.095 ± 0.005	0.0070	0.019	0.10	} M1
		ΣL	0.018 ± 0.002	0.0012	0.0064	0.018	
		ΣM	0.0046 ± 0.0008	0.0003	0.0016	0.0042	
		ΣN	0.0011 ± 0.0005				
629.8	731.6	K	$\leq 0.04^e)$	0.0061	0.017	0.083	E1 or E2, (E1) ^{h)}
641.8	731.6	K	$\leq 0.06^e)$	0.0060	0.016	0.080	

a) From Ref. 8

b) The uncertainties indicated include statistical and background subtraction errors, etc. Not included is an overall normalization uncertainty which is estimated to be $\sim 10\%$ for values from singles spectra and $\leq 50\%$ for values from coincidence data.

c) From Ref. 15.

d) This upper limit was obtained by assuming that the total intensity in the unresolved multiplet in the electron spectrum was due to this transition.

e) Value obtained from the upper limit for the intensity of the unobserved peak in the electron spectrum.

f) Value from coincidence measurements (see text).

g) Average value for the 135.2 keV and 135.5 keV L conversion coefficients obtained after subtracting the estimated intensity of the M1 120.7 M transition from the peak. This indicates that either the 135.2 keV or 135.5 keV transition is E1.

h) Multipolarity deduced from the level scheme.

i) The conversion coefficient shown is the average value for the two lines which are not resolved in the electron spectrum. It is consistent with both transitions being M1.

j) Value obtained using 34% of the observed peak intensity in the electron spectrum, which remains after subtracting the estimated intensity of the unresolved 391.6 L lines.

Table 2
Levels in ^{227}Ra

Level energy ^{a)} (keV)	Level interpretation	
	Model-independent ^{b)}	Adopted-assignments ^{c)}
0	$3/2^+$	$(3/2^+ 3/2^+ [631])$
1.74	$\leq 7/2^+$	
25.77	$1/2, 3/2, 5/2^+; (j = \ell + 1/2)$	$1/2, 5/2^+$
64.08	$\leq 7/2^+$	
84	$j = \ell + 1/2$	$9/2^+$
90.04	$1/2, 3/2^-$	$(3/2^+ 3/2^- [761])$
101.90	$1/2, 3/2, 5/2^-$	$(5/2^+ 3/2^- [761])$
120.71	$1/2, 3/2, 5/2^+$	$1/2^+ (1/2^+ [631])$
139	$j = \ell + 1/2$	$(11/2^+ 3/2^- [761])$
153.28	$\leq 7/2^+$	
161.05	$1/2, 3/2^+; j = \ell - 1/2$	$(3/2^+ 1/2^+ [631])$
176.97	$1/2, 3/2, 5/2^+$	$(5/2^+ 3/2^+ [631])$
228	$j = \ell + 1/2$	$(15/2^+ 3/2^- [761])$
268	$j = \ell - 1/2$	$(7/2^+ 1/2^+ [631])$
284.28	$1/2, 3/2^-$	$1/2, 3/2^-$
296.58	$1/2, 3/2^-$	$1/2^-$
300	$(j = \ell + 1/2)$	$(9/2^+ 1/2^+ [631])$
384.36	$1/2, 3/2^+$	$1/2, 3/2^+$
438.79	$1/2, 3/2, 5/2^+$	$1/2, 3/2^+$
471.57	$1/2, 3/2, 5/2^-$	$1/2, 3/2^-$
475.03	$1/2, 3/2, 5/2^+$	$1/2, 3/2^+$
523.85	$1/2, 3/2, 5/2^-$	$1/2, 3/2, 5/2^-$
675.86	$1/2, 3/2^-$	$1/2^+ 1/2^- [501]$
731.65	$1/2, 3/2, 5/2^+$	

a) From Ref. 8.

b) Parities have been determined relative to the ground state, which is assumed to have positive parity. See text.

c) Assignments in parentheses are less certain.

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Figure Captions

- Fig. 1 Arrangement of the experimental set-up, showing the tape-transport system, the mini-orange electron spectrometer, and the gamma detectors. The tape is operated in a start-stop mode which permits the ions from the ISOLDE beam to be collected for a preselected period and then transported to the detector region for the measuring period.
- Fig. 2 The absolute overall efficiency for electrons in the full-energy peaks for the spectrometer system, as determined with the radioactive sources indicated. See text for procedures and corrections used. The smooth curve was drawn merely to guide the eye.
- Fig. 3 An electron spectrum from the decay of ^{227}Fr to ^{227}Ra . Peaks are labelled with internal conversion lines which contribute to their intensity. In some cases positions are indicated for unobserved peaks for which upper limits on the possible intensities restrict the multipolarities significantly. The inset shows the higher-energy portion of the spectrum.
- Fig. 4 Electron spectrum in coincidence with the 90 keV gamma ray. Coincidence events with the continuum under the 90 keV gamma peak have been subtracted.
- Fig. 5 Partial level scheme for $^{227}_{88}\text{Ra}$. Only transitions for which the multipolarities have been determined in this work are shown. The dashed energy levels were observed only in particle transfer studies⁸⁾, and the arrangement of levels into rotational bands is also taken from Ref. 8. The spin and parity assignments are to a large extent model dependent (see text).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5