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NUCLEAR DECAY SCHEMES IN THE ACTINIUM FAMILY

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July, 1957

ABSTRACT

With magnetic alpha-particle and electron high-resolution spectrographs and scintillation gamma-ray spectrometers, a study was made of the nuclear decay of a number of members of the actinium family - U^{235} , Th^{227} , Ra^{223} , Em^{219} , Po^{215} , and Bi^{211} . Decay schemes are presented for each of these nuclides, together with such correlations as are possible with present theoretical nuclear models.

The decay scheme of U^{235} and a portion of that of Th^{227} are interpretable in terms of the collective model and a spheroidal deformation; the decay schemes of Po^{215} and Bi^{211} display spherical shell-model characteristics; however, the intermediate nuclides present complexities not well understood.

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NUCLEAR DECAY SCHEMES IN THE ACTINIUM FAMILY

I. INTRODUCTION

There has been achieved in recent years a considerable understanding of the decay schemes of many radioactive nuclides. Improved spectroscopic techniques have led through precise measurements to the elucidation of these decay schemes with the removal of many ambiguities. Concurrent with the advances in experimentation have come theoretical contributions, in the form of two widely successful nuclear models -- the shell model of Mayer and Jensen,¹ and the collective model of Bohr and Mottelson.² (There have been many contributors to both models; the above-named are perhaps the principals.) The latter is in essence an extension of the former to include the possibility (now well-confirmed fact) of a nonspherical nuclear shape through which coupled motion of a number of nucleons is achieved. The shell model has been extremely successful in accounting for the several nuclear properties (spin, isomerism, level systems, magnetic and quadrupole moments, etc.) in regions of the periodic system near the closed shells which it predicts. The collective model has met with equal success in accounting for the marked differences in these properties in regions well away from these closed shells, in regions where spherical shape is not stabilized by the shell structure and effects attributable to spheroidal shape are observed.

However, there yet remain the regions between those which are the domain of each model. There has emerged no understanding of these transition regions; each model indicates that the regions might be expected to present complexities. It is of nuclides in such a region that the present study has been undertaken.

The actinium radioactive-decay family has been known since the early days of the study of radioactivity; Hahn and his coworkers were the original identifiers of many of the members.³ Yet the decay schemes have been only imperfectly known, despite several studies, because of their considerable complexity. Recent investigations in this and other

laboratories have revealed the transuranium precursors of actinium, Pu^{239} , Am^{243} , etc., to be quite typical collective-model nuclei;⁴ however, Pa^{231} proved not so readily understood.⁵ It was the prime objective of the present study to determine the decay schemes of the still lighter members Th^{227} , Ra^{223} , and Em^{219} as a contribution toward the understanding of the transition region between the heavy-element collective region ($A \geq 222$) and the spherical, single-particle region around the 82-126 double closed shell. Th^{227} has been known to be somewhat of a curiosity in that it has been reported to have some 11 to 15 alpha groups in abundances of or approaching 1%,⁶ this being the greatest number reported for one nuclide, Ra^{223} following with eight.⁷

It has been possible to establish these decay schemes in considerable detail and precision; a rotational band characteristic of the collective model has been observed in Th^{227} decay; a connection of Em^{219} decay to the spherical region can be offered, but the plethora of nuclear levels in the decays of Th^{227} and Ra^{223} remains unexplained.

II. EXPERIMENTAL METHODS

In this study, the three general types of nuclear spectroscopy -- alpha, electron, and gamma -- have all been employed. The alpha spectra were studied with high resolution electromagnetic spectrographs; the conversion electrons from the internal transitions were studied with permanent magnet spectrographs and with a double focussing electromagnetic spectrometer. The gamma-ray studies were performed with a scintillation spectrometer equipped for coincidence measurements. Details of these instruments and of the chemical purification methods are given in the following section.

A. Alpha Spectroscopy

1. Uniform-Field Alpha-Particle Spectrograph

The first alpha particle spectrograph employed is a 60° -sector, uniform-field magnetic prism of the type designed by Nier for mass spectrometry (Fig. 1). The instrument has been described in detail by Asaro and Reynolds.⁸ The normal path radius is approximately 75 cm; the electromagnet is usually operated in the 4 to 5 kilogauss region. The exciting current is regulated automatically to maintain constancy within two parts in 10^4 of the set value. The sample is placed behind a vertical defining slit some 50 in. from the magnet; the beam is further defined by a pair of adjustable baffles just before the magnet. With the usual 3-in. opening, the instrument has a transmission of 4×10^{-5} of 4π . The focussed beam of alpha particles impinges at 60° to the normal on a photographic plate placed parallel to the field in the plane containing the source and the center of curvature. Nuclear track emulsion (Eastman WTA, 25-micron) is used, and the plate is scanned with a 400-power microscope to obtain the spectrum. The plate is placed horizontally on the microscope stage and is swept across the short dimension, the number of tracks observed in the sweep being recorded as a function of position in the long dimension. The dispersion of the spectrum in kiloelectronvolts of alpha-particle energy per millimeter of horizontal distance has been shown by Asaro to be constant

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Fig. 1. Schematic diagram of uniform-field alpha-particle spectrograph.

within 1% over the entire length of the plate (9 in.),⁹ and is of the order of 3.5 to 4 kev/mm. No attempt is made to operate the spectrograph for absolute energy determinations; instead it is calibrated against the known standards; for high-resolution work, the dispersion, known roughly as a function of the field strength, is also more accurately determined by means of a standard.

The usual operating conditions, with the 3-in. baffle opening and an 0.018- by 0.75-in. defining slit, produce from a thin sample peaks with widths at half-maximum of approximately 6 kev in 6 Mev of particle energy, or a resolution of 0.1%. However, due to the closeness of some of the groups in Th^{227} and Ra^{223} , it was found necessary to use more stringent conditions for these studies. The baffles were closed to 0.5 or 1 in. and a 0.005-in. defining slit was employed. In this arrangement, the peak width was reduced to 2.4 kev, or 0.04% resolution, which is better than any previously reported efforts. Attempts to obtain still higher resolution were unsuccessful.

Preparation of sample for high resolution alpha spectroscopy requires extreme care, as the lines are readily broadened by small amounts of material overlying the active sample. The material to be investigated is first purified from other alpha activities, the procedures being selected which introduce as little as possible extraneous material to contribute radiation-degrading mass to the sample. When the activity is both radiochemically pure and as free of stray mass as possible, it is evaporated from a hydrochloric acid solution onto a trough-shaped tungsten filament. The enclosing bell-jar is evacuated to 0.5 mm Hg pressure and the filament is heated to incipient red, removing any traces of volatile contaminants. A plate of platinum or nickel is then placed above the filament, and after re-evacuation, the activity is sublimed from the filament at white heat onto the cool plate. The sample thus obtained is usually quite thin and uniform, although occasionally line-broadening due to sample thickness is observed.

Ra^{223} presented an additional experimental complication in its short-lived gaseous daughter, Em^{219} . This 4-sec half-life activity¹⁰

is expelled from the sample plate by the kinetic energy of recoil and then moves freely in the vacuum tank of the spectrograph. Being no longer at the object focal point, in its subsequent decay it impinges its alpha particles randomly on the detector plate. The 4 msec¹¹ Po²¹⁵ does likewise, and deposits Pb²¹¹ on the spectrograph walls, building up a source of alpha-emitting Bi²¹¹, which contributes further random tracks to the plate. In the scanning process, a considerable discrimination against these background tracks can be exercised, both from direction of incidence and from length (because of their greater energy). Despite this discrimination, the problem is severe, and in previous work, Asaro was able to observe only those groups of greater than 1% abundance -- indeed the intense peaks were not evident in casual inspection.

To control this problem, a modification of the spectrograph was undertaken. An additional oil-diffusion vacuum pump was placed with its throat immediately below the source, and the opening from the source chamber into the magnet tank was reduced from a 2-in. diameter pipe by means of a gasketed plate containing a 1/8-by 3/4-in. slit. This opening was greater than the width of the beam accepted by the baffle opening, but served to restrict the drift of gas. Finally, the source-defining slit was eliminated altogether from the instrument and was replaced by a similar slit above the filament in the sublimator, so that the deposition of active material was restricted to the useful area of 0.005 by 0.5 in. Thus the large amount of masked-off sample, with its attendant emanation, was removed from the spectrograph. With these modifications, the random background was reduced to the point where, although still observable, it no longer presents a serious limitation on the sensitivity of the alpha spectrograph -- groups of 0.1% being readily observable.

2. Double-Focussing Alpha-Particle Spectrograph

A second alpha-particle spectrograph of considerably different design has recently been developed in these laboratories following the calculations of Judd.¹² The instrument is, in principle, a Siegbahn-Svartholm double-focussing spectrograph which has been modified to

locate the source and receiver positions outside the magnetic field. The magnet covers 180° with a maximum radius of 50 cm, and an optical axis of 35-cm radius. The field is nonuniform, being chosen with a radial dependence which produces focussing in both vertical and horizontal directions. As a result of the external source position and the consideration of third-order cross terms, the field differs considerably from the Siegbahn-Svartholm field, and is given by

$$H = H_0 (1 - 1/2\rho + 0.2089 \rho^2 + 0.473 \rho^3),$$

where $\rho = \frac{r - 35.0}{35.0}$

and $r =$ radial position in cm.

Measurement of the actual fringing effects and consideration of other difficulties in the focus have indicated that a somewhat better choice might have been made for the coefficient of the ρ^3 term. Fields of 9 to 10 kgauss at the normal radius are employed.

The aperture is controlled by baffles along the 90° radius. Transmission of 7×10^{-4} of 4π has been obtained with 0.1% resolution. It is this exceptionally high transmission which is the chief advantage of the instrument, for it permits the studying of extremely long-lived alpha emitters, whose low specific activities, with the requirement of sample thinness, preclude the use of very active samples. For the first time it has been possible to study the alpha spectrum of U^{235} ($t_{1/2} = 7.3 \times 10^8$ years)¹³ by magnetic means.

The usual detector is a nuclear-track plate similar to those used in the Nier spectrograph, and the spectra are evaluated in the same way. As expected from the variation in field, the dispersion varies markedly over the extent of the plate, and likewise the quality of focus -- peaks far from the middle of the plate being broadened and distorted. The Ra^{223} spectrum has served as an excellent calibration of this spectrograph, having also been determined with the Nier instrument, both for dispersion and transmission. These calibrations are shown in Figs. 2 and 3.

Difficulties in comparing energies between runs at different field strengths have arisen. The field is measured at a fixed point

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Fig. 2. Variation of dispersion with position on recording plate of the double-focussing alpha-particle spectrograph.

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Fig. 3. Relative transmission of the double-focussing alpha spectrograph as a function of location of peak on recording plate.

in the spectrograph for each run, and since it is frequently inconvenient to determine energies relative to a standard run at the same field strength, it was hoped that the ratio of the reference fields for successive runs would yield directly the relative particle energies. Fields of the strengths employed are best measured in terms of the frequency of the nuclear magnetic resonance of Li^7 . This can be measured only in a region of small field gradient; therefore the probe is located at a radius of 9 cm, where the field is reasonably constant. Unfortunately, the magnitude of the field is quite large -- about 12 kgauss -- and saturation effects are beginning to appear, with the result that the measured field is not directly proportional to the effective field at 35-cm radius. An approximate calibration curve for this effect is shown in Fig. 4.

Another type of experiment has been made possible by the high transmission of this instrument. The photographic plate is replaced with a zinc sulfide scintillation screen masked except for a narrow vertical slit and coupled through a light-pipe to a photomultiplier tube. The wall of the vacuum chamber in the region of the source position is made of beryllium metal so that gamma rays emitted by the source may be detected by an external sodium iodide scintillation spectrometer (see the diagram in Fig. 5). The pulses from alpha particles of a particular group focussed on the slit before the ZnS screen serve as gates for a coincidence circuit, and the spectrum of coincident photons is recorded by the scintillation spectrometer. The method has been employed extensively on Ra^{223} , yielding considerable information on the decay scheme and the types of radiations. In addition, the angular distribution of one of the gamma rays with respect to the alpha group was determined.

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Fig. 4. Factor to compensate for saturation effects on readings of Li^7 nuclear fluxmeter of the double-focussing alpha spectrograph.

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Fig. 5. Diagram of the double-focussing alpha spectrograph arranged for alpha-gamma coincidence studies.

B. Electron Spectroscopy

1. Permanent-Magnet Electron Spectrographs

High-resolution spectra of conversion-electron lines were obtained through the use of permanent-magnet, uniform-field spectrographs. The source and photographic plate are located within the magnetic field together with a defining slit (see Fig. 6). X-ray-emulsion plates are used, and visible lines are obtained. The source consists of a platinum wire of 0.010-in. diameter on which the active material is electrodeposited. The design is such that the wire is located in a readily reproducible position in the spectrograph. Instruments with field strengths of 50 and 100 gauss were used in the study of the conversion spectra of Th^{227} ; these spectrographs were extensively calibrated by W. G. Smith and J. M. Hollander of this laboratory.¹⁴ The problem of emanation background proved more critical than for the alpha spectrographs, and spectra of Ra^{223} , or even of Th^{227} into which a few percent of Ra^{223} had grown, could not be obtained. It is felt that an improved pumping system might make the experiment possible.

These spectrographs attain a resolution of 0.1% and an energy precision of the same order, but the comparison of line intensities is subject to many complications.

2. Double-Focussing Electron Spectrometer

For the determination of the relative intensities of the conversion lines of Th^{227} , and for all of the electron spectroscopy of Ra^{223} and its daughters, a double-focussing spectrometer of 25.0-cm radius was employed.¹⁵ The detector used was a thin-window Geiger-Müller tube at the focal point of the spectrometer. The magnetic field was swept upward automatically and the counting rate of the G-M tube was recorded on a chart by an automatic potentiometer. The calibration for energy was made against the permanent-magnet data for Th^{227} and also against the well-known Bi^{206} by Rev. F. L. Canavan of this laboratory.

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Fig. 6. Diagram of permanent-magnet electron spectrograph.

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Samples for this instrument were prepared by evaporation of a solution containing the purified activity onto a 1 mm strip of platinum mounted on a brass holder. Resolution of a few tenths of a percent in magnetic rigidity was obtained.

C. Gamma-Ray Spectroscopy

Gamma-ray spectra were determined by means of a scintillation pulse-height spectrometer. Crystals of thallium-activated sodium iodide were used as detectors; their light output was converted to electrical pulses by photomultiplier tubes. After linear amplification, these pulses were analyzed with a 50-channel pulse-height analyzer, which displayed the spectrum on mechanical registers in numbers of counts in successive energy increments. By suitable changes in the gain of the linear amplifier, an arbitrary dispersion could be obtained, and thus any range of energy could be scanned at a given time. The resolution obtained was that which is common for this type of spectrometer -- approximately 8% for the 622-keV radiation of Cs^{137} , somewhat poorer for lower-energy radiation. Scintillation-counter efficiency, being a function of the cross-section for the photoelectric effect, decreases with increasing photon energy; the values of Kalkstein and Hollander for this efficiency have been used throughout this work.¹⁶

The spectrometer was equipped for coincidence spectrometry, in which the spectrum occurring simultaneously with a given radiation (the "gate") is examined. A fast-slow type of apparatus was employed, a block diagram of which is shown in Fig. 7. The pulses from the two detectors, referred to as "signal" and "gate", are divided at the output of the preamplifiers. One portion of the signal pulse is passed through a linear amplifier, the gain of which controls the dispersion of the spectrometer, and into the 50-channel pulse-height analyzer. Here it is recorded on the register corresponding to its height only if the analyzer has simultaneously received a pulse from the fast-slow gating circuit. The other branch of the signal and one branch of the pulse from the gate detector are passed through parallel

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Fig. 7. Block diagram of fast-slow coincidence scintillation spectrometer.

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linear amplifiers and a pulse-shaper which contains a delay circuit which may be adjusted to compensate for differences in the transit or rise times of the two circuits. These matched pulses then enter a fast coincidence circuit which gives an output pulse only if the two detectors received radiation within 0.1 μ sec of each other. The second branch of the gate pulse is analyzed by a single-channel pulse-height analyzer which passes pulses of only a certain selectable height range, thus permitting limitation of the gating pulse to radiations of a certain energy. The output of this pulse analyzer, after amplification, shaping, and delay adjustment, is inspected in a slow circuit for coincidence with the output of the fast circuit. Output of this slow circuit serves as the gating pulse for the 50-channel analyzer.

In one series of experiments, the gating pulse employed was the output of the zinc sulfide detector of the double-focussing alpha spectrograph, the spectrograph serving in the place of the single-channel analyzer for selecting the energy of the gating radiation. The fast coincidence circuit was not employed, to avoid complications from spread in transit times of the alpha particles in the spectrograph. The signal linear amplifier used was of the double-differentiating type, which is able to handle a considerably higher flux of pulses than previous types, thus allowing the use of samples of the order of 10^7 disintegrations per minute.

D. Preparation and Purification of the Active Materials

The uranium used in the study of the alpha spectrum of U^{235} was available in usable form, having undergone an isotope separation after isolation from the ore. By mass, the material was essentially entirely U^{235} , but by alpha activity about 50% U^{234} . The U^{238} content was very small. The only radiochemical contaminant was Th^{231} (UY) which, because of its 25-hr half-life, was at equilibrium with the U^{235} ; the alpha branching of Th^{231} is extremely small and could not interfere in the present study.

The other activities studied in this work are most readily available as decay products of Ac^{227} , a 22-yr half-life, principally

beta emitter.¹⁷ Actinium is present in nature as a product of U^{235} , but the material from which the samples used in the present study were milked had been prepared previously by neutron irradiation of radium and a subsequent separation.

Two methods were employed for the separation of thorium from the equilibrium mixture. In the first, the mixture was introduced onto a Dowex-50, 12% cross-linked, cation exchange resin column operated at 87° C. The loading solution was 0.5 N in HCl, a condition in which actinium, radium, and thorium strongly adhere to the resin, but in which lead and bismuth elute. Prolonged washing with 4 N HNO_3 eluted both radium and actinium, but left the thorium still strongly bound. Thorium, now radiochemically pure, was eluted with a 50% by volume lactic acid solution adjusted with NH_4OH to pH 3. Since extraneous sample mass cannot be tolerated for alpha or electron spectroscopy, it was necessary to extract the activity from the lactic acid solution. The acidity was lowered with NH_4OH to pH 5, and an extraction was performed with 0.4 M thenoyltrifluoroacetone (TTA) in benzene. The benzene-TTA phase was washed with 0.5 N HNO_3 , and the activity was back-extracted into 4 N HNO_3 . After a final wash of this phase with pure benzene, the solution, now radiochemically pure and essentially mass-free, was suitable for the sample preparation proper to each type of spectrograph (Sec. II-A.1, II-B.1, II-B.2).

Because of the rapid ingrowth of Ra^{223} , such extensive purification was not warranted for experiments of long duration, and a simpler procedure was employed. The equilibrium mixture was dissolved in 0.5 N HNO_3 and extracted with 0.4 M TTA in benzene. Under these conditions the thorium is extracted, while the actinium and radium are not. The separation from lead and bismuth is not at all good, but the short half-lives of the isotopes of these elements present rendered initial contamination by them unimportant. The TTA-benzene phase was washed and back-extracted as before.

The separation of radium from the equilibrium mixture can be effected with a TTA extraction only under carefully controlled conditions. The acidity of the aqueous phase must be reduced to a pH of five or greater

in order that actinium be extracted. However, if the solution is allowed to become basic, precipitation of TTA and hydroxides of the heavy elements will occur. Therefore, the acidity was stabilized at pH 5.5 with a sodium or ammonium acetate buffer for the extraction. The radium was then separated from the buffer by cation exchange. The solution was passed through a Dowex-50 cation exchange resin column at room temperature, both the radium and sizeable amounts of the buffer being retained by the resin. The buffer was eluted with 4 N HCl, the radium being retained until elution with 4 N HNO₃. A second separation from actinium is provided by the slow rate of elution of that element -- the radium band well preceding it.

The extraction from the buffered solution with TTA in benzene sometimes proved intractable due to the formation of suspensions or emulsions of unknown character. In these cases, recourse was made to a coprecipitation method. The equilibrium mixture was dissolved in fuming nitric acid, and a saturated solution of lead nitrate was added. Radium nitrate coprecipitates with the lead nitrate. After being washed and dried, the precipitate was dissolved in water, and lead chloride was precipitated by the addition of hydrochloric acid, radium remaining in solution. For the removal of the final traces of lead, the solution was adjusted to 1.5 N in HCl and passed through a column of Dowex A-1 anion exchange resin. Under these conditions lead is strongly retained, but radium is not. To remove any remaining extraneous material, and as a second separation from thorium and actinium, a cation exchange similar to that used in the separation from buffer was also employed.

No attempt was made to prepare a sample of Bi²¹¹ for the alpha spectrograph because of its short (2-min.) half life. Instead, samples of Pb²¹¹ (36-min. half-life) were prepared and the Bi²¹¹ was studied in equilibrium with it. The Pb²¹¹ was milked rapidly from Ra²²³ by the following method. The radium was introduced onto a Dowex-50 cation exchange column in 0.5 N HCl and washed briefly with 4 N HCl. The flow was then stopped for a period of an hour or more to permit the Pb²¹¹ to grow to equilibrium. Then the lead was eluted with a few drops of 4 N HCl and hastily transferred

to the vacuum-sublimation apparatus. The time required for the elution, sublimation, mounting of the sample, and evacuation of the spectrograph was approximately forty minutes.

III. OBSERVATIONS

A. Decay of Th²²⁷ (RdAc)

1. Alpha Spectrum

The decay of thorium-227 by alpha emission to radium-223 has been of note because of the complexity of the alpha spectrum reported by Rosenblum and his co-workers, who first suggested that no less than fifteen alpha groups were emitted by this nuclide but later revised this to eleven (Table I).¹⁸ The alpha spectroscopy is complicated by the close spacings of the groups and by the rapid ingrowth of the daughter, Ra²²³, the alpha groups of which lie in the same spectral region. To minimize the effect of Ra²²³ growth, very large samples of Th²²⁷ (of the order of 10¹⁰ dpm) were employed so the spectra could be obtained in a short time after purification. The intense sources also permitted rigorous baffling to obtain the highest resolution of which the uniform-field instrument was capable. The spectrum thus obtained is shown in Fig. 8, and the data are summarized in Table II. The value for the dispersion used in determining energy differences in this spectrum was obtained from the separation of α_{286} from α_0 , as this difference is accurately known from conversion-electron data (Sec. III-A.3). The energy of α_0 was obtained by calibration against the groups of Cm²⁴², the energies of which were determined by Asaro,¹⁹ in a spectrum of a mixture of Cm²⁴², Th²²⁷, and Ra²²³, as shown in Fig. 9 and Table III.

The principal features of Rosenblum's spectrum were confirmed, but the higher resolution achieved in the present study revealed several of the reported peaks to be composed of numbers of close-lying groups. In particular, the group reported at 5.704 Mev in 15% abundance was resolved into four groups separated from each other by 4.4, 8.4, and 7.8 kev. The groups reported at 5.749 and 5.796 Mev each were revealed to be pairs of groups, separated by 6 and 12 kev, respectively. No group corresponding to that reported at 5.728 Mev was observed, with a limit of 0.3%. In all, fifteen alpha groups were observed in the decay of Th²²⁷. This spectrum will be discussed further in conjunction with the interpretation of the decay scheme in Sec. III-A.5.

Table I. Alpha Groups of Th²²⁷, According to Rosenblum¹⁸

Alpha Energy (Mev)	Abundance (%)	Excited State Energy ^a (kev)
6.030	19	0
6.001	5	29
5.972	21	59
5.952	13	79
5.922	2	110
5.860	4	173
5.796	2	238
5.749	17	286
5.728	1	307
5.704	15	330
5.651	2	386

^aCalculated by present author.

Fig. 8. Alpha-particle spectrum of Th^{227} .

Table II. Alpha Groups of Th^{227}

Alpha-Particle Energy (Mev) ^a	Abundance (%)	Excited-State Energy (kev) ^b	Hindrance Factor ^c
6.036 $\pm$ 0.001	23	0.0	1.1 (2)
6.007	2.8	30.0	6.9 (2)
5.976	24	61.5	5.5 (1)
5.958	3.5	79.9	3.2 (2)
5.914	0.9	124.2	7.4 (2)
5.865	3.0	174.4	1.3 (2)
5.805	1.0	234.9	2.0 (2)
5.793	0.3	247.1	5.3 (2)
5.761	0.3	280.0	3.7 (2)
5.755	21	(286.1) ^b	5.3 (0)
5.712	5.0	329.8	1.3 (1)
5.708	8.7	334.2	7.2 (0)
5.699	4.0	342.6	1.5 (1)
5.692	1.5	350.4	3.7 (1)
5.667	1.9	376.0	2.0 (1)

Alpha-decay energy: 6.218 Mev

- Particle energies are expressed relative to α_0 of Cm^{242} , taken as 6.110 Mev.
- Dispersion was determined from separation of groups to 0.0- and 286.1-kev levels, an energy difference known from the conversion-electron spectrum. The error in the energies of the excited states should be less than ± 0.4 kev.
- Digit in parentheses indicates power of ten to be multiplied.

Fig. 9. Partial alpha-particle spectrum of a mixture of Cm^{242} , Th^{227} , and Ra^{223} .

2. Gamma Spectrum

Due to the complexity of levels, the gamma spectrum is only partially resolved by the scintillation spectrometer. Photons of 50 and 236 kev stand out prominently (Fig. 10); relative intensities and energies of other photons can be estimated, as in Table IV. (Evidence will be presented showing that the 50-kev transition leads to the ground state of Ra²²³.) The intensity of the 50-kev gamma ray was determined from a spectrum obtained at calibrated geometry from a freshly purified sample for which the disintegration rate was determined with a 52%-geometry alpha-particle ionization chamber. This intensity was found to be 0.075 ± 0.01 . 50-kev photons per alpha disintegration, a value which is not in disagreement with the value of 0.15 ± 0.1 obtained by Hyde,²⁰ but which is considerably larger than the 0.03 reported by Rosenblum.²¹ A detailed intensity balance of the decay scheme indicates the present value to be the more reasonable. This high intensity in itself identifies the 50-kev transition as E1.

The coincidence spectrometer revealed the 50- and 236- kev photons to be coincident²² (Table V and Figs. 11, 12, and 13). An upper limit for the K-conversion coefficient of the 236-kev transition is obtained by comparison of the intensity of K x-rays with 236-kev photons in the coincidence spectrum; a comparison with the theoretical calculations of Sliv²³ reveals the transition to be electric dipole (E1). The maximum total conversion coefficient of the 50-kev transition may be obtained by assuming one 50-kev transition for each 236-kev transition; this value is consistent only with an E1 assignment for the 50-kev transition.

The angular distribution of the 236-kev photons with respect to the 50-kev photons was also determined, and an anisotropy of -0.125 was observed, i.e., the difference between the coincidence intensities at 180° and at 90° , normalized to the intensity at 90° , was -0.125. This corresponds to $A_2 = -0.087$ in the usual expansion in Legendre Polynomials

$$W(\theta) = \sum_k A_k P_k(\cos \theta).$$

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Fig. 10. Gamma-ray spectrum of Th^{227} .

Table IV.

Approximate Energy (kev)	Approximate Abundance photons/alpha
49	0.075
207	0.02
237	0.15
257	----
295	0.04
325	0.04

Table V.

236 kev photons per 50 kev photon	0.95
K-conversion coefficient of 236 kev transition (maximum)	0.05 ± 0.02
Theoretical α_k (Sliv) E1	0.046
E2	0.11
50 kev photons per 236 kev photon	0.6 ± 0.1
Maximum total conversion coefficient of 50 kev transition	0.7 ± 0.2
Theoretical for E1 (Rose)	0.65

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Fig. 11. Illustration of the spectral regions used as gating radiations in the study of the cascade of 50- and 236-keV photons in Th^{227} decay.

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Fig. 12. Gamma-ray spectrum coincident with the 236-kev gamma ray of Th^{227} .

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Fig. 13. Gamma-ray spectrum coincident with the 50-kev gamma ray of Th^{227} .

The values of A_2 expected for dipole radiations are given in Table VI for various spin sequences.²⁴ It should be noted that various effects may attenuate an anisotropy, reducing the distribution toward isotropic, but in the absence of admixing of other-multipolarity radiations, the sign of the anisotropy cannot be changed. In a later section (III-A.5a) arguments will be presented showing that the spin of the ground state of Ra^{223} is probably $1/2$; then of the possible sequences, only $3/2 - 3/2 - 1/2$ would conform with the observed anisotropy -- unless admixing of M2 radiation be significant. Conversion-electron data limit M2 admixture of the 50-keV photons to less than $10^{-2}\%$, and of the 236-keV to less than 1% . The former would be entirely insignificant, but the latter may appreciably alter the distribution. The effect of this M2 mixing up to 1% is shown in Table VII, and again only the sequence $3/2 - 3/2 - 1/2$ would conform.

3. Electron Spectrum

The conversion-electron spectrum of Th^{227} was studied with the 50- and 100-gauss permanent-magnet spectrographs and the double-focussing spectrometer. The energy determinations of the former were used to calibrate the latter and also the dispersion of the alpha spectrograph. However, the relative intensities of conversion lines were determined from the double-focussing instrument. Since neither the transmission of the instrument nor the disintegration rate of the sample were known, only relative line intensities were obtained directly. However, these may be related to electrons per alpha disintegration through the measured intensity of the 50-keV photons, the measured abundance of the 236-keV transition in coincidence therewith, and its measured K-conversion coefficient. The conversion coefficient of the 50.0-keV E1 was not used directly because of the possibility of M2 admixture, which cannot readily be evaluated because of the further possibility of additional, unresolved, 50-keV transitions from the several level separations of nearly this energy observed in the alpha spectrum. Thus the uncertainty in electron intensities may be of the order of 20% , although the relative values are better.

Table VI. Theoretical Correlations for Dipole Cascades

Initial	Spins Intemed.	Final	A_2^{24}
1/2	3/2	1/2	+ 0.250
3/2	3/2	1/2	- 0.200
5/2	3/2	1/2	+0.050
3/2	3/2	3/2	-0.200
5/2	3/2	3/2	-0.040
3/2	5/2	3/2	+0.140
5/2	5/2	3/2	-0.160
7/2	5/2	3/2	+0.04
7/2	5/2	5/2	-0.057
5/2	3/2	5/2	+0.010
5/2	5/2	5/2	-0.428
5/2	7/2	5/2	+0.107
9/2	7/2	7/2	-0.0668
11/2	9/2	9/2	-0.0729
13/2	11/2	11/2	-0.0770
15/2	13/2	13/2	-0.0800

Table VII. Effect of Mixing on γ - γ Correlations

Spin Sequence	$A_2(\delta)^{*1}$	$A_2(\delta_{\max})^{*2}$
1/2 - 3/2 - 1/2	$\frac{+0.250 - 0.866\delta - 0.500\delta^2}{(1 + \delta^2)}$	+ 0.157
3/2 - 3/2 - 1/2	$\frac{-0.200 - 0.775\delta + 0.000\delta^2}{(1 + \delta^2)}$	-0.121
5/2 - 3/2 - 1/2	$\frac{+0.050 + 0.592\delta + 0.357\delta^2}{(1 + \delta^2)}$	-0.006
Experimental		-0.087

*1 Taking the 50.0 as unmixed; δ^2 as the ratio of M2 to E1 radiation.

*2 The nearest value to the experimental which can be achieved with the experimental mixing limit, $\delta^2 \leq 0.01$.

The spectra are shown in Figs. 14 and 15, and the lines are tabulated in Appendix A.I. The lines are retabulated in Appendix B.I arranged according to the transitions to which they belong. These transitions are listed, together with their multipolarities and intensities, in Table VIII of this section. Where possible the assignment of radiation type is made on the basis of relative intensities of the several conversion lines of the transition, employing the theoretical conversion coefficients of Rose²⁵ and Sliv,²⁶ without reference to the decay scheme. However, in some instances such arguments are inconclusive, and recourse must be made to the more certain parts of the decay scheme for information on total conversion coefficients and relative parities of initial and final states.

A sizeable number of low-intensity conversion lines cannot at present be assigned. It is possible that at least some of these, having been observed only with the double-focussing spectrometer — and then only weakly, may be spurious, arising from fluctuations in the background counting rate (which was appreciable because of the presence of Ra²²³ and Em²¹⁹).

4. Decay Scheme

From the foregoing data the decay scheme shown in Fig. 16 may be deduced. Table IX presents a comparison of the energies of the levels as determined from the electron spectra with the values obtained from the alpha spectrum and also an intensity balance for each level.

A difficulty is encountered in placing the prominent 50- and 236-keV E1 transitions. In the electron spectrum, lines are observed corresponding to transitions of 234.8 and 236.1 keV, and it cannot be directly determined which of these is the transition coincident with the 50.0-keV E1. However, it may be noted that the sum of 50.0 and 236.1 keV would be in excellent agreement as a cascade from the 286.1-keV level observed both in the electron spectrum (286.1, 29.8 + 256.4 keV) and by the (necessarily) prominent alpha group.

The question yet remains of the order of the two transitions. A weak alpha group is observed at 235 keV of excitation; however the energy

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Fig. 14. Electron spectrograms of Th^{227} , obtained with the 50- and 100-gauss permanent-magnet spectrographs.

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Fig. 15. Conversion-electron spectrum of Th^{227} , from the double-focussing spectrometer. Counting rate in arbitrary units as a function of magnetic rigidity in gauss-cm.

Table VIII. Internal Transitions in Th²²⁷

Energy (kev)	Intensity (%)	Multipolarity
29.8	27	M1-E2
31.6	12	M1-E2
48.2	2.7	E2
50.0	13.6	E1(M2)
61.3	9.0	E2
79.7	4.6	E1
100.1	1.0	E2
113.0	4.2	E2
173.3	~1	E2
205.0	0.4	M1
234.9	2.0	M1
236.1	10.6	E1
247.7	weak	(E2?)
250.3		M1 ^a
256.4	7.1	E2
280.0		M1 ^a
281.8	~2	M1-E2?
286.1	1.5	M1
289.7	~0.9	E2?
296.8	~2.5	E2
300.0	~1	E2?
304.5	~2	M1(E2)?
312.7	3.5	E2
329.7	1.6	E2
334.3	5.2	E2

a. An E1 of the same energy probably also exists.

Fig. 16. Decay scheme of Th^{227} .

Table IX.

Alpha	Energy Check			Adopted	Intensity Balance			
	Electron				Alpha	Internal Trans in	Total in	Internal Trans out
30.0	29.8			29.8	2.8	23.9	26.7	26.9
61.5	61.3	29.8 <u>31.6</u> 61.4		61.3	24	1.7	25	20.7
	50.0				>0.2			
79.9	79.75			79.8	3.5	1.9	5.4	4.6
124.2				124.2	0.9	?		?
174.4	113.0 <u>61.3</u> 174.3			174.4	3.0			1.9
234.9	234.9	205.1 <u>29.8</u> 234.9	173.3 <u>61.3</u> 234.6	234.9	1.0	1.0	2.0	1.9
247.1	247.7			247.1	0.3	0.0	0.3	0.55
280.0	280.0	250.3 <u>29.8</u> 280.1			0.3			
(286.1)	286.1	256.4 <u>29.8</u> 286.2	236.1 <u>50.0</u> 286.1	286.1	21	2.7	23.7	19.1
329.8	329.7	300.0 <u>29.8</u> 329.8	280.0 <u>50.0</u> 330.0	329.8	5.0		5.0	3.9
334.2	334.3	304.5 <u>29.8</u> 334.3	48.2 <u>286.1</u> 334.3	334.3	8.7		8.7	10.8
342.6		312.7 <u>29.8</u> 342.5	281.8 <u>61.3</u> 343.1	342.6	4.0		4.0	3.5
350.4		289.7 <u>61.3</u> 351.0		350.4	1.5		1.5	1.5
376.0		296.8 <u>79.8</u> 376.6		376.0	1.9	0.0	1.9	2.5

agreement is better with 234.8 than with 236.1 kev. The determining evidence in this question is provided in the study by Hyde of the beta decay of Fr^{223} to this same daughter.²⁷ Here two photons are prominent, 80.0- and 49.8 ± 0.3 -kev. Hyde reports that the two are not coincident with each other nor with L x-rays, indicating that both decay to the ground state of Ra^{223} . From the energies and intensities of the transitions observed in the present study, it is evident that the state populated by the 6.036-Mev alpha group must be the ground state of Ra^{223} . Combining these two evidences, the postulation of a state at 49.8 ± 0.3 kev above ground is dictated; it would seem reasonable that the 49.8 ± 0.3 -kev transition of Fr^{223} and the 50.0 ± 0.1 -kev transition of Th^{227} are the same, and thus there exists in Ra^{223} a state at 50.0 kev, receiving less than 0.2% of the alpha decay of Th^{227} .

Within the experimental energy limits, the 250.3- and 280.0-kev transitions may be placed as deexciting either the 280.0- or 329.8-kev level. The 250.3-kev transition appears from K- to L-conversion ratio to be an M1-E2 mixture rather than an E1, and hence is assigned to the transition between the 280.0-kev and 29.8-kev levels. If the 280.0-kev transition were E1, as its assignment to the 329.8-kev level would require, its intensity would be approximately 3%, which is inconsistent with the 50-kev photon - gamma-ray coincidence measurements which revealed a contribution of perhaps 1% from photons of higher than 236.1 kev. Hence it is suggested that both of the possible 280.0-kev transitions occur, and the same may indeed be true for the 250.3-kev transition as well.

The energy of the 100.1-kev E2 transition appears to be about 0.6-kev greater than the separation of the levels between which it is assigned -- a discrepancy a bit larger than expected from data obtained with the permanent-magnet spectrographs. The L lines lie in the region of the KLM Auger electrons, and while they are considerably too intense to be attributed to the Auger effect, it may be that there is sufficient contribution from that source to confuse the reading of the position of the lines.

5. Interpretation of Levels

Despite the complexity of the decay scheme, some progress can be made in interpreting the system of energy levels of Ra^{223} .

a. Ground-state rotational band.

The cascade of mixed M1-E2 transitions with a pure E2 cross-over observed between the 61.3- and 29.8-keV excited states and the ground state is characteristic of a rotational band of the Bohr-Mottelson model.²⁸ The rotational energy for each band member is given by:

$$E_{\text{rot}} = \frac{h^2}{2\mathcal{I}} \left[I(I+1) + (-)^{I+1/2} a(I+1/2) \delta_{K, 1/2} \right]$$

where $\mathcal{I}$ is the moment of inertia, I is the spin of the state, and a is a factor arising from a partial decoupling of the intrinsic motion for $K = 1/2$ states. A comparison of the energy separations 29.8 and 61.3 keV with the above formulation indicates that either the ground state spin is very large (of the order of $31/2$) or is $1/2$, giving rise to the decoupling term. In the latter case, it may be noted further that the 124.2-keV and 174.4-keV levels lie near but below the expected energies for the $7/2$ and $9/2$ members of the band (Table X). The pure E2 transition of 113.0 keV strengthens this interpretation of the 174.3-keV level, while the transition from it to the 124.2-keV level would be obscured by the intense lines of the 50.0-keV E1 transition. The transitions from the weakly populated 124.2-keV level are obscured by lines of other transitions.

The fact that these two states lie significantly below the calculated energies may be readily explained as the result of centrifugal stretching of the nucleus. This effect is well-known in the analogous spectra of diatomic molecules,²⁹ and an approximate account of the effect may be made by replacing the constant moment of inertia of the simple formula by:

$$\mathcal{I}_I = \mathcal{I}_0 [1 + c I(I+1)]$$

In this approximation, Bohr and Mottelson evaluate c as:

Table X. Energies of the $K = 1/2$ Band, Ra^{223}

Spin	Energy		
	Experimental	Calculated (Simple)	Calculated (Stretching)
1/2	(0.0)	(0.0)	(0.0)
3/2	29.8	(29.8)	(29.8)
5/2	61.3	(61.3)	(61.3)
7/2	124.2	131.2	(124.3)
9/2	174.4	187.3	174.1
$\begin{aligned} h^2/2\mathfrak{J} &= 8.12 & 8.44 \text{ kev} \\ a &= +0.22_5 & +0.19 \\ c &= 0 & 5 \times 10^{-3} \end{aligned}$			

Table XI. Comparison of Rotational Constants

Nuclide	$h^2/2\mathfrak{J}_0$	$h\omega_e$
Ra^{222}	19.8 kev	746 kev
Ra^{223}	8.4 ₄	476
Ra^{224}	14.6	713
Ra^{226}	11.6	662
Th^{228}	9.8	905
Th^{229}	6.2	---
Th^{230}	8.9	753
Th^{231}	5.9	---

$$c = -1/2 \left(\frac{\hbar^2}{\mathfrak{S}_0} \right)^2 \left[3 \left(\frac{1}{\hbar\omega_\beta} \right)^2 + \left(\frac{1}{\hbar\omega_\gamma} \right)^2 \right],$$

where $\hbar\omega_\beta$ and $\hbar\omega_\gamma$ are the energies of excitation of the β and γ vibrational modes.³⁰ As an approximation, the two may be taken as equal and replaced by an effective $\hbar\omega_e$, which may then be evaluated from the observed spectrum. Table X shows the fit which may be obtained for the levels in question with suitable choices of a , $\mathfrak{S}_0$, and c . In Table XI and Fig. 17 the values of $\hbar^2/2\mathfrak{S}_0$ and $\hbar\omega_e$ are compared with the corresponding values for other nuclides in the same region, and may be seen to be not unreasonable. A marked lowering of the $\hbar^2/2\mathfrak{S}$ is noted for the odd-mass nuclides, as has been observed previously in higher mass cases.³² The effect may be understood on consideration of the motion of the unpaired particle; preliminary calculations for cases where the intrinsic wave function are known have yielded excellent agreement.³³

A further verification of the assignment of these levels as a rotational band may be sought from the relative populations of the levels in alpha decay. In the treatment of Bohr, Froman, and Mottelson,³¹ the probability for emission of a certain alpha group is given by

$$P = P_0(Z, E) \sum_L c_L \left[\langle I_i L K_i K_f - K_i | I_i L I_f K_f \rangle + (-)^{I_f + K_f} b_L \langle I_i L K_i -K_f - K_i | I_i L I_f -K_f \rangle \right]^2,$$

where $P_0(Z, E)$ carries all of the energy and atomic-number dependence and may be evaluated from the neighboring even-even nuclides. The ratio $P_0(Z, E)/P$ is then the commonly reported hindrance factor, and c_L is the total reduced transition probability for a wave of angular momentum L between the intrinsic nuclear states in question. The bracketed factor describes in terms of Clebsch-Gordan coefficients the distributions of the wave among the various rotational states based on each intrinsic state. The alternation parameter b_L arises from symmetrization of the wave functions and is thus a function of the intrinsic states in question. Neither the c_L nor b_L are functions of the spin

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Fig. 17. Comparison of rotational constants for a number of nuclides.

and hence are the same for all members of one rotational band; in the absence of detailed knowledge of the intrinsic wave functions, c_L and b_L may be considered parameters to be evaluated from the observations. Waves of the lowest possible L values are expected to predominate in any decay.

The parity of the ground state of Th^{227} relative to that of the ground state of Ra^{223} must be established before the choice of even- or odd- L waves can be made. None of the observed alpha transitions have a hindrance factor of approximately unity, which is the usual characteristic of decay to the level having the same intrinsic function as the ground state of the parent. However, if the analogous state is among those observed, it would seem to be either that at 286.1 kev or one of the group near 330 kev. Since all of these are of the same parity as the ground state, it may be concluded tentatively that the parities of the ground states of Th^{227} and Ra^{223} are the same.

From the comparatively low $\log ft$ value (≈ 7) for the beta decay of Ac^{227} to the ground state of Th^{227} , it appears that the spin of the latter is within ± 1 of that of the former, which has been determined by optical methods to be $3/2$.

The sharp alternation in intensities of the alpha transitions suggests that the predominant waves are subject to sizeable effects of the b_L term. This places a restriction on the possible spin of the parent, as the $\langle I_i, L, K_i, -K_f - K_i \mid I_i, L, I_f, -K_f \rangle$ vanish except for the cases $L \geq |K_i + K_f|$, and the waves of $L < |K_i + K_f|$ will not alternate in intensity. Thus the spin of Th^{227} is not $5/2$, for such a state would give rise to a nonalternating $L = 2$ wave.

With the choice $I_i = K_i = 1/2$ for Th^{227} , the observed intensities of the alpha transitions may be accounted for with $L = 0, 2$, and 4 waves by a suitable choice of c_0, c_2, c_4, b_2 , and b_4 as given in Table XII, there being two sets of values for each of the alternating waves. A check on the plausibility of the values may be made by comparing the ratios c_0/c_2 and c_0/c_4 with those observed in the neighboring even-even isotopes and with those predicted from simple alpha-decay theory. As Table XIII shows, the choices (1) and (3) lead to eminently reasonable ratios.

Table XII. Alpha Intensities to $1/2$ Band from $I = 1/2$ State

Alternative	$c_0 = 9.3_5 \times 10^{-3}$	
	c_2	b_2
(1)	7.1×10^{-3}	-1.40
(2)	$1.6_5 \times 10^{-2}$	-0.43 ₃
	c_4	b_4
(3)	$1.5_7 \times 10^{-3}$	-2.13
(4)	7.8×10^{-3}	-0.343

Table XIII. Comparison of the c_0/c_2 and c_0/c_4

	c_0/c_2	c_0/c_4
Th ²²⁷ , choices (1) and (3)	1.31	5.95
Th ²²⁶	1.3	5.3
Th ²²⁸	0.85	13
Theoretical	1.66	5.4

With the choice $I_i = K_i = 3/2$ for Th^{227} , a fit of the alpha intensities may be made using only $L = 2$ and 4 waves ($L = 0$ would be forbidden since $L \geq |K_i - K_f|$ must be satisfied). Here only four parameters are available: c_2 , c_4 , b_2 , and b_4 . For the values of Table XIV, the populations of the $1/2$, $3/2$, $7/2$, and $9/2$ states were used to evaluate the parameters, and the population of the $5/2$ state serves as an independent check, agreeing well within experimental error. Again, the c_2/c_4 ratio is quite reasonable. (Table XV).

Thus the populations of the ground, 29.8-, 61.3-, 124.2-, and 174.3-kev states by alpha transitions is compatible with their assignment as a $K = 1/2$ rotational band if the spin of Th^{227} is either $1/2$ or $3/2$ with the same parity. Calculation of the c_L and b_L from the wave functions of possible intrinsic states in the Nilsson or Rich models might provide a conclusive assignment for the states.^{34,35}

An attempt may be made to identify the $I = 1/2$ intrinsic state of Ra^{223} by comparison of the rotational-energy decoupling parameter, a , with those expected for states which might possibly be occupied by the 135th neutron. In the Nilsson model, no $\Omega = 1/2$ state is available at (or near) the proper occupation number with the reasonably large deformation indicated by the observed moment of inertia. The only possible state, $1/2 + (6, 4, 0)$, has an a which is negative at $\eta = 2$ and 4 and only becomes positive at $\eta = 6$, where it ought to be occupied by the 113th and 114th neutrons, and thus would not seem to be the correct state. In fairness it should be observed that the decoupling parameter is extremely sensitive to the details of the functions, so that rather small adjustments of the level spacings might bring the value into agreement.

Rich calculates that at deformations of about $\delta = 0.4$, the 135th neutron will be in state 82, $\Omega = 1/2$, for which a has the value $+0.50$ at $\delta = 0.2$ and -0.02 at $\delta = 0.4$, thus crossing the experimental value, $a = +0.19$, near the appropriate region. This state corresponds to Nilsson's $1/2 + (6, 3, 1)$, which is, however, much higher-lying, and is usually assigned as the ground state of Pu^{239} -- accounting well for

Table XIV. Alpha Intensities to 1/2 Band from 3/2 State

Wave	2	4		
c_L	1.99×10^{-2}	7.61×10^{-3}		
b_L	-0.575	-0.71		
State	2	4	Total	Experimental
1/2	0.00920	---	0.00920	0.00935
3/2	0.00145	---	0.00145	0.00145
5/2	0.0147	.00368	0.00184	0.0182
7/2	0.00116	.00018	0.00134	0.00134
9/2	---	.00740	0.00740	0.00740
11/2	---	.00023	0.00023	---

Table XV. Comparison of the c_2/c_4

	c_2/c_4
Th^{226}	4.1
Th^{227}	2.6
Th^{228}	15.3
Th^{230}	10.9
Theoretical	3.3

both the observed decoupling parameter and magnetic moment of that isotope.³⁶ Further evidence will be required for a conclusive state assignment in Ra²²³.

b. Spins of the 50.0- and 286.1-kev states.

Since the 50.0-kev level decays by E1 radiation to the $I = 1/2$ ground state, its spin must be $1/2$ or $3/2$; the observation of an anisotropy in the 236.1 - 50.0 kev cascade demonstrates that the spin of the intermediate state is not $1/2$, hence the 50.0-kev state has spin $3/2$ with parity opposite to that of the ground state. From the values of Table VII, it may be seen that spins of $1/2$ or $5/2$ for the 286.1-kev state are inconsistent with the sign of the anisotropy; hence the spin of this state also must be $3/2$. (The observation of M1 radiation from the 286.1-kev level to ground is also inconsistent with $I = 5/2$.) The reason for the sizeable attenuation is not immediately evident.

c. The 329.8-, 334.3-, 342.6-, and 350.4-kev states.

The spins of these states cannot be uniquely determined from the observed radiations; the possible values are indicated in Fig. 16. A somewhat similar grouping of states is observed in the decay of Ra²²³ to Em²¹⁹. It would seem from the rather similar values for the hindrance factors to these states that perhaps they are interrelated. Discussion of the possible origin of these states will be deferred to Sec. IV-C.

d. Spin of the 234.8-kev level.

The multipolarities of the radiations arising from the level at 234.8 kev admit of the possible spins $1/2$ and $3/2$. The apparent absence of M1 contribution to the 173.5-kev E2 transition suggests that $I = 1/2$ is the more likely.

B. Decay of Ra²²³ (AcX)

The alpha decay of Ra²²³ has been the subject of several studies which have not yielded a well-defined decay scheme and have indeed been somewhat in conflict in experimental observations as well as in interpretation. The alpha spectrum of Ra²²³ was first observed with a magnetic spectrograph by Rosenblum and coworkers,³⁷ but a subsequent observation by Asaro³⁸ revealed significant discrepancies - although the latter work, at least, was hampered by the background from Em²¹⁹, as discussed in Sec. II-A.1 (Table XVI).

Making use of the reported alpha spectra and of gamma and conversion-electron spectra measured by Hahn and Meitner,³⁹ by Surugue,⁴⁰ and by Frilley,⁴¹ two groups recently attempted to elucidate the decay by means of nuclear-emulsion techniques. Bayman and Ross⁴² proposed the two alternative decay schemes shown in Fig. 18. Karlik,⁴³ however, considering the reported alpha decay energy of Ra²²³ to be anomalously low, proposed a markedly different scheme and reported emulsion observations in its support (Fig. 19).

In view of the conflicting reports of the alpha spectrum and the considerable difficulties associated with the emulsion method, an extensive reinvestigation of the decay of Ra²²³ was undertaken.

1. Alpha Spectrum

The alpha spectrum of Ra²²³ was studied with the double-focussing spectrograph and subsequently at somewhat higher resolution with the uniform-field instrument. Figures 20 through 23 show the several spectra obtained, and the data are summarized in Table XVII. As in the study of Th²²⁷, the most accurate value of the dispersion was obtained from an energy measured with the permanent-magnet electron spectrographs, in this case for the transition between the group populating the state at 269.6 kev and the highest energy group. The energies of the groups were determined relative to Th²²⁷ and Cm²⁴² (Sec. III-A.1). It is seen that as many as 14 alpha groups may be present, approximately doubling the number previously known.

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Fig. 18. Alternate decay schemes of Ra^{223} according to Bayman and Ross.

Table XVI. Alpha Groups of Ra²²³

Rosenblum ³⁷		Asaro ³⁸	
E _α (Mev)	I (%)	Δ E _α (Mev)	I (%)
5.860	weak		≤ 1
5.730	9	0	11
5.704	53	31	53
5.596	24	140	25
5.528	9	207	9
5.487	2		≤ 1
5.419	3	315	2

Table XVII. Alpha Groups of Ra²²³

Alpha Particle Energy (Mev)	Abundance (%)	Excited State Energy (kev)	Hindrance Factor
5.867	0.96	(0.0)	7.42 (2) ^b
5.862 ?		4.8	~ 1.5 (4)
5.853	0.3	14.4	2.1 (3)
5.830 ?	0.05	38.0	1.0 (4)
5.742 ± 0.002 ^a	10.5	127.0	2.1 (1)
5.712	50.4	158.9	3.6 (0)
5.602	23.6	(269.6)	2.6 (0)
5.534	10.3	338.5	3.1 (0)
5.497	0.86	376.5	2.6 (1)
5.429	2.4	445.6	4.9 (0)
5.360	0.20	515.6	3.1 (1)
5.334	0.07	541.8	7.0 (1)
5.287 ?	} 0.3	589.6	1.0 (1)
5.282		594.6	

Alpha Decay Energy: 5.974 ± 0.002 Mev

^aRelative to Cm²⁴² α₀, 6.110 Mev.

^bFigure in parentheses indicates power of 10 to be multiplied.

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Fig. 19. Alternate decay schemes of Ra^{223} according to Karlik and Matitsch.

Fig. 20. Alpha-particle spectrum of Ra^{223} - double-focussing spectrograph.

Fig. 2L. Alpha-particle spectrum of Ra^{223} — showing region corresponding to ground state proposed by Karlik.

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Fig. 22. Search for low-energy alpha groups of Ra^{223} .

Fig. 23. Alpha-particle spectrum of Ra^{223} at high resolution — uniform-field spectrograph.

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A group is observed at 5.497 Mev, but the intensity of 0.86% is markedly less than that reported by Rosenblum and is such that Asaro would not have expected to observe it.

The high energy group reported by Rosenblum is shown to consist of two low intensity groups separated by 14.6 kev, with the suggestion of a still weaker group between. The existence of the latter could not be confirmed due to the difficulty of obtaining a spectrum with the combined features of sufficiently good resolution and long enough exposure. As will be discussed, the conversion-electron data yield a decay scheme which indicates unambiguously a level 4.8 kev above the ground state; hence a considerable effort was bent toward observation of the corresponding alpha group.

The spectral region which would include an alpha transition to the ground state proposed by Karlik was examined carefully; no such transition was observed, and a limit of $< 0.03\%$ may be established on the intensity of any group in the region, (Fig. 21).

The existence of groups both at 590 and 595 kev below the highest energy group is not completely certain, as the region is quite near the edge of the only available exposure on which they would appear at high resolution, and it cannot be said with certainty that the width of the peak is not due to instrumental aberrations.

2. Gamma Spectra

a. The gamma-ray spectrum of Ra^{223} is not readily obtainable with a scintillation spectrometer because the sample of necessity contains an equilibrium amount of Em^{219} with its considerable spectrum, and a rapidly growing, if not equilibrated, amount of Pb^{211} , Bi^{211} , and Tl^{207} . Po^{215} is also in equilibrium, but apparently is without gamma radiation. The spectra of Pb^{211} , Bi^{211} , and Tl^{207} may be obtained in a separate experiment and subtracted from that of the Ra^{223} -containing mixture by normalization of the 850-kev peaks (Figs. 24 and 25). A separate study of the Em^{219} spectrum is also possible (Sec. III-C.2), but its subtraction would be more difficult. Fortunately, it has been possible to obtain data on the gamma radiation of Ra^{223} by coincidence methods.

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Fig. 24. Gamma-ray spectra of Ra^{223} and its daughter activities.

MU-13840

Fig. 25. Gamma-ray spectrum of Ra^{223} , Em^{219} , and Po^{215} , obtained as the difference of the two spectra of Fig. 24.

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b. The gamma-gamma coincidence spectrometer was used to test the Karlik decay scheme by gating in turn on the K x-rays, the 144- and 154-keV gamma rays together, and the 270-keV gamma ray. In no case was a significant number of coincidence events detected, as would be required by that decay scheme. It may be concluded that the 270-, 154-, and 144-keV photons each proceed directly to the ground state or a state within the K binding energy (98 keV) of it.

c. By means of the double-focussing alpha spectrometer and the experimental arrangement described in Sections II-A.2 and II-C, the gamma-ray spectrum coincident with each of the major alpha groups of Ra^{223} was studied. The solid angle subtended by the gamma-ray detector was calibrated with the 59.6-keV photons from a standard sample of Am^{241} . The Ra^{223} sample had been prepared on a platinum backing plate, which introduced complications from absorption and fluorescence. The absorption correction was determined by comparison of the counting rates of the simple gamma spectrum with the sample facing into the spectrograph in the customary operating position to that with it rotated through 180° , facing the gamma-ray detector. The K x-rays of platinum which were induced by this absorption appeared in the observed spectrum incompletely resolved from the K x-rays of emanation from the Ra^{223} decay and were subtracted by graphical resolution.

The sum of the K-conversion coefficients of the radiations arising from each excited state was obtained by comparison of the intensities of the K x-rays and the gamma rays observed in coincidence with each alpha group and is subject to the uncertainty in subtracting the platinum K-fluorescence. The total internal conversion of these transitions was obtained from the fraction of photons emitted per alpha transition, and is subject to uncertainties due to the sizeable background of stray alpha radiation but is not subject to the uncertainty from platinum fluorescence. The background correction was determined from the alpha counting rates at the foot and crest of the peak corresponding to each transition. The several spectra are shown in Figs. 26 to 31 and are summarized in Table XVIII.

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Fig. 26. Gamma-ray spectrum coincident with α_{127} of Ra^{223} .

MU-13842

Fig. 27. Gamma-ray spectrum coincident with α_{158} of Ra^{223} .

MU-13843

Fig. 28. Gamma-ray spectrum coincident with α_{270} of Ra^{223} .

MU-13844

Fig. 29. Gamma-ray spectrum coincident with α_{338} of Ra^{223} .

MU-13845

Fig. 30. Gamma-ray spectrum coincident with α_{376} of Ra^{223} .

MU-13846

Fig. 31. Gamma-ray spectrum coincident with α_{445} of Ra^{223} .

Table XVIII. Summary of Ra²²³ α - γ Coincidence Study

Alpha Group	Observed Radiation(kev)	Intensity ¹ photons/alpha	α_K
α_{127}	K x-ray	0.68	
	122	0.19	3.6
α_{158}	K	0.54	
	144	0.082	
	154	0.11	
α_{270}	K	0.41	
	270	0.43	0.95
α_{338}	K	0.25	
	145-155	0.05	
	180	0.05	
	270	0.017	
	338	0.49	0.33
α_{376}	K	0.31	
	376	0.45	0.71
α_{445}	K	0.34	
	445	0.48	0.71 ²

2

1. K x-ray intensity in vacancies/alpha; i.e., the Auger effect correction has been made.
2. A possible cascade was not distinguished with certainty from Compton distribution and backscatter peak.

The angular distribution of the 270-kev photons with respect to α_{270} was also determined, and may be described by:

$$W(\theta) = 1 + A_2 P_2(\cos \theta); \quad A_2 = +0.18.$$

Since the spin of the ground state of Ra^{223} is assigned to be $I = 1/2$, the comparison with theoretical values of A_2 is somewhat simplified, as there can be no mixing of different alpha waves. The spin of the 269.6-kev state must be at least $3/2$, and because of the M1 character of the transition the spin of the ground state must lie within ± 1 of that of the 269.6-kev level. The values for some possible spin sequences are listed in Table XIX. That all of the values are greater than the measured one is not surprising, as alpha-gamma correlations are frequently badly attenuated. Because the sense of the correlation cannot be changed by these attenuations, it may be seen that the sense of the observed correlation is consistent only with the 269.6-kev and ground states having the same spin.

3. Electron Spectrum

Fogging of the emulsions by emanation decay made it impossible to observe the electron spectrum of Ra^{223} with the permanent-magnet spectrographs, except for a few prominent lines which were observed to grow into the Th^{227} spectrum. The double-focussing spectrometer proved less sensitive to this background and provided a considerable amount of information. The spectrum is shown in Fig. 32 and the observed lines, belonging to Ra^{223} , Em^{219} , Pb^{211} , Bi^{211} , and Tl^{207} are tabulated in Appendix A.II. Some of the very weak lines (intensities 1 and 2) must be regarded as of questionable validity, and may be due to statistical fluctuations of the background. Those lines which have been assigned to the decay of Ra^{223} are retabulated in Appendix B.II according to the transitions to which they belong. Table XX lists these transitions, together with their probable multipolarities.

The relative intensities of the conversion lines were related to percentages of the disintegrations of Ra^{223} through the K-conversion coefficient of the 269.6-kev transition, employing the Sliv value of

Table XIX. Angular Correlation Between
 α_{270} and 270 kev Photons, Ra²²³

Experimental:

Radiation	Anisotropy	A_2
270 kev	$\pm 0.30 \pm 0.07$	+0.18
K x-rays	$\pm 0.00 \pm 0.07^a$	0.00

Theoretical:

Spin Sequence			$L(\alpha)$	A_2
I_i	I'	I_f		
1/2	3/2	1/2	1 or 2	-0.500
		3/2	1 2	+0.400
		5/2	1 2	-0.100
	5/2	3/2	2 3	-0.400
		5/2	2 3	+0.456
		7/2	2 3	-0.143
	7/2	5/2	3 4	-0.357
		7/2	3 4	+0.475
		9/2	3 4	-0.167
	9/2	7/2	4 5	-0.334
		9/2	4 5	+0.485
		11/2	4 5	-0.182

a. The isotropy of the x-radiation provides a check on the validity of the measurement.

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Fig. 32. Electron spectrum of Ra^{223} and daughter activities - double-focussing spectrometer.

Table XX. Internal Transitions of Ra²²³

Energy (kev)	Intensity (%)	Multipolarity
31.2	1.4	M1
68.4	0.3 ₄	
122.2	11	M1-E2
143.0	~ 1	(M1 ?)
144.1	19	M1 (Some E2 ?)
154.1	28	M1
158.3	3.2	M1
179.6	1.1	M1
269.6	21.4	M1
323.8	4.9	M1
338.0	4.2	M1
371.1	0.7	M2
440.6	0.6	M2
445.6	1.4	M2
580.4	~ 0.4	

0.90 for an M1 transition, with which the measured value of 0.95 is in good agreement.

The appearance of the 371.1-, 440.6-, and 445.7-keV transitions as M2 is perhaps somewhat surprising, but the measured K- and total-conversion coefficients and the observed intensities of the conversion electrons are all consistent with this assignment. An attempt was made to measure the lifetimes of these transitions with a fast-slow coincidence apparatus of 50 μ sec-resolving time, without success. Due to the low population, the radiations are not observable in an alpha-gamma coincidence spectrum unless the individual alpha group is selected by a spectrometer, but the spread in transit times for alpha particles in the present spectrometer is estimated to be such as to make this experiment unfeasible. The formulations of Moszkowski indicate that the half-lives of these transitions ought to be greater than one μ sec; a determination of the life-time would strengthen the present assignment.

4. Decay Scheme

From the data of the previous sections, the principal features of the decay scheme of Ra^{223} may be established with reasonable certainty, and are shown in Fig. 33. An intensity balance for the principal states is shown in Table XXI, together with a comparison of the energy separations determined from the alpha and electron spectra. The very low populations of the states above 500 keV render the transitions which deexcite them so weak as to be unobserved in the present study, with the exception of the tentative transition of 580 keV which apparently arises from the 595-keV level.

In many features the scheme is similar to Bayman and Ross' second proposal, except that the proposed levels at 144 and 322 keV are replaced by a group of levels at ground, 4.8 keV and 14.6 keV. The emulsion observations of Bayman and Ross would seem consistent with the present scheme.

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Fig. 33. Decay scheme of Ra^{223} .

Table XXI. Energy Sums in Ra²²³ Decay and Intensity Balance

Alpha	Energy Check				Adopted	Intensity Balance			
	Electron					Alpha	Intensity Trans in	Total in	Intensity Trans out
4.8	158.6	445.6							
	<u>154.1</u>	<u>440.6</u>							
	4.5	5.0			4.8	?	41.2	?	?
14.4	158.6	338.0							
	<u>144.1</u>	<u>323.8</u>							
	14.5	14.2			14.5	0.3	24.1	24.4	?
127.0	122.2								
	<u>4.8</u>								
	127.0				127.0	10.5	1.4	11.9	11.9
158.9	158.3	154.1	144.1	127.0					
		<u>4.8</u>	<u>14.5</u>	<u>31.2</u>					
		158.9	158.6	158.2	158.6	50.4	1.1	51.5	51.7
(269.6)	269.6	143.1							
		<u>127.0</u>							
		270.1			269.6	23.6	0	23.6	22.4
338.5	338.0	323.8	179.6						
		<u>14.5</u>	<u>158.6</u>						
		338.3	338.2		238.2	10.3	0	10.3	10.5
376.5		371.1							
		<u>4.8</u>							
		375.9			376.2	0.86			0.7
445.6	445.6	440.6							
		<u>4.8</u>							
		445.4			445.6	2.4		2.4	2.1
594.6		580.4							
		<u>14.5</u>							
		594.9			594.6	0.3	--	0.3	0.4

a. The ground group.

While the existence of the level at 4.8 kev above the ground state was not shown unambiguously in the alpha spectra, its existence is evidenced by the necessity that both the 154.1- and 144.2-kev transitions deexcite the 158.0-kev level, in order that a reasonable intensity balance be achieved. This would require an intermediate state either at 4.8 or 153.2 kev. It would not be expected that a 4.8-kev transition would compete favorably with ones of 144.2 and 158.0 kev; hence the latter alternative is unlikely. The state is further confirmed by the observation of radiations of 440.6 and 445.7 kev in the deexcitation of the 445.6-kev level.

As was remarked in Sec. III-A.5c, there is a distinct similarity between the group of three levels observed here as the ground state of Em^{219} and the group of levels at 330 kev in Ra^{223} . The two groups will be further discussed in Sec. IV. That there is some intrinsic relationship among the ground, 4.8-kev and 14.6-kev states, as opposed to a merely happenstance closeness in energy, is suggested by the similarly large values of the alpha hindrance factors to these levels.

b. The excited states.

Few inferences about the spins of the excited states can be drawn from the multipolarities of the observed transitions until the nature of the ground-state complex is better understood, for additional selection rules based on special quantum numbers within the complex may well be operative, rendering of dubious value any present arguments based on the absence of radiation of a certain multipolarity to one member or the other.

C. Decay of Em^{219} (An)

1. Alpha Spectrum

Because of the 3.92-sec half-life,⁴⁴ the spectra of Em^{219} were studied in samples of Ra^{223} with which the emanation was in equilibrium. Since the product nuclei recoil with considerable kinetic energy after alpha emission, they will either be expelled from the source plate or imbedded in it. Those expelled are no longer in focus in the spectrograph; the alpha spectrum obtained from those remaining in the plate shows significant line-broadening due to energy-loss in the mass of source plate covering the now-imbedded emitting atoms of daughter activity. Hence in the spectra shown here, the Em^{219} alpha lines are considerably broader than those of Ra^{223} from the same source, and the lines of Bi^{211} from these equilibrium sources are still broader.

The samples used in the double-focussing electron spectrometer were not prepared by sublimation but by evaporation of a solution and hence were already somewhat thick. No additional broadening is observed.

Rosenblum⁴⁵ reported four alpha groups in the decay of Em^{219} (Table XXII). In the present work (Fig. 34, Table XXII), the three higher energy groups are observed with substantially the same energy

Table XXII. Alpha Groups of Em^{219}

Group	Particle Energy (Mev)	Abundance (%)	Excited State Energy (kev)	Hindrance Factor
<u>Rosenblum⁴⁵</u>				
α_0	6.807 ^a	69	(0)	
α_{270}	6.542	15	270	
α_{397}	6.417	12	397	
α_{622}	6.197	4	622	
<u>This work</u>				
α_0	6.813±0.002	82	(0)	2.4
α_{271}	6.547	13	271.6	1.2
α_{401}	6.419	5	401	1.2
Alpha Decay Energy: 6.940 ± 0.002 Mev				

^a Recalculated by Briggs.

^b Relative to α_0 of Cm^{242} , taken as 6.110 Mev.

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Fig. 34. Alpha-particle spectrum of Em^{219} and Bi^{211} .

separations and roughly similar intensities; however, the lowest energy group is not observed, and an upper limit of 0.2% may be set for the population of any group lying more than 600 kev lower in energy than the ground-state transition of Em^{219} . The presence of the α_{350} of Bi^{211} would obscure a weak Em^{219} group from 600 to 550 kev below the ground state. However, the intensity of α_{350} of Bi^{211} determined from the spectrum with Em^{219} present is 16.2% and 16.7% in two determinations, to be compared with 16.8% in the absence of Em^{219} . Hence, there is no indication of an Em^{219} group in the region, within a conservative limit of 0.5%. A reexamination of Rosenblum's published spectrum reveals that the suggested group was only partially resolved from the Bi^{211} group, and may well be attributed to broadening of that line due to recoil.

2. Gamma Spectrum

The gamma-ray spectrum of Em^{219} was observed through a technique making use of the gaseous state of emanation. A glass apparatus was set up as in Fig. 35 and evacuated. On the opening of the stopcock A, there was a rush of emanation from the Ra^{223} sample into the section of tube under observation by the scintillation spectrometer. The spectrum was recorded in a few minutes; the stopcock was again closed, and after a minute wait, the spectrum due to the deposit of Pb^{211} , Bi^{211} , and Tl^{207} in the tube was recorded for subtraction from the Em^{219} - Po^{215} spectrum. Gamma rays of 270 and 395 kev were observed in a ratio of 1/0.6. (Fig. 36). Since only one alpha transition is observed in Po^{215} decay, it would not be expected to have associated gamma rays, and thus the two photons belong to the Em^{219} decay, agreeing well with the energy differences between the observed alpha groups. There is no evidence for the 590-kev photon reported by Surugue,⁴⁶ and it is now assigned to the decay of Ra^{223} . The small contribution to the Em^{219} spectrum at about 150 kev is due at least partially to backscattered radiation, and perhaps partly to faulty subtraction of background from the Ra^{223} sample.

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Fig. 35. Diagram of apparatus for the study of the gamma-ray spectrum of Em^{219} .

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Fig. 36. Gamma-ray spectrum of Em^{219} .

3. Electron Spectrum

The conversion electrons of the 271- and 401-keV transitions of Em^{219} were observed in the spectrum of Ra^{223} (Appendix B.II). The intensities of the conversion lines in percent of the disintegrations of Em^{219} were determined on the assumption that the equilibrium amount of Em^{219} was retained by the thick sample with little loss due to recoil or volatility. The validity of this assumption is shown by the excellent agreement of the K-conversion coefficient thus determined for the 350-keV transition of Bi^{211} decay with the value determined by other workers and with the theoretical prediction for M1 radiation.

The 271.6-keV transition is assigned as an 80% E2-20% M1 mixture on the basis of K-conversion coefficient and L-subshell ratios. The K-conversion coefficient of the 400.6-keV transition is less certain, due to the low intensity of the K line; the transition appears to be E2, with some M1 admixture possible.

4. Decay Scheme

The decay scheme of Em^{219} derived from the above data is simple and consistent, both as to energies and intensities of the observed spectra (Fig. 37). The small alpha hindrance factors for the three transitions suggest a possible close relation among the three states of Po^{215} and also with the ground state of Em^{219} .

It was noted many years ago by Rosenblum⁴⁷ that the energies of the excited states are in an apparently simple relationship, the second being very nearly 3/2 the energy of the first, but no physical significance could at that time be attached to this fact. Return to this point shall be made in a general discussion of the decay schemes in Sec. IV.

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Fig. 37. Decay scheme of Em^{219} .

D. Decay of Bi²¹¹ (AcC) and Po²¹⁵ (AcA)

1. Bismuth-211

This study of the alpha spectra of Bi²¹¹ and Po²¹⁵ has revealed no disparity with the previous studies, except for somewhat different values for the energies of the groups, determined relative to Cm²⁴², and a small difference in the separation of the Bi²¹¹ groups. (Figs. 38 and 39; Table XXIII.)

Table XXIII. Alpha Groups of Bi²¹¹ and Po²¹⁵

Group	Particle Energy (Mev) ^a	Abundance	Excited State Energy (kev)
Bi ²¹¹ α ₀	6.617 ± 0.002	83.3	(0)
Bi ²¹¹ α ₃₅₀	6.273 ± 0.002	16.7 ± 0.7	350.6
Po ²¹⁵ α ₀	7.360 ± 0.010	100	(0)
Decay Energy Bi ²¹¹ = 6.745 ± 0.002 Mev			
Po ²¹⁵ = 7.500 ± 0.010 Mev			

^a Relative to Cm²⁴² as 6.110 Mev.

Bi²¹¹ exhibits two alpha groups, populating the ground state and an excited state of 350.6 kev (Fig. 40) The conversion lines of the internal transition were observed in equilibrium with Ra²²³, and their intensities were based on the assumption of no escape of recoiling nuclei from the sample. The K-conversion coefficient determined from this assumption and the intensity of the lower energy alpha group is α_K = 0.24, in substantial agreement with the previous value of 0.18 ± 0.03⁴⁸ and in excellent agreement with Sliv's calculated value of 0.22 for an M1 transition. The shell-model assignments for the two states of Tl²⁰⁷ have been discussed in detail by Perlman and Rasmussen.⁴⁹ A limit of 0.2% may be set for the maximum intensity of any unobserved alpha groups not lying within 100 kev of the observed groups or under Em²¹⁹ groups, where less stringent limits must apply.

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Fig. 38. Partial alpha-particle spectrum of Bi^{211} and Cm^{242} .

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Fig. 39. Alpha-particle spectrum of Po^{211} .

MU-13850

Fig. 40. Decay scheme of Bi^{211} .

2. Polonium-215

Only one alpha group has been observed in the decay of Po^{215} . (Table XXIII). A limit of 0.2% may be established for any group from 100 to 500 kev lower in energy, and of 5% for any group from 20 to 100 kev. The energy of the Po^{215} group was determined relative to the ground state group of Em^{219} , which was in turn related through Bi^{211} to Cm^{242} . Unfortunately, the range of the spectrograph is such that no other group of Em^{219} or Bi^{211} could be observed in the same exposure as the Po^{215} , so an internal calibration of the dispersion of the instrument was not possible. Hence, the energy separation was determined by extrapolation of the known variation of dispersion with magnetic field, and corrections amounting to 3.5 kev for relativistic effects and 1 kev for recoil sample attenuation were applied. The value of 7.360 ± 0.010 Mev thus obtained seems significantly less than the 7.382 ± 0.012 Mev listed by Briggs, but must be held with some reservation because of the long extrapolation.

Simple shell model indicates a neutron configuration $(g_{9/2})^3$ for Pb^{211} ; the first excited state might be expected to be of configuration $(g_{9/2})^2 (i_{11/2})^1$. The $(i_{11/2})^1$ has been observed in the decay of Tl^{209} to Pb^{209} to lie 750 kev above the $(g_{9/2})^1$ ground state,⁵⁰ and thus if configuration interaction be neglected, the first excited state of Pb^{211} might also be expected to be at about 750 kev. An alpha group to a state at that energy unfortunately might underlie the α_0 of Bi^{211} , and further would be expected to have a population of less than 0.1% because of the steep energy dependence of alpha decay.

E. Decay of U^{235} (AcU)

1. Alpha Spectrum and Decay Scheme

The extremely low specific activity of U^{235} has restricted the application of high-resolution spectroscopic methods in its study. The alpha spectrum was obtained by means of an ionization chamber by Ghiorso⁵¹ (Table XXIV), but until the construction of the double-focussing alpha spectrograph in this laboratory, it has not been possible to obtain the higher resolution afforded by the magnetic deflection method. For the avoidance of extreme line broadening due to energy degradation within the source, the mass of the active material must be restricted to $50 \mu\text{g-cm}^{-2}$ or less, while the physical extent of the source is also limited by the line-widths desired. In the case of U^{235} , this has meant restricting the sample to activity levels of less than about 250 dpm. The higher transmission of the double-focussing spectrograph has rendered feasible experiments with such samples. An informative alpha spectrum was obtained from a run of two weeks duration with a sample of 500α dpm, of which approximately half were due to U^{235} , the remainder arising from the small fraction of U^{234} present in the mass-separated material.

Table XXIV. Alpha Groups of U^{235} (Ghiorso)

Energy (Mev)	Abundance (%)
4.58	10
4.47 (?)	~ 3
4.40	83
4.20	4

Gamma-ray studies by Stephens,⁵² together with Ghiorso's alpha spectrum, had established a decay scheme (Fig. 41) which indicated the need for improved resolution of the alpha spectrum. Stephens observed a large number of L x-rays in coincidence with the prominent 186-kev photons and postulated that a state receiving considerable alpha population must lie some 25 or 30 kev above the state at 186 kev.

MU-13851

Fig. 41. Decay scheme of U^{235} , according to Stephens.

The alpha spectrum obtained (Fig. 42) is established with less certainty than the others reported in this work because of the necessarily small numbers of events which could be observed, but clearly indicates that two of the peaks of Ghiorso's spectrum are complex. The highest energy group is resolved into two, separated by about 38 kev, in agreement with the Stephens decay scheme. The most intense group is clearly complex, but is not well resolved. Resolution by graphical methods indicates that it contains four component groups, although the uncertainties are such that the possibility of only three groups is not eliminated. Certainly there appear to be more than the two components originally postulated (Table XXV).

Table XXV. Alpha Groups of U^{235}

Particle Energy (Mev)	Abundance	Excited State	Hindrance Factor
4.559	6.7	0	960
4.520	2.7	40	1200
4.370	25	192	11
4.354	35	209	5.4
4.333	14	230	9.7
4.318	7.9	245	13
4.117 ± 0.004^a	5.8	390	1.5
Decay Energy 4.639 ± 0.015 Mev.			
^a Relative to U^{234} , reported as 4.768 ± 0.002 relative to Po^{210} .			

In a subsequent experiment, the energy of the lowest energy group (α_{386}) was determined relative to that of the highest energy group of U^{234} by comparison of the magnetic fields required to bring first one and then the other to focus in the same region of the plate. The U^{234} energy has been determined to be 4.768 ± 0.005 Mev.⁵³

Fig. 42. Alpha-particle spectrum of U^{235} . Each of the given points represents the sum of four adjacent $1/4$ mm scans, providing an averaging to reduce statistical scatter.

The decay scheme of U^{235} as presently known is shown in Fig. 43. The excitation energies listed for the states reflect the greater accuracy of the measurement of the 186-keV photon in comparison with the uncertain resolution of the alpha spectrum. The 109-keV gamma ray reported by Stephens does not fit any of the known level separations and hence cannot be placed with any certainty.

2. Interpretation of Levels

Th^{231} being well away from the closed-shell region, its energy levels as populated in the decay of U^{235} may be profitably discussed in terms of the collective model.

The nuclear spin of U^{235} has been deduced from optical hyperfine studies to be $I = 7/2$.⁵⁴ From the values of the nuclear magnetic dipole and electric quadrupole moments as determined by coulombic excitation cross-sections and transition mixing ratios, Newton⁵⁵ has identified the state in terms of the asymptotic characterizations of Nilsson,⁵⁶ $\pi(N, n_z, \Lambda)$, as $7/2 - (7, 4, 3)$. Since the alpha decay of U^{235} to the 390-keV level of Th^{231} is essentially unhindered, it appears that this level is the same intrinsic state as the parent and hence is assigned $7/2 - (7, 4, 3)$.

Being populated from the $7/2-$ level by a dipole radiation, the 186-keV level must have spin $5/2$, $7/2$, or $9/2$. Because the 145-keV and 186-keV radiations are also dipole, the spins of the ground and 41-keV levels must both lie between $3/2$ and $11/2$. As it is most likely that the state at 41 keV is the first member of a rotational band based upon the ground intrinsic state, a rotational constant may be calculated for the possible spin values (Table XXVI). A comparison with the constants of the neighboring even-even nuclides indicates that while values of 6 or 8 keV are not unreasonable, those of 4.5 keV or less are considerably too small. Thus it would seem that the possible ground-state spins are $3/2+$ or $5/2+$.

As was discussed in Section III-A.5a, the collective model indicates that alpha populations of the various members of a rotational band are simply related by vector addition coefficients. For the

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Fig. 43. Decay-scheme and state assignments for U²³⁵.

present case, the $L = 1$ and $L = 3$ waves, as the lowest of odd parity, would be expected to predominate in the population of the ground and 41-kev states. The ratios of reduced probabilities to be expected for the possible spins of the states are shown in Table XXVII together with the experimentally determined value. There is no $L = 1$ contribution to the $K = 3/2$ sequence, since the model requires $L \geq |K_f - K_i|$. This spin sequence is inconsistent with the observed intensity ratio, while a mixture of $L = 1$ and $L = 3$ waves will yield the proper value with the $5/2, 7/2$ sequence. The value of c_L , or in the more familiar form c_L^{-1} , which is the hindrance factor for the wave, may be compared with the observed c_L^{-1} for the transition populating the 1- state in the decay of U^{234} , Table XXVIII.

On the basis of these arguments, the ground state spin of Th^{231} is $5/2+$, and the 41-kev level is the first rotational member, $I = 7/2+$. In the region of deformation for which the Nilsson state $7/2- (7, 4, 3)$ appears at the proper occupation number to be the ground state of U^{235} , the next lower state, which would be expected to be the ground state of the nuclide with two fewer neutrons, is $5/2+ (6, 3, 3)$. This, then, is considered to be the ground state of Th^{231} .

The possible spins of the 186-kev level are now limited by the multipolarities of the radiations to $5/2$ or $7/2$ with odd parity. In the Nilsson model, the $7/2- (7, 4, 3)$ state, which correlates with the $j_{15/2}$ orbital in the limit of no spheroidal deformation, is sharply separated from other $7/2-$ states. Hence, once this state is assigned to the 386-kev level of Th^{231} , there is within the model little possibility that the 186-kev level be also $7/2-$.

The strong coupling model indicates that the ratio of the reduced transition probabilities for transitions from a single state to members of a rotational band should be given simply by squares of Clebsch-Gordan coefficients. It would seem profitable to apply this test to the 145- and 186-kev $E1$ transitions in Th^{231} , except that in the several cases where the relationship has previously been checked (Np^{237} , Hf^{177} , and others)^{57,58} it has been found to be violated by as much as several orders of magnitude. With this reservation in mind,

Table XXVI. Rotational Constant for Th^{231}

Ground State Spin	$h^2/2\mathcal{I}$ (kev)
3/2	8.2
5/2	5.9
7/2	4.6
Th^{230}	8.9
U^{234}	7.3

Table XXVII
Expected Alpha Intensities to Th^{231} Ground Band

State		Relative Intensity -Theory-		Experimental
K	I	L = 1	L = 3	
5/2	5/2	0.750	0.119	1.2
	7/2	0.222	0.364	0.96
3/2	3/2	(Forbidden)	0.155	
			0.334	

Table XXVIII
Comparison of c_L^{-1} for Ground Band

	c_1^{-1}	c_3^{-1}
U^{235}	850	740
U^{234}	500	~ 500

the ratio of reduced transition probabilities observed for the 145- and 186-keV E1 transitions may be compared with that expected for the population of $I = 5/2$ and $7/2$ rotational states from an $I = 5/2$ state — and also with that expected for the much less-likely possibility $I = 7/2$. The predicted ratio differs for the two cases, being 0.40 for the former and 0.30 for the latter. The experimental value⁵⁹ of 0.40 ± 0.06 is in agreement with the provisional assignment of $I = 5/2$ for the 186-keV level, and in disagreement with an assignment of $I = 7/2$. However, in view of the many known violations, this disagreement cannot at present serve as definitive evidence in the spin assignment.

The parity of the remaining states may be inferred from the rather low hindrance factors for the alpha transitions to them. The odd parity waves seem to be generally highly hindered in this region of nuclides; hence these states are probably of the same parity as the ground state of U^{235} , that is, odd.

The state at 224 keV may be a rotational member based on the 186-keV state. With spins of $5/2$ and $7/2$, the rotational constant is a quite reasonable 5.5 keV. The somewhat uncertain alpha probability ratio of 0.9 is in satisfactory agreement with the 1.05 expected for $L = 2$ to states of these spins. A probable state in the Nilsson scheme is $5/2^- (7, 5, 2)$.

The states at 203 and 239 keV may be members of another rotational band. The energy separation yields reasonable rotational constants for base spins of $3/2$ or $5/2$, although a band with $K = 1/2$, because of its decoupling term, cannot be eliminated. The alpha probability ratio is somewhat uncertain, but does not yield outstanding agreement with either $I = 3/2$ or $I = 5/2$ (Table XXIX). Despite the uncertainties in resolution of the alpha spectrum, it seems clear that the ratio is significantly greater than 1.05, ruling out the $I = 5/2$ possibility. The expected ratio for an $I = 1/2$ band is indeterminate, since the symmetrization term in $b_{1/2}$ will be operative. Possible odd-parity states of the Nilsson model are $3/2^- (7, 6, 1)$ and $1/2^- (5, 0, 1)$. The similarity of the hindrance factors to the 186- and 203-keV states suggest that perhaps the intrinsic functions of the two

states are closely related, in which case the assignment $3/2^- (7,6,1)$ would be preferred. Although the selection rules for alpha decay have not been established for the Nilsson functions, one might expect to observe a sizeable difference in rate for transitions between $7/2^- (7,4,3)$ and the final states $5/2^- (7,5,2)$ and $1/2^- (5,0,1)$ because of the sizeable changes in the asymptotic quantum numbers in the latter case.

Table XXIX. Relative Alpha Intensities to $3/2^-$ and $5/2^-$ Bands

K	I	L = 2	Ratio
$5/2^-$	$5/2^-$	0.416	
	$7/2^-$	0.399	1.04
$3/2^-$	$3/2^-$	0.500	
	$5/2^-$	0.334	1.50
Experimental			
States			
	186, 224		0.9
	204, 239		2.4

The internal transition selection rules based on the Nilsson asymptotic quantum numbers may be compared with the observed transitions. Because of the lack of general familiarity, these rules are summarized in Table XXX for the transitions in question. The selection rules fall into several categories: (1) $L \geq \Delta I$ is a rigid conservation law, independent of the nuclear model; (2) $L \geq \Delta K$ is a selection rule for the deformed nucleus in first order, but states of $K = K_0 \pm 1$ may be mixed by the Coriolis interaction; and (3) the quantum numbers of the Nilsson model, N , n_z , and Λ , become constants of motion only in the limit of extreme axial deformation. Since the nuclear deformation is not extreme, selection rules in N , n_z , and Λ are expected to hinder rather than absolutely forbid the various transitions.

Table XXX. Selection Rules for Internal Transitions in
The Nilsson Model

E1				
ΔK	Operator	ΔN	Δn_z	$\Delta \Lambda$
1	$x+iy$	1	0	1
0	z	1	1	0
M1				
ΔK	Operator	ΔN	Δn_z	$\Delta \Lambda$
1	l_+	0, 2	1	1
	s_+	0	0	0
0	l_z	0, 2	0	0
	s_z	0	0	0
E2				
ΔK	Operator	ΔN	Δn_z	$\Delta \Lambda$
2	$(x+iy)^2$	0, 2	0	2
1	$z(x+iy)$	0, 2	1	1
0	$2z^2 - x^2 - y^2$	0, 2	0, 2	0
M2				
ΔK	Operator	ΔN	Δn_z	$\Delta \Lambda$
2	$l_+(x+iy)$	1, 3	1	2
	$s_+(x+iy)$	1	0	2
1	$l_z(x+iy)$	1, 3	0	1
	$l_+ z$	1, 3	0, 2	1
	$s_z(x+iy)$	1	0	1
	$s_+ z$	1	1	0
0	$l_+(x \pm iy)$	1, 3	1	0
	$l_z z$	1, 3	1	0
	$s_+(x \pm iy)$	1	0	1
	$s_z z$	1	1	0

The observation of a transition directly from the 390-kev level to ground has been reported, but Stephens has shown that the 390-kev peak in the gamma-ray scintillation spectrum is due to the "stack-up" effect in which the cascade photons of 200 kev and 186 kev enter the detector simultaneously.⁶⁰ With the present assignment of states, the failure of an E1 transition of this energy to compete with the 200-kev M1 may be attributed to a forbiddenness in both the operators $(x + iy)$ and (z) . The E1 transition involves $\Delta K = 1$, $\Delta N = 1$, $\Delta n_z = 1$, $\Delta \Lambda = 0$, which is forbidden in n_z and Λ for $(x + iy)$, or in ΔK for operator (z) . The 200-kev M1, however is an allowed transition for the l_+ operator.

The transitions from the 186-kev level require $\Delta K = 1$, $\Delta N = 1$, $\Delta n_z = 2$, $\Delta \Lambda = 1$, which is doubly forbidden in n_z . The apparent delay of 1 msec (Stephens) may be the result of this forbiddenness.

The 203-kev state is not observed to decay to the ground-state band, but rather to cascade through the 186-kev state, indicating that the 203-kev transition to ground must be highly hindered with respect to the 17-kev transition. The transitions for the two possible Nilsson states are most conveniently compared in the form of Table XXXI. The $3/2^- (7,6,1)$ is seen to satisfy the condition of preferring to decay to the $5/2^- (7,5,2)$, but for the $1/2^- (5,0,1)$ the competition of a six-fold hindered E2 with a two-fold hindered M2 is certainly ambiguous.

Table XXXI. Selection Rules for Transitions from the Possible Assignments for the 204 kev Level

Transition	State	
	1/2-(5,0,1)	3/2-(7,6,1)
E1 to ground	$\Delta I = 2$	$\Delta I = 1$
	$\Delta K = 2$	$\Delta K = 1$
	Forbidden	$\Delta N = 1$
		$\Delta n_z = 3$ 2-fold hindered
		$\Delta \Lambda = 2$ 2-fold hindered
42 to ground	$\Delta I = 2$	
	$\Delta K = 2$	
	$\Delta N = 1$	
	$\Delta n_z = 3$ 2-fold	
	$\Delta \Lambda = 2$	
M1 to 186 kev level	$\Delta I = 2$	$\Delta I = 1$
	$\Delta K = 2$	$\Delta K = 1$
	Forbidden	$\Delta N = 0$
		$\Delta n_z = 1$
		$\Delta \Lambda = 1$ Allowed
E2 to 186 kev level	$\Delta I = 2$	$\Delta I = 1$
	$\Delta K = 2$	$\Delta K = 1$
	$\Delta N = 2$	$\Delta N = 0$
	$\Delta n_z = 5$ 5-fold	$\Delta n_z = 1$
	$\Delta \Lambda = 1$ 1-fold	$\Delta \Lambda = 1$ Allowed

IV. GENERAL DISCUSSION

A. Preliminary

In this study of nuclides of the actinium family, we have passed from a nuclear system of typically spheroidal nature, through the intermediate coupling region -- encountering the complexity foretold for it, and into an equally typical single-particle system. The nuclear level system of Th^{231} populated in the alpha decay of U^{235} yielded readily to interpretation in terms of the unified model of Bohr and Mottelson and of Nilsson. On the other hand, the decay of Bi^{211} is clearly interpretable in the single-particle model, and the very featurelessness of Po^{215} decay is single-particle in nature.

Having contributed in the foregoing sections toward the first goal of this thesis -- the providing through precision spectroscopy of detailed knowledge of some decay schemes of the intermediate region, it now remains for us to note what similarities or system can be inferred therefrom.

As one approach, the first effect of the onset of spheroidal shape can be treated as the splitting of the $(2j + 1)$ -fold degenerate spherical-well binding states under the influence of the axial field. Each state would be split into $(j + 1/2)$ doubly degenerate levels characterized by Ω , the projection of j on the nuclear axis. In first order, the splitting of the levels would be of the form ⁶¹

$$E = \eta C \{3\Omega^2 - j(j+1)\},$$

where C represents an interaction constant which might also be some function of the deformation, η . In second order, mixing of states of the same Ω but different j are introduced. It is a procedure of this sort which Nilsson has employed to obtain the functions which have enjoyed considerable success in regions of large deformation. As nucleons are added beyond the closed shell, the initial deformation is expected to be toward oblate shape (negative η), with an early shift to prolate (positive η). ⁶² The usual applications of the model have been in the prolate region.

B. The level schemes of Po^{215} , Em^{219} , and Po^{213}

The first-order splitting formula affords a possible explanation of the levels of Po^{215} . The shell-model state occupied at neutron numbers just above 126 is the $g_{9/2}$, which under small oblate deformation would be split into five levels with energies in terms of ηC as in Fig. 44, the levels being degenerate in $+\Omega$ and $-\Omega$. In the ground state of Po^{215} , the five neutrons beyond the $N = 126$ closed shell would be distributed to fill the $\Omega = 9/2$ and $\Omega = 7/2$ levels with the odd neutron in the $\Omega = 5/2$ level. The low-lying excited states should consist of promotion of the odd neutron to the $\Omega = 3/2$ and $1/2$ states, with excitation energies of $12 \eta C$ and $18 \eta C$, or a ratio of 2:3. The experimental ratio of 271.6:400.6, or 2:2.96, would be in excellent agreement with the model, yielding a splitting constant $\eta C = 22.4$ kev (Fig. 45).

In this model, the ground state of Em^{219} would then be the $\Omega = 3/2$ level, with the $1/2$ level appearing as an excited state, and perhaps the $5/2$ level appearing also by promotion of one of its neutrons to pair in the $3/2$ orbital. The observed levels at 127.0 and 269.6 kev might represent these two configurations, having an energy ratio of 1:2.12, in comparison with the 1:2.00 of the model, and an average $\eta C = 21.8$ kev. The situation is complicated, however, by the appearance of other excited states -- which might of course be from states of different j , and by the apparent splitting of the ground state into a close-lying multiplet. A further point is the wide disparity in alpha hindrance to these levels, in contrast to the similarity in the values for the states in Po^{215} .

Another test of the model would be the levels of Po^{213} , for which the ground state would be the $\Omega = 7/2$ level. The first excited state would be expected to be the $\Omega = 5/2$, at some $18 \eta C$ above ground. The excited state reported by Magnusson⁶³ lies at 437 kev, which would yield $\eta C = 24.3$, not greatly different from the values for Po^{215} and Em^{219} . Pb^{211} contains the same number of neutrons as Po^{213} , and might therefore have been expected to display the same energy levels. However, containing a closed shell of protons, it would be less likely to possess non-

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Fig. 44. Perturbation effect of an oblatly spheroidal deformation on the $g_{9/2}$ level.

Ω	$E(-\eta C)$										
$\pm 1/2$	—	24	—	—	—	—	*	—	—	*	—
$\pm 3/2$	—	18	—	—	—	*	—	—	*	—	**
$\pm 5/2$	—	6	—	*	*	—	—	or **	**	**	*
$\pm 7/2$	—	-12	*	—	**	**	**	*	**	**	**
$\pm 9/2$	—	-36	**	**	**	**	**	**	**	**	**
Nuclide		Po^{213}		Po^{215}		Em^{219}					
Energy	$(-\eta C)$	(0)	18	(0)	12	18	(0)	6	12		
	(kev)	(0)	437	(0)	271.6	401	(0)	127.0	269.6		
$-\eta C$ (kev)			24.3		22.6	22.3		21.2	22.4		

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Fig. 45. Tentative assignment of configurations for some states in the intermediate region.

spherical shape, accounting for the lack of similarity.

The magnitude of the splitting constant has been estimated in the hydrodynamic model by Bohr and Mottelson⁶¹ to be

$$\sqrt{\frac{5}{4\pi}} k \beta \cos \gamma \frac{1}{4j(j+1)},$$

where k is the coupling-constant, about 40 Mev, and β is the deformation. On this basis, a splitting constant of 20 kev would be achieved for the $g_{9/2}$ levels at $\beta \simeq 0.07$, a value which is (as expected) quite small in comparison with the 0.3 to 0.4 found on this model in the clearly rotational region.

C. Level schemes of Em^{219} and Ra^{223}

As has already been pointed out, there is observed in the level systems of both Em^{219} and Ra^{223} an apparent multiplet of close-lying levels, being the ground state of the former and having some 330 kev of excitation in the latter. That there is some direct relation among the several levels in each nuclide to justify the term multiplet has already been argued in Sections III-A.5c and III-B.4a. It remains then to suggest a relationship between the multiplet in Em^{219} and that in Ra^{223} .

The energy spacings of the Em^{219} group, 4.8 and 14.6 kev, are only a bit larger than the corresponding spacings, 4.5 and 12.8 kev, in Ra^{223} and are in approximately the same 1:3 ratio. However, if the states at 38 kev in Em^{219} and 350.4 kev in Ra^{223} are analogous and members of the multiplet, their relative spacings are quite dissimilar — 38 opposed to 20.6 kev.

A plausibility argument may be offered from the alpha-decay hindrance factors. The alpha decay of Th^{227} to the ground-state rotational band is markedly hindered, while that to the multiplet is not — arguing a dissimilarity between the two. The decay of Ra^{223} to the ground multiplet of Em^{219} is also very hindered, arguing a dissimilarity between these two. While things both unlike a common thing are not therefore alike, such likeness would not be inconsistent. Further, one

of the transitions of lowest hindrance in the Ra^{223} decay is that to the 338-kev level; if it is the analogous state to that of the parent, its separation from the ground multiplet is very nearly the same as from the excited multiplet in Ra^{223} . An additional support for identification of the 338-kev level of Em^{219} with the ground state of Ra^{223} is the presence of two levels of the opposite parity not far above in each case.

It is not at all clear what is the origin of this multiplet structure. The first members follow closely an n^2 energy dependence — it may be that this is the $3\Omega^2 - j(j+1)$ splitting described in Section IV-B, rather than the large spacings in Po^{215} , but it is difficult to see how the many levels of these nuclides may be explained if this splitting is only now beginning.

Another source of an n^2 dependence might be found in additional terms of the rotational energy, which is in general given by⁶⁴

$$W_{\text{rot}} = \frac{\hbar^2}{2\mathcal{I}_3} (K - \Omega)^2 + \left(\frac{\hbar^2}{4\mathcal{I}_1} + \frac{\hbar^2}{4\mathcal{I}_2} \right) \{ I(I+1) - K^2 - j(j+1) - \Omega^2 - (-)^{I-j} (j+1/2) (I+1/2) \delta_{j,1/2} \delta_{K,1/2} \}.$$

From the appearances of the spectra in the strong-coupling region, it has usually been considered that $\mathcal{I}_3$ is very much less than $\mathcal{I}_1$ and $\mathcal{I}_2$, so that states of $K \neq \Omega$ would be very high-lying and unobserved. Perhaps the multiplet observed here indicates that the moments are more nearly equal in the intermediate region, or perhaps for one especial intrinsic state, which happens to lie in this region.

Yet another possibility is that the multiplet be a result of a lack of preference for oblate or prolate deformation, giving rise to a low-energy vibrational mode.⁶⁵ The expected change from oblate to prolate must occur in the vicinity of mass 220, for in the even-even nuclei in this region the characteristic rotational bands are beginning to appear.

It is also in this region that the 1- states are observed in the even-even nuclei; it is considered that they are evidence for an additional deformation of inversion non-symmetric shape (pear shape).⁶⁶

Perhaps this phenomenon is not unrelated to the multiplet structure.

Further similarities between these two decay schemes are not apparent, and it is readily admitted that those which have been suggested are quite tenuous. A possible system of intrinsic levels summarizing the above arguments is shown in Fig. 46, but should be regarded with considerable reserve.

Energies of excited states
given in kev.

$\pi\pi\pi 0$
 Po^{213}

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Fig. 46. Tentative level-correlations among some nuclides in the intermediate region.

V. PERORATION

Understanding of the intermediate region remains beyond us. A start has been made: the collective-model interpretations which elucidate the U^{235} decay have been shown to have application to some of the levels of Ra^{223} ; a perturbation from the spherical well may explain the levels of Po^{215} and have some application to Em^{219} ; but many features of Ra^{223} and Em^{219} remain unexplained, and the considerations of the preceding section must be recognized for what they are — speculation. It must be regarded as the principal achievement of this study that while these features are still not understood, they largely do not remain uncertain or unsuspected. There is evident need for further investigation in the intermediate region, on the many other nuclides and, as well, on these subjects of the present study — for just as the newer techniques employed and the higher resolution achieved here have clarified old difficulties and revealed new, still-puzzling phenomena, so too any subsequent studies reaching lower in intensity or finer in resolution will certainly reveal other states and other transitions to contribute to our understanding. It remains only to be hoped that in such studies not too much of the present one be found in error.

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Appendix A-I
Conversion-electron lines in the decay of Th^{227} .

Magnetic Rigidity (gauss-cm)	Energy (kev)	Intensity (%)	Assignment Shell E	Magnetic Rigidity (gauss-cm)	Energy (kev)	Intensity (%)	Assignment Shell E
313	8.53d	0.27		767.12	49.45	0.4	L_I 68.6
322	9.04d	0.84	K_{II} 113.0	773.39	50.09	0.3	L_{II} 68.6
350.29	10.68	1.9	L_I 29.8	797.63	53.18	0.14	L_{III} 68.6
360.68	11.31	6.9	L_{II} 29.8	812.53	55.09	0.16	
375	12.22d	0.57		818.21	55.74		Ra
379.18	12.49	2.2	L_I 31.6	826.35	56.85	0.81	M_{II} 61.3
389	13.20	2.5	L_{II} 31.6	831.63	57.	0.65	M_{III} 61.3
408.73	14.48	8.7	L_{III} 29.8	836.22	58.05	W	M_{IV} 61.3
426	16.16	3.3	L_{III} 31.6	840.46	58.75	W	
470	19.07d	0.23		852.66	60.43	0.62	L_I 79.7
516.93	22.98	W		858.78	61.21	0.24	L_{II} 79.7
522.47	23.47	W		880.12	64.09	0.15	L_{III} 79.7
526.87	23.85	0.40	Ra	887	65.04 d	0.09	$KL_I L_I$ Auger
540.30	25.06	1.2	M_I 29.8	893.456	65.95	0.05	$KL_I L_I$ Auger
543.50	25.35	2.4	M_{II} 29.8	913.21	68.72	0.15	
550.97	26.03	3.6	M_{III} 29.8	918.02	69.40	0.15	K 173.3
558.77	26.76	0.9	M_I 31.6	923.45	70.18		
561.87	27.05	1.5	M_{II} 31.6	953.40	74.51	0.08	M_I 79.7
569.78	27.80	1.3	M_{III} 31.6	958	75.17 d	0.08	M_{II} 79.7
580.79	28.85	2.2	N_{II} 29.8	963	75.93 d	0.08	M_{III} 79.7
581.64	28.93		N_{III} 29.8	975.40	77.75		
589.99	29.75	1.2	L_{II} 48.1	979.32	78.34	0.08	
596.27	30.37		N_I 31.6	985.30	79.23	0.08	
600.73	30.81	1.7	L_I 50.0	992.28	80.29	0.05	
605.17	31.25			996.03	80.85	0.08	L_I or Auger 100.1
608.77	31.64	1.3	L_{II} 50.0	1001.02	81.60	0.40	L_{II} 100.1
620.10	32.77	0.87	L_{III} 48.1	1021.55	84.74	0.32	L_{III} 100.1
638.40	34.64	1.6	L_{III} 50.0	1083.82	94.55	0.43	L_{II} 113.0
657.92	36.75	0.2		1091.34	95.76	0.08	M_{II} 100.1
662.02	37.19	0.2		1094.26	96.24	0.05	M_{III} 100.1
712.68	42.85	3.8	L_{II} 61.3	1103.08	97.51	0.24	L_{III} 113.0
720.04	43.67	0.38	M_{II} 48.1	1123.93	101.09	0.24	K 205.2
725.39	44.32	0.22	M_{III} 48.1	1144.98	104.59	0.09	Ra
733.29	45.28		M_I 50.0	1168.61	108.22	0.23	K 212.1
736.00	45.60		M_{II} 50.0	1171.34	108.99		M 113.0
738.69	45.91	3.4 ²	L_{III} 61.3	1183.27	111.04	0.07	
741.56	46.26		M_{III} 50.0	1190.27	112.25		N 113.0
748.30	46.95	0.11	M_V 50.0	1205.816	114.94	0.13	
756.75	48.10	0.07		1216.14	116.73	W	Ra
763.01	48.86	0.07	N_I 50.0	1223	117.92 d	0.07	

1. d - indicates energy determined with the double-focussing spectrometer only, hence somewhat less precise.
2. An additional contribution from Ra^{223} is also present.

Appendix A-I (cont'd.)
Conversion-electron lines in the decay of Th^{227} .

Magnetic Rigidity (gauss-cm)	Energy (kev)	Intensity (%)	Assignment Shell E	Magnetic Rigidity (gauss-cm)	Energy (kev)	Intensity (%)	Assignment Shell E
1269.97	126.24	0.15	Ra	1840	240.94 d	0.13	Ra
1274	126.97	0.11 d		1887.999	251.56	0.14	
1296.10	130.95	0.40	K 234.8	1905	255.3 d	0.08	N _{II} 256.4
1303.06	132.21	0.49	K 236.1	1952	265.9 d	0.08	Ra
1325.047	136.24	0.20	Ra	1957	267.1 d	0.11	L _{II} 286.1
1334.36	137.59	0.08		1967	270.29 d		L _{III} 286.1
1365.499	143.75	0.05	K 247.7	2003	277.48 d		L _{II} 296.0
1379.72	146.42	0.23	K 250.3	2016	280.45 d	0.08	L _{III} 296.0
1411.617	152.52	0.57	K 256.4	2018	280.91 d	0.08	M _I 286.1
1421.183	154.33	0.05	L 173.3	2035	284.8 d	0.12	L _I 304.5
1438	157.56	0.08 d	L _{III} 173.3	2040	285.97 d		L _{II} 304.5
1492	168.11	0.09 d	M _I 173.3	2047	287.5 d		Ra
1507.82	171.24	0.62	Ra	2054	289.2 d		Ra
1516.107	172.89	W		2071	293.12 d		L 312.7
1524.392	174.15	W		2097	299.15 d		M _I 304.5
1531.730	176.03	0.09	K 280.0	2101	300.09 d		M _{II} 304.5
1540.110	177.70	0.14		2162	314.36 d	0.08	L _I 334.3
1559.21	181.54	W		2185	319.79 d	0.05	
1562.928	182.31	0.57	K 286.1				
1568.33	183.40	W					
1580.04	185.78	0.11	L _I 205.0				
1588.39	187.49	0.67					
1614.678	192.88	0.23	K 296.0				
1630	196.0 d						
1652.045	200.62	0.60	K 304.5				
1690.829	208.78	0.21	K 312.7				
1723	215.6 d	0.11	L _I 234.8				
1729.009	216.88	0.14	L _I 236.1				
1752.045	221.166						
1769.806	225.64	0.12	Ra				
1771	225.8 d	0.09	K 329.7				
1791.74	230.40	0.32	K 334.3				
1804.57	233.2						
1825.774	237.82	0.40	L _{II} 256.4				
1839.937	240.86	0.19	L _{III} 256.4				

Appendix A-II
Conversion-electron lines in the decay of Ra^{223} , Em^{219} ,
 Po^{215} , Pb^{211} , Bi^{211} , and Tl^{207} .

Magnetic Rigidity (gauss-cm)	Energy (kev)	Intensity (%)	Assignment Nuclide	Shell	E ¹	Magnetic Rigidity (gauss-cm)	Energy (kev)	Intensity (%)	Assignment Nuclide	Shell	E
265	6.14					964	76.06				
297	7.70					975	77.69				
300	7.85					988	79.64				
310	8.38					1000	81.45	0.42	Ra	K	149.6
335	9.78					1078	92.62				
347	10.48					1095	96.35				
355	10.97					1103	97.65				
362	11.40					1113	99.29				
388	13.07	1.1	Ra	L _I	31.2	1143	104.25	1.7	Ra	L _I	122.2
472	19.23					1150	105.42	0.36	Ra	L _{II}	122.2
475	19.41					1154	106.10				
500	21.53					1165	107.94	0.12	Ra	L _{III}	122.2
511	27.47					1181	110.67				
518	23.08					1197	113.41				
575	23.69	4.0	Ra	K	122.2	1221	117.57	0.56	Ra	M _{I,II}	122.2
560	26.87	0.3	Ra	M	31.2	1240	170.92	0.1	Ra	N	122.2
567	27.53					1245	121.80				
573	28.10					1269	126.08	2.8	Ra	L _I	144.2
598	30.54					1274	176.96	0.32	Ra	L _{II}	144.2
615	32.25					1290	179.84	0.11	Ra	L _{III}	144.2
630	33.79					1295	130.76				
663	37.30					1325	136.24	4.0	Ra	L _I	154.0
677	38.83					1343	139.57	0.92	Ra	M _{I,II}	144.2
684	39.61					1348	140.48	0.30	Ra	M _{III}	144.2
703	41.76									L _I	158.6
728	44.66	0.84	Ra	K	143.1	1360	142.72	0.19	Ra	N	144.2
738	45.84	10.4	Ra	K	144.2	1386	147.62				
745	46.67					1395	149.31	0.97	Ra	M _I	154.1
755	47.89					1410	152.18				
765	49.11					1414	152.94	0.5	Ra	N _I	154.1
817	55.67	17.	Ra	K	154.1	1421	154.28	0.19	Ra	M _I	158.6
842	58.95					1427	154.43				
845	59.35					1438	157.56				
850	60.02	1.7	Ra	K	158.6	1455	160.85				
860	61.36					1463	162.41	0.1	Ra	L _{II}	149.6
870	62.72					1468	163.40				
890	65.47					1493	168.70				
893	65.88					1508	171.28	9.2	Ra	K	269.5
978	70.83					1519	173.47				
943	72.99					1531	175.87	0.1	Ra	M _{II}	179.6

1. All unassigned lines are weak. Some undoubtedly belong to the decay of Pb^{211} and Tl^{207} ; others may simply be the result of fluctuation of the instrumental background.

Appendix A-II (cont'd.)
Conversion-electron lines in the decay of Ra²²³, Em²¹⁹,
Po²¹⁵, Pb²¹¹, Bi²¹¹, and Tl²⁰⁷.

Magnetic Rigidity (gauss-cm)	Energy (kev)	Intensity (%)	Assignment Nuclide Shell E	Magnetic Rigidity (gauss-cm)	Energy (kev)	Intensity (%)	Assignment Nuclide Shell E
1539	177.47			2180	318.61		
1545	178.68	1.4	Em K 271.6	2185	319.79	0.31	Ra L _I 338.0
1550	179.69			2241	333.14	0.09	Ra M _I 338.0
1597	189.24			2250	335.24	0.8	Bi L _I 350.6
1642	198.54						Pb K 425.0
1651	200.41			2280	342.42	0.20	Ra K 440.6
1687	207.96			2295	347.00	0.39	Ra K 445.6
1693	209.23			2378	366.14		
1703	211.35			2390	369.06		
1725	216.02			2402	371.99		
1737	218.58			2410	373.95		
1741	219.43			2449	383.62	0.18	Em L _{I,II} 400.6
1750	221.37			2456	387.49		
1762	223.96			2490	393.64		
1770	225.68	1.7	Ra K 323.8	2550	408.54		
1815	235.46			2573	414.27		
1824	237.42			2626	477.56	0.17	Ra L _I 445.6
1835	239.84	0.98	Ra K 338.0	2745	451.67		
1888	251.56	1.9	Ra L _I 269.6	2761	461.76		
1890	252.00	0.1	Ra L _{II} 269.6	2788	468.66		
1900	254.23	0.44	Em L _I 271.6	2810	474.29		
1902	254.68	0.51	Em L _{II} 271.6	2825	478.14		
1916	257.80	0.22	Em L _{III} 271.6	2840	481.99	0.07	Ra K 580.4
1949	265.22	3.1	Bi K 350.6	2856	486.10		
1957	267.03	0.21	Em M _{I,II} 271.6	2867	488.94		
1982	272.70	0.22	Ra K 371.1	2896	496.42		
1998	276.34			2928	504.70		
2021	281.20			2934	506.26		
2042	286.42			2950	510.41		
2047	287.56			2975	516.90		
2055	289.41			2988	520.28		
2115	303.34			3055	537.78		
2126	305.92	0.42	Ra L _I 323.8				
2134	307.79	0.32	Em K 400.6				
2138	308.72						
2140	309.20	0.22	Ra L _{III} 323.8				
2145	310.37						
2150	311.54						
2152	312.01						
2157	313.19						

Appendix B-I
Internal transitions in the decay of Th^{227} .

Line Energy (kev)	Shell	Transition Energy (kev)	Intensity (%)	Multipolarity	Remarks
10.68	L _I	29.91	1.9		
11.31	L _{II}	29.95	6.9		
14.48	L _{III}	29.92	8.7		
25.06	M _I	29.81	1.2		
25.35	M _{II}	29.82	2.4		
26.03	M _{III}	29.81	3.6		
obsc.?	M _{IV}		0.4		
	M _V				
28.85	N _{II}	29.89	2.2		
28.93	N _{III}	29.80			
		29.8	26.9	M1-E2	
12.49	L _I	31.66	2.2		
13.20	L _{II}	31.67	2.5		
16.16	L _{III}	31.63	3.3		
26.76	M _I	31.57	0.9		
27.05	M _{II}	31.56	1.5		
27.80	M _{III}	31.67	1.3		
	M _{IV,V}	missing			
	N _{II,III,0}	obsc.			
		31.6	11.7	M1-E2	
	L _I	obsc.			
29.75	L _{II}	48.22	1.2		
32.77	L _{III}	48.21	0.87		
	M _I	missing			
43.67	M _{II}	48.14	0.38		
44.32	M _{III}	48.10	0.22		
	M _{IV,V}	missing			
47.08	N _{II}				
		48.2	2.67	E2	
30.81	L _I	50.04	1.67		M2 photons less 10^{-4}
31.64	L _{II}	50.08	1.32		of E1.
34.64	L _{III}	50.08	1.56		
45.28	M _I	50.09			
45.60	M _{II}	50.07	(1.5)		
46.26	M _{III}	50.04			
47.08	M _{IV,V}				
	Photon		7.5		
		50.0	13.5	E1(M2)	

Appendix B-I (cont'd.)
Internal transitions in the decay of Th^{227} .

Line Energy (kev)	Shell	Transition Energy (kev)	Intensity (%)	Multipolarity	Remarks
	L_I	missing			
42.85	L_{II}	61.32	3.8		
45.91	L_{III}	61.35	3.4		
	M_I	missing			
56.85	M_{II}	61.32	0.81		
57.58	M_{III}	61.30	0.65		
58.10	M_{IV}	61.29	.02		
obsc.	$N_{II,III}$		~0.5		
obsc.	0		.09		
		61.3	9.0	E2	
49.45	L_I	68.68	0.38		
50.09	L_{II}	68.56	0.30		
53.18	L_{III}	68.65	0.14		
		68.6	0.8		Unassigned
60.43	L_I	79.66	0.16		
61.21	L_{II}	79.68	0.16		
64.09	L_{III}	79.53	0.16		
74.51	M_I	79.32			
75.17	M_{II}	79.64	0.24		
75.93	M_{III}	79.80			
	$M_{IV,V}$	missing?			
78.34	N_I	79.54	0.08		
79.23	0				
	Photon		(3.6)		
		79.7	4.6	E1	
80.85	L_I	100.08	0.08		L_I may be an Auger line.
81.60	L_{II}	100.07	0.40		
84.74	L_{III}	100.04	0.32		
95.76	M_{II}	100.23	0.08		
96.24	M_{III}	100.11	0.05		
		100.1	1.0	E2(M1?)	
9.04	K	112.96	0.84		
	L_I	missing			
94.55	L_{II}	113.02	0.43		
97.51	L_{III}	113.01	0.24		
	Photon		(2.7)		
		113.0	4.2	E2	

Appendix B-I (cont'd.)
Internal transitions in the decay of Th^{227} .

Line Energy (kev)	Shell	Transition Energy (kev)	Intensity (%)	Multipolarity	Remarks
59.40	K	113.32	0.14		
154.33	L_{II}	112.80	0.05		
151.50	L_{III} Photon	113.00	0.08 (0.1)		
		113.3	~1	E2	
101.01	K	205.01	0.24		
185.13	L_I Photon	205.01	(0.05) (0.13)		
		205.2	0.4	M1	
130.75	K	234.9	0.40		
215.0	L_I	234.8	0.11		
obsd.	L_{II} Photon		(1.3)		
		234.9	~2.0	M1-E2	
132.4	K	236.13	0.49		
216.88	L_I Photon	236.11	0.01 10.0		Expt. α_K 0.05 Theo. (E1) 0.046 (E2) 0.10
		236.1	10.6	E1	
143.15	K Photon	241.61	0.054 (0.5)		
		241.1	0.6	(E2?)	
140.42	K	250.34	0.23		An E1 of the same energy probably also exists.
obsd.	L_I				
232.6	$L_{II}?$	251.1	0.03		
		250.3	?	M1	
152.52	K	256.44	0.57		
	L_I	missing			
231.82	L_{II}	256.29	0.40		
240.86	L_{III}	256.34	0.19		
	M_I	missing			
251.56	M_{II}	256.03	~0.13		
	M_{III}	missing			
255.3	$N_{II,III}$ Photon	256.3	~0.08 (5.1)		
		256.4	1.1	E2	

Appendix B-I (cont'd.)
Internal transitions in the decay of Th^{227} .

Line Energy (kev)	Shell	Transition Energy (kev)	Intensity (%)	Multipolarity	Remarks
16.03	K	279.95	0.09		An E1 of the same energy probably also exists.
		280.0	?	M1	
177.0	K	281.6	0.14		
262.3	L _I	281.5	0.02		
263.2	L _{II}	281.4	0.02		
obsc.	L _{III}				
		281.8	?	M1 E2?	
182.31	K	286.2	0.51		
261.1	L _{I,II} Photon	286.0	0.11 (0.88)		
		286.1	1.5	M1	
185.18	K	289.10	0.06		
292.24	L _{I,II} Photon	289.52	0.021 (0.8)		
		289.7	~0.9	(probable E2)	
192.38	K	296.80	0.23		
291.5	L _{II}	296.0	0.40		
280.5	L _{III} Photon	296.0	~0.30 (~1.5)		
		297.8	2.5	F?	
176.0	K Photon	299.23	0.083 ~1.2		
		300.0	1.3	(E2)?	
200.1	K	304.1	0.60		
284.3	L _I	304.0	0.12		
285.0	L _{II}	304.5	0.04		
	L _{III}	missing			
300.1	M _{I,II}	304.1	0.04		
	M _{III,IV,V}	missing			
303.8	N _{I,II} Photon		1.9		
		304.5	~2.0	(M1-E2)?	

Appendix B-I
Internal transitions in the decay of Th^{227} .

Line Energy (kev)	Shell	Transition Energy (kev)	Intensity (%)	Multipolarity	Remarks
208.18	K	312.10	0.21		
293.12	L _{I,II}	312.4	0.055		
	L _{III}	missing			
308.0	M _{I,II}	312.9	0.02		
311.5	N		0.02		
	Photon		3.2		
		312.7	3.5	E2	
225.8	K	329.7	0.092		
311.5	L _{II}	330.0	0.03		
	Photon		(1.5)		
		329.7	1.6	E2	
230.40	K	334.3	0.33		(L _I pf 250.3 under)
314.4	L _{II}	333.6	0.015		
317.0	L _{III}	332.5	0.025		
	M _{II,III}	missing			
	Photon		4.8		
		334.3	5.2	E2	

Appendix B-II
Internal transitions in the decay of Ra²²³.

Line Energy (kev)	Shell	Transition Energy (kev)	Intensity (%)	Multipolarity	Remarks
13.1	L _I	31.1	1.1		
26.9	M _I	31.3	0.3		
		31.2	1.4	M ₁	
		68.4	~0.3		No direct observation; suggested by α - γ coincidence study
23.85	K	122.25	1.2		$\alpha_K \sim 3.6$
104.25	L _I	122.30	1.1		
105.4	L _{II}	122.15	0.36		
107.9	L _{III}	122.55	0.12		
117.51	M _{I,II}	122.15	0.56		
	Photon		2.0		
		122.2	11.9	M ₁ -E2	
44.66	K	143.06	0.8		
45.84	K	144.24	10.4		
126.08	L _I	144.13	2.8		
126.96	L _{II}	144.29	0.32		
129.84	L _{III}	144.45	0.11		
139.57	M _{I,II}	144.05	0.92		
140.48	M _{III}	144.01	0.30		
142.12?	N _I	143.81	0.19		
	Photon		4.1		
		144.2	19.1	M ₁ -E2	
55.67	K	154.07	17.		
136.24	L _I	154.29	4.0		
149.31	M _I	153.79	0.97		
152.94	N _I	154.03	0.5		
	Photon		5.5		
		154.1	28.0	M ₁	
60.02	K	158.42	1.7		
140.48	L _I	158.53	0.3		
154.28	M _I	158.76	0.2		
	Photon		(1.0)		
		158.6	3.2	(M ₁)	

Appendix B-II (cont'd.)
Internal transitions in the decay of Ra²²³.

Line Energy (kev)	Shell	Transition Energy (kev)	Intensity (%)	Multipolarity	Remarks
81.45	K	179.85	0.42		
162.41	L _{II}	179.74	0.1		
175.87	M _{II} ?	180.02	0.1		
	Photon		0.48		
		179.8	1.1	(M1-E2)	
171.1	K	269.68	9.2		α_K
251.5	L _I	269.61	1.9		Expt. 0.95
252.0	L _{II}	269.33	0.1		Theo. (M1) 0.90
254.6	L _{III}	obsc. ¹			
265	M	obsc.			
	Photon		10.1		
		269.6	21.4	M1	
225.68	K	324.08	1.7		Sum of 323.9- and 338.0- kev photons observed to be 5.1%
305.92	L _I	323.97	0.42		
	L _{II}	?	0.3		
309.20	L _{III}	323.81	0.22		
	Photon		2.3		
		323.9	4.9	M1	
239.84	K	338.24	.98		
319.79	L _I	337.84	.31		
333.14	M _I	337.95	.09		
	Photon		2.8		
			4.2	M1	
272.70	K	371.1	0.22		α_K
	Photon		0.45		Expt. 0.71
		371.1	0.7	M2	Theo. (M2) 0.76 (M1) 0.27
342.4	K	440.8	0.2		α_K
	Photon		0.4		Theo. (M2) 0.48
		440.8	0.6	M2	
347.00	K	445.40	0.39		α_K
427.56	L _I	445.61	0.17		Expt. 0.35
	Photon		0.83		Theo. (M1) 0.17 (M2) 0.47
			1.4	M2	
482.0?	K	580.4	0.07?		

1. Another, more intense line of the spectrum coincides in energy, obscuring the one in question.

Appendix B-III
Internal transitions in the decay of Em^{219} and Bi^{211} .

Line Energy (kev)	Shell	Transition Energy (kev)	Intensity (%)	Multipolarity	Remarks
<u>Em²¹⁹</u>					
178.68	K	271.78	1.3		Assignment on basis of K and L conversion coefficients.
254.23	L _I	271.1	0.45		
254.6	L _{II}	270.8	0.52		
257.8	L _{III}	271.6	0.22		
267.2	M _{I,II}	271.3	~0.21		
	Photon		8.6	80% E2	
			11.3	20% M1	
307	K	400.8	0.32		α_K 0.32/4.8 = 0.07 Theo. (E2) 0.036 (M1) 0.26
383.6	L _{I,II}	400.5	0.18		
	Photon		(4.8)		
			5.3	E2 (+M1?)	
<u>Bi²¹¹</u>					
265.22	K	350.73	3.1		Photon Intensity deduced from population of state.
	L _{I,II}	350.58	0.8 ¹		
	Photon		(12.8)		
			16.7	M1	
					α_K Expt. 0.24 Theo. (M1) 0.22
1. A line of Pb ²¹¹ coincides in energy.					

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