PHYSICAL REVIEW C VOLUME 4, NUMBER 2 AUGUST 1971

Studies of Lawrencium Isotopes with Mass Numbers 255 Through 260*

Kari Eskola,† Pirkko Eskola, Matti Nurmia, and Albert Ghiorso
Lawrence Radiation Laboratory, University of California, Berkeley, California 94720
(Received 17 March 1971)

Six isotopes of element 103, with mass numbers 255 through 260, have been studied by means of α-particle spectroscopy. The half-lives of the nuclides, and the energies and the intensities of their main α-particle groups were observed to be:

^{255}Lr	22 ± 5 sec	8.37 ± 0.02 MeV (~50%)
^{256}Lr	31 ± 3 sec	8.43 ± 0.02 MeV (34 ± 4%)
^{257}Lr	0.6 ± 0.1 sec	8.87 ± 0.02 MeV (81 ± 2%)
^{258}Lr	4.2 ± 0.6 sec	8.62 ± 0.02 MeV (47 ± 3%)
^{259}Lr	5.4 ± 0.8 sec	8.45 ± 0.02 MeV (100%)
^{260}Lr	180 ± 30 sec	8.03 ± 0.02 MeV (100%)

A large number of target-projectile combinations were used in synthesizing the lawrencium isotopes. Representative excitation curves for producing the nuclides are displayed. Upper limits for decay by electron capture have been determined. α-decay hindrance factors have been calculated using the spin-independent equations of Preston. The α-decay energy systematics of the heaviest elements is discussed.

I. INTRODUCTION

In 1961 an 8.6-MeV, 8-sec α-particle activity was discovered at Berkeley[1] and shown to be an isotope of element 103. In these experiments a target consisting of a mixture of californium isotopes with masses 249–252 was bombarded with ^{10}B and ^{11}B ions, and therefore an unambiguous isotopic assignment was not proposed. It appeared most likely at that time that the activity was due to ^{257}Lr. Subsequent studies in Dubna[2,3] seemed to conflict with this assignment and suggested that ^{257}Lr has a longer half-life of 35 sec, the same as that of ^{256}Lr. In the present work it is shown that ^{257}Lr has a half-life of 0.6 sec and the main α-particle group at 8.87 MeV. An isotopic assignment for the 8.6-MeV activity which is consistent both with the 1961 results and those presented here is ^{258}Lr. The difference in the half-life values is due to relatively poor statistics in the former study.

Six isotopes of lawrencium, with masses 255 through 260, have been observed and studied by means of α-particle spectroscopy. Some of the results reported here were essential to draw conclusions in our recently published work on element 105, hahnium.[4] At that time they were included in the publication without further elaboration.

The mass assignments of various Lr isotopes have been based on cross-bombardment techniques and excitation-function measurements because a study of genetic links to previously known lighter isotopes of Md or Fm is hampered by large electron capture or possibly positron branching. Very little is known of some of the pertinent Md isotopes. In the case of ^{256}Lr a genetic link to ^{260}Ha was established[4] and earlier, ^{256}Lr had been linked to ^{252}Fm by the Dubna group.[5] Recently we have found α-active hahnium precursors for both ^{257}Lr and ^{258}Lr.[6]

II. EXPERIMENTAL

In most of the bombardments either a ^{249}Cf or a ^{248}Cm target was used. The 290-μg/cm^2 ^{249}Cf target had 60 μg of isotopically pure ^{249}Cf electrodeposited from isopropyl alcohol solution in an area of 0.21 cm^2 on a 2.2-mg/cm^2 Be foil, on which 80 μg/cm^2 of Pd had been sputtered. The 41-μg ^{248}Cm target was also prepared by the molecular plating method and had an area of 0.18 cm^2. The isotopic composition of the target was as follows: ^{244}Cm (2.0%), ^{245}Cm (0.06%), ^{246}Cm (3.4%), ^{247}Cm (0.007%), and ^{248}Cm (94.5%). In addition to the two main targets the following targets were also used: ^{243}Am (~600 μg/cm^2), ^{246}Cm (280 μg/cm^2), ^{249}Bk (~3–400 μg/cm^2), and ^{250}Cf (~350 μg/cm^2). Either boron or nitrogen beams accelerated by the Berkeley heavy-ion linear accelerator were used in most of the experiments. Beam levels of 2–4 μA measured as fully stripped ions were typically passed through the targets. The energy of the 10.4-MeV/nucleon particles was adjusted by a stack of Be metal-foil degraders and measured by a solid-state detector intercepting particles scattered from the targets at an angle of 30°.

The reaction recoils from the target were stopped by the helium gas in a small chamber next to the target. The rapidly flowing gas then carried the recoils through a small orifice into a rough vacuum to be collected on a vertically mounted wheel. The wheel was periodically rotated to place the collected transmutation products next to a series of peripherally mounted Si-Au surface-barrier detectors in order to measure their α-particle spectra. The earliest experiments were performed with a five-detector-station system, the stations being arranged at 39° intervals. In this setup the same positions on the 45-cm-diam wheel were not reexamined by the series of five detectors until all 240 steps of the digital motor had been used. The later experiments were performed with a seven-detector-station system with 45° separation between two adjacent stations. To reduce the counting rate caused by long-lived activities, the wheel was advanced a few extra steps at regular chosen intervals.

At each detector station there were four detectors: two movable (mother) crystals which alternately faced the wheel, and two stationary (daughter) crystals to alternately face the mother crystals when they were shuttled off the wheel. By this arrangement a physical separation and an efficient detection of genetically related α activities was possible. A schematic representation of the arrangement of the 28 detectors around the vertical wheel and in each individual station is shown in Fig. 1.

α-decay events recorded by the detectors were amplified by modular units developed in our laboratory, processed by a PDP-9 computer and stored on IBM tape. The 512-channel α-particle spectra covered the range from 6 to 12 MeV. Spontaneous-fission discriminators were set to detect pulses greater than 30 MeV in each detector. Each wheel-cycle and shuttle period was divided into four time subgroups of equal length. Besides the pulse height and the event time, a detector identification signal, as well as signals indicating the prevailing shuttle condition and pertinent time subgroup, were stored by the computer. Data processing, such as spectrum fitting or normalizing the gain on the detectors, and sorting the data was done off line by either PDP-9 or CDC-6600 computers.

III. RESULTS

A. ^{255}Lr

Preliminary results on the decay characteristics of ^{255}Lr have been reported by Druin.[7] His studies of α activities produced by bombarding ^{243}Am target with ^{16}O ions indicated that ^{255}Lr has a half-life of about 20 sec and an α-particle group at 8.38 MeV.

We have produced a 22-sec α activity with an α-particle group at 8.37 MeV by bombarding the ^{249}Cf target with ^{10}B and ^{11}B ions, and a ^{243}Am target with ^{16}O ions. The series of α-particle spectra displayed in Fig. 2 resulted from bombardment of ^{249}Cf with 65-MeV ^{10}B ions. The 8.37-MeV group is somewhat masked by the 8.43-MeV, 3.2-sec

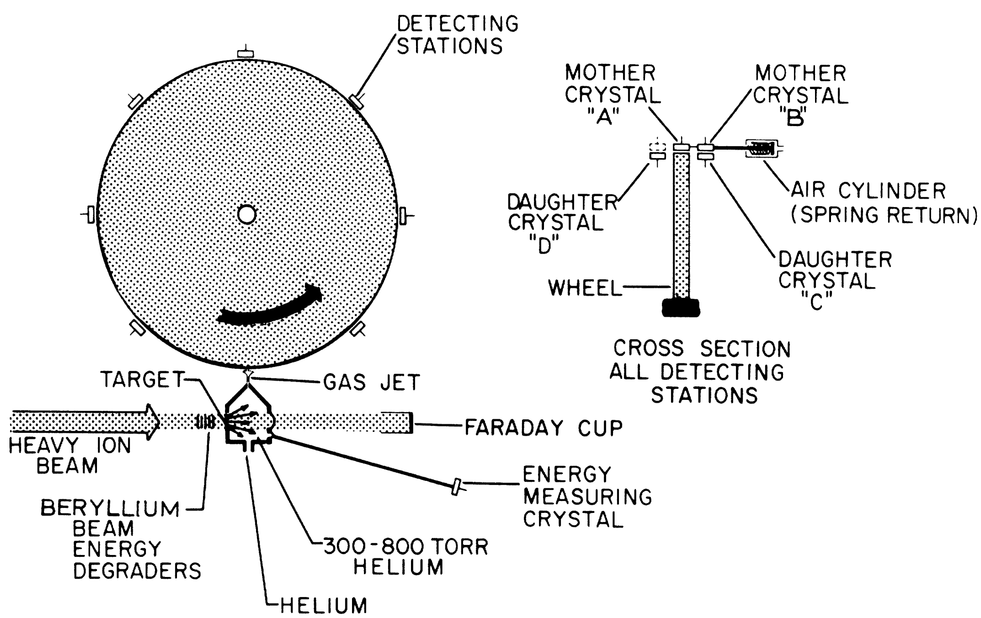

FIG. 1. A schematic representation of the vertical wheel system with seven detecting stations. On the right-hand side a cross section of one of the detector stations is shown.

^{256}No in the first spectrum composed of events recorded during the first 25 sec after the bombardment, but stands out more clearly in subsequent spectra. The use of SAMPO computer program[8] made it possible to resolve the 8.37-MeV group into two components of 8.35 ± 0.02 MeV (~50%) and 8.37 ± 0.02 MeV (~50%). A least-squares analysis gave a half-life of 22 ± 5 sec for the activity. Most of the other activities present belong to well-established isotopes of No and Fm, or were induced by a lead impurity in the target. The α group at 7.75 MeV is too prominent to be due to ^{255}No only and there may be a contribution from the 45-sec ^{250}Md known to have a group at this energy.[9] It is also most difficult to distinguish between the contributions of ^{249}Fm and ^{251}Md in the 7.54-MeV peak.

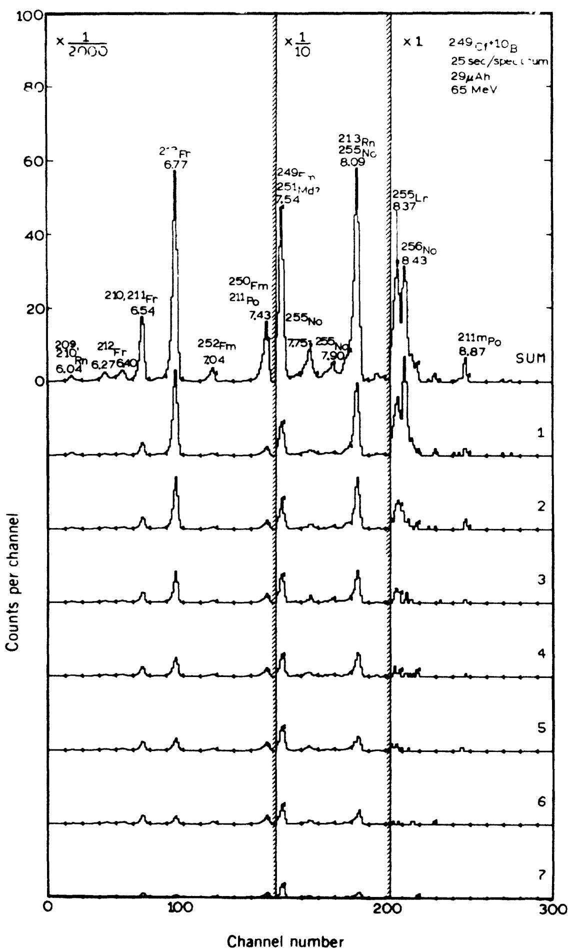

FIG. 2. A series of α-particle spectra produced by bombardments of ^{249}Cf with ^{10}B ions. The individual spectra show the total of counts recorded at each of the seven stations by the two movable detectors when facing the wheel. The sum of the seven spectra is plotted topmost. The wheel-cycle rate, the integrated beam reading, and the bombardment energy are indicated in the figure.

In bombardments of ^{243}Am by both ^{12}C and ^{13}C ions[9] the latter has been found to have a half-life of about 4 min with its most prominent α-particle group at 7.53 MeV.

The α-particle spectra shown in Fig. 2 were recorded by the movable detectors when facing the wheel. The combined spectra recorded by these same detectors when in the off-wheel position and by the stationary detectors facing them were analyzed to find out if there were counts that arose from the decay of ^{251}Md, the α-recoil daughter of ^{255}Lr. All together six α-decay events were observed between 7.5 and 7.6 MeV, while the total number of counts assigned to ^{255}Lr was 129. The calculated ratio of detected mother events to detected daughter events is 2.5, which is approximately $\frac{1}{10}$ of the observed ratio. Thus ^{251}Md seems to decay predominantly by electron capture and

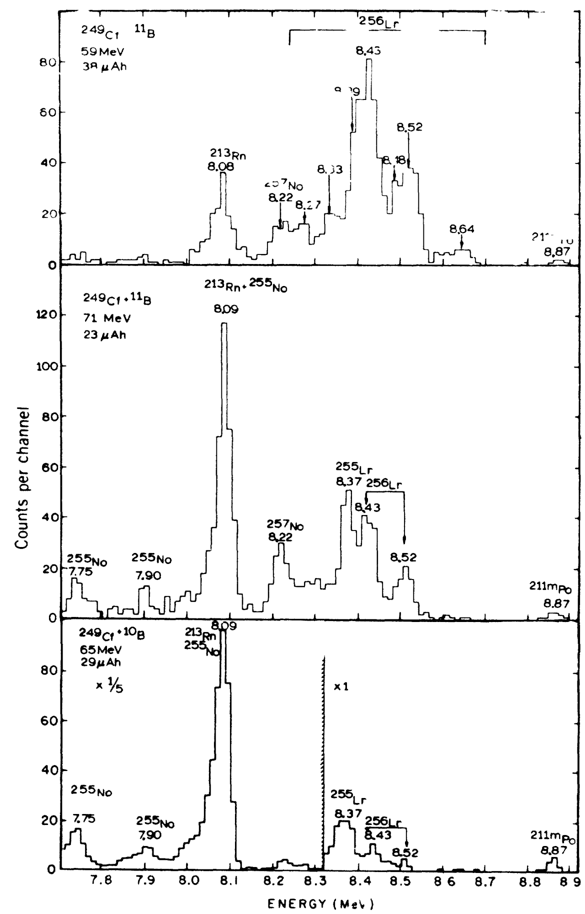

FIG. 3. A comparison of α-particle spectra resulting from bombardments of ^{249}Cf with 59- and 71-MeV ^{11}B ions, as well as 65-MeV ^{10}B ions. In each case the first two time subgroups, i.e., 12.5 sec following the end of each collecting period, has been excluded to eliminate short-lived activities such as the 3.2-sec ^{256}No.

this is borne out by greatly reduced apparent reaction cross sections for its production as measured by its α decay.

Further proof that the 8.37-MeV α-particle activity arises from the decay of ^{255}Lr was furnished by excitation function studies. In Fig. 3 the α-particle spectra from bombardments of ^{249}Cf by ^{11}B ions at 59 MeV and 71 MeV and by ^{10}B ions at 65 MeV are plotted for comparison. The spectra represent the sum of the spectra recorded by the detectors in the on-wheel position and in all cases the first 12.5 sec, i.e., the two first time subgroups out of the four at the first detector station, have been discarded to reduce interference from short-lived activities such as the 3.2-sec ^{256}No. At 59 MeV the complex α-particle spectrum of ^{256}Lr is almost pure, but at 71 MeV the 8.37-MeV group is taking over. At the bottom the 8.37-MeV activity clearly dominates over the ^{256}Lr-induced peaks. The excitation functions for the activities resulting from bombardments of ^{249}Cf with ^{11}B ions and characterized by half-lives of 22, 31, and 0.6 sec, and most prominent α-particle groups at 8.37, 8.43, and 8.87 MeV, respectively, are plotted in Fig. 4. The relatively large uncertainties for the 8.37-MeV α activity reflect the difficulty of separating it from the complex α-particle spectrum of ^{256}Lr. The facts that the excitation functions for the 8.87- and 8.43-MeV activities reach their maxima at about the same energy and that the maximum for the 8.37-MeV activity is about 10 MeV higher are consistent with the activities being produced by $3n$, $4n$, and $5n$ reactions, respectively.[10]

B. ^{256}Lr

The isotope ^{256}Lr was synthesized first at Dubna in experiments where an ^{243}Am target was bombarded with ^{18}O ions.[5] It was identified by the genetic method by which a link was established between the new 45 ± 10-sec α activity and the 23-h ^{252}Fm. In a review article[3] Donets, Druin, and Mikheev give a half-life of 35 sec and the α-particle energy range 8.35–8.50 MeV with 8.42-MeV α particles being most intensive, as best values for the decay characteristics of ^{256}Lr.

We have produced a 31-sec α activity with a complex α-particle spectrum by bombarding ^{249}Cf with ^{11}B ions. The α-particle spectra displayed in Fig. 5 resulted from a bombardment of the ^{249}Cf target with 59-MeV ^{11}B ions. The sum spectrum with the first 12.5 sec following an irradiation excepted is shown in Fig. 3 as discussed earlier. An analysis of the spectrum by SAMPO computer program[8] gives the energies and intensities given in Table I for the α-particle groups of ^{256}Lr. A least-squares analysis of the decay data yielded a value of 31 ± 3 sec for the half-life.

The assignment of the 31-sec α-particle activity to ^{256}Lr is based on the excitation curves displayed in Fig. 4 and a large number of cross bombardments carried out when studying adjacent isotopes

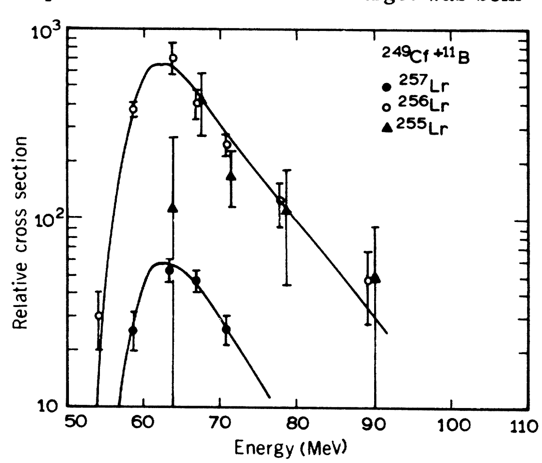

FIG. 4. Excitation curves for Lr activities produced in bombardments of ^{249}Cf with ^{11}B ions. The error bars indicate an uncertainty of one standard deviation.

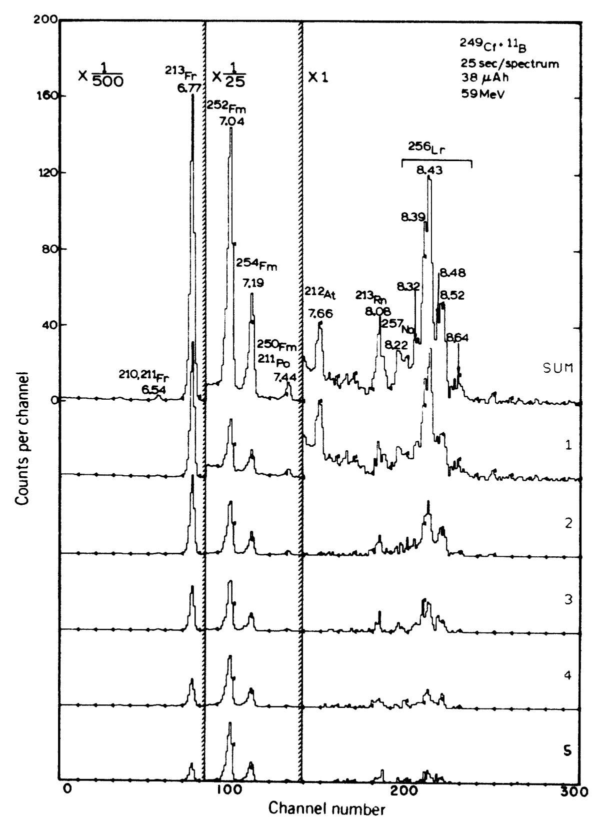

FIG. 5. A series of α-particle spectra produced by bombardments of ^{249}Cf with ^{11}B ions. Both the arrangement of the spectra and the data pertinent to the bombardment correspond to those in Fig. 2.

of Lr or nearby isotopes of No or Rf. Also the activity has been established to have as a precursor a 9.1-MeV, 1.6-sec α-particle emitter.[4]

C. ^{257}Lr

As discussed previously, the 8.6-MeV, 8-sec α-particle activity discovered in Berkeley in 1961[1] and shown to be an isotope of element 103 was tentatively assigned to mass number 257. Subsequent work in Dubna failed to confirm such an assignment and experiments carried out by bombarding a ^{243}Am target with ^{18}O ions suggested that ^{257}Lr has decay properties very similar to those of ^{256}Lr with $8.5 < E_\alpha < 8.6$ MeV and $T_{1/2} = 35$ sec.[2,3]

In our bombardments of the ^{249}Cf target with ^{15}N ions with the primary goal of making isotopes of element 105, a pronounced 8.87-MeV, 0.6-sec α-particle group appeared in the spectra.[4] By producing this activity using three different projectiles, ^{11}B, ^{14}N, and ^{15}N, on the ^{249}Cf target, we have concluded that the activity must be due to ^{257}Lr. The excitation function for the 8.87-MeV, 0.6-sec α-particle activity produced by ^{11}B ions is shown in Fig. 4. It is the very low peak cross section of about 20 nb for the ^{249}Cf(^{11}B, $3n$)^{257}Lr reaction that enabled the 0.6-sec activity to evade being identified in earlier experiments. The excitation functions for the 8.87-MeV, 0.6-sec and the 8.6-MeV, 4.2-sec α activities produced by ^{15}N ions on ^{249}Cf are displayed in Fig. 6. In addition there is an asterisk labeled ^{257}Lr and an arrow marked ^{258}Lr on the same plot. The former shows the measured cross section of ^{257}Lr and the latter an upper limit for the cross section of ^{258}Lr. The values were derived from a 36-μAh bombardment of ^{249}Cf with 81-MeV ^{14}N ions. It is evident that the ratio of the cross sections changes drastically when ^{15}N is substituted by ^{14}N. Such a behavior is in accordance with the assignments of the activities to ^{257}Lr and ^{258}Lr, for then in one case the reactions would be ^{249}Cf(^{15}N, $\alpha 3n$)^{257}Lr and ^{249}Cf-(^{15}N, $\alpha 2n$)^{258}Lr, in the other ^{259}Cf(^{14}N, $\alpha 2n$)^{257}Lr and ^{249}Cf(^{14}N, αn)^{258}Lr. It has been found that a (HI, αn) reaction has a very small cross section compared to the cross sections of (HI, $\alpha 2n$) and (HI, $\alpha 3n$) reactions (cf. Fig. 2 of Ref. 11).

The 8.87-MeV, 0.6-sec activity was also observed in bombardments of ^{249}Cf with ^{12}C and ^{13}C ions.[11,12] At the time when the results of these experiments were reported we were unable to give an unambiguous assignment to the activity, because of its low cross section and interference from 8.87-MeV, 25-sec ^{211m}Po. However, the activity was explicitly excluded from the peaks assigned to rutherfordium isotopes because of its shorter half-life.

The complete display of the series of α-particle spectra produced by bombardments of ^{249}Cf with ^{15}N ions is presented in Ref. 4. Results of an anal-

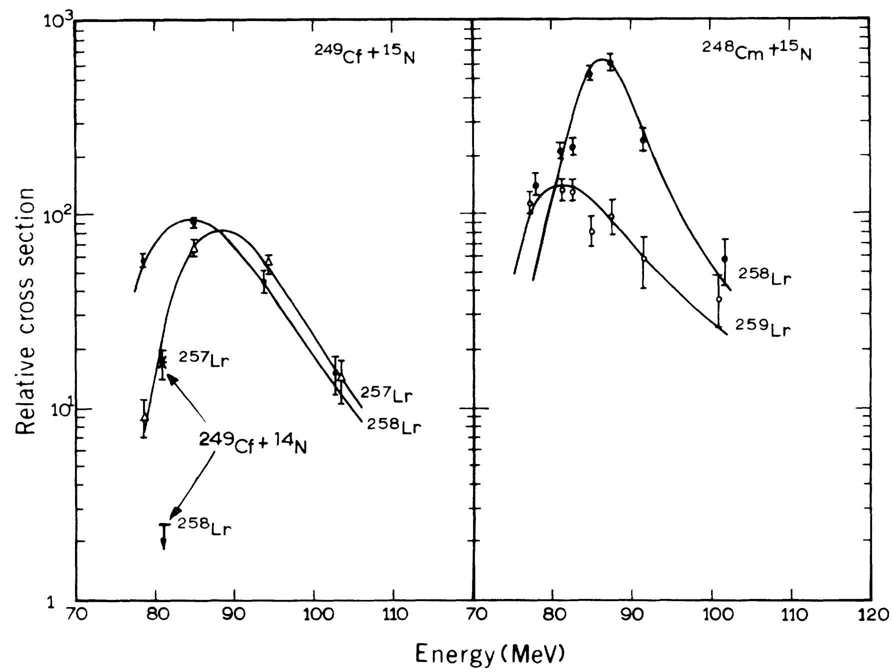

FIG. 6. Excitation curves for the activities assigned to ^{257}Lr, ^{258}Lr, and ^{259}Lr produced from either bombarding ^{249}Cf or ^{248}Cm with ^{15}N ions. The asterisk and the arrow labeled ^{257}Lr and ^{258}Lr indicate the cross section and an upper limit for the cross section for producing the activities by bombarding ^{249}Cf by ^{14}N ions.

ysis of the complex α-particle groups at 8.6 and 8.87 MeV by the SAMPO computer program are shown in Fig. 7 and given in numerical form in Table I as energies and intensities of the α-particle groups assigned to ^{257}Lr and ^{258}Lr. We have recently found an α-active 8.93-MeV, 1.8-sec precursor to the 8.87-MeV, 0.6-sec ^{257}Lr and an 8.45-MeV, 40-sec precursor to the 8.6-MeV, 4-sec ^{258}Lr. In each case the genetic relationship has been established both by the recoil milking method and by time-correlation measurements.[6]

D. ^{258}Lr

Decay properties and ways of producing the 8.6-MeV, 4-sec α activity were already touched upon in the preceding section. Both bombardments of ^{249}Cf and ^{248}Cm by ^{15}N ions produced this activity. A series of α-particle spectra from the latter target-projectile combination is displayed in Fig. 8. In these spectra the peak at 8.61 MeV is also seen to be complex, although the energy resolution in the spectra is not as good as in the spectrum in Fig. 7. Most of the peaks in the spectra have been induced by a lead impurity in the target. The 8.45-MeV, 5.4-sec peak has been assigned to ^{259}Lr. The excitation curves for the 8.6- and 8.45-MeV activities produced in bombardments of ^{248}Cm by ^{15}N ions are shown on the right-hand side of Fig. 6. The peak cross section, about 200 nb, for the 8.6-MeV activity is attained about 8 MeV higher than that for the 8.45-MeV activity, which is compatible with the former being produced in a $5n$ reaction.

The 8.6-MeV, 4-sec α activity was also observed in bombardments of ^{249}Cf with ^{12}C and ^{13}C ions.[11, 12] In the former the activity was produced by the ^{249}Cf(^{12}C, $p2n$)^{258}Lr reaction and the excitation curve was broader than that observed for the ^{249}Cf(^{12}C, $4n$)^{257}Rf reaction.[11] The peak cross sections were almost equal. The 8.6-MeV, 4-sec activity was also observed in a bombardment of a ^{244}Pu target with ^{19}F ions.

According to a recent study by Fields *et al.*,[13] the α-particle daughter ^{254}Md decays predominantly by electron capture. We looked for the α particles emitted by the 3.2-h ^{254}Fm in the off-wheel position and for 620 observed decays of ^{258}Lr some

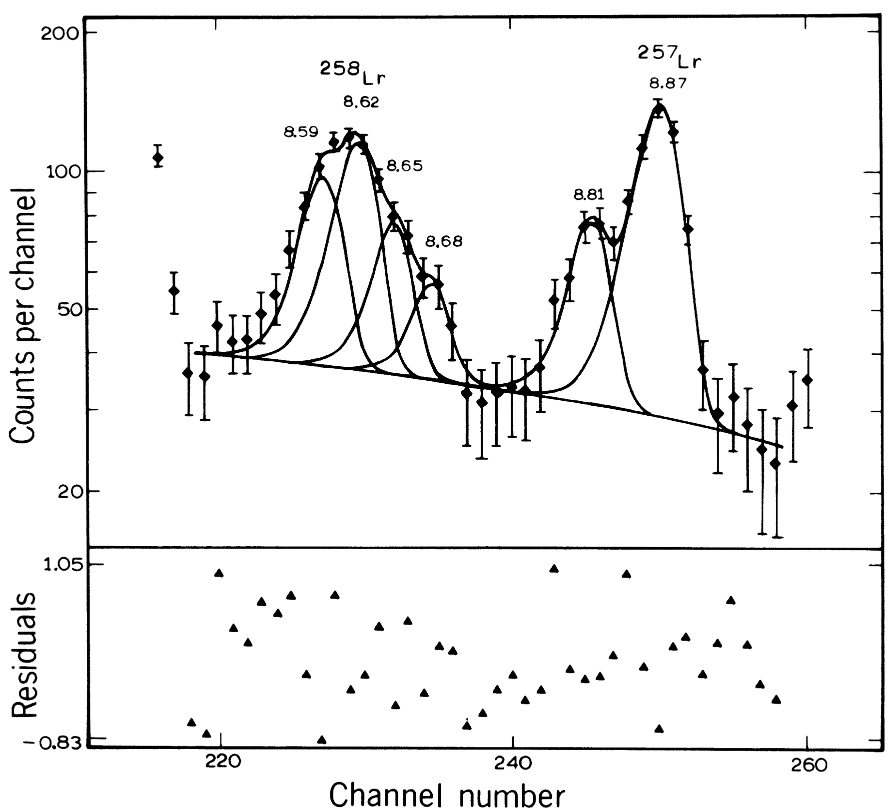

FIG. 7. A fit by SAMPO computer program to the 8.5- to 9.0-MeV α-particle energy region in the sum spectrum resulting from bombardments of ^{249}Cf with ^{15}N ions. The quadruplet at about 8.6 MeV is assigned to ^{258}Lr and the doublet at about 8.85 MeV to ^{257}Lr. The peaks at 6.538 (^{210,211}Fr) and 6.773 MeV (^{213}Fr) were used for both shape and energy calibrations.

300 decays in the 7.13- to 7.22-MeV range were observed. Accounting for the losses due to decay and geometry factors, as well as for the fact that each movable detector only spends half of its time in the off-wheel position, one would expect to detect some 200 decays of ^{254}Fm atoms corresponding to the ^{258}Lr atoms. The excess of daughters is probably due to direct production of ^{254}Md, the electron-capture daughter of which then transfers onto the detectors with low efficiency.

E. ^{259}Lr

The assignment of the 8.45-MeV, 5.4-sec α activity produced in bombardments of ^{248}Cm with ^{15}N ions rests mainly on the excitation curve measurement presented in the right half of Fig. 6. On the basis of excitation curves only, one cannot distinguish between $3n$- and $4n$-reactions and, consequently, ^{260}Lr is an alternative assignment. In recent bombardments of a ^{250}Cf target with ^{15}N ions, both the 8.45-MeV, 5.4-sec and the 8.6-MeV, 4.2-sec activities were observed. This supports the contention that the first activity belongs to ^{259}Lr, because (^{15}N, $\alpha 2n$)- and (^{15}N, $\alpha 3n$)-reaction cross sections are expected to be comparable (cf. Fig. 6), whereas (^{15}N, αn)-reaction cross section leading to ^{260}Lr should be lower by two orders of magnitude according to Sikkeland's calculations[10] and make the yield too small for observation.

A genetic relationship between ^{259}Lr and its α-decay daughter ^{255}Md could not be established. This was because of only 10% α branching of ^{255}Md.[14] The few α-decay events expected could not be distinguished from the background caused by the 7.44-MeV α-particle group of ^{211}Po.

F. ^{260}Lr

In recent bombardments of a 300-μg/cm^2 ^{249}Bk target with 95-MeV ^{18}O ions, we observed an 8.03-MeV, 3-min activity which we assign to ^{260}Lr. A comparison of the amounts of this activity produced when two ^{249}Bk targets differing almost by an order of magnitude in the amount of Pb impurity established that 8.0-MeV ^{215}At replenished by 2.2-min ^{223}Ac could not be the source of the activity. The α-particle spectra resulting from the bombardments will be published shortly in another article dealing with isotopes of hahnium.[6]

To identify the 8.03-MeV, 3-min activity we looked for spontaneous fission events from the decay of ^{256}Fm, which is the electron-capture product of the decay of ^{256}Md, the α-decay daughter of ^{260}Lr. To reduce the number of ^{256}Fm atoms re-

TABLE I. Summary of experimental results on lawrencium isotopes with mass numbers 255 through 260.

	Half-life (sec)	α-particle energy (MeV)	Intensity (%)	α-decay hindrance factor	Upper limit for EC (%)	Ways of production
^{255}Lr	22 ± 5	8.37 ± 0.02	~50	2.4	30	^{243}Am + ^{16}O
		8.35 ± 0.02	~50	2.0		^{249}Cf + ^{10}B, ^{11}B
^{256}Lr	31 ± 3	8.64 ± 0.02	3 ± 2	490	20	^{246}Cm + ^{15}N
		8.52 ± 0.02	19 ± 3	30		^{249}Bk + ^{12}C
		8.48 ± 0.02	13 ± 3	36		^{249}Cf + ^{10}B, ^{11}B
		8.43 ± 0.02	34 ± 4	8.8		
		8.39 ± 0.02	23 ± 5	9.7		
		8.32 ± 0.02	8 ± 2	1.6		
^{257}Lr	0.6 ± 0.1	8.87 ± 0.02	81 ± 2	2.1	15	^{246}Cm + ^{15}N
		8.81 ± 0.02	19 ± 2	6.0		^{249}Bk + ^{12}C, ^{16}O
						^{249}Cf + ^{11}B, ^{12}C, ^{13}C, ^{14}N, ^{15}N
						^{250}Cf + ^{15}N
^{258}Lr	4.2 ± 0.6	8.68 ± 0.02	7 ± 2	55	5	^{244}Pu + ^{19}F
		8.65 ± 0.02	16 ± 3	19		^{246}Cm + ^{15}N
		8.62 ± 0.02	47 ± 3	5.4		^{248}Cm + ^{15}N
		8.59 ± 0.02	30 ± 4	6.8		^{249}Bk + ^{12}C, ^{16}O, ^{18}O
						^{249}Cf + ^{15}N
						^{250}Cf + ^{15}N
^{259}Lr	5.4 ± 0.8	8.45 ± 0.02	100	1.1		^{248}Cm + ^{15}N
						^{250}Cf + ^{15}N
^{260}Lr	180 ± 30	8.03 ± 0.02	100	1.7	40	^{248}Cm + ^{15}N
						^{249}Bk + ^{18}O

coiling from the wheel onto detectors as a result of electron capture decay of ^{256}Md produced directly in the bombardment, a negative 10-V potential was set between the wheel and the detector faces and an Ar gas pressure of about 2 Torr was maintained in the region. In addition extra steps were given to the wheel every 80th of the 40-sec wheel cycles. Even with these prohibitive measures about one and a half times as many fission events were detected as expected in the off-wheel position on the basis of the counts in the 8.03-MeV peak. The timing of the wheel was too fast for effective separation of those fission events that had a ^{260}Lr atom as their predecessor from those that were deposited on the wheel as ^{256}Md atoms. The distribution of the fission events recorded in the off-wheel position showed a decay which is consistent with a 3-min half-life, but the presence of background counts makes the evidence somewhat short of conclusive.

The 8.03-MeV, 3-min α activity was also produced by bombarding a 1.4-mg/cm^2 ^{248}Cm target by 78-MeV ^{15}N ions. The series of α-particle spectra resulting from this experiment is displayed in Fig. 9. The yield of the 8.03-MeV activity assigned to ^{260}Lr corresponds to a cross section of about 2 nb, while the measured peak cross sections for making ^{257}Lr and ^{258}Lr are about 40 nb and 200 nb. The small $3n$-reaction cross section is striking but not in variance with others observed in this region.

IV. DISCUSSION

A summary of experimental data obtained in this study is presented in Table I. The errors given mainly reflect statistical uncertainties, but in the case of the α-particle energies the uncertainty is mostly caused by calibration errors. The α-energy calibration has been based on internal energy standards, the 6.773-MeV peak of ^{213}Fr and the 7.443-MeV peak of ^{211}Po being most suitable for

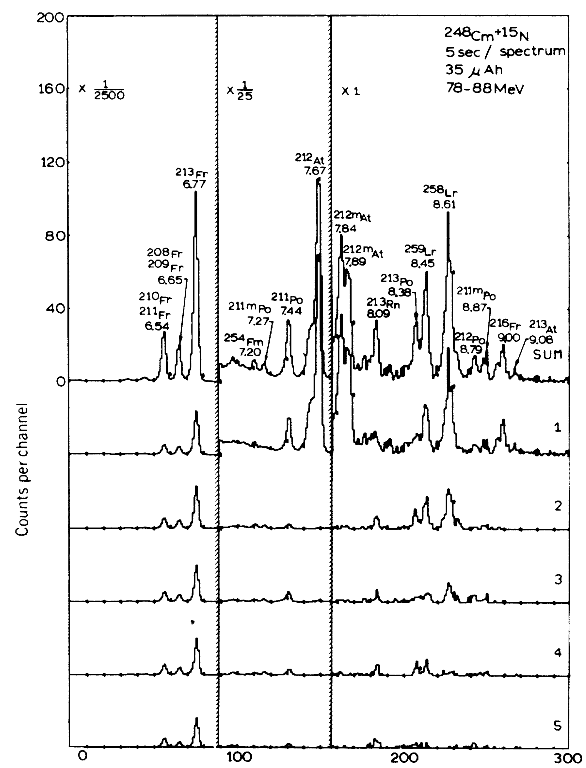

FIG. 8. A series of α-particle spectra produced by bombardments of ^{248}Cm with ^{15}N ions. Both the arrangement of spectra and the data pertinent to the bombardment correspond to those in Fig. 2.

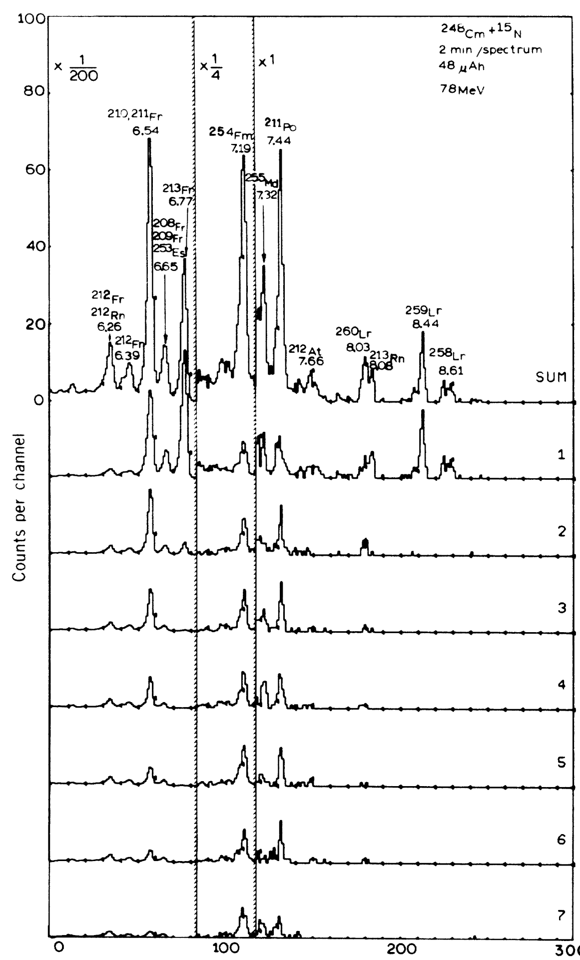

FIG. 9. A series of α-particle spectra produced by bombardments of ^{248}Cm with 78-MeV ^{15}N ions. Both the arrangement of the spectra and the data pertinent to the bombardment correspond to those in Fig. 2.

the purpose. The lineup of the gains and thresholds in all of the 28 detectors was done prior to an experiment by use of pulse generators calibrated by the 6.640-MeV α-particle group of ^{253}Es samples. The final lineup of the spectra was done during the data-handling phase by the CDC 6600 computer using Paatero's method.[15]

α-decay hindrance factors have been calculated using the spin-independent ($l=0$) equations of Preston.[16] This formalism was chosen because its wide use makes it easy to compare hindrance factors with values cited in other works. The radius parameter R for the Lr isotopes was chosen to have values with 0.05-fm increments starting from 9.25 fm for ^{255}Lr to 9.50 fm for ^{260}Lr. This choice was based on the general trend in the behavior of R values for even-even fermium and nobelium α emitters.

Because we have not done any γ-ray spectroscopy to support the level scheme information, only qualitative discussion of finer details of nuclear structure is possible. A cursory glance at α-decay hindrance factors in Table I shows that for each isotope there are transitions with a hindrance factor of less than ten. Such low hindrance factors for odd-mass nuclei are characteristic of favored α decay which leaves the last odd particle in the same orbital in the daughter as in the parent. According to the single-particle level scheme of Nilsson *et al.*,[17] the 103rd proton should occupy the $\frac{9}{2}^+[624\uparrow]$ level in the region of $250<A<270$ for deformation parameter $\epsilon \approx 0.24$ and ϵ_4 distortion of 0.04. A transition from the $\frac{9}{2}^+[624\uparrow]$ level to the $\frac{7}{2}^-[514\downarrow]$ level, which seems to be the ground state for several Md isotopes,[13] is strongly hindered because of a change in relative orientation of orbital and intrinsic spin components Λ and Σ of the projection of the odd-particle angular momentum Ω.

In the case of ^{255}Lr it is possible that the broadness of the 8.37-MeV α-particle peak, which has been interpreted as being caused by two α-particle groups of approximately equal intensity, may instead be due to summation of γ rays or conversion electrons coincident with the α particles. Assuming that the 8.81-MeV α-particle group of ^{257}Lr populates the $\frac{11}{2}^+$ member of the rotational band built on $\frac{9}{2}^+[624\uparrow]$ Nilsson level one obtains a reasonable value of 5.5 keV for the rotational constant, $\hbar^2/2\mathscr{I}$.

Both of the odd-odd isotopes ^{256}Lr and ^{258}Lr have complex α-particle spectra. However, it is difficult to give Nilsson-state assignments to any of the levels populated in Md daughter isotopes on the basis of hindrance factors. Assuming that the odd proton is in $\frac{9}{2}^+[624\uparrow]$ state, the 153rd neutron in $\frac{1}{2}^+[620\uparrow]$, and 155th neutron in $\frac{7}{2}^+[613\uparrow]$ state, an application of the Gallagher-Moszkowski rule gives ground-state spins of 5^- and 8^- to ^{256}Lr and ^{258}Lr, respectively.

An upper limit to electron-capture (EC) branching for most of the Lr isotopes studied is given in Table I. These limits have been obtained by comparing the number of observed α-decay events resulting from the decay of Lr and No isotopes of the same mass number. It has been assumed that none of the No atoms were produced directly by a (HI, pxn)-type reaction. Also it has been assumed that the EC branchings of the No isotopes are negligible. Both for ^{255}No and ^{257}No we have found the α-decay mode to be predominant by studying the genetic sequences $^{259}\text{Rf} \rightarrow {}^{255}\text{No}$ and $^{261}\text{Rf} \rightarrow {}^{257}\text{No}$.[18] Such a measurement was also carried out for ^{256}Lr when ^{260}Ha was first produced.[4] The ratio of the number of observed α-recoil-daughter atoms to that of observed parent atoms for the sequence

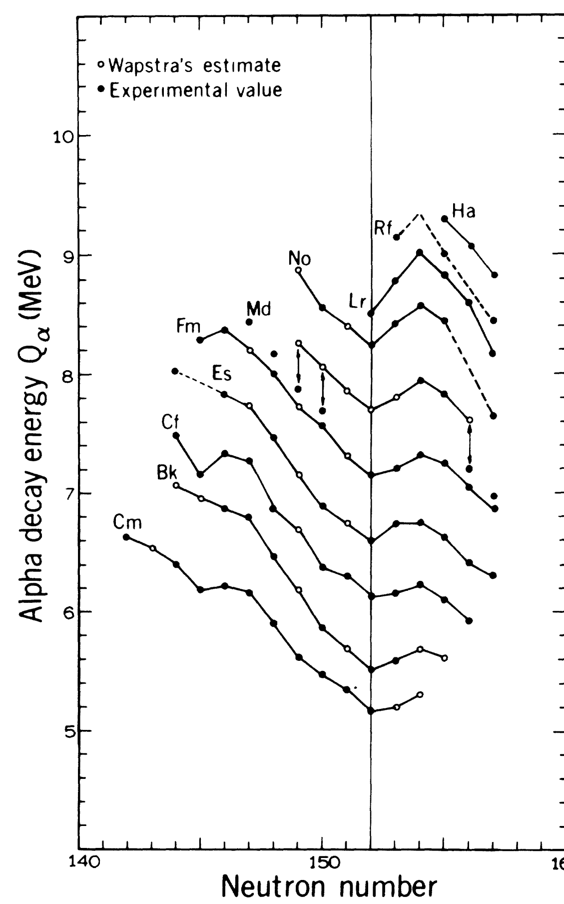

FIG. 10. α-decay energy as a function of neutron number. The black circles correspond to the highest known α-particle group and the open circles are those estimated by Wapstra by interpolation and α-β-decay chains. It is seen that the influence of the $N=152$ subshell on α-decay energies persists up to highest known Z values.

^{260}Ha $\rightarrow$ ^{256}Lr was 2.8 ± 0.4. The calculated ratio based on timing and geometric factors yielded a value of 2.7. On the basis of these values and allowing some uncertainty in the geometry factors, one gets an upper limit of 20% for EC branching of ^{256}Lr. For ^{258}Lr the limit is based on the assumption that ^{258}No decays predominantly by spontaneous fission with a half-life of 1 msec.[19] In the case of ^{259}Lr no meaningful limit could be set for EC branching because 57-min, 7.52-MeV ^{259}No (Ref. 20) was highly discriminated against at the 5-sec wheel-cycle rate used. Because of the abundance of ^{256}Fm produced in the bombardment only a very crude estimate of the upper limit for EC branching of ^{260}Lr is possible. Assuming that ^{260}No decays by spontaneous fission one obtains a value of 40%.

The last column of Table I gives the various target and projectile combinations, which have resulted in making any particular Lr isotope. In many cases Lr isotopes have not been the primary object of study and have been produced by (HI, *pxn*) or (HI, αxn) reactions. The results from all the reactions indicated in the last column of Table I are consistent with one another and this fact supports strongly the mass assignments proposed.

The α-decay energies plotted in Fig. 10 as a function of neutron number represent either an estimate of Wapstra[21] or an experimental value obtained by taking the energy of the highest observed α-particle group and correcting it for recoil energy loss. In addition to the new data discussed earlier in the text, tentative values for ^{243}Es, ^{248}Md, ^{249}Md (Ref. 9), ^{261}Ha and ^{262}Ha (Ref. 6) have been plotted.

It is seen that the influence of $N = 152$-neutron subshell persists through the displayed range of Z values and even seems to become more pronounced with an increase in atomic number. For several mendelevium isotopes both the experimental and estimated Q_α values are plotted to point out how the observed values consistently deviate from the estimated ones by several hundred keV. Exceptions are ^{255}Md, where a γ ray of energy 430 keV has been identified in coincidence with the main α-particle group,[13] and ^{256}Md, where a weak α group has been observed with an energy that agrees with the estimate.[14] According to the single-particle level scheme of Nilsson *et al.*,[17] there is a fairly large gap at $Z = 100$ between the $\frac{7}{2}^-[514\downarrow]$ and $\frac{7}{2}^+[633\uparrow]$ proton levels in the neighborhood of mass number 252 with $\epsilon = 0.23$ and ϵ_4 distortion of 0.04. An α transition from the $\frac{7}{2}^-[514\downarrow]$ level to $\frac{7}{2}^+[633\uparrow]$ level is substantially hindered because of the difference in parity. Thus the favored transition to the $\frac{7}{2}^-[514\downarrow]$ level is preferred even though this level may lie several hundred keV above the ground state.

A behavior quite similar to the one at $Z = 101$ seems to cause an apparent reduction in α-decay energies at ^{258}Md, ^{259}No, ^{260}Lr, and ^{261}Rf, i.e., isotones with $N = 157$. In the case of ^{257}Fm where detailed decay information is available, Asaro and Perlman[22] have explained this by assigning the ground states of ^{257}Fm and ^{253}Cf to $\frac{9}{2}^+[615\downarrow]$ and $\frac{7}{2}^+[613\uparrow]$ Nilsson levels. The favored α transition then goes to the 242-keV $\frac{9}{2}^+[615\downarrow]$ level of ^{253}Cf.

Perhaps the most interesting general trend discernible in the plotted experimental α-decay energies is the apparent reduction in the spacing of curves for successive Z values above nobelium. It is most evident for the $N = 155$ isotones, for which data are available up to hahnium. Although all the evidence for decrease in the rate of change for α-decay energies when going from No to Ha is based on odd-A isotopes, the phenomenon seems general enough to suggest that it is real and may be caused by a local shell effect or a fringe effect of a more remote major shell. The latter could manifest itself as a transition region from deformed nuclear shape to spherical one.

We would like to express our grateful appreciation of the expert help given by the personnel at the heavy-ion linear accelerator in all the phases of this research effort and to our colleague, James Harris, who was instrumental in the preparation of most of the targets.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

†On leave of absence from Department of Physics, University of Helsinki, Helsinki, Finland.

[1]A. Ghiorso, T. Sikkeland, A. E. Larsh, and R. M. Latimer, Phys. Rev. Letters 6, 473 (1961).

[2]G. N. Flerov, Yu. S. Korotkin, V. L. Mikheev, M. B. Miller, S. M. Polikanov, and V. A. Schegolev, Nucl. Phys. A106, 476 (1967).

[3]E. D. Donets, V. A. Druin, and V. L. Mikheev, Ann. Phys. (Paris) 3, 332 (1968).

[4]A. Ghiorso, M. Nurmia, K. Eskola, J. Harris, and P. Eskola, Phys. Rev. Letters 24, 1498 (1970).

[5]E. D. Donets, V. A. Schegolev, and V. A. Ermakov, At. Energ. (USSR) 19, 109 (1965) [transl.: Soviet J. At. Energy 19, 995 (1965)].

[6]A. Ghiorso, M. Nurmia, K. Eskola, and P. Eskola, University of California Radiation Laboratory Report No. UCRL-20487, 1971 (unpublished).

[7]V. A. Druin, Yadern. Fiz. 12, 268 (1970) [transl.: Soviet J. Nucl. Phys. 12, 146 (1971)].

[8]J. T. Routti and S. G. Prussin, Nucl. Instr. Methods

72, 125 (1969).
[9]P. Eskola, University of California Radiation Laboratory Report No. UCRL-20441, 1971 (unpublished).
[10]T. Sikkeland and D. F. Lebeck, unpublished.
[11]A. Ghiorso, M. Nurmia, J. Harris, K. Eskola, and P. Eskola, Phys. Rev. Letters 22, 1317 (1969).
[12]A. Ghiorso, in *Proceedings of the Robert A. Welch Foundation Conference on Chemical Research, Houston, Texas, 1969*, edited by W. O. Milligan (Robert A. Welch Foundation, Houston, Texas, 1970), p. 107.
[13]P. R. Fields, I. Ahmad, R. F. Barnes, R. K. Sjoblom, and E. P. Horwitz, Nucl. Phys. A154, 407 (1970).
[14]R. W. Hoff, E. K. Hulet, R. J. Dupzyk, R. W. Lougheed, and J. E. Evans, to be published.
[15]P. Paatero, Nucl. Instr. Methods 31, 360 (1964).
[16]M. A. Preston, Phys. Rev. 71, 865 (1946).
[17]S. G. Nilsson, C. F. Tsang, A. Sobiczewski, Z. Szymanski, S. Wycech, C. Gustafson, I. Lamm, P. Moller, and B. Nilsson, Nucl. Phys. A131, 1 (1969).
[18]A. Ghiorso, M. Nurmia, K. Eskola, and P. Eskola, Phys. Letters 32B, 95 (1970).
[19]M. Nurmia, K. Eskola, P. Eskola, and A. Ghiorso, University of California Radiation Laboratory Report No. UCRL-18667, 1969 (unpublished).
[20]R. J. Silva, M. L. Mallory, P. F. Dittner, P. Hammons, and J. L. Keller, Jr., unpublished; A. Ghiorso, K. Eskola, P. Eskola, and M. Nurmia, University of California Radiation Laboratory Report No. UCRL-20426 (unpublished).
[21]A. Wapstra, in *Proceedings of the Third International Conference on Atomic Masses, Winnipeg, Canada, 1967*, edited by R. C. Barber (University of Manitoba Press, Winnipeg, Canada, 1967), p. 153.
[22]F. Asaro and I. Perlman, Phys. Rev. 158, 1073 (1967).

PHYSICAL REVIEW C VOLUME 4, NUMBER 2 AUGUST 1971

Decay of ^{162}Tm†

Y. Y. Chu
Chemistry Department, Brookhaven National Laboratory, Upton, New York 11973
(Received 25 March 1971)

The half-life of ^{162}Tm was determined to be 21.77 ± 0.26 min. Eight γ rays in addition to the Er K x rays and the annihilation radiation were observed in the decay of ^{162}Tm. Based on the energies and intensities of these γ rays and the level schemes of the even-mass erbium isotopes, a tentative decay scheme of ^{162}Tm is proposed. The K-capture-to-positron ratio in the decay of ^{162}Tm was found to be 12. The maximum positron energy estimated from this ratio and from other results in this work is in gross disagreement with the calculated decay energy of ^{162}Tm.

I. INTRODUCTION

In the irradiation of enriched ^{162}Er with 6-MeV protons, Wilson and Pool[1] found the Er $K\alpha$ x rays and two γ rays (102 and 236 keV in energy) decaying with 77-min half-life when the irradiated sample was assayed on a scintillation spectrometer. These two γ rays were found to be in coincidence with each other and the energies correspond closely to the calculated values of the energy differences between 0+, 2+, and 4+ levels of the ground-state rotational band in ^{162}Er. They attributed these radiations to the decay of ^{162}Tm. They could not positively identify the annihilation radiation in ^{162}Tm because of the interference of ^{18}F, and no other γ rays with energies up to 3 MeV were observed with the same half-life. These authors concluded that the highly populated members of a $K=2+$ γ-vibrational band observed in the decay of ^{166}Tm[2,3] and ^{168}Tm[3] were not present in the decay of ^{162}Tm. Another investigation[4] of irradiating enriched ^{162}Er with 7-MeV protons found a 90-min component in the decay of the K x rays which was also assigned to ^{162}Tm. However, several attempts to produce ^{162}Tm either by spallation[5] or by other nuclear reactions[6,7] failed to produce the 77-min or the 90-min activity; instead, upper limits between 20 and 45 min for the half-life of ^{162}Tm were established from these experiments. In a study[8] of conversion-electron and positron spectra of the thulium fraction obtained from the spallation of tantalum by 660-MeV protons, conversion lines of the 102-keV transition corresponding to various electron shells in erbium were observed. From the decay of the positrons, a half-life of 21.5 min was found and assigned to ^{162}Tm. In view of these various different results concerning the decay of ^{162}Tm, another careful investigation of ^{162}Tm was clearly in order.

Recently, the levels in ^{162}Er were studied by excitation with neutron-evaporation reactions.[9] Transitions from levels in the ground-state rotational band were found up to spin 12. Neither β- nor γ-vibrational band was excited. In the same study, however, both the ground-state rotational band and β- and γ-vibrational bands in ^{164}Er were excited. The results of these experiments and the knowledge of the levels in other neighboring even-

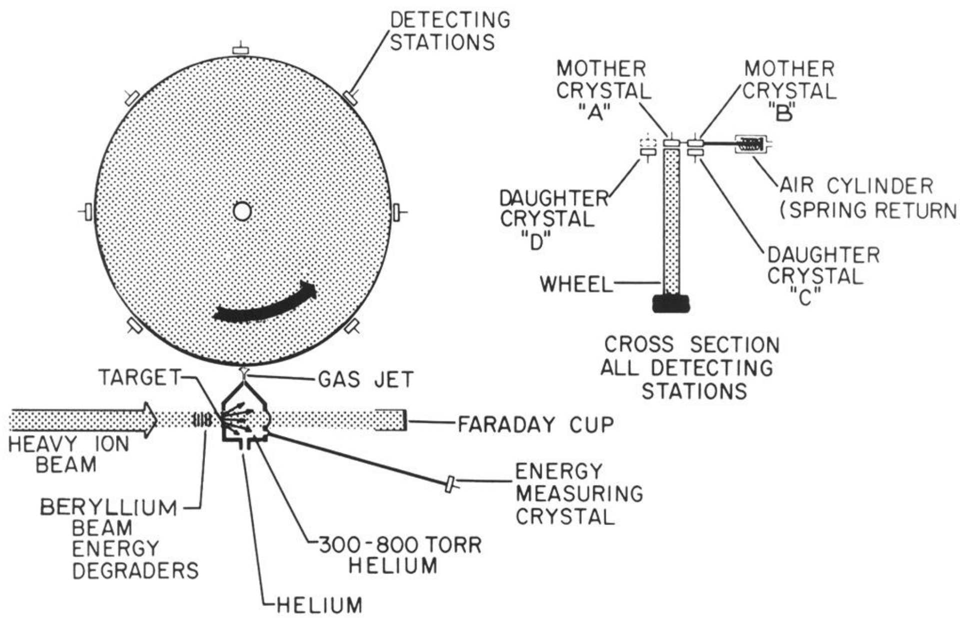

FIG. 1. A schematic representation of the vertical wheel system with seven detecting stations. On the right-hand side a cross section of one of the detector stations is shown.