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STUDIES OF LAWRENCIUM ISOTOPES WITH MASS NUMBERS 255 THROUGH 260[*]

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ABSTRACT

Six isotopes of element 103, with mass numbers 255 through 260, have been studied by means of alpha-particle spectroscopy. The half-lives of the nuclides, and the energies and the intensities of their main alpha-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. Alpha-decay hindrance factors have been calculated using the spin-independent equations of Preston. The alpha-decay energy systematics of the heaviest elements is discussed.

I. INTRODUCTION

In 1961 an 8.6-MeV, 8-sec alpha-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 seconds, 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 alpha-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 alpha-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 alpha-active hahnium precursors for both ^{257}Lr and ^{258}Lr.[6]

II. EXPERIMENTAL

In most of the bombarments either a ^{249}Cf of a ^{248}Cm target was used. The 290-μgm/cm^2 ^{249}Cf target had 60 μgm 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-μgm/cm^2 Pd had been sputtered. The 41-μgm ^{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 μgm/cm^2), ^{246}Cm(280 μgm/cm^2), ^{249}Bk (~600 μgm/cm^2), and ^{250}Cf (~600 μgm/cm^2). Either boron or nitrogen beams accelerated by the Berkeley Hilac 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 alpha-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 diameter wheel were not re-examined 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 alpha 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.

Alpha-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 alpha-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 alpha activities produced by bombarding ^{243}Am target with ^{16}O ions indicated that ^{255}Lr has a half-life of about 20 seconds and an alpha-particle group at 8.38 MeV.

We have produced a 22-sec alpha activity with an alpha-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 alpha-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 ^{256}No in the first spectrum composed of events recorded during the dirst 25 sec after the bombardment, but stands our 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 alpha 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. 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 minutes with its most prominent alpha-particle group at 7.53 MeV.

The alpha-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 alpha-recoil daughter of ^{255}Lr. All together six alpha-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 one tenth of the observed ratio. Thus ^{251}Md seems to decay predominantly by electron capture and this is borne out by greatly reduced apparent reaction cross sections for its production as measured by its alpha decay.

Further proof that the 8.37-MeV alpha-particle activity arises from the decay of ^{255}Lr was furnished by excitation function studies. In Fig. 3 the alpha-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 seconds. 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 alpha-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 alpha-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 alpha activity reflect the difficulty of separating it from the complex alpha-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 alpha-activity and the 23-hour ^{252}Fm. In a review article[3] Donets et.al..give a half-life of 35 sec and the alpha-particle energy range 8.35 - 8.50 MeV with 8.42-MeV alpha-particles being most intensive, as best values for the decay characteristics of ^{256}Lr.

We have produced a 31-sec alpha activity with a complex alpha-particle spectrum by bombarding ^{249}Cf with ^{11}B ions. The alpha-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 seconds 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 alpha-particle groups of ^{256}Lr. A least squares analysis of the decay data yielded a value of 31±3 seconds for the half-life.

The assignment of the 31-sec alpha-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 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 alpha-particle emitter.[4]

C. ^{257}Lr

As discussed previously, the 8.6-MeV, 8-sec alpha-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 alpha-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 alpha-particle activity produced by ^{11}B ions is shown in Fig. 4. It is the very low peak cross section of about 7 nanobarns 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 alpha 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-μahr 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,α3n)^{257}Lr and ^{249}Cf(^{15}N,α2n)^{258}Lr, in the other ^{259}Cf(^{14}N,α2n)^{257}Lr and ^{249}Cf(^{14}N,αn)^{258}Lr. It has been found that an αn reaction has a very small cross section compared to the cross sections of α2n and α3n 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 explicity excluded from the peaks assigned to rutherfordium isotopes because of its shorter half-life.

The complete display of the series of alpha-particle spectra produced by bombardments of ^{249}Cf with ^{15}N ions is presented in Ref. 4. Results of an analysis of the complex alpha-particle groups at 8.6 MeV 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 alpha-particle groups assigned to ^{257}Lr and ^{258}Lr. We have recently found an alpha-active 8.93-MeV, 2-sec precursor to the 8.87-MeV, 0.6-sec ^{257}Lr and an 8.5-MeV, 50-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 alpha 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 alpha-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-MeV 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 nanobarns, 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 alpha 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.

Although the decay properties of the alpha-particle daughter ^{254}Md are unknown, it is expected to decay predominantly by electron capture. We looked for the alpha-particles emitted by the 3.2-hour ^{254}Fm in the off-wheel position and for 620 observed decays of ^{258}Lr some 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 alpha 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 α2n- and α3n-reaction cross sections are expected to be comparable (cf. Fig. 6) whereas 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 alpha-decay daughter ^{255}Md could not be established. This was because of only 10% alpha branching of ^{255}Md.[13] The few alpha-decay events expected could not be distinguished from the background caused by the 7.44-MeV alpha-particle group of ^{211}Po.

F. ^{260}Lr

In recent bombardments of a 600-μgm/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 alpha-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 alpha-decay daughter of ^{260}Lr. To reduce the number of ^{256}Fm atoms recoiling 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 alpha activity was also produced by bombarding a 1.4-mg/cm^2 ^{248}Cm target by 78-MeV ^{15}N ions. The series of alpha-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 one nanobarn, 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 alpha-particle energies the uncertainty is mostly caused by calibration errors. The alpha-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 the purpose. The line-up 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 6.64-MeV alpha-particle group of ^{253}Es samples. The final line-up of the spectra was done during the data-handling phase by the 6600 CDC computer using Paatero's method.[14]

Alpha-decay hindrance factors have been calculated using the spin-independent ($\ell = 0$) equations of Preston.[15] 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 alpha emitters.

Because we have not done any gamma-ray spectroscopy to support the level scheme information, only qualitative discussion of finer details of nuclear structure is possible. A cursory glance at alpha-decay hindrance factors in Table I shows that for each isotope there are transitions with a hindrance factor of less than ten. Such low hindrances factors for odd nuclei are characteristic to favored alpha 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.,[16] the 103rd proton should occupy the $9/2^+[624\uparrow]$ 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 $9/2^+[624\uparrow]$ level to the $7/2^-[514\downarrow]$ level which seems to be the ground state for several Md isotopes is strongly hindered because of a change in parity as well as 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 alpha-particle peak, which has been interpreted as being caused by two alpha-particle groups of approximately equal intensity, may instead be due to summation of gamma rays or conversion electrons coincident with the alpha particles. Assuming that the 8.81-MeV alpha-particle group of ^{257}Lr populates the $11/2^+[624\uparrow]$ state, i.e., it is the first member of the rotational band built on $9/2^+[624\uparrow]$ Nilsson level one obtains a reasonable value of 5.5 keV for the rotational constant $\hbar^2/2\mathfrak{J}$.

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

An upper limit to 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 alpha-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 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 alpha-decay mode to be predominant by studying the genetic sequences $^{259}\text{Rf} \rightarrow {}^{255}\text{No}$ and $^{261}\text{Rf} \rightarrow {}^{257}\text{No}$.[17] Such a measurement was also carried out for ^{256}Lr when ^{260}Ha was first produced.[4] The ratio of the number of observed alpha-recoil-daughter atoms to that of observed parent atoms for the sequence $^{260}\text{Ha} \rightarrow {}^{256}\text{Lr}$ 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 ms.[18] In the case of ^{259}Lr no meaningful limit could be set for EC branching because 57-min, 7.52-MeV ^{259}No (Ref. 19) was highly discriminated against under the experimental conditions 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 pxn or αxn reactions. Both ^{249}Bk and ^{250}Cf targets were used at the very last phase of this work and a more thorough report on these experiments is forthcoming.[6] 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 alpha-decay energies plotted in Fig. 10 as a function of neutron number represent either an estimate of Wapstra[20] or an experimental value obtained by taking the energy of the highest observed alpha-particle group and correcting it for recoil energy loss. In addition to the new data discussed earlier in the text, tentative values for ^{248}Md, ^{249}Md (Ref. 9) and ^{259}No 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. An exception is ^{256}Md, where a weak alpha group has been observed with an energy that agrees with the estimate.[13] According to the single-particle level scheme of Nilsson et al.,[16] there is a fairly large gap at Z = 100 between the $7/2^-[514\downarrow]$ and $7/2^+[633\uparrow]$ proton levels in the neighborhood of mass number 252 with $\epsilon = 0.23$ and ϵ_4 distortion of 0.04. An alpha-transition from the $7/2^-[514\downarrow]$ level to $7/2^+[633\uparrow]$ level is substantially hindered because of the difference in parity. Thus the favored transition to the $7/2^-[514\downarrow]$ 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 alpha-decay energies at ^{258}Md, ^{259}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[21] have explained this by assigning the ground states of ^{257}Fm and ^{253}Cf to $9/2^+[615\downarrow]$ and $7/2^+[613\uparrow]$ Nilsson levels. The favored alpha transition then goes to the 242-keV $9/2^+[615\downarrow]$ level of ^{253}Cf.

Perhaps the most interesting general trend discernible in the plotted experimental alpha-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 alpha-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.

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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
$^{255}\mathrm{Lr}$	22±5	8.37±0.02	~50	2.4	30	$^{243}\mathrm{Am}+^{16}\mathrm{O}$
		8.35±0.02	~50	2.0		$^{249}\mathrm{Cf}+^{10}\mathrm{B},^{11}\mathrm{B}$
$^{256}\mathrm{Lr}$	31±3	8.64±0.02	3±2	490	20	$^{246}\mathrm{Cm}+^{15}\mathrm{N}$
		8.52±0.02	19+3	30		$^{249}\mathrm{Bk}+^{12}\mathrm{C}$
		8.48±0.02	13±3	36		$^{249}\mathrm{Cf}+^{10}\mathrm{B},^{11}\mathrm{B}$
		8.43±0.02	34±4	8.8		
		8.39±0.02	23±5	9.7		
		8.32±0.02	8±2	1.6		
$^{257}\mathrm{Lr}$	0.6±0.1	8.87±0.02	81±2	2.1	15	$^{246}\mathrm{Cm}+^{15}\mathrm{N}$
		8.81±0.02	19±2	6.0		$^{249}\mathrm{Bk}+^{12}\mathrm{C},^{16}\mathrm{O}$
						$^{249}\mathrm{Cf}+^{11}\mathrm{B},^{12}\mathrm{C},^{13}\mathrm{C},^{14}\mathrm{N},^{15}\mathrm{N}$
						$^{250}\mathrm{Cf}+^{15}\mathrm{N}$
$^{258}\mathrm{Lr}$	4.2±0.6	8.68±0.02	7±2	55	5	$^{244}\mathrm{Pu}+^{19}\mathrm{F}$
		8.65±0.02	16±3	19		$^{246}\mathrm{Cm}+^{15}\mathrm{N}$
		8.62±0.02	47±3	5.4		$^{248}\mathrm{Cm}+^{15}\mathrm{N}$
		8.59±0.02	30±4	6.8		$^{249}\mathrm{Bk}+^{12}\mathrm{C},^{16}\mathrm{O},^{18}\mathrm{O}$
						$^{249}\mathrm{Cf}+^{15}\mathrm{N}$
						$^{250}\mathrm{Cf}+^{15}\mathrm{N}$
$^{259}\mathrm{Lr}$	5.4±0.8	8.45±0.02	100	1.1		$^{248}\mathrm{Cm}+^{15}\mathrm{N}$
						$^{250}\mathrm{Cf}+^{15}\mathrm{N}$
$^{260}\mathrm{Lr}$	180±30	8.03±0.02	100	1.7	40	$^{248}\mathrm{Cm}+^{15}\mathrm{N}$
						$^{249}\mathrm{Bk}+^{18}\mathrm{O}$

FIGURE CAPTIONS

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.
2. A series of alpha-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.
3. A comparison of alpha-particle spectra resulting from bombardments of ^{249}Cf with 59 MeV 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 seconds following the end of each collecting period, has been excluded to eliminate short-lived activities such as the 3.2-sec ^{256}No.
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.
5. A series of alpha-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.
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.

7. A fit by SAMPO computer program to the 8.5 to 9.0 MeV alpha-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 MeV (^{210,211}Fr) and 6.773 MeV (^{213}Fr) were used for both shape and energy calibrations.
8. A series of alpha-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.
9. A series of alpha-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.
10. Alpha decay energy as a function of neutron number. The black circles correspond to the highest known alpha-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 alpha decay energies persists up to highest known Z values.

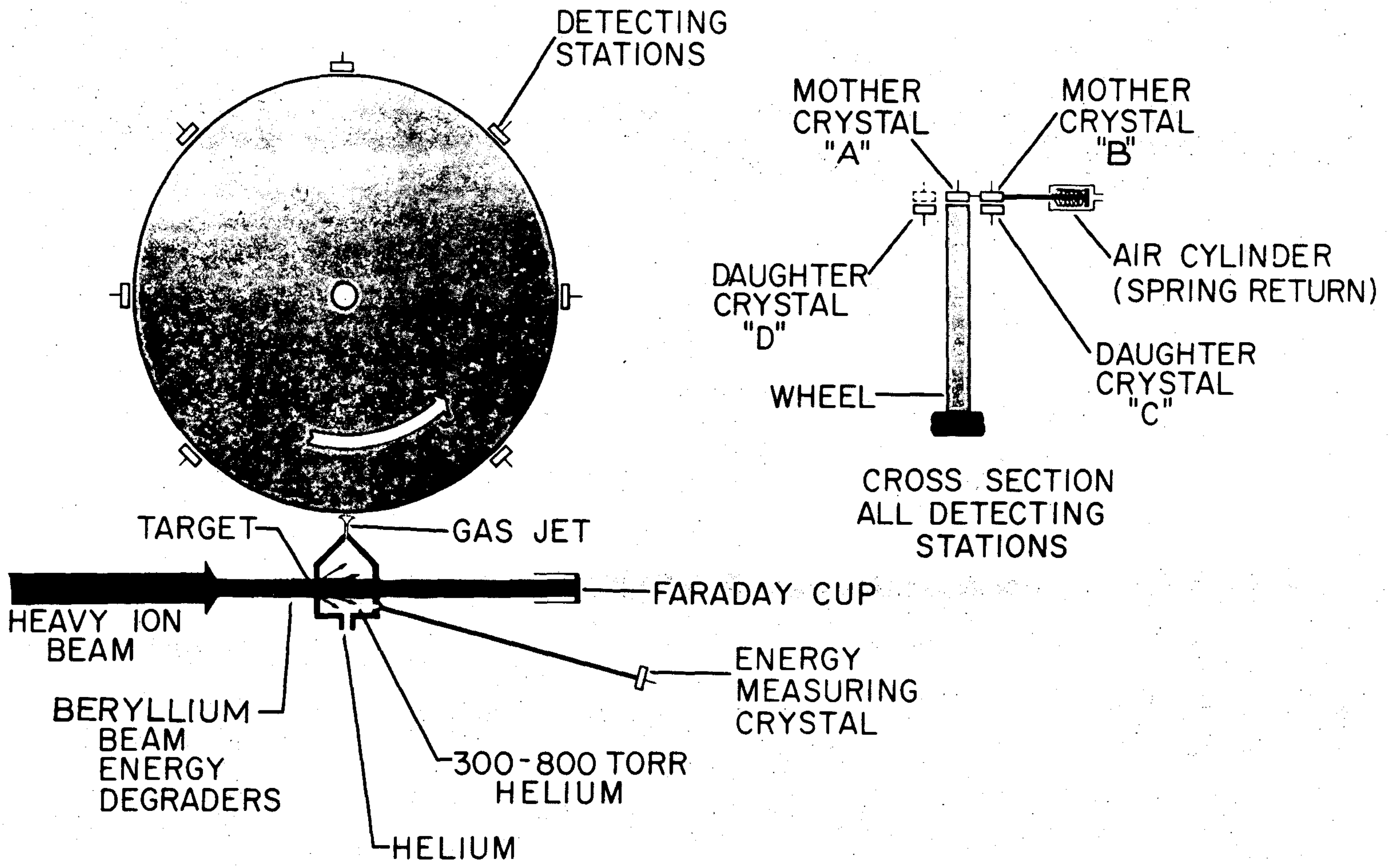

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Fig. 1

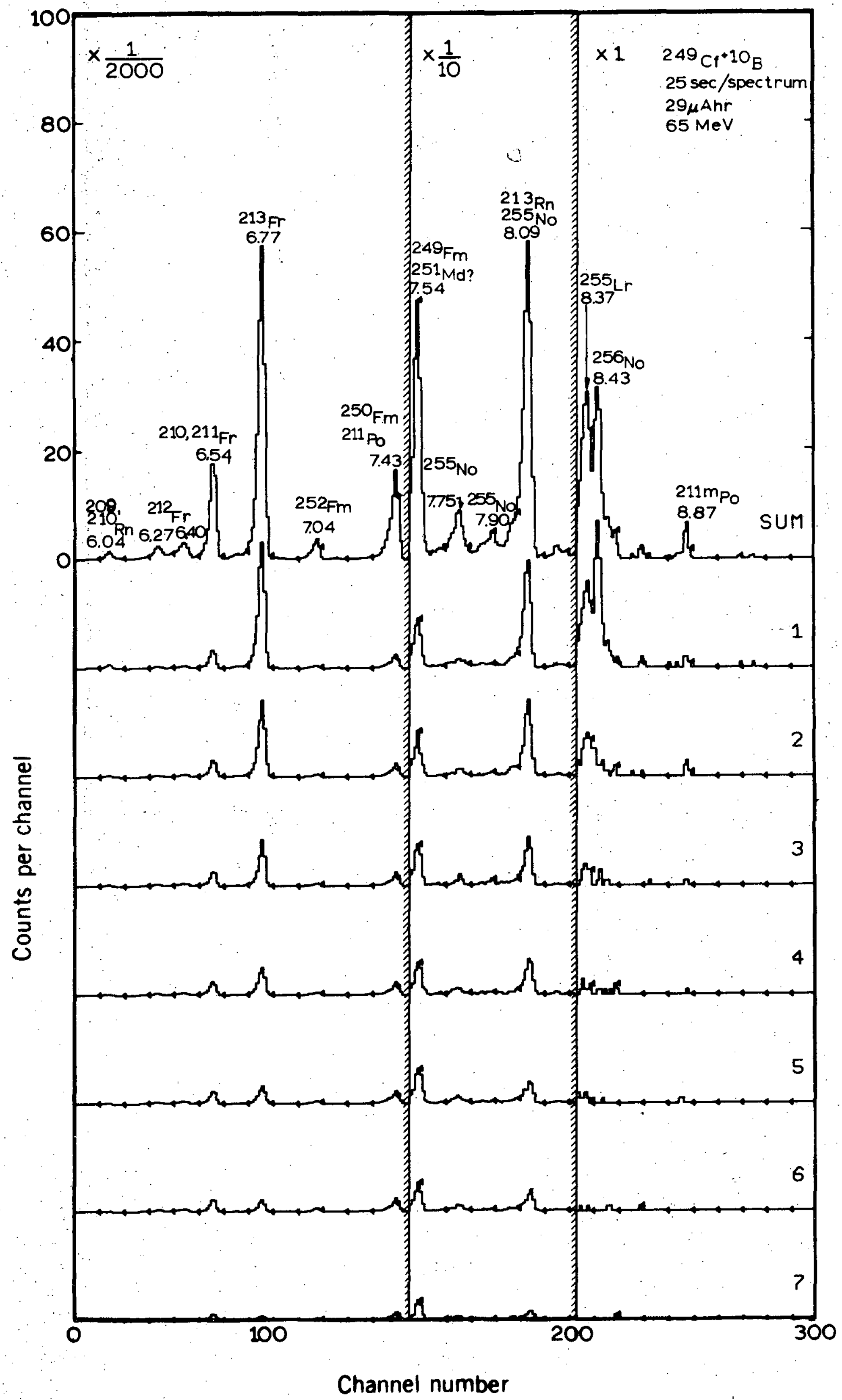

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Fig. 2

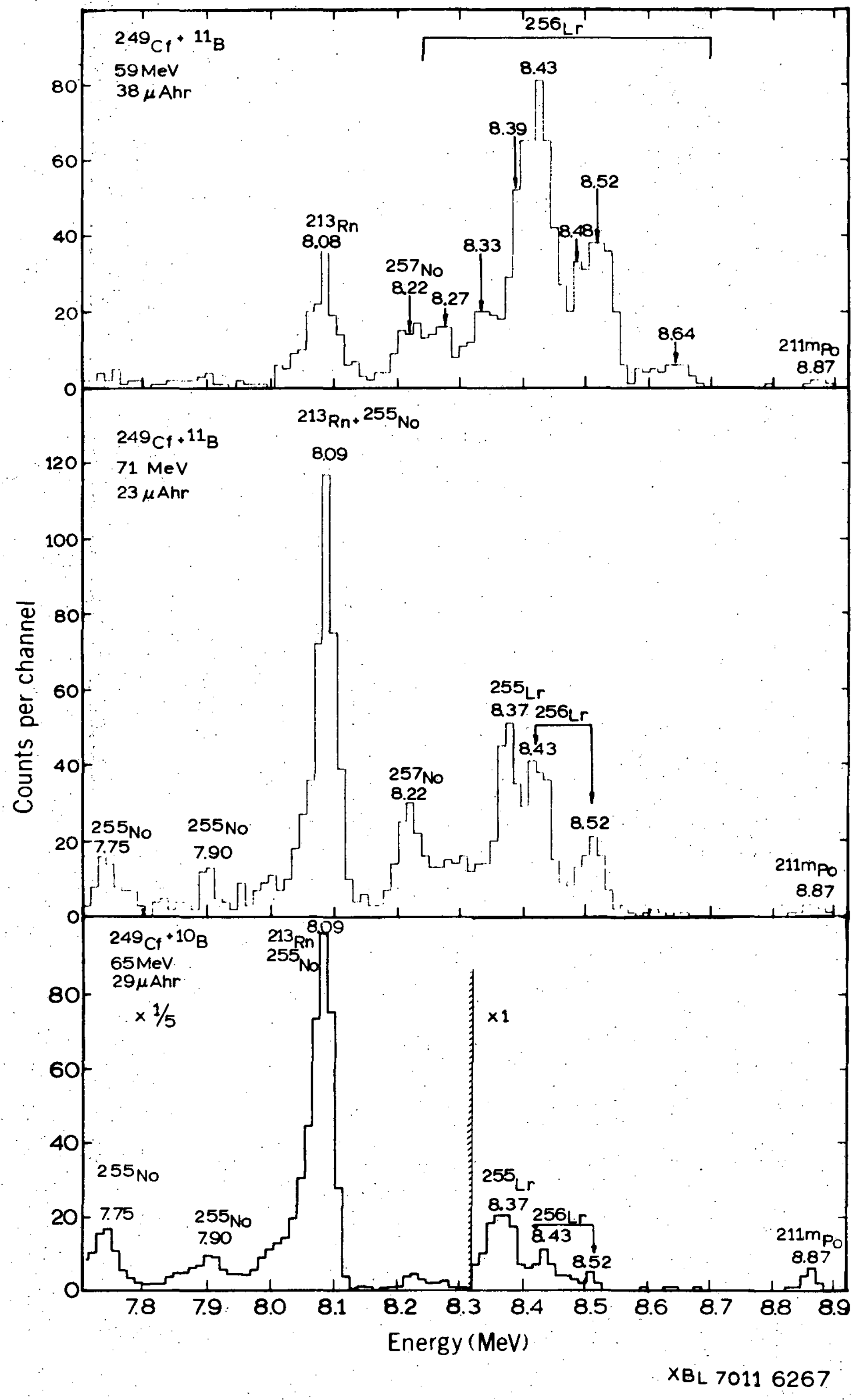

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Fig. 3

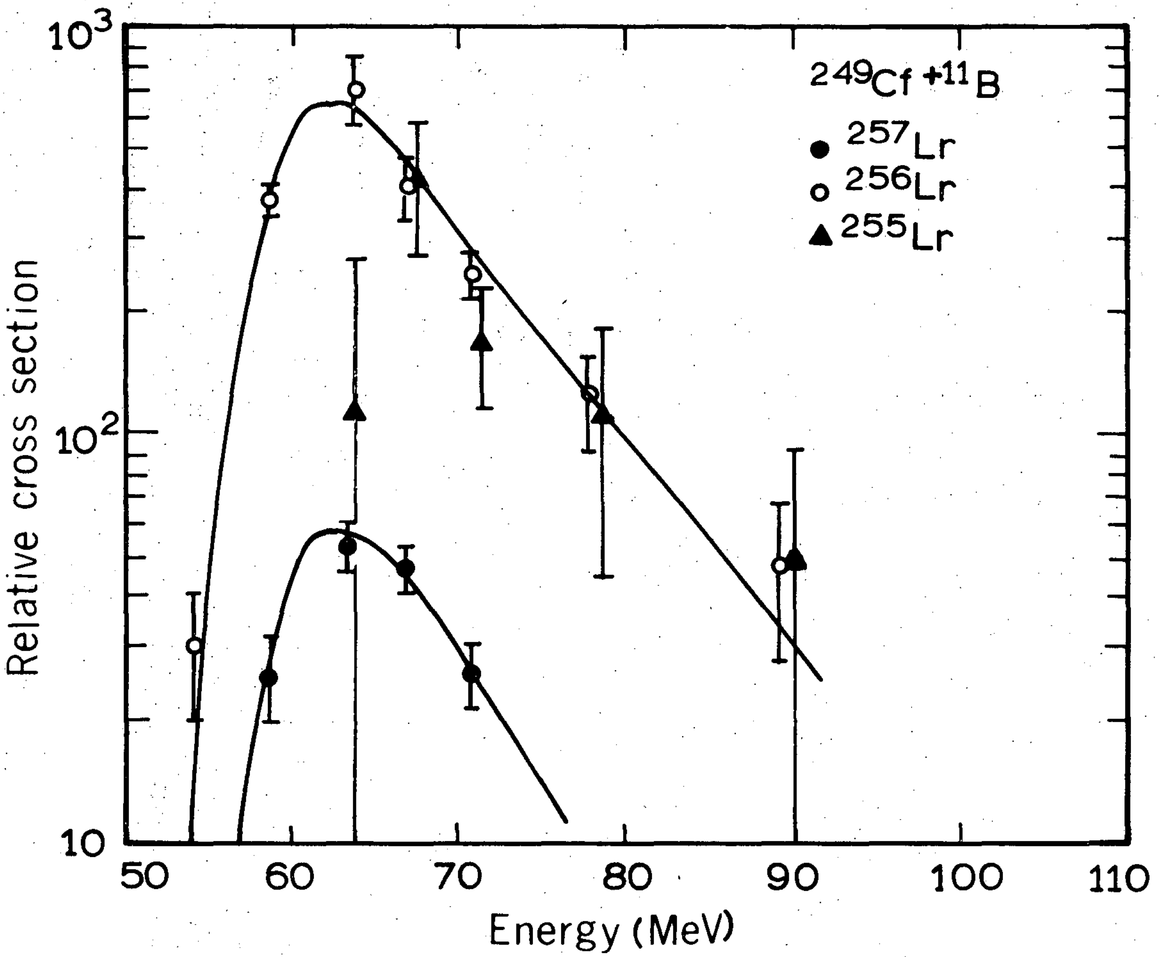

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Fig. 4

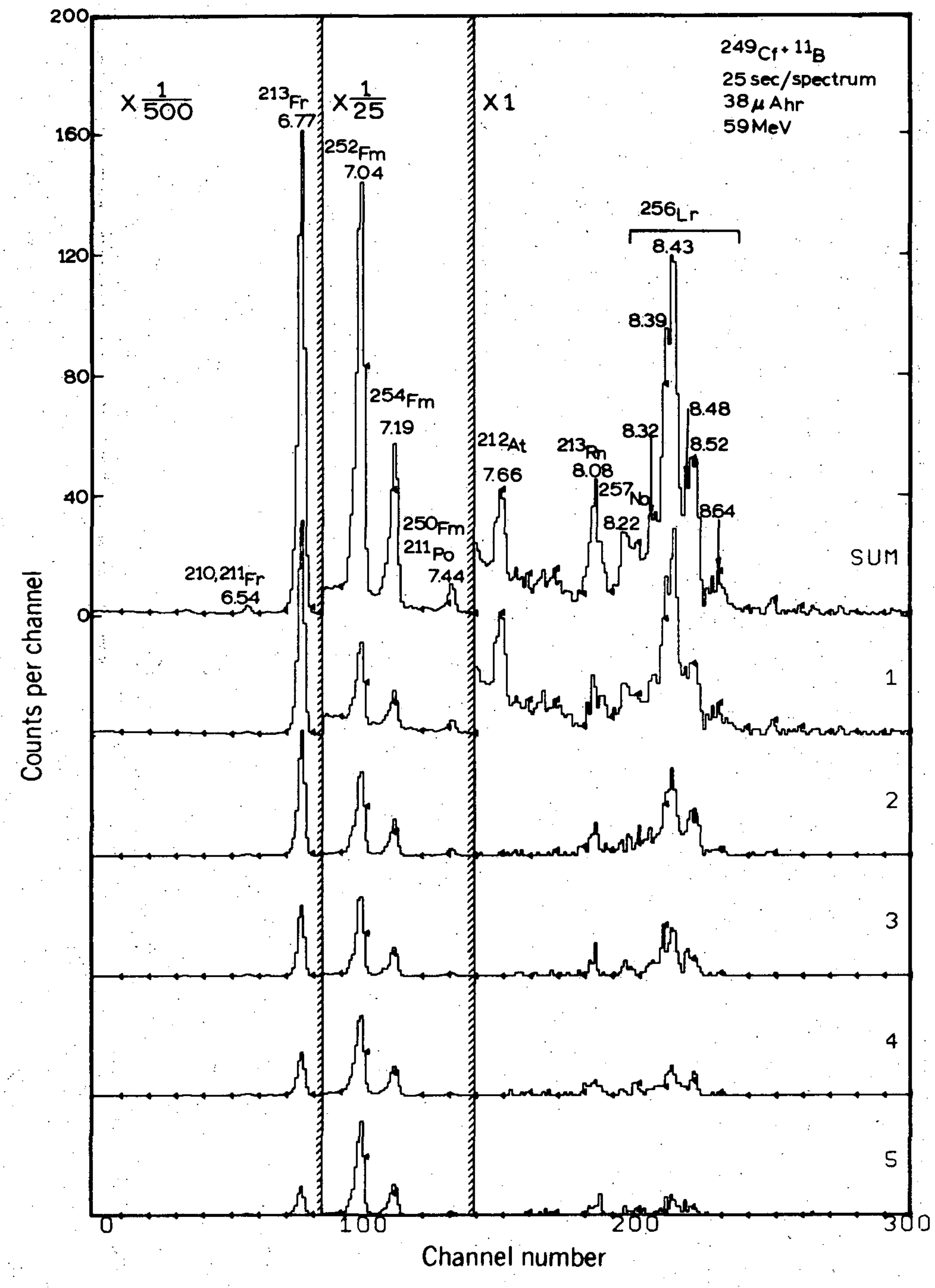

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Fig. 5

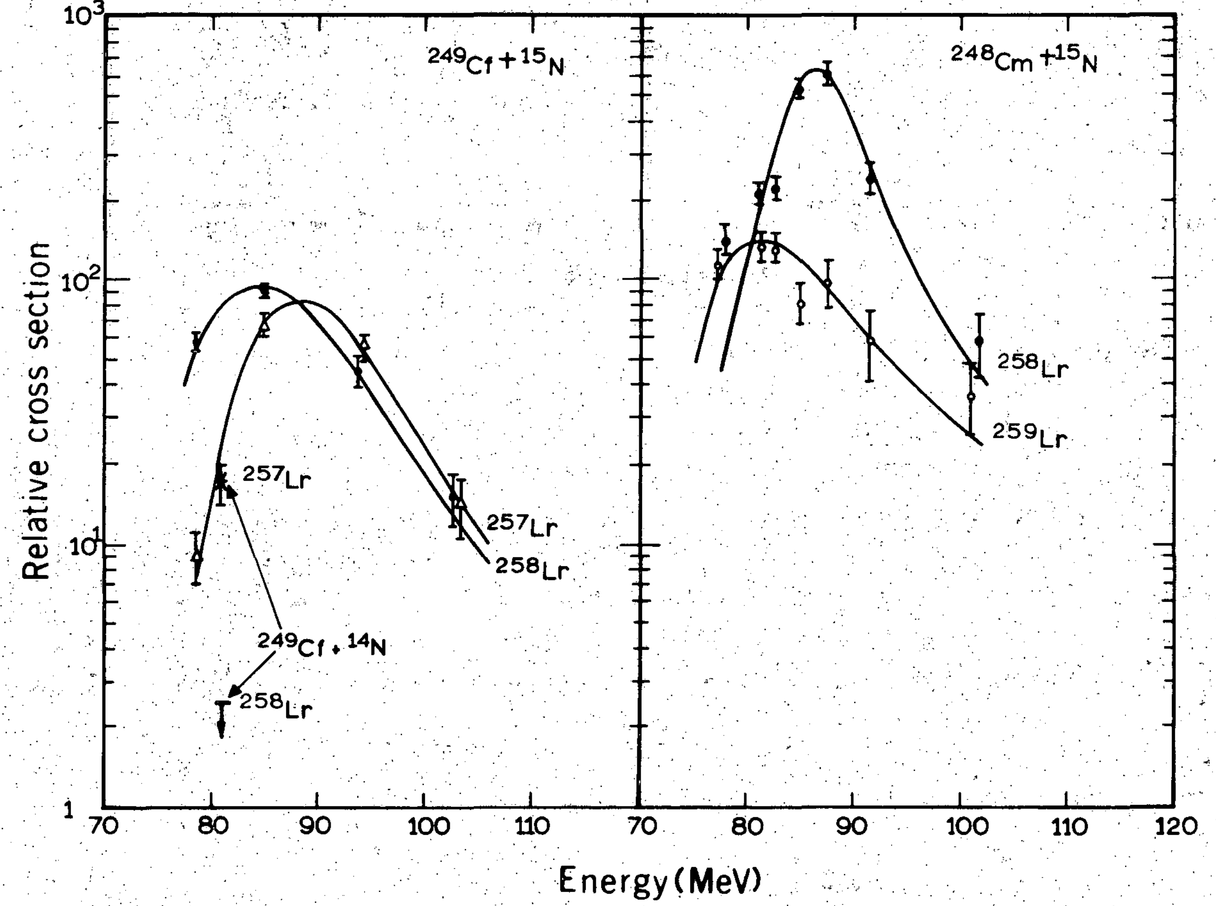

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Fig. 6

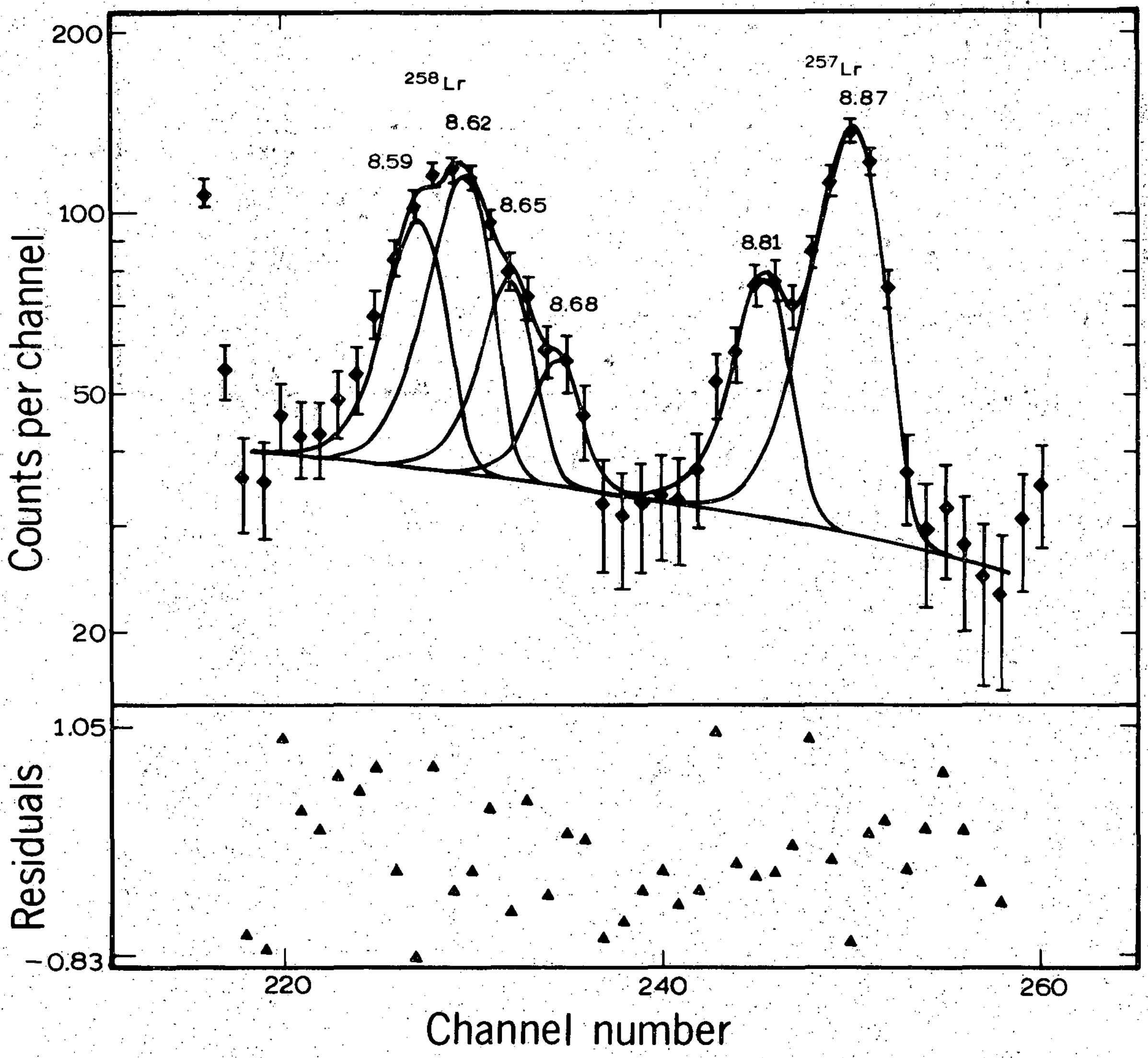

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Fig. 7

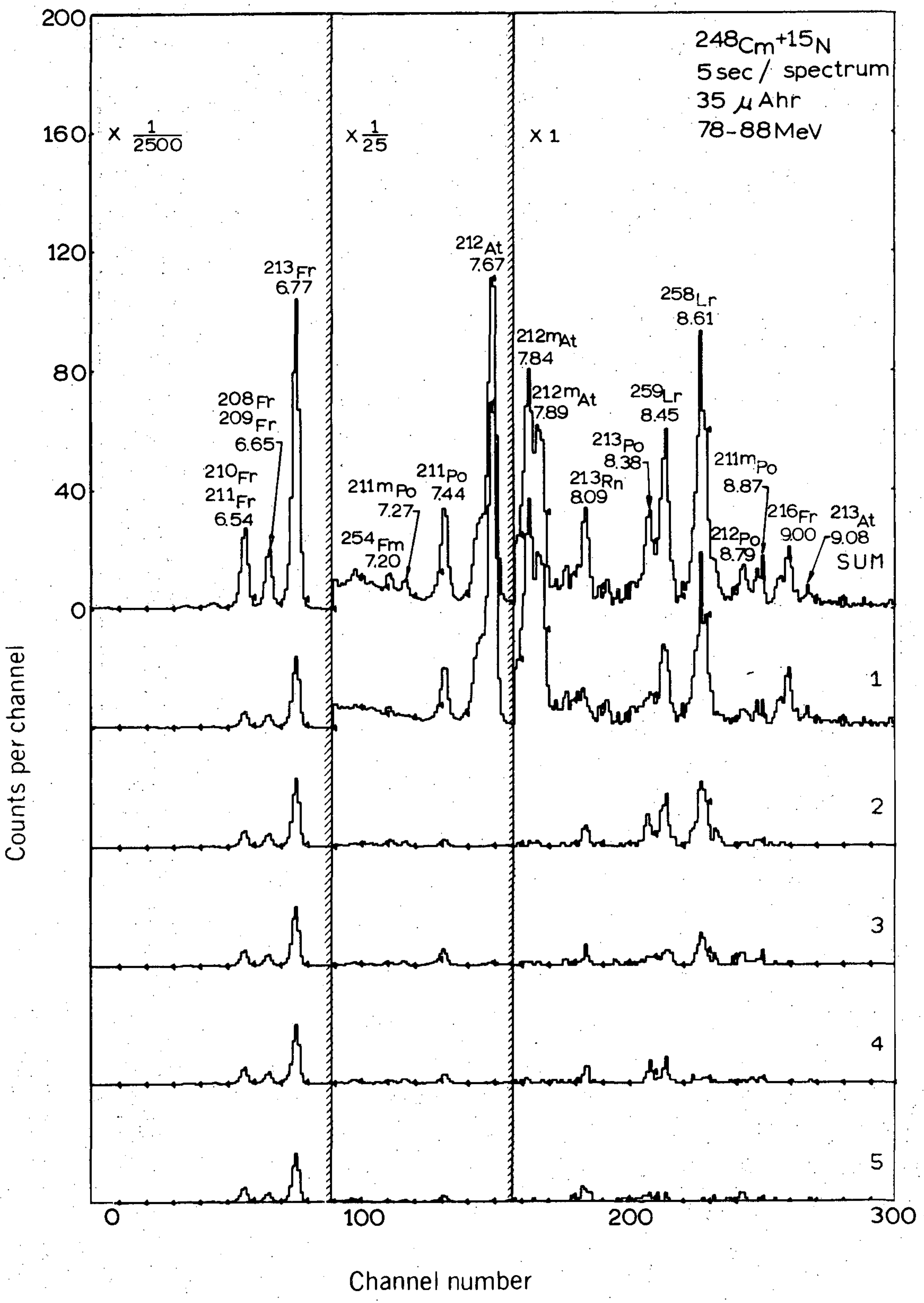

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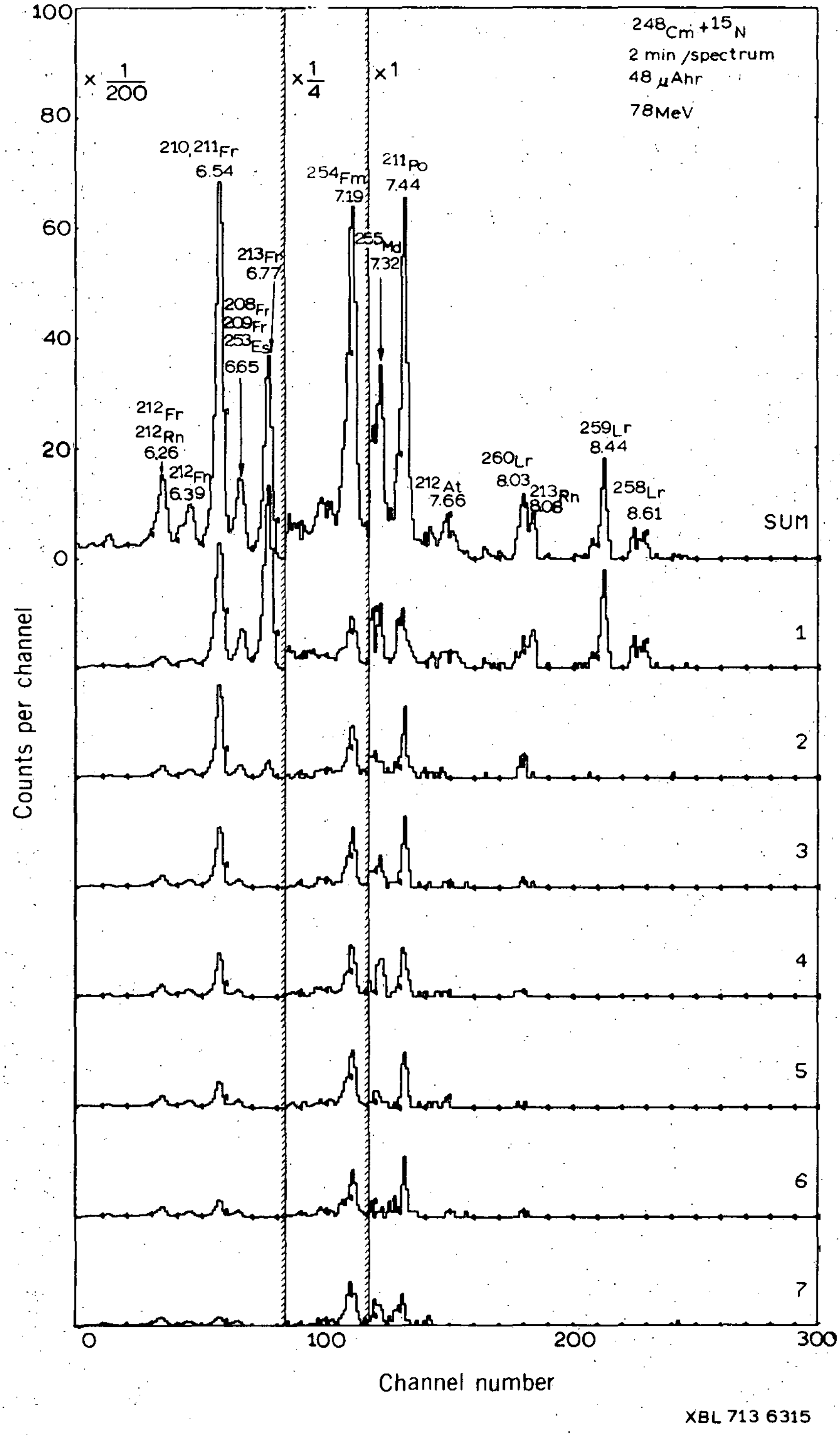
Fig. 8


^{248}Cm + ^{15}N
2 min /spectrum
48 μAhr
78MeV
× 1/200
× 1/4
× 1
^{210,211}Fr 6.54
^{254}Fm 7.19
^{211}Po 7.44
^{255}Md 7.32
^{213}Fr 6.77
^{208}Fr
^{209}Fr
^{253}Es
6.65
^{212}Fr
^{212}Rn
6.26
^{212}Fr 6.39
^{212}At 7.66
^{260}Lr 8.03
^{213}Rn 8.08
^{259}Lr 8.44
^{258}Lr 8.61
SUM
1
2
3
4
5
6
7
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80
60
40
20
0
Counts per channel
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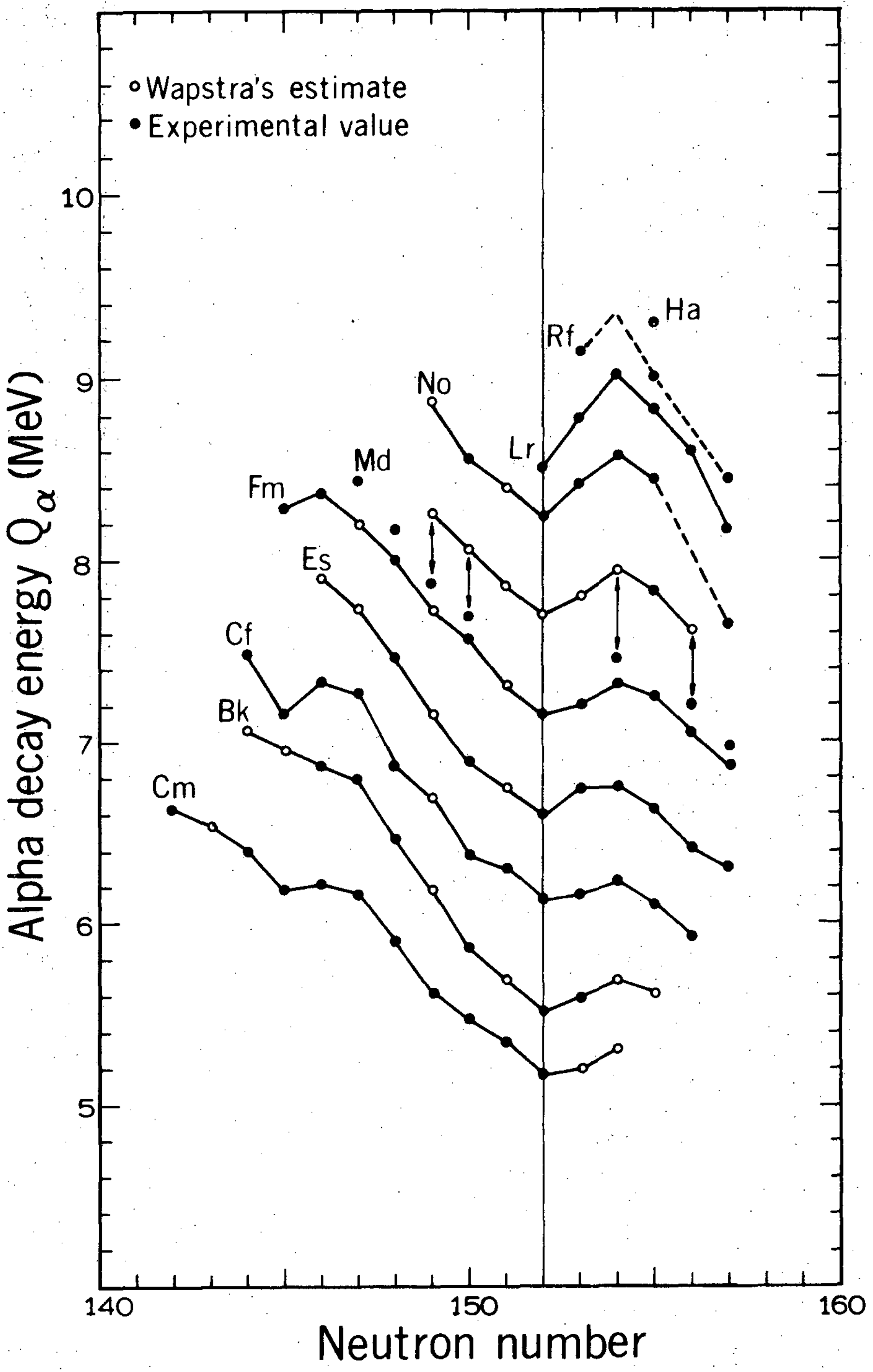
100
200
300
Channel number
XBL 713 6315

Fig. 9



XBL 7012 6271

Fig. 10

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