Nuclear Spectroscopy of Neutron-Deficient Hg Isotopes*†

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In order to extend our knowledge of nuclear level systematics in the Pt-Au-Hg region, neutron deficient isotopes of Hg were produced by high-energy proton bombardment of Au. A technique is described for the analysis of the very complex internal conversion electron spectra present in the decay chains of Hg isotopes produced by Au(p,xn)Hg reactions where $n=1$ to 8 or 9. More or less complete decay chains from Hg to Pt or Ir are postulated for masses 195 to 190 or 189.

INTRODUCTION

AN important aspect of nuclear spectroscopy is the search for systematic behavior of different nuclear properties. The shell model arose from the observations of regularities among the spins and magnetic moments of nuclear ground and isomeric states. Through the study of these properties it was possible to invent a more or less self-consistent scheme of levels with relatively simple rules for their coupling, and a great many phenomena were successfully explained.

However, the fact that some nuclear properties are unexplainable in terms of the simple rules of the shell model suggests that finer details of nuclear structure may play an important role in describing the whole state of affairs, and a search for further regularities in nuclear data seems to be essential.

It was realized in an early stage of nuclear physics that, at least as far as low-energy states are concerned, there is a marked difference between odd-even, even-even, and odd-odd nuclei, and in search for regularities one naturally confines oneself to only one of these subgroups of nuclei. It is also clear that because of the small number of nuclear states in one and the same nucleus which can be reached and properly investigated by present day techniques, one cannot hope to find regularities among the states of a single nucleus. Instead, one should try to see which properties approximately repeat themselves in a complete set of properly chosen nuclei, and to determine what is the trend or variation of these properties as one goes from one nucleus of the set to another.

One knows from experimental evidence which has been so far obtained that the main features of nuclear levels in odd-A nuclei are determined by the odd group. One therefore looks for regularities in the set of nuclei $(Z+2\xi, N+2\nu)$, where ξ and ν are integers. Inasmuch as the techniques for measuring magnetic and quadrupole moments of small quantities of radioactive nuclei have not been fully developed yet, one can hardly speak of any regularities concerning these quantities although some indications for possible regularities have been repeatedly indicated in the literature. The chances at present are much better to establish regularities in energy-level spacings, etc., since a much wider range of nuclei can be compared. The best examples for this are perhaps the different states in the odd neutron isotopes of Sn, Te, Xe, and Ba.[1] In this series the neutrons are filling the shell completed by 82 neutrons.

It was pointed out[2] that a similar, and even more extensive, set of nuclei should be found among the odd isotopes of Ir, Pt, Au, Hg, and Tl, since here both the neutrons and the protons are filling up their respective shells. This set of nuclei could also prove to be of special interest since there are chances to follow the behavior of the spin doublets (the states with $j=l+\frac{1}{2}$ and $j'=l-\frac{1}{2}$) as one adds pairs of nucleons: both $p_{\frac{3}{2}}$ and $p_{\frac{1}{2}}$ states show up in Hg^{199},[2,3] and both $d_{\frac{3}{2}}$ and $d_{\frac{5}{2}}$ show up in Au^{197}.[4]

The study of a complete chain of nuclei is made especially easy by the use of a high-energy accelerator. Starting with an odd-Z element (which therefore has at most two stable isotopes), one can get reactions of the type (p,xn) where x increases as the energy of the bombarding particle is increased. Reactions as high as $(p,9n)$ or higher can be obtained without an appreciable loss in yield due to competing reactions. The resulting radio-isotopes decay mainly by K capture and the study of the internal conversion electron lines is then undisturbed by the presence of a continuous-energy β spectrum.

In the present work the target material was Au which has just one stable isotope—Au^{197}, and Hg isotopes as low as $Hg^{189 \text{ or } 190}$ were produced by going to proton energies as high as 85 Mev. This paper will describe the improved experimental technique employed for ob-

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[1] M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).

[2] de-Shalit, Huber, and Schneider, Helv. Phys. Acta **25**, 279 (1952).

[3] P. M. Sherk and R. D. Hill, Phys. Rev. **83**, 1097 (1951).

[4] J. W. Mihelich and A. de-Shalit, Phys. Rev. **91**, 781 (1953).

taining and analyzing the data for the lighter isotopes of Hg, and the results obtained with this method. A general discussion of the significance of these results is given in the following paper.

METHOD

Preliminary experiments performed with sources produced at the Nevis cyclotron at Columbia University indicated that the complexity of the conversion electron spectrum was too great for analysis by a conventional "single-channel" counter spectrometer. Most of the electron lines were in the energy range of ~10 kev to 300 kev, and there were many different decay rates, including growth of daughter activities. Accordingly, we decided to employ the Brookhaven Laboratory permanent magnet 180° spectrographs, which possess the advantage of recording, photographically, all the lines simultaneously. In addition, these spectrographs have a very good resolving power, a feature which was important, since the number of electron lines per energy interval is very high. Even so, a considerable number of "overlaps" of lines arising from different transitions were observed. However, our analysis enabled us, in most cases, to indirectly resolve these overlapping lines.

Since some of the activities to be studied were of short half-life, a 119-gauss spectrograph was set up at the Harvard Cyclotron Laboratory in order to get the sources in the spectrograph with the least delay.

Besides the primary magnet, others of 100 and 275 gauss were used at Brookhaven to study some of the longer-lived activities. Unfortunately, it was not feasible to follow all the sources in more than one magnet for a time sufficient to get good values of decay rates for long-lived activities. Hence, our electron data for energies greater than 300 kev are sketchy, but the most important problem, for our interests, were the shorter-lived activities in the low-energy region.

The magnets have pole gaps of 12 in.×20 in.×2 in. into which the spectrograph "cameras" are inserted. Calibration of the magnet had been made with conversion lines of Au^{198}, I^{131}, and W^{187}.[5] The spectra were recorded on Eastman No-screen x-ray film (1 in.×15 in.). The task of taking large numbers of spectrograms was facilitated by means of a light-tight "film pack" which enabled one to load the spectrograph in daylight, without removing the spectrograph camera.

In general, the time required to get the spectrograph in operation was ~45 minutes after turning off the cyclotron. In one experiment which we set up to measure a 30-minute activity, a 20-minute irradiation was made, and within 18 minutes after turning off the beam, the Au target was removed, the distillation of the source performed, and the spectrograph put into operation.

The procedure for making the sources was as follows. Au foil (6 layers of 6 mils) was irradiated at the desired position in the cyclotron chamber. After removal, the Au was placed in a quartz container, a thin narrow piece of stable Au foil with Scotch Tape backing (to which Hg would not stick) inserted in a cool portion, the device evacuated by a mechanical pump, and the Au target heated with a flame. The Hg boiled off and condensed on the Au foil. In this way, one produces an ideal source, since essentially only radioactive Hg is deposited on the foil. The thinness of the source is apparent from the sharpness of the electron lines.

Eventually, a furnace was built, which was heated by a nichrome filament operated through a variac. Better control of the heating was then possible. The temperature of the Au was brought to about 850–1000°C.

In retrospect, after analysis of all the data, certain refinements become apparent. Since the Au backing for the source was ~0.005 mil, the Hg-Au amalgam formed on the surface initially will diffuse into the stable Au with a resultant "thickening" of the source with time. This effect was noticed in that the electron lines were very sharp for a fresh source and after a day or two, some loss of sharpness was apparent. If we had used a very thin evaporated Au film on Ni, say, the effect would have been decreased.

The sources were about 0.2 mm wide×1.5 cm long. Sufficient activity was deposited to produce good pictures in 30 minutes with a fresh source produced by high-energy protons, but as the source aged, exposures of several days were required.

All told, some 175 spectrograms were taken and some 250 different electron lines analyzed. Protons up to 105 Mev were used for activation. The problem became complicated since, when the threshold for a new activity (say p,xn) was reached, all the previous reactions requiring a lower energy were still present. The Hg^{197m} produced by (p,n) which has an effective threshold at ~6 Mev was still present with 85-Mev protons. Part of the low-order reaction is possibly due to degraded protons in the target.

Figure 1 is a reproduction of the first spectra obtained from various sources produced by protons of energies from 25 to 65 Mev. Figure 2 is a reproduction of the spectra obtained at increasing times with one of these sources. The reproduction process in making positive prints does not allow one to appreciate the sharpness and clarity of these films.

The following is a discussion of the analysis employed in the assignment of electron lines to various mass numbers of the elements involved and in postulating the decay schemes.

The positions of the lines on the films were measured on a viewer equipped with a vernier caliper. As stated above, the magnets had been calibrated against conversion lines of γ-ray transitions previously measured by the DuMond group. The energy measurements were, in general, quite consistent. Energy sums (e^- kinetic energy plus x-ray absorption edge energy[6]) were

[5] Muller, Hoyt, Klein, and DuMond, Phys. Rev. **88**, 775 (1952).

[6] Hill, Church, and Mihelich, Rev. Sci. Instr. **23**, 523 (1952).

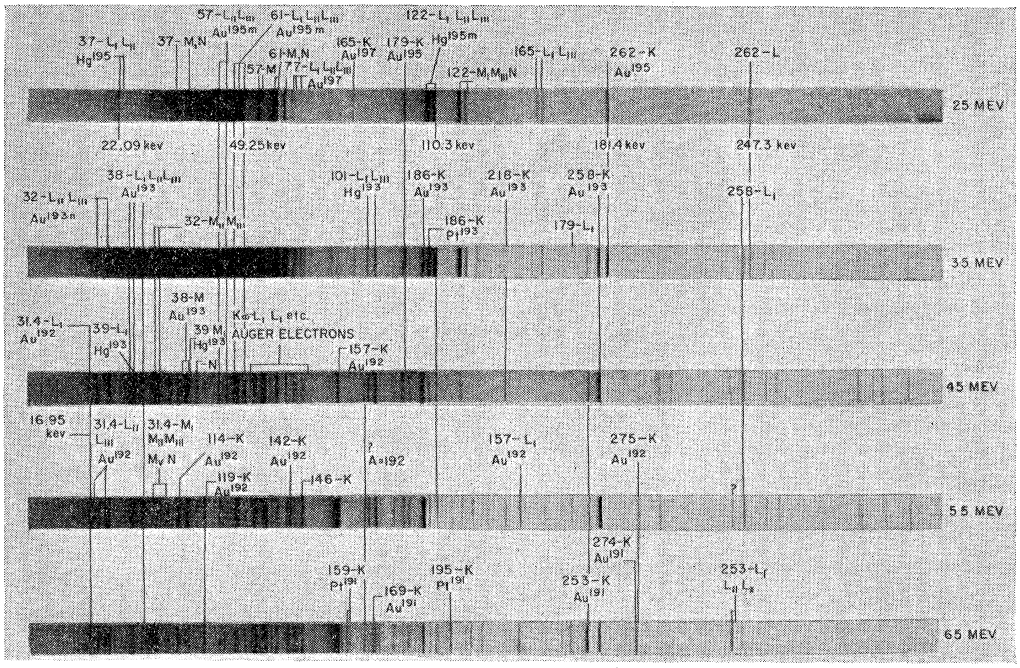

FIG. 1. Conversion electron spectra of Au(p,xn)Hg sources produced by protons of various energies. (119-gauss magnet.)

consistent to about 0.1 kev. In comparing electron lines recorded with different sources and exposures, 0.3 kev was the greatest allowable deviation; it was usually much less.

Photometric measurements were made on a Leeds and Northrup recording microphotometer, used in a standard fashion. A major portion of our photometric measurements were concerned with determining the

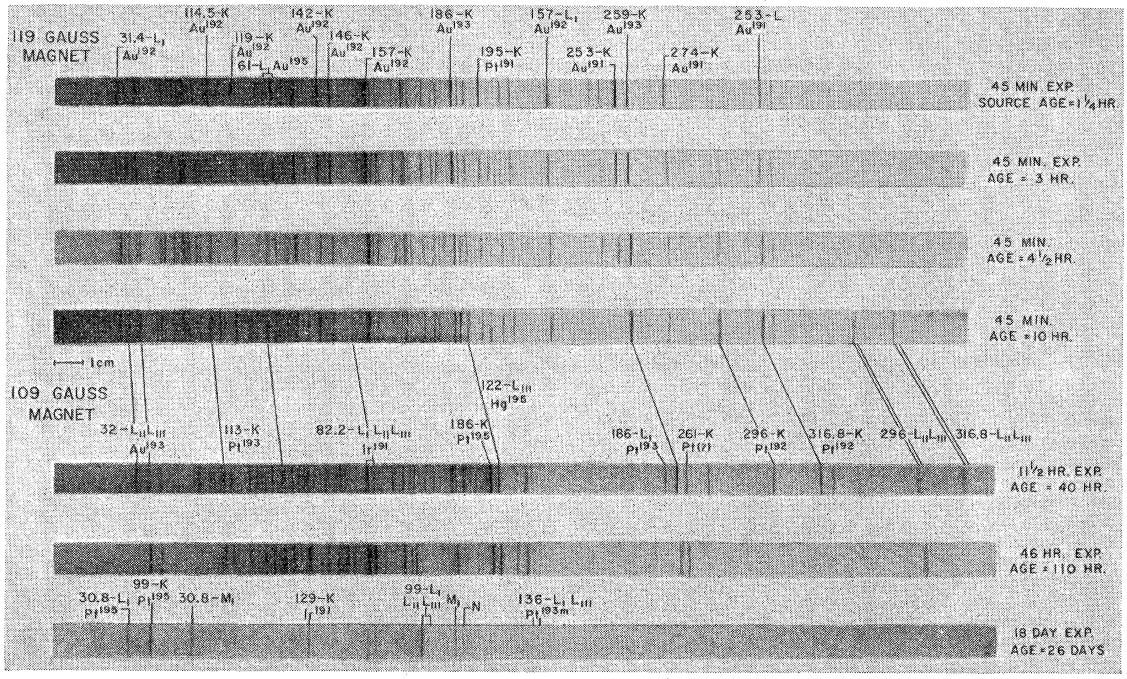

FIG. 2. Conversion electron spectra of Au(p(65 Mev),xn)Hg source taken at successive intervals of time.

decay rate of lines, as compared to an arbitrary standard line of known half-life in Hg^{195m},[7] as well as the excitation functions and thresholds for reactions producing the conversion lines. These excitation functions are taken relative to a transition in Au^{195} which appears at all proton energies. More will be said about this below. In addition, the HNO_3 "washing factor" for certain conversion lines was measured. This last technique consists of dipping the Au-Hg amalgam comprising the source into concentrated HNO_3. The Hg should dissolve easily, leaving the Au, Pt, or Ir daughters. This was of considerable aid in deciding the element in which a transition occurred. Here too, care had to be employed, since the washing factor is dependent on the energy of the electrons and the amalgam thickness (i.e., the age of the source). Further information was obtained by evaporating the Hg at some time after completion of the irradiation, thus allowing the short-lived Hg to decay, with the result that the activity of this short-lived Hg and any of its descendants would be attenuated. Although not any one piece of information on a line would always make its assignment unique, usually a combination of these criteria would.

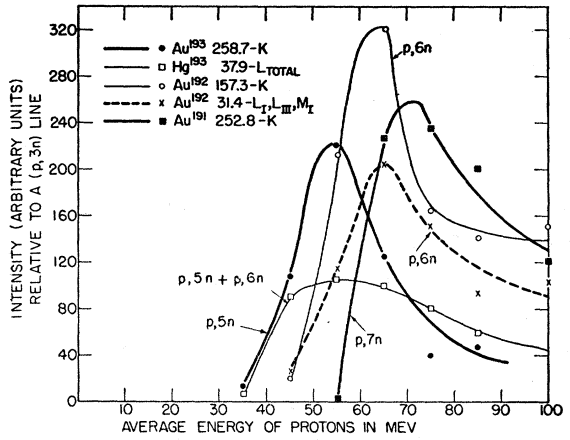

FIG. 3. Typical curves of relative excitation functions of conversion electron lines.

A very useful criterion was the excitation function. For a line of sufficient intensity, and an energy of >70 kev, the peak of this curve was well enough located to place the line in an activity arising in mass 193, 192, or 191. (See Fig. 3.) It will be noted that the excitation curve for the 37.9—L_{total} does not drop as the energy of the protons is increased beyond the peak at 55 Mev. This is due to the fact that the L_{I} line is composite with an electron line arising from a $(p,7n)$ reaction.

The experimental uncertainty in determining the decay rates of individual lines was somewhat greater, although decay rates were measured relative to the 122—L_{III} line (38 hr) in Hg^{195m}. It was desirable to follow some of the sources several half-lives, a procedure which could not always be adhered to for the long-lived daughters. Nevertheless, the decay-rate data were good enough to allow us to group lines together, and in particular, did indicate to us the growth and decay of the long-lived descendents in the decay chains. Figures 4 and 5 show some typical curves.

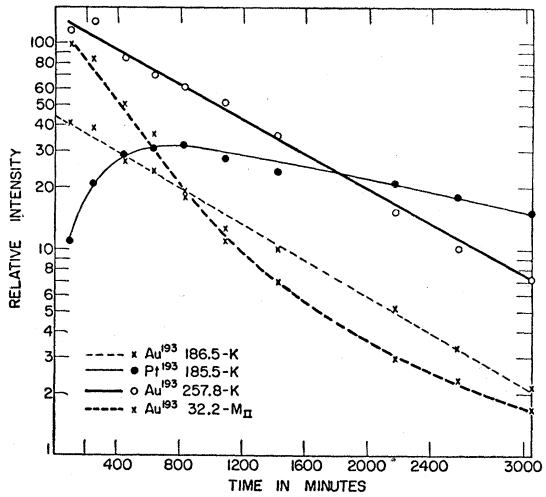

FIG. 4. Typical decay curves of conversion electron lines in the $A=193$ decay chain (produced by 45-Mev protons).

The accurate determination of intensities of conversion lines in a constant-field photographic recording instrument is difficult when considering lines corresponding to considerably different radii of curvature. This is due to the fact that the shape of the image is a function of the distance of the line along the focal plane, as well as of the source characteristics, scattering effects, and detector efficiency effects. We have taken the intensity of a line ($T>50$ kev) as equal to the peak height, corrected by a ρ^{-1} factor (where ρ is the radius of curvature), and used the sensitivity function for no-screen film as determined experimentally.[8]

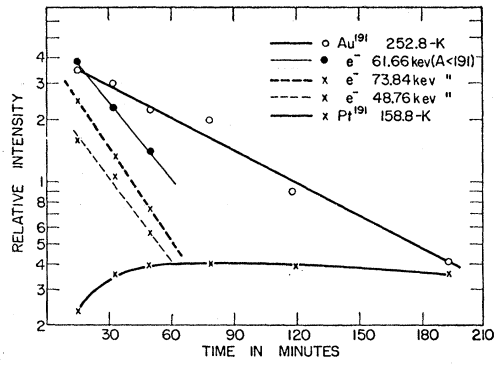

FIG. 5. Typical decay curves of electron lines resulting from activities produced by 85-Mev protons.

[7] Huber, Joly, Scherrer, and Verster, Helv. Phys. Acta **25**, 621 (1952) and private communication to A. de-Shalit.

[8] R. A. Dudley, *Notes for Oak Ridge Autoradiography Course*, 1951 (unpublished); L. Cranberg and J. Halpern, Rev. Sci. Instr. **20**, 641 (1949); J. W. Mihelich (unpublished).

For electron lines of $T<50$ kev, we have corrected our intensity data against the intensity data of Huber, Joly, Scherrer, and Verster, for Hg^{195m}.[7] Admittedly, a more complicated correction could be applied, but since the lines are very sharp because of the effective zero thickness of source, it was felt that this procedure would not give intensities too far from the correct ones. We must attach considerable uncertainty to electron lines of energy <60 kev. For lines of higher energy, the data are much better. For any conversion lines which are reasonably close in energy, our values of relative intensity should be most reliable. Densities above 1.0 were not considered, and at the other extreme only lines which were 3 or 4 times the background photometric fluctuation were seriously measured.

Intensities of all prompt lines are given relative to the sum of the L-line intensities for a 61.2-kev transition in Au^{195}. The intensities of daughter activity lines (Pt or Ir) which grow in are not normalized, but are consistent for lines arising from the same activity.

It was noticed when using a counter spectrometer that the counting background increased with time, indicating evaporation of the Hg from the source. We do not think that any such effect has materially affected our data. No fogging of the films was in evidence, and decay rates for electron lines arising from the same transition were consistent with each other.

TABLE I. Electron lines associated with $A=195$. Intensity integrated over 100 minutes, starting 20 minutes after a 40-minute evaporation of a 1-hr target.

T(kev)	Intensity (arb. units)	Half-life	Assignment	Remarks
22.09	300	38 hr	Hg 36.93—L_I	$M1$
22.62	70		Hg 36.83—L_{II}	
33.17	120		Hg 36.73—M_I	
36.05	50		Hg 36.85—N	
39.40	30		Hg 122.5 —K	$M4$
42.83	115		Au 56.56—L_{II}	$E3$
44.79	115		Au 56.71—L_{III}	
53.35	50		Au 56.50—M_{II}	
53.77	50		Au 56.51—M_{III}	
55.87			Au 56.61—N_{II}	+Auger
107.7	90		Hg 122.6 —L_I	
108.4			Hg 122.6 —L_{II}	
110.3	175		Hg 122.6 —L_{III}	
119.1	30		Hg 122.7 —M_I	
119.8	75		Hg 122.7 —M_{III}	
181.9	150		Au 261.7 —K	$M1$
247.2	20		Au 261.6 —L_I	
46.85	290	38+9 hr.	Au 61.20—L_I	
47.49	270		Au 61.22—L_{II}	$M1+E2$
49.25	250		Au 61.17—L_{III}	
57.90	95		Au 61.32—M_I	
58.15	95		Au 61.30—M_{II}	
58.38	45		Au 61.12—M_{III}	
60.49	50		Au 61.26—N_I	
99.16	30		Au 179.9 —K	$K/L=4.2$
165.4	7		Au 179.8 —L_I	
16.97		>25 days	Pt 30.84—L_I	$M1$
20.40	1000		Pt 98.77—K	
27.47	120		Pt 30.76—M_I	
30.10	30		Pt 30.81—N_I	
85.05	210		Pt 98.92—L_I	$M1$
85.63	35		Pt 98.89—L_{II}	
87.40	10		Pt 98.95—L_{III}	
95.60	55		Pt 98.89—M_I	
96.20	30		Pt 98.83—M_{III}	
98.07	10		Pt 98.78—N	

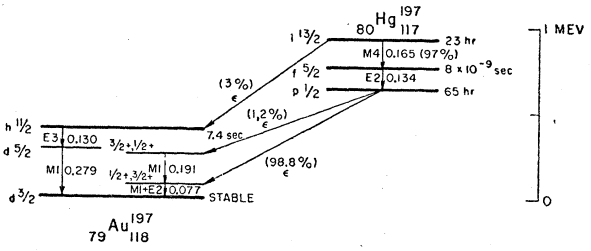

FIG. 6. Decay scheme of Hg^{197m}.

The assignment of multipole orders was made in some cases by K/L ratios, and in other cases, by L-conversion ratios. Considerable empirical data are available to supplement the theoretical data on L-shell conversion of Gellman, Griffith, and Stanley.[9] In particular, $M1$, $E2$, $M1+E2$ mixtures, and $M4$ multipole conversion in the L subshells is fairly well understood.[10] These L conversion data, along with other data, enabled us to assign these multipoles with considerable confidence. For L conversion of $E3$ transitions less empirical evidence is available than for other multipole orders. However, the $E3$ (130 kev) in Au^{197m} [4] is well established and is converted in the L_{II}–L_{III} shells. One also may draw analogies between various isotopes of the same element. It should be emphasized that in most cases we do not have any positive measure of multipolarities, such as K-conversion coefficients,[11] but for these low-energy transitions, L conversion is probably the easiest criterion to employ. Undoubtedly, future work, employing photon and electron counting techniques will be necessary to verify the decay scheme of each isotope.

Unless otherwise stated, our level assignments are those predicted on the strong spin-orbit coupling single-particle shell model.[12]

RESULTS

$A=195$

With a proton irradiation at 19 Mev, no $(p,3n)$ reaction was observed, while at 25 Mev, a very good yield was obtained. Figure 1 shows a "25-Mev spectrum" and Table I lists our conversion electron data.

It will be recalled that Hg^{197m} decays via an $M4$ isomeric transition as well as by a 3 percent K-capture branch to Au^{197m} (7.4 sec). Figure 6 shows the presently accepted decay scheme.[4] All levels are those predicted on the single particle shell model. When the number of neutrons is decreased by two ($A=195$), the levels are

[9] Gellman, Griffith, and Stanley, Phys. Rev. **85**, 944 (1952).
[10] J. W. Mihelich, Phys. Rev. **87**, 646 (1952).
[11] Rose, Goertzel, Harr, Spinrad, and Strong, Phys. Rev. **83**, 79 (1951).
[12] M. G. Mayer, Phys. Rev. **78**, 16, 22 (1950); Haxel, Jensen, and Suess, Z. Physik **128**, 301 (1950).

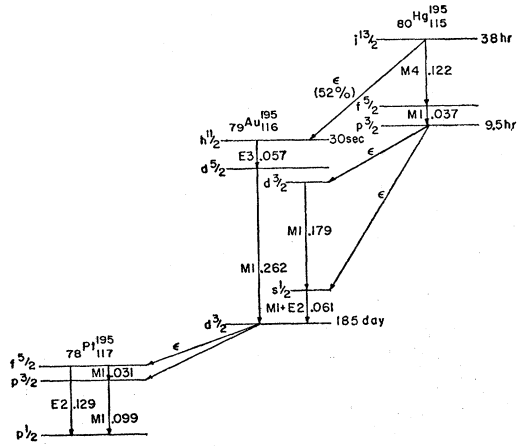

FIG. 7. Decay scheme of Hg^{195m}.

quite analogous to those for $A=197$, except that there are definite changes in the level spacings.

Huber, Joly, Scherrer, and Verster[7] have studied the decay of Hg^{195m}, produced by 25-Mev deuterons on Au.[13] They have determined the lifetimes of the two levels[14–16] in Hg and the 30-sec half-life of Au^{195m}. They have observed all the main γ-ray transitions in Hg and Au, have measured the coincidence spectrum and have determined the intensities of all the electron lines. Our results are in accord with theirs; however, we have examined the electron spectrum with a higher resolution instrument.

Figure 7 shows the level scheme for $A=195$. The levels of a given element are drawn to approximate scale, but the energy differences between isobars are unknown.

In agreement with Huber *et al.*, we find that Hg^{195m} (38 hr) decays via a 122-kev $M4$ ($K/L=0.2$; $L_{III}/L_I=2$) followed by a 36.8-kev $M1$ transition. The 36.8-kev transition converts mainly in the L_I and M_I shells ($L_I:L_{II}:L_{III}=1:0.23:\sim 0$) and should undoubtedly be an $M1$. It is worth noting here that the appearance of the $M1$ second step in Hg^{195m} indicates that the ground state of Hg^{195} is now a $p_{\frac{3}{2}}$ level, (it is $p_{\frac{1}{2}}$ in Hg^{197}) and that the $p_{\frac{3}{2}}$ and $p_{\frac{1}{2}}$ levels have crossed. The 9.5-hr ground state of Hg^{195} decays via K capture, followed by a 179-kev γ ray, (probably $M1$) analogous to the 191-kev γ ray in Au^{197}, and an intense 61.2-kev ($M1+E2$) transition. The 61.2-kev transition has an L-conversion ratio of 1.2:1.1:1.0. By reference to interpolated values of Gellman, Griffith, and Stanley,[9] one may deduce that the mixture is very approximately 5 parts magnetic γ ray to 1 part electric γ rays or 1 part magnetic transitions (N_e+N_g) to 2 parts electric transitions. This transition is analogous to the 77.4-kev γ ray in Au^{197m}.[4] The branching ratio of K capture to the 240- and 61.2-kev levels is ~ 5 percent, assuming that the 179-kev γ ray is $M1$ and assuming a total conversion coefficient of 20 for the 61.2-kev transition.

The isomeric level of Hg^{195m} decays of K-capture to Au^{195m} (30 sec).[7] Au^{195m} decays via 56.5-kev ($L_{II}/L_{III}=1$) and 262-kev transitions ($K/L=5.4$) which are in cascade.[7] By comparing intensities of the 122-kev $M4$ (assumed to be totally converted) and the 262-kev (taken as $M1$ with $\beta_k^1=0.52$), we find that the branching is 52 percent K capture.

All indicated nuclear levels are those predicted by the single-particle model, including the $d_{\frac{3}{2}}$ ground state of Au^{195}.

We should like to amplify the reasons for multipole order assignments in Au. Table II lists the conversion ratios for these transitions. The 56.5-kev transition may be concluded to be $E3$ by several lines of reasoning. The 30-second half-life and the L_{II}/L_{III} ratio are consistent with $E3$. In addition, the 9.5-hr K capture in Hg^{195} is probably first forbidden since it involves the changing of a neutron in one shell into a proton in a neighboring shell. It is then likely that the 38-hr K capture is also first forbidden and since the two levels in Hg have opposite parities, so should the isomeric and ground levels of Au. Since the second transition in the Au decay is ($\Delta I=1$, no), the isomeric transition must involve a change in parity. It is clearly an electric type transition and because of the absence of L_I only $E3$ is compatible with the other data.

Since the $A=195$ activity is present in all irradiations from 25 Mev to 105 Mev, it was decided to use the 122—L_{III} conversion line as a reference for plotting decay rates of conversion lines, and the sum of the L lines of the 61.2-kev transition as the standard against which to compare excitation functions. Hence, our values for lifetime of electron lines is based on the measured half-life (38 hr) of the Hg^{195m} level,[7] and all

TABLE II. Transitions in $A=195$.

Transition	Multipole order	Relative conversion coefficients
122.6 (Hg)	$M4$	$K/L=0.2$ $L_I/L_{II}/L_{III}=1.0:0.2:2.0$ $L/M=2$
36.9 (Hg)	$M1$	$L_I/L_{II}/L_{III}=1:0.2:-$
56.5 (Au)	$E3$	$L_{II}/L_{III}=1$ $M_{II}/M_{III}=1$ $L/M=1.6$
261.6 (Au)	$M1$	$K/L_I=5.5$ L_I conversion
61.2 (Au)	$M1+E2$	$L_I/L_{II}/L_{III}=1.2:1.1:1.0$
179.8 (Au)	$M1$	$K/L>4$
98.8 (Pt)	$M1$	$K/L\geq 4$ $L_I/L_{II}/L_{III}=7:1:0.3$
30.8 (Pt)	$M1$	$L/M=3$ L_I conversion

[13] We are indebted to Dr. O. Huber for his private communication to one of us (A. de-S.) regarding their recent results.

[14] R. W. Fink and E. O. Wiig, J. Am. Chem. Soc. **74**, 2457 (1952).

[15] Douglas, Foster, and Thompson [private communication to Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 469 (1953).]

[16] J. H. Moon and A. L. Thompson, Phys. Rev. **83**, 892 (1951) and private communication to Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).

excitation functions are relative to that for Hg^{195}. At first glance, this would seem to be an unsatisfactory method to obtain excitation functions since the intensity of the 61.2-kev γ ray at a given time will depend on the isomeric ratio, which of course is a function of the proton energy. However, intensities were taken from the first film of each series, and since the 9.5-hr activity is the predominant one for a fresh source, we are effectively drawing an excitation curve relative to the excitation function of Hg^{195} in the ground state.

TABLE III. Electron lines associated with $A=193$. Intensity integrated over 2-hr exposure started 15 minutes after 30-minute evaporation of a source irradiated $1\frac{1}{3}$ hours.

Energy	Intensity (arb. units)	Half-life	Assignment	Remarks
18.21	144	12 hr	Au 31.94—L_{II}	$E3$ in Au^{193m}
19.96	220		Au 31.88—L_{III}	
24.33			Hg 39.17—L_I	Composite with Au^{193} 37.9—L_{II} $M1$ in Mg^{193m}
28.74	60		Au 31.89—M_{II}	
29.18	60		Au 31.92—M_{III}	
29.62	15		Au 31.91—M_{IV}	
31.40	26		Au 32.04—N_{II}	
35.63			Hg 39.19—M_I	
86.39	12		Hg 101.2 —L_I	$M4$ in Hg^{193m}
87.00	weak		Hg 101.2 —L_{II}	
88.95	45		Hg 101.2 —L_{III}	
137.4	13		Au 218.1 —K	$M1$ (?)
177.2	270		Au 257.9 —K	$M1$
204.3	8		Au 218.0 —L_{II}	
206.1	8		Au 218.0 —L_{III}	
210.1	9		Au 290.8 —K	$M4$ crossover
243.4	50		Au 257.8 —L_I	
			257.8 —L_{II}	
			257.8 —L_{III}	
254.9	15		Au 258.3 —M	
257.7			Au 258.5 —N	
261.4	8		Au 342.1 —K	
327.4	1		Au 341.8 —L_I	

12 +6 hour composite half-life (following Hg^{193})

Energy	Intensity	Assignment	Remarks
23.59	65	Au 37.94—L_I	$M1+E2$ in Au^{193}
24.18	105	Au 37.91—L_{II}	
25.97	85	Au 37.89—L_{III}	
34.54	11	Au 37.95—M_I	
34.71	21	Au 37.86—M_{II}	
35.14	16	Au 37.88—M_{III}	
106.0	110	Au 186.7 —K	$M1$ (?)
172.2	10±5	Au 186.6 —L_I	Composite with Pt^{193} 186.2—L_I (80 percent)

(Grow with 12 +6 hr and decay with ~20 hr.)
Complex γ-ray spectrum in Pt^{193}.
Energies: 112.4, 173.5, and 186.2 kev.
Additional other γ rays[21] seen in Au^{193} produced by Pt +d.

Half-life of several days[a]

121.86	7		Pt 135.73—L_I	$M4$ in Pt^{193m} or Au^{194m}
124.27	20		Pt 135.82—L_{III}	
		or	Au 136.2 —L_I	
			Au 136.2 —L_{III}	

Unassigned lines

Energy	Intensity	Half-life
138.6	7	12 hr
301.2	10	12
302.0	12	12
313.7	5	12
265.0	4	?
382.0	8	?

[a] Intensities are not normalized.

We observe two converted γ transitions in Pt^{195}, following the 185-day[17] K capture of Au^{195}. Previously, γ rays of 126, 97, and 29 kev have been observed and multipolarities of $E2$, $M1$, and $M1$, respectively assigned.[1,18] We observed the two lower-energy transitions (which grow in and decay with $T_{\frac{1}{2}}>10$ days) and the L structure is that expected for magnetic dipoles.

In addition, certain high-energy transitions are reported, these energies being: 206, 261, 318, and 558 kev in the 38-hr activity;[15] and 600 and 780 kev in the 9.5-hr activity.[16] We are unable to fit them into the scheme. Apparently, there is considerable energy available for K capture from Hg^{195m}. We can say nothing about the existence or nonexistence of β^+.

Apparently, very little, if any, K capture occurs from the $p_{\frac{3}{2}}$ level in Hg to the $d_{\frac{5}{2}}$ level in Au, although this would be only first forbidden. A conservative upper limit of any 9.5-hr component in the 262-kev γ transition in Au in 10 percent. Also, the K capture to the 240-kev $d_{\frac{3}{2}}$ level, also first forbidden, is quite weak compared to that going to the 61.2-kev $s_{\frac{1}{2}}$ level.

It was hoped that some conclusion could be drawn regarding the isomerit ratio (i.e., the ratio of the production of metastable and ground-state activities) as a function of energy. However, our exposures of spectrograms was made in such a way as to obtain adequate blackening of the film for the activities under investigation. A more consistent schedule of irradiation, source preparation, and exposure time would have to be followed to obtain data on the behavior of the isomeric ratio. Qualitatively, the isomeric ratio for the Hg^{195} does not change greatly as the proton energy is increased from 25 Mev to 65 Mev. As the proton energy is increased, there appears to be a slight reduction in the ratio of production of metastable to ground state, a point which is somewhat surprising.

$A=193$

As one increases the energy of the proton beam above 25 Mev, no new activity definitely ascribable to Hg is observed until the threshold for $(p,5n)$ is reached at an energy slightly below 35 Mev. We shall remark later upon a possible $(p,4n)$ reaction. The Weizsacker mass formula predicts very little energy (less than 80 kev) for the decay of Hg^{194} to Au^{194} and hence, this decay would have a long half-life. It is worth noting that a good yield of $Au(p,6n)Hg^{192}$ is achieved at the expected proton energy of ~50 Mev. Moon and Thompson[16] have noted no Hg^{194} daughter activities when Au is irradiated with protons of the proper energy.

[17] G. Wilkinson, Phys. Rev. **75**, 1019 (1949).
[18] Steffen, Huber, and Humbel, Helv. Phys. Acta **22**, 167 (1949).

Half-lives of 10 hr,[15] 14.5, and 29.0 hr[14] have been reported for Hg^{193}. Au^{193} has published lifetimes of 15.8 hr.[14,17] Several γ-ray transitions are reported,[14] some of which we believe are assigned to the incorrect mass number.

Figure 1 shows a spectrum obtained at 35 Mev. The number of electron lines per interval of film is quite high in the region under 50 kev. We find that the levels present in the two higher odd-A nuclei are present in $A=193$. Our results for this mass are shown in Tables III and IV and Fig. 8.

As we decrease the number of neutrons in these Hg isomers, the K capture/I.T. (I.T.$\equiv$isomeric transition) ratio increases sharply. The $i_{13/2}\rightarrow f_{5/2}\rightarrow p_{3/2}$ transitions in Hg are 101.2 kev $M4(L_I/L_{III}=0.36)$ and 39.2 kev $M1$ (L_I conversion) which decay with a 12-hr half-life. The K-capture of Hg^{193m} ($\sim$84 percent) is followed by a 31.9-kev $E3$ ($L_{II}/L_{III}=0.65$) and 258.7-kev $M1$, ($K/L=5.3$) with the 290.6-kev $M4$ crossover (<3 percent). All three transitions decay with a 12-hr half-life and have the same excitation function (see in Figs. 3 and 4). We have no definite evidence for the multipolarity of the 31.9-kev transition, except that it is electric radiation rather than magnetic. However, shell model prediction and analogy with Au^{195m} and Au^{197m} make the assignment not unreasonable.

TABLE IV. Transitions in $A=193$.

Transition	Multipole order	Relative conversion coefficients
101.2 (Hg)	$M4$	$L_I:L_{III}=0.27$
31.9 (Au)	$E3$	$L_{II}:L_{III}=0.65$
37.9 (Au)	$M1+E2$	$L_I:L_{II}:L_{III}=3:8.5:4$ $L:M=5.3$
257.9 (Au)	$M1$	$K:L=5.4$
135.8 (Pt) or 136.2 (Au)	$M4$	$L_I:L_{III}=0.35$

Here again, the ground state of Hg^{193} is most likely a $p_{\frac{3}{2}}$ level. This level appears to decay to a level in Au($s_{\frac{1}{2}}$) which emits a γ ray of 37.9 kev. On the basis of the L conversion ratio this γ ray is probably an $M1+M2$ mixture, although one is unable to compute the mixing ratio due to the lack of conversion coefficients for transitions of such a low energy. The decay curve of this transition may be decomposed into two components of 12-hr and 6-hr half-lives (Fig. 4). In addition, two electron lines of 105.9 and 39.24 kev are observed. It is most reasonable to assign the 105.9-kev line as the K of a 186.5-kev transition in Au, although no L line is seen, which is surprising since the "K" electron line is fairly intense. It may be the $d_{\frac{3}{2}}\rightarrow s_{\frac{1}{2}}$ transition. The weak and composite 39.24-kev line is not assigned.

Three conversion lines of 12-hr half-life may fit the assignment K, L_{II}, L_{III} in Au for a γ ray of 218.1 kev. K/L and L ratio considerations indicate a possible multipolarity of $E2$, which would be the type transition expected between the $d_{\frac{3}{2}}$ and $s_{\frac{1}{2}}$ levels. However, this energy should be 219.8 kev. A similar situation arose in the case of Au^{197m},[4] where a possible transition between the $d_{\frac{3}{2}}$ and $s_{\frac{1}{2}}$ levels was observed, but which had an energy slightly less than that required.

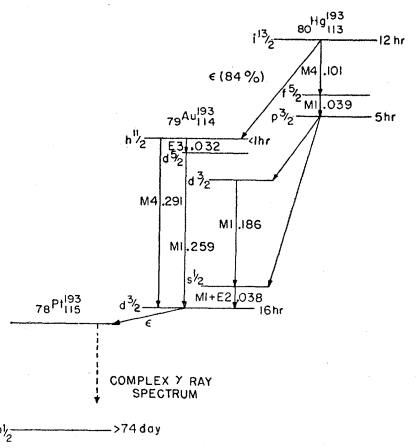

FIG. 8. Decay scheme of Hg^{193m}.

An unsuccessful attempt was made to measure the half-life of Au^{193m}, by use of a Geiger tube setup. Since the 56.6-kev $E3$ in Au^{195m} lives for 30 sec, it would appear that this transition of considerably lower energy (31.9 kev) should have an appreciable half-life. How much this transition is speeded up by internal conversion is difficult to say. An upper limit of the branching via the $M4$ cross-over transition, made by comparing the intensity of electron lines from the $M4$ (101 kev) and the $M1$ (259 kev) transitions is $\sim$3 percent.

The half-life of the ground state of Au^{193} is generally agreed in the literature to be 15 hr.[19] We observe several electron lines which grow in and then decay with a half-life very crudely estimated as 20 hr. These lines also survive the HNO_3 wash and are almost undoubtedly in Pt^{193}. These correspond to γ-ray transitions of the following energies: 112.4, 173.5, and 186.2 kev (see Table III). The Canadian workers[15,16] report a half-life for Au^{193} of 15.8 hr and observe the following γ-ray energies: 15, 60, 84, 93, 109, 165, 177, and 235 kev.

In addition, two weak but interesting electron lines are observed to grow in and decay with a half-life of several days. The energies are 121.9 and 124.3 kev with a relative intensity ratio of 7:20. Swan, Portnoy, and Hill[20] have assigned a 134.9-kev $M4$ transition to Pt^{193m} on the basis of Pt+γ and Ir+d reactions. Our electron lines could correspond very nicely to the L_I and L_{III} lines (energy and intensity-wise) they observe. However, in a later experiment,[21] Pt was irradiated with 22-Mev deuterons in the Brookhaven 60-inch cyclotron and the Au fraction chemically separated. Two lines which appear to be identical with those observed in our

[19] Way, Fano, Scott, and Thew, *Nuclear Data*, National Bureau of Standards Circular No. 499 (U. S. Government Printing Office, Washington, D. C., 1950).
[20] Swan, Portnoy, and Hill, Phys. Rev. **90**, 257 (1953).
[21] J. W. Mihelich and K. Gopalakrishnan (to be published).

TABLE V. Electron lines associated with $A=192$. Intensities integrated over 45-min exposure started 15 min after 30-min evaporation of a 1-hr irradiated source.

Energy	Intensity	$\tau_{\frac{1}{2}}$	Assignment	Remarks
16.95	380	6 hr	Au 31.30—L_{I}	$M1$
17.57	78		31.30—L_{II}	
19.49	85		31.41—L_{III}	
27.92	180		31.34—M_{I}	
28.41	46		31.4 —M_{II}-M_{III}	
30.69	60		31.45—N	
31.3			31.41—O	
33.6	79		114.3 —K	K/L 5 $M1$
61.57	38		142.3 —K	K/L 3
65.26	43		146.0 —K	K/L 5 $M1$
76.68	185		157.4 —K	K/L 3.5 $M1$
100.2	16		114.6 —L_{I}	
127.9	13		142.3 —L_{I}	
131.5	9		145.9 —L_{I}	
134.0	weak		145.9 —L_{II}	
142.8	55		157.2 —L_{I}	
153.7	13		157.2 —M_{I}	
194.3	50		275.0 —K	

Energy	Intensity	$\tau_{\frac{1}{2}}$	Assignment	Remarks
217.4	20	Grow+7-hr decay	Pt 295.8—K	Pt^{192}
238.2	40	Grow+7-hr decay	Pt 316.6—K	Composite
283.1		Grow+7-hr decay	Pt 296.4—L_{II}	
284.3		Grow+7-hr decay	Pt 295.8—L_{III}	
303.7		Grow+7-hr decay	Pt 317.0—L_{II}	
305.5		Grow+7-hr decay	Pt 317.0—L_{III}	
Unassigned lines				
33.17	weak			
39.3	weak			
43.6	6			
44.0	10			
85.0	20	8 hr		
90.4	16	6 hr		
91.0	6			
123.8	20			
16.48	23			
181.9	12			

Hg source (produced by 65-Mev protons) are detected. It then seems unlikely that our transition (if, indeed, our lines are L_{I} and L_{III} electrons) is the same as that reported by Swan *et al.*, since it is difficult to see how the isomeric Pt level could be fed by the Au^{193} ground state. A possible assignment is that of L_{I} and L_{III} lines of an $M4$ transition in Au^{194}, since the energy separation of the lines is not well enough ascertained to make a definite elemental assignment and the K conversion line is too weak to see. This would be consistent with the activation data. If this is a valid assignment, then the upper level of Au^{194} has a low spin (since it is fed by K capture of even-even Hg^{194} which is presumed to have spin zero) and the ground state (39 hr) of Au^{194} should have a high spin. This is not unreasonable since no K capture from this level to the low-lying levels of spin 0 and 2+ in Pt^{194} is reported. However, these conclusions are tentative. But, it would be interesting if the addition of one proton to Pt^{193} (forming Au^{194}) should give rise to levels also leading to an $M4$ transition of almost identical energy.

In the Au fraction of the Pt+d source, a complex γ-ray spectrum attributed to Pt^{193}, following K capture of Au^{193}, is observed via conversion electrons. Some of these transitions were observed in the Hg^{193} source. All that we wish to point out at this time are the following energy sums and the fact that all indicated transitions are observed:

$$117.9+114.0=119.4+112.4=231.9 \text{ kev};$$

$$186.2+256.0=173.5+268.7=442.2 \text{ kev}.$$

$A=192$

Hg^{192} is reported to decay by K capture and/or β^+ emission with a half-life of 5.7 hr[15] or 8.4[14] hr. No information regarding low-energy transitions was available.

In our experiment, at a proton energy of 45 Mev, a new set of conversion lines appeared. See Fig. 1. The excitation function for these lines is shown in Fig. 3, and they appear to be due to the $(p,6n)$ reaction. Many of the lines have measured half-lives of between 5 and 7 hours, and presumably have the same parent. We assign these to Au^{192}, following a 6-hr Hg K capture. At least five transitions in Au are observed. The electron data are listed in Table V and the transitions in Table VI. Figure 9 shows an incomplete decay scheme.

It is interesting to note that the 145.9-kev transition ($K/L=5$) may well be the crossover associated with the 114.5- and 31.4-kev transitions in cascade. In this case, the intense 31.4-kev transition would have to be fed by another intense γ ray, presumably the 157.4-kev transition, or by a K-capture branch. The ground state state of Au^{192} then decays via K capture or β^+ emission to levels in Pt^{192}. The reported half-lives are 5.0, 4.7, and 4.1 hr.[14,17,22]

We observe electron lines, attributed to Pt^{192}, which grow in and then decay with a half-life we roughly measure as 7 hr. Two sets of electron lines fit very nicely the assignment of K, L_{II}, and L_{III} conversion of 295.8-kev and 316.8-kev γ transitions in Pt. Muller *et al.*[23] report energies of 295.9 and 316.5 kev for photons observed in the β^- decay of Ir^{192}. It may be noted that

TABLE VI. Transitions in $A=192$.

Transition	Multipole order	Relative conversion coefficients
31.3 (Au)	$M1$ ($E1$?)	$L_{\mathrm{I}}:L_{\mathrm{II}}:L_{\mathrm{III}}=4.7:1:1$
114.3 (Au)	$M1$	$K/L=5$
142.3 (Au)	?	$K/L=3$
146.0 (Au)	$M1$	$K/L=5$
157.4 (Au)	$M1$ (?)	$K/L=3.5$

[22] A. L. Thompson [private communication to Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953)].

[23] Muller, Hoyt, Klein, and DuMond, Phys. Rev. **88**, 775 (1952).

these two transitions are the two most intense transitions observed as γ rays by Muller *et al.* with their crystal spectrometer, and by internal conversion by Cork *et al.*[24] The 308.5-kev transition which is very intense in Muller's spectrum and also Cork's internal conversion spectrum is not observed in the E.C. of Au^{192}. In addition, in our spectrum, the 316.8-kev transition is ~twice as intense as the 295.8. Both are $E2$ transitions as indicated by their K/L- and L-conversion ratios. Hence, it seems reasonable that the first excited state of Pt^{192} is at 316.8 kev, and since the crossover of 612 kev is observed, that the spins in the first three levels of this nucleus are 0, 2+, 2+.

The odd-odd Au^{192} nucleus is bracketed on both sides by even-even nuclei, which we may assume to have 0+ ground states. Since the ground state of Au^{192} decays to both the first and second excited states of Pt^{192}, its spin is most probably 1−, 2−, or 3−. Any of these is consistent with Nordheim's rule[25] assuming a $d_{\frac{3}{2}}$ proton and a $p_{\frac{3}{2}}$ neutron.

There are a number of lines which cannot be assigned to specific transitions.

$A=191$

Moon and Thompson[14] have assigned a 12.4-hr electron capture activity to Hg^{191}. They produced Hg by the $Au(p,7n)$ reaction and report an abundant yield at 70–80 Mev, with a threshold about 10 Mev lower.

In our experiment, at a proton energy of between 55 and 65 Mev, a set of lines decaying with a half-life of 57±5 min was observed. The excitation curve peaked at 70 Mev. See Figs. 1, 2, 3, and 5. The half-life is based on a series of 45-min exposures started 45 min after completion of a 1 hour irradiation. Several conversion lines fit nicely the assignment of conversion lines of a 252.6-kev γ ray in Au and one line fits the assignment 274.1—K in Au. A set of weak lines are observed which are probably Auger lines, although the possibility of a 13.9-kev γ ray in Au cannot be entirely excluded. The data are presented in Table VII. It is likely that the 252.8-kev γ ray is the $d_{\frac{5}{2}}-d_{\frac{3}{2}}$ transition in Au^{191}.

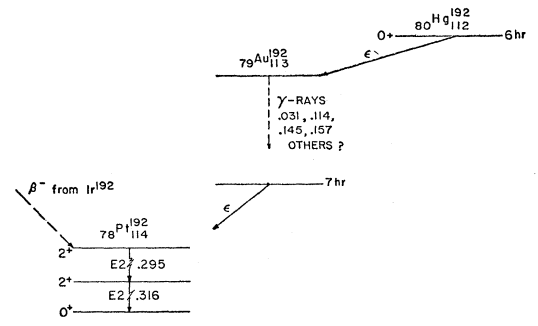

FIG. 9. Partial decay scheme for $A=192$.

[24] Cork, LeBlanc, Stoddard, Childs, Branyan, and Martin, Phys. Rev. **82**, 258 (1952).
[25] L. W. Nordheim, Revs. Modern Phys. **23**, 325 (1951).

TABLE VII. Electron lines associated with $A=191$.

57-minute half-life (intensity integrated over a 45-minute exposure started 15 min after 30-min evaporation of a 1-hr irradiated source).

Energy	Intensity	Assignment	Remarks
10.8	≈30	Auger	Possible Au
11.1	≈20	Auger	13.9—M_{II}, M_{III}, N_{II}
13.3	≈20	Auger	
171.9	270	Au 252.6—K	Composite with Pt^{193} 185.5—L_I Au^{193} 186.6—L_I
193.4	115	274.1—K	
238.3	66	252.7—L_I	Composite with Pt^{192} 316—K
239.0	weak	252.7—L_{II}	
240.8	weak	252.7—L_{III}	
249.3	15	252.8—M_I	

Longer lived lines (intensity integrated during 45′ starting 1½ hr after end of irradiation).

Energy	Intensity	$\tau_{\frac{1}{2}}$	Assignment	Remarks
34.95		1-hr growth (?) +4-hr decay	Pt 47.8—L_{II}	Composite with 37.9—M $A=193$
36.80			48.0—L_{III}	
44.80			47.8—M_{II}	Composite with Au^{195} 56.5—L_{III}
51.56	25	1-hr growth +4-hr decay	Pt 129.9	Composite
77.72	30		91.0—L_{II}	
79.47	25		91.0—L_{III}	
80.34	14		158.7—K	
88.03			91.0—M_{II}	
116.3	8±3		130.3—L_I	
116.8	3		130.1—L_{II}	
88.03	25	~3-hr half-life no growth	Au 168.7—K	? not in $A=192$

3-day half-life after growth of 4 hr.

Energy	Intensity[a]	Assignment	Remarks
20.40	45±20	Ir 96.51—K	Composite with 98.6—K Pt^{195} and Au^{193} 32.2—L_{III}
53.25	20	129.4—K	
69.05	14	82.46—L_I	
69.67	25	82.49—L_{II}	
71.22	23	82.43—L_{III}	
79.59	8	82.49—M_{II}	
80.00	7	82.54—M_{III}	
82.00	5	82.4—N	
83.13	10	96.54—L_I	
83.63	2	96.45—L_{II}	
85.00	2		Very close to Pt^{195} 98.6—L_I $M1+E2$
116.0	6	129.5—L_I	
116.6	2	129.4—L_{II}	
118.2		129.4—L_{III}	
		Unassigned lines	
		$\tau_{\frac{1}{2}}$	
18.6	56	3 hr	
27.02	weak		
69.00			
116.1	30	55 min	
199.4	10		
205.4			Composite with Au^{193} 217.0—L_{III}
251.1	20	55 min	

[a] Not normalized.

The only activity we can definitely assign to Hg^{191} is that of 57 minutes. Other 57-minute lines are observed, as shown in Table VII.

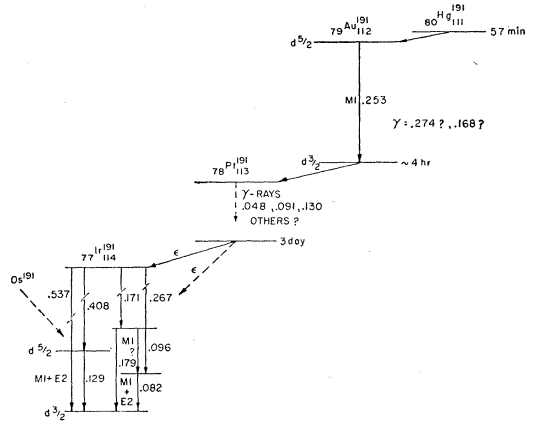

FIG. 10. Partial decay scheme for $A=191$. *Note added in proof.*—A drafting error is present in this figure. Obviously, the 171- and 267-kev transitions do not originate from the same level as the 537- and 408-kev transitions.

Certain lines which grow appear to be in Pt^{191}. These correspond to transitions of 130.0 kev ($M1+E2$ probably) and 91.0 kev (probably an electric transition) and 158.7 kev ($M1$). These lines decay with a half-life of ~4 hr, and are gone in a few hours. Previously reported half-lives are 18 hr and 1 day, which we believe are in error. Moon and Thompson[14] reported converted γ rays of 0.053, 0.064, 0.111, 0.123, 0.666, 0.250, and 0.405 Mev.

Eventually, Ir^{191} transitions grow in and decay with a half-life of ~3 days, following the decay of Pt^{191}. The appearance of these transitions was the criterion for deciding when we had produced the $(p,7n)$ reaction in Au. We observe transitions of 82.5, 96.5, and 129.4 kev; these are presumed to be identical to the ones observed by Swan, Portnoy, and Hill[20] in the decay of Pt^{191}. In Fig. 10 we show a tentative decay scheme for $A=191$. The arrangement of levels in Ir^{191} is that suggested by Swan *et al.*[20]

We should like to amplify our argument concerning the threshold for $(p,7n)$ and the half-life (~1 hr) of Hg^{191}. In all irradiations for which $E_p>35$ Mev, no new activity (which is not a daughter activity) of half-life greater than 8 hours is observed. Furthermore, the assignment of the 82.5-kev γ ray to Ir^{191} as done by Swan, etc. is quite convincing. Hence, once we have observed this transition in a decay chain, we can be certain we have produced Hg^{191}.

To verify that the Ir activity is indeed fed by a short-lived Hg, evaporation of the radioactive Hg (produced by a 65-Mev irradiation) was done at a time shortly after irradiation, 4 hours after irradiation, and 10 hours after irradiation. In the first case, the Ir γ rays appeared strongly, in the second, only weakly, and in the 10-hr case, not at all. Therefore, we feel that there is no Hg^{191} level which lives for several hours.

TABLE VIII. Electron lines associated with $A=190$ or 189. Intensity integrated over a 15-minute exposure started 8 minutes after an 8-minute evaporation of a 20-minute irradiation source.

Energy	Intensity	$\tau_{\frac{1}{2}}$	Assignment	Remarks
14.22	75	25 min	Au 28.6—L_I	
14.90	26		Au 28.6—L_{II}	
16.71	25		Au 28.6—L_{III}	
25.19	40		Au 28.6—M_I	
27.92	20		Au 28.7—N_I	
48.76	95			
61.66	20		Au 142.4—K	?
63.41	46			Composite with Auger-line
73.84	12			?
84.57	3			

$A \leqq 191$

At a proton energy $\geqslant 65$ Mev, other electron lines appear. We can make no definite mass assignments for them.

We observe one electron line (threshold ~65 Mev) with a decay rate corresponding to a half-life of 90 minutes. We are unable to assign the mass number for this activity. Thompson[22] reports a 90-min activity for Hg^{190}. The intensity of our line is too small to plot an adequate excitation curve which might have given a mass assignment. It may be that this follows the ground-state decay of Hg^{191}, since it is produced at a proton energy of 65 Mev.

In addition an electron line of 88.02 kev and good intensity has a 3- or 4-hr half-life from the beginning of the exposure series; i.e., there is no growth. It definitely cannot be in the decay chain of $A=192$. If it is in the $A=191$ chain, it is possibly a 168.7—K in Au following electron capture from an isomeric level of Hg^{191}.

We observe an activity of 25 ± 10 minutes, which is produced by protons of energy greater than 65 Mev. Therefore, the mass number is <191. On the basis of our evidence, we are not able to make a definite mass assignment. Thompson[22] reports a 30-minute activity in Hg^{189}.

Figure 4 shows the decay curve for the electron lines and Table VIII lists the conversion line data. The only definite γ-ray transition is a quite intense 28.6-kev transition whose multipolarity is $M1+E2$ or $E1$. Other short-lived conversion lines are observed.

SUMMARY

The results reported here are not complete or final. What we have attempted to do is to systematically catalog activities belonging to the various masses and elements. In most cases we have determined the half-lives, energies, multipolarities, and electron intensity data for the internally converted γ-ray transitions. The mass-number assignments are made from the excitation-function data, supplemented by the measured half-lives. The elemental assignments are made largely from con-

sideration of the energy separation of conversion electron lines, after the lines are assigned to the same activity from decay rate and excitation curve data.

More definitive experiments are needed, studying each activity separately and in more detail, particularly for the activities belonging to nuclei of mass less than 193.

We are indebted to many people for their generous help in this problem. In particular, we wish to thank W. F. Goodell and the operating crew of the Nevis cyclotron who made the bombardments for the early stages of this work; E. P. Tomlinson who made his high-resolution variable-field spectrometer available to us; W. M. Preston and the crew of the Harvard cyclotron for their hospitality and help in carrying out most of the bombardments; the crew of the Brookhaven 60-inch cyclotron for their irradiation of Pt for some subsidiary experiments; M. Slavin of Brookhaven for his help in running some of the photometry measurements; and M. Goldhaber for helpful discussions.

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Some Regularities in the Nuclear Level Spacings of Hg, Au, and Pt*

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An attempt is made to determine any systematic behavior of nuclear energy levels in a number of heavy elements, as the number of protons (for a fixed neutron number) or neutrons (for a fixed proton number) is changed. Certain regularities in the movement of levels are pointed out and discussed. The occurrence of "pure" $M1$ and mixed $M1+E2$ transitions (in odd-A nuclei) as related to the type of odd particle and the change in orbital angular momentum is summarized. Empirical evidence for L subshell conversion regularities for $M4$ and $E3$ multipole orders is given. An extension of this work is suggested.

I. THE DECAY SCHEMES AND LEVEL MOVEMENTS

THE recent studies of new isotopes of Hg and their daughter activities[1–3] make it possible to look for regularities of level movements in this region of the periodic table. Certain regularities in the Te-Xe-Ba region have been pointed out by Goldhaber and Hill.[4]

We should first remark on the validity of the spin assignments in the previous article.[3] Experimentally only the multipolarity of the radiations have been determined and, in principle, one must have a direct measurement of the spin of at least one state of a nucleus in order to be able to give the spins of the other levels. Since the intensity measurements are not very precise and since no coincidence measurements were done for most of the isotopes, we do not have a good knowledge of the branching ratios of the K captures and, therefore, it is hard to deduce the spins uniquely from the directly measured spin of the last stable isotope in the relatively long chains which have been investigated. We, therefore, have to make use of some general arguments of similarity and of more or less well-established regularities, such as the assignments $i_{13/2}\rightarrow f_{5/2}$ to the $M4$ transitions for odd-neutron nuclei near the end of the 126 shell. This, of course, is not the rigorous way of treating the experimental data which are supposed to prove the similarity in decay schemes. Strictly speaking, our discussion shows only the internal consistency of the regularities mentioned, suggesting that we are not too far from the truth.

The similarity in the decay schemes of the Au and Hg isotopes studied is outstanding (see the previous article). It is best seen when plotting the relative separation of pairs of levels j_1 and j_2 as a function of N or Z. We see (Fig. 1) that the separation of the odd neutron states

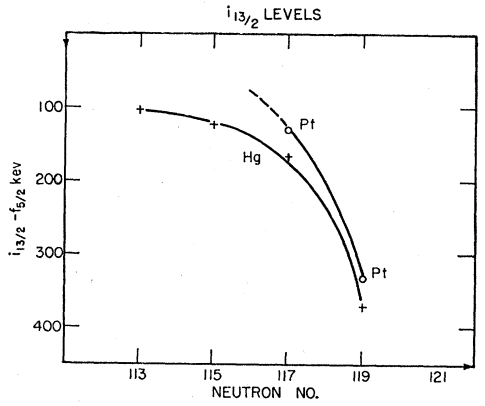

FIG. 1. Separation of $i_{13/2}$ and $f_{5/2}$ levels as a function of neutron number for Hg and Pt.

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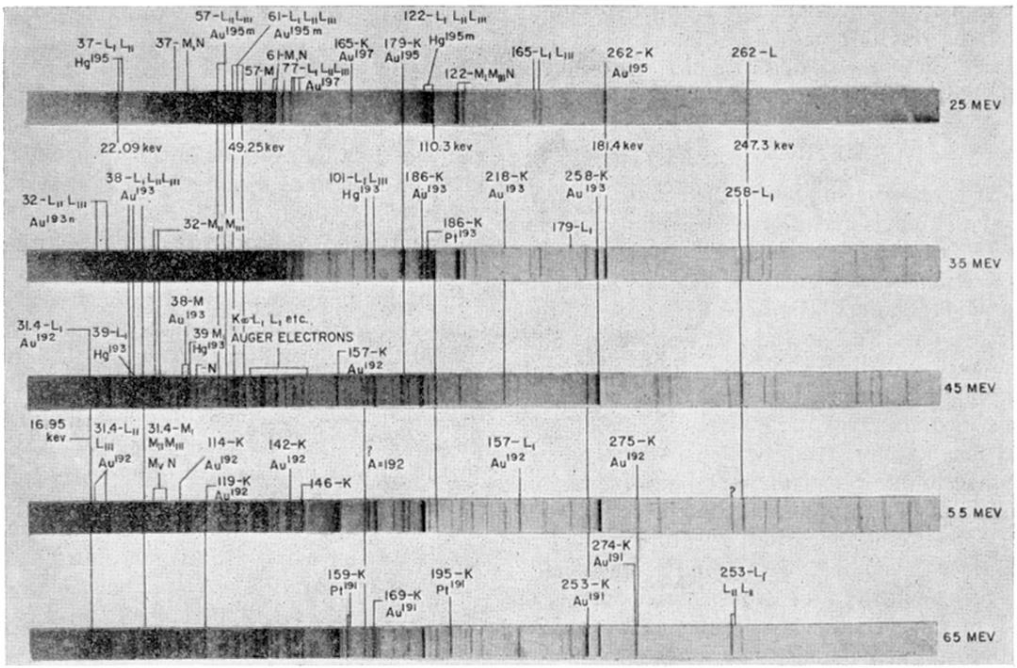

FIG. 1. Conversion electron spectra of Au(p,xn)Hg sources produced by protons of various energies. (119-gauss magnet.)

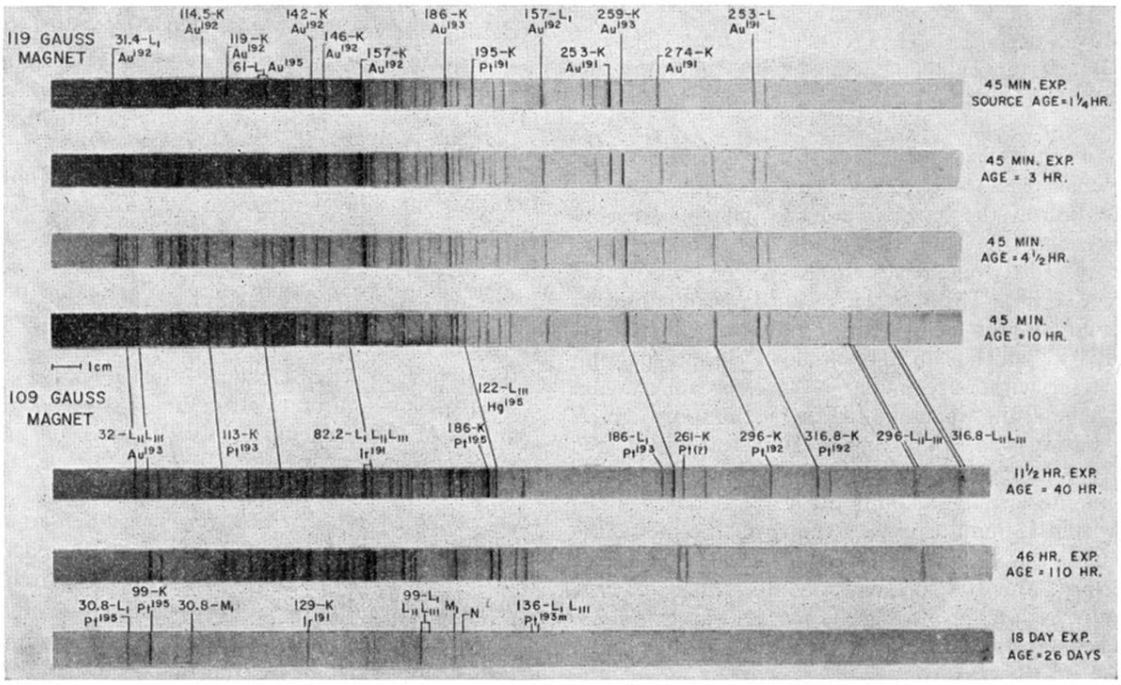

FIG. 2. Conversion electron spectra of Au(p(65 Mev),xn)Hg source taken at successive intervals of time.