and (38) shows that it is not very sensitive to μ. Therefore, by averaging over these values of μ, one obtains a mixed density function separated into relative and center-of-mass coordinates. Figures 1 and 2 show this function for the special cases of Ca^{41} and O^{17}, respectively. In both cases the relationship

$$\rho(r,R)=\rho(0,R)\exp[-4.61(r/R_0)^2]$$
$$=\rho(R)\exp[-4.61(r/R_0)^2] \quad (39)$$

holds approximately, where the function $\rho(R)$ can be read from the figures.

It is interesting to see what the mixed density function is when derived from shell-model wave functions. Figure 3 shows the mixed density function for Ca^{41} derived from the wave functions which were used in this work, those associated with a uniform potential, but vanishing at the nuclear surface. Because of the large amount of s wave in the Ca^{41} nucleus, the function is large at the origin; but this will not affect the spin-orbit calculation, since all the pertinent wave functions vanish at the origin in that case. For the important values of the coordinates r and R, Figs. 1 and 3 agree rather well, and Eq. (39) holds except at the origin.

PHYSICAL REVIEW VOLUME 104, NUMBER 4 NOVEMBER 15, 1956

Spectrum of L Auger Electrons from $_{81}Tl^{208}$ and $_{83}Bi^{212}$ †

J. BURDE AND S. G. COHEN
Department of Physics, Hebrew University, Jerusalem, Israel
(Received July 16, 1956)

A study of the L Auger spectrum emitted from a source of ThB in equilibrium with its decay products has been made by using a thin-magnetic-lens electron spectrometer. The L Auger spectrum coincident with alpha particles has also been measured, and this has been ascribed mainly to $_{81}Tl^{208}$. Since the directly recorded L Auger spectrum is composed mainly from the L spectra of $_{81}Tl^{208}$ and $_{83}Bi^{212}$, the latter spectrum could be obtained by subtraction of the properly normalized alpha coincident spectrum from the directly recorded spectrum. The importance of the effect of nuclear recoil accompanying alpha emission on the shape and energies of the L Auger spectra is discussed and properly taken into account. The energies and intensities of fifteen lines are given for each spectrum, and a classification of these lines are made. From the experimental results the Auger and Coster-Kronig yields for the different L subshells were calculated.

INTRODUCTION

ATOMS which have been ionized in an inner shell will revert to their normal unexcited state by emitting both a characteristic x-ray spectrum and a characteristic electron line spectrum of Auger electrons. These Auger electrons are emitted when a "hole" in a given shell is filled by radiationless transitions involving two electrons in shells of low energy, one of which is ejected from the atom, which is then left in a state of double ionization. In radioactive decay, the processes of internal conversion or orbital electron capture give rise to inner shell ionization. The characteristic x-rays emitted in radioactive decay have been examined experimentally in many instances.[1] The form of the K Auger spectrum and the values of the K-shell fluorescent yield has been the subject of some theoretical treatment.[1] Accurate experimental data on the K Auger spectra and K fluorescent yields has only accumulated fairly recently as a consequence of the development in technique for detecting low-energy electrons. Data concerning L Auger spectra (following on L-shell vacancies) is still most meager, since the electron energies involved are so very low (5–15 kev even for the heaviest elements).

Among the few recent investigations of L Auger spectra, we mention the work of Kobayashi[2] and Bashilov *et al.*[3] on the L Auger spectrum of RaD and Haynes and Ancor[4] on the L Auger spectrum of Au^{199}. In the present work, the authors have examined the L Auger spectrum from thorium active deposit, belonging essentially to the isotopes $_{81}Tl^{208}$ and $_{83}Bi^{212}$. Butt[5] and also Flammersfeld[6] have earlier examined the low-energy electron spectrum from thorium active deposit, but under unfavorable conditions of poor resolution. Their results point to many unresolved lines. These previous investigators were not able to separate the spectra belonging to the different isotopes involved. In this work, higher resolution was used and the Auger spectra from $_{81}Tl^{208}$ and $_{83}Bi^{212}$ were separated by recording coincidences between α particles and Auger electrons in addition to the normal direct Auger spec-

† This article comprises part of the work submitted in a thesis by J. Burde in fulfillment of the requirements for the degree of Doctor of Philosophy of the Hebrew University.

[1] E. H. S. Burhop, *The Auger Effect* (Cambridge University Press, New York, 1952).

[2] Y. Kobayashi, J. Phys. Soc. Japan **8**, 440 (1953).

[3] Bashilov, Dzhelepov, and Chervinskaya, Izvest. Akad. Nauk. S. S. S. R., Ser. Fiz. **17**, 428 (1953).

[4] S. K. Haynes and W. T. Ancor, J. phys. radium **16**, 635 (1955).

[5] D. K. Butt, Proc. Phys. Soc. (London) **A63**, 986 (1950).

[6] A. Flammersfeld, Z. Physik **114**, 227 (1939).

trum. It should be pointed out that a source of ThB prepared by recoil collection from an emanating source of radiothorium is essentially infinitely thin and thus very suitable for measuring the very low-energy electrons concerned, between 5 kev and 15 kev (although care must be exercised in correctly taking into account α-recoil effects).

In a source of ThB in equilibrium with its products, an intense Auger spectra is produced as a result of L-shell ionization. By far the most intense contributions are associated with the three strongest conversion lines in the electron spectrum, the well-known "A" line in $_{81}Tl^{208}$ (ThC") and the F and I lines in $_{83}Bi^{212}$ (ThC).[7] In the former case, the 40-kev transition following the α decay of $_{83}Bi^{212}$ is strongly converted in the L shell ($\alpha_L=16$). In the latter case, the 238-kev transition following the β-decay of $_{82}Pb^{212}$ is converted in the K and L shells ($\alpha_K=0.62$, $\alpha_L=0.107$). It should be noted that K ionization will lead to L ionization as a consequence of either radiative x-ray transitions or Auger transitions involving the L shell. More than 90% of the number of L-shell vacancies are produced in $_{83}Bi^{212}$ by the latter processes. Thus, whereas the directly recorded Auger spectrum will be a mixture of the L spectra of bismuth and thallium, the spectrum obtained by coincidence with the 6.04-Mev α particles (which lead to the 40-kev transition) will yield only the L spectrum of thallium. Both the "single" and "coincident" spectra were investigated.

In this work the importance of the influence of the nuclear recoil associated with α decay on the energies and form of the Auger spectra which are detected experimentally is pointed out. A classification of the observed spectra for $Z=81$ and $Z=83$ is made, in which these recoil effects are properly taken into account.

EXPERIMENTAL METHOD

A thin-lens iron-free spectrometer was used to examine the electron spectrum. Using a carefully adjusted ring focus whose position and dimensions were determined by direct photography of the A and F conversion lines from thorium active deposit, a resolution of 0.8% could be obtained when necessary. Most of the measurements were carried out at about 1% resolution. Care was taken to annul very precisely the effect of the earth's magnetic field by using neutralizing coils, since the earth's field may have a particularly disturbing effect at low energies.

A Geiger counter with a thin window was used as the electron detector. Butt[5] had used the technique of post-acceleration of the electrons which had passed through the spectrometer before entering the Geiger detector. We found this to be unnecessary, using counter windows of about 30 μg/cm,[2] which were made up of alternating foils of Formvar and Zapon supported on a grid of parallel tungsten wires. The window transmission was estimated by measuring the fairly sharply defined cut-off energy and using the experiment results of Lane and Zaffarano.[8] For a typical window the transmissions at 8 kev and 5 kev were 90% and 70%, respectively.

Special attention was paid to the mounting and preparation of the source. This was prepared by recoil collection on a 2-mm diameter thin aluminum foil (0.17 mg/cm^2) which was centered on a 2-cm diameter thin Zapon film, supported on a light aluminum frame. For coincidence measurements, this source holder was situated above a Perspex light guide which transmitted the α scintillations to an E.M.I. photomultiplier. A drawing of the experimental arrangement is shown in Fig. 1 which shows the source and light pipe situated in the entrance chamber of the spectrometer, with the gate valve connecting to the main vacuum chamber

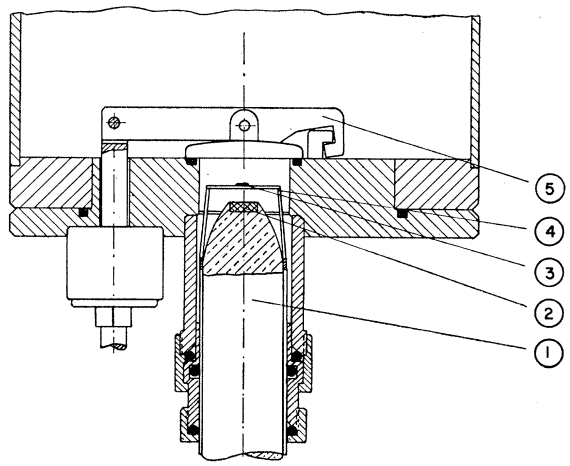

FIG. 1. Drawing of experimental arrangement showing source holder and alpha scintillator. (1) Light pipe; (2) plastic scintillator; (3) source; (4) source holder; (5) gate valve connecting entrance chamber to main vacuum chamber of spectrometer.

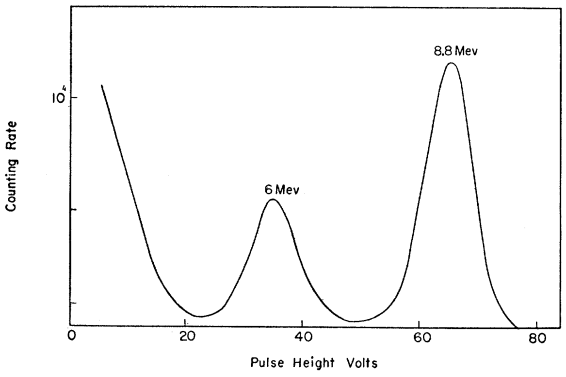

FIG. 2. Differential pulse-height distribution in the thin plastic scintillator, showing the two alpha groups from a ThB source in equilibrium with its products.

[7] K. Siegbahn and T. R. Gerholm, *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1955).

[8] R. O. Lane and D. J. Zaffarano, U. S. Atomic Energy Commission Report ISC 439 (unpublished).

closed. The α scintillator was a thin wafer of plastic scintillator (1,1,4,4 tetraphenyl butadiene in polystyrene), 8 mm in diameter and 0.2 mm thick, which sat in a suitable depression at the top end of the light pipe. The latter was shaped for maximum light collection. The thickness of the scintillator was such that while both groups of α particles from ThC and ThC′ (6 Mev and 8.8 Mev, respectively) lost all the energy in the scintillator and could be nicely resolved, the numerous electrons losing energy in the scintillator all produced smaller pulses and could be discriminated against, despite the fact that the light output per unit energy loss in the plastic scintillator is much greater for electrons. Figure 2 shows a typical differential pulse-height curve obtained from the scintillator and the two groups of α particles are clearly displayed above the electron pulses. In the coincidence measurements the source was about 3.5 mm from the scintillator and a total α-counting rate of about 3 million per minute was used. Despite this high counting rate, no sensible change in the properties of the scintillating plastic was noticed even after some months of continual use. This is in contrast to the behavior of anthracene which shows considerable radiation damage under α bombardment.[9]

Coincidences between the Geiger pulses and α-scintillation pulses were recorded, a resolving time of 3×10^{-7} sec being used. By using a high overvoltage on the counter, no coincidence losses were obtained at this resolving time. The coincidences measurement were carried out by using a discriminator which passed both the low- and high-energy α groups. Since the high-energy group is not coincident with a significant intensity of conversion lines, this may be done without increasing unwanted true coincidences, and is simpler than using a system of pulse analysis which selects only the lower group, although the random coincidence rate is increased.

RECOIL EFFECTS IN THE SPECTRUM OF AUGER ELECTRONS ASSOCIATED WITH ALPHA DECAY

It has been recently shown by the authors[10] that conversion electrons emitted in the de-excitation of excited nuclear states which are formed after alpha decay may show considerable broadening and even shifts in energy, as a consequence of nuclear recoil. The energy of the conversion electrons may be altered on two accounts: on the one hand, electrons may be emitted from recoil nuclei which are still in motion, and on the other hand, recoil nuclei, by virtue of their initial momentum, may penetrate the source backing, so that electrons emitted from these nuclei in a direction outwards from the source backing, will be retarded to some extent, even though the parent source may be infinitely thin. Since Auger electrons are emitted within a very short time after conversion electrons (of the order of 10^{-16} sec for L Auger electrons) they should also show similar effects, in general even to a greater extent, because of the low velocity of the Auger electrons. Thus, if an electron is emitted at an angle θ with respect to the direction of nuclear recoil, then the momentum p of the emitted electron will be $p=p_0[1+(v_n/v_\beta)\cos\theta]$, where p_0 would be the momentum of the electron emitted by a stationary nucleus, v_n is the velocity of the recoiling nucleus at the moment the electron is ejected, and v_β is the velocity of the emitted electron. Assuming there is no angular correlation between the Auger electrons and α particles, it follows that for an ideally thin source situated in vacuum on an ideally thin backing, the resulting momentum distribution will be a rectangle of relative half-width $\Delta p/p$ equal to v_n/v_β. Thus, for the example important in this work, the velocity v_n of the 116-kev recoil nucleus of $_{81}Tl^{208}$ in the 40-kev excited state, produced after the emission of an alpha particle of energy 6.04 Mev, is 3.3×10^7 cm/sec and the energy of the most intense line in the L Auger spectrum produced after the L internal conversion of this transition is about 7.6 kev, corresponding to an electron velocity of 5.2×10^9 cm/sec. The ratio v_n/v_β should thus be about 0.63%. In general, the source will be mounted on a backing which will be greater than or comparable to the range of the recoil nuclei. The average range of the recoil nuclei of $_{81}Tl^{208}$ in aluminum[11] is about 6 μg/cm^2 and they are stopped in about 2×10^{-13} sec. The Auger electrons, emitted from nuclei which have penetrated the backing, will emerge in the perpendicular direction outwards from the source after passing through a thickness of backing material on the average equal to half the average range of the recoil nuclei. The average loss of a 7-kev electron passing through 3-μg/cm^2 aluminum is above 70 ev.[8] Thus, in general, one-half of the Auger electrons emitted in a given direction out of the source will have an increased energy, corresponding to recoil nuclei moving away from the backing, and one-half will have a reduced energy, corresponding to recoil nuclei which have penetrated the source.

The α-coincident arrangement described above, however, effectively selects recoil nuclei which leave the source into the vacuum, and therefore the coincident spectrum of Auger electrons will show increased energies. The momentum displacement will depend on the solid angle which the α counter subtends at the source; if the solid angle is small the mean momentum will be close to the maximum of the recoil distribution, i.e., $p_0(1+v_n/v_\beta)$. In most of the coincidence measurements carried out in this work, the solid angle was

[9] J. B. Birks, *Scintillation Counters* (Pergamon Press, London, 1953).

[10] J. Burde and S. G. Cohen, Phys. Rev. **101**, 495 (1956).

[11] The range distributions of $_{81}Tl^{208}$ recoil nuclei in various materials has been measured in this Laboratory by allowing a beam of recoil nuclei to penetrate thin foils and measuring the 3.1-min $_{81}Tl^{208}$ activity induced in the foils. The average ranges found for Formvar, aluminum, silver, and gold were about 11, 6, 7, and 15 μg/cm^2, respectively [S. G. Cohen and A. Marinov (to be published)].

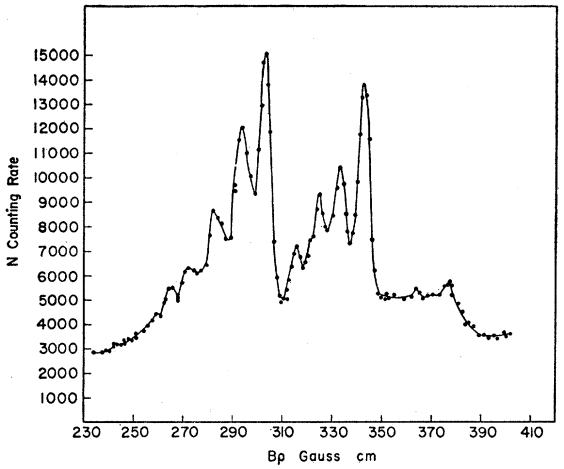

FIG. 3. L Auger spectrum from thorium active deposit observed with a spectrometer resolution of 0.8%.

about 2 steradians, corresponding to an extreme value of $\cos\theta=0.66$. From the coincidence measurements the correction for the recoil can accurately be subtracted in order to obtain the true energy of the Auger lines; for the noncoincident spectra, however, it is more difficult to correct accurately for the retardation of electrons emitted from recoil nuclei which have penetrated below the surface. There is thus a further advantage in using coincidence techniques for examining the Auger spectra following alpha decay.

EXPERIMENTAL RESULTS AND THE CORRECTED L AUGER SPECTRA FOR $_{81}Tl^{208}$ AND $_{83}Bi^{212}$

Figure 3 shows the Auger spectrum recorded without coincidences using a spectrometer resolution of 0.8% (measured on the thorium F line). The results are corrected for the dependence of transmission of the Geiger window on energy and for the decay of the source during the experiment. In this spectrum, we see eleven apparently resolved lines, and it may be thought at first that each "line" represents an Auger transition belonging to a definite atomic number $Z=81$ or 83. That this is not the case, however, follows from an inspection of the α-coincident spectrum. Figure 4 shows the two simultaneously recorded direct and coincident spectra, taken with a resolution of 1.2% (poorer resolution was used in order to obtain a higher coincident counting rate), again corrected for window transmission and decay of the source. The coincident counting rate at the peak of the most intense Auger line was about 100 pulses per minute. The coincident spectrum, which, as explained in the introduction, belongs essentially to $_{81}Tl^{208}$, shows at least fourteen lines, none of which coincide with the peaks in the "singles" spectrum. The latter is in fact compounded from the Auger spectra of $_{81}Tl^{208}$ and $_{83}Bi^{212}$. The spectrum of $_{83}Bi^{212}$ was obtained by subtracting from the direct or composite spectrum the coincident spectrum belonging to $_{81}Tl^{208}$, after applying the proper normalization, and also the necessary corrections to the energies due to the change in recoil effects to be expected in the "singles" spectrum with respect to those obtaining in the coincident spectrum. The normalization factor is equal to the reciprocal of the over-all efficiency of the α-scintillation counter. This was measured experimentally in the actual experimental conditions in which Fig. 4 was obtained by measuring the ratio between the singles and α-coincident counting rate obtained with the 24.5-kev "A" line, resulting from the L conversion of the 40-kev transition.

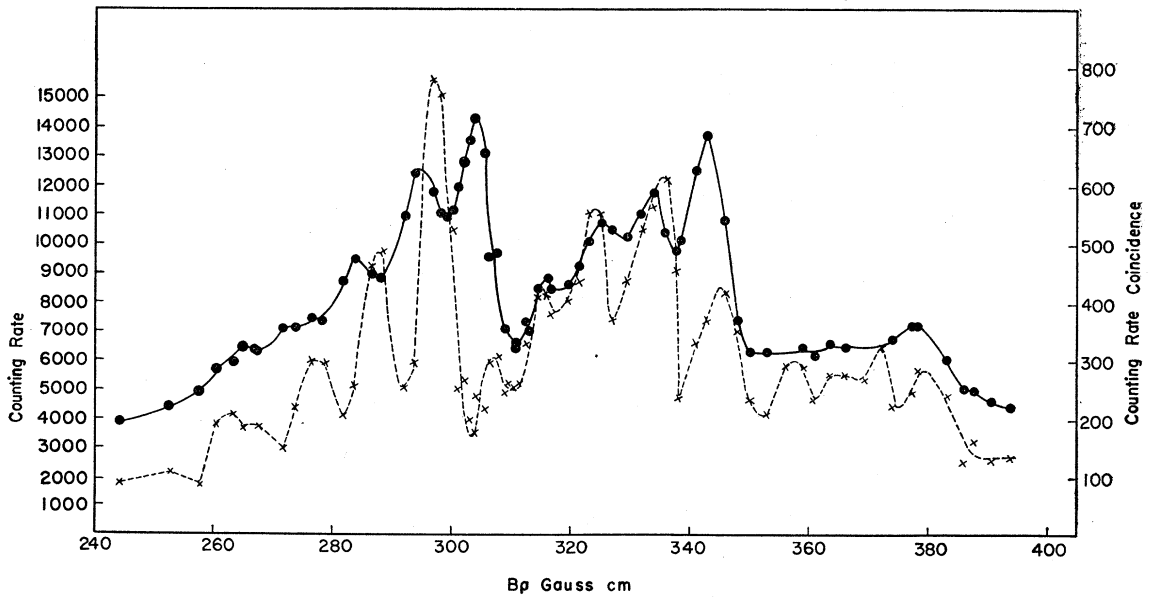

FIG. 4. Direct and alpha coincident L Auger spectra. The full line represents the directly observed spectrum. The broken line is the alpha coincident spectrum.

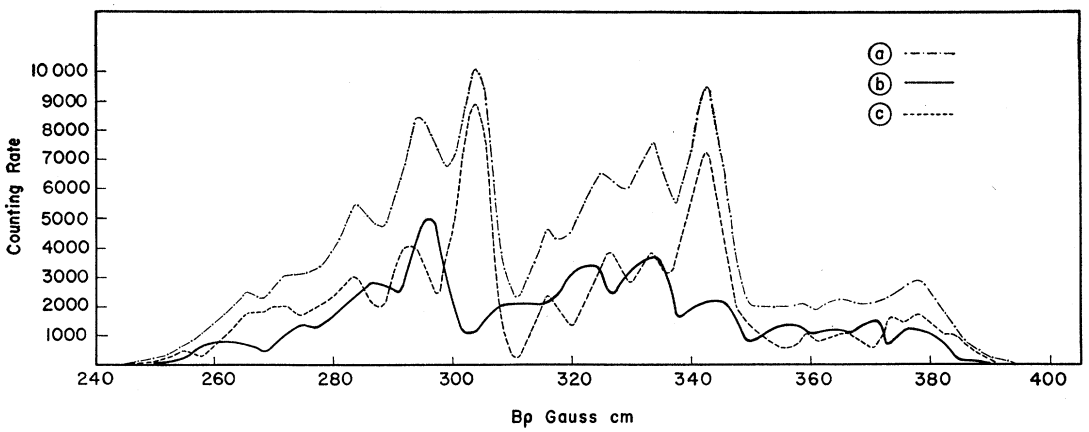

FIG. 5. The L Auger spectrum of $_{83}Bi^{212}$ obtained by the difference between the directly recorded and the alpha-coincident Auger spectra. Curve (a): Directly recorded L Auger spectrum after subtraction of background. Curve (b): Normalized and corrected coincident Auger spectrum. Curve (c): Difference spectrum to be ascribed mainly to the L Auger spectrum of $_{83}Bi^{212}$.

Since every such conversion electron coincides with a 6.04-Mev α particle, this ratio gives directly the efficiency of the α scintillation counter. The necessary correction to the coincidence spectrum, taking into account recoil effects, was obtained in the following way. The coincident spectra was resolved into its component lines. This could be done in a fairly unambiguous way. For each such Auger line, the shape and momentum of the corresponding line to be expected in the directly recorded spectrum of $_{81}Tl^{208}$ was computed as the sum of two close lines of equal intensity: the first line results from Auger electrons which are ejected into the acceptance cone of the spectrometer from recoil nuclei moving out of the source into the vacuum and therefore have momentum between p_0 and $p_0+(v_n/v_\beta)p_0$; the second results from Auger electrons emitted from recoil nuclei which are at rest after having penetrated the source backing.[12] The results of Lane and Zaffarano[8] were used to estimate the average energy loss suffered by electrons in passing through half the average range of the recoil nuclei (3 $\mu g/cm^2$). The finite resolution of the spectrometer was of course taken into account in estimating the final line shapes.

Figure 5 shows once again the observed composite direct spectrum, together with the corrected normalized coincident spectrum of $_{81}Tl^{208}$, and the resultant spectrum obtained by subtraction of the latter from the former. This difference spectrum must be ascribed mainly to the L Auger spectrum of $_{83}Bi^{212}$.

Finally, Fig. 6 shows the two L Auger spectra of thallium and bismuth plotted together for the sake of convenient visual comparison. The thallium spectrum has been corrected for the effect of recoil shifts to give the energies corresponding to the spectrum which would be observed from stationary nuclei.

IDENTIFICATION OF LINES, AND DISCUSSION

From Fig. 6 it is immediately apparent that there is a marked correspondence between the forms of the two Auger spectra. This is to be expected for two elements differing in atomic number by two. On the other hand, apart from the relative displacement of corresponding lines, there are some differences in relative intensities, and there are a few lines which seem only to occur in one or other of the spectra. These differences result from the difference in distribution of vacancies in the L subshells which precede the emission of L Auger electrons in the two cases. We must distinguish here between the initial and final distribution of L vacancies, since the initial distribution will be altered by the possibility of Coster-Kronig transitions which take place between the L subshells. The initial distribution can be estimated for the two isotopes from the knowledge of the various conversion coefficients and for $_{83}Bi^{212}$ the K fluorescent yield, and the relative intensities of the lines in the K x-ray spectrum.

Table I shows the initial distribution of holes in the subshells found in this way. It has been known for some time that the L_I-L_{III} type of Coster-Kronig

TABLE I. Initial distribution of ionization and distribution of Auger electrons in L_I, L_{II}, and L_{III} subshells, per disintegration of ThC.

	$Z=81$			$Z=83$		
	L_I	L_{II}	L_{III}	L_I	L_{II}	L_{III}
Initial distribution of ionization per disintegration of ThC	0.16	0.02	0.01	0.06	0.085	0.16
Distribution of Auger electrons per disintegration of ThC	0.025	0.02	0.05	0.01	0.035	0.10

[12] Measurements of the lifetime of the 40-kev transition in $_{81}Tl^{208}$ by the authors, using recoil shifts of the conversion electrons, give a value of about 1×10^{-12} sec which is considerably greater than the slowing-down time in aluminum (2×10^{-13} sec). J. Burde and S. G. Cohen, following paper [Phys. Rev. **104**, 1093 (1956)].

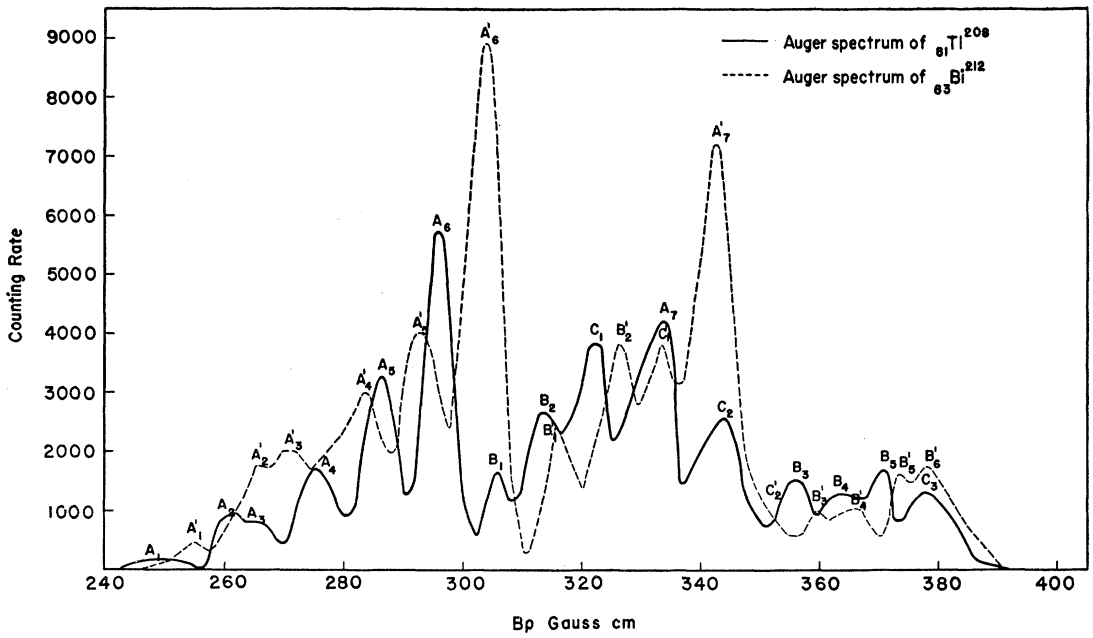

FIG. 6. The L Auger spectra of thallium and bismuth.

transition has a high probability in this region of the periodic table, and hence one will expect the Auger lines originating in the L_{III} subshell to be intense in both isotopes although the amount of initial L_I ionization is appreciable in both cases.

For the identification of the lines, the table of atomic absorption edges prepared by Hill, Church, and Mihelich[13] was used. For some lines, the knowledge of the L binding energies was sufficient to ensure identification on energetic grounds alone. This is so despite the large number of transitions which are energetically possible for the lower energy group of high-intensity lines of the type $L_{III}-MM$ which appear in both spectra in roughly the same ratio of intensities.

Some lines, however, cannot be unambiguously identified on energetic grounds alone, since the large number of *a priori* possible transitions are very large and in some cases more than one energetically possible transition gives the observed energy. In these cases it happens that the ambiguity can be removed taking into account the differences in form between the two spectra together with the distribution of vacancies in the L subshells mentioned earlier. The relative intensities of the group of Auger lines originating in the L_{III} subshell vacancy should be approximately the same for $Z=81$ and $Z=83$. If the intensity of corresponding Auger lines relative to a group of Auger lines which have been definitely assigned to the L_{III} subshell is markedly different for the two isotopes, then it may be assumed that these corresponding lines originate in the L_I or L_{II} subshells. Owing to the fact that the ratio of the number of primary holes in the L_I subshell to that in the L_{II} subshell differs markedly for the two isotopes, one can find out in which subshell the lines originate by comparing the intensities of the corresponding lines for the two isotopes. Thus, for example, the line C_2 appears quite strongly in the thallium spectra but is unresolved and weak in the bismuth spectrum. Similarly, C_1 is much stronger in thallium than the corresponding line in bismuth. Now, from energetic considerations alone, these lines might originate from L_{III} or L_{II} or L_I vacancies. However, the main L_{III} Auger lines show a fixed ratio; thus the lines cannot involve the L_{III} shell; in fact the marked differences in L_I vacancies indicated in the table, shows that these lines involve the L_I shell: this, together with a knowledge of the binding energies, leads to a fairly certain classification of the lines.

Table II shows the classification of the L Auger lines for thallium and bismuth obtained in this way, together with the measured energies and intensities. The energies calculated from the atomic absorption edges, assuming the stated classifications, are also listed. The energy of an atom simultaneously ionized in the M and N shell was estimated in the usual way by taking the sum of the ionization energy of a singly ionized atom in the M shell for the element concerned of atomic number Z with the ionization energy of atom singly ionized in the N shell belonging to element of atomic number $Z+1$.

The L Auger spectrum of $_{83}Bi^{210}$, appearing in the disintegration of RaD, has been investigated by Bashilov

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

TABLE II. Classification of the L Auger lines for thallium ($Z=81$) and bismuth ($Z=83$). The measured energy of each line is compared with the calculated energy for the assumed classification. Intensities are given in percent of the total number of Auger electrons due to the investigated element. Electrons from L_{III}, L_{II}, and L_I subshells are designated by A_i, B_i, and C_i, respectively.

	$Z=81$				$Z=83$				
Auger line	Energy measured kev	Auger transition	Energy calculated kev	Intensity percent	Auger line	Energy measured kev	Auger transition	Energy calculated kev	Intensity percent
A_1	5.48±0.04	$L_{III}-M_IM_{II}$	5.5	0.6	A_1	5.66±0.1	$L_{III}-M_IM_{II}$	5.7	1
A_2	5.95±0.05	$L_{III}-M_IM_{III}$	6.0	5	A_2	6.18±0.1	$L_{III}-M_IM_{III}$	6.2	10.5
A_3	6.18±0.05	$L_{III}-M_{II}M_{III}$	6.3		A_3	6.44±0.1	$L_{III}-M_{II}M_{III}$	6.5	
A_4	6.65±0.03	$L_{III}-M_{II}M_{IV}$	6.7	6	A_4	7.02±0.05	$L_{III}-M_{II}M_{IV}$	7.0	9.5
A_5	7.14±0.02	$L_{III}-M_{III}M_{IV}$	7.2	10.5	A_5	7.49±0.03	$L_{III}-M_{III}M_{IV}$	7.5	11
A_6	7.62±0.02	$L_{III}-M_{IV}M_{IV}$	7.7	15.5	A_6	8.05±0.02	$L_{III}-M_{IV}M_{IV}$	8.0	21
B_1	8.14±0.05	$L_{II}-M_{II}M_{III}$	8.3	5	B_1	8.71±0.06	$L_{II}-M_{II}M_{III}$	8.8	5
B_2	8.6 ±0.07	$L_{II}-M_{II}M_{IV}$	8.8	5	B_2	9.28±0.07	$L_{II}-M_{II}M_{IV}$	9.3	7.5
C_1	9.06±0.03	$L_I-M_IM_{IV}$	9.1	13	C_1	9.68±0.06	$L_I-M_IM_{IV}$	9.7	6.5
A_7	9.68±0.03	$L_{III}-M_{IV}N_{IV}$ / $L_{III}-M_{IV}N_V$	9.7	15.5	A_7	10.21±0.03	$L_{III}-M_{IV}N_{IV}$ / $L_{III}-M_{IV}N_V$	10.2	16.5
C_2	10.27±0.04	$L_I-M_{IV}M_{IV}$	10.4	9.5	C_2	10.7 ±0.1	$L_I-M_{IV}M_{IV}$	10.6	2
B_3	11.02±0.06	$L_{II}-M_{III}N_{II}$	11.0	5	B_3	11.2 ±0.1	$L_{II}-M_IN_{IV}$ / $L_{II}-M_IN_V$	11.2	1.5
B_4	11.52±0.1	$L_{II}-M_{IV}N_{II}$	11.5	1.5	B_4	11.65±0.1	$L_{II}-M_{III}N_{II}$	11.7	2
B_5	11.93±0.1	$L_{II}-M_VN_{IV}$ / $L_{II}-M_VN_V$	11.9	4.5	B_5	12.22±0.1	$L_{II}-M_{IV}N_{II}$	12.2	3
C_3	12.42±0.05	$L_I-M_{IV}N_{IV}$ / $L_I-M_{IV}N_V$	12.4	3.5	B_6	12.61±0.05	$L_{II}-M_VN_{IV}$ / $L_{II}-M_VN_V$	12.6	3

et al.[3,14] and Kobayashi.[2] These spectra resemble closely in form the spectrum of $_{81}Tl^{208}$ obtained in this work and not that of $_{83}Bi^{212}$. This is indeed very reasonable, since the Auger transitions in $_{83}Bi^{210}$ result from the conversion of a magnetic dipole 47-kev transition in $_{83}Bi^{210}$ which leads to a distribution of L subshell vacancies very similar to that produced by conversion of the 40-kev magnetic dipole transition in $_{81}Tl^{208}$.

CALCULATION OF AUGER AND COSTER-KRONIG YIELDS

From the experimental results, one may easily obtain the over-all L Auger yield for the two isotopes. The Auger yield is defined as the total number of L Auger electrons emitted per vacancy in the L shell. For $_{81}Tl^{208}$, the L Auger yield is obtained by comparing under identical geometrical conditions the total number of Auger electrons per coincident α particle with the total number of electrons recorded in the "A" line per coincident α particle. In the calculation, the small contribution to L ionization arising from low-intensity conversion lines other than the "A" line which appear in the de-excitation of the higher excited states of $_{81}Tl^{208}$ was taken into account. (The most intense line of this type is the Ga line of energy 287 kev and intensity of about 1% relative to the A line.) Similarly for $_{83}Bi^{212}$, the number of L Auger electrons was compared with the number of conversion electrons belonging to the F and I lines (corresponding to the K and L conversion of the 238-kev transition), both of which contribute to the number of L vacancies. In the calculation of this Auger yield, small corrections were made for (a) some weak converted transitions appearing in the decay of ThB which contribute slightly to L ionization and (b) the contribution of L Auger electrons belonging to $Z=82$ to the Auger spectrum shown in Curve 2 of Fig. 6. The latter arises from the low intensity lines produced after the β decay of $_{81}Tl^{208}$ and was estimated at about 2% of the total Auger electrons recorded.

In this way the values of 0.50±0.02 was found for the L Auger yield in $_{81}Tl^{208}$ and 0.49±0.03 for $_{83}Bi^{212}$. From measurements of the intensity of the L x-ray spectrum of RaD, Kinsey[15] has obtained the values of 0.47 for the L fluorescence yield (the complement of the L Auger yield) for $_{83}Bi^{210}$.

From the experimental results it is also possible to calculate the separate Auger yields for the different subshells, together with the Coster-Kronig yields, if some very reasonable assumptions concerning these quantities are made. These coefficients are more fundamental quantities than the over-all yields given above, since they do not depend on the mode of ionization of the L subshells and are characteristic of a given atomic number. In this analysis we follow the spirit of Ross *et al.*,[16] who recently calculated the coefficients for $Z=83$ by analyzing the experimental data of many workers (and therefore in some cases these data are somewhat contradictory and confusing) who had measured separately the intensity of x-rays and L Auger lines appearing in this disintegration of RaD. In the present analysis the results are obtained only from the combined experimental data for $Z=81$ and $Z=83$ presented in this work, with the following assumptions:

[14] The authors unfortunately have not been able to see the original paper of Bashilov *et al.* and are acquainted with the spectrum only through the reproduction given in the paper of M. A. S. Ross *et al.*[16]

[15] B. B. Kinsey, Canadian J. Research **26**, **A404** (1948).

[16] Ross, Cochram, Hughes, and Feather, Proc. Phys. Soc. (London) **A68**, 612 (1955).

TABLE III. Auger and Coster-Kronig yields.

	Results of the prsent work: average for $Z=81$ and $Z=83$	Results of Ross *et al.* for $Z=83$
a_1	0.15	0.11
a_2	0.34	0.62
a_3	0.54	0.60
f_{12}	0.24	0.19
f_{13}	0.52	0.58

(1) The L subshell Auger and Coster-Kronig coefficients are assumed to be identical for $Z=81$ and $Z=83$. This is of course only an approximation, but the change may be expected to be small and the results may be interpreted as a kind of average for the two atomic numbers.

(2) Coster-Kronig transitions of the type $L_{II}-L_{III}$ are assumed not to take place. For energetic reasons, transitions of this type can involve only the N shell or shells even further out. Coster-Kronig transitions of the type L_I-L_{II} similarly can involve only the N shell or shells further out. The kinetic energy of the electrons emitted in the Coster-Kronig process will be larger in the latter case than in the former. For example, for $Z=83$ the kinetic energy of the electrons emitted in the $L_I-L_{II}N_{IV}$ transition will be only about 200 ev, whereas for the $L_{II}-L_{III}N$ transition the kinetic energy will be about 1.3 kev. The theoretical treatment of Coster and Kronig[17] for the dependence of transition probability on momentum of the emitted electron shows that the former transition should have a much larger probability than the latter. The only available result based on experiment for the probability of the $L_{II}-L_{III}N$ transition is that given by Ross *et al.*[16] who give a value of 0.06 ± 0.14.

Then, using a notation similar to that of Ross *et al.*,[16] we define $n_1n_2n_3$ to be the primary number of holes in the $L_IL_{II}L_{III}$ subshells of $_{81}Tl^{208}$ per disintegration of ThC, $a_1a_2a_3$ as the separate Auger yields for the L subshells, f_{12} and f_{13} as the Coster-Kronig yields for the L_I-L_{II} and L_I-L_{III} transitions respectively, and $A_1A_2A_3$ as the number of Auger electrons originating from the $L_IL_{II}L_{III}$ subshells per disintegration of ThC. The dashed symbols indicate the corresponding quantities for $_{83}Bi^{212}$. Then, with the above assumptions, we obtain the following equations:

$$a_1n_1=A_1, \tag{1}$$

$$a_2(n_2+f_{12}n_1)=A_2, \tag{2}$$

$$a_3(n_3+f_{13}n_1)=A_3, \tag{3}$$

$$a_1n_1'=A_1'. \tag{4}$$

$$a_2(n_2'+f_{12}n_1')=A_2', \tag{5}$$

$$a_3(n_3'+f_{13}n_1')=A_3'. \tag{6}$$

The A's are known from the spectra and classification, the n's have been calculated, and both are shown in Table I. Equations (1) and (4) yield independent values for a_1, and in principle can be used to examine the reliability of assumption (1). The values obtained are 0.15 and 0.21, respectively. However, as the L_I lines are of very low intensity for $Z=83$, we rely on the former value as being more exact. From the remaining equations the other coefficients are determined. The results are shown in Table III.

The values obtained by the independent analysis of Ross *et al.* for $Z=83$ are also shown.

It is seen that good agreement exists except for a_2. This coefficient is sensitive to the assumed classification of the L Auger lines, and the discrepancy arises in that the classification of the L_{II} lines given by Kobayashi and Bashilov for the L spectra of RaD, on which the analysis is based, differs from our classification.

ACKNOWLEDGMENTS

We would like to take this opportunity of thanking Mr. F. Deutsch for his invaluable assistance in the design of the β spectrometer, Mr. B. Loewenson for his skill and patience in preparing the thin plastic scintillators, and Mr. Eldad Giberman for construction of the coincidence unit.

[17] Reference 1, pp. 71-76.