# The Nuclear Spectra of $Sb^{125}$, $Te^{125*}$, $Cr^{51}$, and $I^{131}$

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The nuclear spectra of $Sb^{125}$, $Te^{125*}$, $Cr^{51}$, and $I^{131}$ have been measured with a magnetic lens spectrometer. $Sb^{125}$ has a beta-ray end point at 0.621 Mev, a lower energy group at 0.288 Mev, and perhaps some groups of still lower energy. The gamma-rays of $Sb^{125}$ are at 0.125 (I.C.), 0.174 (I.C.), 0.431 (I.C.), 0.466, 0.609 (I.C.), and 0.646 Mev. Those marked with the notation (I.C.) are internally converted. The metastable state of $Te^{125}$, daughter of $Sb^{125}$, is characterized by the emission of an internally converted gamma-ray of energy 0.110 Mev. $Cr^{51}$ emits no positrons but decays by $K$-capture accompanied by two gamma-rays of energies 0.323 and 0.267 Mev, the latter being entirely internally converted. $I^{131}$ has a beta-ray end point of 0.605 Mev with a lower energy group at 0.250 Mev. Gamma-rays at 0.080, 0.282, 0.363, and 0.637 Mev are observed. The disintegration schemes of $Sb^{125}$, $Te^{125*}$, and $I^{131}$ are discussed.

## INTRODUCTION

As part of a program for the study of nuclear energy levels, the nuclear spectra of $Sb^{125}$ (2.7 years) and its metastable daughter $Te^{125*}$ (58 days), together with those of $Cr^{51}$ (26.5 days) and $I^{131}$ (8.0 days) have been investigated. The sources which were studied were all obtained from the Isotopes Division of the Oak Ridge National Laboratory. The apparatus used in these experiments was the magnetic lens previously described by the authors.[1]

During the early part of these experiments the lens was equipped with only one field-producing coil and was used as described in our earlier work. While these experiments were in progress, an additional coil, identical with the first, was added to the apparatus and used in a manner similar to that described by Quade and Halliday.[2] These authors have shown that if two coils are placed symmetrically on either side of the midpoint between source and counter, the field is thereby shaped in such a way that spherical aberration is considerably reduced. They describe a procedure for determining the position of minimum spherical aberration empirically. This consists of defining two rays by two annular slits, one near the maximum radius of the vacuum chamber and one nearer the axis. If now, the source consists of a group of electrons having a narrow spread in energy, such as an internal conversion line, two peaks will be focused, one corresponding to the outside ray and one to the inside ray. By moving the coils, these two peaks can be brought nearly into coincidence, showing that spherical aberration has been reduced. This procedure has been applied to the present lens with the result that the resolution has been improved and the intensity, at a given resolution, greatly enhanced.

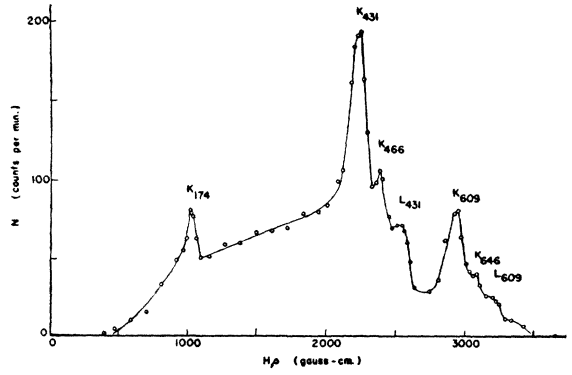


FIG. 1. Spectrum of the secondary electrons ejected by the gamma-rays of antimony 125.

The counters used in these experiments were the usual end window type. For investigating the region above 100 kev, an unsupported mica window having a surface density of 2 mg/cm² was used. When the low energy region was to be studied, however, a window of Zapon lacquer of surface density 0.1–0.3 mg/cm² was used. This window was supported on a brass grid.

## THE NUCLEAR SPECTRUM OF $Sb^{125}$ AND $Te^{125*}$

$Sb^{125}$ was made by bombarding tin with neutrons in the Oak Ridge Pile. It grows[3] from $Sn^{125}$ (9 min.). Recently Friedlander, Goldhaber, and Scharff-Goldhaber[4] have shown that a metastable state of $Te^{125}$, of about two months half-life, is produced by the disintegration of $Sb^{125}$.

The $Sb^{125}$ was separated from the tin by the following procedure: in order to separate small quantities of antimony from large quantities of tin, a piece of metallic iron was introduced into the solution of $SnCl_4$, in HCl solution, containing the parent Sn activity and the product $Sb^{125}$. Antimony was thereby deposited electrochemically on the iron, leaving the tin in solution. The deposit, and some of the iron, was then dissolved in $HNO_3$ and the resulting solution converted to the chloride. A small amount of tellurium carrier was then added and the tellurium was separated as metal by passing $SO_2$ through the solution. After boiling out the $SO_2$, the antimony was separated from the iron by an $H_2S$ precipitation in acid solution. After drying, the

† AEC Fellow.
[1] Kern, Zaffarano, and Mitchell, Phys. Rev. **73**, 1142 (1948).
[2] E. A. Quade and D. Halliday, Rev. Sci. Inst. **19**, 234 (1948).
[3] For earlier investigations on $Sb^{125}$, see G. T. Seaborg and I. Perlman, Rev. Mod. Phys. **20**, 585 (1948).
[4] Friedlander, Goldhaber, and Scharff-Goldhaber, Phys. Rev. **74**, 981 (1948).

$Sb_2S_3$ was used as a source of photoelectrons to measure the gamma-rays. Both $Sb_2S_3$ and evaporated sources of $SbCl_3$ were used as beta-ray sources. The internal conversion electrons of $Te^{125*}$ were studied, using either the Te metal or an evaporated solution of tellurium nitrate as source material.

The gamma-rays of $Sb^{125}$ were studied by allowing them to eject photoelectrons from a lead radiator. The source material was placed in a copper capsule with walls thick enough to stop all beta-rays. Photoelectrons were ejected from a lead radiator, having a surface density of 22 mg/cm², placed upon the base of the cylinder. The diameter of the lead radiator (source diameter) was 1 cm and the counter aperture was also 1 cm. A plot of the secondary electron distribution as a function of the magnetic rigidity (gauss-cm), taken in the lens, is shown in Fig. 1. The energy of the gamma-rays associated with the various $K$ and $L$ peaks of Fig. 1 is shown in Table I, together with the energies of gamma-rays obtained from internal conversion electrons.

The beta-ray spectrum of the source was now measured. In these measurements the counter window was of 1 mg/cm² surface density. The source was $SbCl_3$ of 13 mg/cm² surface density mounted on paper of surface density 0.8 mg/cm². The most striking thing about this spectrum, shown in Fig. 2, is the number of internal conversion lines occurring. It should be remarked that the source as measured had not had the tellurium separated out. It therefore contains lines from $Sb^{125}$ and the metastable daughter $Te^{125*}$. The lines occurring are labeled to correspond to Table I in which the energy of the gamma-rays responsible for the various internal conversion lines is given.

It is difficult to make a Fermi plot analysis of a spectrum containing as many internal conversion lines as the one under consideration. Nevertheless, this has been attempted with the following results: The beta-ray end point of the spectrum comes at 0.621 Mev. A lower energy group having an end point at 0.288 Mev is also found. Below 0.200 Mev, the presence of internal conversion lines makes the analysis extremely unreliable. There is some evidence that groups of still lower energy exist. The ratio of the intensity of the group with end point at 0.288 Mev to that with end point at 0.621 Mev is approximately 2.

In order to investigate the radiations from the $Te^{125*}$ daughter, the source was redissolved and the tellurium separated. The beta-ray spectrum of the metastable $Te^{125*}$, resulting from this separation, is shown in Fig. 3. This is seen to consist entirely of $K$ and $L$ internal conversion lines from a gamma-ray of energy 0.110 Mev. Using the data of Fig. 3, we have calculated that the ratio $N_K/N_L=1.2$. This result is in agreement with the work of Hill, Scharff-Goldhaber, and Friedlander,[5] who made a similar measurement using, however, a photographic plate as a detector. According to Drell[6] this low value $N_K/N_L$ indicates that the transition associated with the 0.110-Mev line is mostly magnetic $2^4$ pole radiation.

[5] Hill, Scharff-Goldhaber, and Friedlander, Phys. Rev. **75**, 324 (1949).

TABLE I. Energies of the gamma-rays of $Sb^{125}$ and $Te^{125*}$.

| Element | How detected | $E_\gamma$(Mev) |
|---|---|---|
| Te | IC($K$,$L$) | 0.110±0.001 |
| Sb | IC($K$) | 0.125±0.001 |
| Sb | IC($K$); Photo ($K$) | 0.174±0.002 |
| Sb | IC($K$); Photo ($K$,$L$) | 0.431±0.004 |
| Sb | Photo ($K$) | 0.466±0.007 |
| Sb | IC($K$); Photo ($K$,$L$) | 0.609±0.006 |
| Sb | Photo ($K$) | 0.646±0.009 |

In trying to make up an energy level diagram one is confronted with the fact that it has not been possible to make accurate measurements on the low energy beta-groups. One must rely, therefore, on energy matching among the many gamma-rays. The strongest gamma-rays are those at 0.431, 0.609, and 0.174 Mev. The lines at 0.646, 0.466, and 0.125 are considerably weaker. The ratio of the intensity of the line at 0.431 to that at 0.609 is found to be 1.43, when due account is taken of the efficiency of production of photoelectrons and its change with energy.

The most plausible scheme, and one in which the energies fit to within 2 percent, is shown in Fig. 4. The two low energy beta-ray transitions shown as dotted lines have not been measured, but are put in merely as a result of the gamma-ray analysis. Experimental evidence exists that there is a low energy group of electrons present but it has not been possible to determine the end point. The lowest energy group must be ex-

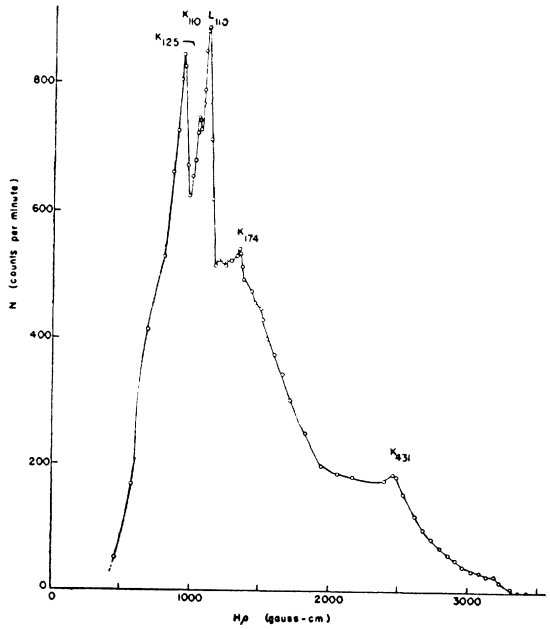


FIG. 2. Beta-ray spectrum of antimony 125.

[6] S. D. Drell, Phys. Rev. **75**, 132 (1949).

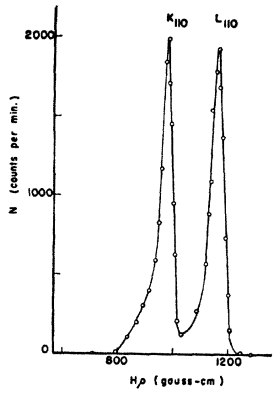


FIG. 3. The internal conversion electron spectrum of tellurium 125*.

tremely weak since the line at 0.646 Mev is of low intensity. Mr. E. T. Jurney of this laboratory has made coincidence measurements[7] on $Sb^{125}$. He finds gamma-gamma-coincidences. There are no beta-gamma-coincidences for electron energies greater than about 0.230 Mev, but there is a sharp rise in the beta-gamma-curve for energies less than this. This would indicate that none of the gamma-rays, except possibly the one at 0.110 Mev due to the metastable level of $Te^{125}$, follows the beta-ray of energy 0.621 Mev.

### THE NUCLEAR SPECTRUM OF $CR^{51}$

The production and investigation of $Cr^{51}$ was first carried out by Walke, Thompson, and Holt.[8] They reported that $Cr^{51}$ (26.5 days) decayed by $K$-capture accompanied by the emission of gamma-rays, whose energies, determined by absorption in lead, were stated to be 0.5 and 1.0 Mev. Miller and Curtiss[9] measured the gamma-rays from this substance, using a magnetic lens spectrometer, and found only one gamma-ray at 0.320 Mev. Bradt, Gugelot, Huber, Medicus, Preiswerk, and Scherrer[10] studied the radiations from $Cr^{51}$ with a 180° type spectrometer. A study of the photoelectrons ejected from a lead radiator showed only one gamma-ray, and that at an energy of 0.330±0.001 Mev. A study of the particles emitted from a thin source

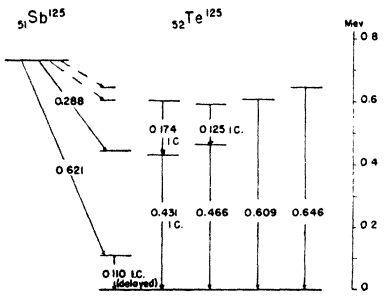


FIG. 4. Tentative energy level diagram for the decay of antimony 125.

[7] To be published shortly.
[8] Walke, Thompson, and Holt, Phys. Rev. **57**, 177 (1940).
[9] L. C. Miller and L. F. Curtiss, Phys. Rev. **70**, 983 (1946).
[10] Bradt, Gugelot, Huber, Medicus, Preiswerk, and Scherrer, Helv. Phys. Acta **18**, 259 (1945).

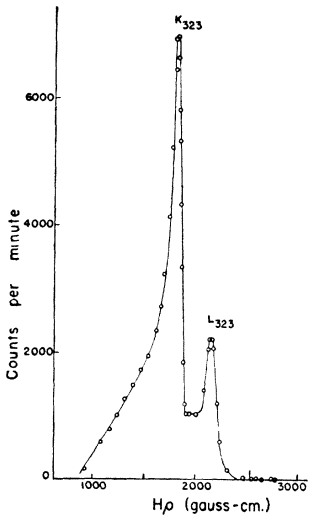


FIG. 5. Spectrum of the secondary electrons ejected by the 323-kev gamma-ray of chromium 51.

showed two internal conversion lines; the one, arising from the gamma-ray at 0.330 Mev, and the second arising from a gamma-ray of energy 0.237±0.001 Mev. The Swiss authors concluded that the second gamma-ray must be essentially 100 percent internally converted. Finally, Kurie and Ter-Pogossian[11] studied the photoelectrons ejected from a uranium radiator and the particles emitted from the source. They established that there was a gamma-ray at 0.320±0.005 Mev but could find no internal conversion electrons.

During the past year, the present authors have made a study of the radiations from $Cr^{51}$, using a source obtained from Oak Ridge. The distribution of photoelectrons from a lead radiator, shown in Fig. 5, shows $K$ and $L$ peaks for a gamma-ray of 0.323±0.005 Mev. There is no evidence for a higher energy gamma-ray, as mentioned by Walke *et al.* The lower energy gamma-ray is not seen in the photoelectron spectrum.

A "beta-ray" source was then investigated in the magnetic lens spectrometer, and two internal conversion lines were found. The energy of the gamma-ray corresponding to the higher energy line is 0.319 Mev, in good agreement with the value of 0.323 Mev obtained from the photoelectron distribution. The energy of the second line corresponds to a gamma-ray of 0.267 Mev, which is somewhat higher than that reported by Bradt *et al.* Aside from this energy discrepancy, the scheme of Bradt *et al.* is confirmed.

### THE SPECTRUM OF $I^{131}$

The spectrum of $I^{131}$ (8.0 days) was originally investigated by Downing, Deutsch, and Roberts[12] who reported that the beta-ray spectrum is simple and that each beta-ray is followed by an 80-kev and a 367-kev gamma-ray in cascade. Recently Metzger and Deutsch,[13]

[11] F. N. D. Kurie and M. Ter-Pogossian, Phys. Rev. **74**, 677 (1948).
[12] Downing, Deutsch, and Roberts, Phys. Rev. **61**, 686 (1942).
[13] F. Metzger and M. Deutsch, Phys. Rev. **74**, 1640 (1948).

on the one hand, and Owen, Moe, and Cook[14] on the other, have reinvestigated the spectrum using sources of higher specific activity, now available from the Oak Ridge National Laboratory. From a measurement of the energy of photoelectrons as well as internal conversion electrons, Metzger and Deutsch find lines at 80, 283, 363, and 638 kev, all lines being internally converted. Owen, Moe, and Cook have studied the beta-ray spectrum and internal conversion lines of this isotope. They find the lines at 83±2, 286±6, and 368±7 kev. They did not look for the line at 0.638 Mev. They found, in addition, internal conversion electrons corresponding to a weak line at 163±3 kev. Recently, they have also studied the distribution of photoelectrons[15] from a uranium radiator and find lines at 364, 284, and 638 kev and, in addition, a very weak line at 163 kev.

The end point of the beta-ray spectrum is given by Metzger and Deutsch as 600±5 kev and by Owen,

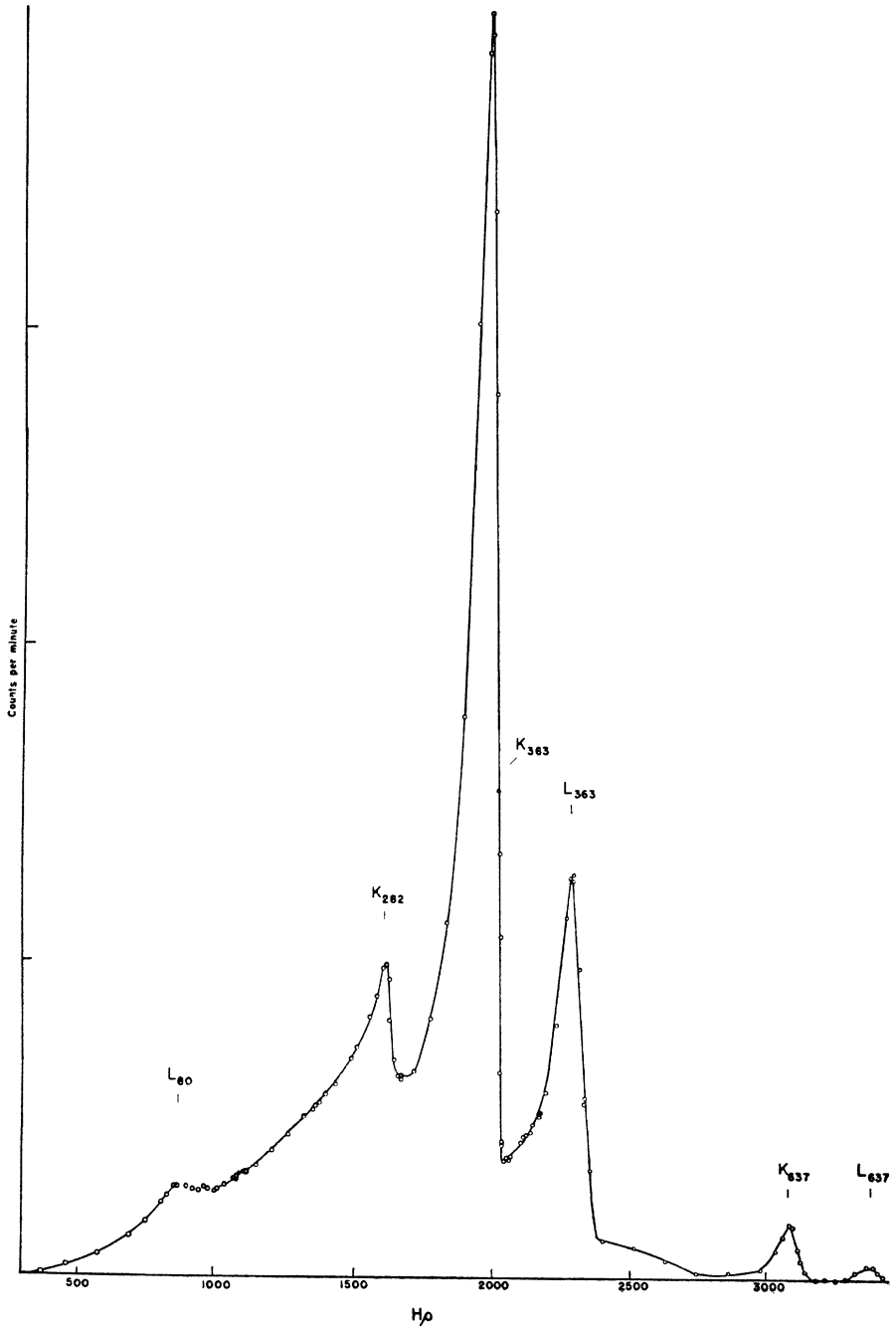


FIG. 6. Spectrum of the secondary electrons ejected by the gamma-rays of iodine 131.

[14] Owen, Moe, and Cook, Phys. Rev. **74**, 1879 (1948).
[15] Moe, Owen, and Cook, Phys. Rev. **75**, 1270 (1949).

TABLE II. Internal conversion in $I^{131}$.

| Energy of gamma-ray kev | Intensity quanta per 100 disintegrations | Conversion coefficient $N_e/N_\gamma$ | $N_K/N_L$ |
|---|---|---|---|
| 80 | 17.9 | 0.17 | 8.4 |
| 282 | 14.2 | 0.079 | — |
| 363 | 82.5 | 0.018 | 4.0 |

Moe, and Cook as 597±5 kev. Metzger and Deutsch made a Fermi analysis of their data and found a second group of electrons at 315±20 kev, while the other authors made no attempt to determine the second group.

In view of the importance of this element in medical research, the Oak Ridge National Laboratory has asked us to make an independent determination of the disintegration scheme of this element. Accordingly, a strong "carrier free" source of $I^{131}$ was furnished this laboratory. For the investigation of the photoelectrons the source was purified in the following way. Iodine carrier was added as KI and the iodide ion was oxidized to free iodine, which was separated out in carbon

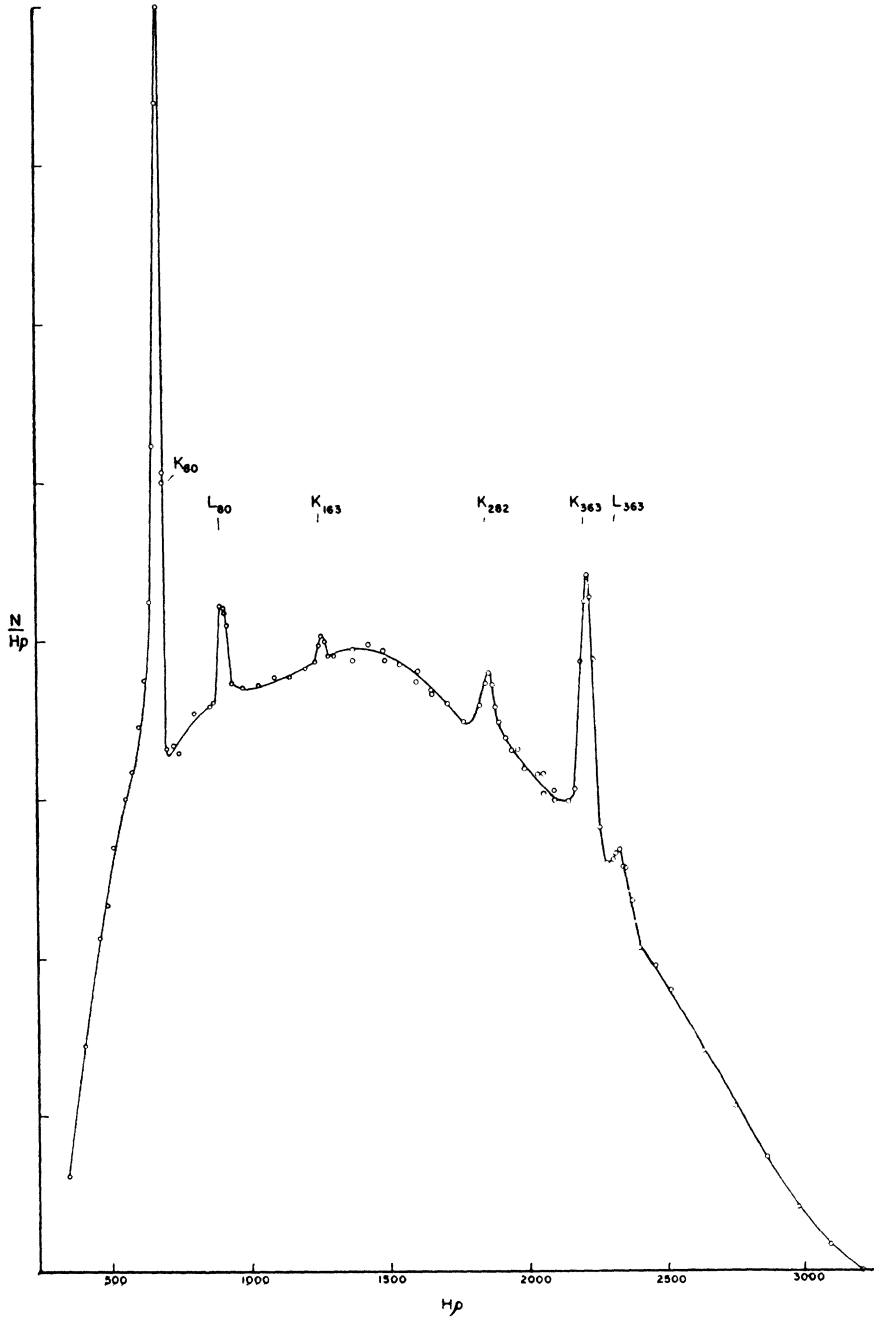


FIG. 7. Beta-ray spectrum of iodine 131.

tetrachloride. The carbon tetrachloride layer was washed several times, after which the iodine was reduced to iodide and precipitated as AgI. The beta-ray source was the unpurified "carrier free" sample.

The distribution of photoelectrons from lead, indium, and copper was studied in the magnetic lens spectrometer. The curve, for which the lead radiator was used, is shown in Fig. 6. The various lines due to the gamma-rays at 637, 363, 282, and 80 kev are shown. On the original curves a very weak line, or bump, which could be attributed to a gamma-ray at 163 kev was also seen. It will be noted that, with the lead radiator, only the line caused by the ejection of photoelectrons from the $L$-shell of lead by the 80-kev line could be observed, and this was only slightly above the counter window cut-off. With the indium radiator, on the other hand, the line due to the ejection of a photoelectron from the $K$-shell of indium could be observed, as well as the other lines. The energies of the lines of $I^{131}$, as determined from the photoelectrons from the various radiators as well as from the position

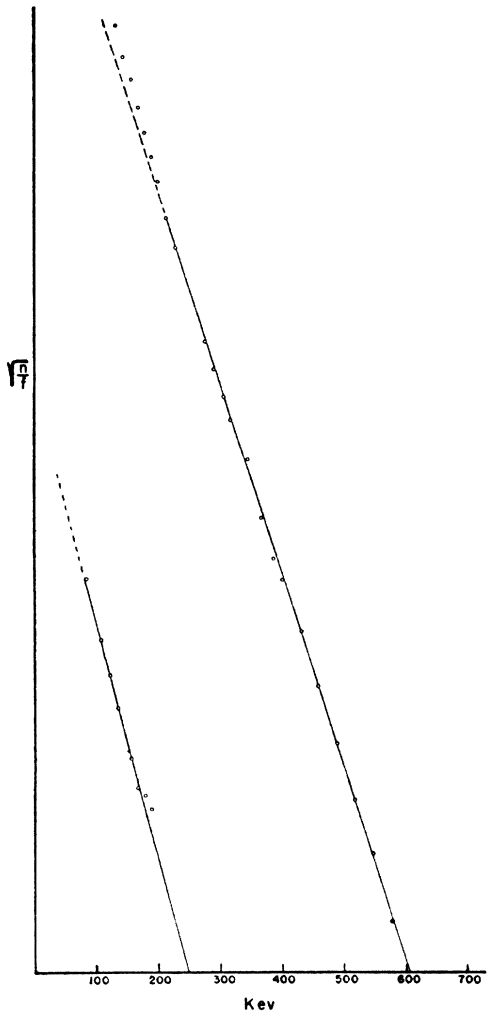


FIG. 8. Fermi plot of the beta-ray spectrum of iodine 131.

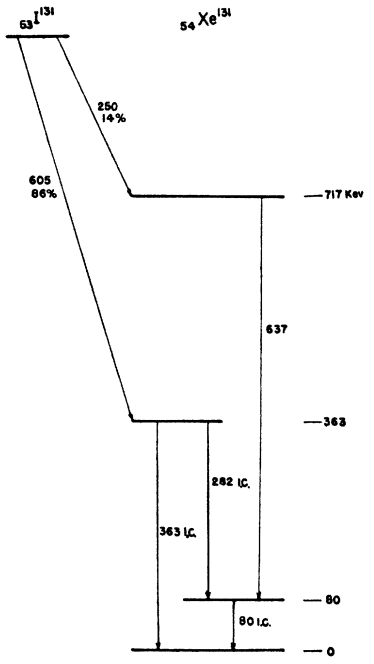


FIG. 9. Proposed energy level diagram for the decay of iodine 131.

of the internal conversion lines, are 80±2, 282±1, 363±2, and 637±2 kev. These values compare extremely well with those given by Lind, Brown, Klein, Muller, and DuMond,[16] using a curved crystal spectrometer, who obtained 80.133±0.005, 284.13±0.1, 364.18±0.1 kev.

The beta-ray spectrum was then measured, using a source of evaporated "carrier free" solution having a surface density of about 0.5 mg/cm² mounted on a Zapon lacquer film of 0.05 mg/cm² surface density.

The results of the measurement are shown in Fig. 7, in which $N/H\rho$ is plotted against $H\rho$. Internal conversion lines corresponding to gamma-rays at 80, 282, and 363 kev are clearly seen. In addition, there is a line corresponding to a gamma-ray at 163 kev. No internal conversion electrons were found for the line at 637 kev.

The decay of this source has been followed for about two months (approximately seven half-lives for the 8.0-day iodine). During this time, the $K$ internal conversion peak for the 363-kev line has decreased by a factor of approximately 1/128 of its original value, while that due to the 163-kev line has decreased by a significantly smaller amount (see note added in proof).

A Fermi plot has been made of the beta-ray spectrum, using an approximation for the Coulomb correction factor, $F(Z,\epsilon)$, given by Bethe and Bacher,[17] for an element with this atomic number. The results are shown in Fig. 8. The end point is at 605±5 kev with another lower energy group at 250±30 kev. The high energy group contains 86 percent of the electrons and the other 14 percent.

[16] Lind, Brown, Klein, Muller, and DuMond, Phys. Rev. **75**, 1544 (1949).

[17] H. A. Bethe and R.'F. Bacher, Rev. Mod. Phys. **8**, 194 (1936). See also C. Longmire and H. Brown, Phys. Rev. **75**, 264 (1949).

Using the values of the energies of beta- and gamma-rays as determined in this paper, the energy level scheme shown in Fig. 9 has been constructed. Energy-wise, there is excellent agreement among all the components of the scheme. The level diagram offered here differs from that of Metzger and Deutsch[13] in putting the 637-kev gamma-ray in cascade with the 80-kev line. Indeed this is required by the new determination of the energy of the low energy group. The branching ratio for the two beta-ray groups is the same as that of Metzger and Deutsch. The relative intensities of the lines were calculated with the help of the Gray curves and yield the following values: $I_{637}=14.2$, $I_{363}=82.5$, and $I_{282}=3.7$ quanta per hundred disintegrations. The ratio $I_{637}/(I_{363}+I_{282})=14.2/86.2$ agrees very well with the ratio of the intensities of the two beta-ray groups. Making use of the proposed disintegration scheme, the relative intensity of the low energy line should be $I_{80}=I_{637}+I_{282}=17.9$ quanta per hundred disintegrations.

The internal conversion coefficients of the lines at 80, 282, and 363 kev have been calculated and are given in Table II together with the ratio $N_K/N_L$, in those cases in which this quantity could be determined. A search was made for internal conversion electrons connected with the line at 637 kev but none could be found.

This research was assisted by the joint program of the ONR and the AEC. The authors wish to thank Professor L. L. Merritt, of the Department of Chemistry, for valuable help with the chemical separations.

*Note added in proof.*—Professor K. Siegbahn has informed us in a private communication that he has also investigated the spectrum of $Sb^{125}$. He has found all of the lines found by us except that at 0.125 Mev and in addition a line at 0.035 Mev. The energies of the lines determined by both investigations agree to better than 5 percent.

In regard to the 165 kev line observed in $I^{131}$, Brosi, DeWitt, and Zeldes (Phys. Rev. **75**, 1615 (1949)) have shown that a metastable $Xe^{131}$, of about 12 day half-life, grows from $I^{131}$. This substance emits an internally converted gamma-ray of energy 165 kev. The exact position of this line in the level scheme must await further investigation.

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# Neutron Cross Sections at 115 ev and 300 ev—I

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Total neutron cross sections for a number of elements were measured at 115 ev and 300 ev with an energy resolution of approximately 10 percent. The cross sections were separated into two parts: a resonance cross section and an asymptotic cross section. The first cross section represented the effect of a neutron resonance in the material studied overlapping the detector. The second cross section was identified either as the potential scattering cross section, or a minimum cross section in the neighborhood of a resonance.

## I. INTRODUCTION

MANY neutron cross sections as a function of neutron energy have been made using instruments having low resolution above 100 ev. It is the purpose of this paper to describe a series of measurements of total neutron cross sections made at two specific energies, but with the high resolution provided by the resonance scattering of Co[1] and Mn.[2] These materials resonantly scatter neutrons at 115 ev and 300 ev respectively, and have therefore been used to detect neutrons at these energies.

## II. APPARATUS AND FLUX CONDITIONS

The equipment used was constructed in 1946–47 under the direction of Alexander Langsdorf, Jr.[1,3] It consisted of an annular enriched $BF_3-4\pi$ proportional neutron counter through which a collimated beam of cadmium filtered neutrons from the Argonne heavy water pile could pass. The neutrons were conducted through the center of the chamber in an evacuated tube (see Fig. 1) and gave an appreciable counting rate only when a scattering foil (termed the "detector") was placed in the center of the chamber transverse to the beam. Due to the presence of a paraffin reflector the counter sensitivity fell off logarithmically with neutron energy (from ~13.5 percent at thermal energies to ~1.7 percent at mean fission energies).

The cadmium filtered neutron flux from the pile obeyed the usual $dE/E$ distribution, but because of the particular way in which the chamber sensitivity varied with neutron energy, the flux was regarded as $dE/E^{1.12}$. That is, a flat detector ($d\sigma_s/dE\simeq 0$) such as Be or C provided a counting rate *vs.* neutron energy which followed a $dE/E^{1.12}$ distribution. A graphical analysis of the experimentally determined sensitivity function ($a-b\log E$) showed that the effective number of natural logarithmic cycles in the neutron spectrum from a flat detector was 8.3. This was used to obtain the power function given above.

Assuming a different sensitivity function of the form

[1] S. Harris, A. Langsdorf, and F. Seidl, Phys. Rev. **72**, 866 (1947); Wu, Rainwater, and Havens, Phys. Rev. **71**, 174 (1947).
[2] M. Goldhaber and A. Yalow, Phys. Rev. **69**, 47 (1946); N. Barbre and M. Goldhaber, Phys. Rev. **71**, 141 (1947); Seidl, Harris and Longsdorf, Phys. Rev. **72**, 168 (1947); Rainwater, Havens, Wu, and Dunning, Phys. Rev. **71**, 65 (1947).
[3] A. Langsdorf, Jr., to be published in Rev. Sci. Inst.