Disintegration of Sb^{124}†

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The radioactive decay of Sb^{124} has been reinvestigated in the large magnetic spectrometer and with scintillation techniques. K and L photoelectron lines are observed for gamma-rays of energy 0.603, 0.641, 0.716, 1.68, and 2.09 Mev. The curved Fermi plot of the highest energy beta-ray group is straightened by a once forbidden correction factor consistent with a general STP beta-interaction for spin change unity. Analysis in this manner gives beta-ray energies and intensities of 2.317 Mev, 21 percent; 1.602, 7 percent; 0.966, 9 percent; 0.61, 49 percent and 0.24, 14 percent. The 0.603-Mev gamma-ray is identified as electric quadrupole. A consistent decay scheme, substantiated by gamma-gamma and beta-gamma coincidences is proposed.

I. INTRODUCTION

THE radioactive decay of Sb^{124} has remained for some time without satisfactory explanation. Early investigations[1,2] showed the presence of a complex beta-spectrum and a number of gamma-rays. It was found, however, that the gamma-rays could not be fitted into a decay scheme consistent with the energies and intensities of beta-groups resulting from an ordinary Fermi analysis of the beta-distribution. More recently it was shown[3,4] that the beta-group of highest energy could be satisfied by the $C_1^{(2)}$ shape[5] predicted uniquely for transitions with parity change and spin change two. Analysis of the beta-distribution on this basis still yielded energy differences inconsistent with the observed gamma-ray energies, as was pointed out at that time.

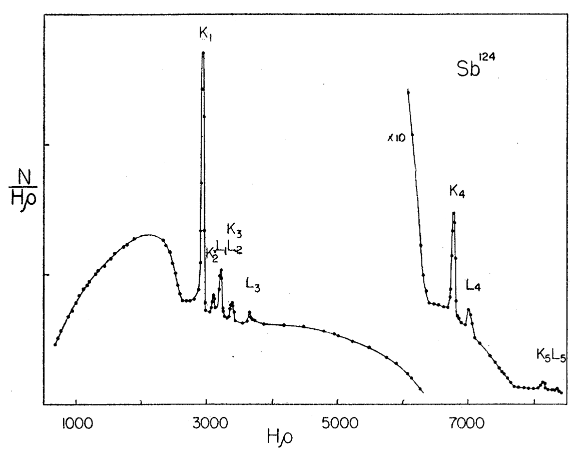

FIG. 1. Photo- and Compton electron spectrum of Sb^{124} from a 10-μg/cm^2 Pb radiator.

Furthermore, studies of angular correlation[6–8] between the highest energy beta-group and the subsequent gamma-ray gave results in disagreement with the spin change two suggested by the $C_1^{(2)}$ shape. A successful attempt was made[9] to fit the angular correlation data and the observed beta-distribution by assuming a pure tensor beta-interaction. A parity change and spin change one were assumed and the ratios of the various nuclear matrix elements involved were used as adjustable parameters. However, since no complete analysis resulting in a satisfactory decay scheme had been carried out and since there now seems to be evidence for a mixed beta-interaction,[10] a re-examination of the problem seemed desirable.

II. EXPERIMENTAL METHOD

The beta-rays and conversion electrons from the gamma-rays were investigated in the large, shaped magnetic field spectrometer.[11] A side window G-M counter was used as detector. The Nylon window was 0.0002 inch thick, resulting in constant transmission of electrons above about 60 kev.

Chemistry was performed on the Sb^{124} source obtained from Oak Ridge. A uniform 2.54 by 0.8-cm beta-source was prepared by thermal evaporation of Sb_2S_3 in vacuum. An aluminum foil of 0.18 mg/cm^2 was used as backing to insure against electrostatic charging of the source. The gamma-source consisted of Sb_2S_3 contained in a 2.54 by 0.6-cm copper box. The walls of the box were sufficiently thick to stop Sb^{124} beta-rays and a 10 mg/cm^2 Pb converter was evaporated on the front face. With these geometries the momentum resolution was one percent.

The scintillation apparatus consisted of two similar channels and a coincidence circuit. Commercially prepared cylindrical NaI(Tl) crystals were employed with RCA-5819 or DuMont K-1177 photomultiplier tubes. A thin (0.05-cm) stilbene crystal was used for beta-

† Assisted in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission, and by a grant from the Frederick Gardner Cottrell Fund of the Research Corporation.

[1] Mitchell, Kern, and Zaffarano, Phys. Rev. **73**, 1142 (1948).
[2] C. S. Cook and L. M. Langer, Phys. Rev. **73**, 1149 (1948).
[3] Langer, Moffat, and Price, Phys. Rev. **79**, 808 (1950).
[4] D. R. Hutchinson and M. L. Wiedenbeck, Phys. Rev. **88**, 699 (1952).
[5] The notation is that of H. M. Mahmoud and E. J. Konopinski, Phys. Rev. **88**, 1266 (1952).
[6] E. K. Darby and W. Opechowski, Phys. Rev. **83**, 676 (1951).
[7] M. Deutsch and D. T. Stevenson, Phys. Rev. **83**, 1202 (1951).
[8] Kloepper, Lennox, and Wiedenbeck, Phys. Rev. **88**, 695 (1952).
[9] M. Morita and M. Yamada, Prog. Theoret. Phys. **8**, 449 (1952).
[10] E. J. Konopinski and L. M. Langer, *Annual Reviews of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Volume 2.
[11] L. M. Langer and C. S. Cook, Rev. Sci. Instr. **19**, 257 (1948).

detection. One half-inch thick cylindrical Lucite light pipes were machined to fit the curvature of the photomultiplier tubes and the light transmitting surfaces were joined with a thin layer of mineral oil. Each channel contained a cathode follower preamplifier, an "Atomic" 204B amplifier, and a single channel pulse-height analyzer of the Johnstone[12] type. For coincidence measurements, the pulses from the two channels were synchronized with a variable delay line, differentiated, and applied to the two control grids of a 6BN6. The coincidence pulse was amplified and passed through a discriminator before being counted. A resolving time of 1.2×10^{-7} second was measured. Different amplifier gains were used for the low and high energy regions and the channels were calibrated with the appropriate 0.661-Mev gamma-ray of Cs^{137} or the 0.87 and 1.12-Mev gamma-rays of Sc^{46}. The high voltage was monitored and maintained to 0.05 percent.

III. RESULTS

Figure 1 shows the conversion electron spectrum. K and L photopeaks from the Pb radiator are observed for gamma-rays of 0.603, 0.641, 0.716, 1.68, and 2.09 Mev. The 0.121-Mev gamma-ray previously reported[2]

TABLE I. Sb^{124} beta- and gamma-rays.

Beta-groups Mev	Percent	log ft	Gamma-rays Mev
2.317 ± 0.005	21	10.5	0.603 ± 0.003
1.602 ± 0.01	7	10.2	0.641 ± 0.005
0.966 ± 0.01	9	9.2	0.716 ± 0.005
$0.61\ \pm0.02$	49	7.8	$1.68\ \pm0.01$
$0.24\ \pm0.02$	14	7.0	$2.09\ \pm0.01$

could be found in neither the photoelectron nor the internal conversion electron distributions and is believed not to be associated with the decay of Sb^{124}.

The beta-ray spectrum as observed and as resolved into groups by a special analysis of the Fermi plot (see Sec. IV) is shown in Fig. 2. The beta-ray and points and intensities are 2.317 Mev, 21 percent; 1.602, 7 percent; 0.966, 9 percent; 0.61, 49 percent; and 0.24, 14 percent. The thin evaporated source and grounding support resulted in complete resolution of the K and L internal conversion lines corresponding to the 0.603-Mev transition. Comparison of the areas of the total beta-spectrum (see decay scheme of Fig. 7) and of the lines yields an internal conversion coefficient of 3.4×10^{-3} and $K/(L+M)$ ratio of 7.9. These values are consistent only with an electric quadrupole transition, in agreement with the conclusion of Metzger[13] and Hutchinson.[4] Beta- and gamma-ray energies are summarized in Table I.

The gamma-ray spectrum obtained with a single channel scintillation spectrometer is shown in Fig. 3.

[12] C. W. Johnstone, Nucleonics 11, No. 1, 36 (1953).
[13] F. R. Metzger, Phys. Rev. 86, 435 (1952).

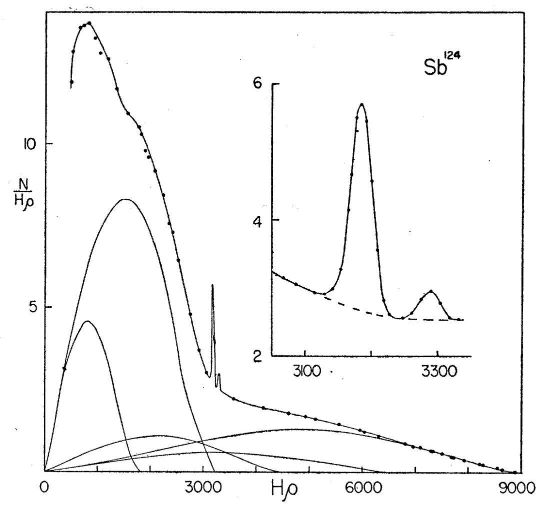

FIG. 2. Beta-spectra and internal conversion lines of Sb^{124}. The inner groups are obtained from the Fermi plot analysis.

Photopeaks from 0.603-, 1.68-, and 2.09-Mev gamma-rays are clearly indicated. The Compton peaks of the 0.603- and 1.68-Mev gammas are at bias settings of 100 and 340, respectively. The broadening above the base of the 0.603-Mev photoline is caused by pairs from the 1.68-Mev gamma, as well as the presence of weak 0.641- and 0.716-Mev gamma-radiation. A weak pair peak from the 2.09 gamma is present at about 250 bias setting.

The solid circles of Fig. 4 show the gamma-gamma coincidence spectrum. One channel was set on the 0.603-Mev photopeak and the high energy region was scanned by the second channel. A larger crystal (1 in.$\times$1 in. diameter) was used for the scanning detector. Although the resolution thus was reduced (compare Fig. 3), the similarity of the coincidence spectrum with that of the high energy channel alone (crosses) clearly indicates that both the 1.68- and 2.09-Mev gammas are in coincidence with the 0.603-Mev gamma. This confirms the recent work of Johansson

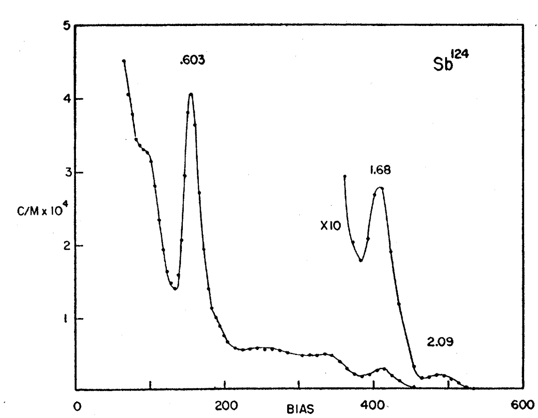

FIG. 3. Gamma-ray spectrum of Sb^{124} from scintillation spectrometer.

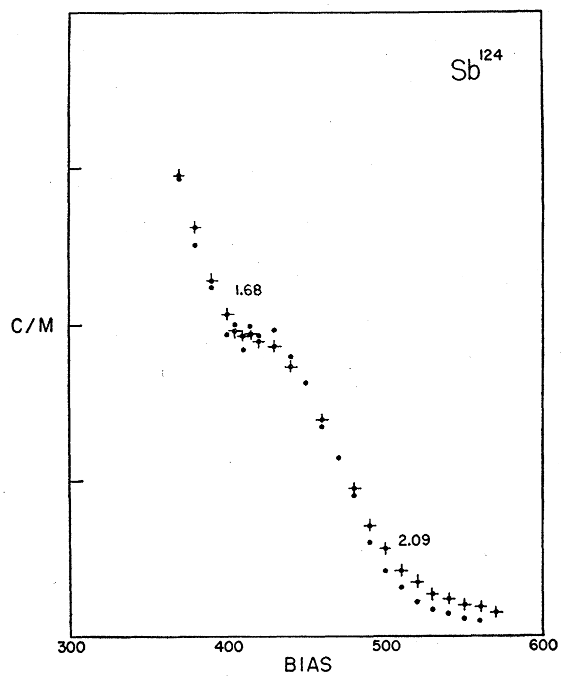

FIG. 4. Gamma-spectrum in coincidence with 0.603-Mev photo line. The crosses are obtained with a single channel. Curves are normalized at bias setting of 200.

and Almquist.[14] The higher level of the singles spectrum above bias 500 is caused by combination pulses of the 0.603-Mev gamma with those of energy 1.68 and 2.09 Mev. Such combination pulses are absent in the coincidence spectrum because the 0.603-Mev gamma and the high energy ones must enter different crystals in order to cause coincidences. The singles level in this region was found to vary as the square of the solid angle, as would be expected for combination pulses. The gamma-gamma coincidences were verified by keeping the fixed channel on the 1.68-Mev photopeak. The photopeak and Compton peak of the 0.603-Mev gamma were obtained as coincidences.

Beta-gamma coincidences were measured as a function of beta energy by interposing aluminum absorbers between the source and beta-detector. The data obtained with the gamma-channel set on the 1.68-Mev photopeak indicate that the 0.61-Mev, 49 percent beta-group is the only one in coincidence with this gamma.

IV. DISCUSSION OF BETA-SPECTRA

The high comparative half-lives for all beta-groups clearly indicate that the transitions are once forbidden and probably also ΔL forbidden. As was pointed out in Sec. 1, the shape of the highest energy beta-group is consistent with the correction factor $C_1^{(2)}$ predicted for $\Delta I=2$, *yes*. However, since this assignment results in no satisfactory decay scheme, it is obviously desirable to find another correction factor which will explain the spectrum. The possibility of spin change zero was eliminated by the absence of transitions directly to the Te^{124} ground state. The absence of detectable numbers of transitions between ground states places a lower limit of $\log ft\approx 14$ for this transition. This is completely inconsistent with the values of $(W_0^2-1)ft=10^{10}$ observed for such transitions with $\Delta I=2$, *yes*. Therefore, a parity change and spin change one were assumed. Mahmoud and Konopinski[5] have given strong evidence for a beta-interaction of the mixed form *STP*. In the case of $(\alpha Z)^2\ll 1$ they give for the correction factor:[15]

$$C_1=G_T^2\left|\int\beta\boldsymbol{\sigma}\times\mathbf{r}\right|^2\left\{\left[\frac{\alpha Z}{2R}(1+x_i-y_i)+\frac{(1+x_i)p^2}{3W}+(1-x_i)\frac{q}{3}\right]^2+\left(\frac{(1+x_i)p}{3W}\right)^2+\frac{(1-2x_i)^2p^2}{18}+\frac{(1+2x_i)^2q^2}{18}+U\frac{p^2+q^2}{12}\right\},$$

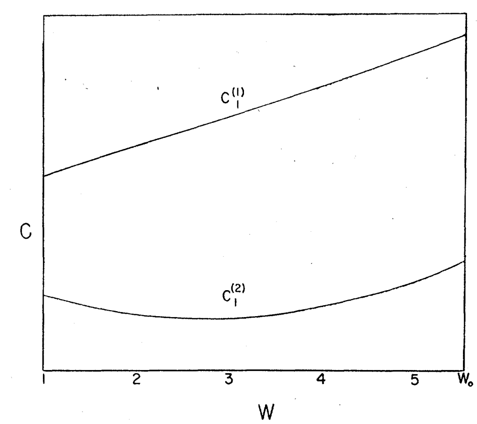

FIG. 5. Once forbidden correction factors $C_1^{(1)}$ and $C_1^{(2)}$.

where $U=\sum|B_{ij}|^2/|\int\beta\boldsymbol{\sigma}\times\mathbf{r}|^2$. It now remains to evaluate the quantities U, x_i, y_i, which appear as ratios of the various nuclear matrix elements involved. Ahrens and Feenberg[16] have advanced theoretical arguments for the ratios x_i and y_i being of order unity. Furthermore the transitions with $\Delta I=2$, *yes*, for which only the matrix elements B_{ij} contribute, all have ft values large compared to other once forbidden transitions. This may be taken as some indication that the matrix elements B_{ij} may yield, in general, much smaller transition rates than the others here involved. Thus a reasonable approximation for $C_1^{(1)}$ is obtained by taking $x_i=y_i=1$; $U<1$. The energy dependence of the correction factor $C_1^{(1)}$ is shown in Fig. 5, together with the factor $C_1^{(2)}$ for comparison in arbitrary units.

[14] S. A. E. Johansson and S. Almquist, Arkiv Fys. **5**, 427 (1952).

[15] A more precise calculation making use of the tables of Rose, Perry, and Dismuke, Oak Ridge National Laboratory Report ORNL-1459, yields essentially the same result for this case.

[16] T. Ahrens and E. Feenberg, Phys. Rev. **86**, 64 (1952).

Figure 6 shows the Fermi plots corrected by these factors. It is clearly evident, as indicated by the arrows, that the factor $C_1^{(1)}$ produces a straight line over a longer energy interval than the factor $C_1^{(2)}$. A slightly higher extrapolated end point is also obtained. The analysis of the beta-ray spectrum was completed assuming that the inner groups can be represented by the allowed shape. This assumption seems reasonable because the 1.602- and 0.966-Mev groups are the only ones which might have forbidden shapes. Since the intensity of these groups is very weak, their exact shape does not seriously effect the analysis. This treatment of the beta-spectra gives differences in end points for all the components which agree remarkably well with the energies of the observed gamma-rays.

V. CONCLUSION

There is now sufficient evidence to prepare the decay scheme of Fig. 7. Beta-gamma coincidences establish that only the 0.603-Mev gamma-ray follows the highest energy beta-group. The beta-ray energies indicate that all the other gammas follow the inner groups and lead to the 0.603-Mev level in Te^{124}. This is further substantiated by the observation of gamma-gamma coincidences between the 0.603- and the 1.68- and 2.09-Mev gammas individually and by beta-gamma coincidences of the 1.68-Mev gamma- with the 0.61-Mev beta-group.

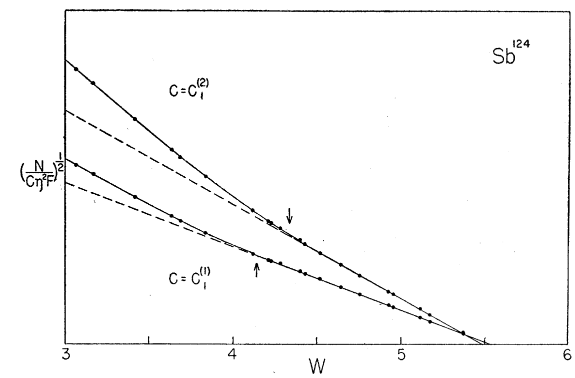

FIG. 6. Fermi plots corrected by the factors $C_1^{(1)}$ or $C_1^{(2)}$.

Te^{124}, being an even-even nucleus, presumably has a ground state with zero angular momentum and even parity. Now, since the 0.603-Mev transition is identified as electric quadrupole, the 0.603-Mev level in Te is assigned even parity and spin 2. The highest energy beta-transition of $\Delta I=1$, *yes* shows then that the ground state of Sb^{124} must have odd parity and spin 3. Unit spin for this state would result in an appreciable number of beta-transitions directly to the ground state of Te^{124}.

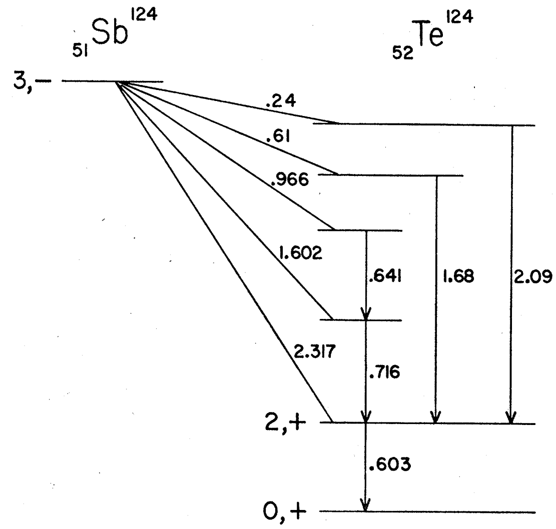

FIG. 7. Decay scheme for Sb^{124}.

Such transitions are not observed. On the basis of the single particle shell model, odd parity for the Sb^{124} ground state is justified by the availability of the $h_{11/2}$ state for one of the odd nucleons.

This decay scheme is consistent with all available evidence, with the possible exception of the beta-gamma angular correlation data. Since no theoretical prediction of beta-gamma angular correlation is available for mixed interactions, comparison with the data is not possible.

This analysis of the Sb^{124} data suggests that certain other disintegrations should be reinvestigated. There is conflicting evidence, similar to that for Sb^{124}, in other cases where the beta-spectrum has been identified as a transition of $\Delta I=2$, *yes*. Where inner groups are evident so that only a relatively short energy region fits the "unique" shape and where $(\alpha Z/2R)^2$ is not large compared to $(W_0-1)^2$, it is possible that the beta-spectrum may permit explanation on another basis.

The authors are indebted to Mr. H. M. Mahmoud and Professor E. J. Konopinski for clarification on some theoretical questions.

Note added in proof:—Since the completion of this work, it has come to our attention that F. R. Metzger (Indiana University Conference on Nuclear Spectroscopy and the Shell Model) has evidence which suggests that the 0.64-Mev and 0.72-Mev gamma-rays are not in coincidence. If this is indeed so, then the detailed decay scheme must be more complicated and the apparent good agreement which we found between the gamma-ray energies and the differences between beta-ray end points may be somewhat fortuitous.