The Disintegration of Ag^{110}

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The disintegration of Ag^{110} has been investigated using spectrometer and coincidence technique. The radiation contains a great number of β- and γ-components and the disintegration scheme is complicated. Four β-components and ten γ-rays have been found and their energies and intensities measured. The 225-day activity is due to an isomeric level in Ag, separated 116 kev from the 24-sec. ground level. The internal conversion coefficient of the γ-ray at 656 kev has been determined to be 2.5×10^{-3} by means of coincidence spectrometry. The disintegration scheme is discussed.

IN a recent communication[1] the author has reported some measurements on the β- and γ-radiation from long-lived Ag^{110} (225 days). It is the purpose of this paper to give a more complete description of the experiments and also to try to formulate a consistent disintegration scheme, which is unusually complicated due to the complex radiation.

β- AND γ-SPECTRUM

The soft part of the β-spectrum was investigated in a lens spectrometer having a G-M tube with a thin Nylon window and adjusted for high transmission and moderate resolution so that a thin sample could be used. The spectrum was then joined together with the harder part of the spectrum, investigated with a large double focusing spectrometer ($\rho=50$ cm) with high resolution. Figure 1 shows the complete spectrum, and Fig. 2 an enlarged part of the spectrum, where a number of internal conversion lines occur. If this spectrum is compared with the corresponding photo-electron (and Compton electron) spectrum as shown in Fig. 3 (obtained with a 3.7μ lead converter) one finds that the γ-radiation consists of 10 different γ-lines of measurable intensities. The energies of the γ-rays vary from 116 kev to 1516 kev. The results are shown in Table I.

Both the β-spectrum (β) and the photo-electron spectrum (γ) have been obtained with small statistical errors, the spectrometer investigations being extended over several weeks. The measurements have been repeated many times, especially over the part where most of the lines occur. All except two of the γ-lines appear in both spectra, in some cases as both K and L lines (conversion lines or photo-lines). The energy values, given in Table I are thus computed as the mean values of, in some cases, several independently obtained values of the γ-energies. (For instance the γ-energy of 885 kev is a mean value of four independent determinations i.e., from the K and L photo-lines and K and L internal conversion lines.) Any uncertainties in the energy determinations are therefore mostly due to difficulties of correcting accurately for straggling effects in the sample. The errors are smaller than 0.5 percent.

The intensities of the internal conversion lines are as expected small (α_K of the order of 10^{-3}) because of the relatively low Z value and the high energies. The softest line at 116 kev is, however, strongly converted. Furthermore the intensity ratio between the K and L conversion lines makes it quite probable that this line is due to a transition from a metastable state. The measured ratio between the intensities of the K and L lines is ~1.3. To get at least some estimate of the half-life of the corresponding state, one can use the computations by Hebb and Nelson.[2] Assuming the radiation to be of essentially electric multipole type, the N_K/N_L ratio obtained for the energy in question is consistent with an effective l-value of 4. If this value is used in the formulas by Segrè-Helmholz[3] the half-life of the state can be estimated to be of the order of days. $l=5$ would give 10^4 years, which however cannot be excluded because of the small intensity of the isomeric transition. Since these formulas necessarily are of quite approximate nature (a deviation of one or two orders of magnitude may still be allowed), there are reasons to believe that the 116 kev level belongs to the 225-day activity of silver.

Since Ag^{110}, produced by slow neutron bombardment of Ag^{109}, is known to give two different half-lives of 225 days and 24 sec.,[4] the simplest explanation of this isomerism is to assume* that the 24-sec. level is the ground state of Ag^{110}. The 24-sec. activity of Ag^{110} is a β-emitter with an upper limit of 2.6 Mev (abs. Al)[5] or 2.8 Mev (cloud chamber).[6] If the 225-day activity partly decays via the 24-sec. ground level of the same nucleus, one would then expect to find also a β-component of the above energy in the radiation. Actually a very small intensity β-component of high energy was found (about 3 percent of the main spectrum), showing itself as a small background in the investigating of the internal conversion spectrum (Figs. 1 and 2). Taking a very strong sample and using a high transmission lens this component was investigated in more detail and treated by Fermi analysis. The upper limit was found

[1] K. Siegbahn, Phys. Rev. 75, 1277 (1949) (cf. also references given in this paper).

[2] M. Hebb and E. Nelson, Phys. Rev. 58, 586 (1940).

[3] A. Helmholz, Phys. Rev. 60, 415 (1941).

[4] G. T. Seaborg and I. Perlman, Rev. Mod. Phys. 20, 611 (1948).

* It is quite unlikely that the isomeric transition takes place after the β-emission since the following nucleus (Cd^{110}) contains an even number of protons and neutrons, which would violate the general rule found by Mattauch (Zeits. f. Physik 117, 246 (1941)).

[5] O. Hirzel and H. Wäffler, Helv. Phys. Acta 19, 214 (1946).

[6] Gaerttner, Turin, and Crane, Phys. Rev. 49, 793 (1936).

to be 2.86 Mev and the spectrum is complex. The Fermi plot deviates from a straight line at 2.12 Mev, which would be the energy of the β-component next to the one at 2.86 Mev in energy.

The main part of the continuous β-spectrum was also treated by Fermi analysis. There is one strong β-component with an upper limit of 87 kev (abundance $\sim$58 percent). The rest of the spectrum consists of essentially one component with the upper limit 530 kev (abundance $\sim$35 percent), but the Fermi plot is not completely a straight line, which might indicate the presence of one or several β-components of very low intensities. The Fermi analysis was unable to give further information on these points.

INTENSITIES OF γ-LINES

The relative intensities of the γ-rays may be estimated from the photo-electron spectrum for those lines, which are completely resolved from each other and when there is no doubt about the form of the Compton electron background. These conditions are rather well satisfied for the lines at 656, 885, 935, 1389, and 1516 kev. These γ-lines happen to be the strongest in the γ-spectrum and are therefore of special importance for the disintegration scheme. The relative γ-intensities have been estimated by dividing the photo-lines by the photo-cross section at the corresponding energies. The result is given in Table II.

According to Table II the γ-lines at 656 and 885 kev

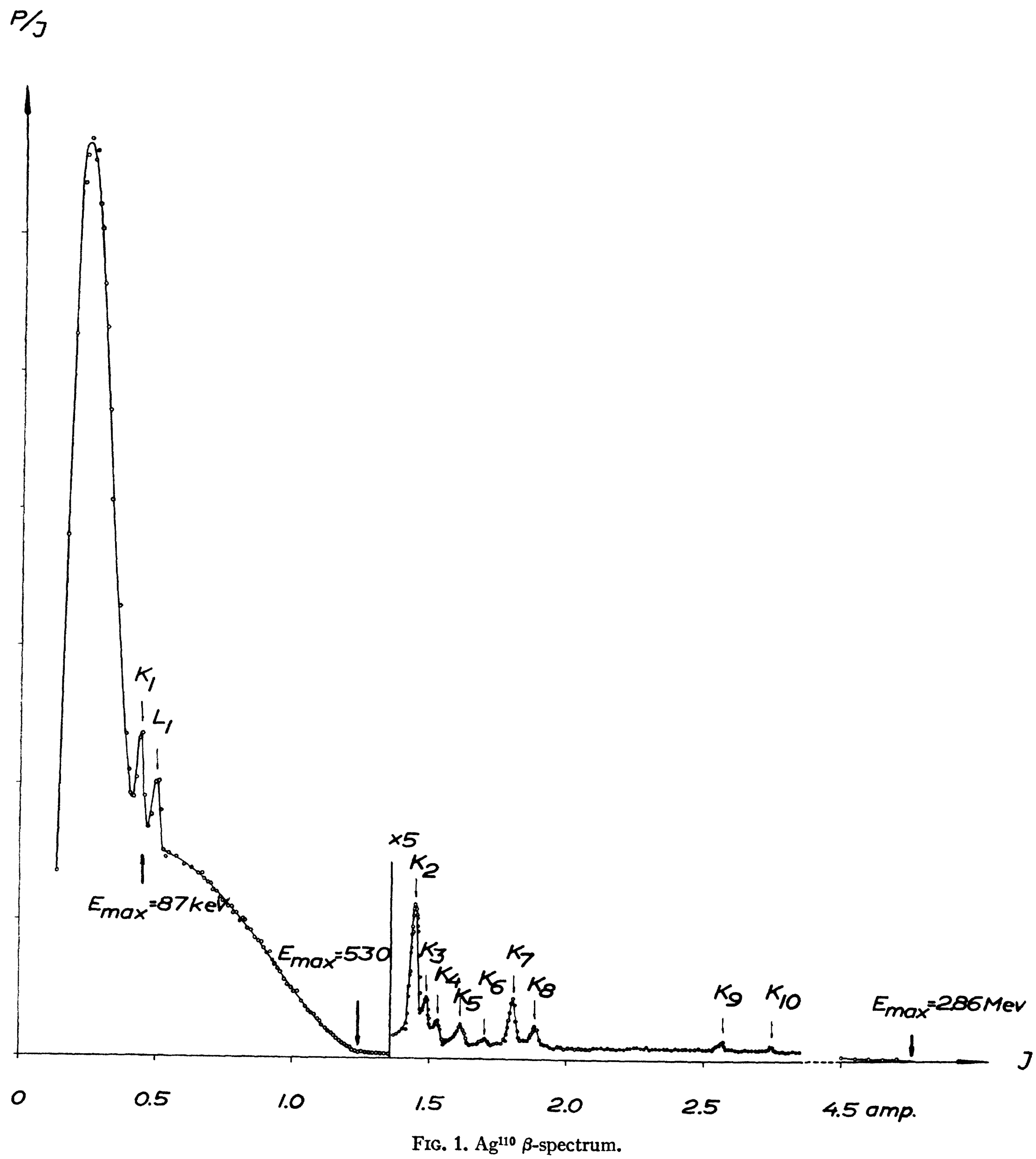

FIG. 1. Ag^{110} β-spectrum.

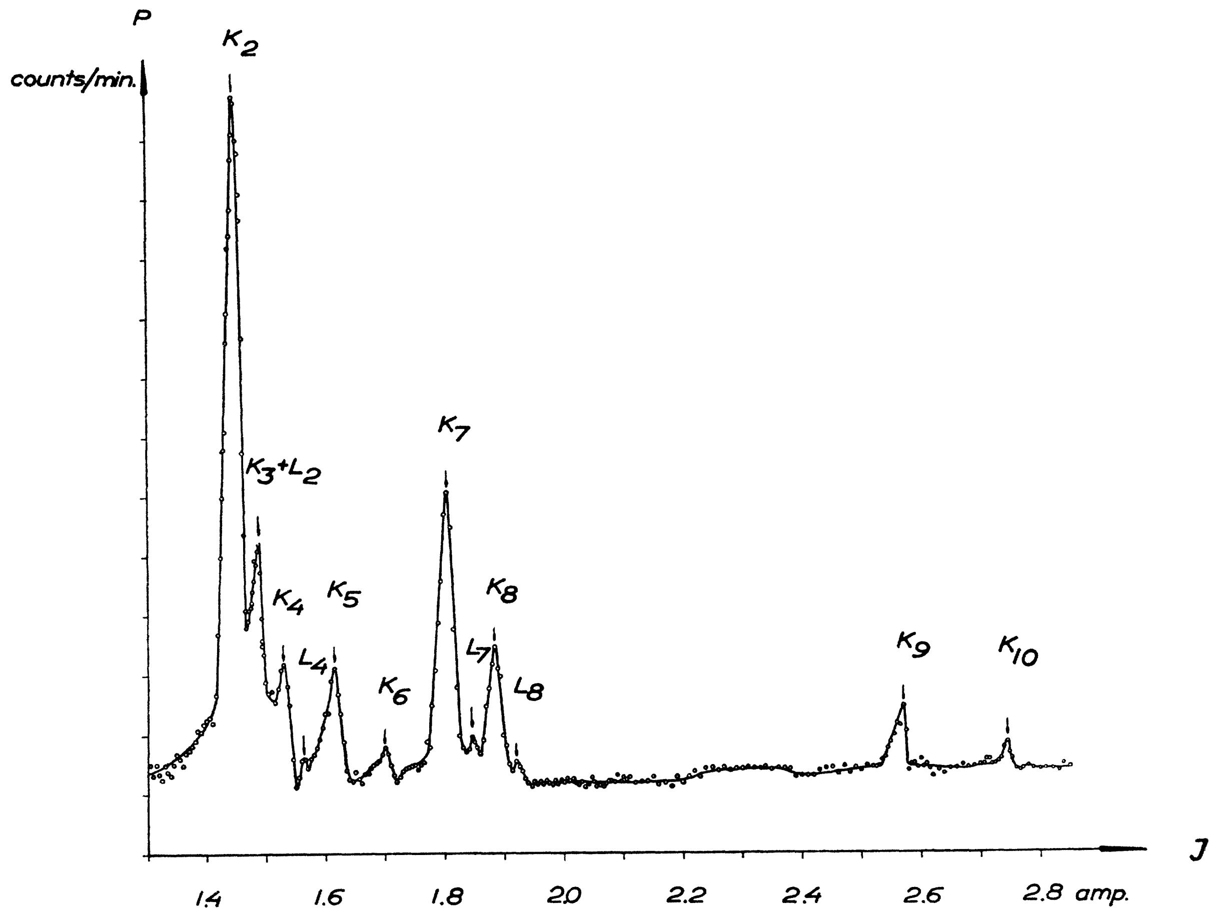

FIG. 2. Enlarged part of internal conversion spectrum of Ag^{110}.

are the most predominant transitions, the other being of less than half their intensities.

The intensities of the remaining part of the γ-rays are more difficult to estimate from the closely spaced photo-lines, since they appear on the slope of a number of Compton electron distributions. This latter spectrum could be taken separately (without lead foil) and then subtracted from the total spectrum but this would introduce great uncertainties since both the height and the form of the Compton spectrum change when the lead foil is removed. Some estimate can be made from the internal conversion spectrum if for simplicity it is assumed that the lines are of the same multipole order. This seems approximately to be the case with the lines in Table II. Under this special assumption one would conclude from the energy dependence of the internal conversion coefficients[7] that the lines at 676 kev (superimposed on the L line of the 656-kev γ-line), 706-kev and 759-kev lines are of almost the same intensity (the 759-kev line being somewhat stronger) and roughly equal to that of the 1516-kev line. The line at 814 kev could have about a third of this intensity.

[7] S. Dancoff and P. Morrison, Phys. Rev. 55, 122 (1939).

INTERNAL CONVERSION COEFFICIENT FOR THE 656-KEV γ-LINE

If the strong γ-line at 656 kev is emitted after all β- and γ-components, the internal conversion coefficient, α, can be determined by comparing the area of the line with the total β-spectrum. One then arrives at the value $\alpha_{656}=2.5\times 10^{-3}$. This value for the coefficient can be obtained in another way. If coincidences ($C_{\beta e^-}$) between conversion electrons (e^-) focused in a spectrometer and the total β-spectrum (β) (β-tube immediately behind the sample) is investigated over the line, α can be computed, provided the efficiency (essentially the spectrometer transmission) of the e^- G-M-tube is known. The efficiency (e_{e^-}) is most easily determined from a βe^- coincidence line having a previously known internal conversion coefficient. Using the relation

$$C_{\beta e^-}/N_\beta = e_{e^-}\cdot\alpha$$

(N_β = counts in β-tube behind the sample) e_{e^-} can then be computed.

Figure 4 shows the K and $L_{\beta e^-}$ coincidence lines from the 411-kev γ-ray of Au^{198}. The spectrometer used was

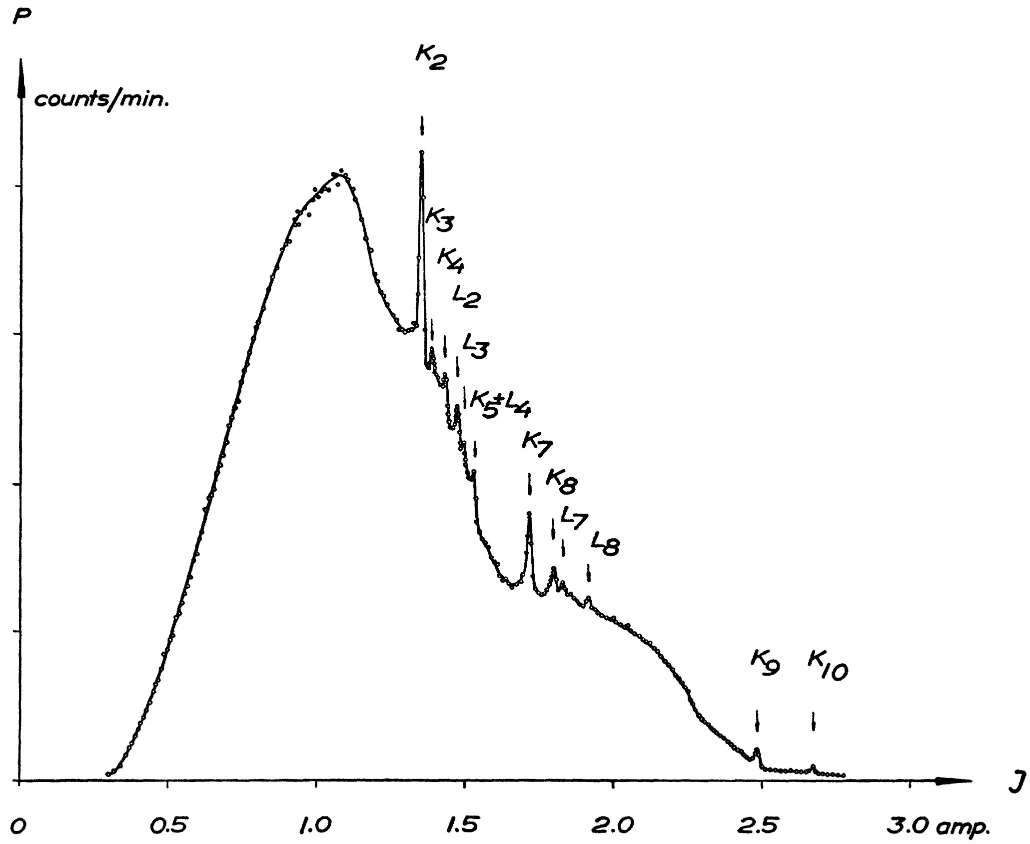

FIG. 3. Secondary electron spectrum of Ag^{110} from a 3.7μ lead converter.

of a high transmission "intermediate image" lens type,[8] which is especially well suited for this purpose, since the small coincidence effect is proportional to the transmission. From the top of the K coincidence line e_e- is determined once and for all. This value is then dependent on the knowledge of α_K for the 411-kev γ-ray. According to the two most recent spectroscopic measurements[9,10] α_K is 3.0×10^{-2} and 3.5×10^{-2} respectively. The maximum deviation from the mean value (3.25×10^{-2}) is thus less than 10 percent.

TABLE I. Energies and estimated intensities of the Ag^{110} γ-lines.

γ-line	γ-energy kev	Estimated intensity of γ-ray	Obtained from
1	116	weak (strongly conv.)	β
2	656	strong	β, γ
3	676	weak	β, γ
4	706	weak	β, γ
5	759	weak	β, γ
6	814	v. weak	β
7	885	strong	β, γ
8	935	medium	β, γ
9	1389	medium+	β, γ
10	1516	medium	β, γ

TABLE II. Relative intensities of the main γ-lines of Ag^{110}.

γ-energy in kev	656	885	935	1389	1516
Rel. intensity	100	81	31	33	17

Figure 5 shows the corresponding βe^- coincidence line for the Ag^{110} 656-kev γ-ray. The full curve is the conversion line itself, inserted in the figure for comparison. As can be seen the βe^- coincidences can be brought to fall on the β-line as expected. From the number of coincidences at the top of the line and with the value for e_e- obtained from the previous measurement on Au^{198} one gets $\alpha_K=2.5\times10^{-3}$ for this line. The full agreement with the above value of $\alpha_K(2.5\times10^{-3})$ is of course partly accidental, the experimental errors being around ±15 percent. In the coincidence experiment the window before the β-G-M counter (behind the sample) was not very thin and absorbed a big portion of the soft β-component ($E_{max}=87$ kev) but not so much of the harder one. If the 676-kev γ-line did not follow the whole β-spectrum, but for instance only the soft part, the number of βe^- coincidences would have been much less and thus also the computed value of α_K.

A value of $\alpha_K=2.5\times10^{-3}$ is consistent with a magnetic

[8] H. Slätis and K. Siegbahn, Phys. Rev. **75**, 1955 (1949), and Arkiv. f. Fys. **1**, No. 17, 339 (1949).

[9] K. Siegbahn and A. Hedgran, Phys. Rev. **75**, 523 (1949).

[10] D. Saxon and R. Heller, Phys. Rev. **75**, 909 (1949).

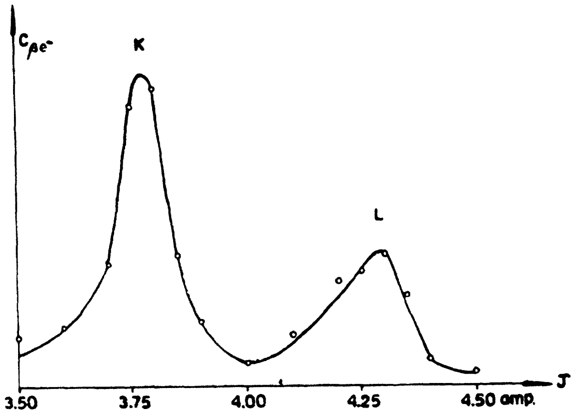

FIG. 4. βe^- coincidence lines of Au^{198} (K and L lines of γ-line at 411 kev).

or electric dipole radiation. According to present existing calculations[7] α_K for electric dipole radiation at this energy is 1.74×10^{-3} and for magnetic 2.74×10^{-3}. Electric quadrupole radiation would give $\alpha_K=5.18\times10^{-3}$.

In the coincidence spectrometer it was further possible to prove experimentally that the 116-kev γ-ray actually was due to a metastable level. The spectrometer resolution was 3 percent so that the K, L, and M lines were resolved. Coincidences were then taken on the lines and on the continuous spectrum around the lines. No βe^- coincidence lines could be found. A small effect due to $\beta\gamma$-coincidences was found between the continuous spectrum and γ-rays counted in the β-tube behind the sample. The effect was the same on the lines and the continuous spectrum. The expected computed coincidence rate if the level were not metastable was about six times the $\beta\gamma$-coincidence effect obtained, which was very far outside any statistical limits of error.

DISCUSSION OF THE DISINTEGRATION SCHEME

Naturally a disintegration scheme, which contains so many β- and γ-components must be expected to be quite complicated, and the scheme proposed here is justified only because it seems to fit the experimental data hitherto obtained.

According to M. Deutsch[11] K-capture constitutes less than 3 percent of all disintegrations, since no K x-rays could be observed. X-rays are of course to be expected because of the presence of the internal conversion lines (particularly those corresponding to the isomeric transition) but according to the above estimates, the intensity of these internal conversion lines is $\lesssim 3$ percent of the total radiation, i.e., consistent with Deutsch's figure. Furthermore positron decay does not occur in any measurable amount since no annihilation radiation can be observed in the photo-electron spectrum.

The scheme shown in Fig. 6 is based on the following arguments:

1. $\beta\gamma$- and $\gamma\gamma$-coincidence measurements

These measurements were performed with calibrated gold γ-tubes. The result for the $\beta\gamma$-coincidence measurements was $C_{\beta\gamma}/N_\beta=(3.62\pm0.20)\times10^{-3}$.

This value was obtained with a 10 mg/cm^2 Al absorber in front of the β-tube in order to absorb the soft component completely. According to the efficiency curve for the γ-tube, the scheme would give (one β-component followed by three γ-rays at 935, 885, and 656 kev) $C_{\beta\gamma}/N_\beta=(3.80\pm0.20)\times10^{-3}$.

The result of the $\gamma\gamma$-coincidence measurements was $C_{\gamma\gamma}/N_\gamma=(1.70\pm0.10)\times10^{-3}$. In this case it is somewhat harder to compare the result with an exact expected value, since all γ-intensities are not accurately known. Some of the transitions, however, are definitely less abundant than others, and with some reasonable assumptions regarding their relative intensities the expected value of $C_{\gamma\gamma}/N_\gamma$ is very likely to be $\sim1.80\times10^{-3}$.

Thus we find that the scheme is consistent with the coincidence measurements. A scheme with essentially two or four γ-rays in cascade instead of three, could not be expected to give agreement with the above results.

2. Energetic considerations

There is no γ-ray which is equal to the well-established difference in energy between the β-components of 87 kev and 530 kev. If the γ-line at 1389 is put after the 87-kev component and the 935-kev γ-ray after the 530-kev component, they end in the same level within the experimental errors. When the two strong γ-lines of 885 kev and 656 kev are put after this level one arrives to a total disintegration energy, which is very nearly the same as that obtained from the knowledge of the hard (but very faint) direct β-transition from the ground state in Ag^{110} ($\tau=24$ sec.) to the ground state in Cd^{110}. The small intensity β-spectrum of 24-sec. Ag^{110} is complex, with another β-component of $E_\beta=2.12$ Mev. This component would have to end at the first excited level in Cd^{110} ($2.86-0.66=2.20$ Mev, i.e., close to the energy

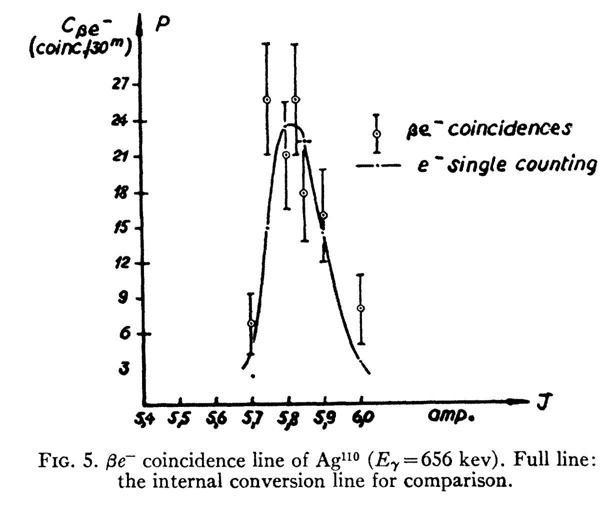

FIG. 5. βe^- coincidence line of Ag^{110} ($E_\gamma=656$ kev). Full line: the internal conversion line for comparison.

[11] M. Deutsch, Phys. Rev. 72, 527 (1947).

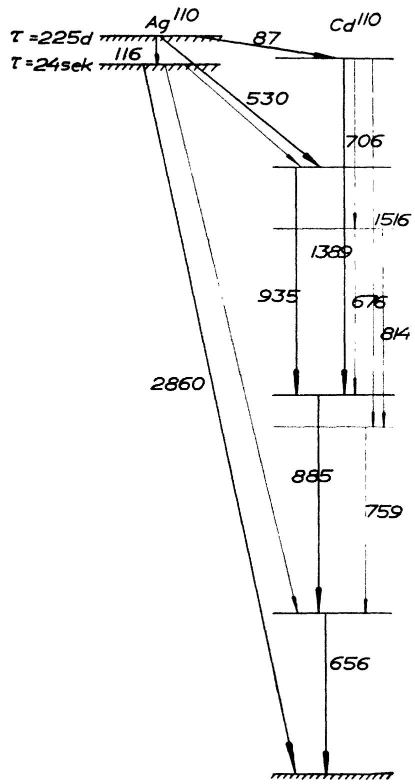

FIG. 6. Disintegration scheme of Ag^{110}, consistent with experimental material.

found above). Since the Fermi analysis offered some possibility for the main spectrum to contain another β-component, except the 87-kev and the 530-kev components, it may occur that a very small proportion of the ground state of Ag^{110} also decays to the level shown in the scheme, though spin considerations make this transition less probable.

The remaining γ-rays have been placed in the scheme according to the following considerations (faint lines in the scheme). Energetically the sum of the γ-rays at 706 kev and 676 kev is inside experimental errors equal to the energy of the γ-ray at 1389 kev and have therefore been put in cascade as an alternative two-step transition. If the 1516-kev γ-ray is assumed to go from the 87-kev level followed by the 759-kev γ-ray, one arrives to the first excited level ($1516+759=2275$; $1389+885=2274$). The one remaining faint γ-ray of 814 kev fits in between two already existing levels.

3. *Intensity considerations*

In the above construction of the levels from the energies of the different γ-rays and β-components intensity considerations have been of important help. As stressed before the intensity estimates are of only approximate nature, and one cannot require the intensity relations in the scheme to fit quantitatively.

The total intensity of the γ-rays leaving the 87-kev β-component is in relative units (see Table II) 67, while the γ-intensity leaving the 530-kev β-component is 31. This has to be compared to the ratio of the two β-components, i.e., 58:35. Furthermore the γ-intensity arriving at the third excited level is 81 (γ-rays at 935, 1389 and 676 kev). Only one γ-ray is leaving this level namely the 885-kev γ-ray. The intensity of this is also 81 according to Table II.

The sum of the intensities of the 1516 kev and the 814 γ-rays is $17+\frac{1}{3}17\sim 22$. The γ-intensity arriving at the first excited level is then $81+22=103$. Only the 656 γ-ray is leaving this level with the intensity 100.

Thus, the intensity relations fit the scheme surprisingly well. Together with the energetic and the additional coincidence data, the scheme describes the disintegration rather well in detail. One can of course not disregard the possibility of the emission of other components of very small intensity, not observed with the present technique. The fact that 7 percent of the β-spectrum did not fit to a straight Fermi plot may indicate the presence of such faint transitions. It is known, however, that deviations from straight lines in the Fermi analysis for forbidden spectra can be expected.

One further point may be briefly discussed here. The *ft.* value of the 2.86-Mev β-component from the 24-sec. level of Ag^{110} is about 10^4 and the transition is certainly allowed. The spin of the Cd^{110} ground state is presumedly zero and since a transition $0\rightarrow 0$ is highly forbidden the spin of the 24-sec. state of Ag^{110} is 1 according to GT selection rules. The spin of the Ag^{109} is known to be $\frac{1}{2}$ and the addition of a slow neutron (for both isomers due to a resonance)[12] will give a spin of 1 or 0 to the nucleus after capture. It is most likely[13] that the neutron cross section connected to the isomer with the spin value, which comes nearest to the nucleus after capture will be the largest. Since the spin of the 225-day Ag must be at least 5 one would expect the 24-sec. cross section to be the largest. This is also the case according to the measurements by Seren, Friedlander, and Turkel,[14] who find the ratio σ 24 sec./σ 225 d to be ~ 47. The assignment of the lower state in Ag^{110} to be due to the 24-sec. isomer is thus consistent with the above picture.

[12] M. Goldhaber, Phys. Rev. **70**, 89 (1946).
[13] E. Segrè and A. C. Helmholz, Rev. Mod. Phys. **21**, 271 (1949).
[14] Seren, Friedlander, and Turkel, Phys. Rev. **72**, 888 (1947).