―
# THE PHYSICAL REVIEW

*A journal of experimental and theoretical physics established by E. L. Nichols in 1893*

SECOND SERIES, VOL. 67, NOS. 11 AND 12 JUNE 1 AND 15, 1945

## Auger Electrons Resulting from *K*-Capture

FRANKLIN MILLER, JR.
*Rutgers University, New Brunswick, New Jersey*
(Received May 10, 1945)

The most intense group of Auger electrons due to x-rays associated with *K*-capture in $Zn^{65}$ would have energies lying in a narrow band within about 300 ev of a maximum value of 7056 ev ($H\rho$284). These would arise from $K-L^2$ transitions in the resulting Cu atom. Electrons from the $K-LM$ transitions would be about $\frac{1}{3}$ as numerous, lying within about 300 ev of a maximum value of 8016 ev ($H\rho$302). The soft electrons which are emitted copiously from $Zn^{65}$ were found to have an absorption limit in collodion of $0.15\pm.03$ mg/cm², approximately 7500 ev. When samples were placed 0.6 to 1.3 cm from the screen of a screen wall-counter filled with $H_2$ at 2 cm Hg pressure, the upper limit (by inspection) was found to be at $H\rho302\pm30$ ($8000\pm1700$ ev). Scattering in the counter gas and absorption in the sample are believed negligible. These data are consistent with the hypothesis that the soft electrons from $Zn^{65}$ are Auger electrons resulting from *K*-capture. Similar results, in less detail, were obtained in deflection experiments with $Fe^{55}$.

WHEN an unstable isotope decays by *K*-capture, the resulting vacancy in the *K*-shell may be filled by an *L*, *M*, ⋯ electron, and the characteristic x-rays of the product atom are emitted.[1] Indeed, one strong proof for *K*-capture has been identification of the atomic number of the atom emitting the x-rays, since if emitted as a result of *K*-capture the energy levels of the *product* atom are involved. It is not necessary, however, that all *K*-capture processes result in emission of an x-ray quantum. By the Auger effect, a radiationless transfer may take place, the single vacancy in the *K*-shell being replaced by two vacancies in the *L*-shell ($K-L^2$ transition), or by a vacancy in the *L* shell and one in the *M* shell ($K-LM$ transition). The energies of the Auger electrons emitted in such transitions depend entirely upon the atomic number of the product atom resulting from *K*-capture.

### EXPERIMENTS WITH $Zn^{65}$

The 250-day isotope $Zn^{65}$ decays by *K*-capture,[1] as well as by emission of positrons of maximum energy[2,3] 0.4 to 0.7 Mev. A $\gamma$-ray of 1.0 Mev is present, but the absence of many fast electrons shows it to be only slightly converted,[4] a result to be expected from the low value of $Z^3$. Compton recoils from the $\gamma$-ray are also observed.[5] Apparently *K*-capture is favored as an alternative process to positron emission, since there is an anomalously high $\gamma/\beta$-ratio, and annihilation radiation is present to an inappreciable extent.[4] Most of the Cu nuclei must be formed in an excited state, giving rise to the $\gamma$-ray. The Cu $K\alpha$

[1] L. W. Alvarez, Phys. Rev. **54**, 486 (1938).

[2] L. DuBridge *et al.*, quoted in J. J. Livingood and G. T. Seaborg, Rev. Mod. Phys. **12**, 30 (1940).

[3] S. W. Barnes and G. Valley, Phys. Rev. **53**, 946(A), (1938).

[4] J. J. Livingood and G. T. Seaborg, Phys. Rev. **55**, 457 (1939).

[5] R. Sagane, Phys. Rev. **55**, 31 (1939).

x-radiation has been found[1] by means of differential absorption measurements.

### Calculated Auger Energies

The energies of the Auger electrons from the resulting Cu atom were calculated to the required

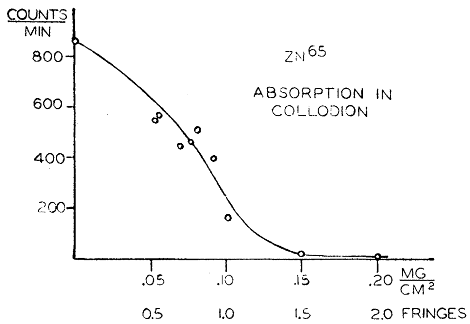


FIG. 1. Absorption in collodion of soft electrons from $Zn^{65}$.

degree of accuracy by the method of Ference,[6] using Slater's[7] screening constant theory. Term values were taken from Siegbahn.[8] The most energetic $K-L^2$ Auger electrons have an energy given approximately by $E_K-2E_{L_{III}}=8954-2(933)=7088$ ev. When account is taken of the extra work required to remove the second $L_{III}$ electron due to changes in screening, a correction factor $\Delta E=2E_2-E_1-E_3=32$ ev must be subtracted, leaving 7056 ev ($H\rho 284$ gauss-cm). If we assume extreme $jj$ coupling, we find the lower limit for $K-L^2$ will be $E_K-2E_{L_I}-\Delta E=6730$ ev ($H\rho 277$), but judging from Ference's experimental work with germanium, these are less numerous. Deviations from $jj$ coupling will determine the detailed structure of the Auger levels, but will not appreciably affect the extreme values here listed. Thus we conclude that the $K-L^2$ electrons are a nearly homogeneous group, lying within about 300 ev of a maximum value of 7056 ev.

Similarly, the $K-LM$ group, which is expected[6] to be about $\frac{1}{3}$ as numerous as the $K-L^2$ group, lies within about 300 ev of a maximum value of $E_K-(E_{L_{III}}+E_{M_{IV,V}})=8016$ ev ($H\rho 302$). The screening correction in this case is negligible.

Direct measurements by Robinson and Cassie[9] on the Auger electrons resulting from photoionization of Cu by Mo $K\alpha\beta$ gave lines between $H\rho 280$ and $H\rho 292$, consistent with the theoretical values derived above.

### Apparatus

A screen wall-counter[10] was constructed having a counter wall 1.9 cm in diameter and 10 cm long. The wall was of copper or galvanized iron window screen, the insulation was of Lucite, and the wire was No. 30 gauge bare copper. The sample could be placed 1.3 cm from the screen, or closer if desired. Decay constants were checked by means of a thin glass-walled argon-oxygen counter. A Neher-Harper[11] quenching circuit and a scale-of-16 scaling circuit[12] were used to record pulses. A cathode-ray oscilloscope was always used to check the behavior of the screen wall counter, which had a cosmic-ray background of about 40 per minute.

Many very soft electrons were found to be emitted by invisibly thin zinc samples electroplated on copper or aluminum foils. A sample giving about one count per minute (above a background of 8) on the glass counter gave about 500 per minute in the screen wall-counter. The $Zn^{65}$ was over 2 years old at the time of the experiments (1943), and the decay curve, obtained from $\gamma$'s registered on the glass counter, was straight over two half-lives, showing a slope of $258\pm 10$ days.

### Absorption Experiments

Thin films of collodion placed 1 mm from the source were used in absorption experiments in the screen wall-counter. The chief error lay in determination of the thicknesses of the films, which were estimated in two ways: (1) from the

TABLE I. Absorption in collodion of soft electrons from $Zn^{65}$.

| Method | Cut-off |
|---|---|
| Color thickness | 0.13 mg/cm² |
| Fringes | 0.15 |
| Weighing | 0.2 |

[6] M. Ference, Phys. Rev. **51**, 720 (1937).
[7] J. C. Slater, Phys. Rev. **36**, 57 (1930).
[8] M. Siegbahn, *Spectroskopie der Röntgenstrahlen* (Verlagsbuchhandlung Julius Springer, Berlin, 1931).
[9] H. Robinson and A. M. Cassie, Proc. Roy. Soc. **A113**, 282 (1928).
[10] W. F. Libby and D. D. Lee, Phys. Rev. **55**, 245 (1939).
[11] H. V. Neher and W. W. Harper, Phys. Rev. **49**, 940 (1936).
[12] H. Lifschutz and J. L. Lawson, Rev. Sci. Inst. **9**, 83 (1938).

interference colors[13] and (2) from the shift of fringes of Na light in a Michelson interferometer. Reasonable agreement was obtained. An index of refraction of 1.5 and a specific gravity of 1.66 were taken for collodion. A very rough check was made with a microbalance. The shape of the absorption curve is shown in Fig. 1; the points at 1.0, 1.5, and 2.0 fringes were determined by the interferometer and that at 1.0 fringe was also determined from the film's color so as to provide overlapping of the two methods. Cut-off was at about $0.15\pm.03$ mg/cm$^2$ (see Table I). Extrapolating Schonland's[14] data for homogeneous cathode rays, an $H\rho$ value of 285 was found (7500 ev).

### Magnetic Deflection Experiments

The screen wall-counter was placed in a longitudinal magnetic field formed by an electromagnet from which pole pieces of diameter 10 cm had been removed. The coils were each 9 cm long and 34 cm in outside diameter, and their centers were 20 cm apart. A rough approximation to Helmholtz coils was thus obtained. The counter was placed at the center of the system, and the magnetic field was explored by a search coil and found to be uniform to within 0.2 percent perpendicular to the axis, and to within 3 percent along the length of the counter. At cut-off a much shorter portion of the axis was used, indicating a more uniform field at cut-off than the outside limits of 3 percent. The constant of the magnet was determined as $99\pm3$ gauss/amp. with the aid of a search coil and a ballistic galvanometer. As the magnet current was increased, eventually only those electrons were counted which left the source in a direction perpendicular both to the field and to the line joining the source to the counter. Thus the radius of curvature was half the closest distance of source to screen. A typical curve is shown in Fig. 2. It will be noted, as found by Libby and Lee,[10] that a sharper cut-off was obtained with $H_2$ gas at 2 cm of Hg than with argon at 1 cm, because of scattering in the counter gas. In each case a trace of alcohol vapor was added to improve the counting characteristics. It is believed that errors due to scattering in the gas and self-absorption in the source were negligibly small. The weighted mean of four runs, made at values of $\rho$ from 0.27 to 0.64 cm, gave an end point (by inspection) of $302\pm30$ gauss-cm, or $E_{max}=8000\pm1700$ ev. The rather large error arises from the difficulty of estimating end points ($\pm5$ percent), lack of homogeneity in the magnetic field ($\pm3$ percent), and uncertainty in $\rho$ ($\pm5$ percent). The sign of the particles was determined as negative, using sloping shields in the counter.

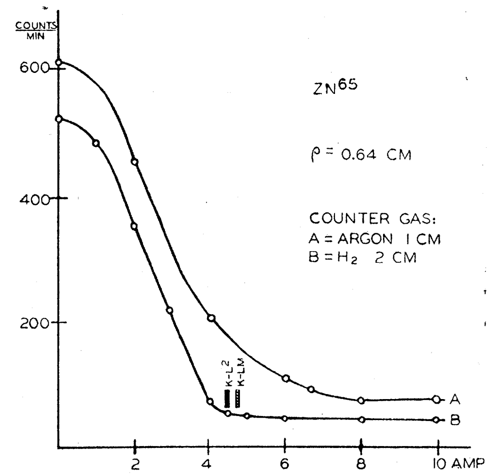


FIG. 2. Magnetic deflection of soft electrons from $Zn^{65}$, using screen wall-counter. A sharper cut-off is obtained when $H_2$ is used as the counter gas. Calculated Auger electron energies are indicated, those arising from the $K-LM$ transitions being less numerous than those arising from the $K-L^2$ transitions.

From the shape of Curve $B$ in Fig. 2, it would seem that the screen wall-counter can be used successfully at least down to 8000 ev electrons, which is considerably lower than the lowest energies measured by Libby and Lee.

### Discussion of Results

Within the experimental errors, it is seen that both the absorption and the deflection experiments are consistent with the interpretation of these electrons as Auger electrons resulting from $K$-capture (See Table II).

Very few of the many experiments involving $K$-capture have been performed under circumstances allowing detection of the extremely low energy Auger electrons. Plesset[15] looked for

[13] O. D. Chwolson, *Traité de Physique* (Libraire Scientifique A. Hermann, Paris, 1906), Vol. 2, p. 596.
[14] B. F. J. Schonland, Proc. Roy. Soc. **A108**, 187 (1925).
[15] E. H. Plesset, Phys. Rev. **62**, 181 (1942).

TABLE II. Maximum Auger energies for $Zn^{65}$.

| Method | Maximum energy (ev) | |
|---|---|---|
| Theory | 7056 | $(K-L^2)$ |
| | 8016 | $(K-LM)$ |
| Absorption | 7500±1500 | |
| Deflection | 8150±1700 | |

electrons from $Zn^{65}$ in the range 20 to 300 kev and found none. Valley and McCreary[16] searched for Auger electrons from $K$-capture in the 6.4 hr. $Cd^{107,109}$, and concluded that electrons of energies <20 kev have little action on the photographic plate. Hemmendinger[17] looked for x-rays from $Mn^{52}$. He found a soft radiation which he was unable to identify, apparently because of absorption in air. Unless the source was placed inside his ionization chamber, this radiation would be considerably harder than the Auger electrons. Hurst and Pool[18] have found "electrons of very low energy associated with the fluorescence yield" in the $K$-capture of $Ag^{106}$. No energy measurements were made, however.

Auger electrons would arise following emission of any strongly converted nuclear $\gamma$-ray. The justification for describing the Auger electrons of this paper as "resulting from $K$-capture" lies in the very small[4,15] internal conversion of the strong[4] 1.0 Mev $\gamma$-ray of $Zn^{65}$. Practically the only way in which an electron leaves the $K$ shell of $Zn^{66}$ is through capture.

16 G. E. Valley and R. L. McCreary, Phys. Rev. **56**, 863 (1939).
17 A. Hemmendinger, Phys. Rev. **58**, 929 (1940).
18 L. K. Hurst and M. L. Pool, Phys. Rev. **65**, 60(A) (1944).

## EXPERIMENTS WITH $Fe^{55}$

A small amount of Fe was available. This sample had been precipitated as $Fe_3PO_4$, and small traces of Mn and Co might have been present. At the time of the measurements, the sample was at least 4 years old, and showed a slow decay period of several years. Many soft electrons from this material were found in the screen counter, presumably from $K$-capture in $Fe^{55}$ (4 year half-life). A sample of purified Fe only a few months old also gave numerous soft electrons when a thin source was electroplated on a copper foil. A main group of maximum $H\rho 220\pm 30$ (4300±1500 ev) was found, and traces of another group up to 20,000 ev possibly were also present. These results are based upon only one run. The calculated Auger maximum energies, however, are 5179 ev $(K-L^2)$, and 5872 ev $(K-LM)$, which are not discordant with the measurements.

## ACKNOWLEDGMENTS

In conclusion, the author wishes to thank Dr. Martin Kamen of the Radiation Laboratory at Berkeley, California, who supplied the Zn and the $Fe_3PO_4$ samples, and Dr. R. Dubach of the Washington University Medical School, who supplied the purified Fe sample.