THE DECAY SCHEME OF ZN^{65}

by

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ABSTRACT

Radiations from Zn^{65} have been studied by means of a thin lens beta ray spectrometer. A spiral baffle was used to separate positrons from negatrons. The gamma ray spectrum in the energy range above 100 kev was found to consist of one gamma ray at 1.11 mev and annihilation radiation at 0.51 mev. One positron group was found with maximum energy at 0.327 mev. No internal conversion electrons were found. A decay scheme has been proposed in which Zn^{65} decays either by K-capture to a 1.11 mev excited state of Cu^{65} or by positron emission to the ground state of Cu^{65}.

ACKNOWLEDGEMENT

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Introduction

Radiations from the Zn^{65} nucleus have been studied by several methods. The samples of Zn^{65} used have been produced by the following reactions[1]:

Zn^{64} (d,p) Zn^{65}
Cu^{65} (d,2n) Zn^{65}
Cu^{65} (p,n) Zn^{65}
Zn^{64} (n,γ) Zn^{65}
Ga^{65} (K-decay) Zn^{65}

Barnes and Valley[2] investigated radiations from copper bombarded by protons, using absorption and cloud chamber techniques. They reported an activity with a half life of about 7 months, consisting of both positron and negatron emission in the ratio of 2:1 and gamma radiation with a gamma to positron ratio of about 60. Absorption measurements in aluminum indicated an end point of 0.7 mev for the positron group. Through the Cu_A (p,n) Zn_A reaction both Zn^{63} and Zn^{65} could be produced from the two stable isotopes Cu^{63} and Cu^{65} by proton bombardment. Livingood and Seaborg[3], however, found a similar activity in an isotope of zinc produced by deuteron bombardment of zinc. They identified the reaction as Zn^{64} (d,p) Zn^{65}. Since there is no stable isotope Zn^{62}, from which Zn^{63} could similarly be produced, they assigned the activity to Zn^{65}.

Delsasso et al[4] also investigated the radiations from copper bombarded by protons, by absorption measurements in aluminum. The absorption curve was separated into three components which were identified as: one positron group, one internal conversion electron and one gamma ray. The The lowest end point only was reported at 0.55 mev. This value could be assigned to either the positron group or the internal converson electron. Fairly intense X-radiation found by them was attributed to both the K-capture and internal conversion processes.

Livingood and Seaborg[3] reported X-rays appropriate approximately to the CuK_α line. Previously Alvarez[5] had showed that there was ho large difference in the absorption of these X-rays in nickel and copper. Livingood and Seaborg concluded from this that the X-rays weee from an element of atomic number less than that of zinc, and assigned them to the CuK_α line. The K-capture process for the decay $Zn^{65} \rightarrow Cu^{65}$ was therefore postulated.

They used magnetic separation of the particles and gamma rays and confirmed the high ratio of gamma rays to particles. Their absorption measurements in aluminum indicated one γ-ray at 1.0 mev and a weak annihilation radiation at 0.5 mev. The half life was given as 250 ± 5 days. Perrier Santangelo and Segre[6] reported a half life of 245 days for a Zn isotope obtained from coppsr which had been bombarded by both protons and deuterons.

Since the CuK_α X-rays could arise from either K-capture process, or internal conversion of gamma rays from the excited Cu^{65}; coincidence studies are required. Good and peacock [7] investigated X-ray γ-ray and $\beta^+\gamma$-ray coincidences. They concluded that 54% of the K-capture precess leads to the ground state of Cu^{65}, while 46% leads to the 1.14 mev[11] excited state, and 2.2% of the disintegrations go by positron emission directly to the ground state. Watase, Itoh and Takeda[8] also found some evidence by X-ray γ-ray coincidence that some part of the K-capture process goes to the ground state.

The Table of Isotopes[1] lists 0.4 mev for the β^+ end point[9] from cloud chamber measurements and 0.32 mev, using a beta ray spectrometer[10]. The existence of internal conversi version electrons is also listed from the work of Livingood and Seaborg[3], but no energies are given.

For the gamma ray energies, 1.14mev ± 3% was reported by Deutsch, Roberts and Elliott[11] and 1.11mev ± 0.5% by Jensen, Laslett and Pratt[12], both from spectrometer studies. The latter found a weak annihilation radiation at 0.51 mev.

The existence of both K-capture and positron emission with the former process highly favored is reasonably certain. At least one γ-ray has been found at 1.11 mev and at least one β^+-group with end point at 0.32 mev, both by spectrometer methods. In view of the work of Good and Peacock, there should be a weaker β^+-group with higher end point energy. The presence of internal conversion electrons has not been confirmed by spectrometer methods, and the energies are therefore not known with any certainty.

In view of these uncertainties it was deemed advisable to repeat the spectrometer study of the gamma ray spectrum, and further, to investigate both positron and negatron spectra separately. The isotope used was obtained by the $Zn^{64}(n,\gamma)Zn^{65}$ reaction from the Chalk River Laboratories of the National Research Council.

Equipment

Spectrometer

The spectrometer is of the thin lens type which has been used in previous researches in this laboratory[13] and elsewhere[14,15,16]. A diagram of the spectrometer is shown in figure 1. Electrons from the source are selected by the baffle B and focussed by the magnetic field on the thin window of the beta ray counter. The baffles A, C, D, and E are added to reduce scattered radiation and prevent direct radiation from reaching the counter. For study of positron spectra an additional spiral baffle was inserted between C and the field coils. Deutsch et al[14] have calculated the pitch of the focussed electrons in their spiral path through the spectrometer. The baffle shown in figure 2 is based on these calculations. Since the pitch is almost a constant for paths

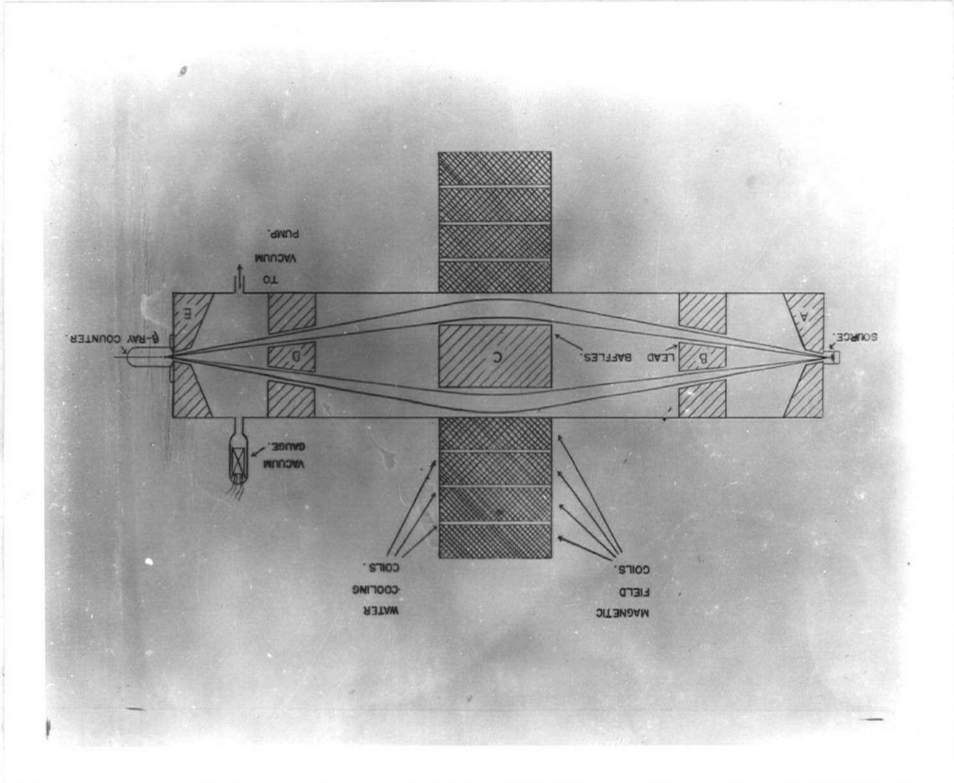


Figure 1. Diagram of the spectrometer.

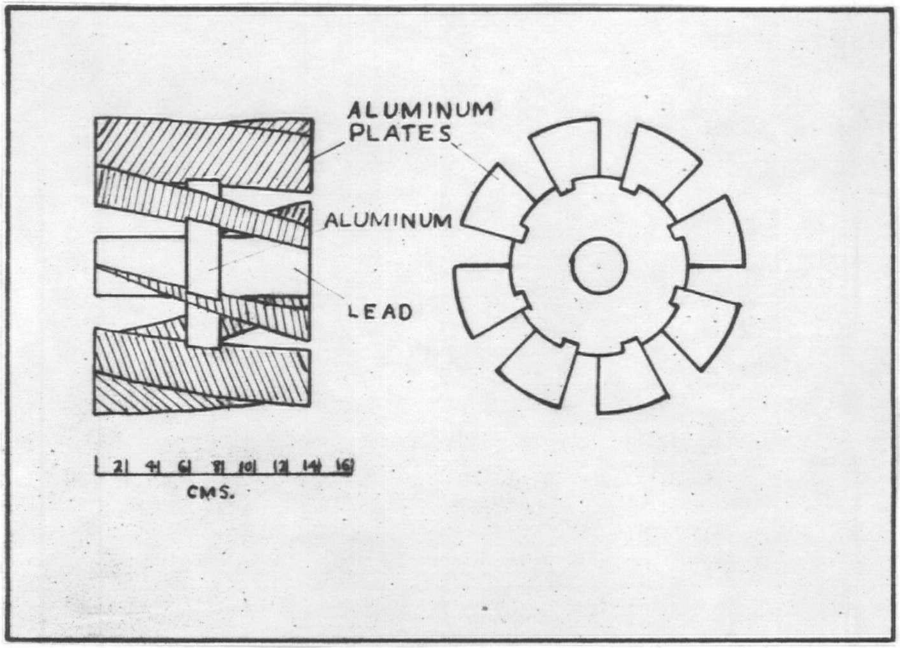


Figure 2. Spiral baffle used with the spectrometer for studying positron spectra.

having different radii, radial baffle plates of constant pitch may be used. Electrons of either sign may be selected by choosing the direction of the magnet coil current; this baffle transmitted 75% of the focussed electrons with one direction of coil current while it reduced the count to background with the opposite direction. The loss of 25% transmission caused by insertion of the baffle must be attributed to a difference between the pitch of the baffle plates and that of the electrons, since the geometric cross section of the plates is much less than 25% of the spectrometer cross section.

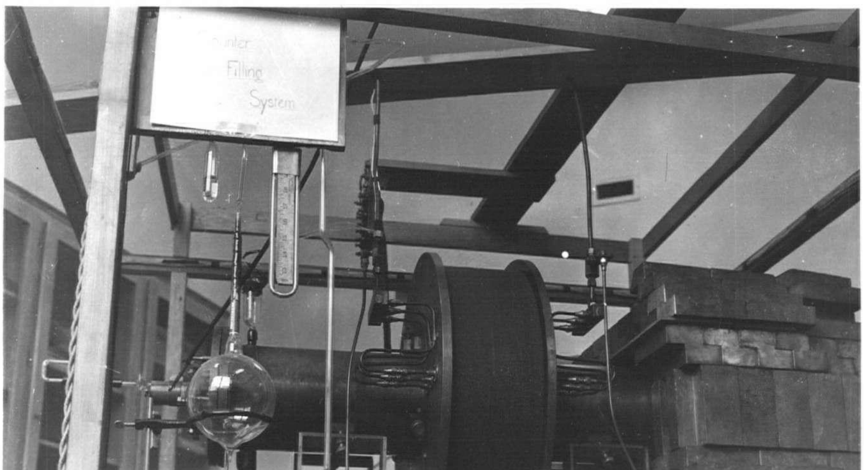


Plate I. Assembled spectrometer.

Plate I shows the assembled spectrometer. The axis of the instrument is aligned with the magnetic meridian and the vertical component of the earth's magnetic field is effectively cancelled by a current through the pair of compensating coils surrounding the instrument. The effect of the remaining axial component may be found by reversing the magnet coil current (with the spiral baffle removed)[11]. It was found that, with the present resolution of 3 to 4% obtained with this spectrometer, no effect could be observed. By use of non-ferromagnetic materials throughout, proportionality between the momentum of the focussed electrons and coil current is therefore preserved.

Deutsch et al[14] have shown the relation between spherical aberration and mean coil radius. Spherical aberration may be minimized by operating with the largest radius permitted by the momentum of the electrons being studied. The magnet coil is therefore wound in four layers having separate terminals, so that the inner layers may be disconnected.

Counters

The thin window Geiger counter, sketched in figure 3, was designed to use a minimum of wax seals. Unstable operation peculiar to wax sealed counters has been experienced in this laboratory. Anode wire and filling tube are brought through the brass envelope with Kovar seals, which are

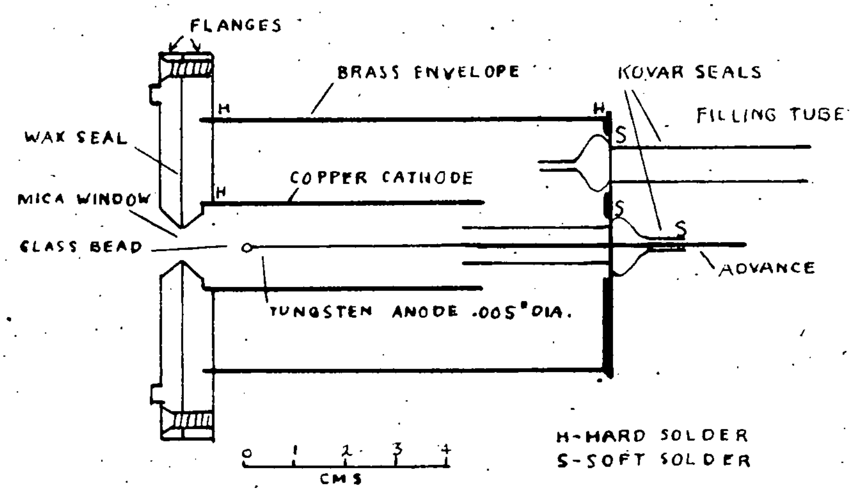


Figure 3. Counter construction

soft soldered to the envelope. All other soldered joints are hard soldered and coated with soft ~~envelope~~ solder. The usual filling tube tap was omitted; the tube was sealed off after a satisfactory filling was obtained.

The mica window, 2.8mg/cm^2, thick, was sealed between the flanges using Cenco Plicene, a wax insoluble in alcohol, with the following technique. Plicene, dissolved in turpentine was painted smoothly on both flanges and allowed to dry. these were then heated to melt the wax and the mica dropped on the counter; air bubbles were pressed out with a rubber tube and the outer flange bolted to the first.

The counter described has operated satisfactorily during the present work.

Amplifiers

The laboratory arrangement required the use of a ten foot pulse cable to carry counter pulses to the scalar. To avoid direct loading of the counter by the cable, a cathode follower was connected to the counter with short leads, as shown in figure 4. The cable connected to the cathode is approximately matched at its output end by the 100 ohm resistor. The following preamplifier is a two stage grounded grid triode amplifier, each stage of which is preceded by a cathode follower. The three volt pulses obtained from the cathode follower are sufficient to saturate the preamplifier, whose output consists of sixty volt pulses of equal amplitude. The scalar discriminator was set at 15 volts to eliminate stray pickup and noise, and then the counting rate was independent of discriminator bias fluctuations. Counter plateaus obtained with this counter and circuit are shown in figure 5.

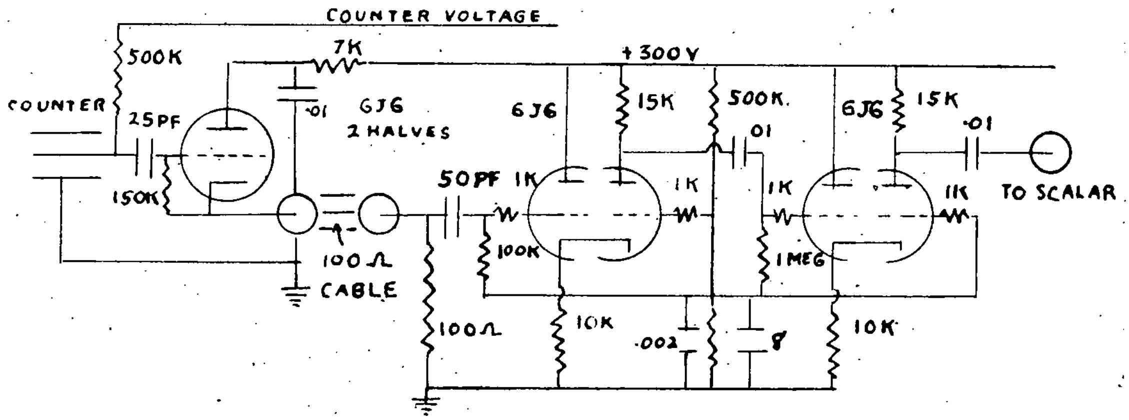


Figure 4. Schematic of cathode follower and preamplifier.

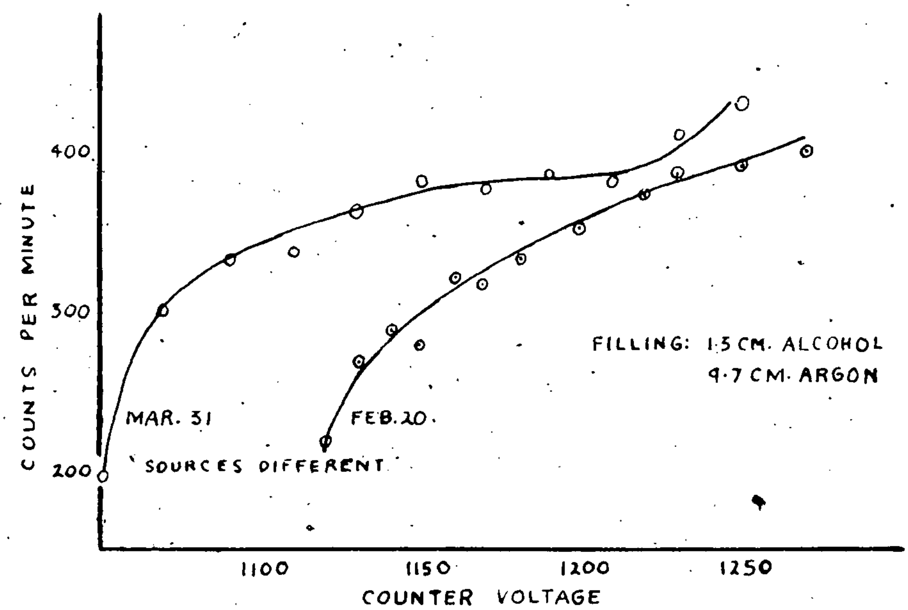


Figure 5. Counting rate of pulses from preamplifier of amplitude greater than 15 volts.

Regulators

Magnet Current Regulator

The regulator is the same as used in previous researches[(13a)] except for the following modifications. The D. C. power is taken from the building supply, whose negative terminal is grounded, instead of from the"floating" generator supply. The A. C. error voltage is then taken between the standard resistor and ground. This modification required an additional stage of A. C. amplification to obtain both error signal inversion and increased voltage gain. The driver stage was modified so that it operated as a tetrode with normal bias for all bias settings of the type 6AS7 control tubes. Bias control for the latter was obtained from a 100,000 ohm potientiometer connected across the driver B supply, with the movable arm grounded; the negative bias supply was then not required.

Magnet current was determined as before by setting the dial box potentiometer. Stability was 0.01% at 10 amperes and 0.1% at 1 ampere with this arrangement.

Compensating Coil Current Regulator

The current carried by the pair of compensating field coils is regulated against line voltage variations by the use of two ballast tubes (type CRC876) in series with the 10 ohm field coils. Since these operate normally with 1.7 amperes, whereas only 1 ampere is required for field compensation, the excess current was shunted by the coils through a rheostat. Current regulation of 0.25% per volt was obtained, which value is sufficient for normal hourly line voltage variations.

Experimental Technique

Arrangement of Sources

A diagram of the source arrangement is shown in figure 6. For gamma ray spectra the active material is inserted into the brass cup from the outside. A screw cap holds this firmly in place. Sufficient brass is left between the active material and the radiator to absorb the beta rays. The radiator, a thin disc of lead or uranium oxide is cemented to the front face.

For beta ray spectra, filings from the active material were cemented with collodion to a thin disc of mica, which fits into the brass cup. The brass is removed from immediately behind the mica to reduce reflections of beta rays. Owing to the low specific activity of the Zn^{65}, the deposit could not be made as thin as was desired; sufficient was added to produce roughly twice background count in the spectrometer.

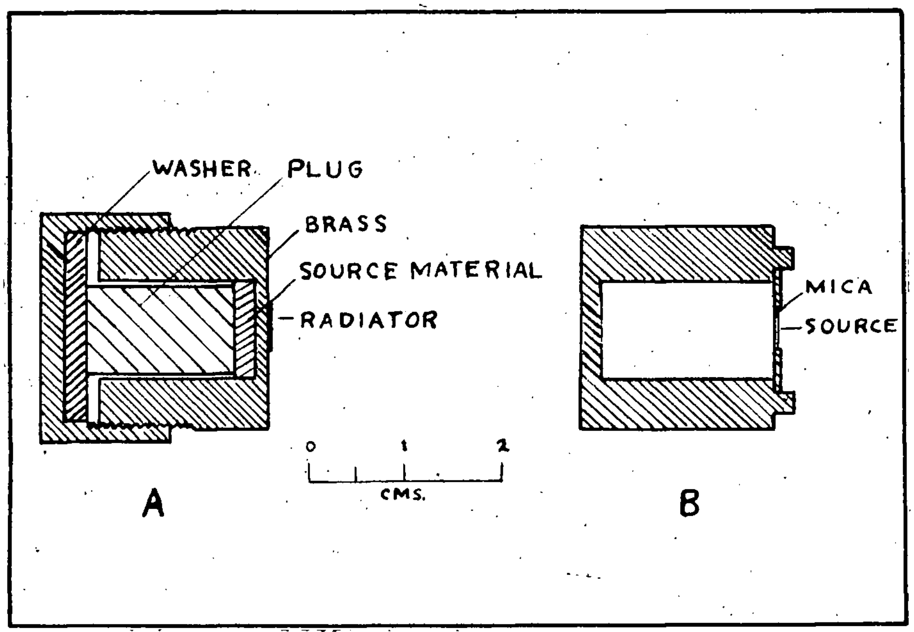


Figure 6. Arrangement of sources. A, Gamma ray source. B, Beta ray source.

Calibration

The spectrometer was calibrated directly in terms of dial box potentiometer reading, which is proportional to the momentum of the focussed electrons. Photoelectrons ejected from the K shell of lead by the 0.607 mev gamma ray of radium were used. This energy value was obtained by Ozeroff (13c) from a similar spectrometer calibrated in terms of the F line of thorium B. The momentum of the photoelectrons was obtained by subtracting the binding energy (0.0875mev) of the K shell. The calibration curves in figure 7 show that both resolution and transmission are improved by using only the magnet coils of large radii. Below are listed the calibration corresponding to peak values and the resolution for each coil combination used.

Coils in series	Width at half maximum	Calibration in gauss-cm. per volt
4 coils	4 %	9600
3 outer	3.6%	6600
2 outer	3.5%	4090
1 outer	3.4%	1915

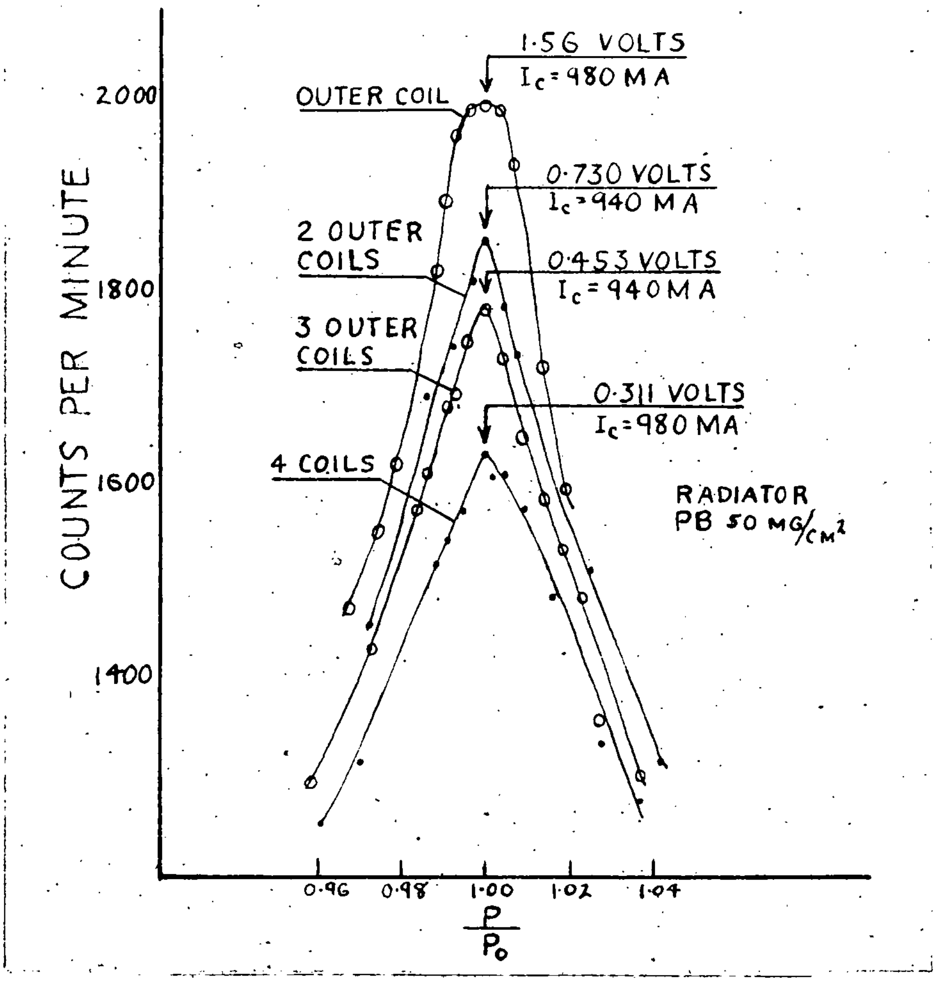


Figure 7. Calibration curves.

The compensating current, I_c, had to be adjusted for maximum peak intensity with each coil combination. Presumably, the difference is due to slight misalignment of the separate coil axes in the horizontal plane. The resolution possibly could be improved for the outer coil alone by realignment of the spectrometer axis with the outer coil axis, in the vertical plane(14), but this was not attempted because the outer coil alone was insufficient for most energies.

Experimental Results

Gamma Ray Spectrum

The gamma ray spectrum is shown in figure 8. Compton background, obtained with the radiator removed, is dotted under the main curve; the difference gives the photoelectrons ejected from the radiator. Several radiators and magnet coils were tried both to obtain high peak intensity and resolution and to eliminate spurious peaks. The two peaks obtained with lead radiators show that little is gained by using a radiator thicker than 50 mg/cm^2. Several small peaks appear on the main curve obtained by using the lead radiator. These could be interpreted either as spurious peaks arising from unusually large statistical deviations or as photoelectron peaks from weak gamma rays. To remove the ambiguity, the region containing these peaks was repeated with the uranium radiator.

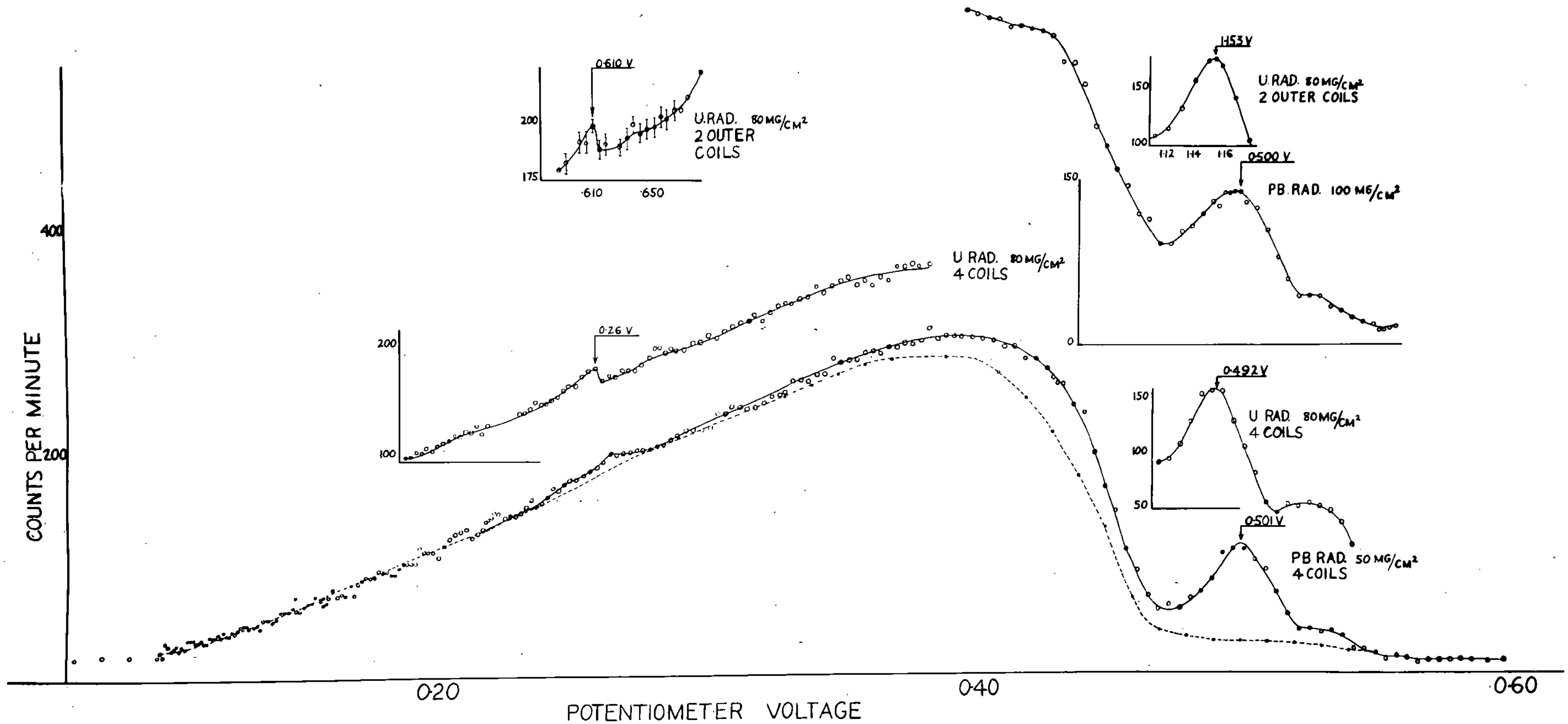


Figure 8. Gamma ray spectrum of Zn^{65}

Since the binding energy of the uranium K-shell is 27.5 kev higher than that of the lead K-shell, a photoelectron peak obtained with the lead radiator must reappear when the uranium radiator is used, but at 27.5 kev lower energy. Only one such peak satisfied this condition. This peak is indicated in figure 8 at 0.26 volts.

The Compton background seemed rather excessive. It was shown that the high intensity was due to the large source area required by the low specific activity. A lead cylinder 2 cm. long and 2 cm. in diameter, with a conical hole drilled to fit over the radiator, reduced the Compton background to ½ but left the photoelectron peak unchanged. The work however was not repeated since repetition was not considered worthwhile for a factor of 2. It is therefore recommended that small sources of high specific activity, when available, be placed directly behind the radiator; and the lead cylinder baffle be used only when necessary, since additional scattering is undoubtedly produced by its use.

Gamma Ray Energies

The gamma ray energies were obtained by adding the K shell binding energies, 115 kev for uranium and 87.5 kev for lead[17], to the photoelectron peaks. These are tabulated below. The center of the photoelectron peak was chosen generally, except in the case of the 100 mg/cm^2 lead radiator. Since this had a definite flat top, the high energy end of the flat top was chosen[12].

Gamma Ray	Radiator	Coils	E_γ in Mev
(1)	U, 80mg/cm^2	4 coils	0.51
	U, 80	2 outer	0.508
(2)	Pb, 50	4 coils	1.107
	Pb,100	4 coils	1.104
	U, 80	4 coils	1.109
	U, 80	2 outer	1.109

Positron Spectrum

The positron spectrum, shown in figure 9, was obtained from the beta ray source with the magnet current reversed; the spiral baffle effectively removed negative particles. The counter was shielded fsom other sources (including a 500 millicurie radium source in a second spectrometer in an adjoining room) with 15 cm. of lead. Background was reduced to 10 counts per minute. The source thickness required to obtain twice background count was 130 mg/cm^2.

The Fermi plot of the positron spectrum, shown in figure 10, was obtained by use of the following approximations. The Fermi relation is given by

$$F = \left[\frac{N}{\eta^2 f}\right]^{\frac{1}{2}} = E_{max} - E$$

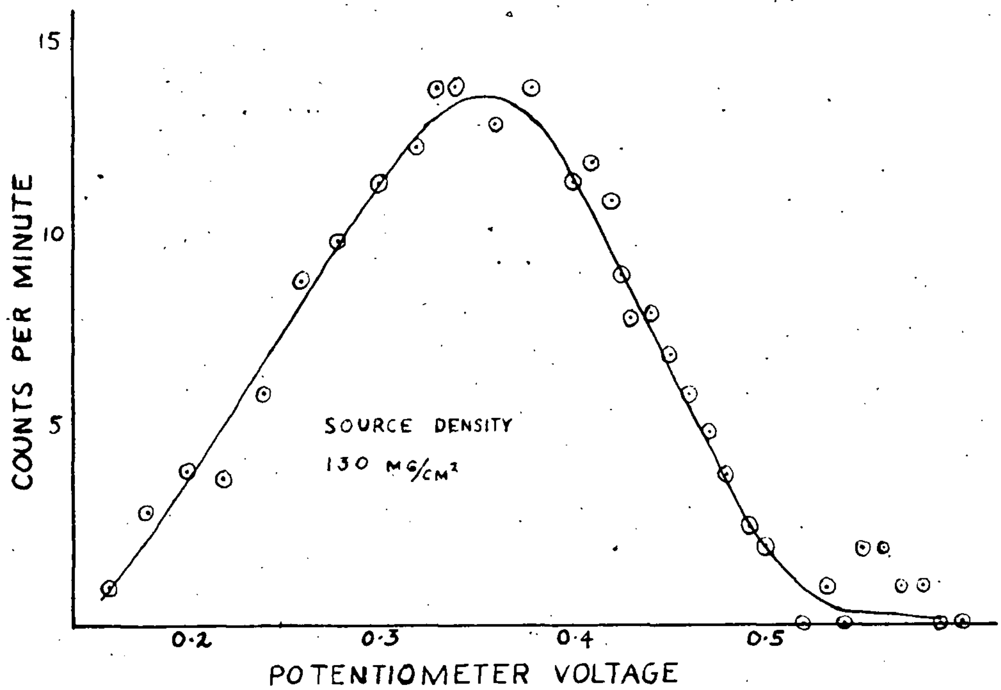


Figure 9. Positron spectrum of Zn^{65}

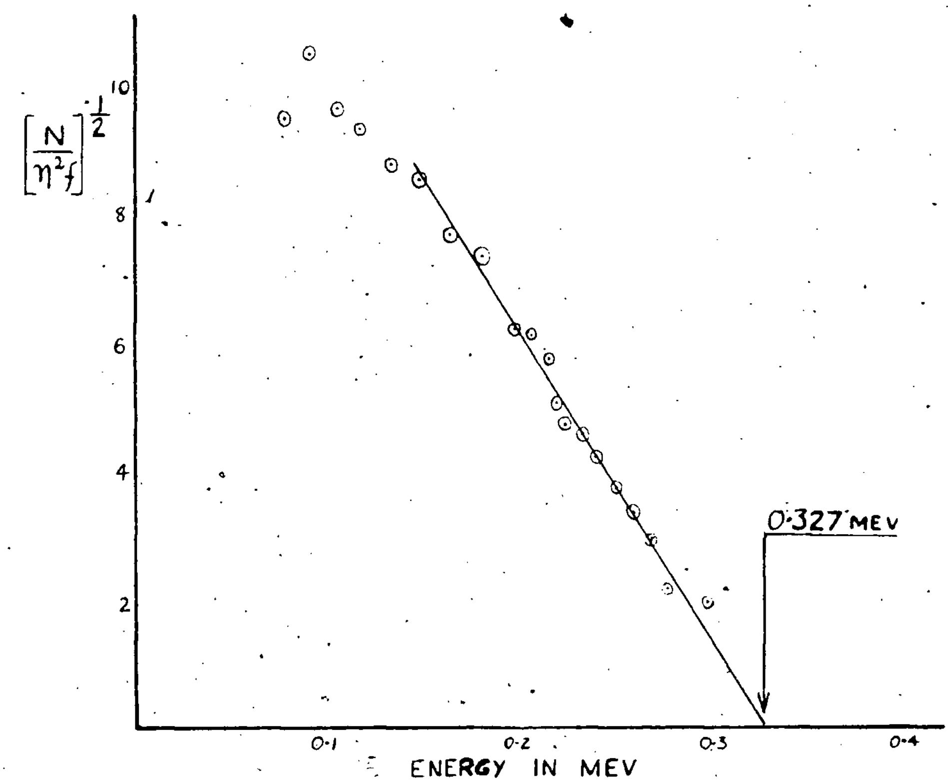


Figure 10. Fermi plot of positron spectrum

where η - momentum of electron in units of m_0c

N - relative number of electrons with momentum η

and $f(Z,\eta) = \eta^{2S} e^{\pi y} \left|\Gamma(1 + S + iy)\right|^2$,

where $S = \sqrt{1 - (Z/137)^2} - 1$

$$y = \frac{Z\sqrt{1+\eta^2}}{137\ \eta} .$$

The approximation discussed concerns the expansion of the gamma function. This was expanded in a Taylor series, to the first power of S only. By a second approximation to the first power, the expression

$$\left|\Gamma(1 + S + iy)\right|^2 \simeq 1 + S\left\{\frac{\Gamma'(1+iy)}{\Gamma(1+iy)} - \frac{\Gamma'(1-iy)}{\Gamma(1-iy)}\right\}$$

The expression in brackets was expanded in series, using a well known expansion for $\frac{\Gamma'(Z)}{\Gamma(Z)}$. The series involved, of the form $\sum_{n=1}^{\infty}\frac{1}{n(n^2+y^2)}$, was approximated by $\int_1^{\infty}\frac{dn}{n(n^2+y^2)}$. The result used in the calculations is

$$\left|\Gamma(1 + S + iy)\right|^2 \simeq \frac{\pi y}{\sinh \pi y}\left\{1 - 2S\gamma + S\log(1 + y^2)\right\}$$

A commonly used approximate expansion for this gamma function is

$$\frac{\pi y}{\sinh \pi y}\left\{1 + 0.4(\alpha Z)^2\right\} .$$

This formula can be obtained from ours by two further approximations.

The Fermi plot of the positron spectrum indicates one postron group with end point at 0.327 mev, with a standard deviation of 0.0037 mev for the 14 points used.

Internal Conversion Electrons

A negatron spectrum was attempted, using the beta ray source. Particular attention was paid to the low energy end in a search for internal conversion lines. None were found, but a distribution was obtained which was identified as a Compton distribution. The existence of Compton electrons is attributed to the high surface density of the source (130 mg/cm^2) and to the relatively intense 1.11 mev gamma radiation.

Conclusions

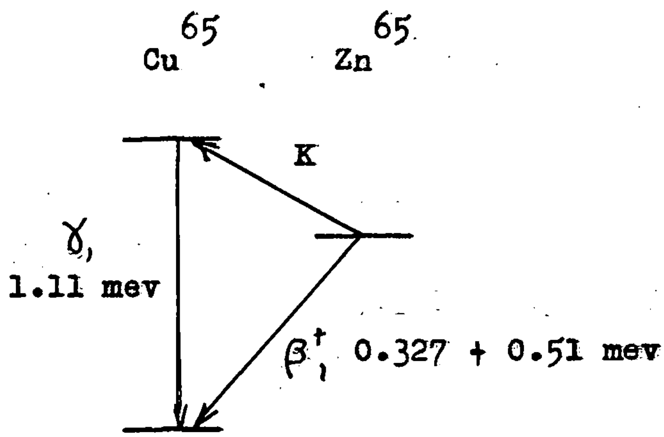
The average values of the gamma ray energies, taken to the number of valid significant figures, are: 0.51 mev and 1.11 mev. The 0.51 mev radiation is identified with annihilation radiation. These results are similar, within 1%, to those reported by Jensen et al[12]. The gamma ray energy is 3% lower than that reported by Deutsch, Roberts and Elliott[11].

The end point of the positron group is 0.327 mev.

This value is 2% higher than that reported by Peacock[10], from spectrometer measurements, and is considerably less than all values reported from cloud chamber and absorption measurements[2,4,9].

Decay Scheme

The following decay scheme based on these results is proposed.



The K-capture process is energetically possible if the energy difference between the initial and final states is less than the rest energy of the electron. This condition is satisfied by the decay scheme. The statement made in the introduction— that a second β^+-group of higher end point energy was required by the results of Good and Peacock[7] — is therefore incorrect. According to their results there is a second K-capture process, approximately equally favored, leading to the ground state of Cu^{65}. They further concluded that 2% of all disintegrations go by positron emission directly to the ground state. Therefore, if only one β^+ -

group exists, the ratio of gamma to positron emission would be approximately 25. Barnes and Valley[2], however, reported a ratio of 60. Further, the reported presence of internal conversion electrons[1,2,3,] has not been confirmed.

It would be possible to estimate the mass of Zn^{65}, assuming that the positron emission leads to the ground state. However, owing to the conflicting results, further work with a source of much higher specific activity is recommended, to determine first the decay scheme with greater certainty.

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