Electrodisintegration of Cu^{63}, Zn^{64}, Ag^{109}, and Ta^{181}†*‡

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The ratio of the (γ,n) photodisintegration cross section to the $(e,e'n)$ electrodisintegration cross section for the isotopes Cu^{63}, Zn^{64}, Ag^{109}, and Ta^{181} was measured for electron energies of 24 to 35 Mev. This ratio was found to decrease with energy in contrast with the Weizsäcker-Williams approximation which predicts a constant ratio. However, the Weizsäcker-Williams method does yield a result which is of the right order of magnitude for Cu, Zn, and Ag and which is within a factor of two of the observed value of Ta.

Assuming approximately one-half of the total photon absorption of nuclei to be attributed to the (γ,n) reaction, then comparison of the experimental results for Cu, Zn, and Ag with calculations of Blair is consistent with the suggestion of Bethe and Levinger that the main absorption mechanism of nuclei for photons is electric dipole with a contribution of ~6 percent electric quadrupole absorption. However, for Ta no simple correlation between experiment and theory was found. This is attributed to a failure of the Born approximation used in the Blair calculations.

I. INTRODUCTION

ELECTRONS are known or expected to interact with nuclei in the following ways: (1) They may interact with the virtual meson cloud surrounding the nucleons. This is equivalent to an interaction with the magnetic moment of the nucleus. At electron energies lower than the meson threshold this interaction appears in the form of elastic scattering of the electron corresponding to that of a square-well potential about 5-kv deep and having a width equal to the classical electron radius. (2) They are expected to interact through inverse beta decay. This process has a very low cross section of the order of 10^{-44} cm^2 and has not yet been observed. (3) The electromagnetic field of the electrons may interact with the charge of the protons. When the energy of the electron is equal to, or greater than, the binding energy of a nucleon, the nucleus may absorb sufficient energy from the bombarding electron by this electromagnetic interaction to cause disintegration by emission of a nucleon. This process is called electrodisintegration, the cross section for which is of the order of $\alpha=1/137$ of that of the corresponding photodisintegration. When the electron energy is increased to the binding energy of two nucleons, the nucleus may decay by emitting two nucleons, and so forth for higher energies and more nucleons.

The present research is concerned with the study of (3) and has been restricted to the special case where the only decay particle is one neutron. In particular the ratio of the cross section σ_{br} for the disintegration of nuclei due to the bremsstrahlung of the electrons (photodisintegration) to the electrodisintegration cross section σ_{el} has been studied.

The electrodisintegration of a few nuclei has been previously observed. The first successful attempt was made in 1939 by Collins, Waldman, and Guth[1] on Be at 1.8 Mev verifying that the electrodisintegration cross section is of the order of α times the photodisintegration cross section. Paul[2] observed electrodisintegration of deuterium at 3.8 Mev and estimated the cross section for that energy to be between 10^{-30} and 10^{-31} cm^2. For Cu^{63}, Ag^{107}, and Ag^{109}, Skaggs *et al.*[3] investigated at 16 Mev the photodisintegration cross section and the electrodisintegration cross section and found the corresponding ratio of these cross sections to be approximately 400 for all three isotopes.

Many theoretical calculations have been made to determine electrodisintegration cross sections. Weizsäcker and Williams[4] have developed a method for calculating the interaction of fast electrons using a correspondence principle argument. By use of this method the electrodisintegration cross section may be calculated provided the corresponding photodisintegration cross section is known. The validity of this method requires that the bombarding electrons are not appreciably diverted by the collision. This is equivalent to assuming that the nuclear excitation energy is small compared with the initial electron energy, which is not valid for the conditions of all electrodisintegration experiments thus far performed including the present one. There are other assumptions made by the Weizsäcker-Williams method which also tend to make it invalid. (1) It neglects the component of the field in the direction of motion of the electron. (2) It completely omits the contribution of the scaler potential. This can be important in the case of quadrupole transitions as can be seen from the calculations of

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‡ This report based on a dissertation submitted for the Ph.D. degree at Stanford University by Karl L. Brown.
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[1] Collins, Waldman, and Guth, Phys. Rev. **56**, 876 (1939).
[2] W. Paul, Naturwiss. **36**, 31 (1949).
[3] Skaggs, Laughlin, Hanson, and Orlin, Phys. Rev. **73**, 420 (1948).
[4] E. J. Williams, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **13**, 4 (1935).

Blair[5] and others. More rigorous calculations of electrodisintegration have been made using multipole expansions of the electromagnetic field of the electron. Dipole cross sections have been calculated by Bethe and Peierls,[6] and Peters and Richman;[7] whereas Wick,[8] Sneddon and Touschek,[9] and Blair[5] have included the electric quadrupole case. Recently Guth and his collaborators[10] have developed a method to calculate transitions higher than electric quadrupole and have included electric dipole-quadrupole interference terms. In this paper we shall refer to the calculations of Blair, which are in agreement with the other authors (except for a numerical error in Sneddon's quadrupole calculation) but which are presented in a form which is convenient for our experimental conditions. In particular, Blair calculates the ratio of the cross section $\sigma_{\rm br}$ for the photodisintegration of nuclei due to the thin-target bremsstrahlung of the electrons to the electrodisintegration cross section $\sigma_{\rm el}$ of the same nuclei. We have added to Blair's results, with his approval, the corrections to the bremsstrahlung formula due to atomic screening and due to bremsstrahlung by orbital electrons. No atomic screening corrections are necessary for the calculation of $\sigma_{\rm el}$ because the principal contribution comes from large momentum transfers.

II. THEORY

It should be pointed out that $\sigma_{\rm br}$ as defined by Blair and as used here is a rather peculiar kind of cross section since it depends upon the properties of the target material preceding the particular nucleus which is undergoing photodisintegration. It is defined as follows:

$$\sigma_{\rm br}(k,E_0)=\frac{N_0 t_{\rm eff}}{A_r}\sigma_{\gamma,n}(k)\phi(E_0,k), \tag{1}$$

where $\sigma_{\gamma,n}(k)$ = the photodisintegration cross section for a nucleus of atomic number Z and mass A, $\phi(E_0,k)$ = the "thin target" cross section for production of bremsstrahlung in a material of atomic number Z_r, and mass A_r, $t_{\rm eff}$ = the thickness in g/cm^2 of the material, Z_r producing the bremsstrahlung, N_0 = Avogadro's number, E_0 = total energy of the bombarding electrons, and k = nuclear excitation energy. Because of the fact that $\sigma_{\rm br}$ depends upon $t_{\rm eff}$, Z_r, and A_r, a more general quantity F is defined which essentially eliminates them from the discussion.[11] The quantity F is defined as

$$F(k,E_0)=\left(\frac{\sigma_{\rm br}}{\sigma_{\rm el}}\right)\left[\frac{A_r}{Z_r(Z_r+\delta)r_0^2N_0t_{\rm eff}}\right], \tag{2}$$

where $r_0=e^2/m_0c^2$ and δ is a factor which determines the magnitude of the contribution of orbital electrons to the production of bremsstrahlung. Throughout the remainder of this work it will be assumed that $\delta=1$. It follows that

$$F(k,E_0)=\frac{\alpha\sigma_{n,\gamma}(k)\phi(E_0,k)/\bar{\phi}}{\sigma_{\rm el}(k,E_0)}, \tag{3}$$

where $\bar{\phi}=Z_r(Z_r+\delta)r_0^2\alpha$ and $\alpha=e^2/\hbar c$.

Blair calculated both $\sigma_{\rm br}$ and $\sigma_{\rm el}$ in the Born approximation assuming a compound-nucleus model.

$\sigma_{\rm br}$ was evaluated for the electric dipole case by the standard method of calculating the transition probability per unit time in terms of the incident photon intensity and the nuclear electric dipole matrix element. Dividing the transition probability by the incident electron flux yielded the cross section $(\sigma_{\rm br})_{\rm E.D.}$. The matrix element was *not* evaluated.

$\sigma_{\rm el}$ was evaluated by calculating the transition probability per unit time and hence the cross section in terms of the matrix element of the perturbing Hamiltonian. The electromagnetic effect of the electrons on the nucleus was represented by a multipole expansion of the Møller potentials which are equivalent to the use of plane-wave solutions for both the incoming and outgoing electrons. The perturbing Hamiltonian for the electric dipole case was then determined by calculating the energy of interaction of the electric dipole approximation of the Møller potentials with the protons in the nucleus. Evaluation of the Hamiltonian matrix element involved the same electric dipole matrix element as occurred in the photodisintegration case. Hence, the matrix element cancelled out when the ratio of $\sigma_{\rm br}/\sigma_{\rm el}$ was taken. A similar calculation was made for the magnetic dipole and electric quadrupole cases.

In all of these calculations the photon intensity was evaluated using the Bethe-Heitler[12] extreme relativistic formula for bremsstrahlung including the atomic screening correction $C(\gamma)$ and adding the contribution of the orbital electrons to bremsstrahlung production by replacing Z_r^2 by $Z_r(Z_r+1)$. The final results are expressed by the following equation:

$$F_T(k,E_0)=(\sigma_{\rm br}/\sigma_{\rm el})(g/t_{\rm eff})$$
$$=\frac{2\pi(E/E_0)[E/E_0+E_0/E-\frac{2}{3}]\times[2\ln(2E_0E/\mu k)-1-2C(\gamma)]}{[1+(E/E_0)^2][\ln(2E_0E/\mu k)]+D}, \tag{4}$$

[5] J. S. Blair (private communication, July 11, 1952); "Summary of Calculations on Electron Disintegration of Nuclei," Department of Physics, University of Illinois, 1948 (unpublished); Phys. Rev. **75**, 907 (1949).
[6] H. Bethe and R. Peierls, Proc. Roy. Soc. (London) **148**, 146 (1935).
[7] B. Peters and C. Richman, Phys. Rev. **59**, 804 (1941).
[8] G. C. Wick, Ricerca sci. **11**, 49 (1940).
[9] I. N. Sneddon and B. F. Touschek, Proc. Roy. Soc. (London) **A193**, 344 (1948).
[10] Thie, Mullin, and Guth, Phys. Rev. **87**, 962 (1952).
[11] In general it is not convenient to eliminate the Z_r dependence in F which arises from the atomic screening correction inherent in $\phi(E_0,k)$.
[12] H. Bethe and W. Heitler, Proc. Roy. Soc. (London) **A146**, 93 (1934).

where $g=A_r/[Z_r(Z_r+1)r_0^2N_0]$; E_0=total energy of incident electron; E=total energy of scattered electron; $\mu=m_0c^2$; $k=E_0-E$=nuclear excitation energy; $C(\gamma)$ =atomic screening term; $D=-2E/E_0$ for electric dipole excitation, =0 for magnetic dipole excitation, $\cong 8E^2/3k^2$ for electric quadrupole excitation.

III. EXPERIMENTAL TECHNIQUE

It must be noted that $F_T(k,E_0)$ evaluates the ratio of the two cross sections for a particular excitation energy k. Experimentally, this is a quantity which is very difficult to measure; however, a quantity

$$F_{\text{exp}}(Z,E_0) = \frac{g}{t_{\text{eff}}}\int_0^{E_0-\mu}\sigma_{\text{br}}(k,E_0)dk \Big/ \int_0^{E_0-\mu}\sigma_{\text{el}}(k,E_0)dk \quad (5)$$

is easily measured and is, in fact, a reasonable approximation of the theoretically defined quantity $F_T(k,E_0)$, provided k is chosen as described below. It should also be pointed out that F_{exp} as defined above cannot be calculated unless the matrix elements (which dropped out in Blair's calculation) are evaluated. However, two observations help to reconcile this difficulty.

(1) F_T is a slowly varying function of k.

(2) The principal contribution of (γ,n) cross sections has been experimentally observed to occur over a relatively small photon energy range. (This is discussed in Sec. VI.) Thus, for any given isotope there is an effective photon absorption energy k_0. Assuming $\sigma_{\text{el}}(k,E_0)$ to have a similar behavior, it is to be expected that

$$F_{\text{exp}}\simeq F_T(k_0,E_0)=\frac{g}{t_{\text{eff}}}\frac{\sigma_{\text{br}}(k_0,E_0)}{\sigma_{\text{el}}(k_0,E_0)}. \quad (6)$$

Therefore, the following procedure has been adopted in this experiment. F_T was averaged over the values of $k<(E_0-\mu)$ for which the (γ,n) cross section is finite, and it is this quantity which is compared with F_{exp}. This averaging is done by using the experimental results quoted in Sec. VI as follows:

$$\bar{F}_T=\int_0^{E_0-\mu}F\sigma_{\gamma,n}(k,E_0)dk \Big/ \int_0^{E_0-\mu}\sigma_{\gamma,n}(k,E_0)dk. \quad (7)$$

It would be ideal if the (γ,n) cross sections were known for each of the different types of excitation, i.e., electric dipole, magnetic dipole, and electric quadrupole. There are, however, no data available to do this. The above procedure is most likely to introduce the greatest error in the quadrupole case as it is expected that the largest contribution to the (γ,n) cross section is from electric dipole absorption.[13] Assuming that the error introduced by the above procedure is small compared to the difference between $\bar{F}_T$ for the different types of excitation, then a comparison of F_{exp} with the theoretical $\bar{F}_T$'s should show the relative importance to photodisintegration and to electrodisintegration of each type of excitation process.

The experiment was one of the "stacked foil" type in which an electron beam passed successively through a thin foil of the element being studied, a copper radiator to produce the bremsstrahlung, and a second thin foil. The resulting foil radioactivities were measured with thin-walled Geiger counters, and from the two observed activities w_1 and w_2 it can be shown that, with the aid of the simplifying assumptions stated below, F_{exp} is given by

$$F_{\text{exp}}=\left[\frac{(x_1/x_2)w_2-w_1}{w_1-k_zw_2}\right]\left(\frac{g}{t_{\text{eff}}}\right), \quad (8)$$

where

$$k_z=(hx_1^2)/2x_2t_{\text{eff}},$$

$$h\cong\frac{Z(Z+1)A_r}{Z_r(Z_r+1)A},$$

$$t_{\text{eff}}=t+[x_1+(x_2/2)]h,$$

and x_1=thickness of first foil in g/cm^2, x_2=thickness of second foil in g/cm^2, t=thickness of copper radiator in g/cm^2. A and Z are the atomic weight and atomic number of the foils and the subscript r refers to the copper radiator.

This equation makes the following assumptions:

(1) The electron beam current is not reduced in traversing the foils and radiator.

(2) The energy of the incident electrons is not reduced.

(3) The bremsstrahlung produced is neither absorbed nor scattered in traversing the remaining distance in the foils and radiator.

(4) There is no backward production of bremsstrahlung.

(5) Multiple scattering effects may be neglected.

(6) There is no gamma contamination in the initial electron beam.

(7) The foil and radiator thicknesses are perfectly uniform.

(8) The only radioactivity observed in the two foils is that due to the (γ,n) and the $(e,e'n)$ reactions.

(9) The efficiency in counting the first foil is exactly equal to that of counting the second foil.

As none of these assumptions can be exactly satisfied, experimental corrections were made when necessary and these will be discussed later.

By inspection of the equation for F_T it can be seen that the optimum difference between the three types of excitation occurs at $E_0\cong 2k_0$, where k_0 is the effective absorption energy for a (γ,n) reaction. k_0 is in the range of 14–18 Mev for all of the isotopes studied, which

[13] See for example, J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 656.

means that 28–36 Mev is the optimum initial electron energy. The experiment was performed over an energy range 24–34 Mev. The lower energy was determined by the uncertainty in the experimental corrections due to energy loss of the electrons between the first and second foils. The upper limit was determined by energy capabilities of the electron linear accelerator. It would be interesting to extend these experiments to both a higher and lower energy if the present limitations could be overcome.[14] A lower energy would give more information about what part of the excitation curve has the maximum magnetic dipole and electric quadrupole contributions; whereas, a higher energy would enable the electric quadrupole and magnetic dipole contributions to be separated. This can be seen by observing that in general the difference $F_T(\text{E.D.})-F_T(\text{E.Q.})$ increases as E_0 increases; whereas, $F_T(\text{E.D.})-F_T(\text{M.D.})$ increases for $E_0\rightarrow 2k$, but decreases for $E_0>2k$. It should be noted at this point that if the Weizsäcker-Williams approximation is used for both the bremsstrahlung formula and for representing the electromagnetic field of the electron, F_T is approximately $8\pi/3$ independent of E_0 and k. This has been shown by Blair.[5] Also it should be observed that $F_T\rightarrow 8\pi/3$ as $k\rightarrow 0$ for dipole absorption but is equal to zero for electric quadrupole absorption.

IV. EXPERIMENTAL ARRANGEMENT

The source of electrons for this experiment was a 35-Mev linear accelerator constructed by Post[15] and Shiren. This machine is pulsed 60 times per second, producing 10^8–10^9 electrons per pulse in a variable energy range of 10–35 Mev. The beam pulse length is about one microsecond.

A one-mil aluminum window was placed at the end of the accelerator so that the foils could be inserted in the target area without disturbing the accelerator vacuum. Beyond this window a wedge magnet bent the electron beam through a 12° angle into the target area. (See Fig. 1.) This magnet selected electrons of the desired energy from the energy spectrum and removed the gamma-ray contamination resulting from electrons striking the sides of the accelerator, the aluminum window, and the magnet chamber. The energy interval was defined to within one or two percent by collimating slits before and after the magnet. The first collimating slit of brass, 1/10 in. wide, was situated at the end of the accelerator and served as a mount for the one-mil aluminum window. The second slit, also 1/10 in. wide, was placed 40 inches beyond the analyzing magnet and was made of carbon to minimize electron scattering and gamma background. The second collimating slit and the analyzing magnet were positioned with respect to the first slit so as to make the horizontal energy focal point of the magnet coincide as nearly as possible with the second slit, thus maximizing the beam intensity. The magnification of the electron optical system was approximately two. The calculations for this system follow the methods of Camac.[16]

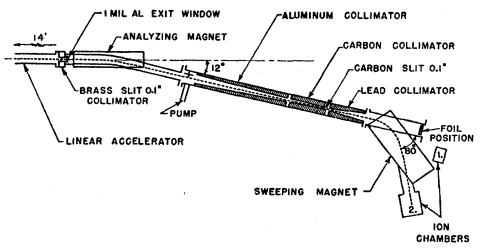

FIG. 1. Experimental arrangement for the activation of the Cu, Zn, Ag, and Ta foils.

Preceding the second slit (see Fig. 1) is a tapered collimator of aluminum designed to allow only those electrons coming from the desired direction to enter the second slit. Beyond the carbon slit is a tapered lead collimator, the purpose of which is to absorb the scattered electrons and gamma rays which are not traveling in the direction of the main electron beam defined by the brass and carbon slits.

Radiographs of the beam made at distances between 0 in. and 12 in. from the end of the lead collimator showed a readily explainable structure. By comparing the two radiographs, the slit image was observed to diverge at the rate to be expected from both the multiple scattering in the accelerator aluminum window and the analyzing magnet's focal properties. On either side of the slit image (main beam) there are bands which correspond geometrically to the electrons scattered at small angles from the aluminum collimators. A third radiograph was exposed at a position 12 in. away from the lead collimator with the electron beam deflected away from the film by a clearing field (magnet No. 2 in Fig. 1). The deflection occurred between the lead collimator and the film. Hence, the electron beam passed through the collimators and slits in a normal fashion but was not allowed to strike the film. The blackening of the film was, then, due entirely to gamma contamination which is normally present within the electron beam and clearly showed that most of the gamma contamination was in the "scatter bands." This fact was used to advantage to reduce the effective gamma background and will be discussed in Sec. V.

The fact that the central part of the beam was mid-way between the two "scatter bands" (on the second radiograph) demonstrated that the wedge magnet was correctly positioned. For first-order theory it can be shown that a slight error in magnet position would have no effect on the energy resolution, but it would shift the central beam relative to the scatter bands and would alter the energy calibration of the machine.

[14] Recently experiments have been performed at lower energies for Cu^{63}. See Scott, Hanson, and Kurst, Bull. Am. Phys. Soc. (New York Meeting) **29**, No. 1 (1954), Abstract JA2.

[15] Richard Freeman Post, Ph.D. dissertation, Department of Physics, Stanford University, June 1952 (unpublished).

[16] M. Camac, Rev. Sci. Instr. **22**, 197 (1951).

Energy Calibration

The beam was shown to have an energy spread of about three percent by taking a radiograph of the beam after it had passed through the collimators and had been deflected by the clearing field magnet. This is quite adequate for the experiment, as F_{exp} is a slowly varying function of energy. The beam energy was calibrated at 18.7 Mev by observing the threshold of the $C^{12}(\gamma,n)C^{11}$ reaction which is known from isotope mass data.[17] The calibration had an internal consistency of three percent which again is adequate for this experiment. The energy calibration was then extrapolated to 35 Mev using the *B-H* curves of the magnet.

Bombardment and Counting Procedure

The experimental procedure was as follows: The two foils and the copper radiator were placed in the vacuum chamber of the second magnet at a position approximately 12 in. from the carbon slit (immediately after the second magnet—see Fig. 1) and were bombarded for a definite period of time after which the foils were removed and inserted in Geiger counters. For fast counting rates, counting was delayed for at least one or two minutes after insertion of the samples in the counters to obviate an effect observed with argon alcohol-quenched counters whereby the counting rate is low by about three percent for the first minute. In the case of zinc a one-hour delay was imposed to allow some unwanted short-lived activity resulting from (γ,p) and (γ,pn) reactions to decay. The tantalum was allowed a 2–2½-hour delay to allow decay of activity resulting from a slight copper content in the aluminum foil holders. This was necessary because of the low tantalum counting rates. To cancel out the difference in efficiency of the two Geiger counters the samples were counted a second time interchanging the samples with respect to the Geiger counters and averaging the two counting rates after making a correction on the second count for the decay of the samples. The usual counter corrections for dead time and background were made.

In order to reduce errors due to spurious counting, the Geiger counters were operated with a multivibrator-quench unit, giving an electronically controlled dead time.

V. EXPERIMENTAL CORRECTIONS

Gamma-Ray Background

In spite of attempts to achieve a clean electron beam, a serious gamma background problem existed. Though the number of gammas in the beam was small compared to the electrons, the photodisintegration cross section is approximately 400 times as great as the electrodisintegration cross section. This gamma background was assessed by carrying out a second bombardment identical to the above except that the second magnet between the collimators and foils was energized, thus deflecting the electron beam away from the foils. Any induced activity in the foils which is of the correct half-life must, therefore, be due to the gamma contamination present in the initial electron beam. When this activity is normalized to the same incident electron beam as a regular bombardment, the background activity may be subtracted from the regular activity thus correcting for the gamma contamination.

The normalization to the same incident beam is achieved by monitoring both bombardments with ionization chambers as shown in Fig. 1. Chamber number one monitors the direct beam and chamber number two, the deflected beam. The ratio of the two chambers is determined by making a series of short runs while the electron beam current is steady—alternating with second magnet off then on (time on = time off), etc. By integrating the current collected in each chamber for equal time, the ratio is given by which the gamma background run may be normalized with the regular runs. To avoid ion recombination effects in the chambers as a result of the intense peak currents of the microsecond pulses, the ion chambers could not be used to monitor the beam directly but were used to monitor part of the scattered beam. As a result it was found that the internal consistency of the normalization procedure was good to only about ten percent. Since the gamma background was found to be of the order of twelve to twenty percent, the background correction has an uncertainty of about two percent.

As was expected, this background was found to depend rather critically upon the collimator alignment and was also found to increase with energy. Background bombardments were alternated with regular bombardments.

Correction for Foil Irregularities

The foils were cut from a large sheet of chemically pure metal with a die of diameter 1¼ in. Immediately around the 1¼-in. hole, several $\frac{3}{16}$-in. diameter pieces of foil were cut to check on the foil uniformity. These were weighed to 1/100 mg, and the results indicated that the copper, zinc, and silver foils were uniform to ± 1 percent and the tantalum to ± 2 percent. Since a large number of foils was used, the effect averages out in the final result; moreover, by pairing the foils so that in alternate runs their positions are interchanged, the error in F due to the nonuniformity can be shown to be reduced to less than ± 0.2 percent in all cases.

Corrections Due to Multiple Scattering

The electrons are incident normally upon the first foil. Yet they are multiply scattered in the first foil, radiator, and second foil resulting in an increase in path length or effective thickness of the foils and radiator. A correction factor must be made for this

[17] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York, 1947), p. 124.

effect. Using the methods of Yang[18] it is shown that this correction should have the form

$$1-k(21/E)^2,$$

where $k=0.020$, 0.017, 0.022, and 0.022 for copper, zinc, silver, and tantalum, respectively.

A second multiple-scattering correction arises as a result of the high gamma background. It has been mentioned previously that a large fraction of the gamma background is contained in the scatter bands of the beam. This fact was used to advantage to reduce the effective background by placing apertures over the Geiger counters in such a way as to shield the counters from the scatter-band activity of the foils. However, this leads to a second difficulty—fortunately a minor one. The beam is about 0.2 mm broader when striking the second foil than it was when striking the first foil as a result of multiple scattering in foil and radiator. Due to the aperture on the counters, this could and does lead to a slight reduction in efficiency of counting the second foil's activity. This effect is estimated to yield a correction factor of $1+[0.005(21/E)]$.

Corrections Due to Other Activities

Since the bombardments are performed at a high incident electron energy, reactions other than (γ,n) are possible. Also where there is more than one isotope in the element being bombarded, competing (γ,n) reactions of different isotopes may cause trouble. This is especially true in the case of silver. It is possible to discriminate against competing reactions in each case by an appropriate choice of the irradiation, delay before counting, and counting time. Moreover, such activities are not in themselves expected to have values of F far removed from the value of F of the desired reaction. Hence, the actual correction to F_{exp} will be much less than the proportion of the undesired activity present. Calculation shows that for our conditions no significant correction is needed except in the case of silver where the $Ag^{107}(\gamma,n)Ag^{106}$ 24.5-minute activity competes with the desired $Ag^{109}(\gamma,n)Ag^{108}$ 2.3-minute activity. By observing the ratio of the activities in the two silver foils as a function of time, it was verified that the necessary correction for the $Ag^{107}(\gamma,n)Ag^{106}$ contamination was $+1.01\pm0.005$, independent of energy. Experimental decay curves for each element were plotted and analyzed to show the expected background reactions; in every case but silver the conclusion was confirmed that the experimental correction necessary was less than ±0.5 percent.

Correction for Activity in Foil Holders

The target foils were mounted in aluminum holders to facilitate a reproducible geometry in both the bombardment and counting. The electron beam is not entirely localized in the foil area and some scattered electrons and gamma rays bombard the target holder. In the case of copper, zinc, and tantalum the holders were an aluminum alloy containing about 4-percent copper. The activity induced in the aluminum has a six to seven second half-life and is not observable after a two-minute delay between bombarding and counting. However, the copper contamination has a ten-minute half-life and is troublesome. For the tantalum runs a two-hour delay allowed the holder's copper activity to decay, but for copper and zinc a correction was made by bombarding and counting blank holders. This led to a small correction factor of the order of 0.5 percent. In the case of silver where it was important to count as soon as possible after bombarding, it was found necessary to make the foil holders out of pure 2S aluminum, thus eliminating all but the foil activity and the aluminum six to seven second activity.

Activity from Backscattered Electrons and Gamma Rays

The electron beam passes through the foils and then emerges upon a polystyrene block. The beam loses energy by ionization in this block without much scattering. There may still be some electrons or gamma rays backscattered from the walls of the second magnet chamber of such an energy that they can induce activity in the foils. An upper limit to this may be obtained by placing foils on the extreme edges of the polystyrene foil mount. Only scattered electrons can reach here. Since the backscattered intensity is certainly non-directional this is an upper limit to the backscattered intensity. The correction is about 1 percent and is shown in the table of results.

Corrections Due to Electron and Gamma-Ray Degradation

Ionization and radiative losses of the electrons combined with pair production and Compton effect losses of the gamma rays in the foils and radiator require a modification of the Bethe-Heitler[12] thin target bremsstrahlung spectrum.

Eyges[19] has calculated a thick-target spectrum by expanding the equations for an electron-initiated shower in powers of the radiator thickness, retaining only the first-order terms. One of the authors[20] has extended this calculation (using a different approach) to include the effects of electron ionization loss and electron energy loss due to radiation of low-energy quanta. Thus, the gamma-ray spectrum inducing activity in the foils will not be that predicted by the Bethe-Heitler equation, nor will the electron-induced activity be exactly that expected from monoenergetic electrons.

Wilson has shown that the equivalent thick-target bremsstrahlung cross section may be expressed to first

[18] C. N. Yang, Phys. Rev. 84, 599 (1951).

[19] L. Eyges, Phys. Rev. 81, 981 (1951).

[20] R. Wilson, Proc. Roy. Soc. (London) A66, 638 (1953).

order in the form

$$\phi'(E_0,k,t)=\phi(E_0-\tfrac{1}{2}\bar{\Delta},\,k)\times\left[1-\frac{Nt}{2A}\left(\int_{E_0-k-\mu}^{E_0-\mu}\phi(E_0,k')dk'+\sigma(k)\right)\right], \quad (9)$$

where $\phi(E_0,k)$ is the Bethe-Heitler cross section for the production of a quantum of energy k by an electron of total incident energy E_0; Nt/A is the number of target nuclei per cm^2; $\bar{\Delta}$ is the average of small energy losses of an electron in traversing a radiator of thickness t and may be expressed in the form

$$\bar{\Delta}=I+\frac{Nt}{A}\int_0^{E_0-k-\mu}k'\phi(E_0,k')dk', \quad (10)$$

where I is the ionization loss which may be taken from the calculations of Halpern and Hall.[21]

$\sigma(k)$ is the cross section for loss of gammas of energy k due to pair production and Compton effect. The integral term in the equation for ϕ' arises from the loss of "effective" electrons by large radiative transfers; these can never again radiate a quantum of energy k.

In order to apply these corrections to this experiment, it is necessary to average

$$[\phi(E_0,k)-\phi'(E_0,k,t)]/\phi(E_0,k) \quad (11)$$

over the values of $k<E_0-\mu$ for which the (γ,n) cross section is finite. The errors due to uncertainty in the shape of this cross section curve have been estimated and included as probable errors of the correction.

Thus far only the gamma induced activity has been discussed. A similar correction is necessary for the electron induced activity. Since the results of this experiment show that F is a slowly varying function of energy, this correction may be made by assuming that the electrons can be considered as a spectrum of "virtual quanta" as in the Weizsäcker-Williams approximation. The modified electron spectrum as a result of degradation has the form

$$\phi'(E_0,k,t)_{el}=\phi(E_0-\bar{\Delta},\,k)_{el}\left[1-\frac{Nt}{A}\int_{E_0-k-\mu}^{E_0-\mu}\phi(E_0,k')_{el}dk'\right] \quad (12)$$

which differs from the gamma spectrum correction case by the omission of $\sigma(k)$. The factor $\frac{1}{2}$ is also omitted since this is a first-order effect resulting directly from the electrons. The quantity

$$[\phi(E_0,k)_{el}-\phi'(E_0,k,t)_{el}]/\phi(E_0,k)_{el} \quad (13)$$

averaged over k thus determines the magnitude of the electron degradation correction.

The combination of these two effects amounts to a correction of from three to ten percent in F which becomes smaller as the energy of the bombarding electrons is increased. These corrections are shown in the table of results.

[21] O. Halpern and H. Hall, Phys. Rev. **73**, 477 (1948).

VI. ACTIVATION CURVES FOR PHOTONUCLEAR (γ,n) REACTIONS

Although a knowledge of the absolute (γ,n) cross sections is not required for this experiment, the relative shape of the cross section as a function of photon energy k is required in order (1) to average F_T over $\sigma_{\gamma,n}(k)$ so that a comparison with F_{exp} may be made and (2) to evaluate the electron and gamma degradation corrections to F_{exp}. Each of the isotopes studied will be discussed separately.

Several experiments have been performed on the photodisintegration of copper. The excitation curve as a function of photon energy for the $Cu^{63}(\gamma,n)Cu^{62}$ reaction has been studied by several investigators.[22–27] The peak absorption energy k_{max} as reported by these investigators is 22, 17.5, 18, 17.5, and 17.5 Mev, respectively; however, the authors differ about the shape of the excitation curve above k_{max}; i.e., whether or not there is a high-energy tail. Strauch,[28] Marshall,[29] and Koch *et al.*[30] have measured the effective excitation energy by absorption techniques. Strauch finds 18 Mev; Marshall reports 17.3 by Compton effect and 21.0 by pair production; and Koch *et al.* find 17.2 Mev. For the purposes of this experiment, an effective energy k_0 of 18.0±0.5 Mev is used. The excitation curve of Katz and Cameron is used with the restriction that there is an uncertainty about the high-energy tail. Katz and Cameron indicate the cross section to be essentially zero above 21 Mev; whereas, Newkirk's results indicate a tail extending to about 30 Mev. With these limits an error is assigned to the degradation corrections and the averaging of F_T.

There are far less data available on the excitation curve of the other elements, but the above results for copper, give some idea as to the reliability of such measurements. For the $Zn^{64}(\gamma,n)Zn^{63}$ reaction, results of Katz and Cameron,[24] Strauch,[28] and Marshall[29] are available. From these results it seems likely that the shape of the excitation curve is similar to copper. The effective absorption energy as determined by Strauch is 19 Mev. Marshall gives 16.6 via Compton effect and 20.0 via pair production. The peak of the Katz and Cameron excitation curve is at 18.7 Mev with the tail having the same behavior as copper. Corrections similar to copper are therefore used for zinc.

[22] G. C. Baldwin and G. S. Klaiber, Phys. Rev. **73**, 1156 (1948).
[23] B. C. Diven and G. M. Almy, Phys. Rev. **80**, 407 (1950).
[24] L. Katz and A. G. W. Cameron, Can. J. Phys. **29**, 518 (1951).
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[26] L. I. Newkirk, Phys. Rev. **86**, 249 (1952).
[27] V. E. Krohn and E. F. Shrader, Phys. Rev. **87**, 685 (1952).
[28] K. Strauch, Phys. Rev. **81**, 973 (1951).
[29] L. Marshall, Phys. Rev. **83**, 345 (1951).
[30] Koch, McElhinney, and Cunningham, Phys. Rev. **81**, 318 (1951).

TABLE I. Experimental results.

Element	F_{exp} (with standard deviation)	Multiple scattering path increases	Multiple scattering affecting counting efficiency	Other activities	Backscatter	Electron degradation (with standard deviation)	Gamma degradation (with standard deviation)	Total correction factor	F_{exp} (corrected) (with probable error)	Electron energy, E_0 (Mev)
Copper	8.11±0.30	0.985	1.004	1 ±0.005	1.01±0.005	1.063±0.021	1.036±0.012	1.108	8.99±0.24	24.5
	7.49±0.23	0.988	1.004	1 ±0.005	1.01±0.005	1.049±0.016	1.031±0.010	1.082	8.10±0.20	27.2
	7.05±0.20	0.990	1.003	1 ±0.005	1.01±0.005	1.027±0.009	1.024±0.008	1.054	7.44±0.16	30.8
	7.28±0.34	0.992	1.003	1 ±0.005	1.01±0.005	1.019±0.002	1.018±0.002	1.042	7.58±0.24	33.7
	6.62±0.18	0.993	1.003	1 ±0.005	1.01±0.005	1.015±0.002	1.015±0.002	1.036	6.85±0.13	35.3
Zinc	8.09±0.20	0.987	1.004	1 ±0.005	1.01±0.005	1.056±0.019	1.030±0.010	1.087	8.78±0.20	24.5
	7.26±0.12	0.991	1.004	1 ±0.005	1.01±0.005	1.028±0.009	1.022±0.007	1.055	7.66±0.11	29.2
	7.33±0.20	0.993	1.003	1 ±0.005	1.01±0.005	1.017±0.002	1.014±0.002	1.037	7.60±0.15	33.8
Silver	6.93±0.12	0.984	1.004	1.01±0.005	1.01±0.005	1.056±0.019	1.029±0.010	1.093	7.58±0.15	24.5
	7.04±0.07	0.987	1.004	1.01±0.005	1.01±0.005	1.035±0.012	1.025±0.008	1.071	7.54±0.10	27.8
	6.59±0.18	0.990	1.003	1.01±0.005	1.01±0.005	1.025±0.003	1.021±0.003	1.059	6.97±0.13	30.8
	6.01±0.14	0.991	1.003	1.01±0.005	1.01±0.005	1.018±0.002	1.018±0.002	1.050	6.31±0.10	33.7
Tantalum	5.93±0.33	0.983	1.004	1 ±0.005	1.01±0.005	1.043±0.008	1.018±0.003	1.058	6.27±0.24	24.0
	5.12±0.25	0.989	1.004	1 ±0.005	1.01±0.005	1.027±0.003	1.015±0.002	1.045	5.35±0.18	29.6
	5.10±0.17	0.991	1.003	1 ±0.005	1.01±0.005	1.019±0.002	1.014±0.001	1.037	5.29±0.12	33.7

For the $Ag^{109}(\gamma,n)Ag^{108}$ reaction, there seem to be only the data of Diven and Almy[23] available. These data show a peak excitation energy of 16 Mev with a pronounced dropoff of the tail at 20 Mev. However, the uncertainty in their results in this region (20–22 Mev) necessitates an introduction of a large estimated probable error to the degradation correction at low energies.

For $Ta^{181}(\gamma,n)Ta^{180}$ the effective excitation energy is lower. Strauch[28] reports a value of 19 Mev, but believes that it is high. This belief is verified by Katz and Cameron who find a peak excitation energy of only 13.9 Mev with the excitation curve dropping to zero around 20–22 Mev. The Katz and Cameron results are used for this experiment.[24]

The copper, zinc, silver, and tantalum excitation curves used in this experiment are summarized in Fig. 2.

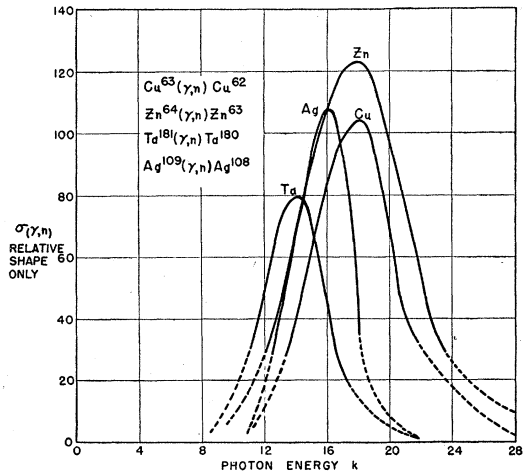

FIG. 2. Photoneutron excitation curves showing the effective photon absorption energy k_0 adopted for this experiment.

It should be emphasized that the curves in this graph indicate only the relative shape, and no inference of relative values of the cross sections for the different elements should be made from them.

VII. RESULTS

The results of this experiment are shown in Table I and in Figs. 3–6. The first column of Table I shows the results obtained from reducing the raw counting data using the formula for F_{exp}. The standard deviation shown with this value of F_{exp} is obtained from the internal consistency of a series of runs at each energy. These include the errors due to foil irregularities, counting statistics, errors of alignment in bombarding and counting geometries, and uncertainty in the gamma

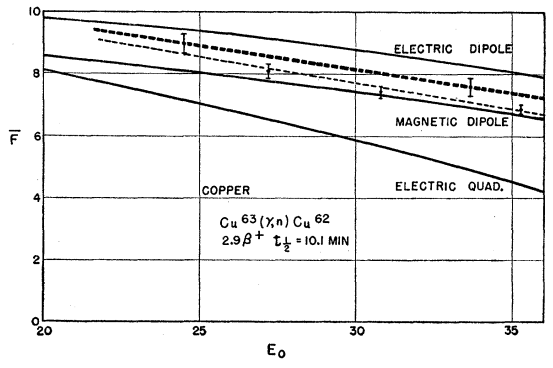

FIG. 3. $\bar{F}_T$ and F_{exp} as a function of initial electron energy E_0 (total energy in Mev). The dashed curves correspond to an effective value of F which assumes the (γ,n) cross section to be 88 percent electric dipole excitation and 12 percent electric quadrupole. The heavy dashed curve assumes the effective excitation energy of the quadrupole cross section to correspond with that of the electric dipole cross section, whereas the light dashed curve assumes the effective quadrupole excitation energy to be 4 Mev lower than that of the electric dipole cross section.

background measurements. A total of 32 copper, 21 zinc, 35 silver, and 17 tantalum activations were carried out, making an average of six for each element at a given energy. Two gamma background runs were made for every three regular runs.

The copper radiator was 1/60 of a radiation length thick, and the foils were approximately 1/340, 1/720, 1/300, and 1/600 radiation length thick for copper, zinc, silver, and tantalum, respectively. With this size radiator, it was found that the ratio of the observed activity in foil two to foil one was of the order of two.

The last column in Table I shows the experimental value of F after the various corrections have been made. The in between columns indicate the size of each correction. The gamma background and foil holder activity corrections are not shown here as they were subtracted directly from the counting data before evaluating F_{exp} in column four.

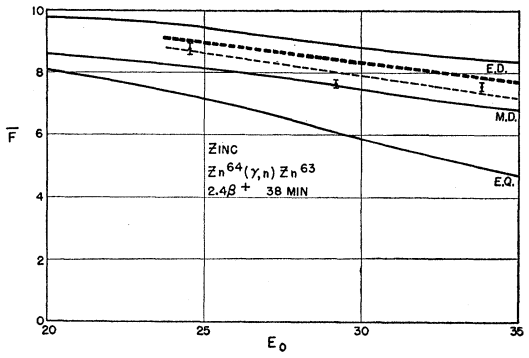

FIG. 4. $\bar{F}_T$ and F_{exp} as a function of initial electron energy E_0 (total energy in Mev). The dashed curves correspond to an effective value of F which assumes the (γ,n) cross section to be 88 percent electric dipole excitation and 12 percent electric quadrupole. The heavy dashed curve assumes the effective excitation energy of the quadrupole cross section to correspond with that of the electric dipole cross section, whereas the light dashed curve assumes the effective quadrupole excitation energy to be 4 Mev lower than that of the electric dipole cross section.

It is the corrected values of F_{exp} with their probable error which are shown in Figs. 3, 4, 5, and 6 as the experimental points. The theoretical curves are those obtained by averaging F_T over the respective (γ,n) cross sections to obtain what has been defined as $\bar{F}_T$.

VIII. DISCUSSION

There are several conclusions which may be drawn from these results.

(1) As has been stated previously, if the photodisintegration cross section is known, the Weizsäcker-Williams method may be used to approximate the electrodisintegration cross section. This method predicts a theoretical value of $F=8\pi/3$ independent of E_0 and k and hence independent of E_0 and Z. By observing Figs. 3–6 it is seen that the Weizsäcker-Williams approximation underestimates the electrodisintegration cross section in comparison with the photodisintegration, but that it yields a result which is within a factor of two of the observed value for tantalum and agrees more closely as Z and E_0 decrease. For copper, zinc, and silver the Weizsäcker-Williams value agrees with the experimental results within 10–15 percent.

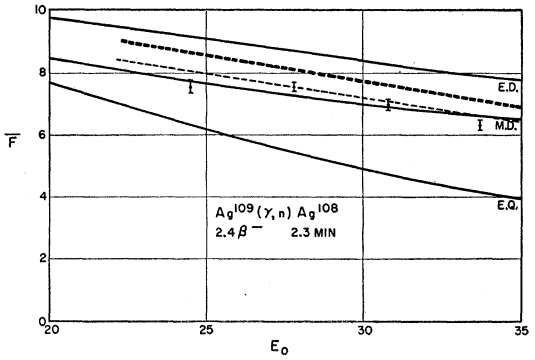

FIG. 5. $\bar{F}_T$ and F_{exp} as a function of initial electron energy E_0 (total energy in Mev). The dashed curves correspond to an effective value of F which assumes the (γ,n) cross section to be 88 percent electric dipole excitation and 12 percent electric quadrupole. The heavy dashed curve assumes the effective excitation energy of the quadrupole cross section to correspond with that of the electric dipole cross section, whereas the light dashed curve assumes the effective quadrupole excitation energy to be 4 Mev lower than that of the electric dipole cross section.

(2) Levinger and Bethe[31] suggest that the main absorption mechanism of nuclei for photons is electric dipole absorption. Using the so-called "sum rules," these authors calculate the integrated photonuclear cross section for dipole absorption to be

$$\int_0^\infty \sigma_{\text{total}}(k)dk \cong 0.044Z \text{ Mev barns}, \qquad (14)$$

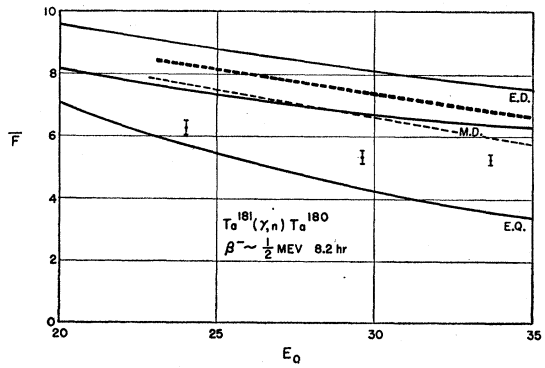

FIG. 6. $\bar{F}_T$ and F_{exp} as a function of initial electron energy E_0 (total energy in Mev). The dashed curves correspond to an effective value of F which assumes the (γ,n) cross section to be 88 percent electric dipole excitation and 12 percent electric quadrupole. The heavy dashed curve assumes the effective excitation energy of the quadrupole cross section to correspond with that of the electric dipole cross section, whereas the light dashed curve assumes the effective quadrupole excitation energy to be 4 Mev lower than that of the electric dipole cross section.

[31] J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950).

where Z is the atomic number of the element. In addition they estimate the total quadrupole absorption to be of the order of 6 percent of the total dipole absorption. By σ_{total} is meant the sum of the cross sections for all such processes as (γ,n), (γ,p), $(\gamma,2n)$, etc. Comparing the value of their integral with the experimentally determined (γ,n) cross sections, it appears that about one-half of the total photon absorption may be attributed to the (γ,n) reaction for the case of Cu^{63}, Zn^{64}, and possibly Ag^{109}. In addition to this there is evidence that electric dipole absorption may be forbidden just above threshold especially in isotopes where the threshold is far below the main dipole absorption peak,[32] whereas electric quadrupole absorption may occur under these conditions. For example, the data of Krohn and Shrader[27] show two peaks—at 13 and 17 Mev; we suggest that the lower energy peak may be due to the quadrupole excitation and the higher energy peak, to dipole excitation.

This suggests that the electric quadrupole contribution to photonuclear absorption is predominately to the (γ,n) reaction. It is expected, therefore, that about 12 percent of the total (γ,n) cross section is due to electric quadrupole excitation. From this and from the definition of F, it follows that the effective value of F would be

$$F_{\text{eff}}=(F_{\text{E.D.}})(F_{\text{E.Q.}})/(0.12F_{\text{E.D.}})+(0.88F_{\text{E.Q.}}). \quad (15)$$

The dashed curves in Figs. 3–6 correspond to the F_{eff} evaluated by this equation. The heavy dashed curve having the larger value of F_{eff} assumes that the effective excitation energy for the quadrupole cross section corresponds to that of the electric dipole, whereas the lower curve (light dash) assumes the effective quadrupole excitation to be $\sim$4 Mev lower than the dipole peak. Inasmuch as the excitation near threshold is predicted to be predominately quadrupole, this lower peak value is a reasonable assumption and comparison of this curve with the experimental points gives a surprisingly good check for copper, zinc, and silver. However, for tantalum the experimental points are low and the question arises as to whether this is a failure of the Blair theory[5] or whether the electric quadrupole excitation becomes more important for higher Z elements. There is no evidence at the present time to indicate that the latter should be the case; thus, a discussion of the Blair theory is appropriate. It should be pointed out beforehand that no mention has been made of the contribution of magnetic dipole excitation. The magnetic dipole cross section is expected to be small compared to the electric dipole cross section but may be comparable to the electric quadrupole cross section.[13] However, by inspection of F_{eff}, which was obtained by a weighted averaging of electric dipole and quadrupole effects, it is seen that F_{eff} is insensitive to the addition of any reasonable contribution of magnetic dipole excitation for all elements studied except tantalum, and therefore it does not influence the results for Cu, Zn, and Ag.

Blair's calculation was made in the Born approximation assuming a compound-nucleus model. The electromagnetic effect of the electrons was represented by use of the Møller potentials which is equivalent to the use of plane wave solutions for both the incoming and outgoing electrons.

The amount of error introduced into the theory by using the Born approximation, by using plane waves to represent the electron even at the nucleus, by assuming a point nucleus, and by using the long-wavelength approximation for multipole moments is uncertain and can probably be determined only by devising a better theory. Blair[5] estimates that these effects restrict the accuracy of his calculations to a 10 percent theory. The Born approximation is expected to be better for low Z elements and this may well account for the fairly good agreement of experiment with theory for copper, zinc, and silver and the disagreement for tantalum.

ACKNOWLEDGMENT

The authors are indebted to Professor W. K. H. Panofsky for his valuable discussions and suggestions which have so greatly contributed to the completion of this research. Generous assistance during the latter phases of the experimental work was given by Arthur Berman.

[32] See for example, K. Strauch, *Annual Reviews of Nuclear Science* (Annual Reviews Inc., Stanford, California, 1953), Vol. 2, p. 110.