integrated cross section of the $Ca^{40}(\gamma,np)K^{38g}$ reaction, the total integrated cross section from 140 to 300 MeV for the $Ca^{40}(\gamma,np)$ reaction is calculated to be 106 ± 32 MeV-mb.

The values for the total integrated cross sections from 140 to 300 MeV for the (γ,np) reactions in S^{32}, Ca^{40}, and Zn^{66} are 109 ± 14, 106 ± 32, and 240 ± 65 MeV-mb, respectively. From considerations similar to those out lined in Sec. B for the $S^{32}(\gamma,np)P^{30}$ reaction, we can estimate the contributions to these integrated cross from quasideuteron-associated processes. In all cases, this estimated contribution is small (25% or less) compared to the observed (γ,np) integrated cross sections. Thus, the main contribution appears to be due to meson-associated processes in all cases. The much larger integrated cross section for the Zn^{66} case thus reflects the increased meson production cross section in the heavier nucleus.[35,36] Again, however, the absence of detailed information about the fraction of the meson emission processes that leads to the (γ,np) product prohibits us from making a quantitative comparison at this time.

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Electrodisintegration of Nuclei by Positrons and Electrons*

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The ratio σ^-/σ^+ of the cross sections for electrodisintegration of nuclei by electrons and positrons has been measured at 27 MeV for target nuclei of ^{12}C, ^{63}Cu, ^{107}Ag, and ^{181}Ta. For ^{12}C and ^{107}Ag the ratio was measured as a function of energy in the region of the giant resonance. The ratio σ^-/σ^+ was determined from activities induced in thin foils which were bombarded by electrons and positrons from an electron linear accelerator. The measured ratio σ^-/σ^+ appears to vary linearly with Z and to be independent of energy in the range covered. The results may be used to estimate the extent to which the plane-wave theory of electrodisintegration fails because of the Coulomb distortion of the electron wave function.

I. INTRODUCTION

THE disintegration of a nucleus by the passage of a fast electron (electrodisintegration) has proved to be an important tool in investigating the nuclear photoeffect. The phenomenon of electrodisintegration is related to the disintegration of a nucleus by real photons as was pointed out by Weizsäcker[1] and Williams[2] in the first theoretical work on this subject. Weizsäcker and Williams considered the nucleus as a point charge and assumed the electron was undeflected as it passed the nucleus. The time-varying electric and magnetic fields seen by the nucleus as a result of the passage of the electron were Fourier-analyzed and a flux of virtual photons was calculated using the Poynting theorem. The cross section for electrodisintegration was then calculated assuming that the flux of virtual photons interacts with the nucleus via the conventional photonuclear process.

Later, Blair[3] and others[4] improved the theory of electrodisintegration by performing Born-approximation calculations using the Møller potential to describe the interaction of the nuclear charge and current with the electron. The ingoing and outgoing electrons were represented by plane waves, the nucleus was assumed to be a point, and the reaction was assumed to take place via a compound nuclear state. These calculations showed that the cross section for electrodisintegration relative to that for photodisintegration can be expressed as a

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[1] C. F. von Weizsäcker, Z. Physik **88**, 612 (1934).
[2] E. T. Williams, Phys. Rev. **45**, 729 (1934); also Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **13**, No. 4 (1935).
[3] J. S. Blair, Phys. Rev. **75**, 907 (1949).
[4] H. Bethe and R. Peierls, Proc. Roy. Soc. (London) **148**, 146 (1935); B. Peters and C. Richman, Phys. Rev. **59**, 804 (1941); G. C. Wick, Ric. Sci. **11**, 49 (1940); I. N. Sneddon and B. F. Touschek, Proc. Roy. Soc. (London) **A193**, 344 (1948); J. A. Thie, C. J. Mullin, and E. Guth, Phys. Rev. **87**, 962 (1952).

function of the energy transferred to the nucleus and the multipole order of the transition involved. Barber,[5] using the formulation of Dalitz and Yennie,[6] has made estimates of the corrections resulting from the inclusion of nuclear-size effects.

Many measurements of the ratio of the cross section for electrodisintegration to that for photodisintegration have been performed with the aims of checking the validity of the electrodisintegration theories and determining the multipolarity of the transitions responsible for the giant resonance of the nuclear photoeffect.[5,7,8] For light and medium-weight nuclei, the results indicate that the giant resonance is predominantly dipole, either electric or magnetic. The good fit to these data with a mixture of approximately 90% electric dipole and 10% electric quadrupole is felt to be consistent with the theoretical descriptions of the giant resonance which successfully explain a large amount of photonuclear-reaction data. However, for heavy nuclei such as gold and tantalum, the measured ratios are higher than the theoretical predictions for a pure electric-dipole interaction by about 20 to 30%.

Barber and Wiedling[8] have discussed three possible explanations for the large disagreement between the theoretical electric-dipole prediction and the experimental results for high-Z nuclei: (1) The intensity of quadrupole transitions in the giant resonance energy region is about equal to the intensity of dipole transitions; (2) the cross section for monopole transitions, which may possibly result from the large monopole resonance proposed by Danos,[9] is 25 or 30% of that for dipole transitions; and (3) the electrodisintegration theory is in error. Barber and Wiedling present arguments that the first two considerations are unlikely and suggest that the third explanation deserves further investigation since the theory neglects the distortion of the electron wave function by the Coulomb field of the nucleus. This explanation seems most likely since Coulomb distortion would be most important for high-Z nuclei and this is where the greatest discrepancy exists between experiment and theory.

In the present work, measurements of the ratio σ^-/σ^+ of the cross sections for the electrodisintegration of nuclei by electrons and by positrons were performed for the purpose of investigating the importance of the Coulomb distortion of the electron wave function in the electrodisintegration process. The departure of σ^-/σ^+ from unity may be considered as a direct measure of the error in the electrodisintegration theory resulting from the neglect of Coulomb distortion effects.

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[6] R. H. Dalitz and D. R. Yennie, Phys. Rev. **105**, 1598 (1957).
[7] K. L. Brown and R. Wilson, Phys. Rev. **93**, 443 (1954); M. B. Scott, A. O. Hansen, and D. W. Kerst, Phys. Rev. **100**, 209 (1956); R. L. Hines, Phys. Rev. **105**, 1534 (1957); L. S. Skaggs, J. S. Laughlin, A. O. Hansen, and I. I. Orlin, Phys. Rev. **73**, 420 (1958).
[8] W. C. Barber, and T. Wiedling, Nucl. Phys. **18**, 575 (1960).
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II. EXPERIMENTAL PROCEDURE

The technique used for this experiment consisted of measuring the activity induced in a thin target foil when bombarded with positrons and then electrons. The activity of the product nuclei from electrodisintegrations in which single neutrons were emitted was counted in a low-background beta counter. After appropriate corrections were applied to the data, the ratio of the activity induced by electrons to that induced by positrons gave the desired ratio σ^-/σ^+ for electrodisintegration.

A schematic drawing of the experimental arrangement is shown in Fig. 1. Beams of positrons and electrons were obtained from the General Atomic electron linear accelerator (LINAC), which is equipped with a positron acceleration system. Low-energy ($\sim$1 to 2 MeV) positrons and electrons produced by bombarding a converter with the intense electron beam from the first section of the LINAC are focused into the following section of the accelerator. Either positrons or electrons from the converter may be accelerated to the desired energy by adjusting the phase and power of the rf applied to the last two accelerator waveguides. Details of this positron acceleration system have been reported previously.[10]

After leaving the accelerator, the beam is translated by two 36° sector magnets as shown in Fig. 1. The energy of the beam is determined by the magnetic field of the first magnet and its entrance and exit slits. An nmr gaussmeter is used to measure the field strength of this magnet. The energy analyzer was calibrated by measuring the magnetic field strengths at which the thresholds for the $^{12}C(\gamma,n)\,^{11}C$ and $^{63}Cu(\gamma,n)^{62}Cu$ reactions occurred. For this experiment the exit slits were set to give a beam energy resolution $\Delta E/E$ of $\sim$2%. The beam is focused by the 36° magnets into a spot having a diameter of less than 1.9 cm at the position of the target foil which is just beyond the 2.5-m-thick shielding wall shown in Fig. 1. After passing through the target foil, the beam is swept by a magnet through an angle of 45° into a Faraday cup. Alignment of the beam is accomplished by steering the beam with trimmer magnets through a 1.9-cm-diam hole in an aluminum collimator located immediately in front of the target foil. The

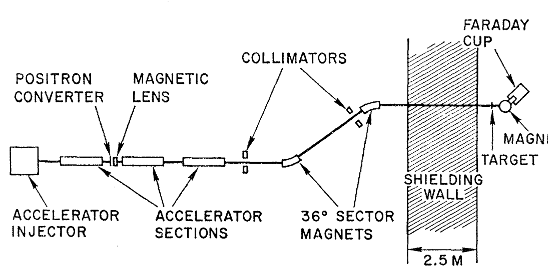

FIG. 1. Schematic of experimental arrangement.

[10] R. E. Sund, R. B. Walton, N. J. Norris, and M. H. MacGregor, Nucl. Instr. Methods **27**, 109 (1964).

collimator is electrically insulated from the beam tube so that the current striking it may be read directly. Both the collimator and the target holder are mounted in the vacuum of the beam tube assembly, and each may be retracted by remote control to a position well out of the beam path.

Prior to each irradiation, a fresh target foil was mounted in the target holder and retracted out of the beam path, while the beam was aligned with the aid of the collimator. Then the collimator was retracted, and the target foil was lowered into the beam path and irradiated with positrons or electrons until a preset amount of charge was collected in the Faraday cup, as indicated by a "leaky" current integrator.[11] The RC time constant of this integrator was set equal to the mean life of the activity being observed in order to compensate automatically for fluctuations in the beam current. After the termination of a bombardment, the target was removed from the vacuum and transferred to the low-background proportional counter, where the β activity was determined. Great care was taken to assure that beam conditions and target orientation were identical for both electron and positron bombardments.

Elemental samples of C, Cu, Ag, and Ta with thicknesses of 0.041, 0.0038, 0.0025, and 0.0013 cm, respectively, and a diameter of 3.8 cm were used for targets. The β activities of ^{11}C (20.5-min half-life), ^{62}Cu (9.9 min), ^{106}Ag (24 min), and ^{180m}Ta (8.1 h) were measured.

There are two mechanisms by which activity is induced in a target foil when it is bombarded by electrons. One is by electrodisintegration and the other by bremsstrahlung which is generated by the slowing down of the electron in the target. The number of bremsstrahlung-induced reactions per incident electron is proportional to the square of the target thickness while the number of electrodisintegration reactions per incident electron depends linearly upon the target thickness. In this experiment, the number of bremsstrahlung-induced reactions was made small ($<10\%$) compared with the number of reactions due to electrodisintegration by choosing a sufficiently thin target. Corrections were applied for the small amount of bremsstrahlung-induced activity.

In the case of bombardment with positrons, an additional source of activity was present due to the positron-annihilation radiation produced in the target. Again, this effect depends upon the square of the target thickness and was usually small for the targets used in this experiment.

Positrons may also excite the nucleus by means of inverse internal conversion,[12] a process in which a fast positron annihilates with a K-shell electron giving rise to a virtual photon with energy equal to the total energy of the positron plus the rest mass of the electron less its binding energy in the K shell. The virtual photon excites the nucleus which subsequently may decay by emitting a neutron. For bombarding energies used in this study, the cross section for this process is approximately equal to $\alpha_K(k)\sigma(\gamma,n)$, where $\alpha_K(k)$ is the K-shell internal conversion coefficient for a photon of energy k, and $\sigma(\gamma,n)$ is the photonuclear cross section. Because of the high excitation energy of the states in the giant-resonance region, $\alpha_K(k)$ is small ($\sim10^{-4}$ to 10^{-5} for Ta). Since the electrodisintegration cross section is of the order of $(1/137)\,\sigma(\gamma,n)$, the excitation of the nucleus by inverse internal conversion is expected to be less than 1% of that due to electrodisintegration and hence not observable in this experiment.

[11] S. C. Snowden, Phys. Rev. **78**, 299 (1950).

[12] R. D. Present and S. C. Chin, Phys. Rev. **85**, 447 (1952). We wish to thank Professor W. C. Barber and Dr. C. Tzara for calling this to our attention.

III. DATA REDUCTION

In this section, the technique used to obtain the corrections for the activity induced by bremsstrahlung and by the annihilation γ rays is discussed.

Let A^- be the activity induced by the passage of the electron beam through the target foil. Then

$$A^- = A_{e^-} + A_b,$$

where A_{e^-} is the activity due to electrodisintegration and A_b is the bremsstrahlung-induced activity. We define $f = A_b/A_{e^-}$ and obtain:

$$A^- = A_{e^-}(1+f)$$

Let A^+ be the activity induced by the passage of the positron beam through the target foil. Then

$$A^+ = A_{e^+} + A_b + A_a,$$

where A_{e^+} is the activity due to electrodisintegration and A_a is that due to the annihilation radiation. We assume the bremsstrahlung contribution is the same for positrons and electrons.

From the above relationships we obtain, noting that $\sigma^\pm \propto A_{e^\pm}$:

$$\sigma^-/\sigma^+ = A_{e^-}/A_{e^+} = (A^-/A^+)(1/(1-C)),$$
$$C = f[(A^-/A^+)(1+(A_a/A_b))-1].$$

The correction term C is usually small and can be readily evaluated. From the work of Brown and Wilson,[7] we obtain

$$f = \frac{Z(Z+1)r_0^2 N_0 \tau F}{2A},$$

where Z is the atomic number of the target nucleus, r_0 the classical electron radius, N_0 Avogadro's number, A the atomic weight of the target, and τ the target thickness in g/cm^2. The quantity F has been determined by Barber[8] for C^{12} and by Brown and Wilson[7] and Skaggs *et al.*,[7] for the other targets used in this experiment.

The annihilation term A_a/A_b was evaluated as follows:

$$A_a/A_b = Z\int_{E_{\rm th}}^{E_{\rm max}} (d\sigma/dk)_a \sigma(\gamma,n)dk \Big/ \int_{E_{\rm th}}^{E-m_0c^2} (d\sigma/dk)_b \sigma(\gamma,n)dk\,,$$

where $\sigma(\gamma,n)$ is the photoneutron cross section of the target nucleus; $(d\sigma/dk)_b$ is the screened Bethe-Heitler differential cross section for the production of a bremsstrahlung x ray of energy k by an electron of total energy E; $(d\sigma/dk)_a$ is the differential cross section for the production of an annihilation γ ray with energy k; and $E_{\rm th}$ is the threshold energy of the (γ,n) reaction. The integral in the numerator was evaluated over the range of γ-ray energies for which the integrand was appreciable. The energy of the annihilation γ ray is a sensitive function of the angle at which the γ ray is emitted with respect to the forward direction, and $(d\sigma/dk)_a$ falls rapidly with k and hence θ. Therefore, in calculating the annihilation activity correction, it is necessary to consider only those γ rays emitted at very small angles, less than 8° in all cases considered in this experiment. Values of $(d\sigma/dk)_a$ were obtained from a computer calculation using a formula derived from the work of Kendall and Deutsch.[13]

IV. RESULTS AND EXPERIMENTAL UNCERTAINTIES

The ratio σ^-/σ^+ for carbon versus total energy of the bombarding particles is shown in Fig. 2. It is apparent that the ratio is consistent with unity throughout the energy range covered.

In Fig. 3 is shown the ratio σ^-/σ^+ versus energy for silver. The ratio, within experimental error, is independent of energy over the range covered and has an average value of 1.24 ± 0.04.

In Fig. 4, the ratio σ^-/σ^+ at 27 MeV for carbon, copper, silver, and tantalum is plotted as a function of Z. It is apparent that within the experimental uncertainties, the data for the ratio σ^-/σ^+ can easily be fitted with a linear function of Z.

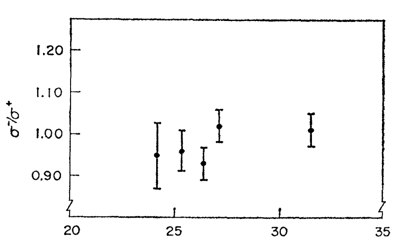

FIG. 2. The ratio σ^-/σ^+ as a function of energy for a ^{12}C target.

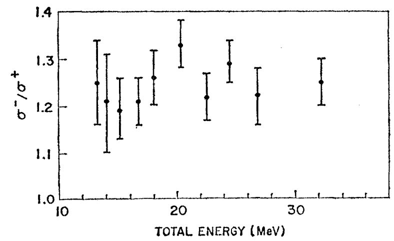

FIG. 3. The ratio σ^-/σ^+ as a function of energy for a ^{107}Ag target.

The total rms uncertainties are indicated by the error bars on the data points in Figs. 2 to 4. The corrections applied to the observed ratio A^-/A^+ for activation by bremsstrahlung radiation were always less than 5% and the uncertainty introduced in σ^-/σ^+ by this correction was negligible ($<1\%$). Except for the cases of C and Ag at the lower energies, the correction for the activation by annihilation radiation was also small and resulted in uncertainties in σ^-/σ^+ less than 2%. At the lower energies, where the energy of the annihilation gamma rays approached the energy of the giant resonance, this correction ranged from 20 to 30% for the carbon data and from 10 to 15% for the silver data. To calculate these corrections, the Livermore data[14] for the ^{12}C(γ,n) cross section and the data of Mutsuro *et al.*,[15] for the ^{107}Ag(γ,n) ^{106}Ag cross section were used. The estimated uncertainty introduced in the ratio σ^-/σ^+ by the correction for annihilation gamma rays at the lower energies is 10% for the carbon data and 5% for the silver data.

The uncertainty assigned to the collection and integration of the beam current is 4%. Most of the electron bombardments were performed with an electron beam current an order of magnitude larger than the positron beam current in order to obtain a larger number of activations. The principal uncertainty in the beam-

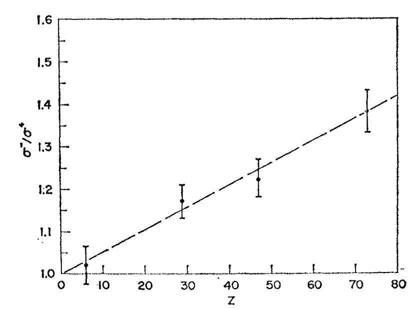

FIG. 4. The ratio σ^-/σ^+ as a function of atomic number at 27-MeV (total) bombarding energy. The straight line is for comparison purposes.

[13] H. W. Kendall and M. Deutsch, Phys. Rev. **101**, 20 (1956). See also F. D. Seward, C. R. Hatcher, and S. C. Fultz, Phys. Rev. **121**, 605 (1961).

[14] S. C. Fultz, J. T. Caldwell, R. R. Harvey, and R. L. Bramblett, Bull. Am. Phys. Soc. **9**, 381 (1964), and R. L. Bramblett, private communication, May, 1964.

[15] N. Mutsuro, Y. Ohnuki, K. Sato, and M. Kimura, J. Phys. Soc. Japan **14**, 1649 (1959).

current integration resulted from the cross calibration of the integrator scales used for the two different beam intensities.

A possible source of error, which was investigated and found to be unimportant in this experiment, was the scattering of the beam out of the collector cup by the target. This effect was observed by raising and lowering the target while monitoring the beam intensity. For the Ag target, it was observed that only 2% of the beam at 27 MeV and 7% at 13 MeV was scattered out of the collector cup. The amount of beam scattered out was essentially the same for both the positron and electron beams. Consequently, this effect does not contribute an uncertainty in the measurement of σ^-/σ^+.

The principal errors associated with determining the target activity were those due to the statistical uncertainty of the decay process. Generally these uncertainties were less than 3%. Background counts were small and could be easily measured and subtracted to obtain the target activity. The counter sensitivity was monitored throughout the experiment by counting a standard source.

Bremsstrahlung contamination of the bombarding beam was checked by removing the target from the usual position and placing it on the beam axis behind the sweep magnet. The foil, exposed in this position, showed no detectable activity, indicating that the bremsstrahlung contamination of the beam was negligible.

V. CHECK FOR LARGE SYSTEMATIC ERRORS

As a check on the existence of any large, systematic errors, a measurement of σ^-/σ^+ for silver at 27 MeV was made using the stacked-foil technique. In this technique the beam first strikes a thin target foil, then a high-Z radiator for the production of bremsstrahlung, and finally another thin foil similar to the first one. The activity in the front foil is due primarily to electrodisintegration while that in the rear foil is due primarily to the bremsstrahlung produced by the passage of the beam through the high-Z radiator. For this experiment the composite of foils consisted of a 0.0025-cm silver foil, a 0.025-cm lead foil, and a 0.0025-cm silver foil. The foils were first exposed to the positron beam and then to the electron beam. By using the bremsstrahlung-induced activity in the third foil as a beam monitor, the ratio σ^-/σ^+ was obtained in a straightforward manner.

A disadvantage of this technique is that the rear foil activity must be corrected for the electrodisintegration activity and, in the case of positron bombardment, for the effects of the annihilation radiation. By using this technique, however, it is possible to measure σ^-/σ^+ without relying on the current integration system described earlier. After correcting for the above-mentioned effects, a value of σ^-/σ^+ of 1.21 ± 0.08 was obtained as compared with a value of 1.22 ± 0.05 obtained by the single-foil technique. The fact that the ratio σ^-/σ^+ obtained by the two different techniques agrees within experimental error suggests that no large systematic errors are present in the experiment.

VI. DISCUSSION

The results of this experiment confirm that the plane-wave theory of electrodisintegration is valid only for light nuclei. In particular, the results indicate that the cross sections for the electrodisintegration of Ta and Au by electrons could be higher than the predictions of the plane-wave theory by about 20%, assuming the effects of Coulomb distortion are symmetric for positrons and electrons. Barber and Wiedling[8] state that their results for Ta and Au are consistent with a pure electric-dipole transition, if the plane-wave theory is too low by 20 or 30%. Noting that quadrupole transitions can contribute only about 6% to the total transition strength for heavy nuclei,[16] it appears that the electrodisintegration data can be explained on the basis of the currently accepted ideas concerning the nuclear photoeffect.

As yet, a theory of electrodisintegration which takes into consideration the Coulomb distortion of the electron wave function has not been developed. Such a theory would certainly be more complicated than the plane-wave theory owing to the difficulties involved in calculating the exact wave functions. Until a better theory is developed, the results of this experiment may be used to estimate the extent to which the plane-wave theory fails because of Coulomb distortion of the electron wave function.

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