Ewald's value for the mass of Ne^{22}, and in the agreement with Middleton's range measurement[15] of the energy of the alpha-particles from $Ne^{22}(d,\alpha)F^{20}$.

We are grateful to Civ. Ing. S. Thulin, Nobel Institute of Physics, for preparing the targets, to Professor W. W. Buechner for valuable advice on his experience with neon targets, and to Mr. H. H. Woodbury of this laboratory for assistance in exposing the plates.

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[15] R. Middleton and C. T. Tai, Proc. Phys. Soc. (London) **A64**, 801 (1951).

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The Beta-Decay of F^{20}†

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The beta-decay of F^{10} has been investigated with a lens spectrometer using sources activated by the $F^{19}(d,p)F^{20}$ reaction. A simple beta-ray spectrum of allowed shape is observed having an end-point energy of 5.406±0.017 Mev. Beta-emission is followed by a 1.631±0.006 Mev gamma-ray from an excited state of Ne^{20}. The gamma-ray energy was checked by comparing with the Sb^{124} gamma-ray, measured as 1.692±0.005 Mev, and by failure to observe photoneutrons from Be. Beta-ray branching to the ground state of Ne^{20}, if present, has a relative intensity of less than 1 percent. The total F^{20} disintegration energy, 7.038±0.018 Mev, is used together with other nuclear data to derive a Ne^{20} mass which is independent of mass spectrographic measurements. The result, $Ne^{20}=19.998794\pm0.000026$ amu, is in agreement with mass spectrographic values.

INTRODUCTION

Up to the present the scale of accurate atomic mass values[1,2] based solely on nuclear measurements has extended only up to F^{20}. Isotopes in the mass region from Ne^{20} to sulfur are interconnected by beta-decay energies and reaction Q-values which have errors of less than 20 kev. However, this group of elements has been linked to O^{16} only through mass spectrographic work owing to the lack of accurate nuclear data connecting the isotopes of fluorine and neon.

Several ways of bridging this gap by means of nuclear measurements are apparent. One such method is the determination of the ground state Q-value of the $Ne^{21}(d,\alpha)F^{19}$ reaction, a problem which might not be expected to be easy because of the relatively low abundance of Ne^{21} in ordinary neon and the difficulty of making a suitable target.

A second possibility consists of determining the total disintegration energy of F^{20}. It is known[3] that this isotope decays to Ne^{20} by emission of hard beta-rays with a half-life of 12 seconds and that most of the beta-rays are in coincidence with 1.6-Mev gamma-rays corresponding to a level in Ne^{20}. Evidence has been found for complexity of the beta- and gamma-ray spectra. Jelley has reported[3] a single beta-ray group of endpoint energy 5.03±0.05 Mev and two gamma-rays of 1.63±0.02 Mev and 2.45±0.06 Mev having an intensity ratio of 8.4 to 1. On the other hand, Littauer has found[4] a weak gamma of 1.0±0.1 Mev in addition to the one of 1.63 Mev. He also reports that the main beta-component has a 5.33±0.05 Mev end point and that 3.5 percent of the beta-decays proceed to the ground state of Ne^{20} and have an end-point energy of 6.74±0.1 Mev. The value 6.66±0.05 Mev given by Jelley as the total F^{20} disintegration energy disagrees beyond the stated errors with 6.96±0.05 Mev obtained from Littauer's data. In either case the probable error is too large to use the result in establishing a mass scale involving only measurements having errors of less than 20 kev.

Because of the desire to obtain a more accurate total disintegration energy and at the same time to examine the possible complexities in the beta- and gamma-ray spectra it was felt that an investigation of the F^{20} beta-decay should be made.

GAMMA-RAY MEASUREMENTS

A lens spectrometer employing ring focus was used to study the gamma-ray spectrum from sources of F^{20} produced by the $F^{19}(d,p)F^{20}$ reaction. A 1.8-Mev deuteron beam at a current of 5 μamp was furnished by the Brookhaven electrostatic accelerator and was allowed to strike a thick CaF_2 target located in a brass cup at the normal source position of the spectrometer. Photoelectric converters consisting of uranium foil were attached to the cup whose walls were thick enough to stop the energetic beta-rays. The spectrometer was located 17 feet from the magnetic analyzer of the accelerator and the beam was brought through an extension tube.

In the first tests in which the spectrometer and accelerator vacuum systems were connected together it was found that N^{13} activity, produced by deuteron bom-

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† Under contract with the AEC.

[1] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).

[2] D. M. Van Patter, Massachusetts Institute of Technology Technical Report No. 57 (1952) (unpublished).

[3] J. V. Jelley, Phil. Mag. **41**, 1199 (1950).

[4] R. M. Littauer, Phil. Mag. **41**, 1214 (1950).

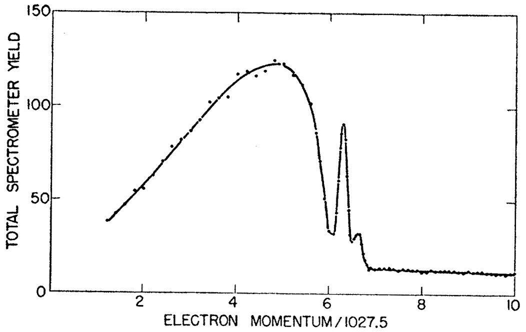

FIG. 1. Spectrum of Compton and photoelectrons due to F^{20} gamma-radiation. A 40-mg/cm^2 U converter was used.

bardment of carbon-containing deposits on the defining apertures, diffused to the detector end of the spectrometer chamber and caused a high and variable background. When the vacuum systems were separated, the background was low and the data were reproducible within the statistical errors.

Because of the short half-life of the F^{20} activity a monitoring technique was used to normalize the spectrometer yield. The monitor was a gamma-ray Geiger counter located near the source end of the instrument, while the spectrometer detector was an end-window Victoreen counter. The monitor was shielded by lead on all sides except in the direction of the source. The procedure for taking data consisted of irradiating the target for 12-15 seconds, shutting off the beam by turning down the accelerator voltage, and recording the spectrometer yield occurring during a fixed number of monitor counts. Only one point was taken for each irradiation and the actual length of the counting interval was generally about 20 seconds. During the target bombardment the voltages on the monitor and spectrometer counter tubes were reduced below threshold in order to avoid the extremely high counting rates due to prompt gamma-rays.

Figure 1 is a curve of total spectrometer yield *versus* momentum taken with a 40 mg/cm^2 thick uranium converter at 3 percent spectrometer resolution. The spectrum has the normal shape expected of a single gamma-ray line and gives no indication of other photoelectron peaks or Compton electron groups being present. The region above 1.6 Mev was examined with particular care in an effort to locate photoelectrons due to the 2.45-Mev gamma-ray reported[3] by Jelley.

The energy of the F^{20} gamma-ray was determined by comparing the photoelectric peaks from a 23.8-mg/cm^2 uranium converter with those produced by the 1.332±0.001-Mev gamma-ray[5] of Co^{60}. In all such measurements the resolution baffle settings were kept fixed and the position of the converter was reproduced as closely as possible. By using data such as that shown in Fig. 2, the F^{20} energy was determined (1) from the K-line peak position, assumed to be shifted by half the energy thickness of the converter, and (2) directly from the high energy extrapolated edge of the K-line according to the technique developed[6] by Hornyak, Lauritsen, and Rasmussen. The average of all such determinations of the F^{20} gamma-ray energy is 1.631±0.006 Mev in agreement with the previous but less accurate measurements.[3,4]

Wattenberg has reported[7] that photoneutrons are produced in Be by F^{20} gamma-rays corresponding to an intensity greater than 10 percent per beta-ray. Since the $Be^9(\gamma,n)Be^8$ threshhold is now established as 1.666±0.002 Mev by the measurement[8] of Mobley and Laubenstein, it would appear that the present result, which indicates that the F^{20} gamma-ray energy is definitely below the $Be(\gamma,n)$ threshhold, represents a discrepancy with the data of Wattenberg.

In order to obtain a check on the F^{20} gamma-ray, a comparison measurement was made on the 1.7-Mev gamma-ray of Sb^{124}. This has been reported as having an energy of 1.708±1 percent according to Kern, Zaffarano, and Mitchell,[9] and Cook and Langer[10] and 1.69±0.02 Mev according to Feister and Curtiss.[11]

The photoelectron spectrum of the 1.7-Mev gamma-ray obtained with a 0.2-mC source of Sb^{124} and the same converter and spectrometer geometry as for Co^{60} and F^{20} is included in Fig. 2. The decreasing yield at the right is part of the Compton spectrum of the weak 2.1-Mev gamma-ray.[9,10] The best average value for the energy, obtained from the peak and from the extrapolated end point of the K line, is 1.692±0.005 Mev.

The close proximity in energy of the Sb^{124} and F^{20} gamma-rays allows these independent values to be compared by measuring the momentum separation of the conversion lines. This was done by matching the

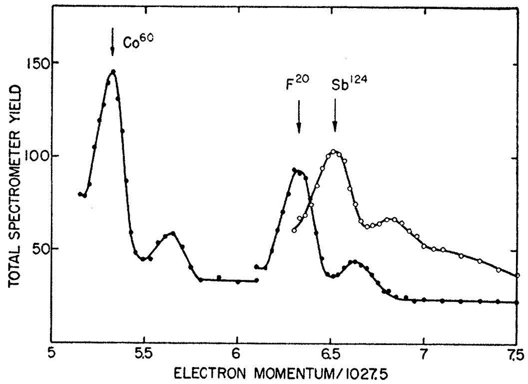

FIG. 2. A comparison of the relative momenta of photoelectron lines from a 23.8-mg/cm^2 U converter due to the gamma-rays of Co^{60}, F^{20}, and Sb^{124}.

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[5] Lind, Brown, and DuMond, Phys. Rev. **76**, 591 (1949).

[6] Hornyak, Lauritsen, and Rasmussen, Phys. Rev. **76**, 731 (1949).

[7] A. Wattenberg, Phys. Rev. **71**, 497 (1947).

[8] R. C. Mobley and R. A. Laubenstein, Phys. Rev. **80**, 309 (1950).

[9] Kern, Zaffarano, and Mitchell, Phys. Rev. **73**, 1142 (1948).

[10] C. S. Cook and L. M. Langer, Phys. Rev. **73**, 1149 (1948).

[11] I. Feister and L. F. Curtiss, J. Research Natl. Bur. Standards **40**, 315 (1948).

two curves over the entire photoelectron spectrum after normalizing to the same amplitude. The energy difference $Sb^{124}-F^{20}$ was found to be 60 kev in agreement with the 61-kev difference according to the direct determinations.

The measured value of the Sb^{124} gamma-ray would mean that an energy of 26±5 kev is available above the $Be^9(\gamma,n)Be^8$ threshhold corresponding to a photoneutron energy of 23±5 kev when the recoil of the Be^8 nucleus is taken into account. Hanson has measured[12] the Sb-Be photoneutron spectrum by examining proton recoils in a proportional counter. He obtained an average neutron energy of 24±3 kev in favorable agreement with the earlier values of Wattenberg, and of Hughes and Eggler,[13] which were 24±15 kev and 35±10 kev, respectively. Hanson's measurement gives an excellent check on the Sb^{124} gamma-ray energy found here and adds further weight to the validity of the F^{20} value.

Finally, in collaboration with M. McKeown a search was made for Be photoneutrons resulting from the gamma-rays of F^{20}. The accelerator target was surrounded by Be and paraffin blocks, and a slow neutron BF_3 detector was placed in this structure. When the 0.2-mC Sb^{124} source was inserted near the fluorine target position, the photoneutron detector yield was about 2400 counts per minute. A gamma-ray counter was used to compare the strength of the Sb^{124} source with the average gamma-ray strength of the F^{20} activity. Irradiations of the target produced F^{20} sources having an average strength of about 2 mC during a 10-sec period immediately following bombardment.

A very weak short-lived photoneutron activity of 10-30 sec half-life was observed above background but the strength was too small to permit a determination of the half-life. If this yield is taken as an upper limit and if the source strength is normalized according to the data on Sb^{124}, then it may be shown that the F^{20} gamma-ray intensity capable of producing photoneutrons in Be corresponds to less than $\frac{1}{4}$ percent per beta-ray. The small yield actually observed could be due to bremsstrahlung or to target impurities. This result would rule out the presence of the 2.45-Mev gamma-ray reported[3] by Jelley.

The photoneutrons assigned to F^{20} by Wattenberg were probably due to the gamma-rays of N^{16}, an activity produced by fast pile neutrons according to the $F^{19}(n,\alpha)N^{16}$ re-action. McKeown has re-examined[14] this case using fluorine sources irradiated in the Brookhaven reactor. A strong photoneutron yield from Be was observed but showed only a single decay period of 7.5 seconds which is the known half-life of N^{16}.

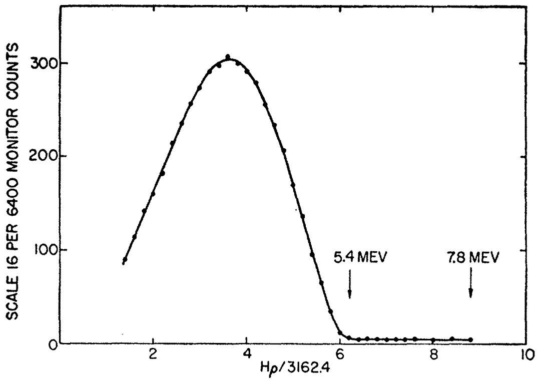

FIG. 3. Total spectrum of F^{20} beta-rays and scattered radiation *versus* momentum, after subtraction of a small room background.

BETA-RAY SPECTRUM

Examination of the F^{20} beta-spectrum was made with the lens spectrometer using BaF_2 targets 1–2 mg/cm^2 thick deposited on 0.05-mil nickel foil (160 kev thick for deuterons). The accelerator beam was first passed through a baffle system, then a central region of the target 8 mm in diameter, and finally into a Faraday cup for current measurement. The BaF_2 was deposited on the spectrometer side of the nickel supporting foil and its location was the same as that occupied by the uranium converter used in calibration measurements. In order to isolate the spectrometer vacuum chamber from the accelerator, thereby eliminating the diffusion of N^{13} activity, a gasketed section having a 0.05-mil nickel window was included in the beam tube baffle system. The two nickel foils thus reduced the beam from an initial energy of 1.9 Mev to about 1.6 Mev by the time the target material was reached. A deutron current of a few tenths μamp was sufficient to produce a usable F^{20} activity.

In all of the F^{20} beta-ray work the spectrometer resolution was 2.7 percent. Calibration of the instrument was carried out with 10-mC sources of Na^{24} prepared by irradiation of Na_2CO_3 in the reactor. A uranium converter 23.8 mg/cm^2 thick and 8 mm in diameter was attached to the source capsule and the position of the K photoelectron line due to the hard gamma-ray was determined. The binding energy of the K shell electrons in U was taken[15] as 115.6 kev and the peak shift due to the converter thickness was assumed to be 12.0 kev. The gamma-ray energy value, $2.753_5\pm0.001$ Mev, recently reported[16] by Hedgran and Lind served as the calibration standard. To insure an accurate extrapolation above the calibration point, the coil current at each regulator setting was checked by measuring the voltage drop across the current shunt with a Leeds and Northrup type K potentiometer. The stability of the current was better than one part in 2000.

The procedure for monitoring the source strength

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[12] A. O. Hanson, Phys. Rev. **75**, 1794 (1949).

[13] D. J. Hughes and C. Eggler, Phys. Rev. **72**, 902 (1947).

[14] The author is indebted to Mr. McKeown for permission to quote his results.

[15] Y. Cauchois, J. phys. et radium **13**, 113 (1952).

[16] A. Hedgran and D. A. Lind, Ark. Fys. **13**, 178 (1952).

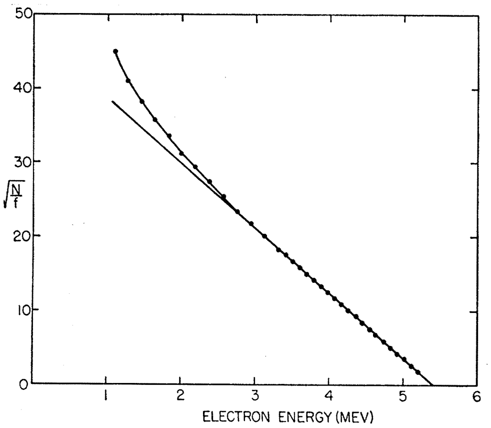

FIG. 4. Kurie plot of the F^{20} beta-ray spectrum.

and taking data was similar to that followed in the gamma-ray measurements already described. In Fig. 3 the curve of spectrometer yield *versus* momentum, after subtraction of a small room background, represents the average data of eight sets of interlaced points. Room background was determined at each point by allowing the F^{20} activity to decay for 10 half-lives and then observing the number of counts occurring in the same length of time as the corresponding counting interval. The magnitude of the room background was generally about $\frac{1}{3}$ as great as the yield shown in Fig. 3 beyond the spectrum endpoint.

The curve above 5.4 Mev is constant within statistics up to 7.8 Mev and is mainly due to scattered gamma- and beta-rays. A beta-ray group having an end point near 7 Mev and a relative intensity of as much as 1 percent would not be consistent with the data. This result is at variance with the 3.5 percent branch to the ground state of Ne^{20} found[4] by Littauer.

A Kurie plot of one of the more detailed runs on the F^{20} beta-spectrum, made after subtraction of the scattered background, is shown in Fig. 4. The calculations were carried out with the help of Fermi function tables prepared[17] by I. Feister and in every case the end point was determined by a least squares straight line fit to the uppermost 20 points. Two secondary values obtained by least squares straight line fits to the upper and lower 10 points of this group were also made, and the resulting end points always agreed with that obtained from all 20 points to within 5 kev. The accurate linearity of the Kurie plot in the upper half of the spectrum is evident from these calculations. The deviation from linearity at lower energies is probably reasonable in view of the source and backing thicknesses used.

The end-point energies obtained from the various runs, each of which was independently calibrated, occurred within a range of 11 kev. The best average value for the end-point energy is found to be 5.406±0.017 Mev, where the assigned error is largely due to the location of the calibration peak. Errors in the correction for the peak shift due to converter thickness, the Na^{24} gamma-ray energy, linearity of the current regulator, and the determination of the end-point energy value were smaller than the calibration error but were included in estimating the over-all probable error.

DISCUSSION

The total F^{20} disintegration energy is found by adding to the sum of the beta- and gamma-ray values determined above the recoil energy imparted to the Ne^{20} nucleus as a result of beta-ray emission. The maximum recoil amounts to 940 ev, and to allow for this a 1-kev correction has been added although it is small compared with the assigned error. The F^{20} decay energy is therefore 7.038±0.018 Mev, where the probable errors of the beta- and gamma-ray measurements have been combined in the usual way.

The result may be used together with other nuclear data to derive a mass value for Ne^{20} which is related to O^{16} by means of nuclear disintegration and decay processes and is therefore independent of mass spectrographic measurements. The mass of F^{19}, 19.004456±(15) amu, quoted by Li *et al.* in their analysis[1] of light element masses as the best fit value according to nuclear reactions, has been taken as the base in calculating the Ne^{20} mass. The Q-value of the $F^{19}(d,p)F^{20}$ reaction, given[18] by Strait *et al.* as 4.373±0.007 Mev, may be combined with Li *et al.*'s F^{19}, giving a mass[19] of 20.006352±(17) amu for F^{20}. When the mass equivalent of the F^{20} disintegration energy found in the present work is subtracted from F^{20} the mass of Ne^{20} is found to be 19.998794±(26) amu. The relationship 1 amu = 931.152 Mev was used to convert the F^{20} disintegration energy to mass units.

It is of interest to compare this result with the most recent mass spectrographic values of Ne^{20}. The data with the highest quoted accuracy are those of Ewald,[20] who reports that Ne^{20} has a mass of 19.998771±(12) amu, while Nier's value[21] is 19.998835±(43) amu. In both cases the Ne^{20} mass was derived by measuring the separation between D_2O and Ne^{20}. Ewald's mass difference for this doublet is 30.688±0.010 mMU which agrees with that of Nier, 30.721±0.039 mMU, well within the combined errors. However, the mass defect of the deuterium atom used in calculating the Ne^{20} mass was different in the two cases. The mass defect of D measured by Ewald is 14.732±0.004 mMU which is in good agreement with the nuclear reaction value[1] 14.735±0.006 mMU, while Nier's measurement gives 14.778±0.008 mMU. Thus, in the calculation of Ne^{20}

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[17] I. Feister (private communication).

[18] Strait, Van Patter, Buechner, and Sperduto, Phys. Rev. **81**, 747 (1951).

[19] This mass is the same as quoted by Li *et al.*, but the calculated error is 0.002 mMU smaller.

[20] H. Ewald, Z. Natursforsch. **6a**, 293 (1951).

[21] A. O. Nier, Phys. Rev. **81**, 624 (1951).

from D_2O-Ne^{20} a discrepancy of 0.092 mMU occurs between Ewald's and Nier's results just from the D mass defect used. If one were to correct Nier's data by using the nuclear reaction (or Ewald's) mass defect for D then his value of Ne^{20} would be $19.998749\pm(43)$ amu. Whether this correction is made or not, the Ne^{20} mass based on the present work agrees with both Ewald and Nier well within the combined probable errors.

The mass of F^{19} measured by Ewald, namely, $19.004414\pm(17)$ amu, and Li *et al.*'s value of $19.004456\pm(15)$ amu from nuclear data do not agree as well as in the Ne^{20} case, since the difference of 0.042 mMU is larger than the sum of the errors. Also, the F^{20} disintegration energy derived from Ewald's values for F^{19} and Ne^{20} and the Q-value of the $F^{19}(d,p)F^{20}$ reaction is 7.019 ± 0.021 Mev, which is lower than the measured value but agrees within the errors. In summary, it appears that Ewald's mass value of Ne^{20} is in satisfactory agreement with nuclear data while his mass of F^{19} may be slightly low.

The F^{20} disintegration energy may be combined with the 4.529 ± 0.007 Mev Q-value of the $Ne^{20}(d,p)Ne^{21}$ reaction,[22] the previously quoted Q of the $F^{19}(d,p)F^{20}$ reaction, and other data relating the d, p, and α masses to predict a ground state Q-value of 6.451 ± 0.022 Mev for the $Ne^{21}(d,\alpha)F^{19}$ reaction. A direct experimental determination of this Q-value would be very worth while.

The linearity of the F^{20} beta-ray Kurie plot and the $\log ft$ value of 5.0, calculated from Moszkowski's curves,[23] show that the transition is allowed according to Nordheim's classification.[24] The accurate linearity exhibited by the least squares analyses previously mentioned is a further argument against the presence of a level in Ne^{20} at 2.45 Mev excited to an extent reported[3] by Jelley. The ground state of the even-even nucleus Ne^{20} doubtlessly has zero spin and even parity, while the first excited state at 1.6 Mev probably has spin 2 and even parity according to the empirical rule[25] of Goldhaber and Sunyar. It would appear that F^{20} should have a spin of 2 or 3 and even parity based on the above assumptions and the lack of transitions to the ground state of Ne^{20}. Using the 1 percent upper limit of intensity previously quoted a transition to the ground state would have a $\log ft$ greater than 7.5 and would therefore be at least first forbidden.[24]

In either case a spin of 2 or 3 and even parity for F^{20} would fit the shell model picture. The odd proton should be $s_{\frac{1}{2}}$ and the odd neutron $(d_{5/2})^3{}_{5/2 \text{ or } 3/2}$. These could combine to give spin 2 or 3 and in all cases the parity would be even.

In connection with the attempts to observe photoneutrons from Be due to F^{20} gamma-radiation an interesting feature was pointed out[26] by Goldhaber. The energy of the F^{20} gamma-ray, according to the present measurement, occupies the unique position of lying below the $Be^9(\gamma,n)Be^8$ threshhold but above the threshhold for the direct breakup of Be^9 into two alpha-particles and a neutron. The threshhold energies of these two processes are known from other information to be about 90 kev apart. The small upper limit of photoneutron yield established in this work shows that the cross section for the three-particle reaction in the neighborhood of 60 kev above threshhold is less than 10^{-30} cm^2.

The author is indebted to M. McKeown for collaborating in the photoneutron measurements and to M. Goldhaber and H. Motz for helpful discussions of the results.

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[22] Van patter, Sperduto, Endt, Buechner, and Enge, Phys. Rev. **85**, 142 (1952).

[23] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).

[24] L. W. Nordheim, Phys. Rev. **78**, 294 (1950).

[25] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).

[26] M. Goldhaber (private communication).