Properties of the Cross Sections for the $S^{32}(\gamma,np)P^{30}$, $Ca^{40}(\gamma,np)K^{38g}$, and $Zn^{66}(\gamma,np)Cu^{64}$ Reactions from 50 to 300 MeV*

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Yield values for the $S^{32}(\gamma,np)P^{30}$, $Ca^{40}(\gamma,np)K^{38g}$, and the $Zn^{66}(\gamma,np)Cu^{64}$ reactions have been determined in the 50- to 300-MeV energy range. Targets of natural sulfur, calcium, and zinc were irradiated with bremsstrahlung from the University of Illinois 300-MeV betatron, and the product yields were determined from measurements of their radioactivities with a gamma-ray scintillation spectrometer. In order to extract cross-section information from the yield data, the $S^{32}(\gamma,np)P^{30}$ reaction yield data from threshold to 90 MeV reported by Bonazzola *et al.* were normalized to our data and used to complete the yield curves near the reaction thresholds. Cross sections averaged over 30-MeV-wide energy bins have been determined for the $S^{32}(\gamma,np)P^{30}$ reaction, but it was possible to determine only the behavior of integrated cross sections in the other two cases because of larger statistical uncertainties in the yield data. The previous work on the $S^{32}(\gamma,np)P^{30}$ reaction at energies below 90 MeV showed that the cross section peaks at a value of 4.3 mb at 28 MeV and then decreases at higher energies. The cross sections resulting from our work reach zero near 100 MeV and then rise, reaching a value of 1.0 mb near 220 MeV. The integrated cross section to 300 MeV is 190±12 MeV mb. The integrated cross sections to 300 MeV for the $Ca^{40}(\gamma,np)K^{38g}$ and the $Zn^{66}(\gamma,np)Cu^{64}$ reactions are 88±14 MeV mb and 400±60 MeV mb, respectively. Using the results of Stein *et al.* on the number of coincident neutron-proton pairs observed from quasideuteron absorption processes in various nuclei, we estimate that events associated with quasideuteron absorption processes account for 25% or less of the observed (γ,np) cross sections above 140 MeV. A mechanism in which a meson is produced and escapes from the nucleus, followed by a nuclear cascade and nucleon evaporation caused by the recoiling nucleon, can account reasonably well for the remainder of the observed cross sections. However, a sizeable contribution from processes in which a meson is reabsorbed cannot be ruled out, because of the absence of detailed information about the fraction of the meson production events that leads to the (γ,np) product.

I. INTRODUCTION

THIS work was undertaken in an attempt to gain information about the mechanism of high-energy photon-induced nuclear reactions. In particular, it is aimed at determining the relative importance of quasideuteron (pseudodeuteron) and meson production processes at energies above 140 MeV in (γ,np) reactions involving light-element target nuclei.

The quasideuteron absorption process was proposed by Levinger.[1] It is a process in which a high-energy photon is absorbed by a neutron-proton subunit (quasideuteron) within the nucleus. The photon's energy is shared by the neutron and proton according to the kinematics of deuteron photodisintegration modified by consideration of the momentum distribution of the subunits within the nucleus. The existance of this photon-absorption process in complex nuclei was demonstrated by experiments performed by Wattenberg and co-workers at MIT[2–5] and by Barton and Smith at Illinois.[6,7] In these experiments, the coincident high-energy neutron-proton pairs were detected from the high-energy photodisintegration of complex nuclei.

In addition to quasideuteron absorption processes, it is also known that the interaction of high-energy photons with nuclei can result in the production of mesons.[8] Although photomeson production has been studied in great detail with hydrogen and deuterium targets, detailed information about this process in complex nuclei is still quite limited.

The purpose of the present study is to determine to what extent these two processes compete as far as a particular type of photonuclear reaction is concerned, i.e., the (γ,np) reaction. Although a lot is known about these two processes from experiments in which the primary particles have been detected, the parts that these processes play in particular types of photonuclear reactions are not understood in any detail because of the lack of experimental cross-section information for specific reactions in this energy range. Quite detailed cross-section information is reported here for the $S^{32}(\gamma,np)P^{30}$ reaction. In addition, less detailed information for the $Ca^{40}(\gamma,np)K^{38g}$ and the $Zn^{66}(\gamma,np)Cu^{64}$ reactions is given. The results indicate that at photon energies above 140 MeV the meson-production processes are more important than quasideuteron processes for these reactions.

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[2] H. Myers, A. Odian, P. C. Stein, and A. Wattenberg, Phys. Rev. **95**, 576 (1954).
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[4] A. Wattenberg, A. C. Odian, P. C. Stein, H. Wilson, and R. Weinstein, Phys. Rev. **104**, 1710 (1956).
[5] P. C. Stein, A. C. Odian, A. Wattenberg, and R. Weinstein, Phys. Rev. **119**, 348 (1960).
[6] M. Q. Barton and J. H. Smith, Phys. Rev. **95**, 573 (1954).
[7] M. Q. Barton and J. H. Smith, Phys. Rev. **110**, 1143 (1958).
[8] See E. H. Bellamy, Progr. Nucl. Phys. **8**, 237 (1960) for a review article on photomeson production.

II. EXPERIMENTAL

A. $S^{32}(\gamma,np)P^{30}$ Reaction

In the experiments described here, the reaction yields were determined from measurements of the P^{30} radioactivity present in sulfur samples that were irradiated with high-energy bremsstrahlung. The radioactivity measurements were made by counting the annihilation radiation from the P^{30} positrons with a gamma-ray-scintillation spectrometer.

Samples weighting 2.25 g of natural powered sulfur that had been purified by benzene extraction from commercial grade sulfur were irradiated in Lucite holders in the collimated bremsstrahlung beam from the University of Illinois 300-MeV betatron. The range of betatron operating energies used in this study was from 50 to 300 MeV with data taken at 10-MeV intervals. An average of fourteen samples were irradiated at each energy. The irradiation times were 10 min. The bremsstrahlung-beam intensity was monitored by a thick-walled copper ionization chamber that had recently been calibrated against a National Bureau of Standards P-2 type ionization chamber.[9,10] The ionization current collected in the chamber was measured with a vibrating-reed electrometer circuit which contained an appropriate RC network to correct for the radioactive decay of the P^{30} product nuclei during the irradiations and eliminate the effects of beam-intensity fluctuations.

The irradiated sulfur samples were placed in 50-ml beakers which were placed on top of a $1\frac{1}{2}$-$\times 1\frac{1}{2}$-in. NaI(Tl) scintillation crystal for the radioactivity measurements. The gamma-ray spectra from these samples were recorded by a Radiation Instrument Development Laboratory 100-channel pulse-height analyzer. For the yield curve measurements, each sample was counted once for 10 min starting 2.5 min after the end of the irradiation. The observed spectra contained only one photopeak; that was the 511-keV photopeak due to the annihilation of positrons. The decay of the 511-keV photopeak was followed for times up to three hours in 25 cases. The betatron energies used in these cases were distributed throughout the 50- to 300-MeV range used in the yield curve study. These decay curves contained two components, the main component having the 2.55-min half-life[11] of P^{30} and the second component having a 20-min half-life. The relative amounts of the two components did not vary with the betatron operating energy. The contribution of the 20-min component in the 10-min counts that were used to obtain the yield curve data was 2.7%; corrections were made for this activity. The source of the 20-min activity is believed to be C^{11} which could be produced by (γ,n) reactions on carbon impurities (benzene) which remained from the purification process.

The absolute P^{30} yields were calculated from the 511-keV photopeak counts by correcting for the absolute counting efficiency of the system. Corrections were made for the geometry, the intrinsic crystal efficiency, the peak-to-total ratio, absorption, the positron annihilation efficiency, and the loss of counts from the 511-keV photopeak due to the summing with bremsstrahlung associated with the positrons. The intrinsic efficiency of the crystal was determined by multiplying a point-source efficiency calculated by Stanford and Rivers[12] by an experimentally determined spread source factor. The other correction factors were either calculated or experimentally determined.

B. $Ca^{40}(\gamma,np)K^{38g}$ Reaction

The yields of this reaction were also measured by determining the radioactivity of the product nuclei. The irradiation, monitor, and counting arrangements were similar to those used in the sulfur experiments. The calcium used was in the form of metal turnings of 99.5% purity which were obtained from the Harshaw Chemical Company. Samples weighing 4.66 g were irradiated for 23 min with the bremsstrahlung beams and were then scintillation counted usually for 6 min to observe the 2.16-MeV gamma ray from the decay of the 7.7 min K^{38g}. The irradiations were made at 10-MeV intervals from 50 to 300 MeV, and an average of eight irradiations were made at each energy. The decay of the 2.16-MeV photopeak was followed in several instances. This showed two components, the main one being the 7.7-min component due to the K^{38g} and the other being a 32-min component due to the 2.13-MeV gamma ray in the decay of Cl^{34m}. The long-lived component gave typically about a 5% contribution to the observed photopeak. Corrections were made for this contribution. The absolute yield values were obtained from the counting data in a manner similar to that outlined for the sulfur experiments in part A.

C. $Zn^{66}(\gamma,np)Cu^{64}$ Reaction

The yields of this reaction were also obtained from measurements of the product radioactivity. Again, the irradiation, monitor, and counting arrangements were similar to those used in the sulfur experiments. In this case, however, it was necessary to chemically separate the copper product in order to observe the Cu^{64} radioactivity. Samples, weighing 10.0 g, of granular natural zinc metal (99.8% pure, supplied by J. T. Baker Chemical Company) were irradiated for periods up to

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[9] J. S. Pruitt and S. R. Domen, *Determination of Total X-Ray Beam Energy with a Calibrated Ionization Chamber*, Nat. Bur. Std. (U. S.), Monograph 48 (1962).

[10] W. P. Swanson, R. A. Carrigan, Jr., and E. L. Goldwasser, Rev. Sci. Instr. 34, 538 (1963).

[11] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.), NRC [60-3-14]. Unless stated otherwise, all decay scheme and isotopic abundance data have been taken from this source.

[12] A. L. Stanford, Jr., and W. K. Rivers, Jr., Rev. Sci. Instr. **29**, 406 (1958).

two hours. The betatron energy range covered was from 70 to 300 MeV with data taken at 10-MeV intervals. Because of the long irradiation times needed, it was possible to perform only two irradiations at each energy. The copper fraction was separated from the target material by an electrolytic technique and was then counted with the scintillation spectrometer system to observe the 511-keV annihilation radiation from the decay of Cu^{64}. Decay curve studies showed that the 511-keV photopeak decayed with a clean 12.8-h half-life after 30 h. Thus, only data recorded after 30 h were used. The counting times used were generally several hours. Again, the absolute yield values were determined in a manner similar to that outlined for the sulfur experiments in part A.

It is possible that Cu^{64} nuclei could also be produced in these experiments by $Zn^{64}(n,p)Cu^{64}$ reactions initiated by secondary neutrons. The results of experiments conducted with the zinc target placed next to the bremsstrahlung beam indicate that the contribution to the yield of Cu^{64} from secondary reactions is less than 1%.

III. RESULTS

A. $S^{32}(\gamma,np)P^{30}$ Reaction

The yield of P^{30} as a function of betatron energy is shown in Fig. 1. In order to calculate cross sections from the yield data, it is necessary to know the yield behavior at all energies above the threshold of the reaction. Although our experiments were not conducted below 50 MeV, we can make use of the yield data of Bonazzola *et al.*[13] to complete the yield curve at the lower energies. They measured the P^{30} yields in sulfur targets from threshold to 90 MeV. Their yield data have been normalized to ours in the 50- to 90-MeV energy range and are plotted in Fig. 1 with the high energy yield data from our experiments. In order to normalize the data, the

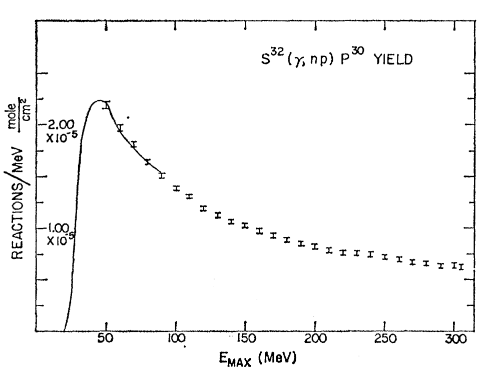

FIG. 1. Yields for the $S^{32}(\gamma,np)P^{30}$ reaction as a function of the bremsstrahlung maximum energy. The solid line shows the yield values of Bonazzola *et al.* (Ref. 13) multiplied by 1.07 to normalize them to our values in the 50- to 90-MeV range. The data points are from the present study.

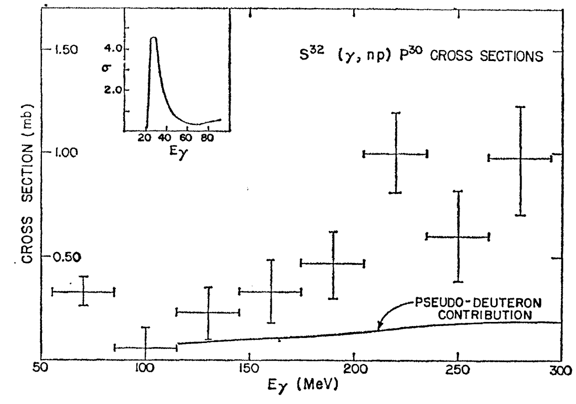

FIG. 2. Cross sections for the $S^{32}(\gamma,np)P^{30}$ reaction. The data points are the results from the present study. The insert shows the normalized low-energy results of Bonazzola *et al.* (Ref. 13). The solid line shows the calculated contribution to the cross section from events associated with quasideuteron absorption processes.

absolute yield values of Bonazzola *et al.* were increased by 7%. This indicates quite satisfactory agreement between the two sets of yield measurements.

The yield data in Fig. 1 were used to calculate cross sections at various photon energies by applying the cross-section analysis method of Penfold and Leiss.[14] The resulting cross-section values for 30-MeV-wide energy bins are shown in Fig. 2. Also shown there are the low-energy cross-section values reported by Bonazzola *et al.* increased by 7%. The cross-section uncertainties indicated in Fig. 2 are only those due to the random fluctuations in the yield data. In addition, there is an estimated 15% uncertainty in the absolute yield values due to the uncertainties in the various factors that were used to obtain the absolute yield values from the counting and monitor data.

Because the cross-section calculations were done with the aid of an IBM-7094 digital computer, it was possible to investigate the effects on the calculated cross sections caused by changing the shape of the bremsstrahlung spectrum used in the analysis and by using different monitor response functions. The bremsstrahlung spectrum shape was modified by changing the value of the screening constant that appears in the Schiff integrated-over-angles bremsstrahlung spectrum[15] from 111 (the value recommended by Penfold and Leiss) to 55. This change increases the relative number of photons near the tip of the bremsstrahlung spectrum by about 10% giving a spectrum similar to the 0° differential bremsstrahlung spectrum. The cross sections calculated using a screening constant of 55 were generally within 10% of those calculated using a value of 111 for the screening constant. The differences were always much smaller than the uncertainties due to the counting statistics. The use of different monitor response functions gives an indi-

[13] G. Bonazzola, O. Borello, S. Costa, and S. Ferroni, Nucl. Phys. 34, 637 (1962).

[14] A. S. Penfold and J. E. Leiss, Phys. Rev. 114, 1332 (1959).

[15] L. I. Schiff, Phys. Rev. 83, 252 (1951).

TABLE I. Integrated cross sections for the $S^{32}(\gamma,np)P^{30}$, $Ca^{40}(\gamma,np)K^{38g}$, and $Zn^{66}(\gamma,np)Cu^{64}$ reactions.

E_{max} (MeV)	$\int_0^{E_{max}} \sigma dE$ (MeV mb) $S^{32}(\gamma,np)P^{30}$	$Ca^{40}(\gamma,np)K^{38g}$	$Zn^{66}(\gamma,np)Cu^{64}$
50	64±2	31±1	128±3
100	79±5	35±5	160±7
140	81±6	35±7	160±20
200	107±8	43±9	270±30
250	150±10	72±11	370±45
300	190±12	88±14	400±60

cation of the effect of the uncertainty in the monitor calibration on the cross-section results. These changes also led to cross-section changes which were smaller than the uncertainties due to the counting statistics. Thus, in this case the accuracy of the cross-section values is limited by the counting statistics and does not appear to be very sensitive to the assumed bremsstrahlung spectrum shape and the monitor response uncertainties.

The main features of the cross sections shown in Fig. 2 are the large peak just above the threshold and the region of moderate cross-section values above 140 MeV. These features are also quite evident in Table I in which the integrated cross sections to several different energies are tabulated.

B. $Ca^{40}(\gamma,np)K^{38g}$ and $Zn^{66}(\gamma,np)Cu^{64}$ Reactions

Within the uncertainties involved, the yield curves for these reactions have the same shape as that for the $S^{32}(\gamma,np)P^{30}$ reaction. However, because fewer experiments were conducted on these reactions than on the $S^{32}(\gamma,np)P^{30}$ reaction, the statistical uncertainties in the yield values are too large to permit the extraction of meaningful cross-section values for small energy ranges. Instead, we will give only values of the integrated cross sections over various energy ranges. Another problem associated with the calculation of cross sections here is that the yield values at the lower energies near threshold are not available for these reactions. In their absence, we have used the low-energy data for the $S^{32}(\gamma,np)P^{30}$ reaction to approximate the low-energy yield behaviors for the $Ca^{40}(\gamma,np)K^{38g}$ and the $Zn^{66}(\gamma,np)Cu^{64}$ reactions by normalizing in the 50- to 90-MeV range. For the $Ca^{40}(\gamma,np)K^{38g}$ case, the low-energy $S^{32}(\gamma,np)P^{30}$ yield values were multiplied by 0.48 to normalize them to our measured K^{38g} yields. In the $Zn^{66}(\gamma,np)Cu^{64}$ case, the normalization factor was 2.00. The small normalization factor in the Ca^{40} case reflects the fact that only that part of the total (γ,np) yield that populates the ground state of K^{38} is observed here. As we will see later, we expect a comparable yield for the isomeric state. The larger normalization factor in the zinc case reflects the larger photon-absorption cross section in the giant resonance region for the heavier nucleus.[16]

The Penfold-Leiss formulation was used to calculate values of the integrated cross sections for these reactions. The resulting values are given in Table I. The uncertainties given there are due only to the statistical fluctuations in the data. The errors in the absolute values due to the uncertainties in the factors used to obtain the absolute yield values from the counting and monitor data are thought to be about 15%. These would largely cancel when making comparisons between the integrated cross sections for the three reactions.

IV. DISCUSSION

Since the behavior of the cross sections for the production of P^{30} at energies below 90 MeV has been studied and discussed previously,[13] we will concentrate our discussion on the cross-section behavior at the higher energies. However, before discussing the cross-section behavior, it is necessary to comment on interfering reactions which may be contributing to the observed cross sections.

A. Other Contributing Reactions

Since the target elements used in this work all consist of more than one stable isotope, it is possible that other photonuclear reactions besides the (γ,np) reaction could be contributing to the observed cross sections in each case. In the case of the production of P^{30} from sulfur targets, reactions involving S^{32}, S^{33}, S^{34}, and S^{36} are all possible. (Natural sulfur consists of 95.0% S^{32}, 0.76% S^{33}, 4.22% S^{34}, and 0.014% S^{36}.)[11] The small abundances of the heavier sulfur isotopes means that any possible reactions involving them as target nuclei and producing P^{30} would have to have cross sections which are greater than the cross sections for the S^{32} reactions in order to contribute significantly to the observed cross sections. Although very little is known in detail about the cross-section behaviors of photonuclear reactions in which two, three, four, or six particles are emitted, it appears unlikely that the more complicated reactions involving the heavier sulfur isotopes will contribute significantly to the production of P^{30}. This statement is based mainly on the results of recent studies on photonuclear reactions by Meyer[17] in which several reactions in O^{16}, F^{19}, Ca^{40}, and V^{51} targets were studied in the 50- to 300-MeV energy range. It was observed that the cross sections for the more complicated reactions were usually appreciably smaller (20% or less) than the (γ,np) cross sections reported here. (Exceptions to this general statement are those reactions in which alpha particles are emitted. In those cases, cross sections comparable to the (γ,np) cross sections may be observed. This is

[16] K. Strauch, Ann. Rev. Nucl. Sci. 2, 105 (1953).
[17] R. A. Meyer, Ph.D. thesis, University of Illinois, 1963 (unpublished).

probably related to the low threshold energies involved.) Similar conclusions can be obtained from the work of Halpern *et al.*[18–20] in which several photonuclear reactions involving medium-weight target nuclei were studied. In general, their observed yields for the production of a partucular product nucleus decrease as the target nucleus from which it is produced is increased in mass number (i.e., as the complexity of the reaction involved increases). It should be pointed out, however, that most of Halpern's data were yield values for 320-MeV bremsstrahlung, so the yield trends cannot be directly used as indications of the cross-section behaviors at high energies because of varying contributions from low-energy reactions as the reaction threshold changes. The yield values could be corrected to estimate the contributions from the higher energy part of the bremsstrahlung spectrum by using the shapes of the cross-section curves for various kinds of reactions that were observed by Meyer.[17] After making corrections of that type, the same general falloff of the yield with increasing complexity of the reaction is still observed, although the the falloff may not be quite as rapid as Meyer's cross-section data would indicate. Thus, the available data seem to indicate that the contribution to the production of P^{30} from the heavier isotopes of sulfur is probably less than 1 or 2% of the S^{32} contribution. Since the accuracy of the cross-section determinations is poorer than this, no attempts were made to correct for the contribution from the heavier isotopes.

The situation for the calcium experiments is quite similar to that for the sulfur experiments because the abundance of the target isotope of interest (Ca^{40}) is 97.0%. Thus, even if the cross sections for the more complicated reactions were comparable to the (γ,np) cross sections, their contribution would be only about 3%.

In the zinc case the situation is somewhat different because the target isotope of interest (Zn^{66}) is not the most abundant isotope. (Natural zinc consists of 48.9% Zn^{64}, 27.8% Zn^{66}, 4.1% Zn^{67}, 18.6% Zn^{68} and 0.6% Zn^{70}.) The interfering reactions producing Cu^{64} involving the most abundant isotopes would be the $Zn^{64}(\gamma,\pi^+)$, $Zn^{67}(\gamma,p2n)$, and the $Zn^{68}(\gamma,p3n)$ reactions. From the values for the $Ni^{60}(\gamma,\pi^-)Cu^{60}$ cross section reported by March and Walker,[21] we estimate that the contribution from the $Zn^{64}(\gamma,\pi^+)$ reaction to the production of Cu^{64} would be about 5%. This would be small compared to the uncertainties in the observed values. Again, utilizing the results of Meyer[17] and Halpern *et al.*[18–20] quoted earlier, we expect that the cross sections for the other two interfering reactions will be small (20% or less) compared to that for the (γ,np) reaction. Since the uncertainties in the integrated cross sections reported in Table I are comparable to this possible contribution, no correction will be made.

In addition to the above reactions involving other target isotopes that could lead to the measured product nuclei, it is possible that other reactions involving the emission of two nucleons besides the (γ,np) reaction could be contributing to the observed yields. For the sulfur case, in addition to the $S^{32}(\gamma,np)P^{30}$ reaction which leads directly to P^{30}, it is possible to produce P^{30} by other reactions on S^{32} target nuclei. Because of the short half-life of S^{30} (1.4 sec)[22] and the expected short half-life of the unknown Cl^{30} compared to the waiting period between the end of the irradiations and the start of the counting periods, reactions producing these nuclei will result in P^{30} nuclei that would be counted in this experiment. These reactions would be the $S^{32}(\gamma,2n)S^{30}$ and the $S^{32}(\gamma,\pi^-2n)Cl^{30}$ reactions. The yields of these other reactions are expected to be relatively small at all energies ($<10\%$) compared to the yield of the (γ,np) reaction. This is based on the results of recent experiments conducted in this laboratory on the yield ratios of $(\gamma,2n)$ plus (γ,π^-2n) to (γ,np) reactions in Cr^{50} and Fe^{54} target nuclei[23,24] and on the magnitude of the cross sections for the $O^{16}(\gamma,2n)O^{14}$ reaction observed by Meyer.[17] It is thought that the results for the $O^{16}(\gamma,2n)$ reaction should be particularly useful in estimating the importance of the $S^{32}(\gamma,2n)$ and the $S^{32}(\gamma,\pi^-2n)$ reactions because O^{16} and S^{32} are analogous nuclei in that they both have equal numbers of neutrons and protons and they both have similar differences between the threshold energies of the $(\gamma,2n)$ and (γ,np) reactions. Thus, the measured P^{30} yield shown in Fig. 1 is thought to be mainly due to the (γ,np) reaction.

In the calcium and zinc cases, the problem of contributions from other reactions involving the emission of two nucleons is not present. In the calcium case, the $Ca^{40}(\gamma,2n)$ and $Ca^{40}(\gamma,\pi^-2n)$ products would decay to K^{38m} and not to the ground state K^{38} that was measured in this experiment. In the zinc case, Cu^{64} can be produced from Zn^{66} by only the $Zn^{66}(\gamma,np)$ reaction as the other possible two nucleon reactions lead to stable product nuclei. These considerations lead us to believe that the cross-section data given in Fig. 2 and Table I are for only the (γ,np) reactions of interest within the statistical uncertainties involved.

B. $S^{32}(\gamma,np)P^{30}$ Reaction

The main feature of the observed cross sections at the higher energies is the rise in cross section above 100 MeV which ultimately reaches values of about 1 mb

[18] R. J. Debs, J. T. Eisinger, A. W. Fairhall, I. Halpern, and H. G. Richter, Phys. Rev. **97**, 1325 (1955).

[19] I. Halpern, R. J. Debs, J. T. Eisinger, A. W. Fairhall, and H. G. Richter, Phys. Rev. **97**, 1327 (1955).

[20] T. T. Sugihara and I. Halpern, Phys. Rev. **101**, 1768 (1956).

[21] P. V. March and T. G. Walker, Proc. Phys. Soc. (London) **77**, 293 (1961).

[22] E. L. Robinson, J. I. Rhode, and O. E. Johnson, Phys. Rev. **122**, 879 (1961).

[23] J. R. Van Hise, Ph.D. thesis, University of Illinois, 1963 (unpublished).

[24] W. B. Walters, Ph.D. thesis, University of Illinois, 1964 (unpublished).

near 200 MeV. That the increase in cross-section values seems to be most rapid above 140 MeV is an indication that meson production is probably the dominate photon-absorption process leading to this reaction. However, since the deuteron photodisintegration cross section also increases somewhat in this energy region,[25] there could also be an appreciable contribution from quasideuteron processes.

In order to estimate the contribution from quasideuteron processes, we refer to the results of Stein *et al.*[5] They measured the number of coincident neutron-proton pairs due to quasideuteron absorption in a large number of nuclei distributed throughout the periodic table. Although they made no measurements on sulfur targets, it is possible to interpolate their results to obtain a value for sulfur because their results show a smooth dependence on the atomic number of the target species. This interpolation gives a value of 305 μb for the cross section for the production of coincident neutron-proton pairs from sulfur. Their results are for photons of 262-MeV energy in the case of deuterium or for photons of slightly higher energy in the case of sulfur because of the higher binding energy (about 280 MeV). Before comparing this result with the results for the $S^{32}(\gamma,np)P^{30}$ reaction, some further considerations must be mentioned. One consideration involves the extrapolation of the result to other photon energies. Another consideration involves the corrections that must be applied to obtain the number of (γ,np) events that are related to the coincident neutron-proton pair results.

The results of Stein *et al.* can be represented by the following relationship:

$$\sigma_{(n-p \text{ pairs})} = 3.0(NZ/A)\sigma_D P(X), \quad (1)$$

where N, Z, and A are the number of neutrons, protons, and nucleons in the target nucleus, σ_D is the cross section for the photodisintegration of the deuteron, and $P(X)$ is the probability that both the neutron and the proton will escape from the nucleus without undergoing any collisions. They have shown that the probability-of-escape factor can be represented by

$$P(X) = 3[2 - e^{-X}(X^2 + 2X + 2)]/X^3, \quad (2)$$

where $X = 2R/\lambda$, in which R is the nuclear radius and λ is the average mean free path for a neutron and a proton in nuclear matter. From the energy dependences of the cross section for the photodisintegration of deuterium[25] and the mean free path for a nucleon in nuclear matter,[26] we can construct the energy dependence for the coincident neutron-proton pair cross section. This gives a cross-section curve that rises slowly between 120 and 300 MeV.

Before comparing these quasideuteron cross sections with the $S^{32}(\gamma,np)P^{30}$ results, we must note that they are not directly comparable. First, there may be quasideuteron absorption events in which the neutron or proton does not directly leave the nucleus because of scattering processes but in which the over-all reaction is still the emission of only a neutron and a proton. These events would contribute to the $S^{32}(\gamma,np)P^{30}$ cross section but would not be detected in the neutron-proton coincidence experiment because they would involve the wrong angles or energies to be observed. We would expect, however, that the number of cases in which one of the nucleons scatters without causing the emission of another particle would be relatively small in number. An estimate of the number of these cases based on the results of the Monte Carlo intranuclear cascade calculations made by Metropolis *et al.*[27] and by Bertini[28] indicates that these cases occur in at most about 5% of the quasideuteron absorption events at 300 MeV and in at most about 9% of the events at 120 MeV.

A second consideration is that the nucleus may be excited sufficiently as a result of the quasideuteron absorption process to evaporate one or more nucleons in addition to the neutron and proton involved in the absorption process. These events would still be observed in the coincident neutron-proton pair experiment but would lead to product nuclei lighter than P^{30}. Reid and Lalovic[29] estimate from a cloud-cahmber investigation of photodisintegration processes in light gases (through neon) that this occurs in about 50% of the quasideuteron absorption events.

The quasideuteron contribution to the $S^{32}(\gamma,np)P^{30}$ cross sections derived from the above considerations is also shown in Fig. 2. The probability of escape function and the corrections just outlined combine to give cross sections that average about 10% of the total quasideuteron-absorption cross section [$3.0\sigma_D NZ/A$ in Eq. (1)]. When comparing this contribution to the measured $S^{32}(\gamma,np)P^{30}$ cross sections, it is seen that quasideuteron processes account for only about 20% of the observed (γ,np) cross section above 140 MeV, indicating that some other mechanism is more important in that energy range.

It is worth mentioning here that the processes which are similar to the quasideuteron absorption process in which high-energy photons are absorbed by *p-p* and *n-n* pairs are probably small in importance and would not contribute significantly to the production of P^{30}. The evidence for this is that the number of coincident proton-proton pairs that are observed is small (about 10%) compared to the number of coincident neutron-proton pairs. They can be accounted for by assuming

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that the initial photon absorption involves a quasideuteron process and then considering the probability for the scattering of the outgoing neutron to give rise to a fast proton.[30,31] Neutron-neutron coincidences have not been studied, but we expect that the results would be similar to the proton-proton results.

As indicated earlier, we also expect that processes involving meson production will contribute to the $S^{32}(\gamma,np)P^{30}$ reaction. Assuming that meson production is a single-nucleon process, production of P^{30} could occur when the recoiling product nucleon from the photoproduction process interacts with the rest of the nucleus to cause the emission of the proper combination of two nucleons. The cross section for the production of P^{30} would then be given by

$$\sigma_{(\gamma,np)}=\sum \sigma_\pi \Gamma_2\,, \tag{3}$$

in which σ_π is the cross section for the production of a meson and Γ_2 is the branching ratio which gives the fraction of the processes in which the proper two nucleons are emitted to produce P^{30}. The sum is taken over all the possible meson production processes (π^+, π^-, and π^0). The meson-production cross sections can be estimated by multiplying the observed cross sections for the photoproduction of charged[32] and neutral[33,34] pions from hydrogen by $32^{2/3}$ which recognizes the $A^{2/3}$ dependence that has been observed for the yields of charged pions[35] (π^+ plus π^-) and for neutral pions.[36] A detailed calculation would include the effects of nucleon motion in the target nucleus, but this will be neglected here.

In order to calculate the branching ratios for the emission of the two nucleons, one would have to consider the possible collisions involving the recoiling product nucleon and their possible subsequent effects due to additional collisions and the ultimate evaporation of nucleons from the excited nucleus. The complexity of the problem suggests that it would be desirable to apply Monte Carlo techniques in much the same way as they have been used to investigate intranuclear cascades initiated by incident nucleons.[27,28] In the absence of such detailed calculations for the processes of interest here, we might use the results of the existing Monte Carlo calculations in order to estimate the expected branching ratios. Because these calculations are for nucleons incident on nuclei rather than for nucleons released within nuclei and because they have not been done for S^{32} we expect that they would yield only very approximate branching ratios for our case. An additional complication that has to be included is that the branching ratio has to be averaged over a spectrum of recoil energies which arise because of the emission of mesons over a range of angles.

Because of the difficulties in arriving at accurate branching ratios, we choose to examine the significance of the results in a different manner than by comparing them with calculated cross sections. Instead, we will calculate apparent observed branching ratios on the assumption that the meson processes are accounting for the rest of the observed (γ,np) cross section and then see whether or not the branching ratios are reasonable. In doing this, we approximate Eq. 3 by

$$\sigma_{(\gamma,np)}=\sigma_{(\text{total }\pi)}\bar{\Gamma}_2\,, \tag{4}$$

in which $\sigma_{(\text{total }\pi)}$ is the sum of the various meson photoproduction cross sections and $\bar{\Gamma}_2$ is an average branching ratio for the emission of the proper combination of two nucleons. The $\bar{\Gamma}_2$'s calculated from the experimental cross sections and calculated meson-production cross sections at different photon energies are given in Table II.

TABLE II. Meson-production mechanism results for the $S^{32}(\gamma,np)P^{30}$ reaction.

E_γ (MeV)	Meson-production cross section[a] (μb)	Meson contribution to (γ,np) cross section[b] (μb)	Apparent observed branching ratio[c]
160	520	230±150	0.44±0.29
190	1140	360±140	0.32±0.12
220	1900	850±190	0.45±0.10
250	2700	420±220	0.16±0.08
280	3650	800±240	0.22±0.07

[a] Given by $32^{2/3}(\sigma_{H^+}+\sigma_{H^0})$ in which σ_{H^+} and σ_{H^0} are the cross sections for π^+ and π^0 photoproduction from hydrogen (Refs. 32, 33, and 34).
[b] Given by the difference between the observed (γ,np) cross section and the calculated quasideuteron contribution shown in Fig. 2.
[c] Obtained by dividing the values given in column 3 by those given in column 2.

Their reasonableness can be assessed by comparing their magnitudes and energy dependence with existing data for nucleon induced reactions in which two nucleons are emitted, i.e., with the results of the Monte Carlo calculations referred to earlier and with experimental (p,pn) excitation functions such as those reported by Meadows *et al.*[37] The branching ratios in Table II are relatively large at the lower photon energies and then drop somewhat at the higher photon energies. This change is paralleled by an increase in the average energy of the recoiling product nucleon from the meson photoproduction event. The experimental (p,pn) excitation functions show this same behavior, tailing off at higher energies to smaller but appreciable values. As far as the magnitudes of the branching ratios are concerned, it

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should be pointed out that there is a considerable variation in what would qualify as reasonable values because of the uncertainty involved in applying the results for nucleon induced reactions on other nuclei to photon induced reactions in S^{32}. About all that can be said at this time is that the magnitudes of the calculated branching ratios are not unreasonable. Thus, we can say that these meson processes could account for the rest of the observed (γ,np) cross section, but the presence of important contributions from other mechanisms cannot be ruled out.

In addition to the meson-associated reactions in which the mesons are emitted, there could also be contributions from processes in which mesons are first produced but later reabsorbed within the nucleus. If the reabsorption was by a pair of nucleons that included the product nucleon from the photoproduction process, these events would contribute to the pseudodeuteron processes already considered.[32] If the reabsorption involved a different pair of nucleons,[39] then the processes might not contribute to the quasideuteron processes because some of the original photon's energy is lost to the recoil nucleon from the production process. The question of how much meson reabsorption occurs at the production site or elsewhere has not been completely answered as yet.[8] If it were possible to establish accurately the extent that the meson emission processes discussed above contribute to this reaction (i.e., if accurate branching ratios could be calculated), it would then be possible to establish whether or not the meson reabsorption processes contribute to this reaction and then possibly set limits on the amount of meson reabsorption at other sites within the nucleus. This type of treatment cannot be made until the more detailed branching ratio calculations are done and experimental cross-section data with smaller statistical uncertainties are available.

Another point of interest that merits further experimental study pertains to the detailed shape of the observed cross-section curve in Fig. 2. It appears that the cross section may drop above about 220 MeV and then begin to rise again near 280 MeV. However, the statistical uncertainties are too large to permit the making of a firm conclusion on this point. If the drop and subsequent rise in cross section are real, it would be very difficult to account for that behavior with the reaction mechanism that involves meson emission processes which was discussed above. It is unlikely that much better cross-section data at the higher energies can be obtained for the $S^{32}(\gamma,np)P^{30}$ reaction in order to further examine the existence of this effect. This is true because of the very large contribution to the yields at the higher energies from reactions involving the low-energy portion of the bremsstrahlung spectrum. However, there may be similar reactions involving other nuclei in which the contribution from low-energy reactions to the high-energy yields is significantly smaller, so that correpondingly better cross-section data can be obtained at the higher energies. Work is currently in progress in this laboratory to find such reactions for further study of the detailed shapes of reaction cross-section curves above the meson-production threshold.

C. $Ca^{40}(\gamma,np)K^{38}$ and $Zn^{66}(\gamma,np)Cu^{64}$ Reactions

The integrated cross sections from threshold to several different maximum energies for the three reactions studied are given in Table I. Because of the relatively large uncertainties involved, we will not attempt to make as detailed comments on the significance of the results as we did in part B for the $S^{32}(\gamma,np)P^{30}$ reaction. Since we are interested mainly in the higher energy region, we shall compare the values of the integrated cross sections between 140 and 300 MeV for the three reactions. From Table I these values are 109 ± 14, 53 ± 16, and 240 ± 65 MeV mb for the (γ,np) reactions in S^{32}, Ca^{40}, and Zn^{66}, respectively.

Before comparing these integrated cross sections, it is necessary to note that in the calcium experiment only the ground-state radioactivity was detected. In order to compare the result for calcium with the other two cases, it is necessary to estimate the cross section for the production of the 0.9-sec isomeric state. We estimate that the cross sections for the spin-3 ground state and the spin-0 isomeric state should be about the same at all energies. This estimate is based on the results of recent studies of isomer ratios in photonuclear reactions by Walters.[24] He has observed that the isomeric yield ratios for several photonuclear reactions remain constant from the giant resonance region to 300 MeV. This is true for all of the reactions that he studied, including (γ,n) $(\gamma,2n)$, (γ,np), and $(\gamma,3n)$ reactions. This implies a relatively constant ratio for the cross sections from near threshold to 300 MeV. Walters has also shown that if information about the spin dependence of the nuclear level density is available for the nuclei involved, then the observed cross-section ratios can be predicted by compound nucleus mechanism calculations of the type outlined by Huizenga and Vandenbosch[40] for (γ,n) reactions. In the present case the necessary level density information can be obtained by fitting the observed isomer ratio for the $K^{39}(\gamma,n)K^{38}$ reaction.[41] These level density parameters can then be used in the calculation of the expected $Ca^{40}(\gamma,np)K^{38}$ isomer ratio. The calculation yields a value of 1.0 for the isomer ratio expected for the $Ca^{40}(\gamma,np)K^{38}$ reaction. Using this ratio and the value previously given for the

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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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