Identification and Yields of $(\gamma,\alpha n)$ Reactions*

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The $(\gamma,\alpha n)$ reaction was studied in several nuclides by irradiation with photons of 50- and 87-Mev maximum energy from the betatron. By use of radiochemical techniques it was shown that C^{11} is produced from oxygen, F^{18} from sodium, P^{30} and P^{32} from chlorine, Ga^{70} from arsenic, As^{74} and As^{76} from bromine, and Zr^{87} from molybdenum. Except for P^{32}, it is proposed that these nuclides are produced by the $(\gamma,\alpha n)$ reaction. The yields of these nuclides relative to N^{13} from the $N^{14}(\gamma,n)N^{13}$ reaction and those of other nuclides observed in this study are given.

INTRODUCTION

STUDIES of the interaction of high energy photons with nuclei[1,2] have shown that the (γ,n) reaction is the most prominent one, and other reactions occur in lower yield. Evidence for reactions in which alpha-particles are emitted has come from several sources. The photodisintegration of carbon into alpha-particles has been reported[3] from photographic plate studies. Other emulsion[4] and cloud-chamber[1] investigations have also reported the emission of alpha-particles. The $Rb^{87}(\gamma,\alpha)Br^{83}$ reaction has been verified radiochemically.[5] More complex reactions involving the emission of an alpha-particle and a neutron have been reported. The reactions $O^{16}(\gamma,\alpha n)C^{11}$ and $Na^{23}(\gamma,\alpha n)F^{18}$ were postulated in order to explain some low intensity species found in irradiated oxygen and sodium.[1,2] The $(\gamma,\alpha n)$ and $(\gamma,\alpha p)$ reactions were also reported from emulsion studies.[6]

This study reports on the radiochemical characterization of the reactions $O^{16}(\gamma,\alpha n)C^{11}$ and $Na^{23}(\gamma,\alpha n)F^{18}$, the yields of these reactions relative to the yield of the (γ,n) reaction on N^{14}, and the characterization and yield determinations of the $(\gamma,\alpha n)$ and other reactions in chlorine, arsenic, bromine, and molybdenum.

Samples were irradiated with photons from the University of Chicago betatron with maximum energies of 50 and 87 Mev. Intensities ranged from 100 to 300 roentgens per minute at 1 meter at 50 Mev, and from 500 to 900 roentgens per minute at 1 meter at 87 Mev, as measured by a Victoreen lead-walled r-meter.

The relative yields reported here are calculated from the ratio of the saturation activity of the nuclide studied to the saturation activity of N^{13} from the reaction $N^{14}(\gamma,n)N^{13}$. The yields are corrected for the number of atoms of the nuclide undergoing the reaction and for the variation in the intensity of the photon beam. In practice, the yield of the reaction relative to $O^{16}(\gamma,n)O^{15}$ was determined, and then the yield relative to $N^{14}(\gamma,n)N^{13}$ was calculated using the factor 2.4 for the relative yield of O^{15} to N^{13} as determined by Perlman and Friedlander.[2]

The mass differences in the proposed nuclear reactions were calculated from nuclear mass values in Mattauch and Flammersfeld[7] where given, or from a liquid drop model formula.[8] For light nuclei, mass differences calculated from the Wigner mass formula[9] are all consistently higher. The thresholds given are the sums of the mass differences and the Coulomb barriers, using $1.5A^{\frac{1}{3}}\times10^{-13}$ cm for the nuclear radius, and are the effective energy values for the reactions to occur in high yield. Results of Haslam and Skarsgard[5] and a report by Haslam[6] indicate that these thresholds may be several Mev too high.

IDENTIFICATION OF C^{11} AND F^{18} FROM IRRADIATIONS OF OXYGEN AND SODIUM

The photoproduction of C^{11} from oxygen was proved by the radiochemical identification of 20.5-min C^{11}. A sample of boric acid was irradiated and dissolved in water containing 10 mg of carbonate carrier in a closed system. The solution was acidified and nitrogen was bubbled through it after first being dispersed through a sintered-glass disk. The CO_2 was passed into a saturated solution of $Ca(OH)_2$, about 0.04*M*, in NaOH, and the $CaCO_3$ precipitate was filtered and counted on an end-window counter. The half-life of the activity found was 20 min and the range of the beta-particles through aluminum corresponded to an energy of about 1.0 Mev. There was also radiation attributable to annihilation radiation. These properties and the chemical behavior correspond to those of C^{11}.

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[1] G. C. Baldwin and G. S. Klaiber, Phys. Rev. **70**, 259 (1946).
[2] M. L. Perlman and G. Friedlander, Phys. Rev. **74**, 442 (1948).
[3] Hänni, Telegdi, and Zünti, Helv. Phys. Acta **21**, 203 (1948).
[4] C. H. Millar and A. G. W. Cameron, Phys. Rev. **78**, 78 (1950).
[5] R. N. H. Haslam and H. M. Skarsgard, Phys. Rev. **81**, 479 (1951).
[6] R. N. H. Haslam, Proceedings of the International Conference on Nuclear Physics and the Physics of Fundamental Particles, Institute for Nuclear Studies, University of Chicago, September 17 to 22, 1951, p. 191.
[7] J. Mattauch and A. Flammersfeld, *Isotopic Report* (Verlag Z. Naturforsch., Tübingen, 1949).
[8] Orear, Rosenfeld, and Schluter, *Nuclear Physics Notes* (University of Chicago, Chicago, 1949), p. 6.
[9] W. H. Barkas, Phys. Rev. **55**, 691 (1939).

TABLE I. Yields of nuclides from oxygen and sodium at 50 Mev.

Compound irradiated	Nuclide studied	Assigned reaction	Yield relative to $N^{14}(\gamma,n)N^{13}$
H_3BO_3, $NaBO_2$, $Na_2B_4O_7\cdot 10H_2O$, $Na_2B_4O_7$ (anhydrous)	1.9-min O^{15}	$O^{16}(\gamma,n)O^{15}$	2.4[a]
	10.1-min N^{13}	$O^{16}\{\gamma,H^3;\ \gamma,p2n\}N^{13}$	0.022 ±0.009
	20.5-min C^{11}	$O^{16}(\gamma,\alpha n)C^{11}$	0.044 ±0.013
Na_2CO_3, $Na_2B_4O_7\cdot 10H_2O$, $Na_2B_4O_7$ (anhydrous)	20.5-min C^{11}	$C^{12}(\gamma,n)C^{11}$	2.3[a]
	112-min F^{18}	$Na^{23}(\gamma,\alpha n)F^{18}$	0.17 ±0.02

[a] Values from Perlman and Friedlander (see reference 2).

Activity measurements on oxygen-containing samples irradiated at 50 and 87 Mev, where no chemical separation was done, showed the presence of the 2-min O^{15}, the 20-min C^{11}, and a species of 10-min half-life, probably N^{13}.

The formation of F^{18} from Na^{23} was studied by the chemical separation of the 112-min F^{18} from 5 g of irradiated $NaNO_3$. The $NaNO_3$ was dissolved in water, 3 mg fluoride carrier was added, and PbClF was precipitated.[10] (If more than 5 g of $NaNO_3$ was used, no PbClF precipitate was formed.) The PbClF precipitate was dissolved, PbClF was reprecipitated, redissolved, and a scavenging precipitation of PbS was made. A small amount of lead carrier was added to remove the excess sulfide, the resulting PbS was removed, and finally PbClF was reprecipitated, weighed, and counted on an end-window tube. The half-life of the activity was 112 min, and the range of the particle radiation in aluminum corresponded to an energy of 0.62 Mev. Annihilation radiation was also present. These nuclear and chemical properties are consistent with those of F^{18}.

YIELDS OF NUCLIDES FROM OXYGEN AND SODIUM

A study of the yields of the nuclides produced in oxygen and sodium relative to the yields of O^{15} from the reaction $O^{16}(\gamma,n)O^{15}$ and C^{11} from the reaction $C^{12}(\gamma,n)C^{11}$ was made at the betatron at a maximum energy of 50 Mev. Samples of Na_2CO_3, boric acid, $NaBO_2$, borax ($Na_2B_4O_7\cdot 10H_2O$), and $Na_2B_4O_7$ (anhydrous) were irradiated. The chemical composition of the boron compounds was determined by titration. After irradiation, the samples were spread on Scotch tape which was held on a thin copper foil. The copper foil was put into a brass cylinder which was thick relative to the range of the beta-particles and the sample was then put around a thin-walled cylindrical Geiger-Müller counter for activity determination. The counter wall was made from gold-plated plastic sheet covered with rubber hydrochloride which was wrapped over a brass frame.[11] Q-gas was flowed through the counter at atmospheric pressure. The thickness of the counter wall was about 3.5 mg/cm^2 and the sample thickness was about 4 mg/cm^2.

The nuclides studied for yield measurements were C^{11}, N^{13}, O^{15}, and F^{18}. Monitors of appropriate half-life for each activity were used in order to intercompare runs. The results are given in Table I. The relative yield of F^{18} to N^{13} was measured by first determining the relative yield in Na_2CO_3 of F^{18} to C^{11} from the reaction $C^{12}(\gamma,n)C^{11}$, and then using Perlman and Friedlander's[2] value 2.3 for the relative yield of the reaction $C^{12}(\gamma,n)C^{11}$ to $N^{14}(\gamma,n)N^{13}$. The "assigned reaction" column in Table I gives the reaction proposed for the production of the nuclide in question. (See comments at end of this section and in Discussion section.)

The large errors in the yield values for the nuclides from oxygen are due mainly to difficulties in analyzing the decay curves for the 10- and 20-min activities because of the similarity in half-lives and poor counting statistics. There was also a systematic difference in the yields of O^{15} and C^{11} from boric acid and the sodium borate compounds, the boric acid having yields of O^{15} and C^{11} about one-half those of the sodium borate compounds. Since the relative yield of C^{11} from oxygen to $N^{14}(\gamma,n)N^{13}$ is determined by first measuring the relative yield to O^{15}, little error is introduced for this reason. On the other hand, the yield of N^{13} from oxygen did not vary systematically with different compounds, and the yield given in Table I for this nuclide is that found for the sodium borate compounds. Earlier work[12] on the bombardment of boric anhydride with protons of less than 1-Mev energy showed a loss of radioactive carbon from the target material similar to that observed in these experiments with boric acid.

The thresholds calculated for possible reactions of O^{16} leading to C^{11} are as follows:

$$O^{16}(\gamma,\alpha n)C^{11},\ 32\ \text{Mev};$$

$$O^{16}(\gamma,H^3 2n)N^{11}\xrightarrow{\beta^+}C^{11},\ 43\ \text{Mev};$$

$$O^{16}(\gamma,5n)O^{11}\xrightarrow{2\beta^+}C^{11},\ 98\ \text{Mev}.$$

Since the production of C^{11} was observed at 50-Mev maximum energy, the most likely reaction for its production is $O^{16}(\gamma,\alpha n)C^{11}$.

Thresholds calculated for the production of N^{13} from O^{16} by various reactions are as follows:

$$O^{16}(\gamma,H^3)N^{13},\ 28\ \text{Mev};$$

$$O^{16}(\gamma,p2n)N^{13},\ 38\ \text{Mev};$$

$$O^{16}(\gamma,3n)O^{13}\xrightarrow{\beta^+}N^{13},\ 46\ \text{Mev}.$$

From these values it would appear that the production

[10] W. W. Scott, *Standard Methods of Chemical Analysis* (D. Van Nostrand Company, Inc., New York, 1939), fifth edition, p. 405.

[11] This counter was developed by Professor W. F. Libby and Mr. T. Sugihara, Mr. R. L. Wolfgang, and Mr. R. L. Schuch.

[12] H. R. Crane and C. C. Lauritsen, Phys. Rev. 45, 497 (1934).

TABLE II. Data on activities studied in photon reactions.

Compound irradiated	Reacting nuclide	Nuclide studied	Reaction	Calculated threshold (including Coulomb barrier) Mev	Yield at 50 Mev relative to $N^{14}(\gamma,n)N^{13}$
H_3BO_3, $NaBO_2$, $Na_2B_4O_7\cdot 10H_2O$, $Na_2B_4O_7$ (anhydrous)	O^{16}	20.5-min C^{11}	$O^{16}(\gamma,\alpha n)C^{11}$ $O^{16}(\gamma,H^3 2n)N^{11}$ $O^{16}(\gamma,5n)O^{11}$	32 43 98	0.044±0.013
		10.1-min N^{13}	$O^{16}(\gamma,H^3)N^{13}$ $O^{16}(\gamma,p2n)N^{13}$ $O^{16}(\gamma,3n)O^{13}$	28 37 46	0.022±0.009
Na_2CO_3, $Na_2B_4O_7\cdot 10H_2O$, $Na_2B_4O_7$ (anhydrous)	Na^{23}	112-min F^{18}	$Na^{23}(\gamma,\alpha n)F^{18}$ $Na^{23}(\gamma,H^3 2n)Ne^{18}$ $Na^{23}(\gamma,5n)Na^{18}$	27 41 80	0.17±0.02
LiCl	Cl^{35} Cl^{37}	2.55-min P^{30}	$Cl^{35}(\gamma,\alpha n)P^{30}$ $Cl^{37}(\gamma,\alpha 3n)P^{30}$ $Cl^{35}(\gamma,H^3 2n)S^{30}$ $Cl^{35}(\gamma,5n)Cl^{30}$	29 47 48 71	0.17[a]
		14.1-day P^{32}	$Cl^{37}(\gamma,\alpha n)P^{32}$ $Cl^{35}(\gamma,He^3)P^{32}$ $Cl^{35}(\gamma,2pn)P^{32}$	26 30 38	0.47[b] (0.24)[c]
		25-day P^{33}	$Cl^{37}(\gamma,\alpha)P^{33}$ $Cl^{35}(\gamma,2p)P^{33}$	15 25	0.47[b] (0.12)[d]
$Na_2HAsO_4\cdot 7H_2O$	As^{75}	20-min Ga^{70}	$As^{75}(\gamma,\alpha n)Ga^{70}$	28	0.21
		14.3-hr Ga^{72}	$As^{75}(\gamma,He^3)Ga^{72}$ $As^{75}(\gamma,2pn)Ga^{72}$	32 40	0.011
		5-hr Ga^{73}	$As^{75}(\gamma,2p)Ga^{73}$	31	0.0079
		52-min Zn^{69}	$As^{75}(\gamma,\alpha pn)Zn^{69}$	41	<0.0031
		2.2-min Zn^{71}	$As^{75}(\gamma,He^3p)Zn^{71}$	47	<0.0007
NH_4Br	Br^{79} Br^{81}	17.5-day As^{74}	$Br^{79}(\gamma,\alpha n)As^{74}$ $Br^{81}(\gamma,\alpha 3n)As^{74}$	30 46	0.12[e]
		26.8-hr As^{76}	$Br^{81}(\gamma,\alpha n)As^{76}$ $Br^{79}(\gamma,He^3)As^{76}$ $Br^{79}(\gamma,2pn)As^{76}$	30 34 42	0.055[f] (0.041)[g]
		40-hr As^{77}	$Br^{81}(\gamma,\alpha)As^{77}$ $Br^{79}(\gamma,2p)As^{77}$	18 33	0.065[f]
		90-min As^{78}	$Br^{81}(\gamma,He^3)As^{78}$ $Br^{81}(\gamma,2pn)As^{78}$	35 43	0.014
		12-hr Ge^{77}	$Br^{81}(\gamma,He^3p)Ge^{77}$	52	<0.00044
		2.1-hr Ge^{78}	$Br^{81}(\gamma,3p)Ge^{78}$	52	<0.0013
MoO_3	Mo^{92} Mo^{94}	1.5-hr Zr^{87}	$Mo^{92}(\gamma,\alpha n)Zr^{87}$ $Mo^{92}(\gamma,H^3 2n)Nb^{87}$ $Mo^{92}(\gamma,5n)Mo^{87}$ $Mo^{94}(\gamma,\alpha 3n)Zr^{87}$	31 46 54 67	0.13[h]

[a] Yield at 87 Mev relative to $N^{14}(\gamma,n)N^{13}$ at 87 Mev for production from Cl^{35} only.
[b] Yield calculated for production from Cl^{37} only.
[c] Yield calculated for production from Cl^{35} and Cl^{37} assuming combined yield of (γ,He^3) and $(\gamma,2pn)$ reactions ½ that of $(\gamma,\alpha n)$ reaction.
[d] Yield calculated for production from Cl^{35} and Cl^{37} assuming yield of $(\gamma,2p)$ reaction on Cl^{35} equal to yield of (γ,α) reaction on Cl^{37}.
[e] Yield calculated for production from Br^{79} only.
[f] Yield calculated for production from Br^{81} only.
[g] Yield calculated for production from Br^{79} and Br^{81} assuming yield of $Br^{79}(\gamma,He^3)As^{76}$ reaction is equal to that of $Br^{81}(\gamma,He^3)As^{78}$ reaction, or 0.014.
[h] Yield calculated for production from Mo^{92} only.

of N^{13} from O^{16} at 50 Mev could occur by either the $O^{16}(\gamma,H^3)N^{13}$ reaction or the $(\gamma,p2n)$ reaction.

The production of F^{18} from Na^{23} by the following reactions have thresholds as listed:

$$Na^{23}(\gamma,\alpha n)F^{18},\ 27\ \text{Mev};$$

$$Na^{23}(\gamma,H^3 2n)Ne^{18}\xrightarrow{\beta^+}F^{18},\ 41\ \text{Mev};$$

$$Na^{23}(\gamma,5n)Na^{18}\xrightarrow{2\beta^+}F^{18},\ 80\ \text{Mev}.$$

From these data it would appear that the major production of F^{18} from Na^{23} at 50 Mev is due to the $Na^{23}(\gamma,\alpha n)F^{18}$ reaction. These data on the yields of the reactions in O^{16} and Na^{23} and the thresholds for the other possible reactions are listed in Table II.

YIELDS OF NUCLIDES FROM CHLORINE, ARSENIC, BROMINE, AND MOLYBDENUM

Chlorine, in the form of LiCl, was irradiated with 50-Mev photons, and phosphorus was separated first as

ammonium phosphomolybdate and finally as magnesium ammonium phosphate.[13] Appropriate holdback carriers were added to remove any possible impurities. The samples, counted on an end-window counter, showed a half-life of about 18 days, a mixture of 14.1-day P^{32} and 25-day P^{33}.[14,15] When an absorber was used to eliminate the weak beta-particles of P^{33}, the half-life observed was 14.1 days. An absorption curve in aluminum gave a beta-range corresponding to the maximum energy of the beta-rays of P^{32} of 1.7 Mev. No gamma-rays were observed. There was also a weak beta-component of about 0.25 Mev from P^{33}. An activity with a 2.5-min half-life, probably 2.55-min P^{30}, was found by doing one rapid ammonium phosphomolybdate precipitation.

The yields at 50 Mev of P^{32} and P^{33}, and of P^{30} at 87 Mev, relative to $N^{14}(\gamma,n)N^{13}$ are given in Table II. These relative yields, and those of the nuclides reported later in this paper, were obtained using an end-window counter rather than the cylindrical counter used for the yield determinations in oxygen and sodium. The O^{15} activity from the reaction $O^{16}(\gamma,n)O^{15}$ in thick samples of $NaNO_3$ was used for activity comparison, after corrections were made for the sample thickness using the data for self-absorption from Perlman and Friedlander.[2] The calculated thresholds and yields of the various nuclides are given in Table II.

Arsenic was studied by irradiating $Na_2HAsO_4 \cdot 7H_2O$ with 50-Mev photons and analyzing for the desired nuclides. Radioactive gallium was separated from HCl solution by extracting into ether with 5 mg of gallium carrier. The gallium was then re-extracted into water, precipitated as gallium oxyquinolate and counted on an end-window counter. Analysis of the decay curves showed activities of 20-min, 5-hr, and 14-hr half-life. The chemical identification of the activities as those of gallium and the half-life characteristics correspond to those of 20-min Ga^{70}, 5-hr Ga^{73}, and 14.3-hr Ga^{72}, respectively. The yields of these nuclides and the thresholds for possible reactions for their formation are given in Table II.

Zinc was also separated from an irradiated sample of $Na_2HAsO_4 \cdot 7H_2O$ by a rapid precipitation of zinc mercuric thiocyanate. No activity of 52-min Zn^{69} or 2.2-min Zn^{71} was observed. Limiting yields of these nuclides are given in Table II.

Bromine in the form of NH_4Br was irradiated with 50-Mev photons. The NH_4Br was dissolved in water in the presence of 10 mg of arsenic and germanium carriers, and As_2S_3 and GeS_2 were precipitated with H_2S. Arsenic and germanium were then separated from each other by distillation of the chlorides. As_2S_3 was precipitated and counted on an end-window counter. An activity of 17.5-day half-life was observed. The radiations emitted consisted of particles with ranges in aluminum corresponding to energies of about 0.8 and 1.4 Mev, and some γ- or annihilation radiation. These chemical and nuclear properties correspond to those of 17.5-day As^{74}. Also found in the arsenic sample were activities of 36-hr and 90-min half-life. The 36-hr activity was assumed to be a mixture of the 26.8-hr As^{76} and 40-hr As^{77}, and the 90-min activity was probably 90-min As^{78}.

The yields of As^{74}, As^{76}, As^{77}, and As^{78} are reported in Table II. In the calculation of the yield of As^{74} it was assumed that 35 percent[16] of the disintegrations are electron capture processes. Thresholds for proposed nuclear reactions and the yields of the arsenic nuclides are given in Table II.

Germanium was precipitated as GeS_2 from the volatilized chloride and counted. No activity of 2.1-hr Ge^{78} and 12-hr Ge^{77} was observed. Limiting yields for these nuclides were calculated and are given in Table II.

Molybdenum was irradiated as MoO_3 which was then dissolved in ammonium hydroxide. The solution was acidified, zirconium carried was added, a LaF_3 scavenging precipation was made, and $BaZrF_6$ was precipitated, dissolved, and reprecipitated several times. Finally, zirconium cupferrate was precipitated, ignited, and counted. Half-lives of 1.5 hr and 67 hr were apparent. The 1.5-hr half-life can be assigned to 1.5-hr Zr^{87}, and the 67-hr half-life is probably due to contamination of Mo^{99} from the reaction $Mo^{100}(\gamma,n)Mo^{99}$. The relative yield of Zr^{87} and possible reactions for its formation are given in Table II.

The errors in the yield values given in Table II are difficult to estimate except in the cases of C^{11}, N^{13}, and F^{18} where numerous experiments were performed. In other cases, the main effort was directed toward the chemical identification of the nuclides produced, and less attention was given to the accuracy of the yield values. In these cases, it is estimated that the error may be as large as a factor of 2.

DISCUSSION

The assignment of the reaction responsible for the production of the observed nuclide can be made in many cases from energy or yield considerations. In these cases, the yield of the nuclide as given in Table II can then be considered as the yield of the reaction. Those nuclides which can be produced by the $(\gamma,\alpha n)$ reaction originate, in the main, in this reaction at 50 Mev. In some cases, the apparent yield of the reaction will be higher than that for the $(\gamma,\alpha n)$ reaction if the observed radioactive nuclide can be produced from more than one reacting nuclide (see P^{32} below). A summary of yield values of photon reactions from this study and elsewhere is given in Table III. A discussion

[13] W. F. Hildebrand and G. E. F. Lundell, *Applied Inorganic Analysis* (John Wiley and Sons, Inc., New York, 1929), pp. 38, 581.

[14] Sheline, Holtzman, and Fan, Phys. Rev. **83**, 919 (1951).

[15] Jensen, Nichols, Clement, and Pohm, Phys. Rev. **85**, 112 (1952).

[16] L. G. Elliott, as reported by Way, Fano, Scott, and Thew, *Nuclear Data*, National Bureau of Standards Circular No. 499 (1950).

of the reaction assignments for the observed nuclides of Table II follows:

C^{11}: An examination of the threshold values for the $(\gamma,\alpha n)$, $(\gamma,H^3 2n)$, and $(\gamma,5n)$ reactions from Table II indicates that C^{11} is formed from oxygen by the $O^{16}(\gamma,\alpha n)C^{11}$ reaction.

N^{13}: Both the $O^{16}(\gamma,H^3)N^{13}$ and $O^{16}(\gamma,p2n)N^{13}$ reactions are energetically possible, as seen in Table II.

F^{18}: Threshold values of the reactions in Table II suggest the formation of F^{18} by the reaction $Na^{23}(\gamma,\alpha n)F^{18}$.

P^{30}: Since the only yield value for P^{30} from chlorine given in Table II is that at 87 Mev, energy considerations alone make it difficult to assign the most probable reaction. On the other hand, the relative yield value is in the range of the $(\gamma,\alpha n)$ yields, making it likely that the $Cl^{35}(\gamma,\alpha n)P^{30}$ reaction is the one responsible for the formation of P^{30}.

P^{32}: Energy considerations allow for the $Cl^{37}(\gamma,\alpha n)P^{32}$ reaction and the $Cl^{35}(\gamma,He^3)P^{32}$, or its equivalent $Cl^{35}(\gamma,2pn)P^{32}$, reaction for the production of P^{32}. Although the yield of the (γ,He^3) reaction in this mass range has not been determined, a comparison of the $(\gamma,\alpha n)$ reaction with the (γ,He^3) reaction on Br^{81} shows that the latter is about $\frac{1}{3}$ as prominent at mass 81. In As^{75} this ratio is about 1/20. If one assumes that the contribution of the (γ,He^3) reaction at mass 35 is $\frac{1}{3}$ that of the $(\gamma,\alpha n)$ reaction, then the yield of P^{32} from the $Cl^{35}(\gamma,He^3)$ reaction would equal that from the $Cl^{37}(\gamma,\alpha n)$ reaction because of the relatively greater abundance of Cl^{35}.

P^{33}: The production of P^{33} is possible energetically by the reactions $Cl^{37}(\gamma,\alpha)P^{33}$ and $Cl^{35}(\gamma,2p)P^{33}$. The very meagre yield data on (γ,α) and $(\gamma,2p)$ reactions make it difficult to decide on the more prominent reaction. An examination of the data of Table III indicates that in this mass range the $(\gamma,2p)$ reaction and (γ,α) reaction may have roughly equal yields. If this assumption is made, then the yield of P^{33} from the $Cl^{37}(\gamma,\alpha)$ reaction is $\frac{1}{3}$ that from the $Cl^{35}(\gamma,2p)$ reaction.

Ga^{70}: The only reaction possible for the production of Ga^{70} is the $As^{75}(\gamma,\alpha n)Ga^{70}$ reaction. As^{75} is the only stable isotope of arsenic, and Ga^{70} is shielded from β^+ decay of As^{70} by the stable nuclide Ge^{70}.

Ga^{72}: Both the (γ,He^3) and $(\gamma,2pn)$ reactions on As^{75} are energetically possible for the production of Ga^{72}.

Ga^{73}: The only possible reaction for the production of Ga^{73} from As^{75} is the $As^{75}(\gamma,2p)$ reaction. This reaction is the only $(\gamma,2p)$ reaction unambiguously assigned in this work.

Zn^{69} and Zn^{71}: The activity observed in the isolated zinc fraction was very small. Only limiting values for the yields of the $As^{75}(\gamma,\alpha pn)Zn^{69}$ and $As^{75}(\gamma,He^3p)Zn^{71}$ reactions could be calculated.

As^{74}: The reaction for the production of this nuclide from bromine is the $Br^{79}(\gamma,\alpha n)As^{74}$ reaction. The contribution of the $Br^{81}(\gamma,\alpha 3n)As^{74}$ reaction is neglected because of the high threshold.

As^{76}: Both the $Br^{81}(\gamma,\alpha n)As^{76}$ and $Br^{79}(\gamma,He^3)As^{76}$ reactions are energetically possible. If one assumes the yield of the (γ,He^3) reaction in Br^{79} and Br^{81} to be equal and the yield of the (γ,He^3) reaction to be $\frac{1}{3}$ that of the $(\gamma,\alpha n)$ reaction, then the yield of As^{76} from the (γ,He^3) reaction will be about 30 percent that from the $(\gamma,\alpha n)$ reaction.

As^{77}: An examination of the yield data on (γ,α) and $(\gamma,2p)$ reactions of Table III indicates that the (γ,α) reaction is several-fold more prominent than the $(\gamma,2p)$ reaction in this mass region. The major production of As^{77} is, therefore, thought to be due to the $Br^{81}(\gamma,\alpha)As^{77}$ reaction.

As^{78}: The photoproduction of As^{78} from bromine can be ascribed to two possible reactions, $Br^{81}(\gamma,He^3)$ and $Br^{81}(\gamma,2pn)$. The high threshold of the $Br^{81}(\gamma,2pn)As^{78}$ reaction makes this reaction improbable relative to the $Br^{81}(\gamma,He^3)As^{78}$ reaction.

Ge^{77} and Ge^{78}: No activity of 12-hr Ge^{77} or 2.1-hr Ge^{78} was observed in the germanium fraction from irradiated bromine. The low limiting values calculated for the yields of the (γ,He^3p) and $(\gamma,3p)$ reactions on Br^{81} are consistent with the high thresholds.

Zr^{87}: The high thresholds of reactions other than the $Mo^{92}(\gamma,\alpha n)Zr^{87}$ reaction make it improbable that they contribute much to the yield.

The data of Table III include the relative yields of the reactions just discussed, and those of (γ,n), (γ,p), $(\gamma,2n)$, (γ,pn), $(\gamma,2p)$, $(\gamma,p2n)$, and (γ,α) reactions studied by Perlman and Friedlander,[2] Perlman,[17] Diven and Almy,[18] Johns and co-workers,[19] Haslam and Skarsgard,[5] Katz and Penfold,[20] Strauch,[21] Haslam and co-workers,[22] Katz and co-workers,[23] Stephens and co-workers,[24] Marshall,[25] Halpern and Mann,[26] Sheline, Holtzman, and Fan,[14] and Haslam.[6] The yields reported are given as mentioned earlier, namely, the ratio of the saturation activity of the nuclide observed to that of N^{13} from the $N^{14}(\gamma,n)N^{13}$ reaction. In those cases where cross-sectional data were given, the yields were calculated by comparing the integrated cross section for the production of the nuclide in question with that of the $Cu^{63}(\gamma,n)Cu^{62}$ reaction and correcting for the energy dependence of the photon intensity. The relative yield of the $Cu^{63}(\gamma,n)Cu^{62}$ reaction to the $N^{14}(\gamma,n)N^{13}$ reaction was taken to be 35.00.[2]

As noted by Perlman and Friedlander,[2] the yield of

[17] M. L. Perlman, Phys. Rev. **75**, 988 (1949).
[18] B. C. Diven and G. M. Almy, Phys. Rev. **80**, 407 (1950).
[19] Johns, Katz, Douglas, and Haslam, Phys. Rev. **80**, 1062 (1950).
[20] L. Katz and A. S. Penfold, Phys. Rev. **81**, 815 (1951).
[21] K. Strauch, Phys. Rev. **81**, 973 (1951).
[22] Haslam, Johns, and Horsley, Phys. Rev. **82**, 270 (1951).
[23] Katz, Johns, Baker, Haslam, and Douglas, Phys. Rev. **82**, 271 (1951).
[24] Stephens, Halpern, and Sher, Phys. Rev. **82**, 511 (1951).
[25] L. Marshall, Phys. Rev. **83**, 345 (1951).
[26] J. Halpern and A. K. Mann, Phys. Rev. **83**, 370 (1951).

TABLE III. Summary of yields of photon reactions at 50 Mev. Numbers in boldface type, results of this paper; lightface type, data of Perlman and Friedlander (see reference 2) except where noted.

Reacting nuclide	(γ,n)	(γ,p)	$(\gamma,2n)$	(γ,pn) (γ,d)	$(\gamma,2p)$	(γ,H^3) $(\gamma,p2n)$	(γ,He^3) $(\gamma,2pn)$	(γ,α)	$(\gamma,\alpha n)$	Assumed (γ,n) yield	Ratio $(\gamma,\alpha n)/(\gamma,n)$
C^{12}	2.3, 2.6,[a] 1.7,[b] 2.4[c]	2.3[d]	<0.003[e]							2.3	
N^{14}	1.00									1.00	
O^{16}	2.4					**0.022**			**0.044**	2.4	0.018
O^{18}		5.5[f]								2.5	
F^{19}	2.8		0.15							2.5	
Na^{23}									**0.17**	2.5	0.068
Al^{27}	3.1	4.4[d]			0.14					2.5	
Si^{30}		6.6								2.6	
P^{31}	7.1, 6.3[g]		<0.1[e]		0.15					2.7	
S^{32}				0.15[g]						2.8	
S^{34}				6.6[h]						2.9	
Cl^{35}	2.4								**0.17**[i]	2.9	0.071
Cl^{37}								**0.47,[i] 0.12**[i]	**0.47,[i] 0.24**[i]	2.9	0.19,[i] 0.096[i]
K^{39}	2.6									3.1	
Cr^{50}	12[j]									9.0	
Fe^{54}	15,[j] 22[k]									14	
Fe^{57}		7.6								18	
Co^{59}		5.1[d]								22	
Ni^{58}	>6.0,[j] 17[k], 12*	16.6[l]								22	
Ni^{62}		5.0								28	
Cu^{63}	35		2.5		0.16[m]					30	
Cu^{65}	32,[j] 42,[a] 63[n]							**0.36,[p] 0.43**[q]		35	
Zn^{64}	26,[j] 29,[a] 44,[k] 37[c]		1.3[a]	6.5[a]		1.6[r]				35	
Zn^{66}				3.3[a]						39	
Zn^{68}		2.4[a]								42	
Ga^{69}	44									44	
Ga^{71}	44									44	
Ge^{70}				3.4[e, j]						46	
Ge^{74}		2.5[e, j]								46	
Ge^{76}	54[e, j]									46	
As^{75}					**0.0079**		**0.011**		**0.21**	46	0.0046
Br^{79}									**0.12**[i]	46	0.0026
Br^{81}							**0.014**	**0.065**[i]	**0.055,[i] 0.041**[i]	46	0.0012,[i] 0.00089[i]
Rb^{87}								0.015[s]		46	
Nb^{93}		4.4[d]								46	
Mo^{92}									**0.13**[i]	46	0.0028
Mo^{98}		3.1								46	
Ru^{102}		3.6								46	
Ag^{109}	46, 105[t]									46	
Pd^{110}	39									46	
Sb^{121}	46, 70[n]									46	
Sb^{123}	116[n]									46	
I^{127}	>30[j], 75*									48	
Pr^{141}	76[j]									70	
Ta^{181}	26[n]									84	
Re^{187}	86									86	

[a] Data of Strauch (see reference 21) calculated from relative cross sections obtained with 200- and 322-Mev photons. Yield of $Cu^{63}(\gamma,n)Cu^{62}$ set equal to 35.00.
[b] Data of Haslam and co-workers (see reference 22) from photon irradiations up to 27 Mev. Yields calculated from cross sections using value of integrated cross section for $Cu^{63}(\gamma,n)Cu^{62}$ of 0.63 Mev barn. Relative yield of Cu^{63} set equal to 35.00.
[c] Data of Marshall (see reference 25) at 50-Mev photon energy. Yield calculated from cross section, using cross section for $Cu^{63}(\gamma,n)Cu^{62}$ of 0.77 Mev barn. Relative yield of Cu^{63} set equal to 35.00.
[d] Data of Halpern and Mann (see reference 26) up to 24-Mev photon energy. Yield calculated as in b.
[e] Irradiations at 100 Mev.
[f] Data of Stephens and co-workers (see reference 24), up to 25-Mev photon energy. Yield calculated as in b.
[g] Data of Katz and Penfold (see reference 20), up to 28-Mev photon energy. Yield calculated as in b.
[h] Data of Sheline, Holtzman, and Fan (see reference 14) at 50 Mev. Yield obtained by assuming (γ,p) yield equal to 6.0, and using measured ratio of 0.79 for P^{33} to P^{32} from sulfur.
[i] See comments in footnotes to Table II.
[j] Data of Perlman (see reference 17).
[k] Data of Katz and co-workers (see reference 23), up to 24-Mev photon energy. Yield calculated as in b.
[l] Data of Halpern and Mann (see reference 26) by measurement of protons emitted from Ni^{58} and Ni^{60}.
[m] Data of Perlman and Friedlander (see reference 2) neglecting contribution of $Cu^{65}(\gamma,\alpha)Co^{61}$.
[n] Data of Johns *et al.* (see reference 19), up to 25-Mev photon energy. Yield calculated from relative cross sections. Yield of $Cu^{63}(\gamma,n)Cu^{62}$ set equal to 35.00.
[p] Calculated from data of Perlman and Friedlander (see reference 2) assuming total yield of Co^{61} originating in $Cu^{65}(\gamma,\alpha)Co^{61}$
[q] Data of Haslam (see reference 6), up to 26-Mev photon energy. Cross section estimated and yield calculated as in b.
[r] Data of Strauch (see reference 21). Effective activation energy 57 Mev. Little yield expected at 50 Mev.
[s] Data of Haslam and Skarsgard (see reference 5), up to 28 Mev photon energy. Yield calculated as in b.
[t] Data of Diven and Almy (see reference 18), up to 22-Mev photon energy. Yield calculated as in b.
* *Note added in proof.*—Dr. G. Friedlander has kindly called to our attention new measurements on the electron capture to β^+ ratios of Ni^{57} (Friedlander, Perlman, Alburger, and Sunyar, Phys. Rev. **80**, 30 (1950)) and I^{127} (M. L. Perlman and G. Friedlander, Phys. Rev. **82**, 449 (1951)). The numbers in Table III are based on these new measurements.

the (γ,n) reaction shows an increase with increasing atomic number, although from their data and those of Perlman[17] it would appear that this increase occurs somewhat abruptly in the mass regions 60 and 140. The yields of the other reactions of columns 3 to 10 do not show this general increase with atomic number. In

fact, it would appear that the yields of the (γ,p) and (γ,pn) reactions are fairly constant over the range where the (γ,n) yield increases appreciably. In these cases, it would appear that the increased Coulomb barrier causes a reduction in the yield just compensating the increased absorption cross section evidenced by the (γ,n) yields. The $(\gamma,\alpha n)$ yields are also fairly constant in the mass range 23 to 92. The ratio of the $(\gamma,\alpha n)$ to the (γ,n) yield for the same reacting nuclide given in the last column of Table III, shows a sharp decline at higher masses despite the fact that the calculated thresholds (see Table II) do not vary appreciably with increasing mass.

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The Absorption of Slow π^- Mesons by He^3

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A theoretical investigation of the absorption of π^- mesons by He^3 has been carried out in the impulse approximation, using the operators of the weak coupling theory. A similar calculation of π^- absorption in hydrogen and deuterium when compared with experiment fixes the constants in the theory. Consequently the branching ratios between the 6 competing absorption processes in He^3 can be predicted unambiguously. Comparison of these ratios and of the calculated γ-ray spectrum with experiment should provide a good test of the theory.

I. INTRODUCTION

EXPERIMENTAL results[1,2] on the π-meson reactions with hydrogen and deuterium and their theoretical interpretation[3] have greatly extended our knowledge concerning π-mesons. It is now well established, in particular, that the charged π-meson possesses spin 0 and odd parity. We investigate theoretically in this paper the slow π^- meson reactions in He^3 in an attempt to determine how much more can be learned about the meson-nucleon interaction and about the He^3 and H^3 nuclei. The method followed throughout is that of Tamor,[4] based on a "weak coupling" treatment of the meson-nucleon interaction and on a phenomenological description of the nuclear forces. The defects of the "weak coupling" approximation are well known; in many instances, however, it leads to results in reasonable agreement with experiment. For example, Tamor obtained a ratio 2.1 between the nonradiative and the γ-absorption of slow π^- by deuterium on the basis of the $PS(PV)$ theory, in good agreement with the experimental result 2.4 ± 0.4. Therefore, the possibility exists that such "weak coupling" treatments are adequate to describe processes involving real mesons of moderate energy, in particular to describe the absorption processes of negative π-mesons by nuclei. Moreover, the treatment presented here may be viewed as an entirely phenomenological approach and many of the results would hold even if the "weak coupling" approximation were to break down completely; this point will be elaborated later on.

Three types of reactions involving slow mesons may take place in He^3:

(a) the pure absorption	$\pi^-+He^3\rightarrow 2n+p$	(p)
	$\pi^-+He^3\rightarrow n+d$	(d)
(b) the γ-absorption	$\pi^-+He^3\rightarrow 2n+p+\gamma$	$(p\gamma)$
	$\pi^-+He^3\rightarrow n+d+\gamma$	$(d\gamma)$
	$\pi^-+He^3\rightarrow H^3+\gamma$	$(t\gamma)$
(c) the π^0-absorption	$\pi^-+He^3\rightarrow H^3+\pi^0$.	$(t\pi^0)$

It can be shown that the absorption processes take place chiefly from the K shell, or at least from an s state of the mesic atom. Although the absorption from p states is more favored than in the deuterium and hydrogen cases, it is still quite negligible.[5]

It is easy to see how the absorption in He^3 compares with the reactions in hydrogen and deuterium. Reactions $(t\gamma)$ and $(t\pi^0)$ are obviously the analogs of the hydrogen reactions:

$$\pi^-+p\rightarrow n+\gamma$$
$$\pi^-+p\rightarrow n+\pi^0.$$

[1] Panofsky, Aamodt, Hadley, and Phillips, Phys. Rev. **80**, 94 (1950); Aamodt, Hadley, and Panofsky, Phys. Rev. **80**, 282 (1950).

[2] Cartwright, Richman, Whitehead, and Wilcox, Phys. Rev. **81**, 652 (1951); Clark, Roberts, and Wilson, Phys. Rev. **83**, 649 (1951); Durbin, Loar, and Steinberger, Phys. Rev. **83**, 646 (1951).

[3] R. E. Marshak, Revs. Modern Phys. **23**, 137 (1951).

[4] S. Tamor, Phys. Rev. **82**, 598 (1951).

[5] The absorption rate from a p state goes as Z^6 whereas the radiative transition rate from the p to s state goes as Z^4. Furthermore, the absorption is favored in He^3 since the He^3 nucleus contains a greater proportion of large momenta than the deuteron. But, contrary to the deuterium case, the operator $[\boldsymbol{\sigma}\cdot\boldsymbol{\nabla}\phi(0)]$ does not contribute to the p absorption (same selection rule as references 8 and 16) so that the only contribution will come from the small recoil term $(\mu/M)(\boldsymbol{\sigma}\cdot\mathbf{P})[\mathbf{r}\cdot\boldsymbol{\nabla}\phi(0)]$ ($\phi(\mathbf{r})$ meson wave function in the p state considered; $\boldsymbol{\sigma}$, $\mathbf{P}$, $\mathbf{r}$ spin, momentum, and position of the absorbing nucleus).