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$(\gamma,2n)$ Reactions in Light Elements*

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The yields at several energies for the reactions $C^{12}(\gamma,2n)C^{10}$, $O^{16}(\gamma,2n)O^{14}$, $F^{19}(\gamma,2n)F^{17}$, $Na^{23}(\gamma,2n)Na^{21}$, $P^{31}(\gamma,2p)Al^{29}$, and $P^{31}(\gamma,2pn)Al^{28}$ were measured using the x-ray beam from the University of Illinois 300-Mev betatron. It was found that the ratio of integrated cross sections of the $(\gamma,2n)$ to (γ,n) reactions in F^{19} and in Na^{23} is of the order of 0.1 and approximately 1–2 orders of magnitude smaller for C^{12} and O^{16}. The small $(\gamma,2n)$ yields for C^{12} and O^{16} are consistent with statistical competition between emitted particles if the gamma-ray absorption decreases rapidly with energy above the giant resonance.

INTRODUCTION

IN the medium-weight elements where the $(\gamma,2n)$ cross section has been measured, it is found that $\int\sigma_{\gamma,2n}dE$ is about 10% of $\int\sigma_{\gamma,n}dE$ and agreement is found between the measured ratio of $\sigma_{\gamma,2n}/\sigma_{\gamma,n}$ and that calculated from a statistical theory.[1] In light elements the $\int\sigma_{\gamma,2n}dE$ might not remain a constant fraction of $\int\sigma_{\gamma,n}dE$ both since neutron binding energies vary rapidly, and since statistical theory may not be applicable. This experiment measures some $(\gamma,2n)$ yields relative to (γ,n) and indeed finds that the ratio of $\int\sigma_{\gamma,2n}dE$ to $\int\sigma_{\gamma,n}dE$ is not constant from element to element.

MEASUREMENTS

The $(\gamma,2n)$ and other reactions measured were studied with the 300-Mev betatron of the University of Illinois. The yields were measured by detecting the radioactivity of the residual nucleus in a 5-in.×4-in. NaI crystal connected to a 100-channel pulse-height analyzer; since some of the reactions involved short-lived products, a pneumatic system was used to transfer the samples from the 300-Mev machine to the counting room. The reactions investigated were $C^{12}(\gamma,2n)C^{10}$, $O^{16}(\gamma,2n)O^{14}$, $F^{19}(\gamma,2n)F^{17}$, $Na^{23}(\gamma,2n)Na^{21}$, $P^{31}(\gamma,2p)Al^{29}$, and $P^{31}(\gamma,2pn)Al^{28}$. Table I contains data on the nuclei involved.

TABLE I. Data for the reactions investigated.

Parent nucleus	Reaction	Daughter nucleus	Half-life	γ radiation measured
C^{12}	(γ,n)	C^{11}	20.5 min	0.511 Mev
C^{12}	$(\gamma,2n)$	C^{10}	10 sec	0.72 Mev
O^{16}	(γ,n)	O^{15}	2.1 min	0.511 Mev
O^{16}	$(\gamma,2n)$	O^{14}	76 sec	2.3 Mev
F^{19}	(γ,n)	F^{18}	112 min	0.511 Mev
F^{19}	$(\gamma,2n)$	F^{17}	70 sec	0.511 Mev
Na^{23}	$(\gamma,2n)$	Na^{21}	23 sec	0.511 Mev
P^{31}	(γ,n)	P^{30}	2.5 min	0.511 Mev
P^{31}	$(\gamma,2p)$	Al^{29}	6.6 min	1.28 Mev
P^{31}	$(\gamma,2pn)$	Al^{28}	2.3 min	1.78 Mev

The half-lives were checked using an Esterline-Angus chart recorder and found to be correct to within 10%; the (γ,n) yields were compared and found to be consistent with the Perlman and Friedlander[2] results. To obtain the ratio of the integrated cross sections,

$$\int_0^{100\text{ Mev}}\sigma_{\gamma,2n}dE\Big/\int_0^{100\text{ Mev}}\sigma_{\gamma,n}dE,$$

from the measured yield ratios, rough activation curves (Fig. 1) were taken to locate the positions of the maximum cross sections; a spectral and a counting efficiency correction were then applied to the yield ratios to give the integrated cross sections. Table II contains the integrated cross sections of the different reactions relative to (γ,n). The nitrogen results of Panofsky and Reagan[3] are included. Subsidiary information is included in the last column.

TABLE II. Relative integrated cross sections.

Element	(γ,n)	Position of the peak for (γ,n)	$(\gamma,2n)$	Position of the peak for $(\gamma,2n)$
C^{12}	1	23 Mev	0.003	42 Mev
N^{14}	1	24 Mev	0.007[a]	
O^{16}	1	22 Mev	0.002	40 Mev
F^{19}	1	20 Mev	0.14	32 Mev
Na^{23}	1	20 Mev	0.05	32 Mev
P^{31}	1	20 Mev	0.06 $(\gamma,2p)$ 0.08 $(\gamma,2pn)$	45 Mev $(\gamma,2p)$ 50 Mev $(\gamma,2pn)$

[a] The (γ,n) integrated cross section was taken from reference 4.

TABLE III. Thresholds.[a]

Element	(γ,n)	(γ,p)	$(\gamma,2n)$	(γ,np)	$(\gamma,2p)$
C^{12}	18.7	16.0	32	27.5	27.2
N^{14}	10.5	7.5	30.9	12.5	21.1
O^{16}	15.6	12.1	28.9	23.0	22.3
F^{19}	11.3	7.9	19.5	16.0	24.0
Na^{23}	12.4	8.8	23.5	19.2	16.3[b]
P^{31}	12.4	7.3	23.6	17.9	21.1 (30.2)[c]

[a] Masses from Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951); C. W. Li, Phys. Rev. **88**, 1038 (1952); A. H. Wapstra, Physica **21**, 367, 385 (1955).
[b] Semiempirical mass for F^{21} was used.
[c] This is the threshold for the reaction $P^{31}(\gamma,2pn)Al^{28}$.

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[1] Montalbetti, Katz, and Goldemberg, Phys. Rev. **91**, 659 (1953).

[2] M. L. Perlman and G. Friedlander, Phys. Rev. **74**, 442 (1948).

[3] W. K. W. Panofsky and D. Reagan, Phys. Rev. **87**, 543 (1952).

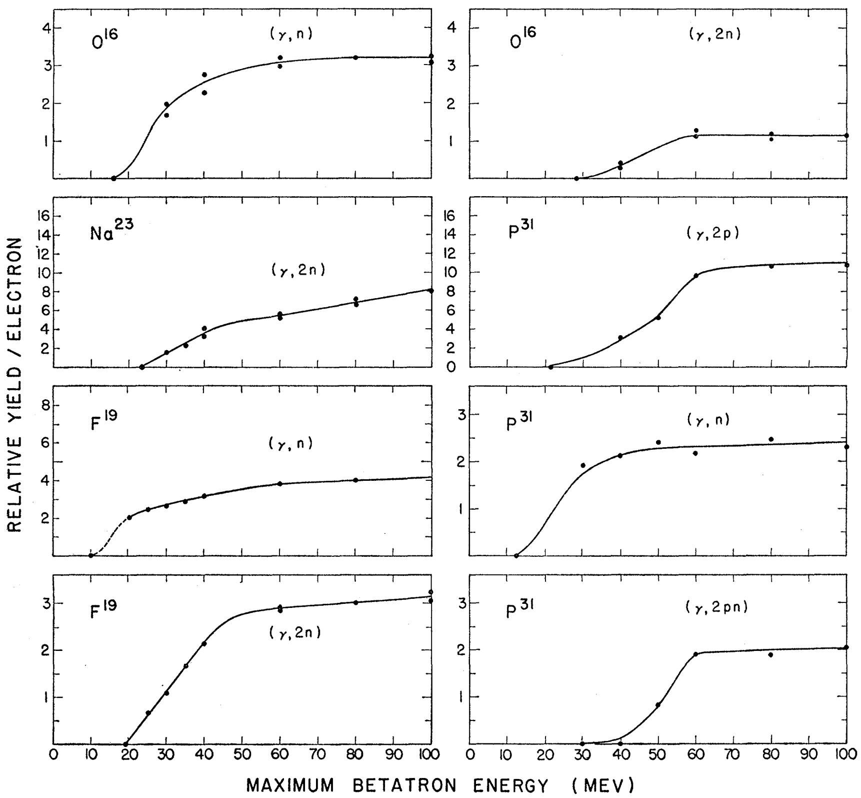

FIG. 1. The energy dependence of several photonuclear reactions. The relative yield scales of different graphs are independent.

DISCUSSION

The fluctuations in the ratio of integrated cross sections for (γ,2*n*) reactions as one goes from C^{12}, N^{14}, O^{16}, (~0.2%) to F^{19} and Na^{23} (~10%) are rather striking. The main difference between these elements appears to lie in the location of the thresholds as can be seen in Table III. The (γ,2*n*) threshold for C^{12}, N^{14}, O^{16} is ~30 Mev and the threshold for F^{19} and Na^{23} is ~20 Mev.

The low (γ,2*n*) yield in N^{14} might be attributed to competition with (γ,*np*) [4] since this reaction has such a low threshold. One way the low values of $\int\sigma_{\gamma,2n}dE/\int\sigma_{\gamma,n}dE$ in C^{12} and O^{16} can be explained without involving special reaction mechanisms or giving up statistical theory, is by noting that if the gamma-ray absorption cross section falls off rapidly enough at energies above the giant resonance, any high-threshold multiple-particle process will be suppressed. Since the peak of the giant resonance is about 20 Mev for the elements investigated, the (γ,2*n*) process sets in "off resonance" in C^{12} and O^{16} but still inside the giant resonance in F^{19} and Na^{23}; if the absorption cross section falls off sufficiently 10 to 20 Mev above the peak of the resonance, the contribution of the (γ,2*n*) process can be quite negligible in C^{12} and O^{16} but still appreciable in F^{19} and Na^{23}. We tried several shapes for the absorption cross section with tails (above 35 Mev) of the type E^{-1}, E^{-2}, and E^{-3} and calculated the ratio of the integrated cross sections assuming statistical competition to be valid and further considering only the competition of (γ,*n*) and (γ,2*n*); this seems to be justified in the above elements considering the thresholds involved. This calculation, admittedly rough, shows that we can explain the results for the integrated cross sections assuming a tail of the type E^{-3} above 35 Mev although E^{-2} is not excluded; actually the results are not very sensitive to a power law between E^{-2} and E^{-3}.

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[4] E. R. Gaerttner and M. L. Yeater, Phys. Rev. 77, 714 (1950).