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Neutron Photoproduction Cross Sections of Silicon, Phosphorus, and Sulfur*

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The absolute (γ,n) cross sections of natural silicon, phosphorus, and sulfur have been measured using the bremsstrahlung from the 70-MeV synchrotron at the University of Virginia. Yield points were taken at 0.5-MeV intervals from 12 to 30 MeV in each case. The absolute measurements were made utilizing a Halpern-type detector, a modified version of an NBS ionization chamber, and a calibrated Ra–Be neutron source. A minimum of 20 runs was made for each element, with less than 1% standard deviation in the yield points contributed by the major isotope. The data were analyzed from 12 to 30 MeV by the Leiss Penfold technique using 2 interlacing 1-MeV bin widths and also using $\frac{1}{2}$-MeV bin widths. Our results show that each cross section is composed of several discrete resonances, with at least 4 resonances resolved in each cross section.

I. INTRODUCTION

RECENT determinations of the photoneutron cross sections for light nuclei have shown the existence of a complicated structure in the giant resonance region.[1–5] A number of calculations of the positions of the energy levels in this region using configuration mixing have been performed recently and successfully reproduced some of the major features of the level structure in the photonucleon cross sections in oxygen and calcium.[6,7] The simplest calculation uses the particle-hole interaction as the residual interaction, and a recent schematic calculation[8] has shown that in the case of nuclei with unfilled shells, the effect of the residual two-body interaction between the single pair and many pair configurations produces a distribution of transition strength among a much larger number of states. In this paper we wish to report the results of measurements of the photoneutron cross sections for natural silicon, phosphorus, and sulfur, in which we have found evidence for structure distributed over a large number of levels.

EXPERIMENTAL PROCEDURE

The measurements were made utilizing the bremsstrahlung of the 70-MeV synchrotron at the University of Virginia, a modified version of an NBS ionization chamber,[9] and a calibrated Ra-Be neutron source. The yield curves were measured from 10 to 30 MeV in $\frac{1}{2}$-MeV energy steps, using a Halpern-type detector[10] with eight BF_3 counters arranged in two sets. The counting system was gated in such a manner that the neutrons were counted for a 700-μsec period following a 20-μsec delay after the synchrotron beam burst. This eliminated the high background during the beam and less than 1% of the reaction neutrons were gated out. The NBS chamber had been recalibrated earlier in this laboratory for use as a transmission chamber. This calibration and the Ra-Be source strength were known within 5%, and the total neutron detection efficiency was 2.5%. The ion chamber drift and counting efficiency were monitored daily and varied less than 1% over the course of the yield measurements.

The samples were cylinders 14.5 cm in length and 3.75 cm in diameter, and each sample contained less than 0.5% impurities. The phosphorus and silicon samples were powder encased in a Lucite cylinder with $\frac{1}{2}$-mil Mylar ends. The sulfur target was a solid cylinder of the same dimensions. The energy scale of the synchrotron had been established by measuring the (γ,n) thresholds of Bi, Mn, Au, P, and C with less than 100-keV uncertainty at 15 MeV.

Because the use of bremsstrahlung requires an unfolding technique in which large numbers are subtracted with small differences, it is necessary to obtain extreme reproducibility in the measurements of the yield curves. A minimum of twenty yield curves were measured for each element with less than 1% statistical error in the yield points contributed by the major isotope. Figure 1 gives a representation of the reproducibility obtained in the yield curve measurements for phosphorus. The upper figure shows the results of the yield curve measurement at 23 MeV for each day of the run. The solid line is the mean value of the yield points at this energy, and the dashed lines give the limits of counting statistics. The yield points were found to lie within the expected limits of statistical counting fluctuations. The lower figure gives a similar display of the yield measurements at 23.5 MeV. At

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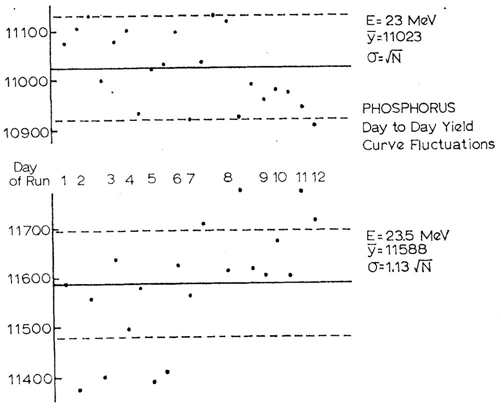

FIG. 1. Day-to-day variations in the yield measurement for phosphorus at 23 and 23.5 MeV.

each energy the standard deviation of each yield point from the mean was calculated, and the error assigned to the average yield at each energy point was the larger of simple counting statistics or the standard deviation at that point. This was a realistic appraisal of the error involved in the yield points, and in general the error varied from 1.1 to 1.2 times the error attributable to counting statistics alone.

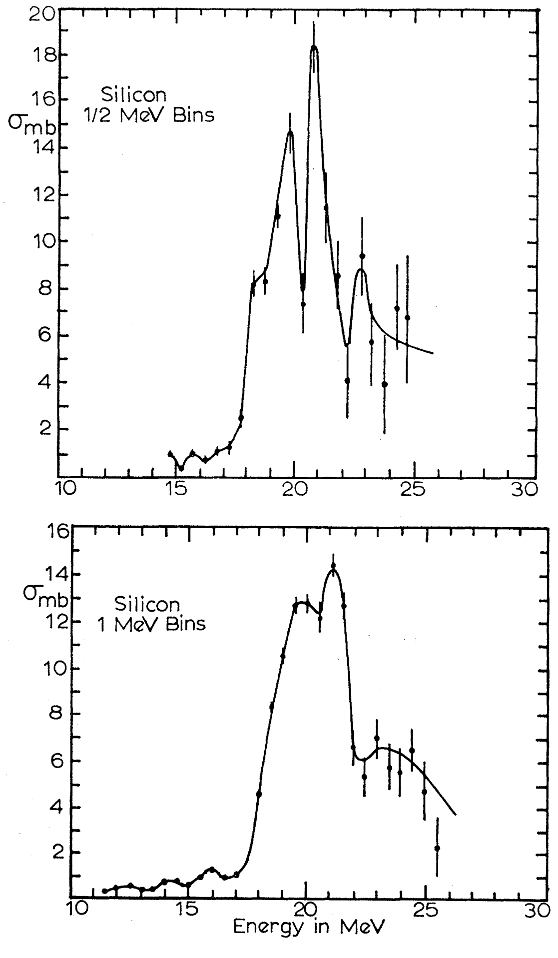

FIG. 2. Si(γ,n) cross section unfolded using $\frac{1}{2}$-MeV bins (top curve) and 1-MeV bins (lower curve).

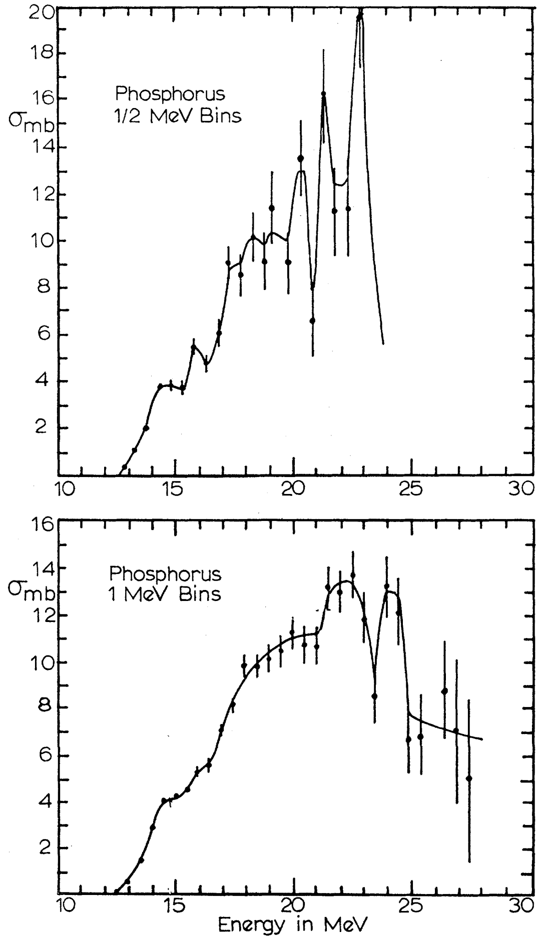

FIG. 3. P(γ,n) cross section unfolded using $\frac{1}{2}$-MeV bins (top curve) and 1-MeV bins (lower curve).

The data used were the average of two separate yield curve measurements taken at one month intervals. The data were unfolded utilizing the Leiss-Penfold technique[11] using both 1-MeV and $\frac{1}{2}$-MeV bin widths, and no smoothing of any type was applied to the data. The data for each measurement were also unfolded separately and the cross sections determined from each set of data were found to agree within the limits of uncertainty shown by the error bars on the cross section curves. The value of the cross section uncertainty at each energy is a result of a similar unfolding of the errors assigned to each yield point. However, since the Leiss-Penfold matrix elements decrease rapidly after the first three, and since the error determination involves the sum of the squares of these elements, only

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the first three terms were used in the computation of the error at each point. The results of the (γ,n) cross section measurements for silicon, phosphorus, and sulfur are presented in Figs. 2–4. In each figure the upper curve gives the result of the $\frac{1}{2}$-MeV bin width unfolding while the bottom curve is a result of unfolding using one-MeV bin widths with two sets of interlacing points. The greater resolution of the smaller bin widths can be seen in each cross section, as each resonance level is more sharply defined. However, the increase in resolution is offset somewhat by the increased error in the cross section and the greater tendency toward oscillation at the higher energies, which is a characteristic of this type of unfolding procedure.

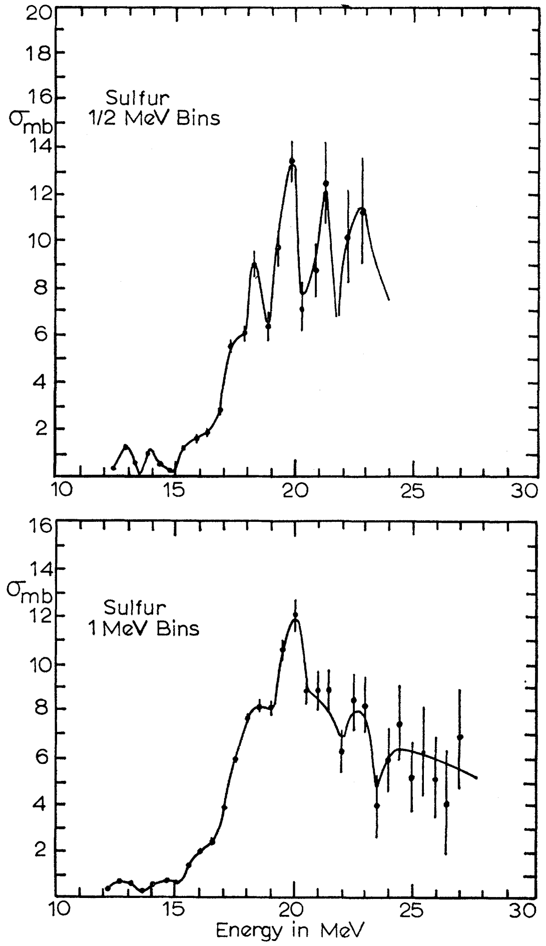

FIG. 4. $S(\gamma,n)$ cross section unfolded using $\frac{1}{2}$-MeV bins (top curve) and 1-MeV bins (lower curve).

III. RESULTS

Table I lists the abundances and the neutron thresholds for the isotopes of each element. The series of small resonances prior to the threshold of the major contributing isotope is due to the contributions of the minor isotopes. Presented in Table II is a comparison of the integrated cross sections of several elements obtained from the experimental photoneutron cross sections measured in this laboratory.[1,12,13] For most elements the integrals extend from threshold to 28 MeV. No corrections have been made for neutron multiplicity in those cases in which the $(\gamma,2n)$ thresholds lie below 28 MeV. A comparison of these integrated cross sections with the classical dipole sum rule calculation is given in column 5. With the exception of argon the percentage of the dipole sum exhausted by the photoneutron reaction is much lower than expected. Published results of the photoproton integrated cross sections in this region show that these values are not significantly larger than those for (γ,n).[14–16] Thus a significant contribution to the dipole strength must exist from high energy effects above the region presently investigated.

TABLE I. Abundances and (γ,n) and $(\gamma,2n)$ thresholds for the isotopes of the elements measured in this determination.

Isotope	Abundance	(γ,n) Threshold	$(\gamma,2n)$ Threshold
Si^{28}	92.27%	16.9 MeV	30.4 MeV
Si^{29}	4.68	8.5	
Si^{30}	3.05	10.6	
P^{31}	100	12.4	23.7
S^{32}	95.02	15.1	24.2
S^{33}	0.75	8.65	
S^{34}	4.21	11.4	

TABLE II. Integrated cross-section values obtained from the (γ,n) cross sections of elements measured in this laboratory.[a]

Element	Limits of integration threshold to	$\int \sigma dE$ MeV-mb	Dipole sum rule $X=0$ MeV-mb	% of DSR exhausted by (γ,n)
O	31MeV	46	240	19
Mg	29	84	360	23
Al	28	97.5	405	24
Si	28	80	420	19
P	28	127	465	27
S	28	81	480	17
Ca	28	74	600	12
N	25	60	210	29
	50	116		55
Ar	25	392	600	65
	50	598		100
Li	25	39	105	37
	50	93		89

[a] See Refs. 1, 12, and 13.

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Table III. Summary of data from this experiment giving energy positions of levels found in our cross sections and corresponding data from other experiments.

	University of Virginia		Gove[a]		Kimura[b]
Element	E(MeV)	σ(mb)	E(MeV)		E(MeV)
Si	16.0	1.2			
	18.5	8.4	18		
	19.75	14.7	18.9		18.9
	20.75	18.4	20		20.0
	22.75	9.4	21.4		21.4
	24.25	7.1			
	University of Virginia		Mutsuro[c]		
	E(MeV)	σ(mb)	E(MeV)	σ(mb)	
			13.5	6	
P	14.75	3.9	14.6	8	
	15.75	5.6	15.8	14	
	17.25	9.2	(17)	(17)	
	18.25	10.2	17.5	21	
	19.25	11.5	19.0	22	
	20.25	13.6	20.3	22	
	21.25	16.4			
	22.75	19.5			
	24.25	13.2			
	University of Virginia		Mutsuro[c]		
	E(MeV)	σ(mb)	E(MeV)	σ(mb)	
S	16	1.7	15.7	7	
	17.5	6.0	16.8	10	
	18.25	9.0	17.9	20	
	19.75	13.4	18.75	11	
	21.25	12.5	19.7	16	
	22.75	11.3			
	24.0	9.0			

[a] See Ref. 19.
[b] See Ref. 20.
[c] See Ref. 5.

The cross-section curves show that the photoneutron reaction cross section in this region is composed of many discrete states. Table III lists the peak cross-section values and energy position for each state, and also gives a comparison of these energy levels with those obtained by other investigators. Column 2 lists the results of Mutsuro *et al.*,[5] who have made a similar photoneutron cross-section measurement to 22 MeV for sulfur and phosphorus. The energy positions of the levels appear to agree well in the case of phosphorus, but the correspondence is not as good for the sulfur data. Our sulfur data, however, show agreement with the $P^{31}(p,\gamma_0)S^{32}$ measurements of Kimura *et al.*,[17] and Gemmel and Jones,[18] who have found quite complicated structure in the ground-state gamma-ray yield, with three major resonances occurring at 17.7, 18.2, and 19.7 MeV. Firk and Rae[3] measured the energy spectrum of neutrons from sulfur and also found neutron groups corresponding to these gamma-ray energies. These states agree well with the first three major levels found in our measurement. The silicon data can be compared to several $Al^{27}(p,\gamma_0)Si^{28}$ measurements[14,19,20] in which major states were seen at approximately 18.2, 18.9, 20.0, and 21.4 MeV. These do not agree with the resonance levels found in this photoneutron determination. The energy spectra of the inverse reaction experiments display much more structure than can be seen in our photoneutron cross-section measurements, as our resolution is restricted by the width of the energy bins used in unfolding the data. The shape of each of our measured cross sections and the positions of the levels are in agreement with the total absorption cross-section measurements of Dular *et al.*[21] if their energy scales are displaced approximately 0.5 MeV.

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