Cross Sections of Gamma-Proton Reactions*

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(Received April 6, 1951)

Using the University of Pennsylvania betatron, the energy dependences of the $\gamma-p$ cross sections of C, Al, Co, Ni, and Cb have been measured. The cross-section curves exhibit the resonance character found in $\gamma-n$ reactions. The significant parameters of each of the curves are tabulated. From the data of this paper and the known $\gamma-n$ cross-section data, the sum of neutron and proton integrated cross sections is evaluated for carbon and nickel.

INTRODUCTION

THE excitation functions for $\gamma-n$ reactions, which have been measured for many nuclei, exhibit broad resonances of about 6-Mev half-width,[1,2] and maxima in the vicinity of 20 Mev. This single resonance character is consistent with the measurements of Kerst and Price,[3] who have shown that the total neutron yields from elements bombarded by bremsstrahlung of maximum energy 22 Mev are not appreciably different from the yields resulting from bombardment by 320-Mev bremsstrahlung.

Recent theories[4] have been able to explain this dependence of cross section on energy by predicting that σ_a, the probability of forming a compound nucleus by photon absorption, should manifest a resonance behavior. The theory also predicts that information on σ_a as a function of excitation energy should permit a determination of the degree of correlation between particles in a nucleus and, consequently, lead to discrimination among various nuclear models.

A study of the yields of protons from elements irradiated with x-rays from a 23.5-Mev betatron[5] indicated that for many nuclei the $\gamma-p$ reaction furnishes a large contribution to σ_a. Since $\gamma-p$ cross-section curves are known for only one element,[6] the method employed to obtain the proton yield data has been used to measure the $\gamma-p$ excitation functions of five elements.

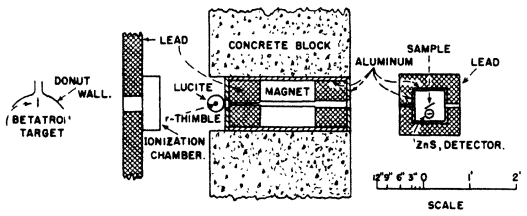

FIG. 1. General experimental arrangement.

PROCEDURE

The arrangement of the experimental apparatus, as shown in Fig. 1, was essentially the same as that described in reference 5, in which there is also given a detailed description of the use of ZnS screens for the direct detection of photoprotons. The present experiment consisted of the measurement of proton yields from a sample as the maximum energy of the x-ray beam was varied in one-Mev steps from the threshold of the reaction in a given element to 24 Mev. During each exposure at a fixed energy, the total irradiation was measured by an ionization chamber monitor; the current from the monitor was integrated in the conventional manner. The monitor was calibrated against a Victoreen 100-r thimble meter embedded in a Lucite block of 8-cm diameter. The integrated current reading of the monitor was then converted by means of a geometric factor into r units of radiation striking the sample. The maximum energy of the betatron was controlled up to an energy of 20 Mev by an integrator-expander circuit[7] and above 20 Mev by manual adjustment of the current through the betatron magnet. The energy scale was calibrated in terms of known thresholds for photoneutron reactions, and each point on the energy scale is accurate to ± 0.2 Mev.

The energy distribution in the forward direction of the x-ray beam has been calculated[8] and also determined experimentally.[9] The measured and calculated spectra agree within about 20 percent. We have used the calculated spectrum, modified by the amount of absorbing material between the betatron target and the sample, to convert the yield curve for each element into a cross-section curve. For all data except that for nickel, the donut wall, the ionization chamber (0.7-cm aluminum), and the Lucite block were in the path of the beam. The Lucite block was not present when the nickel data were taken.

RESULTS

The elements investigated were C, Al, Co, Ni, and Cb. The pertinent properties of the samples are listed

* Assisted in part by the joint program of the ONR and AEC.
[1] Johns, Katz, Douglas, and Haslam, Phys. Rev. **80**, 1062 (1950).
[2] B. C. Diven and G. M. Almy, Phys. Rev. **80**, 407 (1950).
[3] D. W. Kerst and G. A. Price, Phys. Rev. **79**, 725 (1950).
[4] M. Goldhaber and E. Teller, Phys. Rev. **74**, 1046 (1948). J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950).
[5] A. K. Mann and J. Halpern, Phys. Rev. **82**, 733 (1951).
[6] Stephens, Halpern, and Sher, Phys. Rev. **82**, 511 (1951).
[7] Katz, McNamara, Forsyth, Haslam, and Johns, Can. J. Research **28**, 113 (1950).
[8] L. Schiff, Phys. Rev. **70**, 87 (1946).
[9] H. W. Koch and R. E. Carter, Phys. Rev. **75**, 1950 (1949); **77**, 165 (1950).

in Table I. With the exception of nickel, all of the elements are of single isotopic composition.[10] Nickel is of particular interest because of its previously measured high yield. Furthermore, these elements cover most of the range of Z (6 to 41) over which the proton yields are sufficient for the performance of the experiment. The target thicknesses, which correspond to a proton range of about 5 Mev, represent a compromise between a high yield to background ratio and low target self-absorption.

The energy distributions of protons from photonuclear reactions have an appreciable component below 5 Mev, and, consequently, the effect of proton absorption must be considered in the treatment of the data.[11] From proton range data and the energy distributions measured with photographic emulsions, it is possible to calculate an approximate absorption correction. However, the correction obtained in this way is quite sensitive to the magnitude of the low energy components of the proton spectrum, where the measurements are least reliable. In order to determine the effect of absorption with greater precision, we have measured the yield curves for several sample thicknesses of the same element under identical conditions. The curves for two samples of aluminum are shown in Fig. 2, which also shows the data obtained without a target in the scattering chamber. Within the precision of the measurements and independent of the energy in the range from 15 to 24 Mev, the yield from the thick sample is approximately 1.4 times greater than that from the thin sample. Additional data for a 19-mg/cm^2 sample substantiate this result with a factor between the 37-mg and 19-mg samples of 1.7 at all energies in the same energy range. The fact that the relative number of protons lost by absorption does not depend on the excitation energy (in this energy region) indicates that the proton energy spectrum is insensitive to the maximum energy of the bremsstrahlung. The reasons for this are that the peak of the proton spectrum produced by incident monochromatic radiation varies only slightly with the energy of that radiation; and that, when the reactions are caused by bremsstrahlung, the distribution in number of the bremsstrahlung changes as the maximum excitation energy changes so that variations in the proton spectrum are further reduced.

The cross-section curves obtained from two such yield curves as presented in Fig. 2 should be identical in shape and should differ only by a scale factor change of the absolute cross-section coordinate. The magnitude of the scale factor change is a direct measure of the increased target absorption in the thicker sample. Using the data for the three aluminum samples of different thickness, it is possible to extrapolate to the absolute cross-section values for a thin target. For the 73-mg/cm^2 aluminum sample, the total correction for absorption is a factor of 2.1. This factor is smaller by about 30 percent than that previously estimated[5] from proton range data and measured proton energy distributions. The new value has been used in the application of absorption corrections to both carbon and aluminum, and should be accurate to about 15 percent. From data taken at 23 Mev for two different thicknesses of copper, the estimated correction factor for the cobalt and nickel samples is 1.6. This is again 30 percent smaller than the value used previously. The factor for columbium was obtained by reducing the calculated value by 30 percent.

TABLE I. Properties of the elements investigated.

Element	Z	A	Percent abundance	Sample thickness (mg/cm^2)	Proton binding energy (Mev)	Coulomb barrier (Mev)
Carbon	6	12	98.9	38	16.0	2.1
		13	1.1		16.1	
Aluminum	13	27	100	73	7.1	3.8
Cobalt	27	59	100	113	6.6*	6.4
Nickel	28	58	67.4	104	7.5*	6.7
		60	26.7		8.8*	
Columbium	41	93	100	114	6.3*	8.5

* Calculated from the mass formula.

The yield curves for carbon, cobalt, nickel, and columbium are presented in Figs. 3–6, respectively, and the cross-section curves for each of the elements are given in Figs. 7–11. Each of the curves exhibits a resonance character similar to that found in $\gamma-n$ reactions. Increased proton absorption and diminishing yield prevent measurements of cross sections at energies below about 15 Mev. The numerical values of the significant parameters of each curve are listed in Table II. The values for carbon are in agreement with those

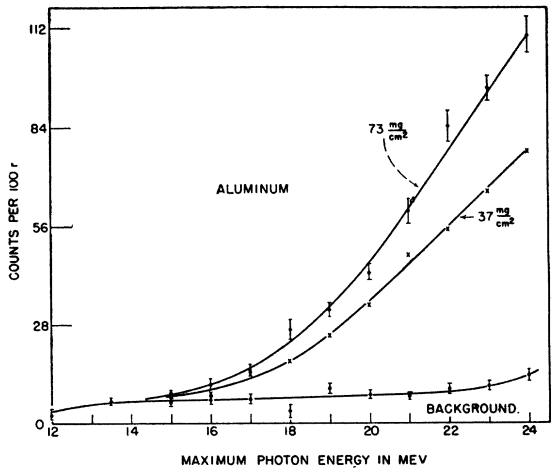

FIG. 2. Proton yield curves for aluminum samples of two thicknesses.

[10] Any effect arising from the presence of C^{13} is negligible in comparison with the statistical errors attached to the measurements. This is also true of the nickel isotopes 61, 62, and 64.

[11] It should be noted that part of the absorption is the result of the presence of air (7.3 cm) and a thin (0.00035 in.) aluminum foil in the scattering chamber. For details, see reference 5.

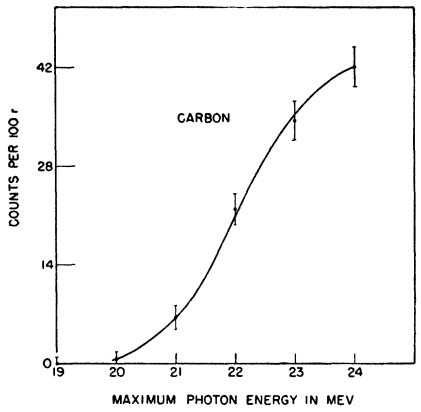

FIG. 3. Proton yield curve for carbon.

determined in a preliminary investigation.[12] The errors given in the table arise primarily from two causes. First, the reduction of the yield data to a cross-section

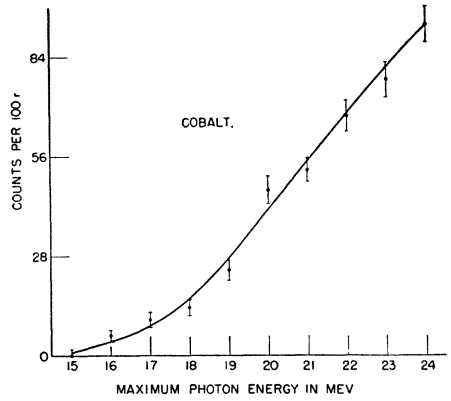

FIG. 4. Proton yield curve for cobalt.

curve involves the subtraction of numbers of approximately equal magnitude. Second, the uncertainty in the correction for proton absorption is reflected in the values of the parameters. Errors resulting from non-

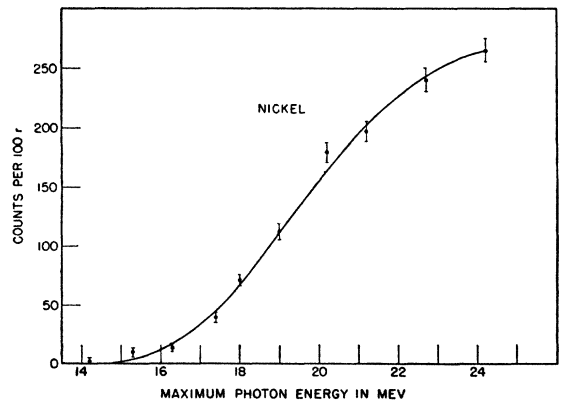

FIG. 5. Proton yield curve for nickel.

[12] A. K. Mann and J. Halpern, Phys. Rev. **80**, 470 (1950).

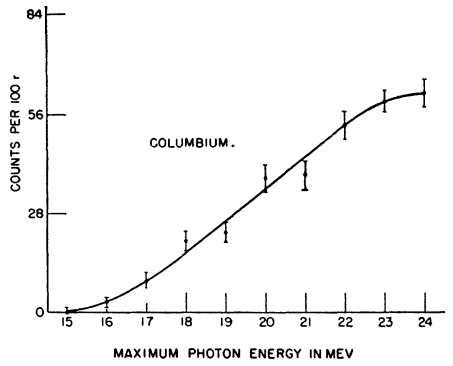

FIG. 6. Proton yield curve for columbium.

isotropic proton emission and from uncertain knowledge of the counter efficiency are expected to be small.[5]

DISCUSSION

The widths of the cross-section curves at half-maximum are about equal in magnitude and the same

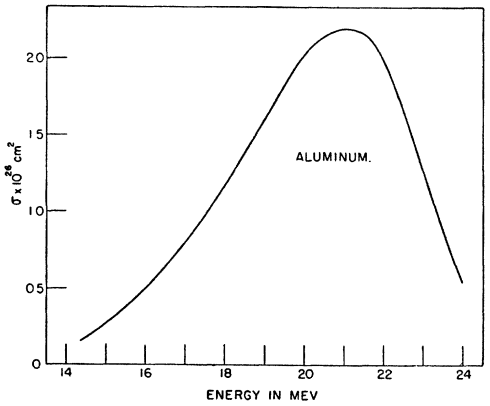

FIG. 7. Gamma-proton excitation function for aluminum.

as those for $\gamma-n$ reactions, except for carbon which is considerably narrower than the others. This result might be expected in view of the possible large alpha-

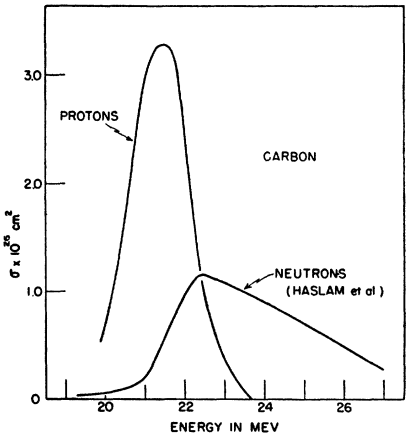

FIG. 8. Gamma-proton excitation function for carbon. The $\gamma-n$ cross-section data of Haslam *et al.* are shown for comparison.

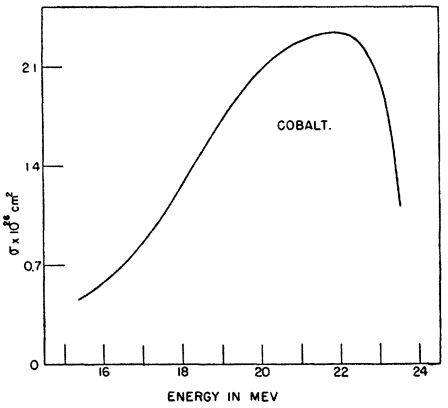

FIG. 9. Gamma-proton excitation function for cobalt.

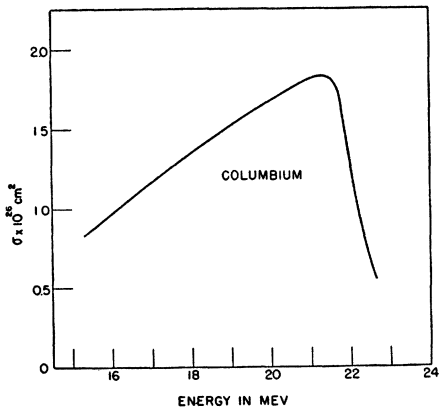

FIG. 11. Gamma-proton excitation function for columbium.

particle correlation in carbon. However, the $C^{12}(\gamma-n)$ cross-section curve of Haslam *et al.*,[13] which is shown in Fig. 8, is not appreciably different in width from the other $\gamma-n$ and $\gamma-p$ excitation functions.

The energies at which the cross-section maxima occur are the same for all elements except nickel, for which it is about 2.5 Mev lower in value. This difference manifests itself in a comparison of the yield values with the integrated cross sections, because the yields are proportional to the integrated cross sections only if the half-widths of the resonances are small compared to the energy at resonance and if the variation from element to element of the resonance energy is also small. The first criterion is approximately satisfied by all of the curves observed thus far. However, a shift of 2.5 Mev in the resonance energy of nickel means that the number of photons at that energy when the betatron is operated at 23.5 Mev is greater than the number at the resonance energy for the other elements by a factor of 1.6. If the nickel yield value is reduced by this factor, satisfactory agreement obtains between all of the integrated cross section and yield values in Table II.

Using the results of this paper and the $\gamma-n$ cross-section data of Haslam *et al.* and of Katz *et al.*[14] (Fig. 10), it is possible to evaluate the sum of the neutron and proton integrated cross sections for carbon and nickel. For carbon, $\int(\sigma_{\gamma-n}+\sigma_{\gamma-p})dE=0.018Z$. For nickel, $\int(\sigma_{\gamma-n}+\sigma_{\gamma-p})dE=0.023Z$. The proton data for nickel are for the natural element, while the neutron data are for Ni^{58}. The maximum possible value of the Ni^{58} $\gamma-p$ integrated cross section would obtain under the assumption that Ni^{60} makes no contribution to the result for the natural element. For this case, $\int(\sigma_{\gamma-n}+\sigma_{\gamma-p})dE=0.029Z$. The theory of Levinger and Bethe[4] predicts that the integrated cross section for all photonuclear processes in a given isotope should equal $0.030Z(1+0.8x)$, where x is the fraction of attractive exchange force for the neutron-proton potential.

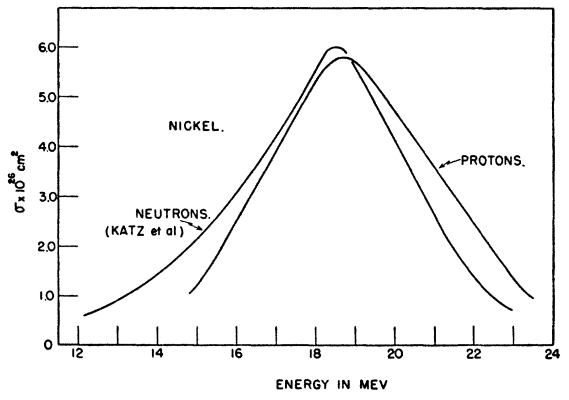

FIG. 10. Gamma-proton excitation function for nickel. The $\gamma-n$ cross-section data of Katz *et al.* are shown for comparison.

TABLE II. Summary of results.

Element	Energy at peak σ (Mev)	Maximum σ (barns)	Width at half-max. (Mev)	$\int\sigma dE$ (Mev-barns)	Yield at 23.5 Mev* (protons/mole $-\gamma$ $\times10^{-8}$)
Carbon	21.5±0.5	0.034±0.008	1.7±0.5	0.063±0.016	1.8±0.3
Aluminum	21.2±0.5	0.022±0.006	5.4±0.5	0.12 ±0.03	4.0±0.8
Nickel	18.7±0.5	0.058±0.015	5.4±0.5	0.32 ±0.08	12.0±2
Cobalt	21.5±0.5	0.024±0.006	5.7±1.0	0.14 ±0.04	3.7±0.7
Columbium	21.3±0.5	0.018±0.005	6.6±1.0	0.12 ±0.03	3.6±0.7

* The values in this column were taken from the data of reference 5 modified to include the revised absorption corrections.

[13] Haslam, Johns, and Horsley, Phys. Rev. **82**, 270 (1951).

[14] Katz, Johns, Baker, Haslam and Douglas, Phys. Rev. **82**, 271 (1951).