The study of the statistical properties of slow-neutron resonances (see, for example, Garg *et al.*[44]) and the theoretical studies of complex spectra[22] have yielded much information on the actual distributions and correlations of R-matrix parameters, which are of course, much more complicated than those of any of the models discussed above. Work now in progress employs further generalizations of these models, as well as numerical methods to investigate the implications of unitarity and its effect on cross sections and their fluctuations for more realistic distributions of resonance parameters and for larger numbers of competing channels.

[44] J. B. Garg, J. Rainwater, and W. W. Havens, Jr., Phys. Rev. **137**, B547 (1965).

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Proton-Capture Gamma Rays from Be^8, C^{12}, Mg^{24}, and Ca^{40} in the Giant-Resonance Region*

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The 90° yield for gamma rays from Be^8, C^{12}, Mg^{24}, and Ca^{40} was determined for (p,γ) reactions using 10.4- to 14.5-MeV protons from the Columbia University variable energy cyclotron. For $B^{11}(p,\gamma)C^{12}$ the yields to both the first excited state and the ground state of the residual nucleus are presented. In the case of $K^{39}(p,\gamma)Ca^{40}$, only the ground-state yield was determined. Because the ground-state yields are very small, we report only the yield due to transitions to the first excited state for the $Li^7(p,\gamma)Be^8$ reaction and the combined first excited and ground-state yields for the $Na^{23}(p,\gamma)Mg^{24}$ reaction. In the region investigated, the yield curves exhibit a considerable amount of fine structure in all cases except $Li^7(p,\gamma)Be^8$. Fine-structure peaks were observed for the following excitation energies: 21.9, 22.4, 22.7, 23.0, 23.3, 24.1, 24.7, and 25.4 MeV for $Na^{23}(p,\gamma_0+\gamma_1)Mg^{24}$; at 18.8, 19.2, 19.5, 20.0, 21.0, and 21.7 MeV for $K^{39}(p,\gamma_0)Ca^{40}$; at 25.5, 26.9, 28.0, and 28.45 MeV for $B^{11}(p,\gamma_1)C^{12}$; and at 25.5, 27.45, 28.0, and 28.9 MeV for $B^{11}(p,\gamma_0)C^{12}$. A comparison with other experimental results shows that some of these peaks have not been previously observed.

I. INTRODUCTION

GIANT-RESONANCE phenomena have been extensively investigated by photonuclear reactions.[1] The source of the incident photons has been bremsstrahlung radiation in most of the photonuclear work, but more recently some experiments have been performed using monochromatic γ rays. Since the advent of variable energy cyclotrons and tandem accelerators, however, (p,γ) reactions have been used to investigate the giant-resonance region of nuclear excitation by the inverse process. The (p,γ) reactions have several distinct advantages, namely, (1) continuously variable, monochromatic beams are more readily attainable for protons than gamma rays; (2) nuclei with unstable ground states can be studied by the inverse reaction and not by the direct photonuclear reaction; (3) transitions resulting from de-excitation to low-lying excited states can be investigated by the inverse reaction provided the states are sufficiently well separated. The (p,γ) reactions provide only the proton widths of the giant resonance, whereas all the particle widths are required to obtain the total cross section for photonuclear reactions.

At the time these experiments were undertaken, the work that was reported employing these (p,γ) reactions was confined to proton energies below 10 to 11 MeV.[2–6] In some instances, this corresponded to energies below the peak of the giant resonance. Since the energy of the Columbia University 36-in. cyclotron had not been varied previously, the energy variation having been accomplished in conjunction with these experiments, as required, it was decided to extend the earlier (p,γ)

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[1] M. E. Toms, Naval Research Laboratory Report No. 22, 1963 (unpublished).

[2] J. K. Bair, H. B. Willard, C. W. Snyder, T. M. Hahn, J. D. Kington, and F. P. Green, Phys. Rev. **85**, 946 (1952).

[3] D. S. Gemmel, A. H. Morton, and E. W. Titterton, Nucl. Phys. **10**, 33 (1959).

[4] D. S. Gemmel, A. H. Morton, and W. I. B. Smith, Nucl. Phys. **10**, 45 (1959).

[5] H. E. Gove, A. E. Litherland, and R. Batchelor, Nucl. Phys. **26**, 480 (1961).

[6] N. W. Tanner, G. C. Thomas, and E. D. Earle, Nucl. Phys. **52**, 29 (1964).

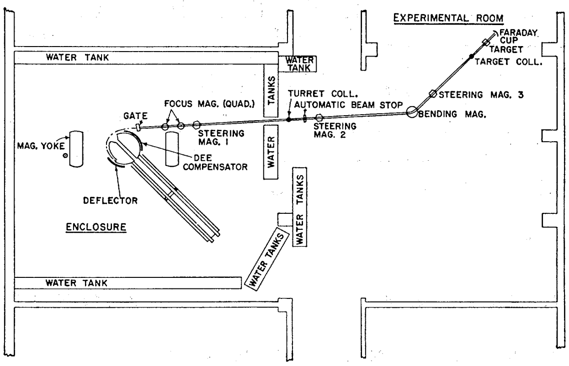

FIG. 1. Experimental layout (schematic).

experiments to higher energies and not to repeat the measurements at lower energies that had been previously reported. Consequently, the energy of the cyclotron was varied between 10.4 to 14.5 MeV. We investigated the following reactions: $Li^7(p,\gamma)Be^8$, $B^{11}(p,\gamma)C^{12}$, $Na^{23}(p,\gamma)Mg^{24}$, and $K^{39}(p,\gamma)Ca^{40}$. The purpose of the present experiments is to extend the energy range well into and beyond the giant-resonance peak, to study giant resonances built on low-lying excited states of the residual nucleus, and to investigate the fine structure in the giant resonance.

Preliminary results of the work presented in this paper have been previously reported.[7] The region between 10.4 and 12.4 MeV in which most of the fine structure occurs was subsequently reinvestigated at smaller energy intervals. Additional precautions were taken to prevent target deterioration, so that it was not necessary to change targets during the course of the measurements in this energy region. A more extensive and detailed report of this work was presented in a dissertation by one of the authors.[8]

II. EXPERIMENTAL PROCEDURE

A. Apparatus

The physical layout of the experiment is illustrated in Fig. 1. The transport system for the external proton beam consisted of a set of magnetic quadrupole lenses of 2-in. aperture, a bending magnet which deflected the beam through an angle of about 30°, and three sets of steering magnets located as shown. Two graphite collimators were used, located at the object and image positions of the bending magnet, with the quadrupoles adjusted to focus the beam at the first collimator. The target position was located about 42 ft from the cyclotron exit gate and 18 ft beyond the bending magnet. This arrangement resulted in negligible background contribution to the γ-ray spectra in the region of interest due to radiation emanating from the cyclotron enclosure and various parts of the beam-transport system.

The proton beam was stopped in a graphite-lined Faraday cup located 36 in. behind the target. The proton energies were determined by range-energy measurements by means of two aluminum absorber wheels mounted on the front of the Faraday cup. The wheels were rotated by means of two motors and a Geneva-type positioning mechanism operated by remote control from the cyclotron console. The proton energy was varied in steps of about 100 keV over the entire energy region investigated and the measurements were repeated twice for the alkali targets at intervals of 40 to 60 keV, between 10.4 to 12.5 MeV, the region where most of the structure occurs. An estimate of the energy spread in the beam striking the target was obtained by determining the energy spread in the extremities of the beam striking the second collimator. It was thus found that the beam width was $\frac{3}{4}$- to 1-in. wide across the second collimator with an energy spread of 70 ot 100 keV. Since the collimator aperture was $\frac{1}{4}$ in. in diam, it is estimated that the beam passing through the collimator to the target had a spread of about 25 keV.

The alkali targets (Li, Na, and K) were made from natural metals, rolled to thicknesses of 5 to 8 mg/cm^2 between $\frac{1}{4}$-mil Mylar sheets. The targets were prepared in a nitrogen-filled dry box and transferred to the target chamber which was constructed in a turret design that made possible the introduction of any one of three targets in the beam path or retraction of all three from the beam without breaking vacuum. The target chambers are equipped with inlet and outlet valves and were evacuated immediately after removal from the dry box and maintained in vacuum thereafter. Target thicknesses were determined by measuring the change in range of the protons when passing through the target and these tests were repeated periodically to check for target deterioration. Self-supporting boron targets, of 4 to 10 mg/cm^2, were prepared from a suspension of amorphous B^{11} (98.63% enrichment) in benzene containing a drop of polystyrene solution to serve as a binding agent.

The γ-ray detector was a 5×5 in. NaI(Tl) crystal, surrounded by an anticoincidence shield consisting of a hollow cylinder of plastic scintillator, 10-in. o.d., $5\frac{1}{2}$-in. i.d., and 8-in. long, with four symmetrically mounted

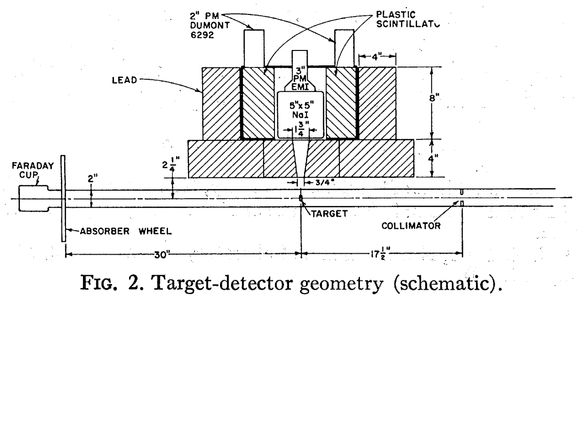

FIG. 2. Target-detector geometry (schematic).

[7] L. Feldman, B. B. Baliga, and M. Nessin, Bull. Am. Phys. Soc. 8, 290 (1963).

[8] B. B. Baliga, Ph.D. thesis, Columbia University, 1963 (unpublished).

DuMont 6292 photomultiplier tubes. An EMI 9578A photomultiplier tube was used for the NaI(Tl) crystal, because it was found to have much greater gain stability against counting rate than other tubes that were tested. Lead shielding, 4-in. thick, was used in the front and sides with a conically tapered collimator, subtending a solid angle of 0.5% at the target. The target-detector geometry is shown in Fig. 2. The anticoincidence shield reduced the cosmic-ray background in the region of interest by a factor of 6 to 9. The resolution of the spectrometer was estimated to be 14%.

The block diagram of the electronics is shown in Fig. 3. The pulses from the EMI tube are fed to a linear amplifier and through a bias circuit before going to the analyzer. The bias circuit reduces counting losses by rejecting pulses due to low-energy radiation incident on the NaI crystal. The pulses from the four DuMont tubes in the anticoincidence scintillator are added, stretched, amplified and then fed to the anticoincidence gate of the 256-channel pulse-height analyzer.

B. Gamma Spectra

Typical γ-ray pulse spectra observed at 90° to the proton beam for each reaction investigated are shown in Figs. 4 to 7. More than one peak appears in each spectrum. In each case the peak furthest to the right is due to the highest-energy γ ray and, therefore, results from transitions to the ground state. The other peaks correspond to transitions to the various excited states of the product nuclei.

γ-ray spectra of the type illustrated were achieved only after a good deal of experimentation to reduce all source of background and pile-up of low energy pulses. The proton-beam intensity, the geometry, and the location of various items in the beam-transport system, previously described, represent an optimization of the various parameters involved. The pile-up problem was controlled by keeping the beam intensity low and by using a small target-detector solid angle. Reducing the beam intensity by a factor of 2 resulted in no observable improvement in the spectra, indicating that for the beam currents used, pile-up did not introduce any appreciable distortion. Background runs taken with the target out of the beam path produced spectra in the low-energy region that were similar in shape to target-in spectra but greatly reduced in yield and with negligible yield in the region of the γ-ray peaks for the (p,γ) reactions reported in these experiments.

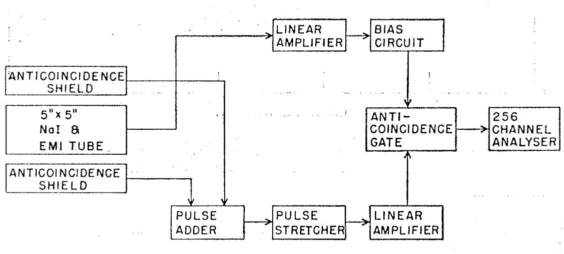

FIG. 3. Block diagram of the electronics.

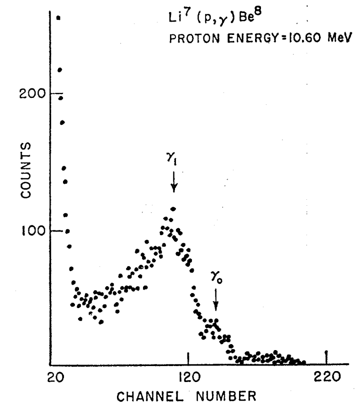

FIG. 4. γ-ray spectrum from the reaction $Li^7(p,\gamma)Be^8$.

C. Analysis of the Spectra

The spectra are analyzed by first subtracting a cyclotron-off background normalized to the region of the (p,γ) spectra well above the γ-ray peaks and then subtracting a low-energy background. The yield is determined from the spectra resulting after both background subtractions are made. The method used for separating contributions due to overlapping peaks will be described further on.

A typical cyclotron-off background spectrum obtained over a week-end and with no sources of radiation nearby is shown in Fig. 8. This background is due to cosmic rays and its contribution to the (p,γ) spectra is estimated from such data. The cosmic-ray background was determined from time to time and very little variation was observed.

The general low-energy background for the target both in and out of the beam was found to be an exponential function of the pulse height. After cosmic-ray background subtraction, a semilogarithm plot of the spectra resulted in a straight line for the low-energy portion of all the measured spectra up to about pulse-

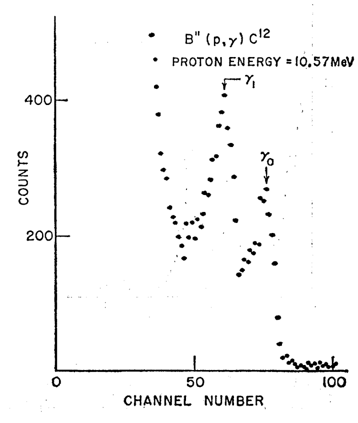

FIG. 5. γ-ray spectrum from the reaction $B^{11}(p,\gamma)C^{12}$.

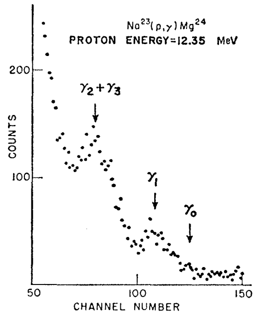

FIG. 6. γ-ray spectrum from the reaction $Na^{23}(p,\gamma)Mg^{24}$.

height analyzer (PHA) channel 45. The general background beyond channel 45 was therefore accounted for by a straight-line extrapolation in the semilog plot. The spectra resulting after the above described background subtractions do not exhibit the long low-energy tail, extending to zero pulse-height, characteristic of scintillation spectra of high-energy γ rays.[9,10] Instead, the low-energy tail of the observed spectra ends at some channel above zero pulse-height, probably because of the method of background subtraction. The relative yield is determined using the entire area under this resulting peak. Line-shape corrections were later applied to calculate absolute cross sections.

The separation of the contributions of overlapping peaks was accomplished by reconstructing the more intense peak, which, in all cases except for K^{39}–Ca^{40}, corresponds to the lower-energy γ ray, due to deexcitation to the first-excited state. The high-energy slope of the lower-energy peak is extrapolated to zero intensity, assuming a standard shape. Its contribution is then subtracted from the combined yield and the high-energy low-intensity peak is constructed, and the yield under the peak is estimated. Figure 9 illustrates the method in the case of a γ spectrum obtained with 12.147-MeV protons for the $B^{11}(p,\gamma)C^{12}$ reaction. The important consideration in determining the shape of the yield curve is the consistency of the method in maintaining the same relative accuracy.

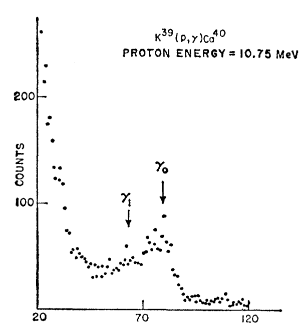

FIG. 7. γ-ray spectrum from the reaction $K^{39}(p,\gamma)Ca^{40}$.

[9] J. Kockem and N. Starfelt, Nucl. Instr. Methods 4, 171 (1959).
[10] W. F. Miller and W. J. Snow, Rev. Sci. Instr. 31, 39 (1960).

III. EXPERIMENTAL RESULTS

A. $Li^7(p,\gamma)Be^8$

Figure 4 shows a typical γ-ray pulse spectrum for this reaction resulting from 10.60-MeV protons incident on a Li target, 160-keV thick. The yield for transitions to the ground state is not reported, since it is very small and its determination involves rather large uncertainties. It was used, however, to subtract the contribution of the ground-state transitions from the combined yield, to determine the yield of the dominant γ peak, which is due to transitions to the first-excited state in Be^8. In this case, the ground-state yield represents a small correction and therefore introduces a much smaller uncertainty. The resulting yield curve, Fig. 10, exhibits resonance structure in the vicinity of 28.6-MeV excitation energy. There appears to be additional structure, as, for example, the valley at 28.9 MeV and peak at 29.0 MeV, even though the solid curve has been drawn to average it out. We have avoided identifying a valley or peak on the basis of one or two points and therefore confirmation is required by further investigation at smaller energy intervals using thinner targets. This is also true of the fine structure that is indicated at excitation energies of 26.7, 26.9, 27.5, and 27.8 MeV.

This reaction has been investigated at lower proton energies by Bair *et al.*[2] (up to 5 MeV), by Gemmel, Morton, and Titterton[3] (up to 7.7 MeV), by Tanner, Thomas, and Earle[6] (up to 9 MeV), and also by Mitchell and Taylor[11] (up to 9 MeV), and by Perry, Mainsbridge, and Rickards[12] (up to 11 MeV). The excitation curve reported by Perry *et al.*[12] is for the combined yield, $(p, \gamma_0+\gamma_1)$, and exhibits a broad resonance with the peak at 7.3 MeV and with constant negative slope from the peak to 11.0 MeV. The region from 10.5 MeV, as shown in Fig. 10, is less steep and would actually appear as a plateau if fitted to the curve reported below 11 MeV.

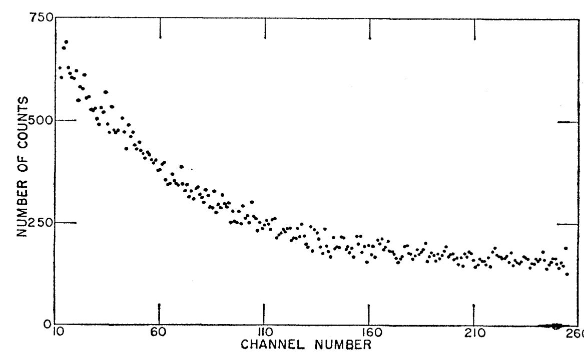

FIG. 8. Spectrum of cosmic-ray background with anticoincidence circuit taken for 40 h.

[11] I. V. Mitchell and R. B. Taylor, Nucl. Phys. 44, 664 (1963).
[12] R. R. Perry, B. Mainsbridge, and J. Rickards, Nucl. Phys. 45, 586 (1963).

Neither experimental nor theoretical work has been reported on the corresponding photonuclear reaction, since the Be^8 nucleus is unstable.

B. $B^{11}(p,\gamma)C^{12}$

Figure 5 presents a γ-ray pulse spectrum, typical for this reaction, resulting from 10.57 MeV protons incident on a B^{11} target, about 314-keV thick. The peaks corresponding to de-excitation to the ground and first-excited states are quite distinct and better separated than in the other reactions studied, making possible more accurate separation of the peaks and yield determinations. This is due to the fact that the first-excited state in C^{12} at 4.43 MeV above the ground state is much higher than in the other cases and the yields for both transitions are relatively larger.

The yield curves for transitions to both the first-excited state and the ground state of C^{12} are shown in Fig. 11. The ground-state yield is the smaller of the two throughout the energy region investigated. However, studies at lower energies[5,13,14] show that the ground-state yield is larger for proton energies below 9 MeV. The yield for (p,γ_1) exhibits peaks at 25.5, 26.9, 28.0, and 28.45 MeV, whereas peaks in the ground-state yield occur at 25.5, 27.45, 28.0, and 28.9 MeV. The peaks at 25.5 MeV that are observed for both (p,γ_0) and (p,γ_1) occur very close to the lowest-energy data obtained in these experiments. The position of these peaks, therefore, could not be accurately determined and were obtained mainly by comparison with work done at lower energies which overlapped this region.[5,13]

The $B^{11}(p,\gamma)C^{12}$ reaction has probably been investigated more extensively than any other (p,γ) reaction. Our results are in good agreement in the region of overlap with other work done at lower energies,[5,13,14] and they are also consistent with the higher-energy results (E_p=15–25 MeV) reported by Reay, Hintz, and Lee.[15] The ground-state-yield curve is known from the earlier work to exhibit very little fine structure, with a broad resonance peaking at an excitation energy of 22.5 MeV. The small peak at 25.5 MeV as described above has been previously reported,[5,13,14] and we observe three additional peaks at 27.45, 28.0, and 28.9

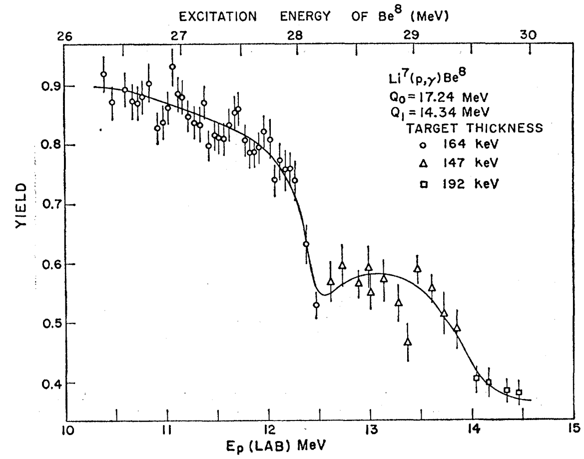

FIG. 10. Yield curve for $Li^7(p,\gamma_1)Be^8$. An upper estimate for the ground-state yield has been subtracted from the combined yield for the ground and excited state.

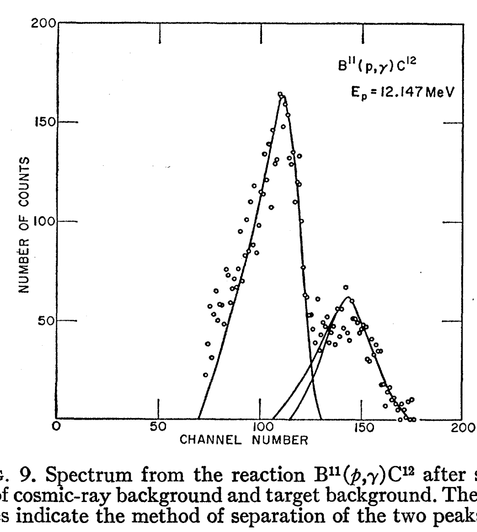

FIG. 9. Spectrum from the reaction $B^{11}(p,\gamma)C^{12}$ after subtraction of cosmic-ray background and target background. The smooth curves indicate the method of separation of the two peaks.

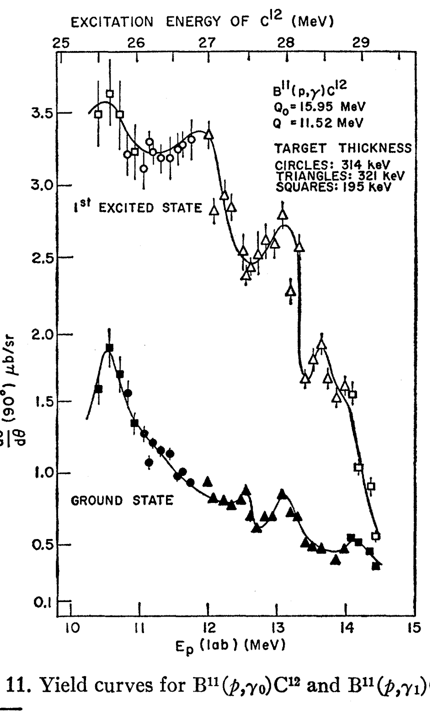

FIG. 11. Yield curves for $B^{11}(p,\gamma_0)C^{12}$ and $B^{11}(p,\gamma_1)C^{12}$.

[13] J. A. Becker and J. D. Fox, Nucl. Phys. **42**, 669 (1963).
[14] R. G. Allas, S. S. Hanna, L. Meyer-Schützmeister, and R. E. Segel, Nucl. Phys. **58**, 122 (1964).
[15] N. W. Reay, N. M. Hintz, and L. L. Lee, Jr., Nucl. Phys. **44**, 338 (1963).

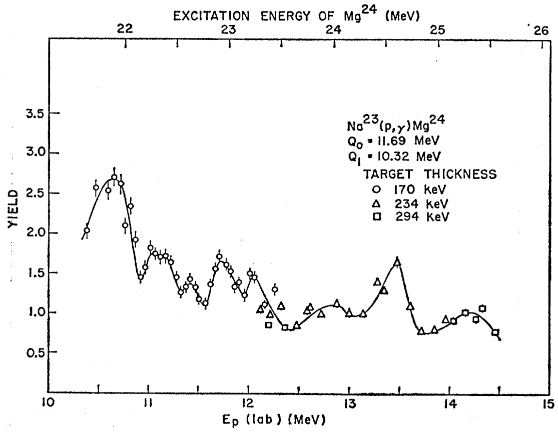

FIG. 12. Yield curve for $Na^{23}(p,\gamma_0+\gamma_1)Mg^{24}$.

TABLE II. Comparison of C^{12} excitation energies (in MeV) at which fine-structure peaks have been observed.

Present experiment (p,γ)	Gove *et al.*[a] (p,γ)	Becker and Fox[b] (p,γ)	Allas *et al.*[c] (p,γ)	Dodge and Barber[d] (γ,p)
	22.25(γ_1)	22.1(γ_1)	22.1(γ_1)	...
	22.5 (γ_0)	22.5(γ_0)	22.6(γ_0)	22.5
	23.6 (γ_1)	23.6(γ_1)	23.7(γ_1)	23.2, 23.9
25.5 (γ_0,γ_1)	25.5 (γ_0,γ_1)	25.5(γ_0,γ_1)	25.5 γ_0	25.6
			25.6 γ_1	
26.9 (γ_1)		26.9(γ_1)	26.8(γ_1)	26.6
27.45(γ_0)		...	...	27.14
28.0 (γ_0,γ_1)		...	28.0(γ_1)	27.9
		...	28.1(γ_0)	
28.45(γ_1)		...	...	...
28.9 (γ_0)				28.9

[a] Reference 5. [b] Reference 13. [c] Reference 14. [d] Reference 16.

shown in Fig. 11 which are still smaller. In the photonuclear reaction, $C^{12}(\gamma,p)B^{11}$, reported by Dodge and Barber,[16] four small peaks were observed at excitation energies above 25 MeV, occurring at 26.6, 27.1, 27.9, and 28.9 MeV. We did not observe the peak at 26.6 MeV. The yield curve for (p,γ_1) shows considerably more structure. In addition to the peaks at 25.5 and 26.9 MeV that have been previously reported,[5,13,14] we have also observed small peaks at 28.0 and 28.45 MeV. The peaks at 28.9 MeV in the (p,γ_0) yield and at 28.45 MeV in (p,γ_1) are probably the small anomalies reported by Allas *et al.*[14] at proton energies of 13.2 MeV for (p,γ_0) and at 13.1 MeV for (p,γ_1).

Table II presents the summary of our results for the $B^{11}(p,\gamma)C^{12}$ reaction together with those reported by other experiments. Absolute cross sections, calculated for various energies corresponding to the peaks in the yield curves for both the ground and first-excited transitions, are presented in Table III.

C. $Na^{23}(p,\gamma)Mg^{24}$

A typical γ-ray pulse spectrum for 12.35-MeV protons incident on a Na^{23} target, about 170-keV thick, is shown in Fig. 6, with the identification of peaks as indicated. The excitation function, shown in Fig. 12, represents the combined yield for transitions to the ground and first-excited states in Mg^{24}. The contribution of the ground-state transitions was not determined because it could not be done with reasonable reliability because of its small yield, and small separation, 1.34 MeV, from the first-excited state. An estimate of the upper limit of the ground-state yield was made, however, and found to be between 6 to 10% of the combined yield over the region investigated. The lowest-energy peak in the spectrum (Fig. 6) around channel 80 is attributed to transitions to both the second- and third-excited states in Mg^{24} which are located at 4.12 and 4.24 MeV above the ground state. Although this peak appears to be well resolved, its yield determination is subject to large uncertainties because the peak falls too close to the low-energy background, and also because this happens to be a region where spurious peaks occurred in some of the spectra due to rf pick-up from the cyclotron.

The yield curve exhibits a great deal of structure, with peaks occurring at the following excitation energies in Mg^{24}: 21.9, 22.4, 22.7, 23.0, 23.3, 24.1, 24.7, and 25.4 MeV. This reaction has been studied at lower proton energies by Gemmel, Morton, and Smith[4] from 5 to 7.7 MeV and by Gove, Litherland, and Batchelor[5] from 4 to 11 MeV. Appreciable structure also appears in the yield curves reported at these energies. The highest-energy peak reported by Gove *et al.*[5] is in good agreement as to shape and energy with the corresponding

TABLE I. Absolute cross sections for $Li^7(p,\gamma_1)Be^8$, calculated at peaks of yield curve, assuming isotropic angular distributions.

Proton energy (MeV)	Cross section (μb)
10.86	11.9±2.0
11.15	12.4±2.0
11.74	11.0±1.7
12.05	11.0±1.8
13.18	8.3±1.6

[16] W. R. Dodge and W. C. Barber, Phys. Rev. **127**, 1746 (1962).

TABLE III. Absolute cross sections for $B^{11}(p,\gamma_0)C^{12}$ and $B^{11}(p,\gamma_1)C^{12}$, calculated at peaks of yield curve, assuming isotropic angular distributions.

Proton energy (MeV)	Cross sections (μb) $\sigma(\gamma_0)$	$\sigma(\gamma_1)$
11.76	23.2±6.5	44.7±10.5
12.55	20.5±5.7	35.7± 8.9
13.09	18.7±4.4	37.6± 9.4
13.98	10.8±2.9	25.1± 6.2
14.19	15.6±5.0	22.7± 8.8

TABLE IV. Absolute cross sections for $Na^{23}(p, \gamma_0+\gamma_1)Mg^{24}$, calculated at peaks of yield curve, assuming isotropic angular distributions.

Proton energy (MeV)	Cross sections (μb)
10.68	78.0±21.8
11.15	50.4±13.0
11.45	38.2± 9.4
11.74	48.2±12.6
12.00	43.5±13.6
12.91	31.6± 8.4
13.51	38.7± 9.8
14.30	25.8± 6.1

peak at 21.9 MeV shown in Fig. 12. To our knowledge there are no other results available for comparison with the corresponding photonuclear work[17] having been carried out at excitation energies below 22 MeV.

The absolute cross sections have been calculated at energies corresponding to the peaks in the yield curve and are given in Table IV.

D. $K^{39}(p,\gamma)Ca^{40}$

A typical γ-ray pulse spectrum is shown in Fig. 7, obtained with 10.75-MeV protons incident on a target, 165-keV thick. The major peak in the vicinity of channel 80 is due to transitions to the ground state in Ca^{40}. There is evidence of a small peak in the vicinity of channel 60 which may be due to transitions to one or more of the excited states in Ca^{40} as reported by Hafele, Bingham, and Allen.[18] The yield for the ground-state transitions has been determined and is presented in Fig. 13. Considerable fine structure is exhibited with peaks occurring at excitation energies of 18.8, 19.2,

TABLE V. Comparison of Ca^{40} excitation energies (in MeV) at which fine-structure peaks have been observed.

Present experiment	Tanner *et al.*[a]	Hafele *et al.*[b]	Firk *et al.*[c]	Baglin *et al.*[d]	Mien *et al.*[e]
(p,γ)	(p,γ)	(p,γ)	(γ,n)	(γ,n)	(γ,n)
	···	15.2			
	···	16.2		15.9	16.6
	···	···	17.3	···	···
	···	18.2	18.1	17.9	18.0
18.8	18.8	18.7	18.7	18.5	···
19.2	···	19.0	19.3	18.9	19.3
19.5	19.6	19.4	···	19.2	···
20.0	20.0	19.8	19.9	19.7	···
···	···	20.3	···	···	20.3
21.0	···	21.0	21.0	20.6	21.5
21.7	···	22	22	···	···

[a] Reference 6. [b] Reference 18. [c] Reference 19. [d] Reference 20. [e] Reference 21.

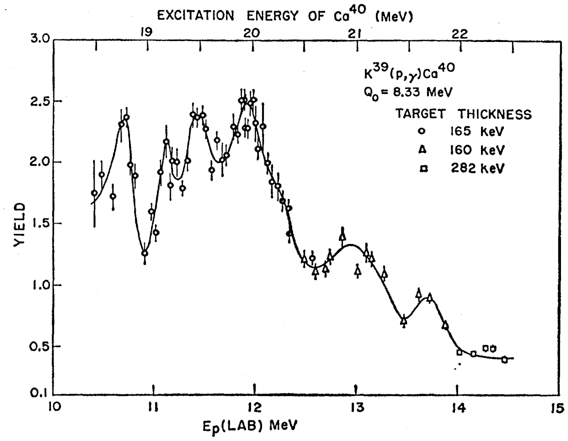

FIG. 13. Yield curve for $K^{39}(p,\gamma_0)Ca^{40}$.

19.5, 20.0, 21.0, and 21.7 MeV. The proton energy range covered, 10.4 to 14.5 MeV, corresponds in this case to a range of excitation energies from 18.5 to 22.5 MeV, extending over most of the giant-resonance region for this reaction, including the peak. These fine-structure peaks which we had previously reported[7,8] have been confirmed by the recent work of Hafele *et al.*,[18] who also reported a peak at 20.3 MeV, which appears as a bump on the steeply descending slope of the yield curve shown in Fig. 13. There is also good agreement in the yield curve reported by Hafele *et al.*[18] and the present paper with regard to shape and relative magnitude of the peaks. The work of Tanner, Thomas, and Earle[6] exhibits the same gross shape for the yield curve, with fine-structure peaks reported at 18.8, 19.6, and 20.0 MeV, in good agreement with the corresponding peaks reported above, but these authors do not report the peaks at 19.2, 20.3, 21.0, and 21.7 MeV shown in Fig. 13.

It is of interest to compare the peaks observed with (p,γ) reactions with those obtained from photoneutron experiments on Ca^{40}. Several recent (γ,n) experiments[19–21] have been completed with improved tech-

TABLE VI. Absolute cross sections for $K^{39}(p,\gamma_0)Ca^{40}$, calculated at peaks of yield curve, assuming isotropic angular distributions.

Proton energy (MeV)	Cross sections (μb)
10.75	43.0±9.1
11.18	31.2±7.5
11.45	39.8±9.6
11.94	39.2±8.6
13.04	24.7±7.3
13.75	21.1±5.9

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niques compared to earlier experiments. Table V presents a summary of results of (p,γ) and (γ,n) work for K^{39}–Ca^{40}. The absolute cross sections at energies corresponding to the peaks in Fig. 13 are given in Table VI.

IV. DISCUSSION

Theoretical calculations based on the particle-hole formalism of Brown and Bolsterli[22] have been carried out for the giant resonance in C^{12} by Vinh-Mau and Brown[23] using zero-range particle-hole forces and predict $T=1$ states at 18.7 MeV (6.5%), 22.2 MeV (75%), 23.9 MeV (0.5%), and 34.3 MeV (18%). The percentages in parentheses refer to the percentage of the dipole strength in each level. Very similar results, for both energies and dipole strengths, are obtained by Gillet[24] and by Gillet and Vinh-Mau[25] using finite-range forces. The prediction that the major portion of the dipole strength is in the 22.2-MeV level is in close agreement with the position of the main peak in the yield curve for ground-state transitions previously reported.[5,13,14] The prediction of the 34.3-MeV level has also been verified.[15] The predicted level at 23.9 MeV may correspond to the observed level at 25.5 MeV. The observed yield, however, as shown in Fig. 11 and as reported by Becker and Fox[13] and Allas *et al.*,[14] is much greater than the predicted 0.5%. None of the minor peaks shown in Fig. 11 has been accounted for by the theoretical work.

In the case of Ca^{40}, calculations determining the excitation energies for dipole states and their relative strengths have been reported by several authors. These can be summarized as follows. Brown, Castillejo, and Evans,[26] using a Soper mixture of forces, have found the dipole strength concentrated in states at 19.2 MeV (55%) and 20.6 MeV (44%); Balashov, Schevchenko, and Yudin[27] find dipole states at 16.3 MeV (7%), 18.4 MeV (7%), and 19.2 MeV (78%), whereas Lee[28] finds the dipole strength in states at 19.8 MeV (85%) and 22.1 MeV (13%). Gillet has also reported results very similar to those above. As can be seen from Fig. 13, the major portion of the giant resonance in Ca^{40} is contained in the region between 18.5 and 20.5 MeV, in good agreement with the theoretical predictions. Thus it is clear that the theoretical results are corroborated by the experimental results in the giant resonances of C^{12} and Ca^{40} insofar as the energy of the main component of the dipole state is concerned. However, none of the features of the observed fine structure has as yet been accounted for theoretically. Attempts to identify the observed fine structure in terms of the individual particle-hole states predicted theoretically[23,26] have been carried out by Baliga[8] for the work reported in this paper and by Becker and Fox[13] for C^{12}. However, the recent work by Allas *et al.*[29] indicates that this procedure is not justified. The argument presented is that the experimentally determined γ-ray angular distributions vary very little with energy throughout the giant-resonance region for each case investigated, whereas theoretical calculations based on the particle-hole formalism predict angular distributions that differ widely for transitions from different individual particle-hole states. Therefore, the conclusion of Allas *et al.*[29] is that the observed fine structure in the giant resonance is due to a single giant-resonance state or configuration, which may be a mixture of individual particle-hole states and is spread out over many actual nuclear levels. Thus the fine structure observed in the giant resonance is yet to be satisfactorily explained.

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