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Proton Angular Distributions for (α,p) Reactions on C^{12}, Al^{27}, and P^{31}†*

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Angular distributions of protons corresponding to single and multiple levels of excitation have been measured for the reactions $C^{12}(\alpha,p)N^{15}$, $Al^{27}(\alpha,p)Si^{30}$, and $P^{31}(\alpha,p)S^{34}$ using 42-Mev alpha particles. Distributions corresponding to the ground state and third-excited state of N^{15} and to the ground state and first-excited state of S^{34} show pronounced diffraction-like structure. Distributions from Si^{30} show a marked lack of structure. The data indicate that simple phasing relationships between distributions from levels of even and odd parity, predicted by models based on the plane-wave Born approximation, do not agree with experiment. The ground-state distribution from N^{15} is in agreement with the theories of Butler and Bhatia. However, the observed distribution from the third-excited state of N^{15} does not agree with the predictions of these theories. Total cross sections obtained for the ground state and third-excited state of N^{15} were large compared with those for low-level transitions in the reactions on phosphorus and aluminum. These in turn have much larger cross sections than those for $Na^{23}(\alpha,p)Mg^{26}$, $F^{19}(\alpha,p)Ne^{22}$, and $Cl^{35}(\alpha,p)Ar^{38}$, which were too small to be investigated with our apparatus. There is some indication from this investigation that those distributions which show pronounced angular structure have cross sections that are more highly dependent on bombarding energy than those that lack structure.

I. INTRODUCTION

Most recent experimental work on (α,p) reactions has consisted of investigations of ground-state transitions.[1–6] Hunting and Wall[1,2] obtained angular distributions for ground-state transitions in many reactions at 30.5 Mev. The ground-state transition in $C^{12}(\alpha,p)N^{15}$ has been the subject of investigations by Nonaka *et al.*,[3] Priest *et al.*,[4] and by Kondo *et al.*[5] for alpha-particle energies below 38 Mev. This transition was also investigated by Sherr and Rickey[6] with 42-Mev alpha particles. Heretofore, experimental difficulties have made it impossible to obtain distributions for single excited states of N^{15}. Kondo *et al.*[5] have also obtained angular distributions for transitions to the ground and first excited states of Si^{30} in $Al^{27}(\alpha,p)Si^{30}$ using 21.8- and 22.2-Mev alpha particles.

Many of these angular distributions show an oscillatory structure with forward peaking which agrees

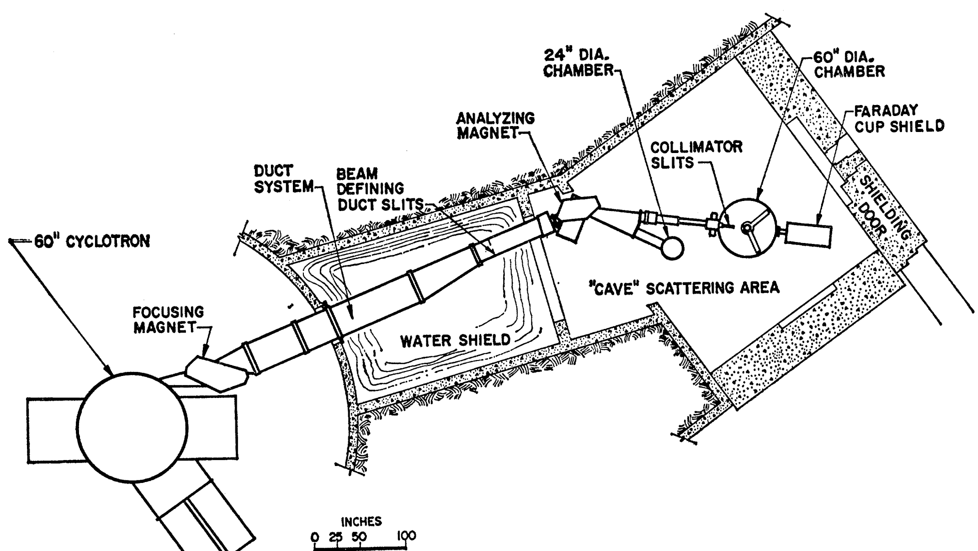

Fig. 1. External beam system of the University of Washington cyclotron.

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1 C. E. Hunting and N. S. Wall, Phys. Rev. **108**, 901 (1957).
2 C. E. Hunting and N. S. Wall, Phys. Rev. **115**, 956 (1959).
3 I. Nonaka, H. Yamaguchi, T. Mikumo, I. Umeda, T. Tabata, and S. Hitaka, J. Phys. Soc. Japan **14**, 1260 (1959).
4 J. R. Priest, D. J. Tendam, and E. Bleuler, Phys. Rev. **119**, 1301 (1960).
5 M. Kondo, T. Yamazaki, S. Yamabe, J. Phys. Soc. Japan **16**, 1091 (1961).
6 R. Sherr and M. Rickey, Bull. Am. Phys. Soc. **2**, 181 (1957).

qualitatively with the plane-wave Born approximation theories of Butler[7] and Bhatia.[8] It is of interest to test whether proton distributions corresponding to different excited levels in the same final nucleus exhibit a relative phasing depending only on the relative parities of the final nuclear levels. Such a relationship can be inferred[9] from the success of the theory of Blair[10] in describing elastic and inelastic scattering of alpha particles. The experiment reported here is a study of proton distributions to low-lying states selected to test the hypothesis that the relative phasing of these distributions reveals the relative parities of the final nuclear states.

Even though theory predicts that the ground state and third excited state distributions in $C^{12}(\alpha,p)N^{15}$ should be described by the same expression, it is clear from the work reported here that this is not the case and that no simple phasing relationship exists. Unfortunately, the angular distributions obtained for $Al^{27}(\alpha,p)Si^{30}$ show very little structure even though the angular resolution of the detector was sufficient to show any possible structure. Consequently, this reaction did not provide a test of the phasing hypothesis. On the other hand, the angular distributions obtained for $P^{31}(\alpha,p)S^{34}$ show diffraction structure, but the small cross sections encountered made an accurate test of the phasing hypothesis in this case extremely difficult.

II. APPARATUS

The experiment used the 42-Mev alpha-particle beam of the University of Washington cyclotron. The external beam system is shown in Fig. 1. To distinguish between alpha particles, protons, and deuterons a $dE/dx-E$ scintillation detector was used, a cross section of which is shown in Fig. 2. The angular resolution of the detector was 1.2 deg. A variable degrader (Fig. 3) was used to reduce counting rates at small scattering angles by absorbing scattered alpha particles. It was also used as an aid in resolving peaks in the pulse height spectrum. The dE/dx portion of the detector is a plastic phosphor optically coupled to a DuMont 6291 photomultiplier with a thermal setting plastic. The E portion is a CsI(Tl) phosphor coupled to a

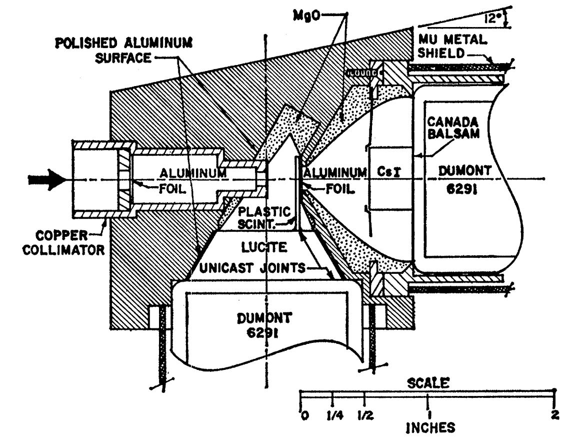

FIG. 2. Sectional view of the $dE/dx-E$ detector parallel to the scattering plane.

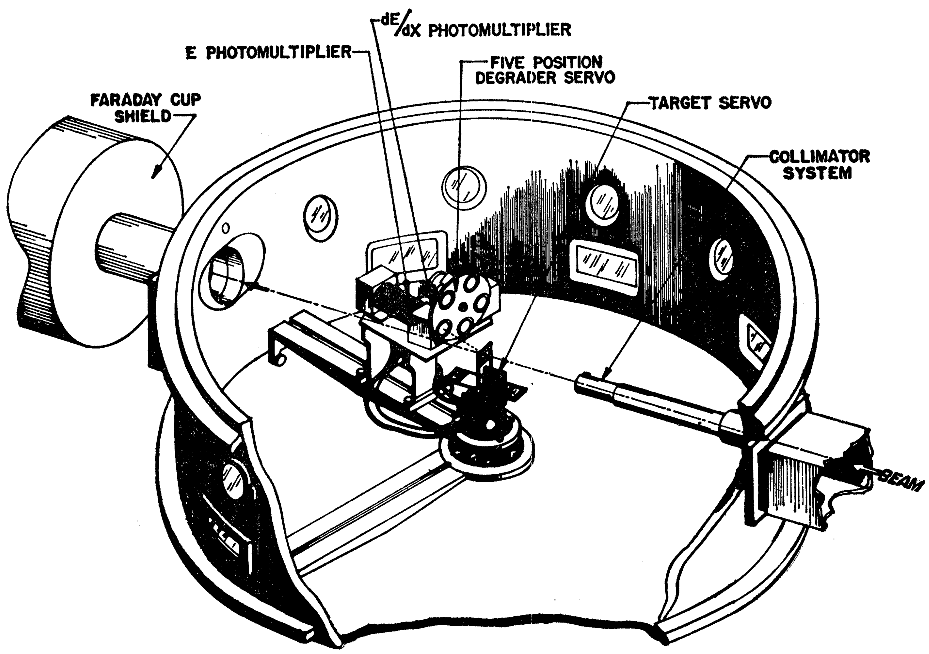

FIG. 3. Arrangement of experimental apparatus in the 60-in. scattering chamber. The chamber contains two arms, a table, and a target stanchion each of which may be positioned remotely to an angular precision of $\pm 0.1°$. The $dE/dx-E$ detector was mounted on the upper arm with the degrader mechanism mounted directly in front of it.

[7] S. Butler, Phys. Rev. **106**, 272 (1957).
[8] A. Bhatia, K. Huang, R. Huby, and H. Newns, Phil. Mag. **43**, 485 (1952).
[9] J. S. Blair (private communication).
[10] J. S. Blair, Phys. Rev. **115**, 928 (1959).

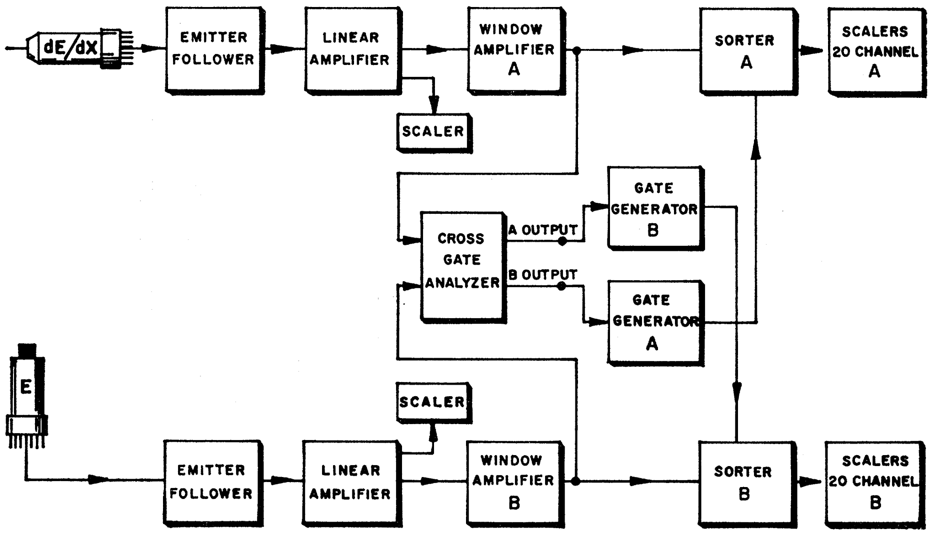

FIG. 4. Block diagram of the electronic circuitry.

similar photomultiplier with Canada balsam cement. Both scintillators are housed in $\frac{1}{8}$-in. thick magnesium oxide reflectors. The energy resolution obtained for protons was between 1 and 2% full width at half-maximum. For a 2-Mev energy loss in the dE/dx detector a resolution of 10% allowed unambiguous separation of protons from other kinds of particles.

A schematic diagram of the electronic apparatus is shown in Fig. 4. The dE/dx spectrum was displayed in one 20-channel pulse-height analyzer and the E spectrum in another. The E spectrum was gated by the dE/dx spectrum so that only protons were counted. The dE/dx spectrum was gated in turn by that portion of the proton E spectrum of interest. This "cross-gating" technique provided continuous observation of the gating boundaries and resulted in more stringent discrimination against unwanted particles.

A polystyrene target 0.001-in. thick was used in the carbon experiment, and an aluminum foil 0.0005-in. thick was used in the aluminum experiment. Both

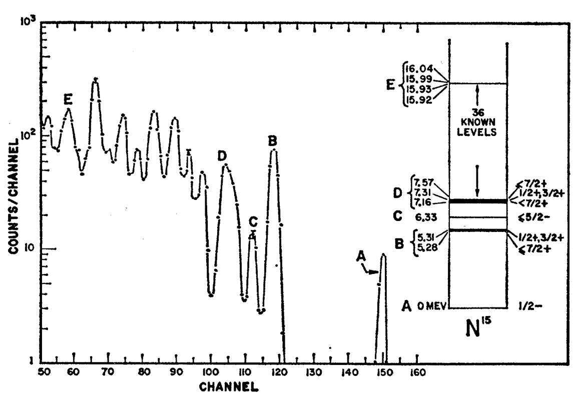

FIG. 5. Proton spectrum at 90° laboratory angle from $C^{12}(\alpha,p)N^{15}$. The labels on various peaks refer to the level diagram of N^{15} shown at the right.

these targets were uniform and free from interfering contaminants. The phosphorus target was made by evaporating a slurry of red phosphorus suspended in distilled water on a thin polystyrene backing. Unfortunately, this target was very fragile and nonuniform, thus limiting the accuracy of the data obtained.

III. RESULTS

A. Carbon

Figure 5 shows a typical proton spectrum for $C^{12}(\alpha,p)N^{15}$ at 90° laboratory angle. Proton peaks corresponding to excited levels[11] in N^{15} are indicated in the figure. Angular distributions for the ground state and the third-excited state are shown in Fig. 6. Both these distributions show strong oscillatory structure and have roughly the same differential cross sections at forward angles. Each point in Fig. 6 represents the average of several separate runs. The differential cross sections assigned are in error by less than 10% near the maxima. Errors shown in Fig. 6 and other angular distributions are statistical.

Angular distributions of unresolved peaks corresponding to the first and second excited states of N^{15} and to the fourth-, fifth-, and sixth-excited states are shown in Fig. 7. Neither of these distributions shows pronounced structure. The differential cross sections assigned are in error by less than 7%. The third distribution shown in Fig. 7 corresponds to a group of levels of 15.9- to 16.0-Mev excitation. This distribution was obtained in a preliminary experiment for which the estimated error in cross sections is 15%.

B. Aluminum

A proton spectrum at 30° laboratory angle for $Al^{27}(\alpha,p)Si^{30}$ is shown in Fig. 8. Positions of probable levels of Si^{30} at 6.5, 9.4, 10, and 11 Mev are indicated.

[11] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 180 (1959).

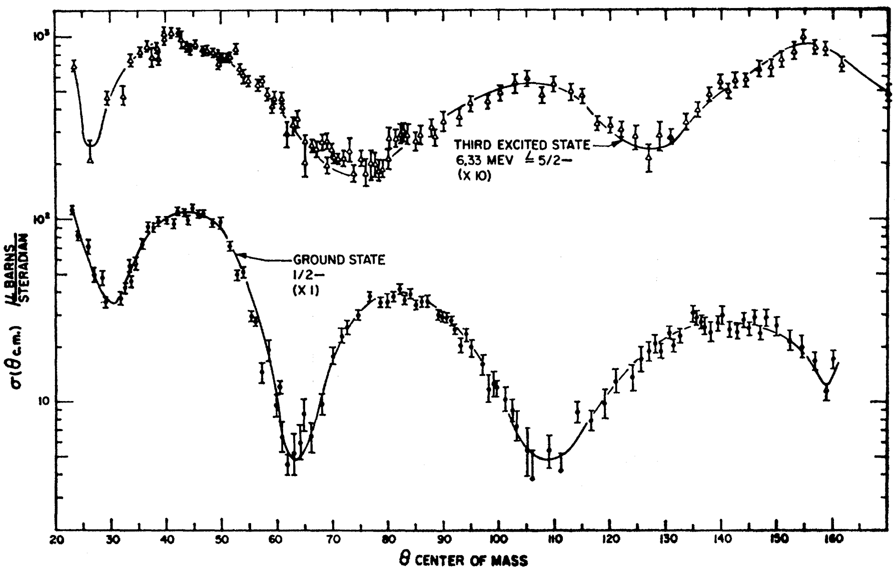

FIG. 6. Angular distributions of protons from $C^{12}(\alpha,p)N^{15}$ corresponding to the ground state and third excited state in N^{15}.

Angular distributions of protons corresponding to the ground state, first-excited state, and second- and third-excited states of Si^{30} are shown in Fig. 9. These distributions show a marked lack of structure, are of small cross section, and decrease rapidly with increasing scattering angle. A check was made at backward angles which showed that the distributions do not increase in this region. The differential cross sections are in error by no more than 7%.

C. Phosphorus

Figure 10 shows a proton spectrum at 30° laboratory angle for $P^{31}(\alpha,p)S^{34}$. Angular distributions of protons corresponding to the ground state and first excited state of S^{34} are shown in Fig. 11. Both distributions show pronounced structure, but are incomplete because of the experimental difficulties encountered when working with such small differential cross sections. The uncertainty in the relative cross sections is less than

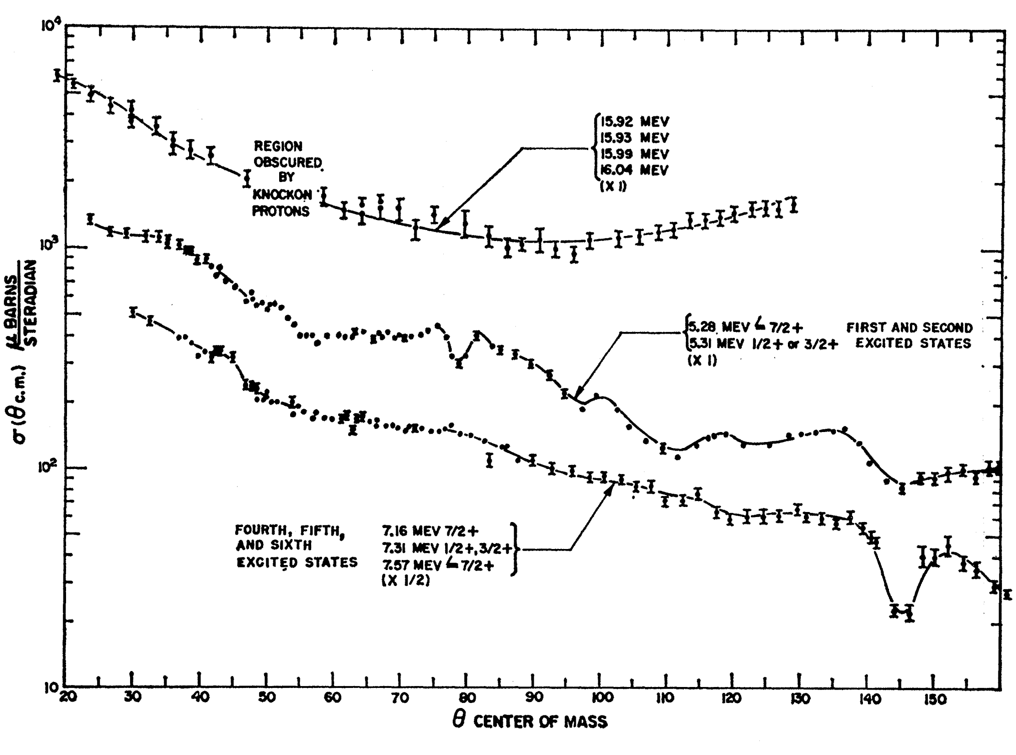

FIG. 7. Angular distributions of protons from $C^{12}(\alpha,p)N^{15}$ corresponding to multiple levels in N^{15}.

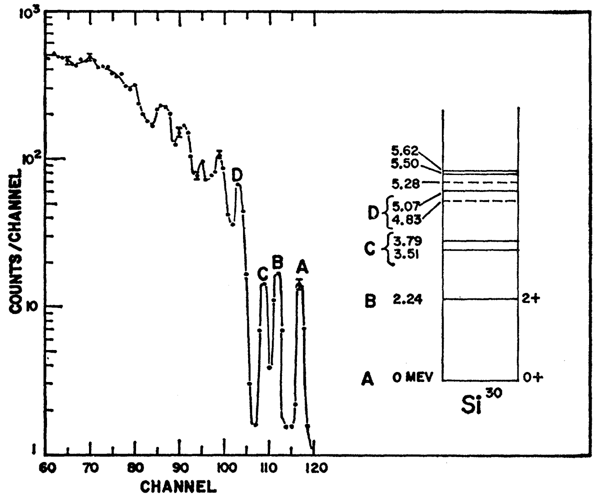

FIG. 8. Proton spectrum at 30° laboratory angle from $Al^{27}(\alpha,p)Si^{30}$. The labels on various peaks refer to the level diagram of Si^{30} shown at the right.

10%. However, the uncertainty in absolute cross section is 30% because of uncertainties in target thickness and uniformity.

D. Other Targets

$F^{19}(\alpha,p)Ne^{22}$, $Cl^{35}(\alpha,p)Ar^{38}$, and $Na^{23}(\alpha,p)Mg^{26}$ were found to have cross sections that were even less than those for phosphorus at 42 Mev and consequently were too small to study with our apparatus.

E. Total Cross Sections

Total cross sections are given in Table I for transitions to the ground state and other levels studied in $C^{12}(\alpha,p)N^{15}$. These cross sections were obtained by numerically integrating their respective angular distributions. The curves were projected to 0° and 180°, and the uncertainty of these extrapolations is reflected in the estimated errors. Approximate total cross sections are also given in Table I for $Al^{27}(\alpha,p)Si^{30}$ and $P^{31}(\alpha,p)S^{34}$. In reality the cross sections given are lower limits on the actual cross sections because the observed angular distributions are incomplete. However, they probably are close to the actual values since investigation showed that none of the distributions increased at larger scattering angles.

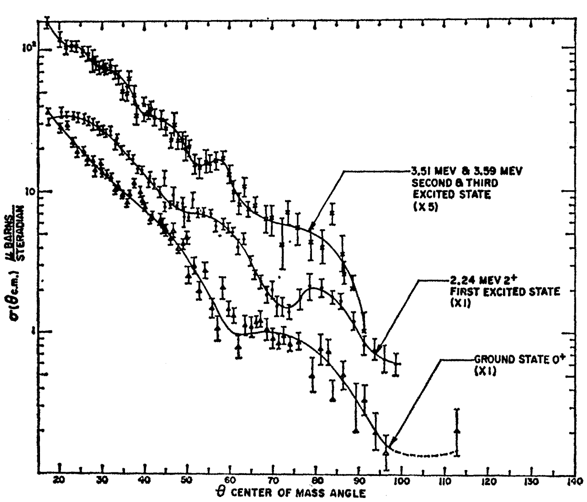

FIG. 9. Angular distributions of protons from $Al^{27}(\alpha,p)Si^{30}$ corresponding to the four lowest states of Si^{30}.

IV. INTERPRETATION

A plane-wave Born approximation treatment of (α,p) reactions may be characterized by three possible interaction mechanisms: (1) tripping of a striton from the alpha particle by the nucleus; (2) direct interaction of the alpha particle with one nuclear proton and the subsequent ejection of that proton; or (3) heavy-particle stripping, or the shearing of a proton from the nucleus in the totally inelastic impact of the alpha particle with the nucleus. The present theories of (α,p) reactions are an outgrowth of the stripping theories proposed by Butler[12,13] or Bhatia *et al.*[8] The latter theory has been extended by El Nadi[14] to encompass triton stripping.

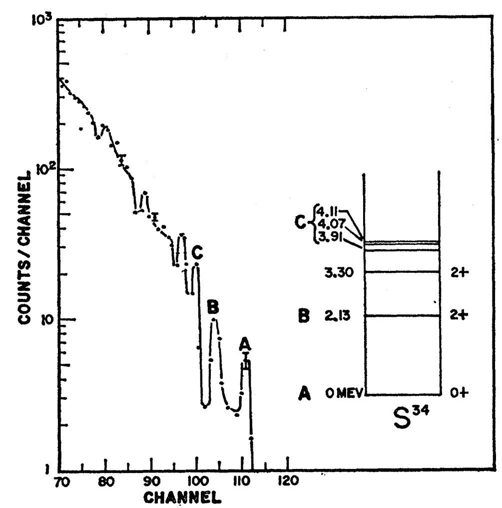

FIG. 10. Proton spectrum at 30° laboratory angle from $P^{31}(\alpha,p)S^{34}$. The labels on various peaks refer to the level diagram of S^{34} shown at the right.

For the stripping mode, conservation of angular momentum and parity demand that the orbital angular momentum l_c of the captured triton must be equal to

[12] S. Butler, Proc. Roy. Soc. (London), **A208**, 588 (1951).
[13] S. Butler and O. Hittmair, *Nuclear Stripping Reactions* (John Wiley & Sons, Inc., New York, 1957).
[14] M. El Nadi, Phys. Rev. **120**, 1360 (1960).

one for the ground-state transition in $C^{12}(\alpha,p)N^{15}$. The same requirements demand that l_c equal one for the third-excited state on N^{15} if the value $\frac{3}{2}-$ is used for the final nuclear spin.[15] With $l_c=1$, the cross section given by Butler[12,13] is

$$d\sigma(\theta)/d\Omega \propto (q^2+\alpha^2)^{-2} \times[\sin(qR)+\alpha^2R^2(1+\alpha R)^{-1}j_1(qR)]^2, \quad (1)$$

where q is the momentum transferred to the initial nucleus, R is the interaction radius, and α is a constant which depends on the reaction mode. The Bhatia expression for the same cross section is

$$d\sigma(\theta)/d\Omega \propto [j_1(qR)]^2. \quad (2)$$

For the direct-interaction mode Butler obtains the same expression as Eq. (1) with suitable reinterpretation of constants. The Bhatia expression is the same for either mode. We need not consider the third mode, heavy stripping, since none of the observed angular distributions shows the increase in cross section at large scattering angles which characterizes this mode. Figure 12 compares the experimental angular distribution of the N^{15} ground state with the theoretical predictions of Bhatia, *et al.*[8] and those of Butler[12,13] for various interaction radii. For a direct interaction one notes that an interaction radius of 5.7 f fits the experimental curve, while a 5.0-f radius fits the data just as well for the stripping mode.

If $l_c=1$ for the third excited state[15] of N^{15}, then once the interaction radius is determined, the same theoretical expression should describe the angular distribution for this state. Therefore, if the ground-state distribution and that for the third-excited state of N^{15} are

TABLE I. Summary of total cross sections and limits on total cross sections for levels[a] studied in N^{15}, Si^{30}, and S^{34}.

Reaction	Level of excitation (Mev)	Spin and parity	Total cross section (microbarns)
$C^{12}(\alpha,p)N^{15}$	0	$\frac{1}{2}-$	550 ± 85
	5.28	$\frac{7}{2}-$	4960 ± 740
	5.31	$\frac{1}{2}+$, $\frac{3}{2}+$	
	6.33	$\frac{5}{2}-$	780 ± 185
	7.16	$\frac{7}{2}+$	4320 ± 645
	7.31	$\frac{1}{2}+$, $\frac{3}{2}+$	
	7.57	$\frac{7}{2}+$	
$Al^{27}(\alpha,p)Si^{30}$	0	0+	40_{-4}^{+6}
	2.24	2+	60_{-4}^{+8}
	3.51		38_{-4}^{+6}
	3.59		
$P^{31}(\alpha,p)S^{34}$	0	0+	17.5_{-5}^{+6}
	2.13	2+	20_{-6}^{+8}

[a] Data on excitation energy, spin, and parity were taken from F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 180 (1959); P. Endt and C. Braams, Revs. Modern Phys. **29**, 683 (1957).

[15] If the value $\frac{5}{2}-$ is assumed for the spin of the third-excited state of N^{15}, $l_c=3$. However, for $l_c=3$, the observed distribution cannot be fitted with either Eq. (1) or Eq. (2) even with a change in R.

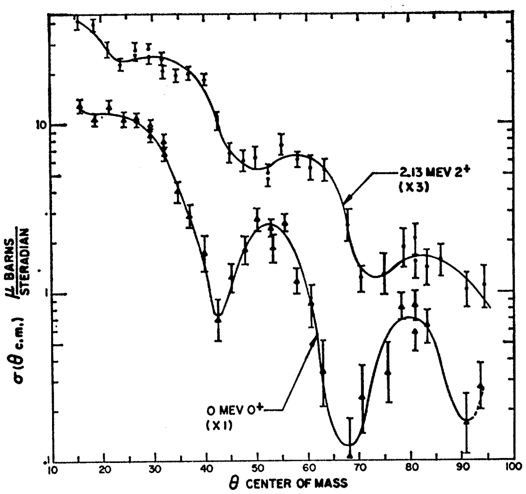

FIG. 11. Angular distributions of protons from $P^{31}(\alpha,p)S^{34}$ corresponding to the ground state and first-excited state of S^{34}.

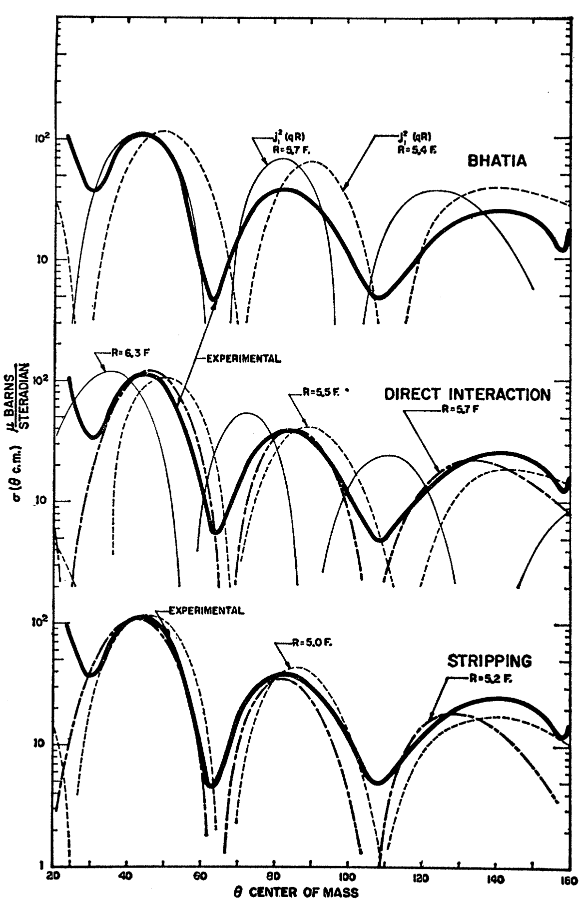

FIG. 12. Comparison of theoretical and experimental angular distributions for the ground-state transition in $C^{12}(\alpha,p)N^{15}$. The heavy lines represent the experimental distributions.

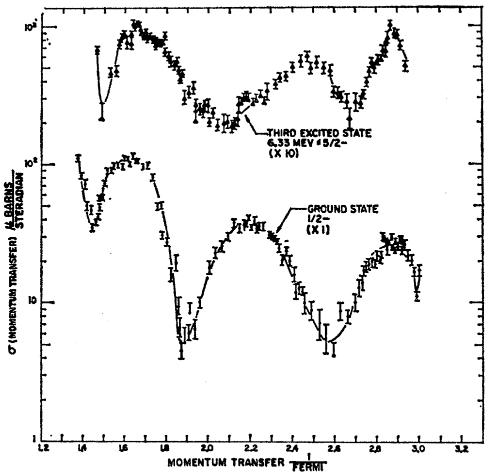

FIG. 13. Proton distributions vs momentum transfer corresponding to the ground state and third-excited state of N^{15} in the reaction $C^{12}(\alpha,p)N^{15}$.

plotted vs momentum transfer q they should be in phase. Thus observation of these two distributions serves to test the theory that the phasing of angular distributions may be used to determine the relative parities of states. Figure 13 shows both distributions plotted vs momentum transfer. It is evident that the central maxima are too far out of alignment to be described by the same function even with any reasonable change in interaction radius. Therefore, existing plane-wave theories fail to describe these distributions. In particular, no simple phase relationship between the two distributions is observed.

Unfortunately, even though the angular distributions for $P^{31}(\alpha,p)S^{34}$ show a pronounced structure the errors due to the small cross sections made a comparison with theory of little use. The lack of structure in the angular distributions from $Al^{27}(\alpha,p)Si^{30}$ prevented any attempt to make a comparison of theory with experiment. It has been shown by Butler *et al.*,[16] in a classical calculation based on the optical model of the nucleus, that the filling of minima in angular distributions may be due to absorption of the incident or emergent particle. This calculation indicates that for a fixed interaction radius R the positions of the relative maxima and minima should occur at the same momentum transfers q independent of the incident alpha energy. While Kondo *et al.*[5] have shown this is not completely true, it is striking to note the similarity in the distributions from aluminum for the energies 21.8, 30.5, and 42 Mev. A comparison of this work with that of Hunting and Wall,[1,2] Nonaka *et al.*,[3] and Kondo *et al.*[5] indicates that the distributions from $P^{31}(\alpha,p)S^{34}$ and $C^{12}(\alpha,p)N^{15}$ which show strong angular structure have cross sections that are roughly 10 times smaller at 42 Mev than at 30.5 Mev. On the other hand, the distributions from $Al^{27}(\alpha,p)Si^{30}$ which lack structure and show filling of minima are similar in shape at 42, 30.5, and 21.8 Mev and have cross sections that only vary by a factor of about 2 over this energy range. It might prove constructive to explore the hypothesis that those reactions which show pronounced structure are more dependent on incident alpha energy than those that do not.

ACKNOWLEDGMENTS

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[16] S. Butler, N. Austern, and C. Pearson, Phys. Rev. **112**, 1227 (1958).