Angular Distributions of Protons from the 19-Mev Alpha-Particle Bombardment of Na^{23}, Al^{27}, and Si^{28}†

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Using ~19-Mev alpha particles, angular distributions have been obtained for the three highest-energy proton groups from (α,p) reactions with Na^{23}, Al^{27}, and Si^{28}. The differential cross sections are interpreted with the aid of an expression similar to that given by Butler for the "knock-out" process, and normalizing factors G, approximately proportional to the product of two reduced widths, are extracted. Reasonable looking fits are obtained for most of the angular distributions with the l values allowed by the theory. Both the reduced total cross sections, $\sigma/(2J_f+1)$, and the G factors increase for the ground-state transitions in the series $F^{19}-Na^{23}-Al^{27}$, but decrease for the excited-state transitions. These trends are shown to be in agreement with arguments based on the shell model and the knock-out mechanism. The cross sections for Si^{28} are unexpectedly large, indicating either a strong $s_{\frac{1}{2}}{}^2$ component for the last two protons in Si^{28} or alpha-particle stripping.

I. INTRODUCTION

THE measurement of the angular distributions of protons from (α,p) reactions induced by ~19-Mev alpha particles on targets of Na^{23}, Al^{27}, and Si^{28} to be presented here is a followup to the work of Priest, Tendam, and Bleuler[1] on targets of C^{12} and F^{19}. An endeavor is made to establish some systematics over a range of target nuclei, to analyze the angular distributions in the light of direct-interaction theories, and to correlate the data with the shell-model configurations of the nuclei involved.

The interpretation of a direct (α,p) reaction depends on whether the alpha particle is treated as an unalterable unit or not. In *alpha-particle stripping*, the target nucleus captures one proton and two neutrons (or possibly a triton as a unit) from the alpha particle, with the second proton flying on. In this case, the information to be gained deals with the structure of the final nucleus as being composed of the initial nucleus as a core and a triton or three nucleons. In the *knock-out* or the *heavy-particle stripping* processes, on the other hand, the initial nucleus is regarded as consisting of a core and a last proton. The proton is released in the reaction and the residual nucleus is formed as a system of core plus captured alpha particle. The cross section, then, will depend on the structure of both the initial and the final nucleus, with a common core. This makes the interpretation of the results more difficult, especially since little is known about the (core+alpha) structure of the final nucleus. For the ground states, the assumption of zero orbital angular momentum is reasonable. The excited states, however, could either be formed as $l=0$ systems, with excited cores (which would have to be present in the initial nucleus), or the system could be in a $l=2$ or $l=4$ rotational state (in the cases considered here, all parities are even). The energy for $l=2$ is of the order of 1.5 Mev, as are the energies of the first excited states. Because of this complication one would prefer to interpret (α,p) reactions as alpha-stripping processes, but the large energy needed to strip a proton from an alpha particle, 19.8 Mev, makes this process appear less probable. In the following, only the knock-out mechanism and heavy-particle stripping will be considered.

The targets chosen for this investigation are all members of the $d_{\frac{5}{2}}$ shell. In interpreting the cross sections for the series F^{19}, Na^{23}, and Al^{27}, we shall assume that the structures of the residual even-even nuclei are similar and that the variations are due to differences in the shell-model structure of the target nuclei. In the case of F^{19}, the small cross section for the ground-state transition was interpreted as being due to a lack of a common O^{18} core for F^{19} $(=O^{18}+p)$ and Ne^{22} $(=O^{18}+\alpha)$.[1] The explanation was advanced that the last two neutrons in the O^{18} core of F^{19} may be in a $(d_{\frac{5}{2}}{}^2)_2$ or a $(s_{\frac{1}{2}}{}^2)_0$ configuration (coupled to a total $\frac{1}{2}^+$ state with a $d_{\frac{5}{2}}$ or a $s_{\frac{1}{2}}$ proton, respectively), whereas in Ne^{22} they would form a $(d_{\frac{5}{2}}{}^2)_0$ system. This interpretation would be in agreement with the larger cross sections observed for the excited-state transitions, since 2^+ states could be formed either by $l=0$ alpha particles captured to the 2^+ core or by $l=2$ alpha particles captured to the 0^+ core. The present investigation of the $Al^{27}(\alpha,p)Si^{30}$ reaction was expected to test this interpretation *by contrast*; since the $\frac{5}{2}^+$ ground state of Al^{27} may be interpreted as being chiefly a 0^+ core with a $d_{\frac{5}{2}}$ last proton, the ground-state transition should be strong whereas the excited states of Si^{30} should be formed with reduced probability because the alpha particle would have to be captured with nonzero angular momentum. For Na^{23}, the cross-section trend should be similar to that for the F^{19} target. Since the last three protons of Na^{23} are probably predominantly in a $(d_{\frac{5}{2}}{}^3)_{\frac{3}{2}}$ system, the Ne^{22} core would involve a $(d_{\frac{5}{2}}{}^2)_2$ configuration for the last two protons which would be found in the ex-

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[1] J. R. Priest, D. J. Tendam, and E. Bleuler, Phys. Rev. 119, 1301 (1960).

cited states of the final nucleus Mg^{26} rather than in the ground state.

The Si^{28} target was chosen for a comparison between odd-Z and even-Z targets. It was anticipated that the (α,p) cross section would be smaller than for Al^{27} because of the closure of the $d_{\frac{5}{2}}$ shell at Si^{28}.

The only previous work pertaining to these considerations is that of Hunting and Wall[2] on the reactions $Na^{23}(\alpha,p_{0,1})Mg^{26}$ and $Al^{27}(\alpha,p_{0,1})Si^{30}$ at an incident energy of 30.4 Mev (p_0 and p_1 indicate the proton groups leaving the residual nucleus in the ground state and the first-excited state, respectively). Their results agree with expectation insofar as the ground-state cross section for Al^{27} is larger than that for Na^{23} by a factor 5, within a stated uncertainty of close to a factor 2. Also, in the case of Na^{23}, the cross section for the first-excited-state transition is larger than the ground-state cross section by about a factor 10, whereas for Al^{27}, the ratio is only about 2. No data are available for F^{19} or Si^{28} at this energy.

The results to be presented for $E_\alpha \sim 19$ Mev confirm the arguments given for the series $F^{19}-Na^{23}-Al^{27}$, but show unexpectedly large cross sections for Si^{28}.

II. EXPERIMENTAL PROCEDURE

The measurements were carried out using the 19-Mev external cyclotron beam. The focussing and energy analyzing systems are adequately described elsewhere.[3] The final collimation was achieved by focussing the beam on a collimator containing two $\frac{1}{8}$-in. circular apertures 7 in. apart. With a $\frac{1}{4}$-in. object aperture for the analyzing magnet, the analyzed beam had an rms spread of 50 kev.[1]

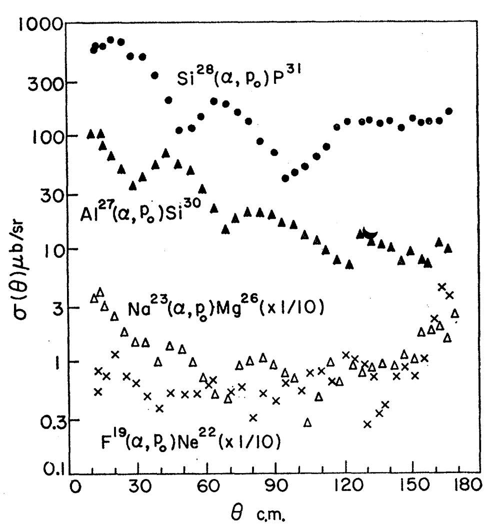

FIG. 1. Ground-state angular distributions of protons from ~19-Mev alpha-particle bombardment of F^{19}, Na^{23}, Al^{27}, and Si^{28}. The F^{19} and Na^{23} data have been displaced downward by one decade.

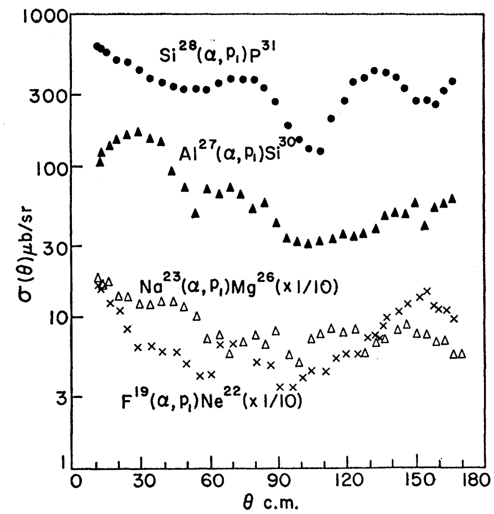

FIG. 2. First-excited-state angular distributions of protons from ~19-Mev alpha-particle bombardment of F^{19}, Na^{23}, Al^{27}, and Si^{28}. The F^{19} and Na^{23} data have been displaced downward by one decade.

The protons were detected in a $\frac{1}{8}$-in. thick CsI(Tl) crystal in front of which was placed sufficient aluminum or tantalum to stop the scattered alpha particles. This was used in conjunction with a DuMont-6291 photomultiplier tube whose signal was fed to a White cathode follower and subsequently to a twenty-channel pulse-height analyzer. Other reaction products did not contribute to the high-energy proton spectra because of the large negative Q values and selective absorption. The crystal, phototube, and mounting could be rotated continuously about the target from 11.3° to 169.7° in the laboratory system. The solid angle subtended by the detector was a cone of $(1.71\pm0.03)10^{-4}$ steradian. The energy resolution obtained with this system was approximately 5% (full width at one-half maximum) for 12-Mev protons.

The targets were about 1 mg/cm² in total thickness and were mounted at the center of the reaction chamber. The sodium target was in the form of sodium hydroxide which had been vacuum evaporated on a $\frac{1}{4}$-mil Mylar backing. The Na content of the target, whose composition was uncertain, was determined by comparing the yield of the ground-state proton group from the $Na^{23}(\alpha,p)Mg^{26}$ reaction with that for a known NaCl target (with the latter, only the ground-state proton group can be resolved easily). This was also checked by bombarding the two targets with deuterons and comparing the Na^{24} gamma activities induced. The sodium content was found to be 0.522 mg/cm² with a standard error of 5%. Assuming no water content in the target, the NaOH thickness was 0.91 mg/cm² which is equivalent to 250-kev energy loss for normally incident 19-Mev alpha particles. The commerical alumi-

[2] C. E. Hunting and N. S. Wall, Phys. Rev. **108**, 901 (1957); **115**, 956 (1959).

[3] J. R. Priest, D. J. Tendam, and E. Bleuler, Phys. Rev. **119**, 1295 (1960).

num foil target was 0.927 mg/cm² thick with a standard error of 3%, resulting in an energy loss of 230 kev. The silicon target was in the form of fused quartz of 1.16 mg/cm² (310 kev energy loss), of which only 0.500 mg/cm² is the isotope Si^{28}. During the actual bombardment, the targets were inclined at an angle of 45° to the incident beam. Thus the thickness traversed by the beam is $\sqrt{2}$ times the values given here.

III. EXPERIMENTAL RESULTS

The observed angular distributions for the (α,p) transitions induced by ~19-Mev alpha particles on F^{19}, Na^{23}, Al^{27}, and Si^{28} and corresponding to discrete states in the residual nuclei Ne^{22}, Mg^{26}, Si^{30}, and P^{31}, respectively, are shown in Figs. 1–3. The fluorine data have been taken from Priest *et al.*[1] and are included here in order to compare the magnitudes of the cross sections and the forms of the angular distributions for all odd-Z members of the $d_{\frac{5}{2}}$ shell. The counting statistics are given approximately by the size of the triangles shown on the figures. The estimated standard error of the differential cross section, excluding counting statistics, is 5% for the aluminum and silicon targets, 6% for the sodium target. The differential cross sections for the reactions with Na^{23}, Al^{27}, and Si^{28} have been tabulated by Ploughe.[4]

Figure 1 shows the angular distributions of the protons from the (α,p_0) reactions. As a matter of convenience, the data for the F^{19} and Na^{23} targets have been displaced downward by a factor of 10. The apparently large cross section observed[1] for large angles in the case of fluorine is seen to be just comparable to that obtained for sodium. With the exception of the curious little dip in the F^{19} angular distribution near 135°, the cross sections for the odd-A target nuclei are comparable in the angular range 120° to 150°.

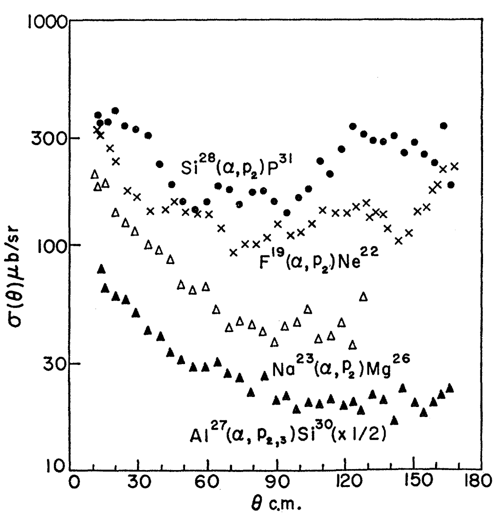

FIG. 3. Second excited-state angular distributions of protons from ~19-Mev alpha-particle bombardment of F^{19}, Na^{23}, Al^{27}, and Si^{28}. The cross section plotted for Al is the average for the two unresolved transitions to the second and the third excited state.

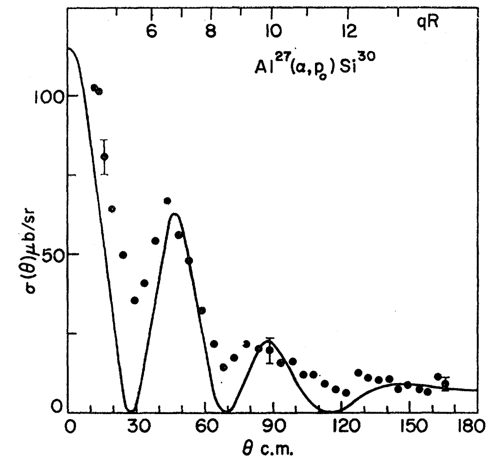

FIG. 4. Comparison of the differential cross section for the $Al^{27}(\alpha,p_0)Si^{30}$ reaction at 18.7 with Eq. (2) for $l=2$, $R=(5.6)10^{-13}$ cm, and $G=7.0$.

In Figs. 2 and 3 are shown the measured angular distributions of protons which leave the residual nucleus in an excited state. Again, the data for $F^{19}(\alpha,p_1)Ne^{22}$ and $Na^{23}(\alpha,p_1)Mg^{26}$ shown in Fig. 2 have been displaced by a factor of 10. The differential cross sections for the p_1 group from the odd-A targets are comparable at ~70°. No region of comparable cross sections exists in the second-excited-state angular distributions shown in Fig. 3. The experimental technique used was not capable of resolving the proton groups from the second and third excited states of Si^{30}. Thus one half the combined cross section for the reaction $Al^{27}(\alpha,p_{2,3})Si^{30}$ is plotted in Fig. 3.

Most of the angular distributions show, at least in the forward angles, the oscillatory pattern characteristic of direct interactions. A few of the distributions also show substantial cross sections at large angles.

IV. DISCUSSION

Comparison with Earlier Work

The differential cross sections for Na and Al given in Figs. 1 and 2 may be compared to those measured at 30.4 Mev by Hunting and Wall.[2] The distributions show the same general trend, but at 30.4 Mev the cross sections drop much more rapidly with increasing angle, show no backward rise, and the oscillatory patterns present at 19 Mev are smeared out at the higher energy to the extent that they are barely recognizable. As expected, the cross sections at 30.4 Mev are lower than at 19 Mev. In the region of the forward peaks (~20°), the ratio is about 3 for $\sigma(p_1)$ and $\sigma(p_0)$ with Al and for $\sigma(p_1)$ with Na, but about 8 for $\sigma(p_0)$ with Na.

[4] W. D. Ploughe, Ph.D. thesis, Purdue University, Lafayette, Indiana, June, 1961 (unpublished).

TABLE I. Total cross sections for (α,p) reactions.

Target	F^{19}	Na^{23}	Al^{27}	Si^{28}
J_i	$\frac{1}{2}+$	$\frac{3}{2}+$	$\frac{5}{2}+$	0^+
Q_0 (Mev)	1.70	1.84	2.38	−1.91
E_α (Mev)	18.9	18.7	18.7	18.35
$\sigma(p_0)/(2J_f+1)$	0.10 mb	0.13 mb	0.31 mb	1.0 mb
J_f	0^+	0^+	0^+	$\frac{1}{2}+$
$\sigma(p_1)/(2J_f+1)$	0.16 mb	0.21 mb	0.15 mb	0.98 mb
E_1 (Mev), J_f	1.28, 2^+	1.83, 2^+	2.24, 2^+	1.26, $\frac{3}{2}+$
$\sigma(p_2)/(2J_f+1)$	0.34 mb[a]	0.15 mb	0.07 mb[b]	0.47 mb
E_2 (Mev), J_f	3.35, ···	2.97, 2^+	···, ···	2.23, $\frac{5}{2}+$

[a] The final-state spin is assumed to be 2.
[b] One-half the total cross section for the reactions leading to the unresolved 3.51-Mev and 3.79-Mev states, with J_f taken to be 2.

Total Cross Sections

The angular distributions were integrated to yield the total cross sections for the transitions to the different levels of the final nuclei involved. Since a comparison of cross sections is more meaningful if the final-state statistical weights are removed, Table I lists the values of the total cross sections, divided by $(2J_f+1)$, where J_f is the spin of the residual nucleus. The table also shows the spins of the target nuclei, the energy release in the ground-state reactions, the laboratory energy of the incident alpha beam in the center of the targets, and excitation energy and spin of the final states.

In order to discuss these cross sections on the basis of a direct-interaction mechanism, one should subtract a compound-nucleus contribution (and possibly interference terms). An estimate for the $F^{19}(\alpha,p_0)Ne^{22}$ cross section, based on the formalism of Blatt and Weisskopf[5] and using the level-density formula given by Lang and LeCouteur,[6] with a characteristic-level shift as given by el Nadi and Wafik,[7] yields a cross section which exceeds the measured cross section by a factor of about ten.[4] Most probably, the cross section for the formation of the compound nucleus was grossly overestimated. Since no reliable calculations for the compound-nucleus contribution can be performed, it can only be stated that for F^{19}, $\sigma_{CN}/(2J_f+1)$ must be less than the smallest value observed, i.e., 0.10 mb. From the trend of the level densities and Q values for (α,n) and (α,p) reactions, it can be concluded that the compound-nucleus contributions for the other targets should be smaller. In the discussion to follow, they will be neglected; the main effect of their subtraction would be to enhance the variations of the direct-interaction cross sections.

For the odd-Z targets, the trends of the cross sections shown in Table I are in agreement with the arguments given in the introduction. The cross sections for the $Si^{28}(\alpha,p)P^{31}$ are unexpectedly large; similarly large cross sections have been observed recently by Martin *et al.*[8] for the reaction $Ca^{40}(\alpha,p)Sc^{43}$ at 21.9 Mev.

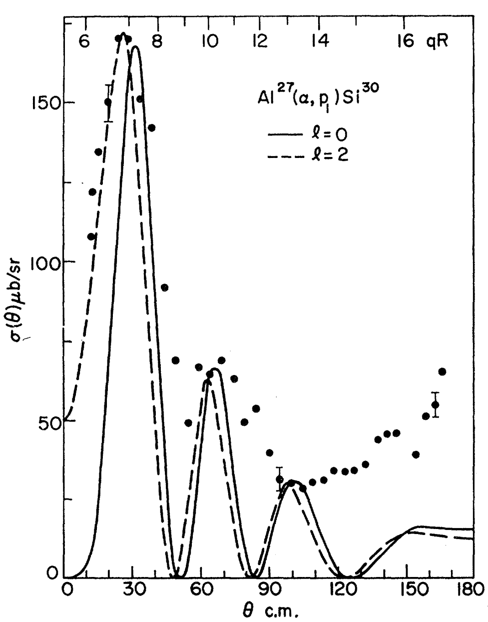

FIG. 5. Comparison of the differential cross section for the $Al^{27}(\alpha,p_1)Si^{30}$ reaction at 18.7 Mev with Eq. (2) for $R=(7.0)10^{-13}$ cm. The solid curve is for $l=0$ and $G=1.9$, the dashed curve for $l=2$. The value $l=4$ is also allowed, but no reasonable fit could be obtained for any radius.

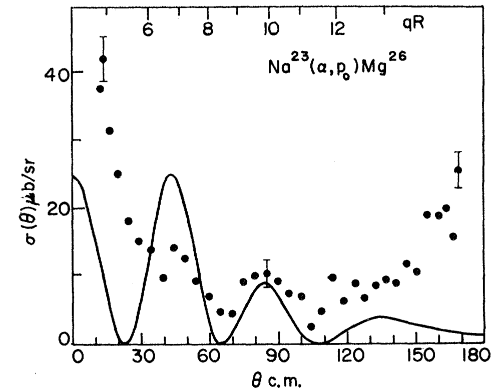

FIG. 6. Comparison of the differential cross section for the $Na^{23}(\alpha,p_0)Mg^{26}$ reaction at 18.7 Mev with Eq. (2) for $l=2$, $R=(6.0)10^{-13}$ cm, and $G=1.8$.

Comparison with Direct-Interaction Theory

In Figs. 4–11 the experimental cross sections are compared to the angular distributions predicted by the simplest direct-interaction theories for the knock-out process and heavy-particle stripping.

[5] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952).
[6] J. M. B. Lang and K. J. LeCouteur, Proc. Phys. Soc. (London) **A67**, 586 (1954).
[7] M. el Nadi and M. Wafik, Nuclear Phys. **9**, 22 (1959).
[8] H. J. Martin, M. B. Sampson, and D. W. Miller, Phys. Rev. **121**, 877 (1961).

Knock-out process

The formula given by Eq. (40) of Butler[9] was modified somewhat, following the general procedure of Banerjee.[10] The initial (final) nucleus, with total angular momentum J_i (J_f), is assumed to be a system consisting of a core and a proton (alpha particle), with orbital angular momentum $l'\hbar$ ($l''\hbar$), reduced mass μ' (μ''), and separation energy $\epsilon'=(\hbar K')^2/2\mu'$ $[\epsilon''=(\hbar K'')^2/2\mu'']$. The angular-momentum transfer is then given by $\mathbf{l}=\mathbf{l}'-\mathbf{l}''$. With the customary assumption that the spin of the core remains unchanged in the reaction, the possible l values are given by

$$|\mathbf{J}_i+\mathbf{J}_f+\tfrac{1}{2}|_{\min}\leq l\leq J_i+J_f+\tfrac{1}{2}, \qquad (1)$$

and the parity condition that l is odd (even) if initial and final state have different (same) parity. If a single l value is allowed the resulting formula may be written as[4]

$$\sigma(\vartheta)=G\left\{\frac{k_p}{k_\alpha}\frac{\mu_p\mu_\alpha}{\mu'^2}(2J_f+1)(K'K''R\gamma_l)^{-2}\right\}\times\left\{\frac{K^2}{K^2+q^2}\right\}^2 X_l^2(qR,KR). \qquad (2)$$

Here, $\mathbf{k}_\alpha$ and $\mathbf{k}_p$ are the wave vectors of the incident alpha particle and the outgoing proton in the center-of-mass system; μ_α and μ_p the reduced masses [e.g., $\mu_\alpha=m_\alpha A_T/(A_T+4)$, where m_α is the mass of the alpha particle, A_T the mass number of the target nucleus; $\hbar k_\alpha=(2m_\alpha E_\alpha)^{\frac{1}{2}}A_T/(A_T+4)$, where E_α is the alpha-particle energy in the laboratory]. The quantity γ_l is given by

$$\gamma_l(KR)=h_l(iKR)/iKh_{l+1}(iKR), \qquad (3)$$

where h_l is the spherical Hankel function of order l, R is the cutoff or interaction radius, and $K=K'+K''$. The first two factors in expression (2) are independent of the scattering angle. It enters only through the magnitude of the momentum transfer, $\hbar q$, given by

$$\mathbf{q}=[(A_T-1)/A_T][\mathbf{k}_\alpha-(A_T/A_T+3)\mathbf{k}_p]. \qquad (4)$$

The third term in (2) is a slowly varying form factor, whereas the oscillatory pattern of the cross section is contained in X_l:

$$X_l(qR,KR)=j_l(qR)-q\gamma_l(KR)j_{l+1}(qR) = -\frac{1}{iKh_{l+1}(iKR)}W(j_l(qR),h_l(iKR)), \qquad (5)$$

where W is the Wronskian as used by Butler.[9]

The dimensionless quantity G contains the unknown nuclear information. It is given by the expression[4]

$$G=\frac{V_0^2A^2B^2|h_l(iKR)|^2}{(2\pi\hbar^2)^2/\mu'^2R^4}, \qquad (6)$$

where V_0 is the space integral of the assumed zero-range

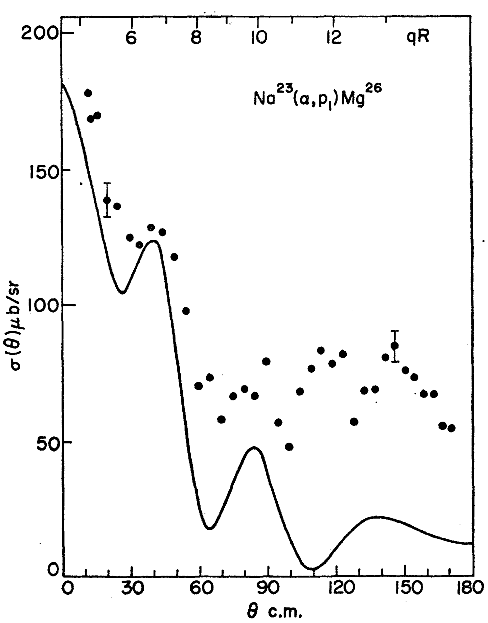

FIG. 7. Fit to the differential cross section for the $Na^{23}(\alpha,p_1)Mg^{26}$ reaction at 18.7 Mev using $\sigma(\vartheta)\propto(q^2+K^2)^{-2}(X_0^2+X_2^2+0.2X_4^2)$ with $R=(6.0)10^{-13}$ cm. The curve should be considered only as indicative of the type of fit possible with the least number of parameters.

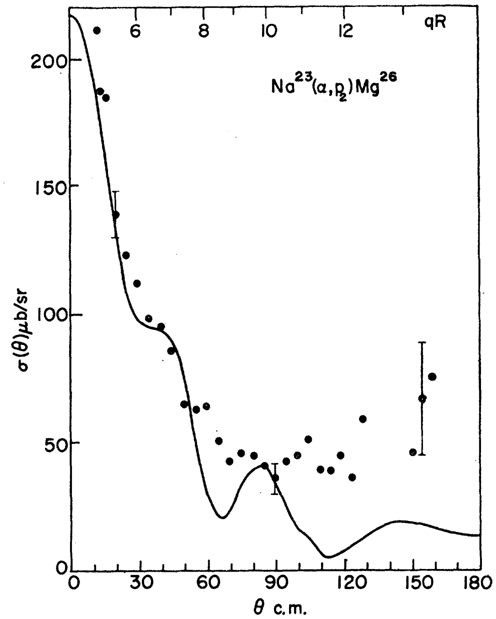

FIG. 8. Fit to the differential cross section for the $Na^{23}(\alpha,p_2)Mg^{26}$ reaction at 18.7 Mev using $\sigma(\vartheta)\propto(q^2+K^2)^{-2}(X_0^2+X_4^2)$ with $R=(6.0)10^{-13}$ cm. The curve should be considered only as indicative of the type of fit possible with the least number of parameters.

[9] S. T. Butler, Phys. Rev. **106**, 272 (1957).

[10] M. L. Banerjee, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press, Inc., New York, 1960), Part B.

interaction potential between the proton and the alpha particle. The factor $|h_l(iKR)|^2$ is retained in G to make it contain, approximately, the product of two reduced widths. The latter would involve the amplitudes of the initial and final nuclear systems near R: $\sim Ah_{l'}(iK'R)$ and $Bh_{l''}(iK''R)$ whose product is roughly proportional to $h_l(iKR)$, with $K=K'+K''$.

If more than one value of l is allowed by the selection rules (1), the contributions of different l values may interfere with each other.[9] However, in this paper such interference terms will be neglected and Eq. (2) will simply be summed over the allowed values.

Heavy-particle stripping

For the reactions with Si, an attempt was made to add a heavy-particle stripping term in order to reproduce the rise of the cross section at large angles. The expression for the cross section, again obtained from the general procedure of Banerjee,[10] using the square-well approximation of Owen and Madansky[11] for the initial nucleus, is[4]

$$\sigma(\vartheta) \propto \left\{\frac{1}{\lambda^2-q_p^2}+\frac{1}{K'^2+q_p^2}\right\}^2 \times\{X_{l'}(q_p\rho,K'\rho)X_{l''}(q_\alpha R,K''R)\}^2, \quad (7)$$

with $\mathbf{q}_p=\mathbf{k}_p+\mathbf{k}_\alpha/A_T$, $\mathbf{q}_\alpha=-\mathbf{k}_\alpha-4\mathbf{k}_p/(A_T+3)$, and

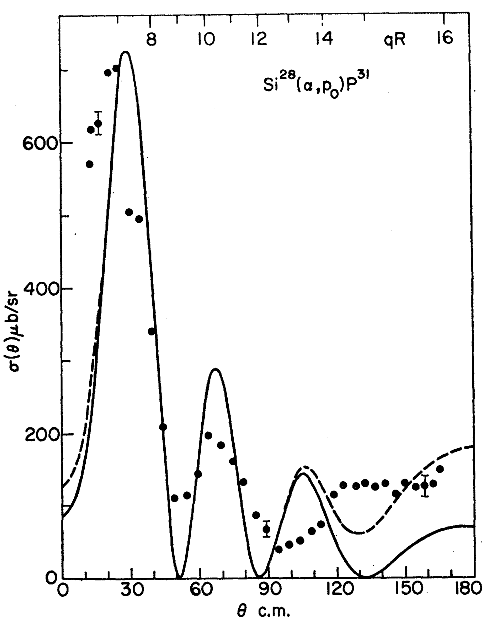

FIG. 9. Theoretical fits to the differential cross section of the $Si^{28}(\alpha,p_0)P^{31}$ reaction at 18.35 Mev. With $R=(7.0)10^{-13}$ cm, the solid curve is Eq. (2) for $l=0$ and $G=13.5$. The dashed curve shows the type of fit obtainable by the addition of an incoherent heavy-particle stripping term, according to Eq. (7) with $\rho=(4.5)10^{-13}$ cm, $R=(7.0)10^{-13}$ cm, $\lambda=(1.07)10^{13}$ cm^{-1} ($V=35$ Mev), $l'=2$, and $l''=0$.

[11] G. E. Owen and L. Madansky, Phys. Rev. **105**, 1766 (1957).

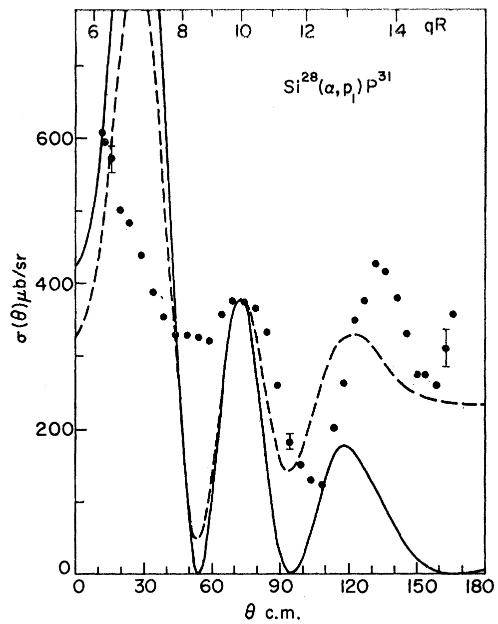

FIG. 10. Theoretical fits to the differential cross section of the $Si^{28}(\alpha,p_1)P^{31}$ reaction at 18.35 Mev. With $R=(6.5)10^{-13}$ cm, the solid curve is Eq. (2) for $l=2$ and $G=8.3$. The dashed curve shows the type of fit obtainable by the addition of an incoherent heavy-particle stripping term.

$\lambda^2+K'^2=2\mu'V/\hbar^2$, where V is the depth of the square-well potential. Its radius was taken to be $\rho=(1.22A^{\frac{1}{3}}+0.70)10^{-13}$ cm. The solution of the square-well problem, with given ϵ', was chosen such that $V\sim40$ Mev The interaction radius R was taken to be the same as for the knock-out process. No interference terms were included.

Discussion of fits

In calculating the curves of Figs. 4 to 11, the core masses were assumed to be those of the corresponding free nuclides in the ground state. The interaction radii, l values, and nuclear factors, G, used for the knock-out processes are listed in Table II which includes the F^{19} data of Priest *et al.*[1] The interaction radii were chosen independently for best fit, except those shown in parentheses. It is obvious from Table II that the trends observed in the total cross sections (Table I) are much enhanced in the variations of the factor G.

$Al^{27}(\alpha,p)Si^{30}$

The experimental angular distribution for the ground-state transition (Fig. 4) shows nice agreement with the calculated curve, as might be expected if Al^{27} has a strong single-particle $d_{\frac{5}{2}}$ component. It appears that in this case the contribution from heavy-particle stripping or other exchange effects is very small. For the transitions to the first excited state of Si^{30}, the allowed l values are 0, 2, or 4. In Fig. 5, a fit with either $l=0$ or $l=2$ is shown to be acceptable and the figure also il-

TABLE II. Nuclear factors G, l values, and interaction radii R used to fit the (α,p) differential cross sections with the knock-out formula (2).

Target		F^{19}	Na^{23}	Al^{27}	Si^{28}
p_0:	G	0.09	1.8	7.0	13.5
	l	0	2	2	0
	R	(5.1 f)	6.0 f	5.6 f	7.0 f
p_1:	G	0.35	...[a]	1.9	8.3
	l	2	0, 2, 4	0 (2)	2
	R	5.1 f	(6.0 f)	7.0 f	6.5 f
p_2:	G	1.2	...[a]	...[b]	1
	l	2	0, 2, 4	...	2
	R	(5.1 f)	(6.0 f)	...	6.6 f

[a] Not fitted with unique l value.
[b] Not evaluated since this proton group is an unresolved doublet.

lustrates the fact that (α,p) reactions distinguish less well between different l values than deuteron stripping because the momentum transfer (or qR) is quite large in the forward direction. No fit has been attempted to the angular distribution for the third proton group ($p_{2,3}$) which is an unresolved doublet. The interaction radius for the p_0 group, 5.6 f, is in fair agreement with the one found by Hunting and Wall[2] at 30.4 Mev, 5.0 f.

$Na^{23}(\alpha,p)Mg^{26}$

As stated in the introduction, the predominant $(d_{\frac{5}{2}}{}^3)_{\frac{5}{2}}$ configuration of the last three protons in Na^{23} is not expected to connect directly with the ground state of Mg^{26} by an (α,p) knock-out process. The reaction could go either via a spin flip of one of the core protons or via a $d_{\frac{3}{2}}$ admixture, e.g. $(d_{\frac{5}{2}}{}^2)_0 d_{\frac{3}{2}}$ or $(d_{\frac{3}{2}}{}^2)_0 d_{\frac{5}{2}}$. The fit for the ground-state transition (Fig. 6) is much less

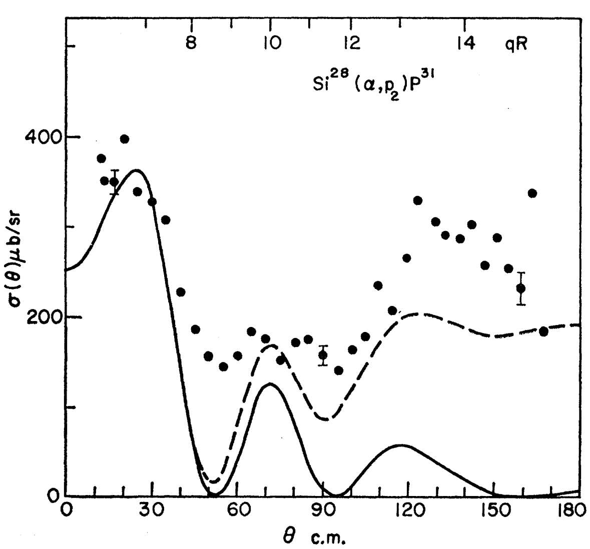

FIG. 11. Theoretical fit to the differential cross section of the $Si^{28}(\alpha,p_2)P^{31}$ reaction at 18.35 Mev. With $R=(6.6)10^{-13}$ cm, the solid curve is Eq. (2) for $l=2$ and $G=1.8$. The dashed curve shows the type of fit obtainable by the addition of an incoherent heavy-particle stripping term.

satisfactory than in the case of Al^{27} (Fig. 4). It is not known whether this is due to the inhibition of the reaction or whether the difference is accidental and would disappear if a proper distorted-wave calculation were performed. Figures 7 and 8 are only given as examples for the kind of agreement obtainable with mixtures of different l values. No implication that the coefficients of the $X_l{}^2$ functions have any particular significance is intended.

$Si^{28}(\alpha,p)P^{31}$

According to Eq. (1) only $l=0$ is allowed for the ground-state transition (Fig. 9); with the reasonable assumption that the alpha particle is captured into an s orbit ($l''=0$), the ejected proton should also come from an s state ($l'=0$). The surprisingly large cross section—if the knock-out interpretation is retained—then necessitates the assumption of a sizeable admixture of a $s_{\frac{1}{2}}{}^2$ configuration in the ground state of Si^{28} which is, on the basis of the shell model, usually considered to be $d_{\frac{5}{2}}$ closed subshell. The present result is consistent with the studies of Rubin[12] on the $Al^{27}(d,n)Si^{28}$ reaction. He found a relatively small cross section for the transition to the ground state which would proceed by capture of a $d_{\frac{5}{2}}$ proton. It would appear that the closed $d_{\frac{5}{2}}$ shell is not the predominant configuration of Si^{28}. Additional evidence for the $s_{\frac{1}{2}}$ admixture as well as for a strong $d_{\frac{3}{2}}$ admixture to the ground-state configuration of Si^{28} is given by MacFarlane and French.[13]

The theoretical knock-out angular distributions for the p_0 and p_2 groups (Figs. 9, 11) agree reasonably well with the experimental data at forward angles, whereas for the p_1 group (Fig. 10) a deviation is observed very similar to the one found by Priest *et al.*[1] for the $C^{12}(\alpha,p_0)N^{15}$ reaction. The broken curves show the degree of improvement possible by adding an incoherent heavy-particle stripping term.

This attempt to improve the fit may not really be justified. Too many things have been neglected. First, Coulomb effects have been ignored in the development of the theory, and for alpha particles they should be more important than for an incident particle of unit charge. Second, the nuclear distortion of the incoming and outgoing waves have been neglected, although the distortion of the incoming wave for (alpha, nucleon) processes has recently been taken into account by Henley.[14] Third, any contribution by compound-nucleus formation has been ignored. This question has received some recent attention by Weidenmuller.[15] Fourth, no account has been taken here of possible interference between the knock-out and heavy-particle-stripping

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processes. Finally, there is no experimental evidence whether the dominant part of the process, giving rise to the forward peak, is correctly described as a knock-out or as an ordinary stripping reaction, since both mechanisms give rise to the same angular distribution. Despite the fact that the binding energy of a proton in the alpha particle is 19.8 Mev, and in Si^{28} only 11.6 Mev, it is possible that for Si^{28} the alpha stripping process is important. Though Si^{28} is probably not simply a closed $d_{\frac{5}{2}}$ shell, it is an exceptionally stable nucleus and the final product of the (α,p) reaction, P^{31}, may well have a strong component of $Si^{28}+p+2n$ (or $Si^{28}+H^3$). Henley[14] has suggested that measurements of the polarization of the outgoing protons might resolve this question since it should be different for the two processes. Due to the small cross sections, such experiments will not be easy.

V. SUMMARY

The trends of the cross sections for the (α,p) reactions with F^{19}, Na^{23}, and Al^{27}, both as far as the variations between the target nuclei and as far as the variations between the different states of the residual nuclei are concerned, have been found to be in agreement with arguments based on the shell model and on the interpretation of the reactions as knock-out processes. The large cross section for the reaction $Si^{28}(\alpha,p_0)P^{31}$ would indicate, in this picture, a strong $(s_{\frac{1}{2}}{}^2)$ component for the last two protons in Si^{28}. On the other hand, the possibility cannot be excluded that this reaction proceeds by an alpha stripping mechanism.

Expansions of these studies in several directions suggest themselves: (a) polarization measurements to distinguish between reaction mechanisms, especially for Si^{28}, (b) measurement of the (α,p) reactions with the remaining abundant members of the $d_{\frac{5}{2}}$ shell, Ne^{20} and Mg^{24}, (c) repetition of the measurements for several alpha-particle energies, as has been done for the $C^{12}(\alpha,p)N^{15}$ reaction,[1,16] in order to ascertain that the trends observed are not accidental and particular to the energies employed, (d) interpretation of the results in terms of the collective properties of the nuclei involved.

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