# Inelastic Scattering of 12-Mev Protons on Lithium, Carbon, Magnesium, and Silicon*

HOMER E. CONZETT
*Radiation Laboratory, University of California, Berkeley, California*
(Received September 14, 1956)

The angular distributions of protons from the reactions $Li^7(p,p')Li^{7*}$ ($Q=-4.61$ Mev), $C^{12}(p,p')C^{12*}$ ($Q=-4.43$ Mev), $Mg^{24}(p,p')Mg^{24*}$ ($Q=-1.36$ Mev), and $Si^{28}(p,p')Si^{28*}$ ($Q=-1.78$ Mev) have been measured, and the cross sections for the reactions have been obtained.

The lithium distribution has been analyzed in terms of (a) inelastic scattering proceeding through formation and decay of the compound nucleus, and (b) direct inelastic scattering of the Austern, Butler, McManus theory. An assignment of $J=5/2^-$ to the 4.61-Mev level of $Li^7$ is consistent with all the experimental evidence to date; however, the intermediate coupling shell model prediction of $7/2^-$ should not be ruled out completely. The carbon, magnesium, and silicon distributions indicate that the statistical theory of the compound nucleus does not apply and, also, that the direct-interaction type of scattering is negligible. It appears that the reactions involving these nuclei proceed through only a few or several levels of the intermediate nuclei.

For each reaction, the cross section has been compared with estimates of the cross sections for formation of the compound nucleus. The results are in qualitative agreement with the theory of decay of the compound nucleus through competing channels.

## I. INTRODUCTION

THE technique of inelastic scattering has been employed extensively and has been a valuable method for the determination of nuclear energy levels, because the scattering nucleus is excited at the expense of the kinetic energy of the incoming particle. Angular distributions of these inelastically scattered particles can be expected to give more detailed information concerning the nature of the process because these distributions must reflect the additional requirements of conservation of angular momentum and parity.

At present there are two types of theory that attempt to explain and predict angular distributions of nuclear reaction products, including inelastically scattered particles. The first is based on the Bohr assumption[1] of the formation and subsequent decay of a compound nucleus; a partial-wave analysis[2] of which yields the theoretical angular distributions. If the reaction proceeds through a single level of the compound nucleus, the distribution is symmetric about the center-of-mass scattering angle $\theta=90°$. If more than one level is important in the reaction, the distribution can become more complex because interference terms between outgoing waves of different parity are present in the expression for the differential cross sections. Finally, if the reaction proceeds through the continuum region of the compound nucleus, the region of excitation where the level width exceeds the level spacing, and many levels are involved, the theory[3] takes a statistical average over them and assumes that the interference terms between outgoing waves of different parity cancel out; this again results in an angular distribution that is symmetric about $\theta=90°$.

The second type of theory considers the mechanism of inelastic proton scattering to be either a direct interaction[4] between the incident proton and a nucleon in the surface region of the target nucleus, or excitation[5] of the nuclear rotational states of the Bohr-Mottelson[6] model, which assumes that the interaction takes place at the surface. Both treatments result in angular distributions of the scattered protons of the form

$$d\sigma/d\Omega\sim\sum_l[C_lj_l(qa)]^2,$$

where $l\hbar$ is the orbital angular momentum transferred to the nucleus in the collision,

$$q=|\mathbf{k}_i-\mathbf{k}_f|$$

is the momentum change of the scattered proton, $a$ is the nuclear radius, and $j_l(qa)$ is the regular spherical Bessel function of order $l$. Selection rules that apply are

$$|\mathbf{J}_i+\mathbf{J}_f|\equiv\Delta J=l,\ l\pm1 \quad\text{and}\quad \pi_i\pi_f=(-1)^l$$

for the spins and parities of the initial and final states of the target nucleus.

Angular distributions of protons scattered inelastically from $Mg^{24}$, exciting the nucleus to 1.368 Mev, have been measured at proton energies of 4.7, 7.3, 9.6, 10, and 18 Mev.[7-11] With the exception of the 9.6-Mev data, they are all asymmetric about $\theta=90°$, and Fischer's analysis of his 10-Mev results is based on a combination of distributions given by the statistical theory of the compound nucleus and by the direct interaction theory. Similar experiments have been done

* This work was done under the auspices of the U. S. Atomic Energy Commission.

[1] N. Bohr, Nature **137**, 344 (1936).
[2] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).
[3] L. Wolfenstein, Phys. Rev. **82**, 690 (1951).
[4] Austern, Butler, and McManus, Phys. Rev. **92**, 350 (1953); G. R. Satchler, Proc. Phys. Soc. (London) **A68**, 1037 (1955).
[5] S. Hayakawa and S. Yoshida, Proc. Phys. Soc. (London) **A68**, 656 (1955); Progr. Theoret. Phys. (Japan) **14**, 1 (1955).
[6] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab. Mat.-fys. Medd. **29**, No. 16 (1953).
[7] E. H. Rhoderick, Proc. Roy. Soc. (London) **201**, 348 (1950).
[8] H. E. Gove and H. F. Stoddart, Phys. Rev. **86**, 572 (1952).
[9] Baker, Dodd, and Simmons, Phys. Rev. **85**, 1051 (1952).
[10] G. E. Fischer, Phys. Rev. **96**, 704 (1954).
[11] P. C. Gugelot and P. R. Phillips, Phys. Rev. **101**, 1614 (1956).

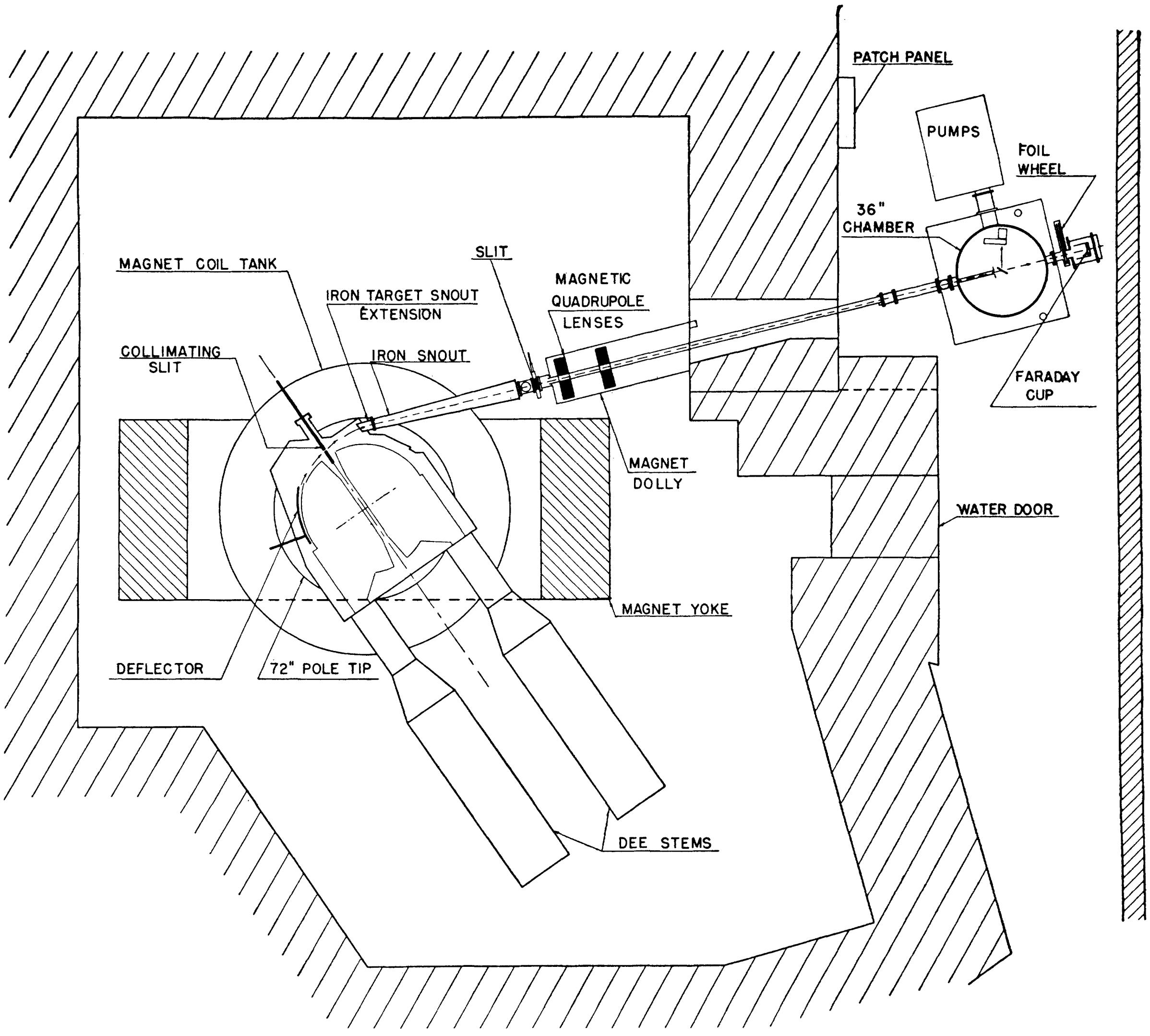


FIG. 1. Diagram of the experimental arrangement.

on the 4.43-Mev level of $C^{12}$ at 7.3 Mev,[8] 9.5 Mev,[12] 10 Mev,[10] 14–19 Mev,[13] and 31 Mev.[14] The shape of the distribution changes little in going from 7.3 to 19 Mev, but that at 31 Mev is peaked strongly at forward angles, thereby showing the predominance of a direct-interaction type of scattering. Similarly, results on the 822-kev level of $Fe^{56}$ at 17 Mev[15] and on several levels of $Be^9$ at 31 Mev[16] are peaked near the forward direction.

The experiments described here were undertaken to extend the measurements on $C^{12}$ and $Mg^{24}$ to the energy region of 12-Mev protons and to investigate in the same manner the inelastic scattering from levels in $Li^7$ and $Si^{28}$.

## II. EXPERIMENTAL METHOD

### A. General Procedure

The general experimental details concerning the scattering chamber, the counter telescope, and the beam-monitoring and energy-measuring methods have been given by Ellis and Schecter.[17] A diagram of the experimental arrangement is shown in Fig. 1. The external 12-Mev proton beam of the Crocker Laboratory 60-inch cyclotron was directed at a thin target located at the center of an evacuated scattering chamber. After passing through the target, the beam was collected in a Faraday cup located behind the chamber. Protons scattered from the target were detected by a

[12] Burcham, Gibson, and Rotblat, Phys. Rev. **92**, 1266 (1955).
[13] Brookhaven National Laboratory Report BNL-331, January, 1955 (unpublished), p. 86; R. W. Peele, Phys. Rev. (to be published).
[14] G. J. Hecht, University of California Radiation Laboratory Report UCRL-2969, April, 1955 (unpublished).
[15] Schrank, Gugelot, and Dayton, Phys. Rev. **96**, 1156 (1954).
[16] Benveniste, Finke, and Martinelli, Phys. Rev. **101**, 655 (1956).
[17] R. E. Ellis and L. Schecter, Phys. Rev. **101**, 636 (1956).

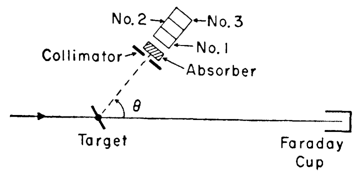


Fig. 2. Schematic diagram of the counter arrangement.

telescope of three proportional counters contained within a single vacuum-tight unit. A remotely controlled absorber changer, permitting insertion of variable amounts of aluminum absorber, was located between the telescope and an aperture defining the solid angle for scattering. A schematic diagram of this detector arrangements is shown in Fig. 2. Protons of the particular energy under investigation were required to pass through an appropriate amount of absorber and to stop in the range foil separating the second and third counters. Thus, per unit of charge collected in the Faraday cup, the protons with a range between $R$ and $R+\Delta R$ were counted. A plot of these counts *versus* range gave the differential range curve of the proton group. Since the area under such a curve is proportional to the number of protons that stopped in the range spanned by the curve, measurement of these areas as a function of scattering angle yielded the relative differential cross sections. Determinations of target thickness, the solid angle for scattering, and the $\Delta R$ of the detector provided the information necessary for the calculation of the absolute differential cross sections.

At least one complete range spectrum was run for each target so that the various particle groups could be noted and identified. Figure 3 shows the spectrum of protons scattered from the polystyrene target at a scattering angle of 50°. Differential range spectra including just the proton group of interest were then taken over the entire range of scattering angles available. In Fig. 3, this was the group corresponding to the excitation of $C^{12}$ to its 4.43-Mev level. Smooth curves were drawn through the experimental points, and the areas under the curves were calculated by use of Simpson's one-third rule. Typical range curves of the other proton groups measured are shown in Fig. 4. The calculated cross sections were then converted to the center-of-mass system, and these data comprise the final experimental results.

## B. Targets

In order to minimize contamination the lithium target was prepared in an argon-filled dry box and transferred in an argon atmosphere to the scattering chamber. Since the target could not be handled for weighing, its thickness (in mg/cm$^2$) was determined indirectly. The beam's mean range in aluminum was determined with the target in the beam and with the target removed. The difference in range gave the thickness of the target in aluminum equivalent. This was converted to mg/cm$^2$ of lithium, using the range-energy data of Aron, Hoffman, and Williams.[18] It is believed that this determination of the target thickness was accurate to 5%.

A 2-mil polystyrene $(CH)_n$ foil was used for the carbon target; the magnesium target was a 0.7-mil foil of normal isotopic material.

Silicon targets were made by employing the vacuum evaporation technique. Silicon monoxide was heated by radiation from tungsten filaments at approximately 2000°C. The evaporated monoxide was deposited on an acetate film, backed by a thin sheet of Electromesh, a fine nickel-plated copper screen mesh, lapped smooth to receive the deposit. The acetate film had been formed by spreading a few drops of a solution of DuPont cement dissolved in amyl acetate on a water surface. After the silicon monoxide was deposited to the desired thickness, a target frame was cemented to the monoxide surface. The backing was then removed by dissolving away the acetate film in a bath of acetone.

## C. Errors

The error in the area $A$ under a differential range peak, had two contributing sources. One was the error in the estimate of the background subtraction. A smooth curve, usually a straight line, was drawn through the minima or the extended background level on both sides of the peak, thus defining the background level under the peak. The possible error in the definition of this level was estimated, and the related error in $A$ was calculated. The other source was the statistical counting errors on the points through which the peak itself was drawn. The relative error in the area was calculated by applying the law of propagation of errors to Simpson's formula.

With the exception of lithium, the target thickness was determined from measurements of the area and the weight of a target section through which the beam

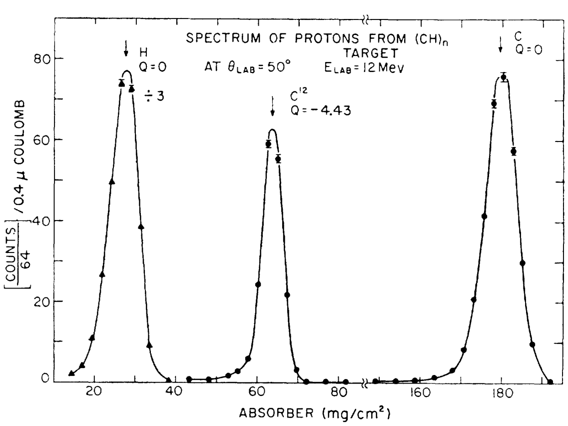


Fig. 3. Differential range spectrum of protons from CH target at $\theta_{\rm lab}=50°$.

[18] Aron, Hoffman, and Williams, Atomic Energy Commission Report AECU-633, 1949 (unpublished).

had passed. (The indirect method of measuring the lithium target thickness has been described above.) The estimated errors in these determinations were 5% for lithium, 0.5% for carbon, 2.0% for magnesium, and 2.5% for silicon. These errors were combined with the estimated errors of 0.75% in beam current integration, 1% in measurement of the detector solid angle, and 1% in the determination of the detector range bite. Errors in the other parameters were negligible.

## III. RESULTS AND CONCLUSIONS

### A. General Considerations

Figures 6 through 9 contain the experimentally determined differential cross sections for the inelastic scattering of 12-Mev protons to the 4.61-Mev level of $Li^7$, the 4.43-Mev level of $C^{12}$, the 1.368-Mev level of $Mg^{24}$, and the 1.78-Mev level of $Si^{28}$. Because the analysis of the results is concerned especially with the shape of the angular distribution, the relative errors alone are indicated on all plots of differential cross section *versus* center-of-mass scattering angle. This procedure serves to define more clearly the shape of the distribution.

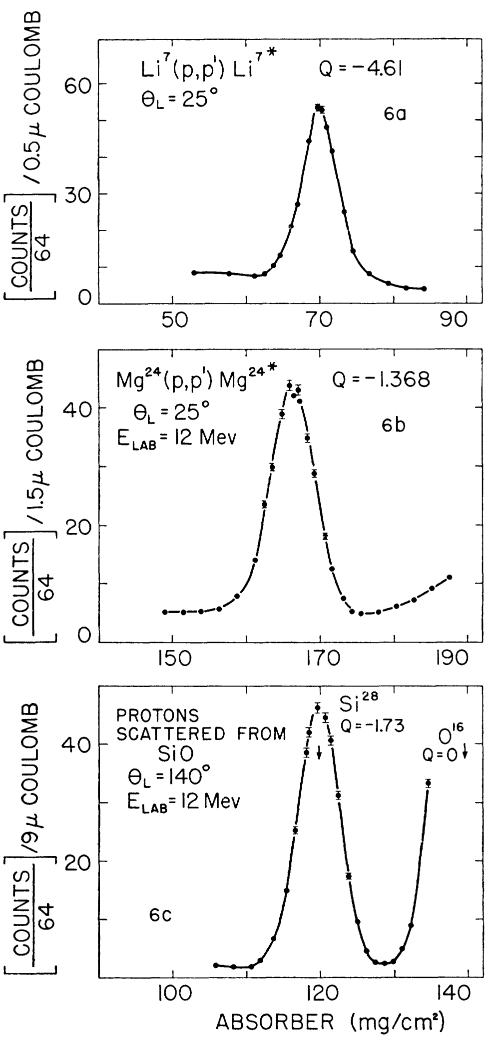


FIG. 4. Examples of the proton groups whose angular distributions were obtained.

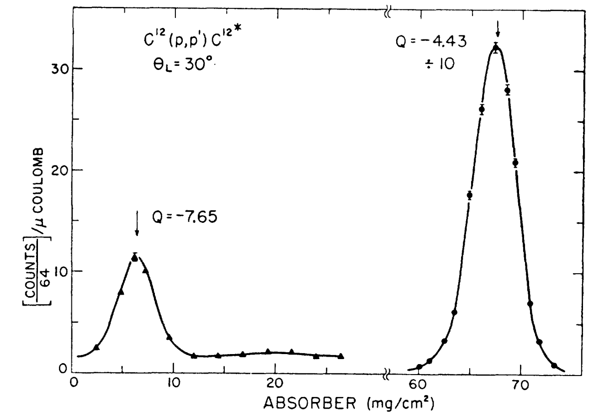


FIG. 5. Section of differential range spectrum of protons from CH target at $\theta_{lab} = 30°$.

At a laboratory angle of 30°, a differential range spectrum was taken which included the proton group corresponding to the excitation of the 7.65-Mev level of $C^{12}$. This spectrum is shown in Fig. 5. Hecht[14] had been unable to detect this group in the bombardment of carbon with 31-Mev protons. From the areas under the two peaks in Fig. 5, one obtains directly the relative values of the differential cross sections for inelastic scattering to the two corresponding levels of carbon. Thus, at the laboratory angle of 30° the cross section for scattering to the 4.43-Mev level is 35 to 40 times as large as that for scattering to the 7.65-Mev level. No attempt was made to obtain the angular distribution of the smaller proton group because its mean range was below the range threshold of the detector at scattering angles exceeding 50°. Vaughn[19] has measured the angular distributions of 48-Mev alpha particles scattered inelastically from carbon, and his results are similar with respect to the ratio of the cross sections for the scattering to the two levels.

As a check on the reliability of the experimental technique, the differential *p-p* cross section was measured at $\theta_L = 50°$ (Fig. 3.) The value obtained was 44.8 ±1.3 mb/sterad at 100° in the center-of-mass system, which compares well with the value of 42.5±2.5 mb/sterad interpolated from the data at 8, 10, and 14.5 Mev.[20]

The angular distributions have been analyzed in terms of the distributions given by the theory of the formation and decay of an intermediate (compound) nucleus and by the direct interaction theory. This analysis, in terms of simple addition of the contributions

[19] F. J. Vaughn, University of California Radiation Laboratory Report UCRL-3174, October, 1955 (unpublished).

[20] Wilson, Lofgren, Richardson, Wright, and Shankland, Phys. Rev. 72, 1131 (1947).

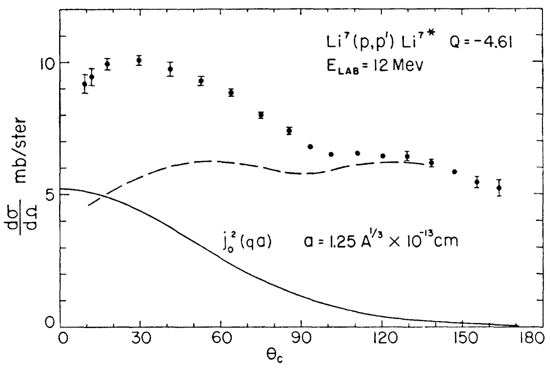


FIG. 6. Angular distribution of protons from the reaction $Li^7(p,p')Li^{7*}$, $Q=-4.61$ Mev.

from the two distinct mechanisms of inelastic scattering, is justified by the incoherent natures of the processes.

For each of the targets bombarded, the cross section for formation of the compound nucleus has been calculated by use of the asymptotic formula

$$\sigma_c \simeq \pi(a+\lambda\!\!\!^{-})^2[1-V/E],$$

where

$$a=1.4\times A^{\frac{1}{3}}\times 10^{-13}\text{ cm},\quad V=Ze^2/(a+\lambda\!\!\!^{-}),$$

and $E$ is the kinetic energy in the center-of-mass system. This expression reproduces the more exactly calculated values within 15% for $E/V>1.2$.[2] These cross sections can be compared with the measured inelastic proton cross sections to give an estimate of the fraction of the reaction cross section contributed by this one decay mode. This expression for $\sigma_c$ cannot be used, of course, where there is no overlapping of levels in the region of excitation of the compound nucleus.

### B. Lithium

The angular distribution of protons corresponding to the excitation of the 4.61-Mev level of $Li^7$ is shown in Fig. 6. The excitation energy of the intermediate nucleus, $Be^8$, was 27.69 Mev, with an energy spread of about 260 kev. The statistical condition is assumed to be satisfied at this high excitation, yielding a contribution symmetric about $\theta=90°$ to the distribution. Because the experimental distribution shows a broad peak near the forward angles, $j_0^2(qa)$ proved to be the function that represented the contribution to the distribution from the direct interaction mechanism. In fitting the data, $j_0^2$ was calculated over a range of values of $a$, the nuclear radius. Each calculated $j_0^2$ was subtracted from the experimental distribution and the $j_0^2$ was selected that give a resulting curve (dashed in Fig. 6) symmetric about 90°. The best fit to the data was obtained with $a=1.25A^{\frac{1}{3}}\times 10^{-13}$ cm, but values of $a$ in the interval from $1.20A^{\frac{1}{3}}\times 10^{-13}$ cm to $1.35A^{\frac{1}{3}}\times 10^{-13}$ cm gave satisfactory agreement within the experimental errors assigned to the data.

The selection rules given by the direct-interaction theory can now be applied to give information about the 4.61-Mev level of $Li^7$. The value $l=0$ has been determined from the order of the Bessel function that fits the data, therefore we have $\Delta J=0$, $\pm 1$ with no parity change. The ground state of $Li^7$ is a $(3/2,-)$ state[21]; thus, application of the selection rules above yields an assignment of $J=1/2$, $3/2$, or $5/2$ and odd parity to the 4.61-Mev level of $Li^7$.

Erdös *et al.*[22] have obtained angular distributions of tritons from the $Li^7(\gamma,t)He^4$ reaction by exposing lithium-loaded emulsions to the radiation from a 31-Mev betatron. Their analysis of the distribution of the triton group corresponding to $E_\gamma \simeq 4.7$ Mev leads to an assignment of $J=5/2^-$ to the 4.61-Mev state of $Li^7$, with $J=3/2^-$ possible but unlikely.

Levine, Bender, and McGruer[23] have recently obtained an angular distribution of 14.5-Mev deuterons scattered from this level in $Li^7$. The differential cross section increases with center-of-mass angle in the interval from 17° to 90°, the extent of the distribution. The distribution is not in accord with the prediction of the theory of Huby and Newns,[24] which similarly describes inelastic deuteron scattering in terms of a direct interaction of one member of the deuteron pair at the nuclear surface. Their selection rules are identical with those for inelastic proton scattering given above, but Summers-Gill[25] has pointed out that spin flip of the colliding nucleon of the deuteron pair is not to be expected, because it would cause the deuteron to break up and be lost from the $(d,d')$ reaction. This restriction results in $\Delta J=l$, $\pi_i\pi_f=(-1)^l$; hence $J_f=5/2^-$ state could not be reached from the $J_i=3/2^-$ ground state in an $l=0$ transfer by the direct-interaction mechanism. The requirement that $l\geq 2$ (true also for $J_f=7/2^-$) would suppress the direct-interaction contribution to the reaction. Thus it is seen that the experimental evidence on this state is consistent with an assignment of $J_f=5/2^-$; this is not in agreement with the $J=7/2^-$ prediction of the shell model intermediate-coupling interpretation.[26] However, $J=7/2^-$ should not be completely ruled out, because it is quite possible to fit the data of Fig. 6 with the expression

$$\frac{d\sigma}{d\Omega}=\sum_{n=0}^{4} A_n \cos^n\theta,$$

corresponding to $s$, $p$, and $d$ waves contributing to the reaction. Thus the entire cross section could be accounted for by compound-nucleus formation, and $J_f=7/2^-$ would be allowed. The triton angular dis-

[21] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

[22] Erdös, Stoll, Wächter, and Wataghin, Nuovo cimento **12**, 639 (1954).

[23] Levine, Bender, and McGruer, Phys. Rev. **97**, 1249 (1955).

[24] R. Huby and C. H. Newns, Phil. Mag. **42**, 1442 (1951).

[25] R. G. Summers-Gill, University of California Radiation Laboratory Report UCRL-3388, April, 1956, (unpublished).

[26] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953); D. Kurath, Phys. Rev. **101**, 216 (1956).

tributions from Erdös *et al.* are somewhat sketchy and suffer from poor statistics, hence a positive assignment of spin and parity to this level awaits more definite experimental evidence. Inelastic scattering of 48-Mev alpha particles and 24-Mev deuterons presently under way at this laboratory is expected to help in making the assignment.

Schulten[27] has made calculations using wave functions composed of mixtures of single-particle functions with spin-orbit coupling, and his results lead to states of $Li^7$ at 4.02, 4.48, and 5.16 Mev with $J=5/2$, $3/2$, and $5/2$, respectively. As yet, there has been no experimental evidence supporting this level scheme.

The measured inelastic proton-scattering cross section is $\sigma_i=95.1\pm5.6$ mb, 80% of which is contributed by the component symmetric about $\theta=90°$. The result,

$$\sigma_i(\text{sym})/\sigma_c=0.16,$$

indicates the strong competition provided by other modes of decay of the intermediate nucleus, of which the principal ones are neutron or proton emission leading to the formation of one of the several available states of $Be^7$ or $Li^7$.

### C. Carbon

The angular distribution of protons corresponding to the excitation of the 4.43-Mev level of $C^{12}$ is shown in Fig. 7. Fischer's data at 10 Mev[10] are plotted for comparison. Qualitatively, the shapes of the distributions are similar, each exhibiting peaks at forward and backward angles with the minimum near 95°. Also, the forward peak is the larger, thus the distribution is not symmetric about 90°. In addition to the increase in the cross section at 12 Mev, the forward peak has shifted approximately from 35° to 10° and the backward peak from 140° to 165° with the change in energy. At proton energies of 7.3 Mev,[8] 9.5 Mev,[12] and through the range from 14 Mev to 19.5 Mev[13] the distribution maintains the same general shape and indicates that the direct-interaction mechanism plays no important role. At 31 Mev[14] the distribution has changed markedly, becoming strongly peaked near the forward direction.

The ground state of $C^{12}$ is a $(0,+)$ and the 4.43-Mev level is a $(2,+)$ state.[21] Thus, we have $\Delta J=2$ with no parity change, therefore, any contribution to the angular distribution from direct-interaction-type scattering would be given by $j_2^2(qa)$. This function is not peaked in the forward direction, and it proved impossible to fit the data of Fig. 9 with a $j_2^2$ in combination with a curve symmetric about 90°.

The excitation of the intermediate nucleus, $N^{13}$, was 12.82 Mev. There is little or no information available on the level structure of $N^{13}$ at this excitation, but it can be inferred from the level scheme[21] of its mirror nucleus, $C^{13}$. It is apparent that no more than two or three levels take part in the reaction. so the statistical condition of many states' being excited is not satisfied. The situation probably is more nearly that one resonance in $N^{13}$ is responsible for the major part of the cross section, $\sigma_i=246.0\pm6.0$ mb, with small additions coming from the wings of the neighboring resonances. This could explain both the near symmetry of the angular distribution and the fact that this near symmetry is maintained over such a large energy interval. The shifting of the peaks toward $\theta=0°$ and $\theta=180°$ with the increase in energy shows that the partial waves of higher orbital angular momentum are contributing more strongly to the reaction, as is possible at the higher energy. Further support to this picture is given by the large increase in the total cross section between 10 and 12 Mev. The ratio $\sigma_i(12\text{ Mev})/\sigma_i(10\text{ Mev})$ is about 1.6, and if a sufficient number of levels of $N^{13}$ participated in the reaction one could use the expression

$$\sigma_i=\sigma_c T_i/\sum T,$$

where $T_i$ is the barrier transmission coefficient for proton emission to the 4.43-Mev state and the sum is taken over the transmission coefficients of all possible decay channels. Since the threshold for the $(p,n)$ reaction is 18.5 Mev, the only important modes of decay are proton emission to the available states of $C^{12}$. Using tables of Coulomb functions,[28] we calculated the coefficients for emission to the 0, 4.43, and 9.61-Mev levels at 12- and 10-Mev incident proton energy, taking $1.4A^{1/3}\times10^{-13}$ cm for the nuclear radius. In view of our experimental evidence, emission to the 7.65-Mev level was taken to be 3% of that to the 4.43-Mev level. With $\sigma_c(12)\simeq\sigma_c(10)$, the calculated ratio

$$\sigma_i(12)/\sigma_i(10)\simeq(T_i/\sum T)_{12}(\sum T/T_i)_{10}=1.14$$

shows that the energy dependence of the cross section cannot be explained in terms of barrier penetrability alone. A more nearly resonant excitation of $N^{13}$ with the 12-Mev protons is the more plausible explanation for the larger cross section.

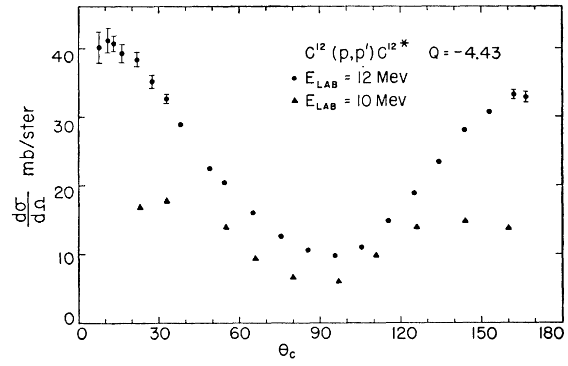


FIG. 7. Angular distribution of protons from the reaction $C^{12}(p,p')C^{12*}$, $Q=-4.43$ Mev.

[27] R. Schulten, Z. Naturforsch. 8a, 759 (1953).

[28] Bloch, Hull, Broyles, Bouricius, Freeman, and Breit, Revs. Modern Phys. 23, 147 (1951).

The ratio

$$\sigma_i/\sigma_c = T_i/\sum T = 0.36$$

calculated from the transmission coefficients is to be compared with that obtained from the inelastic cross sections measured on the other elements, and it is noted that this ratio qualitatively reflects the effect of the different number of competing modes of decay of the compound nucleus in each of the four cases.

### D. Magnesium

The angular distribution of protons leading to the excitation of the 1.368-Mev level of $Mg^{24}$ is shown in Fig. 8. Curves of the 10- and 18-Mev data are plotted for comparison. The ground state of $Mg^{24}$ is a $(0,+)$ state and the 1.368-Mev level is a $(2,+)$ state.[21] Thus, as for $C^{12}$, an appropriate fit to the data would be a combination of $j_2^2$ and a curve symmetric about 90°. The increase in the cross section forward of 40° ruled out this possibility.

Unlike the carbon distribution, the shape of the magnesium distribution apparently changes quite significantly with variation of the incident proton energy in the range from 4.7 to 18 Mev.[7–11] This variation is readily explained by assuming that several levels of the intermediate nucleus are excited, but not so many as to satisfy the statistical condition. Then the outgoing waves of different parity can interfere, giving asymmetric distributions. With the change in energy of the incident beam a different group of levels would be excited, the interference terms would have changed, and a completely dissimilar distribution could result. The formula

$$\omega(E) = 0.43 \exp[2(0.45E)^{\frac{1}{2}}]/\text{Mev}$$

agrees fairly well with the experimentally determined average level densities for $Al^{27}$ at 9.0-Mev excitation, and therefore it is used to estimate the average level density for $Al^{25}$ at 13.68 Mev, the excitation of our intermediate nucleus. The result is $\omega \simeq 60$ levels per Mev, so that with an energy spread of 160 kev we estimate that approximately ten levels of the intermediate nucleus would be excited on the average. This hardly qualifies as "many" in the sense of the statistical assumption, and the region of excitation is certainly not the continuum where the level width exceeds the level spacing. Therefore, the statistical assumption probably should not be made. The strong forward peak in the 12- and 18-Mev data suggests a contribution from a direct-interaction type of scattering even though the surface interaction theories do not provide a fit. Gugelot and Phillips[11] suggest it may be necessary to consider the effect of the internal structure of the nucleus. Hayakawa *et al.*[29] have approached this in their calculations of angular distributions of protons knocked out of a Fermi gas model of the $Fe^{56}$ nucleus by a single nucleon-nucleon collision; their results are peaked in the forward direction.

The measured inelastic cross section was $\sigma_i = 232.2 \pm 7.4$ mb and $\sigma_i/\sigma_c \simeq 0.35$. The threshold for the $(p,n)$ reaction is 14.6 Mev, so the competing processes are essentially only those of proton emission from $Al^{25*}$ to the ground state and the several other available excited states of $Mg^{24}$. These are more numerous than with $C^{12}$ as the target nucleus, but the barrier transmission coefficient for proton emission to the 1.368-Mev state of $Mg^{24}$ is larger, relatively, than that for the proton emission to the 4.43-Mev state of $C^{12}$, and thus offsets the competition furnished by the more numerous decay channels.

The ratios $\sigma_i(18\text{ Mev}):\sigma_i(12\text{ Mev}):\sigma_i(10\text{ Mev}) = 0.65:1.1:1$ were calculated by integrating over the range of angles covered by the 10-Mev data, thus the forward peak was not included at 12 and 18 Mev. The marked decrease in the cross section at 18 Mev results from the competition afforded by the energetically possible neutron emission from the compound nucleus.

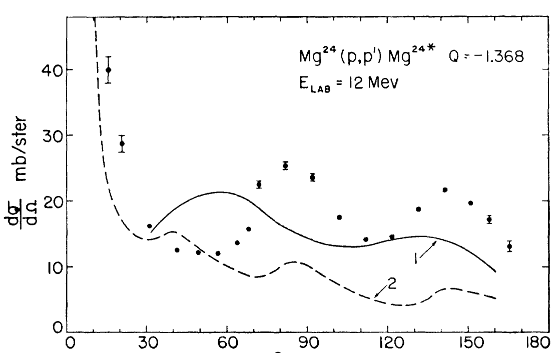


FIG. 8. Angular distribution of protons from the reaction $Mg^{24}(p,p')Mg^{24*}$, $Q = -1.368$ Mev. Curve 1: 10-Mev results from reference 10. Curve 2: 18-Mev results from reference 11.

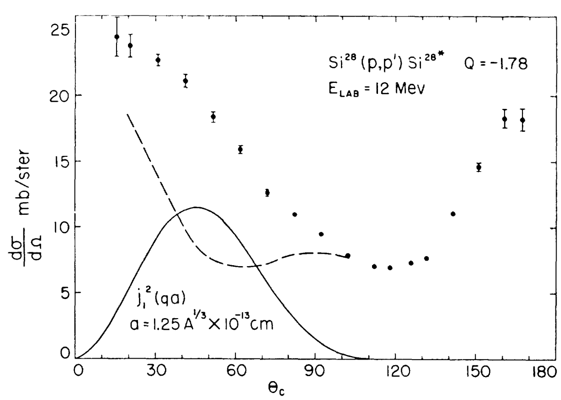


FIG. 9. Angular distribution of protons from the reaction $Si^{28}(p,p')Si^{28*}$, $Q = -1.78$ Mev.

[29] Hayakawa, Kawai, and Kikuchi, Progr. Theoret. Phys. (Japan) **13**, 415 (1955).

### E. Silicon

The angular distribution of protons corresponding to the excitation of the 1.78-Mev level of $Si^{28}$ is shown in Fig. 9. A satisfactory fit to the data was made with the combination of a contribution symmetric about 90° and a $j_1^2(qa)$ for a value of $a=1.25A^{\frac{1}{3}}\times10^{-13}$ cm. The analysis was very sensitive to variations in $a$ because slight shifts in the position of the $j_1^2$ peak destroyed the symmetry of the dashed curve. For example, values of $a=1.20A^{\frac{1}{3}}\times10^{-13}$ cm and $1.30A^{\frac{1}{3}}\times10^{-13}$ cm gave appreciably poorer results in fitting the data.

The ground state of $Si^{38}$ is a $(0,+)$ state and the 1.78-Mev level is a $(2,+)$ state.[21] Thus, we have $\Delta J=2$ with no parity change between the two states. As before, the selection rules require the order of the Bessel function (describing the direct-interaction distribution) to be $l=2$. It was not possible to fit the data with a $j_2^2$ function because its peak is too narrow when $a$ is chosen so that the peak falls near 45° as is required. The value $l=1$ satisfies the selection rule on angular momentum, but this odd value of $l$ is ruled out by the selection rule on parity.

At the 14.14-Mev excitation of the intermediate nucleus, $P^{29}$, with an energy spread of 300 kev, it is estimated that approximately 20 levels would be excited. The fact that the silicon distribution is somewhat closer to symmetry about 90° suggests an approach toward the condition required by the statistical assumption.

The integrated inelastic cross section was $\sigma_i=164.8 \pm 4.4$ mb and $\sigma_i/\sigma_c \simeq 0.25$. Since the threshold for the $(p,n)$ reaction is 14.9 Mev, there is again no neutron emission from the $P^{25*}$ nucleus competing with the proton emission to the ground state and the available excited states of $Si^{28}$.

### F. Conclusions

The observed angular distribution of protons scattered inelastically from $Li^7$, leading to the formation of the 4.61-Mev state, can be explained by a combination of the statistical theory of the compound nucleus and of the Austern, Butler, and McManus theory. Distributions of protons scattering to levels in $C^{12}$, $Mg^{24}$, and $Si^{28}$ are not explained by either or both of the theories. It is thought that the statistical theory is not applicable because the required condition that the reaction proceed via the continuum region of the intermediate nucleus is not fulfilled. Since $C^{12}$, $Mg^{24}$, and $Si^{28}$ are tightly bound even-even nuclei, it follows that the direct-interaction mechanism could be almost completely suppressed and the incident proton be captured by the target nucleus whenever it reached the nuclear surface. It is suggested that the reactions involving these nuclei proceed by way of only a few levels of the intermediate nucleus.

It is reasonable that the direct-interaction type of theory could be applied more successfully to the inelastic scattering of deuterons and alpha particles. Competition from formation and subsequent decay of an intermediate nucleus would be slight, because once a deuteron or alpha particle had been captured by the target nucleus there would be little probability of its reemission. The experimental results of inelastic alpha-particle scattering from lithium, carbon, and magnesium,[19,30] inelastic deuteron scattering from carbon,[31] and inelastic alpha-particle and deuteron scattering from beryllium[25] confirm this belief.


#### ACKNOWLEDGMENTS

It is a distinct pleasure to thank Professor A. C. Helmholz for his guidance, and interest in all phases of the work; Dr. Robert E. Ellis, Dr. Frank J. Vaughn, and Dr. Robert G. Summers-Gill for their active participation in obtaining the data; the late G. Bernard Rossi, Mr. William B. Jones, and the members of the 60-in. cyclotron crew for providing excellent cyclotron operation; Mr. Daniel J. O'Connell for preparing the SiO target; and Mr. Fred E. Vogelsberg for his maintenance of the electronic equipment.


[30] H. J. Watters, Phys. Rev. **103**, 1763 (1956).
[31] Freemantle, Gibson, and Rotblat, Phil. Mag. **45**, 1200 (1954).