$(p,p'\gamma)$ Angular Correlations at Low Energy*

H. J. HAUSMAN, G. F. DELL, AND H. F. BOWSHER
Department of Physics, The Ohio State University, Columbus, Ohio
(Received December 4, 1959)

At an incident proton bombarding energy of 6.5 Mev, angular correlations have been measured between protons scattered inelastically from various even-even nuclei and the decay gamma rays from the first excited states of these nuclei. Among the angular correlation experiments reported are $C^{12}(p,p'\gamma)$ 4.4 Mev, $Ne^{20}(p,p'\gamma)$ 1.63 Mev, $Si^{28}(p,p'\gamma)$ 1.78 Mev, and $S^{32}(p,p'\gamma)$ 2.25 Mev, which were done for proton detector angles of 60°, 90°, and 120°. The measured angular correlation functions are all of the form $A+B[\sin^2 2(\theta-\theta_0)]$, where θ_0 is the axis of symmetry. None of the symmetry directions agreed with predictions of the simple direct-reaction theories. However, the symmetry direction for the correlation functions changed with proton detector angle for the experiments on C^{12}, Ne^{20}, and S^{32}; for the experiment of Si^{28} the angular correlation functions were symmetric about 90°, independent of proton detector angle. The results of the angular correlation experiments appear to be consistent with a collective interaction involved in these direct-type reactions rather than a nucleon-nucleon type collision at the nuclear surface.

INTRODUCTION

A NUMBER of angular correlation experiments have been performed in this laboratory between the proton group leading to the first excited state of a bombarded target nucleus and the decay gamma ray from that state. The purpose of the experiments was to investigate the presence of direct reaction mechanisms at low-particle bombarding energies, and to ascertain, if possible, the nature of the direct-reaction mode. From the results of experiments conducted in this laboratory during 1958[1] and from the work reported by Seward,[2] it appeared that angular correlation experiments were a sensitive test for determining the presence of direct reactions at these energies. The angular correlation experiments reported here involved the first excited states of Li^7, C^{12}, Ne^{20}, Si^{28}, S^{32}, and Cr^{52}. The experiments have been examined in the light of the simple direct-reaction theories and comparisons made between theoretical predictions and experimental results.

Direct reactions have been defined[3] as those reaction processes whose calculation requires only the consideration of a small number of all the degrees of freedom of the nuclear system. This is in contrast to the compound nucleus description of nuclear reactions wherein many intermediate degrees of freedom are involved. There is now a considerable body of experimental evidence of nuclear reactions which cannot be explained within the framework of compound nucleus theory. Some of these experiments involve the inelastic scattering of n, p, d, and α particles from target nuclei.[4] The angular distributions often show diffraction-like oscillations of the type which have become well known for deuteron stripping. These distributions are usually characterized by a strong forward peak with subsequent peaks decreasing in amplitude with increasing scattering angle. Also, (p,pn), $(p,\alpha n)$, and $(p,2p)$ experiments performed by Cohen et al.[5,6] were in serious disagreement with predictions based on compound nucleus theories. The angular distributions of scattered protons in (n,p) reactions were found to have more high-energy protons than would be consistent with the Maxwellian spectrum predicted by statistical theories. Finally, the angular correlations between the inelastically scattered projectiles and gamma rays from the low-lying excited states of the bombarded targets have shown distributions inconsistent with compound nucleus theory.

For a surprising number of cases, simple direct-reaction theories have been able to explain qualitatively, and in many cases quantitatively, the experimental observations noted above. A large number of theoretical papers on the theory of direct reactions have appeared in the literature.[7] These simple theories assume in general plane waves for the incident and final unbound particles, and that the reaction proceeds through some single step interaction. Although direct reactions may take place throughout the volume of a nucleus as well as on the surface, the surface region reactions are those which are responsible for the striking diffraction-like angular distributions. In addition, the nuclear surface is subject to deformation of quadrupole shape.

Many of the angular distributions reported in the literature are ambiguous as to whether direct processes are occurring or not. In particular, at low-particle bombarding energies—the energy range of interest at this laboratory—there are rather wild fluctuations, as a

* Supported in part by the U. S. Atomic Energy Commission.
[1] H. A. Lackner, G. F. Dell, and H. J. Hausman, Phys. Rev. **114**, 560 (1959).
[2] F. T. Seward, Phys. Rev. **114**, 514 (1959).
[3] N. Austern, *Fast Neutron Physics* (Interscience Publishers, Inc., New York, 1959), Chap. V.
[4] As examples: R. M. Eisberg, Phys. Rev. **94**, 739 (1954); H. J. Watters, Phys. Rev. **103**, 1763 (1956); and P. G. Gugelot and M. Rickey, Phys. Rev. **101**, 1614 (1956).
[5] B. L. Cohen, E. Newman, R. A. Charpie, and T. H. Handley, Phys. Rev. **94**, 620 (1954).
[6] B. L. Cohen, Phys. Rev. **108**, 768 (1957).
[7] As examples: N. Austern, S. Butler, and H. McManus, Phys. Rev. **92**, 350 (1953); S. T. Butler, Phys. Rev. **106**, 272 (1957); S. Hayakawa and S. Yoshida, Progr. Theoret. Phys. (Kyoto) **14**, 1 (1957); J. S. Blair and E. M. Henley, Phys. Rev. **112**, 2029 (1958); D. M. Chase, L. Wilets, and A. R. Edmonds, Phys. Rev. **110**, 1080 (1958); S. T. Butler, N. Austern, and C. Pearson, Phys. Rev. **112**, 1227 (1958); and J. S. Blair, Phys. Rev. **115**, 928 (1959).

function of energy, in the angular distributions of inelastically scattered particles.[1,2] Sherr[8] and others have pointed out instances wherein angular distribution experiments were ambiguous but angular correlation measurements—$(p,p'\gamma)$, $(\alpha,p\gamma)$, and $(d,p\gamma)$—gave clear evidence for a simple direct process. In the simple theories, gamma rays should be correlated with the recoil vector $\mathbf{q}=\mathbf{k}_i-\mathbf{k}_f$, where $\mathbf{k}_i$ is the wave vector of the incident particle and $\mathbf{k}_f$ is the wave vector of the outgoing particle. The $\mathbf{q}$ vector is the momentum transferred to the target nucleus and should be the polar axis for the subsequent gamma-ray emission pattern. Only for a direct process will there be a well-marked correlation with $\mathbf{q}$. In the plane wave approximation, Satchler[9] has shown that the angular correlation function $W(\theta)$ should be of the form (for a $0+\rightarrow 2+\rightarrow 0+$ reaction)

$$W(\theta)\sim A\sin^2 2(\theta_\gamma-\theta_q), \tag{1}$$

where θ_q is the momentum transfer direction, and θ_γ is the gamma-ray detector angle. A more refined calculation, such as by Levinson and Banerjee,[10] where distortions of the projectile wave functions were taken into account, leads to a correlation function of the form

$$W(\theta)\sim A+B\sin^2 2(\theta_\gamma-\theta_0), \tag{2}$$

where θ_0, the axis of symmetry, does not always agree with θ_q.

A statistical theory compound process will not select this polar axis. The angular correlations apparently survive the complicating features which lead to ambiguities in the angular distributions. At low-particle bombarding energies, however, the projectile wave functions are considerably distorted at the nuclear surface and consequently the measured angular correlation function would be expected to deviate from that predicted in the plane wave approximation. In particular, one would not expect the polar axis, or axis of symmetry, for the angular correlation to agree in detail with the momentum transfer direction $\mathbf{q}$.

The angular correlation technique was used not only to detect the presence of direct reactions at low energies, but also to attempt to determine whether the direct reaction mode was via nucleon-nucleon single particle excitation or whether the excitation was via a collective interaction. The nature of the inelastic scattering process for rotational excitation of a deformed nucleus is different from that for single particle excitation. In the case of rotational excitation of a deformed nucleus, the physical process involves no excitation of the internal motions of the nucleus. The impinging particle sees the nucleus as an optical well of deformed shape; by virtue of the deformation it can exert a torque on the nucleus, setting the nucleus into rotation. Also, the physical picture is not consistent with the use of plane waves as projectile wave functions since the very potential which induces the inelastic transition is the one which distorts wave functions from plane waves.

The qualitative theoretical treatment of rotational excitation is simplified when one is limited to even-even nuclei. In this case, one examines inelastic transitions from the $J=0$ ground state to the low-lying excited rotational states, $J=2$, 4. The low-lying states of a nucleus having a stable deformation from spherical shape are viewed as states of rotation of this deformed body rather than as states of vibration of the amount of deformation. For heavy nuclei, such stable deformations are found well away from closed shells; for light nuclei, considerable deformations may exist even for nuclei quite close to closed shells. Should rotational excitation be responsible for direct excitation of the low-lying levels of light even-even nuclei, then one should see differences in the angular correlations from deformed nuclei and from spherically symmetric nuclei.

APPARATUS

The Ohio State University Cyclotron Scattering System, see Fig. 1, has been described in detail elsewhere.[11] The accelerated cyclotron beam is extracted electrostatically from the cyclotron vacuum system. The beam

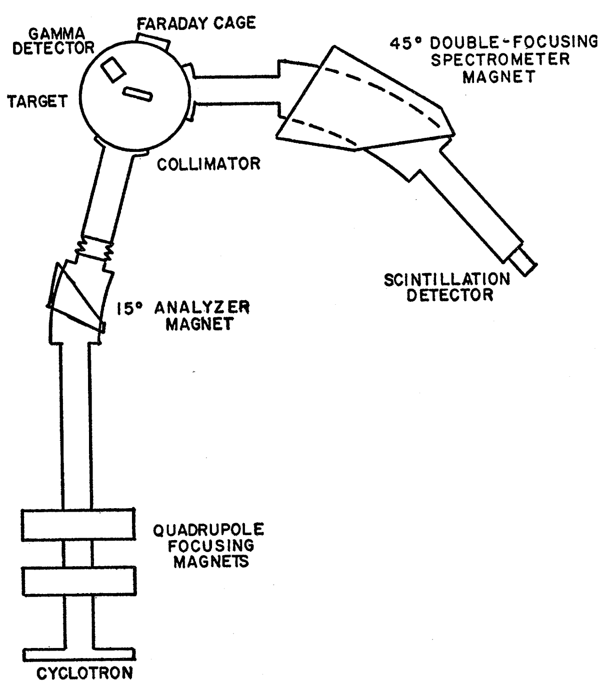

FIG. 1. Block diagram, not to scale, of The Ohio State University cyclotron scattering system.

[8] R. Sherr, *Proceedings of The University of Pittsburgh Conference on Nuclear Structure*, June, 1957, edited by S. Meshkov (University of Pittsburgh and Office of Ordnance Research, U. S. Army, 1957).

[9] G. R. Satchler, Proc. Phys. Soc. (London) **A68**, 1037 (1955).

[10] C. A. Levinson and M. K. Banerjee, Ann. Phys. **3**, 1037 (1955).

[11] H. J. Hausman, Scattering Studies with the Ohio State University Cyclotron, Atomic Energy Commission Reports Nos. 1, 1957, 2, 1958, and 3, 1959 (unpublished).

enters a 2 in. o.d. brass pipe and passes through the field of a pair of quadrupole focusing magnets. The beam then passes through the field of the 15° deflecting magnet and is focused at the center of the scattering chamber. The final beam collimator is a 0.025 in. aperture. The beam is finally collected in a Faraday cage. A large double-focusing magnet, which will rotate about the center of the scattering chamber, has recently been added to the system for high-resolution energy analysis of the charged particles emitted from the bombarded targets. The analyzing magnet has not been used in the experiments described in this report.

For the angular correlation experiments, there were two radiation detectors attached to the scattering chamber. The first was a thin CsI crystal attached to a Lucite light pipe which in turn was attached to an E. M. I. 9536B multiplier phototube; the second detector was a 1-in. diameter by 2-in. long NaI crystal attached via a Lucite light pipe to a second E. M. I. 9536B phototube. The CsI detector was used to detect the spectrum of charged particles emitted from the thin bombarded targets, while the NaI crystal was used to detect gamma rays emitted from the same targets. Changes in the charged particle detector angle were accomplished by changing the orientation of the Lucite light pipe attached to the photomultiplier. The gamma-ray detecting crystal was attached to a Lucite rod which passed vertically through a vacuum seal located in the rotating lid of the scattering chamber. A remotely controlled selsyn system was used to change the angular position of the gamma-ray detector.

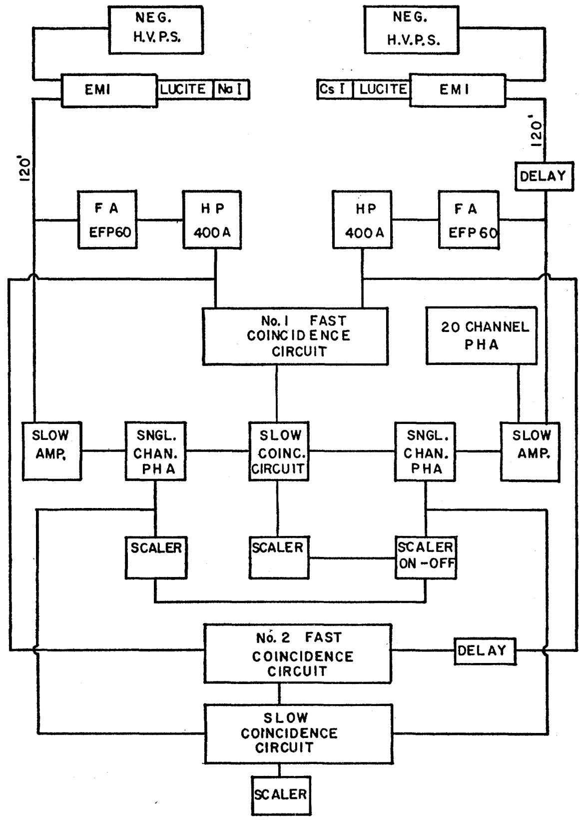

FIG. 2. Block diagram of the fast-slow coincidence circuit. The resolving time of each circuit is 30 milli-microseconds.

Accidental Fast-Slow Coincidence Circuit

The cyclotron beam is modulated at the frequency of 11.2 Mc/sec and particles are accelerated only during one-half cycle of the acceleration period. Consequently, the instantaneous beam current is very large compared to the time average beam current. Since the number of accidental coincidences recorded varies as the square of the source strength—or proportional to the square of the beam intensity—whereas the true coincidences recorded vary as the first power of the source strength, errors could result in determining the accidental counts from the time average beam. In order to eliminate this potential source of error a second fast-slow coincidence circuit was added to the detector system (see Fig. 2). Pulses from the output of the fast amplifiers were conducted to the inputs of the original and the new fast coincidence circuits (called No. 1 and No. 2). A delay equivalent to the time between cyclotron pulses was inserted in the signal line to one of the inputs of No. 2 circuit. The outputs of No. 1 and No. 2 fast coincidence circuits went to the inputs of two separate triple slow (approximately 1 microsecond) coincidence circuits. Proton and gamma-ray amplitude pulses fed the other two inputs of the two slow triple coincidence circuits.

Should a scattered proton of the correct energy be detected during one cyclotron accelerating pulse, the probability that a true coincidence occurs between that proton and its coincident gamma ray is the probability that the coincident gamma ray strikes the gamma-ray detector and is detected. This probability is proportional to the factor $\epsilon_\gamma\Omega_\gamma$ where ϵ_γ is the efficiency of the gamma-ray detector and Ω_γ is the solid angle of the gamma-ray detector. The probability that an accidental coincidence occurs is the probability that any gamma ray strikes the gamma-ray detector during the same accelerating pulse. This probability depends on the gamma-ray detector singles rate. Consequently, the accidental coincidence rate could be determined by measuring the coincidences between protons detected in one cyclotron accelerating pulse and the gamma rays detected in an adjacent cyclotron pulse. Coincidence circuit No. 1 was arranged to measure all coincidences between protons and gamma rays, of the correct energies, occurring during the same cyclotron accelerating pulse, while coincidence circuit No. 2 measured coincidences between protons in one cyclotron pulse and gamma rays in an adjacent cyclotron pulse. Circuit No. 1 then measured the sum of true plus accidental coincidences occurring during a run while the circuit No. 2 measured only the accidental coincidences during the same run.

The efficiencies and resolving times of the two coin-

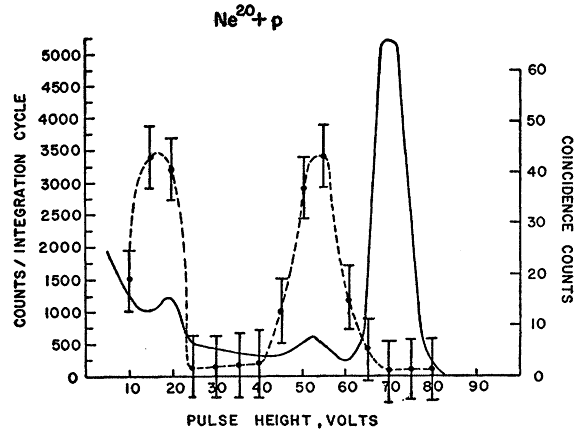

FIG. 3. The solid curve is the spectrum of protons scattered from a gaseous neon target at a laboratory detector angle of 90°. The dotted curve is a plot of net coincidence counts between inelastically scattered protons and decay gamma rays from Ne^{20} as a function of analyzer base-line.

cidence circuits were adjusted to be the same. Initial alignment of the two circuits was accomplished utilizing a fast pulser and running the two circuits in parallel. The two circuits were then adjusted to have the same efficiencies and the same resolving time. With the two circuits still in parallel, coincidences were observed between inelastically scattered protons and decay gamma rays from a bombarded target. A variable delay network was inserted prior to the fast amplifiers and a coincidence delay curve (coincidence counts versus delay in cable) run for both No. 1 and No. 2 circuits. If the coincidence delay curves were observed to be the same, i.e., equal peak counting rates and equal resolving times, then a second variable delay network was inserted in the gamma-ray lead between the input of No. 1 and No. 2 circuits. With the first delay network adjusted so that circuit No. 1 was set at the center of its coincidence delay curve, a second coincidence delay curve was taken using the second variable delay network. The second variable delay network was then adjusted so that circuit No. 2 was at the center of its coincidence delay curve. After this alignment, circuit No. 1 measured coincidences between protons and gamma rays in the same cyclotron pulse, while circuit No. 2 measured coincidences between protons in one cyclotron pulse and gamma rays in an adjacent cyclotron pulse.

Another test made prior to each angular correlation run was to measure the true coincidence rate, No. 1 minus No. 2, as a function of scattered proton energy; i.e., with a fixed window on the proton pulse height analyzer, net coincidence counts were recorded as a function of analyzer base line. Figure 3 is a plot of the spectrum of protons scattered from a neon gas target at an angle of 90° with respect to the incident beam direction. Plotted as an overlay on this spectrum are the net coincidence counts as a function of analyzer base line. There are two peaks in the true coincidence curve corresponding to the first and second excited states of Ne^{20} at 1.63 Mev and 4.26 Mev. Although the total recorded coincidences were highest when the proton window bracketed the elastic proton peak, the net coincidence counts were zero within statistical limits.

EXPERIMENTS

In order to increase the solid angle of the detectors, the two crystals were each placed approximately 1 in. from the target. Small geometrical misalignments could induce large errors in the correlation functions under these conditions. Consequently, it was necessary to align the system carefully. Targets could be aligned on center to within 0.003 in. The absolute angular position of the rotating detector could be set to ±1.5°.

$Li^7(p,p'\gamma)$ 0.48 Mev

One of the experiments chosen to test for geometrical misalignments was $Li^7(p,p'\gamma)$ 0.48 Mev. The 0.478 Mev first excited state in Li^7 is known to have a spin of $\frac{1}{2}$.[12] From the theory of angular correlations,[13] it is known that the complexity of the correlation function is limited. In particular, if the intermediate state involved in the cascade has either spin $\frac{1}{2}$ or 0, the angular correlation

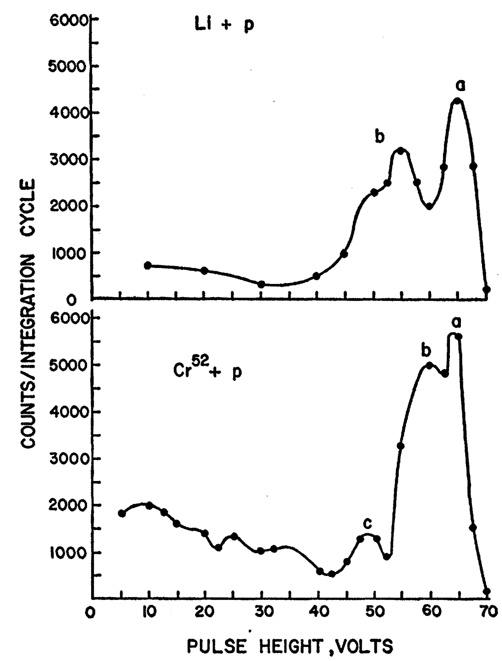

FIG. 4. The upper curve is the spectrum of protons scattered from a thin natural lithium target at a detector angle of 90° with respect to the incident beam direction. The lower curve is the spectrum of protons scattered from a thin chromium target evaporated onto a Formvar backing. The abscissas have not been normalized.

[12] S. H. Levine, R. S. Bender, and J. N. McGruer, Phys. Rev. **97**, 1249 (1955).

[13] M. E. Rose, *Elementary Theory of Angular Momentum* (John Wiley & Sons, Inc., New York, 1957).

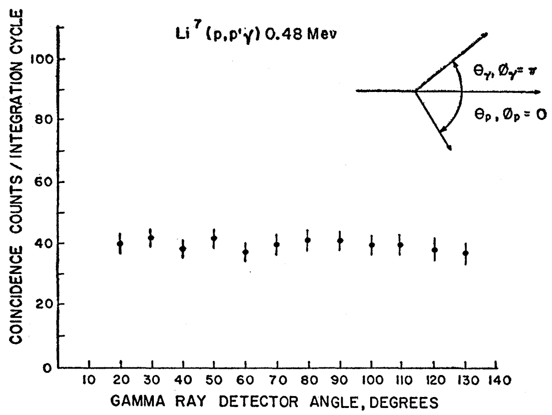

FIG. 5. The angular correlation between the proton group leading to the 0.48 Mev first excited state in Li^7 and the decay gamma rays from that state. The proton detector angle is 90° with respect to the incident beam direction.

function is isotropic, i.e.,

$$W(\theta)=\sum_{\nu} A_\nu P_\nu(\cos\theta)$$

$$\nu_{\max}\leqslant \mathrm{Min}(2I_b,2L_1,2L_2),$$

where I_b = spin of the intermediate state; L_1, L_2 = angular momentum carried by the cascade radiation. Any deviation of the measured angular correlation function from isotropy would have indicated geometrical misalignments.

The spectrum of charged particles emitted from a thin natural lithium target when bombarded by 6.5-Mev protons is shown in Fig. 4. Peak *a* is the unresolved proton group corresponding to the elastic scattering of protons from carbon, which comprises the target backing material, and oxygen, which is in the form of an oxide of lithium. Peak *b* corresponds to the proton group leaving Li^7 in its 0.478 Mev first excited state. Since the 0.478-Mev peak could not be resolved from the elastic peak, it was necessary to place both peaks in the window of the amplitude analyzer. The base line of the gamma-ray amplitude analyzer was set such that all pulses corresponding to gamma rays having energies greater than 0.35 Mev were counted. Figure 5 shows the angular correlation of protons, scattered at a lab angle of 90° with respect to the incident beam direction, with gamma rays from the first excited state in Li^7. Within statistical limits, the distribution was isotropic indicating little or no geometrical asymmetries in the scattering system.

$Cr^{52}(p,p'\gamma)$ 1.44 Mev

The work of Seward[2] indicated that $(p,p'\gamma)$ reaction mechanisms are predominantly compound nucleus when proton energies are below the Coulomb barrier and that direct reactions become appreciable as soon as the energy of both the incident and scattered protons are above the barrier. Since the Coulomb barrier for protons on chromium is about 6 Mev, it was felt that an angular correlation experiment on this nucleus would indicate whether it would be profitable to examine nuclei of higher atomic weight for evidence of direct interactions. For energies below 7 Mev, Seward was able to fit the $Cr^{52}(p,p'\gamma)$ 1.44-Mev angular correlation assuming only a compound-nucleus type reaction.

Chromium targets were prepared by evaporating metallic chromium onto thin Formvar backings. The spectrum of protons scattered from Cr^{52} at a detector angle of 90° is shown in Fig. 4. Peaks a and b correspond to protons scattered elastically from Cr^{52} and C^{12}, whereas peak c corresponds to protons leaving Cr^{52} in its 1.44 Mev first excited state. The incident proton beam current was decreased to approximately 10^{-3} microamperes in order to keep the ratio of true to accidental counts between 4:1 and 6:1. The results of the angular correlation between protons leaving Cr^{52} in its 1.44 Mev first excited state and the gamma rays from that state are shown in Fig. 6. The proton detector position is 90°. The angular correlation curve is isotropic, in agreement with pure compound-nucleus type reaction.

$C^{12}(p,p'\gamma)$ 4.4 Mev

A considerable number of experiments have been performed on the inelastic scattering of protons leaving C^{12} in its 4.4 Mev first excited state.[14] These experiments range in energy from 6.5 Mev to 96 Mev. Even at energies as high as 10 Mev, some of the angular distributions of the inelastically scattered protons have been measured as being symmetric about 90° (center-of-mass coordinates). However, for a fairly small change in incident beam energy, from 9.49 to 9.58 Mev, asymmetries in the angular distributions have been noted.[15]

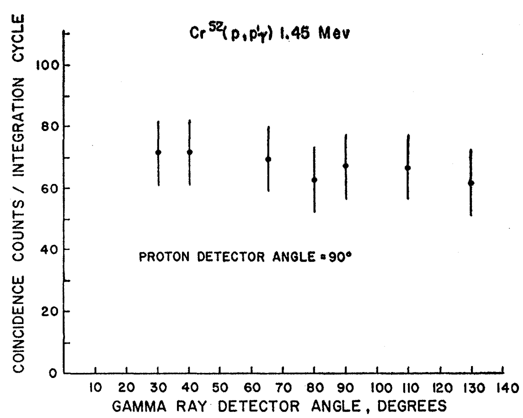

FIG. 6. The angular correlation between the proton group leading to the 1.44 Mev first excited state in Cr^{52} and the decay gamma rays from that state.

[14] (As examples) H. E. Gove and H. F. Stoddart, Phys. Rev. **86**, 572 (1954); W. E. Burcham, W. M. Gibson, A. Hossain, and J. Rotblat, Phys. Rev. **92**, 1266 (1953); R. W. Peelle, Phys. Rev. **105**, 1311 (1957); and K. W. Brockman, Phys. Rev. **110**, 163 (1958).

[15] W. M. Gibson, D. J. Prowse, and J. Rotblat, Proc. Roy. Soc. (London) **A243**, 237 (1957).

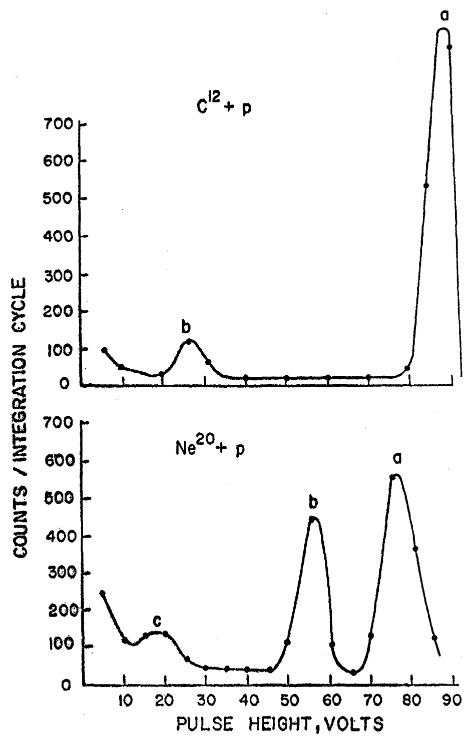

FIG. 7. The upper curve is the spectrum of 6.5-Mev protons scattered from a thin Formvar target at a detector angle of 90°. The lower curve is the spectrum of protons scattered from a gaseous neon target at a detector angle of 60°.

At higher energies the angular distributions tend to be asymmetric about 90° and are peaked in the forward direction. Angular correlation experiments performed by Sherr at 16.6 Mev agreed surprisingly well with predictions of the simple direct-reaction theories.

This data can be understood within the framework of the compound-nucleus and direct-reaction models. At low-particle bombarding energies the number of channels available for decay of the compound nucleus is seriously limited due to the high excitation energy of the first few excited states in C^{12}, 4.4 and 7.6 Mev, and because of the energy required for competing reactions such as (p,d) or (p,α). Consequently, the probability is high that the compound nucleus will decay to the first excited state at 4.4 Mev. Since the direct-reaction contribution to the reaction cross section is predicted to be small, its contribution to the angular distribution may be unobservable because of the large compound nucleus contribution. At high bombarding energies the number of channels open for compound nucleus decay is large. The probability of compound nucleus decay to the first excited state is consequently decreased and direct processes to the first excited state may then become observable.

The spectrum of protons scattered from thin Formvar targets is shown in Fig. 7. Peaks a and b correspond, respectively, to the elastic peak from C^{12} and the inelastic group leading to the 4.4 Mev first excited state in C^{12}. For the angular correlation runs, the window of the proton analyzer was set to bracket the first excited state group while the base line of the gamma-ray analyzer was set so that all gamma-ray pulses having an energy greater than 1 Mev were counted. The proton detector was set at laboratory angles of 90° and 120° with respect to the incident beam direction. At forward angles, the elastic scattering of protons from hydrogen in the target gave rise to a large scattered proton group which overlapped the 4.4-Mev level in carbon. Consequently, only two proton detector angles were used in the angular correlation experiments.

The results of the angular correlation runs are shown in Fig. 8. The experimental points are shown with their statistical standard deviations. The smooth curve is a weighted least-squares fit to the experimental data. The equations representing the angular correlation functions have been corrected for the finite solid angle of the gamma-ray detector.[16] The point θ_R, represented on the curve, is the classical nuclear recoil direction $\mathbf{q}=\mathbf{k}_i-\mathbf{k}_f$. The angle θ_0 is the symmetry axis for the measured correlation, i.e., (2).

$Ne^{20}(p,p'\gamma)$ 1.63 Mev

Angular distributions of protons inelastically scattered from Ne^{20} have been done by Freemantle et al.,[17] Gibson et al.,[15] and by Kondo and Yamazaki.[18] Again,

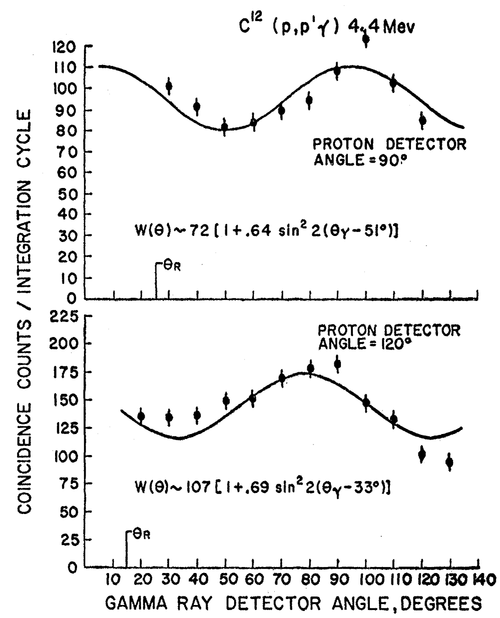

FIG. 8. The angular correlation between the proton group leading to the 4.4 Mev first excited state in C^{12} and the decay gamma rays from that state. θ_R is the classical nuclear recoil direction.

[16] M. E. Rose, Phys. Rev. **83**, 716 (1951).

[17] R. G. Freemantle, D. J. Prowse, A. Hossain, and J. Rotblat, Phys. Rev. **96**, 1270 (1954).

[18] M. Kondo and T. Yamazaki, J. Phys. Soc. (Japan) **13**, 771 (1958).

as in the case with C^{12}, the angular distributions tend to be symmetric about 90° (c.m.) at energies below 10 Mev. The angular correlation of inelastically scattered protons and decay gamma rays was undertaken with the expectation that these experiments would be more sensitive to direct reactions than the angular distribution experiments.

A gas target was used for the neon experiments. The spectrum of protons scattered from the gaseous neon target is shown in Fig. 7. Peak *a* is the proton group corresponding to protons elastically scattered from Ne^{20}, peak *b* is the proton group corresponding to the first excited state at 1.63 Mev, and peak *c* is the proton group corresponding to the second excited state at 4.26 Mev. Since the 1.63-Mev proton group is well resolved, the window of the proton analyzer was set to bracket this peak. The baseline of the gamma-ray analyzer was set to count all pulses greater than 0.7 Mev. The position of the gamma-ray analyzer baseline was determined empirically for this experiment, as well as all the angular correlation experiments. The ratio of true to accidental coincidences varied from 3:1 to 9:1 for the neon experiments.

The results of the angular correlation runs are shown in Fig. 9. The experimental points are shown with their statistical standard deviations. The smooth curve is a weighted least-squares fit to the experimental data. The angular correlation functions, printed on the curves,

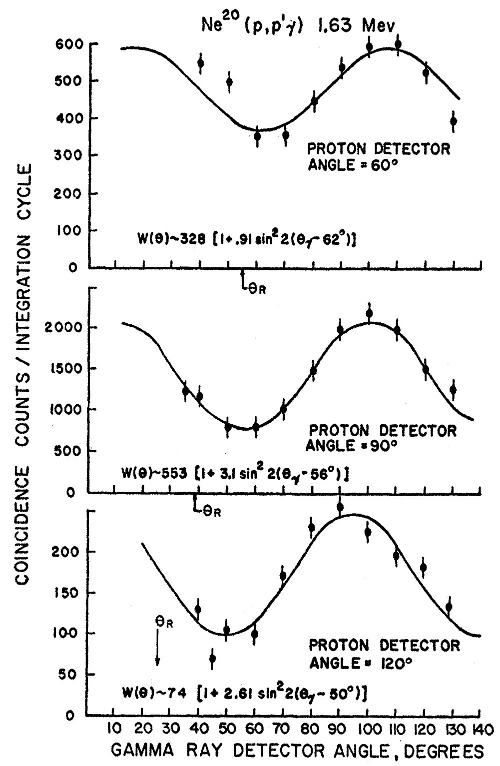

FIG. 9. The angular correlation between the proton group leading to the 1.63 Mev first excited state in Ne^{20} and the decay gamma rays from that state. θ_R is the classical nuclear recoil direction.

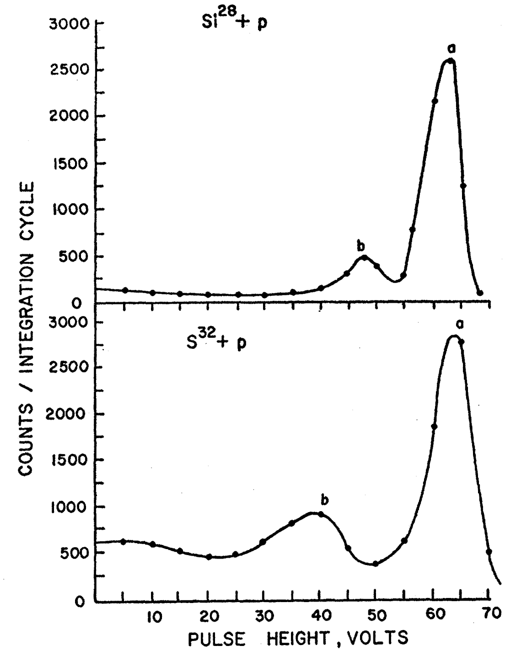

FIG. 10. The upper curve is the spectrum of 6.5-Mev protons scattered from a thin quartz fiber at a detector angle of 90°. The lower curve is the spectrum of protons scattered from a sulfur target covered with a thin evaporated layer of gold. The abscissas are not normalized.

have been corrected for the finite geometry of the gamma-ray detector. The curves correspond to laboratory proton detector angles of 60°, 90°, and 120° with respect to the incident beam direction. Calculated classical nuclear recoil directions θ_R, are indicated on the curves.

$Si^{28}(p,p'\gamma)$ 1.78 Mev

Angular distribution experiments of protons inelastically scattered from Si^{28} have been reported by Yamabe et al.[19] from 4.8-Mev to 5.7-Mev bombarding energy, and by Greenlees et al.[20] from 8.0- to 9.4-Mev bombarding energy. For the reported cases, the angular distributions of protons leading to the 1.78 Mev first excited state in Si^{28} have not been symmetric about 90° (c.m.).

Silicon targets were prepared by drawing quartz fibers down to a diameter estimated as being less than 0.001 in. Two or three fibers were then mounted on a target holder and a thin coating of gold evaporated onto the fiber surfaces. The spectrum of protons scattered from the quartz targets is shown in Fig. 10. Peak *a* comprises the proton groups corresponding to elastic scattering from gold, silicon, and oxygen, and peak *b* corresponds to the proton group leading to the 1.78 Mev first excited state in Si^{28}. The window of the proton analyzer was set to bracket peak *b*, while the baseline of the gamma-ray

[19] S. Yamabe, M. Kondo, T. Yamazaki, and A. Toi, J. Phys. Soc. (Japan) **13**, 777 (1958).
[20] G. W. Greenlees, L. G. Kuo, J. Lowe, and M. Petravic, Proc. Phys. Soc. (London) **71**, 347 (1958).

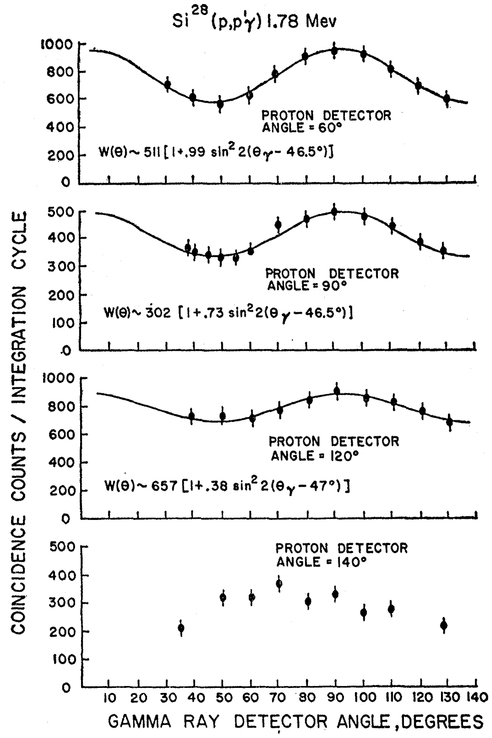

FIG. 11. The angular correlation between the proton group leading to the 1.78 Mev first excited state in Si^{28} and the decay gamma rays from that state.

analyzer was set to count all pulses corresponding to gamma-ray energies greater than 0.7 Mev.

The results of the angular correlation runs are shown in Fig. 11. The experimental points are shown with their statistical standard deviations. The smooth curves are weighted least-square fits to the experimental data. The angular correlation functions have been corrected for the finite geometry of the gamma-ray detector. The curves correspond to laboratory proton detector angles of 60°, 90°, 120°, and 140°. The experimental points were so scattered for the 140° correlation run, that no attempt was made to fit the data. The ratio of true to accidental coincidence counts ranged from 2:1 to 6:1.

$S^{32}(p,p'\gamma)$ 2.25 Mev

S^{32} was chosen as a target for angular correlation experiments because of (a) the nuclear ground state deformation, (b) the well-resolved nature of the excited states, and (c) the simplicity of the theoretical angular correlation function for $0+\rightarrow 2+\rightarrow 0+$ transitions. Targets were initially prepared by evaporating sulfur onto thin Formvar backings. However, the sulfur was re-evaporated from the Formvar backing when the target was bombarded by the proton beam. A successful target was prepared by first evaporating sulfur onto Formvar and then evaporating a thin gold film onto the sulfur. The gold film was sufficiently thick to conduct heat away from the sulfur surface.

The spectrum of protons scattered from the sulfur target is shown in Fig. 10. The broad peak *a* corresponds to protons elastically scattered from gold, sulfur, and carbon. Peak *b* corresponds to inelastically scattered protons leaving S^{32} in its 2.25 Mev first excited state. The width of the peaks is ascribed to the energy loss in target. Since the proton group corresponding to the 2.25-Mev excited state is resolved from the elastic proton group, the window of the proton analyzer was set to bracket this group. The baseline of the gamma-ray analyzer was set to count all pulses corresponding to gamma-ray energies greater than 1 Mev.

The results of the angular correlation runs are shown in Fig. 12. The experimental points are shown with their statistical standard deviations. The smooth curves are weighted least-square fits to the experimental data. The angular correlation functions have been corrected for the finite geometry of the gamma-ray detector. The curves correspond to laboratory proton detector angles of 60°, 90°, and 120°. The classical nuclear recoil directions were calculated on the basis of an incident beam energy of 6.5 Mev.

CONCLUSIONS

Of all the investigations conducted at this laboratory for evidences of direct reactions at low energy, only the angular correlation experiments between the protons leading to the 1.37 Mev first excited state of Mg^{24} and the decay gamma rays agree with the predictions of the simple direct-reaction theories. That is, the symmetry direction for the angular correlation measured agrees with the classical nuclear recoil direction, $\mathbf{q}=\mathbf{k}_i-\mathbf{k}_f$.

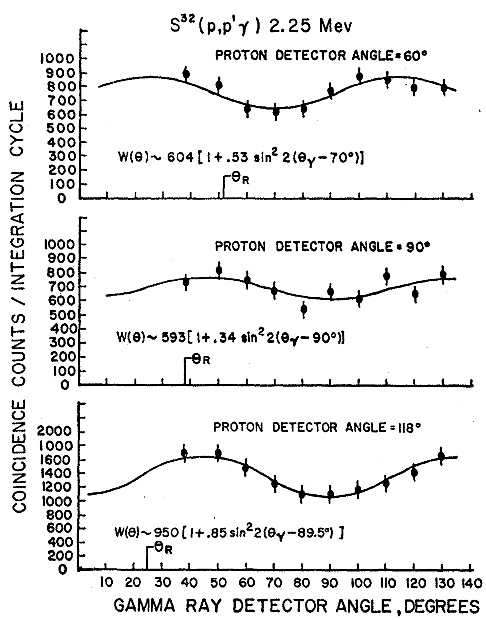

FIG. 12. The angular correlation between the proton group leading to the 2.25 Mev first excited state in S^{32} and the decay gamma rays from that state. θ_R is the classical nuclear recoil direction.

The **q** vector is the momentum transferred to the target nucleus and should be the polar axis of the subsequent gamma-ray emission pattern. The measurements on Mg^{24} were taken for three separate proton detector directions, hence three different values for **q**, and there was agreement with the predictions of the simple theories at all detector angles. The results of other angular correlation experiments involving the first excited states of C^{12}, Ne^{20}, and S^{32} cannot be explained within the framework of compound nucleus theory but yet do not agree with the simple direct-reaction theories. The exact agreement of these experimental results with the predictions of the simple theories should not be expected since these theories all treat the incident and outgoing particle wave functions as plane waves near the nuclear surface. Especially at these low energies, one should expect serious distortion of the projectile wave functions and hence only a qualitative agreement of experimental results with the simple theory.

The nuclei C^{12}, Ne^{20}, Mg^{24}, Si^{28}, and S^{32} all have even numbers of protons and neutrons and have measured first excited states of spin 2 and even parity. The angular correlation experiments involving these first excited states are of the form $0+\rightarrow 2+\rightarrow 0+$. Consequently if a quantization axis exists in the inelastic scattering reaction, the form of the angular correlation function should be $\sin^2 2(\theta-\theta_0)$. Moreover, should a direct process be involved in the reaction, one would expect a correlation between the measured symmetry direction and the classical nuclear recoil direction **q**. The angular correlations measured in this laboratory between the protons leading to the first excited states of the above nuclei and the gamma rays from these states all have the form of Eq. (2). The measured angular correlation functions for experiments on C^{12}, Ne^{20}, Mg^{24}, and S^{32} were different, i.e., had different symmetry directions for different proton detector angles. The measured correlation functions for the nucleus Si^{28}, however, were all symmetric, within experimental accuracy, about 90° independent of proton detector angle.

It is difficult to assess the role of compound nucleus contribution in the energy range of these experiments. The excitation energy of the compound nucleus is certainly not high enough so that one is in the statistical region, i.e., the excitation energy of the compound nucleus is not so high that a statistically large number of overlapping states exist within the energy spread of the incident beam. At the same time, at these energies, the compound nucleus is not excited to the region wherein only a single level is excited. We are indeed in that region of compound nucleus excitation wherein only a finite number of states are excited within the energy spread of the incident beam. This is just the region where analysis is difficult, since a finite number of excited overlapping states of different parities could give rise to angular distributions of inelastically scattered protons which are not symmetric about 90°.

However, there are some generalizations that can be made concerning the compound nucleus contributions. Satchler[21] has worked out the general formula for the angular correlation of three nuclear radiations, for instance $(p,p'\gamma)$, when continuum theory is applied to the compound nucleus state. For this case, the interference terms for overlapping states disappear on taking a statistical average and the outgoing partial waves are incoherent. For the case of an even-even target nucleus, wherein one excites a $J=2+$ state followed by $E2$ emission, the angular correlation has an axis of symmetry only for the special cases where either there is pure S-wave absorbtion of the incident proton or there is pure S-wave emission from the compound nucleus. However, for the general case where more than one partial wave can contribute to the reaction, the angular correlation has no axis of symmetry. There is the possibility that an axis of azimuthal and axial symmetry could exist for the angular correlation in the case where a finite number of levels of the compound nucleus interfere. However, for an axis of symmetry to exist under these conditions, there would have to be a definite relationship between the parameters of the interfering compound states. While such a relationship might exist for a particular compound nucleus at a particular excitation energy, the likelihood is small that such relationships exist for all of the compound states involved in these experiments. Even should such an angular correlation be describable, for a particular compound nucleus, in terms of overlapping interfering states, it is not clear as to why the symmetry axis would change for different particle detection angles. One must conclude that compound nucleus processes alone do not appear to explain the angular correlations observed.

It has been pointed out by Wildermuth and Kanellopoulos[22] that very probably the low-energy levels of most nuclei possess collective features; for deformed nuclei it is practically always to be expected that the lowest excited states can be described approximately by rotational wave functions, because for a given angular momentum these excitations are energetically more favored. The regular structure of the low-energy levels of even-even nuclei supports this hypothesis. The experiments reported by Helm[23] and by Fregeau and Hofstadter[24] on the inelastic scattering of 187-Mev electrons from light even-even nuclei are additional evidence for the hypothesis of collective excitations for these lowlying states. The inelastic cross sections for the formation of the first excited states of nuclei such as C^{12}, Mg^{24}, Si^{28}, and S^{32} were compared to the inelastic cross sections to the same states predicted by the Weisskopf single-particle model excitation. The ratio of the measured cross section to the single particle cross section varied

[21] G. R. Satchler, Phys. Rev. **94**, 1304 (1954).
[22] K. Wildermuth and Th. Kanellopoulos, Nuclear Phys. **9**, 449 (1958).
[23] R. H. Helm, Phys. Rev. **104**, 1466 (1956).
[24] J. H. Fregeau and R. Hofstadter, Phys. Rev. **99**, 1503 (1955).

from 2.3 to 1 for C^{12} to 9.1 to 1 for Mg^{24}. The ratio of the measured lifetime to the Weisskopf estimate of the first excited state in C^{12}, Si^{28}, and Ne^{20} by Devons et al.[25] and of the first excited state in Mg^{24} and Si^{28} by Ofer and Schwarzschild[26] all show enhancement of the $E2$ transition probability over the single particle estimate. The exhaustive analysis of the low-lying states of Mg^{25} and Al^{25} by Litherland et al.[27] indicates that the Mg^{24} ground state has a prolate distortion and that the low-lying states of Mg^{24} are well described by the rotational model. Also the work of Cohen and Rubin[28] on the anomalous inelastic scattering of 23-Mev protons by various medium weight nuclei indicates that collective levels that are strongly excited in Coulomb excitation experiments are also strongly excited in inelastic proton scattering, and vice versa. Finally, Cohen[29] has pointed out that striking similarities have been observed between medium energy (p,p') and (d,d') angular distribution experiments. The nucleon-nucleon collision model for direct reactions is inapplicable to (d,d') reactions since it would be very improbable for deuterons to have high energy collisions without breaking up.

In view of the above experimental evidence and in view of the low single particle excitation cross sections predicted at these bombarding energies, it seems consistent to interpret the existence of direct processes in the angular correlation experiments reported here as due to collective excitations rather than as nucleon-nucleon collisions. The existence of permanent nuclear ground state distortions means that the collective excitations are either rotations of the entire nucleus about an axis perpendicular to the symmetry axis of the fixed distortion or as vibrational oscillations of the nuclear shape about this spheroidal shape. In either case, the nuclear ground state wave function becomes more nearly spherically symmetric as the nuclei approach a closed shell. At a closed shell the excitation energy of a rotational state would be very high. Consequently, at or near a closed shell the low-lying states could be single particle states. At low-particle bombarding energies, the observation of direct excitation of these single particle states is difficult because of the low cross section for single particle excitation and the large compound nucleus contribution through the same states.

On a pure j-j coupling picture, the Si^{28} core corresponds to the closing of the $d_{\frac{5}{2}}$ shell for both protons and neutrons and indicates a tendency for the nuclear wave function to have a high degree of spherical symmetry. If the low-lying states of Si^{28} are not collective states but are single particle states, the contribution to the reaction cross section of direct excitation of these states would be expected to be small compared to the total reaction cross section. The results of the angular correlation experiments reported here show that the symmetry axis for the experiments on carbon, magnesium, neon, and sulfur changed for different proton detector angles while the symmetry axis for Si^{28} remained fixed in space independent of proton detector angle. If the criteria stated earlier for the presence of direct reactions in $0+ \rightarrow 2+ \rightarrow 0+$ angular correlation experiments is valid (i.e., the $\sin^2 2\theta$ form of the correlation function and the change in symmetry direction with change in nuclear recoil direction), then the experiments on carbon, neon, magnesium, and sulfur show the presence of direct reactions while the experiments on silicon do not necessarily show the presence of a direct reaction. These results appear to be consistent with the description of Si^{28} as a spherically symmetric nucleus and the other nuclei investigated as having permanent ground state distortions.

Unfortunately, there are some serious discrepencies with this description of Si^{28}. The electron scattering experiments by Helm showed that the ratio of the measured inelastic cross section to the single particle cross section for the first excited state of Si^{28} was 6 to 1. This result indicates that the first excited state does show some collective behavior. It has also been pointed out by Bromley[30] that the experiments by the Chalk River group[31,32] on the low-lying levels of Si^{29} indicate that Si^{28} would be expected to have a stable oblate deformation. He also points out that Broude et al.,[33] using an analysis similar to the Chalk River group, were able to get a good fit to the P^{31} data with the same oblate deformation implied for S^{32} as for Si^{28}. From these results, one would expect the same angular correlations on S^{32} as on Si^{28}.

It is clear that the present experiments do not unambiguously determine the nature of the direct-reaction mode for the nuclei investigated. Experiments are now in progress on S^{32} and Si^{28} which may clarify some of the anomaly concerning the interpretation of the angular correlation experiments on these nuclei.

ACKNOWLEDGMENTS

We wish to thank Paul Weiler, Kingston George, and members of the cyclotron staff for their help in operating the cyclotron. We also appreciate the assistance of Jack Murphy in target preparation, and Don Wyer, and Ahmed Abdel-Bary in calculations. We are indebted to Professor Bernard Margolis for many helpful discussions.

[25] S. Devons, G. Manning, and J. H. Towle, Proc. Phys. Soc. (London) **A69**, 173 (1956).
[26] S. Ofer and A. Schwarzschild, Phys. Rev. Letters **3**, 384 (1959).
[27] A. E. Litherland, H. McManus, E. B. Paul, D. A. Bromley, and H. E. Gove, Can. J. Phys. **36**, 378 (1958).
[28] B. L. Cohen and A. G. Rubin, Phys. Rev. **111**, 1568 (1958).
[29] B. L. Cohen, Phys. Rev. **116**, 426 (1959).
[30] D. A. Bromley (private communication).
[31] D. A. Bromley, H. E. Gove, E. B. Paul, A. E. Litherland, and E. Almquist, Can. J. Phys. **35**, 1042 (1957).
[32] D. A. Bromley, H. E. Gove, and A. E. Litherland, Can. J. Phys. **35**, 1057 (1957).
[33] C. Broude, L. L. Green, and J. C. Willmott, Proc. Phys. Soc. (London) 1122 (1958).