$Si^{28}(p,p'\gamma)$ Angular Correlations*

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Angular correlations have been measured between protons scattered inelastically from a Si^{28} target and the decay gamma rays from the 1.78-Mev first excited state of the target nuclei. The incident proton bombarding energy was varied between 5.8 Mev and 7.0 Mev. The angular correlation experiments were performed for proton detector angles of 37°, 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. When the incident proton beam energy was 7.0 Mev, the symmetry direction was found to be 90° (center of mass) independent of the proton detector angle. These results agree with the prediction of a compound-nucleus theory. This suggests the existence of a strong compound nucleus resonance in P^{29} at an excitation energy of 9.6 Mev. For lower proton beam energies, the symmetry direction θ_0 shifts with a change in the proton detector angle or a change in the proton beam energy. These results are consistent with a direct-reaction mechanism.

INTRODUCTION

A NUMBER of angular correlation experiments have been performed in this laboratory between the inelastically scattered protons, which leave the target nuclei in their first excited state, and the decay gamma rays from that state. The purpose of the experiments was to search for the presence of direct reactions at low proton bombarding energies. The results of the angular correlation experiments on C^{12}, Ne^{20}, Mg^{24}, Si^{28}, and S^{32} targets have been reported in two earlier articles.[1,2] These experiments were performed at proton detector angles of 60°, 90°, and 120° with an incident beam energy of 7.0 Mev. The angular correlation data were fitted by the least-squares method to the function $A+B\sin^2[2(\theta-\theta_0)]$, where θ_0 is the axis of symmetry.

All of these targets have even-even nuclei with a 0+ ground state and a 2+ first excited state. If, in the (p,p') scattering process, the excited target nuclei are polarized along some axis θ_q, the angular distribution of the decay gamma rays will be

$$W(\theta)=A\sin^2[2(\theta-\theta_q)].$$

The simple direct-reaction theories,[3] which assume a plane-wave description of the incoming and outgoing protons, predict that the polar axis θ_q is in the direction of the classical nuclear recoil. This is the direction of 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 results of the angular correlation experiments performed on Mg^{24} agree with the predictions of the simple direct-reaction theories. The correlation function was measured for three different proton detector angles; 60°, 90°, and 120°. This gave three different classical nuclear recoil directions. In each case the symmetry axis of the correlation function agreed, within experimental error, with the nuclear recoil direction.

The angular correlation experiments, which were performed on C^{12}, Ne^{20}, and S^{32}, revealed that the symmetry axes of the correlation functions did not coincide with the predicted polar axes of the simple direct-reaction theories. However, the measured symmetry axes were found to depend on the proton detector angle. These results are not surprising. For low proton bombarding energies, a plane-wave projectile wave function would not be expected to be a good approximation. A more refined calculation which includes the effects of the distortion of the projectile wave function was made by Banerjee and Levinson.[4] This calculation leads to an angular correlation function of the form,

$$W(\theta)=A+B\sin^2[2(\theta-\theta_0)],$$

where the symmetry axis, θ_0, only approximates the classical nuclear recoil angle, θ_q. The predictions of this distorted wave theory were compared with the data collected by Sherr and Hornyak,[5] who investigated the $C^{12}(p,p'\gamma)$ angular correlations. Their incident beam energy was 16.6 Mev. The predictions of the distorted wave direct-reaction theory were found to be in good agreement with the correlation data. This theory was not actually applied to C^{12}, Ne^{20}, and S^{32} for an incident proton beam energy of 7.0 Mev. However, the symmetry axes of the measured angular correlation functions were observed to shift in a regular manner with a change in the proton detector angle and with a change in bombarding energy. This strongly indicates the presence of a direct reaction.

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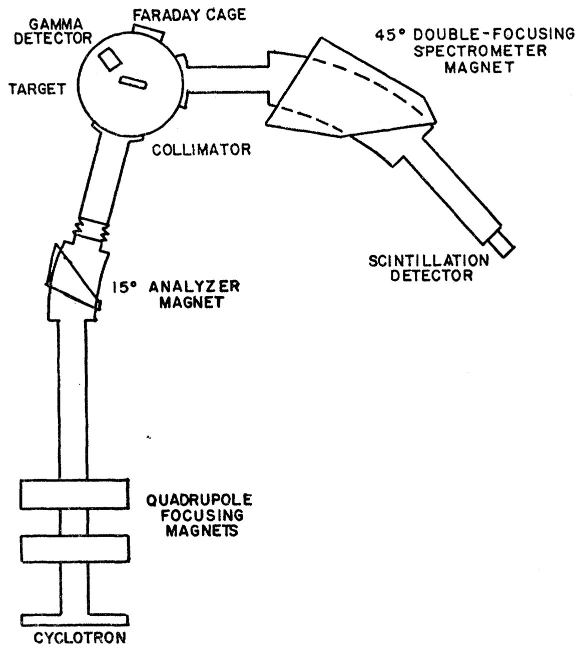

FIG. 1. A schematic drawing of the Ohio State University Cyclotron scattering system. The drawing is not to scale.

For Si^{28} the angular correlation data were found to fit to a function of the form,

$$W(\theta)=A+B\sin^2[2(\theta-90°)],$$

independent of the proton detector angle. This is contrary to the predictions of direct-reaction theories. This symmetry of the correlation function about 90° (c.m.) agrees with the predictions of a compound-nucleus formation theory. This suggests the existence of a strong nuclear resonance in the compound nucleus, P^{29}, at an excitation energy of 9.6 Mev. If a resonance actually exists at this energy, then at an incident proton beam energy which is unable to excite such compound-nucleus resonances, the correlation function would be expected to be radically different. The results of the angular correlation experiments on Si^{28} at various beam energies between 5.8 Mev and 7.0 Mev is the subject of this paper.

SCATTERING SYSTEM

The Ohio State University cyclotron scattering system (see Fig. 1), has been described elsewhere.[6] The 7.0-Mev beam, extracted electrostatically from the cyclotron vacuum system, is diverging as it enters the 2-inch o.d. brass pipe. The magnetic field of the quadrupole focusing magnets forces the protons into paths parallel to the axis of the brass pipe. The beam is then bent through an angle of 15° by the field of the deflecting magnet. A collimator, which has a circular hole with a diameter of 0.025 inch, is located in the entrance port of the scattering chamber. The proton beam, after passing through the collimator, bombards the target located at the center of the chamber. Finally, the beam is collected in a Faraday cage.

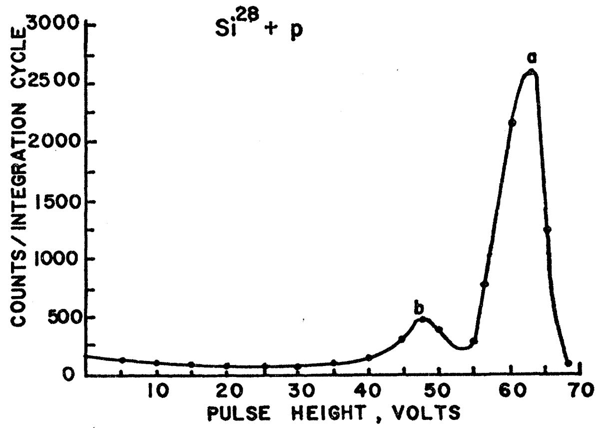

FIG. 2. Spectrum of 7.0-Mev protons scattered from a thin quartz target at an angle of 90° with respect to the incident beam direction.

There are two radiation detectors attached to the scattering chamber. The first is a $\frac{3}{16}$-inch diameter by 0.020-inch thick CsI crystal. It is attached to a Lucite light pipe which in turn is attached to an E.M.I. 9536B multiplier phototube. The second detector is a 1-inch diameter by 2-inch long NaI crystal. It is attached via a Lucite light pipe to a second E.M.I. 9536B phototube. The CsI detector is used to detect the protons scattered from the thin bombarded targets, while the NaI crystal is used to detect the decay gamma rays emitted from the same targets. By changing to a Lucite light pipe of

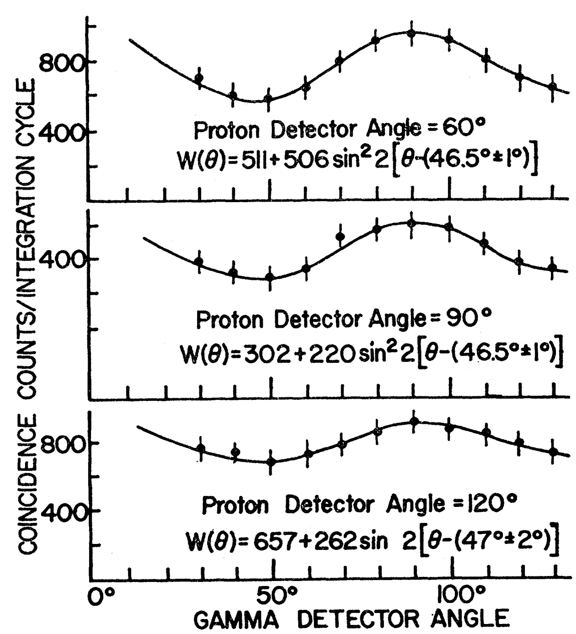

FIG. 3. $Si^{28}(p,p'\gamma)$ 1.78-Mev angular correlation. The incident beam energy is 7.0 Mev. The target is No. 1. See reference 2.

[6] H. J. Hausman, U. S. Atomic Energy Commission Progress Report, 1959 (unpublished).

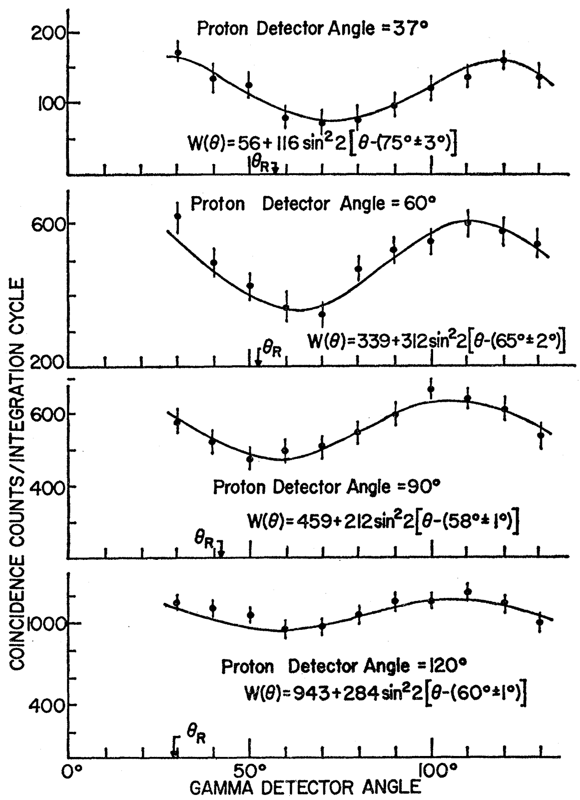

FIG. 4. $Si^{28}(p,p'\gamma)$ 1.78-Mev angular correlation. The incident beam energy is 7.0 Mev. The target is No. 2. θ_R is the classical nuclear recoil direction.

a different shape, it is possible to change the proton detector angle. The gamma-ray-detecting crystal is attached to a Lucite rod which passes vertically through a vacuum seal located in the rotating lid of the scattering chamber. A remotely controlled selsyn system is used to change the angular position of the gamma-ray detector.

In order for a coincidence count to be recorded by the electronic circuitry, the following requirements must be met. A proton and a gamma ray must be detected within the resolving time (approximately 25 nanoseconds) of a fast coincidence circuit. The energy of the detected proton must lie within some preset energy window while the energy of the detected gamma ray must exceed a preset energy threshold. Some of these recorded coincidences are the result of the detection of a gamma ray in time coincidence with the detection of an unrelated proton. These coincidences shall be referred to as "accidental" coincidences.

Since this electronic circuitry cannot differentiate the coincidences between related radiations from those of unrelated radiations, a second coincidence circuit was added. This circuit matched protons of one cyclotron pulse with the gamma rays related to protons of the previous cyclotron pulse. The number of these coincidences equals, within statistics, the number of accidental coincidences recorded by the first circuit. The corrected number of coincidences occurring during a run was taken to be the difference between the recorded counts of the two circuits.

EXPERIMENTS

A Si^{28} target was prepared by drawing a quartz fiber down to a diameter estimated as being less than 0.001 inch. The fiber was then attached to a target holder and a thin coating of gold evaporated onto the fiber surface. The gold was used to carry away the heat which results from the bombardment of the target by the incident proton beam. An energy spectrum of the protons scattered from the quartz fiber is shown in Fig. 2. Peak *a* comprises the proton groups corresponding to elastic scattering from gold, silicon, and oxygen. 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 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. 3. The incident proton beam energy is 7.0 Mev. The curves correspond to laboratory proton detector angles of 60°, 90°, and 120°. The experimental points are shown with their statistical standard deviations.

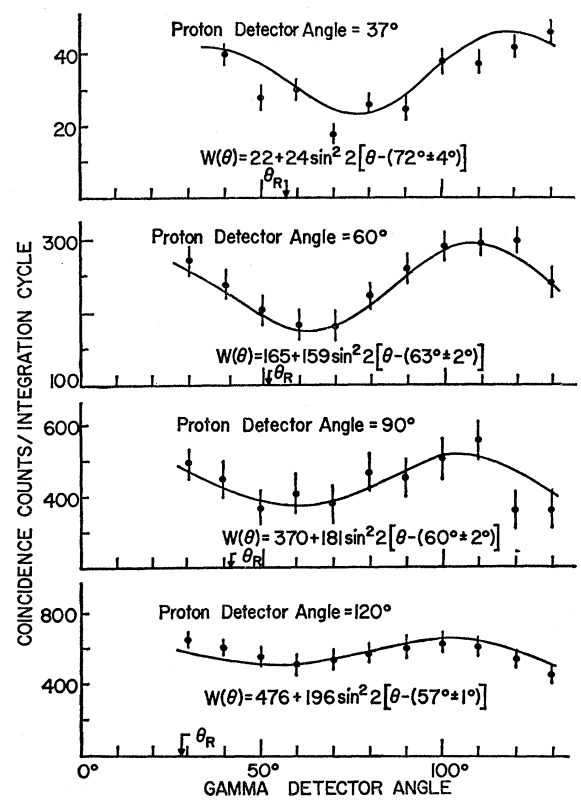

FIG. 5. $Si^{28}(p,p'\gamma)$ 1.78-Mev angular correlation. The incident beam energy is 6.7 Mev. The target is No. 2. θ_R is the classical nuclear recoil direction.

The smooth curves are weighted least-squares fits to the experimental data. The angular correlation functions, printed on the curves, have been corrected for the finite geometry of the gamma-ray detector. The ratio of the true to accidental counts ranged from 2:1 to 6:1. Before the correlation runs could be repeated at lower beam energies, the thin silicon target broke. This target will be designated as target No. 1.

A second silicon target (called target No. 2) was prepared by the method used in preparing target No. 1. However, the diameters of the two quartz fibers may have differed. Also, there may have been different amounts of gold plated onto the two quartz fibers. Before the beam energy was changed, the angular correlation experiments were repeated on target No. 2. The results of these runs are shown in Fig. 4. The proton detector angles are 37°, 60°, 90°, and 120°. None of the correlation functions are symmetric about 90°(c.m.). Also, the symmetry axis of the correlation function shifts in a regular manner with the change in the proton detector angle. These last four runs indicate the presence of a direct interaction occurring in the (p,p') reaction. These results do not agree with those obtained from the target No. 1 experiments.

A possible explanation for this difference in the results is based on the assumption that the thickness of the two targets was not the same. As the protons pass through a target, they lose energy as a result of atomic collisions and ionization interactions. Consequently, if the two targets had a different thickness, the amount of energy lost by the protons due to the atomic interactions would not be the same for both targets. A test of this possible explanation is to see if, for a different beam energy, the target No. 2 angular correlation results would agree with the above target No. 1 results.

The incident proton beam energy was degraded by placing a thin platinum foil in the path of the beam. The

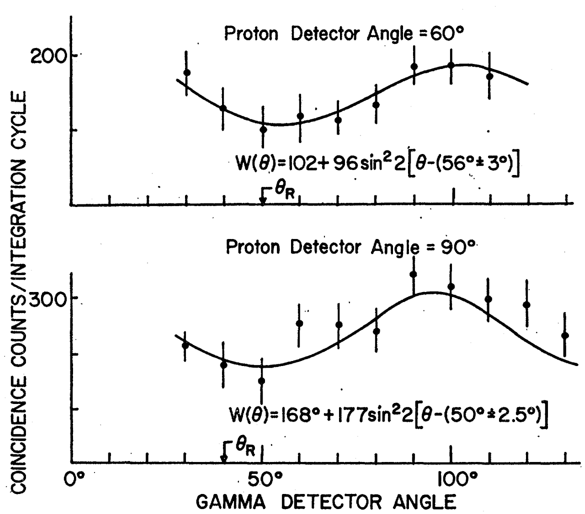

FIG. 6. $Si^{28}(p,p'\gamma)$ 1.78-Mev angular correlation. The incident beam energy is 6.3 Mev. The target is No. 2. θ_R is the classical nuclear recoil direction.

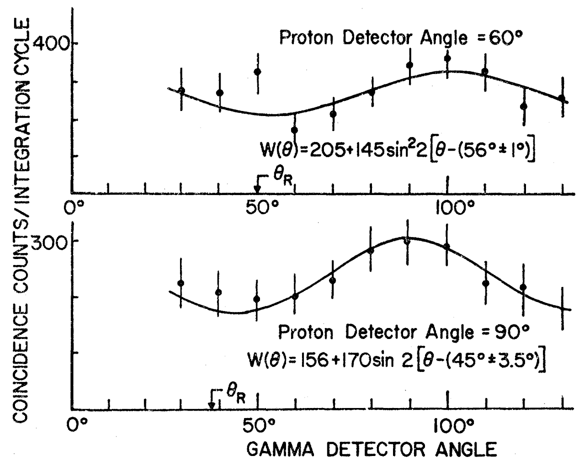

FIG. 7. $Si^{28}(p,p'\gamma)$ 1.78-Mev angular correlation. The incident beam energy is 5.8 Mev. The target is No. 2. θ_R is the classical nuclear recoil direction.

angular correlation runs were taken on target No. 2 at several different beam energies in the range 5.8 Mev to 6.7 Mev. The results of the runs are shown in Figs. 5, 6, 7, and 8. The proton detector angles were 37°, 60°, 90°, and 120°. At none of these energies are the results similar to those obtained with target No. 1. Since the incident beam energy could not be increased above 7.0 Mev, it was not possible to check whether higher energy protons incident on target No. 2 would give the results of target No. 1. However, decreasing the thickness of the target has nearly the same effect as increasing the incident beam energy.

A thin target (called target No. 3) was then prepared. Figure 9 shows the results of an angular correlation run made on target No. 3. The proton detector angle was 60°. The incident beam energy was 7.0 Mev. The results approximate those obtained from target No. 1. The incident beam energy was then reduced to 6.5 Mev. An angular correlation run was then made on target No. 3. The results of this run are shown in Fig. 9. They resemble the results obtained for the case in which target No. 2 was bombarded by 7.0-Mev protons. It now appears that the thickness of target No. 1 was nearly the same as that of target No. 3, whereas, target No. 2 was thicker.

CONCLUSIONS

Except for the case of the inelastic scattering of 7.0-Mev incident protons from a Si^{28} target, the above angular correlation experiments indicate that the inelastic scattering of protons from the light even-even target nuclei occurred predominantly by a direct-reaction process. For the case of Si^{28} nuclei bombarded by 7.0-Mev protons, the angular correlation experiments indicate the (p,p') reactions proceeded mainly by a compound-nucleus mechanism.

Since, at the low incident proton energies used in these experiments, the compound-nucleus decays have only a small number of decay modes available, a large

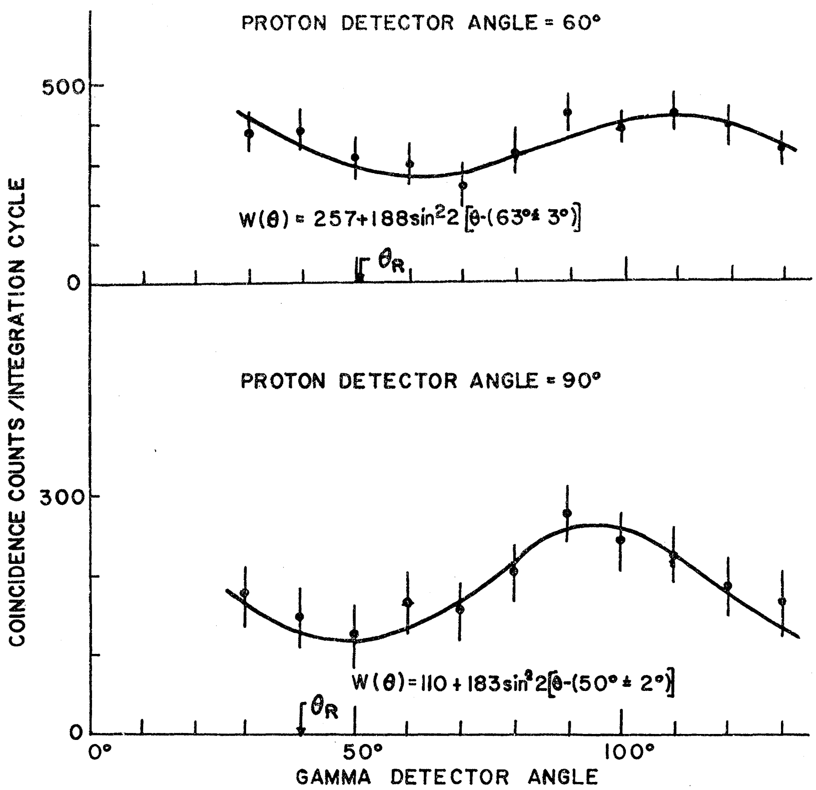

FIG. 8. $Si^{28}(p,p'\gamma)$ 1.78-Mev angular correlation. The upper curve is for an incident beam energy of 6.5 Mev; the lower curve is for an incident beam energy of 6.2 Mev. The target is No. 2. θ_R is the classical nuclear recoil direction.

fraction of these decays would lead to the final target nuclei being left in their first excited state. Consequently, in order for direct-reaction processes to be appreciably compared to the compound-nucleus processes, the direct reactions must involve some type of a collective interaction such as exciting the rotational levels of a deformed target nucleus. The cross section for exciting these collective states in nuclei have been shown to be large.[7] The explanation of the angular correlation experiments appears to be that the (p,p') reactions occur by a compound-nucleus mechanism if a strong compound-nucleus resonance occurs, otherwise the reaction proceeds mainly by a direct reaction involving some type of a collective interaction. This explanation suggests the presence of a strong nuclear resonance in P^{29} at 9.6 Mev.

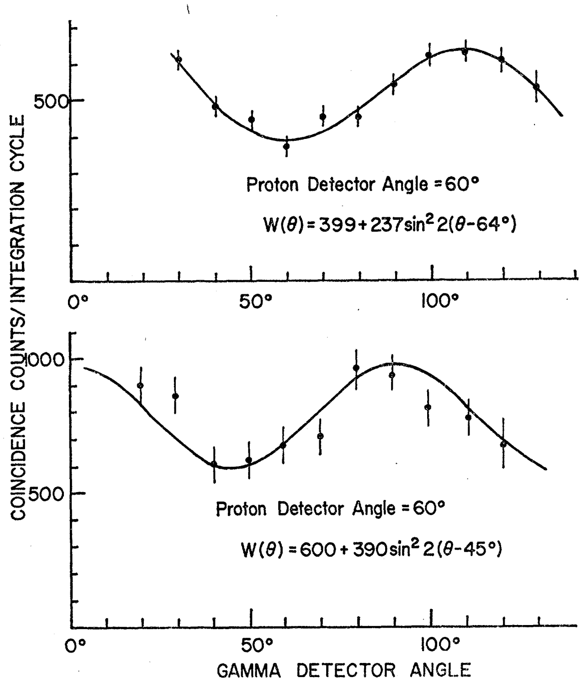

FIG. 9. $Si^{28}(p,p'\gamma)$ 1.78-Mev angular correlation. The target is No. 3. The upper curve is for a proton bombarding energy of 6.5 Mev; the lower curve is for a proton bombarding energy of 7.0 Mev.

The number of coincidences recorded for the runs in which the correlation function was symmetric about 90° (c.m.) was measured to be approximately twice the number of coincidences recorded for the remaining runs. This increase in the reaction cross section at approximately 7.0-Mev bombarding energy also suggests the onset of a compound nucleus resonance.

ACKNOWLEDGMENTS

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[7] B. L. Cohen, Phys. Rev. **116**, 426 (1959); J. S. Blair, Phys. Rev. **115**, 928 (1959).