$S^{32}(p,p'\gamma)$ Angular Correlations from 5.7 to 6.34 Mev

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Angular correlations have been measured between protons scattered inelastically on S^{32} and the 2.25-Mev γ rays from the decay of the first excited state. Measurements were made at incident proton energies of 5.7, 6.02, 6.2, and 6.34 Mev, the position of the proton detector being at 60°, 90°, 120°, and only in one case at 150°. The experimental correlations functions are all of the form $A+B\sin^2[2(\theta-\theta_0)]$, where θ_0 defines the axis of symmetry. At 6.02-Mev incident proton energy, θ_0 is only slightly different from the recoil angle θ_R; it is thereby inferred that the reaction goes mainly through a direct interaction mechanism. At 6.34 Mev, θ_0 remains close to 90° for any scattering angle, in agreement with the compound nucleus theory. This fact suggests the presence of a strong resonance in the Cl^{33} compound nucleus. The correlations curves measured at 5.7 and 6.2 Mev are consistent with a competition between both reaction mechanisms.

I. INTRODUCTION

In the last few years the existence of a direct-interaction (DI) mechanism has been emphasized in a series of papers[1-5] reporting on the $(p,p'\gamma)$ inelastic scattering by even-even nuclei at low energies. In these works the $(p,p'\gamma)$ angular correlation was measured, the protons leaving the nucleus in its first excited level. In some theoretical investigations[6-8] of the angular correlation function, the mechanism DI is assumed; this function displays an axis of symmetry related to the recoil direction of the nucleus. No such axis is implied by the compound nucleus mechanism (CN), except in a few very special cases.

Satchler[6] has shown that in the Born approximation the angular correlation functions between inelastically scattered protons and the corresponding γ rays of $E2$ type has the form $A\sin^2[2(\theta-\theta_R)]$, where θ is the detector angle and θ_R the angle made by the recoil momentum with the direction of the incident beam. By taking into account the distortion of the plane waves, Levinson and Banerjee[7] found for the same function the expression

$$W(\theta)=A+B\sin^2[2(\theta-\theta_0)], \qquad (1)$$

where θ_0 is the symmetry axis of the correlation function, which only approximates θ_R. More recently, Blair and Wilets[8] have found the same expression for $W(\theta)$ by using the adiabatic approximation and the theorems concerning the elastic scattering, but their θ_0 is related to the proton scattering angle $\theta_{p'}$, by $\theta_0=\pi/2-\theta_{p'}/2$.

All the above-mentioned theoretical assumptions imply in fact a shift of the θ_0 axis following the change in the proton detector angle which fixes the recoil direction of the nucleus. It is, therefore, apparent that the experimental evidence of the existence of an axis of symmetry and its shift with the recoil direction is a sufficient proof that a DI occurs. The CN theory in some cases may provide correlation functions which are approximately symmetric around 90° whatever the proton detector angle. If there exists any CN contribution, it will manifest itself by a deviation from (1); the shift of the symmetry axis which follows the changes in the proton detector angle remains, however, evident.

The existence of curves symmetric around 90° at a particular energy and the DI being evident at neighboring energies suggest the presence of a strong resonance in the compound nucleus at that energy. In this case the CN contribution dominates.

In this work we have investigated the existence of the DI at low energies in the $(p,p'\gamma)$ inelastic scattering by S^{32}. For this purpose we have measured the p'-γ angular correlation at energies ranging from 5.7 to 6.34 Mev and at various proton scattering angles.

II. EXPERIMENTAL METHOD

The source of protons is the U-120 cyclotron of the Institute for Atomic Physics in Bucharest. The protons used in the present work had energies of 5.7, 6.02, 6.2, and 6.34 Mev with a spread of about 150 kev. The above-mentioned energies have been computed by using the operating parameters of the cyclotron. The geometry of the scattering system is shown in Fig. 1. The protons are electrostatically extracted, enter a stainless pipe, and pass through the magnetic field of a pair of quadrupolar lenses and of a deflecting magnet. The beam deflected at 13° arrives focused at the center of the reaction chamber where the target and the detection system are located. The width of the proton beam which enters the reaction chamber is reduced to a 15-mm diameter cross section by interposing a tantalum diaphragm.

The beam reaching the target is defined by means of a tantalum tubular collimator with four circular slits of 4 mm in diameter and antiscattering shields. The target, having the form of a thin film of sulfur, is placed in the middle of the chamber of 4 cm from the colli-

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[5] H. Taketani and W. P. Alford, Bull. Am. Phys. Soc. **5**, 38 (1961).
[6] G. R. Satchler, Proc. Phys. Soc. (London) **A68**, 1037 (1955).
[7] G. A. Levinson and M. K. Banerjee, Ann. Phys. (New York) **2**, 499 (1957).
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mator. The reaction chamber was equipped with 4 mobile arms separately adjustable from θ_0 to 360°. On two of these arms two scintillation counters were placed. The positioning of the arms bearing the two counters, of the proton collimator, and of the target with respect to the center of the chamber has been optically realized and has been checked by measuring the angular distribution of protons elastically scattered by gold. Within the statistical errors, the obtained distribution coincided with the Coulombian one, indicating thereby the absence of any important asymmetry in the scattering system.

One of the counters was a NE 102 plastic scintillator, 1.5 mm thick and 40 mm in diameter, and was connected to an RCA 6655 A photomultiplier. The other consisted of a NaI crystal of 40-mm length and 40 mm in diameter, connected to an RCA 5819 photomultiplier. The plastic scintillator has been used to detect the protons scattered by the sulfur target, while the NaI scintillator detected the γ radiation. The plastic scintillator was shielded by a tantalum collimator having a rectangular slit of 8×36 mm. The proton detector angle as well as that of the γ-rays detector could be continuously changed by external Selsyn system. The proton detector was located at 8 cm from the target while the γ-ray detector was only at 4 cm. The correlation was measured by means of a slow-fast coincidence circuit (see Fig. 2) built in our laboratory. The resolving time of the fast coincidence circuit has been measured and found to be 26 nsec. The sulfur target was obtained by vacuum evaporation on a glass plate and afterwards detached by sinking it in distilled water. In this way, free sulfur targets of 2-cm diam and of thickness below 2 mg/cm², mounted on aluminum rings, were obtained. The target had to be changed after a certain number of runs because of the evaporation. Each time the target was changed, supplementary runs were performed at the same energy and proton detector angle as previously; within the statistical errors, the two sets of data agreed. The angular correlations were measured at low intensities of the incident beam in order to obtain a favorable ratio of the real coincidences over the accidental ones. The counting rate was in most of the runs below 1 count/sec, yielding a ratio of the real coincidences to the accidental ones better than 50:1. The number of accidental coincidences was periodically measured by inserting a delay line in one of the branches of the coincidence scheme, thus ensuring the coincidence of the protons from one cyclotron pulse with the γ rays corresponding to the following one. The rate of the accidental coincidences determined in this manner agrees, within statistical fluctuations, with the calculated one. The number of coincidences was monitored at a preset number of counts in the proton detector.

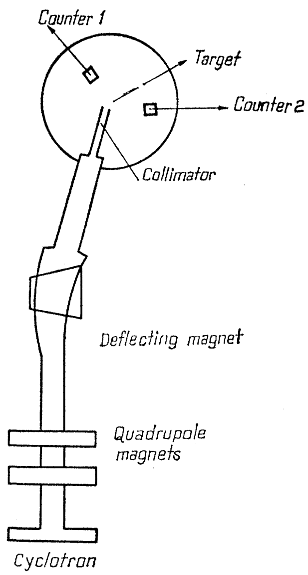

FIG. 1. Block diagram of the cyclotron scattering system.

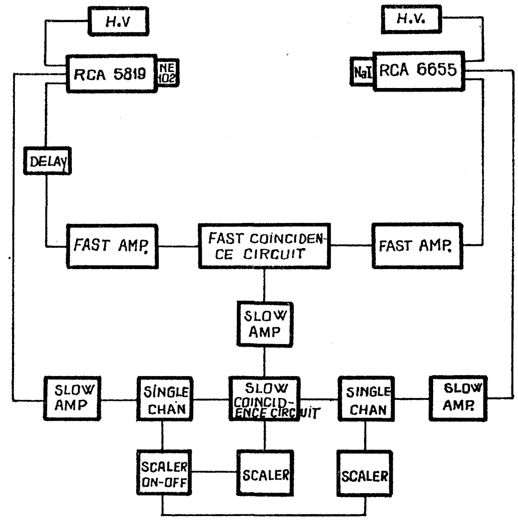

FIG. 2. Block diagram of the slow-fast coincidence circuit.

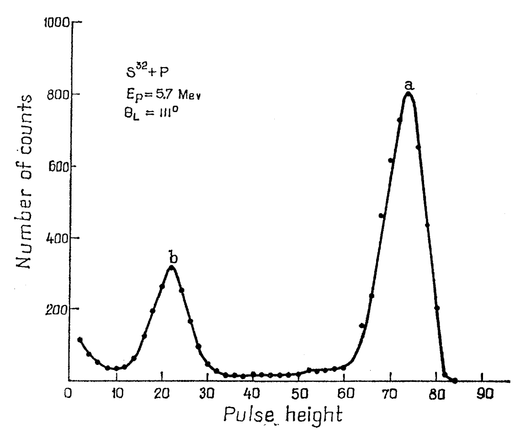

FIG. 3. Spectrum of 5.7-Mev protons scattered from a sulfur target at a counter angle of 111°.

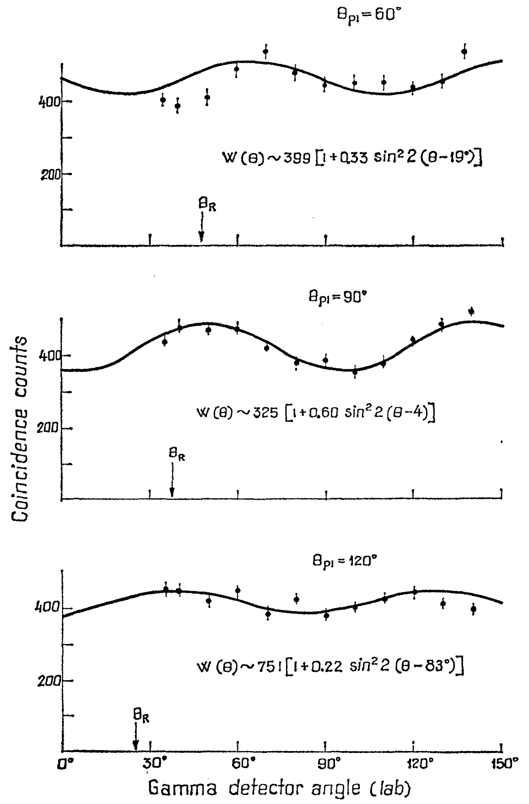

FIG. 4. $S^{32}(p,p'\gamma)$ angular correlation at an incident beam energy of 5.7 Mev. θ_R is the nuclear recoil direction.

III. RESULTS

The angular correlation functions measured on S^{32} by Hausman, Dell, and Bowsher[3] at 6.5 Mev and by Taketani and Alford[5] at 5.85 and 6.9 Mev, display a symmetry axis close to 90°; a slight dependence of the proton detector angle may be noticed. The experimental data are therefore consistent with CN as well as with a DI. As the contributions of the two mechanisms are energy dependent, we decide to investigate the effect thoroughly, by measuring the angular correlation on S^{32} at different incident proton energies.

An energy spectrum of the protons scattered by S^{32} is shown in Fig. 3. The peak *a* corresponds to the protons elastically scattered by sulfur, whereas the peak *b* corresponds to the protons which leave the S^{32} nucleus in its 2.25-Mev first excited state. The window of the proton analyzer is set to bracket the peak *b* completely, whereas the threshold of the γ-ray analyzer is set to count all the ray pulses of energies higher than 1 Mev. In Figs. 4–7 the results obtained in measuring the angular correlations at incident proton energies of 5.7, 6.02, 6.2, and 6.34 Mev and at proton scattering angles $\theta_{p'}$ of 60°, 90°, and 120° are shown; at 6.02 Mev a measurement has also been carried out at 150°.

The experimental points are shown with their statistical standard deviation. Each correlation curve represents an average over at least 3 runs. The consistency of the data corresponding to the curve drawn at 6.02 Mev and $\theta_{p'} = 120°$ has been checked by repeating the measurements after a fortnight lapse; the agreement with the previous runs was found to be very good. The smooth curves in these figures represents the best least-squares fits to the experimental points. The angular correlation functions on each figures have been corrected by taking into account the finite solid angle of the γ-ray detector.[9] The θ_R angle corresponds to the classical nuclear recoil direction, while θ_0 represents the symmetry axis of the measured correlation curves.

The results obtained in correlation measurements at 5.7 and 6.02 Mev indicate a strong dependence of θ_0 on the recoil direction of the nucleus. The shift of the symmetry axis proceeds in the same sense as that of the recoil direction. It should be mentioned that at 6.02 Mev the symmetry axis θ_0 closely follows the recoil

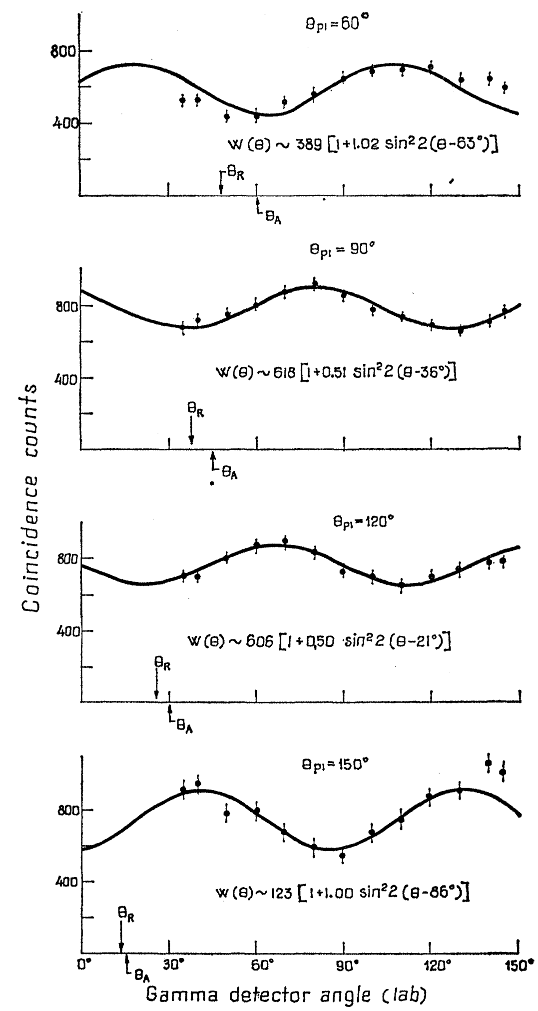

FIG. 5. $S^{32}(p,p'\gamma)$ angular correlation at an incident beam energy of 6.02 Mev. θ_R is the nuclear recoil direction and θ_A is the adiabatic axis of symmetry.

[9] M. E. Rose, Phys. Rev. **91**, 610 (1953).

direction θ_R and the adiabatic symmetry axis θ_A. This fact proves that the DI is dominant at these energies. The correlation curves on S^{32} obtained at 6.34 Mev are approximately symmetric around 90° in agreement with the conclusions following from the compound nucleus theory, thus suggesting the existence of a strong resonance in the compound Cl^{33} nucleus. At 6.2-Mev incident proton energies the correlation curves, although having the form (1), are characterized by a symmetry axis θ_0 which shifts without any apparent rule when the proton detector angle is changed. It is very possible that owing to the spread in the incident beam energy the form of the correlation curve is disturbed in the vicinity of the 6.34-Mev resonance.

IV. CONCLUSIONS

The angular correlation measurements reported in this work (the one at 6.34 Mev being excepted) indicate the presence of a DI in the (pp') reaction on the even-even S^{32} nucleus. The existence of a small number of decay modes of compound nucleus allows, however, for some CN contribution, which may be important. For even-even nuclei the DI dominates if the reaction involves a collective excitation of the rotational or vibrational states of the deformed nucleus. From this point of view our results seem to confirm the conclusion drawn by Hausman, Dell, and Bowsher,[3] namely that this is the interaction mechanism responsible for the direct reaction and not the nucleon-nucleon collision. At an incident proton energy corresponding to a resonance in the compound nucleus, the contribution of CN increases considerably and the angular correlation displays the corresponding features, e.g., symmetry around 90°.

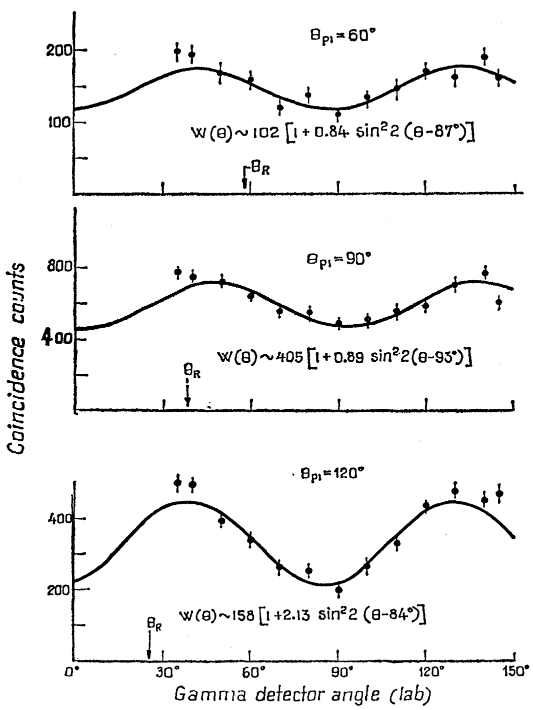

FIG. 6. $S^{32}(p,p'\gamma)$ angular correlation at an incident beam energy of 6.2 Mev. θ_R is the nuclear recoil direction.

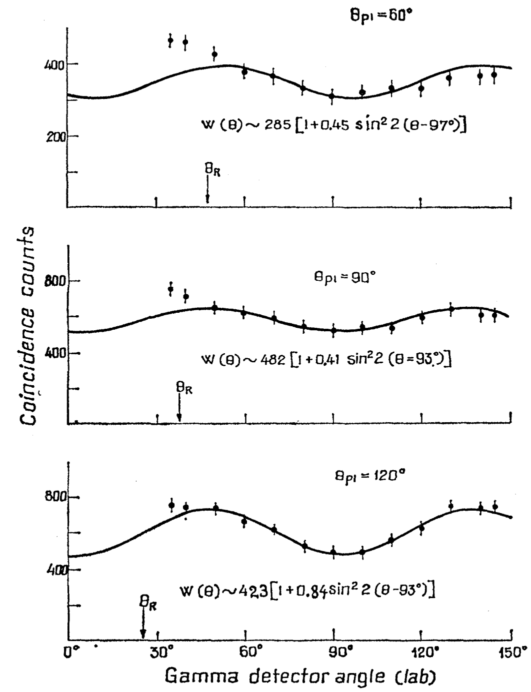

FIG. 7. $S^{32}(p,p'\gamma)$ angular correlation at an incident beam energy of 6.34 Mev. θ_R is the nuclear recoil direction.

The analysis of the angular correlation curves at 6.34 Mev suggests the existence of a strong resonance in the compound Cl^{33} nucleus. The existence of such a resonance is also confirmed by the energy dependence of the cross section of the $(p,p'\gamma)$ reaction.[10] A similar anomaly in the behavior of the angular correlation curves at resonance energies has also been noticed by Bowsher, Dell, and Hausman[4] for Si^{28}. These authors assert a DI character of the correlation curves between 5.8 and 6.7 Mev, but at 7.0 Mev the corresponding curve is symmetric around 90° owing to a resonance in the compound P^{29} nucleus.

It should be mentioned, however, that for the Mg^{24} nucleus investigated by Seward[1] the DI character of the correlation curve is not destroyed by the 6.66-Mev resonance, the θ_0 axis closely following the recoil axis. It is quite possible that in this case owing to the strong deformation of the Mg^{24} nucleus, the DI plays a principal role even at resonance energies.

ACKNOWLEDGMENTS

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