FINAL-STATE INTERACTIONS IN THE REACTION $He^3(He^3, 2p)He^4$†

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Final-state interactions in the reaction $He^3(He^3, 2p)He^4$ have been studied in a number of recent experiments[1,2] by measuring both p-p and p-α coincidence spectra. These investigations have shown that the dominant process in this reaction is the sequential decay through the $\frac{3}{2}^-$ Li^5 ground state. They produced no good evidence for a strong proton-proton interaction corresponding to the singlet state of the two-proton system similar to that observed for the singlet state of the deuteron.[3,4] In order to look at this interaction more closely, we have observed p-p coincidence spectra at smaller angles between the two protons and at lower incident energies than used by the previous workers. Two sets of measurements were made, the first using a 1.15-MeV He^{3+} beam from the University of British Columbia Van de Graaff accelerator, and the second using a 5-MeV He^{3+} beam from the Chalk River tandem accelerator. The proton-proton interaction can be seen in the small-angle spectra and preliminary calculations indicate that a nuclear attraction between the two protons must be considered as well as the Coulomb repulsion in order to explain the observed structure.

The protons were observed with two solid-state detectors mounted inside a He^3 gas target chamber so that the detectors and the active target volume defined a plane perpendicular to the beam axis (Fig. 1). One detector could be rotated with respect to the other in this plane. The reaction volume was determined by a cylindrical slit concentric with the beam axis, and the active area of the detectors. Detectors with an angular resolution of 11° were used in most of the measurements. With this configuration the minimum accessible angular separation of the geometrical axis of the detectors was 22°. In order to observe p-p coincidences at even smaller angles between the two protons, two fixed detectors of angular resolution 4°, mounted with an average separation of 6°, were used. With a beam current of 0.25 μA the counting rates were typically 2-20 coincidence events per minute, depending on the beam energy and detector angles used. The coincidence-resolving time of 20 nsec was sufficiently short to yield a negligible random-coincidence rate.

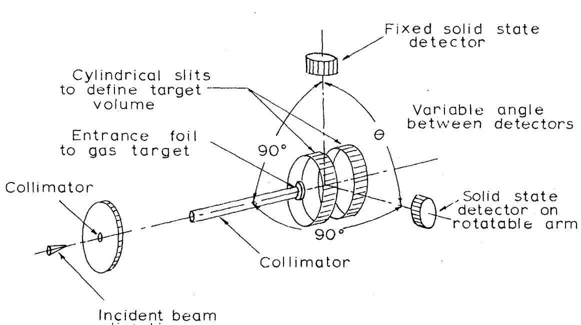

FIG. 1. Schematic diagram of detector-target arrangement.

Two-dimensional coincidence spectra (T_{p_1} vs T_{p_2}) were accumulated in a 60×60 array using a PDP-1 computer which was also programmed to display the theoretical kinematic contours simultaneously with the experimental events. The contours are of the form

$$T_{p_1} + T_{p_2} + a(T_{p_1} T_{p_2})^{1/2} \cos\theta = b,$$

where θ is the angle between the directions of protons 1 and 2, and a and b depend on the particle masses, the incident energy, and the reaction Q value.

Proton-alpha coincidences were removed either by being rejected because they produced events in regions which were kinematically forbidden to p-p coincidences, or by using a thin foil in front of the detectors to stop the alpha particles. The latter method had to be used at large angles between the protons where the p-p and p-α contours overlap. A typical two-dimensional spectrum is shown in Fig. 2 for an angle of 6° between the detectors. The solid curve represents the kinematically allowed energies for p-p coincidences at this angle. Some p-α coincidences can be seen just above the lower discrimination level. Also shown in Fig. 2 are the energy histograms obtained by summing the p-p events lying within a nine-channel interval along the kinematic contour.

Similar histograms were obtained for runs at different angles between the detectors and at different incident energies. These histograms,

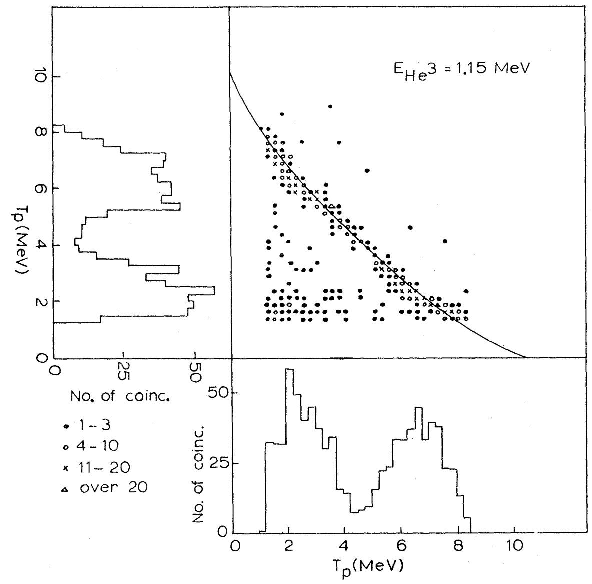

FIG. 2. Proton-proton coincidence spectra for an angle of 6° between the protons, both protons observed at an angle of 90° with respect to the beam direction. The energy histograms represent the projections of events along the predicted contour onto the proton-energy axes.

normalized to the same number of single-proton events in both detectors, are shown in Fig. 3 as a function of the angle between the detectors for incident energies of 1.15 and 5.00 MeV. Since the results for $\theta = 6°$ were obtained using a different set of detectors, the normalization of this spectrum to the other spectra can only be considered accurate to 20%. The normalization was obtained using an alpha source located at the target volume to determine the solid angles subtended by the two different counting systems.

We have calculated the shapes of the energy spectra expected from the final-state interactions using the generalized density-of-states function of Phillips, Griffy, and Biedenharn.[5] This formalism treats the three-particle breakup as a well-separated time sequence of two-body decays through an intermediate state. The energy dependence of the interaction is contained in the density-of-states function which is given by

$$\rho(E_{p\alpha}) = \frac{1}{\pi}\frac{d}{dE_{p\alpha}}(a^+\beta_1{}^+ + a^-\beta_1{}^-)$$

for the Li^5 system, and by

$$\rho(E_{pp}) = \frac{1}{\pi}\frac{d}{dE_{pp}}(a_0\beta_0)$$

for the p-p system. Here $\beta_1{}^+$ and $\beta_1{}^-$ are the nuclear phase shifts for the $J=\frac{3}{2}$ and $J=\frac{1}{2}$ states of Li^5 (the sum of the corresponding p-wave phase shift for proton-He^4 elastic scattering and the hard-sphere phase shift) and a^+ and a^- are the relative contributions of the two states. Similarly, β_0 is the nuclear phase shift for s-wave proton-proton scattering.

The calculated energy spectra, after the transformation from the center of mass of the intermediate system to the corresponding laboratory energies of the final-state protons, are shown in Fig. 3, superimposed on the experimental results. The solid curves represent the contribution from the states in Li^5 and the dotted curves represent the summed spectra when the contribution from the singlet p-p state is added. Kinematics effectively separates the contributions from the two processes, the p-α interaction important for large angles between the protons and the p-p interaction important only for angles below about 60°.

The relative contribution of the two states in Li^5 was adjusted for the best fit at $\theta = 180°$. The ratios chosen were $a^+/a^- = 0.5$ for $E_{He^3} = 1.15$ MeV and $a^+/a^- = 4.0$ for $E_{He^3} = 5.0$ MeV. The contribution from the singlet p-p state was normalized to fit the results at $\theta = 6°$. The calculations for the breakup through Li^5 give a reasonable fit to the data for the angles at which this process is important. The observed deviations may in part be due to the assumption that the breakup of the intermediate state is isotropic. There is also a loss of coincidence events at both ends of the spectra due to the foil in front of the detectors which was not considered in the calculations.

The states in Li^5 cannot account for the shape of the spectra observed at angles less than 60°. The density-of-states formalism using the singlet p-p phase shifts predicts the two peaks observed experimentally at $\theta = 6°$. The dip in the cross section is due to the fact that coincidence events observed with $\theta = 6°$ and $T_p = 4.5$ MeV correspond to an excitation in the two-proton system of 25 keV, well below the Coulomb barrier. There is some er-

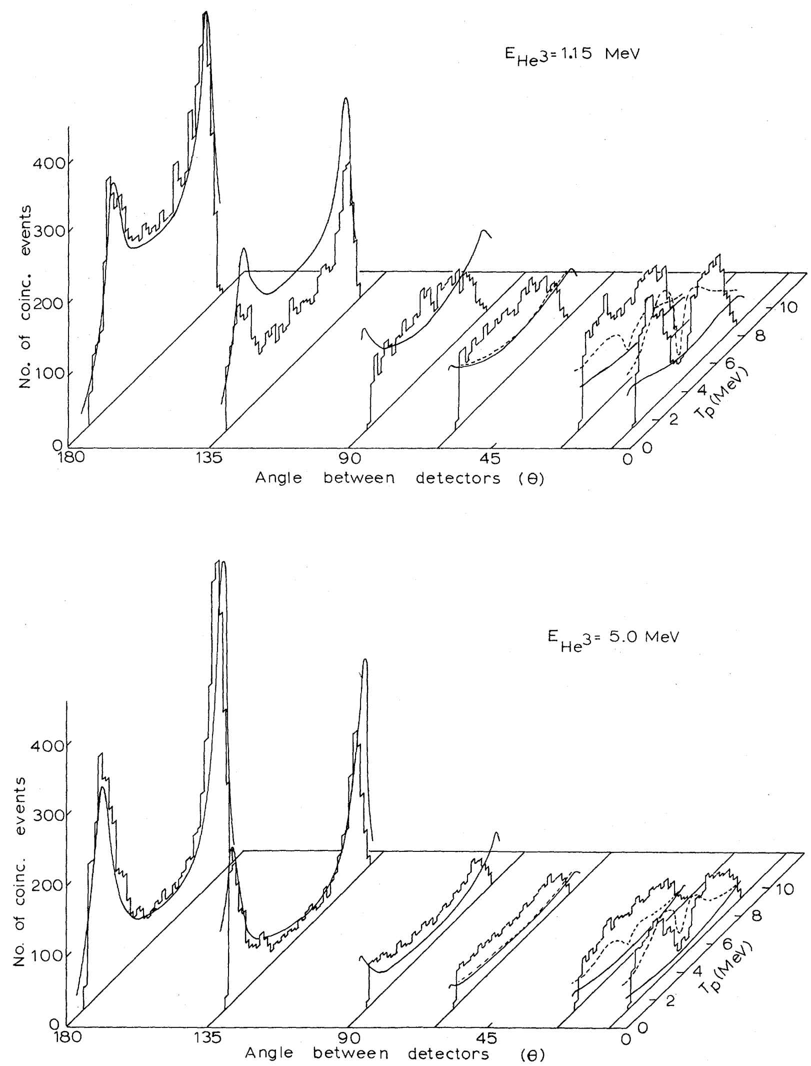

FIG. 3. Isometric projection of coincidence spectra as a function of angle between the detectors. The spectra were taken with He^3 bombarding energies of 1.15 and 5.0 MeV.

ror in the positions of the calculated peaks as well as the relative intensity at other angles. This is not unexpected as the short interaction time involved in the singlet p-p state would make the breakup considerably more complicated than a well-separated time sequence of two-body decays. Further theoretical as well as experimental work is under way in order to get a better understanding of the final-state proton-proton interaction.

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