The He^3 (He^3, $2p$)He^4 Reaction*

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The $He^3(He^3, 2p)He^4$ reaction has been studied at a bombarding energy of 4.9 MeV by measuring the energy spectra of all pairs of reaction products detected in coincidence. The measurements were performed using the singly charged He^3 beam from the 5.5-MeV Van de Graaff accelerator of the Bonner Nuclear Laboratories. The beam, having an initial energy of 5.5 MeV, entered a cylindrical cell filled with He^3 gas to a pressure of 20 cm Hg through a molybdenum-foil window 1.4 mg/cm^2 thick. The reaction products emerged from the cell through a continuous slot in its wall which was covered with a 0.9-mg/cm^2-thick Mylar foil. These particles were detected by lithium-drifted solid-state detectors which viewed the reaction volume through rectangular slits having an angular resolution of 8.8°. The chamber is illustrated in Fig. 1. In the measurements, one counter was fixed at 60° with respect to the beam direction and the other counter was positioned successively at 40°, 60°, 75.1°, 80°, and 100° on the opposite side of the beam. The reaction energy available at these angles was continuous to about 15 MeV for protons and 7 MeV for alpha particles. Experimentally, protons above 1 MeV and alpha particles above 2.5 MeV could be detected. A third counter, fixed at 30°, monitored the reaction by measuring the yield of elastically scattered He^3 particles.

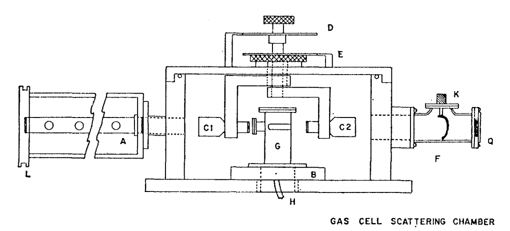

FIG. 1. Diagrammatic view of the scattering chamber used in the measurements. The counters, C1 and C2, can be independently located. The gas cell, G, is described in the text. A denotes a device for defining the beam direction.

The proton–proton and the proton–alpha energy correlations were recorded by an on-line, two-dimensional computer–analyzer system[1] which was gated by signals from a Cosmic coincidence circuit operating at a resolving time of 0.15 μsec. The background of accidental coincidences in the spectra was recorded in parallel by the same computer–analyzer gated by an identical coincidence circuit except that one input signal was delayed by 0.3 μsec. The coincidence timing was set using p–p coincidences from the elastic scattering of protons from hydrogen and p–α coincidences from the $D(He^3, p)He^4$ reaction. A block diagram of the electronics is shown in Fig. 2. Measurements of the spectra at each of the five pairs of angles were made consecutively with constant amplifier gain. An internally consistent energy scale was derived by fitting each of the 13 useful p–p and p–α spectra obtained with the calculated kinematic locus to which it corresponded. The resulting energy scale was thus subject to these 13 constraints and is believed accurate to ±150 keV.

The spectra are projected as functions of the energy of the detected proton in order to examine the variation of intensity along the three-body locus. These projections are shown in Figs. 3 and 4. In certain regions of the spectrum the curves may overlap, which precludes accurate separation of the events for projection purposes. In these regions the projections have been drawn with dashed lines. The axes, T_1 and T_2, refer to the energy of the proton detected in the 60° fixed counter and the movable counter, respectively.

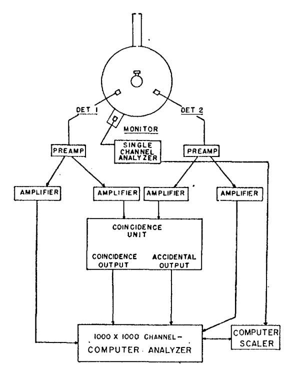

FIG. 2. Block diagram of the electronics system.

In the study of the mechanism of a reaction involving three particles in the final state, it is desirable to determine the fractions of the reaction cross section for a direct transition to the final state and for delayed transitions, due to final-state interactions, through various intermediate states. In the present instance, the possible intermediate states are the broad $\frac{3}{2}^-$ and $\frac{1}{2}^-$ levels in Li^5 and the singlet state of the two-proton system. The presence of the $\frac{3}{2}^-$ Li^5 ground state in the spectra is readily apparent. However, in the case of the $\frac{1}{2}^-$ first excited state, due to its large width (3–5 MeV), no discernible peak can be expected. In addition, there is no obvious method of separating the

* Supported in part by the U. S. Atomic Energy Commission.
[1] A. C. L. Barnard, R. Keyes, J. Buchanan, T. A. Rabson, and G. C. Phillips, Bull. Am. Phys. Soc. 9, 488 (1964).

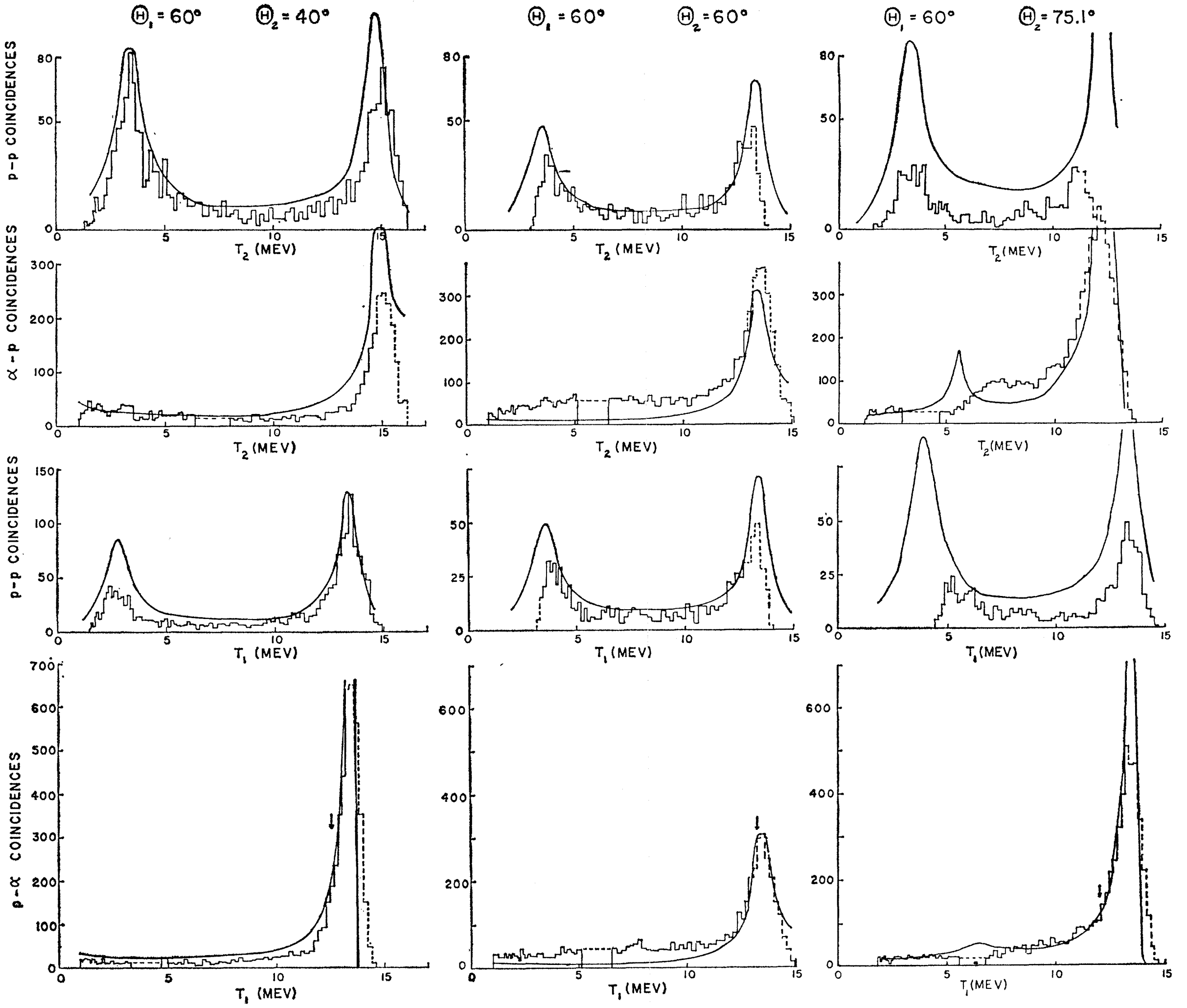

FIG. 3. Projections of the coincident yield at moving counter angles of 40°, 60°, 75.1° for a fixed counter angle of 60°. The curves are calculations of the energy spectra using a form of the generalized density of states. An arrow indicates the normalization point for each set of spectra.

contribution from this level from that of the direct transition.

We have calculated the shape of the energy spectra at the angles measured, assuming the energy dependence of the final-state interaction to be given by the Phillips, Griffy, and Biedenharn[2] generalized density-of-states function. For the reaction mechanism

$$a+A\rightarrow b+B^*\rightarrow b+c+C, \qquad (1)$$

the cross section is given by

$$\sigma=\frac{\mu_a\mu_b k_b}{4\pi^2\hbar^4 k_a}\mid\langle b+B\mid H'\mid a+A\rangle\mid^2\rho(E) \qquad (2)$$

with

$$\rho(E_{p\alpha})=\pi^{-1}(d/dE)(\delta_1{}^{+}+\delta_1{}^{-}+2\phi_1) \qquad (3)$$

for the Li^5 system, and

$$\rho(E_{pp})=\pi^{-1}(d/dE)(\delta_0+\phi_0) \qquad (4)$$

for the p–p system. In the curves shown, the relative contributions for the various intermediate states have been taken to be unity for the Li^5 levels and 1% for the two proton system. $\delta_1{}^{+}$ and $\delta_1{}^{-}$ are the elastic scattering phase shifts for the $J=\frac{3}{2}$ and $J=\frac{1}{2}$ scattering of protons from He^4.[3] δ_0 is the phase shift for s-wave elastic proton–proton scattering.[4] The hard-sphere phase shifts, ϕ_L, are evaluated at 3 F for the p–α system and 2.5 F for the p–p system. The energy spectra

[2] G. C. Phillips, T. A. Griffy, and L. C. Biedenharn, Nucl. Phys. **21**, 327 (1960).

[3] A. C. L. Barnard, C. M. Jones, and J. L. Weil, Nucl. Phys. **50**, 604 (1964), and references contained therein.

[4] G. C. Phillips (private communication); L. Hulten and M. Sugawara, *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1957), and references therein; D. J. Knecht, S. Messelt, E. D. Berners, and L. C. Northcliffe, Phys. Rev. **114**, 550 (1959).

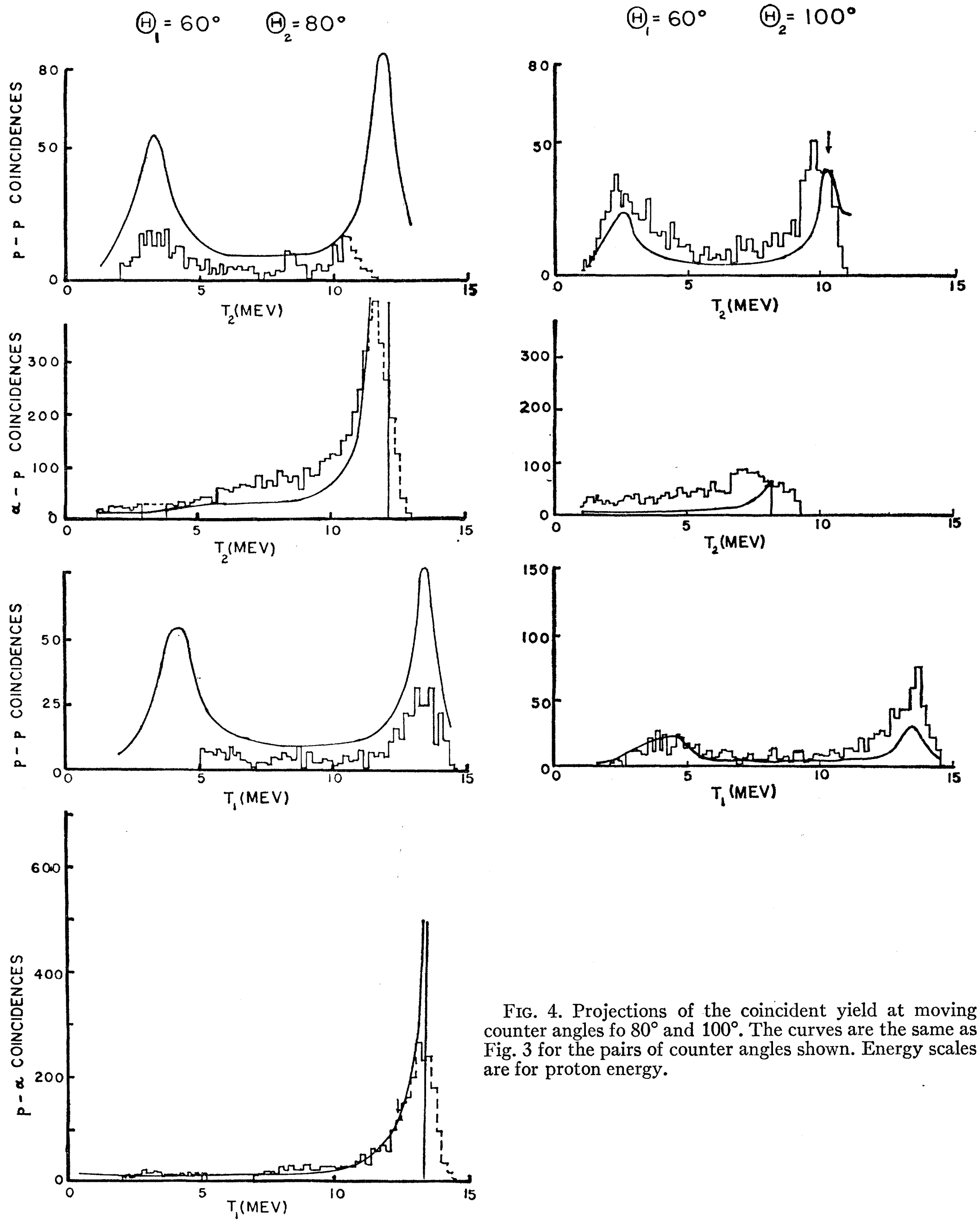

Fig. 4. Projections of the coincident yield at moving counter angles fo 80° and 100°. The curves are the same as Fig. 3 for the pairs of counter angles shown. Energy scales are for proton energy.

shown are the sums of cross sections for each process after these cross sections are transformed to laboratory coordinates.

The calculations show peaks at the proper positions for decay through the Li^5 ground state. However, because of the inexactness of the fits obtained, no quantitative statement concerning the reaction mechanism can be made at this time. Calculations employing other formulations of the final state interaction and investigation of the effects of angular correlations on the spectra are being carried out.

Discussion

Bacher: Have you seen any indications of interference effects as mentioned by Dr. Phillips in his first talk?

Aldridge: No; we have not seen any definite indication of interference.

BAHTIA: Why was molybdenum preferred for the entrance window rather than Mylar?

ALDRIDGE: Mylar could not withstand the heating from the incident He^3 beam.

ZUPANČIČ: Did you see any indication of a proton–proton interaction in your data?

ADRIDGE: The data for $\theta_2=75.1°$ shows, perhaps, some indication of a very weak proton–proton interaction. This angle is near the recoil axis for a zero relative energy diproton. At other angles, the curves fall smoothy from the Li^5 g.s. peak, but here, there appears to be an enhancement of the yield below the peak to about 7 MeV.

TEMMER: The next paper bears on the same subject, so perhaps there will be additional discussion then.

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p–He^4 Final-State Interaction in $He^3(He^3, 2p)He^4$ †

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INTRODUCTION

The $He^3(He^3, 2p)He^4$ reaction, leading to a three-body final state consisting of an alpha particle and two protons, has been investigated at bombarding energies from 3 to 18 MeV using a He^3 beam from the ONR–CIT tandem accelerator. The motivation for this work has been twofold; to gain an understanding of the reaction mechanism over a wide range of bombarding energy and to develop a consistent method for determining the total reaction cross section that can be extended to lower bombarding energies. What follows is a preliminary report dealing with general features of the experimental results.

Two target configurations were employed in the experiment. For single-counter angular distributions below 12 MeV, the He^3 gas target was contained at a typical pressure of 0.03 atm in a 25-cm-diam gas scattering chamber with an entrance window of 1000-Å nickel foil before the beam collimator and an exit window of 6250-Å nickel foil in front of the Faraday cup. A solid-state $(dE/dx)-E$ telescope consisting of a 48-μ surface-barrier transmission detector and a thick lithium-drifted silicon detector was operated within the He^3 gas target. For single-counter results above 12 MeV and for coincidence spectra, a small gas cell with entrance and exit windows of 2.3-mg/cm² Haver foil was positioned in the center of the large chamber and operated at a typical He^3 target pressure of 0.5 atm.

SINGLE-COUNTER SPECTRA

Single-counter results in the form of separate proton and alpha-particle energy spectra have been obtained at laboratory angles between 15° and 160° for bombarding energies from 3 to 15.6 MeV. The counter telescope was able to separate protons and alpha particles with energies down to 2 MeV. Since the final-state Q value for this reaction is +12.86 MeV, the telescope enabled a major portion of the energy spectrum for each particle to be separated, regardless of the angle or bombarding energy.

The proton spectra are all characterized by a pronounced peak at the high-energy end, corresponding to a sequential decay through the $\frac{3}{2}^-$ Li^5 ground state. In order to determine that portion of the reaction which proceeds through the ground state, this high-energy proton peak is fitted with a spectral shape calculated from the phase shifts[1] for the scattering of protons from He^4. The method employed in calculating the spectral shapes[2] involves the use of a generalized form of the spectral measure function derived by Gel'fand and Levitan.[3,4] This function can be shown to represent an accurate approximation in sequential decay processes where the final state interaction of the first particle may be neglected.

Figure 1 shows a typical proton energy spectrum obtained at a He^3 bombarding energy of 9.94 MeV and a laboratory angle of 20°. The dots represent the experimental data and the solid curve represents the fitted spectral shape. A fit was obtained by matching the area under the theoretical curve above the vertical dashed line to the number of experimental counts greater than that energy. The arrows bracketing a region at the low-energy end of the spectrum indicate the range of proton energies expected at this angle from the subsequent breakup of the Li^5 ground state (calculated here for the resonance energy of the state).

† Supported by the U. S. Office of Naval Research [Nonr-220(47)].

[1] A. C. L. Barnard, C. M. Jones, and J. L. Weil, Nucl. Phys. **50**, 604 (1964).
[2] T. A. Tombrello, Bull. Am. Phys. Soc. **9**, 704 (1964).
[3] I. M. Gel'fand and B. M. Levitan, Izv. Acad. Nauk SSSR, Math. Ser. **15**, 309 (1951).
[4] R. G. Newton, J. Math. Phys. **1**, 319 (1960).