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)].

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[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).

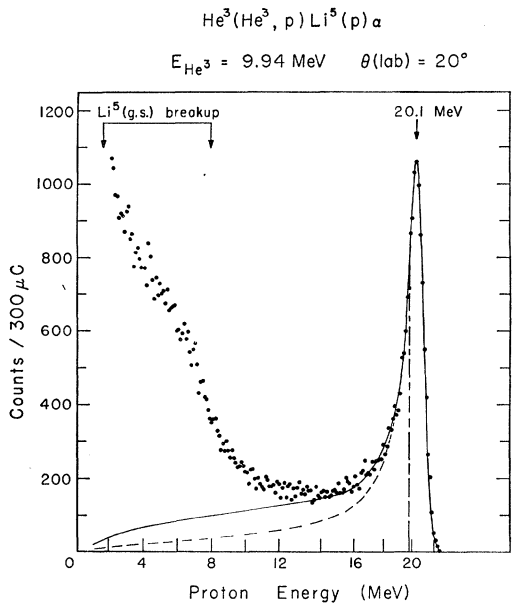

FIG. 1. A typical proton spectrum taken at a He^3 bombarding energy of 9.94 MeV and a laboratory angle of 20°. Solid dots represent counts per channel in the observed spectrum. Fitted curves take into account the nonlinear conversion from channel number to particle energy. The solid curve is calculated from the spectral measure function as described in the text and the dashed curve is that obtained from the R-matrix expression. The two curves merge and exhibit the same form over the region of the sharp peak at 20.1 MeV.

The fit to the observed spectrum over the region from 12 to 18 MeV in the proton energy was significantly improved over that given by the usual R-matrix expression[5] by the use of the spectral measure function technique. (A direct comparison of these fits is made in Fig. 1.) Since this is the region where one would expect to see the effects of sequential decay through the broad $\frac{1}{2}^-$ first excited state in Li^5, it is apparent that the nature of the fit in this region is important for an understanding of the reaction mechanism.

Figure 2 shows a proton spectrum taken at a bombarding energy of 15.56 MeV and a laboratory angle of 20°. The high-energy proton group appears narrower here because of the extreme nonlinearity of the energy scale at the high-energy end. The double peaking of those protons from the decay of the Li^5 ground state reflects the fact that this decay is peaked forward and backward along the direction of the Li^5 recoil. This effect is seen only at high momentum transfer because at lower momentum transfers the width of the ground state causes the two peaks to overlap strongly.

Absolute differential cross sections, subject to the systematic errors inherent in the fitting procedure, have been derived from these spectral fits for that portion of the reaction that proceeds through the Li^5 ground state. Properly transformed to the center of mass, these angular distributions are symmetric about 90°, as expected for identical particles in the initial state. The deviation from isotropy of these center-of-mass curves is not large (≈15% at 4 MeV), but it tends to increase slightly with increasing bombarding energy.

COINCIDENCE SPECTRA

In addition to the singles spectra, p–α and p–p coincidences have been investigated at a He^3 bombarding energy of 9.91 MeV for a variety of angle pairs, using a second thick counter in conjunction with the counter telescope. Conventional coincidence techniques with a resolving time of 200 nsec were used with a 64×64 two-dimensional multichannel analyzer. Similar runs were made with a large delay in one side of the coincidence circuit to determine the effects of random coincidences.

Figure 3 shows p–α coincidences for a proton angle of +100° and an alpha-particle angle of −30°. The solid curve represents the kinematically allowed energies for p–α coincidences at this pair of angles. Points along this curve correspond to particular relative energies between pairs of particles in the final state. The spread of experimental counts across this curve is due to the finite angular resolution of the two counter collimators (±4° for each collimator). For this case the angles were selected to give a maximum coincidence counting rate for the ground state transition, repre-

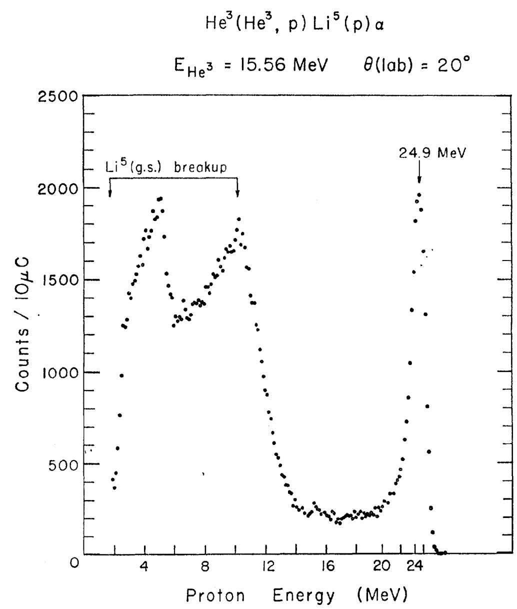

FIG. 2. Proton spectrum for a He^3 bombarding energy of 15.56 MeV and a laboratory angle of 20°. See Fig. 1 and text for discussion.

[5] A. M. Lane and R. G. Thomas, Rev. Mod. Phys. **30**, 257 (1958).

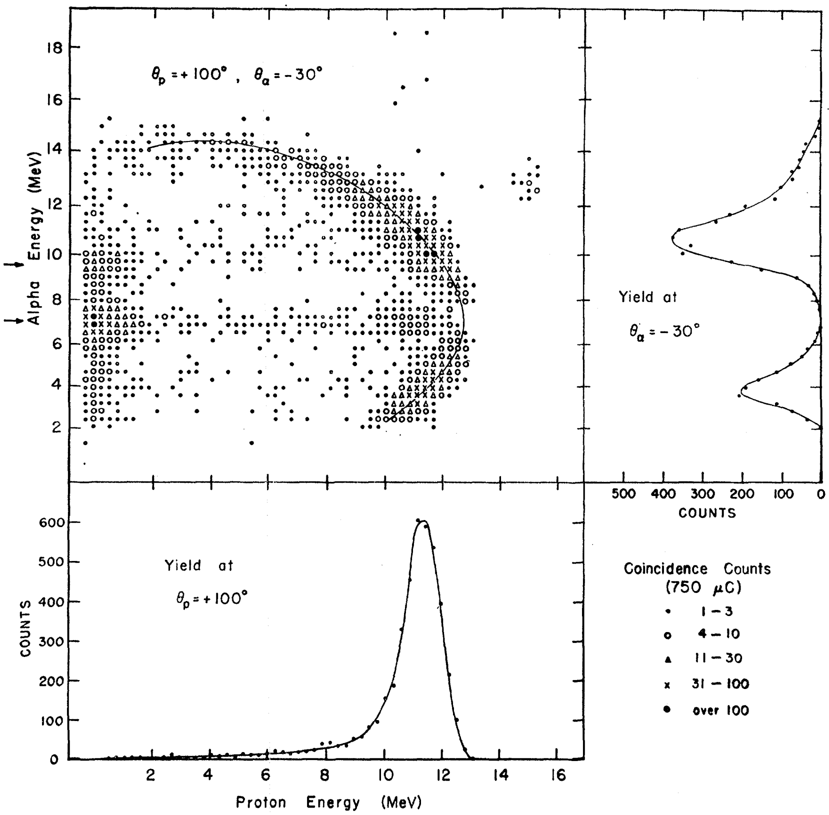

FIG. 3. Proton and alpha-particle coincidences for a proton angle of $+100°$ and an alpha-particle angle of $-30°$ with respect to the beam direction. The spectrum was taken with a He^3 bombarding energy of 9.91 MeV.

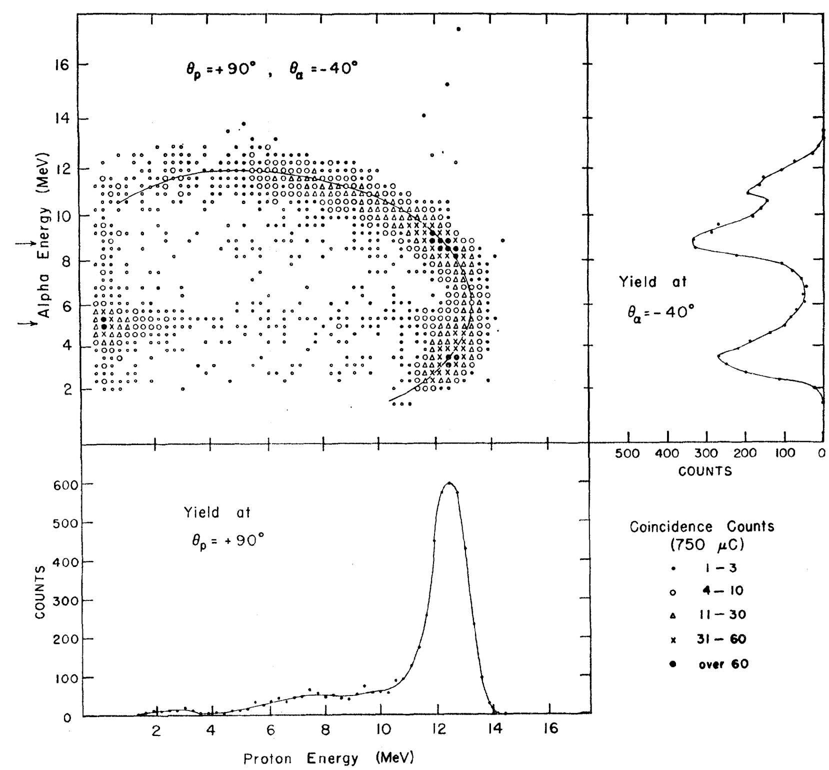

FIG. 4. Proton and alpha-particle coincidences for a proton angle of $+90°$ and an alpha-particle angle of $-40°$. See Fig. 3 and text for discussion.

sented in the spectrum by the two regions of enhanced counting rate for a proton energy of 12 MeV and alpha-particle energies of 5 and 10 MeV. The points shown are the raw data with randoms [indicated here by arrows at $E(\alpha)=7$ and 9.5 MeV] due to He^3's elastically scattered from the gas and the gas cell foil into the forward alpha detector. In the sum spectra the randoms have been subtracted. The sum spectrum for the proton yield shows the sharp peak due to the ground-state reaction mode. The isolated group of coincidence counts at a proton energy of 15 MeV and an alpha-particle energy of 13 MeV is due to the reaction $D(He^3, p)He^4$ arising from a slight deuterium contaminant in the target gas.

Figure 4 shows a $p-\alpha$ coincidence spectrum for a proton angle of $+90°$ and an alpha-particle angle of $-40°$. The ground-state transition again shows up quite prominently. Of particular interest in this spectrum is the region represented by a proton energy of 5 MeV and an alpha-particle energy of 12 MeV. This region corresponds to a low p–p relative energy—down to a few keV. The absence of counts in this region indicates the lack of importance of a strong p–p final-state interaction in the reaction mechanism at these energies. The sum spectrum for the proton side again shows the peak characteristic of the ground-state transition. The extra peak that appears in the alpha-particle coincidence yield shows the misleading effects one can produce by summing across a coincidence spectrum in which the allowed curve becomes perpendicular to one axis.

CONCLUSION

It is of interest to note that, while there is sufficient energy available in the intermediate state for additional final-state interactions to occur, this reaction maintains a particular sequential decay mechanism over a rather broad energy range. It appears, from appropriate fits to the singles spectra, that the major portion of the observed high-energy proton spectrum can be reconstructed on the basis of a sequential decay through the Li^5 ground state. The contributions to these spectra from the broad first excited state or from interference effects between the two states remain to be clarified.

Discussion

JARMIE: What is the He^3 bombarding energy where you do not see this proton–proton interaction?

BACHER: This was at a He^3 bombarding energy of 10 MeV.

JARMIE: In the magnetic analyzer experiments of tritons on tritons we did at Los Alamos some years ago, we distinctly saw the neutron–neutron interaction, but this was with a bombardment energy of 3 MeV.

BACHER: Right. And that was by looking in detail at the high-energy end of the alpha-particle spectrum, I believe.

JARMIE: Your data was a singles spectrum, too?

Bacher: No. We were referring to the coincidence spectrum of Fig. 4. We also plan to do this more carefully and get better resolution in the alpha-particle spectrum with a 180° spectrometer. We have looked for alpha particles which could correspond to protons coming off together with a low relative energy. These alpha particles would show up, because it is a region which is kinematically unfavorable for the sequential decay. We have not been able to see any effect as yet.

JARMIE: If I may continue for the moment. In the singles spectra where we did see the n–n virtual state, it was not strong at all, and I am not surprised that you had a problem of picking it up in the p–p case.

O'CONNELL: I think the experiment you described has been done recently by a group in Moscow in the recent *Physics Letters*, where they looked at the alpha singles with 20-MeV bombardment, and they do see a peak at the highest possible energy.

BACHER: Yes. I calculated some kinematics for the points they actually ran. The effect appears to be peaked sharply forward.

ZUPANČIČ: If we believe in the final-state interaction theory, then the diproton enchancement should be rather inconspicuous.

BACHER: We have looked carefully for some sign of an interaction, and have not been able to see any.

PHILLIPS: Apparently we have other points of disagreement, and one of these is whether or not there is such a thing as the diproton. It is a very poetic word, but I believe you will see a little bit later some evidence from Rice on the breakup of the three-nucleon system that does indeed indicate that there is something like a diproton.

DONOVAN: You must have been mistaken in your statement that you made that the kinematic region is inaccessible for the sequential process. The mechanism has nothing to do with the kinematics. There is no region that is allowed in one case and not allowed in the other. You can always postulate an energy level or a direct process and go to any allowed part of a kinematic region. It just depends on energetics. I was referring to your remark that you looked at the alphas, and if there were a diproton, you would get a peak which was removed kinematically above the allowed region for any sequential process. This can't be true.

BACHER: Yes; that is quite right. What I was saying was it was above the region where you expect a lot of counts due to the ground state of Li^5. You do see a sharp peak due to that transition at a lower alpha-particle energy.

DONOVAN: To amplify the diproton business a little bit: The discussion of Dr. Zupančič was presented on the basis of the known p–p interaction, but to get a little additional physical insight there was an argument made a while back that the diproton should be, if anything, sharper than the singlet deuteron, because if you prepare it in a final-state interaction it is created inside of a Coulomb barrier, and then has to penetrate out of it. And in fact this argument is very valid in many systems, but it is not valid for the S state of two nucleons, for the simple reason that the wave function is such that at low energies it is very much extended spatially, and in fact in the case of the diproton there is so much of the wave function outside of the Coulomb barrier that the presence of the barrier actually shortens the lifetime, rather than lengthening it, so this argument is specious. This gives a physical picture of why the diproton is very broad.