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T(T,2n)^{4}He and ^{3}He(^{3}He,2p)^{4}He: The Reaction Mechanism from Solar Energies to 10 MeV*

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Abstract. We have studied the energy dependence of the reaction mechanism of the T(t,2n)^{4}He reaction at stellar energies and of its charge symmetric analog reaction ^{3}He(^{3}He,2p)^{4}He at energies up 10 MeV. We find that the reaction mechanism changes dramatically over this energy range in part due to the interference of the two identical fermions in the three-body final state.

This contribution describes a study of the Charge Symmetric reactions T+T and ^{3}He+^{3}He carried out at the laser facilities OMEGA and the National Ignition Facility (NIF) and at the tandem accelerator facility at Cal Tech. The ^{3}He(^{3}He,2p)^{4}He reaction reaction is of scientific interest because it completes over 98% of the p-p reaction chain in the Sun. Describing and measuring these reactions is complicated by the three body final states ^{4}He+2n and ^{4}He+2p which contain identical fermions. At low energies the reaction mechanism is dominated by the $L = 0$ (s-wave) partial wave. The shapes of the energy spectra of the neutrons and protons are determined by the stronger nucleon-^{4}He interaction and the weaker nucleon-nucleon interaction.

At OMEGA and the NIF the neutron spectra were determined by very fast Neutron Time-of-Flight detectors (TOF) and by a Medium Resolution Spectrometer (MRS) with a CD_2 foil to convert the neutrons into deuterons which could be momentum-analyzed in the magnetic field. Track detectors positioned along the MRS focal could be analyzed after the run. The properties of these detectors have been determined by previous measurements of n+D and D+T reactions. At Cal Tech the proton energy spectra were determined by a pair of solid-state detectors that used standard particle identification techniques to separate the charge-one protons from the charge-two alpha particles. While the measurements at the laser facilities measured the total cross section, the measurements at the accelerator laboratory could be measured at different angles with respect to the beam allowing an angular distribution of the protons and α particles to be determined at each beam energy. The targets were also very different. At OMEGA and the NIF the high pressure gases (at about 8 atm) were contained in small (3-mm diameter) capsules. At the NIF these were positioned inside a holram to enhance the reaction yield. The targets were positioned at the center of a large reaction chamber and lasers impinged on the targets creating fusion as the capsules collapsed and heated rapidly. At Cal Tech the ^{3}He beam entered the gas-filled scattering chamber through a thin (2500 Angstrom) foil. It exited through

*This contribution is dedicated to the memory of Tom Tombrello, my Ph.D. advisor at Cal Tech, who died in 2014.

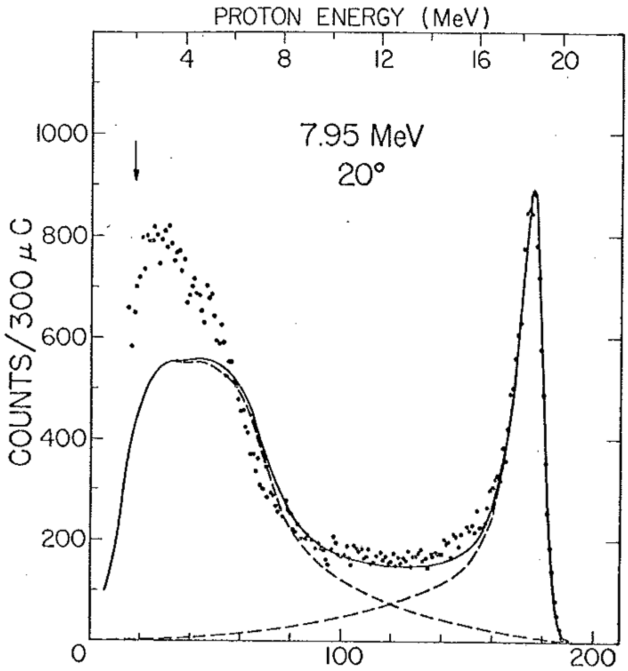

Figure 1. Proton energy spectrum measured at 20° and for a ^{3}He energy of 7.95 MeV [3].

a thicker foil so that the total charged could be integrated with a calibrated Faraday Cup, thus allowing the cross section for ^{3}He+^{3}He to be determined at each beam energy. The counter telescope could be positioned at angles with respect to the beam between 15° and 150°. State-of-the art detectors (in 1965) were used to stop the high-energy protons.

In addition to the s-wave initial state at the laser facilities, the energy spectra of the final state neutrons and protons are dominated by the strong nucleon-^{4}He final state interaction. This interaction is p-wave ($L = 1$) and has two components. The $3/2^-$ component corresponds to the ^{5}He ground state and the $1/2^-$ component corresponds to the ^{5}He excited state. Of less importance is the weaker n-n or p-p final state interaction. A new reaction model has been developed by Carl Brune at Ohio University, Dan Sayre at Lawrence Livermore National Laboratory, and by Gerry Hale at Los Alamos National Laboratory [1]. It is a based on an extended R-matrix which can handle both the three body final states and the presence of identical fermions.

Studies of the T+T reaction at solar energies provide an excellent account of the new measurements which were published recently in Physical Review Letters [2]. At solar energies the $1/2^-$ state is more strongly populated than the $3/2^-$ state by a factor of about 2:1. Fitting the low energy portion of the neutron spectrum also shows the importance of the oriented decay of the $3/2^-$ state. Because of the large energy available in the three-body final state, it is also possible that p-waves ($L = 1$) may play a role.

Gerry Hale has developed new reaction models to extend this work to higher energies. For spectra and calculations above 2 MeV we find that the $3/2^-$ state is more strongly populated than the $1/2^-$

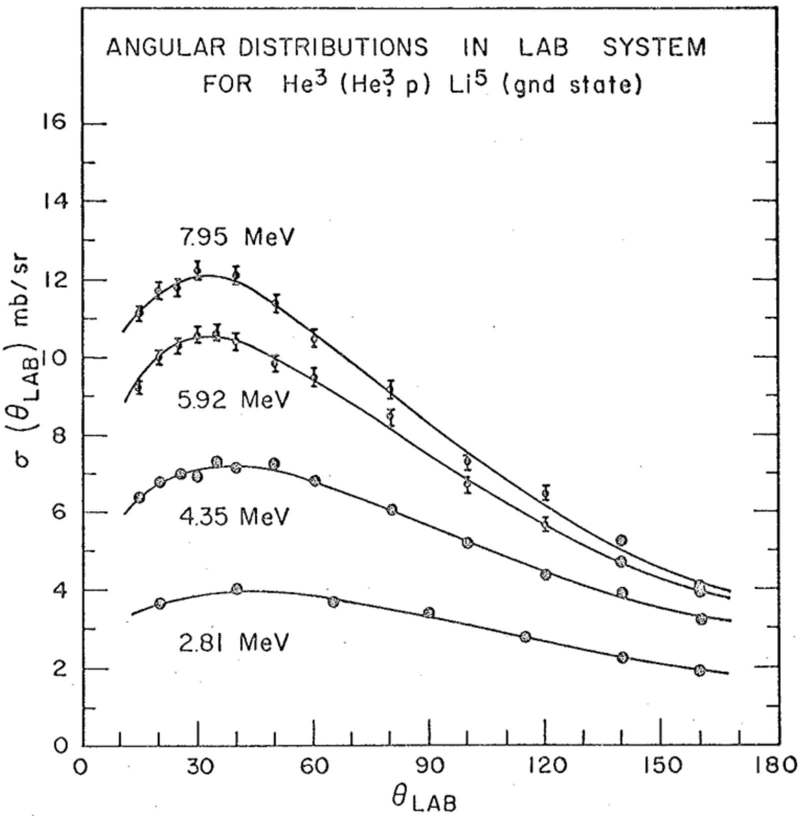

Figure 2. The evolution of the ^{3}He(^{3}He, p)^{5}Li(g.s) angular distribution with the incident ^{3}He energy [3].

state by a factor of about 2:1. This important difference from the factor at Solar energies is the result of including the interference terms for the identical fermions in the three-body final state. First we show several results from my Ph.D. thesis at Cal Tech [3]. In Figure 1, the proton spectrum at 7.95 MeV and 20° is fitted with a sequential decay model including the oriented decay of the recoiling ^{5}He nucleus which affects the shape of the proton spectrum below 6 MeV. The fit to the high energy portion of the spectrum is excellent. Next we show in Figure 2 angular distributions of this sequential decay model from 2.81 MeV up to 7.95 MeV. It is clear that the p-wave contribution is increasing with increasing energy. Finally, in Figure 3, we show a two dimensional plot of proton energy spectra at 20° from between 4 MeV and 18 MeV. Note how the overall yield increases dramatically above 12 MeV. There are some deuterons above 12 MeV due to the d+d final state.

Studies of the Charge Symmetric Reactions T+T and ^{3}He+^{3}He have shown how recent improvements in both experiment and theory have led to a new understanding of these reactions at Solar energies. For the ^{3}He+^{3}He reaction above 2 MeV the significant change in the reaction mechanism is

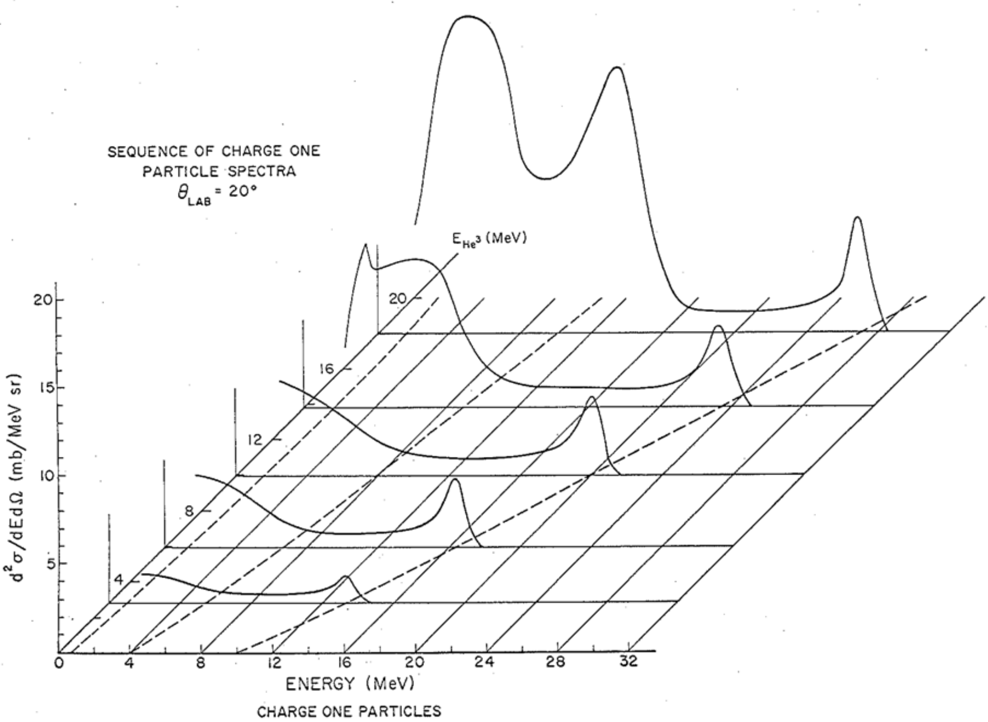

Figure 3. The evolution of the ^{3}He + ^{3}He proton spectrum at θ_{lab} = 20° with the incident ^{3}He energy [3].

understood to result from the interference between the two identical fermions in the final state. Less well understood is the increasing importance of p-wave in the spectra above 2 MeV. In the future we hope to make observations of the ^{3}He+^{3}He reaction at Solar energies with approved time at the NIF facility.

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