Reinterpretation of the ^{2}H(d,pp)nn reaction at 80 MeV

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Leeman *et al.* measured ^{2}H(d,pp)nn cross sections at 80 MeV. They interpreted their results in terms of double spectator processes and had limited success in fitting their spectra. We obtain good fits to all their reported data by assuming final-state interactions between both final n-p pairs and ignoring the double spectator process.

[NUCLEAR REACTIONS ^{2}H(d,pp)nn, $E=80$ MeV; calculated $\sigma(E_1E_2,\theta_1,\theta_2)$ assuming n-p final-state interactions. Improved fits over original interpretation assuming double spectator process.]

Leeman *et al.*[1] have searched for the double spectator process (DSP) in the ^{2}H(d,pp)nn reaction at 80 MeV. They observed proton-proton coincidences under conditions where the neutron from the target could (but did not necessarily) remain at rest in the lab while the other neutron maintained the projectile velocity. Their plane-wave Born approximation (PWBA) calculations based on the DSP imperfectly reproduced the data, and they speculated that formation of two singlet deuterons contributed to the observed yield at one geometry.

In contrast, I obtain good fits to all their reported data by assuming final-state interactions (FSI) between both final n-p pairs and ignoring the DSP. Both the Wigner and the $V_{\sigma\tau}$ components of the nucleon-nucleon force can cause double breakup, and so the four-body final state is assumed to be an incoherent mixture of two $^1S_0$ (singlet deuteron) and two $^3S_1$ n-p pairs.

The geometry of the experiment is shown in Fig. 1. Two protons are detected with equal lab energies E at equal coplanar lab angles θ. The n-n center-of-mass (c.m) velocity $\vec{V}_{nn}$ and the magnitudes of the n-n relative velocities $\vec{V}'_3$ and $\vec{V}'_4$ are then determined. But the n-n emission angles α,ϕ in the n-n c.m. frame are completely undetermined and predictions must be integrated over α and ϕ.

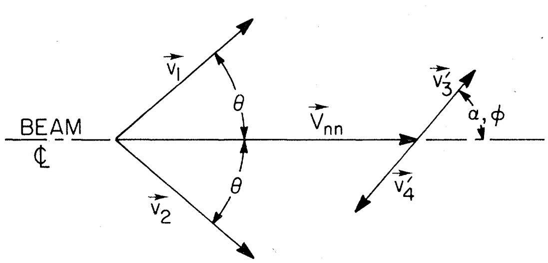

FIG. 1. Geometry for ^{2}H(d,pp)nn reaction.

Watson and Migdal[2,3] have shown that, when a final-state n-p pair have small enough relative momentum $\hbar k$, their wave function may be written

$$\psi_{np}=\frac{e^{-1\delta}\sin\delta}{k}f(r)\ , \tag{1}$$

where δ is the elastic scattering phase shift and r is their separation. Thus, the square modulus of our matrix element contains a factor $(\sin^2\delta/k^2)$ for each n-p pair which, at relevant k's, is larger for the $^1S_0$ state. Therefore, the yield $Y(E,\theta)$ is given by

$$Y(E,\theta)=A\int\left\{\left[\frac{\sin^2\delta_1}{k^2}\right]_L\left[\frac{\sin^2\delta_1}{k^2}\right]_R+\eta\left[\frac{\sin^2\delta_3}{k^2}\right]_L\left[\frac{\sin^2\delta_3}{k^2}\right]_R\right\}\times\rho_F\sin\alpha\, d\alpha\, d\phi\ , \tag{2}$$

where ρ_F is the density of final states. The subscript $L\,(R)$ designates the proton detected on the left (right) of the beam and the neutron emitted nearest to it. The singlet and triplet n-p phase shifts δ_1 and δ_3 were calculated from the effective range parameters of Guratzsch *et al.*.[4] The normalization A and triplet-to-singlet ratio η were the only parameters adjusted while fitting 48 data points. The units used in Eq. (2) for $Y(E,\theta)$,

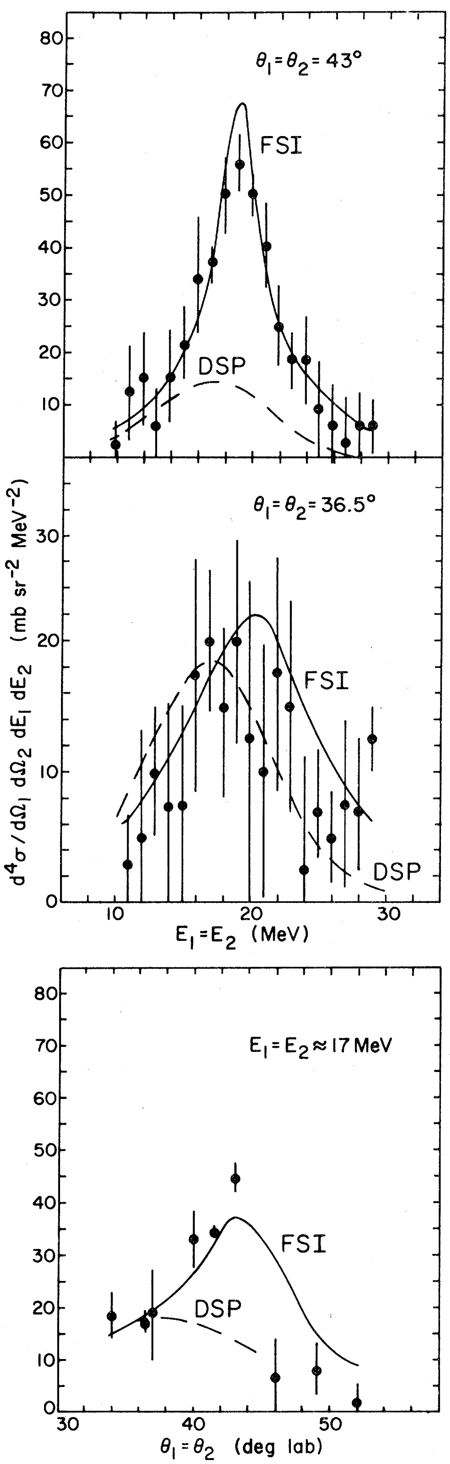

FIG. 2. Data for $^2H(d,pp)nn$ reaction at 80 MeV, with original predictions assuming double spectator processes (DSP) and our predictions assuming final-state interactions (FSI) between both final n-p pairs. FSI predictions are for parameters $\eta = 4.0$ and $A = 9.0\times10^{-5}$ MeV$^{-7/2}$, in Eq. (2).

A, k, and ρ_F are mb sr^{-2} MeV^{-2}, MeV$^{-7/2}$, fm^{-1}, and MeV$^{3/2}$ sr^{-3}, respectively.

The data, my FSI predictions, and the original DSP fits are shown in Fig. 2. Generally the FSI fits are superior to those for the DSP. In particular the FSI theory predicts the peak center more accurately at $\theta=36.5°$, where Leeman *et al.*[1] attributed the discrepancy between observations and DSP predictions to multiple scattering. The best fit was obtained with normalization $A=9.0\times10^{-5}$ MeV$^{-7/2}$ and a ratio $\eta=4$. A χ^2-per-point (denoted $\chi_1{}^2$) of 1.15 was then achieved. $\chi_1{}^2$ rose to 1.7 for a statistical mixture ($\eta=9$) of singlet and triplet states, and to 2.7 for $\eta=0$. With $\eta=4$, the $^1S_0$ state contributes 0.56 of the total yield at $\theta=43°$, and 0.33 of the total 36.5° yield; these fractions substantially exceed the ratio (1:10) of $^1S_0$ to total spin states. Thus the singlet deuteron FSI has greater intrinsic strength than the triplet states, but the latter also participate.

The data points contributing most heavily to $\chi_1{}^2$ are those in the lower panel of Fig. 2, with $\theta\geq 43°$. One of these data ($E=17$ MeV, $\theta=43°$) has different values of 37 and 44 mb/(sr^2 MeV^2) in the upper and lower panels, respectively, of Fig. 2. If both were set at the lower value our $\chi_1{}^2$ would drop to 0.98.

Relativistic kinematics were used throughout these reported calculations. To check the work a quite different nonrelativistic program was written. It gave similar results though the lowest $\chi_1{}^2$, again obtained for $\eta=4$, was 1.39. This is because, for fixed θ, relativity contracts the n-n opening angle and consequently raises the yield at $\theta=36.5°$ relative to that at 43°. Folding energy and angular resolution into the nonrelativistic calculations decreased $\chi_1{}^2$ from 1.39 to 1.32. Folding was omitted from the reported relativistic calculations where it would have been much more cumbersome to include it.

These results do not prove the complete absence of the DSP which, in fact, has a broad energy dependence similar to that of the $^3S_1$ n-p FSI. I agree with Leeman *et al.*[1] that measurements at higher bombarding energies, where correlation angles for the n-p FSI are still smaller, would better establish the relative importance of the two reaction mechanisms.

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