Attenuation and p-p and p-n quasifree scattering in deuteron breakup

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A new energy-dependent-core model for attenuation effects in quasifree scattering is used to explain the difference in quasifree scattering cross sections for the two kinematically equivalent modes of deuteron breakup under proton bombardment.

[NUCLEAR REACTIONS ^{2}H(p,pp), (p,pn), E = 20–100 MeV; ^{4}He(p,pt), ($p,p\,^3$He), E = 47 MeV; calculated σ.]

An important problem in quasifree scattering (QFS) theory is the explanation of the large difference in the observed cross sections for the two kinematically equivalent modes of deuteron breakup under proton bombardment.[1] At low to intermediate proton energies, the (p,pn) cross sections are much larger than the (p,pp) cross sections; in addition, the ratio of the two is strongly energy-dependent. An approach, based on the exact Faddeev-Amado formalism, was developed by Cahill[2] to describe these results; his calculations, which indicate the importance of spin statistics and the Pauli exclusion principle, were found to agree well with experiment at the one value of bombarding energy chosen, namely 14 MeV. Cahill's work was extended by Wallace[3] and subsequently, by Cheng and Roos,[4] to analyze p-d breakup at 65, 85, and 100 MeV. Although these latter calculations agree with experiment, they are suspect since Wallace's code is beset by numerical inaccuracies[5] and the nucleon-nucleon interaction used is restricted to S-wave separable potentials. The introduction of realistic potentials would make these calculations numerically difficult and out of reach at the present time. In the search for a less prohibitive model, any appeal to the simple plane wave impulse approximation (PWIA) is doomed to failure as the PWIA is too naive and its gross defects obscure the effects of the Pauli exclusion principle.

However, in a recent series of publications,[6,7] we have shown that it is unnecessary to abandon PWIA as a viable instrument for low-energy QFS analyses provided one includes attenuation effects on the dominant impulse approximation mechanism. In the framework of our new attenuation model, the PWIA is modified by a factor which takes the expected absorption into account. Thus, the QFS angular distribution for the general breakup reaction $X(p_1,p_1p_2)S$ is given by

$$\left(\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_1}\right)_{\text{expt}} = T\left(\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_1}\right)_{\text{PWIA}}, \tag{1}$$

where the transmission factor

$$\begin{aligned} T &= T_{p_1 S}\, T_{p_2 S} \\ &= \int \psi^*(\vec{r}_{p_1 S})\, T(\sigma_{p_1 S}, \vec{r}_{p_1 S})\psi(\vec{r}_{p_1 S})d\vec{r}_{p_1 S} \\ &\quad\times \int \phi^*(\vec{r}_{p_2 S})T(\sigma_{p_2 S}, \vec{r}_{p_2 S})\,\phi(\vec{r}_{p_2 S})d\vec{r}_{p_2 S}, \end{aligned} \tag{2}$$

ψ and ϕ are the relative cluster functions of p_1 and p_2 with the spectator nucleus S, $\sigma_{p_i S}(E_{p_i S})$ is the total scattering cross section of p_i on S taken at the relative energy $E_{p_i S}$, and the transmission

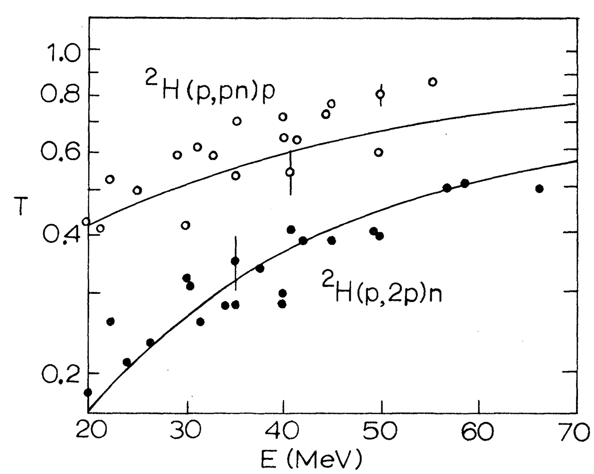

FIG. 1. The experimental and attenuation model transmission factors for ^{2}H(p,pp)n and ^{2}H(p,pn)p QFS from 20–70 MeV incident energy.

TABLE I. The experimental and theoretical ^{2}H(p,pp)n QFS peak cross sections.

Incident energy (MeV)	θ_{p_1} (deg)	Expt.	$d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ (mb/sr^2 MeV) Faddeev	Atten. model	PWIA
65	43.6	4.93 ± 0.16	4.46	4.26	7.59
	40.0	4.60 ± 0.23	4.40	4.53	7.55
	36.0	4.00 ± 0.21	4.16	4.34	7.36
	33.0	3.70 ± 0.21	3.86	4.00	7.14
	30.0	3.70 ± 0.22	3.44	3.49	6.85
	27.0	3.00 ± 0.20	2.95	2.99	6.50
	24.0	2.10 ± 0.21	2.47	2.50	6.11
85	43.6	4.87 ± 0.14	4.30	4.27	6.10
100	43.6	4.81 ± 0.14	4.75	4.80	6.23

probability

$$T(\sigma_{p_i S}, \vec{r}_{p_i S}) = \frac{1}{2}\left[1 + \left(1 - \frac{\sigma_{p_i S}}{4\pi r_{p_i S}^2}\right)^{1/2}\right], \quad \sigma_{p_i S} < 4\pi r_{p_i S}^2$$

$$= 0, \quad \sigma_{p_i S} \geq 4\pi r_{p_i S}^2 . \quad (3)$$

At the quasifree peak, the relative energy $E_{p_i S}$ is defined by

$$E_{1S} = \frac{E - E_{\text{sep}}}{1 + \sin^2\theta_1/\sin^2\theta_2} , \quad (4)$$

where $E = E_{1S} + E_{2S} + E_{\text{sep}}$.

TABLE II. The experimental and theoretical ^{2}H(p,pn)p QFS peak cross sections.

Incident energy (MeV)	θ_{p_1} (deg)	Expt.	$d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ (mb/sr^2 MeV) Faddeev	Atten. model	PWIA
65	63.5	3.50 ± 0.46	6.49	6.98	7.76
		2.70 ± 0.59			
	56.8	7.20 ± 0.56	7.34	7.60	8.74
	49.4	6.80 ± 0.46	7.15	7.02	8.67
		6.30 ± 0.57			
	43.5	7.00 ± 0.38	6.61	6.33	8.33
	34.9	6.80 ± 0.53	6.99	5.20	8.39
		6.70 ± 0.54			
	26.6	2.30 ± 0.23	5.05	4.20	8.76
	19.0	1.00 ± 0.28	3.35	3.14	8.48
		1.90 ± 0.19			
85	64.0	4.40 ± 0.66	5.96	6.30	6.90
	55.0	5.60 ± 0.57	6.41	6.60	7.33
	49.0	5.40 ± 0.43	5.81	6.00	6.75
		4.90 ± 0.49			
	43.5	4.80 ± 0.43	4.39	5.00	5.90
	37.0	4.20 ± 0.33	4.70	5.20	5.98
	27.0	4.70 ± 0.43	4.52	3.88	6.93
		4.90 ± 0.40			
	19.0	3.40 ± 0.34	3.53	3.03	7.05
100	64.0	5.90 ± 0.90	5.79	6.24	6.50
	59.2	7.00 ± 0.70	6.15	6.39	6.87
	54.2	6.00 ± 0.11	5.85	5.89	6.54
	43.5	5.00 ± 0.35	4.25	4.50	4.98
	33.2	3.50 ± 0.46	4.17	3.93	5.24
	28.1	5.50 ± 0.94	4.12	3.48	5.79
	23.0	3.80 ± 0.57	3.87	3.30	6.24

In applying our model to the two modes of p-d breakup, we find that the (p,pn) QFS has two identical spin-half particles (protons) interacting in one of the exit channels and therefore one of the cluster functions to be used in Eq. (2) must represent an unbound state. We expect a difference between (p,pp) and (p,pn) reactions to surface in our evaluation of the transmission factor and hence of the cross section, at each quasifree peak. To represent the Pauli exclusion principle at work, we assume the p-p cluster function to be the continuum wave function near threshold[8]

$$\psi_{p-p}=\frac{a_s}{r}\left(1-\frac{r}{a_s}-e^{-\xi r}\right) \tag{5}$$

and with it, have obtained the results displayed in Fig. 1. It is clear that our model reproduces the experimental QFS data rather well over the broad range of incident energies considered, a significant achievement. We have also found further support for our model's validity in the ^{4}He-$(p,p^3\mathrm{He})n$ and $^4\mathrm{He}(p,pt)p$ QFS data of Rogers *et al.*[9] The cross section ratio of (p,pt) to $(p,p^3\mathrm{He})$ is

$$\frac{d^3\sigma(t)}{d^3\sigma(^3\mathrm{He})}\simeq\frac{T_{pp}\,T_{pt}\,d\sigma_{pt}}{T_{pn}\,T_{n^3\mathrm{He}}d\sigma_{p^3\mathrm{He}}}\simeq\frac{1}{T_{pn}} \tag{6}$$

as $T_{pp}\approx 1$, $T_{pt}\approx T_{n^3\mathrm{He}}$, and $d\sigma_{pt}\approx d\sigma_{p^3\mathrm{He}}$. Near the quasifree peaks, this ratio, obtained from Figs. 8 and 11 of Ref. 9 is 1.7. Our result from Fig. 1 is 1.9.

An even more sensitive test of the attenuation model is provided by the angular-distribution experiments of Cheng and Roos. Their Faddeev-Amado analysis of the coplanar, energy-sharing spectra for p-d breakup at three intermediate energies, though deficient in the respects we have already mentioned, gave reasonable fits to experiment except at extreme angles where the Coulomb interaction is important in one of the exit channels. Our model predicts angular distributions in extremely close agreement with the Faddeev-Amado and experimental results. This is illustrated in the entries on Tables I and II.

In conclusion, we make two observations stemming from our model's success here and in Refs. 6 and 7. These are that we have a model that allows greater physical insight into the QFS process than does the complexity of multiple-scattering amplitudes in Faddeev-Amado and that we have at our disposal a realistic and viable method of QFS analysis which makes it unnecessary, at this stage, to discard PWIA in favor of more exact and laborious methods.

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