Proton-Induced Breakup Differential Cross Sections in the *pd* Scattering

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Abstract

The *nd* and *pd* breakup differential cross sections for the nucleon laboratory energies $E_N \leq$ 65 MeV are examined using the energy-independent quark-model nucleon-nucleon interaction fss2. The Coulomb effect is incorporated by the sharp cut-off Coulomb force, acting between quarks, without the phase-shift renormalization for the breakup amplitudes. Our model yields the results very similar to the meson-exchange potentials, including disagreement with experimental data for some specific kinematical configurations. This includes the notorious space star anomaly of the *nd* and *pd* scattering at E_N = 13 MeV. The shape of the *pp* final-state interaction peak in E_d = 130 MeV *dp* scattering data from KVI is not correctly reproduced, probably because the half off-shell behavior of the two-proton t-matrix is not appropriate in our Coulomb treatment.

1 Introduction

In spite of the great success of rigorous three-body approaches [1] to the neutron-deuteron (*nd*) and proton-deuteron (*pd*) scattering, some three-nucleon ($3N$) observables are not well reproduced in the nucleon laboratory energies $E_N \leq$ 65 MeV even with the recent accurate treatments of the Coulomb force [2, 3]. This is particularly true for deuteron breakup processes. It is therefore worthwhile to reexamine the NN interaction itself if the present-day realistic force is the most appropriate one to start with.

In previous studies [4, 5], we have applied the quark-model (QM) baryon-baryon interaction fss2 to problems of nucleon-deuteron (Nd) elastic scattering. This interaction model fss2 [6] describes available NN data in an accuracy comparable to the modern meson-exchange potentials. By eliminating the inherent energy dependence of the resonating-group kernel, fss2 was found to yield a nearly correct triton binding energy, S-wave *nd* scattering lengths and low-energy eigenphase shifts without introducing the $3N$ force [7, 8]. The so-called A_y puzzle at low energies $E_n \leq$ 25 MeV is somewhat improved in this model [5]. In this study, we examine deuteron breakup differential cross sections for various decaying kinematics in the energy range of $E_N \leq$ 65 MeV [9], by incorporating the Coulomb force approximately. Our main motivation is to determine if the quite different off-shell properties, originating from the strong nonlocality of the QM baryon-baryon interaction, affect the deuteron breakup differential cross sections. In contrast to the elastic scattering amplitude, the breakup amplitude covers a wide momentum region of the three-body phase space. It is found unfortunately that fss2 gives predictions very similar to the meson-exchange potentials and does not improve much the discrepancies between the theoretical and experimental results.

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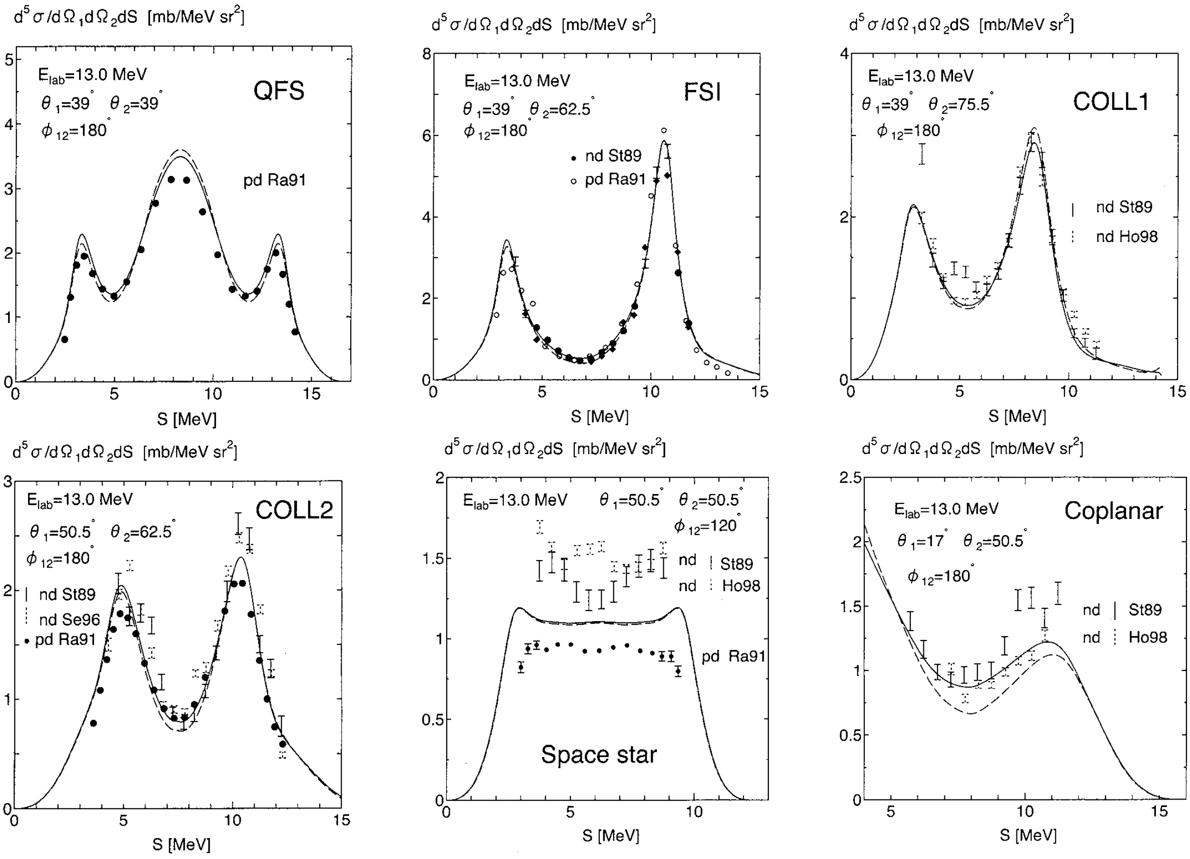

Figure 1: Breakup differential cross sections for the reactions $d(p,2p)n$ (solid curves) and $d(n,2n)p$ (dashed curves) at $E_N = 13$ MeV, compared with the experimental data.

2 Coulomb treatment

In the present calculation, the error-function type Coulomb force between two protons is treated as the three-body symmetric operator in the isospin formalism. The breakup amplitudes of the *ppn* system acquire an almost common phase factor, which does not contribute to the breakup differential cross sections. We therefore neglect this phase factor as a first step and calculate the breakup differential cross sections directly using the Coulomb modified breakup amplitudes. The sharp cut-off radius of the Coulomb force acting between quarks is chosen to be $\rho = 8$ fm and the two-nucleon angular momenta up to $I_{\max} = 4$ are included with the momentum discretization points specified by n_1-n_2-n_3=6-6-5 in the notation of Ref. [4].

3 Results

Figure 1 shows the breakup differential cross sections for the reactions $d(p,2p)n$ (solid curves) and $d(n,2n)p$ (dashed curves) with the nucleon incident energy $E_N = 13$ MeV. We find that the Coulomb effect is rather small in these examples and our results are very similar to the predictions by the meson-exchange potentials, given in Refs. [1, 10] and [2]. A slight overestimation of the peak in quasi-free scattering (QFS) is reduced by the Coulomb effect and the agreement with the *pd* experimental data [11] or more recent one [12] from Kyushu university group is improved. The *np* final state interaction (FSI) peaks are generally well reproduced. In the collinear (COLL1, COLL2) and coplanar (Coplanar) cases, the most recent *nd* data [13] agree well with theoretical

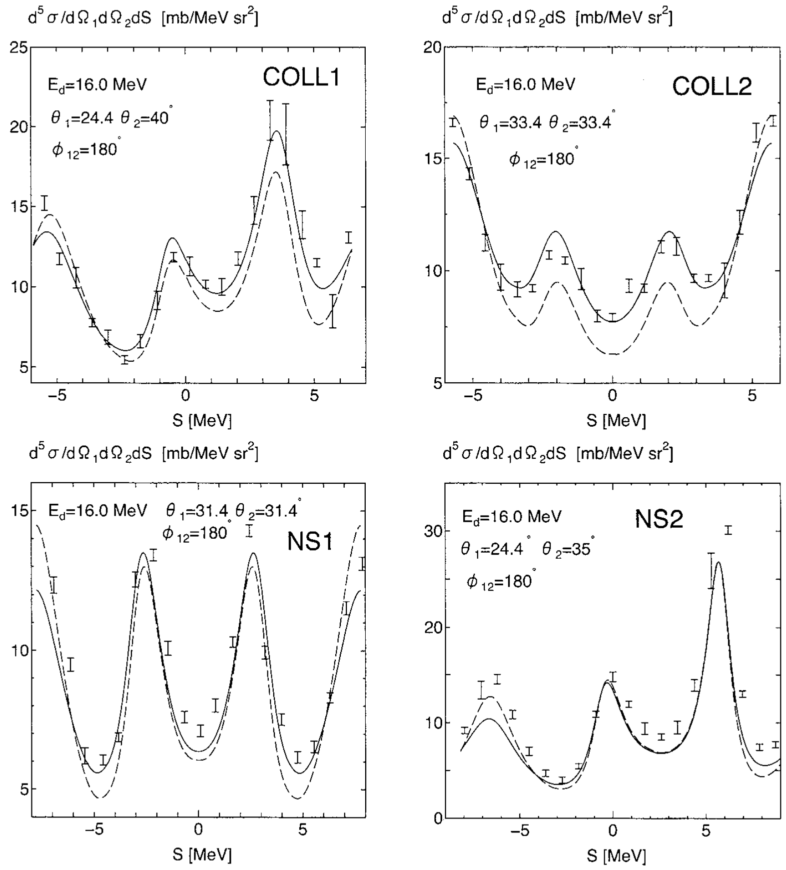

Figure 2: Breakup differential cross sections for the reaction $H(d,2p)n$ with $E_d = 16$ MeV (solid curves), compared with the experimental data [14].

predictions. The space star result is located just between the lower *pd* data and the higher *nd* data, which is the same feature as other predictions by the meson-exchange potentials. This disagreement of breakup differential cross sections at $E_n = 13$ MeV was reported a long time ago, and is still an unsolved problem called space star anomaly [13].

We compare in Fig. 2 the breakup differential cross sections for the reaction $H(d,2p)n$ at $E_d = 16$ MeV (solid curves) with the experimental data [14]. The Coulomb effect from the dashed curves (no Coulomb) to the solid curves (with Coulomb) clearly improves the agreement with the experimental data in collinear (COLL1, COLL2) and the non-standard (NS1) configurations, although not perfect.

Very accurate KVI data for the $H(d,2p)n$ reaction with $E_d = 130$ MeV [15, 16] are compared with our predictions in Fig. 3. Here we find that the *pd* calculations with the Coulomb effect (solid curves) generally improve the agreement with experiment except for the dip structure seen at the *pp* final state interaction for the first panel ($\theta_1 = \theta_2 = 13°$ and $\phi_{12} = 20°$). A more accurate treatment of the Coulomb force, reproducing the correct low-energy behavior of the half-on shell two-proton t-matrix, is apparently needed for the improvement [16]. For the large azimuthal angles $\phi_{12} \sim 180°$, the underestimation of the breakup differential cross sections may not be only due to the flaw in the Coulomb treatment.

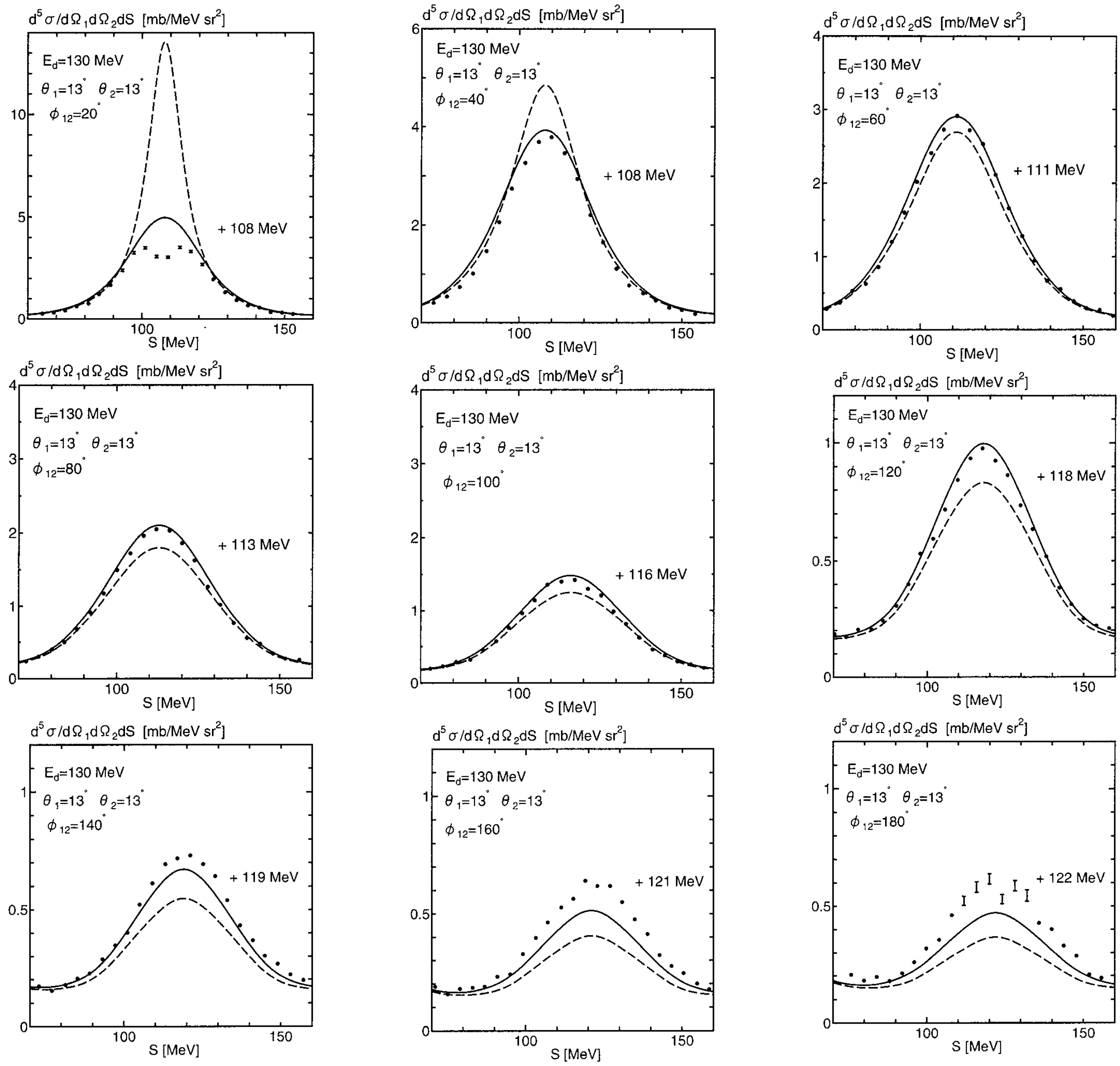

Figure 3: Breakup differential cross sections for the reaction $H(d,2p)n$ with $E_d = 130$ MeV (solid curves), compared with the experimental data [16]. Here $\theta_1 = \theta_2 = 13^\circ$ and ϕ_{12} are changed from 20° to 180° with a step of 20°. The results in the no-Coulomb case are also shown in the dashed curves.

4 Summary

We have applied our energy-independent quark-model nucleon-nucleon interaction fss2 to the *nd* and *pd* breakup differential cross sections for $E_N \leq 65$ MeV. The Coulomb effect is incorporated in the screened Coulomb approach without the phase-shift renormalization. This procedure seems to give a reasonable result when the effect of the Coulomb force is not so strong as the *pp* final state interaction. An exception of this rule is the space star anomaly at $E_N = 13$ MeV, in which the effect of the Coulomb force is small and yet a big difference of the *nd* and *pd* data is experimentally observed.

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