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Nucleon-Deuteron Breakup Differential Cross Sections Derived from the Quark-Model $NN$ Interaction

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Abstract The $nd$ and $pd$ breakup differential cross sections for $E_N \leq 65$ 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 for some specific kinematical configurations. This includes the notorious space star anomaly of the $nd$ and $pd$ scattering at $E_N = 13$ MeV. The KVI data for the breakup differential cross sections of $E_d = 130$ MeV $d$ $p$ scattering are reasonably reproduced by taking the Coulomb cut-off radius $\rho = 16$ fm.

Keywords Nucleon-deuteron scattering · Quark model nucleon-nucleon interaction

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 $E_N \leq 65$ MeV region even with the recent accurate treatment of the Coulomb force [2, 3]. This is particularly true for nucleon-induced 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 neutron-deuteron ($nd$) elastic scattering. This interaction model fss2 [6] describes available $NN$ data in a comparable accuracy with 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 $3N$ breakup differential cross sections for various decaying kinematics in the energy range of $E_n \leq 65$ MeV [9]. 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 $3N$ 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 similar to the meson-exchange potentials and does not improve much the discrepancies between the theoretical and experimental results.

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2 Coulomb treatment

In the present calculation, the Coulomb force 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 too much 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 Coulomb cut-off radius is chosen to be $\rho = 16$ fm and $l_{\text{max}} = 4$ with $n_1-n_2-n_3=6-6-5$ is used in the notation of Ref. [4].

3 Results

Figure 1 shows the breakup differential cross sections for the reactions $d(p, 2p)n$ (solid curve) and $d(n, 2n)p$ (dashed curve) with the nucleon incident lab. 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, 2, 10]. 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 well reproduced. In the collinear (COLL1, COLL2) and coplanar cases, the $nd$ data [13] agree well with theoretical 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) 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] 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, although the dip structure seen at the $pp$ final state interaction in Fig. 3(a) ($\theta_1 = \theta_2 = 13^\circ$ and $\phi_{12} = 20^\circ$) is not sufficiently suppressed for $\rho = 16$ fm. A more accurate treatment of the Coulomb force, reproducing the correct low-energy behaviour of the half-off shell $pp$ $t$-matrix, may be necessary for the improvement [13]. Too large cross section peaks in Figs. 3(a), (b) and the underestimation in Figs. 3(g) - (i) with the large azimuthal angles $\phi_{12} \sim 180^\circ$ may not be ascribed to the flaw of the Coulomb treatment.

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 reasonable results in the case of rather moderate Coulomb effects. 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 empirically observed.

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Fig. 3 Breakup differential cross sections for the reaction $H(d,2p)n$ with $E_d = 130$ MeV (solid curves), compared with the experimental data [15]. Here $\theta_1 = \theta_2 = 33^\circ$ and $\phi_{12}$ are changed from $20^\circ$ to $180^\circ$ with a step of $20^\circ$. The calculated curves are shifted by about 100 MeV with respect to $S$ to fit the experimental origin. The cut-off Coulomb radius $r = 16$ fm is used.

References
