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Quark-Model Nucleon-Nucleon Interaction Applied to Nucleon-Deuteron Scattering

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Abstract We have examined the neutron-deuteron low-energy effective-range parameters, the differential cross sections and the spin polarization observables of the elastic nucleon-deuteron scattering up to the incident nucleon energy E_N=65 MeV using the quark-model nucleon-nucleon interaction fss2. These observables are consistently described without introducing three nucleon forces except for the nucleon analyzing power $A_y(\theta)$ and the deuteron vector analyzing power $iT_{11}(\theta)$ in the low-energy region $E_N \leq 25$ MeV. The long-standing A_y puzzle is slightly improved, but still remains. We have incorporated the screened Coulomb force to the proton-deuteron scattering problem by modification of the Vincent-Phatak approach for the sharp cutoff Coulomb force. The Coulomb effect on the elastic scattering observables is discussed.

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

1 Introduction

The three-nucleon (3N) system is most appropriate to study the underlying nucleon-nucleon (NN) and 3N interaction. The extensive investigation of the 3N force effect have been carried out on the basis of the meson-exchange potentials (1; 2) and of the chiral effective field theory. (3; 4) Since the 3N force effect is expected to be appreciable in the case of the incident nucleon energy $E_N > 100$ MeV, most studies are concerned with the intermediate- and high-energy region. On the other hand, there exist the discrepancies in 3N observables between the experimental data the present calculation including the 3N and Coulomb force in the low-energy region. (5; 6; 7; 8; 9; 10) Therefore, it is worthwhile to examine the off-shell properties of the NN interaction in 3N systems.

The QCD-inspired SU_6 quark model (QM) is a unified model describing interactions for full octet-baryons. The QM fss2 describes available NN data in a comparable accuracy with the modern meson-exchange potentials. (11) The QM NN interactions are constructed in the framework of the resonating group method (RGM) for two three-quark clusters. The short-range repulsion is described by an effective one-gluon exchange, while the medium and long-range attraction is dominated by effective meson-exchange potentials between quarks. The QM NN interactions are therefore characterized by the nonlocality which results from the antisymmetrization of six quarks and by the energy dependence inherent to the RGM. The short-range repulsion is described by nonlocal quark-exchange kernels, which have quite different off-shell properties from the phenomenological core in meson-exchange potentials. The energy dependence is eliminated by the

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off-shell transformation utilizing a square root of the normalization kernel. (12) This transformation yields an extra nonlocality, whose effect was examined in the Faddeev calculations for the triton and the hypertriton. (13) The deficiency of the triton binding energy by fss2 is about 350 keV, which is smaller than 0.5–1 MeV predicted by the standard meson-exchange potentials. It is therefore interesting to examine the predictions by the QM *NN* interaction for the 3*N* scattering system.

A comparison with the proton-deuteron (*pd*) data is desirable since they are abundant and more accurate than those of the neutron-deuteron (*nd*) scattering. Therefore, we should take the Coulomb force into account for the accurate comparison with the experimental data. On the other hand, the three-body problems including the Coulomb force are very challenging because of its long-range nature. In recent years, some advanced treatment based on the Kohn variational approach (5), on the screening and renormalization approach (6; 7; 8), and on the coordinate space Faddeev integral equations (9; 10). Our Coulomb treatment in this contribution is the modification to the approach (14) based on the Vincent-Phatak method (15; 16) for the sharp cutoff Coulomb force. The general framework of the our Coulomb potential and its application to the 3*N* problem is discussed in another contributions of ours. In this contribution, we will show the results on the *pd* elastic scattering observables and discuss the Coulomb effect in the low energy region.

2 *Nd* Elastic Scattering

We have applied our QM *NN* interaction fss2 to the elastic nucleon-deuteron (*Nd*) scattering in the Faddeev formalism for composite systems. The Alt-Grassberger-Sandahs (AGS) equations (17) are solved in the momentum representation. The channel-spin formalism, which is convenient for discussing the elastic scattering, is used. The calculations are made in the isospin basis and the charge independence breaking of the *NN* force is not included. We should note that our calculations do not introduce 3*N* forces. In the *pd* calculation, the sharp cut-off Coulomb force $(1/r)\theta(\rho - r)$ is introduced at the quark level, which leads to the error function Coulomb force at the nucleon level. The screened Coulomb potential between the proton and the deuteron is obtained by folding the Coulomb potentials between two protons with the realistic deuteron wave function. The scattering amplitudes are obtained from the connection condition for different asymptotic forms of the total wave function. We choose the value of the cutoff radius ρ to be 9 fm (for $E_p \leq 3$ MeV) or 8 fm (for $E_p > 3$ MeV). In incorporating the Coulomb force in the isospin basis, we use the effective 2*N* *t*-matrix in the isospin 1 channel, $t_{\mathrm{eff}} = (2/3)t_{pp} + (1/3)t_{np}$. (18) The *NN* interaction up to $I_{\max} = 4$, which corresponds to the $(E_N)_{\max} = 65$ MeV, is included in this calculations.

We have first calculated the elastic and breakup total cross sections (19) and the low-energy effective-range parameters of the *nd* scattering; namely, the doublet and quartet *nd* scattering lengths ${}^2a_{nd}$ and ${}^4a_{nd}$, and analyzed the low-energy eigenphase shift. (20) The spin-doublet low-energy eigenphase shift is sufficiently attractive to reproduce predictions by the Pisa Group (21), which are calculated using the AV18+Urbana 3*N* force. This result is consistent with the reproduction of the small ${}^2a_{nd}$ and the large triton binding energy without introducing 3*N* forces, which is due to the deuteron distortion effect which is sensitive to the description of the short-range repulsion of the *NN* force.

We have also examined the elastic differential cross sections $(d\sigma/d\Omega)$, the nucleon analyzing power $(A_y(\theta))$ and deuteron vector $(iT_{11}(\theta))$ and tensor $(T_{2m}(\theta))$ analyzing power up to $E_N = 65$ MeV. Some examples are shown in Fig. 1 and 2. Fig. 1 implies that the Coulomb force is very important to reproduce spin observables at $E_N \leq 5$ MeV in the whole angles. The Coulomb effect is confined to the forward region for higher energies. In Fig. 2, the calculation using fss2 for *pd* scattering (solid curve) and for *nd* scattering (dashed curve) resembles closely except for forward angles. The experimental data of the differential cross sections and polarization observables are reasonably reproduced except for the vector analyzing powers $A_y(\theta)$ and $iT_{11}(\theta)$ in the low-energy region $E_N \leq 25$ MeV. These observables are more sensitive to the truncation of the model space than the differential cross sections. They are also very sensitive to the Coulomb effect and are affected by the slight change of eigenphase shifts. The long-standing A_y puzzle for the large discrepancy between the theory and experiment in the low-energy region $E_N \leq 25$ MeV is slightly improved in our calculations, compared with the results obtained by the AV18 potential, although the puzzle still remains. The deficiency of $A_y(\theta)$ at the maximum point is about 15–20% in our calculation, which is smaller than 20–30% in the predictions by the AV18 potentials. (See Fig. 2 of (22).) A similar situation holds for the maximum of $iT_{11}(\theta)$. Moreover, the enhancement of $A_y(\theta)$ in the forward angle region with $\theta_{\mathrm{cm}} \leq 60^\circ$ is not sufficiently in this calculation. Our calculations do not reproduce the behavior of $A_y(\theta)$ and $iT_{11}(\theta)$ in this region simultaneously with one cutoff radius ρ, as can be seen in recent calculations by other groups.(5; 6; 7) The tensor

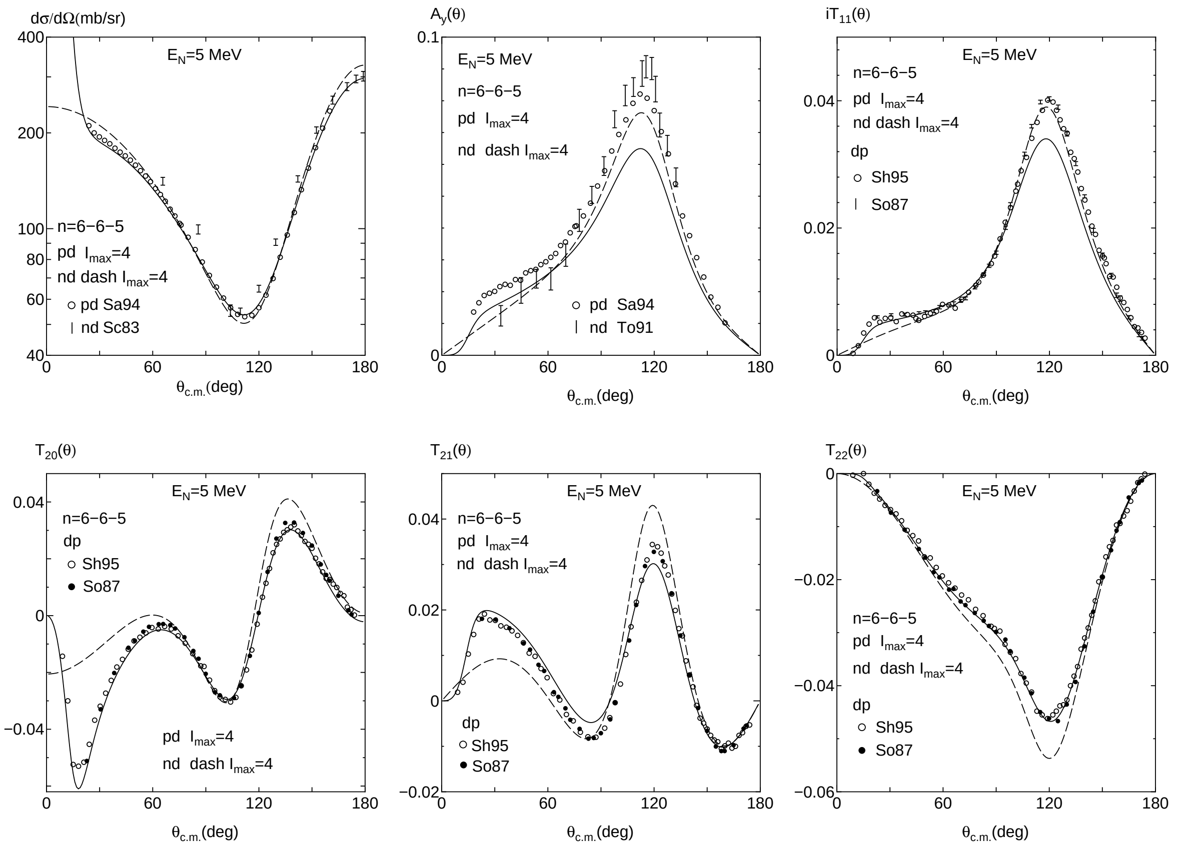

Fig. 1 The elastic scattering observables at $E_N = 5$ MeV, compared with the *nd* and *pd* (or dp) experimental data. The solid curve shows the results of the *pd* prediction using fss2 with the screened Coulomb force and the dashed curve shows the *nd* calculation. All the experimental data of the deuteron analyzing powers are for the dp scattering. These panels show (a) the elastic differential cross section $(d\sigma/d\Omega)$, (b) the nucleon vector analyzing power $A_y(\theta)$, (c) the deuteron vector analyzing power $T_{11}(\theta)$, (d) the deuteron tensor analyzing power $T_{20}(\theta)$, (e) $T_{21}(\theta)$ and (f) $T_{22}(\theta)$. The experimental data are taken from Refs. 23 for Sa94 (*pd*), 24 for Sc83 (*nd*), 25 for To91 (*nd*), 26 for Sh95 and 27 for So87.

analyzing powers $T_{20}(\theta)$, $T_{21}(\theta)$ and $T_{22}(\theta)$ are largely influenced by the Coulomb effect. In particular, the shape of $T_{20}(\theta)$ and $T_{21}(\theta)$ at the forward angle $\theta_{\rm cm} \le 60^\circ$ is greatly modified, giving better reproduction of the deuteron-proton (dp) experimental data. For $T_{22}(\theta)$, the Coulomb effect raise the observables at the minimum point, which result in the good agreement with the experimental data.

3 Summary

We have applied our QM *NN* interaction fss2 to the elastic *Nd* scattering in the Faddeev formalism for composite systems. The triton binding energy, the *nd* low-energy effective-range parameters and the *Nd* elastic scattering observables below $E_N = 65$ MeV is examined. We have incorporated the screened Coulomb force, which is consistent with the sharp cutoff Coulomb force at the quark level, to the *pd* scattering problem by modification of the Vincent-Phatak approach for the sharp cutoff Coulomb force. There is no clear discrepancy between our calculation and the experimental data except for the nucleon analyzing power $A_y(\theta)$ and deuteron vector analyzing power $iT_{11}(\theta)$ in the energy region $E_N \le 25$ MeV, although our calculation does not include any $3N$ forces. The long-standing A_y puzzle in the low-energy region $E_N \le 25$ MeV is slightly improved in our calculations, compared with the results obtained by the AV18 potential, although the puzzle still remains. The behavior of the differential cross sections and analyzing powers at the forward angles $\theta \le 60^\circ$ are very well reproduced by the Coulomb effect.

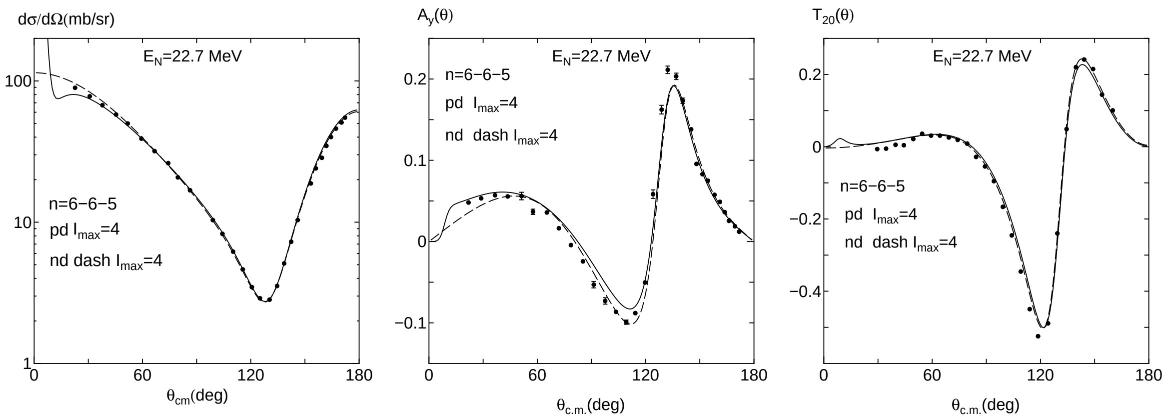

Fig. 2 Same as Fig. 1, but for E_N=22.7 MeV, compared with *pd* (or *dp*) experimental data. These panels show (a)$(d\sigma/d\Omega)$, (b) $A_y(\theta)$ and (c) $T_{20}(\theta)$. The experimental data are taken from Ref. 28.

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