Coulomb effects in nucleon-deuteron polarization-transfer coefficients

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Coulomb effects in the neutron-deuteron and proton-deuteron polarization-transfer coefficients $K_y^{y'}$, $K_z^{x'}$, $K_y^{x'x'-y'y'}$, and $K_y^{z'z'}$ are studied at energies above the deuteron breakup threshold. Theoretical predictions for these observables are evaluated in the framework of the Kohn variational principle using correlated basis functions to expand the three-nucleon scattering wave function. The two-nucleon Argonne v_{18} and the three-nucleon Urbana IX potentials are considered. In the proton-deuteron case, the Coulomb interaction between the two protons is included explicitly and the results are compared to the experimental data available at $E_{lab} = 10, 19, 22.7$ MeV. In the neutron-deuteron case, a comparison to a recent measurement of $K_y^{y'}$ by Hempen *et al.* at $E_{lab} = 19$ MeV evidences a contribution of the calculated Coulomb effects opposite to those extracted from the experiment.

The three-nucleon ($3N$) system is an excellent testing ground for the nuclear interaction. The last generation NN interactions can be used to calculate $3N$ bound and scattering states and important conclusions about the capability of those interactions to reproduce the $3N$ dynamics can be derived from a comparison to the experimental data. In the $3N$ system the potential energy consists of a sum of the pairwise NN interaction and a term including a pure three-nucleon interaction (TNI). The TNI term is not very well known and, in general, its strength is fixed so as to reproduce the experimental $A = 3$ binding energy. Due to recent advances in the solution of the $3N$ continuum, the possibility of using the $3N$ scattering data to improve the TNI is at present feasible. Because of this, a correct treatment of the Coulomb interaction in the description of the proton-deuteron reaction is required, which has been a difficult problem until recently. However, the $3N$ continuum is largely dominated by the NN interaction, so the specific sensitivity of particular observables to the TNI is of interest.

Here we focus attention on the polarization-transfer coefficients $K_y^{y'}$, $K_z^{x'}$ and $K_y^{x'x'-y'y'}$, $K_y^{z'z'}$ in the three-nucleon system. These coefficients are sensitive to the tensor force and their study from an experimental and theoretical point of view provides information about parts of the nuclear interaction not completely under control. For example, in the $2N$ system the mixing parameter ϵ_1, which is directly related to the tensor force, has been studied very recently in a double polarized neutron-proton experiment at low energy [1]. The results appear to be in disagreement with the predictions of the modern NN interactions. On the other hand, the calculations of ϵ_1 and several others $2N$ phase-shift and mixing parameters using these new interactions, which describe the $2N$ data with $\chi^2/N \approx 1$, show non-negligible differences between the different models. These differences are related possibly to an incomplete database or to a low sensitivity of some parameters to a large number of observables. To pin down the noncentral parts of the NN interaction necessitates measurements using polarized beams or targets which, in general, are difficult to perform. Though the picture of the

$2N$ system is still open to improvements, it is natural to extend the study of the nuclear interaction to the $3N$ system.

The polarization-transfer coefficients $K_y^{y'}$, $K_z^{x'}$ and $K_y^{x'x'-y'y'}$, $K_y^{z'z'}$ have been measured very recently in the elastic reaction $D(\vec{p},\vec{p})d$ and $D(\vec{p},\vec{d})p$ at $E_{lab} = 19$ MeV, respectively [2]. Furthermore, the coefficient $K_y^{y'}$ has been measured at the same energy for the neutron-deuteron reaction [3] allowing interesting comparisons to calculations with or without the Coulomb interaction. In the mentioned works, a number of calculations for these observables have been performed by the Bochum group solving the Faddeev equations in momentum space. Different modern NN interactions have been considered as well as the Tucson-Melbourne TNI. The main conclusions from Refs. [2,3] are (i) the nucleon coefficients $K_y^{y'}$, $K_z^{x'}$ show a scaling behavior with the triton binding energy whereas the deuteron coefficients $K_y^{x'x'-y'y'}$, $K_y^{z'z'}$ do not, and (ii) the nucleon coefficient $K_y^{y'}$ shows appreciable Coulomb effects in its minimum at the center of mass angle $\theta_{c.m.} \approx 110°$. A definitive conclusion about the capability of the theory to describe these coefficients cannot be extracted from Ref. [2] since the Coulomb interaction was neglected in the calculations. On the other hand, in the case of $K_y^{y'}$ it was possible to make a direct comparison to the n-d data of Ref. [3]. A spreading of the predictions of the pure NN forces at the minimum of $K_y^{y'}$ has been observed. This spreading has been related to differences in the deuteron D-state probability and the triton binding energy given by the different NN models. However, when the TNI was included, and its cutoff dependence fixed to reproduce the experimental value of the triton binding energy, the predictions did not show such a spreading any more. All calculations underestimated the minimum by about 10%.

The main results of the present paper are given in Figs. 1–3. In Figs. 1 and 2 the polarization-transfer coefficients calculated for a few potential models at $E_{lab} = 19$ MeV are shown. In Fig. 3 the results for $K_y^{y'}$ are given at other two
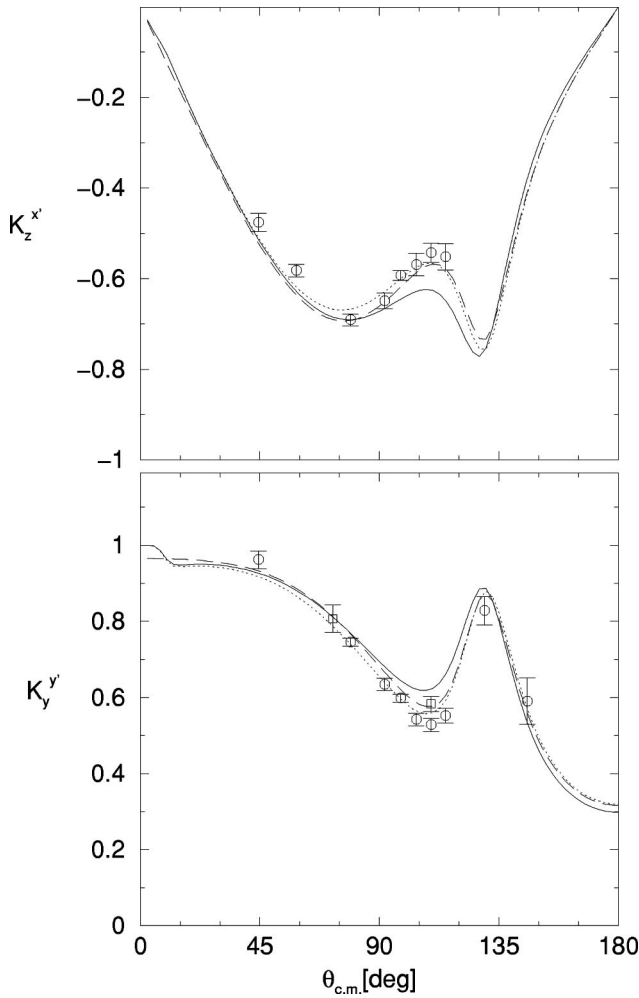
FIG. 1. The polarization-transfer coefficients $K_z^{x'}$ and $K_y^{y'}$ at $E_{lab}=19$ MeV. Calculations are shown for $p\text{-}d$ scattering using the AV18 (solid line) and AV18+UR (dotted line) potentials and for $n\text{-}d$ scattering using the AV18 potential (long-dashed line). Experimental points for $p\text{-}d$ scattering (circles) and for $n\text{-}d$ scattering (squares) are from Refs. [2,3], respectively.

energies, $E_{lab}=10$ and 22.7 MeV. The calculations have been made using the Kohn variational principle (KVP) with an expansion of the scattering wave function in terms of the pair correlated hyperspherical harmonic basis [4]. The use of the KVP to describe proton-deuteron scattering at energies above the deuteron breakup has been discussed by the authors in Ref. [5]. Details of the method are given in Ref. [6] together with results of the nucleon-deuteron cross section and vector and tensor analyzing powers up to $E_{lab}=30$ MeV.

In Fig. 1 the theoretical predictions for $K_y^{y'}$ and $K_z^{x'}$ are compared to the experimental data of Refs. [2,3]. Calculations for proton-deuteron scattering have been made using the Argonne v_{18} (AV18) potential [7] (solid line) and also with the inclusion of the Urbana (UR) [8] TNI (dotted line). The potential model AV18+UR has the property of repro-
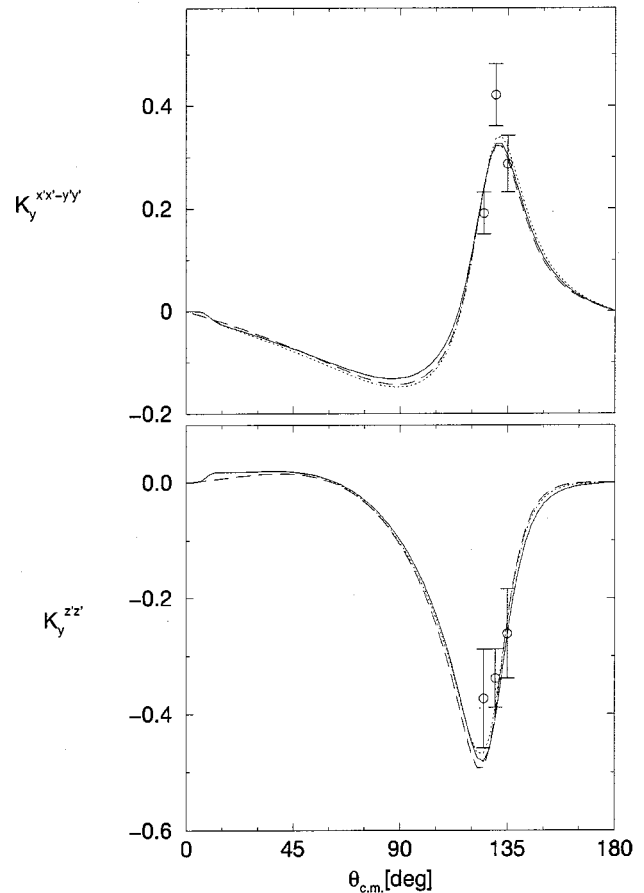

FIG. 2. The polarization-transfer coefficients $K_y^{x'x'-y'y'}$ and $K_y^{z'z'}$ at $E_{lab}=19$ MeV. Calculations are shown for $p\text{-}d$ scattering using the AV18 (solid line) and AV18+UR (dotted line) potentials and for $n\text{-}d$ scattering using the AV18 potential (long-dashed line). Experimental points for $p\text{-}d$ scattering (circles) are from Ref. [2].

ducing the ^{3}He binding energy [9]. A neutron-deuteron calculation using AV18 is also shown (long-dashed line). Results are given in Fig. 2 for the coefficients $K_y^{x'x'-y'y'}$ and $K_y^{z'z'}$ and in Fig. 3 for the coefficient $K_y^{y'}$ at $E_{lab}=10$ and 22.7 MeV. Experimental data are from Refs. [2,10,11].

Let us discuss first the results for the nucleon coefficients $K_y^{y'}$ and $K_z^{x'}$ at $E_{lab}=19$ MeV. The $p\text{-}d$ AV18+UR and the $n\text{-}d$ AV18 curves are very close to each other showing that Coulomb and TNI effects are of the same size. Moreover, the AV18+UR calculations for $p\text{-}d$ scattering reproduce the $p\text{-}d$ data reasonably well. A comparison of the AV18 $p\text{-}d$ and $n\text{-}d$ curves shows that the Coulomb interaction tends to increase the absolute values of $K_z^{x'}$ and $K_y^{y'}$ at $\theta_{c.m.}\approx 110^\circ$ in the maximum and the minimum, respectively. Conversely, the $n\text{-}d$ $K_y^{y'}$ datum at the minimum (shown by a square in Fig. 1) is above the corresponding $p\text{-}d$ datum. In other words, the inclusion of the Coulomb interaction in the calculations in-
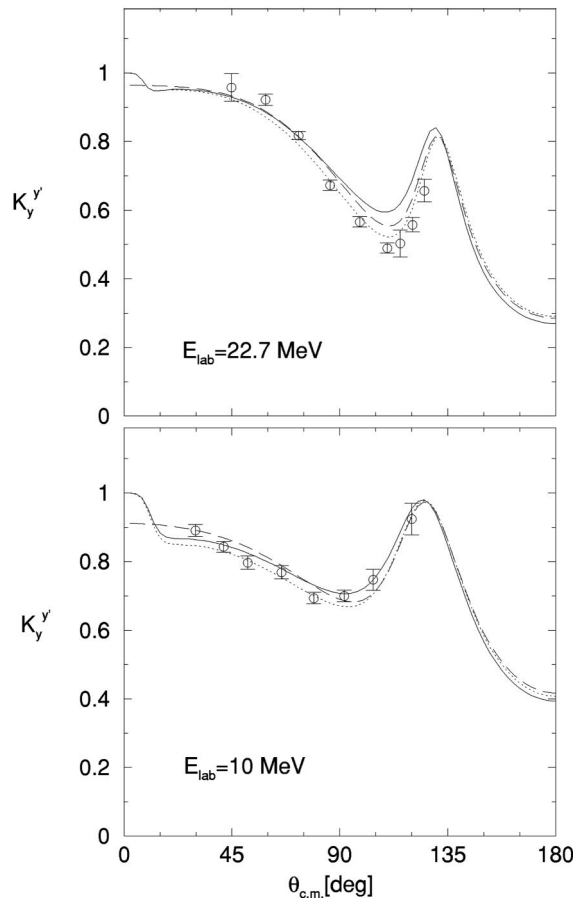
FIG. 3. The polarization-transfer coefficient $K_y^{y'}$ at $E_{lab} = 10$ and 22.7 MeV. Calculations are shown for *p-d* scattering using the AV18 (solid line) and AV18+UR (dotted line) potentials and for *n-d* scattering using the AV18 potential (long-dashed line). Experimental points for *p-d* scattering (circles) are from Refs. [10] (10 MeV) and [11] (22.7 MeV).

creases $K_y^{y'}(110°)$, contrary to the experimental observation. The fact that the *n-d* curve describes the *n-d* $K_y^{y'}(110°)$ datum should be taken with caution since when the Tucson-Melbourne TNI is included, the theoretical *n-d* predictions

shift below the *p-d* data, as has been analyzed in Ref. [3]. This conflict between theory and experiment at relatively low energy is of interest. However, a larger number of data points seems to be necessary before formulating a final conclusion.

The results for the deuteron coefficients $K_y^{x'x'-y'y'}$ and $K_y^{z'z'}$ given in Fig. 2 are less sensitive to Coulomb and TNI effects. The *p-d* AV18 curve seems to underestimate the maximum of $K_y^{x'x'-y'y'}$ as well as to overestimate the minimum of $K_y^{z'z'}$ both at $\theta_{c.m.} \approx 130°$. The *p-d* AV18+UR curve slightly improves the description, but larger TNI effects seem to be necessary to correctly describe these peaks. Certainly smaller error bars would allow a more conclusive analysis.

In Fig. 3 the energy dependence of $K_y^{y'}$ can be analyzed. At $E_{lab} = 10$ MeV the three curves are close to each other and describe reasonably well the experimental points of Ref. [10]. The minimum observed at higher energies is very shallow here and Coulomb and TNI effects are small. Conversely, at $E_{lab} = 22.7$ MeV we observe a well-pronounced minimum in which Coulomb and TNI effects are even larger than at $E_{lab} = 19$ MeV. Again the AV18+UR curve gives the better description of the data of Ref. [11].

In conclusion, there are appreciable Coulomb and TNI effects in the polarization-transfer coefficients. The two contributions are of the same order of magnitude, the same situation being observed in the calculation of the three-nucleon binding energy. In fact, the triton binding energy calculated with any of the new local *NN* interactions is $B_t \approx 7.6$ MeV [12]. When the Coulomb potential and TNI terms are taken into account, with the TNI strength fixed to reproduce the experimental binding, the value $B(^3\text{He}) \approx 7.7$ MeV is obtained. So, the scaling property found in the coefficients $K_y^{y'}$ and $K_z^{x'}$ explains why the *p-d* AV18+UR and the *n-d* AV18 are close to each other. On the other hand, the explanation of the opposite value of the calculated Coulomb effects and those extracted from the experimental data is not clear at the moment. New measurements of the nucleon-deuteron polarization-transfer coefficients could be useful for a more extensive analysis of the discrepancies observed.

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