No evidence for large charge-symmetry breaking effects in the ^3P_J nucleon-nucleon interactions

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Rigorous calculations of proton-deuteron and neutron-deuteron analyzing power $A_y(\theta)$ angular distributions in the incident nucleon energy range from 1 to 3 MeV are presented. It is shown that the sizable difference in the magnitude of $A_y(\theta)$ for p-d and n-d scattering is caused by the Coulomb interaction in the case of p-d scattering and is not due to charge-symmetry-breaking effects in the ^3P_J nucleon-nucleon interactions. The calculated relative difference in the angular region of the $A_y(\theta)$ maximum is in agreement with the existing experimental data. [S0556-2813(97)01901-8]

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Experimental progress over the last 15 years made it possible to definitely establish small differences between proton-deuteron (p-d) and neutron-deuteron (n-d) analyzing power $A_y(\theta)$ data in the incident nucleon (N) energy range from 3 to 14 MeV. These differences occur both at forward angles and in the region of the maximum in the $A_y(\theta)$ angular distribution around $\theta_{\mathrm{c.m.}}= 90°–120°$. Except for electromagnetic effects (i.e., Rutherford scattering, Mott-Schwinger interaction, etc.) which are known to be important at forward scattering angles, p-d scattering is governed by p-p and n-p nuclear forces while n-d scattering is governed by n-n and n-p nuclear forces. Therefore, the comparison of p-d and n-d data in the angular region of the maximum of $A_y(\theta)$ (in the following referred to as "$A_y^{\max}$") can provide estimates of possible charge-symmetry-breaking (CSB) effects in the underlying N-N interaction. Since $A_y(\theta)$ in N-d scattering has been shown to be extremely sensitive to the ^3P_J N-N interactions [1], it is not surprising that attempts have been made to extract information about CSB in these interactions [2–4]. Based on quark-model studies [5], sizable CSB effects are predicted to exist.

The theoretical studies of Refs. [2–4] were hampered by two shortcomings. First, rigorous $3N$ calculations of the n-d $A_y(\theta)$ using realistic N-N potential models fail to describe the magnitude of $A_y(\theta)$ by more than 25%. Second, rigorous $3N$ p-d calculations that include the Coulomb interaction exactly were not available. Nevertheless, the detailed studies of Witała and Glöckle [2] clearly demonstrated that a set of ^3P_J N-N interactions can be found that not only describes the n-d and p-d $A_y(\theta)$ data around $A_y^{\max}$, but also p-p and n-p observables. In the latter work, the $A_y^{\max}$ difference was attributed completely to CSB in the ^3P_J interactions. However, the resulting ^3P_J phase shifts exhibit a much larger degree of CSB and charge-independence breaking than expected from theoretical studies. In addition, the sign of the CSB effects was opposite from that predicted by meson-exchange-based N-N potential models. The approach of Takemiya [3] provided a good description of p-d and n-d $A_y(\theta)$, but at the same time the N-N $A_y(\theta)$ data were poorly reproduced, as was later pointed out by Witała, Glöckle, and Takemiya [6]. Furthermore, Takemiya assumed, like Witała and Glöckle, that the $A_y^{\max}$ difference was solely caused by CSB. On the other hand, in Ref. [7] it was argued that most, if not all, of the observed $A_y^{\max}$ difference is due to the Coulomb interaction in the case of p-d scattering and not due to CSB in the ^3P_J N-N interactions. Very recently, this conclusion was questioned in a paper by Soldi, Vlahovic, and Slaus [4] where strategies were described to firmly establish the size of CSB in the ^3P_J N-N interactions.

In this Brief Report we want to point out that the $A_y^{\max}$ difference is theoretically well understood. In fact, the main result was already published by the Pisa group in short form in Ref. [8]. Using the pair correlated hyperspherical harmonic method and the Argonne AV14 [9] and AV18 [10] N-N potentials the Pisa group [11] treated the Coulomb interaction in p-d scattering in a rigorous way. This approach is currently limited to energies below the deuteron breakup threshold (i.e., to incident nucleon energies $E_N<3.33$ MeV). Fortunately, accurate p-d and n-d $A_y(\theta)$ data are available at $E_N=3$ MeV [12,13]. Similar to the situation for n-d scatter-

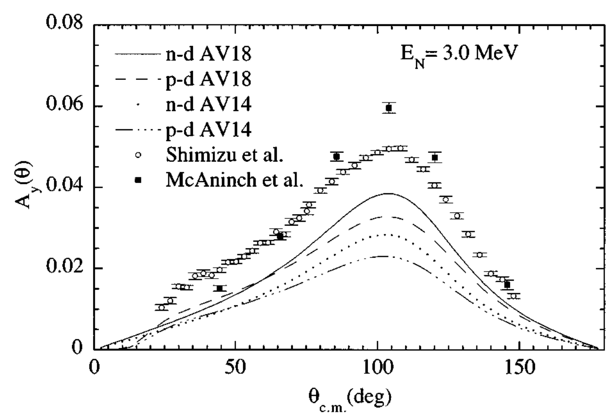

FIG. 1. Comparison of n-d [13] and p-d [12] analyzing power $A_y(\theta)$ data and rigorous calculations at $E_N=3.0$ MeV.

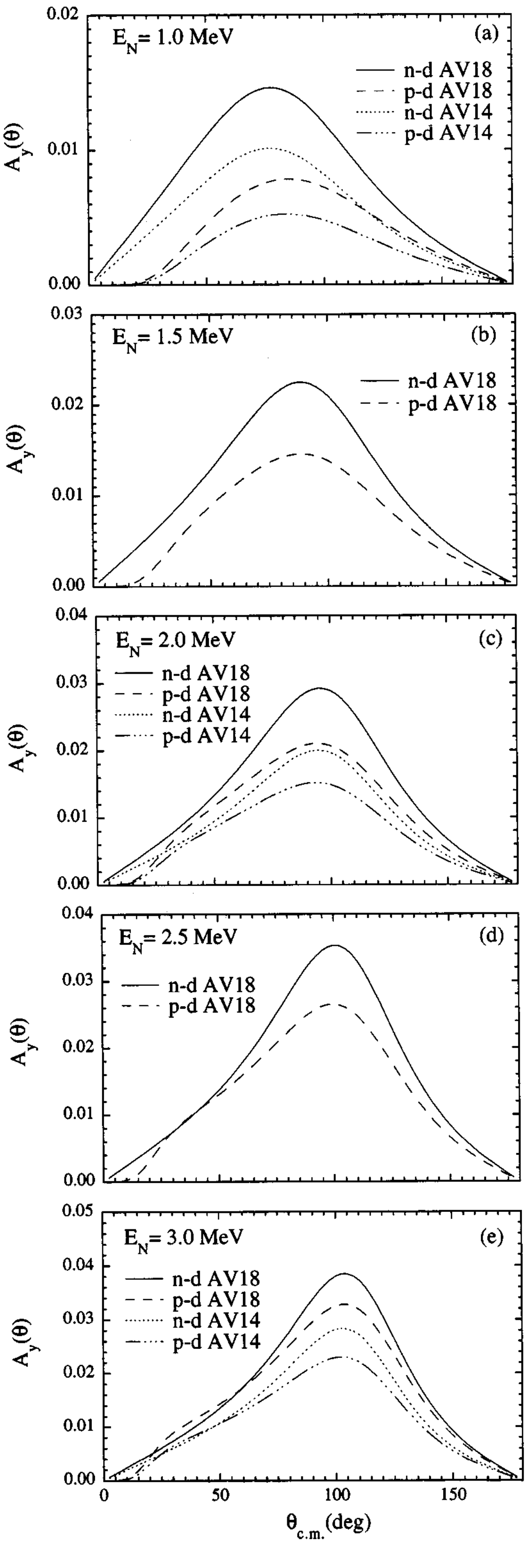

FIG. 2. Calculated *n-d* and *p-d* analyzing power $A_y(\theta)$ angular distributions between E_N=1.0 and 3.0 MeV.

ing below and above the deuteron breakup threshold [14–16], the *p-d* calcualtions underestimate the *p-d* $A_y(\theta)$ data considerably. Figure 1 shows calculated $A_y(\theta)$ angular distributions at E_N=3 MeV for *n-d* (solid and dotted curves) and *p-d* (dashed and dash-dotted curves) scattering in comparison to *n-d* (solid squares [13]) and *p-d* (open circles [12]) data. Clearly, the calculations using both the new

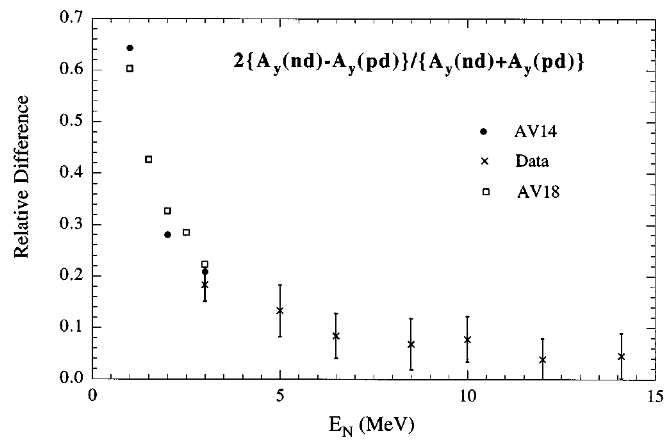

FIG. 3. Calculated (solid circles and open squares) and measured (crosses with error bars) energy dependence of the relative difference between the *n-d* and *p-d* analyzing power $A_y(\theta)$ obtained at the maximum of the $A_y(\theta)$ angular distribution. The experimental results at E_N=5.0 MeV and above were taken from Ref. [7].

AV18 and the older AV14 *NN* potentials fail to describe the experimental data by a considerable amount. This phenomenon is referred to as the ''$A_y(\theta)$ puzzle'' and it represents the most spectacular discrepancy between rigorous 3*N* calculations and experimental scattering data. However, more important for the present work is the difference between the solid and dashed curves (AV18) and the dotted and dash-dotted curves (AV14). It clearly documents the $A_y^{\max}$ difference referred to above. The AV14 potential does not contain any charge dependence in the ^3P_J interactions. Therefore, the difference between the dotted and dash-dotted curves is caused solely by the Coulomb interaction. It should be mentioned that the AV14 potential does not provide an optimal description of the *N-N* $A_y(\theta)$ data. Therefore, it is not too surprising that the predictions calculated with AV14 deviate even further from the experimental *N-d* data than the calculations using AV18. The latter potential is fitted to the *N-N* database of the Nijmegen group [17] and describes the experimental data with χ^2 per datum of 1.09. The AV18 potential includes a small charge dependence in the ^3P_J phase shifts, i.e., $^3P_J(n\text{-}p) \neq {}^3P_J(p\text{-}p) \neq {}^3P_J(n\text{-}n)$.

Figure 2 represents the calculated *n-d* and *p-d* $A_y(\theta)$ in the incident nucleon energy range from 1 to 3 MeV in 0.5 MeV steps. Experimental *n-d* data are not available below E_n=3 MeV. At E_N=1.0 MeV [see Fig. 2(a)] the calculated *p-d* $A_y(\theta)$ is about a factor of 2 smaller than the *n-d* $A_y(\theta)$ in the angular range of interest. This observation holds for both AV14 and AV18. At E_N=1.5 and 2.5 MeV [see Figs. 2(b) and 2(d)] calculations were performed with the AV18 potential only. Figure 2 shows clearly how the difference between the *n-d* and *p-d* $A_y(\theta)$ increases with decreasing incident nucleon energy. In order to make a more quantitative comparison, the relative difference between the *n-d* and *p-d* $A_y(\theta)$ at the maximum of $A_y(\theta)$ is given in Fig. 3 as a function of E_N. The crosses with error bars represent the-experimentally observed relative differences. As expected from simple Coulomb-force arguments [7], the relative difference increases dramatically with decreasing E_N. At E_N=3 MeV, the only energy where a comparison can be made, the calculated and the experimentally observed relative differences agree rather well. In addition, at this energy the AV14 and AV18 potential models give almost identical results. At 1.0 and 2.0 MeV small differences are visible between the AV14 and AV18 predictions. These differences are difficult to interpret because of the AV18 potential's superior description of the *N*-*N* $A_y(\theta)$ in comparison to AV14. Therefore, it is not clear whether the inherent charge dependence of AV18 is responsible for this fact. Obviously, accurate experimental *n*-*d* data are needed below $E_n=3$ MeV to verify the calculations shown in Fig. 3 [*p*-*d* $A_y(\theta)$ data exist at $E_p=1.0$ [18], 2.0 [12], and 2.5 MeV [12]]. Of course, rigorous *p*-*d* calculations that include the Coulomb force exactly are required above $E_p=3.33$ MeV to allow for a comparison with the experimental data given in Fig. 3 for these energies.

In summary, at $E_N=3$ MeV the calculated relative difference between the *n*-*d* and *p*-*d* $A_y(\theta)$ in the region of the maximum in the angular distribution agrees with the experimental result. Since the *N*-*N* potentials used in the rigorous calculations were either charge independent (AV14) or contained CSB contributions (AV18) in the ^3P_J *N*-*N* interactions, we conclude that the Coulomb interaction, and not CSB, is responsible for the vast majority of the sizable A_y^{max} difference observed between *n*-*d* and *p*-*d* data at low incident nucleon energies.

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