Energy Dependence of Possible Charge-Independence- and Charge-Symmetry-Breaking Effects in $NN^3P_J$ Interactions from Three-Nucleon Continuum Studies

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Abstract. A recent study of charge-independence- and charge-symmetry-breaking effects in the $^3P_J$ nucleon-nucleon interactions has been extended down to 5 MeV nucleon energy. It has been found that charge-independence-breaking effects are almost energy independent in the entire energy range investigated. Possible charge-symmetry-breaking effects in the $^3P_J$ $NN$ interactions exhibit a rather strong energy dependence at very low energies.

1 Introduction

The recent advances in the theoretical treatment of the three-nucleon (3N) continuum make it possible to test different nucleon-nucleon (NN) interactions quantitatively by comparison of theoretical 3N predictions with 3N scattering data [1]. A good overall description of the 2N data has now been achieved over a wide range of energies with modern NN interactions based on meson-exchange dynamics, like the Argonne [2], Bonn [3, 4], Nijmegen [5] and Paris [6] potentials (in alphabetical order). All these potentials are in one way or the other fitted to parameters obtained from NN phase-shift analyses. Therefore, the quality of the potential models is directly related to the correctness of the phenomenological $NN$ phase shifts. This fact is quite unsatisfactory, since specific phase-shift parameters depend only weakly on the available $NN$ data and, therefore, cannot be determined accurately enough at the present time. Thus, the dependence on present $NN$ phase shifts causes some of the extracted potential parameters to be somewhat ambiguous. As an example we refer to the tensor component of the $NN$ interaction [4]. Although considerable experimental effort has been devoted during the last few years to a better determina-

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tion of the $^3S_1-^3D_1$ mixing parameter $e_1$ in neutron-proton scattering, the situation appears almost as unsafe as before [7]. Therefore, experimental data at positive energies still do not provide sufficient constraints for selecting between the rather different tensor force parametrizations used in modern potential models.

Recently, it was shown [8] that in addition to the $3N$ bound states, the $3N$ continuum can also provide information about the $NN$ tensor force. $3N$ calculations for the nucleon-to-nucleon spin-transfer coefficient $K'_y(\theta)$ in neutron-deuteron $(nd)$ elastic scattering at 22.7 MeV revealed that this observable depends sensitively on the $^3S_1-^3D_1$ force component. The experimental data [8] (from proton-deuteron $(pd)$ scattering) clearly favor the weak tensor force of the Bonn-A potential over the stronger tensor interactions specific to all other realistic $NN$ potential models. This result was obtained by neglecting possible $3N$ force contributions.

Over the past 50 years it has always been assumed that the nuclear part of the free proton-proton $(pp)$ interaction is practically equal to that of the free neutron-neutron $(nn)$ interaction in the same $^3S_1+^1L_J$ states, i.e., the $NN$ interaction in these states has been assumed to be charge symmetric. The charge independence of the $NN$ force refers to the assumption that the $nn/pp$ and neutron-proton $(np)$ interactions are equal in corresponding free $2N$ states. Breaking of these symmetries is expected from the up-down quark-mass difference and from electromagnetic interactions among quarks. The difference between the experimental $pp$ scattering length $a_{pp} = -17.3 \pm 0.3$ fm and the $np$ scattering length $a_{np} = -23.715 \pm 0.015$ fm is a measure of charge-independence breaking (CIB) in the $^1S_0$ state [9]. The comparison of the recommended value for the phenomenological $nn$ scattering length $a_{nn} = -18.5 \pm 0.5$ fm with $a_{pp}$ suggests in addition a small charge-symmetry breaking (CSB) in the $^1S_0$ state [9].

Experimental information on CIB and CSB in higher angular-momentum $NN$ states is sparse. A low-energy $NN$ phase-shift analysis indicates surprisingly large CIB effects in all three $^3P_J$ phase-shift parameters [10]. Very recently, it was shown in ref. [11] that the significant disagreement between $3N$ continuum calculations and data for the analyzing power $A_y(\theta)$ in $pd$ elastic scattering in the 10–23 MeV energy range can be resolved by assuming the $^3P_J$ $NN$ interactions to be charge dependent. Besides this CIB it was also demonstrated that CSB of the $^3P_J$ force components can be the reason for the small differences observed experimentally between the $pd$ and $nd$ $A_y(\theta)$ data at the maximum of the angular distribution. However, an alternative explanation of the latter effect seems also plausible [7, 12]. Consider $pd$ scattering and the slowing-down of the incident proton in the Coulomb field of the deuteron. Compared to $nd$ scattering at the same bombarding energy, the nuclear part of the $pd$ interaction is exerted at a slightly lower energy. Due to the rapid decrease of the magnitude of $A_y$ with decreasing energy, a slightly smaller $A_y$ is expected for $pd$ scattering, in agreement with the experimental findings [7, 12].

Very recently, accurate $nd$ $A_y(\theta)$ data became available at 5, 6.5, and 8.5 MeV [13]. From these data valuable information about the energy dependence of CIB effects can be obtained by comparing with $3N$ calculations using the modified $nn$ and $np$ $^3P_J$ forces of ref. [11], which were deduced from the simultaneous fitting of $2N$ and $3N$ data mainly at energies above 10 MeV. Besides the study of CIB effects in $^3P_J$ states, the comparison of $pd$ data with calculations based on the modifications to the $pp$ $^3P_J$ forces proposed in ref. [11] can provide unique information about CSB.