Observables in proton-deuteron scattering are sensitive probes of the nucleon-nucleon interaction and three-nucleon force effects. Several facilities, including the KVI, allow a detailed study of few-nucleon interactions below the pion-production threshold exploiting polarized proton and deuteron beams. In this contribution, some recent results are discussed and interpreted exploiting rigorous Faddeev calculations. Furthermore, an experimental inconsistencies between two measurements of the cross section in elastic proton-deuteron scattering at 135 MeV/nucleon is reviewed.

Keywords: nuclear forces; few-body systems; elastic and inelastic scattering.

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1. Introduction

The nucleon-nucleon potential (NNP) has been studied extensively by investigating the properties of bound nuclear systems and, in more detail, via a comparison of high-precision two-nucleon scattering data with modern potentials based on the exchange of bosons. A few of the modern NNPs were facilitated by a partial-wave analysis, which provides a nearly model-independent analysis of the available scattering data. The modern NNPs reproduce the world database with a reduced chi-square close to one and have, therefore, been accepted as high-quality benchmark potentials. The precision of modern NNPs has given scientists the confidence to study in detail the three-nucleon potential (3NP) that was already predicted in 1939 by Primakoff et al. Compelling evidence of 3NP effects has come from various recent theoretical and experimental studies. For example, for light nuclei, Green’s function Monte Carlo calculations employing the high-quality NNPs clearly underestimate the experimental binding energies and, therefore, show that NNPs are not sufficient to describe the three-nucleon and heavier systems accurately. Deficiencies of theoretical predictions based on pair-wise nucleon-nucleon potentials have been observed in three-nucleon scattering observables as well.

Most of the present-day 3NNs are based on a refined version of the Fujita-
Miyazawa force in which a $2\pi$-exchange mechanism is incorporated by an intermediate $\Delta$ excitation of one of the nucleons. Later, more refined ingredients have been added as in Urbana IX and Tucson-Melbourne (TM') allowing for additional processes contributing to the rescattering of the mesons on an intermediate excited nucleon. A different approach is provided by the Hannover theory group, where the $\Delta$-isobar is treated on the same basis as the nucleon, resulting in a coupled-channel potential CD-Bonn+$\Delta$ with pair-wise nucleon-nucleon and nucleon-$\Delta$ interactions mediated through the exchange of $\pi$, $\rho$, $\omega$, and $\sigma$ mesons. Within this self-consistent framework, the $\Delta$-isobar excitation mediates an effective 3NP with prominent Fujita-Miyazawa and Illinois ring-type contributions.

One of the experimental programs at KVI focuses on obtaining high-precision data in the few-nucleon scattering processes below the pion-production threshold. The goal is to study the details of the nucleon-nucleon and three-nucleon interactions through a comparison with predictions from state-of-the-art effective nucleon-nucleon potentials and models based on a chiral-symmetry expansion. For this purpose, cross sections and analyzing powers are measured in few-nucleon scattering processes. The focus of the few-body program at KVI is mainly oriented towards understanding three- and, more recently, four-nucleon systems by exploring $p+d$, $d+p$, and $d+d$ reactions with polarized proton and deuteron beams. Different final states have been observed which includes the elastic, break-up, and radiative capture reactions. In this paper, some recent results for the elastic proton-deuteron scattering are presented. Elsewhere in these proceedings, preliminary results for the proton-deuteron break-up channel, M. Eslami-Kalantari et al., and elastic deuteron-deuteron channel, A. Ramazani-Moghaddam-Arani et al., are discussed.

2. Recent results and observations in elastic proton-deuteron scattering

In the last decade, high-precision data at intermediate energies in elastic $Nd$ and $dN$ scattering for a large energy range together with rigorous Faddeev calculations for the three-nucleon system have proven to be a sensitive tool to study the 3NP. In particular, a large sensitivity to 3NP effects exists in the minimum of the differential cross section. Precision data for a large energy interval for the differential cross section and analyzing power have come from recent experimental studies at KVI, Research Center for Nuclear Physics (RIKEN), and RCNP.

A comparison between data and results from Faddeev calculations showed that our present understanding of the 3NP is not sufficient to describe all the observables in the elastic channel. Even at relatively low energies, ≈100 MeV/nucleon, significant discrepancies appear, in particular in the tensor-analyzing powers. Figure shows the results of a measurement of the vector and tensor analyzing powers in the elastic deuteron-proton scattering process. The data were obtained at the RIKEN facility in Japan using a polarized deuteron beam and were analyzed by the experimental nuclear-physics group at the KVI. Note that the data represented...
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Fig. 1. Vector and tensor analyzing powers in the elastic $\vec{d} + p$ scattering at an incident deuteron beam energy of $E_{\text{lab}}^d = 180$ MeV. The open triangles are data from Ref. [11] and the open squares are data from Ref. [12]. The dark gray bands at the top of the panels represent the systematical uncertainty (2σ) for every data point. The other dark gray bands correspond to calculations including only two-nucleon potentials. The light gray bands represent calculations including an additional Tucson-Melbourne TM' three-nucleon force as well. The solid lines correspond to results of a Faddeev calculation using the AV18 two-nucleon potential combined with the Urbana-IX (UIX) three-nucleon potential. The dotted lines represent the results of a coupled-channel potential CDB+Δ calculations.

by the filled circles are of superb precision with respect to data taken earlier for these observables. Furthermore, rigorous Faddeev calculations incorporating state-of-the-art NNPs cannot describe the tensor observables $T_{22}$ and $T_{21}$. The inclusion of three-nucleon force effects does not remedy the deficiency either.

The differential cross sections at relatively low energies, 50–100 MeV/nucleon, are described reasonably well by calculations based on our present understanding of NNPs and 3NPs. Towards larger incident energies, the contribution of the 3NPs increases dramatically. This is illustrated in the top panel of Fig. 2 which depicts the
Fig. 2. The relative difference between the calculations by the Hannover-Lisbon theory group and the measured cross sections for the elastic $p + d$ reaction as a function of beam energy for a center-of-mass angle, $\theta_{c.m.} = 140^\circ$. The top panel shows the differences with a calculation based on the CD-Bonn potential and the Coulomb interaction, whereas for the bottom panel an additional $\Delta$ isobar has been taken into account. Open squares are data from Ref. [14], open triangles are data from Refs. [16, 17, 20, 21], open circle is from Ref. [22], open star is from Ref. [23], crosses are from Ref. [24], star is from Ref. [25], open cross is from Ref. [26], diamond is from Ref. [27] and the filled circle is from Ref. [28]. The shaded band represents the result of a line fit through the data excluding the results obtained at KVI, RIKEN and RCNP. The width of the band corresponds to a $2\sigma$ error of the fit.

Relative difference between various experimental cross sections taken at a center-of-mass angle, $\theta_{c.m.} = 140^\circ$ and a corresponding calculation based on a CD-Bonn NNP by the Hannover-Lisbon theory group. The discrepancy between data and calculation at 200 MeV/nucleon is more than 100%. A large part of this deficiency can be remedied by the inclusion of a $\Delta$ isobar, as a model for the 3NP and illustrated in the bottom panel of Fig. 2. Note, however, that a significant deviation in the order of 30% at 200 MeV/nucleon remains. Discussions are ongoing whether these discrepancies are due to short-range 3NP or relativistic effects which are not completely or consistently accounted for in the present models.

In the past years, a discussion was initiated within the nuclear physics community on the reliability of the experimental data taken at an incident energy of 135 MeV/nucleon. At this energy, the differential cross-section data obtained at KVI were found to be significantly larger than those measured at RIKEN and at RCNP, as can be observed in Fig. 2. The KVI data (open squares) deviate significantly from predictions of state-of-the-art Faddeev calculations incorporating modern NNNPs and 3NNPs at this energy, whereas the results obtained at RIKEN and RCNP (open tri-
angles) imply that the cross section can be described reasonably well exploiting the same potentials. A fit through the world database revealed that the data taken at RIKEN and at KVI deviate 8σ and 3.5σ from the expected trend, respectively. The trend is shown as shaded band with its width corresponding to a 2σ error of the fit. Note that a more recent measurement taken at KVI using the Big Instrument for Polarization Analysis, fits well the expected trend (filled circles). Similar analyses have been carried out at different center-of-mass angles. From this, we concluded that the previously-published data taken at KVI and RIKEN/RCNP suffered likely from an overall normalization problem.

3. Summary and conclusions
The three-nucleon scattering process at intermediate energies has demonstrated to be a sensitive tool to study the details of few-nucleon forces. Accurate experimental data have grown rapidly in the last decade, thereby, revealing many new insights in the few-nucleon system. Furthermore, the calculations presently on the market are of very high quality: ab-initio, self-consistent, and with the ability to include effects such as Coulomb and relativity.

In spite of the impressive accuracy in the data as well as in the calculation, there are still several discrepancies to be understood in the three-nucleon scattering process at intermediate energies. In particular, large deficiencies have been observed in polarization observables and in the differential cross section at relatively high energies. Part of these discrepancies might be due to short-range three-nucleon force effects or relativistic effects which have not been taken into account so far.

Although the statistical uncertainty of the experimental data has meanwhile reached sufficient precision for most of the observables, there remains a large uncertainty due to systematic effects. The latter uncertainty is - in general - difficult to estimate and can easily result in inconsistencies between data sets taken at different laboratories. It is of crucial importance that these inconsistencies are taken seriously. The most generic approach would be to perform a partial wave analysis, albeit not completely model independent, of all available three-nucleon scattering data similar to what has been done for the nucleon-nucleon scattering data by the Nijmegen group.

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