Three-nucleon force effects in proton-deuteron break-up studied with BINA at 135 MeV
Eslami-Kalantari, Mohammad

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2009

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.
1. Introduction

The modern concept of the atom emerged at the beginning of the 20th century, in particular as a result of Rutherford’s experiments. An atom is composed of a dense nucleus surrounded by an electron cloud. The nucleus itself can be decomposed into smaller particles. After the discovery of the neutron in 1932, there was no longer any doubt that the building blocks of nuclei are protons and neutrons (collectively called nucleons). The electrons, neutrons and protons were later joined by a fourth particle, the neutrino, which was postulated in 1930 in order to reconcile the description of β-decay with the fundamental laws of conservation of energy, momentum and angular momentum.

Around the year 1800, four forces were considered to be basic: gravitational, electric, magnetic and the barely comprehended forces between atoms and molecules. By the end of the 19th century, electricity and magnetism were understood to be manifestations of the same force: the electromagnetic force. Later, it was shown that atoms have a structure and are composed of a positively charged nucleus and an electron cloud; the whole held together by the electromagnetic interaction. Overall, atoms are electrically neutral. At short distances, however, the electric fields between atoms do not cancel out completely, and neighboring atoms and molecules influence each other. The different kinds of “chemical forces” (e.g., the van-der-Waals force) are thus expressions of the electromagnetic force.

When nuclear physics developed, two new short-ranged forces joined the ranks. These are the nuclear force, which acts between nucleons, and the weak force, which manifests itself in nuclear β-decay. Today, we know that the nuclear force is not fundamental. In analogy to the forces acting between atoms being effects of the electromagnetic interaction, the nuclear force is a result of the strong force binding quarks to form protons and neutrons. These strong and weak forces lead to the corresponding fundamental interactions between the elementary particles.

Subatomic physics is distinguished from all other sciences by one feature: it is a playground of three different interactions, and two of them act only when the objects are very close together. Biology, chemistry, and atomic and solid-state physics are dominated by the long-range electromagnetic force. Large-distance phenomena in the universe are ruled by two long-range forces, the gravitational and electromagnetic force. Subatomic physics, however, is a subtle interplay of three interactions (the strong, the electromagnetic and the weak) and the strong and the weak vanish at atomic and larger distances. The hadronic (or strong, or nuclear) force holds nuclei together, its range is very short, but it is strong. The strong interaction is much stronger than the electromagnetic interaction. If it were a long-range potential, as is the electromagnetic potential, the whole universe would collapse; or the universe would not have evolved from the Big Bang. The weak interaction has an even shorter
Chapter 1: Introduction

range and it is weaker than the electromagnetic interaction, as its name indicates. Figure 1.1 shows different scales in the hierarchy of the structure of matter. As we probe the atom with increasing magnification, smaller and smaller structures become visible: the nucleus, the nucleons, and the quarks.

![Image showing different scales in the hierarchy of the structure of matter.]

Figure 1.1: Length scales and structural hierarchy in (sub)atomic structure [1]. To the right, typical excitation energies and spectra are shown. Smaller bound systems possess larger excitation energies.

The weak interaction is not the subject of this thesis and, therefore, it is not further discussed. In the following, the concepts of the strong force in the nuclear system will be described.

1.1 The two-nucleon force

It is known that the electromagnetic force is exerted through the exchange of virtual photons; since the photon is massless, the range of the electromagnetic force is infinite. In the same way, Yukawa proposed in 1935, that the pair-wise nucleon-nucleon (NN) force is mediated by an exchange of a particle [2, 3]. Later, this particle, the pion, was discovered and its mass was found to be close to the mass predicted by Yukawa using the finite range of the nuclear force of $\sim 2$ fm. Combining the fact that the strong force has a short interaction range of about 2 fm with
Heisenberg’s uncertainty principle provides the mass of the exchanged particle:

\[ mc^2 = \frac{\hbar c}{\Delta r} \approx \frac{197 \text{ MeV} \cdot \text{fm}}{2 \text{ fm}} \approx 100 \text{ MeV}. \tag{1.1} \]

This particle is now called the pion, or \(\pi\)-meson, with a mass of 134.98 MeV for \(\pi^0\) and 139.57 MeV for \(\pi^\pm\). Based on the exchange of various mesons, the central component of the nucleon-nucleon potential could be divided into three regions: a long-range part at the distance between the two nucleons of about 2 fm, a middle-range part between 0.7 and 2 fm and a short-range part below 0.7 fm, as shown schematically in Fig. 1.2. The longest range attractive two-nucleon force (2NF) is due to the exchange of pions and for the shorter ranges, the exchange of two pions and heavier mesons contribute to the interaction [4, 5].

At present, existing 2NF models provide an excellent description of the high-quality database of proton-proton and neutron-proton scattering and of the properties of the deuteron, such as the binding energy. For a three-nucleon system, it is not enough to use only NN interactions to describe the experimental observables. As Fig. 1.3 shows, for the simplest three-nucleon system, the triton, an exact solution of the three-nucleon Faddeev equations employing only 2NFs clearly underestimates the experimental binding energy [6]. This indicates that 2NFs are not sufficient to describe the three-nucleon system accurately. For heavier systems, the deviations between the calculated and the measured binding energies become even larger [6]. Deficiencies of theoretical predictions based on pair-wise nucleon-nucleon potentials have been observed in three-nucleon scattering observables as well. For example,
exact solutions of the Lippmann-Schwinger equations (Faddeev calculations) [7, 8] solely based on modern NN interactions fail to describe high-precision differential cross sections of proton-deuteron elastic scattering at intermediate energies obtained at many laboratories including KVI [9, 10, 11] and RIKEN [12].

Figure 1.3: Binding energies of the ground and excited states of light nuclei. The experimental results are compared with AV$_{18}$ and AV$_{18}$+IL2 [6].

1.2 The three-nucleon force

All the modern NN potentials, as explained in section 2.2, are able to give very precise predictions for two-nucleon scattering observables at the intermediate range of energies. Note, however, that for the low energy regime it was recently shown that the Nijm93 NN phase-shift analysis overestimates the $n-p$ analyzing power at $E_n=12.0$ MeV [13]. The next step in understanding nucleonic interactions is to apply these two-nucleon potentials to three-nucleon systems. In a three-nucleon system, the interaction between two of the nucleons may be influenced by the presence of the third nucleon. For systems in which the internal degrees of freedom are frozen (a rigid system), the effect of the third system can be analytically calculated using the superposition rules. For a dynamic system like the nucleon, corrections emerge
1.2. The three-nucleon force

when these degrees of freedom are taken explicitly into account. The presence of a third nucleon in a three-nucleon system can influence the characteristics of all three nucleons. This extra effect, which goes beyond the two-body interaction, will be referred to as the three-body force effect in this thesis and for the nucleonic systems it is called the three-nucleon force (3NF) effect. Later we will use the notation of 3NF to abbreviate the three-nucleon forces and the three-nucleon potential as well. To show the importance of the 3NF, one needs to solve the Schrödinger equation with the relevant potential:

\[ H\psi = E\psi, \]

where

\[ H = -\sum_i \frac{\hbar^2}{2m_i} \nabla_i^2 + \sum_{i>j} v_{ij}, \]

and where \( v_{ij} \) is the NN potential. The solution clearly shows that the NN potential is not sufficient. As shown in Fig. 1.3, calculations using the Green’s Function Monte-Carlo method [6], demonstrate that the AV_{18} NN potential fails to predict the experimental results for binding energies of light nuclei. It seems that one must consider an additional three-nucleon potential, \( v_{ijk} \), to explain the experimental observables. Adding the Illinois-2 [6] three-nucleon potential (3NP), the calculations come closer to the experimental results, especially for the first few light nuclei. As can be seen in Fig. 1.3, even adding a 3NP is not adequate to account for the differences between the theoretical calculations and the measurements for some of the states, especially for heavier nuclei. This discrepancy may be resolved by adding a four-nucleon or higher potential. One presumes that the four-nucleon potential (4NP) is much smaller than 3NP, just as the 3NP is smaller than the NNP \(^1\). Thus, the larger discrepancies cannot be explained by the 4NP. Rather, the existence of large discrepancies might be a sign that the present 3NPs need to be modified.

Apart from the binding energy, there are phenomena such as scattering that can be addressed in a three-nucleon system. There is a variety of evidences which show the discrepancies between measured scattering observables, such as cross sections and analyzing powers, and theoretical calculations based solely on a 2N potential. Measurement of the differential scattering cross sections in three-nucleon systems is one of the tools to study the nature of the 3NF. More detailed information can be obtained by measuring other observables such as analyzing powers. For instance, the spin-dependent part of the 3NF can be studied specifically by measuring the vector (and tensor) analyzing powers using polarized proton (and deuteron) beams.

In the last few years, high-precision measurements of the elastic reaction were carried out at KVI and at other laboratories with the aim of studying 3NF effects. Measurements of the cross section and vector analyzing power in the elastic proton-deuteron scattering have been performed at various beam energies less than 250

\(^1\) The hierarchy and relative strength of few-nucleon potentials are understood in the framework of chiral perturbation theory.
MeV [9, 10, 11, 12, 14, 15, 16, 17, 18]. Results of these measurements show a systematic discrepancy between data and calculations using three-nucleon potentials in which the size of the discrepancy increases with increasing beam energy. Part of these deficiencies could be attributed to relativistic corrections which are not properly included in the theoretical models. In fact, all calculations are derived from the Lippmann-Schwinger equations, which are based on the non-relativistic Schrödinger equation.

Contrary to the elastic reaction, the break-up reaction has a very rich phase space. The number of free parameters in the three-body break-up scattering is larger than in the elastic reaction and it, therefore, gives access to a larger kinematical phase space.

There is a long history of break-up studies at low energies (~10 MeV). These measurements have been performed in the past at Bonn, Cologne, TUNL, and Kyushu producing interesting results. In particular, the so-called symmetric space-star configuration appears rather puzzling. In this configuration, the plane in the center of mass system spanned by the outgoing nucleons is perpendicular to the beam axis, and the angles between the nucleons are 120°. At $E_{\text{lab}} = 13$ MeV, the proton-deuteron ($pd$) and neutron-deuteron ($nd$) cross-section data deviate significantly from each other. Theoretical calculations based on both phenomenological and chiral nuclear forces have been carried out for the $nd$ case and are unable to describe the data. In addition, the Coulomb effect was found to be far too small to explain the differences between the $pd$ and $nd$ data. Recently, proton-deuteron break-up data for a similar symmetric constant relative-energy configuration have been measured in Cologne [19] at $E_d = 19$ MeV. The results of this experiment show a large deviation between the theory and the data.

For a complete picture of the underlying dynamics of three-nucleon forces, one also needs to study the reaction phase space at higher energies. A systematic study of observables of the break-up reaction has been started at KVI using SALAD [20] by a collaboration between Krakow, Katowice and KVI. This collaboration proved the feasibility of conducting high-precision measurements of the observables of the break-up reaction for a large part of the kinematical phase space. The cross sections and tensor-analyzing powers of the $d^+ + p \rightarrow p + p + n$ reaction have been published for a beam energy of $E_{\text{lab}}^{d^+} = 130$ MeV [21, 22, 23]. The data were compared with predictions of calculations based on various NN and 3N potentials. The discrepancies between the data and theoretical calculations gave evidence of 3NF effects in this energy range. Furthermore, a large part of the disagreement between data and the theoretical calculations has been explained by including the Coulomb-force effects in the 3NF calculations [24, 25, 26] as demonstrated in the right panel in Fig. 1.4.

In the same figure, a comparison between the break-up data and calculations based on $\chi$PT is presented. It is shown that these calculations, based on a low-energy expansion of QCD, describe reasonably well the scattering data at these energies. Hence, $\chi$PT is becoming a powerful tool to describe scattering observables in particular for energies of less than 100 MeV/nucleon.
1.3. Outline of the thesis

In the following chapter, a brief overview of the theoretical framework that is used to describe three-nucleon systems will be given and different nucleon-nucleon, and three-nucleon potential models are presented. Also, the formalism for vector-polarized beams that has been used for the data analysis is explained in the next.

Figure 1.4: The cross sections of the $\bar{d} + p \rightarrow p + p + n$ reaction are shown for the indicated configuration for a beam energy of $E_{lab}^d = 130$ MeV. The left panel shows a comparison with predictions based on two-nucleon forces (2N), 3NF (TM’), and $\chi$PT (NNLO, NNNLO). The right panel shows the effect of the Coulomb interaction. In the left panel, the green, brown, cyan, and violet bands represent the NNLO, NNNLO, 2N, and 2N+TM’, respectively. In the right panel, cross section for the configuration $(1, 1, 12) = (15^\circ, 15^\circ, 20^\circ)$ is shown. The solid line shows the predictions of the CDB+$\Delta$ potential including the Coulomb interaction and the dashed line shows the predictions without the Coulomb interaction. The dash-dotted line combined with the right-hand scale present the dependence on $S$ (the energy correlation between the two scattered protons) of the relative energy between the two protons emerging from the break-up process [22, 24].

To investigate the behavior of 3NF effects at higher energies, the $\bar{p} + d \rightarrow p + p + n$ reaction was performed at $E_{lab}^p = 190$ MeV at KVI using BINA [27]. Figure 1.5 shows some of the new insights into three-nucleon systems at higher energy for the case in which the energy per nucleon is a factor of 3 larger than in the previous experiment [27]. This figure indicates that there is a discrepancy between the data and the theoretical calculations in the analyzing powers, specially for low relative azimuthal scattering angles. To extend the database for the investigations of the behavior of 3NF effects, an experiment was performed in 2006 to study the $\bar{p} + d$ break-up reaction at the energy of 135 MeV using a polarized proton beam. This experiment and its results are the main focus of this thesis.

1.3 Outline of the thesis
Figure 1.5: The left panel represents the comparison of the results of the cross-section measurements for a few selected configurations with all existing theoretical predictions for the $\bar{p} + d$ break-up reaction at $E_{\text{lab}} = 190$ MeV. The right panel shows the same results but for the analyzing powers. In both panels the NN band (light gray) is composed of various existing two-nucleon calculations, namely CDB, Nijm1I, Nijm1II, and AV$_{18}$. The 3N band (dark gray) shows the same NN potentials including the TM' (3N) potential. The lines represent the predictions using the CDB potential from the Hannover-Lisbon group (dotted), AV$_{18}$+UIX (black short-dashed), CDB+$\Delta$ (blue solid), CDB+Relativistic (blue dash-dotted), and CDB+$\Delta$+Coulomb (red long-dashed) potentials in every panel. The errors are statistical and the cyan band in each panel depicts the systematic uncertainties (2$\sigma$) [27].

Chapter 3 will cover extensively the experimental setup of this work. The most important aspects of all instruments and facilities which have been used to perform the proton-deuteron break-up experiment will be outlined. Specifically, BINA and all its components are described in detail in this chapter.

In chapter 4 the data analysis for the $\bar{p} + d$ break-up reaction is explained while chapter 5 covers the results of the $\bar{p} + d$ reaction and the conclusions drawn from them. Finally, a summary and conclusions of the whole thesis will be presented in chapter 6.