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Cross-section and analyzing-power measurements in three and four-nucleon scattering

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Chapter 1

Introduction

The most fundamental questions in nuclear physics are related to the forces which bind nucleons, protons and neutrons, together to form the building blocks of matter, nuclei. Already in 1935, Yukawa successfully proposed to describe the nucleon-nucleon (NN) force with an exchange of a particle [1], similar to the electromagnetic interaction which can be represented by an exchange of a photon. Later, this particle, the pion, was discovered [2–4] and its mass was found to be close to the mass predicted by Yukawa. Meanwhile, and for a large part inspired by the original idea of Yukawa, various phenomenological NN potentials have been derived [5–9], which are all able to fit the proton-proton and proton-neutron scattering data with extremely high precision. In some of these models, the longest-range, attractive two-nucleon force (2NF) is described by the exchange of pions and the repulsive shorter ranges by the exchange of two pions and heavier mesons [10]. More recently, NN potentials have become available which are derived from the basic symmetry properties of the fundamental theory of Quantum Chromodynamics (QCD) [11, 12]. These so-called chiral-perturbation (χPT) driven models construct systematically a NN potential from a low-energy expansion of the most general Lagrangian with only the Goldstone bosons, e.g. pions, as exchange particles.

Although much has been learned about the interaction between two nucleons, it remains questionable whether this knowledge is sufficient to describe the interaction between more than two nucleons. Already for the simplest three-nucleon system, the triton, an exact solution of the three-nucleon Faddeev equations employing 2NFs clearly underestimates the experimental binding energy [13], showing that 2NFs are not sufficient to describe the three-nucleon system accurately. In a three-nucleon system, the interaction between two of the nucleons may be influenced by the presence of the third nucleon. This extra effect comes from a force which is beyond the two-nucleon interaction and will be referred to as three-nucleon force in this thesis (3NF). A well-known example of such a force is the Fujita-Miyazawa force [14] in which all three nucleons interact via a 2π-exchange mechanism with an intermediate Δ excitation of one of the nucleons.

1.1 Three-nucleon force studies in three-nucleon scattering processes

To provide a better understanding of 3NF effects, differential cross sections and polarization observables have been measured extensively in proton-deuteron and neutron-deuteron scattering systems. The data have been compared to the predictions of rigorous Faddeev calculations which are based on the modern NN potentials including the various models for the 3NF effects. One of the “smoking guns” was the discrepancy found with the measured angular distributions in elastic nucleon-deuteron scattering, in particular at scattering angles for which the total cross section is at its minimum. Furthermore, the three-body break-up channel has been predicted to be an ideal probe to study 3NF effects. At low incident beam energies, up to 30 MeV, the differential cross sections, tensor-analyzing powers and spin-transfer coefficients in nucleon-deuteron scattering are described rather well using solely two-nucleon potentials. Here, the effect of the 3NF is predicted to be small. In contrast, the description of the analyzing power fails leading to the well-known A_y puzzle. At intermediate energies, 50-200 MeV/nucleon, the effect of the 3NF becomes significant and grows with increasing bombarding energy. Generally, including 3NF effects to the modern potentials improves the comparison with differential cross-section data [15–27]. However, a comparison between theory predictions and data for the polarization observables revealed various large discrepancies [16–18, 22, 28–34], which demonstrated that spin-dependent parts of the 3NFs are poorly understood.

Apart from disagreements between data and the predictions by theory, some of the experimental data are not consistent with each other. One of the worst cases is the disagreements in the differential cross section of the elastic $\vec{p}+d$ reaction at $E_{\rm p}^{\rm lab}$=135 MeV. Figure 1.1 represents these cross section data as a function of the center-of-mass angle, $\theta_{\rm c.m.}$. The open triangles are data from Ref. [19] and the open squares data from Ref. [17, 18]. The solid curve represents the results of a coupled-channel calculation by the Hanover-Lisbon theory group and is based on the CD-Bonn potential including the Coulomb interaction and an intermediate Δ-isobar. The results of a similar calculation excluding the Δ-isobar and accounting only for the 2NF, shown as a dotted curve. The observed inconsistency for the differential cross section, as shown in Fig. 1.1, initiated a discussion within the nuclear-physics community on the reliability of the experimental data and on how to interpret the data in terms of underlying physics, such as 3NF effects. It is, therefore, of importance to review these observations with respect to three-nucleon scattering data taken at other energies and in other channels. In this thesis, we present the results of an independent measurement of the cross section using the BINA setup installed at the KVI. Furthermore, a systematic analysis of the discrepancy is made including data taken at other laboratories as well.

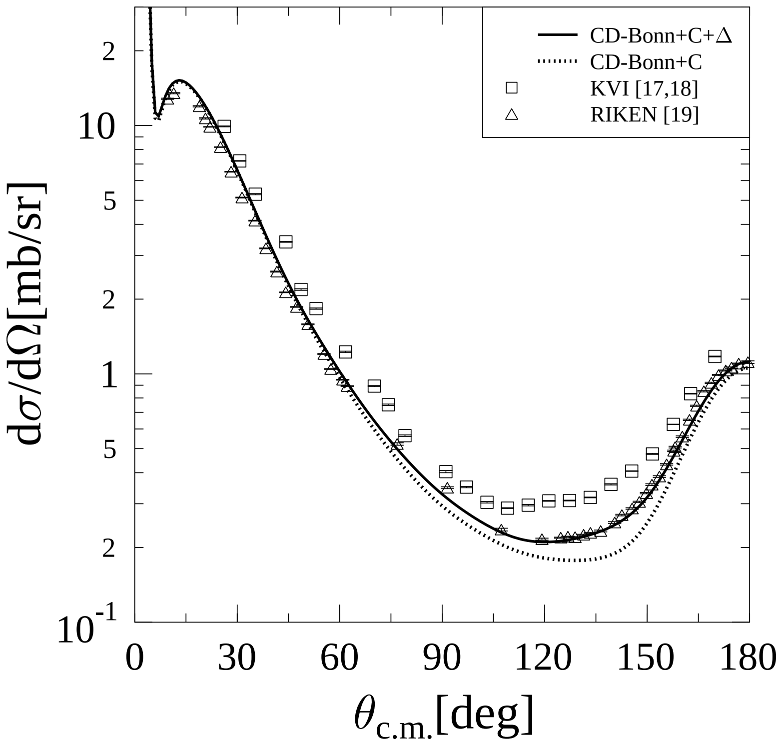

Figure 1.1: The differential cross section of the elastic $\vec{p}+d$ reaction at $E_{\mathrm{p}}^{\mathrm{lab}}$=135 MeV as a function of the center-of-mass angle, $\theta_{\mathrm{c.m.}}$. The open squares are data from Ref. [17,18] and the open triangles are data from Ref. [19]. The solid curve represents the results of a coupled-channel calculation by the Hanover-Lisbon theory group and are based on the CD-Bonn potential including the Coulomb interaction and an intermediate Δ-isobar. The results of a similar calculation excluding the Δ-isobar and accounting only for 2NF are shown as a dotted curve.

1.2 Three-nucleon force studies in four-nucleon systems

The 3NF effects are in general very small in the three-nucleon system, which requires statistically high-precision data and - moreover - a good control of systematic uncertainties. For some observables the effects reveal themselves at specific configurations or towards higher incident energies. Another complementary approach is to look into systems for which the 3NF effects are significantly enhanced in magnitude. For this, it was proposed to study the four-nucleon system. Naively, one might expect that the 3NF effects increase by the argument that the number of three-nucleon combinations with respect to two-nucleon combinations gets larger with increasing number of nucleons. We, however, note that the saturation of 3NF effects sets in very quickly for large nuclei as well). This simple counting rule is supported by a comparison between predictions and data for the binding energies of light nuclei [35], which is depicted in Fig. 1.2. Here, the predictions of a Green's function MonteCarlo calculation based on the Argonne V18 [6] NN interaction (AV18) and the Illinois-2 (IL2) 3NF [36, 37] are compared to experimental data. While a calculation which only includes the AV18 NN potential deviates significantly from the experimental results, a calculation which includes as well a 3NF compares much better to the data, especially for the first few light nuclei. Note that the effect of the 3NF on the binding energy for the triton is ∼0.5 MeV, whereas the effect increases significantly for the four-nucleon system, ^{4}He, to ∼4 MeV. For heavier nuclei, even adding the 3NF as modeled in the present calculations, is not enough to resolve the discrepancy between the theoretical predictions and the measurements. One might argue that the discrepancies for the binding energies of the heavier nuclei stem from four-nucleon force (4NF) effects. These higher-order many-body potentials are, however, predicted by χPT approaches [38] to be negligible compared to 3NF effects. Therefore, the large discrepancies cannot likely be explained by a missing 4NF or even higher-order nuclear-force effects.

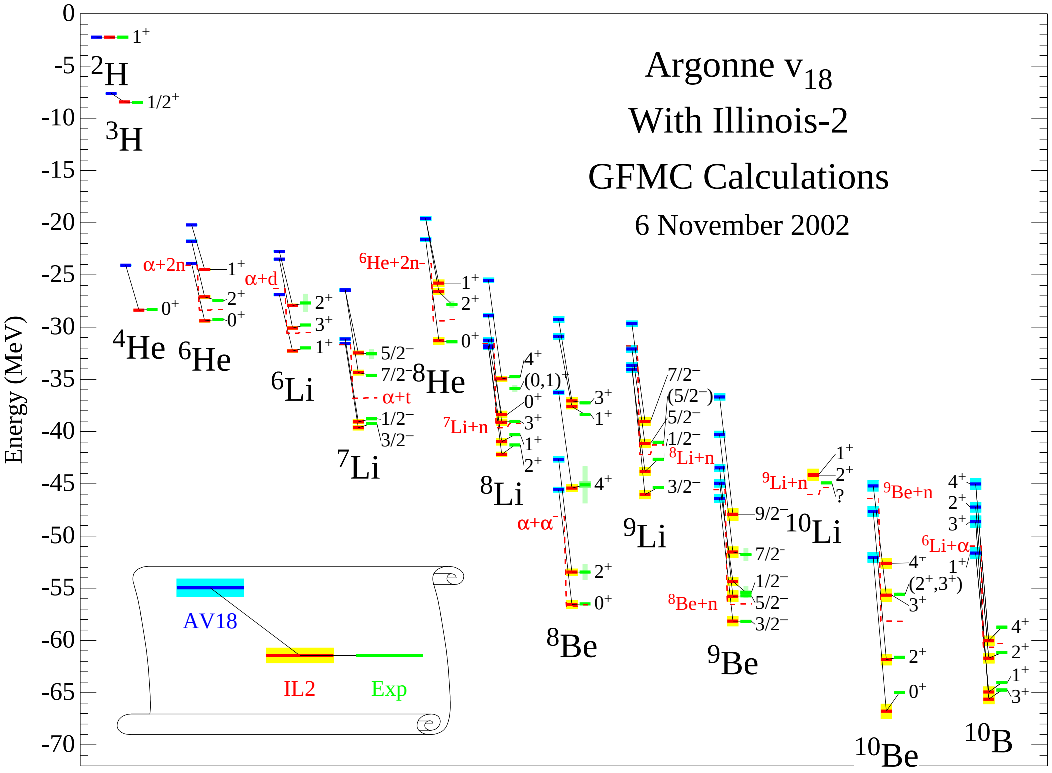

Figure 1.2: Binding energies of the ground and excited states of light nuclei. The experimental results are compared with the predictions of a Green's function MonteCarlo calculation based on the AV18 and AV18+IL2.

The importance of understanding in detail the forces which play a role in the four-nucleon system becomes also evident in a recent observation of charge-symmetry breaking (CSB) by the IUCF experimental group via a non-zero measurement of the cross section of the reaction, $d + d \rightarrow \alpha + \pi^0$ [39]. The total cross section for neutral-pion production was reported to be 12.7 ± 2.2 pb at a beam energy of 228.5 MeV and 15.1 ± 3.1 pb at

231.8 MeV. The theory of the strong interaction between quarks, QCD, is approximately invariant under what is called charge symmetry. In other words, if we swap an up quark with a down quark, then the strong interaction will look almost the same. This symmetry is related to the concept of “isospin”. Aside from trivial Coulomb effects, the CSB mechanism is responsible for the mass difference between protons and neutrons. Hence, the observation by the IUCF group in principle allows one to determine the mass difference between the up and down quark. For an unambiguous determination it is crucial to understand the underlying reaction dynamics, such as initial-state interactions. Following the CSB experiment, the IUCF group performed a set of angular distribution measurements of the cross sections and analyzing powers for $\vec{d}+d$ elastic scattering at 231.8 MeV. These data could be used to check the four-nucleon calculations used to describe the entrance channel in the theoretical treatment of the CSB reaction. The theoretical formalism used to describe the data is so far developed in an approximate way using the lowest-order terms in a Born series expansion of the Yakubovsky equations [40] developed for the four-nucleon system [41]. This approximation is expected to be valid for deuteron bombarding energies larger than 100 MeV and for low momentum transfers. Large deviations between calculations and data from IUCF are observed, which hinders the extraction of the up-down quark mass difference [42].

The experimental database in the four-nucleon system is presently poor in comparison with the three-nucleon system. Most of the available data were taken at very low energies, in particular below the three-body break-up threshold of 2.2 MeV. Also, theoretical developments are evolving rapidly at low energies [43–46], but lag behind at higher energies. The experimental database at these energies is very limited [47–49]. This situation calls for extensive four-nucleon studies at intermediate energies. This thesis describes a comprehensive measurement of cross sections and spin observables in various $d+d$ scattering processes at 65 MeV/nucleon, namely the elastic and three-body break-up channels. With these data, we have drastically enriched the four-nucleon scattering database. The extensive database of spin and cross section observables in various deuteron-deuteron scattering processes as presented in this thesis together with precise and ab-initio calculations can potentially reveal many details of 3NF effects.

1.3 Outline of the thesis

The theoretical background of this work is given in the next chapter. The scattering formalism for a two-, three-, and four-body system and a description of the cross section and analyzing powers are discussed briefly.

Chapter 3 is devoted to introduce the experimental setups which were used for the experiments discussed in this thesis. The procedure of producing polarized beams of protons and deuterons is given. The different components of the detection system, BINA, are introduced as well.

The analysis procedure, results, and the discussion of the $\vec{d}+p$ elastic scattering at 65 MeV/nucleon and $\vec{p}+d$ elastic scattering at 135 MeV are presented in Ch. 4.

Chapter 5 contains the analysis procedure of the $\vec{d} + d$ scattering at 65 MeV/nucleon. The identification of the elastic and break-up channels and the measurement of the beam polarization are discussed in detail. Results and the discussion for the elastic and three-body break-up channels are presented in Ch. 6. Finally, the summary, conclusions, and outlook of this work are presented in Ch. 7.