Virtal-photon capture in the three-nucleon system

Garderen, Elsa Diane van

CHAPTER 1

INTRODUCTION

1.1 Nuclear physics and the nucleon-nucleon interaction

One of the prime aims of Nuclear Physics is to study the nuclear force and to explain the structure of the nucleus. Atoms consist of an electron cloud which surrounds the atomic nucleus (see Fig. 1.1). The electromagnetic forces acting in the electronic shells of atoms are described by the *quantum electrodynamics* (QED) theory, which has been accurately tested.

Against the repulsive electromagnetic force which acts in the nucleus, the *strong force* binds the composing elements of the nucleus, *protons* and *neutrons*, together. The origin of the strong force lies in the structure of the nucleons, which are formed out of *quarks*, carrying a *color* charge. Quarks are bound in the nucleons by colored *gluons*.

The theory which describes the strong interaction is *quantum chromodynamics* (QCD). This name comes from the Greek *chromos*, which means ”color”, and refers to the color charge of quarks and gluons. This theory was developed by D. Gross, D. Politzer and F. Wilczek who obtained the Nobel Prize in 2004 for the discovery of asymptotic freedom in the theory of the strong interaction. At the highest energies, QCD describes the strong force quantitatively. In order to describe the forces between two nucleons, this theory should be applicable at large distances (i.e. low energies), but for these distances, the coupling constants are large and perturbation methods cannot be applied.

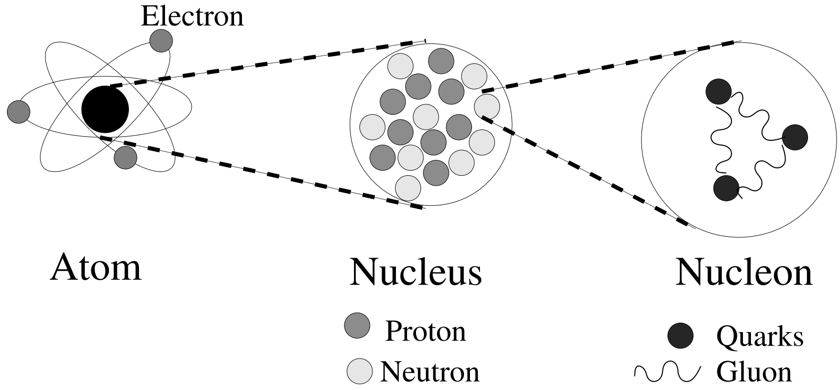

Figure 1.1: Constituents of matter, from the atom to the quarks.

Instead, the theories using the so-called *effective* potential models, based on the field theory approach, are used [Sto 93] [Sto 94] [Wir 95] [Mac 96]. They are today considered as a state-of-the-art tool to understand the multi-nucleonic systems.

The most basic way to investigate the interaction between nucleons is the study of proton-proton elastic scattering: $p + p \rightarrow p + p$ (see Fig. 1.2-left). When a proton beam is aimed at a proton target, part of the energy of the first proton is transmitted to the second one. This reaction has been well studied in the last fifty years. The observables obtained from the analysis of the experimental data were used to refine the parameters of the theoretical models ($\chi^2/data \approx 1$).

A step further in our understanding of the strong force is the investigation of proton-proton inelastic scattering ($p+p \rightarrow p+p+\gamma$, Fig. 1.2-middle) [Mah 04], where a photon is coupled to the hadronic currents of the two protons. This allows a much richer and independent interchange of energy and momentum compared to the elastic channel, and tests the nucleon-nucleon interaction at different kinematics. This relatively easy study, where all three exit particles can be accurately measured, leads to a system which presents the advantage of being kinematically over-determined: the knowledge of the energies and of the momenta of two of the three particles is sufficient to reconstruct the four-momentum of the third one. Consequently, by detecting all three emitted particles, one is able to select background-free events, from which precise conclusions on the validity of the models can be drawn.

However, the cross section of the previous reaction can only be expressed

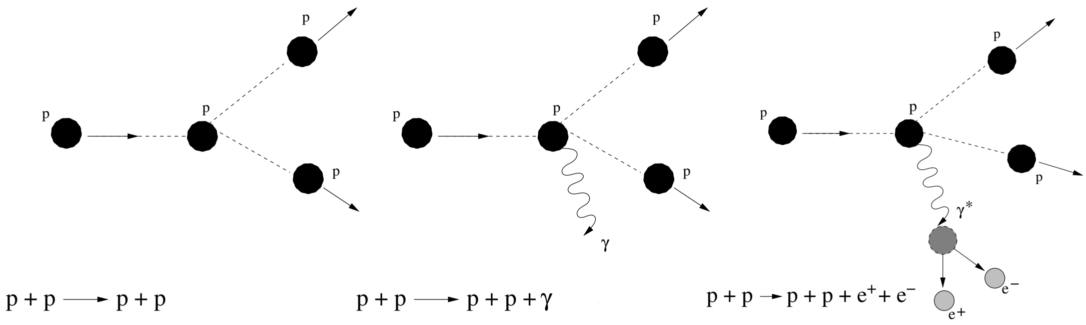

Figure 1.2: Proton-proton elastic scattering (left), inelastic scattering (middle), and virtual-photon inelastic scattering (right) processes.

as a function of the transversal components of the nuclear currents involved in this process. To gain a better knowledge on the nuclear currents, the study of the virtual-photon p-p inelastic scattering process ($p + p \rightarrow p + p + \gamma^*$, Fig. 1.2-right) is of great interest: It involves a so-called virtual-photon, which is not mass-less, and is detected experimentally as a dilepton pair: e^+e^-. The cross section of this reaction presents the particularity of being decomposed into not only transversal but longitudinal parts [Mes 99]. Therefore, its investigation improves substantially our understanding of the nuclear currents by providing us with more degrees of freedom.

Yet, our knowledge of the proton-proton scattering is not sufficient to precisely describe the nucleon-nucleon force. Indeed, in the nucleus, nucleons are interacting with each other, and can consequently not be considered as free particles. Moreover, in systems consisting out of more than two nucleons, the interaction between any two nucleons is influenced by the presence of the other particles.

A first step towards understanding the effects of multi-nucleon reactions is the investigation of proton-deuteron elastic scattering ($p+d \rightarrow p+d$). This study has been performed at the KVI and led to accurate extractions of the cross sections and the analysing powers [Erm 03].

To improve our knowledge on the three-nucleon interaction, the study of the proton-deuteron bound state formation, called *capture reaction*, is of special interest for the investigation of the nuclear currents. Therefore, results of the experimental study of the two following radiative capture reactions will be presented in this thesis:

- $d + p \rightarrow^3 \mathrm{He} + \gamma$, real-photon capture (see Fig. 1.3-left)

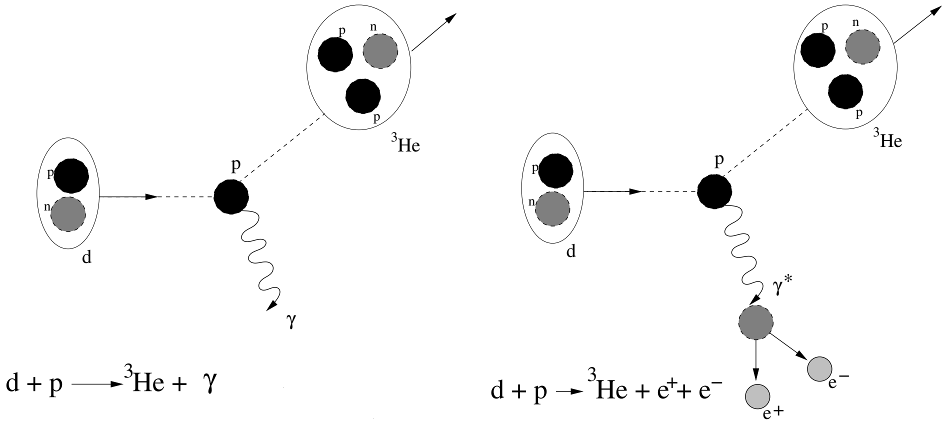

Figure 1.3: Proton-deuteron real-photon (left) and virtual-photon (right) capture processes.

- $d + p \rightarrow^3 \mathrm{He} + \mathrm{e}^+ + \mathrm{e}^-$, virtual-photon capture (see Fig. 1.3-right)

The originality of this work is correlated to the use of a setup which allowed us to differentiate between both reactions: It was composed of a spectrometer dedicated to the detection of ^{3}He, and of a spherical detector surrounding the target to detect photons and dilepton pairs. Therefore, by doing a pulse-shape analysis (see Chapter 5), it was possible to detect background-free virtual-photon capture events, whose cross section was expected to be low (in the order of 1 nb/sr, i.e. a factor $1/\alpha \approx 137$ lower than the real-photon capture cross section, where α is the fine structure constant).

The aim of the study of these two reactions is to improve our knowledge on the nuclear currents and the reliabilities of our theoretical models.

1.2 The deuteron-proton radiative capture

1.2.1 The real-photon capture

Experimentally, the real-photon proton-deuteron capture is well known. Many experiments have been performed over the last 40 years, covering almost the full phase-space and using proton energies from 100 to 500 MeV, [Did 70], [Cam 84], [Pic 87], [Sch 87], [Joh98], [Yag 02]. Calculations and experimental data are globally in good agreement.

The last study of this reaction was performed at the Research Center of Nuclear Physics (RCNP), Osaka University, Japan. Based on the recent finding that discrepancies between the three-nucleon binding energy and the cross section of the nucleon-deuteron scattering process can be explained by the introduction of a 2-pion exchange force (2π3NF), RCNP aimed to show the influence of 2π3NF in the proton-deuteron capture reaction. To do so, they used a polarized deuteron beam of 200 MeV [Yag 02] and a setup which allowed them to detect the ^{3}He only. They concluded that the meson exchange currents involving 2π3NF reproduce their extracted cross section fairly well, but not the analysing powers, i.e. the asymmetry of the cross sections depends on the polarization of the incoming particle.

The results for the angular distribution deduced from RCNP's data are shown in Fig. 2.3 p. 21 where they are compared to the predictions, at 200 MeV, of the two theoretical models, the *relativistic gauge-invariant* (full line) and the *covariant impulse approximation* (dashed line) (see description of the models in section 2.1). It can be concluded that they are in good agreement with the relativistic gauge-invariant model. Moreover, as shown on Fig. 6.2 p. 81, our results agree with the same theory. Both data sets are thus consistent with each other.

It has moreover to be mentioned that the study of the analysing powers has also been performed at the KVI in 2003, for a deuteron beam of 180 MeV and 130 MeV. For these results we refer to [Meh 05].

1.2.2 The virtual-photon capture

As explained above, the virtual-photon reaction is of great interest because it is expected to provide us a better knowledge of the longitudinal and interference currents. This reaction, however, has been little studied due to the expected low cross section. Moreover, existing results do not cover the whole phase-space or are not accurate. Worldwide, we can only refer to the experiments of:

- the The Svedberg Laboratory (TSL), Uppsala university, Sweden, with the PACMAN detector [Höi 90], which could detect virtual photons at only two polar angles: $40°$ and $80°$. They performed experiments at two proton energies: 98 and 176 MeV, for invariant masses smaller than 8 MeV (see Table 1.1) [Joh98].

		$E_p =$	98 MeV	$E_p =$	176 MeV
		$\theta_{lab} = 40°$	$\theta_{lab} = 80°$	$\theta_{lab} = 40°$	$\theta_{lab} = 80°$
$d\sigma/d\Omega(p,\gamma)$	[nb/sr]	279±11	186±18	130±8	83±12
$d\sigma/d\Omega(p,e^+e^-)$	[nb/sr]	1.31±0.09	0.97±0.18	0.52± 0.05	0.23±0.08

Table 1.1: Differential cross section obtained at TSL for M_γ ¡ 8 MeV [Joh98].

- the Kernfysisch Versneller Instituut (KVI), Groningen, the Netherlands, with SALAD and TAPS to detect the ^{3}He and the leptons, respectively, using a proton beam of 190 MeV. Data were obtained for center-of-mass angles from $40°$ to $160°$, but with low statistics (about 300 background-free events for the virtual-photon capture) [Mes 99]. This experiment served as a pilot study for the extraction of the cross sections and the response functions.

  The conclusions of that work were that the theories [Kor 98] [Kor 99] used to describe this reaction underestimated the data. Yet, by increasing the *energy-dependent phenomenological factor* (see Section 2.1.2 p. 18), the discrepancy tended to be reduced. Moreover, the response functions were in good agreement with the predictions. Though, the little statistics of the experiment could not allow sharp conclusions to be drawn.

The input of the present work in the worldwide knowledge of the three-body nucleon interaction is consequently of great interest, since it provides high-statistics p-d virtual-photon capture data, covering a broad angular distribution.

1.3 Outline of this thesis

In this thesis, the different observables and theories describing the real- and the virtual-photon capture reactions are presented in Chapter 2. The terms *matrix element*, *phase-space factor*, *leptonic angles*, *cross section* and *response functions* are introduced. The theoretical models are also explained and compared to each other.

To compare the data to the predictions of the theory, simulations were performed using the numerical Monte-Carlo method: An event generator produces kinematically allowed events and throws them over 4π. The simulation-program selects those events that would have been registered by our detectors, i.e. the events which were emitted in the acceptance range of the detectors, and whose energies were large enough to pass the energy thresholds imposed by the electronics. This method is explained in Chapter 3.

Further, the experimental setup is described in Chapter 4. A deuteron beam of 180 MeV and a liquid hydrogen target were used. This chapter also presents the two detectors used in this experiment:

- the Big Bite Spectrometer (BBS), for detection of the ^{3}He and
- the Plastic Ball, for photons and electron-positron pairs.

Chapter 5 presents the observables that we can access in the collected data-set. The methodology used for their analysis is also explained.

Results are shown in Chapter 6. Comparisons are made between data and theories, for both real- and virtual-photon capture reactions.

Final remarks and conclusions on this work are presented in Chapter 7.