Subproject H5: Few-Nucleon Systems

M. Distler / W. Heil

H5.1 Theory

H5.1.1 New inversion methods for the Lorentz Integral Transform

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Within standard scattering theory, the evaluation of the electromagnetic response function \( R(\omega) \) of a target requires the explicit evaluation of scattering states which becomes more and more involved with increasing mass number \( A \) and finally practically impossible. An elegant solution for this problem offers the Lorentz Integral Transform (LIT) proposed about a decade ago [1]. Within this approach, one calculates at first an integral transform of \( R(\omega) \) with a Lorentzian-shape kernel

\[
L(\sigma_R; \sigma_I) = \int d\omega \frac{R(\omega)}{(\omega - \sigma_R)^2 + \sigma_I^2}, \quad \sigma_R, \sigma_I > 0. \tag{H5.1}
\]

It can be shown that \( L(\sigma_R; \sigma_I) \) can be explicitly obtained using solely bound-state methods so that a tedious calculation of continuum wave functions is not necessary. Hence the LIT approach has proven to be an important progress opening up the possibility to carry out microscopic calculations not only for reactions of classical few-body systems (deuteron, three-body nuclei), but also for reactions of more complex nuclei, see, e.g., the detailed reference list in [2].

The price one has to pay for these advantages is a necessary inversion of the integral transform which has to be treated with great care. In the present work [2], three new inversion techniques for the Lorentz Integral Transform are introduced which lead for inversions of rather complicated response functions considerably better results than the standard inversion method. These new methods extent therefore the range of applicability of the LIT approach considerably.


H5.1.2 General Survey of Polarization Observables in Deuteron Electrodisintegration

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Polarization observables in inclusive and exclusive electrodisintegration of the deuteron using a polarized beam and an oriented target are systematically surveyed using the standard nonrelativistic framework of nuclear theory but with leading order relativistic contributions included. The structure functions and the asymmetries corresponding to the various nucleon polarization
components are studied in a variety of kinematic regions with respect to their sensitivity to real-
listic $NN$-potential models, to subnuclear degrees of freedom in terms of meson exchange cur-
rents, isobar configurations and to relativistic effects in different kinematical regions, serving
as a benchmark for a test of present standard nuclear theory with effective degrees of freedom.


H5.1.3 Spin Asymmetry and Gerasimov-Drell-Hearn Sum Rule for the Deuteron

H. ARENHÖVEL, A. FIX, and M. SCHWAMB

An explicit evaluation of the spin asymmetry of the deuteron and the associated GDH sum rule
is presented which includes photodisintegration, single and double pion and eta production
as well. Photodisintegration is treated with a realistic retarded potential and a corresponding
meson exchange current. For single pion and eta production the elementary operator from
MAID is employed whereas for double pion production an effective Lagrangean approach
is used. A large cancellation between the disintegration and the meson production channels
(Fig. H5.1) yields for the explicit GDH integral a value of $27.31 \mu b$ to be compared to the sum
rule value $0.65 \mu b$.


H5.1.4 The generalized Gerasimov-Drell-Hearn sum rule for deuteron electrodisinte-
gration

H. ARENHÖVEL

The generalized Gerasimov-Drell-Hearn sum rule $I_{\gamma d}^{GDH}(Q^2)$ for deuteron electrodisintegration
d$(e,e')np$ as function of the squared four-momentum transfer $Q^2$ is evaluated by explicit inte-
gration. The calculation is based on a conventional nonrelativistic framework using a realistic
$NN$-potential and including contributions from meson exchange currents, isobar configurations
and leading order relativistic terms. Good convergence is achieved. The prominent feature is a
deep negative minimum, $I_{\gamma d}^{GDH} = -9.5 \text{ mb}$, at low $Q^2 \approx 0.2 \text{ fm}^{-2}$ which is almost exclusively
driven by the nucleon isovector anomalous magnetic moment contribution to the magnetic
dipole transition to the $^{1}S_0$-state. Above $Q^2 = 20 \text{ fm}^{-2}$ the integral $I_{\gamma d}^{GDH}(Q^2)$ approaches zero
rapidly (Fig. H5.2).


H5.1.5 $\pi^0$-photoproducton on the deuteron via $\Delta$-excitation using the Lorentz Integral
Transform

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Usually, the Lorentz Integral Transform (LIT) is applied to electroweak reactions on various
nuclei solely for energies well below the pion threshold, where solely nucleonic degrees of
freedom are explicitly taken into account. In the present work [1], we have studied whether it
is possible to extend the LIT approach to higher energies where in addition the $\Delta$-isobar and/or explicit pionic degrees of freedom should be considered. In standard approaches, the latter are usually projected out in favour of so-called effective operators. However, it turns out that the energy-dependence of the latter leads to serious conceptual problems within the LIT approach. They can be overcome by using an extended Fock space which should contain explicitly all relevant degrees of freedom, i.e. both nucleonic as subnucleonic ones. This avoids therefore energy-dependent effective operators as basic ingredients of the relevant interaction and allows the extension of the LIT approach to higher energies. In the present work, we have moreover tested successfully within a simplified approach for $\pi^0$-photopion production on the deuteron the numerical applicability of this concept.

Figure H5.2: Generalized Gerasimov-Drell-Hearn integral as function of $Q^2$ for deuteron electrodisintegration $d(e, e' n)p$. Left panel: separate current contributions from normal nonrelativistic theory (N) and successively added meson exchange currents (MEC), isobar configurations (IC), and relativistic contributions (RC). Right panel: results of the complete calculation (T) for different potential models and for vanishing anomalous nucleon magnetic moments (labeled “point particle”).

H5.1.6 Incoherent pion photoproduction on the deuteron with polarization observables

A. Fix and H. Arenhövel

Photoproduction of pions on the deuteron has two main but complementary points of interest. The first one is to obtain information on the elementary reaction on the neutron by using the deuteron as an effective neutron target. A prerequisite for this is that one has reliable control on off-shell and medium effects. In order to minimize such effects, quasi-free kinematics is preferred. The second but not secondary aspect is just the influence of a nuclear environment on the production process, for the study of which off-quasi-free kinematics is better suited.

We have exploited the role of polarization observables in incoherent pion photoproduction on the deuteron with particular emphasis on the influence of final state interaction in the $NN$- and $\pi N$-subsystems of the final state [1, 2]. The elementary $\gamma N \rightarrow \pi N$ amplitude was taken from the MAID model. The influence of final state interactions on total and semi-exclusive cross sections $d(\gamma, \pi)NN$ was investigated by including complete rescattering in the final $NN$- and $\pi N$-subsystems.

For the calculation of the $NN$-rescattering contribution we have taken the separable representation of the realistic Paris potential from [3] and included all partial waves up to $3D_3$. Similarly, $\pi N$-rescattering was evaluated using a realistic separable representation of the $\pi N$-interaction from [4] and taking into account all partial waves up to $l = 2$.

As the calculations show, for charged pion-production the influence of $NN$-rescattering is moderate whereas $\pi N$-rescattering is almost negligible. Much stronger influences of $NN$-rescattering are seen in neutral pion production, which is due to the elimination of a significant spurious coherent contribution in the impulse approximation. Sizeable effects are also found in some of the beam, target and beam-target asymmetries of the differential cross section.

In the unpolarized total and semi-exclusive differential cross section $d^2\sigma/d\Omega_q$, where only the direction of the produced pion is measured, the influence of final state rescattering is quite small for charged pion production for photon energies up to 1 GeV. For $\pi^0$-production the influence is much larger. However, the dominant part of FSI-effect arises from the removal of a
spurious coherent contribution in the impulse approximation when \( NN \)-rescattering is switched on. This is demonstrated by a modified IA, where the deuteron wave function component in the final \( NN \)-plane wave is projected out. The remaining FSI-effect is comparable to charged pion production.

A very interesting and still open question concerns the disagreement between theoretical and experimental results for \( \gamma d \to \pi^0 n p \) in the second resonance region (see Fig. H5.3). Although our calculation explains the strong smearing of the resonance structure, the data are overestimated by about a factor of 1.5. Hopefully, new measurements of the ratio \( R = d\sigma(\gamma, \pi^0 n)/d\sigma(\gamma, \pi^0 p) \) for quasifree photoproduction on neutrons and protons can clarify the situation. The old data from [5, 6], pointing to \( R = 1 \) in the second resonance region, seem to be in disagreement with the results of [7].

As polarization observables we have considered all beam, target and beam-target asymmetries of the semi-exclusive differential cross section. Many of them are quite sizeable, in particular the photon asymmetry \( \Sigma^l \) (an example is given in Fig. H5.4) and various vector asymmetries. The tensor asymmetries are in general considerably smaller. They are often quite insensitive to final state rescattering. Only a few, \( T_{21} \) and \( T'_{21} \), show a larger influence in charged pion production.

![Figure H5.3: Total cross section for \( \pi^- \) (left panel) and \( \pi^0 \)-photoproduction (right panel) on the deuteron. Solid curves: IA + \( NN \)- and \( \pi N \)-rescattering. Experimental data from Benz et al. [8] and from Asai et al. [9] for \( \pi^- \)- and from Krusche et al. [7] for \( \pi^0 \)-production.](image)

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H5.1.7 Double pion photoproduction on nucleon and deuteron

A. Fix and H. Arenhövel

Double pion photoproduction is usually considered as a complementary reaction serving as the main source of information which cannot be obtained otherwise, e.g. from single pion photoproduction. In particular, this process is quite promising for the study of the so-called “missing” resonances which are only weakly coupled to the $\pi N$ channel [1]. The analysis of the various theoretical approaches is usually focused on the experimentally favorable case where the target is a proton, whereas the results on the neutron depend on the model assumptions used for extracting the data from measurements on the deuteron or on other light nuclei. The neutron data are obviously needed for a systematic analysis of the isotopic spin structure of the elementary amplitude. The main question arising in this connection is, what is the role of “nuclear effects”, e.g., Fermi motion, final state interaction, and two-nucleon production contributions, which prevent a model independent study of the neutron amplitude.

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Figure H5.4: Differential cross section and linear photon polarization asymmetry for semi-exclusive $\pi^-$ photoproduction on the deuteron. Notation of curves: dashed: IA; dotted: IA from Lee and Sato [11]; solid: IA + $NN$-rescattering. The data are for the differential cross section from Benz et al. [8] and for the linear photon asymmetry from the LEGS-collaboration (LEGs-exp.L3b) [10].

Our calculation [2] of $\gamma N \rightarrow \pi \pi N$ followed the traditional phenomenological Lagrangean approach with Born and resonance contributions on the tree level. Multiple scatterings within the $\pi N$ and $\pi \pi$ subsystems were effectively taken into account by introducing nucleon and meson resonances, respectively. For the resonance contributions, the final two-pion state then results from a two-step decay via intermediate quasi-two-body channels for which we take here $\pi \Delta$, $\rho N$ and $\sigma N$ channels. The resonances included in the model were those which are localized in the mass region up to 1.8 GeV and classified with four stars in the Particle Data Group compilation [3]. The hadronic coupling constants were fitted to the corresponding decay widths taken from [3].

In Fig. H5.5 the total cross section for the various charge configurations of $\pi \pi$ photoproduction on the deuteron is presented. It reproduces qualitatively the form of the elementary cross section (dotted curves) except that they are slightly smeared out by the Fermi motion especially around the resonance peaks. This fact together with the obviously quite small influence of $NN$ rescattering in the final state support the approximate validity of the spectator model. Even in the "neutral" $\pi^+ \pi^-$ channel, which is by far the most important channel, FSI leads to a lowering by only 10% of the plane wave cross section. Thus it is significantly smaller than what had been found in single neutral pion production on the deuteron $\gamma d \rightarrow \pi^0 np$ where this effect lead to a reduction by about 30%. The coherent $\pi^+ \pi^-$ photoproduction cross section, presented in Fig. H5.6, comprises only about 6% of the corresponding incoherent cross sections in Fig. H5.5, whereas the $\gamma d \rightarrow \pi^0 \pi^0 d$ cross section turns out to be vanishingly small.

Figure H5.5: Total cross section for incoherent double pion photoproduction on a deuteron for different charge channels. Solid and dashed curves are obtained with and without final $NN$ interaction. Dotted curves show the corresponding elementary cross sections. In $\pi^+ \pi^-$ and $\pi^0 \pi^0$ channels they are calculated as a sum of the cross sections on a proton and a neutron. The data are from Ref. [4] (circles) and Ref. [5] (triangles).
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Figure H5.6: Total cross sections for coherent double pion photoproduction on a deuteron. The solid and the dashed curves represent the $\pi^+\pi^-$ and $\pi^0\pi^0$ channels, respectively. The $\pi^0\pi^0$ cross section is multiplied by a factor 50.


H5.1.8 Signature of the $\eta NN$ configuration in coherent $\pi^0$ photoproduction on the deuteron

A. Fix

In a recent experiment photoproduction of a neutral pion on the deuteron was considered in the energy region around the $\eta$ threshold [1]. In the region of very backward pion angles quite a pronounced bump-like structure was observed. This phenomenon was investigated in [2] within a theoretical frame including intermediate $\eta NN$ configurations. It has been shown that a strong coupling between $\pi N$ and $\eta N$ states in the energy region of the $S_{11}(1535)$ resonance leads to a significant admixture of the $\eta NN$ configuration to the $NS_{11}$ intermediate states. What is more important, in contrast to pions, slow $\eta$ mesons interact strongly with nearby nucleons. As predicted in a variety of investigations, this dynamical feature leads to highly correlated $\eta NN$ states, which should manifest themselves in the $s$-wave part of the $\pi^0$ photoproduction amplitude. According to our results there are different dynamical aspects which are responsible for appearance of the bump in the $\gamma d \rightarrow \pi^0 d$ cross section.

(i) The first most obvious question is to what extent the structure under consideration can be caused by the cusp-like structure in the elementary amplitude $\gamma N \rightarrow \pi^0 N$ in the $S_{11}$ channel near the $\eta$ threshold. The case in point is the strong coupling between the $\pi N$ and $\eta N$ states in the region of the $S_{11}(1535)$ resonance resulting in a very pronounced cusp in the electric dipole amplitude $E_{0+}$ for pion photoproduction at $E_{\gamma} \approx 710$ MeV. Turning to the process on the nucleon, which is bound in the deuteron, the elementary amplitude might undergo an energy
shift and a broadening of its structure due to Fermi motion. The calculation shows that the $S_{11}(1535)$ resonance itself does in principle produce a slight shoulder close to the $\eta$ threshold, which, as mentioned before, is a signature of the cusp in the $E_0^+$ multipole smeared out by the Fermi motion in the deuteron. However, this resonance contributes little to the coherent reaction on the deuteron, so that this cusp-like structure turns out to be invisible in the cross section. Hence, the slight enhancement observed in the otherwise monotonic behaviour of the IA cross section (dashed line in Fig. H5.7) is not related to the $\eta NN$ dynamics and should be ascribed to properties of the elementary pion production amplitude in this region.

(ii) A bump-like structure could also arise from an additional mechanism, appearing when the elementary photoproduction process is embedded into the deuteron. Namely, the anomalies are caused by the three-particle unitary cut in the amplitude $\gamma d \to \pi^0 d$ starting at the energy of the $\eta$ threshold. This cut arises because of the possibility to exchange a physical $\eta$ meson between the $S_{11}$ resonance excited on one of the nucleons and the second nucleon. The exchange mechanism is characterized by a pole which becomes a cut by the loop integration. Thus, the opening of a new physical channel leads to an additional contribution in the imaginary part of the amplitude reflecting a new inelasticity. Such a picture is typical for coupled channels and, if the corresponding dynamical equations are exactly solved, results in the three-body unitary relation. Because here we take into account only the leading term in the multiple scattering series, the whole amplitude does not fulfil the unitary relation. However, the $\eta NN$ three-body cut appears already at this level and influences the amplitude at the branch point (dash-dotted line in Fig. H5.7)

(iii) A sizable attraction in the $\eta NN$ system leads to a strong correlation between all three particles. It is worth noting that in some work the $\eta NN$ interaction is predicted to generate even a bound state in the quasi-deuteron configuration $(J^P; T) = (1^-; 0)$. Results provided by more sophisticated models [3] show, however, that the fundamental $\eta N$ interaction is likely to
be too weak for yielding binding of the $\eta NN$ system, so that only a virtual (antibound) state can be generated. Although the pole ‘recedes’ to the nonphysical region, it remains quite close to the zero energy. As a result, the virtual state strongly influences physical processes involving an $\eta$ meson (solid line in Fig. H5.7).


H5.1.9 Binding of charmonium with two- and three-body nuclei

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As pointed out in [1] with regard to charmonium-like mesons, for example $\eta_c$, which do not contain $u$- and $d$-quarks, the main contribution to the meson-nucleon interaction is expected to originate not from the effective, but from fundamental QCD degrees of freedom, namely from few-gluon exchange. In this way, using the Pomeron exchange model, one can deduce a Yukawa-type potential for the $\eta_c$-nucleon system [1] which leads to binding of $\eta_c$ mesons already with few nucleon systems.

First attempts to calculate the binding of $\eta_c$-mesons with light nuclei have been made in Ref. [1] on the basis of variational calculations, and in Ref. [2] where the folding model was used. Both calculations involve a Yukawa form for the basic $\eta_cN$ interaction. Our results for the binding energies of $\eta_c d$ and $\eta_c^3$He, presented below, are obtained within the AGS theory. Similar to [1, 2] we use a Yukawa type $\eta_cN$ potential $V_{\eta_cN}(r) = -ae^{-\alpha r}/r$ with $\alpha = 0.6$ GeV. The parameter $a$ is varied between 0.4 and 0.6.

The $\eta_c d$ binding energy is presented in Fig. 1 by the solid line where they are also compared to those obtained using the so-called Bateman method (dashed line). In contrast to the results of [1] and [2], we find only one bound state lying in the region $-2$ MeV $\leq E_b \leq -5$ MeV, when the parameter $a$ is varied between 0.4 and 0.6 GeV.

In the case of $\eta_c^3$He system, the four-body formalism developed in Ref. [3] and Ref. [4] for the interaction of isoscalar-pseudoscalar mesons with three-body nuclei was used. The calculations are based on separable representations of the two- and three-body kernels of the basic AGS equations so that, as a consequence, the resulting integral equations have the same structure as the three-body equations.

Varying the potential strength $a$ between $a = 0.4$ and $a = 0.6$, the $\eta_c^3$He binding energy changes from $-1.3$ MeV to $-14.5$ MeV. These results exhibit essential differences to the predictions of the folding model as well as to the variational calculations.
Figure H5.8: Binding energy of $\eta_c d$ system as function of the strength $a$ of the Yukawa potential. The results obtained with the Bateman and Hilbert-Schmidt representation of the $\eta_c N$ potential are presented by the dashed and the solid lines, respectively.


H5.1.10 On the treatment of $\Delta$-contributions in electromagnetic $pp$-knockout reactions

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Electromagnetically induced two-nucleon knockout is a promising tool to study correlations in nuclei. A reliable interpretation of experimental data requires the precise knowledge of the contributing reaction mechanisms, i. e. electromagnetic one-body as well as two-body currents, isobar-configurations as well as final state interactions. In the present work [1], we have studied systematically the contribution from the $\Delta$-current, which has to be under control in order to extract information on correlations. Different possible parametrizations are discussed which have been extracted either from $NN$- or alternatively from $\pi N$-scattering data and where in addition medium modifications have been considered. It turns out that the sensitivity of the cross sections on the chosen $\Delta$-parametrization, as well as on the chosen correlation function, may depend strongly on chosen kinematics. Therefore, the investigation of different mutually supplementing kinematics is necessary to resolve the uncertainties in the theoretical ingredients and extract clear and unambiguous information on correlations.

H5.2 The polarized $^3$He target

J. Krimmer W. Heil for A1

Polarized $^3$He is a suitable substitute for a polarized neutron target as the spin of $^3$He is mainly carried by the neutron due to the high probability for the two protons to be in the S-state [1]. A polarized $^3$He-target can be used e.g. to extract the electric form factor of the neutron via quasi elastic scattering of polarized electrons [2].

A sufficient target density requires a pressure of the $^3$He-gas of about 5 bar in the target cells and initial polarization values of more than 70 % for a minimization of the measuring time.

The $^3$He polarizer in Mainz operates according to the Metastability Exchange Optical Pumping (MEOP)[3, 4] principle. The $^2 S_1$ state is reached via a gas discharge at pressures of 0.8-1.0 mb and is then optically pumped by circularly polarized laser light at 1083 nm. Nuclear polarization of the $^2 S_1$ state is transferred to unpolarized ground state atoms via collisions. The polarized gas is compressed to the desired pressures of about 5 bar in a nonmagnetic piston compressor where less than 2% of its initial polarization is lost[5]. As a result, more than 70% $^3$He polarization can be obtained at a yield of 2 bar l/h[6, 7].

After filling at the polarizer, the target cells are brought to the experiment in special transport containers made from soft-iron and $\mu$-metal which provide a homogeneous guiding field inside by means of permanent magnets and are shielded against external magnetic stray fields.

The $^3$He-polarization inside a target cell at the electron beam decreases exponentially with the total relaxation time $T_{1}^{total}$:

$$\frac{1}{T_{1}^{total}} = \frac{1}{T_{1}^{grad}} + \frac{1}{T_{1}^{dipole}} + \frac{1}{T_{1}^{beam}} + \frac{1}{T_{1}^{wall}}$$

The field induced relaxation time $T_{1}^{grad}$ is larger than 1000 hours at a relative gradient of the holding field of $5 \cdot 10^{-4}$ cm$^{-1}$ and a pressure of $p=5$ bar and thus can be neglected. The dipole-dipole interaction of the $^3$He atoms gives an upper limit for suitable pressures in the target cell, given by $T_{1}^{dipole} = \frac{163 \text{ h}}{p \text{ bar}} = 163 \text{ h}$ (p = 5 bar) [8]. In the electron beam $^3$He$^+$ ions and $^3$He$_2^+$ molecule ions are produced. The latter process which shows a catalytic action can be eliminated by adding small amounts ($10^{-3}$) of N$_2$ as quenching gas. The former process results in $T_{1}^{beam}$ of 150 hours for our target geometry and an electron current of 10 $\mu$A [9].

A large contribution to the total relaxation rate comes from the interaction of the $^3$He atoms with the container walls. It has been observed that the $T_1$ time of glass cells decreases drastically after exposure to a large magnetic field (1.5 T) for example at a MRI tomograph. This effect is caused by ferromagnetic impurities at the inner glass surfaces. However, the original $T_1$ time can be regained by a proper demagnetization procedure [5]. Note, that even a cell which hasn’t seen a strong magnetic field shows some ferromagnetic behaviour. Thus, it is necessary to demagnetize each cell before usage. Further more wall relaxation due to adsorption and dissolution play a role. The first one can be diminished by a coating with cesium, which reduces the sticking time to a minimum due to the low adsorption energy of Cs. Dissolution can be eliminated by adding small amounts of N$_2$ as quenching gas.
minimized by using a non permeable glass, e.g. aluminosilicate or by simply Cs-coating which also closes the pores of a more porous glass, like quartz.

Theoretical interest in a quantitative understanding of wall relaxation processes exists since long [10]. In the "historical" models paramagnetic impurities, e.g. iron, have been assumed to cause relaxation via dipolar coupling. It has been observed, however, that glass containers made from a special iron free Supremax glass, and ordinary Supremax cells have similar relaxation rates. A new model, which takes into account Fermi-contact interaction with dangling bond type defects in the glass matrix, can describe the temperature dependence and the absolute values of relaxation rates with realistic parameters [11, 12, 13]. Thus, relaxation due to adsorption and dissolution is solely due to Fermi-contact interaction with paramagnetic centers.

Figure H5.9: Sketch of a target cell used for electron scattering experiments. The numbers are given in mm.

A sketch of a target cell used for electron scattering experiments is given in Fig. H5.9. The electron beam runs in the horizontal direction. A prototype target cell has been manufactured from aluminosilicate glass (GE 180) for tests of different materials of the entrance and exit windows. To show the influence of different window materials, relative relaxation times are given in Tab. H5.1 where the reference time $T_{1,ref}^{wall}$ has been obtained from the measurements with the titanium foils. However, the foils with the longest relaxation times are not feasible for an electron scattering experiment because the diamond windows cannot stand the required $^3$He pressure and titanium produces too much background in the beam due to its large atomic number. To minimize the background, beryllium is the ideal window material but it shows depolarizing effects. A good compromise is a beryllium window which is covered by a thin aluminum foil to prevent a direct contact of beryllium with the polarized $^3$He-gas.

For electron scattering experiments a mean target polarization of 60-65 % is desired. This can be achieved when the target is exchanged twice a day and when the total relaxation time $T_1^{total}$
is larger than 50 hours. Therefore, the wall relaxation time has to be larger than 80 hours, due to the limitations via $T_{1}^{beam}$ and $T_{1}^{dipole}$. This $T_{1}^{wall}$ has already been reached in a previous experiment with cesium-coated quartz cells [2].


H5.3 Structure of the $^{3}$He

D. ROHE for A1

$^{3}$He is quite suitable for investigating reaction mechanisms like FSI and MEC as well as the nucleon-nucleon interaction in the medium. Among other methods [1, 2] Faddeev calculations using realistic N-N potentials and treating the full reaction in an exact way are available [3]. The technique to produce polarized $^{3}$He of several bar pressure and high polarization are advanced and suitable for nuclear physics experiments. Hence the spin structure of $^{3}$He can also be studied. Its spin structure is particularly interesting because the neutron carries most of the spin of $^{3}$He in kinematics close to the quasielastic peak. This feature is exploited when measuring the electric form factor of the neutron. On the other hand, corrections on $G_{en}$ have to be applied to account for nuclear effects not present at a free neutron. These corrections are provided by the theory and therefore its reliability has to be tested.

In 2003 a large amount of data were taken at MAMI at the three-spectrometer hall of the A1 collaboration to examine the structure of $^{3}$He. In the wings of the quasielastic peak, i.e. at large missing momentum $p_{m}$, two scintillator arrays detected neutrons and protons from
the reaction $^3\text{He}(\bar{e}, e'n)$ and $^3\text{He}(\bar{e}, e'p)$. These data are sensitive to the D-state contribution in the wave function and are under analysis. Simultaneously two high resolution magnetic spectrometers detect the scattered electron and the knocked-out proton in coincidence. Here a separation of the two- (2BB) and three-body breakup (3BB) could be performed. A resolution of 1 MeV (FWHM) was achieved which is mainly due to energy straggling on the 1-2 mm glass of the target cell. The kinematics was limited to the central region of the quasielastic momentum distribution at $Q^2$ of 0.31 (GeV/c)$^2$. Each hour the target spin was turned to measure the parallel, perpendicular, antiparallel and antiperpendicular asymmetry alternately with the purpose to reduce the systematic errors. The target cell was of the same type as already used for previous $G_{en}$ measurements [4, 5]. Averaged over the beam time period and accounting for relaxation a target polarization $P_T$ of $(49.8\pm0.3\text{ (stat.)}\pm2\text{ (syst.)})\%$ was obtained.

From the measured kinematic variables in the two spectrometers, the missing energy is reconstructed according to

$$E_m = E - E_e - T_p - T_R.$$  \hfill (H5.2)

Here, $E$ ($E_e$) is the initial (final) electron energy and $T_p$ is the kinetic energy of the outgoing proton. $T_R$ is the kinetic energy of the (undetected) recoiling ($A-1$)-system, which is reconstructed from the missing momentum under the assumption of 2BB. The resulting $E_m$ distribution reconstructed from the data is shown in fig. H5.10 by the thick solid line. The resolution is limited mainly by the properties of the target cell and not by the resolution of the spectrometers. The FWHM of 1 MeV allows a clear separation of the $E_m$-regions where only 2BB or 2BB and 3BB contribute. The $E_m$-region from 4.0 to 6.5 MeV is interpreted as pure 2BB. This cut was chosen to avoid any contribution from the 3BB-channel (starting at 7.7 MeV) considering the experimental $E_m$ resolution. In agreement with ref. [8], the yield of the 3BB is negligible beyond 25 MeV. Therefore the cut for the 3BB-channel was made from 7.5 to 25.5 MeV in the $E_m$ spectrum. Because the 3BB resides on the radiative tail of the 2BB, the latter has to be accounted for in the analysis of the 3BB-region of the measured spectrum. To this end, the tail was calculated in a Monte Carlo simulation which accounts for internal and external bremsstrahlung, ionization loss and experimental energy resolution adjusted to the experimental distribution. The simulated 2BB distribution is shown as thin red line in fig. H5.10. Subtracting this from the data leads to the distribution belonging to the 3BB channel which is also shown in fig. H5.10.

The ratio of the Monte Carlo simulation of the 2BB to the experimental data in the region of the 3BB is denoted by $a_{23}$. For the region $7.5 < E_m < 25.5$ MeV it amounts to $a_{23} = 0.434 \pm 0.002$ (stat.) $\pm 0.015$ (syst.). Then the asymmetry $A_{3BB}$ for the 3BB-channel is extracted from the asymmetry $A_{2+3BB}$ in the 3BB region by accounting for the contribution from the radiation tail

$$A_{3BB} = \frac{A_{2+3BB} - A_{2BB} a_{23}}{1 - a_{23}}.$$  \hfill (H5.3)

All asymmetries are corrected for target and electron polarization. In fig. H5.11 the parallel and perpendicular asymmetries $A_{3BB}$ and $A_{2BB}$ are compared to two calculations of the Bochum-Krakow group. One uses PWIA only (dot-dashed), the other accounts for full FSI and MEC (solid line). The effect of MEC is negligible in this kinematics. The data integrated over the total detector acceptance are in good agreement with the calculation including FSI.

The calculation shows that the FSI contribution is small in the 2BB while it is large in 3BB. This suggests that the main contribution of FSI results from the rescattering term which does
CHAPTER 2. EXPERIMENTS AT MAMI AND THEORY

not exist in the 2BB, and not from direct FSI. This was also confirmed by further examination of the theoretical result by Golak [6].

In the 2BB channel the spins of the neutron and proton in the recoiling deuteron are coupled to one, therefore they are parallel. Consequently, in a simplified picture, the spin of the second (knocked-out) proton must be antiparallel to the deuteron spin and thus to the spin of $^3$He. Correct coupling of the spins 1 and 1/2 to 1/2 leads to 33 % polarization of the knocked-out proton relative to that of the polarized $^3$He-target. This is precisely what is observed as $A_{2BB}$. In the 2BB channel, the polarized $^3$He-target can thus be interpreted as a polarized proton target.

For the 3BB channel the situation is different. In PWIA the asymmetry is almost zero for the 3BB which reflects the fact that the two protons, which are predominantly in the $S$-state and thus have opposite spin orientation, now contribute equally to the knock-out reaction. The inclusion of FSI, however, leads to an asymmetry, which is larger and opposite in sign compared to the 2BB. The main effect comes from the np t-matrix (rescattering term). Since different spin combinations of the singlet and triplet np t-matrix contribute, the $^3$He target cannot be interpreted as a polarized proton target in the 3BB channel.

This work is published in [9].

H5.4 The electric form factor of the neutron at low $Q^2$

D. ROHE FOR A1

The electromagnetic form factors of the nucleon are a strong constraint of any nuclear theory on the nucleon or quark level. In particular the surprising result that the proton electric form factor strongly deviates from the dipole form factor at large $Q^2$ [10, 11], renewed the interest in describing all form factors satisfactorily in one model. Recent calculations are using promising ansatzes like lattice QCD, Regge parameterization for the General Parton Distribution (GPD) and relativistic quark models. However, at low $Q^2$ the experimental data points for $G_{en}$ show...
a large variation and large error bars. Therefore they provide only less guidance for theories. This region is particularly interesting because it is sensitive to a possible meson cloud. In a phenomenological model of the nucleon of Friedrich and Walcher [12] the neutron is decomposed into a bare neutron $n_0$ and a polarization part. In the polarization part the neutron exists as a bare proton $p_0$ surrounded by a pion cloud. The data are fitted by an ansatz consisting of two dipole form factors for the smooth part and two Gaussians to account for a possible bump. The meson cloud is found at $Q^2 \approx 0.2$ (GeV/c)$^2$ in the electric and magnetic form factors of the proton as well as the neutron and appears there as a dip or bump. Their result for the electric form factor of the neutron, $G_{en}$, is shown by the solid line in fig. H5.12.

In this figure the experimental results are also shown for $G_{en}$ from double polarization measurements performed at MAMI, JLAB and NIKHEF using a polarized electron beam and polarized target or alternatively by detecting the polarization of the knocked-out nucleon. Since no free neutron target of sufficient density exists, the deuteron and $^3$He are used as targets. Polarized $^3$He is suitable to be used as a polarized neutron target, since there is high probability the protons reside in the $S$-state and therefore the spin of $^3$He is essentially carried by the neutron [22]. This property of the $^3$He-spin structure can be best exploited in the quasielastic reaction $^3$He($\bar{e}, e'n$) with restriction to small missing momenta as well as in the inclusive $^3$He($\bar{e}, e'$) reaction near the top of the quasielastic peak. However, the measurement is affected by the structure of the nucleus, Meson Exchange Currents (MEC) and Final State Interactions (FSI). Therefore corrections provided by theory have to applied to the experimental result. The deuteron structure and non-PWIA contributions are well described by the theory of Arenhövel [23] which proved to be reliable at low as well as high $Q^2$. In the case of $^3$He the Schrödinger equation for the three-body system can be solved exactly by means of the Faddeev formalism [3, 24]. The theoretical results were tested by comparing it to measured quantities like the target asymmetry $A_y$ which is in particular sensitive to non-PWIA contributions [5]. However,
Figure H5.12: \(G_{\text{en}}\) extracted from quasielastic scattering of polarized electrons from \(D\), \(\bar{D}\), and \(^3\text{He}\). The data are taken from refs. [13, 14, 15, 16, 17, 5, 18, 19, 20]. The dashed line represents the Galster fit [21] and the solid curve the result of [12]. The hollow triangle is the preliminary result of the ongoing analysis. For some of the experimental data points the correction due to the reaction mechanism beyond PWIA is indicated by the size of the arrows.

As can be seen from fig. H5.12 the database in the region where a signature of the meson cloud might appear is still scarce. Therefore data on \(G_{\text{en}}\) were taken at \(Q^2 = 0.15\) and 0.25 (GeV/c)\(^2\) using the reaction \(^3\text{He}(e,e'\bar{n})\) in quasifree kinematics. The electrons were detected in spectrometer A and the neutrons in a segmented scintillator array. The asymmetry, with respect to the electron helicity, contains an interference term \(G_{\text{em}}G_{\text{mn}}\) which amplifies \(G_{\text{en}}\) by \(G_{\text{mn}}\). The sensitivity to \(G_{\text{en}}\) is largest in the perpendicular asymmetry \(A_{\perp}\), where the direction of the target spin is perpendicular to the momentum transfer. In contrast the parallel asymmetry \(A_{\parallel}\) does not depend on form factors (for \(G_{\text{en}}\) small) and therefore can be used for normalization. Measuring the asymmetry has the advantage that no absolute cross section measurements are required which avoids the effort (and systematic errors) of determining absolute efficiencies, solid angles and luminosity.

The electron-target asymmetry is obtained via

\[
A_{\text{exp}} = \frac{N^+L^+ - N^-L^-}{N^+L^+ + N^-L^-},
\]

where \(L^+ (L^-)\) are the integrated charge and \(N^+ (N^-)\) the number of events for positive (negative) electron helicity. The electron helicity is flipped every second randomly. The experimental asymmetry has to be corrected for the polarization of the electron beam \(P_e\) and the target \(P_r\). It contains the electromagnetic form factors but also depends on the reaction mechanism involved.
To evaluate the correction factor on the parallel and perpendicular asymmetries 9 kinematics were chosen, equally distributed on the momentum-angle acceptance of spectrometer A. The correction is already sizable at \( Q^2 = 0.25 \text{ (GeV/c)}^2 \), in particular at small electron angles and momenta. In this region the theory predicts a huge contribution from MEC, such that \( A_\perp \) has to be corrected by a factor 15. Therefore this part of the acceptance was neglected in a first analysis. The correction factors were weighted by the number of events in the bins. Averaged over the 8 angle-momentum bins the correction factor for \( A_\perp \) is 1.65 and for \( A_\parallel \) is 1.06. The statistical error of the preliminary result from this integral analysis is 15 % and shown in fig. H5.12 as a hollow triangle.

To compare the experimental asymmetries on a bin-by-bin basis a Monte Carlo simulation is needed to account for the events which are shifted to another bin by the radiative process. Further, the direction of the momentum transfer moves a few degrees over the acceptance of spectrometer A whereas the spin direction is fixed. Therefore the asymmetries measured contain contributions from both parallel and perpendicular asymmetries. To account for both effects in the simulation the theoretical asymmetries averaged over the acceptance of the hadron detector were fitted as a function of the electron angle and momentum. The angles between target spin and momentum transfer obtained in the simulation were compared to the data and good agreement is achieved for each bin. The asymmetry measured for perpendicular spin alignment is shown in fig. H5.13 as a function of the electron momentum and angle and compared to the theory (solid line). This preliminary result shows good agreement with the calculation of Golak. In the meantime better calculations were done using an improved \(^3\text{He} \text{ wave function and consistent pi- and rho-like MEC.} \)

H5.5 $^3\text{He}(\bar{e}, e'\bar{p})d$ - A Triple Polarisation Experiment at MAMI

M. WEINRIEFER FOR A1-COLLABORATION

The forces between two and more nucleons have been under investigation by theorists and experimentalists during many years [1, 2]. By the availability of polarised $^3\text{He}$-targets polarisation degrees of freedom became more and more important. During the period of this annual report a feasibility study for a triple polarisation experiment was made [3]. This new kind of experiment is possible due to a proton polarimeter build for spectrometer A [4], that allows to measure the polarisation of the recoil proton. Together with a polarised $^3\text{He}$-target and a highly polarised beam it is possible to measure simultaneously three degrees of freedom. With the results of such an experiment one can test different nuclear models and investigate the spin structure of $^3\text{He}$. This would give additional information for various experiments that use polarised $^3\text{He}$ as an effective neutron target.

In planning such an experiment one has to take care of the various limitations given by the three spectrometer setup. The main constraints are the possible angles of the spectrometers...
and the measurable momenta. The values are given in table H5.2. To get an impression of the remaining kinematics the limits are plotted in the $\omega - q$-plane in figure H5.14. The remaining white region represents the measurable region.

<table>
<thead>
<tr>
<th></th>
<th>spectrometer A</th>
<th>spectrometer B</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum angle</td>
<td>degree</td>
<td>18</td>
</tr>
<tr>
<td>maximum angle</td>
<td>degree</td>
<td>160</td>
</tr>
<tr>
<td>minimum momentum</td>
<td>MeV/c</td>
<td>450</td>
</tr>
<tr>
<td>maximum momentum</td>
<td>MeV/c</td>
<td>735</td>
</tr>
</tbody>
</table>

Table H5.2: Kinematical limits give by the three spectrometer setup.

Figure H5.14: Possible kinematics for a triple polarisation experiment. The red and green areas are cut away by the minimum and maximum electron angle, the blue one due to the minimum proton angle. The maximum proton angle is too large to give a limit in this picture. The magenta region is cut away by the minimum proton momentum and all kinematics in the cyan region produce a proton momentum too large to be detected. The black line represents the pion threshold.

During a test beam time in February 2005 the focal plane polarimeter (FPP) was calibrated and tested with quasi-elastic scattering on carbon and elastic scattering on hydrogen. During the last days of this beam time a quasi-elastic scattering experiment on unpolarised $^3$He was done. The kinematics for this test experiment was motivated by an existing shielding box of the polarised target. The three kinematical setups of the test beam time are listed in table H5.3.

The main reason for the elastic scattering experiment on hydrogen was to test the FPP. For this measurement precise theoretical calculations exist. So this is a good test for the calibration of the FPP and it gives some confidence in the measured proton polarisation of the helium experiment. The data measured is shown in figure H5.15. A good agreement of the hydrogen data with theory can be seen. The boundary condition points in the plots refer to a polarisation calculation under the assumption that the polarisation in y-direction should be zero. This can
be done because a longitudinal polarised beam was used together with an unpolarised target so there should be no polarisation along the y-axis.

Figure H5.15: Polarisation of elastic scattering on hydrogen (left) and quasi-elastic scattering on helium (right). The boundary condition points are shifted to the right so one can differentiate better between with and without boundary condition.

The cross section measured in the quasi-elastic helium data is shown in figure H5.16. It is compared to a PWIA calculation because at the moment there is no better model available. It can be seen that there is no large disagreement between the data and theory.
Figure H5.16: Cross section measured in quasi-elastic scattering on $^3$He. The blue line represents a PWIA simulation.

The data used to calculate the proton polarisation was taken with a rate of approximately 0.65 Hz. This is due to the fact that only about 2% of the data are accepted by the polarimeter cuts in the analysis. The target used in the test beam time was a high pressure - low temperature target (18 bar, 20 K). The polarised target will be used at 5 bar and 300 K so a factor of about 50 in luminosity will be lost. To get sufficient data for small error bars it would take in this kinematics about 900h of beam. This can be reduced dramatically by measuring different kinematics with a higher virtual photon flux. An experiment with a polarised target will be performed at the end 2006 / at the beginning of 2007.


H5.6 Hadrons in the Nuclear Medium

H5.6.1 Introduction

Electromagnetically induced two-nucleon knockout is a powerful tool to investigate the role of correlated nucleon-nucleon motion in the nucleus. The (e,e’pp) reaction, which has been investigated previously, is particularly sensitive to the central NN-correlation induced by the strong repulsive NN-force at short distances. A natural extension to the previous (e,e’pp) studies are measurements of the (e,e’pn) reaction where tensor correlations, which are dependent on the
spin and spatial orientation of the two nucleons, are thought to play a dominant role. These correlations result in the emission of two nucleons through the absorption of a virtual photon via one-body electromagnetic currents.

The study of correlations is hampered by several other channels which contribute to two-nucleon knockout as well: The two nucleons can be ejected via two-body currents where the virtual photon can couple to mesons or to intermediate $\Delta$s. Also final state interactions of an ejected nucleon and the nucleus may lead to two-nucleon knockout. The choice of reaction and kinematics can be made to favour one of these processes over the others though all of them must be understood if one wants to separate out one particular channel, in particular correlated behaviour in this case.

Measurements of the $(e,e'pn)$ reaction were performed for the first time by the Amsterdam-Glasgow-Mainz-Tübingen collaboration, which brought together the essential know-how and instruments for such measurements:

- The large-solid-angle HADRON3 detector from NIKHEF, Amsterdam, for the detection of the proton.
- The Glasgow-Tübingen TOF detector system for the detection of the neutrons which have been previously used in the A2-collaboration.
- The high-resolution electron spectrometers of the A1-collaboration

$^3$He and $^{16}$O have been selected as target nuclei as for both of these there already exist $(e,e'pp)$ data. Furthermore, there are various theoretical models with which the data can be compared including full Faddeev-calculations for the $^3$He.

### H5.6.2 Experimental Set-up

The measurements were carried out in the A1-hall at MAMI using a beam energy of 855 MeV. For $^3$He the high-pressure cryogenic gas target with a diameter of 8 cm was used. This was operated at 15 K and 1.9 MPa which, together with beam currents of up to 4 $\mu$A, corresponds to a luminosity of $2 \cdot 10^{36}$ cm$^{-2}$s$^{-1}$. For $^{16}$O the measurement was made using the waterfall target [1] with a target thickness of 50 mg cm$^{-2}$. Beam currents of 10 and 20 $\mu$A were used corresponding to luminosities of 1 and $2 \cdot 10^{35}$ cm$^{-2}$s$^{-1}$ respectively.

For both targets the scattered electrons were detected with spectrometer B [2] (5.6 msr, $\Delta p/p = 15 \%$) allowing the reaction vertex position to be reconstructed with a resolution of $\leq 1$ mm. The protons were detected in the direction of $q$ For the $^3$He target the HADRON3 [3] detector from NIKHEF was used for this purpose. HADRON3 is a multi-layer scintillator detector which has an angular acceptance of $\pm 14^\circ$ in both the in-plane and out-of-plane directions and a proton energy acceptance range of 70 to 255 MeV. For the $^{16}$O target spectrometer A (28 msr, $\Delta p/p = 20 \%$) was used for detection of the ejected protons. Spectrometer A has a better energy resolution compared to HADRON3 which was essential for this measurement for separation of different excited states in the residual nucleus. The neutrons were detected with the Glasgow-Tübingen TOF detector system [4]. This is a time-of-flight array comprising of 96 bars of scintillator which were placed at a distance of 7.5 m at backwards angles with respect to the beam direction. At that distance the in- and out-of-plane acceptances of the TOF system were $\pm 23^\circ$ and $\pm 11^\circ$ respectively. The bars were arranged into three stands of
four layers of eight bars, three neutron detection layers behind a veto layer for discrimination between charged and neutral particles. The neutron detection efficiency varies as a function of the neutron energy and was determined by means of simulations with the Stanton code [5, 6] and from careful analysis of the measured events themselves [7].

H5.6.3 Kinematics

In order to optimise the contribution of correlated nucleon pair knockout to the cross section the measurements were performed in the so-called 'dip'-region. Here the ejected nucleons receive enough energy to pass the relevant detector thresholds while unwanted contributions from the Δ-resonance are expected to be minimal. As the energy transfer increases contributions from the Δ-resonance are expected to increase.

$^3$He

The measurement with the $^3$He target was performed at various kinematic settings, the $q$-$\omega$ ranges covered by the different kinematics are shown in figure H5.17. The kinematics were chosen to be similar to those of a previous $^3$He(e,e'pn) measurement allowing a direct comparison to be made between the two sets of results.

![Figure H5.17: The q-$\omega$ ranges covered by the different kinematic settings (labelled) used in the $^3$He(e,e'pn) reaction measurement. The dotted horizontal lines represent the q range used when studying the cross section dependence on $\omega$ and the dotted vertical lines show the $\omega$ range covered when studying the cross section dependence on q.](image-url)

To investigate the coupling mechanism of the virtual photon to the nuclear system cross sections were measured at various values of the three-momentum transfer, $q$, and cross sections produced as a function of this for a constant band in energy transfer, $\omega$, as shown by the vertical band in figure H5.17.

Measurements at different energy transfers were taken to study the reaction mechanism as a function of the invariant mass of the photon and two-nucleon final state. This allows the
Figure H5.18: The $^3$He(e,e'pn) cross section shown as a function of the missing momentum, $p_m$, for the A2 kinematics. The red line represents Faddeev calculations of the reaction for one-body currents only. The blue line includes contributions from one-body and meson exchange currents.

 relative importance of one- and two-body hadronic currents to be investigated. Cross sections as a function of $\omega$ were produced for a constant band in $q$ as shown by the horizontal band in figure H5.17.

The Y1 kinematics was taken at two different settings where the proton detector was placed at different angles with respect to the trajectory of the photon. This allowed the dependence of the cross section on the photon-proton opening angle to be studied.

$^{16}\text{O}$

The measurement with the $^{16}\text{O}$ target was performed at one kinematic setting with $\omega = 215$ MeV and $q = 316$ MeV/c. This measurement was taken in super-parallel kinematics in which, theoretically, the influence of the $\Delta$-resonance is suppressed. The kinematics was the same as in a previous $^{16}\text{O}(e,e'pp)$ measurement carried out by the A1-collaboration [8] and was chosen so that a direct comparison can be made between the results of the two experiments.

H5.6.4 Results

$^3\text{He}$

Missing momentum

Figure H5.18 shows the experimental cross section as a function of the missing momentum of the reaction, $p_m$, for the A2 kinematics. $p_m$ represents the momentum of the unobserved proton in the final state and thus, for the direct (e,e'pn) reaction mechanism, probes the momentum of the ejected pn-pair in the initial state. Figure H5.18 also shows Faddeev calculations [9] of the reaction showing the contribution to the cross section from one-body currents (red line) and
including meson exchange currents (blue line). These theoretical curves are preliminary and work is currently being carried out to check that the cross sections calculated from the Faddeev amplitudes are correct. Currently the theoretical calculations show that the main contribution to the cross section is from reactions involving one-body hadronic currents, the inclusion of meson exchange currents has the greatest effect at higher missing momentum and increases the cross section by \( \approx 20\% \) up until 250 MeV/c above which the contribution is greater. As can be seen the theoretical cross section as it currently stands over-predicts the data at low missing momenta but shows better agreement at higher missing momenta.

**Momentum transfer**

![Figure H5.19: The \(^3\)He(\(e,e'pn\)) cross section shown as a function of the momentum transfer of the virtual photon, \( q \), for \( 235 \leq \omega \leq 256 \text{ MeV} \) and \( 0 \leq p_m \leq 225 \text{ MeV/c} \).](image)

Figure H5.19 shows the experimental cross section as a function of the momentum transfer of the virtual photon for constant \( \omega \) (vertical band in figure H5.17). This variable probes the coupling mechanism of the photon with the nuclear system. As can be seen, the cross section increases with increasing \( q \). This is the opposite to what was seen in the previous \(^3\)He(\(e,e'pp\)) measurement where the cross section decreased with increasing \( q \) [10]. Unfortunately there are no theoretical (\(e,e'pn\)) cross sections with which to compare the results at this time.

**Energy transfer**

Figure H5.20 shows the experimental cross section as a function of the energy transfer of the virtual photon for constant \( q \) as shown by the horizontal band in figure H5.17. Again, unfortunately there are no theoretical cross sections with which to compare the results at this time. What is interesting here is that the cross section decreases as \( \omega \) increases while one might expect it to increase as \( \omega \) nears the \( \Delta \)-resonance region. Again this result disagrees with the previous (\(e,e'pp\)) measurement where an increase in cross section was observed with increasing \( \omega \) [10]. Calculations of the \(^3\)He(\(e,e'pp\)) measurement predicted that the cross section would fall with increasing \( \omega \) as is seen with this measurement.
**CHAPTER 2. EXPERIMENTS AT MAMI AND THEORY**

![Graph](image)

**Figure H5.20:** The $^3\text{He}(e,e'\text{pn})$ cross section shown as a function of the energy transfer of the virtual photon, $\omega$, for $370 \leq q \leq 390$ MeV and $0 \leq p_m \leq 225$ MeV/c.

**Photon-proton opening angle**

Figure H5.21 shows the experimental cross section as a function of the proton-photon opening angle, $\theta_{qp}$, determined using the cross product of the two particle trajectories. As can be seen the cross section falls fairly sharply as the angle $\theta_{qp}$ increases.

$^{16}\text{O}$

Figure H5.22 shows the $^{16}\text{O}(e,e'\text{pn})$ cross section as a function of the excitation energy of the residual $^{14}\text{N}$ nucleus. The positions of the ground state and the first three low lying excited states in $^{14}\text{N}$ are marked. There is a prominent peak around the energy expected for the 3.95 MeV ($1^+$) state in $^{14}\text{N}$. Given the resolution of the experiment ($\leq 3.0$ MeV FWHM) this peak will also contain contributions from the 2.31 MeV ($0^+$) and 7.03 MeV ($2^+$) excited states if they have been populated. The $^{14}\text{N}$ ground state appears to be at most rather weakly excited.

There is a second strong peak centred at $\approx 11$ MeV which corresponds to states in the continuum region in the residual $^{14}\text{N}$ nucleus. The width of this peak is such that several states probably contribute and it is not possible to make a reasonable attribution of this peak to any particular states.

Theoretical calculations of the $^{16}\text{O}(e,e'\text{pn})$ reaction for transitions to the lower lying states in $^{14}\text{N}$ have been carried out by the Pavia group [11]. The 3.95 MeV ($1^+$) state is predicted to have a cross section roughly one order of magnitude stronger than the ground state which is similar to what is observed in figure H5.22, where no significant signal due to ground state transitions is observed. The theoretical calculations predict the strength of the 7.03 MeV ($2^+$) transition to be comparable to that of the 3.95 MeV ($1^+$) state. Transitions to the 2.31 MeV ($0^+$) state are predicted to be roughly one order of magnitude smaller than for these other two excited states.
Figure H5.21: The $^3$He(e,e'pn) cross section shown as a function of the proton-photon opening angle, $\theta_{qp}$, for $0 \leq p_m \leq 225$ MeV/c, determined using the cross product of the two particle trajectories.

Figure H5.22: The $^{16}$O(e,e'pn) cross section shown as a function of the excitation energy of the residual $^{14}$N nucleus. The positions of the four lowest states in $^{14}$N are shown by the arrows.
Distorted wave calculations of the $^{16}\text{O}(e,e'\text{pn})$ reaction have also been carried out by the Gent group for four low lying excited states in $^{14}\text{N}$ which are expected to have strong two-hole character relative to the $^{16}\text{O}$ ground state [12]. Similarly to the Pavia calculations the Gent cross section calculations predict that transitions to the 3.95 MeV ($1^+$) state to be an order of magnitude larger than those to the other neighbouring states. While our measurement does not give insight into these relative strengths, it gives a much larger cross section than the predicted one.

The data are compared in figure H5.23 with the calculations from the Pavia group [11] which include the sum of contributions of transitions to the 2.31 MeV ($0^+$), 3.95 MeV ($1^+$) and 7.03 MeV ($2^+$) states. The calculations do not reproduce the measurement well and underestimate the measured cross section at low missing momenta by roughly a factor 10. At momenta above 100 MeV/c there is fair agreement between the data and theory. Figure H5.23 also shows the cumulative contributions of the Pavia calculations from 1-body, seagull, pion-in-flight and isobar currents. The largest contribution to the theoretical cross section comes from the isobar currents and in the Pavia calculations the dominant contribution to these are from tensor correlations.

![Figure H5.23](image)

Figure H5.23: The $^{16}\text{O}(e,e'\text{pn})$ cross section shown as a function of the missing momentum for events in the range $2 \leq E_x \leq 9$ MeV compared to calculations of the Pavia group. Calculations for transitions to the first three excited states, 3.95 MeV ($1^+$), 2.31 MeV ($0^+$) and 7.03 ($2^+$) are included in the calculations. The dashed line shows the cross section for the one body part of the reaction only; the dotted line also includes the $\pi$-seagull term; the dashed dotted includes the one-body, $\pi$-seagull term and pion-in-flight terms and the solid line is for the complete cross-section including contributions from the $\Delta$-resonance.

Figure H5.24 shows the residual $^{14}\text{N}$ excitation spectrum cut into two regions of missing momentum: a) $p_m \leq 100$ MeV/c and b) $100 \leq p_m \leq 200$ MeV/c. The group of states from $2 \leq E_x \leq 9$ MeV is present in both missing momentum regions. The excitation energy distribution is somewhat broader and weaker in the higher missing momentum region. This variation in strength suggests that the strong 3.95 MeV ($1^+$) state has its maximum strength at low recoil...
momentum. Figure H5.24 (b) also shows apparent strength around 0 MeV which is absent in figure H5.24 (a). This may suggest that the $^{14}$N ground state has most of its strength in the higher missing momentum region. The group of higher energy residual states in $^{14}$N have nearly all of their strength in the higher missing momentum range as can be seen in figures H5.24 (a) and (b).

Figure H5.24: The $^{16}$O(e,e'pn) cross section shown as a function of the excitation energy of the residual $^{14}$N nucleus for two different missing momentum regions, $0 \leq p_m \leq 100$ MeV/c in figure a and $100 \leq p_m \leq 200$ MeV/c in figure b. The positions of the four lowest states in $^{14}$N are shown in both plots.

[5] Nucl. Inst. and Meth. 100 (1972) 355  

H5.6.5 Development of a Solid State Detector[1]

M. Makek for the A1-Collaboration

The physics case

The development of a solid state (silicon) detector is motivated by the investigation of narrow, bound Deltas in the $^{12}$C(e,e'p\pi^-)$^{11}$C reaction [2]. Such a detector can detect the outgoing low-energy proton covering much larger solid angle than each of the three spectrometers.
The concept of the detector

The detector is a telescope consisting of 7 layers of silicon and one scintillator layer. The scintillation detector has got 3 mm plastic scintillator and is used for triggering. The first silicon layer is a double-sided strip detector of 300 $\mu$m thickness, with 24 strips in horizontal and vertical direction each, where the strips are 1 mm wide. The second silicon layer is a 300 $\mu$m thick detector and the following four are of 1000 $\mu$m thickness. The last layer is used as veto. Figure H5.25 shows schematic graph of the detector telescope.

The solid state detector (mounted 8 cm from the target) covers a solid angle of 78 msr. The energy range for protons is 24 - 38 MeV.

Detector tests and calibration

Test measurements in 2004 and 2005 showed that low energy background could be efficiently suppressed with 1 mm thick Aluminum plate in front of the telescope. The measurements showed a good timing resolution of 1.3 ns(FWHM), which is shown in figure H5.26(left). The charged baryons could be identified via energy loss in each layer, which is shown in figure H5.26(right). Angle and energy calibration were made via $p(e,e'p)$ reaction on polyethylene target.

Figure H5.25: Schematic graph of the telescope, showing scintillation detector(front) and five stacked silicon detectors(back).

Figure H5.26: Left: coincidence timing peak of the solid state detector and spectrometer A. Right: energy loss in the second vs. energy loss in the third silicon layer. One observes protons, deuterons and tritons.
Measurement of the $^{12}$C($e, e' p\pi^-)$ $^{11}$C reaction

The $^{12}$C($e, e' p\pi^-)$ $^{11}$C reaction was measured during 10 days beamtime in 2005. Spectrometer A was used for detection of electron, spectrometer C for the pion and solid state detector for the proton. The missing mass spectrum (with mass of $^{11}$C subtracted) is shown in figure H5.27.

The measurement showed an increase in leakage current of silicon detector during the beamtime. This was being compensated by increase in the bias voltage. Long term stability and efficiency of the detector under beam currents higher that 20 $\mu$A still have to be studied.

![Figure H5.27: The missing mass spectrum (with mass of $^{11}$C subtracted) of the triple coincidence reaction $^{12}$C($e, e' p\pi^-)$ $^{11}$C.](image)
