Two- and three-nucleon emission reactions measured using photon and electron probes.

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Abstract and Summary

Nuclear mean-field models [1] are highly successful in describing a wide range of properties of atomic nuclei, including their structure, binding energies, and the spins and parities of their quantum states. However, by their very nature, mean-field models cannot account for the effects of residual two- and three-body forces between nucleons. In particular they over-predict the measured occupancy of valence nucleon orbits in a wide range of nuclei and under-predict the occupancies of states above the Fermi surface [2]. It has long been thought that this transfer of occupation from valence to higher-lying energy levels may be due to interactions, or correlations, between nucleons, which are not described by mean-field models.

The electromagnetic interaction is well understood [3]. Hence electron and photon probes provide an excellent means of studying the internal structure of nuclei and the interactions between nucleons. This thesis describes an extensive programme of photon- and electron-induced experiments, most of which were led by the author, which studied the ejection of two, or three, correlated nucleons from atomic nuclei, in order to deduce information about the interactions between them. This work was carried out over a period of many years, primarily at the electron Microtron facility (MAMI) of the University of Mainz, Germany [4]. The author was assisted in this work by six Research Associates and ten Research Students working on different aspects of the programme.

A wide range of experiments was carried out on several light nuclei: ^{3}He, ^{4}He, ^{6}Li, ^{12}C and ^{16}O. Real photon experiments used the tagged-photon technique [A1] to measure the energy of incident photons. Many different aspects of two-nucleon emission reactions were studied, including their photon energy dependence, missing energy dependence, recoil momentum dependence, angular dependence, dependence on kinematic conditions, isospin dependence and their dependence on photon linear polarisation. The work was extended to study the contribution of three-body interactions in ^{3}He and ^{12}C by looking at the simultaneous emission of three nucleons from light nuclei, as well as the emission of proton-deuteron pairs.

Collaborations were formed with nuclear theoreticians working in Valencia, Ghent and Pavia in order to provide a detailed interpretation of the data obtained. This involved filtering the predictions of theory calculations through the physical acceptance of the experimental apparatus to allow meaningful comparisons with measured observables.

The author joined the CLAS collaboration at the Jefferson Lab 6.0 GeV electron accelerator at Newport News, Virginia, USA in 2009. The Jefferson Lab facilities allowed nucleon-nucleon correlations to be studied with higher energy probes, permitting electron scattering measurements to be carried out at large values of four-momentum transfer and at values of Bjoerken-x greater than 1. This latter condition explicitly requires the participation of more than one nucleon. Several key results from this work have advanced our understanding of nucleon-nucleon correlations. The previously-noted strong isospin dependence of nucleon-nucleon correlations was observed to persist at higher energies, even though the detailed mechanisms evolve with energy transfer. In addition, the strong observed charge dependence of the high-momentum fraction of nucleons within the nucleus has been related to the isospin dependence of the correlations. Finally, evidence has been found which supports a connection between short-range correlations (SRC) and the "EMC effect", in which the structure function for Deep Inelastic Scattering (DIS) of leptons on nucleons in heavy nuclei is strongly suppressed compared to the same reaction in light nuclei.

The author led the programme of two- and three-nucleon emission studies at Mainz from the mid-1980s onwards, writing and presenting seven experiment proposals [5-11] which were approved by the Mainz International Programme Advisory Committee. These proposals provide a strong rationale for undertaking these investigations.

Throughout his Mainz work, the author worked closely with academic colleagues from the University of Glasgow, as well as physicists from Mainz, Edinburgh and Tübingen. The Glasgow research group designed, constructed, tested and subsequently upgraded, two tagged photon spectrometers which underpinned and enabled the photon-induced experiments described in this thesis. The author took responsibility for the design, production, installation and testing of two "trigger" proton detector hodoscopes. The first detector array was used in experiments at photon energies up to

180 MeV, while the second was used in experiments at higher energies. Correlated neutrons and protons were detected in a separate “time-of-flight” scintillation detector array [12], developed jointly by physicists from Glasgow and Tübingen universities. The author directed the analysis of the majority of the data obtained from the experiments at Mainz, while other Glasgow research staff developed data collection and analysis software. Colleagues from Tübingen, Mainz and Edinburgh contributed cryogenic targets and analysed the data from the remaining experiments.

The author’s work on equipment development is detailed in section A of this thesis. The author contributed to the design, installation and testing of the initial tagged photon spectrometer at the Mainz laboratory, before leading the development and production of two detector hodoscopes used to detect protons from photon-induced reactions. He also made contributions to studies of diamond radiators which were used to produce linearly polarised photons used in some of the later experiments.

Section B forms the central part of this thesis. The papers in this section describe the results and interpretation of an extended programme of two- and three-nucleon emission reaction studies carried out at Mainz under the leadership of the author. In addition to directing the experimental work, the author led the drafting, revision and production of the majority of the papers in this section. He initiated close working relationships with three different groups of theoretical physicists in order to carry out calculations to interpret the experimental data. Some of these theoreticians are co-authors on particular papers.

The papers in Section C report results from a small number of selected experiments at the higher energy 6.0 GeV Jefferson Laboratory electron accelerator. This work provides valuable additional insight into correlations between nucleons in atomic nuclei and shows how this field has developed with the availability of higher energy electromagnetic probes. The author was co-investigator on a major Jefferson Lab grant [13] which laid the foundations for the analyses reported in this section.

Section D contains a recent conference review paper by the author which provides a concise and succinct summary of the most important work included in this thesis.

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Declaration

This thesis has been composed entirely by the author, who is also the author, or a co-author, of each of the published papers included in this work. The scientific work described in these papers has been carried out by the author in the context of international collaborations of experimental and theoretical nuclear physicists working primarily at electron accelerator laboratories in Germany and in the United States of America. The author's contribution to each paper is detailed in the "Abstract and Summary" and in the "Context of Work" sections of this thesis. None of the material included in this D.Sc. degree submission has been included in a submission for any other higher degree or diploma.

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Context of Work

Introduction

While the structure of atomic nuclei is well described by nuclear mean field models [1], the detailed properties of the interactions between nucleons, which bind the nucleus together, are not so well known. High-energy electrons and photons are ideal tools to study these interactions, as the electromagnetic interaction is extremely well described by the theory of Quantum Electrodynamics (QED) [3]. In addition, the electromagnetic interaction coupling strength ($\alpha \sim 1/137$) is small, so the probe does not significantly perturb the nucleus under investigation. In contrast, hadronic probes, such as high energy pions, interact strongly and have significant initial state interactions. It is therefore difficult to disentangle the interaction of hadronic probes with the target nucleus from the nucleon-nucleon interactions being studied.

Particles have a deBroglie wavelength λ given by λ=h/p, where h is Planck's constant and p is its momentum. It follows that the higher the energy of the probe, the shorter its deBroglie wavelength, and the shorter the distance scale it is able to probe. For instance, the deBroglie wavelength of a 100 MeV electron is the same order as the size of a light nucleus, whereas that of a 5 GeV electron is considerably less than the size of an individual nucleon. These energies are typical of the earliest and latest experiments reported in this thesis.

At sufficiently high energies electromagnetic probes interact with individual quarks within a nucleon in a process known as Deep Inelastic Scattering (DIS) [14]. The DIS cross sections scale with the Bjorken-x variable $x_B = Q^2/2M\nu$, where Q^2 is the four-momentum transfer squared, ν is the energy transfer from the electron to the target nucleon and M is the nucleon mass. Bjorken-x can be regarded as the fraction of the nucleon momentum carried by the emitted particle(s) and is an important variable for studies at high electron energies. Note that if x_B exceeds one, this necessarily implies the involvement of more than one nucleon.

Two major technical advances occurred in the 1970s and 1980s which revolutionised measurements of electron- and photon-induced reactions. The first was the development of 100% duty cycle electron accelerators which overcame the poor signal-to-background ratios which beset experiments at earlier low-duty-factor accelerators. The experiments described in this thesis were carried out at the Mainz electron microtron [4] and at the CLAS detector [15] at the Jefferson Lab recirculating electron accelerator. Both of these are state-of-the-art 100% duty cycle accelerators.

High energy photons may be generated from bremsstrahlung radiation created by passing an electron beam through a thin radiator. This produces a continuous energy spectrum of photons from zero up to a photon end-point energy equal to the energy of the electron beam. A strong electromagnet may then be used to deflect the ongoing electron beam away from the photon beam incident on the nuclear target.

The initial method used to carry out experiments with photons of a known energy was the “bremsstrahlung-difference” technique [16]. This involved taking two measurements, each with slightly different end-point energies. Subtracting suitably normalised spectra from the two measurements gave information about reactions produced by photons of energies between the two end-point energies. This technique was slow and produced data with large statistical uncertainties.

The advent of “photon tagging”, described in detail in paper [A1], overcame the drawbacks inherent in the bremsstrahlung-difference technique. It completely removed the residual electron beam while simultaneously measuring the individual energies of photons across the bremsstrahlung distribution. This greatly increased the efficiency of photon-induced experiments. The Glasgow nuclear physics research group has led the development of the tagged-photon technique at several major international nuclear physics laboratories and all of the photon-induced experiments described in this thesis made use of this technique.

It was evident from a range of (e,e’p) single proton knockout experiments carried out on nuclear targets from ^{7}Li to ^{208}Pb in the 1980s and the early 1990s [2], that there was a systematic reduction of between 30% and 40% in the observed spectroscopic strength of nucleon valence orbitals, compared to predictions of nuclear mean-field models. In addition, the occupancies of states just above the Fermi surface in the same nuclei were observed not to be empty. This apparent shifting of strength from valence to higher-energy orbitals, could only be explained by processes beyond the mean-field model description of nuclei. This provided a major motivation for studying specific nucleon-nucleon interactions in atomic nuclei.

The author led a range of experiments at the Mainz electron microtron from the mid-1980s onwards, to investigate the detailed properties of correlated pairs, and triples, of nucleons emitted from light nuclei. A total of seven experiment proposals, were written, presented and accepted by the Mainz International Programme Advisory Committee [5-11]. These formed the rationale and basis for the programme of work described in section B, the central part of this thesis.

Scientific Equipment and Technical Papers

Paper A1 describes the detailed design, construction and commissioning of a tagged photon spectrometer for use at the Mainz 180 MeV electron microtron MAMI-A. In the tagged-photon technique, real photons are produced by bremsstrahlung scattering of electrons off a thin radiator. The energy lost by each electron is given to a real photon emitted at a small forward angle. The magnetic spectrometer bends the main electron beam away from the photon beam as well as focusing the bremsstrahlung-scattered electrons onto an array of detectors located at its focal plane. The energy of each photon is determined, on an event-by-event basis, from the difference between the initial electron beam energy and the energies of the electrons measured in the magnetic spectrometer. A timing coincidence between the bremsstrahulung-scattered electrons and particles emitted in photo-reactions allows individual “tagged” photons to be associated with the reaction products they produce.

The “Glasgow” tagged-photon spectrometer at Mainz consisted of a Quadrupole-Dipole-Dipole electromagnet combination. The magnetic optics produced point-to-point electron focussing in the horizontal bend plane. The bremsstrahulung-scattered electrons were transported to an array of scintillation detectors located in the magnetic focal plane of the spectrometer. The position of the detected electrons along this focal plane allowed their energies to be deduced. The spectrometer and detector array was capable of measuring photon energies from 80-174 MeV, at count rates up to $5 \times 10^7 s^{-1}$. Two additional dipole electromagnets were included in the design to transport the residual electron beam safely away from the experimental area.

The spectrometer was designed by members of the Glasgow Nuclear Physics Research Group in the period 1982-1985 in order to facilitate a wide range of photon-induced experiments at the Mainz microtron, including papers [B1-B6, B9, B11] of this thesis. The author worked on the design, procurement, testing and commissioning of this major scientific instrument.

Paper A2 describes the design, construction, testing and commissioning of a large solid-angle proton detector hodoscope used as the "trigger" detector in nucleon emission reactions in experiments carried out at Mainz up till~1990. It consisted of two thin ΔE layers of plastic scintillator used to measure the differential energy loss of charged particles, followed by a stack of three thick plastic scintillator bars to measure the total energy E deposited. Plotting the differential energy loss ΔE against the total energy E allowed protons to be identified and separated from other charged particles, such as electrons and charged pions. Neutral particles were excluded as they do not leave a signal in the thin ΔE scintillator detectors.

The first thin ΔE scintillator was located close to the target, to identify charged particles originating from this position. The second ΔE layer consisted of five thin scintillator sheets arranged vertically in front of the thick total energy E bars. The timing difference between signals detected at both ends of each ΔE element was used to determine the vertical position of the detected particle. Three thick scintillator bars were stacked horizontally behind the five thin ΔE vertical scintillators. These provided a measure of the total energy E of the detected particles and allowed their horizontal positions to be determined from the time difference between signals from each end of each bar. The hodoscope detected protons of energies from 25 to 125 MeV. A second layer of horizontal bars was later added, behind the first layer, to extend this range up to 190 MeV. The hodoscope had an energy resolution of 2.8 MeV at a proton energy of 60 MeV.

A coincidence between signals from the two ΔE scintillation layers and the E scintillator indicated a particle of interest and triggered the electronic readout of all signals from the hodoscope, as well as signals from the tagged-photon spectrometer and other detector arrays.

This detector was used to detect protons in all of the two- and three-nucleon emission experiments carried out at the 180 MeV electron Microtron MAMI-A [B1-B6, B9, B11]. The author was responsible for the design, construction and testing of this hodoscope and wrote the scientific paper.

Paper A3 describes a larger 6-layer hodoscope "PiP", designed to detect protons of energies up to ~280 MeV, as well as pions of energies up to 250 MeV, following the upgrade of the Mainz electron microtron (MAMI-B) to energies of 840 MeV at the end of the 1980s. It's design was first reported by the author at the "Future Detectors for Photonuclear Experiments" conference held in Edinburgh in 1991) [17]. Paper A3 gives a more detailed account of its design, construction and performance than reported in [17].

The first energy loss ΔE detector is a ring of thin vertical scintillator elements placed close to, and almost completely surrounding, the target. This is an improvement over the previous detector as this arrangement presents the same thickness of material to particles emitted from the target at all polar angles. Its segmentation allows for larger counting rates as well as providing multiple particle detection capability. It also provides a more accurate "start time" trigger signal for the reaction. The second thin ΔE layer consists of five segmented vertical plastic scintillator sheets located just in front of the four thick layers. This layer provides vertical position information and defines the solid-angle of the hodoscope. It has better ΔE energy-loss resolution than the first layer. These two thin layers are followed by four thick E layers of horizontal scintillator bars which are used to stop and measure the energies of high energy protons, or charged pions, emitted from the target.

Overall the hodoscope had a timing resolution of ~1.1ns, a polar angular resolution of ~3.5°, an azimuthal angular resolution of~5.8°, a proton energy resolution of ~3.1 MeV, at 60 MeV, and covered polar angles from 25° to 155° in three different settings.

This detector was used to detect protons in all the two- and three-nucleon emission reactions carried out using tagged photons at Mainz after the MAMI-B energy upgrade [B7, B8, B10, B12-B24, B26 and B30]. The author lead the design, construction and testing of this second detector array and wrote the text of both [17] and [A3]. The charged particle detectors described in [A2] and [A3] were central to the programme of studies described in section B of this thesis.

An important step forward in measurements of two- and three-nucleon emission reactions is the use of linearly polarised photons. This allows a new observable, the photon asymmetry Σ, to be studied. Σ reflects the strength of the azimuthal variation of the cross section through the relation $\sigma(\phi)=\sigma_o(1+P\Sigma\ \cos 2\phi)$, where σ_o is the unpolarised cross section, P is the degree of linear polarisation of the photon beam, and ϕ is the azimuthal angle of the emitted particles with respect to the direction of the photon polarisation. Theoretical calculations indicate that Σ is more sensitive to details of the reaction process than cross section measurements made with unpolarised photons [18].

Linearly polarised photons may be produced using a crystal radiator, in which the small momentum mismatch inherent in the bremsstrahlung radiation process is absorbed coherently by the crystal lattice structure. Thin diamond crystals are generally used as they have ideal properties for this process. The degree of photon linear polarisation depends on the ratio of coherent polarised photons to incoherent bremsstrahlung photons produced in the crystal. This ratio is strongly dependent on the orientation of the crystal. For a given crystal orientation, linearly polarised photons are concentrated in a coherent photon energy peak. They also have a more focussed forward-momentum cone than unpolarised bremsstrahlung photons. Hence the degree of photon linear polarisation can be enhanced by small-angle collimation of the photon beam.

Paper A4 discusses a range of methods used to select the best diamond crystals for producing linearly polarised photons. Thin crystals minimise multiple electron scattering, which broadens the distribution of linearly polarised photons and reduces the average photon polarisation. Lattice defects, the mosaic structure of the diamond and radiation damage are also expected to determine the maximum degree of linear polarisation. Several methods, including optical polaroid analysis, x-ray topography and rocking curve measurements, were used to study the properties of thin diamond crystals. This work showed that featureless polarised light and topographic images corresponded to narrow rocking curves, typical of diamonds with few lattice defects.

Studies of radiation damage were carried out by focussing an electron beam on different areas of a thin diamond radiator previously used to produce linearly polarised photons at Mainz. These radiation damage studies revealed a slight broadening of the "coherent edge" at the high-energy side of the coherent peak. The author contributed to the studies of the radiation-damaged diamond crystal reported in this paper.

Paper A5 describes an investigation of the angular distribution of coherent bremsstrahlung radiation produced by diamond radiators. Measurements were made of the angular distribution, in the photon beam, of the enhancement of coherent photon production from a diamond radiator, compared to incoherent bremsstrahlung radiation. Estimates of photon polarisation can be obtained directly from these enhancement spectra or by using Monte Carlo models with parameters fitted to the measured enhancement spectra [19]. These studies showed the expected reduction in the enhancement, and hence the photon polarisation, as the range of angles within the photon beam is increased. They also showed very good agreement between the measured enhancement spectra and the Monte Carlo modelling for a range of different experimental conditions.

This work confirmed the benefits of collimating photon beams in order to increase the degree of linear photon polarisation and confirmed that Monte Carlo models of linear photon polarisation provided a very good method of calculating photon polarisation.

The author took data for the experimental studies described in this paper and contributed to their interpretation. The work described in [A4, A5] has improved our understanding of the important factors which affect the degree of linear polarisation in photon production using thin diamond radiators and has allowed us to optimise the efficiency and effectiveness of experiments carried out using polarised photons.

Papers describing experimental work at the Mainz Microtron (MAMI)

Paper B1 reports the first results from the $^{12}C(\gamma,pn)$ reaction in which a correlated proton and neutron are ejected from the target nucleus. This work was carried out using 83 – 133 MeV photons. A perdeuterated polythene target allowed calibration data to be obtained simultaneously from the $^{2}H(\gamma,pn)$ reaction. The experiment had a missing energy resolution of ~8 MeV which was sufficient to select proton-neutron pairs emitted from $(1p)^2$ and (1p)(1s) nuclear orbitals in ^{12}C.

Momentum distributions of the recoil nucleus, extracted from the data, were compared to a quasi-deuteron calculation, in which it is assumed that the photon interacts directly with a correlated neutron-proton pair, with the remainder of the target nucleus acting as a spectator. The data were also compared with a phase-space distribution where there is no correlation between the emitted particles. Both calculations took into account the acceptance of the detector system.

For the lower missing energy region, where both the proton and neutron are emitted from 1p shell-model orbitals, the shape of the recoil momentum spectra agreed closely with the quasi-deuteron calculations, but disagreed with the phase-space calculations. This provided a strong indication that the incident photon was absorbed on an interacting proton-neutron pair, with the remainder of the target nucleus taking no active part in the process. At higher missing energies, where it was expected that one nucleon would be emitted from the more strongly bound 1s shell-model orbital, the differences between the two calculations were not sufficient to say which model was a better fit to the data.

The data published in this paper were analysed by research student S.N. Dancer under the supervision of the author. The quasi-deuteron model used for comparison with the data was developed by the author, who also wrote the text of this paper.

Paper B2 is a summary report on a range of (γ,pn) experiments carried out at energies up to 180 MeV on ^{12}C, ^{6}Li and $^{3,4}He$ targets. The aims of this work were to obtain a quantitative understanding of the photon interaction mechanism in light nuclei in preparation for more detailed studies of nucleon-nucleon correlations. The report was published in 1988 by the University of Mainz as part of a review of scientific work, "Physics for MAMI-A", carried out at the 180 MeV electron microtron.

The analysis of the $^{12}C(\gamma,pn)$ reaction data at photon energies 113-133 MeV extends the results reported in [B1]. In addition to previously reported proton-neutron pair momentum spectra, the component of the pair momentum along the photon axis was also presented. The new distributions agree well with predictions of a quasi-deuteron interaction model and disagree with models of uncorrelated phase-space processes. The strength of the reaction was found to be ~60% of that expected on the basis of the number of contributing nucleons. This reduction in strength was attributed to the effects of final state interactions (FSI) which are expected to absorb or scatter a proportion of the outgoing nucleons. The role of FSI is a topic which is explored further in subsequent papers, especially [B6].

^{6}Li has a particularly simple structure with two loosely bound nucleons outside a strongly bound α-core. Ejection of the loosely bound proton-neutron pair is expected to behave very similarly to the breakup of deuterium, while emission of nucleons from the α–core can be compared with (γ,pn) reactions on ^{4}He. The missing energy resolution was sufficient to separate these two cases. For the ejection of the loosely bound proton-neutron pair, it was seen that the recoil α-core had little recoil momentum, stayed intact, and acted as a spectator in the reaction. The recoil momentum distribution, up to ~100 MeV/c, agreed well with predictions of a quasi-deuteron interaction. The strength of the interaction was observed to be close to the expected quasi-deuteron value, indicating rather little FSI in the case of the emission of the lightly bound outer shell nucleons. In contrast, reactions at higher missing energy, which broke up the α-core, had much larger recoil momenta, indicating the involvement of many nucleons.

In ^{4}He several breakup channels including (γ,pn), (γ,pp) and (γ,pd) were measured and angular distributions from all three channels were presented. A comparison of the data from the first two channels aimed to allow an estimate of the isospin (charge state) dependence of the two-nucleon emission reaction to be obtained, whereas measurements of reactions involving three emitted nucleons are sensitive to the nature of 3-nucleon interactions. The full results of these comparisons are reported in papers [B4] and [B5].

The ^{12}C and ^{4}He data reported in this paper were analysed by research students S.N. Dancer and S.M. Doran, respectively, under the supervision of the author. The ^{6}Li data were analysed by collaborating physicists from the University of Mainz. The author wrote the text of this report.

Paper B3 extends two-nucleon photo-emission measurements in the photon energy range 80-131 MeV to the double-closed-shell ^{16}O nucleus. Both the (γ,pn) and (γ,pp) channels were studied and the results were compared with the previously measured ^{12}C (γ,pn) reaction.

This paper provides a detailed description of the experiment, equipment calibration and data analysis as well as including a detailed description of a new method, developed by the author, to subtract data from correlated background processes. It also provides details of the Monte Carlo quasi-deuteron and phase-space models developed by the author for the interpretation of the experimental data.

The ^{16}O(γ,pn) missing energy spectrum was found to be similar to that of ^{12}C, with a concentration of strength at low missing energies corresponding to the emission of 1p-shell nucleon pairs. Again the recoil momentum distribution for reactions at low missing energies is well described by a quasi-deuteron mechanism.

In contrast, very little strength was observed in the $^{16}O(\gamma,pp)$ two-proton emission reaction. At low missing energies the (γ,pp) strength was estimated to be just 2% of the (γ,pn) strength. This strong isospin suppression indicates there is very little direct photon absorption on pairs of charged nucleons, compared to absorption on pairs of differently charged nucleons. In contrast to (γ,pn), the (γ,pp) channel has most of its strength at high missing energies, where FSI are expected to play a significant role. It was postulated that in this region charge-exchange final state interactions could transfer strength from initial (γ,pn) absorption to the (γ,pp) channel.

The author designed the ^{16}O distilled water target used in the measurement, directed the experiment, carried out the detailed data analysis of the $^{16}O(\gamma,pn)$ and (γ,pp) data reported in this paper and wrote the text of the publication.

Letter B4 reports measurements of the $^{4}He(\gamma,p)^{3}H$ reaction at photon energies from 80 to 160 MeV. This work was carried out to investigate the mechanism responsible for single nucleon knockout from ^{4}He. The traditionally expected mechanism was quasi-free knockout (QFK) in which the photon interacts with a single proton and the rest of the target nucleus does not take any active part in the process. However, previous $^{4}He(e,e'p)$ data showed anomalous behaviour in that the measured cross section was greater than QFK models predicted. It was also noted that the cross section for the complementary reaction $^{4}He(\gamma,n)$, in which an uncharged neutron is emitted, was significantly higher than expected in QFK.

The measured $^{4}He(\gamma,p)^{3}H$ missing energy spectrum showed a clear separation of two-body proton-tritium breakup, from events in which the residual nucleus disintegrated. A detailed analysis of the scaling of the two-body photodisintegration cross section, with the momentum mismatch between the incoming photon and the outgoing proton, showed that the QFK process could not describe the data at momenta greater than 300 MeV/c. In contrast, a quasi-deuteron model of photon absorption on a proton-neutron pair, where the neutron is then reabsorbed into the residual nucleus, was able to describe the data well, up to momentum mismatch values of ~500 MeV/c. This work showed that photon absorption on correlated nucleon pairs also contributes significantly to single-nucleon-knockout reactions.

The data analysis for this letter was carried out by University of Mainz research student H. Schmieden, working in close collaboration with the author. The author composed the text of this letter.

Paper B5 reports studies of two-nucleon emission from ^{4}He in the photon energy range 80 – 131 MeV. Measurements showed that three-body ^{4}He(γ,pn)d reactions, leaving a residual deuteron, dominated over four-body ^{4}He(γ,pn)pn reactions which completely broke up the ^{4}He target. Complementary ^{4}He(γ,pp)nn measurements, which also lead to four-body breakup, confirmed the weakness of the complete disintegration mode. The three-body breakup recoil momentum spectrum was found to be well described by a quasi-deuteron mechanism. In contrast, there was insufficient sensitivity at these relatively low photon energies to clearly identify the main mechanisms contributing to four-body breakup which occurred at higher missing energies.

The data analysis for this study was carried out by research student S.M. Doran, under the supervision of the author. The author composed the text of this paper.

Paper B6 provided an estimate of the FSI of low energy neutrons produced in photoreactions by comparing the ^{12}C(γ,pn) and ^{12}C(γ,p) reaction cross sections measured simultaneously at photon energies from 80 to 157 MeV. In this energy range the ratio of the two reaction cross sections, after correction for detector acceptance effects was found to be 80±8%. This confirmed that photon interactions with a two-body quasi-deuteron comprised the majority of the (γ,p) cross section. The analysis also inferred that the transmission of the low energy outgoing neutrons, in the energy range 20-45 MeV, was at least 80% and showed that FSI of the outgoing neutrons was small.

The data analysis for this paper was carried out by a post-doctoral researcher, P.D. Harty, working closely with the author. The author composed the text of the publication.

Paper B7 is a summary of all the work on two-nucleon photon absorption on light nuclei carried out up to 1993, presented to the 1993 International Nuclear and Particle Physics Conference held in Glasgow. It includes a lot of data taken with the 180 MeV electron Microtron MAMI-A, as well as the first data taken with the upgraded 840 MeV Mainz electron Microtron MAMI-B.

The paper opens with a review of theoretical treatments and summarises previous experimental work on this topic. It highlights results from [B1-B6] as well as presenting additional, more detailed, data on the $^{12}C(\gamma,pn)$ and $^{12}C(\gamma,pp)$ reactions at photon energies 145-157 MeV. Detector threshold effects have a smaller effect on this data, compared to previously published data at lower photon energies. In the case of the $^{12}C(\gamma,pn)$ the data agree well with models of photon absorption on correlated proton-neutron pairs, at missing energies corresponding to the emission of nucleons from $(1p)^2$ and (1p)(1s) orbitals, and clearly disagree with phase-space predictions. Interestingly the $^{12}C(\gamma,pp)$ data also agree with absorption on nucleons in $(1p)^2$ orbitals, even for high missing energy.

A systematic study of the photon dependence of the $^{12}C(\gamma,pp)/^{12}C(\gamma,pn)$ cross section ratio was reported, which taken together with previously published results at higher energy, showed that the (γ,pp) strength increased linearly from ~1% of the (γ,pn) strength at 100 MeV to ~25% at 600 MeV.

Preliminary tagged photon data, taken at MAX-Lab, University of Lund, Sweden [20] with high resolution detectors, compared the $^{12}C(\gamma,p)$ and (γ,n) missing energy spectra. These studies showed a remarkably similar structure of excited states in the residual nucleus with similar strength. This was interpreted as being consistent with a large initial two-nucleon absorption mechanism, plus final state re-absorption of one of the nucleons in both of these mirror isospin channels.

Preliminary $^{6}Li(\gamma,pn)$ and (γ,pp) data were presented at photon energies up to 800 MeV which confirmed a strong angular correlation between the outgoing particles for both reaction channels. The $^{6}Li(\gamma,pn)$ showed that the ejection of $(1p)^2$ nucleons was stronger than breakup of the α-core at low photon energies, but at photon energies above 200 MeV α-core breakup became more important. A comparison of the strengths of the ^{6}Li(γ,pn) and (γ,pp) reaction cross sections showed that (γ,pn) was stronger at low photon energies, but the strength of both reactions channels became similar at photon energies above 500 MeV where total breakup of ^{6}Li dominated.

The data presented in this paper were obtained by the full Glasgow-Edinburgh-Tübingen-Mainz collaboration. However, the interpretation of the results was the responsibility of the author.

Paper B8 reports an extensive study of the ^{12}C(γ,p) reaction at photon energies from 200 MeV to 500 MeV carried out at MAMI-B. One-nucleon-emission data are compared with coincidence data in which a correlated neutron, proton or pion is detected in quasi-deuteron kinematics. The data are compared with two theoretical models: a semi-classical Fermi gas model developed by the Valencia group [21] and a more detailed (γ,2N) nuclear physics treatment from the Ghent theory group [22].

The Valencia model calculations are performed in a Monte-Carlo framework which facilitates the application of detector thresholds, acceptances and efficiencies to the model. The model is able to distinguish separate processes contributing to the measured spectra including photon absorption on a nucleon pair (2N), 2N absorption plus final state interactions (2N+FSI), absorption on three nucleons (3N) and (3N+FSI), and two processes involving quasi-free absorption of a photon where the produced pion is reabsorbed or emitted (QFπ). The final case also involves FSI to produce two nucleons in the final state.

At E_γ=200 MeV the ^{12}C(γ,p) differential cross section, plotted as a function of proton energy, agrees reasonably well with the Valencia model description of 2N absorption at all measured proton angles from 61^o to 120^o. At higher photon energies additional mechanisms are observed to contribute to the differential cross section.

Requiring a coincidence with a neutron detected in the time-of-flight detector placed on the opposite side of the target, enhances the 2N and Nπ contributions which together now account for all of the measured cross section. The latter mechanism contributes indirectly via FSI. 3N and NNπ absorption appear to be negligible in this channel.

Requiring a coincidence with a second proton picks out photon absorption on 2N, 3N and Nπ processes. Within the 2N contribution there is little direct absorption on proton–proton pairs, with most of the strength coming from proton-neutron absorption + FSI. Requiring a coincidence with a charged pion picks out initial absorption on Nπ and NNπ clusters.

Comparisons of the experimental spectra with predictions of the more detailed Ghent 2N-absorption models [22], show good agreement with (γ,p) and (γ,pn) at 200 MeV. However, the calculations do not agree at higher energies where additional mechanisms become important. For (γ,pp) the calculations of absorption on proton-proton pairs do not account for the experimental data, even at the lowest photon energies. The interpretation is that this channel is intrinsically weak and is fed in large part through FSI following a range of initial photon absorption mechanisms.

The data presented in this paper were analysed by research student G. Cross, under the joint supervision of the author and postdoctoral researcher J.C. McGeorge. The author wrote the Monte Carlo code to analyse the Valencia model results presented in this paper.

Paper B9 presents the results of a detailed study of the ^{12}C(γ,pn) and (γ,pp) reactions measured at MAMI-A at five photon energies between 80 and 157 MeV. Cross section data are obtained assuming a quasi-deuteron, or a phase-space interaction. The phase-space prediction for (γ,pn) exceeds the previously measured total photon absorption cross section, while a comparison of the quasi-deuteron prediction with the total cross section indicates a combined transmission of 71% for both outgoing nucleons in agreement with paper [B6].

Detailed modelling of the (γ,pn) recoil momentum distributions gives excellent agreement with the quasi-deuteron interpretation. The (γ,pp) data cross sections are significantly weaker than (γ,pn), but the exact values depend on whether a quasi-deuteron mechanism or a phase-space model is applied. The recoil momentum distributions for this channel indicate a quasi-deuteron process, which is thought to be predominantly populated via FSI.

The data presented in this paper were analysed by post doctoral researcher J.C. McGeorge, working closely with the author. The Monte Carlo quasi-deuteron model developed by the author is presented in an appendix to this paper.

Paper B10 is a review of theoretical and experimental work on two-nucleon photoemission, written and presented by the author to the Conference on Perspectives in Nuclear Physics at Intermediate Energies, Trieste, Italy, 1995.

The theoretical review discusses the reasons why single nucleon knockout of high energy protons is suppressed in quasifree-knockout, but may occur if the photon interaction occurs with two or more nucleons. It discusses the formalism required to include nucleon-nucleon correlations in theoretical treatments and the dominance of proton-neutron absorption which led to early semi-empirical quasi-deuteron treatments. It goes on to discuss more recent detailed treatments from the Ghent [22] and Pavia [23] theoretical groups.

The experimental review outlines the recent two-nucleon emission reactions measured at MAMI-A and MAMI-B, which are central to this thesis, as well as earlier work in Japan using a ^{3}He target by the TAGX collaboration [24].

Looking to the future, the paper makes the case for extending two-nucleon emission reactions to look at photon asymmetry Σ, since recent theoretical treatments [23] have shown this observable is very sensitive to details of the photon absorption mechanism.

Letter B11 reports MAMI-B measurements of the ^{6}Li(γ,pn) and ^{6}Li(γ,pp) reactions from 114 to 600 MeV. The (γ,pn) missing energy spectra exhibit three peaks: the lowest due to emission of $(1p)^2$ nucleons, the second due to breakup of the α-core and a third peak at missing energies of ~250 MeV which is thought to correspond to multi-step reactions such as quasi-free pion production, where the pion is either rescattered or reabsorbed. Cuts on quasi-deuteron angular correlations between the two outgoing nucleons emphasise the first peak, while excluding a tight angular correlation enhances the second and third peaks. The (γ,pp) missing energy spectra are a factor of ~5 weaker and only exhibit the second and third peaks. This channel has less sensitivity to the angular correlation between the two detected nucleons.

The author participated in the collection of the data reported in this letter, while the data analysis was carried out by collaborating physicist P. Grabmayr from the University of Tübingen.

Letter B12 reports results of missing energy and recoil momentum spectra for both the $^{12}C(\gamma,pn)$ and $^{12}C(\gamma,pp)$ reactions, measured at MAMI-B, extending up to photon energies of 400 MeV.

The $^{12}C(\gamma,pn)$ missing energy spectra show that the prominent peak at E_m<40 MeV, attributed to proton-neutron emission from 1p orbitals, becomes less prominent as the photon energy increases and becomes indistinct at E_γ > 300 MeV. In contrast the $^{12}C(\gamma,pp)$ missing energy spectra do not exhibit any such peak at any photon energy.

Above missing energies of ~80 MeV the missing energy spectra for both isospin channels exhibit a similar shape, although the (γ,pn) yield is a photon-energy-dependent factor of between 6x (at 150-200 MeV) and 3x (at 350-400 MeV) stronger than the (γ,pp) yield, after corrections have been made for photon flux, detector solid angles and detector efficiencies. Calculations using the Valencia model [21] indicate the dominant mechanism in this missing energy region is expected to be quasi-free pion production, followed by pion reabsorption on two-nucleon pairs, for both isospin channels.

The recoil momentum spectra for photon energies 200-400 MeV were reported for both reaction channels, for three missing energy regions, E_m< 40, 40<E_m<70 MeV and 100<E_m<200 MeV. Three models were used to compare to the data: a quasi-deuteron model, a two-nucleon emission phase-space model and, for higher missing energies, a phase-space model involving the emission of two nucleons and a pion. In all cases the models took into account detector thresholds and solid angles.

As at lower photon energies, the (γ,pn) E_m< 40 data agreed with the quasi-deuteron model and disagreed with the 2N phase space model. The data also show that the quasi-deuteron model provides a good description of the (γ,pn) data for 40 <E_m< 70 MeV where the photon is expected to be absorbed predominantly on 1p1s nucleon pairs. While the (γ,pn) data do not fit the quasi-deuteron predictions so well at these missing energies, they are closer to the quasi-deuteron predictions than the 2N phase-space predictions.

It is noted that there is excess strength above the quasi-deuteron prediction for recoil momenta greater than 350 MeV/c in both reaction channels. This excess is small for (γ,pn), but is larger for (γ,pp). This may indicate that the role of FSI is stronger in the (γ,pp) case.

In the 100<E_m<200 MeV missing energy region the shapes of both the (γ,pn) and (γ,pp) recoil momentum distribution are similar. None of the models gives a very good fit to the measured data, by the 2Nπ phase-space model comes closest.

The analysis of the data reported in this letter was carried out by postdoctoral researcher P.D. Harty, in close collaboration with the author.

Short Note B13 reports further ^{12}C(γ,pn) and ^{12}C(γ,pp) missing energy spectra taken at photon energies up to 600 MeV. These data are compared with calculations obtained using the Valencia model [21].

For ^{12}C(γ,pn) the results showed a very good agreement with the strength and shape of the missing energy spectrum, even at high photon energies and high missing energies. In the case of (γ,pp) the model also predicted the correct shapes of the missing energy spectra, although it over-predicted the strength by a factor of around 3.5.

This comparison showed that in $^{12}C(\gamma,pn)$ the direct absorption on nucleon pairs (2N) was the major mechanism at low missing energies (<50 MeV), but reduced in strength as the photon energy increased. Above this missing energy the cross section had contributions from 2N+FSI, 3N, 3N+FSI and QFπ mechanisms. The 2N mechanism also contributed to the (γ,pp) channel at low missing energy, but its contribution was significantly smaller than 2N+FSI the other contributing mechanisms.

The author contributed to the data taking and wrote the Monte Carlo code to incorporate the Valencia model results reported in this note. The data analysis was undertaken by research student T. Lamparter from the University of Tübingen.

Short Note B14 reports measurements of another experimental observable: the angular distribution of the $^{12}C(\gamma,pn)$ reaction. The data were obtained for photon energies 120-150 MeV by taking measurements in three different, but overlapping, angular settings of the proton hodoscope PiP with arrays of time-of-flight detectors [12], used to detect corresponding neutrons, positioned in quasi-deuteron kinematics.

The data from the three different detector settings showed good consistency in the overlap regions. The measured angular distribution peaked at proton laboratory angles of ~80^{o} in the lab. It was compared with the angular distribution of the $d(\gamma,p)$ reaction [25] and with calculations of the angular distribution of the $^{16}O(\gamma,pn)$ reaction previously published by the Ghent theory group [26], scaled to account for the differing number of contributing proton-neutron pairs in ^{12}C compared to ^{16}O. The calculations included contributions from the π-seagull, the π-in-flight and the ρ-seagull terms. The measured $^{12}C(\gamma,pn)$ angular distribution did not agree with the angular distribution from deuterium, but did have a broadly similar shape to the Ghent $^{16}O(\gamma,pn)$ calculations.

The author wrote the proposal for this experiment, designed the experiment and wrote the paper. The data analysis was carried out by research student T.T.H Yau under the supervision of the author.

Letter B15 investigates the photon energy and angular dependence of $^{12}C(\gamma,pn)$ and $^{12}C(\gamma,pp)$ reactions at photon energies up to 400 MeV in quasi-deuteron kinematics, which emphasises direct absorption on nucleon-nucleon pairs. Cross sections are reported for missing energy regions below 40 MeV, and for 40 to 70 MeV, corresponding to emission of $(1p)^2$ and (1p)(1s) nucleon pairs, respectively. The ratio between the two isospin channels is also obtained. The data are compared with theoretical calculations that account for the medium-dependence of the Δ-propagator. The results show that the cross sections peak in the Δ-resonance region, for both reaction channels and for both missing energy regions. The $(\gamma,pp)/(\gamma,pn)$ ratio increases monotonically with photon energy for both missing energy regions, reaching ~12% for $(1p)^2$ emission at 380 MeV, and ~24% for (1p)(1s) emission at the same photon energy.

Significant differences are seen in the angular distributions for both reactions for missing energies below 40 MeV, in three separate photon energy regions. Theoretical calculations carried out to interpret the data reproduce the broad shapes of the measured distributions, although the magnitude is not accurately reproduced. The calculations fit best in regions where Meson Exchange Currents (MEC) are expected to dominate, but the calculations do not include short-range effects which are expected to be important in other kinematic regions. It is concluded that different microscopic mechanisms are responsible for the two reactions channels.

The author wrote the proposal for this experiment, designed the experiment and wrote the paper. The data analysis was carried out by research student T.T.H. Yau under the author's supervision. The author also established a collaboration with theoretical physicist, and co-author, J. Ryckebusch, who provided theoretical predictions to compare with the measured data.

Paper B16 extended the study of two-nucleon knockout reactions to include more complex multi-particle final states. Measurements were made of the $^{12}C(\gamma,pn)$, (γ,pp), (γ,ppp), $(\gamma,pp\pi^{\pm})$ and $(\gamma,p\pi^{\pm})$ reactions using photons of energy 250 to 600 MeV. The missing energy spectra obtained were compared with predictions of the Valencia model [21].

It was found that the Valencia model provided a good description of the $^{12}C(\gamma,pn)$ and $(\gamma,pp\pi^{\pm})$ missing energy spectra in two broad photon energy ranges: 250-400 MeV and 400-600 MeV. It also provided a good account of the shapes of the other three reaction channels but generally overestimated the strength of these reactions. Attempts were made to improve the agreement between theory and data by varying some of the model parameters, but no clear insight was obtained in this process.

The data reported in this paper was analysed by research assistant P.D. Harty under the supervision of the author.

Paper B17 discusses the differences that can arise between values of theoretical observables calculated at the kinematic centre of an experimental data bin, and theoretical calculations which are averaged, using Monte Carlo sampling, over the complete phase space of the bin. These differences can be significant where the observables in question, and/or the reaction cross section, have a large variation within an experimental bin. This paper quantified these differences using examples of experimental binning from previous $^{12}C(\gamma,pn)$ and (γ,pp) data analyses, including data from papers [B14] and [B15].

While this work identified that effects appeared to be more significant in the (γ,pn) data than in the case of the (γ,pp) reaction, it concluded that it is necessary for theoretical calculations to be averaged over the entire acceptance of experimental bins in order to provide an accurate comparison.

This investigation was carried out by three physicists who all contributed their specific expertise to this problem. The author provided the experimental data required for this study.

Paper B18 investigated photon absorption on three correlated nucleons by measuring the $^{12}C(\gamma,pd)$ reaction over a range of photon energies from 150 to 400 MeV, and over a wide range of angles of the emitted proton. As in the case of the $^{12}C(\gamma,pn)$ reaction, there is an observable peak at low missing energies for photon energies up to 300 MeV indicating photon absorption on a proton-deuteron pair, with the remainder of the target nucleus acting as a spectator. This peak was observed to be more pronounced for forward proton angles.

The cross section was compared to the ^{3}He(γ,pd) reaction and showed a similar energy and angular dependence for photon energies above 250 MeV. Recoil momentum spectra were compared with a simple model of photon absorption on three nucleons from $(1p)^3$ orbitals at low missing energy and from $(1p)^2(1s)$ orbitals at higher missing energy. This “spectator” model showed very good agreement with the measured recoil momentum spectra in both missing energy regions. The success of the spectator model and the similarities with the ^{3}He(γ,pd) reaction indicate direct photon absorption on three nucleons.

This data was analysed by research student S. McAllister under the supervision of the author. The author wrote the text of this paper.

Paper B19 presents measurements of the ^{12}C(γ,pn) and ^{12}C(γ,pp) reactions in a wide range of kinematics at photon energies up to 700 MeV. The measurements included quasi-deuteron kinematics, kinematics with a wider nucleon opening angle and extreme kinematics with both nucleons emitted on the same side of the photon beam line. This extreme kinematics required a very large nuclear recoil momentum, and/or the emission of additional undetected particles in the final state. The data were compared with Valencia model [21] predictions.

Direct 2N emission was evident in ^{12}C(γ,pn) in quasi-deuteron kinematics at low missing energies for all photon energies up to 700 MeV. At wider opening angles direct 2N emission only contributed up to 400 MeV. In the extreme kinematics direct 2N emission only contributed up to 200 MeV. The reactions were dominated by more complex processes involving more nucleons and/or final state interactions at higher photon energies and higher missing energies. The Valencia model predicted the general shapes, but overestimated the strength of the reactions in these kinematic regions.

The contribution of direct 2N emission to the $^{12}C(\gamma,pp)$ reaction was small and was confined to photon energies below 400 MeV and to the first two kinematic regions, with the cross section dominated by more complex processes in all kinematic regions. Again, while the Valencia model predicted the general shape of the measured spectra, it greatly overestimated the strength of the reactions in all kinematic regions.

The author proposed and designed this experiment and wrote the text of the paper. The data analysis was carried out by research student D.P. Watts under the supervision of the author.

Paper B20 studied the contribution of photon absorption on three-nucleon clusters in the $^{12}C(\gamma,ppn)$ reaction. Missing energy ($E_{3m} = E_\gamma - E_{recoil} - T_{p1} - T_{p2} - T_n$) spectra were obtained for photon energies from 200 to 700 MeV and compared with predictions of the Valencia model [21]. The Valencia model predicts a small contribution to the total reaction strength from direct absorption on three-nucleon clusters, with most of the cross section coming from more complex two-step processes. The model significantly overestimates the overall strength of the measured missing energy spectra. However, if the contribution from the strongest process, pion photo-production followed by pion reabsorbtion, is reduced by a factor of 0.3 in the model, the shape and strength of the missing energy spectra are then reproduced well at all photon energies. There is some supporting evidence from previous $^{12}C(\gamma,pN)$ studies [B8, B19] that this component is also overestimated by the Valencia model in these reactions.

Kinematic cuts on the invariant mass of the emitted neutron and the most forward going proton are made to suppress two-step processes involving pion reabsorption. These cuts increase the proportion of events where the photon is absorbed on three nucleons (with or without FSI) to nearly half of all the events remaining after the cut. While establishing the strength of photon absorption on three nucleons, it is not possible to cleanly extract a sample of such events. In addition this enhancement is made at the expense of a large reduction in the total number of recorded events and the results after this cut have poor statistical accuracy.

The analysis of the data reported in this paper was carried out by research student, D.P. Watts, in close cooperation with the author.

Paper B21 reports the first measurement of the $^{12}C(\gamma,pn)$ reaction using linearly polarised photons of energies E_γ = 180 to 340 MeV. The measured photon asymmetry Σ provides a new observable which is sensitive to the details of the photon interaction mechanism. As before, data for $(1s)^2$ and (1s)(1p) nucleon emission were selected on the basis of missing energy cuts. The measured asymmetry for $(1s)^2$ two-nucleon emission had the same sign and a similar photon energy dependence to the photo-disintegration of deuterium, but Σ had a smaller amplitude. The Σ data were also similar in magnitude to the few available data points from other light nuclei, including ^3He [27], ^6Li [28] and ^{16}O [29]. Theoretical calculations carried out for comparison with the measured data did not agree well with experimental data. Σ at higher missing energies was observed to be lower in magnitude and displayed a different photon energy dependence from the $(1s)^2$ data.

This author wrote the proposal for this experiment. The data analysis was carried out by research student S. Franczuk under the author's supervision. The author wrote the text of this paper.

Paper B22 presents more detailed information on reactions with polarised photons. Σ can be expressed in terms of cross sections parallel $\sigma_{\parallel}$ or perpendicular σ_L to the plane of photon polarisation: $\Sigma = (\sigma_{\parallel} - \sigma_L)/((\sigma_{\parallel} + \sigma_L)$. In addition to presenting Σ data, this paper extracts and presents the separate cross sections $\sigma_{\parallel}$ and σ_L which combine to produce Σ. This is done for both the $^{12}C(\gamma,pn)$ and (γ,pp) reactions, for three missing energy regions. The data are compared with theoretical model predictions for $\sigma_{\parallel}$ and σ_L which clearly indicate the need for improvements in the theoretical treatment.

The second half of this paper discusses which kinematic regions are most sensitive to short-range correlations (SRC) and proposes further experiments to investigate this topic in more detail.

The author was responsible for all of the analysis and discussion presented in this paper.

Paper B23 compares the $^{12}C(\gamma,pp)$ and $^{12}C(\gamma,pn)$ reactions using linearly polarised photons of energies E_γ = 160 to 350 MeV. Whereas the $^{12}C(\gamma,pn)$ reaction shows a peak in the cross section at low missing energies, which is not apparent in the $^{12}C(\gamma,pp)$ reaction, the $^{12}C(\gamma,pp)$ photon asymmetry Σ shows a strong, negative, peak at low missing energies, where direct absorption on proton-proton pairs is expected. In contrast the $^{12}C(\gamma,pn)$ reaction shows no sharp missing energy structure in Σ. Moreover the strength of the $^{12}C(\gamma,pp)$ asymmetry is larger than that of the $^{12}C(\gamma,pn)$ reaction, which indicates that direct absorption on two-proton pairs does not occur as FSI following initial absorption on proton-neutron pairs, which is a stronger initial process.

This paper also reports the angular dependence of polarised cross sections for the two reactions and makes comparison with theoretical calculations using the Ghent model [22,26]. Strong differences are seen between the angular polarised cross sections for both the $^{12}C(\gamma,pp)$ and the $^{12}C(\gamma,pn)$ reactions. Unfortunately the theoretical models do not agree well with any of the measurements, which prevents any more detailed interpretation from being made.

The author proposed and designed this experiment and wrote the text of the paper. The data analysis was carried out by research student C. Powrie under the supervision of the author.

Paper B24 is a conference report, written and presented by the author, which summarises the polarised photon taken on $^{12}C(\gamma,pp)$ and $^{12}C(\gamma,pn)$ reactions, giving a more detailed account than previous papers on this topic. It presents additional polarised angular distribution cross sections which there was insufficient space for in paper [B22] and also presents the recoil momentum dependence of Σ for both reaction channels. Strong differences are seen between the angular polarised cross sections for both the $^{12}C(\gamma,pp)$ and the $^{12}C(\gamma,pn)$ reactions for both missing energy regions and for all of the measured photon energy ranges. For $^{12}C(\gamma,pn)$ the measured Σ data do not show a strong dependence on recoil momentum, while there is some observed variation for $^{12}C(\gamma,pp)$. The data are compared with state-of-the-art calculations provided by the Ghent theoretical group. However, the detailed agreement between the experimental measurements and the theory was not good.

Paper B25 reported new polarised photon measurements of the $^{12}C(\gamma,pp)$ reaction made at Mainz using the Crystal Ball detector. These measurements used a completely different proton detector system compared to the previously reported measurements [B23]. The data extended over a larger photon energy range: 200-450 MeV and gave a more detailed investigation of the angular range of the reaction and its dependence on the proton-proton opening angle.

The photon asymmetry Σ was also measured with smaller photon energy binning and greater statistical accuracy than previously. The data agreed reasonably well with the previous data in the regions of overlap. They confirmed the distinct negative peak previously observed in the photon asymmetry Σ at low (γ,pp) missing energies. Moreover, a cut on back-to-back kinematics using the angle $\alpha=|\phi_1- \phi_2|$, constructed from the difference in azimuthal lab angles of the two detected protons, showed a further strong enhancement in the magnitude of Σ. This enhancement also persisted to higher values of missing energy, indicating a strong polarisation dependence of direct emission of proton-proton pairs. A strong angular dependence of Σ were measured and presented for the first time.

This experiment was proposed and organised by the author. The data were analysed by research student J. Robinson under the supervision of the author.

Paper B26 studied the photon asymmetry Σ of the $^{12}C(\gamma,pd)$ reaction at photon energies from 170 to 350 MeV. At low missing energies Σ was observed to be similar to that of $^{3}He(\gamma,pd)$ for E_γ below the Δ-resonance. The asymmetry in ^{3}He is known to be sensitive to three-nucleon forces. At higher energies the observed values of Σ were similar to those of two-step processes observed in $^{12}C(\gamma,pp)$.

The analysis of the data reported in this paper was carried out by research assistant D.P. Watts, in close collaboration with the author.

Paper B27 describes a virtual photon electron scattering measurement of the $^{16}O(e,e'pn)^{14}N$ reaction in super-parallel geometry. The experiment was carried out in the A1 electron scattering hall at Mainz with the emitted proton detected in magnetic spectrometer A and the scattered electron measured in magnetic spectrometer B. The correlated neutrons were detected in the Glasgow/Tübingen array of scintillator time-of-flight detectors [12], which were physically transported, closing the public highway, from the Mainz A2 (real photon) experimental hall.

Whereas experiments with real photons are sensitive to transverse components of the interaction, electron scattering is sensitive to longitudinal interactions. The longitudinal cross sections depend on one-body currents, which are expected to be more sensitive to short-range correlations between nucleons. To fully explore the two-nucleon emission processes it is therefore important to measure reactions with both real and virtual photons.

The kinematic settings were centred on an energy transfer of 215 MeV and momentum transfers around 316 MeV/c. The energy resolution of ~2.1 MeV was able to distinguish two groups of states in the residual nucleus at excitation energies 2-9 MeV and 9-15 MeV. The data for the low-lying group of states were compared with state-of-the-art theoretical calculations produced by the Pavia theoretical group. While these calculations indicated a strong contribution from one-body terms, the overall strength of the calculations was an order of magnitude weaker than the measured data, which severely limited the interpretation of the measured data.

The electron scattering data reported in this paper were analysed by research student D. Middleton under the supervision of the author. The nuclear theoreticians from Pavia, who provided calculations to interpret the measurements reported in this paper, were also co-authors of this paper.

Paper B28 compares the mirror reactions $^{3}He(e,e'pp)$, measured at the AmPS electron scattering facility in Amsterdam, and the $^{3}He(e,e'pn)$ reaction, measured in the A1 electron scattering facility in Mainz. Both reactions lead to the complete breakup of the ^{3}He target nucleus and were carried out at comparable kinematic settings in order to compare the interaction of virtual photons with proton-proton and proton-neutron pairs.

The (e,e'pn) cross section, at momentum and energy transfers centred on 300 MeV/c and 220 MeV, was observed to be an order of magnitude larger than the (e,e'pp) cross section. Some detailed differences in the dependence on the energy transfer were observed at high momentum transfers around 380 MeV/c.

The data analysis for this work was performed by research student D. Middleton, under the supervision of the author.

Paper B29 reports more detailed results from the ^{3}He(e,e'pn) reaction measured in five different kinematic settings. These regions were chosen to allow the cross section dependence on missing momentum and on momentum transfer to be separately studied. The data obtained have good statistical accuracy and clearly map out a smooth dependence on these key variables. They are compared with non-relativistic continuum Fadeev 3-body calculations using state-of the art nuclear potentials from the Argonne and Bonn theoretical groups.

In contrast to previously measured ^{3}He(e,e'pp) data, the calculations over-predict the measured cross sections by a factor of five at low values of the momentum of the recoil proton, although this factor becomes smaller as the recoil momentum increases, and the calculations agree with the measured data above 200 MeV/c. This work indicated that further refinements to the theoretical calculation were required to fully understand the reaction process and to understand the differences compared to the previous ^{3}He(e,e'pp) measurements.

The data analysis for this work was completed by research assistant D. Middleton working in close collaboration with the author.

Paper B30 compares the ^{16}O(e,e'pn) cross sections first reported in [B27] with improved theoretical treatments of two-nucleon emission carried out by physicists from Pavia. The same model is also compared with new real photon measurements of the $^{16}O(\gamma,pn)$ reaction. The new theoretical treatment resolves the differences between theory and experiment reported in [B27] for the virtual photon measurements. In contrast, however, the theory over-predicts the strength of the real photon reaction measured at low missing momentum. At higher missing momenta the data are not sufficiently accurate to draw any definite conclusions.

The data analysis for this work was completed by research assistant D. Middleton working in close collaboration with the author. The nuclear theoreticians from Pavia, who provided calculations to interpret the measurements reported in this paper, were also co-authors of this paper.

Papers describing experimental work at the Jefferson Laboratory

In 2004, the author gave an invited talk on the “Short range structure of nuclei” to the PN12 workshop on “The physics of nuclei with 12GeV electrons” at Jefferson Lab [30]. Subsequent to this the author was invited to take part in discussions about setting up a “Data mining” collaboration to reanalyse data taken at the Jefferson Lab CLAS detector. The CLAS detector had a very large acceptance and was run for much of the time with an open trigger. Consequently large quantities of useful data, previously taken on a range of different reaction channels, had not been fully analysed. A major aim of this work was to look for signatures of nucleon-nucleon correlations from data taken with nuclear targets.

These discussions resulted in a 2007 grant application to the American DOE funding agency [13] to support a researcher at Jefferson Lab to reanalyse previously accumulated data. This proposal was modified slightly and resubmitted in 2010 [31]. The author was a co-author of the original proposal [13] and a named co-investigator on the resulting DOE grant. The papers described in this section are all related to this initial data mining initiative [13], and to subsequent data mining programmes [31].

Letter C1 reports a measurement of the ^{3}He(e,e'pp)n reaction at an incident electron energy of 4.7 GeV. The data were analysed to extract the strength of the reaction in kinematics where the virtual photon interacts with a single leading nucleon, leaving a residual spectator nucleon-nucleon pair. It is observed that these pairs are emitted predominantly back-to-back. The distributions of pair total momentum and pair relative momentum were observed to be very similar for both proton-proton and proton-neutron pairs. The overall ratio of proton-proton to proton-neutron pairs was found to be roughly 1:4, consistent with the number of possible isospin pairings and the known ratio of single nucleon emission cross sections σ_{ep}/σ_{en}. However, a more detailed analysis showed that the ratio of proton-proton to proton-neutron pairs, corrected for σ_{ep}/σ_{en}, increases rapidly from very small values as the total pair momentum increases. This is interpreted as indicating that proton-neutron interactions are dominated by tensor interactions, which are absent from proton-proton pairs, at low total pair momentum.

Paper C2 investigated the sensitivity of two different kinematic regions in the ^{3}He(e,e'pp) reaction to SRC. Absorption on proton-proton pairs was selected by requiring one high momentum proton and a low momentum neutron spectator. The proton-proton absorption data were subdivided into two cases: one where both protons were ejected at forward angles with respect to the momentum transferred from the electron, and the second where one proton was emitted at a forward angle and the other at a backward angle. The pair relative momentum distributions were compared with 3-body Fadeev theoretical calculations.

The distributions were observed to be very different in shape for the two kinematic regimes, but both agreed reasonably well with the theoretical Fadeev calculations. The forward-backward proton-proton pair distribution fell off with increasing pair relative momentum and agreed well with the expected initial state pair momentum distribution. The effect of FSI was relatively small in this kinematic setting. In contrast the observed forward going proton-proton pair relative momentum distribution exceeded the expected initial state pair momentum distribution at high values of relative momentum and the calculations indicated that most of the strength observed in this kinematic setting was due to FSI. The conclusion of this paper was that selecting kinematic regions where FSI were small would be the best way of studying the effects of SRC.

It has long been argued that SRC interactions are responsible for shifting nucleons, in atomic nuclei, to momenta significantly above the Fermi surface [2]. **Paper C3** reports a new analysis of exclusive and semi-exclusive electron scattering measurements on ^{12}C, ^{27}Al, ^{56}Fe and ^{208}Pb. In A(e,e'pp) reactions proton-proton pairs interacting through SRC were identified from detected forward-backward pairs, as in [C2]. As FSI are suppressed in these kinematics, these events are sensitive to proton-proton SRC. In contrast A(e,e'p) reactions are sensitive to both proton-neutron and proton-proton interactions. From an analysis of ratios of the exclusive A(e,e'pp) and semi-exclusive A(e,e'p) reaction cross sections, normalised to ^{12}C, where neutron-proton pair interactions are known to outnumber proton-proton pairs by a factor of ~20, the fraction of high momentum proton-proton and proton-neutron pairs was extracted for the three heavier nuclei. It was found that neutron-proton pairs dominated in all three heavier nuclei. This is attributed to the large tensor component in neutron-proton interactions, which is not present in proton-proton pairs. In the paper it was argued that an important consequence of the dominance of neutron-proton interactions is that protons in heavy nuclei will have a larger fraction of particles with momenta above the Fermi surface. The reason is that since heavy nuclei have fewer protons than neutrons, on average protons experience more short-range interactions than neutrons, and this results in them having higher average momenta. A more detailed and quantitative analysis of this effect is presented in [C4].

Deep Inelastic Scattering (DIS) of high energy electrons and muons probes the internal structure of nucleons. It has long been known that the nuclear environment has a strong influence on this process [14]. The ratio of DIS cross sections in nuclei, compared to deuterium, is observed to decrease with increasing x_B over between 0.25 and 0.75, where x_B (Bjoerken-x) is the momentum fraction carried by the emitted particle. Moreover the gradient of the reduction in the DIS cross section ratio with x_B systematically varies by a factor of two between ^{12}C and ^{208}Pb. This phenomenon is known as the EMC effect.

Following on from [C3], **Letter C4** reports a more detailed analysis of exclusive A(e,e'pp) and semi-inclusive A(e,e'p) reactions in ^{12}C, ^{27}Al, ^{56}Fe and ^{208}Pb. Low initial-momentum events were selected on the basis of missing energy less than ~90 MeV and missing momentum less that 250 MeV/c. On the other hand, high initial-momentum events were selected from quasi-elastic events by requiring that the outgoing nucleon was emitted with most of the transferred momentum in the general direction of the momentum transfer with a cut on missing momentum greater than 300 MeV/c. It was observed that the ratio of low-momentum neutrons to protons was equal to 1.0 in ^{12}C but increased to ~1.5 in ^{208}Pb. Analysing the data in a different way, the fraction of high momentum protons, relative to ^{12}C, increased with neutron excess to ~1.5 in ^{208}Pb, while the fraction of high momentum neutrons showed no increase with neutron excess. This provides a quantitative confirmation of the general conclusions presented in [C3].

Letter C5 reports an analysis of DIS electron scattering measurements obtained by the CLAS collaboration that splits the DIS cross section into terms corresponding to electron interactions with uncorrelated protons, uncorrelated neutrons and correlated SRC pairs. Using DIS data from a range of heavy nuclei as well as SRC probabilities extracted from simultaneously measured quasi-elastic proton emission cross sections, the variation in the DIS component from correlated SRC pairs was extracted and shown to have a uniform magnitude and slope, independent of the particular heavy nucleus studied. This work shows an important new connection between SRC and the EMC effect.

<u>Summary and conclusions</u>

Paper D1 is a recent conference report which provides a succinct summary of the most important results reported in this field and discusses most of the papers included in this thesis. The author was invited to give this presentation to the 24th European Few Body Conference held in Surrey in 2019. This paper was composed solely by the author.

In conclusion the work reported in this thesis has provided a major advance in our knowledge and understanding of electromagnetically induced two- and three-nucleon emission reactions. It has demonstrated the important role of direct absorption of real and virtual photons on correlated pairs of nucleons in atomic nuclei. Direct absorption has been shown to be important in both (γ,pn) and (γ,pp) reactions, although the detailed contributing mechanisms are known to be different in both cases. In the (γ,pn) case the strongest signal of direct photon absorption on correlated nucleon pairs is a peak at low missing energies in the measured reaction cross sections, whereas for (γ,pp) there is a clear signal in the measured photon asymmetry.

The programme of experiments has explored different kinematic conditions and has been included polarisation degrees of freedom. Detailed comparisons of the measured data have been carried out with state-of-the art theoretical models. The level of agreement with the measured data has not been particularly good, leaving considerable room for further improvements in theoretical treatments.

Initial absorption on correlated nucleon pairs has also been shown to be important in single–nucleon knockout reactions in light nuclei. Investigations of three-nucleon emission reactions have shown some interesting similarities with the same reactions in ^{3}He. While varying the kinematic conditions has enhanced the contribution from absorption on three-nucleon clusters, it has not proved possible to extract data where this mechanism dominates.

Experiments at higher energies from Jefferson Lab have allowed nucleon-nucleon correlations to be explored at shorter range and in heavier nuclei. This work has identified specific kinematic regimes where FSI are suppressed allowing a clear SRC signal to be identified. Detailed analysis has extracted the high-momentum fraction of nucleons in nuclei, shown that this is associated with SRC, and shown that due to the dominance of neutron-proton SRC the proton high-momentum fraction in heavy nuclei is larger than the high-momentum fraction of neutrons. Finally, a simultaneous measurement of quasi-elastic and DIS electron scattering in a wide range of nuclei has revealed an intriguing connection between SRC and the EMC effect.

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[6] MacGregor IJD "Photoejection of np pairs from ^{12}C by 80 – 160 MeV photons."
Proposal MM622, Mainz MAMI-A Programme Advisory Committee, 1986: pp.5.

[7] MacGregor IJD "Study of the ^{12}C(γ,NN) reaction mechanism."
Proposal A2/6-93, Mainz Programme Advisory Committee, 1993: pp.11.

[8] MacGregor IJD "Photon Asymmetry of the ^{12}C(γ,NN) reaction."
Proposal A2/1-94, Mainz Programme Advisory Committee, 1994: pp.14.

[9] MacGregor IJD "Angular distribution of the ^{4}He (γ,2N)reactions"
Proposal A2/11-97, Mainz Programme Advisory Committee, 1997: pp.16.

[10] MacGregor IJD "Study of short range effects in the ^{12}C(γ,NN) reaction."
Proposal A2-2/98, Mainz Programme Advisory Committee, 1998: pp.11.

[11] MacGregor IJD and Watts DP "Photon asymmetry measurements of the ^{16}O(γ,pp) reaction for photon energies up to 400 MeV."
Proposal A2-6/05, Mainz Programme Advisory Committee, 2005: pp.17.

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doi.org/10.1016/S0168-9002(97)01068-1

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Appendix A: Details of Publications included in this Thesis

The papers which form this thesis are presented in four sections. Section A describes scientific equipment and technical developments which facilitated experimental research on two- and three-nucleon emission reactions led by the author at Mainz. Section B, the central part of this thesis, reports the scientific outcomes of this work. Section C describes experimental work on nucleon-nucleon correlations carried out at the Jefferson Laboratory in the USA, extending these studies to higher energies and providing additional physics insight into the processes involved. Section D comprises a recent review paper by the author which summarises all of the work of this thesis.

A) Scientific Equipment and Technical Developments

A1 Kellie JD, Anthony I, Hall SJ, et al.
A tagged photon spectrometer for use with the Mainz 180 MeV microtron.
Nucl. Instr. Meth. Phys. Res. A 1985; 241: 153-168.
doi: 10.1016/0168-9002(85)90526-1

A2 MacGregor IJD, Dancer SN, Annand JRM, et al.
A large solid angle detector for medium energy charged particles.
Nucl. Instr. Meth. Phys. Res. A 1987; 262: 347-352.
doi: 10.1016/0168-9002(87)90872-2

A3 MacGregor IJD, Annand JRM, Branford D, et al.
PiP - A large solid angle scintillation telescope for detecting protons and pions.
Nucl. Instr. Meth. Phys. Res. A 1996; 382: 479-489.
doi: 10.1016/S0168-9002(96)00844-3

A4 Kellie JD, Clive PJM, Yang GL, et al.
The selection and performance of diamond radiators used in coherent bremsstrahlung experiments.
Nucl. Instr. Meth. Phys. Res. A 2005; 545: 164-180.
doi: 10.1016/j.nima.2004.12.042

A5 Glazier DI, Livingston K, Owens RO, et al.
Angular distribution of coherent bremsstrahlung.
Nucl. Instr. Meth. Phys. Res. A 2012; 664: 132-139.
doi: 10.1016/j.nima.2011.10.053

B) <u>Experimental work at the Mainz Microtron (MAMI)</u>

B1 Dancer SN, MacGregor IJD, Annand JRM, et al.
Investigation of the $^{12}C(\gamma,pn)$ reaction using tagged photons.
Phys. Rev. Lett. 1988; 61: 1170-1173.
doi: 10.1103/PhysRevLett.61.1170

B2 Dancer SN, MacGregor IJD, Annand JRM, et al.
(γ,np) reactions in ^{12}C , ^{6}Li and $^{3,4}He$.
In: Drechsel D, Walcher T, editors. Physics with MAMI-A. Institut für Kernphysik, Johannes Gutenberg Universität Mainz, Germany, 1988: 46-49.

B3 MacGregor IJD, Annand JRM, Anthony I, et al.
The $^{16}O(\gamma,2N)$ reaction measured with tagged photons.
Nucl. Phys. A 1991; 533: 269-291.
doi: 10.1016/0375-9474(91)90490-W

B4 Schmieden H, MacGregor IJD, Owens RO, et al.
Scaling of the $^{4}He(\gamma,p)t$ reaction in the E_{γ} = 80–160 MeV region.
Phys. Lett. B 1993; 314: 284-288.
doi: 10.1016/0370-2693(93)91237-H

B5 Doran SM, MacGregor IJD, Annand JRM, et al.
The $^{4}He(\gamma,2N)$ reaction measured with tagged photons.
Nucl. Phys. A 1993; 559: 347-367.
doi: 10.1016/0375-9474(93)90158-T

B6 Harty PD, MacGregor IJD, McGeorge, JC et al.
Neutron propagation in ^{12}C for energies 20 to 45 MeV.
Phys. Rev. C 1993; 47: 2185-2189.
doi: 10.1103/PhysRevC.47.2185

B7 MacGregor IJD.
Photon absorption on nucleon pairs.
In: MacGregor IJD, Doyle AT, editors.
Proc. Int. Conf. on Nuclear and Particle Physics, Glasgow, UK.
Institute of Physics Conference Series 1993; 133: 93-111. ISBN 0-7503-0289-5

B8 Cross GE, MacGregor IJD, McGeorge JC, et al.
Proton photoproduction from ^{12}C.
Nucl. Phys. A 1995; 593: 463-487.
doi: 10.1016/0375-9474(95)00318-U

B9 McGeorge JC, MacGregor IJD, Dancer SN, et al.
(γ,2N) reaction in ^{12}C.
Phys. Rev. C 1995; 51: 1967-1976.
doi: 10.1103/PhysRevC.51.1967

B10 MacGregor IJD.
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B11 Grabmayr P, Ahrens J, Annand JRM, et al.
Excitation functions for the two-nucleon photoabsorption in ^{6}Li.
Phys. Lett. B 1996; 370: 17-21.
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B12 Harty PD, MacGregor IJD, Grabmayr P, et al.
The contribution of 2N photon absorption in $^{12}C(\gamma,2N)$ reactions for E_γ = 150–400 MeV.
Phys. Lett. B 1996; 380: 247-252.
doi: 10.1016/0370-2693(96)00508-4

B13 Lamparter T, Ahrens J, Annand JRM, et al.
On photonuclear reaction mechanisms at intermediate energies.
Z. Phys. A 1996; 355: 1-3.
doi: 10.1007/s002180050069

B14 Yau TTH, MacGregor IJD, Ahrens J, et al.
The angular distribution of the $^{12}C(\gamma,pn)$ reaction for E_γ=120−150 MeV.
Eur. Phys. J. A 1998; 1: 241-244.
doi: 10.1007/s100500050055

B15 MacGregor IJD, Yau TTH, Ahrens J, et al.
Mechanisms in the $^{12}C(\gamma,pn)$ and (γ,pp) reactions.
Phys. Rev. Lett. 1998; 80: 245-248.
doi: 10.1103/PhysRevLett.80.245

B16 Harty PD, MacGregor IJD, Ahrens J, et al.
Investigation of multiparticle final states in ^{12}C photoreactions.
Phys. Rev. C 1998; 57: 123-128.
doi: 10.1103/PhysRevC.57.123

B17 Ireland DG, MacGregor IJD, Ryckebusch J.
Interpretation of two-nucleon photoemission data.
Phys. Rev. C 1999; 59: 3297-3303.
doi: 10.1103/PhysRevC.59.3297

B18 McAllister SJ, McGeorge JC, MacGregor IJD, et al.
The (γ,pd) reaction in ^{12}C.
Phys. Rev. C 1999; 60: 1-6.
doi: 10.1103/PhysRevC.60.044610

B19 Watts DP, MacGregor IJD, Ahrens J, et al.
The ^{12}C(γ,NN) reaction studied over a wide kinematic range.
Phys. Rev. C 2000; 62: 1-15.
doi: 10.1103/PhysRevC.62.014616

B20 Watts DP, Ahrens J, Annand JRM, et al.
Three-nucleon mechanisms in photoreactions.
Phys. Lett. B 2003; 553: 25-30.
doi: 10.1016/S0370-2693(02)03186-6

B21 Franczuk S, MacGregor IJD, Ahrens J, et al.
^{12}C(γ,pn) photon asymmetry for E_γ=180–340 MeV.
Phys. Lett. B 1999; 450: 332-338.
doi: 10.1016/S0370-2693(99)00184-7

B22 MacGregor IJD.
Recent γNN Results and Future Plans.
In: Garcia-Recio C, Grabmayr P, Lallena AM & Owens R, editors.
Proc. 4th Workshop on electromagnetically induced two-nucleon emission,
Granada, Spain 1999: 339-352. ISBN: 84-699-1645-9

B23 Powrie CJY, McGeorge JC, MacGregor IJD, et al.
Polarized photon measurements of ^{12}C(γ_{pol},pp) and ^{12}C(γ_{pol},pn) reactions
for E_γ = 160-350 MeV.
Phys. Rev. C 2001; 64: 034602: 1-9.
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B24 MacGregor IJD.

Two-nucleon emission with polarised photons.

In: Grabmayr P, editor. Proc. 5th Int. Workshop on Electromagnetically Induced 2-Hadron Emission, Lund, Sweden 2001: 314-324.

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B25 Robinson J, MacGregor IJD, Annand JRM, et al.

Measurements of $^{12}C(\gamma_{pol},pp)$ photon asymmetries for E_{γ}= 200–450 MeV.

Eur. Phys. J. A 2013; 49: 1-9.

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B26 Watts DP, Annand JRM, Beck R, et al.

Dependence of the $^{12}C(\gamma_{pol},pd)$ reaction on photon linear polarisation.

Phys. Lett. B 2007; 647: 88-92.

doi: 10.1016/j.physletb.2007.02.013

B27 Middleton DG, Annand JRM, Barbieri C, et al.

First measurements of the $^{16}O(e,e'pn)^{14}N$ reaction.

Eur. Phys. J. A 2006; 29: 261-270. doi: 10.1140/epja/i2005-10314-9;

Erratum: Eur. Phys. J. A 2006; 30: 469. doi: 10.1140/epja/i2006-10131-8

B28 Middleton DG, Annand JRM, Ases Antelo, M et al.

$^{3}He(e,e'pp)$ and $^{3}He(e,e'pn)$ reactions at AmPS and MAMI.

Few-Body Sys. 2008; 44: 171-174.

doi: 10.1007/s00601-008-0283-x

B29 Middleton DG, Annand JRM, Ases Antelo M, et al.

Investigation of the exclusive $^{3}He(e,e'pn)^{1}H$ reaction.

Phys. Rev. Lett. 2009; 103: 152501: 1-5.

doi: 10.1103/PhysRevLett.103.152501

B30 Middleton DG, Annand JRM, Barbieri C, et al.
Knockout of proton-neutron pairs from ^{16}O with electromagnetic probes.
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C) Experimental work at the Jefferson Laboratory

C1 Baghdasaryan H, Weinstein LB, Laget JM, et al.
Tensor correlations measured ^{3}He(e,e'pp)n.
Phys. Rev. Lett. 2010; 105: 222501: 1-5.
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C2 Baghdasaryan H, Weinstein LB, Laget JM, et al.
Comparison of forward and backward pp pair knockout in ^{3}He(e,e'pp)n.
Phys. Rev. C 2012; 85: 064318: 1-8.
doi: 10.1103/PhysRevC.85.064318

C3 Hen O, Sargsian M, Weinstein LB, et al.
Momentum sharing in imbalanced Fermi systems.
Science 2014; 346: 614-617.
doi: 10.1126/science.1256785

C4 Duer M, Hen O, Piasetzky E, et al.
Probing high-momentum protons and neutrons in neutron-rich nuclei.
Nature 2018; 560: 617-621.
doi: 10.1038/s41586-018-0400-z (PMID:30104596)

C5 Schmookler B, Duer M, Schmidt A, et al.
Modified structure of protons and neutrons in correlated pairs.
Nature 2019; 556: 354-358.
doi: 10.1038/s41586-019-0925-9 (PMID:30787453)

D) Review and Summary

D1 MacGregor IJD.
Short range nucleon correlations studied with electron and photon probes.
In: Stevenson P, editor. Proc. 24th Eur. Few Body Conf., Surrey, UK, 2019.
SciPost Phys. Proc. 2020; 3: 010: 1-16.
doi: 10.21468/SciPostPhysProc.3.010