Two-nucleon emission experiments at MAMI Mainz

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Abstract. The series of two-nucleon removal experiments performed with real and virtual photons at the DC electron accelerator MAMI in Mainz are described. As targets the nuclei $^6$Li, $^{12}$C and $^{16}$O have been used as well as the few body systems $^3$He, $^4$He. The role of the various competing reaction mechanisms has been clarified. Despite many technical improvements a satisfying microscopic description of the data is missing.

1. Introduction
The complete microscopic description of the atomic nuclei had always been the goal in nuclear physics. This desire has not diminished with progress in time, much more the interest has shifted from the very stable isotopes towards the super-heavies and the halo nuclei as well towards the drip line due to astrophysical investigations. A proper description and understanding of nuclear structure is a prerequisite for the more complex investigations of time development of the low-density halo nuclei as well as the compact neutron stars.

Starting from the liquid drop models by Bohr and Weizsäcker in the 30ies and the independent particle shell models by Göppert-Mayer and Haxel, Jensen and Suess many complex techniques have been developed to find the correct wave function of the nuclear many body systems. Based on modern Nucleon-Nucleon (NN) potentials variational Monte Carlo calculations [1, 2, 3, 4] achieve good agreement for the energies of ground and low lying excited states of light nuclei up to mass $A=16$. Other ab initio calculations are based on no-core shell model or the Lorentz-Transform methods. All in common is the need to add thee-nucleon (3N) forces to achieve good agreement with the experimental results.

Furthermore, it was shown [5, 6, 7] that the different phase equivalent potentials have different expectation values for e.g. the kinetic energy or the one-pion exchange term. As these vary within a factor 2 in these nuclear matter estimates, there no surprise that the single-particle momentum distributions or the pair momentum distributions depend on the NN potential used. As examples, these are shown in Figs. 1 and 2 take from refs. [8, 9, 10]. Interestingly, the 3N contributions play a minor role here.

On the other hand, it is well known that the concept of an independent particle model (IPM) is intuitive but a rather idealistic one which is proven by theoretical arguments (e.g. [5]) and experimental evidence [11, 12, 13, 14, 15, 16]. The description of nuclei via an IPM must be corrected by the so-called Nucleon-Nucleon correlations. These are rather model dependent as they describe the deviation from the single particle behavior. Furthermore, the definition of the electro magnetic currents used decisively determines the results of the calculations and thus the respective interpretation through NN correlations.

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In particular at intermediate energies as available at the electron accelerator MAMI in Mainz various other reaction mechanisms can contribute to the observed cross sections. Different meson exchange currents and isobaric currents compete with irritating final-state effects and the sought-after contributions from NN correlations in this energy regime [17, 18, 21, 22, 24]. It must be realized that finding high momentum components by themselves is no proof of NN correlations as the experimental finding is related to physics in the final states whereas the theoretical concepts place them in the initial state. Still, it has been the strong attempt to clarify the field through the series of experiments with real and virtual photons at Mainz (A2- and A1 collaboration). The combination of different probes and different pairs emitted should help to disentangle the various contributions. In particular, to perform two-nucleon knockout experiments on $^{16}$O with high enough energy resolution to separate the final states in the mass $A=14$ systems. Starting from a $T=I=0$ nucleus the quantum numbers of the final states serve as spin/isospin filter for the selected pair of emitted nucleons. This should reduce the uncertainties in the wave functions to be used for the comparative calculations. The main interest was on the first excited state in $^{14}$N which is isobaric analog state to the $^{14}$C ground state.

The second nucleus of interest is $^3$He as this is the lowest mass nucleus which is non-trivial. The kinematically overdetermined $^2$H is used for calibration purposes. $^3$He is the only nucleus where microscopically calculations exist. Furthermore, the experimental complications of a liquid target are compensated by the relaxed need for energy resolution due to the simple nuclear structure.

2. Experiments at MAMI

The experiments in Mainz have been performed within the A1- and A2 collaboration with strong contributions from groups at Amsterdam, Glasgow and Tübingen. The DC Microtron [26] delivered an extremely stable beam of 855 MeV into the “tagger-hall” of the A2 collaboration. The photons are tagged by a magnetic spectrometer [27, 28] and collimated (see Fig. 3). About 7 m downstream the thin radiator foil the photons hit the target, e.g. the liquid $^4$He [29] or liquid water target [30, 31], which is surrounded by a double layered thin plastic PID/Veto counter. The protons are detected in PiP [32], a thick plastic hodoscope ranging up to 250 MeV protons while neutrons are recognized in the time-of-flight (TOF) array [33].

First experiments where performed with $^6$Li and $^{12}$C targets [34, 35, 36, 38, 39, 40, 41, 42,
Figure 3. Experimental hall ("tagger hall") of the A2 collaboration with a typical PiP-TOF setup and a sketch of the liquid $^4$He target.

43, 44, 45, 46] and summarized [47, 48]. In these experiments the energy resolution of 6 to 9 MeV was considerably better than those from the 80ies as it allowed to separate the major shell to be distinguished where the two nucleon were emitted from. Due to this and the comparison with model calculations the major contributions could be identified [35, 36]. The clear back-to-

Figure 4. Angular correlation for the $^{12}$C(γ,np) reaction within the photon range 120–150 MeV. Black squares indicate the 3 kinematical settings.

Figure 5. Projection of the yield along the ridge seen in Fig. 4 (white squares) on to the proton angle in comparison with various predictions.
back emission from low excitation regions of the daughter nucleus (low missing energy) is seen in Fig. 4. Three kinematical settings are combined [40] and exhibit a clear ridge in the anti-diagonal with almost constant sum of the kinetic energies of the two emitted nucleons. White squares along the ridge indicate the regions of integration used for the point in the projection plot (Fig. 5). The discrepancy between the data and the curve assuming a Fermi-smeared np-pair emitted based on the generic deuteron-photodisintegration tells us more complex processes at work. However, the comparison with the other curves from various calculations is not satisfying as apparently some ingredients are still missing [21, 22].

This is corroborated with very recent measurements with the Crystal Ball which covers nearly $4\pi$ (Fig. 6) and thus avoids the argument of poorly covered phase space. The disadvantage is the insensitivity to the neutrons; proton detection is sufficient for a comparison of the D($\gamma$,np) results with the $^{12}\text{C}(\gamma,\text{pp})$ reaction in the range of photon energies between 310 and 450 MeV. The graphs in Fig. 7 indicate an astonishing agreement between the two data sets for the asymmetry [49] at the same time as one notices a factor two of discrepancy to the model calculations. Since the ($\gamma$,pn) cross sections are up to a factor 20 larger than the ($\gamma$,pp) a leakage due to final state interaction can explain both above facts.

The measurements on $^4\text{He}$ of cross sections and asymmetries corroborate the conclusion about the dominance of the pn channel feeding via final state interactions the weaker pp channel. The missing energy spectra for the $^4\text{He}(\gamma,\text{pn})$ and $^4\text{He}(\gamma,\text{pp})$ are compared in Figs. 8 and 9, respectively, assuming a two-nucleon emission for the reconstruction of a two-body missing energy $E_m$. The second enhancements around $E_m \sim 300$ MeV are produced through real $\pi$-production; they are of comparable size. Notice the different abscissa needed to display the low $E_m$ range where the interesting 2N processes take place. The peak in the pn channel occurs around 28.5 MeV, the breakup energy of the $\alpha$ particle. Fig. 10 displays those events where 3 nucleons have been detected which indicates the complete breakup of $^4\text{He}$. Therefore, the dominant part is concentrated again at low $E_{2\text{m}}$; event at higher energy are considered
Figure 8. Two-body missing energy distribution for the $^4$He($\gamma$,pn) reaction. In green the 3N contribution from Fig. 10 is included.

Figure 9. Two-body missing energy distribution for the $^4$He($\gamma$,pp) reaction showing the 3N part in green.

Figure 10. Three-body missing energy distribution for the $^4$He($\gamma$,pnp) reaction. In green the complete photodisintegration is shown excluding the $\pi$-production.

to be accompanied by $\pi$ production. The purely 4N-breakup data marked in green have been displayed also in the other two Figs. 8 and 9 after appropriate scaling for acceptances. The relative contributions are evident, saying that the pp channel is contaminated by about 50%.

For the $^{16}$O($\gamma$,np) reaction the best results still come from the low photon data taken at Lund [50].

Turning to the experiments with virtual photons one realizes that the intensity of the electron beam amount to several tens of $\mu$A compares to a few nA for the real photons. The layout of the magnetic spectrometers [51] accounts for the background. However, the energy of the neutrons must be determined via time of flight by scintillator arrays; as these should be

Figure 11. Various random contributions observed in the (e,e'pn) experiments from Ref. [52].

Figure 12. Timing spectra for the (e,e'pn) reaction (top, [52]) compared to the (e,e'pp) using Si-strips for the proton detection (bottom, [61]).
large for a reasonable solid angle at distances of about 8 m the background becomes a problem due to the missing heavy shielding. This is immediately reflected in the random backgrounds as shown in Fig. 11 from Ref. [52]. The largest contribution arises through random neutron signals combined with true electron-proton coincidences. Comparing the respective timing spectrum (top) with that from the (e,e'pp) reaction (bottom) in Fig. 12 clarifies the differences.

Nevertheless, despite the poor statistical accuracy the summed cross section for the lowest three states in $^{14}\text{N}$ could be extracted and compared to model calculations. The first results shown in Fig. 13 were disappointing, however hard work on proper orthogonalized wave functions and considering not only the distortion of the outgoing nucleon in the field of the residual nucleus but also the final state interaction between the two emitted nucleons resulted in very satisfying description of the $^{16}\text{O}(e,e'pn)^{14}\text{N}$ momentum distribution, as seen in Fig. 14.

Figure 13. Model prediction for the lowest 3 states excited in the $^{16}\text{O}(e,e'pn)$ reaction [62].

Figure 14. Improved wave functions and considering final state interaction between the outgoing nucleons improves the description of the data.

The $^{3}\text{He}(e,e'pn)$ reaction has been investigated in several kinematical settings similar to a previous experiment [53, 54, 55] at NIKHEF. To increase the count rate, and since no high energy resolution is required for this nucleus, the proton spectrometer has been replaced by a scintillator hodoscope HADRON. The results [56] are shown in Figs. 15 and 16 and compared to model predictions by Faddeev calculations. It is noticed that the inclusion of MEC currents does not

Figure 15. Missing momentum distribution for the $^{3}\text{He}(e,e'pn)$ reaction in comparison to Faddeev calculation.

Figure 16. The cross section for the $^{3}\text{He}(e,e'pn)$ reaction as function of momentum transfer $q$. 
improve the description of the data. In particular the dependence on momentum transfer $q$ is not understood. The failures here are of different quality than that for $^3\text{He}(e,e'pp)$. The same model achieves a quite good description of asymmetries [57] in single nucleon knockout on $^3\text{He}$ or for estimates of the neutron electric form factor [58]. The reasons for the varying success is not understood. More work needs to be done on the theoretical side.

3. Summary
Triple coincidence experiments have been performed where two nucleons were ejected from light atomic nuclei through the electro magnetic interaction of real or virtual photons. Despite the big technical improvements with respect to the the first generation of experiments from the 80ies it was not possible to resolve individual final states with good statistics, e.g. for $^{16}\text{O}$. The summation of several final states allows to much freedom for the nuclear structure calculations in testing the current operators at the same time assigning contributions from different wave functions.

Much more, the deficiencies of calculations for the three-body system $^3\text{He}$ are not understood. A consistent description of single- and two-nucleon knockout reaction should be sought after with highest priority. The nucleus $^3\text{He}$ is the most simple system to test electro magnetic currents and wave functions. The interpretation of the present $^3\text{He}$ data must be more advanced before new experiments search for higher resolution or larger kinematical ranges. Whenever the reaction mechanisms are fixed, new attempts on heavier nuclei, e.g. $^{12}\text{C}$ or preferably $^{16}\text{O}$ should be undertaken.

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