

## Photo and Electrodissintegration of Few Body Systems Revisited

J.-M. Laget\*

CEA/Saclay, DAPNIA-SPhN, F91191 Gif-sur-Yvette, France

**Abstract.** Twenty years after P. Sauer released the state of the art Faddeev solution of the bound state three nucleon systems, I revisit photo and electrodisintegration of few body systems with a special emphasis on the prospects opened at Jefferson Laboratory.

### 1 Introduction

In the 80' P. Sauer, and his group at the University of Hanover, solved the Faddeev equations for the three nucleon systems [1, 2] with the state of the art realistic NN potentials [3]. Simultaneously a vigorous experimental program was developed at Saclay. Thanks to the availability of an  $^3\text{He}$  and a Tritium targets, the isoscalar and isovector components of the charge and the magnetic elastic form factors of the three nucleon systems were determined [4]. They remarkably agreed with the predictions of the Hanover group. The key to this success was not only the “tour de force” in operating the radioactive target, which was only made possible by an environment of high technology, but also the close collaboration between a theoretical and an experimental team.

I met Peter at this occasion and, starting from his wave functions, I extended my diagrammatic approach [5] to the disintegration channels of the three nucleon systems [6]. An experimental program was ongoing not only at Saclay but also at NIKHEF and Bates, in order to determine the wave function of the few body systems. Again, the experiments confirmed that Peter's wave functions were doing a good job up to nucleon momentum of 500 MeV/c.

However, it became evident that the energy and the duty factor of the available electron accelerators were not sufficient to map out the wave function at higher momentum. Kinematical limits prevented to increase significantly the momentum transfer. Rescattering and interaction effects were not negligible at such a low energy. Finally the low duty factor prevented to single out

---

\* *E-mail address:* jlaget@cea.fr

the very small cross sections, associated with high momentum transfers, from background.

One of the reasons to built CEBAF at Jefferson Laboratory (JLab) was to overcome these drawbacks. The energy was increased by one order of magnitude (600 MeV to 6 GeV) and the duty factor by two orders of magnitude (1% to 100%). About seven years of operation have produced a few jewels in the disintegration of few body systems.

This meeting in honor of P. Sauer provides me with a good opportunity to revisit the field in view of recent achievements and to evaluate future developments.

## 2 The Two Body Disintegration Channels

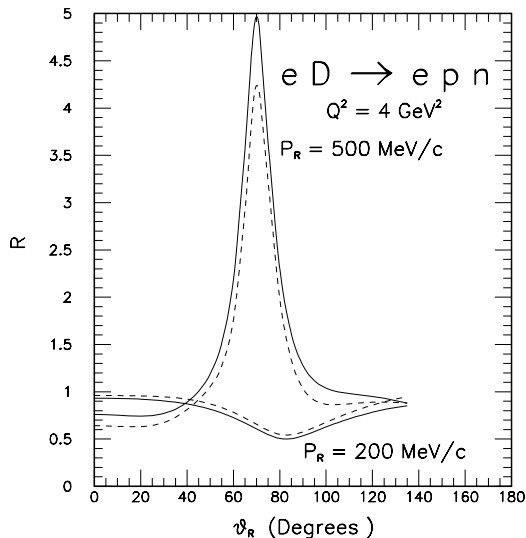
The primary goal of the study of the (e,e'p) reaction on nuclei was, and still is, the determination of the high momentum components of the nuclear wave function, in view of the study of short range correlations and possible exotic configurations.

### 2.1 The Low Energy Regime

In the past the spectral functions measured at Saclay or Amsterdam suffered for large corrections (about a factor two or more) due to Final State Interactions (FSI) and Meson Exchange Currents (MEC). A survey of the state of the art at that time can be found in ref. [6]. The corresponding experiments were performed at low values ( $\sim 0.3 \text{ GeV}^2$ ) of the virtuality  $Q^2$  of the exchanged photon.

When CEBAF was decided, a common belief was that increasing  $Q^2$  was the way to suppress FSI and MEC contributions. This was partly true, since both the FSI and MEC amplitudes involve a loop integral, which connects the nuclear bound and scattering states and which is expected to decrease when  $Q^2$  increases as form factors do. But this was partly wrong, since the singular part of the FSI integral does not depends on  $Q^2$ , besides the trivial momentum dependency of the elementary operators. It comes from unitarity, and corresponds to the propagation of an on-shell nucleon. It involves on-shell elementary matrix elements and it is maximum when the kinematics allows for rescattering on a nucleon at rest. This happens in the quasi-free kinematics, when  $X = Q^2/2m\nu = 1$  (being  $\nu$  the energy of the virtual photon).

Fig. 1 exhibits these features. It shows the angular distribution, against the neutron angle  $\theta_R$ , of the ratio between the full cross section of the D(e,e'p)n reaction and the quasi free contribution, when the momentum  $P_R$  of the recoiling neutron is kept constant. FSI are maximum near  $\theta_R = 70^\circ$  where  $X = 1$  and on-shell rescattering is maximized. At low values of the recoil momentum ( $P_R = 200 \text{ MeV}/c$ ), on-shell nucleon rescattering reduces the quasi free contribution, as expected from unitarity (a part of the strength of the quasi elastic channel is transferred to inelastic ones). At high values of the recoil momentum ( $P_R = 400 \text{ MeV}/c$ ) the quasi free contribution strongly decreases as the nucleon



**Figure 1.** The ratio between the full cross section and the contribution of the quasi-free scattering.

momentum distribution: on-shell rescattering takes over and dominates.

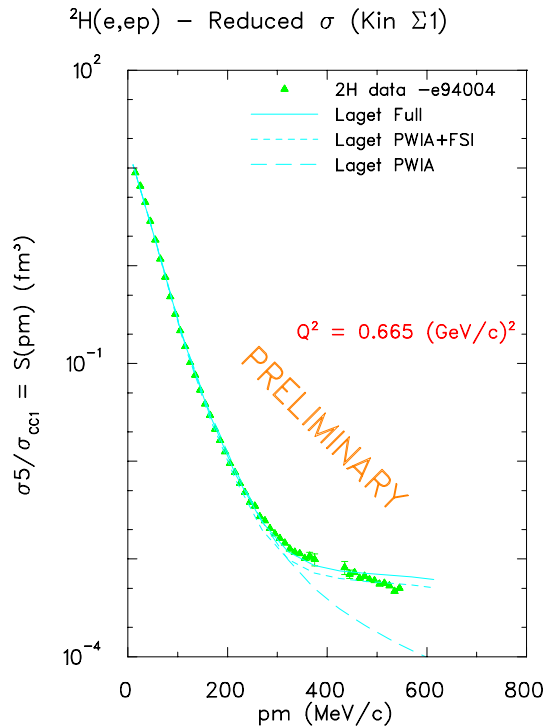
An experiment [7] recently performed at JLab confirms this behavior. Fig. 2 shows the recoil momentum distribution up to 600 MeV/c, in the quasi elastic kinematic ( $X=1$ ). Above  $P_R = 400$  MeV/c, FSI (dashed line) dominate while MEC (full line) contribute to a lesser extent.

Although the virtuality ( $Q^2 = 0.665$  GeV<sup>2</sup>) of the exchanged photon is about twice as much than what was achieved twenty years ago, the relative kinetic energy of the two outgoing nucleons ( $T_L = Q^2/2m = 337$  MeV) is still low enough to rely on the partial wave expansion of the np scattering amplitude. The curves are the results of the original model [8], where both the on-shell and half off-shell np scattering amplitudes are solution of the Lippman-Schwinger equation with the same potential (Paris) as for the bound state.

## 2.2 The High Energy Regime

At higher energies (let's say when the relative kinetic energy of the outgoing fragment exceeds 500 MeV or so), too many partial waves enter into the game and their growing inelasticities prevent to compute the scattering amplitude from a potential. It is better to use a global parameterization of the NN scattering amplitude. On general ground, it can be expanded as follows

$$T_{NN} = \alpha + i\gamma(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot \boldsymbol{n} + \text{spin - spin terms} \quad (1)$$



**Figure 2.** The momentum distribution in the  $D(e,e'p)n$  reaction at  $X=1$ .

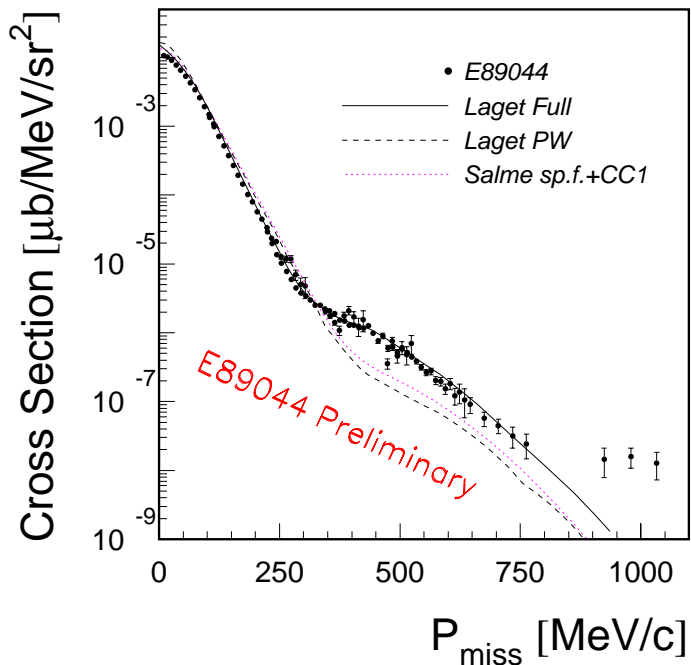
Above 500 MeV, the central part  $\alpha$  dominates and is almost entirely absorptive, and takes the simple form

$$\alpha = \frac{k}{4\pi} (\epsilon + i) \sigma_{NN} \exp\left[\frac{b}{2}t\right] \quad (2)$$

In the forward direction its imaginary part is related to the total cross section  $\sigma_{NN}$ , while the slope parameter  $b$  is related to the angular distribution of NN scattering. Both can be determined from the experiments performed at Los Alamos, Saturne and Cosy. The ratio  $\epsilon$ , between the real and imaginary part of the amplitude, is small and does not exceed 0.2. The spin-orbit and spin-spin terms are related to polarization observables, but I have not yet implemented them in the three body codes.

Such a parameterization is very convenient to compute the rescattering amplitude, but leads only to an accurate prediction of its singular part (on-shell scattering). Contrary to low energy, there is unfortunately no way to constrain the half-off part of the NN scattering amplitude, and one can get only estimate of the principal part of the rescattering amplitude. It turns out that it does not dominate at high energy. So, the method is founded on solid grounds in

the quasi-elastic kinematics ( $X \sim 1$ ). Away, it tells us in which kinematics FSI are minimized.



**Figure 3.** The momentum distribution in the  ${}^3\text{He}(e, e'p)d$  reaction at  $X=1$  and  $Q^2 = 1.55 \text{ GeV}^2$ .

Fig. 3 shows how well this method reproduces the cross section of the  ${}^3\text{He}(e, e'p)d$  reaction recently measured at JLab [9] at  $Q^2 = 1.55 \text{ GeV}^2$ , in the quasi-free kinematics ( $X=1$ ). At such a high virtuality, the relative kinetic energy between the outgoing proton and deuteron is  $T_L = 850 \text{ MeV}$ , where the NN cross section reaches its maximum and becomes flat around  $\sigma_{NN} = 47 \text{ mb}$ . Again, FSI reduces the quasi-free contribution below  $300 \text{ MeV}/c$  and overwhelms it by more than a factor five around  $500 \text{ MeV}/c$ . Details on the model are given in ref. [10].

To summarize, a fair agreement with the recent JLab data has been reached in the quasi-elastic regime, up to recoil momentum of the order of  $1 \text{ GeV}/c$ , provided that the NN scattering amplitude relevant to the same energy range is used. In order to determine the high momentum components of the nuclear wave function, one has to go away the quasi-elastic kinematics: as demonstrated in Fig. 1, this occurs in parallel or anti-parallel kinematics, where on-shell nucleon rescattering is suppressed.

### 3 The Three Body Disintegration Channels

Two body short range correlations are the primary source of high momentum components in the nuclear wave function. Since they are strongly coupled to high energy state in the continuum, two nucleon production experiments are the natural way to reveal them. However, above the pion production threshold, one must eliminate meson production channels and perform exclusive experiments. CLAS (CEBAF Large Acceptance Spectrometer) at JLab is the ideal detector for disentangling and studying multiparticle channels.

However, CLAS is not an hermetic detector: there is a hole in the forward direction as well as in the backward direction; also the coils, which provide the toroidal electromagnetic field, induce dead zones in the acceptance. So the only fair way to compare the data to any theory is to use the same cuts. To that end, G. Audit and I, we have developed a Monte Carlo programme which simulates the  ${}^3\text{He}(e,e'2p)n$  and  ${}^3\text{He}(\gamma,2p)n$  reactions within the CLAS acceptance. The event generator is the code which I developed twenty years ago and which I updated to take into account the high energy parameterization of the NN scattering amplitude, as well as relativistic effects.

Let me discuss first the real and then the virtual photon sectors.

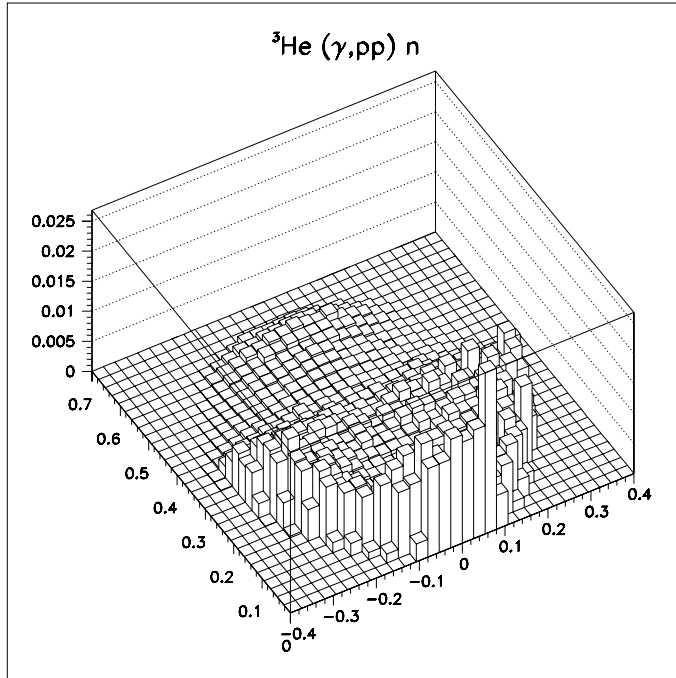
#### 3.1 Real Photons

Fig. 4 shows the result of such a simulation within the CLAS acceptance. The model [11] has been calibrated against previous data recorded below 800 MeV in restricted parts of the phase space: two magnetic spectrometers [12, 13] in the two body disintegration sector (neutron at rest); two magnetic spectrometers [14] and DAPHNE detector [15] in the three body disintegration sector.

CLAS results [16] enlarge the available data set, not only by covering the full phase space but also by extending the energy range in a single shot. Cuts can be made in various places of the Dalitz plot, in order to emphasis different mechanisms and access different aspects of the three body dynamics. For instance, the peak at bottom of the Dalitz plot (small  $T_n$ ) corresponds to the disintegration of a pair of protons at rest. Since this pair has no dipole moment, MEC associated with the  $\Delta$  resonance are suppressed and one can probe higher order MEC. The peaks on the left and right edges of the Dalitz plot correspond to rescattering within a proton neutron pair, while the other proton takes almost all the available energy. Finally, in the center of the Dalitz plot the energy is shared by the three nucleons: this is the place where three nucleon effects dominate. Preliminary results show a clear distinction between two and three body effects and follow the trends of the model. I refer to ref. [16] for a more detailed account of the preliminary CLAS data.

#### 3.2 Virtual Photons

The  ${}^3\text{He}(e,e'2p)n$  reaction was advocated [8] as the best way to access two proton correlations in few body systems. In particular, in kinematics where the

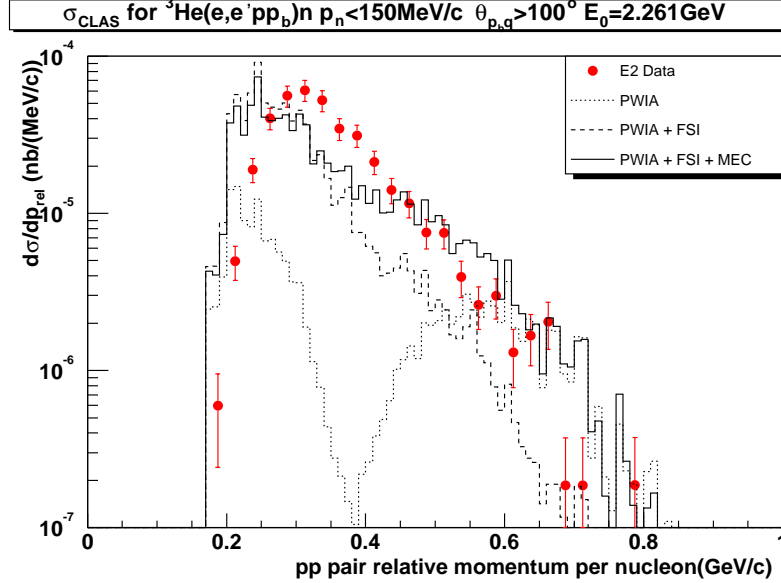


**Figure 4.** The Dalitz plot of the  ${}^3\text{He}(\gamma,pp)n$  reaction at 550 MeV. The bottom-right axis is proportional to the difference  $T_1 - T_2$  between the kinetic energy of the two protons, while the left axis is proportional to the kinetic energy of the neutron  $T_n$ .

neutron is almost at rest, the transverse part of the amplitude is suppressed since the pair of proton has no dipole moment. It also turns out that three body mechanisms are suppressed, since they prefer kinematics where the momentum transfer is shared by the three nucleon. On the contrary, the coupling of a longitudinal photon to the proton pair is not suppressed, and the only sizeable correction is due to FSI between the two outgoing protons.

CLAS provides us with the first comprehensive study of this channel [18, 19]. Fig. 5 shows the momentum distribution of the pair of protons almost at rest in  ${}^3\text{He}$ . The plane wave calculation exhibits the characteristic node of the S-wave part of its wave function, which is the only one which survives when the pair is at rest. Of course, FSI fill in this hole (nature does not like holes!), and MEC contribute moderately at high momentum. Both the theory and the experiment are integrated within the same cuts (for instance, the fall off of the cross section below  $0.2 \text{ GeV}^2$  reflects the CLAS acceptance) and there is no normalization factor (absolute comparison). The wave function of P. Sauer does a good job in a configuration where it has never been checked before.

Increasing the virtuality from  $Q^2 \sim 1 \text{ GeV}^2$  up to a few  $\text{GeV}^2$  will provide



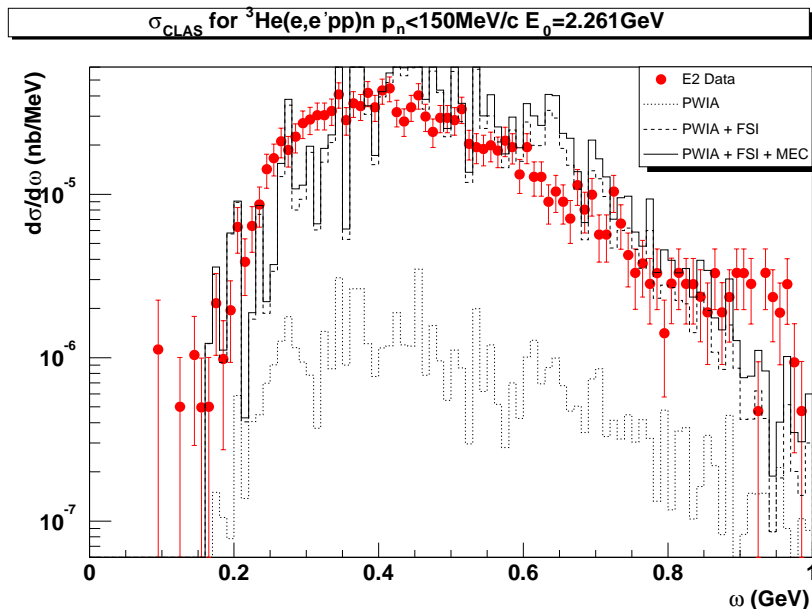
**Figure 5.** The cross section of the  ${}^3\text{He}(e,e'pp)n$  reaction, when the neutron is almost at rest (CLAS preliminary). The fast proton is emitted forward, while the slow proton is emitted backward. The dotted line corresponds to one body processes. The dashed line includes FSI. The full line includes also MEC.

us with a more stringent test. Since this kinematic is far from the quasi-elastic one, on-shell nucleon rescattering is not dominant, and FSI and MEC will be suppressed.

On the contrary, on-shell nucleon rescattering dominates the cross section in the kinematics reported in Fig. 6. Here the two protons are required to be emitted in a symmetric way around the direction of the virtual photon, and the cross section is plotted against the energy of the virtual photon. The good agreement between the theory and the experiment tells us that our description of the on-shell rescattering matrix element is fine over a wide energy range ( $0.2 < T_L < 2$  GeV).

Other cuts have been applied to CLAS data. For instance, one can select a very fast neutron and look for a proton pair almost at rest in  ${}^3\text{He}$ . In a plane wave picture, this gives access to the relative wave function of the two protons. However, in the interesting situation where the relative momentum between the two protons is large, the three nucleons share the total energy and momentum and three body mechanisms contribute significantly. I refer to ref. [20] for a more detailed accounts of such a study.





**Figure 6.** The cross section of the  ${}^3\text{He}(e,e'pp)n$  reaction, when the neutron is almost at rest (CLAS preliminary). The two protons are emitted in a symmetric way against the virtual photon direction. The dotted line corresponds to one body processes. The dashed line includes FSI. The full line includes also MEC.

#### 4 Perspectives

The operation of CEBAF at Jefferson Laboratory, over the past few years, has confirmed the expectations which we had twenty years ago, but has enlarged in a considerable way the data set, both in accuracy and in energy as well as momentum range.

In the real photon sector, the three body photo disintegration of  ${}^3\text{He}$  is dominated by three body mechanisms related to the on-shell propagation of a pion between the three nucleons. The extension to the virtual photon sector gives access to three body Meson Exchange Currents, which may be related to three body forces.

In the virtual photon sector, the two-body electrodisintegration of  ${}^3\text{He}$ , and of a pair of two nucleons bound in  ${}^3\text{He}$ , opens windows on the momentum distribution at short distance. However special care has to be taken in order to avoid on-shell nucleon scattering which dominates the electrodisintegration cross section in a well defined part of the phase space, namely near the quasi free kinematics. The best candidate to study the short range components of the nuclear wave function is the parallel kinematics, where the outgoing nucleons are emitted along the direction of the virtual photon. In that kinematics FSI

and MEC contributions are reasonably small and are expected to decrease when the virtuality  $Q^2$  increases in the range of several  $\text{GeV}^2$ .

Alternately, one may take advantage of the strong on-shell scattering contribution to study the rescattering of exotic components of the nucleon (and other hadrons) wave function. The study of Color Transparency (CT) is an example of such a possibility. CT is a natural consequence of QCD. When a photon of high virtuality  $Q^2$  interacts elastically with a nucleon, it selects configurations with small transverse extension which undergo less rescattering when they travel in the nuclear medium. However it turns out that in the range of virtuality currently available ( $Q^2 < 6 \text{ GeV}^2$ ) the lifetime of such small configurations is comparable to the internucleon distance and much smaller than the radius of a nucleus. This explains why no signal of Color Transparency has been reported so far. A better way would be to work in kinematics where rescatterings between nucleons are maximized, such as in Fig. 1. At low virtuality  $Q^2$  the height and the width of the rescattering peak are on solid grounds, since the matrix element depends of on-shell elementary amplitudes (which can be borrowed from the corresponding elementary channels) and on the low momentum part of the nuclear wave function. At higher virtuality, CT will cause the peak to decrease and its width to increase. I refer to my contribution in ref. [21] for a more detailed discussion.

While the present energy of CEBAF (6 GeV) allows to test this conjecture at low virtuality ( $Q^2 < 6 \text{ GeV}^2$ ), only its energy upgrade to 12 GeV will allow to reach high enough virtuality ( $Q^2 \sim 12 \text{ GeV}^2$ ) to see the effects of color transparency.

*Acknowledgement.* This work was supported in part by the European Commission under Contract HPRN-CT-2000-00130.

## References

1. Ch. Hajduk and P. Sauer: Nucl. Phys. **A369**, 321 (1981)
2. Ch. Hajduk, P. Sauer and W. Struensee: Nucl. Phys. **A405**, 581 (1983)
3. Lacombe et al.: Phys. Lett. **B101**, 139 (1981)
4. B. Frois: In: *Modern Topics in Electron Scattering* (Eds. B. Frois and I. Sick). World Scientific 1991
5. J.-M. Laget: Phys. Rep. **69**, 1 (1981)
6. J.-M. Laget: In: *Modern Topics in Electron Scattering* (Eds. B. Frois and I. Sick)p.290. World Scientific 1991
7. P. Ulmer et al.: Phys. Rev. Lett. **89**, 062301 (2002)
8. J.-M. Laget: Phys. Lett. **B199**, 493 (1987)

9. D. Higinbotham: In: *International Symposium on Electromagnetic Interactions in Nuclear and Hadron Physics*, 4-7 December 2001, Osaka, Japan. World Scientific (to appear)
10. J.-M. Laget: Nucl. Phys. **A579**, 333 (1994)
11. J.-M. Laget: J. Phys. **G14**, 1445 (1988)
12. G. Audit et al.: Phys. Lett. **B227**, 331 (1989)
13. G. Audit et al.: Phys. Lett. **B312**, 57 (1993)
14. G. Audit et al.: Phys. Rev. **C44**, R575 (1991)
15. G. Audit et al.: Nucl. Phys. **A614**, 461 (1997)
16. S. Niccolai: Few Body Systems Suppl. (to appear); In *XVIII Conference on Few-Body Problems in Physics*, 8-14 September 2002, Bled (Slovenia)
17. J.-M. Laget: Phys. Rev. **C35**, 832 (1987)
18. B. Zhang: Thesis. MIT 2002 (unpublished)
19. S. Gilad et al.: In: *5<sup>th</sup> Workshop on Electromagnetically induced Two Hadron Emission*, Lund, Sweden, 13-16 June 2001
20. L. Weinstein: Eur. Phys. J. (to appear); nucl-ex/0209014
21. J.-M. Laget: In: *Exclusive and Semi-Exclusive Processes at High Momentum Transfer*, Newport-News, USA, 19-22 May 1999, p.13. World Scientific 2000