PRESENT STATUS OF ELECTROMAGNETIC REACTIONS ON THE DEUTERON ABOVE PION THRESHOLD

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The present status of the theoretical description of electromagnetic reactions on the deuteron above pion threshold is reviewed. Three major topics are considered: (i) retardation effects in π-meson exchange contributions to NN-interaction and meson exchange currents in deuteron photodisintegration above π-threshold in the ∆-resonance region, (ii) off-shell effects in the one-body current treated in a simple pion cloud model in deuteron photodisintegration in and above the ∆-resonance region, and (iii) final state interaction effects in photoproduction of π and η mesons on the deuteron.

1. Introduction
In view of the fact that at present QCD in the non-perturbative regime can at best be described by effective degrees of freedom only, one uses a framework with meson, nucleon and isobar degrees of freedom. Hadron properties are either described phenomenologically or by effective quark models. The central question then is: How accurate is this effective description, and where is the borderline beyond which explicit quark-gluon degrees of freedom have to be considered? It is very likely that no clear cut answer exists.

However, the study of electromagnetic reactions on few-nucleon systems may give at least a partial answer because lightest nuclei (deuteron, helium-3) allow reliable theoretical descriptions, and approximations, which are unavoidable in more complex many-body systems, are not necessary. Therefore, such systems constitute reliable test laboratories for the investigation of effective degrees of freedom. Furthermore, the electromagnetic interaction is well known and sufficiently weak, in order to allow conclusive interpretations in terms of charge and current matrix elements. Finally, reactions above pion threshold are of particular interest with respect to explicit meson degrees of freedom and internal baryon structure.

The main points of interest are (i) the role of meson and isobar degrees of freedom in medium energy reactions, (ii) many-body phenomena, induced by the effective description in terms of meson, nucleon and isobar d.o.f., e.g., the role of pion retardation in NN interaction and two-body meson exchange operators, and (iii) properties of the neutron like, e.g., the elementary π and η photoproduction on the neutron, in other words, the use of light nuclei as effective neutron targets. Particularly suited are quasi-free reactions on the deuteron in order to minimize final

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state interaction effects. However, for a reliable interpretation it is mandatory to correct for medium influences as, e.g., described by two-body effects.

2. Pion Retardation in $d(\gamma, p)n$ above Pion Threshold

Most sophisticated theories of photodisintegration in the $\Delta$ region, which are based on a coupled channel approach and use a $\Delta$ excitation operator from a fit of $\pi$ photoproduction on the nucleon, encounter various problems\(^1\) (see Fig. 1): (i) Under-
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Fig. 3. Differential cross sections (upper panels) and photon asymmetries (lower panels) of deuteron photodisintegration from $^2$H. Notation as in Fig. 2. Exp. as in Fig. 1.

disappeared completely. Thus any realistic description of e.m. reactions on light nuclei in this energy regime has to use retarded interactions and MEC.

3. Off-shell Effects in One-Body Current

It is a well-known fact that the e.m. current of a particle with internal structure becomes in general more complicated in an off-shell situation. Consider, for example the e.m. current of a proton. Its on-shell Dirac current is determined by two structure functions, the Dirac and Pauli form factors $F_1(q^2)$ and $F_2(q^2)$, respectively, which depend on $q^2$, the four momentum transfer squared, only. However, for e.m. reactions on nuclei the interacting nucleons are off-shell, i.e. $p^2 = W'^2 \neq M^2 \neq W^2 = p^2$. In this case, one has ten additional structure functions depending not only on $q^2$ alone but also on the off-shell masses $W'$ and $W$. The problem is that for the off-shell structure functions one needs a dynamical model for the internal structure, because these form factors are intimately connected to the underlying hadronic interaction. Thus, such a model has to be consistent with the $NN$-interaction. Moreover, off-shell effects as such are not independently observable. Recently, we have completed a study of off-shell effects in deuteron photodisintegration using a consistent dynamical approach in which the nucleon is dressed by pion loops, i.e. the internal nucleon structure is described by a pion

Fig. 4. Electromagnetic current of a nucleon dressed with a meson cloud.
cloud. Correspondingly, one finds for the e.m. one-nucleon current the representation depicted in Fig. 4. For the resulting off-shell one-nucleon current one finds in the nonrelativistic limit

$$\langle \vec{p}', e' | j(0) | \vec{p}, e \rangle = 2 \beta(e', e) \vec{p}' + \gamma(e', e) \vec{k} + i\vec{\sigma} \times (\delta(e', e) \vec{p}' + \epsilon(e', e) \vec{k}) ,$$

with $\vec{k} = \vec{p}' - \vec{p}$, and $e'$ and $e$ denote final and initial nucleon energies, respectively. The structure functions fulfil the on-shell condition, i.e. for $e' = p'^2/2M$ and $e = p^2/2M$

$$\beta(e', e) = -\gamma(e', e) = \frac{1}{2M} , \quad \delta(e', e) = 0 , \quad \epsilon(e', e) = \frac{\mu}{2M}.$$ 

The correct on-shell current is ensured by an appropriate counter term. Within this meson-nucleon model, which is also used for the $NN$-interaction including retardation effects, one finds a sizeable influence from off-shell effects on the differential cross section of deuteron photodisintegration in and above the region of the $\Delta$-resonance as is seen in Fig. 5. They show up predominantly at forward and backward angles, leading to a decrease of the cross section. In the future, more realistic nucleon models should be studied with respect to such off-shell effects.

4. Final State Interaction in Incoherent Pion Photoproduction

Meson photoproduction on the nucleon provides valuable information on its internal structure and serves as a test of hadron models. The production on light nuclei is of particular interest because it allows one to study the elementary neutron amplitude, medium effects and nuclear structure. Recently, we have completed a calculation of pion photoproduction on the deuteron including besides the impulse approximation complete rescattering in all two-body subsystems as depicted in Fig. 6. Deuteron

![Fig. 6. Diagrams for incoherent pion photoproduction on the deuteron: (a) impulse approximation (IA), (b) $NN$ rescattering, (c) $\pi N$ rescattering.](image-url)
wave function and \( \pi N \) interaction are taken from the Paris potential, and the \( \pi N \) and \( NN \) interactions in separable form. The complete \( T \)-matrices are obtained from solutions of the corresponding LS-equations. For \( NN \) rescattering all partial waves with \( J \leq 3 \), and for \( \pi N \) rescattering \( S \) through \( D \) waves are included. Total cross sections are shown in Fig. 7. For charged pion production the rescattering effect is small, but for neutral pion production quite sizeable, which mainly stems from the fact that in IA quite a fraction of the coherent production is included due to the non-orthogonality of the final plane wave to the deuteron bound state. In all cases \( \pi N \)-rescattering is very small compared to \( NN \)-rescattering due to the much weaker \( \pi N \)-interaction. The inclusion of such rescattering contributions leads to a satisfactory description of the experimental total cross sections for \( \pi^- \) as well as for \( \pi^0 \) production as shown in Fig. 7. A corresponding good agreement is achieved for the differential cross sections of \( \pi^0 \) production depicted in Fig. 8. One readily notices that the major rescattering effects appear at forward meson angles. This is also true for charged pion production\(^6\).

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**Fig. 7.** Total cross section for pion photoproduction on the deuteron from\(^6\). Dashed: IA; solid: IA+complete rescattering; data: Asai et al., Phys. Rev. C 42, 837 (1990), Benz et al., Nucl. Phys. A 65, 158 (1973) (ABHHM), Chiefari et al., Lett. Nuovo Cim. 13, 129 (1975) (Frascati).

**Fig. 8.** Differential cross sections for \( d(\gamma, \pi^0)pn \) from\(^6\). Dashed: IA; solid: IA+complete rescattering; Exp.: Krusche et al., Eur. Phys. J. A 6, 309 (1999).
5. Two-Body Effects in Coherent Eta Photoproduction

Photoproduction of \( \eta \) mesons is an interesting tool for studying the \((s = 1/2)\)-

nucleon resonances. The \( S_{11}(1535) \) plays a special role because of its strong coupling
to the \( \eta \) channel. While the incoherent reactions yields estimates of the modulus
of the neutron amplitude, the coherent process provides the phase information.
Furthermore, the deuteron with \( T = 0 \) serves as isospin filter and thus yields the
ratio of isoscalar to proton amplitude \( A_s/A_p \). Until recently, a seeming discrepancy
was noted between extraction from the coherent reaction, \( |A_s/A_p|_{coh} \approx 0.2 \), and
from the incoherent one, \( |A_s/A_p|_{incoh} = 0.09 \). The latter value was extracted from
the incoherent production on the deuteron, yielding at resonance \( \langle \sigma_n/\sigma_p \rangle_{res} = 0.66 \).

In recent work on coherent photoproduction on the deuteron\(^7\) we have taken for
the elementary production amplitude a coupled channel model of\(^8\), which considers
the channels \( \pi N \to \pi N, \pi N \to \eta N, \gamma N \to \pi N, \) and \( \gamma N \to \eta N \). Specific features
of the model are the inclusion of self energy contributions from \( \pi \) and \( \eta \) loops and the dressing of the e.m. vertex by hadronic rescattering. A good description of

\[ \eta \] photoproduction on the proton is achieved with the important result that the dressing leads to complex values for proton and neutron amplitudes, i.e.,

\[ A_n = (-114 - i1.7) \times 10^{-3} \text{GeV}^{-1/2}, \quad A_p = (120.9 - i66.1) \times 10^{-3} \text{GeV}^{-1/2}, \]

yielding the ratios

\[ \left| \frac{\sigma_n}{\sigma_p} \right|_{\text{res}} = |A_n/A_p|^2 = 0.68 \approx 2/3, \quad A_s/A_p = 0.25 \exp(-0.969). \]

Thus there is no contradiction for this ratio anymore between the extraction of this ratio from the coherent and the incoherent reaction.

In the left panel of Fig. 9 the various mechanisms, taken into account in\(^7\), are displayed. The box labeled Born contains disconnected diagrams where the photon is absorbed by one nucleon and the \( \eta \) is emitted by the other. Hadronic rescattering is indicated by boxes \( T_{NN}, T_{NR}, T_{RN}, \) and \( T_{RR} \) and meson exchange current contributions by boxes \( N[2] \). As resonances “R” we have included \( P_{11}(1440), S_{11}(1535) \) and \( D_{13}(1520) \). The hadronic interaction is considered in static as well as retarded form as displayed in the right panel of Fig. 9. For coherent \( \eta \) photoproduction on the deuteron, the effect of various mechanisms on the differential cross section are displayed in the left panel of Fig. 10. One notes an opposite effect between static and retarded rescattering. The total cross section is shown in the right panel of Fig. 10, where a sizeable influence from all two-body effects is seen. Furthermore, the first order rescattering approximation overestimates considerably the total cross section. For the differential cross section a reasonable though not perfect agreement with experiment is achieved as is shown in the left panel of Fig. 11. In the right panel of this figure the photon asymmetry is displayed. One notes a sizeable influence from hadronic rescattering but little effect from MEC.

6. Final State Interaction in Incoherent Eta Photoproduction

Near threshold the impulse approximation yields a very small cross section for \( \langle \gamma, \eta \rangle np \) due to the large momentum mismatch and indeed fails drastically compared to experiment yielding a cross section much too low.
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Fig. 12. Left panel: Total cross section for \( d(\gamma, \eta)np \) from \(^9\): dashed: IA, solid: IA + rescattering, dash-dotted: IA + \( NN \) rescattering, data: inclusive \( \gamma d \rightarrow \eta X \) from \(^\vphantom{^9}11\). Middle and right panels: \( \eta \)-meson spectra at forward emission angles for two different photon energies and angles: dotted: IA, solid: IA + \( NN \) rescattering, dashed: without the deuteron \( D \)-wave in the \( NN \)-rescattering contribution. The excitation energy \( E_{np} \) in the final \( NN \)-system is indicated at the top abscissa.

Fig. 13. Differential cross sections near threshold from \(^9\). Dotted: IA, dashed: IA + \( NN \) rescattering; solid: IA + complete rescattering. Exp. from Krusche et al., Phys. Lett. B 358, 40 (1995).

Fig. 14. \( \eta \) meson spectrum for \( d(\gamma, \eta)np \). Dotted: IA, dashed: first order rescattering, solid: complete thr-body calculation.

Therefore, we first have performed an approximate treatment of FSI\(^9\) in complete analogy to pion photoproduction on the deuteron, i.e. taking into account only complete rescattering in the two-body \( \eta N \) and \( NN \) subsystems in the final state. In the following, this is called first order rescattering. In this case the \( NN \) t-matrix is determined from the Bonn OBEPQ potential and for the \( \eta N \) t-matrix an isobar model is taken describing the intermediate \( S_{11}(1535) \) excitation. The first order rescattering, restricted to s-waves of \( NN \) and \( \eta N \) subsystems in view of the near-
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threshold region, leads to a considerable improvement (see left panel of Fig. 12). The spectrum of the outgoing $\eta$ meson (middel and right panels of Fig. 12) shows the distinct signature of the final state $NN$ rescattering exhibiting the prominent $^1S_0$ peak near the $NN$ scattering threshold. The differential cross sections near

![Graph](image)

threshold are shown in Fig. 13. The left panel of Fig. 13 indicates that first order rescattering still fails to explain quantitatively the enhancement of the data right above threshold. This is corroborated by very recent more precise near-threshold data of Hejny et al.\textsuperscript{12}.

For this reason, we then have performed a three-body treatment of the final state interaction\textsuperscript{10}, because the very strong effect in first order rescattering suggests that a genuine three-body treatment is required. A considerable simplification is achieved by restriction to only $s$-waves which is justified because of threshold region. For the $NN$ interaction a simple Yamaguchi form is used. The resulting $\eta$ spectrum is displayed in Fig. 14 where again one notes clearly the $^1S_0$ peak as in Fig. 12. However, for the lower photon energy one readily sees a substantial underestimation of the first order rescattering compared to the three-body calculation, although the forms are similar. Total and differential cross sections are shown in Fig. 15. The inclusive total cross section data exhibit a distinct enhancement near threshold which is reproduced by the 3-body approach (left panel of Fig. 15) but not in first order, the latter being considerably lower right at threshold. This is also the case for the differential cross sections (middel and right panels of Fig. 15). It remains to be seen, whether a more realistic treatment of the $NN$-interaction is also able to describe the data.

7. Conclusions and outlook

In summary, we may conclude that the electromagnetic probe is a very important tool in order to reveal the internal structure of hadrons. Only the new generation of high duty cycle machines allows one to exploit its full power and the thrust of future experimental research lies on the study of exclusive reactions. Polarization observables will give us much more detailed information and thus will provide much more stringent tests for theoretical models.

Reactions on the deuteron are of particular importance for testing present theoretical frameworks for describing strong interaction physics in terms of effective degrees of freedom, thus serving as a test laboratory. Of special interest are e.m. reactions above the pion threshold. An important example is photodisintegration with respect to the study of retardation and off-shell effects.
Furthermore, meson production on the deuteron offers the possibility to study the elementary production amplitude on the neutron provided one has the two-body effects from final state interaction and e.m. current under control. In particular, the $\eta N$-interaction can be studied in incoherent eta production near threshold. However, a first order rescattering calculation as used, e.g. in\textsuperscript{13}, is not reliable for that purpose, because right above threshold a three-body approach is mandatory.

Finally, for increased energy and momentum transfers, the effects which arise from relativity should be carefully considered.

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