APPLICATION OF PQCD TO DIFFERENT DEUTERON ELECTROMAGNETIC PROCESSES

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Abstract

We review recent data on electron and photon interactions with deuteron: elastic and inelastic electron-deuteron scattering, π^0 photoproduction on deuteron, and deuteron photodisintegration, with specific interest to polarization observables in the kinematical region where quark and gluon degrees of freedom should have to be explicitely included in the models. We compare the recent data with the predictions of pQCD. The scale where pQCD applies, after taking into account the new data is shifted to shorter distances.

Key-words: electromagnetic interaction, polarization, pQCD, deuteron

1 Introduction

In the *Istitutional plan* [1] of the Jefferson Laboratory, one can read *'In the traditional view, the atom's nucleus appears as a cluster of nucleons -protons and neutrons. A deeper view reveals quarks and gluons inside the nucleons. Cebaf's continuous energetic beams of probing electrons let physicists examine how the two view fit together. Ultimately, the process of bridging the views will yield a complete understanding of nuclear matter..'*

The deuteron is the simplest nuclear system, where to test the properties of quarks and nucleons (for a review, see for example [2]). Traditionally, electron-hadron scattering is considered the most precise way to get information on the hadron structure (Fig. 1):

- the electron vertex is expressed in terms of QED (care, however should be taken with respect to radiative corrections when comparing to experiment),
- the mechanism is supposed to be one-photon exchange (although at large momentum transfer 2γ-exchange can be competitive [3]) ,
- the hadron structure is contained in the hadron vertex and usually expressed in terms of form factors.

The pertinent observables, playground for theory and experiment, are the differential cross section and the polarization phenomena, which can be very precisely measured, due to the high intensity and the high degree of polarization of the electron beam of JLab.

QCD predicts scaling laws, following the number of fields involved in the initial and final state of the reaction [4]. These laws can also be derived independently from QCD, from the probability of keeping the hadrons intact after the interaction, in the hypothesis that the momentum is equally shared among the constituent quarks [5]. A strong

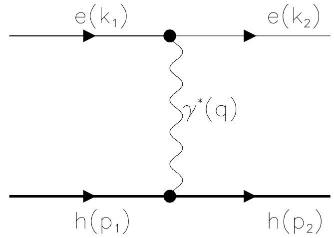

Figure 1: One-photon approximation for *eh*-elastic scattering

hypothesis of pQCD is hadron helicity conservation, which holds for vector interaction between gluons and massless quarks. This picture is intimately related to the kinematical condition that the transverse momentum of the quarks has to be negligible, compared to the transverse momentum brought in the reaction.

A more phenomenological formalism, based on the reduced nuclear amplitudes [6], gives predictions on cross sections for elastic and inelastic electron-hadron processes, in a perturbative approach, where the composite structure of the nucleons is taken into account by introducing phenomenological form factors.

Here we will review QCD predictions and compare with the recent data on electron-proton and electron-deuteron elastic scattering, deuteron photo-disintegration and coherent pion photoproduction on deuterons.

2 Elastic electron scattering

The *ed* elastic scattering cross section has been measured up to $Q^2 = 6$ GeV^2 [7] and the authors suggested that the data about the structure function $A(Q^2)$, in the range of momentum transfer $2 \leq Q^2 \leq 6$ GeV^2, are a good indication of the validity of the predictions of pQCD. Following [6], one can define a generalized deuteron form factor, $F_D(Q^2)$, $F_D(Q^2) = \sqrt{A(Q^2)}$, and a reduced deuteron form factor $f_D(Q^2)$:

$$f_D(Q^2) = \frac{F_D(Q^2)}{F_N^2(Q^2/4)}, \tag{1}$$

where F_N is the nucleon electromagnetic form factor. The (Q^2)-behavior of $f_D(Q^2)$ (at large Q^2) can be predicted in the framework of pQCD, in the following form:

$$f_D(Q^2) = N\frac{\alpha_s(Q^2)}{Q^2}\left(ln\frac{Q^2}{\Lambda^2}\right)^{-\Gamma}, \tag{2}$$

where N is the normalization factor (which is not predicted by QCD), α_s is the running QCD strong interaction coupling constant, Λ is the scale QCD parameter, and Γ is determined by the leading anomalous dimension, here $\Gamma = -\dfrac{8}{145}$.

In [7] it was shown that the QCD prediction (2), which can be applied to asymptotic momentum transfer, is working well already for $Q^2 \geq 2$ GeV^2, with a plausible value of the parameter $\Lambda \simeq 100$ MeV, in agreement with the values determined by many other possible methods [8] (see Fig. 2).

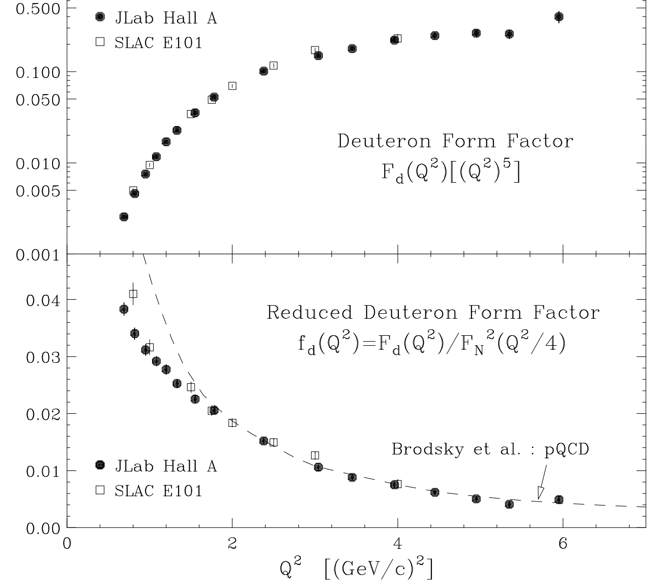

Figure 2: Reduced deuteron form factor (from [7])

Let us analyze the predictions given by Eqs. (1) and (2) in more detail, with respect to the value of the parameter Λ and, in particular, to the choice of the nucleon form factors in Eq. (1). In ref. [6], the nucleon form factor F_N was parametrized in dipole form:

$$F_N(Q^2) = G_D = \frac{1}{(1+Q^2/m_D^2)^2},\ m_D^2 = 0.71\ \mathrm{GeV}^2, \tag{3}$$

and it was not rigorously identified as magnetic or electric. The dipole form of the nucleon electromagnetic form factors was consistent with the experimental data for three of the four nucleon form factors, G_{Mn}, G_{Mp}, and G_{Ep}:

$$G_{Ep}(Q^2) = G_{Mp}(Q^2)/\mu_p = G_{Mn}(Q^2)/\mu_n = G_D,\ \mu_p = 2.79,\ \mu_n = -1.91.$$

The $(1/Q^2)^2$-behavior of these form factors are in agreement with quark counting rules considerations [6]. The fourth, G_{En}, was assumed negligible in the discussed region of Q^2 [9]. Recently, more precise data [10], based on the polarization method [11], showed that the Q^2-dependence of the nucleon electromagnetic form factors is not universal, and that the electric proton form factor strongly deviates from the usual dipole representation. We will use, for the description of the data [10], a fit of the form:

$$G_{Ep}(Q^2) = \frac{1}{(1+Q^2/m_D^2)^2}(1-0.129Q^2), \tag{4}$$

where Q^2 is expressed in GeV^2. The important question is, then, which parametrization of nucleon form factors to use in calculating the reduced deuteron form factor $f_D(Q^2)$, Eq. (1), and what are the consequences of different choices on the apparent value of the parameter Λ. In Fig. 3 we show different data sets and best fits, using Eq. (2), corresponding to the following possibilities:

1. We replace in Eq. (1) $F_N(Q^2/4)$ by the fit (4) of new data on the proton electric form factor, G_{Ep}:

$$f_D(Q^2) = \frac{F_D(Q^2)}{G_{Ep}^2(Q^2/4)}.$$

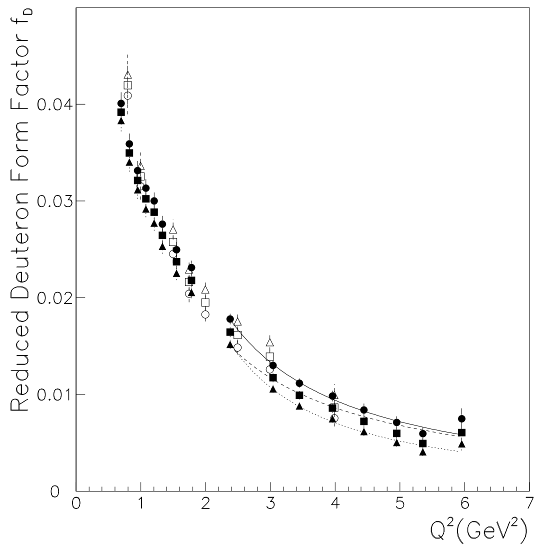

Figure 3: Data set corresponding to the reduced deuteron form factor for different choices of the nucleon form factors: circles (case 1), squares (case 2), and triangles (case 3). Open symbols are from [12], solid symbols from [7].

This yields to the data set represented by circles and to the fit reported as a solid line (case 1).

2. We replace in Eq. (1) $F_N^2(Q^2/4)$ by the product of F_N (Eq. 3) and G_{Ep} from Eq. (4):

$$f_D(Q^2) = \frac{F_D(Q^2)}{F_N(Q^2/4)G_{Ep}(Q^2/4)}.$$

The f_D data are shown as squares and the best fit by the dashed line (case 2).

3. We show, for comparison, the previous results of Ref. [7], using the dipole parametrization Eq. (3). The data are represented by triangles and the fit by the dotted line (case 3).

In all these three cases, instead of normalizing the QCD prediction, (2), to the data at $Q^2 = 4$ GeV^2, as in Ref. [7], we have fitted the data beyond $Q^2 = 2$ GeV^2, with two free parameters, a global normalization N and Λ. We found that even a relatively small change in nucleon form factors, causes a relatively large instability in the value of Λ (see Table I). Note that the reduced form factor f_D has logarythmic (i.e. relatively weak) dependence on the parameter Λ, Eq. (2). For the case 3, we obtain a different value for the parameter Λ, as compared with Ref. [7]. This is due to the different normalization procedure.

A similar situation occurs if one uses the Dirac and Pauli form factors, $F_1 = (G_E + \tau G_M)/(1+\tau)$ and $F_2 = (G_M - G_E)/(1+\tau)$, with $\tau = Q^2/(4M_p^2)$, (M_p is the proton mass) instead of the Sachs form factors G_E and G_M.

In principle, both sets of nucleon form factors correspond to an equivalent description of the electromagnetic structure of the nucleon, but the physical properties associated to these two sets of form factors are different. F_1 and F_2 correspond to non spin-flip

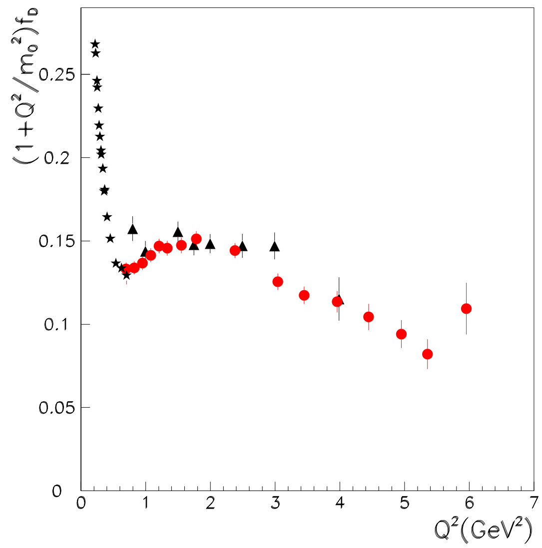

Figure 4: Data set corresponding to the reduced deuteron form factors multiplied by $(1 + Q^2/m_0^2)$. Triangles are from [12], stars from [9], solid circles from [7].

and spin-flip form factors, and pQCD predicts an asymptotic behavior as $1/Q^4$ and $1/Q^6$ respectively, so that the ratio Q^2F_2/F_1 should be constant. Again the new data contradict this prediction and show, instead, that the ratio $\sqrt{Q^2}F_2/F_1$ is nearly constant.

The values of the fitting parameters N and Λ are summarized in Table 1. The values which can be obtained for Λ may differ of many order of magnitudes, for the different possible choices of the nucleon form factors for the calculation of the reduced form factor $f_D(Q^2)$. The normalization parameter N also shows large sensitivity to the choice of the nucleon form factor.

In [6] another interesting prediction, concerning the scaling behavior of the reduced deuteron form factor, was done:

$$f_R = \left(1 + \frac{Q^2}{m_0^2}\right) f_D(Q^2) \simeq const, \tag{5}$$

where $m_0^2 = 0.28$ GeV^2 is a parameter related to the Q^2-behavior of the pion form factor. This prediction was confirmed by the previous $A(Q^2)$ data [12], in the limit of their accuracy. In Fig. 4 one can see that the new, more precise data about $A(Q^2)$ [7], are not consistent with Eq. (5) as they show an evident dependence of the product f_R on Q^2 (calculated here with dipole nucleon form factors). This behavior can not be changed by varying the parameter m_0, or the choice of the nucleon form factor.

One should also take into account the fact that the elastic *ed*-scattering is sensitive to the isoscalar combination of the nucleon form factors G_{Es} and G_{Ms}, with $2G_{Es} = G_{Ep} + G_{En}$ and $2G_{Ms} = G_{Mp} + G_{Mn}$. So the corresponding linear combination of proton and neutron form factors seems more adequate for the parametrization of F_N. In the case of dipole parametrization of all nucleon electromagnetic form factors, an isoscalar combination will only bring a different normalization. But, if one takes $G_{En} \neq 0$, two other possibilities: $F_N^2 = G_{Es}^2$ and $F_N^2 = G_{Es}G_{Ms}$ would lead to different results and different values for the parameter Λ.

Case	N	$\Lambda[GeV^2]$
(1): $F_N^2 = G_{Ep}^2$	0.16 ± 0.04	0.20 ± 0.13
(2): $F_N^2 = G_{Ep}G_{Mp}$	0.43 ± 0.04	0.0014 ± 0.007
(3): $F_N^2 = G_{Mp}^2$	0.06 ± 0.02	0.648 ± 0.243

Table 1: Values of the fit parameters (see text).

3 The photon-deuteron reactions

In case of photon induced reactions, pQCD suggests scaling laws in the variable s, (s is the total energy squared: $s = M_p^2 + 2E_\gamma M_p$ where E_γ is the initial photon energy) which relate the cross section to the number of fields in the initial and final channel as

$$\frac{d\sigma}{dt} = \frac{1}{s^{n-2}}. \tag{6}$$

From Eq. 6 one finds power laws as s^{-11} for the deuteron photosintegration cross section and s^{-13} for coherent pion photoproduction on deuteron.

Concerning deuteron photosintegration, recent experimental data are available, on the cross section [14, 15] and on polarization observables, induced by circularly polarized photons [16]. The scaling regime seems to be reached for $E_\gamma \geq 1$ GeV, at $\theta_{cm} = 90^0$ but not at smaller angles [15]. A further experiment [14] shows however that the scaling regime is reached at various angles, for different E_γ corresponding to the same value of transferred perpendicular momentum, $p_\perp \simeq 1.3$ GeV. This result has been considered as the *evidence for the onset of quark effects in a nuclear reactions* [17]. However, polarization phenomena do not support this interpretation, [16]: more exactly the induced polarization vanishes, as expected for helicity conservation, whereas the polarization transfer coefficients are large and positive.

The data on the reaction $\gamma + d \to d + \pi^0$ have been extended up to $E_\gamma = 3$ GeV, for $\theta_{c.m.} = 90^0$ and 136^0. The scaling seems to be reached at the larger angle, for $E_\gamma \geq 1$ GeV, but the formalism of RNA, which should work better in non-perturbative regime, is not consistent with the data, at any angle. A new reformulation of this problem, in case of pion photoproduction has been recently done [19], assuming the scaling of the deuteron form factors. However, these predictions also strongly depend on the choice of the nucleon electromagnetic form factors in the definition of the reduced nuclear matrix element.

4 Discussion and Conclusions

We have shown that the recent data obtained at JLab on different electromagnetic reactions involving deuteron, are not consistent with pQCD predictions. We discussed the sensitivity of the reduced deuteron form factor to different choices of nucleon form factors. However, the generalized deuteron form factor is derived from the structure function $A(Q^2)$, which is a quadratic function of the three deuteron electromagnetic form factors. It would be more natural to include the electric, quadrupole or magnetic deuteron form factors, G_E, G_Q, and G_M in the calculation of f_D.

The deuteron magnetic form factor has been measured, (through the SF $B(Q^2)$) up to $Q^2 = 2.77$ GeV^2 [20]. The structure function $B(Q^2)$ shows a dip for Q^2=1.9 GeV^2, which characterizes the two-nucleon structure of the deuteron and it is related to a node in the S-wave function. It is naturally reproduced by 'classical' calculations, although its precise location depends on all ingredients of deuteron structure, as wave functions, and meson exchange currents (in particular the $\rho\pi\gamma$-term). In framework of pQCD this dip could also be reproduced, under the assumption that that the one spin-flip helicity amplitude is present, and with the help of two parameters [21].

The t_{20}-data, measured up to Q^2=1.9 GeV^2, do not follow the asymptotic behavior predicted by QCD [13]. Calculations based on IA show the good trend, but corrections are added to reproduce the data. However it is not evident that the same corrections improve the quantitative agreement with the three observables simultaneously.

The asymptotic properties of the FF can be discusses in a general and model independent way, through a comparative study in the space-like (SL) and time-like (TL) regions. Form factors are analytical functions of q^2, being real functions in the SL region (due to the hermiticity of the electromagnetic Hamiltonian) and complex functions in the TL region. The Phràgmen-Lindelöf theorem [22] gives a rigorous prescription for the asymptotic behavior of analytical functions: $\lim_{q^2\to-\infty} F^{(SL)}(q^2) = \lim_{q^2\to\infty} F^{(TL)}(q^2)$. This means that, asymptotically, the FFs, have the following constrains: 1) the time-like phase vanishes and 2) the real part of the FFs, $\mathcal{R}eF^{(TL)}(s)$, coincides with the corresponding value $F^{(SL)}(q^2)$. The Rosenbluth separation of $|G_E|^2$ and $|G_M|^2$ in TL region, has not been realized yet.

The existing data on G_M in the TL region, obtained under the assumption that $|G_E| = |G_M|$, are larger than the corresponding SL values. This has been considered as a proof of the non applicability of the Phràgmen-Lindelöf theorem, or as an evidence that the asymptotic regime is not reached [23]. An extrapolation to high q^2 of the TL experimental data indicates that the Phràgmen-Lindelöf theorem would be satisfied by the magnetic proton FF, only for $s(q^2) \geq 20$ GeV^2. This conclusion is nearly independent on different assumptions concerning $|G_E|$ [24].

Note, in this respect, that the Sachs form factor (which are related to the distributions of the electric charge and magnetic moment of the nucleon in the Breit system), are not equivalent to the Dirac and Pauli FF (which enter into the parametrization of the electromagnetic current in a relativistic and gauge-invariant form, valid in any coordinate system). Their asymptotic behavior is different [25].

The last experimental data about the differential cross sections for other deuteron electromagnetic processes, $\gamma + d \to d + \pi^0$ and $\gamma + d \to n + p$ also show a deviation from the QCD predictions concerning the reduced matrix elements.

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