Deuteron Elastic Scattering, Photo- and Electro- Disintegration

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I present a very brief review of our understanding of the structure of the deuteron in three exclusive photo-reactions: elastic scattering and photo- and electro- disintegration. I point out several nice, recent results, along with outstanding issues.

1. INTRODUCTION

In this proceedings I discuss the structure of the deuteron, investigated in elastic scattering and photo- and electro- disintegration. Many details can be found in several recent reviews of these topics, [1–3], to which the reader is referred for further insight into this too-brief discussion. Elastic scattering, at fixed $W = m_d$ is best described by hadronic theories, conventional nonrelativistic theories or effective field theories at low momentum transfer, or fully relativistic theories at high momentum transfer. Deuteron photodisintegration has been measured to high W and q ; low energy approaches are extremely difficult to apply to the high-energy data, but some quark models have promise. Deuteron electrodisintegration has largely been measured in near quasifree kinematics, at modest q . Existing data tend to agree reasonably well with hadronic models.

2. ELECTRON DEUTERON ELASTIC SCATTERING

Unpolarized ed elastic scattering is described by two structure functions, referred to as A and B . Since ed elastic scattering depends on three form factors – a common choice is G_C , G_M , and G_Q – much effort has also been put into polarization measurements, particularly t_{20} , to determine the form factors. The major recent experimental advances include the high Q^2 measurements of A and t_{20} at Jefferson Lab. The major recent theoretical advances include the refinements of conventional relativistic theory, and the developments of pionless effective field theory, and chiral perturbation theory.

The ability of theorists to describe deuteron elastic scattering is impressive. The decrease in A by eight orders of magnitude is generally reproduced by theory. Similarly, the fall in B by about 5 orders of magnitude is well reproduced, except perhaps in the region

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of the minimum, $Q^2 \approx 2 \text{ GeV}^2$. Theories also describe t_{20} well. Of particular note are recent chiral perturbation theory calculations, which work well to moderate $Q^2 \approx m_\rho^2$ [4].

The general success of theory should not be ignored, even as we proceed to a more critical assessment. There is an unfortunate trend for different experiments to report t_{20} or cross section data with systematic shifts of $1 - 2 \sigma$ that exceed quoted uncertainties. These discrepancies make it difficult to assess exactly how precise the theoretical models are. Better G_E^n data would also aid this assessment.

For comparison with theories, several areas for improvement stand out. Most obvious is an improved determination of the B structure function at large Q^2 [5]; even at low Q^2 B is generally determined to $\approx 10 \%$ at best. No reasonable technique exists to extend polarization measurements to higher Q^2 [3]. The disagreements in A at high Q^2 are exceeded by theoretical uncertainties, but a new high-precision measurement at low Q^2 is desirable [6]. High precision, low Q^2 polarization data are being obtained by the Bates BLAST collaboration [7]. The structure function A at low Q^2 is understood to 1-2 %, but the agreement of the data and theory is generally only at the level of several percent – I believe that we should be more ambitious. Even at high Q^2 , hadronic theories continue to work well, and there is no *need* to employ quark degrees of freedom.

3. DEUTERON PHOTO-DISINTEGRATION

3.1. Low energies

There are several nice advances in low-energy deuteron photodisintegration from the past several years. Polarization measurements from TUNL demonstrate that photodisintegration at energies of a few MeV, in an energy region appropriate for understanding baryosynthesis, is well predicted in both conventional calculations and in chiral perturbation theory [8]. Mainz theoretical work [9] shows the importance of meson retardation, explaining cross sections and polarization observables up through the Δ resonance region. New data sets for $d\sigma/d\Omega$ and the Σ asymmetry from Mainz [10] and LEGS [11] systematically cover wide energy and angle ranges, in good agreement with each other. New double polarization data are also being taken at LEGS, up to 570 MeV [12].

3.2. Kinematic differences

As the photon energy increases, the difference in the kinematics of deuteron photodisintegration and ed elastic scattering becomes apparent. In elastic scattering, the virtual photon transfers an energy and momentum correlated so that $W = m_d$. In photodisintegration, $|\vec{q}| = \omega$, so that $W = \sqrt{2\omega m_d + m_d^2} > m_d$, and resonances are explicitly excited. Indeed, there are 286 channels, combinations of on-shell, four-star resonances, that can appear in the intermediate state as the photon energy increases to 4 GeV. While a detailed microscopic hadronic calculation appears obviously intractable, using quark degrees of freedom provides a natural way to sum over all the resonance contributions.

Might the resonances appear strongly in the intermediate state in ed elastic scattering? Figure 1 contrasts W^2 of the struck nucleon in photo-disintegration and in elastic scattering. For ed elastics, the momentum transfer exceeds the energy transfer, so that W^2 of the struck nucleon *decreases*, moving away from the resonance region.

Figure 1. The invariant mass squared for the nucleon that absorbs the incoming photon as a function of the photon energy, in deuteron photo-disintegration and ed elastic scattering. The solid line is for a free nucleon. The dashed lines are for nucleons in the deuteron, with a momentum of 200 MeV/c. It makes little difference whether the spectator is put on shell, or both nucleons are put equally off shell.

Figure 2. Angular distributions for $\gamma d \rightarrow pn$. The TQC curves [24] are based on a fit to the 4 GeV angular distribution, with $\theta_{cm} = 37 - 90^\circ$; the TQC formula overpredicts these lower energy data, so all curves have been multiplied by 1/2 to be on the same scale. The dashed curves, calculated with a single normalization parameter, are symmetric about 90° . The dashed-dotted curves include an asymmetry term.

3.3. High energies

Jefferson Lab has been a focus of activity, with publications from three cross section measurements [13–15] and a polarization experiment [16]; there have also been Σ asymmetry measurements from Yerevan [17]. In addition, cross section data will soon be published from Jefferson Lab Hall B [18]. There are also very recently obtained Σ asymmetry and cross section measurements from SPring-8 [19], for energies from about 1.5 – 2.4 GeV and c.m. angles from about $0 - 45^\circ$, and a recoil proton polarization angular distribution at 2 GeV from Jefferson Lab Hall A [20].

Theory has also advanced; there are 5 nonperturbative quark models that have been compared to the data: the reduced nuclear amplitudes model [21], the quark-gluon string model (QGS) [22], the hard rescattering model (HRM) [23], the quark interchange model (TQC) [24], and a constituent quark model [25]. While the QGS model pictures photo-disintegration as occurring through three-quark exchange, all other models can be viewed

as differing implementations of the idea that the photon is absorbed on a quark, with the two nucleons sharing momentum through the interchange of two quarks (and gluons).

The high-energy cross sections from Jefferson Lab generally show the onset of approximate scaling for $p_T > 1.3$ GeV [14]. Figure 2 shows that the angular distributions are somewhat asymmetric, but have similar shapes across a wide range of energies. The QGS prediction (not shown) also agrees well with the data; furthermore, it predicts that interference of isoscalar and isovector photon couplings leads to local minima at 0 and 180° . This prediction will be tested with the data from Hall B [18] and SPring-8 [19].

It has been difficult to make a definitive interpretation from the high energy photodisintegration cross sections about the most effective way to describe the reaction mechanism. This is in part because the theories have roughly similar kinematic dependences, and most involve some parameters, such as an overall normalization, that is fit to the data. This observation leads to polarization observables, and to interest in pp photodisintegration (in ^3He) [26], which is however beyond the scope of these proceedings.

For polarization measurements, the basic issue is whether the reaction has a complicated spin structure, or whether the spin observables indicate a smooth approach towards limits expected from hadronic helicity conservation (HHC). To date, HHC has not been observed experimentally in other reactions, the clearest example being pp elastic scattering.

The Σ asymmetry [17] stays large, perhaps increasing towards 1, as E_γ increases above 1 GeV. The accepted HHC limit has been that $\Sigma \rightarrow -1$; however Grishina *et al.* [22] pointed out that this limit assumes isoscalar photon coupling. An isovector photon coupling results in $\Sigma \rightarrow +1$. Thus, the Σ asymmetry does not actually test HHC.

Figures 3 and 4 show recoil polarization data. The lowest energy polarization transfer data from Jefferson Lab agree well with hadronic calculations – there were no previous measurements. In contrast, the large peak in the induced polarization just above the Δ resonance remains unexplained; it was this large difference that led to much speculation about dibaryons in deuteron photodisintegration, and to many experiments in the late 1970s and early 1980s. Above 500 MeV, the magnitude of the induced polarization decreases rapidly, and above 1 GeV it is consistent with 0, with HHC, and also with an HRM estimate [28] that the induced polarization is small for energies of a few GeV. In particular, there is no indication in these data of oscillations in the polarization, present in the calculations of [27], as would be expected from dominant resonances.

The polarization transfer coefficients have maxima near 1 GeV, and appear to steadily decrease above this energy. This behavior is also consistent with HHC. The QGS prediction, the dotted-dashed curve, that $C_{z'}$ is moderately large and gradually increases with energy, is not inconsistent with the higher-energy data, given the large uncertainties.

3.4. Photodisintegration conclusions

For photodisintegration conventional hadronic theories work well at low energies. The theories begin to fail for energies just above the Δ resonance peak for p_y . Theoretical arguments and data suggest that the contributions of numerous resonances in the hadronic picture must be summed. While several quark models are promising, one cannot yet say that we understand the limits of their validity. Analysis of data already taken at Jefferson Lab Halls B and A and at SPring-8 should help to clarify the reaction mechanism; pp photodisintegration would also be very useful.

Figure 3. The induced polarization p_y in $\vec{\gamma}d \rightarrow pn$. Hadronic calculations are from (Kang) [27], and (Schwamb and Arenhövel) [9]. The quark calculations is from (Sargsian) [23,28]. HHC implies $p_y \rightarrow 0$ as $1/t$, the short dashed curve.

Figure 4. Polarization transfers [16] $C_{x'}$, $C_{z'}$ in $\vec{\gamma}d \rightarrow pn$. The full (open) symbols are the data in the lab (c.m.) frame. The hadronic calculation (MEC) is from [9]. The quark calculation (QGS) is from [22]. HHC implies $C_{x'} \rightarrow 0$ as $1/t$, and $C_{z'} \rightarrow 0$ as $1/t^2$.

4. DEUTERON ELECTRO-DISINTEGRATION

Deuteron electrodisintegration is kinematically more complicated than either photodisintegration or elastic scattering. The four unpolarized response functions depend on three kinematic variables; Q^2 , W , and p_{miss} are often used; the cross section depends on two additional kinematic variables, usually ϵ and ϕ_{pq} . I focus here on experiments with W in the quasifree peak region, rather than in the threshold, dip, or Δ resonance regions. I largely omit determinations of the neutron form factors; while this has been a very successful program, it does not directly address the deuteron structure.

4.1. Quasifree cross sections

Many experiments have measured quasifree cross sections, starting at least as early as 1962 [29], with the first “modern” experiment at Saclay [30], and with the most recent results from Jefferson Lab [31]. Many, particularly early, experiments are discussed in the plane wave impulse approximation (PWIA). If the PWIA were valid, then the cross section depends on the probabilities of scattering from a nucleon in the nucleus and of

finding a nucleon at some particular energy and momentum. The asymptotic neutron momentum is the momentum the neutron had in the nucleus; the nuclear momentum distribution is directly measured. This interpretation is invalid as physics is omitted, but it remains common to report data using:

$$\frac{d^5\sigma}{d\Omega_e \omega d\Omega_p} = f_{recoil} K \sigma_{CC1} \sigma_{reduced}. \quad (1)$$

In the equation, the left side is the experimental cross section, f_{recoil} is a recoil factor, K is a kinematic factor, σ_{CC1} is a *model* for the off-shell ep cross section, and $\sigma_{reduced}$ has no real theoretical meaning, but does have somewhat less kinematic variation than does the experimental cross section.

Figure 5. Reduced cross section from [31].

Figure 6. Asymmetry A^V in $\vec{d}(e, e'p)$ [39].

The recent work of Ulmer *et al.* [31] were taken in quasifree perpendicular kinematics, $|p_p| \approx |\vec{q}|$, $x \approx 1$, and $Q^2 \approx 0.7 \text{ GeV}^2$. This is larger Q^2 than most earlier $d(e, e'p)$ measurements, and some reaction mechanism effects, such as meson-exchange currents and isobar contributions, should be suppressed in this experiment as compared to earlier work, allowing a simpler interpretation. Figure 5 shows that for small missing momenta, there is a systematic overprediction of the cross section by the various theoretical models, by several percent; final state pn rescattering is largely responsible for moving strength to high missing momenta, where the cross section is greatly increased.

4.2. Response functions and polarizations

The deuteron can be studied in more detail with separated response functions:

$$\sigma_{unpolarized} = \sigma_L + \sigma_T + \sigma_{LT} \cos \phi + \sigma_{TT} \cos 2\phi. \quad (2)$$

The angle ϕ is the angle between the plane containing the incoming and scattered electrons, and the plane containing $\vec{q}$ and the outgoing proton. The benefit of separating the various terms is that each shows different sensitivities to the ingredients of the theories. With most experimental setups largely coplanar, the easiest term to separate is σ_{LT} , as $\cos \phi$ reverses sign when the proton is at larger vs. smaller angle than $\vec{q}$. It is easier experimentally to determine an asymmetry A_{LT} than an absolute cross section difference σ_{LT} , but at the cost of losing physics sensitivity.

The asymmetry A_{LT} was first suggested to be particularly sensitive to relativistic effects in [32]: A_{LT} is small and results from a destructive interference in the current, $\approx 2\Re[J^{0*}(J^+ - J^-)]$. Relativistic effects were first seen experimentally in a NIKHEF experiment [33], perhaps surprisingly at $Q^2 \approx 0.2 \text{ GeV}^2$. We also note subsequent measurements at SLAC [34], at $x \approx 1$ and $Q^2 \approx 1 \text{ GeV}^2$, and at NIKHEF [35], though at $Q^2 \approx 0.2 \text{ GeV}^2$ and in the dip region. Perhaps the best measurement to date of the relativistic effects – although the deuteron was not the target – is $^{16}\text{O}(e, e'p)$ from Jefferson Lab Hall A [36].

With the addition of polarized beam, there is a new, fifth response function, with

$$\sigma = \sigma_{unpolarized} + \sigma'_{LT} \sin \phi, \quad (3)$$

and the corresponding asymmetry A'_{LT} . The first measurements, from Bates OOPS [37], demonstrated the technique, but with poorer precision than one would like; the data were consistent with both a simple plane wave calculation as well as a full calculation including reaction mechanism effects. A subsequent much more precise measurement [38] was in very good agreement with a complete calculation.

Polarization observables give added sensitivity to the deuteron structure, even without response function separations. Many of these measurements have been directed towards the neutron form factors. A particularly nice recent measurement studying the deuteron structure was [39]. Figure 6 shows the asymmetry measured with an internal vector-polarized target at NIKHEF, integrating over the quasifree peak for $Q^2 \approx 0.2 \text{ GeV}^2$. The largest effect in the calculation comes from inclusion of the deuteron d state, and the data for $p_{missing}$ from about 0 – 400 MeV/c are in good agreement with the full calculation. In particular, the precise data at low missing momentum, and the lack of model sensitivity of the calculations in this region, indicate that reaction mechanism effects are under control, and thus neutron form factors can be reliably extracted.

4.3. Conclusion and future experiments

The electrodisintegration program is very promising for improving our understanding of the deuteron structure, but it has not yet lived up to its promise. (G_E^n extractions have been very successful.) There are small, but significant, differences in the unpolarized cross sections. Response function separations and polarization measurements are difficult experiments; there are relatively few measurements often with limited statistics. We can be hopeful that this situation will change in soon, with recent experiments [40,41] under analysis, and additional experiments [42] awaiting beamtime.

Jefferson Lab Hall A experiment 01-020 [40] is a systematic high-precision study across the quasifree peak (and beyond), up to $p_{miss} \approx 500$ MeV/c, for $Q^2 = 0.8, 2.1, 3.5$ GeV². The goals of the experiment include studies of A_{LT} , investigation of rescattering effects, and sensitivity to the short-distance deuteron structure, in kinematics which suppress exchange currents and isobars. The data were obtained during 2002.

The Jefferson Lab Hall B E5 group of experiments took ≈ 20 million events for deuteron electrodisintegration, in three different beam / toroid configurations. Major goals of the experiments include extracting G_M^n from quasifree $(e, e'n)$ electrodisintegration and studying high-momentum nucleons in the deuteron. The open, nearly 4π geometry of CLAS, along with the use of polarized beam, make response function separations possible, particularly the out-of-plane, fifth response function R'_{LT} .

5. CONCLUSIONS

The deuteron is made up of hadrons ... and of quarks and gluons. Hadronic theories, both conventional and effective field theories, work well for elastic scattering, electrodisintegration, and low-energy photodisintegration. There is a need for improved data in elastic scattering. In electrodisintegration, there is a need for understanding the low p_r differences between data and theory, and for more systematic kinematic coverage – which will soon be available. There is no compelling need here for quark theories, and indeed no existing quark theories that provide good descriptions of existing data over wide kinematic ranges. For high energy photodisintegration, theoretical arguments along with the trends of the data suggest the use of quark models. Several such models exist, all within a factor of two of existing data – our standards here are not as high as for low energy elastic ed scattering. A series of upcoming experiments should provide sufficient data that we can begin to rule out some of these models, and better understand the underlying reaction mechanism.

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