SEARCHING FOR QUARKS IN THE DEUTERON

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The deuteron has been studied in numerous elastic scattering and photodisintegration experiments over a wide range of momentum transfers. A primary motivation is investigating the validity of theories based on hadronic vs. quark degrees of freedom. It is often thought that hadronic approaches will break down at large momentum transfers, and it will be necessary to use quark degrees of freedom. I will very briefly review the status of our understanding of the underlying theoretical issues, the world data sets for elastic scattering and photodisintegration, and the ability of hadronic and quark based theories to explain the data. Hadronic theories appear to provide good explanations for elastic scattering, but photodisintegration is very difficult to understand.

1 Introduction

The structure of the deuteron is the preeminent problem of few body nuclear physics. It provides the most stringent tests of our understanding of nuclear structure with microscopic models. The deuteron lacks some of the complications of heavier nuclei, and has been investigated experimentally over a large kinematic range.

A prime interest in the recent past, motivating experimental studies in the GeV range, is whether one should use quark or hadronic degrees of freedom to describe the deuteron. It is possible to formulate the hadronic theory for the reaction in many different frameworks, some of which will be discussed below. Various approaches should in principle give equivalent correct answers, if the theory is formulated completely and consistently and the calculation converges. Approximations and truncations lead to variations between the theories, and between theories and (presumably correct) data. Using quark degrees of freedom in this view is merely an alternate formulation, that will provide better convergence and agreement with data in some kinematic regimes. Thus, a better question might be: in what kinematic regimes does each theory provide a concise and accurate description of the data?

In this proceedings, we will briefly cover how well various approaches agree with elastic scattering and photodisintegration data. This presentation is based on a significantly longer work ¹, from which several of the figures

Figure 1. Experimental data for A , B , and t_{20} compared to eight calculations, described in the text. The calculations, in order of the Q^2 of their minima in B , are: CK (long dot-dashed line), PWDM (dashed double-dotted line), AKP (short dot-dashed line), VDG full calculation (solid line), VDG in RIA (long dashed line), LPS (dotted line), DB (widely spaced dotted line), FSR (medium dashed line), and ARW (short dashed line).

have been taken.

2 Elastic scattering

Figure 1 shows several theoretical calculations, to be described below, which provide generally good descriptions of t_{20} , A , and B . It is impressive that theories can reasonably describe the deuteron as the structure functions decrease over about 8 orders of magnitude. The large variations in the predictions for B near the apparent minimum make it clear that these data need to be improved, to firmly determine that the minimum exists, as well as to better determine its location. The disagreement between the higher Q ($= \sqrt{Q^2}$) A data and the theories is not as significant. At higher Q , the calculations are sensitive to poorly defined aspects of the theory, such as the $\rho\pi\gamma$ exchange current and the form factor associated with the additional term in the nucleon current, required by current conservation for the bound nucleon.

Figure 1 is not useful to see precisely how well we do understand the deuteron. Is theory good to 2% or 20%? The 10% differences between the Jefferson Lab Hall A and Hall C data are not visible in this plot, and the slight systematic differences between some of the t_{20} data sets also do not seem to be very important. (There is insufficient space in these proceedings to reference the complete data set; please see instead recent fits ² and reviews by Garçon and Van Orden ³, by Sick ⁴, and by Gilman and Gross ¹.)

We now turn to a more precise examination of the A data at low Q . Here, pQCD and quark models are of little concern, but there are effective field theory (EFT) and chiral perturbation theory (χ PT) calculations, as well as conventional theories. Recent χ PT calculations ⁵ provide very good descriptions of B up to Q about 0.3 GeV, and of A and t_{20} up to Q about 0.5 GeV. This may indicate a relatively larger short range contribution to B . However, as we shall demonstrate below, there are possible questions about the exact size of A at low Q . Due to limited space and because they predict the structure functions over a larger range reasonably well, the focus will be on conventional calculations of the low Q A data.

Figure 2 shows the data for A at low Q . The data have been divided by a "fit" function, which depends on Q and some constants, to remove much of the Q dependence and to enable differences to be seen. The data sets generally overlap well, except for the 10% disagreement between the Mainz ⁶ and Saclay ⁷ data sets at $Q = 0.2 - 0.4$ GeV. This is difficult to understand from comparison of experiments, since both experiments overlap well with each other and with Monterrey ⁸ at lower Q , both are cross checked with the very precise Mainz ep measurements ⁹ at these Q s, and the Saclay measurements agree well with the higher Q , although less precise, experiments. The underlying origin of the difference is cross sections at 50° , 60° , 80° , and 90° (lab) taken at 298.9 MeV

Figure 2. The data for A at low and moderate Q , divided by a fit function to take out much of the Q dependence of A , so that data sets may be compared.

(300 MeV) at Mainz (Saclay). For these data $\sigma/\sigma|_{NS} = A + B \tan^2(\theta/2)$ differs by almost 10%. The correction for the slight difference in Q is only about 1%. It is difficult to understand this large a disagreement for these two high precision experiments.^a

This difference may appear small and unimportant, but, to put it in perspective, a 10% uncertainty in A in a region in which its magnitude is $10^{-1} - 10^{-2}$ is much greater than a 100% uncertainty in B in a region in which its magnitude is 10^{-7} . Furthermore, ambiguities in the theory are much reduced at lower Q , and the difficulty of getting cancellations exactly right, for precise reproduction of the position of minima, is well known. Thus, we conclude that the potential problems with A at low Q are at least as significant in assessing how well we understand the deuteron as the question of the minimum in B .

A set of conventional nonrelativistic calculations is shown in Fig. 3. The calculations (in order of decreasing magnitude at $Q = 0.1$ GeV) use W16 (long dot-dashed), CD Bonn (short dashed), AV18 (solid), IIB (short dot-dashed), and Paris (long dashed) wave functions. The W16 and IIB models use the S and D wave functions of a relativistic model, neglecting the P -state components. The models vary by about $\pm 2\%$, and are generally larger (smaller)

^aNote that the tabulated Mainz cross sections in ⁶ have some typographical errors. For three of the data points, the tabulated cross section is a factor of 10 different from the tabulated $\sigma/\sigma|_{NS}$, which appears to be correct. One assumes a typographical error. For a fourth point, the difference is a factor of 8.1, and $\sigma/\sigma|_{NS}$ again appears to be correct.

Figure 3. The data for A at low and moderate Q , divided by the fit function, compared to five nonrelativistic calculations described in the text.

than the Saclay (Mainz) data. Along with the assumption that relativistic corrections are small and under control at low Q , this variation suggests that a $\approx 2\%$ theoretical description of the form factors should be possible. Note that there is a long standing discrepancy of this size in conventional calculations with the quadrupole moment. In the pionless EFT approach, there is a short distance four nucleon one photon coupling, which is unknown and can be adjusted to give the quadrupole moment.

It is important to assess how accurately the nucleon form factors are known, in considering how precise the calculations might be. In a pure wave function model, the structure function results from a sum of deuteron body form factors multiplied by isoscalar nucleon form factors. The first problem is that the ep data base is largely made up of 4 – 5% cross sections, although these are some more precise experiments. The second point is that the Platchkov data were used, with a Paris potential calculation plus calculated corrections, and the knowledge of G_{ep} , to extract G_{en} . These G_{en} values were the major input to the “MMD” fits¹⁰ to the nucleon form factors. The MMD form factor parameterization was then an input to these calculations. Thus, the logic is somewhat circular, as the Platchkov A data affect the input to the theoretical A calculations. However, the MMD parameterization

Figure 4. The data for $A(Q)$, compared to eight relativistic calculations. Left panels show the propagator and instant-form results: FSR (solid line), VDG in RIA approximation (long dashed line), ARW (medium dashed line), and PWDM (short dashed line). Right panels show the front-form CK (long dashed line) and LPS (short dashed line), the point-form AKP (medium dashed line) and the quark model calculation DB (solid line).

appears to get the isoscalar electric form factor about correct, slightly underestimating G_E^n and overestimating G_E^p . A refit to the proton and neutron data base, omitting the Platchkov G_{En} values, would be desirable.

Figure 4 compares seven relativistic calculations and one quark model calculation to the $A(Q)$ data. All of these calculations were done without the $\rho\pi\gamma$ meson-exchange current, which is not under good control, and but appears in modern calculations to have a negligible effect at low Q . The calculations include both propagator formulations and Hamiltonian dynamics (instant, point, and front form calculations), as well as a nonrelativistic quark model calculation. While there have been many investigations concerning the implications of pQCD and helicity conservation on the deuteron properties,

Table 1. The eight theories shown in Figures 1 and 4.

model	$J?$	A	B	t_{20}
Carbonell and Karmanov (CK) ¹¹ front-form, dynamical light front	no	Saclay	no	OK
Phillips, Wallace, Devine, and Mandelzweig (PWDM) ¹² propagator "equal-time"	no	low	no	OK
Allen, Klink, and Polyzou (AKP) ¹³ point form	no	Saclay	no	no
Van Orden, Devine, and Gross (VDG) ¹⁴ propagator, Gross equation	yes	Mainz	OK	OK
Lev, Pace, and Salmé (LPS) ¹⁵ front-form, fixed light front	no	Saclay	OK	no
Dijk and Bakker (DB) ¹⁶ nonrelativistic quark compound bag	yes	high	OK	OK
Forest, Schiavilla and Riska (FSR) ¹⁷ instant form, no v/c expansion	yes	Mainz	OK	OK
Arenhövel, Ritz and Wilbois (ARW) ¹⁸ instant form, v/c expansion	yes	Mainz	no	OK

we consider these limits to not be of concern here.

Table 2 summarizes the calculations, ordered by the Q^2 of the minimum for B . The column labelled J assesses which calculations have more complete currents ¹, while the columns labelled A , B , and t_{20} assess whether the agreement with these observables is good, though only up to about 1 GeV² for A . The more technically complete calculations tend to agree better with B and t_{20} than do the others, and they also favor the Mainz data rather than the Saclay data. Note that ARW calculation involves a v/c expansion which is suggested by the authors to not be valid much beyond 1 GeV.

Comparing the W16 and IIB models in Figure 3 with the VDG model in Figure 4, from which they come, indicates that the relativistic corrections are likely small. However, if we compare the nonrelativistic calculations to the data, it is not clear what to conclude about the size and sign of the relativistic corrections. If the Mainz data are correct, both the VDG and FSR calculations provide a good account of the full data set, and the ARW calculation is good over its claimed range. However, if the Saclay data are correct, it appears that *no* conventional calculation is entirely satisfactory.

We conclude that there are several hadronic theories that provide good qualitative agreement with the deuteron electromagnetic structure. It is possible that the agreement is actually as good as $\approx 2\%$, but problems in the ep and ed databases prevent this precise an assessment. There is no apparent

need to use anything but nucleon and meson degrees of freedom to understand the elastic scattering, and there is no satisfactory quark based model. Understanding A at low Q^2 is an often unnoticed but important issue.

3 Photodisintegration

The kinematics for photodisintegration and elastic scattering are actually quite different, despite similar beam energies; quark models may indeed be quite appropriate for photodisintegration. In elastic scattering, the energy and momentum transfer are matched so that in the deuteron rest frame $W = m$ independent of the beam energy or Q^2 . The two nucleon system is never far off shell, and there is little need to consider $\Delta\Delta$, quark, or other exotic components to the wave function.

In photodisintegration, $W \gg m_d$, and the two nucleon system is far off shell. As $E_\gamma \rightarrow 4$ GeV, all known baryon resonances can be excited off shell, and 286 distinct combinations of 2 on-shell known (four star) baryons occur. With the uncertainties in the baryon's masses, widths, decay channels, and interactions, and with the numerical problems inherent in such coupled channels calculation, one cannot be optimistic about the prospects for a microscopic hadronic theory. Quark degrees of freedom may provide an appropriate averaging over all the combinations of resonances.

The agreement of the best microscopic theory available with data starts to break down by $E_\gamma \approx 400$ MeV, just above the Δ resonance. Observables coming from imaginary interferences, such as p_y and T , appear more difficult to describe than real interferences, such as Σ and C_x , or sums of amplitudes squared, such as C_z and $d\sigma/d\Omega$. Figure 5 compares calculations to the asymmetry and p_y , both of which have extensive data sets. Conventional hadronic calculations by Schwamb and Arenhövel (SA) ¹⁹ and Kang *et al.* reproduce Σ at least qualitatively, but neither reproduces p_y well at all. The SA calculation is similarly detailed to the recent elastic scattering work; the Kang calculation is much simpler, except for including 17 well established resonances, and it reasonably reproduces the cross section up to 1.6 GeV.

Two quark model calculations, the QCD rescattering model ²¹ and the quark gluon string model ²² show reasonable agreement with the cross section above about 1 GeV. The QCD rescattering model relates the photodisintegration to nucleon nucleon scattering. It relies on the dominance of quark exchange diagrams at higher energies, and assumes the photon is absorbed on the exchanged quarks. The prediction that p_y is small at high energy appears correct. Estimates in this model of the polarization transfers are also qualitatively correct. The quark gluon string model ²² uses a Reggie genera-

Figure 5. Some photodisintegration polarization excitation functions at $\theta_{cm} = 90^\circ$, compared to theoretical calculations. Top panel: Kharkov data for the induced polarization p_y . There were experimental difficulties for the higher energy data sets. Middle panel: Other world data for p_y . Lower panel: Several data sets for the linearly polarized photon asymmetry Σ ; several other data sets with only a few points each were omitted.

ization of the nucleon exchange Born term. It is based on the dominance of planar graphs in QCD and has been applied successfully to other high energy reactions. Results from polarization calculations are expected soon.

We conclude that construction of a conventional microscopic hadronic calculation appears to be not possible in the near future. Promising quark models exist, with reasonable agreement with the high energy data – though certainly not the several percent agreement of elastic scattering. However, the models are not yet sufficiently tested to conclude that our understanding of high energy deuteron photodisintegration is satisfactory.

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