EXCLUSIVE NUCLEAR REACTIONS: CAN YOU COUNT ON THE DEUTERON?

ANL/CP--73704

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DE91 017321

ABSTRACT

Three of the simplest nuclear reactions - 1) electron-deuteron elastic scattering, 2) electro-disintegration of the deuteron near threshold and at high momentum transfer, and 3) photodisintegration of the deuteron at high energy - were believed to have unique signatures for QCD effects in nuclei. The progress in the past few years with regard to these reactions will be traced and the results will be compared with recent theoretical predictions.

INTRODUCTION

During the past decade there has been much speculation that electro-magnetic probes of the deuteron might first reveal the onset of QCD effects in nuclear reactions. Generally, this speculation was based on the fact that the deuteron is the simplest nucleus and the electromagnetic interaction is the best understood probe of the nucleus. In addition, since the deuteron contains the smallest number of quarks of any of the nuclei, then one might expect the onset of asymptotic scaling at achievable laboratory energies. I shall discuss three of the simplest nuclear reactions, electron-deuteron elastic scattering at high momentum transfer, electro-disintegration near threshold and at high-momentum transfer, and photodisintegration of the deuteron at high energy. In particular, new measurements of tensor polarization at MIT-Bates and analyzing power at Novosibirsk in electron-deuteron scattering will be discussed in light of recent advances in meson-exchange models. In addition, the energy and angular dependence for two-body deuteron photodisintegration at high energy will be discussed in view of data from SLAC.

ELECTRON-DEUTERON ELASTIC SCATTERING

The cross section for electron-deuteron elastic scattering is well known up to a very high momentum transfer. The differential cross section is given by the expression¹⁾

$$\frac{d\sigma}{d\Omega} = \sigma_M [A(Q^2) + B(Q^2) \tan^2(\frac{\theta}{2})]$$

where σ_M is the Mott cross section, θ is the electron scattering angle, Q is the four-momentum transfer, $A(Q^2)$ and $B(Q^2)$ are related to the monopole (G_C), quadrupole (G_Q), and magnetic (G_M) form factors of the deuteron by

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Fig. 1. Selected data and theoretical calculations for $A(Q^2)$ and $B(Q^2)$ for electron-deuteron elastic scattering. The three theoretical calculations were selected to give the best overall agreement for $A(Q^2)$, $B(Q^2)$ and T_{20} . The solid curve represents the calculations of Ref. 6, the dashed from Ref. 7 and dash-dot from Ref. 8.

$$A(Q^2) = G_C^2 + \frac{8}{9} \eta^2 G_Q^2 + \frac{2}{3} \eta G_M^2$$

$$B(Q^2) = \frac{4}{3} \eta (1 + \eta) G_M^2$$

where $\eta = Q^2/4M_d^2$ and M_d is the mass of the deuteron. Some selected measured values²⁻⁵⁾ for $A(Q^2)$ and $B(Q^2)$ are shown in Fig. 1. The most notable feature is that $B(Q^2)$ exhibits a second maximum near a momentum transfer of 2.5 (GeV/c)². This feature occurs naturally in a hadronic model of the deuteron, but would be very difficult to describe in terms of a quark model. The three curves shown in Fig. 1 represent the available theoretical calculations⁶⁻⁸⁾ which simultaneously give the best description of $A(Q^2)$, $B(Q^2)$ and T_{20} .

the tensor analyzing power. The calculations of Hummel and Tjon⁶⁾ and Chung et al.⁷⁾ are relativistic and use the Gari-Krumpelmann form factors of the nucleon. The calculation of Schiavilla and Riska⁸⁾ is nonrelativistic, explicitly includes the pair current and makes use of the Höhler form factors of the nucleon. All three calculations employ the Argonne V14 description of the deuteron. The tensor analyzing power T_{20} is given by

$$T_{20} = -\sqrt{2} [X(X+2) + Y/2] / [1+2(X^2+Y^2)]$$

in which

$$X = \frac{2}{3} \eta(G_Q/G_C), \quad Y = \frac{1}{3} \eta(G_M/G_C) .$$

Clearly, a measurement of T_{20} will permit the monopole and quadrupole form factors to be deduced.

Fig. 2. Schematic diagram of the experimental arrangement for measuring T_{20} with an internal polarized deuterium gas target in the VEPP-3 electron storage ring at Novosibirsk. The polarized atoms are injected into a windowless storage cell from an atomic beam source. Only one of the four pairs of electron and deuteron detectors are illustrated.

The recent tensor analyzing power⁹⁾ and polarization¹⁰⁾ measurements were performed at Novosibirsk and MIT-Bates, respectively. The experiment at Novosibirsk was a feasibility study conducted as a collaboration between Argonne and Novosibirsk for internal polarized targets in electron storage rings. In particular, a tensor polarized deuterium gas target was contained in a windowless storage cell in the 2-GeV VEPP-3 ring at Novosibirsk. A schematic diagram of the experiment apparatus is shown in Fig. 2. The storage cell consisted of a drifilm coated Al cell which is 94 cm in length and has an elliptical aperture to the electron beam

of 46 X 24 mm. A guide magnetic field is placed around the target to define the axis of quantization and to minimize depolarization induced by the time-varying magnetic field produced by high current pulses of electrons moving through the target. Polarized deuterium atoms from the Novosibirsk atomic beam source were injected into the storage cell. Four nearly identical pairs of electron and deuteron detectors were used to identify the elastic scattering events as described in more detail in Ref. 9. The results for T_{20} from this feasibility study are given by the darkened diamonds in Fig. 3.

Fig. 3. Results for T_{20} as a function of Q^2 . The diamonds represent the present results of the phase I internal target feasibility test at Novosibirsk, while open points represent new work from an experiment at Bates in which a recoil deuteron polarimeter was employed. The data at lower Q^2 is from Refs. 11 and 12. The (·-·) curve is the simple perturbative QCD model of Carlson, the dotted curve is from Sitarsky et al., while the remaining three curves are the same as those in Fig. 1.

Recent results¹⁰⁾ from an experiment at MIT-Bates are also shown in the figure as crosses. These data were obtained by detecting the tensor polarization t_{20} of the recoiling deuteron in a polarimeter. This experimental arrangement is shown schematically in Fig. 4. Here, the electrons from the Bates Linac impinge on a liquid deuterium target and the scattered electrons are detected in the OHIPS spectrometer, while the recoil deuterons are transported to the polarimeter by a QQDQQD system. The polarimeter is based on d-p elastic scattering and was calibrated at Saturne II.

Again in Fig. 3, the theoretical calculations⁶⁻⁸⁾ that simultaneously best describe $A(Q^2)$, $B(Q^2)$ and T_{20} are shown. It is clear that a recently proposed model¹³⁾ which is based on perturbative QCD and another¹⁴⁾ which has a high percentage of pre-existing deltas in the deuteron are ruled out by the present data.

These curves are given by the dash-dot and dotted curves in the figure.

In order to constrain the theoretical calculations further, it is essential to have improved T_{20} results at large momentum transfer and better nucleon form factors, especially G_{En} measurements. The latter quantity will be described at this Conference by P. Eosted. The ultimate goal of the Novosibirsk work is to produce the highest quality T_{20} data available. In particular, it is expected that the systematic error in the

Fig. 4. Schematic diagram of the experiment at MIT-Bates to measure t_{20} in e-d scattering where the polarization of the recoil deuterons is measured in the AHEAD polarimeter.

T_{20} measurements will be only ~5%, as achieved in the feasibility test in Novosibirsk. Since new detectors as well as new targets are required for the next phase of the Novosibirsk experiment, the T_{20} collaboration¹⁵⁾ has grown to include the NIKHEF, LNPI and Tomsk groups. The next phase of the Novosibirsk experiment will use a new target cell, which gives approximately a factor of 7 larger target thickness, should begin shortly.

The final phase of the internal target work involves replacing the Novosibirsk atomic beam source with the laser-driven source being developed at Argonne. This source is based on spin-exchange

optical pumping and the details have been described elsewhere.¹⁶⁾
If one defines the figure of merit F as

$$F = I_{inj} p_{zz}^2$$

where I_{inj} is the intensity of polarized atoms injected into the storage cell, then the present status of the laser-driven source is compared with the Novosibirsk source¹⁷⁾ in Table I.

TABLE I

Source	I_{inj} (s^{-1})	P_{zz}	F (s^{-1})
Atomic Beam Source (Novosibirsk)	5×10^{15}	0.95	4.5×10^{15}
Laser-Driven Source (ANL)	2.5×10^{17}	0.15	5.6×10^{15}
High-Field LDS (expected)	5×10^{17}	0.4	8.0×10^{16}

The presently achieved figure-of-merit for the laser-driven source is comparable with the atomic beam source. However, by operating the optical-pumping cell in a high magnetic field and using a Ti-Sapphire laser, it is expected to improve the figure-of-merit by more than an order of magnitude.

ELECTRODISINTEGRATION OF THE DEUTERON

Electrodisintegration of the deuteron near threshold and at high momentum transfer is widely believed to be a sensitive test of the short-range part of the deuteron wave function and meson-exchange currents. Although this reaction has many similarities to magnetic electron deuteron elastic scattering, it is an isovector rather than isoscalar process and it is far more sensitive to the relatively well-known isovector meson-exchange current.

In addition, it has been suggested^{18,19)} that this reaction would be a good test of the Hybrid Quark Hadron (HQH) model, a model in which the deuteron is described as a 6-quark cluster below $r = 1$ fm and the usual N-N interaction elsewhere. A characteristic of this model is the presence of a prominent second maximum above a momentum transfer of 1 (GeV/c)² as indicated by the curves of Cheng and Kisslinger¹⁸⁾ and Yamauchi et al.¹⁹⁾ in Fig. 5.

Two new experiments have been performed in the past few years to extend the data to well above 1 (GeV/c)^2 . Experiment NE4 at SLAC extended²⁰⁾ the data to more than 2.3 (GeV/c)^2 as shown by the square boxes in the figure. Clearly, there is a change in the slope of the data near 1 (GeV/c)^2 and this change of slope is supported by the preliminary Bates data,²¹⁾ the darkened circles in the figure, which will be reported by R. Miskimen at this Conference. The difference in the cross section between the SLAC and Bates data may be due to the better energy resolution in the Bates experiment, which permitted integration over only 3 MeV above the threshold rather than 10 MeV as in the SLAC data.

Fig. 5. Selected data for the $d(e, e')np$ reaction near threshold. The curves from Kisslinger et al. and Yamauchi et al. are the results of Hybrid Quark Hadron models, while the other curves are more conventional nonrelativistic calculations of Ref. 22.

Although the conventional models²²⁾ provide a better representation of the data than the HQH models, as indicated in the figure, none describe the data adequately. One of the obvious omissions from the present calculations is the lack of relativistic corrections. Before any detailed conclusions, a theoretical approach similar to that already employed for the electron-deuteron elastic scattering should be applied to electro-disintegration.

PHOTODISINTEGRATION OF THE DEUTERON

Results²³⁾ for the differential cross section at high energy were obtained from SLAC experiment NE8. The experiment involved focussing electrons from the SLAC NPAS injector in the energy range 0.8 to 1.8 GeV in steps of 0.2 GeV onto a Cu bremsstrahlung radiator. The photons from this process irradiated a liquid deuterium target and the photoprotons were momentum-analyzed in the 1.6-GeV spectrometer. A time-of-flight system and dE/dx detectors were used to identify protons. An aerogel Cerenkov detector was used to check that no pions were leaking through the particle identification system.

The preliminary results at a reaction angle of 90° and 114° are shown as the darkened points in Fig. 6 and compared with previous data as well as a meson-exchange calculation by T.-S. H. Lee.²⁴⁾ Results exist also at $\theta_{cm}=143^\circ$, but these results await collaboration²⁵⁾ approval before publication and are not shown here. The disagreement with the meson-exchange model prompted us to consider other energy dependences, e.g. that expected from constituent counting rules²⁶⁾ and the reduced nuclear amplitude analysis.²⁷⁾

Fig. 6. Preliminary cross sections from experiment NE8 at SLAC for the $\gamma d \rightarrow p n$ reaction are given by the solid points, the remaining data are from Ref. 28. The solid curves are predictions of T.-S. H. Lee.

A new meson-exchange calculation by the Bonn group was presented at the PANIC 90 meeting and their results are presented in Fig. 7 for 90° . In this calculation, Y. Kang et al.²⁹⁾ included all nucleon resonances with spin $\leq 5/2$. This very ambitious approach agrees better with the data as shown in the figure. One concern regarding this calculation is that the πNN cutoff was changed arbitrarily by 40% for photon energies above 700 MeV. This procedure can change the energy dependence remarkably and most likely accounts for the improved agreement of the energy dependence of the data. It is safe to say that no meson-exchange calculation can simultaneously explain the energy dependence of the cross section both above and below 1.0 GeV with a constant πNN cutoff.

CONSTITUENT COUNTING IN PHOTOREACTIONS

The application of the constituent counting rules has been very successful³⁰⁾ in describing the high-momentum transfer results for electron elastic scattering from the pion and the nucleons. These results are well known and lend support to the claim that asymptotic scaling has been achieved. While it is generally believed that the constituent counting rules can successfully describe the high momentum transfer results, there is disagreement regarding the underlying reason for their success. While S. Brodsky et al.³⁰⁾ argue that asymptotic scaling has been observed, N. Isgur³¹⁾ contends that this apparent scaling behavior is not founded in perturbative QCD.

Fig. 7. The cross section for the $\gamma d + pn$ reaction at $\theta_{cm} = 90^\circ$. The open circles are from experiment NE8 at SLAC. The solid curves represents the meson-exchange calculation of Y. Kang et al. and it includes nucleon resonances up to $J \leq 5/2$.

The constituent counting rules have met with great success in describing exclusive photoreactions at high photon energy. The most celebrated case³²⁾ is found in the $\gamma p \rightarrow \pi^+ n$ reaction at $\theta_{\text{cm}} = 90^\circ$. According to the constituent counting rules the differential cross section at a fixed center of mass angle is given by

$$\frac{d\sigma}{dt} \sim \frac{1}{s^{n-2}}$$

where s and t are the usual Mandelstam variables and n is the total number of constituents in the initial and final states. The success of these rules is shown clearly in Fig. 8. Above an s of 5 GeV^2 , the differential cross section has a $1/s^7$ dependence as expected.

It is not surprising that reactions involving only a single nucleon in the initial state can be described by quark degrees of freedom. However, for an initial state involving a nucleus it would be very surprising, since the quarks are believed to be confined to the hadrons and it would be very unlikely for all the quarks in the nucleus to occur in a very small region as implied by the constituent counting rules. Thus, it is very interesting to compare a photo-nuclear reaction to the asymptotic scaling prediction. Data for two-body photodisintegration of the deuteron were taken at SLAC (experiment NE8) at three angles (90° , 114° , and 143°) and in the energy range from 0.8 to 1.8 GeV. These results for 90° and 114° are plotted as $s^{11} d\sigma/dt$ as a function of E_γ in Fig. 9. At the highest energies the results are consistent with the expected $1/s^{11}$ dependence.

Fig. 8. The cross section for the $\gamma p \rightarrow \pi^+ n$ reaction at $\theta_{\text{cm}} = 90^\circ$. The cross section at high s is consistent with the s^{-7} dependence expected from constituent counting rules.

Fig. 9. $s^{11}d\sigma/dt$ for the $\gamma d \rightarrow pn$ reaction at $\theta_{cm}=90^\circ$ and 114° as a function of photon energy. The NE8 results are preliminary. The energy dependence of the data at the highest energies is remarkably consistent with the s^{-11} dependence expected from the constituent counting rules (dotted curve). The solid curves are the meson-exchange calculations of T.-S. H. Lee.

This is a very surprising result and at first appears to be at variance with the elastic electron-deuteron scattering data. After all, if we have not seen evidence for the onset of asymptotic scaling by a Q^2 of 4 GeV^2 in e-d scattering, why do the data near a photon energy of 1.5 GeV appear to be consistent with asymptotic scaling? The main problem is how to compare the two experiments on the same scale. The important scale is the momentum transferred to the individual quarks in the two reactions. For a matter of simplicity we will consider only the momentum transferred to the nucleons in the deuteron in the two cases. In the case of e-d scattering the average momentum transfer to a nucleon in the deuteron is just $(Q/2)^2$. It turns out that the magnitude of momentum transfer³³ to a nucleon in the deuteron in the photodisintegration process is approximately $2m_d T_d$. For the same momentum transfer to a nucleon in e-d scattering at $Q^2 = 4 \text{ (GeV/c)}^2$, the corresponding photon energy is 1.1 GeV in the photodisintegration process. Thus, the fact that the photodisintegration data are consistent with asymptotic scaling above a photon energy of 1.3 GeV is not inconsistent with existing electron-deuteron scattering data.

The main problem with making a strong conclusion regarding a consistency with the constituent counting rules is that the s-range of the consistency with the rules is rather small. It would be extremely desirable to extend the s-range and proposals³⁴⁾ have been submitted to SLAC and CEBAF as the only two avenues for extending the data to higher energy.

REDUCED NUCLEAR AMPLITUDES AND DEUTERON PHOTODISINTEGRATION

Brodsky and Chertok³⁵⁾ proposed that one could better see the onset of scaling in electron scattering from nuclei if the nucleon form factors were first removed from the cross section data. This approach represents a significant departure from conventional models of electron scattering. In the conventional picture the scattering amplitude for the impulse approximation depends on the product of the nucleon form factor and the body form factor of the nucleus. However, in the reduced nuclear amplitude model the scattering amplitude depends on the product of the nucleon form factors for each nucleon in the nucleus. This factorization has been shown to be valid in the limit that the nucleons are unbound, and it is argued that at very high momentum and energy transfers that binding effects are small.

Brodsky and Hiller²⁷⁾ have first applied the reduced nuclear amplitude analysis to two-body photodisintegration of the deuteron. At that time the highest energy data were at a photon energy of 1 GeV. The prediction for the differential cross section from this model is given by

$$\frac{d\sigma}{d\Omega} = \frac{1}{[s(s-M_d^2)]^{1/2}} F_p^2(t_p) F_n^2(t_n) f(\theta_{cm})^2 / p_T^2 \quad (1)$$

where the F_i are the nucleon form factors, $t_i = (p_i - p_d)^2$, and p_T is the transverse momentum.

Here $f(\theta)$ is the reduced nuclear amplitude that is expected to have no energy dependence where this model is valid. The results for $f^2(\theta)$ from experiment NE8 are given in Fig. 10. At an angle of 90° and 114° the data do not show a strong energy dependence for $f(\theta)$ at photon energies above 1 GeV. However, the results at 143° are in worse agreement with the model. Again, it is essential to extend these measurements to higher energy as a more stringent test of the model.

According to the Brodsky-Hiller model, the amplitude $f(\theta)$ should be peaked in the forward and backward directions. This prediction is based on the photodisintegration of a meson into a $q\bar{q}$ pair. One might argue that this is similar to the $\gamma d \rightarrow pn$ case since the nucleon form factors have been divided out and one is left with two point-like fermions in the reduced amplitudes. In particular, the diagrams that are considered by Brodsky and Hiller are shown in Fig. 11. The results in terms of the Mandelstam variables for massless constituents is given by

Fig. 10. The reduced nuclear amplitude $f^2(\theta)$ for the $\gamma d \rightarrow pn$ reaction at angles of $\theta_{cm}=90^\circ$ and 114° as a function of photon energy. The energy dependence appears to be in reasonable agreement with that expected by Brodsky and Hiller. The solid curves are the same calculations as those of Fig. 9.

$$f^2(\theta) = N \frac{(ue_1 + te_2)^2}{tu} \quad (2)$$

where N is an arbitrary normalization constant and the e_i are the strengths of the couplings of the photon to the quarks in the meson. This is clearly peaked in the forward and backward directions. Although the extracted $f(\theta)$ do not show a forward backward peaking, it is interesting to note that the measured angular distributions show an enhancement at large angles and high energy. For a photon energy of 1.5 GeV the preliminary cross section at 143° is twice that at 90° . Unfortunately, there is no forward angle data at high energy and it is the intent of the proposals submitted to SLAC and CEBAF to provide new data at not only high energy, but also forward angles.

A new meson-exchange calculation by Lee and Coester³⁶⁾ is based on light-front dynamics. This calculation can explain some of the backward enhancement, however, an arbitrary inelasticity must be added to the final state interaction for this purpose.

Fig. 11. Two of the QCD graphs used by Brodsky and Hiller to calculate the expected angular dependence of the reduced nuclear amplitude $f^2(\theta_{\text{cm}})$ for the $\gamma d+pn$ reaction.

It is very unlikely that a meson-exchange calculation will give the same amount of fore-aft enhancement that is predicted by Brodsky and Hiller. Even if we set $f^2(\theta) = 1$ in Eq. (1) so that the fore-aft peaking of Eq. (2) is ignored, the fore-aft peaking given by Eq. (1) is enormous and increases rapidly with energy. The prediction of Eq. (1) for $f^2(\theta) = 1$ and photon energies of 1.5, 2.5 and 4.0 GeV are shown in Fig. 12. Clearly, a strong forward or backward peaked angular distribution would be signature for this model. The new data from the experiments proposed at CEBAF and SLAC would resolve this issue.

Fig. 12. The angular distribution expected by Brodsky and Hiller for the $\gamma d+pn$ reaction according to Eq. (1) where $f^2(\theta_{\text{cm}}) \equiv 1$.

SUMMARY

The new T_{20} data for e-d scattering clearly constrain the nuclear models. Only a few of the numerous calculations are in reasonable agreement with $A(Q^2)$, $B(Q^2)$ and T_{20} . Further constraints will arise from better measurements of the nucleon form factors and better data for T_{20} . The quality of data for $A(Q^2)$ and $B(Q^2)$ are unprecedented in electron scattering. "Smoking gun" signatures for QCD in e-d scattering have been ruled out by the T_{20} data below 1 (GeV/c)².

Presently, there is evidence to suggest that both the constituent counting rules and the reduced nuclear amplitude model can give the energy dependence of the high energy $\gamma d + pn$ data. An extension of the measurement to higher photon energy is essential to eliminate at least one of these asymptotic models. The highest energy angular distribution for the $\gamma d + pn$ reaction appears to be enhanced at large angles. Angular distributions will be essential in order to further constrain the models, and further theoretical work on meson-exchange models will be essential in order to provide reliable predictions at high energy.

Finally, it appears that you can count on the deuteron in future experiments to give answers to specific questions.

ACKNOWLEDGEMENTS

I wish to thank J. Cameron and R. Miskimen for sending me their preliminary results for t_{20} and the cross sections for the $D(e, e')$ reaction, respectively. I wish to thank T.-S. H. Lee and F. Coester for permission to discuss their preliminary calculations and for many useful discussions.

I am especially grateful to the members of the electron-deuteron collaboration including K. P. Coulter, R. Gilman, E. R. Kinney, R. S. Kowalczyk, J. Napolitano, D. H. Potterveld, L. Young, and A. Zghiche at Argonne; S. I. Mishnev, D. M. Nikolenko, S. G. Popov, I. A. Rachek, A. B. Temhykh, D. K. Toporkov, E. P. Tsentalovich, and B. B. Wojtsekhowski at Novosibirsk; C. W. de Jager, G. Retzlaff, and H. de Vries at NIKHEF-K; S. Belostotsky, V. Nelubin, and V. Sulimov at Gatchina; and V. Stibunov at Tomsk.

Finally, I wish to express my sincere thanks to members of the SLAC NE8 collaboration including S. J. Freedman, D. F. Geesaman, R. Gilman, M. C. Green, H. E. Jackson, E. Kinney, R. Kowalczyk, C. Marchand, J. Napolitano, J. Nelson, and B. Zeidman at Argonne; D. Beck, G. Boyd, D. Collins, B. W. Filippone, J. Jourdan, R. D. McKeown, R. Milner, D. Potterveld, R. Walker, and C. Woodward at Caltech; R. E. Segel and T.-Y. Tung at Northwestern University; P. Bosted at American University/SLAC; Z.-E. Meziani at Stanford University; and R. Minehart at University of Virginia.

This work supported by the U. S. Department of Energy, Nuclear Physics Division, under contract W-31-109-ENG-38.

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