# Constraints on the $NN$ Interaction: Deductions from $^2H(\gamma,n)p$

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It is shown that low-energy deuteron photodisintegration data provide evidence that the traditional view of the $NN$ interaction mediated by the exchange of mesons between two almost-point nucleons breaks down for a separation distance of less than about 1.5 fm. The discrepancy can be remedied by a phenomenological modification of the theory in which the extended nature of the nucleon is explicitly recognized.

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It is well known that on-shell $NN$ scattering data and the experimentally observed deuteron properties have not been adequate in imposing constraints on the short and intermediate range of the $NN$ interaction. We have no unambiguous prescription for the short-range nonlocal effects, the meson-nucleon vertex functions under the off-shell conditions prevailing in a nucleus, and the treatment of the intermediate nonnucleonic, isobaric states; further, the contribution of the two-pion exchange to the intermediate range of the interaction is not definitive, based as it is on incomplete knowledge of the $N\bar{N}\rightarrow\pi\pi$ amplitudes.

On the other hand, recent developments in quantum chromodynamics[1] explain hadron spectroscopy in terms of confined quarks and gluons[2] and suggest the possibility that at short distances when two "nucleonic" quark bags overlap, there is an alternative scenario to the traditional one of the nuclear force mediated by mesonic exchange; instead, quark interchange and gluon exchange among quarks is suggested as the mechanism for the nuclear force. In this case, it may not be appropriate to describe the two-nucleon state as that of two point particles.

The analysis of low-energy $^2H(\gamma,n)p$ data presented here, while not supporting exclusively this new mechanism for strong interactions, does nevertheless suggest strongly that at least some aspects of the traditional model for the two-nucleon system, based on the solution of Schrödinger's equation for two point particles interacting by a nonzero range force, are not realistic.

We are concerned here with the total cross section of $^2H(\gamma,n)p$ for $E_\gamma < 100$ MeV.[3-5] The cross section in this energy region is dominated by $E1$ transitions to $P$ and $F$ partial waves while the $M1$ contribution is significant near the threshold only and the $E2$ begins to become measurable at the high end of this energy region.

The simplest calculation of the total cross section in time-dependent perturbation theory can be done under the following approximations: (a) employ the largest pieces of the impulse-approximation $E1$ and $M1$ operators in the long-wavelength limit; (b) neglect the $D$-state admixture in the deuteron while for the $S$ state employ its asymptotic form with a normalization corrected for the effective range of the interaction, e.g.,

$$U(r)=(2\gamma)^{1/2}[1-\gamma r_{0t}]^{-1/2}e^{-\gamma r}, \qquad (1)$$

where $\gamma=(M\epsilon_D)^{1/2}/\hbar$, $\epsilon_D$ is the binding energy; and $r_{0t}$ is the triplet-state effective range. (c) Neglect final-state interaction in the $S$ and $P$ waves; (d) neglect admixture of $F$ waves in the final state; (e) neglect mesonic-exchange currents, isobaric admixture, and relativistic effects. Then the $E1$ contribution to the total cross section is

$$\sigma(E1)=\frac{8\pi}{3}\left(\frac{e^2}{\hbar C}\right)\frac{1}{\gamma^2}\left(\frac{\gamma k}{\gamma^2+k^2}\right)^3\frac{1}{1-\gamma r_{0t}} \qquad (2)$$

and the $M1$ contribution is

$$\sigma(M1)=\frac{2\pi}{3}\left(\frac{e^2}{\hbar C}\right)\left(\frac{\hbar}{MC}\right)^2(\mu_p-\mu_n)^2\frac{\gamma k(1-\gamma a_s)^2}{(k^2+\gamma^2)(1+k^2a_s{}^2)}, \qquad (3)$$

where $a_s$ is the singlet scattering length.

Equations (2) and (3) are precisely the results one obtains in a dispersion analysis of $^2H(\gamma,n)p$, by keeping the deuteron and nucleon poles only in the intermediate state, in the zero-range approximation.[6] We shall therefore refer to the sum of Eqs. (2) and (3) as the "pole" term. Not surprisingly, the bulk of the total cross section is given by this term as seen in the inset in Fig. 1 where we compare the result from a more complete calculation, which we performed without approximations (b), (c), and (d), to the pole-term contribution.

In addition to being the major contribution to the total cross section, the pole term is the one contribution that we understand firmly, since it does not depend on the "shape" of the $NN$ force but depends only on the shape-independent parameters $\gamma$ and $r_{0t}$ which are in turn fixed by the very accurately known deuteron binding energy $\epsilon_D$, and the $n$-$p$ scattering length $a_t$; we recall that $\gamma = a_t^{-1} + \frac{1}{2}\gamma^2 r_{0t}$. Hence, for the purpose of extracting information on the shape of the $NN$ force and the nature of the $NN$ theory, we must look for deviations from the pole term.

It is for this reason that we plot in Fig. 1 the ratio $\sigma/\sigma_{\rm pole}$ [curves $Y$, $A(R)$, $Y$(MEC), $A(N)$, $H(E1+M1)$, $P$, SSSC, SSCA] where $\sigma$ is the full calculation of the total cross section done by us and other authors[4,13,14] and $\sigma_{\rm pole}$ is the sum of Eqs. (2) and (3). The ratio remains significantly close to 1.

We should also remark that $\gamma$ and $r_{0t}$ fix the $S$-wave part of the $NN$ theory for $r > 2.5$ fm and hence, we are constrained not to alter the theory in the long-range region. Further, most $NN$ models reproduce the shape-independent parameters, and for the purpose of further discussion it is sufficient to consider only the eight theoretical curves in Fig. 1. The results of other theoretical calculations fall within the band defined by these eight curves.

Our own calculation, marked $H(E1+M1)$, is the ratio of the two results shown in the inset; we have used the potential of Lassila *et al.*[15] Curve $Y$ is the calculation of Ref. 13 also with the hard-core Yale potential of Ref. 15 and curve $Y$(MEC) is the modification of $Y$ due to effects of mesonic-exchange currents on the $E1$ and $M1$ transitions. Curves $A(N)$ and $A(R)$ are the calculations in Ref. 4 without ($N$) and with ($R$) the inclusion of isobars in the deuteron; this calculation as well as curve $P$ calculated in Ref. 14 has used the Hamada-Johnston potential.[16] The disagreement between curves $A(N)$ and $P$ and between $A(N)$ and $Y$ has no obvious explanation, but it is not critical for the purposes of our analysis. The $NN$ models used in the above calculations feature 6–7% $D$-state admixture in the deuteron. We have included two results[13] identified by SSSC and SSCA in Fig. 1, obtained with supersoft core potentials[17] and $D$-state ad-

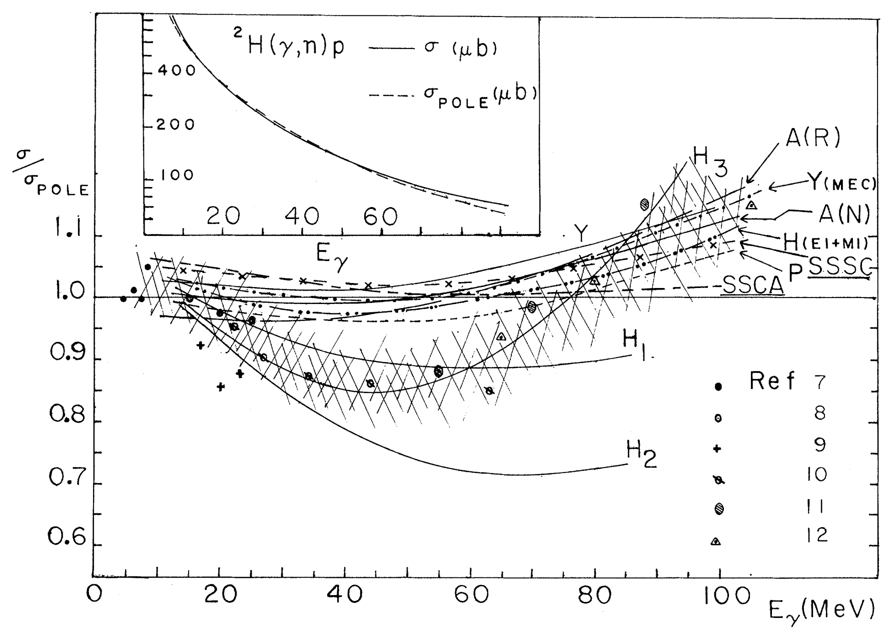


FIG. 1. Inset, total cross section for $^2$H($\gamma$, $n$)$p$. Solid line, result of a full calculation in the $E1+M1$ approximation. Dashed line, pole term. The eight curves marked $Y$, $A(R)$, $Y$(MEC), $A(N)$, $H(E1+M1)$, $P$, SSCA, and SSSC, as well as curves $H_1$, $H_2$, and $H_3$ are the results of theoretical calculations as explained in the text. The experimental points are from Refs. 7–12.

mixture of 5.45% and 4.43%, respectively. Final-state interactions are taken fully into account in all these calculations and all the $n$-$p$ scattering partial waves necessitated by $E1$, $M1$, and higher multipole transitions, are included.

We note that the eight theoretical curves define a band whose width may be considered a measure of theoretical uncertainty in the calculation of $^2$H($\gamma$,$n$)$p$ employing the traditional $n$-$p$ model.

In Fig. 1 we show also experimental points, $\sigma_T^{\mathrm{exp}}/\sigma_{\mathrm{pole}}$, from six different experiments on $^2$H($\gamma$,$n$)$p$.[7-12] We have included data which, we have reasons to believe, are most reliable. A full account of the experimental situation will be published elsewhere.[18] The cross-hatched band guides the eye along the experimental points and has a width of approximately (±) 2 standard deviations.

There is a striking qualitative difference between theory and experiment. The theoretical and experimental bands cross at 10 MeV and again in the region of 80–90 MeV, but their respective slopes are very different at these points and they differ by about 15% at 50 MeV, or approximately 4 standard deviations, while the overall uncertainty of the data, except that of Ref. 9, is about 4%. The data points from Ref. 9 have an overall normalization uncertainty of about 7%; they have been included in Fig. 1 because they enhance the definition of the slope in the low-energy region.

There seems to be no known change in the characteristics of the $NN$ theory, within the framework of the two (pointlike) nucleon picture, that may eliminate the discrepancy. Large changes in the strength of the core and the $D$-state admixture are not effective as seen by noting that both curve $Y$ and curve SSCA are fundamentally different from the experimental band. Meson-exchange currents (MEC) are equally ineffective as seen by comparing the data with $Y$(MEC). In this latter we have included contributions to $E1$ and $M1$ operators from all the important two-body diagrams.[5] Our current understanding of MEC[19] leaves little latitude for additional changes. The largest MEC effects are in the current density which affects the $M1$ operator. The $M1$ transition, however, is important only very close to the threshold. Hence, the total MEC contribution to $\sigma$ is rather moderate in the region under consideration as seen by comparing $Y$ and $Y$(MEC).

Given that the long-range part of the $NN$ theory is experimentally fixed as discussed earlier, it appears necessary to investigate the inner region, $r < 2.0$ fm, for an explanation of the discrepancy displayed in Fig. 1. If we abandon momentarily the traditional view of the nucleonic deuteron, and admit a quark-bag structure for each of the two nucleons of radius close to 1.0 fm, we would expect that at a separation distance of about 1.5 fm the two bags overlap sufficiently to have lost their separate identity. Hence, within this distance, the deuteron can no longer be described by $S$ and $D$ partial wave solutions of the Schrödinger equation for two point nucleons.

A crude way to test this speculation is to "punch" a hole in the two-nucleon $S$ and $D$ states of the deuteron at a radius between 1 and 2 fm without changing the overall normalization, thus leaving the outer region intact and allowing at the same time for admixture of nonnucleonic deuteron states. Indeed a hole at $r = 1.22$ fm—this is in effect a hole in the transition charge and magnetic matrix elements—produces a theoretical cross section represented by curve $H_1$ in Fig. 1, while a hole at $r = 1.57$ fm produces curve $H_2$. We note that the slope of $H_1$ follows extremely well the experimental band up to $E_\gamma \approx 55$ MeV, while $H_2$ deviates from it quickly showing that in this case we have drained too much strength from the deuteron wave function.

For the purpose of supplying crudely the intermediate range effects missing from $H_2$, we undertake the following exercise. We assume that for $0 \le r \le 1.57$ fm the deuteron is described by a radial function

$$U(r) = N_s'(e^{-\gamma r} - e^{-\alpha r}) \qquad (4)$$

($N_s' = 1.06$ fm$^{-1/2}$, $\alpha = 1.0$ fm$^{-1}$) representing a nonnucleonic state with the parameters $N_s'$ and $\alpha$ chosen so that it contributes approximately 20% to the deuteron wave function; it is further assumed that this state allows $E1$-like transitions to the final $n$-$p$ partial waves but that these transitions are not coherent to the $E1$ transitions from the $S$ and $D$ waves of the two-nucleon deuteron ($r > 1.57$ fm). This becomes possible in the quark-bag model, for example, if one or more of the quark configurations admixed in the deuteron[20] build up their strength in the short and intermediate range. By adding incoherently this contribution to the cross section from the region $r < 1.57$ to that from the nucleonic deuteron ($r > 1.57$ fm), we obtain curve $H_3$ which shows a remarkable qualitative agreement with the experimental band. The change from $H_2$ to $H_3$ is foremost an intermediate-range effect, e.g., $1.0 \le r \lesssim 1.57$ fm.

If we changed $N_s'$ and $\alpha$, we would shift $H_3$ up or down but it is crucial that its shape would not change. We must emphasize that what we have done is not to continue the nucleonic deuteron from $r = 1.57$ fm to the origin via Eq. (4); this would have produced results within the theoretical band in Fig. 1. Instead, we have admitted a novel state for the deuteron in this region, whose character is not specified here but is not in disagreement with the picture of two overlapping bags each of radius close to 1 fm.

In conclusion, our objective in this work is twofold. First, we demonstrate that the traditional picture of a meson-mediated interaction between two pointlike nucleons valid at all separation distances is not sufficient to explain low-energy data on deuteron photodisintegration. This is true independently of the details of the *NN* model. Second, we show that the discrepancy with the experimental data can be resolved if we assume that the two-nucleon description of the deuteron ceases to be valid in the range from the origin to some point between 1.2 and 1.6 fm. This is in agreement with results emerging from some recent work on quark-bag descriptions of the two-body system.[1]

It appears to us that the nature of the *NN* system at intermediate as well as short range must come under intense scrutiny.

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