Implications of forward photodisintegration for the deuteron D state and the N-N interaction

M. E. Schulze,* D. P. Saylor, and R. Goloskie
Department of Physics, Worcester Polytechnic Institute, Worcester, Massachusetts 01609
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It is shown that the data on forward photodisintegration is consistent with the value of 0.0203 ± 0.0006 fm$^{-1/2}$ for the asymptotic D state amplitude and a value of the pion-nucleon coupling constant of 0.075 ± 0.004, where the latter is in good agreement with other determinations. This value of A_d is consistent with a value suggested by nucleon-nucleon scattering data but apparently inconsistent with the traditional value derived from fitting the measured quadrupole moment.

[NUCLEAR REACTIONS $d(\gamma,p)n$ data compared with model predictions. Deduced deuteron D-state wave function at large r.]

INTRODUCTION

Several authors[1-4] have compared the cross section for forward photodisintegration of the deuteron[4] with calculations based on "realistic" potential models. The generally expressed opinion is that the comparison between theory and experiment may be interpreted as indicating that the 6.5–7% D states of the Reid soft core[5] (RSC) and Hamada Johnston[6] (HJ) deuterons are unrealistically large.

Our purpose is to make use of these theoretical and experimental results in order to make a quantitive statement as to how big the D state would have to be in order to fit the data. The key to achieving this result is to recognize that the D state contribution to low energy photodisintegration is determined by two quantities, the asymptotic D wave normalization A_d, which determines the size of the D state at extremely larger r, and the strength of the one pion tensor force (measured by f^2), which determines how the D state wave function of $w(r)$ bends down from its asymptotic form,

$$W(r) \xrightarrow[r\to\infty]{} A_d e^{-\gamma r}[1+3/(\gamma r)+3/(\gamma r)^2] , \qquad (1)$$

as r decreases with "the range of nuclear forces."

The models we shall use are the HJ and RSC potentials and three Feshbach-Lomon boundary condition models[7] designated FL(Pd) where Pd is the D-state percentage.

The calculations we shall employ were made according to the theory as described by Partovi.[8] Partovi's paper establishes the formalism and is also useful because it gives tables which allow one to answer questions about the relative contribution of the various terms to the final result. Also very useful is the basic paper of de Swart and Marshak[9] which is restricted to the most important term, the $E1$ terms computed with the Seigert operator. Their analysis of this single most important contribution allows one to establish the sensitivity of the final result to model parameters such as the ^3P phase shifts.

One of the chief conclusions reached by de Swart[10] in his work is that low energy photodisintegration is expected to be sensitive to asymptotic parameters including the phase shifts and the deuteron asymptotic normalization and, in contrast, to be quite insensitive to the idosyncracies of model wave functions within the range of nuclear forces. His view was that deuteron photodisintegration data should serve as a test of the validity of asymptotic parameters and as a source of further information about asymptotic parameters that are not so well determined by nucleon-nucleon scattering data.

Traditionally, it has been believed that exchange currents are of minor importance in the theory of low energy photodisintegration. This view was held because the calculation depends mainly on the part of the wave function beyond the range of nuclear forces and the most important contributions are those Siegert terms which depend on charge rather than current. These charge terms are expected to be insensitive to particular mesonic effects.

In recent years, however, there has developed substantial interest in mesonic corrections. Explicit calculations[11,12] have been made of the correction to the zero degree cross section based on the version of the theory in which these corrections are largest. These corrections would be of marginal importance, but there are reasons to believe[13] that this version is not the appropriate one. Whichever version is correct, known exchange current effects remain refinements of negligible or marginal significance on a scale determined by the current experimental error, and the expectation that low energy deuteron photodisintegration depends on asymptotic quantities remains valid within the context of nuclear theory as it has developed. One would expect that the predictions of theory would be accurate to a very few percent assuming that the model used reproduces the asymptotic parameters reasonably accurately.

The appropriate way to proceed is to identify those asymptotic parameters which may contribute to the discrepancy and then proceed from there. Using the tables and formulas in de Swart and Partovi, one can easily make estimates of the sensitivity of the zero degree cross section to the various asymptotic parameters on which it depends. For 22 MeV the various asymptotic parameters can be classified into three groups on the basis of their sensitivity. The first, most sensitive group consists only of A_d. A 10% change in this parameter can produce about a 20% change in the cross section. The second, less sensitive group consists of the three ^3P phase shifts and the s-state asymptotic amplitude A_s. A 10% change in these parameters produces about a 1% change in the predicted cross section. The third, least sensitive group contains all of the rest for which one need not make an estimate of sensitivity.

If one is going to attribute the discrepancy between theory and experiment in this case to asymptotic quantities, that quantity must be A_d. It is appropriate that this point should be given emphasis: If the disagreement between theory and experiment in forward photodisintegration is to be resolved by changing an asymptotic parameter, that will have to be a 15% reduction of A_d from the value 0.0235 fm^{-1} characteristic of those models which have a quadrupole moment Q of about 0.286 fm^2 and which predict model cross sections which are too large as compared with experiment by about 30%. This rough estimate essentially anticipates our final result.

Now we will turn to the question of the remarkable sensitivity of the higher energy photodisintegration predictions to the precise value of f^2 assumed in the models. In going from the FL(4.58) to the RSC to the FL(5.20), A_d increases monotonically from 0.0228 to 0.0230 to 0.0232. Based on the expected sensitivity to the on-shell parameters, we expected the predictions of the two FL models to bracket the RSC prediction. This is not the case as one can see by referring the Table I. The reason was not immediately apparent to us. Also, the RSC wave function has a D-state percentage of 6.46% rather than the 5% one might have guessed on the basis of the FL models. It eventually became apparent that the reason for these differences is that the RSC has an one-pion exchange potential (OPEP) tensor force coupling between the S and D states which is 9% weaker than the FL models. For the initial D state, this is very significant.

TABLE I. Experimental results and model experiments.

E_γ (MeV)	Exp.	FL(4.58)	$d/d\Omega$(μb/sr) FL(5.2)	FL(7.53)	HJ	Reid	Parametric
24±3	5.20±0.35	6.18	6.37	6.7	6.7	6.35	5.27
33±3	5.60±0.30	6.5	6.8	7.27	7.15	6.75	5.16
42±3	4.70±0.25	6.67	6.83	7.5	7.25	6.98	5.17
77±6	4.4 ±0.3	5.7	6.05	6.75	6.7	6.7	4.41
102±8	4.2±0.3	4.85	5.25	5.9	6.12	6.25	3.94
122±0.25	3.7±0.25	4.3	4.60	5.25	5.82	6.02	3.86

ANALYSIS

In order to refine our estimate of the proper value of A_d, it is necessary to have a model of the dependence of the cross section on the asymptotic parameters based on rather broad theoretical considerations. To this end we have focused our attention on the $E1$ matrix elements, for they are the most important terms by far. According to the theoretical framework[8–10] this matrix element is proportional to

$$\langle E1\rangle \alpha \int_0^\infty rv(r)w(r)dr \ , \qquad (2)$$

where v/r and w/r are the final ^3P and initial ^3D radial wave functions. Because we expect that $v(r)$ behaves like r^2 for small (but not too small) r the integrand in Eq. (2) should behave as $r^3w(r)$ making short range contributions insignificant. For the ^3F final state wave function, which we have ignored so far, the short range contributions would be even less significant. We, therefore, expect that these matrix elements will depend almost linearly on A_d in the low energy region, an observation consistent with the analysis of de Swart.[10]

The higher energy dependence of the cross section on f^2 is understandable from an investigation of the contributions to $E1$ from the one pion exchange region, near 1.7 fm. These contributions become progressively more important as the photon energy increases. In this region, the D state deviates from its asymptotic form primarily because of the tensor coupling of the D state to the S state leading to the conclusion that this deviation should be proportional to the product of f^2 and A_s. To emphasize this last statement, we show in Fig. 1 the behavior of three different D state functions computed with the HJ potential. The first wave function w_0 has a D state which vanishes asymptotically and an S state asymptotic to $A_s e^{-\gamma r}$. w_0 grows from S state through the tensor coupling force and will be approximately linearly dependent on the product of A_s and f^2 until the S state (not shown) deviates appreciably from its asymptotic form. The second D state function w_2 has an S state which vanishes asymptotically and a D state which is asymptotic to Eq. (1). The value of this function at any point is linearly dependent on the value of A_d. The dependence of this function on f^2 is significant only at small radii because the S state, asymptotically zero, is small into the one pion region and its effect on the D state is minimal. We observe in Fig. 1 that w_2 remains close to its asymptotic form in this region of r.

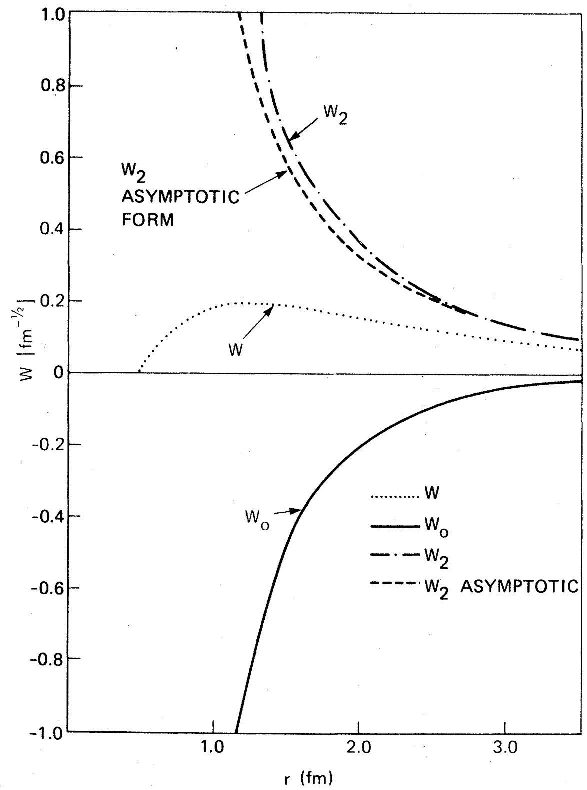

FIG. 1. d states of solutions for the HJ potential corresponding to the following asymptotic boundary conditions: (1) for W_0, $u \rightarrow A_s e^{-\gamma r}$, and $W \rightarrow 0$; (2) for W_2, $u \rightarrow 0$, and $W \rightarrow A_d e^{-\gamma r}$; (3) for W, $u \rightarrow A_s e^{-\gamma r}$, and $W \rightarrow A_d e^{-\gamma r}$; (4) for W_2 asymptotic, same as (2) with no potential.

The third D state function w is the standard HJ model D state and is the sum of w_0 and w_2. Because the former is closely proportional to f^2 in the one pion range and the latter is linearly dependent on A_d almost exclusively in this region, the $E1$ matrix elements each may be written as a sum of two terms, one proportional to A_d and the other proportional to f^2.

In our analysis, A_s is treated as a known constant rather than a variable. The present knowledge of the binding energy and the ground state effective range determine this quantity to a few tenths of a percent under very general considerations. Also, its role is of a secondary importance in forward breakup of the deuteron.

The final state functions v are independent of A_d, of course, and their contributions to the $E1$ matrix elements are much less dependent on f^2 than the w functions for several reasons. The important v

functions are not a small component coupled by means of the tensor force to a large component as is the w function. Secondly, the long range tensor coupling term is weaker by a factor of 3. Finally, with positive kinetic energy scattering solutions the potentials are relatively less important in determining the development of the wave function than for the bound case.

Because the zero degree cross section is a sum of the absolute squares of such matrix elements, we find that the cross section is primarily a function of A_d^2. Alternatively, the square root of the cross section is nearly a linear function of A_d. Thus, we may expect to reproduce faithfully the important features of the A_d and f^2 dependence of the square root of the zero degree cross section by an expansion retaining only first order terms in these parameters. That is,

$$\sigma^{1/2}=aA_d+b(f^2-f_{\rm FL}^2)+c \ . \tag{3}$$

For convenience, we have chosen to expand about the values

$$A_d=0 \text{ and } f^2=f_{\rm FL}^2 \ ,$$

where $f_{\rm FL}^2$ is the FL value of the pion coupling constant.

For our analysis to be valid, the important final states should be identical for different models. This condition is well approximated generally, and is exactly so for the three FL models.

We have repeated the analysis for other parametrizations of the forward photodisintegration cross section in terms of A_d and f^2. In all cases, the results have been very similar.

In Fig. 2, we show the predicted values of the square root of the cross section for forward photodisintegration as a function of variable A_d. As predicted, the three FL points on each graph show nearly linear behavior of the square root of the cross section versus A_d. For comparison, the HJ and RSC predictions from the work of Arenhövel

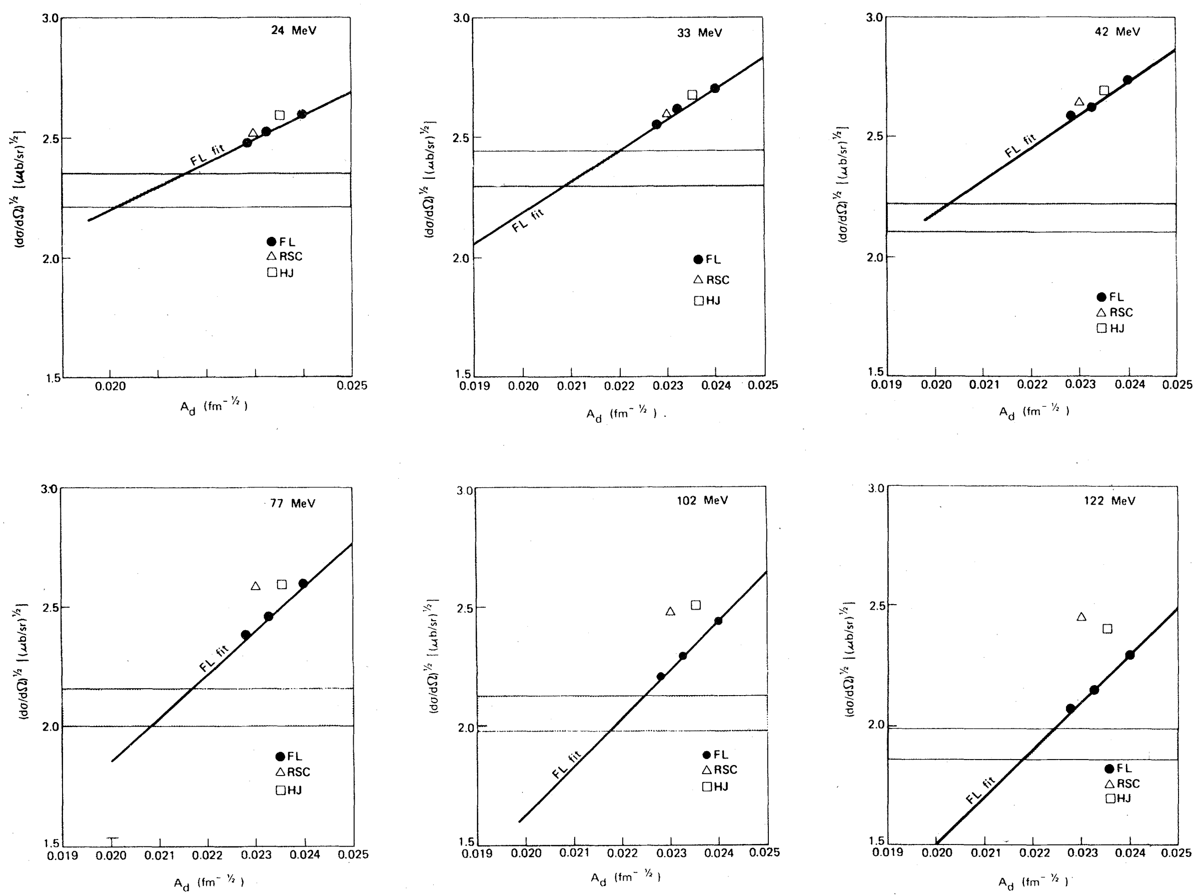

FIG. 2. The square root of the differential cross section for forward photodisintegration vs model d-state asymptotic amplitude. The line is the "best" fit to the FL model data.

TABLE II. Some important constants of the models.

Model	$A_d(f_m^{-1/2})$	g^2	f^2	M_π (MeV)	A_s $(f_m^{-1/2})$	Q (f_m^2)
HJ	0.02354	(14.5)	0.080	139.4	0.8853	0.285
RSC	0.023	14.0	(0.0757)	138.13	0.87758	0.280
FL(4.58)	0.02284	14.94	(0.0807)	137.98	0.886	0.272
FL(5.20)	0.02325	14.94	(0.0807)	137.98	0.886	0.277
FL(7.53)	0.024	14.94	(0.0807)	137.98	0.886	0.289
Parametric Model	0.0203±0.0006		0.075±0.004			

and Fabian are included.

The measured and model cross sections are given in Table I and some of the characteristics of the potential models are tabulated in Table II. Note that there are differences between the values of the coupling constant and the pion masses.

At the three lowest energies, the predictions are nearly model independent except for the dependence on A_d. At the higher energies there are differences between the models which we attribute primarily to the differences in the values of f^2 and the pion masses in these models. As expected, these differences grow in importance as the photon energy increases and forces of one pion range become more important. The differences in the final state wave functions are assumed negligible because the ^3P phase shifts are small so that the differences in the final state wave function will be very small, particularly in the region of the large r. In this regard, the three FL models are especially helpful because the important final states are unchanged from model to model.

At the three higher energies, the forces of one pion range became significant. This trend increases the differences between HJ, RSC, and FL, all of which have different values.

The first step in our analysis has been to determine a and c from the three FL calculations at each energy by linear regression. Then, the value of b at each energy is found by minimizing the square of the differences of the model predictions of HJ or RSC with the FL parametric fit at the correspondence value of A_d. The constants a, b, and c are tabulated in Table III and the parametric model predictions from these are shown in Table I.

Before the value of b is determined, the pion-nucleon coupling constants used for the HJ and RSC models were adjusted for the slight differences of the masses and S state asymptotic amplitudes used relative to the FL values by the rather arbitrary prescription which describes fairly precisely the effect of small changes in these parameters on the intermediate range D state function

$$f_{\text{eff}}^2 = f^2 \frac{m_\pi^2 M_{\text{FL}}^2 A_s}{m_{\pi_{\text{FL}}}^2 M^2 A_{s_{\text{FL}}}} . \tag{4}$$

Also listed in Table III are the values of A_d needed to bring each model into agreement with experiment where the differences in f^2 are ignored. We note that at the three lower energies, these values of A_d are almost identical for all three models. The differences at the higher energies can be attributed to the differences in f^2 for the three models. The value of A_d adopted is the weighted average of the three lowest energy values

TABLE III. Parametric fit constants for model predictions and A_d values from extrapolation to the measured values.

Energy (MeV)	a	b	c	A_d intercept FL	RSC	$(\text{fm}^{-1/2})$ HJ	±
24	88.06	−5.317	0.4753	0.020 50	0.020 28	0.020 04	0.000 87
33	125.6	−5.934	−0.3145	0.021 36	0.021 15	0.021 09	0.000 51
42	138.4	−8.638	−0.5900	0.019 93	0.019 58	0.019 75	0.000 42
77	181.9	−29.99	−1.769	0.021 26	0.020 30	0.020 84	0.000 39
102	194.0	−46.52	−2.225	0.020 03	0.020 68	0.021 35	0.000 38
122	188.6	−64.23	−2.236	0.022 05	0.020 19	0.020 95	0.000 34

$$A_d = 0.0203 \pm 0.0006 \text{ fm}^{-1/2} \, . \qquad (5)$$

The uncertainty quoted is the rms deviation of these three values.

Once the value of A_d is chosen, one can obtain a value of f^2 at each energy that best reproduces the data. These are shown in Fig. 3. As expected, the value of f^2 is poorly determined at the three lowest energies because the model predictions are relatively insensitive to forces on one pion range. The three higher energy values for f^2 are consistent with one another and are well determined. The value adopted in Table III for f^2 is the value determined at 77 MeV. This is the lowest energy at which a satisfactory determination of f^2 was obtained. This value will be least affected by high order terms arising from the short range behavior of the wave functions. Thus, we adopt the conservative value

$$f^2 = 0.075 \pm 0.004 \, . \qquad (6)$$

Our analysis has not considered the uncertainties in the values of the model predictions resulting from the fact that the data was presented in graphical form and was not available in tabular form. The errors depend mainly on the differences between the model predictions which can be read to the level of about a percent.

The experimental data and the model predictions are displayed in Fig. 4. The two parameter fit using the values of A_d and f^2 obtained in this work is also included and is in good agreement with the six data points.

A slightly lower value of A_d implies a considerably lower value for the D state percentage. Our experience with models using an OPEP potential

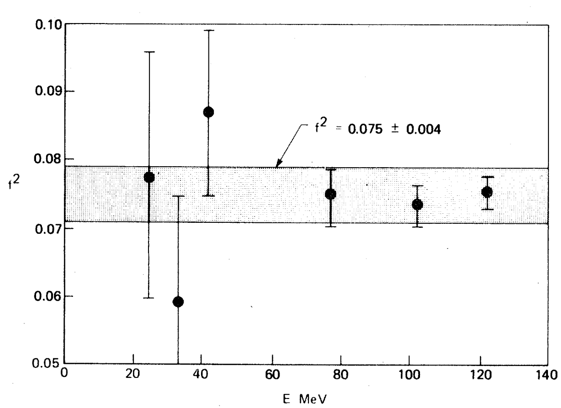

FIG. 3. Measured value of f^2 vs photon lab energy.

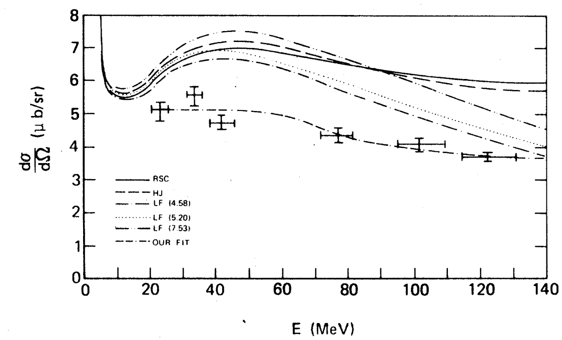

FIG. 4. Differential scattering cross section for forward photodisintegration vs photon lab energy.

significantly modified only at short range ($r \lesssim 1.5$ fm) in order to produce $A_d \sim 0.020 \text{ fm}^{-1}$ have consistently produced D state percentages within the range from 2.5–3.5 %.

OTHER ESTIMATES OF A_d

There exist other values of A_d and other measurements sensitive to A_d or the ratio of A_d to A_s, η. For a quantity to be considered to represent a measurement of A_d or η, there must be substantial evidence that the poorly understood intermediate and short range effects are disentangled. On this basis, we discount the claims of Conzett *et al.*[14] and Grüebler *et al.*[15] who attempt to determine η by means of pole extrapolation based on a Legendre series approximation to a function of the cross section, energy, tensor analyzing power, and scattering angle suggested on theoretical grounds. In order to claim to have removed the "inside" effects, their sequence of values for η must converge to a stationary value. There is essentially no evidence for such convergence. Colby and Haeberli[16] have shown that the experimental precision is insufficient to determine the higher order necessary for convergence.

In our opinion, the analysis of these experiments relies on isolating the contribution to a stripping reaction from a region in which the ratio $w(r)/u(r)$ is close to its asymptotic value, η. For this to be true $w(r)$ must be very close to $A_d e^{-\alpha r}$. In the region beyond the range of OPEP we can also write

$$w(r) = A_d(1 + 3/(\alpha r) + 3/(\alpha r))^2)e^{-\alpha r} \, .$$

Hence, if the ratio $w(r)/u(r)$ is to be within 10%

of η, r must be so large that

$$3/(\alpha r)=0.1$$

or

$$\alpha r=30 \ .$$

The factor $e^{-\alpha r}$ is then e^{-30}, which is small enough to guarantee that the contribution of this region is negligible in any practical experiment. The derivation of a reasonable value of η by this method should be viewed as fortuitous, spurious, and misleading.

Recently, Stephenson and Haeberli[17] have quoted a value for η obtained from the tensor analyzing power of the $^{208}Pb(d,p)^{209}Pb$ reaction at sub-Coulomb energies. The value of η they reported is not to be taken as a final value because the analysis did not take into account a number of corrections. As mentioned in Ref. 17, some of the corrections are expected to be as large as 5%, so that a reduction of their final value by some 10% is certainly a possibility. When these theoretical questions have been resolved in a satisfactory manner, the method of sub-Coulomb stripping may well yield a value of η with a precision comparable to the value from forward photodisintegration of the deuteron.

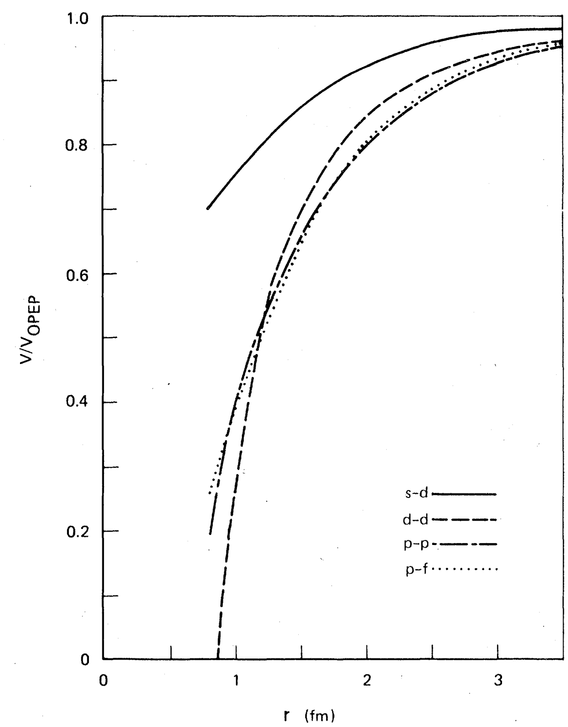

FIG. 5. Radial dependence of the equivalent tensor force between states of definite angular momentum. See text for details.

η ON THE BASIS OF NUCLEAR FORCE PHENOMONOLOGY

In searching for other evidence which might tie in with our result $\eta=0.023$, rather than the traditional value of 0.026, we came across an interesting characteristic of the phonomenological tensor force which is well exemplified by the HJ potential. To demonstrate this feature, we eliminate the quadratic spin-orbit operator and write the HJ potential in the form

$$V=V_c+V_tS_{12}+F_{LS}\vec{L}\cdot\vec{S} \qquad (7)$$

thereby defining the tensor potential V_t. For the HJ potential, the V_t's so defined are explicitly dependent on the orbital angular momentum. We define $V_t^{d\text{-}d}$ as its component between D states, $V_t^{s\text{-}d}$ as its component connecting S and D states, etc. In order to show the deviation of these tensor forces from the OPEP value, we plot the ratio of V_t to the OPEP value in Fig. 5. Clearly, the curves for D-D, P-P, and P-F, are very close to each other, and it is reasonable to say that they are sensibly the same. However, the S-D curve is distinctly different. In the context of the present paper, this pattern has an obvious interpretation as follows. Hamada and Johnston assumed, in accord with the conventional wisdom of the time, that the experimental quandrupole moment was equivalent to an accurate measurement of A_d or η and that

$$Q=Q_{\text{impulse}}=(\tfrac{1}{50})^{1/2}\int_0^\infty (uw-w^2/\sqrt{8})r^2dr \ . \qquad (8)$$

An implication of recent work on mesonic corrections[18] to Q is that the relation assumed by Hamada and Johnston is not precisely valid. In order to achieve a fit to Q assuming $Q=Q_{\text{impulse}}$, they were forced to have a value of η 15% larger than its "actual" value and in order to accomplish this they were forced in the model to have a tensor force coupling the S and D states which is stronger than the actual force.

It is reasonable to speculate that the actual tensor force is a pure isovector exchange force such as π exchange or a mixture of π exchange and ρ exchange. Thus,

$$V_t^{s\text{-}d}=V_t^{d\text{-}d}=\tau_1\cdot\tau_2V_t=-3V_t \ , \qquad (9)$$

$$V_t^{p\text{-}f}=V_t^{p\text{-}p}=\tau_1\cdot\tau_2V_t=V_t \ , \qquad (10)$$

where V_t is state independent. Because η is very insensitive to the short range phenomonology ($r \leq 1$ fm), one should be able to predict the proper value of η using V_t as it is known on the basis of fitting P states and P-F mixing in p-p scattering and fitting D states in n-p scattering. Based on a number of models we have constructed[19] using HJ phenomonology for the intermediate range tensor force, we conclude that the value of η predicted on this basis is 0.0228 ± 0.0004, which compares favorably with the value obtained from forward photodisintegration, 0.0229 ± 0.0007.

SUMMARY

Based on photodisintegration data, it has been concluded that the value of the deuteron D to S asymptotic ratio is close to 0.023 and significantly smaller than the traditional value close to 0.026. There is significant circumstantial evidence supporting the correctness of this new value of η. In particular, the known value of f^2 is derived from the same analysis and a consistent low value of η is derived from nuclear force phenomenology on the basis of quite conventional assumptions about the structure of the nucleon-nucleon tensor force.

There are reasons for caution, however. Our experience with models which have values of A_d which are 15% smaller than the traditional value is that they also have quadrupole moments about 15% smaller than experiment. A large contribution to Q from inside the nuclear range ($r_0 = 1.75$ fm) is more like 7% rather than 15%. If we try to make up this shortfall in Q by displacing the charge associated with the inside nucleons radially, that displacement would be such that the inside nucleons would appear to be twice as far apart as in conventional deuteron models (one would have to turn the inside part of the deuteron inside out). The size of this discrepancy suggests a nearly complete breakdown of traditional physics within r_0 as one might expect on the basis of the quark bag model. If we assume there is such a breakdown, which can no longer be considered unlikely,[20,21] we are forced to question whether the conventional assumptions in this paper will prove consistent with the new physics of the deuteron as it emerges.

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*Present address: Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts.

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