Tensor polarization and magnetic form factor and the percentage D state of the deuteron

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The elastic electron-deutron electric and magnetic form factors $A(q)$ and $B(q)$ and tensor polarization $T_{2\pm1}$ have been calculated for a family of phase equivalent deuteron wave functions with a percentage D state P_D varying from 4.5 to 7.5% (generated by unitary transformation from the super-soft-core potential of de Tourreil and Sprung). It is demonstrated that measurements of $T_{2\pm1}$ for momentum transfers in the range $0 \lesssim q \lesssim 6$ fm^{-1} would not allow us to discriminate between *all* physically reasonable deuteron wave functions with different P_D. We also find that accurate measurements of $B(q)$ in the region $4 \lesssim q \lesssim 6$ fm^{-1} are likely to narrow down the allowable range of values of P_D *a priori*, without the need of difficult measurements of $T_{2\pm1}$.

[NUCLEAR STRUCTURE ^{2}H electric, magnetic form factors, tensor polarization calculated: phase equivalent deuteron wave functions; P_D of deuteron wave function.]

I. INTRODUCTION

Recently Haftel, Mathelitsch, and Zingl[1] have calculated the electron-deuteron (*ed*) tensor polarizations T_{20} and $T_{2\pm1}$ (Ref. 2) for several nucleon-nucleon (NN) potential models in the literature. They conclude that measurements of T_{20} for momentum transfers $2 \lesssim q \lesssim 5$ fm^{-1} would mainly distinguish between potentials with different S wave off-shell behavior while not distinguishing between potentials with a different deuteron percentage D state P_D. This conclusion is consistent with that of Allen and Fiedeldey[3] that the measurement of the *ed* tensor polarization T_{20} out to momentum transfers $q \approx 4.5$ fm^{-1}, together with the experimental data on the *ed* electric form factor $A(q)$, would not necessarily allow us to distinguish between a P_D varying from 4.5 to 7.5%. The uncertainty in P_D is in a large measure due to the large experimental uncertainty in the neutron electric form factor G_{En}, which is the least well known of the nucleon electric and magnetic form factors.[4,5] The reason is that G_{En} determines the fit to $A(q)$ even though T_{20} itself is independent of G_{En} in the nonrelativistic impulse approximation (IA) which we employed. In fact we found that if we rather unrealistically assume that $A(q)$ and T_{20} are exactly known out to $q = 20$ fm^{-1}, the uncertainty in P_D still amounts to about 2.5%, by varying G_{En} in the range between zero and the scaling model.[6] A Fourier-Bessel inversion procedure was used to extract the deuteron wave function from A and T_{20}.

Haftel *et al.*[1] furthermore suggest that measurements of $T_{2\pm1}$ in the range $3 \lesssim q \lesssim 5$ fm^{-1} can distinguish between interactions with different P_D. However, their results appear to indicate that in this region $T_{2\pm1}$ would mainly discriminate between the realistic NN potentials on the one hand and separable potentials like the Graz[7] and Doleschall[8] potentials on the other hand. Although these separable potentials can, by taking the pair meson-exchange current (MEC) (Ref. 9) into account, be made to fit the data on $A(q)$, it appears inconsistent to include such a correction when the potentials themselves do not include the one-pion-exchange potential (OPEP). Furthermore, most separable potentials, as a result of not having the OPEP tail, do not fit the accurately measured asymptotic D-S state ratio of the deuteron wave function η.[10,11]

In an investigation of the usefulness of additional experimental data in elastic *ed* scattering, such as the tensor polarizations T_{20} and $T_{2\pm1}$, one can adopt one of the following criteria:

(1) Such measurements are useful if they allow us to discriminate between competing NN potentials in the literature, which is the point of view adopted by most investigators (for example, Refs. 1 and 12).

(2) Such measurements should, to be of a value commensurate to their difficulty, allow us to determine properties of the deuteron wave function like P_D unambiguously. For instance, to show that $T_{2\pm1}$ determines P_D, it is, strictly speaking, necessary to show that $T_{2\pm1}$ would dis-

criminate between all physically reasonable deuteron wave functions having different P_D values. If it should prove possible to generate at least one family of such deuteron wave functions for which this is not the case, then we should conclude that those data would *not* allow us to determine *the* P_D of the deuteron.

We shall in general adopt the second criterion in this investigation as before[3] and will be mainly concerned with P_D, which has proved to be a very elusive property of the deuteron. Some authors have recently expressed doubts about the measurability of P_D.[13] However, it is clear that P_D is well defined in terms of the usual nonrelativistic potential models employed in few-nucleon problems (and in nuclear model calculations), where it is of fundamental importance. It represents a measure of the tensor force component of the NN interaction and is therefore a theoretical quantity of fundamental importance, even if it should not be directly measurable. Here we shall investigate, using a family of strictly phase equivalent NN interactions (unlike those considered by Haftel *et al.*) which satisfy the known deuteron constraints,[11] whether the data on $A(q)$ and $B(q)$ and assumed data on T_{20} and $T_{2\pm1}$ would allow us to narrow down the uncertainty in P_D.

II. THE SCATTERING OBSERVABLES

We very briefly summarize the equations for the elastic *ed* scattering observables $A(q)$, $B(q)$, T_{20}, and $T_{2\pm1}$ in the nonrelativistic impulse approximation.

The unpolarized cross section for elastic *ed* scattering is given by Gourdin[14] as

$$\left(\frac{d\sigma}{d\Omega}\right)=\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}\{A(q)+\overline{B}(q)\,[1+2(1+\nu)\tan^2\theta/2]\}$$

$$\equiv\left(\frac{d\sigma}{d\Omega}\right)N\,, \tag{1}$$

where $(d\sigma/d\Omega)_{\text{Mott}}$ is the point scattering of the electron from the deuteron, $\nu=q^2/4m_d^{\,2}$, and θ is the electron scattering angle. The electric and magnetic form factors $A(q)$ and $B(q)$ are given in terms of the charge, quadrupole, and magnetic form factors G_0, G_2, and G_M by[15]

$$A=G_0^{\,2}+G_2^{\,2}\,, \tag{2}$$

$$B=\tfrac{4}{3}\,\nu(1+\nu)G_M^{\,2}=2(1+\nu)\overline{B}\,, \tag{3}$$

where

$$G_0=2G_{ES}C_E\,, \tag{4}$$

$$G_2=2G_{ES}\,C_Q, \tag{5}$$

and

$$G_M=\frac{m_d}{m_p}(2G_{MS}C_S+G_{ES}C_L)\,. \tag{6}$$

In Eqs. (4)–(6), C_E, C_Q, C_S, and C_L are the deuteron structure functions (integrals over the S- and D-wave components of the deuteron wave function, as given for instance by Sprung,[15] and

$$2G_{ES}=G_{Ep}+G_{En}\,, \tag{7}$$

$$2G_{MS}=G_{Mp}+G_{Mn}\,, \tag{8}$$

are isoscalar form factors defined in terms of the electric and magnetic charge form factors of the proton and neutron.

The tensor polarizations T_{20} and $T_{2\pm1}$ for the recoil deuterons in *ed* scattering from aligned deuterons are given in terms of the charge, quadrupole, and magnetic form factors by[16,17]

$$T_{20}=\frac{2G_0G_2+(G_2^{\,2}/\sqrt{2})}{G_0^{\,2}+G_2^{\,2}}\,, \tag{9}$$

and[1,17]

$$T_{2\pm1}=\pm\left(\frac{3}{2}\right)^{1/2}\left(\frac{\epsilon-\nu}{N}\right)G_MG_2\tan\frac{\theta}{2}\,, \tag{10}$$

where $\epsilon=p/m_d$, with p the magnitude of the incident electron momentum and N is defined in Eq. (1).

III. THE PERCENTAGE D STATE OF THE DEUTERON

To establish whether the data on $A(q)$ and $B(q)$ and assumed pseudodata on T_{20} and $T_{2\pm1}$ obtained from our reference potential, the super-soft-core (SSC) potential of de Tourreil and Sprung,[18] would allow us to narrow down the uncertainty in P_D, we employ some members of a family of deuteron wave functions generated from the SSC potential wave function in Ref. 3. The details of these wave functions are given in Table I of Ref. 3 and those we employ here (I_1 with $P_D=4.54\%$, SSC with $P_D=5.45\%$, I_4 with $P_D=6.52\%$, and I_6 with $P_D=7.55\%$) are plotted in Fig. 1. These smooth and well behaved deuteron wave functions are obtained by means of strictly finite range unitary transformations with a cut-off radius $R=2.0$ fm. The requirement of continuous first and second derivatives at $R=2.0$ fm means that in practice they only differ for $r<1.8$ fm.

Fits to $A(q)$ in the IA for I_1, I_6, and the SSC potential are shown in Fig. 2. The fits which cluster around the SSC fit were obtained by varying the poorly known neutron electric form factor G_{En} within the maximal and minimal fits given by Bertozzi *et al.*[4]:

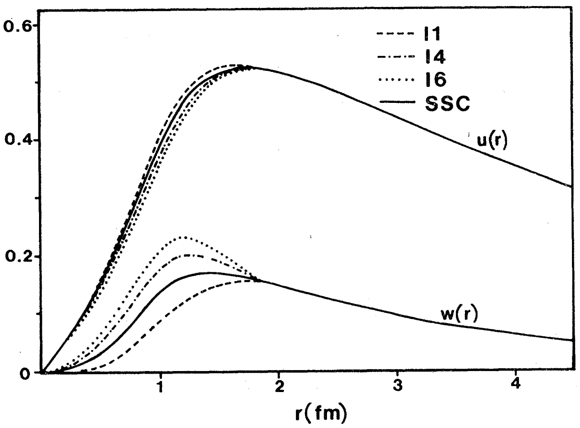

FIG. 1. The $^3S_1$ and $^3D_1$ partial-wave components $u(r)$ and $w(r)$ of the deuteron wave functions I_1 (P_D=4.54%), I_4 (P_D=6.52%), and I_6 (P_D=7.55%) of Ref. 3 together with those of the SSC potential (P_D=5.45%).

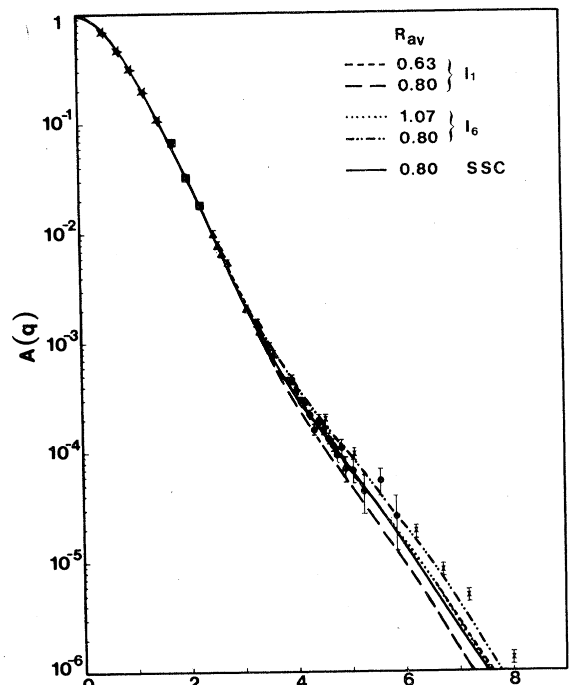

FIG. 2. The deuteron electric form factor $A(q)$ for the deuteron wave functions I_1 and I_6 and for the deuteron wave function of the SSC potential. Shown are $A(q)$ calculated in each case for a fixed G_{En} and also in the case of I_1 and I_6 with G_{En} adjusted for a better fit to $A(q)$ [or the $A(q)$ given by the SSC wave function]. The value of R_{av} in Eq. (11) is indicated in each case. The sources of the experimental points can be identified in Ref. 3.

$$G_{En}=[1+\tfrac{1}{12}q^2(R_{av}^2-0.06)]^{-2}-[1+\tfrac{1}{12}q^2(R_{av}^2+0.06)]^{-2}, \quad (11)$$

with $R_{av}=0.63$ and 1.07, respectively. These G_{En} fits are consistent with the experimentally measured thermal neutron slope[19] of G_{En} at $q=0$ fm^{-1}. The SSC wave function was fitted using the best fit G_{En} of Bertozzi *et al.*, i.e., $R_{av}=0.80$. These G_{En} are plotted in Refs. 3 and 4. In view of the possibility that G_{En} could be determined by a quark model[20] we also consider the case of a fixed G_{En}, that given by Eq. (11) with $R_{av}=0.80$ (this fit is in reasonable agreement with the calculation of Ref. 20). These fits are also shown in Fig. 2. Haftel *et al.* use $G_{En}=0$ throughout their calculation, which is in disagreement with the known slope of G_{En} at $q=0$ fm^{-1}.

We then calculated $B(q)$ in the IA for I_1 and I_6, using the two different G_{En} in each case, and also for the SSC potential (see Fig. 3). A fit to the experimental values of $B(q)$ (Refs. 21 and 22) in the IA for the SSC potential required a neutron magnetic form factor G_{Mn} 10% below the values of $|G_{Mn}|$ given by the "scaling law"[23]

$$\frac{G_{Mn}}{\mu_n}=\frac{G_{Mp}}{\mu_p}, \quad (12)$$

where μ_p and μ_n are the proton and neutron magnetic moments in nuclear magnetons and $G_{Mp}=\mu_p(1+q^2/18.235\text{ fm}^{-2})^{-2}$. This is consistent with the experimental results on G_{Mn} (Ref. 24) which has been measured up to $2(\text{GeV}/c)^2$ with uncertainties ranging from 10% to 40%. The same G_{Mn} was used for the calculations with I_1 and I_6. It is clear that even varying G_{En} the variation in $B(q)$ for $q\gtrsim 4$ fm^{-1} is much greater than that for $A(q)$. It also appears that at least for $0\lesssim q\lesssim 6$ fm^{-1}, $B(q)$ is not very sensitive to G_{En}.

The values of T_{20} for I_1, I_4, and I_6 are within ±4% of T_{20} for the SSC potential (our pseudodata) in the range $0\lesssim q\lesssim 4.5$ fm^{-1}, which is within the expected experimental error on the proposed experiments.[25] These results are given in Ref. 3. In the IA T_{20} is independent of G_{En}.

The results for $T_{2\pm1}$, both with G_{En} fixed and adjusted for a better fit to $A(q)$, are shown in Fig. 4. The same G_{Mn} has been used as in calculating $B(q)$. We have also plotted $T_{2\pm1}$ for the deuteron wave function I_4 of Fig. 1. As can be seen from Eq. (10), $T_{2\pm1}$ is proportional to G_MG_2 and Haftel *et al.*[1] suggest that dividing through by the experimentally known G_M should allow us to separate out the quadrupole form factor (and hence P_D). Since there are only data on $B(q)$ in

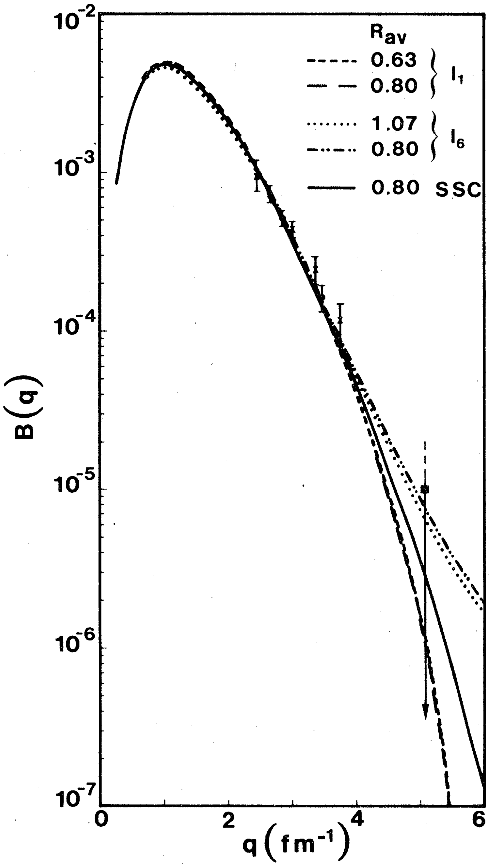

FIG. 3. The deuteron magnetic form factor $B(q)$ for the deuteron wave functions I_1 and I_6 and for the deuteron wave function of the SSC potential. Shown are $B(q)$ calculated in each case for a fixed G_{En} and also in the case of I_1 and I_6 using the G_{En} which gave a better fit to $A(q)$. The value of R_{av} in Eq. (11) is indicated in each case. The sources of the experimental points can be identified in Refs. 21 and 22.

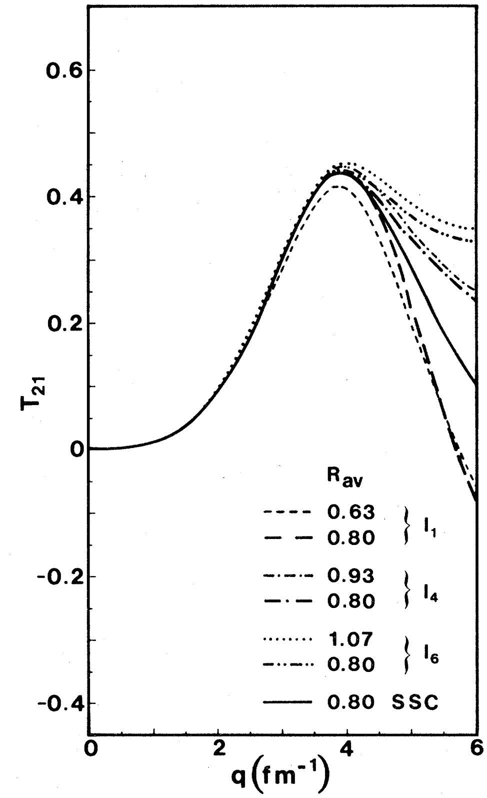

FIG. 4. The *ed* tensor polarization $T_{2\pm1}$ for the deuteron wave functions I_1, I_4, and I_6 and for the deuteron wave function of the SSC potential. Shown are $T_{2\pm1}$ calculated in each case for a fixed G_{En} and also in the case of I_1, I_4, and I_6 using the G_{En} which gave a better fit to $A(q)$. The value of R_{av} in Eq. (11) is indicated in each case.

the range $0 \lesssim q \lesssim 4$ fm^{-1} (Ref. 21) and a single point with large error bars at $q \approx 5$ fm^{-1} (Ref. 22) we have not extended our calculations beyond $q \cong 6$ fm^{-1}. It is clear that $T_{2\pm1}$ is very insensitive to P_D for $q \lesssim 4$ fm^{-1}, especially for a fixed G_{En}. If G_{En} has been adjusted to maintain a good fit to $A(q)$ [or the $A(q)$ produced by the SSC potential] then the sensitivity of $T_{2\pm1}$ to P_D is slightly larger in this region. On the other hand, $T_{2\pm1}$ appears to become extremely sensitive to P_D for $4 \lesssim q \lesssim 6$ fm^{-1}, although this sensitivity is somewhat reduced if we allow P_D to vary only between 4.5 and 6.5%, the physically most interesting range. The sensitivity of $T_{2\pm1}$ to G_{En} is once again rather weak.

To investigate whether the wide latitude in the fit to $B(q)$ allowed by the experimental data for $4 \lesssim q \lesssim 6$ fm^{-1} is not, to some extent, responsible for the sensitivity of $T_{2\pm1}$ to P_D in that region, we also plot $T_{2\pm1}(q)/G_M(q)$. This is equivalent to fixing the fit to $B(q)$ for all our deuteron wave functions and eliminating $G_M(q)$ as a source of variability in $T_{2\pm1}(q)$. The results are plotted in Fig. 5 and indicate that the sensitivity of $T_{2\pm1}$ to P_D indeed has its source largely in the wide latitude allowed by the experimental data on $B(q)$ for $q \gtrsim 4$ fm^{-1} and is therefore partly spurious. Improved data for $B(q)$ seem likely to eliminate some of the deuteron wave functions we have used *a priori* as well as many of the so-called realistic NN interactions. Figure 5 also shows that if G_{En} is varied to produce a good fit to $A(q)$, then the sensitivity of $T_{2\pm1}/G_M$ to P_D is even more reduced.

The pair MEC have not been incorporated in our calculations, which are based purely on the nonrelativistic impulse approximation. However, the results of Haftel *et al.*[1] indicate that the pair MEC depend mainly on the deuteron S-wave behavior at short distances. From Fig. 1 it is seen

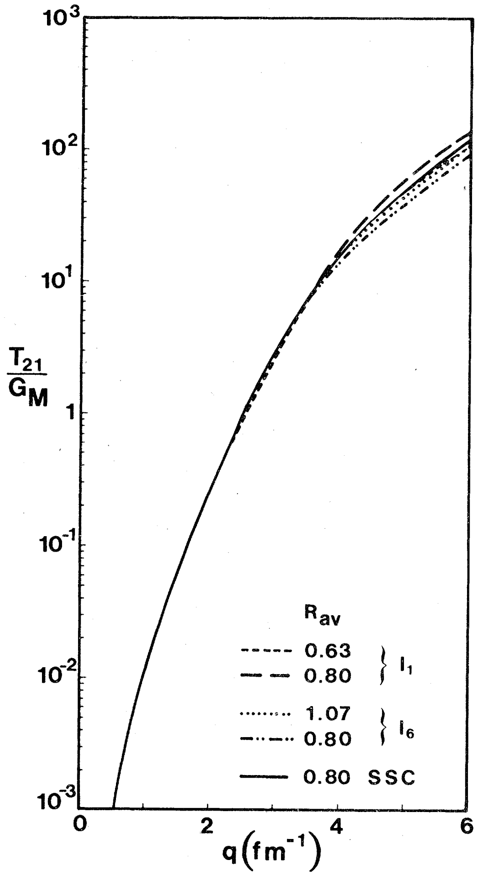

FIG. 5. The ratio T_{21}/G_M for the deuteron wave functions I_1 and I_6, and for the deuteron wave function of the SSC potential. Shown are T_{21}/G_M calculated in each case for a fixed G_{En} and also in the case of I_1 and I_6 using the G_{En} which gave a better fit to $A(q)$. The value of R_{av} in Eq. (11) is indicated in each case.

that our family of deuteron wave functions has very similar S wave functions at short distances and these MEC should therefore be nearly identical for them. On the other hand, Haftel *et al.*[1] fixed $G_{En}=0$ in all cases. However, it appears that G_{En}, especially through its effect on the fit to $A(q)$, is more important than the MEC (see also Arnold *et al.*[5]). The results of Haftel *et al.*[1] for the Paris,[26] Bonn,[27] Reid,[28] and Nijmegen[29] potentials indicate that there is very little sensitivity of $T_{2\pm1}$ to P_D for these potentials for $q \lesssim 4$ fm^{-1} and only a little more for $4 \lesssim q \lesssim 6$ fm^{-1}, even when the MEC are included.

IV. CONCLUSION

We have mainly used criterion 2 of Sec. I to assess the usefulness of measurements of $A(q)$, $B(q)$, T_{20}, and $T_{2\pm1}$ in determining P_D. As has already been shown,[3] measurements of $A(q)$ and T_{20} together would not allow us to determine P_D, due to a large extent to the uncertainty in the neutron electric form factor G_{En}. It is also clear from our results here that, at least for $q \lesssim 4$ fm^{-1}, $T_{2\pm1}$ cannot be used to determine the percentage D state of the deuteron P_D (although it may be of some use in terms of criterion 1 of Sec. I). For 4 fm$^{-1} \lesssim q \lesssim 6$ fm^{-1} our family of deuteron wave functions might serve to indicate that $T_{2\pm1}$ could discriminate between some competing potentials (criterion 1) but we cannot draw a positive conclusion in terms of criterion 2 about using $T_{2\pm1}$ to fix P_D, due to the large experimental uncertainty in $B(q)$ in this region. Narrowing the range of variation allowed in $A(q)$ and especially $B(q)$ and taking the uncertainty in G_{En} into account reduces the sensitivity of $T_{2\pm1}(q)$ to P_D considerably.

To enable us to make use of possible future measurements of T_{20} and $T_{2\pm1}$ in determining P_D it therefore appears essential to improve the data on $B(q)$ especially, but also that on $A(q)$, and in particular our knowledge of G_{En}. It seems likely that improved measurements of $B(q)$ [which appears not to be as sensitive as $A(q)$ to G_{En}] could more clearly discriminate between interactions with varying P_D. In this context we refer to the proposal by Arnold *et al.*[30] to measure $B(q)$ at large q. Their calculations for the realistic NN interactions indicate that they produce very different values of $B(q)$ in this region. It is significant that the same is true for the family of deuteron wave functions we considered here. It appears therefore that some details of the deuteron wave function are more clearly visible in $B(q)$ than in $A(q)$ and it seems that if we only consider interactions which fit such improved data on $A(q)$ and $B(q)$ for $4 \lesssim q \lesssim 8$ fm^{-1}, the measurement of $T_{2\pm1}$ is not likely to improve our ability to determine the properties of the deuteron very much, unless the experiments are carried out at high accuracy and for $q \gtrsim 4$ fm^{-1}. In the case of $T_{20}(q)$ the position is more favorable since a significant improvement of our knowledge of $G_{En}(q)$, maybe even from theory, could dramatically improve our ability to disentangle $G_0(q)$ and $G_2(q)$ from the data on $A(q)$ and $T_{20}(q)$, and hence our knowledge of P_D in particular and the deuteron wave function in general. However, until such an improvement in our knowledge of $G_{En}(q)$ is forthcoming, an accurate measurement of $B(q)$ appears to be a more promising approach to the determination of properties of the deuteron like the P_D than the much more difficult measurement of the electron-deuteron tensor polarizations $T_{20}(q)$ and $T_{2\pm1}(q)$.

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