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The $A(q^2)$ deuteron structure function: the contribution of exchange currents associated with the $\Delta\Delta$ component and the neutron charge form factor

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Abstract. In the present work, contributions to the deuteron electromagnetic structure due to exchange currents involving the $\Delta\Delta$ component are studied. For a 0.88% probability of this component, it is found that a substantially important contribution to the deuteron charge form factor is obtained. It comes just second in order of importance after that of the pion-pair current. This $\Delta\Delta$ contribution has its origin in the usual pair current, but at the quark level. Taking into account this new contribution implies a modification of the neutron charge form factor, $G_E^n(q^2)$, which has been derived from the measurement of the structure function, $A(q^2)$. An interesting observation is made about the derivation of this form factor. This calls for an extension of the accurate determination of $A(q^2)$ to higher values of q^2.

PACS. 13.40.Fn Deuteron charge form factor – 13.75.Cs Neutron charge form factor; Isobar contribution – 25.45.De Meson exchange currents

1 Introduction

The neutron charge form factor is currently receiving a lot of attention. Many experiments involving polarized electrons and polarized targets aim to a better determination [1–7], free of the uncertainties that affect its determination from the measurement of the deuteron structure function, $A(q^2)$. In this approach, some nucleon-nucleon interaction model has to be assumed for describing the deuteron. Furthermore, contributions due to the meson exchange nature of the NN interaction and the effective character of its modelization have to be considered. These are usually accounted for by meson exchange currents [8–10], possibly generalized [11]. The most quoted one is the so-called pion-pair term. At low q^2, its contribution decreases the deuteron charge form factor and enhances the quadrupole one. There are many other meson exchange contributions which may show up at high momentum transfers. Some of these contributions involving the excitation of the nucleon to higher energy states were considered as negligible (or omitted) in previous studies or analysis [9,10,12–15]. For a moderate momentum transfer ($q^2 = 1 - 3$ $(Gev/c)^2$), the most important excitations are essentially the $\Delta(1232MeV)$ resonance and the Roper resonance ($N^*(1440MeV)$). Their contributions are necessary to satisfy the electromagnetic current conservation equation at a level where the nucleon and its excitations are considered as active degrees of freedom. They are therefore the direct result of gauge invariance and some track of them should be left when effective nucleon degrees of freedom are employed to describe the deuteron. They differ from those contributions to the charge and quadrupole form factors that have been considered in the literature and are due to a $\Delta\Delta$ component in the deuteron wave function [16–19]. These ones involve the direct coupling of the photon to the Δ resonance.

In this work, we concentrate on a contribution involving the Δ excitation [20]. It originates from the usual pair term contribution, but at the level of quarks instead of nucleons with two quarks as spectators. This approach allows one to reproduce the $\gamma\pi NN$ coupling entering the usual pion-pair term at the nucleon level using the standard relations derived in a non-relativistic limit such as $M_N = 3\,m_q,\ g_{\pi NN} = 5\,g_{\pi qq}$. It also produces a $\gamma\pi N\Delta$ coupling of which size is similar to the above $\gamma\pi NN$ coupling. This feature is expected as the Δ excitation is nothing but a nucleon of which the whole spin and isospin structure of its constituent quarks has been modified. Being of the second order in the strong interaction, the effects we are considering may be compared to those involving the usual deuteron D-state component. The effect of a $\gamma\pi N\Delta$ coupling was also considered in [21], but for real transverse photons instead of virtual longitudinal ones.

In the following, we will successively consider the transition potential and charge densities from a NN to a $\Delta\Delta$ state, the corresponding contribution to the deuteron charge and quadrupole form factors, and finally the consequences for the neutron charge form factor derived from the study of the structure function, $A(q^2)$.

Throughout the paper, we adopt the notation: $q^2 = \vec{q}^2$. There is no justification to introduce here the extra variable, Q^2, which in some relativistic approaches and depending on the conventions, remedies to the inconvenience of a negative value for q^2.

2 The deuteron $\Delta\Delta$ component and the associated exchange currents

To evaluate the contribution involving the $\Delta\Delta$ component in the deuteron [13], we have first to determine its wave function. This is calculated using a first order perturbation theory. In this aim, the transition potential V^T, from the NN component to the $\Delta\Delta$ component has to be precised. It may be considered as the sum of contributions due to π- and the ρ-exchanges (Fig. 1b):

$$V^T_{\pi+\rho} = \left(\frac{f^2_{\pi N\Delta}}{m^2_\pi} K^2_{\pi N\Delta}(\vec{k}^2) \frac{\vec{S}_1.\vec{k}\ \vec{S}_2.\vec{k}}{\vec{k}^2 + m^2_\pi} + \frac{f^2_{\rho N\Delta}}{m^2_\rho} K^2_{\rho N\Delta}(\vec{k}^2) \frac{\vec{S}_1 \times \vec{k}\ .\ \vec{S}_2 \times \vec{k}}{\vec{k}^2 + m^2_\rho} \right) \vec{T}_1.\vec{T}_2. \quad (1)$$

where $K_{\alpha N\Delta}(\vec{k}^2) = \frac{\Lambda^2_\alpha - m^2_\alpha}{\Lambda^2_\alpha + \vec{k}^2}$ is the hadronic form factor used to describe the meson-nucleon delta vertex; $\vec{S}_i$ and $\vec{T}_i$ are respectively the generalized spin and isospin Pauli matrices describing the transition from the N state ($S = 1/2, T = 1/2$) to the Δ state ($S = 3/2, T = 3/2$) with a transfer of spin and isospin equal to 1. For completeness, the hermitic conjugate of $V^T_{\pi+\rho}$, corresponding to a transition from the $\Delta\Delta$ component to the NN component, should be added to (1).

The ρ-exchange contribution has the effect to reduce the pion-exchange component of the tensor force in (1) as it does for the NN interaction. Concerning the spin scalar part of the transition potential, the two contributions due to the π- and ρ-exchanges add together and give rise to a strong short range interaction. This one is given by a $\delta(\vec{r})$ function in absence of vertex form factor in (1). As often done on the basis of a strong repulsion at short distances, which prevents nucleons to be close to each other, this short range contribution to the transition potential is neglected. The factor, $\frac{\vec{k}^2}{\vec{k}^2 + m^2_\alpha}$, in (1) is therefore replaced by -$\frac{m^2_\alpha}{\vec{k}^2 + m^2_\alpha}$ [22]. It is likely that this approximation should be reconsidered in view of the most recent developments in deriving NN interaction models. The Q-Bonn models for instance [23] give rise to a deuteron S-wave which, with the normalization $\frac{u(r)}{r}$, is far to vanish at small distances. The essential point here is that the long range part of the transition operator given by (1), which is less uncertain, is retained.

In the expression of the above transition potential, we introduced a set of parameters (such as the cut-off and coupling constants) that are not completely determined but are chosen so that to give a suitable value for the $\Delta\Delta$ component probability in the deuteron. With an appropriate choice of the cut-off and coupling constants ($\Lambda_{\pi N\Delta} = \Lambda_{\rho N\Delta} = 1000 MeV$, $\frac{f^2_{\pi N\Delta}}{4\pi} = 0.35$ and $\frac{f^2_{\rho N\Delta}}{4\pi} = 9.13$), we managed to obtain a probability $P_{\Delta\Delta} = 0.88\%$, using the NN wave function of the Paris potential [24]. This value is acceptable compared to those obtained in previous theoretical studies which gave probabilities between 0.45 and 3% [12]. This is also consistent with the result of an old experiment that provided an upper limit of 0.4% [25], which however supposes some interpretation. This one is partly ambiguous as the probability of a $\Delta\Delta$ component in the deuteron, like the deuteron D-state probability, is model dependent and, therefore, cannot be measured (see [11,26] for practical examples and further references).

The effective electromagnetic current operators due to the π- and ρ-exchanges, represented in Fig. 1a, are calculated from a non-relativistic constituent quark model. For this, we consider the Lagrangian density describing the direct coupling of π and γ with quarks :

$$\mathcal{L}_{\pi qq}(x) = i g_{\pi qq} \bar{\Psi}_q(x)\ \vec{\tau}_q \gamma^5\ \Psi_q(x)\ \vec{\phi}^\pi(x), \quad (2)$$

$$\mathcal{L}_{\gamma qq}(x) = i \bar{\Psi}_q(x)\ Q \gamma^\mu\ \Psi_q(x)\ A_\mu(x), \quad (3)$$

where Q is the quark charge.

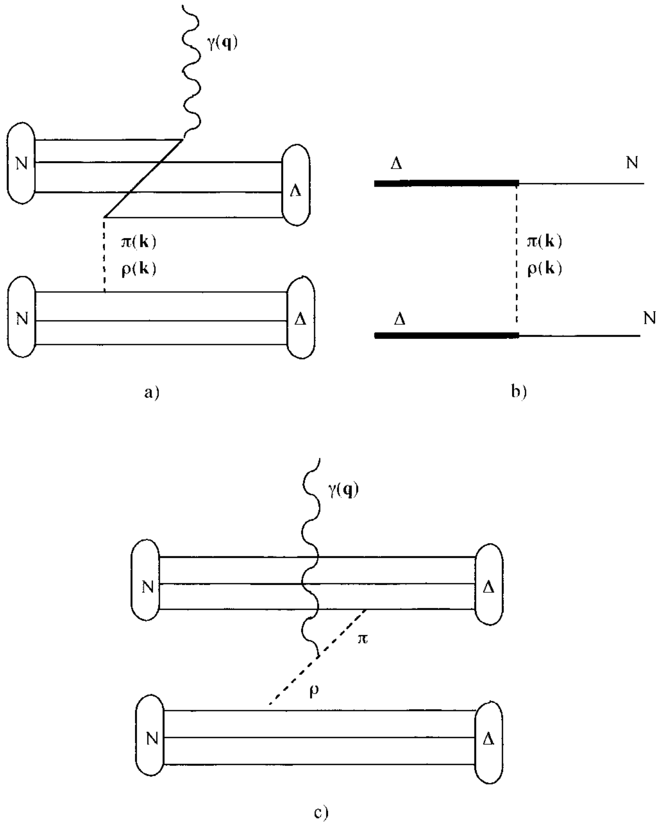

Fig. 1. a The $NN \leftrightarrow \Delta\Delta$ transition current contribution with π- and ρ-exchanges, denoted respectively by $\Delta\Delta(\pi)$ and $\Delta\Delta(\rho)$; **b** The π- and ρ-exchange contributions to the transition potential V^T; **c** The $\rho\pi\gamma$ coupling contribution with excitation of the NN component to the $\Delta\Delta$ one

In the constituent quark model, the coupling constant $g_{\pi qq}$ is related to $g_{\pi NN}$ and $f_{\pi N\Delta}$ as follows:

$$\frac{g_{\pi qq}}{2m_q} = \frac{3}{5}\frac{g_{\pi NN}}{2m_N} = \frac{1}{2\sqrt{2}}\frac{f_{\pi N\Delta}}{m_\pi}. \quad (4)$$

Using (2) and (3), the isoscalar part of the charge density operator due to the π-exchange, which is represented in Fig. 1a and is labelled by $\Delta\Delta(\pi)$, is given by:

$$\rho^{\Delta\Delta(\pi)} = \frac{F_{\gamma\pi N\Delta}(\vec{k}_\pi, \vec{q})}{M_N}(\frac{f_{\pi N\Delta}}{m_\pi})^2 K_{\pi N\Delta}(\vec{k}^2_\pi) \times \frac{\vec{S}_1.\vec{q}\;\vec{S}_2.\vec{k}_\pi}{\vec{k}^2_\pi + m^2_\pi}\vec{T}_1.\vec{T}_2 + (1 \leftrightarrow 2) + \; h.c.. \quad (5)$$

$F_{\gamma\pi N\Delta}(\vec{k}_\pi, \vec{q})$ is the function representing the $\gamma\pi N\Delta$ vertex form factor. In the constituent quark model with harmonic oscillator wave functions, this would contain the factor, $exp(-\vec{q}^2b^2/6) \, . \, exp(-\vec{k}^2_\pi b^2/6)$, which is the product of two form factors, respectively electromagnetic and hadronic, and an extra factor, $exp(2\vec{q}.\vec{k}_\pi b^2/6)$, which, consistently with the neglecting of higher baryon excitations, is irrelevant here [27]. This form factor is unfortunately irrealistic for the case of high momentum transfers. By analogy with the usual π-pair current, the form factor given by the constituent quark model is replaced by $G^S_M(q^2) \;\; K_{\pi N\Delta}(\vec{k}^2)$. The latter gives an acceptable description of the $\gamma\pi N\Delta$ vertex form factor. In this case, the expression of the charge density can be re-written as:

$$\rho^{\Delta\Delta(\pi)} = \frac{G^S_M(q^2)}{M_N}(\frac{f_{\pi N\Delta}}{m_\pi})^2 K^2_{\pi N\Delta}(\vec{k}^2_\pi) \times \frac{\vec{S}_1.\vec{q}\;\;\vec{S}_2.\vec{k}_\pi}{\vec{k}^2_\pi + m^2_\pi}\;\vec{T}_1.\vec{T}_2 + (1 \leftrightarrow 2) + \; h.c.. \quad (6)$$

It is noted that the above expression of $\rho^{\Delta\Delta(\pi)}$ is similar to that of the usual isoscalar pair contribution to the charge density with the spin and isospin Pauli matrices replaced by the transition matrices, $\vec{S}$ and $\vec{T}$ [9]. There is no contribution corresponding to its isovector part.

The contribution of the ρ-exchange is obtained in a similar way and the charge density operator in this case is given by :

$$\rho^{\Delta\Delta(\rho)} = \frac{G^S_M(q^2)}{M_N}(\frac{f_{\rho N\Delta}}{m_\rho})^2 K^2_{\rho N\Delta}(\vec{k}^2_\rho) \times \frac{\vec{S}_1 \times \vec{q}\;.\;\vec{S}_2 \times \vec{k}_\rho}{\vec{k}^2_\rho + m^2_\rho}\;\vec{T}_1.\vec{T}_2 + (1 \leftrightarrow 2) + \; h.c. (7)$$

As for the π-exchange, there is no isovector contribution. The absence of this piece, which only holds at the $\frac{1}{M_N}$ order retained in the present work, arises from the fact that the unit operator in isospin space, 1, cannot connect the nucleon and the Δ states.

3 Contribution to form factors

The contribution of the $\Delta\Delta$ component to the deuteron charge form factor, calculated from (1,6,7), is shown in Fig. 2. The result we obtained is to be compared to the contribution of the pion-pair current, also shown in the figure. The latter is considered until now as the most important contribution to the exchange currents at low momentum transfers. It is noticeable that the $\Delta\Delta$ contribution associated with a π-exchange, (1), which is denoted $\Delta\Delta(\pi)$, is almost as important as the contribution from the π-pair current at low momentum transfers in the range $0 - 40fm^{-2}$. It even becomes more important beyond a transfer momentum of $50fm^{-2}$ up to $120fm^{-2}$. This is a direct consequence of the short range nature of the deuteron $\Delta\Delta$ component. The $\Delta\Delta$ contribution to the deuteron charge form factor in the case of ρ-exchange, denoted $\Delta\Delta(\rho)$, is far less important than that due to the $\Delta\Delta(\pi)$ contribution. This is mainly a consequence of a large mass of the ρ particle. This contribution becomes significant only at very high momentum transfers, which is in relation with its very short range character.

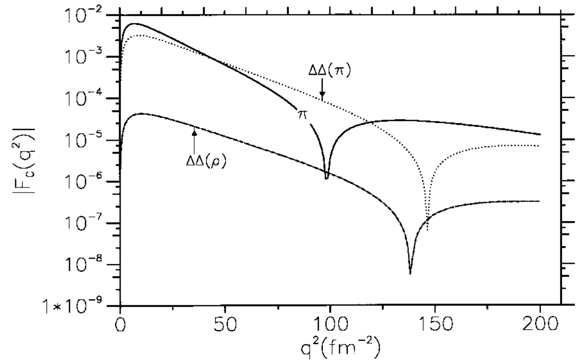

Fig. 2. The contribution of $\Delta\Delta(\pi)$ and $\Delta\Delta(\rho)$ to the deuteron charge form factor. The Paris wave function [24] is used. As a reference, the contribution of the usual pion-pair term (denoted π) is also given

For the quadrupole form factor $F_Q(q^2)$ (Fig. 3), the contribution of $\Delta\Delta(\pi)$ at low q^2, which was shown to be important in the case of the charge form factor, has a weak effect in this case. Similarly, the $\Delta\Delta(\rho)$ contribution is practically negligible compared to that of the π-pair current. However, the $\Delta\Delta(\pi)$ contribution becomes quite important for momentum transfers beyond $70fm^{-2}$, where it compares to the usual pion-pair current contribution.

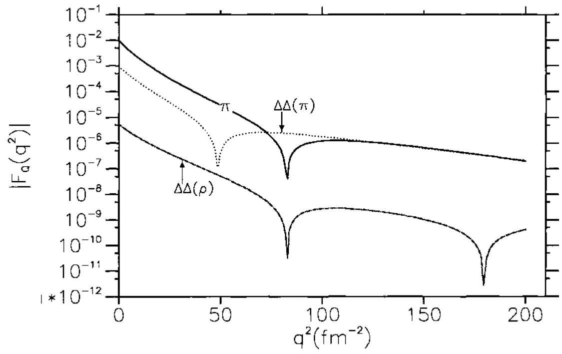

Fig. 3. Same as Fig. 2, but for the deuteron quadrupole form factor

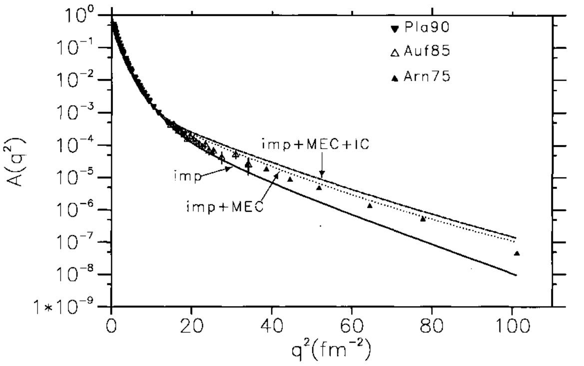

Fig. 4. The deuteron structure function $A(q^2)$ with the inclusion of the isobaric contribution "IC" ($\Delta\Delta(\pi)$, $\Delta\Delta(\rho)$ and $\Delta\Delta$ in impulse approximation) and the usual mesonic exchange contribution, "MEC", π, ρ, ω pair current and $\rho\pi\gamma$ coupling [9] (*dot-dashed line*). For a comparison, the structure function $A(q^2)$ in the impulse approximation (*continuous line*) and including usual meson exchange currents (*dotted line*) are also shown. The data are taken from [15,29,30]

From electron-deuteron elastic scattering, one can determine the structure function $B(q^2)$, which involves the deuteron magnetization, and $A(q^2)$, which is of interest here. In the absence of a neutron target, this one was generally used to deduce the neutron charge form factor, $G_E^n(q^2)$ [15,28]. This is why it is important to have a good knowledge of theoretical ingredients (NN interaction model and corresponding exchange currents) needed for the $A(q^2)$ structure function calculation. Consequently, adding the above new contributions neglected in previous analyses of experimental data will lead to a new value of $G_E^n(q^2)$.

The effect of the isobaric $\Delta\Delta(\pi)$ and $\Delta\Delta(\rho)$ contributions on the structure function, $A(q^2)$, is shown in Fig. 4. The effect of the $\Delta\Delta$ contribution with direct coupling of the photon to the Δ resonance (impulse approximation), which was considered in various works [12,13,16–19], but has a minor effect, is also taken into account. Altogether, they re-inforce the previously quoted ones (pair currents of π, ρ, ω and the $\rho\pi\gamma$ coupling), but the result is a larger disagreement with experimental data for momentum transfers ranging from $30 fm^{-2}$ to $100 fm^{-2}$ [29]. We will not attach too much importance to this disagreement as in the corresponding q^2 range, many improvements should be considered, including relativistic effects, better vertex form factors and other nucleon excitations. Only the size of the $\Delta\Delta(\pi)$ contribution relatively to the usual pair term contribution is likely to have some qualitative relevance.

At smaller momentum transfers, in the range $0 < q^2 < 30 fm^{-2}$, we believe that the new contributions have also a quantitative relevance. As they strenghten the old ones, they lead to a smaller total charge form factor at quite low q^2. This effect, which can be interpreted as an apparent "swelling" of nucleons, also leads to a greater mean square radius of the deuteron $< r_d^2 >$. Far from solving the disagreement with an analysis of experimental data concerning the deuteron charge form factor at very low momentum transfers performed by Sprung et al. [31], it is making it stronger, requiring that the matter radius of the deuteron be even further away from the values predicted by NN interaction models. Since then, the situation has changed. Atomic physics experiments [32,33] have taken over, showing the absence of difficulty [34]. This was confirmed later on by a reanalysis of the original measurements that led to the problem [35].

We have also studied other isobaric contributions, not considered until now, such as the contribution of the Roper resonance $N^*(1440 MeV)$ associated with σ- and ω-exchanges [36], and found that they had no significant effect on the deuteron electromagnetic structure. This is mainly due to the small probability of the NN^* component in the deuteron, $P_{NN^*} = 0.13\%$. The contribution of the $\rho\pi\gamma$ coupling with the excitation of the NN component into the $\Delta\Delta$ one (Fig. 1c) has also been calculated [37], but the effect is negligible compared to the $\Delta\Delta(\pi)$ contribution and has little influence on the discussion given in the next section.

4 Corrections to the neutron charge form factor

The aim of the present study was to achieve a better determination of the neutron charge form factor, $G_E^n(q^2)$, poorly known until now. This poor knowledge is due to the absence of a neutron target, replaced by the deuteron one. Furthermore, the determination of $G_E^n(q^2)$ with a good accuracy is limited by experimental difficulties, relative errors on $G_E^n(q^2)$ which can reach 20% at $q^2 = 15 fm^{-2}$ [15,28], and also by uncertainties in theoretical calculations. Since $G_E^n(q^2)$ is extracted from electron-deuteron elastic scattering, more precisely from the structure function $A(q^2)$, any modification in the calculation of this quantity, $\delta A(q^2)$, will induce a variation, $\delta G_E^n(q^2)$, of the derived neutron charge form factor, $G_E^n(q^2)$. The variation of $G_E^n(q^2)$ is approximatively given by the equation:

$$\frac{\delta G_E^n(q^2)}{G_E^S(q^2)} \simeq \frac{\delta A(q^2)}{2A(q^2)}. \tag{8}$$

It is assumed that the proton charge and magnetic form factors, and the neutron magnetic form factor are well known. The newly determined neutron charge form factor is given by:

$$G_E^{n(new)}(q^2) = G_E^{n(old)}(q^2) - \delta G_E^n(q^2). \tag{9}$$

To these new contributions due to isobaric exchange currents, we may correct for off-energy shell effects, when determining $G_E^n(q^2)$ [11,36,38,39]. It follows that the pseudo-data obtained from the analysis of Saclay experimental results [15,28] using the Paris model wave function [24] should be modified (Fig. 5a). Globally the various corrections tend to give a decrease of the calculated structure function, $A(q^2)$, in the range of momentum transfers from $0 fm^{-2}$ to $14 fm^{-2}$, and to give an increase beyond. As a

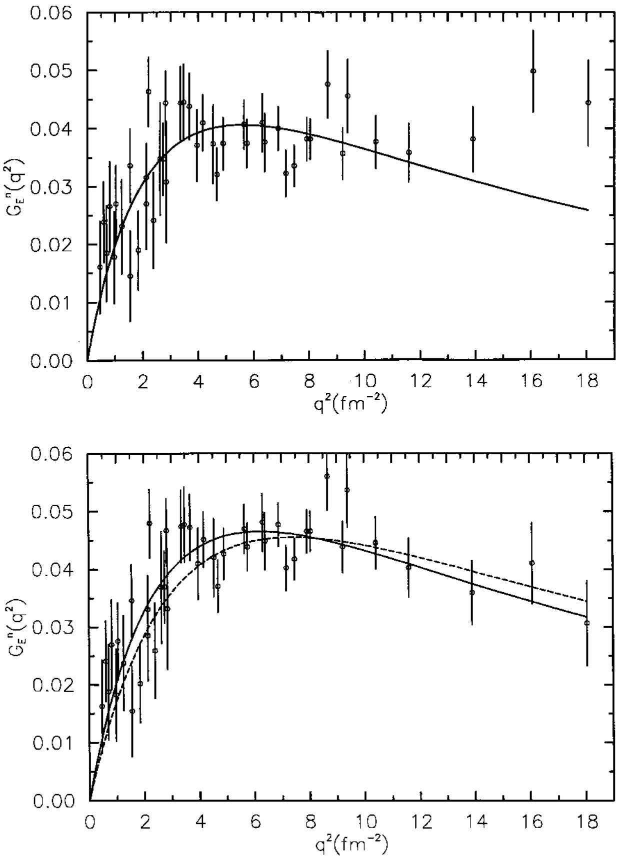

Fig. 5. **a** The neutron charge form factor $G_E^n(q^2)$ as obtained in [15] with the Platchkov et al. parametrization fit. **b** The new result obtained for the neutron charge form factor $G_E^n(q^2)$. The solid and dashed lines respectively represent the fit for the Platchkov et al.'s and Galster's parametrizations [40]. The (pseudo-)data are taken from [15]

consequence, the value of $G_E^n(q^2)$ should increase in the first range and decrease beyond.

In Fig. 5b, we show results concerning $G_E^n(q^2)$ obtained in the present study. In comparison with the fit of references [15,28] reproduced in Fig. 5a, a much better agreement with experimental data is achieved. The solid line in Fig. 5b is the new fit obtained for the neutron charge form factor $G_E^n(q^2)$ with fit parameters $a = 1.25$ and $b = 14$, where the Platchkov et al.'s parametrization is adopted [15,28]. The value of χ^2 (for 43 points) is 39.3 in this particular fit, instead of 58.2. The dashed line represents the new fit using the Galster parametrization for $G_E^n(q^2)$ [40] with a parameter $\rho = 9$. The value of χ^2 in the latter case is around 47.8, instead of 64.5. To appreciate the improvement, it is reminded that the χ^2 expected on a pure statistical error basis is 43.

While the improvement in the fit looks spectacular, which is mainly due to accounting for the two last points at $q^2 = 16 fm^{-2}$ and $q^2 = 18 fm^{-2}$, some caution is in order. First, it is implicitly assumed that the form factor is quite smooth. One cannot totally exclude however that the form factor evidences some structure. Second, there is some uncertainty in the calculations, in the impulse approximation as well as in the meson exchange current part. As a result, the good agreement we got may look fortuitous. Whatever is the final understanding, we nevertheless believe that there is some founding in this agreement. The comparison of predictions for the structure function, $A(q^2)$ [16,17,41], often shows a pattern comparable to the correction we incorporated. This one has its origin in the fact that around $q^2 = 12 - 14\ fm^{-2}$, the contribution to $A(q^2)$ of the quadrupole form factor takes over the charge one. This correction may be due to either an enhancement of the quadrupole form factor, a decrease of the charge form factor or both as here. It is therefore quite conceivable that the position of the two last points off the fitted form factor in Fig. 5a is not a statistical fluctuation, but, on the contrary, the result of an incomplete theoretical analysis. A correction, which modifies in the same way both form factors, would give rise to a different pattern. The present analysis would be transparent to it and, thus, would still authorize some doubt as to the value of $G_E^n(q^2)$ it provides.

The difference with the Platchkov et al.'s conclusion deserves some explanation. It has its origin in different corrections. These ones include the $\Delta\Delta(\pi)$ and $\Delta\Delta(\rho)$ contributions considered in this work, but also some difference at the level of the usual pair term contribution. Platchkov et al. included the corrections derived by Tjon et al. [42] rather than those obtained by Gross et al. [43], which are closer to those we considered. It is not clear to us that the former should be the appropriate ones in the case where the pseudo-vector πNN coupling is employed.

5 Conclusion

In this work, we considered the contribution of exchange currents associated with the excitation of a $\Delta\Delta$ component in the deuteron. We found that it was far from being negligible. A more rigorous calculation is necessary however, especially at high momentum transfers. This requires, among other things to go beyond a perturbative calculation and solve a system of coupled channel equations. The estimate of the contribution at low momentum transfers is probably more reliable. Its incorporation in the previous analysis of the $A(q^2)$ structure function leads to a new value of the neutron charge form factor. The improvement we got in fitting the experimental data suggests that the requirement that the neutron charge form factor varies smoothly could allow one to get rid of some theoretical uncertainties. With this respect, we believe that it would be quite interesting to extend the accurate determination of the $A(q^2)$ structure function to values of q^2 higher than in [15]. We cannot exclude that this approach could still compete with other ones to get a reliable neutron charge form factor.

These other approaches involve quasi-elastic scattering of polarized electrons on a ^3He polarized target, a deuteron target with the measurement of the neutron polarization or on a deuteron target with a vector polarization. From now on, the two first experiments have been performed at MAMI [1]. Other experiments are in preparation at various places (MAMI, ELSA, TJNAF). All of them offer the advantage of a strong sensitivity to $G_E^n(q^2)$. Their interpretation is also less sensitive to NN interaction models or to meson exchange currents. The main difficulties are technical. If they can be made under control, then these approaches could definitively overcome the use of the elastic structure function, $A(q^2)$, for the determination of the neutron charge form factor. The present spreading of the values of $G_E^n(q^2)$ obtained by these methods around $q^2 = 9fm^{-2}$ at MAMI [1] indicates that an accurate determination of the neutron charge form factor may require more time than previously foreseen.

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