ELECTROMAGNETIC INTERACTIONS AND
MESONIC DEGREES OF FREEDOM IN NUCLEI

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ABSTRACT

We discuss the different aspects of electromagnetic interactions in nuclei, in connection with the parametrization of the Nucleon-Nucleon potential in terms of mesonic degrees of freedom. Meson-Exchange Currents are derived in perturbation theory, and we shall first detail their relation with our present description of nuclear and nucleon structure. From a quantitative point of view, they can be related to the Nucleon-Nucleon potential by the conservation of the current, and we shall show how this relation can be used to determine precisely all the parameters of the leading contributions (electromagnetic and hadronic form factors). The relationship between Meson-Exchange Currents and relativistic corrections are then discussed in the light of the recent experimental results on two- and three-body form factors.

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Abstract: We discuss the different aspects of electromagnetic interactions in nuclei, in connection with the parametrization of the Nucleon-Nucleon potential in terms of mesonic degrees of freedom. Meson-Exchange Currents are derived in perturbation theory, and we shall first detail their relation with our present description of nuclear and nucleon structure. From a quantitative point of view, they can be related to the Nucleon-Nucleon potential by the conservation of the current, and we shall show how this relation can be used to determine precisely all the parameters of the leading contributions (electromagnetic and hadronic form factors). The relationship between Meson-Exchange Currents and relativistic corrections are then discussed in the light of the recent experimental results on two- and three-body form factors.

The understanding of Meson-Exchange Currents (MECs) has made a lot of progress these last years, in the light of experimental results on two- and three-body elastic and inelastic form factors up to momentum transfers of about 1 GeV/c. We would like to discuss here what is the standard model of MECs, or in other words, what are the properties of MECs that are now under theoretical control. From a qualitative point of view, it is important to realize that the electromagnetic (elm) properties of nuclei can not be disentangled, on the one hand, from the modification of the elm properties of the nucleon when it is embedded in the nuclear medium, and on the other hand, from the description of the interactions between nucleons in nuclei, or from the content of the nuclear wave function. We shall discuss this particular point in sect. 1, while in sect. 2 we shall detail how the conservation of the current can give us all the information on electromagnetic and hadronic form factors we need in order to determine unambiguously the two-body elm current. In sect. 3 we shall make a connection between the perturbative expansion of electromagnetic operators (giving rise to MECs) and non-perturbative

relativistic calculations in the few-body system (Relativistic Impulse Approximation (RIA)).

We would like to emphasize here that the understanding of MECs is absolutely necessary in order to reveal the relevant degrees of freedom in nuclei, for momentum transfer of about 1 GeV/c. This is the only way one can interpret correctly all the available experimental results on the two- and three-body systems, and check whether our present description of the NN potential in terms of meson-exchange (π, ρ and ω mesons for the most important contributions) has some reality or not.

1. Meson-Exchange Currents and Nucleon/Nuclear Structure

Let us first recall here how the elm properties of the free nucleon (charge radii, magnetic moments, form factors) are understood at low and medium energy, starting for instance from a bag description for the confinement of the quarks. In this picture, the elm properties involve a priori two different parts. The first one comes from the direct coupling of the photon to the quark content of the nucleon, and is determined, roughly speaking, by the quark confinement radius R_C (bag radius). The second part involves the electromagnetic coupling to the polarization cloud mediated by the pion field outside the bag. It is thus easy to understand that the elm properties of the nucleon are automatically modified in the nuclear medium. First of all, the quark degrees of freedom inside the confinement region can be excited in the medium so that components other than the pure nucleonic one can be present in the nuclear medium (isobar, radial excitations of the nucleon). Secondly, the pion field surrounding the nucleon is expected to change in the medium, from Pauli blocking as well as from higher order Δ -hole polarization. Contributions from heavier mesons can be deduced as well in terms of 2π and 3π exchange. *All these corrections are accounted for properly in perturbation theory by taking into account MECs.*

In this framework, it is expected that MEC operators will depend on the nature of the NN potential, and on the corresponding equation of motion used to calculate the nuclear wave function. As an example, we shall mention in the following the Paris potential [1] used in the Schrödinger equation, or the Bonn potential [2] used in a non-relativistic reduction of the Bethe-Salpeter equation, including retardation effects (energy-dependent potential). In the latter case, an explicit πNN component is included in the two-body wave function. It amounts to about 3.5% in the deuteron, almost equally separated into S- and D-state components [3].

From a quantitative point of view, the relation between the NN potential -and equation of motion- and the electromagnetic operator is expressed by the conservation of the current. In the *Schrödinger* formalism for instance, and in the limit of small momentum transfer, it is given by :

$$\nabla \mathbf{J} + i [\mathbf{H}, \rho_0] = 0 \quad (1)$$

where $H=T+V$, T being the non-relativistic kinetic energy and V the *energy-independent* NN potential, while ρ_0 is the one-body charge density operator. Writing $\mathbf{J} = \mathbf{J}^1 + \mathbf{J}_{\text{ex}}$, the one-body operator $\mathbf{J}^1$ is associated to the kinetic part of the total Hamiltonian, while the two-body current $\mathbf{J}_{\text{ex}}$ comes from the interaction between the two nucleons. In the following, we shall mainly discuss MECs associated with the Paris potential since these are well documented and have a large experimental support.

The continuity equation (1) is only a constraint that the total elm current should of course satisfy. It can not determine the exact current, since only its longitudinal component is involved in (1). The theoretical assumptions that have to be made in order to define completely MECs can be summarized as follows. As we already mentioned, we first have to define the relevant degrees of freedom in nuclei, at low and medium energies. In the standard description of nuclear structure, we are dealing with nucleonic and mesonic degrees of freedom. The elementary interactions between these are expressed in an effective Lagrangian, incorporating all the fundamental symmetries we know are important at that scale, and in particular chiral symmetry.

In the non-relativistic limit, one can thus derive a NN potential, and all the parameters of the Lagrangian (coupling constants), as well as vertex renormalizations (form factors) are fitted to NN phase shifts and various observables, or inferred directly from $\pi\pi$ and πN amplitudes. They may in principle be calculated from the underlying theory (QCD), but they involve non-perturbative aspects which are not yet tractable quantitatively.

Finally, one also has to define what are, from a theoretical point of view, the free nucleon elm properties, i.e. what are the elm form factors of the free nucleon up to momentum transfer of about 1 GeV/c. The only theoretical model we have up to now is the well-known Vector Meson Dominance (VMD) model [4]. This model can be further modified in order to take into account the intrinsic structure of the nucleon [4.b]. We would like to emphasize here that the (theoretical) knowledge of the nucleon form factors is essential for extrapolating MEC operators at high momentum transfer.

With these assumptions in mind, MECs are unambiguously defined, and we show in Figs. 1 the first order diagrams which one can think of. The contributions of Figs. 1.a,b,c are respectively the contact diagrams associated with the derivative nature of the meson-nucleon vertices, the pair diagrams involving intermediate antinucleon states, and the

Figs. 1 : First order Meson-Exchange Currents

mesonic diagrams corresponding to the direct coupling of the photon to the charged mesons. All these contributions are necessary in order to satisfy the continuity equation (1).

The first two diagrams are associated with the tensor part of the NN potential, very well described in terms of π - and ρ -exchange, while the pair diagrams (mainly σ , ω and ρ exchange) correspond to the NN spin-orbit potential [5]. We shall come back later to the particular pair diagram associated with σ -exchange. All the parameters involved in these diagrams are fixed from the NN potential or from the description of the electromagnetic form factors in the VMD model. We shall discuss in more detail in Sect. 3 the relationship between the contribution of Fig. 1.b (pair diagrams) and the non-perturbative results from relativistic calculations.

As we already mentioned in the introduction, the diagram of Fig. 1.d involves nucleon excited states and is associated with the quark structure of the nucleon. This diagram gives only a small contribution in the few-body systems but is non-negligible as the density increases. The contribution of the N^* radial excitation (Roper resonance) for instance can account (qualitatively at least) for the apparent swelling of the nucleon confinement size in the nuclear medium [6]. Finally, the contribution of Fig. 1.e is important for isoscalar magnetic transitions (" $\rho\pi\gamma$ " diagram). While it is not constrained whatsoever in the standard approach of MECs, it has been related, in the framework of the Skyrme model for the nucleon structure, to the baryon current ("topological" current) [7] associated with the chiral anomalies of QCD. The equivalent $\rho\pi\gamma$ coupling constant may be fixed in principle from this connection. In the framework of the VMD model, it is related to the $\gamma \rightarrow 3\pi$ coupling constant. A first determination of this coupling has been reported recently and analyzed in terms of a chiral effective Lagrangian of the Skyrme type [8].

The discussion of the experimental evidence for MECs can be found in ref.[9]. We would just like to emphasize here that one should be very careful in comparing experimental results with theoretical predictions. As we can imagine from our previous discussion, it is important to have a clear definition of the theoretical model of MECs, and a check of its internal consistency, independently of any comparison with experimental results. In other words, the validity of our model of MECs comes not from the comparison between theory and experiment, but rather from the consistency of the model with respect to current conservation, the choice of the NN potential and the non-relativistic expansion of the covariant elm operator.

2. Structure of Meson-Exchange Currents and Gauge Invariance

The continuity equation (1) or its covariant extension at high momentum transfer [10] can be used to relate both elm and hadronic form factors entering in the operator $\mathbf{J}$, to the elm form factors of the charge density operator and to the hadronic form factors of the NN potential. In the non-relativistic expansion, this equation must be satisfied order by order in a $1/M$ expansion. To illustrate that point, let us consider the most important contribution

associated with π -exchange. As far as the elm form factors are concerned, it is a priori expected that the contributions of Fig. 1.b and 1.c should be proportional to the nucleon elm form factors F_1 and F_2 and to the pion form factor F_π , respectively. The former are defined according to :

$$J_\mu^1(q^2) = \Psi [F_1(q^2) \gamma_\mu + i F_2(q^2) / 2M \sigma_{\mu\nu} q^\nu] \Psi \quad (2)$$

where $J_\mu^1(q^2)$ is the covariant one-body current operator and F_1 and F_2 are the Dirac and Pauli form factors associated with the longitudinal and transverse part of the current.

The strength of the contact diagram of Fig. 1.a is related at small momentum transfer to the axial form factor $g_A(q^2)$, via the well-known soft-pion theorems. In leading order, the only contributions to π -MECs are the contact and pionic diagrams of Figs. 1.a,c. The conservation of the current implies however that the elm form factor should be the same for both contributions, unless one considers other (off-shell) processes to compensate for the difference of the form factors. The equality of the pionic and axial form factors is in fact very well verified experimentally, since the radii associated with $F_\pi(q^2)$ and $g_A(q^2)$ are 0.66 fm and 0.68 fm respectively. The second requirement of current conservation is that the form factors must be also consistent with the charge density operator ρ_0 . Following the parametrization (3) of the covariant current, one can write up to order $1/M^2$:

$$\rho_0 \equiv \langle N(p') | J_0^1 | N(p) \rangle = F_1(q^2) - [F_1(q^2) + F_2(q^2)] \left[\frac{q^2}{4M^2} + i \frac{\mathbf{q} \cdot \boldsymbol{\sigma} \times \mathbf{p}}{4M^2} \right] \quad (3)$$

so that the leading part is proportional to $F_1(q^2)$. This part (more precisely its isovector piece, F_1^V , for the leading order isovector MECs), is the only one which contributes to eq.(1) [10]. The radius associated with $F_1^V(q^2)$ is 0.78 fm experimentally, but only 0.70 fm if the neutron electric form factor is neglected.

The situation is thus the following. In the simplest approximation, where one restricts to the contributions of Figs. 1, with the nucleonic current (2), the continuity equation imposes a unique choice for the electromagnetic form factors in the MEC operators. At small momentum transfer ($q^2 \approx m_\pi^2$), soft-pion theorems are predictive and the common form factor should be $g_A(q^2)/g_A(0)$, or $F_\pi(q^2)$. At higher momenta, the extension of the continuity equation (1) implies that the relevant form factors are rather $F_\pi(q^2)$ or $F_1^V(q^2)$ [10]. These form factors are identical in the pure VMD model, with a radius of 0.62 fm, and their difference can be attributed to the different finite size of the nucleon and pion (quark confinement radius of about 0.5 and 0.4 fm respectively) only [4.b]. Phenomenologically, one or the other can be used to calculate MEC operators in leading order. For historical reasons, $F_1^V(q^2)$ is usually assumed. The only ambiguity left is the small difference between these two form factors, which is of the order of 15% at $q=1\text{GeV}/c$, i.e. of the same importance as the electric form factor of the neutron.

The choice of F_1^V in the isovector contributions of Figs. 1.a,b,c is also

supported experimentally up to momentum transfer of about 1 GeV/c, for the deuteron electrodisintegration differential cross-section at threshold, and in the isovector magnetic form factor of the three-body systems, including MECs associated with the Paris potential [9].

We would like now to turn to the question of hadronic form factors. It is usually believed that electron scattering experiments at high momentum transfer, for $q^2 \approx 1 \text{ (GeV/c)}^2$, are able to investigate the very short-range content of the nuclear wave function, for let us say $r < 0.5 \text{ fm}$ (this distance corresponds to an overlap region of about 1/3 of the volume of each nucleon, for $R_C = 0.5 \text{ fm}$). This is certainly true if all the momentum is transferred to only one nucleon. However, for elastic scattering, the cross-section in the Impulse Approximation (IA) drops very rapidly at high momentum, and the dominant contributions come from two-body operators, e.g. MECs. This is particularly true for purely isovector magnetic transitions, and to a lesser extent for isoscalar magnetic and charge transitions. The momentum is thus shared by two nucleons, a much more favourable situation. Consequently, the sensitivity of the cross-section to the very short-range part of the wave function is much reduced. As an illustration, we plot in Fig. 2 the radial density $\beta(r)$ of the dominant M1 transition amplitude in the deuteron electrodisintegration at threshold, for $q \approx 1.1 \text{ GeV/c}$ ($q^2 = -30 \text{ fm}^{-2}$), defined as :

$$\langle d | M1 | ^1S_0 \rangle = iq / \sqrt{2\pi} \int_0^\infty dr \beta(r, q) \quad (4)$$

We represent in this figure the contribution from ρ -exchange only. The solid line indicates the bare exchange current (without hadronic form factors), while the dashed line incorporates a form factor with a cut-off parameter of $\Lambda_\rho = 1.5 \text{ GeV/c}$, in a monopole parametrization. The dash-dotted line corresponds to MECs associated with the 2π ($J=1, T=1$) contribution of the Paris potential, according to the derivation of refs.[11].

Fig. 2 : Radial density of isovector ρ -MECs, as defined in eq.(4)

As one can see very clearly from this figure, the contribution of ρ -MECs is peaked at about 0.8 fm for momentum transfer as large as 1.1 GeV/c. This is not of particularly short range, and compatible with the theoretical, medium-range, part of the Paris potential, and a confinement radius of about 0.5 fm for the nucleon [12]. Part of the damping of MECs at very short distances is due to the strong correlations in the nuclear wave function coming from the repulsion in the NN potential, the other part being due to phase space factors. As a consequence, the total cross-section will not be very sensitive to any modification of the very short-range part of the wave function. This kind of conspiracy against the manifestation of the quark degrees of freedom in nuclei may in principle be also valid at higher momenta, since the momentum could be transferred preferably to 3 or even more nucleons.

The second implication of Fig. 2 is that it is of some importance to keep track of the 2π content of the ρ -resonance, as is done in the Paris potential. Due to its distributed mass, the true ρ -meson contribution (denoted "generalized" ρ in Fig. 2) is of slightly larger range than the fixed mass ($m_\rho=776$ MeV) particle of zero width which is usually considered (indicated by dashed line in this figure). The difference between the two contributions is more pronounced at small momentum transfer [13]. From a phenomenological point of view, one may define an effective ρ -exchange by fitting the parameters of ρ -MECs (m_ρ , Λ_ρ and κ_ρ) to get the same MECs as the one given by the Paris potential. An overall agreement over the whole range of momentum transfer up to 1 GeV/c, can be obtained with :

$$\begin{aligned} m_\rho &= 600 \text{ MeV}, \\ \Lambda_\rho &= 1.1 \text{ GeV/c}, \\ \kappa_\rho &= 5.6 \end{aligned} \tag{5}$$

As expected, the mass of this effective ρ -meson is smaller than the bare mass, while the cut-off parameter is much smaller, and smaller than the pion cut-off parameter ($\Lambda_\pi=1.25$ -1.4 GeV/c). The ρ N tensor coupling constant κ_ρ is smaller than the strong value usually quoted ($\kappa_\rho=6.6$). This smaller value may be justified once the iteration of the one-pion-exchange is subtracted out from the ρ -meson contribution. We checked that the NN tensor potential obtained with the parameters (5), together with π -exchange, is in very good agreement with the Paris potential. These new parameters should be used in all one-boson-exchange approximations to the 2π exchange mechanism in the ρ -channel.

Note that for distances much less than 0.8 fm, the "generalized" ρ -MECs can not be deduced anymore from the Paris potential, since this latter is purely phenomenological at small distances. In the intermediate region, $r \approx 0.5$ -1 fm, MECs are strongly modified by hadronic form factors, as we discussed above. From a theoretical point of view, it is important to realize that these form factors have *a priori* two different contributions. First of all, they take into account the finite size of the nucleon. With a quark confinement radius of 0.5 fm for the nucleon, this leads to a rather short-range cut-off. However, vertex renormalization from multi-meson configurations may also be important [14]. Such contributions are visualized in

Fig. 3 : Typical contributions to the hadronic form factors, for π, ω -exchange (a), and for ρ, σ -exchange (b).

Figs. 3. We would like to emphasize that these corrections are quantitatively very different for π - and ω -exchange on the one hand, and ρ - and σ -exchange on the other hand. The former involve at least π and ρ mesons in the intermediate state, i.e. lead to a rather short-range cut-off, larger than about 1.2 GeV/c. The latter are strongly coupled to 2π exchange and therefore are associated to a cut-off parameter Λ less than, let us say, 1.2 GeV/c. This is compatible with the parametrization of the effective ρ -meson exchange given in (6).

These values for the form factors are consistent with the Paris NN potential through the continuity equation (1), and lead to a rather nice description of isovector form factors (deuteron electrodisintegration at threshold and magnetic form factors of ^3He and ^3H) [9]. The cut-off parameters used in the Bonn potential do not take into account the renormalization from multi-meson states and are therefore of much smaller range, in particular for σ - and ρ -NN form factors ($\Lambda=2$ and 1.5 GeV/c respectively). Consequently, the tensor part of the NN potential is rather different. Because of the strong tensor coupling constant κ_ρ which is used in the Bonn potential, together with a short range ρ NN form factor, this part becomes positive at distances less than about 0.4 fm, and the D-state wave function of the deuteron has a node at the same distance. The tensor potential is thus weaker in the Bonn parametrization than in the Paris derivation. This should partly explain the different D-state probabilities quoted for these two potentials ($P_D=5.75$ and 4.25% for the Paris and Bonn potentials respectively). As we already mentioned in the introduction, the energy dependence of the Bonn potential should be responsible for the remaining difference.

3. Meson-Exchange Currents and Relativistic Corrections

It is implicit from the description of electromagnetic operators in the framework of MECs that a perturbative expansion of the operator, in terms of Feynman diagrams for instance, is meaningful for momentum transfers of about 1 GeV/c. While the isovector current operators we discussed in the preceding section are of non-relativistic $1/M$ order, this is not true for the isoscalar current (order $1/M^3$) nor for the charge operators (relative corrections of order $1/M^2$ also).

Different approaches have been proposed these last years to account for relativistic corrections non-perturbatively. The relativistic nuclear wave function can be calculated "exactly" (from a numerical point of view) in the two-nucleon system, starting from a

given relativistic equation [15,16,17] (note that there is no consensus yet about the right equation of motion to be used). The deuteron elastic form factors calculated in the RIA incorporate automatically -and to all orders- the pair diagrams of Fig. 1.b, together with kinematical corrections to the wave function. However, for obvious numerical reasons, the calculation is almost always restricted to the IA [15,16], and therefore all exchange corrections of the type indicated in Figs. 1a,c,d,e are left aside. Consequently, the current is no longer conserved.

Furthermore, from a quantitative point of view, it turns out that purely relativistic corrections, in the RIA, are not very important for momentum transfer less than 1GeV/c. This is particularly clear if we compare the electromagnetic form factors of the deuteron calculated in presently available RIA and the non-relativistic limit. Note that in order to have a fair comparison, the non-relativistic limit must be calculated with the Bonn potential, since the two-body wave function includes in that case an explicit π NN component, as the relativistic calculations do (energy-dependent potential), and both correspond to a low D-state probability.

We show in Fig. 4 the deuteron elastic form factor $B(q^2)$ (directly related to the magnetic form factor). The solid line is the result of the non-relativistic IA with the Bonn

Fig. 4 : Elastic form factor $B(q^2)$ of the deuteron. The dashed and dot-dashed lines are obtained in the relativistic IA, with two different assumptions for the equation of motion (see text), and the solid line is the non-relativistic IA calculated with the energy-dependent Bonn potential.

potential, while the dashed and dot-dashed lines are the relativistic calculations of refs.[15,16]. The main difference between these two is in the asymmetric treatment of the two nucleons in the so-called "Gross equation" (one nucleon is restricted on the mass shell), while in the second approach, both nucleons can be off mass shell. They also assume different forms for the πNN coupling. In the first calculation, a mixing of pseudoscalar and pseudovector coupling is used, while in the second, a purely pseudovector coupling is taken into account. From the analysis of the πN amplitude, it is however expected that the pseudovector coupling is more appropriate [18] in relativistic calculations involving only linear couplings. Therefore, the results indicated by a dash-dotted line in Fig.4 should be more reliable. In that case, purely relativistic corrections associated with the pair diagrams of Fig. 1.b, together with recoil corrections and relativistic corrections to the one-body current are very small for momentum transfer less than about 1GeV/c and negligible compared to other MEC corrections.

Among these latter, the most important comes from the contribution of Fig. 1.e (" $\rho\pi\gamma$ " exchange current), and can account for the experimental data till about $q=1$ GeV/c. However, recent data taken at SLAC [19] show a minimum of diffraction at about 1.4GeV/c, while the simplest non-relativistic calculation, including only the " $\rho\pi\gamma$ " current does not [9]. As we indicated above in Fig. 4, relativistic corrections reduce the form factor at high momenta, and may help in getting the minimum of diffraction at the right place. A consistent calculation at the $1/M^3$ order remains to be done. Very similar results have been obtained for the isoscalar magnetic form factor of the three-body systems [9].

The situation is somewhat different for charge transitions. While the $A(q^2)$ form factor of the deuteron (combination of charge and quadrupole form factors) is not sensitive to MECs but rather to the electric form factor of the neutron, the isoscalar and isovector charge form factors of the three-body systems are much more interesting. They show a minimum of diffraction at a relatively small momentum transfer, $q \approx 0.65$ GeV/c, and the simple IA result cannot account for it, as indicated in Fig. 5 (dashed line). Some relativistic corrections have already been calculated [20] (contact π -exchange current, relativistic corrections to the one-body charge operator given in eq.(4)) and are indicated by solid lines in Fig. 5. A large discrepancy still persists around the first minimum. Several new contributions may explain such difference. First of all, MECs are rather complicated to calculate at that order, since they involve non-local terms which have been neglected. Furthermore, a consistent calculation of short-range processes (ρ -exchange and hadronic form factors) has not yet been achieved. Short-range corrections from isobar degrees of freedom associated with 2π exchange [21] can give also non-negligible contributions. In the simple OBE approximation, they are simulated by the pair diagram of Fig. 1.b with σ -exchange. The equivalence of these two approaches has not yet been proved quantitatively, as far as the elm current is concerned

Finally, a modification of the three-body wave function is expected from purely three-body forces. This is certainly a very interesting question which requires going beyond the present parametrization of the three-body force, limited to too small momentum transfer for the moment. New measurement of the charge form factor of ^3He around the second maximum

Fig. 5 : Isoscalar and isovector charge form factors of the three body systems. The dashed line is the non-relativistic IA calculation (using the Paris potential) and the solid line includes MEC and relativistic corrections as calculated in [18] (see text). The shaded area indicates a fit to the experimental results [8], while the dot-dashed line shows the highest momentum transfer available.

($q^2 \approx 10-15 \text{ fm}^{-2}$) may indicate also that the experimental form factor has been overestimated up to now. If this is confirmed, the remaining discrepancy between experiment and the present model of MECs may be much reduced. These questions have certainly to be settled before one can think of investigating the quark degrees of freedom in the three-body wave function.

We would like to emphasize, in conclusion, that MEC operators cannot be disentangled from the impulse approximation contribution, and that both one- and two-body operators have to be calculated consistently order by order. This is the only way the electromagnetic current can satisfy the continuity equation associated with the NN potential we start from to calculate the nuclear wave function.

Consequently, the most natural way to describe electromagnetic operators is to calculate them in perturbation theory, by considering first order MECs. In such a scheme, one can clearly identify the leading contributions and extract all the physical information from the most recent electron scattering experiments. Quantitatively, it turns out that the most important corrections we have to deal with in calculating MECs are short-range contributions associated with heavy meson exchange and hadronic form factors. These contributions are now rather well understood up to about $q \approx 1 \text{ GeV}/c$, and correspond to relative distances of about 0.5-1 fm.

In order to investigate the very short-range part of the two-body wave function, for $r < 0.5 \text{ fm}$, and to eliminate the ambiguity in the choice of electromagnetic form factors, it has

been necessary to rely up to now on rather crude models for the nucleon structure at medium energies. To go further, and in the perspective of the new generation of electron machines, it is important to have a unified view of the long- and short-wavelength components of the nucleon structure, in terms of mesonic degrees of freedom on the one hand, and quark components on the other hand.

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