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FEW-NUCLEON SYSTEMS, MESON-EXCHANGE CURRENTS
AND Δ -EXCITATIONS

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ABSTRACT

In the light of the present description of the Nucleon-Nucleon potential in terms of meson-exchange, we discuss first of all what are the most interesting contributions to the nuclear wave function, paying particular attention to 2π exchange associated with isobar components in the wave function. Direct evidence for mesonic degrees of freedom in nuclei is revealed by electromagnetic interactions, giving rise to the so-called Meson-Exchange Currents. We shall detail the important aspects of these currents at low and medium energies by studying neutron radiative capture by protons and deuterons on the one hand, and the photodisintegration of the deuteron on the other hand.

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Abstract : In the light of the present description of the Nucleon-Nucleon potential in terms of meson-exchange, we discuss first of all what are the most interesting contributions to the nuclear wave function, paying particular attention to 2π exchange associated with isobar components in the wave function. Direct evidence for mesonic degrees of freedom in nuclei is revealed by electromagnetic interactions, giving rise to the so-called Meson-Exchange Currents. We shall detail the important aspects of these currents at low and medium energies by studying neutron radiative capture by protons and deuterons on the one hand, and the photodisintegration of the deuteron on the other hand.

It is now widely recognized that the relevant degrees of freedom in nuclei, at low and medium energies, are nucleons and low-lying mesons (π , ρ and ω), as given by the present parametrization of the Nucleon-Nucleon (NN) potential for energies less than a few hundred MeV. Furthermore, it is expected that the electromagnetic interaction is the best tool to investigate these degrees of freedom from an experimental point of view. However, in order to achieve this goal, one needs to understand precisely what are the different components of the electromagnetic current in nuclei, i.e. Meson-Exchange Currents (MECs), in connection with our description of the nuclear wave function and the NN potential. We shall discuss in sect. 1 from a qualitative point of view the general structure of the NN potential, paying particular attention to the 2π exchange mechanism involving isobar components in the intermediate state. In sect. 2, we discuss the different components of the electromagnetic current, and develop the standard model of MECs. In sect. 3 we detail how neutron radiative capture by protons and deuterons can give us interesting information on both MECs and the nuclear wave function. The relationship between MECs and relativistic corrections are discussed in sect. 3 and illustrated by the photodisintegration of the deuteron for energies less than 150 MeV.

1. STRUCTURE OF THE FEW-NUCLEON SYSTEMS

The long-range part of the NN potential is certainly the most accurately known and is generated from the exchange of π -meson (One-Pion-Exchange-Potential, OPEP). This part of the potential provides an extremely good description of the overall static properties of the deuteron [1], and gives rise to a large tensor component in the wave function. The medium- and short-range parts of the interaction can be generated as well from two- and three-pion exchange, although such a construction is much more complicated.

The most natural way to take into account multiple π -exchange is to use dispersion relation technics to evaluate the typical contributions shown in Fig. 1. The important ingredients in the calculations are the πN and $\pi\pi$ scattering amplitudes, as

Fig. 1 : Two-pion exchange contribution to the NN potential from $\pi\pi$ and πN amplitudes

represented by hatched boxes in this figure. The part which comes from two uncorrelated pions is shown in Figs. 2. It involves isobar components in the intermediate states, and both crossed and uncrossed diagrams contribute and are important.

It turns out, however, that the general amplitude of Fig. 1 can be parametrized, in first approximation, by the exchange of heavier mesons and give rise in particular to the concept of the $\sigma(0^+,0)$ particle (for the S channel) and in the P channel to the $\rho(1^-,1)$ resonance.

Figs. 2 : Uncorrelated two-pion exchange mechanism at intermediate range

In perturbation theory, this equivalence can be represented by the diagram of fig. 3, in the case of the S channel for instance. The hatched boxes correspond to 2π vertex corrections which may involve isobar intermediate states as indicated in fig. 4. The mass and coupling constant are fixed from a fit to the available NN phase shifts and observables, and one finds approximately $m_\sigma \approx 550$ MeV and $g_\sigma^2/4\pi \approx 5-10$. In the One-Boson-Exchange (OBE) approximation, the strength of the σ -exchange potential could in principle be calculated. The term associated with correlated 2π -exchange is fixed by the $\pi\pi$ amplitude, while the uncorrelated contributions of Figs. 2 can be calculated explicitly. The renormalization factors

Fig. 3 : Scalar-isoscalar meson exchange contribution to the NN potential equivalent to 2π exchange at intermediate range

Fig. 4 : Elementary contribution to the σNN vertex renormalization

at the σNN vertex (hadronic form factor) can also be estimated, as indicated in Fig. 4. Because of the 2π exchange in the intermediate state, a relatively small cut-off parameter is expected, of the order of 1 GeV/c in a monopole parametrization of the form factor for instance, while it is about 1.25-1.4 GeV/c at the πNN vertex (πp exchange in the intermediate state in this last case).

In the same spirit, the 3π contribution to the NN potential may be simulated in first approximation by πp exchange mechanism. In the OBE approximation, it contributes mostly to the $\omega(1^-,0)$ meson channel, and is simulated by increasing the bare ωNN coupling

constant. Typical fits to NN phase shifts lead to a total strength of about $g_{\omega}^2/4\pi \approx 15-20$.

The potential constructed in this way is momentum (and/or energy) dependent. This is certainly not very surprising, since at short distances the potential has no reason to be local. The shape for the momentum-dependent part is generally restricted to relative distances smaller than 1 fm. We can find in the literature several parametrizations of the NN potential, and they may be classified according to their description of the medium- and short-range part. Let us mention here the Paris potential [2], constructed from dispersion relations to take into account explicitly all the information on 2π - and part of the 3π -exchange contribution. On the other hand, the Bonn parametrization [3] relies on the perturbation expansion in terms of π , ρ and ω exchanges. A phenomenological σ -exchange is included to account for the attraction in the S-channel $\pi\pi$ amplitude, but the two-meson diagrams of figs. 2 are explicitly taken care of. Finally, the potential constructed by the Nijmegen group [4] is a pure OBEP, since 2π and 3π exchange are simulated by phenomenological σ - and ω -exchanges.

For energies of the order of a few hundred MeV, the energy dependence of the Paris potential is transformed into a new momentum dependent term, and the potential can be used very easily in a Schrödinger formalism. On the other hand, the Bonn potential is implicitly momentum- and energy-dependent, and includes all retardation effects in the meson exchange diagrams. We shall detail in the following sections the electromagnetic currents associated with the Paris potential, since these are the most accurately known and are well documented. Because of the energy dependence of the Bonn potential, the analysis of electromagnetic operators is more difficult in that case and poorly known at the present time.

For low momentum transfer processes, we are mainly concerned with the long-range part of the nuclear wave function, largely dominated by the π -exchange mechanism. This part dominates almost completely the central part of the deuteron wave function. Furthermore, from an analysis of the experimental effective range parameter, it has been shown that this part can account for about 94% of the total normalization of the deuteron wave function (for an energy-independent potential) [1]. The remaining part is due to the tensor component, essential to get the right binding energy of the deuteron on one hand, and of nuclear matter on the other hand. It is important to realize here that in the Bonn parametrization of the NN potential, an explicit π NN component is included in the two-body wave function through the energy dependence of the potential. It amounts to about 3.5% in the deuteron, almost equally separated into S- and D-state components. This should explain, qualitatively at least, the different D-state probabilities quoted for the Paris ($P_D=5.75\%$) and Bonn ($P_D=4.25\%$) potentials [5].

For sufficiently large distances, ($r > 1.5$ fm) the tensor part of the wave function is very close to its asymptotic form, defined as :

$$w(r) \rightarrow \eta A_S e^{-\alpha r} (1 + 3/\alpha r + 3/(\alpha r)^2), \quad (1)$$

where η is the D/S ratio. It is given by [4] :

$$\eta = 2\sqrt{8}/A_S M \int_0^\infty r' dr' j_2(r') V_T(r') = \int \eta(r') dr'. \quad (2)$$

In this expression, $j_2(r')$ is the regular solution of the homogeneous Schrödinger equation for the D-state component. If rescattering is neglected, it is equivalent to the spherical Bessel function $j_2(i\alpha r')$.

The dominance of the π -exchange mechanism for large distances is illustrated in Fig. 5 where we show the radial density $\eta(r)$ defined in eq. 2, using different assumptions for the NN potential [1]. The solid line is the exact result from the Paris NN potential, while the dash-dotted line corresponds to the OPEP only. This part accounts for about 95 % of η . The radial dependence of the correction is indicated by a dashed line. It is concentrated around 1 fm, and is expected to arise from 2π exchange (ρ contribution to the tensor potential).

Other small components are expected to contribute also to the deuteron wave function. We mentioned above the possibility of exciting $N\Delta$ and $\Delta\Delta$ components in the two-body wave function. In the uncrossed approximation, only the $\Delta\Delta$ components can contribute to the deuteron wave function. Quantitatively, 3S_1 , 3D_1 , 7D_1 and 7G_1 states can be generated from the S- and D-wave NN components [6]. The dominant contributions is by far the 7D_1 component. The transition potential $V_{\Delta\Delta} : {}^3S_1 (NN) \rightarrow {}^7D_1 (\Delta\Delta)$ is reasonably well approximated by the tensor part of π - and ρ -exchange. It has been argued, however, that

Fig. 5 : Radial density of the deuteron D/S asymptotic ratio defined in (2), as a function of the relative distance between the two-nucleons, taken from ref. [1]. The solid line represents the exact calculation with the Paris potential, and the dash-dotted line is obtained with the OPEP only. The dashed line is the difference between the two calculations.

explicit 2π exchange contributions besides the ρ -meson contribution are not completely negligible. Fortunately, from a practical point of view, they can be incorporated in the transition potential simply by reducing the range of the potentials [7,8].

The $\Delta\Delta$ -component probabilities in the deuteron we obtain in such a scheme are detailed in table 1. We also report in this table the results corresponding to a transition potential deduced from π -exchange without form factors. One can note that because of the tensor nature of the transition potential, the ρ meson acts as a natural cut-off of π -exchange and therefore decreases by about a factor of three the $\Delta\Delta$ -component probability calculated from π -exchange only. Furthermore, the total potential is then much less dependent on the range of the cut-off parameters of the hadronic form factors. This is particularly important for further developments on the three-body forces and isobar contributions to MECs.

	3S_1	3D_1	7D_1	7G_1	Total
π -exch. (%)	0.05	0.05	1.5	0.2	1.8
$\pi\rho$ -exch. (%)	0.05	0.05	0.3	0.05	0.45

Table 1 : Probabilities of the isobar components in the deuteron for two different assumptions. The first line corresponds to a π -exchange transition potential calculated without form factors, while the second line includes in addition ρ -exchange and form factors. Explicit 2π exchange contributions have been included in the results of the second line according to ref. [7].

The $N\Delta$ component in the np ($T=1$) system can be generated as well. It is worthwhile noting that the probabilities of the $\Delta\Delta$ and $N\Delta$ components in this particular $T=1$ channel are of the same order of magnitude, although the energy denominator in the $\Delta\Delta$ intermediate state is much larger. This is due to the strong coupling constant $g_{\pi N\Delta}$ which is $\sqrt{72/25} g_{\pi NN}$ in the constituent quark model. Other components involving radial excitations of the nucleon (the Roper resonance for instance, $M=1440$ MeV) are expected to contribute for less than 0.2% in the normalization of the deuteron wave function.

We can thus reasonably assume that the components associated to nucleon excitations in the deuteron wave function contribute to about 0.5%. This probability, with a corresponding D-state probability of about 5.5%, is consistent with the model independent estimate of the S-wave component from the effective range parameter we mentioned above

2. ELECTROMAGNETIC INTERACTIONS AND MESON-EXCHANGE CURRENTS

Let us first recall here how the electromagnetic properties of the free nucleon (charge radius, magnetic moment, 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 electromagnetic 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 electromagnetic properties of the nucleon are automatically modified when the nucleon is embedded 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 (isobar, radial excitations of the nucleon, etc...). 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. We illustrate in Fig. 6 how a typical MEC correction arises from Pauli blocking on the pionic contribution to the free nucleon magnetic moment. 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.*

Fig. 6 : Pionic contribution to the magnetic moment of the nucleon. When the nucleon is embedded in the nuclear medium, the intermediate state indicated by a cross on Fig. 6.a is forbidden from the Fermi sea. The corresponding modification of the nucleon magnetic moment is precisely taken into account by the mesonic exchange current of Fig. 6.b

Quantitatively, the relation between the NN potential and the electromagnetic current in the nucleus is expressed by the conservation of the current. In the non-relativistic *Schrödinger* formalism, and in the limit of small momentum transfer, this condition is given by:

$$\nabla \mathbf{J} + i [\mathbf{H}, \rho_0] = 0 \quad (3)$$

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. If one writes $\mathbf{J} = \mathbf{J}^1 + \mathbf{J}_{ex}$, 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, and are the so-called MECs. From eq. (3) one can expect a priori two types of contributions. The first one is associated to the isospin dependence of the NN potential (isovector currents), and the second to its momentum dependence. Note that only the longitudinal part of the current is constrained by the continuity equation (3).

In this framework, MECs are unambiguously defined, and we show in Figs. 7 the first order diagrams which one can think of. The contributions of Figs. 7.a,b,c are respectively the contact (seagull) diagram associated with the derivative nature of the meson-nucleon vertices, the pair diagram involving intermediate antinucleon states, and the mesonic diagram 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 diagrams a and c are associated with the (isospin dependent) tensor part of the NN potential, very well described in terms of π - and ρ -exchange, while the pair diagram (mainly σ , ω and ρ exchange) corresponds to the NN spin-orbit potential (momentum-dependent part).

Figs. 7 : First order Meson-Exchange Currents: a) seagull , b) pair, c) mesonic
d) isobaric and e) " $\rho\pi\gamma$ " and " $\omega\pi\gamma$ " diagrams. They are indicated here in the static approximation for simplicity.

As we already mentioned in the introduction, the diagram of Fig.7.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 becomes 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. Finally, the contribution of Fig. 7.e is important for isoscalar magnetic transitions. While it is not constrained whatsoever in the standard approach of MECs (transverse current), it has been related, in the framework of the Skyrme model for the nucleon structure, to the baryon current ("topological" current) [9] associated with the chiral anomalies of QCD. The equivalent $\rho\pi\gamma$ coupling constant may be fixed in principle from this connection.

However, all the operators associated to these diagrams do not appear at the same level, in a $1/M$ expansion for instance. Because of the continuity equation (3), the isovector magnetic current is of leading $1/M$ order. The long-range part (π -exchange of figs.7.a and c) is given by the well-known soft-pion limit, and relies only upon the general structure of the underlying theory, namely chiral symmetry, current algebra and PCAC [10]. Short-range corrections associated to ρ -exchange and hadronic form factors can be deduced from eq.(3), for a given NN potential [11]. Relativistic corrections to the soft-pion limit (contribution of the pair diagram of Fig. 7.b and non-static corrections), as well as corrections to the impulse approximation current are of order $(1/M)^3$. At zero momentum transfer, they contribute to the deuteron magnetic moment, in qualitative agreement with the experimental moment. These various corrections are however rather difficult to calculate, and there is no consistent calculation available at that order. The leading isovector currents, soft-pion limit and short-range corrections, are on the other hand under control through the continuity equation (model-independent contributions).

As far as the charge density is concerned, there is no contribution to MECs in order $(1/M)^0$. Corrections arise at the $(1/M)^2$ order (mainly the contact term of fig. 7.a associated with π -exchange), but they have also to be calculated consistently with relativistic corrections to the impulse approximation charge operator. We shall come back to that point in sect. 4.

In first order (one-meson exchange), the only correction to the electromagnetic current associated with the isobar degree of freedom in the nuclear wave function is the isobaric diagram of Fig. 7.d. For small relative energy between the two nucleons, it is relatively small compared to the contact and pionic contributions of Figs. 7.a,c, and involves only S to D transitions (tensor component). The high momentum behaviour of all these contributions can be tested very nicely in the deuteron electrodisintegration near threshold for instance [12]. Second-order contributions can involve $\Delta\Delta$ components in the deuteron, and are associated with the 2π exchange contributions to the NN potential indicated in Figs. 2.,

Fig. 8 : Second order isobar contributions to Meson-Exchange Currents.
Only a limited set of corrections is indicated here.

together with πp and $p p$ exchange. We indicate in Fig. 8 a (very) limited set of contributions only. It is rather easy, but very tedious, to calculate all the contributions at that order. To our knowledge, a consistent calculation of all these contributions has only been done for the deuteron magnetic moment [13]. As we mentioned in the preceding section, the contributions of (both correlated and uncorrelated) 2π exchange are simulated in the OBE approximation by a single σ -meson exchange, with a coupling constant fitted to the NN phase shift, while πp exchange contributions are simulated by increasing the bare ωNN coupling constant. In this simple representation, MEC operators associated to the two-meson exchange part of the NN potential, as given in Fig. 8, are restricted to the pair diagram of Fig. 7.b with σ and ω exchange. They are related, through the continuity equation (3) to the spin-orbit part of the NN potential (note that there is no one-pion exchange contribution to the spin-orbit potential). The equivalence of the two representations of the intermediate range attraction in the NN potential has not yet been confirmed quantitatively, as far as MECs are concerned [14].

3. A TEST CASE: NEUTRON RADIATIVE CAPTURE

Two kinds of experiment can provide complementary information on the electromagnetic currents. Electron scattering experiments on the two- and three-body systems (elastic and inelastic form factors) are particularly interesting since they can investigate the momentum dependence of MECs, and hence the radial dependence of the operators. A complete set of experimental results are now available up to momentum transfer of about 1 GeV/c [15]. Various questions related to electromagnetic and hadronic form factors can thus be studied, as well as the contribution of relativistic corrections to MECs. On the other hand, low-energy, real photon experiments are sensitive to lowest order MECs only, and are free from ambiguity arising in the parametrization of electromagnetic form factors at high momentum transfer.

Historically, the radiative neutron capture by protons was the first,

unambiguous indication that MEC corrections to the isovector current operator play an important role in electromagnetic transitions [16]. A preliminary study of the MEC corrections to the axial current in the beta decay of the triton was already known [17], and provided similar information. As we mentioned earlier, the contributions of MECs can be classified in three different groups. The most important one corresponds to the long-range part of the NN potential, and is related to relative distances of about 1.4 fm (at zero momentum transfer). The intermediate range corresponds to 2π exchange (mainly ρ -exchange for isovector transitions), together with corrections from the hadronic form factors at the πNN and ρNN vertices. They contribute mostly for relative distances of the order of 0.8-1 fm. Finally, the very short range part of the current, for $r \leq 0.5$ fm for instance, is relatively unknown at the present time, and involves ultimately the intrinsic structure of the nucleon.

We illustrate these different parts in Fig. 9, where we plot the radial density of the M1 amplitude dominant in the thermal neutron capture by protons [18], according to :

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

Fig. 9: Radial density of the dominant M1 transition in the thermal np capture, as defined in eq.(4). The solid line (soft-pion limit) corresponds to π -MECs (seagull and mesonic diagrams) calculated without form factors. The dashed line (short-range contributions) incorporates ρ -MECs together with corrections from hadronic form factors. The contribution of the isobaric diagram is not included here.

The solid line corresponds to the π -exchange current in the soft-pion limit (long wavelength limit, i.e. without hadronic form factors), while the dashed line represents short-range contributions associated with ρ -exchange and hadronic form factors. Note that because of the correlations in the nuclear wave function induced by the strong repulsion in the NN potential at short distances, the very short-range MEC corrections do not contribute appreciably. The dominance of the soft-pion contribution is very clear in that figure.

The elementary np capture cross-section is particular from many points of view. First of all, the experimental cross-section is known with a very high accuracy [19] :

$$\sigma^{\text{exp}} = 334.2 \pm 0.5 \text{ mb} \quad (5)$$

while a careful analysis of the Impulse Approximation (IA) contribution to the cross-section is available [20]. The most important uncertainty in the theoretical calculation of this part comes from the asymptotic behaviour of the initial-state wave function, since the momentum transfer carried by the photon is almost zero. One thus arrives at the following estimate of the IA contribution :

$$\sigma^{IA}=302.2\pm 4\text{mb} \quad (6)$$

Explicit calculations with realistic NN potentials confirm this analysis. After correcting the $T=1$ scattering length according to experiment, one obtains the following cross-sections [21] in the IA :

$$\sigma = \begin{cases} 305 \text{ mb (TS)} \\ 302 \text{ mb (Paris)} \\ 300 \text{ mb (RSC)} \end{cases} \quad (7)$$

for the de Tourreil-Sprung (TS) [22], Paris, and Reid soft core (RSC) [23] potentials respectively. The small differences between these results are essentially due to the different short-range repulsion (the TS potential is very soft while the RSC potential has a rather hard core, the Paris potential lying in between the two). The 10.5% discrepancy between experiment and one-body contribution is thus significant, and cannot be accounted for by any change in the nuclear wave function only.

The transition involved in this process connects the S and D states of the deuteron to the 1S_0 scattering state at zero energy, so that one can expect a sizeable correction from isovector MECs. The dominant contributions come from the seagull and mesonic diagrams of Figs.7.a and c associated with π -exchange. Corrections from the first order isobar contribution are also sizeable. All the different results are summarized in table 2 as a function of the relative correction to the IA amplitude. Depending on the NN potential, a correction of about $\delta^{exp} \approx 5.2 \pm 0.8\%$ is needed in order to recover the experimental cross-section.

The soft-pion limit (long-range π -exchange contribution to the mesonic and seagull diagram without hadronic form factors) is indicated in the first line of this table for the particular case of the TS potential. Note that the transition to the D-state of the deuteron represents about 40% of the total correction. The mesonic current is about 20% of the seagull contribution, with opposite sign. The correction from the isobar diagram is also indicated in table 2 with the separate contribution of π - and ρ -exchange. It includes the full,

	Seagull + Pair (1)			Mesonic (2)			Total (1+2)			Isobaric
	SS	SD	tot.	SS	SD	tot.	SS	SD	tot.	SD
$\pi\text{-MEC}_{SP}$	2.85	0.57	3.42	-1.14	0.57	-0.57	1.70	1.15	2.85	1.35
S.R.			0.23			0.07			0.30	-0.70
Total			3.65			-0.50			3.15	0.65

Table 2: Different contributions to the thermal np capture amplitude, relatively to the impulse approximation. The line $\pi\text{-MEC}_{SP}$ denotes MECs associated with π -exchange without hadronic form factors (soft-pion limit), while the line denoted S.R. represents MECs associated with ρ -exchange together with corrections from the hadronic form factors at the πNN and ρNN vertices.

non-static propagator for the $N\Delta$ intermediate state. Note that this diagram involves only S to D transitions. The original estimate of this contribution was $\delta \approx 1.50\%$ [16]. Even larger corrections can also be found in the literature. The correct treatment of the $N\Delta$ intermediate state, avoiding the static approximation, together with the natural cut-off due to ρ -exchange reduce the contribution of this diagram by about a factor of 2.5.

Finally, the short range corrections to the mesonic and seagull diagrams are indicated in table 2. They incorporate both ρ -meson contributions and corrections from the hadronic form factors (a phenomenological monopole form in momentum space is used with cut-off parameters $\Lambda_\pi = 1.25$ GeV/c and $\Lambda_\rho = 1.5$ GeV/c). The ρ -contribution is calculated here in leading order. The total contribution of short-range processes is indeed small for this low momentum transfer process, and at least of the same order of magnitude as the uncertainty in the nuclear wave function. The total correction due to short-range phenomena, together with the isobar contribution amounts to about $\delta^{s.r.} \approx 0.95\%$ so that the complete calculation gives $\delta^{th.} \approx 3.80\%$ with the TS potential. This correction is $\delta^{th.} \approx 3.90\%$ and $\delta^{th.} \approx 4.15\%$ with the Paris and RSC potentials respectively.

The remaining discrepancy between theory and experiment is of the order of $1.2 \pm 0.2\%$ of the IA amplitude, depending on the nuclear wave function. No explanation is yet given for this small discrepancy. It may originate either from other MEC operators, such as the " $\omega\pi\gamma$ " isovector contribution given in Fig. 7e, or alternatively from a small defect in the nuclear wave function, and hence in the large IA matrix element. Second-order contributions involving $N\Delta$ and $\Delta\Delta$ intermediate states are expected to cancel each other to a very high extent. The remaining discrepancy fixes the limit of the present understanding of the isovector MECs at zero momentum transfer, as well as of the two-body wave functions. On the experimental side, the total cross-section (5) should also be confirmed by new measurements.

The range of the hadronic form factors mentioned above corresponds roughly to a confinement radius of the quark in the nucleon of the order of 0.5 fm. A smaller range (or larger radius) will increase even more the discrepancy between theory and experiment. For example, with a nucleon r.m.s. confinement radius of 0.7 fm, the corrections to the IA amplitude is only $\delta^{th.} \approx 3.50\%$ for the TS potential [24].

The similar process for the three-body system, $n+d \rightarrow {}^3\text{H} + \gamma$, was also investigated very early [25]. Contrary to the thermal np capture, the IA cross-section is not dominant since it proceeds through the S' (mixed symmetry) and D components of the ${}^3\text{H}$ wave function, with about 1% and 8% probability respectively. The completely symmetric S-state component is almost orthogonal to the unbound nd state. The dominant contribution is also a M1 transition, and MEC corrections are expected to be of the same type as those discussed above. As we mentioned in sect. 3, they are rather well under control through the continuity equation (3). Their contributions are given in table 3 for the TS potential, taken from ref.[26]. Experimentally, the total cross-section is [27]:

$$\sigma^{\text{exp.}} = 0.518 \pm 0.018 \text{ mb} \quad (8)$$

while the IA contribution amounts to :

$$\sigma^{\text{IA.}} = \begin{cases} 0.439 \text{ mb (RSC)} \\ 0.343 \text{ mb (TS)} \\ 0.258 \text{ mb (TS mod.)} \end{cases} \quad (9)$$

The IA contribution is indicated in ref.[26] for two different potentials (RSC and TS). The last result noted (TS mod.) has been calculated with a modified version of the TS potential in order to have the correct asymptotic normalization and includes in addition some three-body correlations. The correction due to MECs are summarized in table 3 (calculated with TS potential) and presented in a form similar to the corrections obtained for the thermal np capture of table 2, since the transitions involved are very similar. The short range part of MECs in this table includes in addition to ρ -exchange small contributions from ω -exchange and " $\omega\pi\gamma$ " processes, but does not include any corrections from hadronic form factors. The

δ	Scagull + Pair (1)			Mesonic (2)			Total			Isobaric
	SS	SD	tot.	SS	SD	tot.	SS	SD	tot.	SD
π -MEC	62	12	74	-34	12	-22	28	24	52	43
S.R.			4			≈ 0			18	-15
Total			78			-22			70	28

Table 3: Different contributions to the thermal neutron capture by deuterons. The quantity δ indicated in this table is defined as $\sigma^{\text{IA+MEC}} = \sigma^{\text{IA}}(1+\delta)^2$, where σ is the total (doublet + quartet) cross-section. The lines are the same as in table 1. (see text for the exact content of the line S.R.).

results quoted in this table are therefore an upper limit for the short range part of MECs and it explains why the short range contributions given in table 3 are relatively large compared to those of table 2. The isobar contribution indicated in the table is calculated in the static limit, and overestimates the exact contribution by about 70%, if one extends the results of the two-body capture. All these corrections give a total cross-section (IA and MECs) of about 0.75 mb with the TS potential, and 0.87 mb (0.635 mb) with the RSC (TS mod.) potentials. Short-range corrections from hadronic form factors, and a better treatment of the isobar contribution will reduce the theoretical prediction by a sizeable amount.

The precision of the last published experimental result indicated in (8) is not as good as that of the np capture ($<1\%$) but is nevertheless sufficient to discriminate between different NN potentials. Indeed, this process may be considered as a good candidate for testing the small S'- and D-state components in the ^3H wave function [28], assuming that MEC corrections are fixed from the two-body np capture cross-section. The comparison of the results reported in tables 2 and 3 confirm this point of view. As already indicated in ref.[26], the cross-section is also sensitive to the three-body correlations in the wave function. The thermal neutron capture by deuterons *must* therefore be studied together with static properties of the three-body systems, in order to check the validity of the different assumptions one can make about the components of the three-body wave function. The main difficulty is essentially on a technical level, since one has to calculate the nd wave function in the continuum. The results obtained in this particular calculation seem to indicate that nuclear wave functions with three-body correlations, together with a correct asymptotic normalization are preferred (result noted TS mod.). A calculation of the IA and MEC contributions with the (more realistic) Paris potential should be made.

The situation may in fact improve very rapidly, since new and very interesting results are reported by K. Abrahams and collaborators at this symposium [29]. The total cross-section indicated in (9) involves both transitions to doublet and quartet states for the unbound initial state. As detailed in ref.[26], MECs increase the doublet cross-section by about a factor of 5, while they decrease the quartet contribution by 25 %. Furthermore, the balance between doublet and quartet contributions is sensitive to the detail of the nuclear wave function. By measuring the circular polarization of the photon in $\text{D}(n,\gamma)$, these authors have been able to disentangle both contributions. With the present accuracy, the results confirm the main conclusions we presented above in the case of the total cross-section. However, as mentioned by the authors, further investigations will be able to pin down precisely the two contributions to the cross-section. This is certainly of utmost importance in order to investigate the small components of the nuclear wave-functions, and in particular the role of the three-body force in the three-body systems.

4. MESON-EXCHANGE CURRENTS AND RELATIVISTIC CORRECTIONS

It is implicit from the description of electromagnetic operators 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 [30] (note that there is no consensus yet about the right equation of motion to be used). However, for obvious numerical reasons, the calculations are restricted to the IA, and therefore all exchange corrections of the type indicated in Figs. 7.a,c,d,e are left aside. The contribution of Fig. 7.b, on the other hand, is calculated exactly to all orders. Consequently, the electromagnetic current is no longer conserved. In the present state of the art, the perturbative expansion we developed in sect. 2, leading to MECs, is therefore to be preferred.

Of course, for charge transitions or isoscalar magnetic transitions for which MECs are of relativistic order, a consistent treatment of all contributions is absolutely necessary. Quantitatively, relativistic corrections to the elastic form factors of the deuteron are rather small, and only sizeable for momentum transfer larger than 1 GeV/c [8]. On the other hand, the interest in the deuteron photodisintegration cross-section has recently been revived in the light of relativistic corrections to the IA and MEC operators [31]. The interesting quantity turns out to be the forward differential cross-section for photon energy in the range 0-140 MeV for which experimental results are available [32]. In leading order, the photodisintegration of the deuteron at zero degree proceeds only through the D-state of the deuteron, and has a large contribution from the E1 transition associated with the charge density operator. While the non-relativistic charge operator is of order 1, MECs and relativistic corrections to the IA are of order $(1/M)^2$. Corrections to the M1 transition arise from MECs only.

Although the IA differential cross-section is sensitive to the particular NN potential [33], it can be noted that only the long-range part of the D-state wave function is concerned. This part is mostly dependent on the unambiguous π -exchange contribution to the asymptotic normalizations that each realistic NN potential should reproduce correctly. The IA results for this process are shown in Fig. 10 (dash-dotted line) for the Paris potential. Even with large experimental errors, the discrepancy for large E_γ is meaningful, and of the order of 50%. Taking into account MEC corrections to the current operator in the M_1 transition corrects the differential cross-section at low energy (small dashed line). These corrections correspond to the usual seagull, mesonic and isobar diagram of Figs. 7.a,c and d [11b]. Corrections to the E_1 transition are of relativistic order since they involve the charge density operator. Thus both MEC corrections (mostly the seagull term) and relativistic (kinematical) corrections to the IA charge operator (spin-orbit and Darwin-Foldy contributions) have to be considered [31]. The inclusion of the one-body relativistic corrections are indicated in this figure by the long-dashed line while the complete calculation including MEC and relativistic corrections up to order $(q/M)^2$ is indicated by the solid line. This last result also takes into account relativistic corrections to the nuclear wave function ([34] as calculated in [31.b]).

The largest contribution comes from the relativistic corrections to the IA charge operator and reduces almost entirely the large discrepancy between IA and experimental results in the whole range of available photon energy. This is certainly the clearest evidence that genuine relativistic corrections may be important for specific transitions, at low and medium energies. Further corrections due to MECs to the charge and current operators are of

Fig. 10 : Deuteron photodisintegration cross-section at zero degree as a function of the photon energy, taken from [32]. Dash-dotted line: Impulse approximation (IA) contribution; small dashed line: IA and MEC corrections to the M1 magnetic multipole; long dashed line: with further inclusion of relativistic corrections to the one-body charge operator; solid line: total result with MEC corrections to the charge operator. The wave functions are calculated with the Paris potential. The experimental results have been taken from ref. [32], the two new measurements reported at this symposium are indicated by empty boxes.

relatively minor importance. This result is expected to be largely model-independent since short-range corrections to the MEC contribution are rather small for the M1 transitions, as we saw in the preceding section, and the correction to the charge density is dominated by an unambiguous relativistic (kinematical) correction to the IA charge density.

On the experimental side, the situation is not so clear. The tail of the differential cross-section at zero degree is relatively well known for $E_\gamma > 50$ MeV, although the error bars are still large. The region $E_\gamma < 50$ MeV is however not so well understood, and all the experimental results available up to now are not compatible among themselves. As indicated by A. De Graeve and collaborators [35], the dip around 10 MeV is confirmed. This part of the cross-section is given mostly by the M1 transition, and may depend slightly on the NN potential. On the other hand, the various experimental results at energies between 15 and 50 MeV are not yet consistent. It would be rather difficult in fact, from a theoretical point of view and in the present understanding of MECs and relativistic corrections, to accommodate the latest experimental point mentioned at 15 MeV. Further confirmation of the experimental results is certainly of great importance.

Similar features appear also for the differential cross-section at fixed energy. The results are summarized in Fig. 11 for a set of two different photon energies, and with the most recent experimental results [36]. As in Fig. 10, the dash-dotted line represents the cross-section in the IA approximation calculated with the Paris potential, the small dashed line includes MEC corrections to the M1 operator associated to the same NN potential [11.b] together with isobar corrections. The solid line is the result from the relativistic calculation already discussed above. The agreement with the latest experimental results is of the same - very good - quality as for the forward photodisintegration cross-section [31.a,b]. The exact shape of the differential cross-section can only be accounted for with relativistic corrections to the charge density operator. The analyzing power for the reaction $n+p \rightarrow d+\gamma$ at $E_\gamma = 180$ and 270 MeV is also shown in Fig. 11 with the same notation. Corrections from the relativistic charge density operator are not yet available for these energies.

Fig. 11 : Differential cross-section and analysing power of the deuteron photodisintegration for two different energies. The lines are the same as in Fig. 10.

We presented in this review only a few particular aspects of the mesonic description of nuclear structure, and its consequences for electromagnetic interactions in nuclei. Three different parts can be separated out in the NN potential and electromagnetic operators. The first one corresponds to the well-known π -exchange mechanism, and we detailed how it appears in the asymptotic behaviour of the deuteron wave function, and how it leads to large MEC corrections to the thermal np and nd captures (isovector currents).

The medium-range contribution, associated with 2π exchange is now rather well understood quantitatively, and a consistent description of MEC operators and the NN potential is possible through the conservation of the electromagnetic current. We show in particular how a new generation of polarization experiments $D(\vec{n}, \gamma)$ will be able to test very precisely the three-body wave function, and may have access to the three-body force in nuclei.

The short-range part of the NN potential ($r \leq 0.5$ fm) is almost purely phenomenological at present. It is associated to 3π -exchange but large corrections from the intrinsic structure of the nucleon can be expected.

Apart from isovector MECs which are now rather well under control, very clear evidence of genuine relativistic (kinematical) corrections in nuclei can be found in the deuteron photodisintegration cross-section at medium energies. Precise experimental measurements in the region $E_\gamma = 10-50$ MeV are still required in order to give definite predictions on MEC corrections and the deuteron wave function.

The various information which one can collect from neutron radiative capture or photodisintegration of the deuteron is rather complementary to those given by the elastic

and inelastic form factors of the few-body systems. It is more concerned with the content of the nuclear wave function (and the NN potential), since now MECs are rather well understood at low momentum transfer. On the other hand, electron scattering experiments at high momentum transfer are much more sensitive to the detail of the electromagnetic current (electromagnetic and hadronic form factors for instance). The results obtained these last few years on both theoretical and experimental sides can give us some confidence in our understanding of the mesonic degrees of freedom in nuclei at low and medium energies.

REFERENCES

- [1] T.E.O. Ericson and M. Rosa-Clot, *Ann. Rev. Nucl. Part. Sci.* **35** (1985) 497.
- [2] M. Lacombe *et al.*, *Phys. Rev.* **C21** (1980) 861.
- [3] R. Machleidt, K. Holinde and Ch. Elster, *Phys. Rep.* **149** (1987) 1.
- [4] M.M. Nagels, T.A. Rijken and J.J. de Swart, *Phys. Rev.* **D17** (1978) 768.
- [5] B. Desplanques, "Deuteron D-state probability and frequency-dependent NN interactions" Preprint IPNO/TH 87-26, Orsay.
- [6] G.H. Niephaus, M. Gari and B. Sommer, *Phys. Rev.* **C23** (1981) 504.
- [7] J.W. Durso *et al.*, *Nucl. Phys.* **A278** (1977) 445.
- [8] J.-F. Mathiot, Physics Reports, in preparation.
- [9] E.M. Nyman and D.O. Riska, *Nucl. Phys.* **A468** (1987) 473.
- [10] M. Rho, *Ann. Rev. Nucl. Part. Sci.*, **34** (1984) 531.
- [11] a. D.O. Riska, *Phys. Scrip.* **31** (1985) 471.
b. A. Buchmann, W. Leidemann and H. Arenhövel, *Nucl. Phys.* **A443** (1985) 726.
- [12] J.-F. Mathiot, *Nucl. Phys.* **A412** (1984) 201.
- [13] W. Jaus, *Nucl. Phys.* **A314** (1979) 287.
- [14] B. Desplanques, private communication
- [15] B. Frois and C.N. Papanicolas, *Ann. Rev. Nucl. Part. Sci.*, (1987) to be published.
- [16] D.O. Riska and G.E. Brown, *Phys. Lett.* **38B** (1972) 994.
- [17] M. Chemtob and M. Rho, *Phys. Lett.* **29B** (1969) 540.
- [18] J.-F. Mathiot, *Phys. Lett.* **187B** (1987) 235.
- [19] A.E. Cox *et al.*, *Nucl. Phys.* **74** (1965) 497.
- [20] H.P. Noyes, *Nucl. Phys.* **74** (1965) 508.
- [21] J.-F. Mathiot, *Phys. Lett.* **115B** (1982) 174.
- [22] R. De Tourreil and D.W.L. Sprung, *Nucl. Phys.* **A201** (1973) 193.
- [23] R.V. Reid, *Ann. Phys.* **50** (1968) 411.
- [24] J.-F. Mathiot, Chr. Bargholtz and G.E. Brown, *Nucl. Phys.* **A397** (1983) 365.
- [25] E. Hadjimichael, *Phys. Rev. Lett.* **31** (1973) 183.
G. Konopka, M. Gari and J.G. Zabolitsky, *Nucl. Phys.* **A290** (1977) 360.

- [26] J. Torre and B. Goulard, Phys. Rev. **C28** (1983) 529.
- [27] V.P. Alfimenko *et al* ,Sov. J. Nucl. Phys. **32** (1980) 771.
E.T. Jurney, P.T. Bendt and J.C. Browne, Phys. Rev. **C25** (1982) 2820.
A.C. Phillips, Nucl. Phys. **A184** (1972) 337.
- [28] T.E.O Ericson and N.Lo Iudice, preprint CERN-TH 4652/87
- [29] K. Abrahams *et al.* , special invited paper at this symposium.
- [30] M.J. Zuilhof and A. Tjon, Phys. Rev. **C24** (1981) 736.
R.G. Arnold, C.E. Carlson and F. Gross, Phys. Rev. **C21** (1980) 1426.
- [31] a. A. Cambi, B. Mosconi and P. Ricci, Phys. Rev. Lett. **48** (1982) 462.
b. A. Cambi, B. Mosconi and P. Ricci, J. of Phys. **G10** (1984) L11.
c. J.L. Friar, B.F. Gibson and G.L. Payne, Phys. Rev. **C30** (1984) 441.
d. W. Jaus and W.S. Woolcock, Nucl. Phys. **A431** (1984) 669.
- [32] S. Platchkov, Nucl. Phys. **A446** (1985) 151c.
- [33] H. Arenhövel and W. Fabian, Nucl. Phys. **A282** (1977) 397.
M. Gari and B. Sommer, Phys. Rev. Lett. **41** (1978) 22.
E. Hadjimichael, Phys. Lett. **85B** (1979) 17.
- [34] J.L. Friar and B.F. Gibson, Phys. Rev. **C15** (1977) 1779.
- [35] A. De Graeve *et al.*, contribution to this symposium.
- [36] J.M. Cameron *et al.* , Nucl. Phys. **A458** (1986) 637.