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Low Energy Inclusive Processes and High Energy Exclusive Reactions in Heavy Nuclei[1]

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ABSTRACT. Some low energy properties of nuclei, namely binding energy, number of Δ-resonances in the ground state and longitudinal electromagnetic response to low momentum probes are examined in the frame of a bosonic loop expansion within a mesonic theory. It is shown that these quantities require a 1-loop calculation. Furthermore, it it shown that at this order in the loop expansion the results are extremely sensitive to the high momentum behaviour of the effective interaction. A high energy electron accelerator is shown to be the mosto convenient tool to explore the effective nuclear interaction in the required region.

1 Introduction

The present paper is mainly devoted to low energy nuclear phenomena. We shall consider, in particular, the binding energy, the number of Δ-resonances in the ground state and the response to an electromagnetic probe at low momentum transfer.

This kind of topics seems not to fit with the purpose of the workshop, namely to study which kind of information on nuclei can be achieved with a 15 GeV electron accelerator. We wish to show the contrary, i.e. that only high energy experiments can solve the uncertainties hidden in low energy phenomena like the above noted ones.

This seemingly paradoxical statement will be discussed and (we hope) clarified throughout this paper. We only anticipate here the key of our reasoning. It is well known, the pion propagation in the nuclear medium is unavoidably linked to a residual interaction (usually simulated by the Landau parameter g') embodying the effect of short range correlations (SRC). We shall see that 1-loop corrections to the mean field (a precise definition of them being deferred to the next section) critically depend upon the q-behaviour of g', which can by no means be constant. Thus only experiments at high transferred momentum, like $(e, e'2p)$ or $(e, e'pn)$, able to detect SRC, can provide the needed informations to consistently describe those properties which critically depend upon the pion propagation in the nucleus.

In sect. 2 we shall introduce the formalism defining the mean field and its quantum fluctuations, in sect. 3 we shall discuss the effect of SRC, sects. 4, 5 and 6 will be devoted to the analysis of the binding energy, the number of Δ's in nuclear matter and the longitudinal e.m. response respectively. Finally sect. 7 is devoted to the description of the exclusive experiments which, hopefully, can solve the uncertainties displayed by the previous calculations.

2 The Formalism

To illustrate the formalism, we introduce a simplified model of nonrelativistic (n.r.) nucleons and pions interacting via the n.r. lagrangian

$$\mathcal{L}_{\rm int}(x) = i\frac{f_\pi}{m_\pi}\psi^\dagger(x)\left(\nabla\cdot\sigma\vec{\tau}\cdot\vec{\phi}(x)\right)\psi(x)\,. \tag{1}$$

This because by one side we are mainly interested to pion propagation, and, on the other one, this model is sufficient to fix the language and provide the ideas we need. Generalizations will be introduced when required.

Next we add a coupling with an external pion-like classical source, $\vec{J}(x)$, in term of which a generating functional can be defined as

$$Z[\vec{J}] = \int \mathcal{D}[\psi^\dagger, \psi, \vec{\phi}]\, e^{iS + i\int dx\, \psi^\dagger(x)\left(\nabla\cdot\sigma\vec{\tau}\cdot J(x)\right)\psi(x)} \tag{2}$$

with

$$S = \int dx\, dy\, \left\{\psi^\dagger(x)G_0^{-1}(x,y)\psi(y) + \frac{1}{2}\vec{\phi}(x)D_0^{-1}(x,y)\vec{\phi}(y)\right\} + \int dx\, \mathcal{L}_{\rm int}(x) \tag{3}$$

G_0 and D_0 being the free nucleon and pion propagators respectively.

Once Z is known, many quantities can be accessed by means of functional derivatives [1]: to exemplify the polarization propagator is

$$\Pi^{ij}_{\rm tot}(x,y) = i\frac{\delta^2 \log Z}{\delta J_i(x)\delta J_j(y)}\bigg|_{J=0}\,. \tag{4}$$

In the present form, eq. (2) can be expanded perturbatively or at most some classes of diagrams can be summed up. What is lacking is a criterion to choose the class of diagrams, besides of course the feasibility of the calculations.

To get it we integrate functionally on the fermion fields in (2), thus constructing an effective action $S^B_{\rm eff}$ containing as true degrees of freedom only the bosonic ones, but on the other hand exactly equivalent to (2) as far as physical results are concerned

[1] Talk presented at the Workshop on European Electron Facility, Mains, October 7–9, 1992

(see refs. [1,2,3] for more details on the derivations. See also [4] for field-theoretical applications). With a shift of the integration variable $\phi(x)$, in fact, Z turns out to be

$$Z[\vec{J}] = \int \mathcal{D}[\vec{\phi}] e^{iS^B_{\rm eff} + \int dx\, \vec{\phi}\cdot J} \tag{5}$$

with

$$S^B_{\rm eff} = \frac{1}{2}\int dx\, dy\, \vec{\phi}(x) D_0^{-1}(x,y)\vec{\phi}(y) - V_\pi \tag{6}$$

the effective vertices of the theory being

$$V_\pi = -i{\rm Tr}\sum_{n=2}^{\infty}\frac{1}{n}\left\{i\frac{f_\pi}{m_\pi}\left(\sigma\cdot\nabla\vec{\tau}\cdot\vec{\phi}\right)G_0\right\}^n . \tag{7}$$

The multilinear nonlocal vertices contained in V_π keep memory of the presence of nucleons, as they describe closed fermion loops with any number of external pionic legs (see fig. 1).

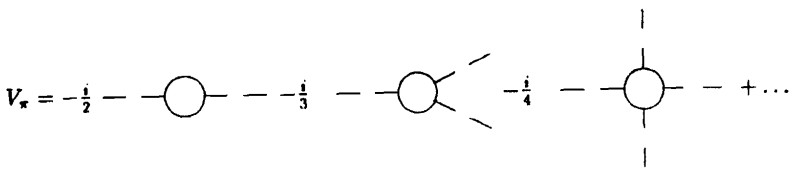

Figure 1: The vertices of the effective action V_π

The effective action is the tool we need, since we can carry out a semiclassical expansion starting from it. Without describing technical details, which can be found in the above quoted references, we give here a qualitative discussion. Thanks to the absence of tadpoles the mean field propagation of the pion is given by the bilinear terms of the effective action, i.e.

$$\frac{1}{2}\int dx\, dy\, \vec{\phi}(x) D^{-1}_{\rm m.f.}(x,y)\vec{\phi}(y) = \frac{1}{2}\int dx\, dy\, \vec{\phi}\left[D_0^{-1}(x,y) - \Pi^{(2)}(x,y)\right]\vec{\phi}(y)\,, \tag{8}$$

$\Pi^{(2)}(x,y)$ being the first term of the series of fig. 1. The corresponding pion propagation is illustrated in fig. 2.

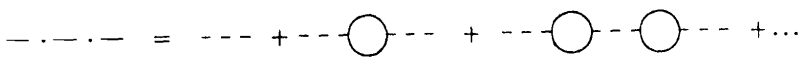

Figure 2: Mean field pion propagation

Other possible processes at the mean field level are for instance $\pi \to 2\pi$ or $2\pi \to 2\pi$, as illustrated in fig. 3

The classification of the possible mean-field-level diagrams is very simple: they are all the tree diagrams with respect to the mean field pion propagation (dash-dotted line in fig. 2).

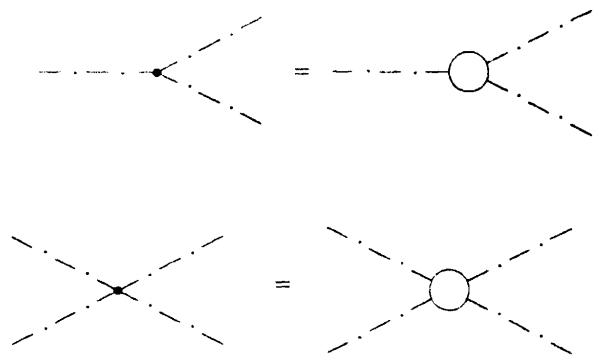

Figure 3: Possible processes at the mean field level

We remind that this classification is purely topological, no matter what kind of π-N interaction and of nucleon propagator (relativistic or not) we choose neither it reminds the presence (or the absence) of the nuclear medium. So for instance the $\pi \to 2\pi$ process is forbidden in the vacuum and in an infinite nuclear medium, while it is allowed in a finite system.

Finally we discuss the mean field property more relevant to us. *For any process we are considering at the mean field level no integrations are allowed on the meson momenta. The only integration occurs in the fermionic loops hidden in V_π, but this is always cut by k_F. Thus the energy range explored at the mean field level is the one of the external momenta plus, at most, k_F.* Thus a mean field calculation is self-consistent also in the sense that internal processes involve the same energy and momentum range as the external probes.

The situation is dramatically different at the next level of complications.

The classification of the diagrams is, again, very simple. The semiclassical expansion is indeed a loop expansion, the loops being counted in terms of the mean field boson propagation (again the dash-dotted line of fig. 2). Thus the quantum fluctuations around the mean field (1-loop corrections) correspond to all the diagrams with one bosonic loop. To exemplify the 1-loop corrections to the pion propagator are shown in fig. 4.

Now, at 1-loop level *no cut exists, in principle, on the boson loop momentum.* Consequently new energy and momentum regions are explored.

Two comments are in order:

1. A physical cutoff must nevertheless exist, in order to force the convergence of the loop integral.

2. Situations exist (and we shall examine some of them) for which the mean field approximation fails. In these cases the previously quoted cutoff becomes the crucial parameter of the theory.

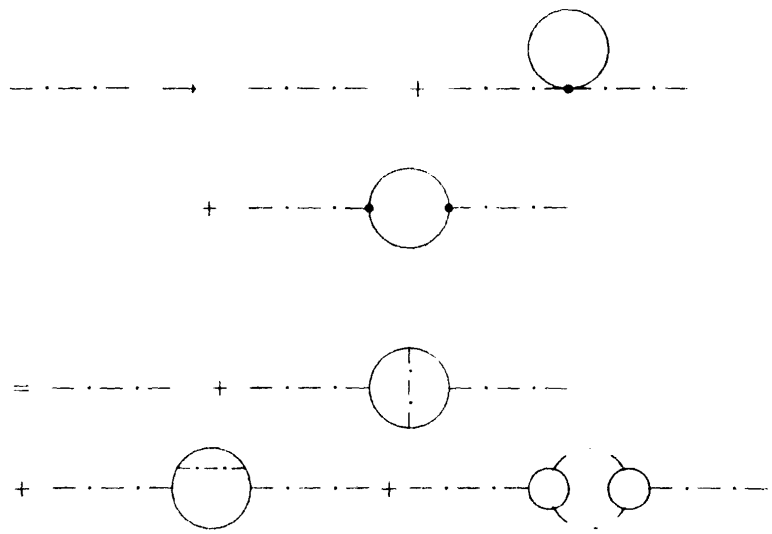

Figure 4: 1-loop corrections to the pion propagator and their explanation in terms of fermions

3 1-Loop Corrections and SRC

Now we wish to clarify the meaning of the last comments. Consider for example the subdiagram of fig. 5, contained in one of the diagrams of fig. 4 (more precisely the one with a self-energy insertion in the fermion loop). This is the simplest pathological diagram and has the advantage of displaying the disease in an immediate way.

Let $\mathbf{p}$ be the momentum circulating inside the boson loop. If we assume for the pion exchange the classical form

$$V_{\text{OPEP}} = -\frac{f_\pi^2}{m_\pi^2}\frac{(\boldsymbol{\sigma}_1\cdot\mathbf{p})(\boldsymbol{\sigma}_2\cdot\mathbf{p})}{\mathbf{p}^2+m_\pi^2}\vec{\tau}_1\cdot\vec{\tau}_2 \tag{9}$$

we see that in fig. 4 we have to evaluate it between a particle-hole pairs in the spin-longitudinal channel, where V_{OPEP} reads

$$V_{\text{OPEP}}^{(\text{long})} = -\frac{f_\pi^2}{m_\pi^2}\frac{\mathbf{p}^2}{m_\pi^2+\mathbf{p}^2} \tag{10}$$

and we immediately recognize that the loop integral over $\mathbf{p}$ diverges.

This statement seems to be (and it is, indeed) ingenuous, since it is clear that the diagram *must* converge. The point is to explain why it does: there are at least three good reasons for that, listed below, the most relevant being the last one:

1. we know that in a covariant renormalizable theory (like the pseudoscalar one) the diagram is finite. The disturbing divergence quoted above comes from the

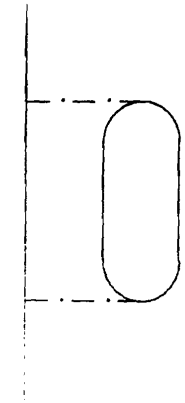

Figure 5: A self-energy insertion

$\mathbf{p}^2$ factor in the numerator of (10). Why relativity weakens the p-behaviour of the πNN vertex? The reason is that a compensation comes from the antinucleon components. This sets to $2M$ (M being the nucleon mass) the natural cutoff imposed by the relativity. Such an outcome is not satisfactory: would this be the main reason ensuring convergence, then all dynamics up to 2 GeV should be accounted for in order to make 1-loop calculations reliable: a very hard job.

2. The nucleons are not pointlike: a form factor at the πNN vertex should also ensure convergence. We know (see for instance the analysis of ref. [5]) that a good value for the cutoff is in this case $\Lambda_\pi \simeq 1.3$ GeV/c: quite an improvement with respect to the previous item, but still a big value.

3. Finally let us remind SRC. We see that $V_{\text{OPEP}}^{(\text{long})} \to 1$ as $\mathbf{p}\to\infty$. In coordinate space this means that a $\delta(\mathbf{r})$ is active, while we know that SRC suppress it. Thus V_{OPEP} must be replaced by its correlated version. This can be done in two different ways:

   (a) following [6] we make the replacement

   $$V_{\text{OPEP}}(r) \to g(r)V_{\text{OPEP}}(r) \tag{11}$$

   $g(r)$ being the pair correlation function. A simple model for $g(r)$ is also suggested by [6] in the form

   $$g(r) = 1 - j_0(q_c r) \Longrightarrow g(q) = \delta^{(3)}(\mathbf{q}) - \frac{2\pi^2}{q_c^2}\delta^{(1)}(q-q_c) \tag{12}$$

   $g(q)$ being the Fourier transform of $g(r)$. q_c is usually taken of the order of the ω-meson mass.

(b) Correlations are usually accounted for in the pion propagation by embodying them in g'. Even from the definition of the Landau parameters it is clear however that this is correct in the limit of small pion momentum: in order to get the correct high-momentum behaviour too, we have to write $V_{\rm OPEP}$, projected on the spin-longitudinal channel, as

$$V_{\rm OPEP}^{\rm (long)} = -\frac{f_\pi^2}{m_\pi^2}\frac{\mathbf{p}^2}{\mathbf{p}^2+m_\pi^2} \to \frac{f_\pi^2}{m_\pi^2}\left\{g'_L(\mathbf{p}) - \frac{\mathbf{p}^2}{\mathbf{p}^2+m_\pi^2}\right\} \tag{13}$$

with the condition

$$g'_L \xrightarrow[p\to\infty]{} 1 \tag{14}$$

In the present calculations we shall put

$$g'_L(p) = 1 + (g'_0 - 1)\left[\frac{q_c^2}{p^2+q_c^2}\right]^2 \tag{15}$$

where g'_0 denotes the value of the Landau parameter in the static limit.

The two possible versions of the correlated interaction are more or less equivalent: as pointed out in ref. [7] the correlated Pion plus Rho Exchange Potential has the correct behaviour at high momenta and corresponds, in the static limit, to $g'_0 \simeq 0.65$, a quite reasonable value.

In the remaining of this paper we wish to show the sensitivity of some low-energy properties of nuclei to the parameter q_c, which is the lowest one of the 3 cutoffs discussed before and, consequently, the dominant one in the 1-loop calculations.

4 The Nuclear Binding Energy

One of the most widely studied topics in the nuclear physics, namely the saturation point of the nuclear matter, is the first example we shall be concerned with. Let us resume some well known facts:

1. the long range part of the N-N potential (usually ascribed to the one pion exchange) is responsible for a great part of the nuclear binding. As an example, in fig. 7 the B.E. is plotted for the Reid Soft Core potential (calculations follow the scheme of ref. [8]) with and without the pion tail. Needless to say, the difference is dramatic.

2. We know that the deuteron ground state is well described by means of $V_{\rm OPEP}$ only and that its tensor part is decisive in providing the binding, the central part being largely insufficient. The same is expected in nuclear matter too. ***But the mean field approximation (fig 6a) is known to kill the tensor force contributions.*** Thus at least two pion exchanges have to be accounted for: ***just what 1-loop corrections do.*** Thus to account for the main contribution to the nuclear binding we cannot stop ourselves to the mean field level, but a 1-loop calculation is required.

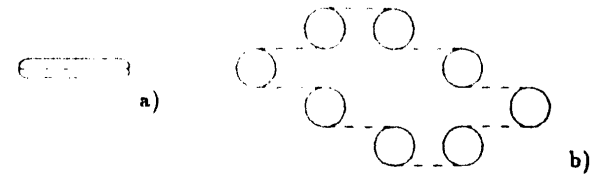

Figure 6: Binding energy diagrams: mean field (a) and 1-loop corrections (b).

To this purpose we generalize the Brückner-GellMann formula [9,10], used in evaluating the correlation energy of an electron gas in the jellium model, which sums up the class of diagrams of fig 6b. The explicit calculation for the jellium model is a classical result which can be found in textbooks [10]; its generalization to the pion physics, even in presence of a potential-like residual interaction summarized by g' does not present any conceptual difficulty: the explicit derivation can be found in [11] and the final formula reads

$$\frac{B.E.}{N} = \frac{E_0}{N} - \frac{3}{2\rho}\int\frac{d^3k}{(2\pi)^3}\log\left[1 - \frac{f_\pi^2}{m_\pi^2}\left(g'(k) - k^2 D_0(k)\right)\Pi^0(k)\right] \tag{16}$$

where ρ denotes the nuclear density, Π^0 is the usual Lindhard function and E_0 denotes the uncorrelated ground state energy (actually the kinetic term). To be more realistic one has to add the Δ-holes contributions as well, and this is done by adding to Π^0 the corresponding Δ-hole Lindhard function with the correct coupling constants and form factors.

In fig. 7 the results of the calculation are reported: solid line represents the standard lowest order Brückner theory with Reid Soft Core (RSC) potential and the dotted line is the same calculation but without the pion tail in the RSC interaction. Dashed and dot-dashed lines represent the repulsive part of RSC plus the correlation energy evaluated according to eq. (16) with different values of q_c (600 MeV/c and 900 MeV/c respectively). Here g' has not been included at the lowest order level, since such a contribution has been already accounted for in the RSC repulsive part. Of course the procedure of simply adding a background coming from RSC-OPEP to the results of the Brückner-GellMann formula is questionable and the results cannot be thought as realistic. Our aim was however to show how the results depend upon the critical parameter q_c, and this scope has been clearly reached, as fig. 7 shows: for the chosen value of g'_0 in fact the existence or not of a cutoff in the effective interaction is decisive in establishing even the stability of the nuclear matter.

5 Δ-components in the Nuclear Ground State

Next we look to the number of Δ's in the ground state. This is again a good check for a 1-loop approximation because, simply, a mean field calculation provides a vanishing result.

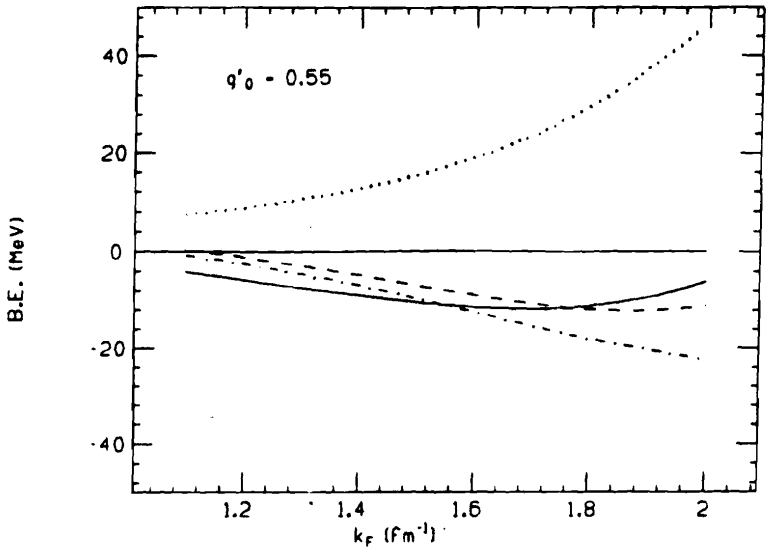

Figure 7: Nuclear binding energy versus k_F

The starting point is the relation [12,13]

$$N_\Delta = -\frac{\partial}{\partial(\delta M)} B.E. \tag{17}$$

Here $B.E.$ means nuclear binding energy and δM is the mass difference between the Δ and the nucleon.

Next we choose the class of diagrams to be summed up. For sake of simplicity we report here the results corresponding to the diagrams of fig. 8 with π- plus ρ-meson exchange and using the expressions (11,12) in order to account for correlations. Calculations are carried out with $q_c = 500$ MeV/c and 800 MeV/c respectively. The cut-off in the πNN and ρNN vertices is assumed to be in both cases $\Lambda = 1.3$ GeV/c. The results are listed in the table below (with obvious meaning of the symbols). More details concerning calculations can be found in [13].

The result we are presently interested in is the following: by changing the range of the correlations from 500 MeV/c to 800 MeV/c we have almost doubled the percentage of Δ's in nuclear matter.

Let us remind, to conclude this section, that a much more refined calculation based on a microscopical input like the Bonn potential can be found in ref. [12], giving more or less the same final result. It is clear however that there the correlations are fixed once forever.

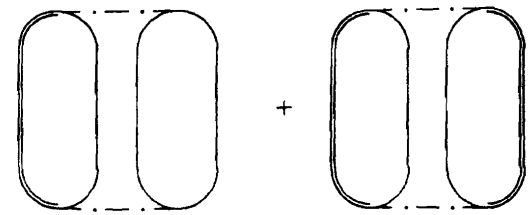

Figure 8: Diagrams for the evaluation of N_Δ

	$q_c = 500$ MeV/c	$q_c = 800$ MeV/c
$P^{\Delta\Delta}(\pi)$	0.17%	0.62%
$P^{N\Delta}(\pi)$	0.15%	0.68%
$P^{\Delta\Delta}(\rho)$	1.8%	2.8%
$P^{N\Delta}(\rho)$	1.9%	2.9%
P^{tot}	4.04%	7.0%

Table 1: Percentage of Δ's in nuclear ground state

6 The Longitudinal Electromagnetic Response

The last topic we want to discuss is more a hope than a proof of the relevance of 1-loop corrections. As a matter of fact it is well known that it has been impossible, up to now, to simultaneously explain the size of longitudinal and transverse e.m. responses in the Quasi Elastic Peak (QEP) region. In particular in the longitudinal case the peak seems to be strongly reduced with respect to the indications of the Free Fermi Gas (FFG) model and, moreover, strongly reshaped too (see for instance the experimental data of refs. [14,15]; see also [1] for a comparison with the suggestions of the FFG model).

From a theoretical point of view, what we called before mean field approximation turns out to be nothing but the Lindhard function, i.e. we find the FFG again. Detailed calculations are given in [2], but for a shortened discussion it is sufficient to remind (2) and replace the external source with an external classical e.m. current. Then calculations proceed along the same path, but the mean field, instead of being provided by the series of fig. 2, simply reduces to the first term of the series because the intermediate pion has quantum numbers different from those of the incoming γ-ray.

Since, as we have already reported, the mean field approximation in this case seems to fail, it is at least reasonable to look for the 1-loop corrections. Aside we observe that they are insufficient to explain experimental data (see [16]); on the other hand one could improve the agreement with the data by including, in different complicated ways the SRC (there are in fact calculations which provide a good agreement with the experimental longitudinal response: for a recent extensive review see [17]),

but in such a case the transverse response is systematically underestimated.

We are presently carrying out further calculations to estimate the effect of the ρ-meson exchange at the 1-loop order both in the longitudinal and transverse channel; in the present paper however we are looking for the sensitivity of 1-loop calculations to the range of SRC.

The diagrams we evaluate are those of fig. 9, other 1-loop corrections (those

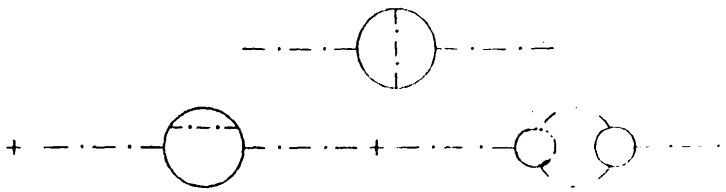

Figure 9: 1-loop diagrams for the longitudinal response

containing the pion-in-flight and the contact terms) being by far less relevant in the longitudinal channel.

Numerical calculations are very heavy even using the simplifying results of ref. [18] which enable one to drop out all but one θ-functions in the integrals. For sake of brevity we reproduce here only one set of results at 300 MeV/c. In fig. 10 the one loop corrections are presented with q_c = 600 MeV/c (dashed line) and q_c = 900 MeV/c (solid line) and in fig. 11 our results are compared with experimental data (same conventions as fig 10; dotted line denotes the results of the FFG) So far the corrections are not sufficient to explain the lowering of the longitudinal response. To improve the agreement with the data two further corrections are needed:

1. the ρ-meson must be included in the calculations. Its effects on the number of Δ's in the ground state (sect. 5) gives some insight on its relevance in the present case),

2. the effective interaction in the scalar-scalar and scalar-isoscalar channels (Landau parameters f and f') should also be accounted for.

Concerning the former topic, calculations are still in progress. The latter correction can strongly improve the results (a calculation is reported in [16]) but the problem is translated to the determination of the Landau parameters: in fact the complicated structure of the diagrams explicitly evaluated there affects the definition of f and f' (in other words one has to avoid double counting). So these kind of results is not free from ambiguities.

Nevertheless figs. 10 and 11 again display the dramatic dependence of a 1-loop calculation from the parameter q_c: just our initial purpose.

7 Conclusion: the Exclusive Reactions

Concluding our discussion we have seen that

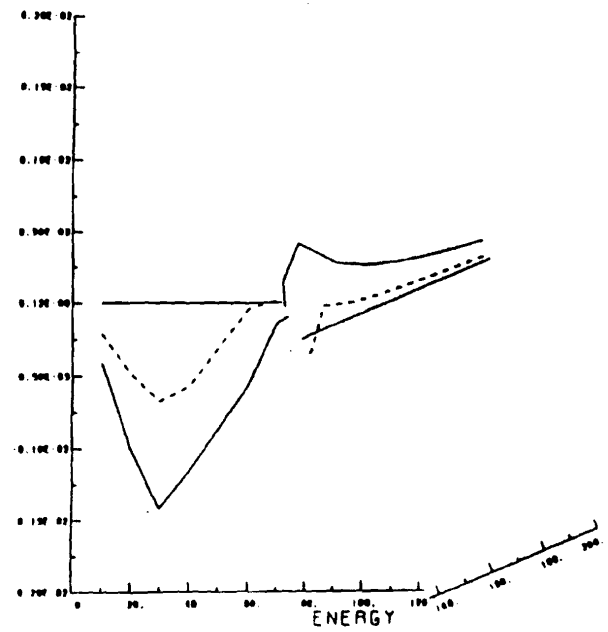

Figure 10: The 1-loop corrections to the longitudinal response with a transferred momentum of 300 MeV/c

1. 1-loop correction are often decisive in providing a good description of the nuclear ground state and low energy processes like the response in the QEP even at not too high momentum transfer (for lighter values of q our reasoning holds *a fortiori*).

2. The crucial parameter in the 1-loop calculation is the range of the effective interaction (q_c) as it dominates the convergence of the loop integral.

Thus we conclude that only a good knowledge of the effective interaction in the various channels (here we focused our attention on the pion channel but the argument can and must be generalized) can provide the input for a reliable 1-loop calculation and hence to determine consistently the previously discussed nuclear properties.

However, the relevance of determining q_c goes well beyond the topics discussed in this paper. In fact, depending upon its value, we shall have informations about the physics which must be accounted for in order to have a predictive theory. Two scenarios are possible: either this cutoff is low enough to still allow a description in terms of nucleons and mesons (plus at most some resonance) or it is so high that the quark structure of hadrons comes into play. Thus the knowledge of q_c can give us important insights on the feasibility of a mesonic field theory in nuclei.

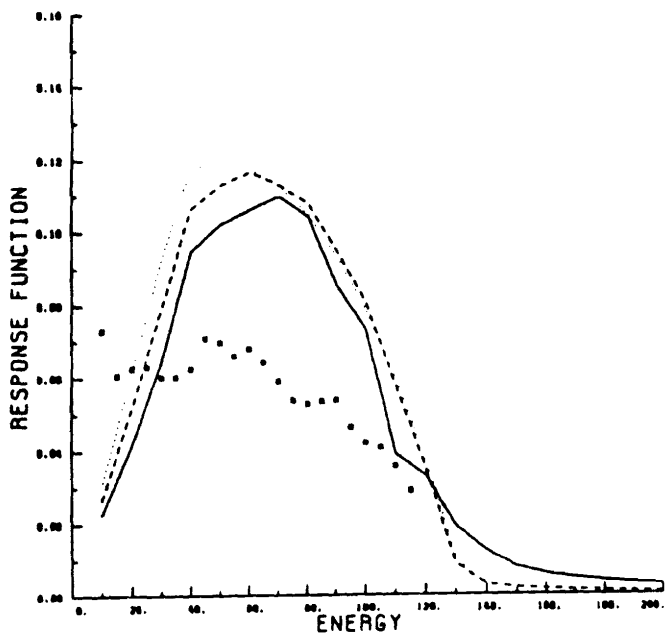

Figure 11: Experimental and theoretical longitudinal response at 300 MeV/c. Data from refs. [14,15]

Now we ask for an experimental determination of these crucial quantities. Clearly we need exclusive processes like that of fig. 12, which cross section (at least in the

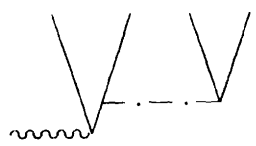

Figure 12: An exclusive process able to determine q_c

low density limit) is directly proportional to the effective interaction in the selected channel.

Thus we have to look for reactions like $(e, e'2p)$ or $(e, e'pn)$. The relative momentum of the two ejected nucleons must reach at least 1 GeV/c (or more) and we have to look for angular correlations and for spin polarizations of the outgoing nucleons to select the corresponding Landau parameters. Since we have to account for the momentum eventually carried by the holes inside the daughter nucleus and since we cannot select a particularly convenient kinematics (at least if we need a 4π measure,

the one required to separate the contributions of the different relative waves for the two nucleons), simple kinematics shows that a transferred momentum of at least 1.5~2 GeV/c is desirable. Furthermore the luminosity should be sufficient to detect the two nucleons in an energy and momentum region in which the cross sections can be very small: (we are indeed far from the QEP region, and we know that the tails of the QEP are mainly due to pion emissions, a reaction in which we are not interested in: thus reasonably we could estimate in a 10% at most of the QEP the 2p-2h contribution).

Thus, in order to improve the counting rate, we look for a favourable kinematical situation able to increase σ_M. From

$$q = 2E \sin \frac{\theta}{2} \tag{18}$$

we immediately obtain

$$\sigma_M = e^4 \frac{\cos^2 \frac{\theta}{2}}{4E^2 \sin^4 \frac{\theta}{2}} = e^4 \frac{4E^2 - q^2}{q^2} \,. \tag{19}$$

Thus the best situation is obtained for a high energy of the beam and a small scattering angle for the electrons, so to maintain q fixed.

Thus in conclusion experiments with a many GeV electron beam are required to achieve the experimental informations needed to self-consistently describe many nuclear properties even in the low energy and momentum domain.

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