NUCLEAR PHYSICS WITH ELECTROWEAK PROBES

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ABSTRACT

The last few years activity of the Italian community concerning nuclear physics with electroweak probes is reviewed. Inclusive quasi-elastic electron-scattering, photon end electron induced one- and two-nucleon emission are considered. The scattering of neutrinos off nuclei in the quasi-elastic region is also discussed.

1 Introduction

In this paper I present the results obtained by the Italian community in the years 2002-2004 in the field of the theoretical study of lepton scattering off medium and heavy nuclei (A>4) [1]-[39]. These results are the product of numerous collaborations with many foreigner colleagues, their number is about the same of that of the Italian authors.

The range of the problematics covered by the various publications is wide, and I have organized my presentation as follows. First, I shall discuss some general issues concerning the lepton-nucleus interaction. Then I shall present the results of inclusive electron scattering, total photon absorption and those obtained by studying one- and two-nucleon emission processes. Last, I shall be concerned about the application to the neutrino scattering of the nuclear models used to investigate the electron scattering processes.

Since in writing this article I used numerous abbreviations, in order to facilitate the reader, I give their meaning in Table 1.

FG	Fermi gas
FSI	final state interaction
LDA	local density approximation
LIT	Lorentz inverse transform
LRC	long range correlations
MEC	meson exchange currents
MF	mean field
OB	one body
PWBA	plane wave Borm approximation
RFG	relativistic Fermi gas
RPA	random phase approximation
SRC	short range correlations
WS	Woods Saxon

Table 1: Acronyms used in the article

In the study of the lepton scattering off nuclei it is possible to separate the description of scattering process from that of the nuclear structure. The first, and quite obvious, reason is that projectile and scattered lepton are clearly distinguishable from the hadrons composing the nucleus. In addition, the fact that electroweak processes are well described already at the first-order perturbation theory, helps a lot. In effect, all the calculation I have examined have been done by considering that a single gauge boson is exchanged between the lepton and the target nucleus (see Fig. 1). In addition, also the PWBA has been adopted. With these approximations, the cross section expressions for both electrons [40] and neutrinos [41] scattering processes show a factorization of the leptonic and hadronic variables.

The leptonic vertex is treated within the relativistic theory, since the energies involved are much larger than the leptons masses. On the other hand, the nuclear vertex is usually treated with non-relativistic quantum many-body theory.

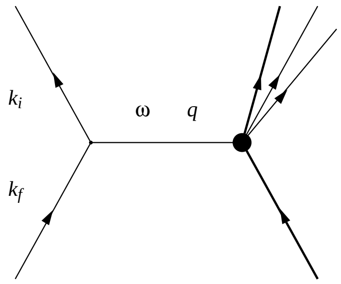

Figure 1: One-boson exchange diagram showing the symbols adopted for the kinematics variables in the scattering process lepton-nucleus. The left vertex represents the lepton, whose four vectors are indicated with $k \equiv (\epsilon, \mathbf{k})$. With ω and $\mathbf{q}$ I label energy and momentum transfer respectively. The boson exchanged are the photon, in the case of the electromagnetic interaction, an the Z^o and $W^\pm$ in the case of the weak interaction.

2 The electron-nucleus interaction

From now, up to section 4, I shall restrict my discussion to the electromagnetic case. The OB electromagnetic currents are obtained by summing the currents generated by each nucleon. Gauge invariance, i.e. the charge-current conservation law, is not satisfied if only these currents are considered. This indicates the need of including other type of currents, produced by the exchange of mesons between the interacting nucleons and generically called Meson Exchange Currents (MEC).

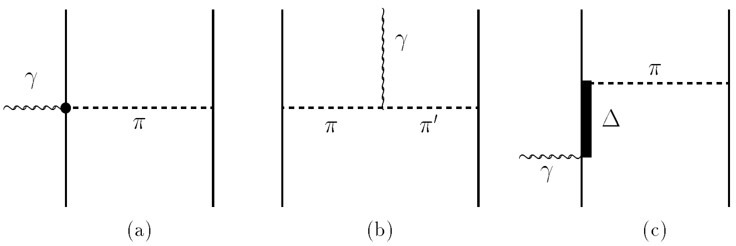

Figure 2: Meson Exchange Diagrams considered in the various calculations. Contact or seagull (a), pionic or pion in flight (b), Δ-current (c).

Gauge invariance indicates the need of MEC, but it does not define them in a unique and unambiguous manner. The various methods used to describe the MEC agree on the fact that the main contributions come from the three diagrams presented in Fig. 2. The most relevant terms are the seagull, diagram (a), the and pionic, diagram (b). They are of the same order of magnitude but they have different sign. They contribute to the electromagnetic field of the nucleus only if the exchanged pion is charged. This means that with these two diagrams only proton-neutron pairs are involved.

At energies far from the peak of the nucleonic Δ-resonance the MEC Δ-current terms, diagram (c), are generally smaller than the seagull and pionic ones. The Δ-currents contribute to the electromagnetic field of the nucleus also when the pion exchanged is chargeless. In this case, the two nucleons involved are of the same type. This observation is relevant for the two-nucleon emission processes.

The validity of the non relativistic reductions used to describe the electromagnetic field of the nucleus has been studied by investigating the ideal system of the Fermi gas (FG) [3]-[9]. The strategy consists in comparing the results obtained for a relativistic Fermi Gas (RFG), which is an exactly solvable model, with those obtained in ordinary non relativistic FG, where various non-relativistic reductions of the currents have been adopted.

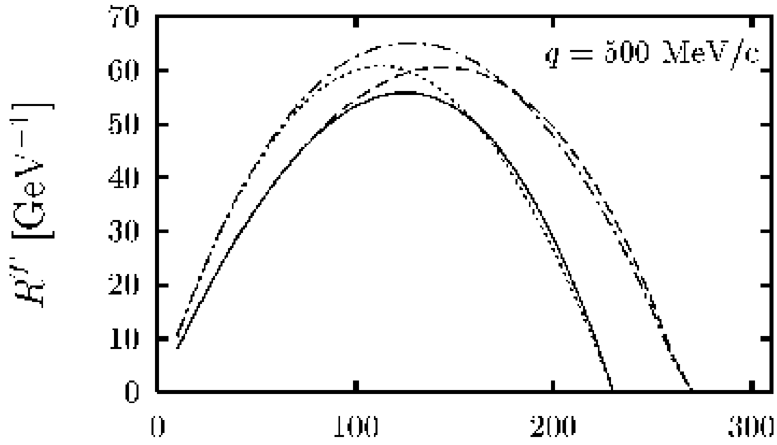

Figure 3: Inclusive transverse response. The quantity on the x axis is the excitation energy in MeV. Full line RFG with OB currents only, dashed line FG with OB only, dotted line RFG with OB and MEC, dashed dotted line FG with OB and MEC.

An example of the results of this investigation [4] is given in Fig. 3 where the RFG results obtained with and without MEC are compared with the analogous results obtained in non relativistic FG. This figure shows the transverse response as a function of the nuclear excitation energy for a given value of the momentum transfer. In these results the effect of the relativity is relatively large. The height of the peak is reduced by about 20%, and also the width of the response is reduced by relativity. On the other hand, the effect of the MEC does not seem to be sensitive to relativity. The shift produced by the MEC on the OB responses is about the same on both RFG and FG results.

The effects shown in Fig. 3, are much weaker in finite nuclei calculations. In Fig. 4 an example of this result is seen. The quantity shown in the figure is the reduced cross section of the ^{16}O(e,e'p)^{15}N reaction as a function of the missing momentum [16]. Also in this case the nuclear wave functions have been described within a MF model. A real WS potential is used to generate the single particle wave functions of the ^{16}O ground state. The parameters have been fixed to reproduce the charge radius and the single particle energies around the Fermi surface. The particle wave function in the nuclear final state, has been obtained by using a complex optical potential whose parameters have been fixed to describe the elastic cross sections of the scattering process between the emitted nucleon and the remaining nucleus with A-1 nucleons.

The result of the calculation where all the MEC diagrams of Fig. 2 are considered is shown by the full line. The dotted line, almost perfectly overlaps the full line, shows the results obtained with the OB currents only. The dashed-dotted line has been obtained by adding to the OB currents only the seagull term. The results of this calculation

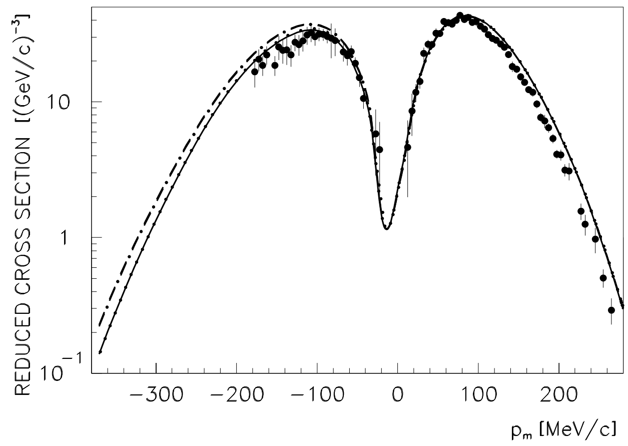

Figure 4: Reduced cross section of ^{16}O(e,e'p)^{15}N calculated in the mean field model, as explained in the text, and compared with experimental data [42]. The full line has been calculated by using all the MEC disgrams shown in Fig. 2. The result obtained with OB current only is shown by the dotted line almost exactly overlapping the full line. The dot dashed line shows the result obtained by adding to the OB current the seagull diagram.

show that the contributions of the various MEC diagrams cancel each other. In this process the effect of the MEC is so small that they cannot be disentangled by a comparison with the data.

The effects of relativity are also strongly reduced in finite systems [43]. An example of these results is presented in Fig. 5 where the ^{16}O(e,e'p)^{15}N reduced cross sections calculated with two different mean field models are compared. The full line shows the result obtained with a relativistic MF, while the dotted line has been obtained with a non relativistic calculation. Here relativity lowers the height of the maximum by about 10%. More relevant is the fact that the shapes of the cross sections are only slightly modified. Even though Fig. 3 and Fig. 5 show different quantities, it is evident that the global effect of relativity is smaller in finite systems than in FG calculations. A possible explanation of this can be related to the procedures used to define the parameters of the nuclear mean fields in the finite nuclei calculations. In both relativistic and non-relativistic calculations, these parameters are fixed so as to reproduce the same quantities. It is plausible that in this fitting procedure some relativistic effects are effectively included. This is not the case of the FG calculations, where the comparison is done between two ideal systems without any phenomenological parameter to fix.

3 Nuclear structure and electron scattering

In the previous section, I have discussed some source of uncertainties in the description of the reaction mechanism between electron and nucleus. These uncertainties can affect the cross sections on average by a 10%, maximum 20%. The uncertainties insit in the nuclear structure produce much larger effects on the cross sections. As a reminder of this, I would like to briefly recall a set of problems still open which, however, are not at the moment under the attention of the community.

(a) The high momentum data of the elastic scattering cross sections are not well reproduced. As a consequence the theoretical charge distributions are unable to the describe the empirical distributions in the center of the nucleus. In spite of some attempts [44] indicating the physical effects responsible for this discrepancy, to the best of my knowledge, there is not a single, fully consistent, calculation able to give a reasonable description of these data.

(b) The (e,e') theoretical cross sections in the discrete excitation usually overestimate the data [46], as shown, for example, in Fig. 6.

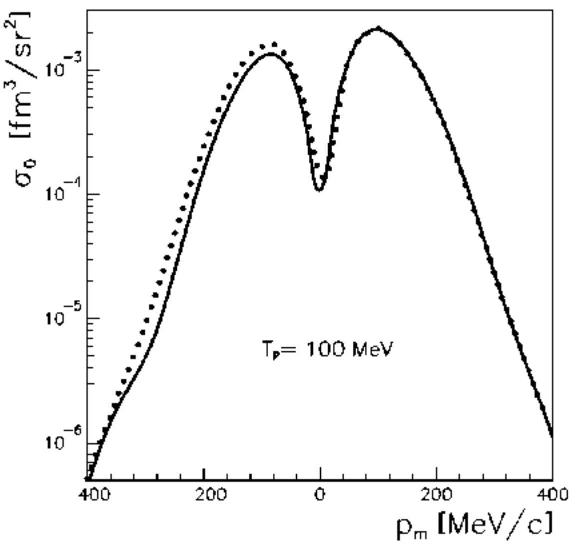

Figure 5: Reduced cross section of ^{16}O(e,e'p)^{15}N. The full line shows the result obtained with a relativistic mean field, the dotted line with a non relativistic one.

(c) The continuum RPA results for total photo-absorption cross sections in the giant resonances region, are able to reproduce the energies of the resonances, but they overestimate the sizes of the cross sections and underestimate their widths, as shown in Fig. 7.

The problems I have just mentioned are due to the limitations of the theoretical models used to calculate the cross sections and the other observables. In medium-heavy nuclei the nuclear excited states are usually described by using the MF model or the RPA. In both these descriptions only one-particle one-hole excitations, and eventually their linear combinations, are considered.

These unsatisfactory results are related to the limitations of the nuclear models adopted and not to the basic assumptions of the theory used to describe atomic nuclei. This information come from the results obtained in the few-body systems (A$\leq$4) [48]. In these systems the many-body Schrödinger equation describing a set of interacting nucleons, is solved without making approximations, and the agreement with electromagnetic experimental data is remarkably superior to what is obtained in heavier systems.

Recently the technique of the Lorentz Inverse Transform (LIT), previously used in few-body systems, has been applied with great success to heavier nuclei, up to A=7 [30, 31, 32, 33]. A more detailed description of the LIT theory is presented elsewhere in these proceeding [49]. Here, I simply want to point out the fact that this technique accounts for all the possible decay channels of the nuclear excited state. On the contrary, the MF model, and also the continuum RPA, consider only the decay in the single nucleon emission channel.

The MF model is unable to describe low-energy data, but it is quite successful in the quasi-elastic region dominated by single-particle dynamics. In the following subsections I present the results obtained in this energy region, considering separately the inclusive processes from those where one, or two, nucleons are emitted and measured in coincidence with the scattered electron.

3.1 Inclusive scattering: (e,e')

An example of the agreement between Frascati data [50] on ^{16}O and the results obtained with the relativistic MF model [20] is shown in Fig. 8. The same high-quality agreement is obtained for the other measured kinematics. The main point of the calculation is the careful treatment of the Final State Interaction (FSI). As already discussed in

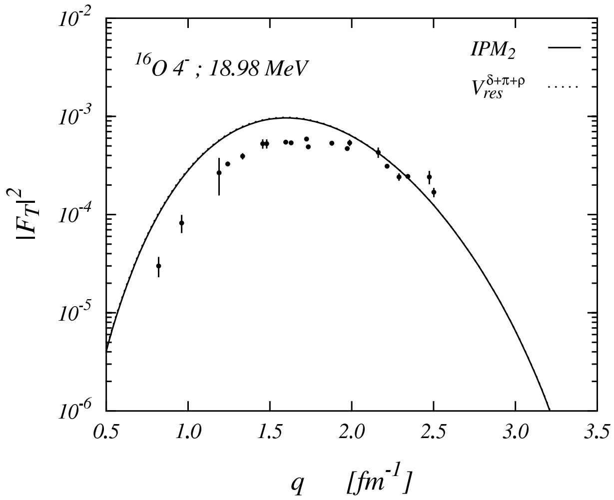

Figure 6: Comparison between (e,e') transition amplitudes calculated with RPA, full line, and Independent Particle Model, dashed line, with experimental data [45]

Sect. 2, in this MF model, the FSI are taken into account by using a complex optical potential. The imaginary part of the potential removes flux from the elastic channel. In inclusive experiments the total flux should be conserved. What is removed from the elastic channel should go in other decay channels. A more detailed description of the technique used to conserve the flux is presented elsewhere in these proceedings [51].

The same model [20] has been used to study the separated longitudinal and transverse responses of ^{40}Ca and ^{12}C. In ^{40}Ca the MIT data [52] are well reproduced, while the comparison with Saclay data [53, 54] suffers the well known failures: the longitudinal responses are overestimated, while the transverse ones are underestimated. The comparison with the separated responses of ^{12}C, measured at various values of the momentum transfer [55], shows a reasonable agreement with the longitudinal responses while the transverse ones are always heavily underestimated. Old calculations of the ^{12}C responses done within a non relativistic framework [56] produce very similar results. This indicates that the effect of the relativity is negligible.

The Frascati (e,e') [50] data have been studied by using a different technique [57]. The basic nuclear model is again the non-relativistic MF. In this case the responses have been calculated with a real potential. The results obtained have been folded with Lorentz functions whose parameters have been fixed to reproduce the energy behavior of the volume integrals of the optical potential. In spite of the technical differences, this approach contains the same physics as that of the Pavia group, and the results obtained are very similar. Also in this case [38] the Frascati data [50] are rather well reproduced. The same kind of agreement is obtained [57] with the MIT ^{40}Ca responses [52]. The comparison with ^{40}Ca and ^{12}C Saclay data, shows the same problems described above [57, 58]. The two different techniques used to treat FSI produce very similar results.

3.2 One-nucleon emission: (e,e'N) and (γ,N)

The same MF model used to describe the inclusive data has been utilized to study the single-nucleon emission processes induced by electromagnetic probes. The basic ingredients of the models are the two MF potentials. A real potential that describes the ground state of the target nucleus, and a complex optical potential to treat the emitted nucleon wave function.

The results obtained for the (e,e'p) cross sections in various nuclei are able to reproduce rather well the behavior of the data after a quenching rescaling factor is applied [40]. This rescaling factor is called spectroscopic factor and it does not depend upon the kinematics of the experiment. This is evident since observables related to the ratio of cross

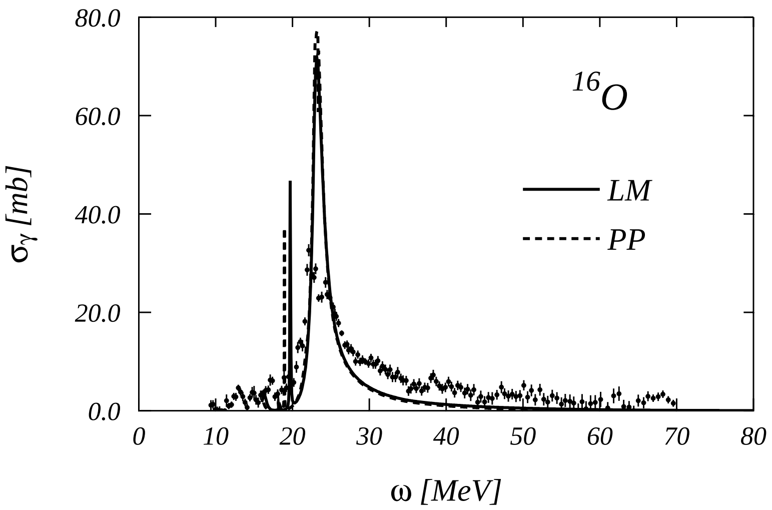

Figure 7: Total photon absortpion cross sections calculated within the continuum RPA frwmework with two different residual interactions compared with the data [47].

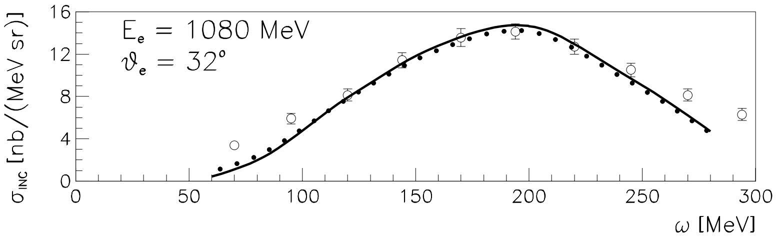

Figure 8: Inclusive electron scattering cross section on ^{16}O nucleus calculated in the framework of the relativisti mean-field model and compared with the Frascati experimental data [50]. The two lines have been obtained by using two different approximations.

sections are well reproduced without the use of the spectroscopic factor [6]. Furthermore, cross sections measured in very different kinematic conditions are well reproduced by the same spectroscopic factors [24].

The spectroscopic factor is a model dependent quantity, as is deducible, for example, in Fig. 5. In this figure the ^{16}O(e,e'p)^{15}N reduced cross sections calculated [43] with relativistic (full line) and non relativistic (dotted line) MF models are compared with the experimental data [42]. In Fig. 9 the full line has been multiplied by 0.7 while the dotted line by 0.65. This indicates that spectroscopic factors contain some relativistic effects. These effects are not sufficient to explain a large part of the spectroscopic factors. It is necessary to go beyond the MF model, or in other words, to include correlations. The investigation of the effects induced by the correlations has been conducted by using two different approaches.

The basic quantities necessary to calculate the cross sections are the Fourier transforms of the transition densities induced by the current operators $J(\mathbf{r})$:

$$W(\mathbf{q}) = \int d^3r \, e^{i\mathbf{q}\cdot\mathbf{r}} < \Psi_f \mid J(\mathbf{r}) \mid \Psi_0 > \quad . \tag{1}$$

In the approach adopted by the Pavia group these quantities are calculated as:

$$W(\mathbf{q}) = \int d^3r \, e^{i\mathbf{q}\cdot\mathbf{r}} \; \chi(\mathbf{r}) J(\mathbf{r}) \; < \Psi^{A-1}(\mathbf{r}) \mid \Psi_0^A > \tag{2}$$

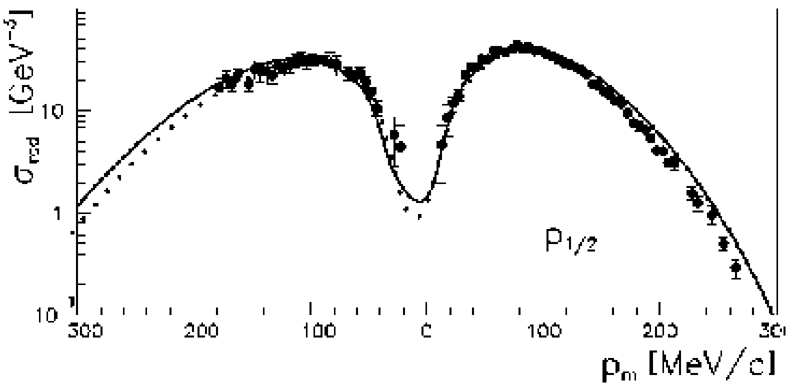

Figure 9: Reduced cross section of ^{16}O(e,e'p)^{15}N compared with the experimental data [42]. The full line shows the result obtained with a relativistic mean field, while the dotted line with a non relativistic mean field. Contrary to Fig. 5 the two results have been multipied by two different spectroscopic factors to reproduce the data at best (see text).

where $\chi(\mathbf{r})$ is the wave function of the emitted, and detected, nucleon. The important quantity is the overlap function between the wave function describing the ground state of the target nucleus and the wave function describing the state of the nucleus composed by A-1 nucleons. All the complications related to the correlations are contained in the overlap function. The formalism developed by the Pavia group is independent from the methods used to estimate the overlap function. In the MF model the overlap function is the single particle wave function of the nucleon below the Fermi surface.

The approach used in Lecce makes an ansatz on the expression of the nuclear wave function which is supposed to be the product of a symmetrized many-body correlation function F and a Slater determinant.

$$W(\mathbf{q}) = \int d^3r\, e^{i\mathbf{q}\cdot\mathbf{r}} \;\; < \Phi_f \mid F^\dagger J(\mathbf{r}) F \mid \Phi_0 > \tag{3}$$

The Slater determinant $\mid \Phi_0 >$ describing the ground state is composed by all the single particle states below the Fermi surface, while $\mid \Phi_f >$ contains a hole and a particle states. The same correlation function has been used for both ground and excited states. The many-body correlation function is written as a product of two-body correlation functions. A cluster expansion is done, and only the terms containing a linear dependence from the two-body correlation function are retained [59]. This approach is more tuned to investigate the so-called short-range correlations (SRC) due to the hard core repulsion of the nucleon-nucleon potential.

In spite of the differences, the results obtained by the two approaches are very similar. In general, for the considered processes, the effects of the SRC are very small. Certainly the inclusion of the SRC does not reduce sensitively the values of the spectroscopic factors. As an opposite example of the behavior of the correlation, I like to quote the results obtained in ^{40}Ca by using overlap functions produced by the Generator Coordinate Method. In this case the spectroscopic factors are even larger than those of the MF model calculation [17, 60].

From the qualitative point of view, the results obtained with the two methods described above, show that the presence of SRC does not modify sensitively the shapes of the (e,e'p) cross sections [13, 59]. The differences between cross sections obtained with and without SRC are within the accuracy of the experimental data. An interesting deviation from this general trend is the case of the ^{32}S nucleus [13], which should be worth further investigation.

A relatively large effect produced by the SRC has been found in the (γ,p) reaction on the ^{16}O nucleus [16, 34]. In Fig. 10 the cross sections of this process, calculated with OB currents only (thin full line), with the inclusion of SRC (dotted line) and by further adding the MEC (thick full line) are compared with the experimental data [61]. The relative effect produced by the SRC on the OB cross section is quite large. Unfortunately, in this kinematic region, the effects of the MEC are even larger.

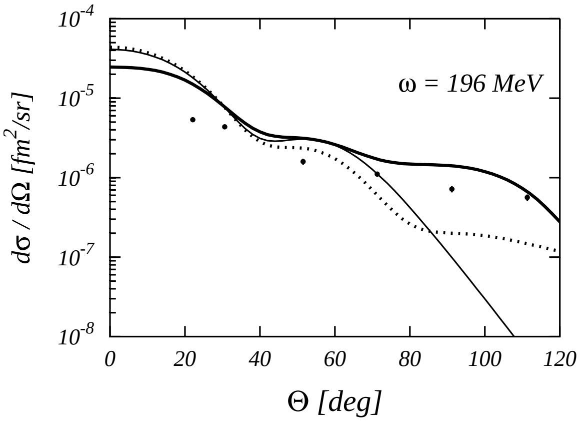

Figure 10: Cross sections of the ^{16}O(γ,p)^{15}N process as a function of the proton emission angle compared with the experimental data [61]. The thin full line shows the result obtained with OB currents only. The inclusion of SRC produces the dotted line. When also the MEC are included, the thick full line is obtained.

3.3 Two-nucleon emission: (e,e'NN) and (γ,NN)

In the processes discussed so far, the effects of the SRC correlations have been obscured by the presence of the uncorrelated OB terms, or by the MEC currents. It is possible to eliminate the contribution of the OB terms by considering processes where two nucleons are emitted and detected. In this case the only mechanism competing with the SRC are the MEC. When two-like nucleons are emitted, the only terms of the MEC contributing to the cross section are the Δ-current diagrams, the (c) diagrams of Fig. 2, where the exchanged pion is chargeless.

From the theoretical point of view the description of the two-nucleon emission processes has been treated as a straightforward extension of the single nucleon emission case.

In the Pavia approach Eq.(2) is extended as:

$$W(\mathbf{q}) = \int d^3r \, e^{i\mathbf{q}\cdot\mathbf{r}_{12}} \; \chi_1(\mathbf{r}_1)\chi_2(\mathbf{r}_1)J(\mathbf{r}_{12}) \; < \Psi^{A-2}(\mathbf{r}_{12}) \mid \Psi_0^A > \tag{4}$$

with the obvious meaning of the symbols. Now the quantity containing the correlations is the two body-overlap function, between the target ground state and the state with A-2 nucleons.

In the Lecce approach the transition density of Eq. (3) is calculated by using a Slater determinant $\mid \Phi_f >$ with two particles in the continuum and, obviously, two holes.

In both approaches the interaction between the two emitted nucleons is not considered. This problem has been investigated by the Pavia group [25, 26], by using an approximation. The interaction between the two emitted nucleons has been considered, as has the interaction between each nucleon and the A-2 nucleus. The simultaneous interaction of two nucleons between themselves and with the remaining A-2 nucleus has been neglected. This would be a genuine three-body problem. The results obtained considering the ^{16}O nucleus as a target show that the interaction effect is relevant in (e,e'pp) reaction, but it is negligible in (e,e'pn) reaction. More interesting is the fact that in the (γ,pp) reaction the effect is always negligible.

In order to obtain information on the SRC it is necessary to disentangle the two nucleon emission induced by the correlations from that produced by the MEC. We have already seen that the emission of two-like nucleons eliminate the MEC seagull and pionic diagrams, and also part of the Δ-current terms. It is possible to find kinematic situations where the SRC dominate on the remaining Δ-current terms [12], as is shown in Fig. 11. When the ^{16}O(e,e'pp)^{14}C reaction leads to the ground state of the ^{14}C nucleus, the Δ-currents contribution is much smaller than that of the SRC. The situation is reversed when the nuclear final state is the excited 1^+ state in ^{14}C.

A detailed study of the momentum dependence of the Δ-current contributions [36] shows that they are minimized at small values of the momentum transfer. In photon reactions these contributions are much smaller than those of the SRC for all the ^{14}C final states. From this point of view the two-proton emission induced by real photons with energy far from the Δ resonance peak, is the ideal tool to investigate SRC [36].

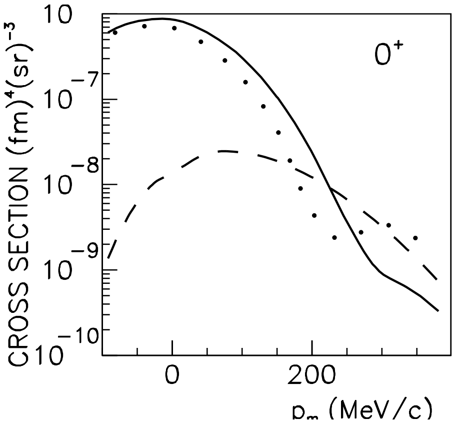

Figure 11: Cross sections of the ^{16}O(e,e'pp)^{14}C process leading to the ground state of the ^{14}C, as a function of the initial momentum of the emitted pair. The dadhed line has been calculated by considering the Δ-current only. The dotted line with the SRC only, and the full line with both contributions.

The role of the tensor terms of the SRC is however quenched in the emission of two-like nucleons. The contribution of these terms is significant only in (e,e'pn) processes [12].

4 Neutrino-nucleus interaction

In Fig. 12 the electron scattering cross section is compared with that of neutrino scattering in the same kinematic conditions. All the cross sections have been calculated for the same energy of the projectile and the same scattering angle. The nuclear transitions have been calculated by using the continuum RPA.

The three cross sections have quite a different behavior. This is expected for the charge exchange reactions but it is surprising when electron scattering and neutrino charge conserving neutral current reactions are compared. In this case the particle-hole configuration space describing the nuclear excitation is the same in both processes.

The reason for this difference can be traced by making a multipole decomposition of the cross sections. In the electron scattering case the 1^- excitation is responsible for the 98% of the total cross section. On the contrary, in the (ν,ν') case the 1^- contributes only to the 33% of the cross section, while the main contribution, 58%, is due to the the 2^- multipole [37].

This result is due to the fact that in the neutrino cross section the main contributions are given by the transverse axial vector term of the current operator. This operator excites both natural and unnatural parity states. In electron scattering the main contribution is due to the charge operator exciting natural parity states only. The dominance of the axial vector term is a quite general result. Also the charge exchange reactions are dominated by this term of the current, and this is the dominant term for all the neutrino cross sections also in the quasi-elastic region [62].

As a consequence of this, it is necessary to be careful in relying on the fact that a good description of electron scattering data implies a good description of the neutrino-nucleus cross section. In spite of this warning, electron scattering is still the best guide we have to determine the prediction power of our nuclear models. The extension to the neutrino scattering of the electron scattering formalism is quite straightforward. In these last two years,

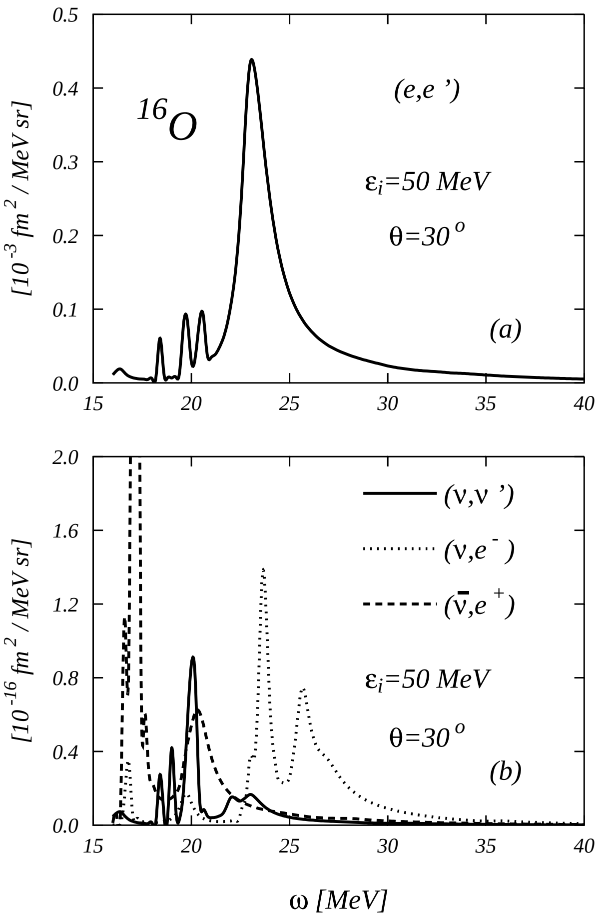

Figure 12: Comparison between electron (above) and neutrino (below) scattering cross sections. The energy of the incoming lepton and the scattering angle are the same in all the reactions considered.

almost all the Italian groups working in electron scattering have applied their techniques to calculate neutrino-nucleus cross-sections. The calculations have been mainly done in the quasi-elastic region [1, 11, 21, 22, 27, 28, 29, 38].

As I have previously pointed out the main correction to the naif MF model is due to the FSI. The FSI calculated with a folding model model [28, 38, 63], produces a reduction of the total neutrino-nucleus cross section by about 10%. This is due to the fact that the FSI spreads the strength of the response and part of it is moved to excitation energies kinematically prohibited.

The role of the correlations have been estimated to be relatively large [27, 28]. The peak of the ^{16}O(ν,e$^-$)^{16}F cross section for 1 GeV neutrinos is reduced by about 20%. This effect has been estimated by comparing FG results with those obtained by using a correlated spectral function in a local density approximation (LDA). It will be interesting to disentangle the LDA effects from those produced by the correlations.

The neutrino-nucleus scattering in the quasi-elastic regime has been found to be the ideal tool for studying the strangeness content of the nucleon [1]. In this case one has to separate the cross sections where a neutron is emitted from those where a proton is emitted. The calculations done in a FG model show about a 25% difference between the results obtained with and without strangeness in the nucleon form factor [64]. This large effect has been recently confirmed by a finite nucleus calculation with a relativistic MF model [22, 51].

5 Conclusions

In these last two years, the activity of the Italian community regarding nuclear physics with electroweak probes has concentrated on the region of the quasi-elastic peak. In this region, the nuclear excitation is dominated by the single-particle dynamics, therefore MF models with OB currents are the starting point of the description of the nuclear excitation. Other effects induced by MEC, FSI, SRC and collective modes, are relatively small, and can be treated as perturbations of the MF results. There is a convergence of the results obtained with different models and techniques, and many of the uncertainties and problems presented and discussed in the past [65, 66, 67] have been resolved.

The comparison with the experimental data is still problematic. Concerning the inclusive experiments, the Frascati ^{16}O inclusive cross sections are well reproduced [20, 38], as well as the ^{40}Ca MIT-Bates separated responses [20, 57]. The same models are unable to describe the the Saclay ^{40}Ca and ^{12}C separated responses. I think that at present the major problems are on the experimental side. Experiments to obtain separated responses in ^{16}O are necessary, and the incompatibility between the ^{40}Ca data measured at MIT and at Saclay should be clarified.

The situation regarding one-nucleon emission processes is slightly clearer. The same MF models used to describe inclusive experiments are able to reproduce extremely well the shapes of the cross sections [17]. The open problem is the understanding of the spectroscopic factor needed to obtain quantitative agreement with the data. Contrary to some claims [68, 69] it has been shown that the spectroscopic factor is a number [6, 24], model dependent, but independent form momentum and energy transfer.

The search for effects induced by SRC has shown that the best way of studying them is the use of two-nucleon emission processes. Since the Δ-current terms become small at low momentum transfer, in the two-nucleon emission processes real photons seem to be a better tool than electrons [16, 36]. In this field the various approaches provide similar results, indicating that the theoretical uncertainties are kept under control.

Even though the neutrino scattering is dominated by the axial part of the current, absent in electron scattering, the above mentioned results suggest that the same models could provide a good description of the quasi-elastic neutrino scattering. This is a very important information for the existing and planned experiments which use the nucleus as a detector to investigate the properties of the neutrinos and their sources.

Furthermore neutrino-nucleus experiments in the quasi-elastic region, are perhaps the best tool we have for information on the strange content of the nucleon [1, 22]. The conservative estimate of the nuclear structure uncertainties, that resulted to be of the same order of the searched effects, should be updated. In our present understanding of the quasi-elastic excitation this uncertainty is reduced, therefore the strangeness effects could be identified.

Electron scattering off nuclei is a precision tool to control and investigate our understanding of nuclear structure. The evaluation of these cross sections should be used as a benchmark to verify the validity of approaches aimed at predictions in other nuclear physics fields. In these last few years the theories have improved remarkably, and there are signs indicating the possibilities of even greater improvements in the coming years.

It is however disappointing to notice that many of the experimental data are old, incomplete, and quite often not accurate enough to disentangle interesting effects. I join G. Orlandini [33] by pointing out the need of a major experimental program to investigate medium-heavy nuclei with electromagnetic probes.

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