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Weak response of nuclei

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Abstract. We discuss some differences and similarities between electron and neutrino scattering off atomic nuclei. We find that, in the giant resonance region, the two processes excite different nuclear modes, therefore the weak and the electromagnetic nuclear responses are rather different. In any case, the scattering of electrons and photons is the best guide we have to test the validity of our nuclear models and their prediction power. The experience in describing electromagnetic excitations of the nucleus, suggests that, when the nucleus is excited in the continuum, the re-interaction between the emitted nucleon and the remaining nucleus should not be neglected. A simple model taking into account this final state interaction is proposed, and applied to the neutrino scattering off ^{16}O nucleus.

PACS. 25.30.Pt Neutrino scattering – 24.30.Cz Giant resonances

The great activity of the last fifteen years in neutrino physics has attracted great attention to the interaction between neutrinos and atomic nuclei. At present, the main interest in the neutrino-nucleus interaction is related to the goal of investigating the properties of the neutrinos, or of the neutrino sources such as stars, supernovae, earth etc. . In this perspective the nucleus is considered as detector, and therefore the nuclear response to weakly interacting probes should be well controlled.

Our knowledge about the interaction of electrons and photons with the nucleus can be used as a guide to make prediction about neutrino-nucleus processes. Both electromagnetic and weak interactions can be well described within a perturbation expansion of the scattering amplitudes. Furthermore, the tensor structure of the electromagnetic current is identical to that of the vector part of the weak current.

In Fig. 1 we present a direct comparison between electron and neutrino double differential cross sections off ^{16}O target nucleus. The results, shown in the figure as a function of the nuclear excitation energy, ω, have been obtained for the same values of the projectile energy ϵ_i= 50 MeV, and of the scattering angle $\theta = 30^o$. The cross sections have been calculated in first order plane wave Born approximation, i.e. considering the exchange of a single boson, either a photon, a Z^o or a $W^{\pm}$, and by describing the lepton wave functions in terms of plane waves. The nucleus is excited above the nucleon emission threshold, and we describe the transition of the nucleus from its ground state to the excited state in the continuum region by using the Continuum Random Phase Approximation (CRPA) whose equations are solved as described in [1,2]. The results shown in the figure have been obtained by using a zero range Landau-Migdal interaction. The cross

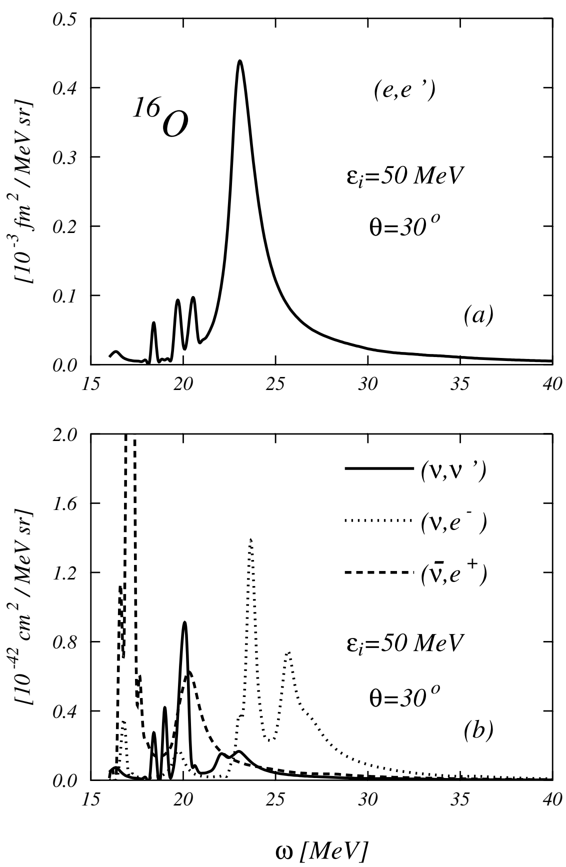

Fig. 1. Doubly differential cross sections $d^2\sigma/d\epsilon_f d\Omega$ for scattering of electrons, panel (**a**), and neutrinos, panel (**b**), as a function of the nuclear excitation energy. The lepton incoming energy ϵ_i, and the scattering angle are the same for all the reactions considered

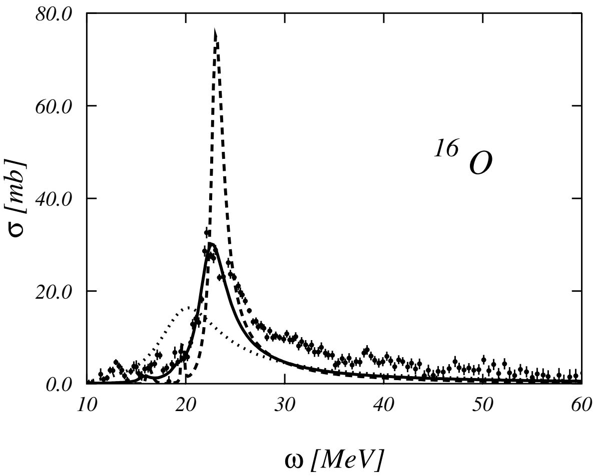

Fig. 2. Total photoabsorption cross section compared with the data of [3]. The *dashed lines* show the continuum RPA results, the *dotted lines* have been obtained using the folding with asymptotic parameters, the *full lines* using the energy dependent folding

sections have been obtained by summing all the positive and negative multipole excitations up to a maximum value of the total angular momentum, $J = 6$.

The shapes of the cross sections shown in Fig. 1 are rather different. The difference between electron and charge exchange neutrino processes was expected, since the basic particle-hole transitions inducing charge exchange excitations are quite different from those involved in the charge conserving excitations. The noticeable difference between electron and charge conserving neutrino scattering is more surprising, since in this case the basic particle-hole transitions are the same. We made a multipole decomposition of the cross sections to understand this difference, and we found that the relevant multipoles forming the cross sections are different for the electron and neutrinos. The 1^- excitation is responsible for the 93% of the electron scattering cross section. The remaining is due for the 6% to the 2^+ and for about a 1% to the 0^+. The situation is quite different for the (ν, ν') cross section: 58% 2^-, 33% 1^-, 6% 0^-, 2% 1^+ and about 1% 3^+. This difference between electron and neutrino scattering is due to the fact that in neutrino scattering the nuclear transitions are dominated by the axial transverse operator, absent in electromagnetic excitations. This fact is not related to the specific kinematics of Fig. 1 but it is more general. We made calculations also in the quasi-elastic regime, with ϵ_i=1 GeV. In this case the shapes of the various cross sections are very similar, showing a single large peak at the same value of the nuclear excitation energy. However, even in this case, for the neutrino scattering the main contribution to the cross section is induced by the axial current operator. These results suggest caution in the comparison between electron and neutrino cross sections. While in electromagnetic excitations the vector transition operator excites mainly natural parity states, the nuclear excitations produced by neutrinos are ruled by the axial vector part of the transition operator which excites without any preference both natural and unnatural parity states. For this reason, being able to reproduce electron scattering cross sections does not necessarily imply a good control of the neutrino cross sections.

In spite of the words of caution expressed above, electromagnetic excitations are still the best benchmarks we have to test our description of nuclear excitations. The limits of our capacity of describing nuclear excitations in the continuum region can be well summarized by the results shown in Fig. 2 where we compare the experimental total photon absorption cross sections of the ^{16}O nucleus [3] with various theoretical cross sections. The dashed line show the result obtained with the CRPA used in Fig. 1 [1,2]. The features of these calculations are well known in the literature and they are common to all the continuum RPA results. They are rather independent from the residual interaction and from the technique used to treat the continuum. While the position of the resonance is well reproduced, the CRPA cross sections overestimate the size of the experimental cross sections and they underestimate their width. It is commonly believed that these problems could be solved by considering many-body effects beyond RPA, such as many-particle many-hole excitations [4].

Many body effects are relevant not only in the giant resonance region but also in the quasi-elastic peak. Also in this case the CRPA results do not provide a good description of experimental data [5]. The inclusion of many body effects beyond RPA, called in this context final state interactions (FSI), greatly improves the agreement with the data [5,6,7]. To take into account the effect of the FSI in the quasi-elastic region we have developed a phenomenological model [5]. After assuming that the FSI are independent from the multipolarity of the nuclear excitation we can express the FSI response S^{FSI} in terms of the RPA response S^{RPA} as:

$$S^{FSI}(|\mathbf{q}|,\omega) = \int_0^\infty dE \;\; S^{RPA}(|\mathbf{q}|,E) \left[\rho(E,\omega) + \rho(E,-\omega)\right]$$

where the folding function is given by:

$$\rho(E,\omega) = \frac{1}{2\pi} \frac{\Gamma(\omega)}{[E-\omega-\Delta(\omega)]^2 + [\Gamma(\omega)/2]^2}$$

The quantities Δ and Γ are linked by a dispersion relation

$$\Delta(\omega) = \frac{1}{2\pi} P \int_0^\infty d\omega' \;\; \frac{\Gamma(\omega')}{\omega' - \omega}$$

therefore we only have to fix the values of the $\Gamma(\omega)$ function. We used the prescription of taking the energy average between the single particle widths of both particle and hole wave functions:

$$\Gamma(\omega) \sim \frac{1}{\omega} \int_0^\omega d\epsilon \left[\gamma(\epsilon_F + \epsilon + \omega) + \gamma(\epsilon_F + \epsilon - \omega)\right]$$

The γ widths are fixed to reproduce the values of the volume integrals of the imaginary part of the optical potential

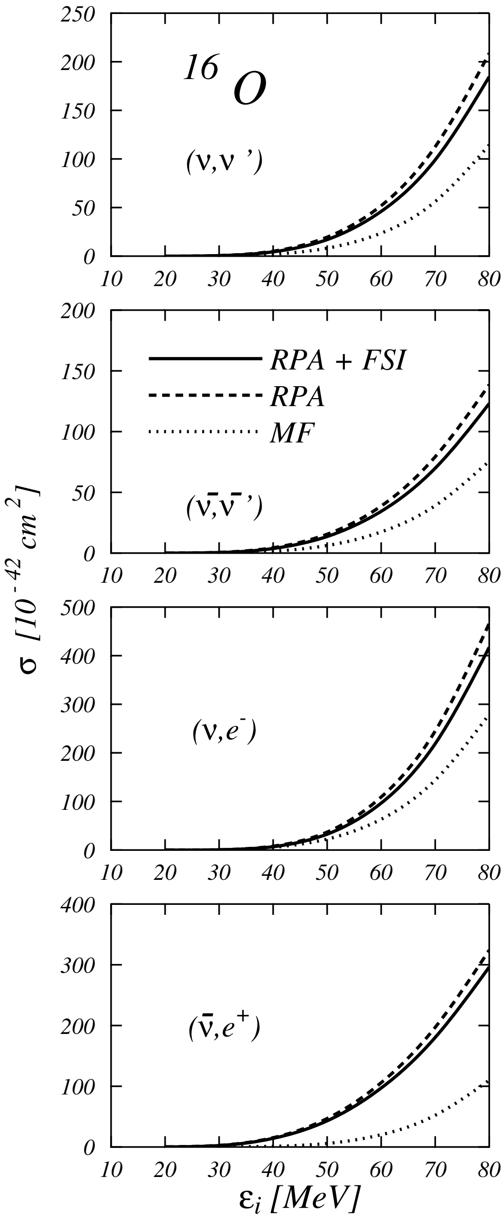

Fig. 3. Total inelastic cross sections as a function of the neutrino, or antineutrino, incoming energy

[8]. We have used the following parameterization:

$$\gamma(\epsilon) = A_\Gamma \left(\frac{\epsilon^2}{\epsilon^2 + B_\Gamma^2} \right) \left(\frac{C_\Gamma^2}{\epsilon^2 + C_\Gamma^2} \right) \qquad (1)$$

with A_Γ=11 MeV, B_Γ=20 MeV and C_Γ=110 MeV. Our CRPA results, corrected in this way to consider the FSI effects, reproduce rather well the quasi-elastic longitudinal and transverse responses of ^{12}C and ^{40}Ca [6] and the total inclusive cross section of ^{16}O [9].

The success of this model in reproducing the quasi-elastic responses pushed us to adopt it also in the giant resonance region. The result obtained by a straightforward application of the model to the total photoabsorption cross section is shown by the dotted line of Fig. 2. Evidently the FSI effects are overestimated. The values

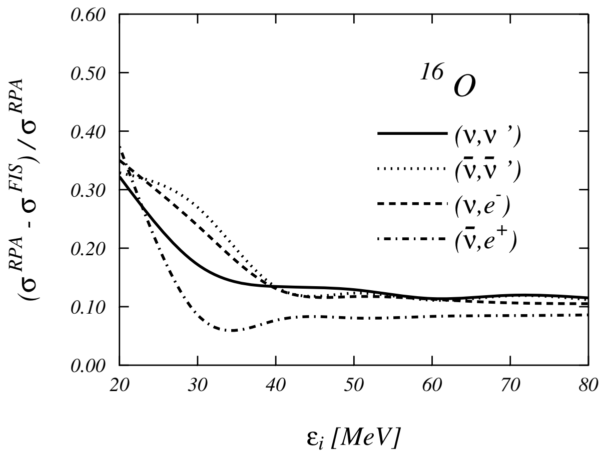

Fig. 4. Relative differences between the cross sections of Fig. 3

of the constants have been fixed to reproduce many body effects which modify mainly the motion of the single particle as if the nucleon moves in an optical potential. These are the most important effects in the quasi-elastic region, but in the giant resonance region more complicated many-particle many-hole excitations become important as it has been shown in [10]. The approximation of using optical potential parameter is also related to the assumption of the independence of the FSI from the multipole excitation. This assumption is plausible in the quasi-elastic regime where many multipoles contribute to the total cross section with comparable strength, but it is hardly justified in the giant resonance regime, usually dominated by few excitation multipoles.

To take into account the peculiarities of the giant resonance region we modify the values of the parameters of (eq:par). We used a set of energy dependent parameters. For energies above the giant resonance region ($\omega > 40$ MeV) we use the asymptotic values given above. We fix for $\omega = 10$ MeV the values $A_\Gamma = 6$ MeV and $B_\Gamma = 60$ MeV and we let them evolve linearly as a function of the excitation energy ω up to their asymptotic values. These parameters have been fixed to reproduce at best the photoabsorption data. The resulting cross section is shown in Fig. 2 by the full line.

The procedure described above has been used also for the ^{12}C nucleus, where we could test the validity of our model by comparing its results with the (few) inclusive electron scattering data in the giant resonance region [11]. Also in this case the inclusion of FSI improves noticeably the agreement with the data.

The results of Fig. 2 show that the main effect of the FSI is to move strength from the peak of the resonance to higher energies. For neutrinos of few tens of MeV part of strength goes in a region kinematically forbidden. This implies that the total cross section is reduced with respect to that predicted by the CRPA. This effect is evident in Fig. 3 where we show the total inclusive cross sections for various neutrino and antineutrino reactions as a function of the neutrino incoming energy. The CRPA results are shown by the dashed lines, while the inclusion of the FSI effects produces the full lines. For sake of comparison also the results obtained with a pure mean field model are shown (dotted lines).

The first, rather obvious remark, is the large difference between mean field and CRPA prediction, showing the inadequacy of the mean field in describing the cross sections in this energy region. The second remark is that, as we have expected, the FSI reduce the total cross section. This effect is more relevant at low neutrino energies, since for an analogous shift of the strength, the kinematically forbidden region, is larger. To have a better idea of this effect we plotted in Fig. 4 the relative difference between CRPA and FSI total cross sections. This figure shows that the relative reduction is of about the 35% for neutrinos of 20 MeV and it reaches a value of about the 10% above the 40 MeV.

The relevance of FSI in the quasi-elastic excitation region has been pointed out in other publications [9,12]. Here we have shown that for neutrino of few tens of MeV the effects of FSI can be even more relevant. The consequences on the detection of supernovae neutrinos are under investigation.

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