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NEUTRINO REACTIONS AND NUCLEAR SHADOW

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ABSTRACT

We discuss the high energy spin-isospin collective modes, in the region of the delta resonance and their signature in neutrino reactions.

The collective modes arise from the coupled propagation of pions and deltas. In a schematic model there are two such modes, one at low energy, the pion branch, which lies below the free pion and delta branches, the other, the collective delta, branch lies entirely in the time-like region, above the free branches. At large momenta the collective delta branch acquires a strong pionic component.

We summarize the status of the detection of the pion branch by hadronic probes. We then turn to the possible detection of the collective branches in neutrino reactions. Here the momentum transfer is space like, so that the collective delta branch is not accessible in these reactions. It should, however, manifest its existence by a loss of strength, as compared to the free situation, which should produce a shadow effect in the delta region. We make an estimate of the shadow in the schematic model. This shadow arises from the real part of the optical potential and the collective nature of the nuclear response in the delta region, in contradistinction with the usual one which arises from the absorptive part of the potential.

This article is dedicated to Torleif without whose patience my nuclear physics career would not have been.

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A central theme in nuclear physics in the last decade has been the exploration of the low energy collective modes in nuclei as seen by probes which couple to the nucleon spin and isospin. These phenomena are intimately linked to nuclear pion physics. An extreme case, not realized in nuclei, is referred to as pion condensation, while the observed modes are the Gamow-Teller ones. Such investigations are presently extended into the energy range corresponding to the delta isobar. Here new types of collective modes develop, based on an interplay between the free branches associated with the delta excitation itself on the one hand and with the pion branch on the other one.

These modes have a pionic character, i.e. they can be displayed when the coupling of the probe to the nucleon spin is parallel to the momentum transfer, the so called (spin) longitudinal coupling. Only such probes can see these states, which severely limits the possibilities of observation. Beside the physical pions the most extensively used ones are other hadronic probes acting as sources of virtual pions. Neutrinos have also been suggested and discussed as a possible mean of detection^{1,2}. This last possibility is based on the fact that, in the forward direction, the inelastic neutrino cross-section is proportional to the pion one, according to the Adler theorem³. The aim of the present article is to discuss neutrino reactions as means of

detection of the collective modes and the signatures of such modes in neutrino experiments.

The plan of the paper is as follows: we will first describe the collective states in a schematic model so as to focus on those features which are essential in the context of our discussion. We will then briefly summarize the status of their detection with hadronic probes and finally turn to the question of neutrino reactions.

It is well known that the propagation of pions in nuclear matter is dominated by the πN p-wave scattering, a phenomenon linked to the pion coupling to the delta isobar or, in nuclear many-body language, to the excitation of delta-hole states. Due to the p-wave nature of the scattering the equation of propagation is similar to the one for an electromagnetic wave in a dielectric. For our purpose we can ignore the perturbations produced by the πN s-wave interaction. The analogy with a dielectric is further strengthened by the existence of a Lorentz-Lorenz renormalization of the p wave πN amplitude in the expression of the optical potential.

Experimentally, an important observation is that the total pion nucleus cross section in the Δ -resonance region is not linear in the nucleon number A , but rather is proportional to $A^{2/3}$ and thus exhibits an important shadowing effect. Its appearance is associated with a shift of the delta peak position in the total cross section

towards lower energies. These two features are related to the coupled propagation of pions and deltas in the nuclear medium, which we now illustrate schematically.

For this purpose we use a simplified two level model proposed by Guichon and Delorme⁴ and we consider the case of infinite nuclear matter: we first neglect the delta width, as well as the two-nucleon pion absorption. In this case, and as long as the interactions between nucleons and deltas are ignored, the imaginary part of the pion propagator $\mathfrak{D}(q, \omega)$ and of the pionic response $R(q, \omega)$ are non vanishing in the (ω, q) plane only along the lines $\omega = \omega_\pi = (q^2 + m_\pi^2)^{1/2}$ and $\omega = \omega_\Delta$, respectively. Here $\omega_\Delta = [(q^2 + M_\Delta^2)^{1/2} - M]$ is the free delta excitation energy.

$$\text{Im } \mathfrak{D} = \frac{\pi}{2\omega_\pi} \delta(\omega - \omega_\pi);$$

$$\dot{R} = -\pi^{-1} \text{Im } \Pi_\Delta = \frac{C}{2\omega_\Delta} \delta(\omega - \omega_\Delta) \quad (1)$$

with $C = (4/9)(f^*/m_\pi)^2 \rho$, where f^* is the $\pi N \Delta$ coupling constant ($f^{*2}/4\pi = 0.32$), ρ is the nuclear density and Π_Δ is the Δ hole polarization propagator.

The coupling between the propagation of the Δ -hole and pion states generates collective states which correspond to the singularities of the dressed pion propagator i.e., which obey the equation

$$\omega^2 - q^2 - m_\pi^2 - q^2 \tilde{\Pi}_\Delta(q, \omega) = 0, \quad (2)$$

where $\tilde{\Pi}_\Delta$ is the Δ hole polarization propagator, renormalized by the Lorentz-Lorenz effect

$$\tilde{\Pi}_\Delta = \Pi_\Delta / (1 - g' \Pi_\Delta). \quad (3)$$

here g' is the Landau-Migdal parameter for the mixing of Δ h states. To keep the discussion to the essential points we have ignored the form factors.

Ignoring for the moment this renormalization the quantity $\tilde{\Pi}_\Delta$ reduces to the free delta hole polarization propagator Π_Δ . The collective branches which correspond to the singularities of the dressed pion propagator then obey the following second order equation in ω^2

$$(\omega^2 - \omega_\Delta^2)(\omega^2 - \omega_\pi^2) - Cq^2 = 0, \quad (4)$$

which has the solutions

$$\omega_{1,2}^2 = \frac{1}{2} [\omega_\pi^2 + \omega_\Delta^2 \pm ((\omega^2 - \omega_\Delta^2)^2 + 4Cq^2)^{1/2}] \quad (5)$$

The first root, ω_1 , reduces to ω_π when q goes to zero, this is the pion branch. The second one, ω_2 , which reduces to ω_Δ for $q=0$, corresponds to the delta like branch. These distinctions and denominations apply only at small momenta. With increasing momentum the mixing between the pion and the delta becomes so strong that one cannot speak anymore of the dominance of one state. We have a mixture of both, the "pisobar". The evolution of their energy with increasing momentum can be visualized from the two level picture of ref 4: when the energies of the bare branches are equal, $\omega_\pi = \omega_\Delta$ the

eigenstates are repelled in such a way that no crossing occurs. At large momenta and in a realistic description the energies of the two eigenstates should approach the bare energies, but this time it is ω_2 which tends towards ω_π while ω_1 approaches ω_Δ , as can be expected from the crossing of ω_π and ω_Δ . The ordering of the states is the following one:

$\omega_2 > \omega_\Delta > \omega_\pi > \omega_1$ for small q values, i.e. below the crossing point between ω_π and ω_Δ , while it is $\omega_2 > \omega_\pi > \omega_\Delta > \omega_1$ above the crossing point. The introduction of the Lorentz-Lorenz effect, i.e. the replacement of Π_Δ by the renormalized propagator $\tilde{\Pi}_\Delta = \Pi_\Delta/(1-g\Pi_\Delta)$ does not alter the previous conclusions but only changes the numerical values of $\omega_1(q)$ and $\omega_2(q)$. Now $\omega_2(q=0)$ is no longer equal to ω_Δ as a consequence of the collectivity induced by the repulsive short-range force embedded in g' . The position of the two collective branches is illustrated in fig. 1.

As Chanfray has done⁵ it is interesting to explore the strengths for probes which couple either to the pion or to the delta-hole state. In the first case one probes the imaginary part of the pion propagator, while in the second case one probes the response, i.e. the imaginary part of the delta-hole polarization propagator. The two quantities have the same singularities, namely the collective branches. They behave quite differently however: ImD only couples

to the pion part of the states, while the response couples to the delta-hole part of the eigenstates.

$$\text{ImD}(q, \omega) = \pi \left[\frac{Z_1(q)}{2\omega_1} \delta(\omega - \omega_1(q)) + \frac{Z_2(q)}{2\omega_2} \delta(\omega - \omega_2(q)) \right];$$

$$\begin{aligned} R(q, \omega) &= -\pi^{-1} \text{Im } \Pi_\Delta \\ &= C \left[\frac{Z_1(q)}{2\omega_1} \delta(\omega - \omega_1(q)) + \frac{Z_2(q)}{2\omega_2} \delta(\omega - \omega_2(q)) \right], \end{aligned} \quad (6)$$

where the probabilities $Z_1(q)$ and $Z_2(q)$ are given by

$$Z_1(q) = \frac{\omega_2^2 - \omega_\pi^2}{\omega_2^2 \cdot \omega_1^2}, \quad ; Z_2(q) = \frac{\omega_\pi^2 - \omega_1^2}{\omega_2^2 \cdot \omega_1^2}, \quad (7)$$

Notice that since Z_1 and Z_2 are probabilities their sum $Z_1 + Z_2 = 1$. In addition $Z_1(q=0) = 1$, while $Z_2(q=0) = 0$. The probability Z_1 is close to unity at small momenta, which reflects the fact that the pion branch is essentially of pionic nature; at large momenta it is the "delta" branch which has pionic character, so that Z_2 is then close to unity. The evolution of Z_1 with momentum is shown in fig. 2.

The experimental display of these states is of great interest: it would be an instructive example of nuclear collective states at very high excitation energies, in contrast to the usual collective states which have an excitation energy of only a few MeV or a few tens of MeV. Here the collectivity takes a step of more than a hundred MeV. Two questions arise in connection with this problem. The first one is whether these collective features, namely two branches, one below and one above the energies of the bare states, survive a more

realistic treatment in finite nuclei. If they exist, the second question is how to explore them. The first point has been investigated by Delorme and Guichon⁶ who have done a detailed study both of the collective nature of the spin-isospin response in the delta region and also of the detection of the pionic branch in hadronic reactions. They have taken into account the finite width of the delta modified by the medium effects and also the possibility of a two-nucleon pion absorption through channels other than delta excitation which is already included in the modified delta width. To incorporate the finite nuclear size they calculate the bare polarization propagator in a semi-classical approximation. As this approach is not suited to treat the collective effect in the vicinity of physical pions, they have solved the RPA equations exactly, using the semi-classical bare quantity as input. Their investigation shows that the main features of the simplified model are preserved even if the collective states are quite broad. While the free longitudinal response only exhibits the delta branch, the RPA one shown in fig 3 (taken from ref 6) displays the two collective states as prominent bumps with a valley between them.

The exploration of these collective features requires the use of a probe which can couple to pion-like states. The physical pions themselves possess this property but do not offer the independent variations in ω and q needed to display the existence of these states.

The information that they provide is limited to the line $\omega = (q^2 + m_\pi^2)^{1/2}$, which falls in the valley between the collective peaks and, thus, to the shadow phenomenon, which indicates that some strength has moved elsewhere. Nor can the collective branches be explored with photons, in spite of their coupling to the spin-isospin of the nucleons by the magnetic term. Here the spin coupling is a transverse one and therefore insensitive to the pion propagation. Indeed the excitation of the delta resonance by real photons displays little or no collectivity: there is no shadowing effect nor any strong shift in the peak position.

One has therefore to resort to virtual pions. Two possibilities have emerged. The first one is to utilize hadrons as a source of the virtual pions. Several probes have been used: ($^3\text{He}, T$), (p, n), ($\bar{d}, 2p$). The charge-exchange nature of these reactions insures the isovector character of the interaction. But the spin component of the NN isovector interaction contains both longitudinal and transverse spin parts. These cannot be separated without polarization data, which are not available nor in the case of the ($^3\text{He}, T$) nor in that of the (p, n) reactions. The spectacular outcome of the ($^3\text{He}, T$) experiment⁷ is the existence of a downward shift of the delta peak position of about 70 to 80 MeV, practically constant for a series of nuclei from C to Pb. In this experiment the energy of the ^3He projectile is 2 GeV, which leads, in the forward direction, to the following relation between the

energy and momentum transfer: $\omega \approx 0.8q$. The corresponding line crosses the expected position of the pion branch. It is therefore tempting to attribute the downward shift to the collective nature of the spin longitudinal response⁸. However the highly peripheral nature of the probe (the densities explored are only about 15% of the central density) makes this interpretation *a priori* questionable.

A detailed analysis of this experiment has been performed by Delorme and Guichon⁶. They first built the elementary NN- Δ N interaction from π and ρ exchange with antisymmetrization properly accounted for. With a composite projectile such as ^3He the knowledge of the transition form factor $^3\text{He-T}$ is needed. The transverse one is known from (e,e') scattering. For the longitudinal one which is bound to be different, owing to the D-wave content of the 3-body wave function, they assume a similar functional dependence with one adjustable parameter which they obtain from the fit to the data for a proton target at various angles. The resulting fit leads to a slower momentum variation of the longitudinal form factor than for the transverse one, which favours the longitudinal interaction at large momenta. This is to be expected from the S-D interference, which is destructive in the transverse case and constructive in the longitudinal one. In addition it turns out that their fitted value matches the result of a calculation⁹ with three-body Faddeev wave functions. They have another adjustable parameter which is a

normalization factor; it is remarkable that it does not deviate from unity by more than 15%. With this input they are able to account for the data on the hydrogen target quite well.

For a nuclear target they introduce the distortion of the projectile by an eikonal approximation. With an arbitrary normalization (which deviates from unity by less than 25%) they are able to reproduce the set of experimental data for a variety of nuclei at various angles, although the cross-section varies by an order of magnitude. They find that an appreciable fraction of the shift is indeed due to the collective nature of the response (≈ 30 MeV in Pb); the rest is due to various effects, such as the form factor variation which distorts the response. Their work shows that even in the far periphery of the nucleus, the response retains its collective character, quite a remarkable result. A similar conclusion was reached in ref. 10) One would indeed like to see the collective states fully developed as should occur inside the nucleus.

The (p,n) probe a priori seems better suited to achieve this goal since it penetrates more deeply in the nuclear interior. However the experiments¹¹ reveal in fact less shift than the ^3He ones. This result, at first surprising, is interpreted in the description of ref 6: part of this effect is due to the ^3He form factor, which favors the longitudinal interaction over the transverse one, while this selection does not

occur for a (p,n) probe. The excitations are then predominantly transverse, which decreases the collective shift. However the third probe used to excite the delta, the ($\vec{d},2p$) one¹² raises a problem. It displays a downward shift but its transverse content, which this time can be measured from the polarization analysis, is larger than expected (in the ratio 3 to 1 to the longitudinal part in C), which should eliminate totally the shift of collective origin. However in the region of the quasi elastic peak where the NN interaction is known the ($\vec{d},2p$) experiment also gives too much transverse component. Its results are yet to be understood. In spite of the strong indications provided by the ($^3\text{He,T}$) results in favour of the collective nature of the response the hadron probes remain delicate to interpret.

These difficulties are not present with the other type of probes which can be used as sources of virtual pions, namely neutrino reactions. Here the probe fully penetrates the nucleus. In addition the weak interaction is perfectly known and the type of response probed is fully predictable. The problems here are of another nature: the neutrino energy is not measurable and the energy resolution on the final lepton energy is quite poor. In spite of that we will see that some important messages can be obtained from these reactions. The experiments that we will discuss are inclusive ones where only the final lepton is detected: $\nu(\bar{\nu}) + A \rightarrow \mu^-(\mu^+) + X$. In the CERN Charm II experiment¹³ the final muon energy k' is measured, as well as the

muon angle θ . The incident neutrino energy k can be considered as unknown since the information on the neutrino spectrum ($10 \leq k \leq 30 \text{ GeV}$) is too rough to be of any use. However, in this experiment some important information on the energy transferred to the nuclear system is available albeit with a poor energy resolution. In a set of data a cut is applied on the events which eliminates all those which correspond to an energy transfer larger than $\omega \geq 300 \text{ MeV}$. The cut is such that the only possible excitations of the nucleus are the quasi elastic ones and the delta excitation, together with the continuous spectrum of 2particle-2hole excitations, and with some additional small tail from higher nucleonic excitations, such as the N^* resonance. This is the energy region where we expect the large collective effects of the pion branch to occur. In the conditions of this experiment, where the incident energy is very large as compared to the energy transfer, and near the forward direction we will see that even without the knowledge of the neutrino energy relevant information can be extracted using only that of the transverse muon momentum. Further physical information would be obtained if the energy transfer could be measured with a precision better than 100 MeV, which is beyond present possibilities.

The inclusive cross-section on nuclei for the reaction $\nu(\bar{\nu}) + A \rightarrow \mu^-(\mu^+) + X$ is

$$\frac{d^2\sigma}{d\Omega dk'} = \frac{G^2 k^2}{8\pi^2} \cos^2 \frac{\theta}{2} \left\{ \frac{Q^2}{2} G_V^2(Q^2) R_C(q, \omega) + \frac{\omega^2}{2} G_A^2(Q^2) R_L(q, \omega) + \left(\frac{Q^2}{q^2} + 2tg^2 \frac{\theta}{2} \right) (G_A^2(Q^2) + G_M^2(Q^2) \frac{q^2}{4M^2}) R_T(q, \omega) \pm \frac{2(k+k')}{M} tg^2 \frac{\theta}{2} (G_A^2(Q^2) G_M^2(Q^2) R_T(q, \omega)) \right\} \quad (8)$$

where G is the weak coupling constant, k and k' the initial and final lepton momenta, $q = k - k'$, $\omega (= k - k')$ if the muon mass is ignored) is the four-momentum transferred to the nucleus and $Q^2 = q^2 - \omega^2$. In expression (8) terms of order M^{-2} have been neglected. In addition we have assumed that only purely nuclear states have been excited, the generalization to states with a delta excitation will be introduced later. The nucleon weak coupling constants are taken with the usual values: $g_V(0)=1$, $g_A(0) = -1.25$, $g_M(0) = 4.71$. The various quantities R in eq. (8) represent the nuclear responses with the following indices: C for charge, L for spin longitudinal, and T for spin transverse

$$R_a(q, \omega) = \sum_n \langle n | \sum_i O_a^i e^{iqx_i} | 0 \rangle |^2 \delta(E_n - E_0 - \omega), \quad (9)$$

where 0 are the operators responsible for the transition to the excited states n with

$$O_C^i = \tau_i^\pm; \quad O_L^i = \sigma_i \cdot \hat{q} \tau_i^\pm; \quad O_T^i = \frac{1}{\sqrt{2}} (\sigma_i \cdot \hat{q} (\sigma_i \cdot \hat{q})) \tau_i^\pm; \quad (10)$$

Note that for a free Fermi gas the three responses R_C , R_L and R_T are identical. As mentioned, expression (8) is restricted to purely nuclear, i.e. low energy, excitations. At high energy transfer, $\omega \approx 300$ MeV, a nucleon can be transformed into a delta, generating a new type of response which should be added to expression (8). The charge operator does not connect the nucleon to the delta, except for

a small quadrupole transition which will be ignored. The neutrino cross-section arising from the excitation of the delta then writes

$$\frac{d^2\sigma^\Delta}{d\Omega dk'} = \frac{G^2 k^2}{8\pi^2} \cos^2 \frac{\theta}{2} \left\{ \frac{\omega^2}{2} G_A^2(Q^2) R_L^\Delta(q, \omega) + \left(\frac{Q^2}{q^2} + 2tg^2 \frac{\theta}{2} \right) (G_A^2(Q^2) + G_M^2(Q^2) \frac{q^2}{4M^2}) R_T^\Delta(q, \omega) \pm \frac{2(k+k')}{M} tg^2 \frac{\theta}{2} G_A^2(Q^2) G_M^2(Q^2) R_T^\Delta(q, \omega) \right\}, \quad (11)$$

where G_M and G_A are the magnetic and axial coupling constants for the $N\Delta$ transition. The responses R_a^Δ are defined by

$$R_a^\Delta(q, \omega) = \sum_n \langle N | \sum_i (O_a^\Delta)^i e^{iqx_i} | 0 \rangle |^2 \delta(E_N - E_0 - \omega), \quad (12)$$

$$\text{with} \quad (O_L^\Delta)^i = S^i \cdot \hat{q} \tau_i^\pm; \quad (O_T^\Delta)^i = (S^i \cdot \hat{q} (S^i \cdot \hat{q})) \tau_i^\pm \quad (13)$$

Here N is a nuclear state containing one delta excitation and S and T are the transition spin and isospin operators respectively, connecting spin and isospin 1/2 and 3/2 states. Using PCAC and the Chew-Goldberger-Low-Nambu (CGLN) model¹⁴ the coupling constants G_M and G_A are related to the $\pi N\Delta$ coupling constant f^* by

$$G_M/g_M = G_A/g_A = f^*/f = 2. \quad (14)$$

As for the Q^2 variations of these form factors we will assume that they are the same as those of the corresponding nucleon form factors. As a consequence of the scaling properties embedded in

eq.(14) the balance between the longitudinal and transverse components is not altered by the delta excitation in the free case when the transverse and longitudinal responses are equal. However, the collectivity of the responses produces a contrast between the longitudinal and transverse ones. While in the quasi elastic region this collectivity is mild and the contrast moderate, it is extremely strong in the delta energy region, since the longitudinal response is totally reshaped by the ph force with the appearance of the collective pion and delta branches.

The question that we will now discuss is how the collectivity of the longitudinal response affects the neutrino cross-section. We will first see which regions of the (ω, q) plane are explored in neutrino reactions. The momentum and energy transfer are given respectively by

$$q^2 = k^2 + k'^2 - 2kk' \cos \theta, \quad \omega = k - k'. \quad (15)$$

(neglecting the lepton mass). As the neutrino energy is not measured, its elimination in (15) gives the following relation between ω and q

$$q^2 - (\omega + 2k'\sin^2\theta/2)^2 = k'^2\sin^2\theta. \quad (16)$$

This equation defines a hyperbola which crosses the q -axis at $q = 2k'\sin\theta/2$. Each couple of values, (k', θ) defines a different hyperbola and the neutrino cross section integrates the responses along this curve. In our previous work² we focused on the case of

relatively low energy neutrinos, of a few hundred MeV while here I will be concerned with the problem of high energy neutrinos (k of the order of 20 GeV). We also restrict the discussion to forward directions, $\sin\theta \approx \theta$. The transverse muon momentum is defined as $p_T = k'\theta$. In the region of the pion branch, i.e. $\omega \gtrsim 200$ MeV, the quantity $2k'\sin^2\theta/2 \approx p_T^2/2k'$ can be neglected as compared to the energy ω on the l.h.s. of eq. (16) and the hyperbola then depends on one parameter only, the quantity p_T , with the equation: $q^2 - \omega^2 \approx p_T^2$. For a given p_T value the experiment measures the integral of the neutrino cross section along the hyperbola, with a weight factor $W(\omega)$ which depends on the cut in ω applied to the selection of events. For simplicity we will assume in the following that this factor is a constant. In the forward direction, $p_T \approx 0$, the hyperbola reduces to the photon line $q = \omega$. Along this line $Q^2 = 0$ and only the longitudinal response enters in the cross section, as expected from the Adler theorem.

When one leaves the forward direction, the other responses also enter, in particular the transverse one, which contains the delta excitation but without collectivity. We will consider typical values of p_T between 0 and 0.3 GeV/c. In this range the longitudinal response remains dominant and we will neglect the other contributions. In order to discuss the main features expected for the neutrino cross section we will use the schematic model described previously. One

feature is immediately apparent: the neutrino reactions can only probe the space-like region, $q > \omega$. The upper collective branch however lies in the time-like region, since it is above the free pion line $\omega_2 > \omega_\pi > q$. It is therefore not accessible in neutrino reactions where the four momentum transfer is always space-like. The strength contained in this upper branch is lost in neutrino reactions and a shadow is therefore expected to occur. It can be evaluated in a semi-quantitative way from the schematic model and the expressions of the responses given previously.

We will take as an example the case $p_T = 0.2$ GeV/c. We first consider the intercept of the corresponding hyperbola with the free delta branch which occurs at the point $q_0 = 400$ MeV/c for the momentum and $\omega_0 = 346$ MeV for the energy. When the interactions are introduced the intercept of the hyperbola with the collective branches, i.e. the pion branch occurs for a value of the momentum $q_1 = 280$ MeV/c and of the energy $\omega_1 = 196$ MeV (for a Landau-Migdal parameter $g' = 0.5$). At this point the corresponding factor Z_2 has the value $Z_2 \approx 0.3$ and the longitudinal neutrino cross section, which in the free case is equal to $B\omega_0/q_0^2 = .197B$ with $B = (16\pi^2)^{-2}G_A^2k^2G_A^2(p_T^2)$, becomes $BZ_2(q_1)\omega_1/q_1^2 = .075B$ once the interactions are introduced. The difference introduced by the collectivity, hence the shadow effect, is quite pronounced, it decreases the cross-section by nearly a factor of 3. Notice that it arises essentially from the factor Z_2 which is quite

small (0.3), the modification of the kinematical factor ω/q^2 between the free point and the collective one being unimportant.

The model is certainly oversimplified. First notice that we have considered only the delta region while in actual experiments the quasi elastic region also enters, suppressing part of the shadow effect. Second we have taken a constant value for the experimental cut-off factor $W(\omega)$. If W increases with decreasing energy, the pion branch is favoured over the free delta one and the shadow will hence be less pronounced. In addition a realistic treatment of the finite Δ width and of the finite nuclear size will reduce the amount of shadowing but we expect the main features of the simple model to survive since part of the delta strength is displaced by the interactions at high energy, where it will escape detection, as is shown in fig 3. The neutrino reactions in that respect offer an information which is complementary to the one provided by physical pions. For the last probes it is observed that the strength along the line $\omega = (q^2 + m_\pi^2)^{1/2}$ is decreased in nuclei. But even a mild deformation of the response could achieve such a result. For neutrinos instead one integrates the response along a curve. If a loss of strength is observed, then it can only be due to a violent modification of the nature of the response, as occurs with the appearance of a collective branch ω_2 in the time like region. We

believe that the observation of a shadow effect is within experimental reach.

With increasing transverse momentum, i.e. with increasing angle, the longitudinal response becomes less dominant. In the free case the transverse and longitudinal responses give equal contributions along the line $\omega \approx 0.7q$. For smaller ω values the transverse part dominates. We expect therefore the shadow effect to disappear progressively when the transverse momentum becomes larger than $p_T \approx 0.4$ to 0.5 GeV/c, owing to the increasing contribution of the transverse response.

To go beyond the shadow and to display the pion branch itself, i.e. a downward shift of the energy transfer from the free delta energy to the energy of the pion branch, requires information on the energy transfer with a resolution better than ≈ 100 MeV, which has not been achieved in present experiments.

Notice that in the forward direction the shadow effect in neutrino reactions is linked to those of soft pions. It is therefore relevant for the Adler-Weisberger relation¹⁵ and the quenching of the axial coupling constant, which I proposed long ago¹⁶. It is important to point out that the shadowing that we are discussing here is of a different nature than the one which can be observed¹⁷ at larger energy transfers, ($\omega > 1$ GeV) where it arises from the absorptive part of the pion optical potential which is known. Here

instead we are discussing a reshaping of the pionic response by its collective nature, which cannot be probed by physical pions, so that neutrinos are used instead to learn about pionic phenomena.

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Figure captions.

- Fig. 1. Evolution with momentum of the collective branches for a value of the Landau-Migdal parameter $g' = 0.5$. Also shown are the free branches (from ref. 5).
- Fig. 2. Evolution with momentum of the probability $Z_1(q)$ (from ref. 5).
- Fig. 3. The expected behavior of the collective longitudinal response in Pb (from ref. 6).

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- Figure 1 -

- Figure 3 -

- Figure 2' -