

# Coherent Neutrino–Nucleus Scattering

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We review coherent scattering of neutrinos on nuclei by coupling the weak currents to vector and axial-vector meson states. The couplings are obtained from known reactions, like  $\tau$ –lepton and vector meson decays. We compute and present the cross sections as functions of energy and momentum transfer for various kinematic regions, including those which are relevant to oscillation experiments. The results are presented in figures and are consistent with numerical values used in the interpretation of oscillation experiments.

## 1. Introduction

Coherent scattering occurs when photons or neutrinos interact with two or more particles and the amplitudes from the various particles in the target add up. Coherent phenomena have been observed in electromagnetic interactions when photons interact with nuclei or atoms or layers of atoms, as is the case with Bragg scattering. A consequence of coherence is an increase of the cross-section becoming proportional to the square of the number of particles in the target leading to increased counting rates. A reaction where coherent scattering has been reported [1]–[8] is

$$\nu + \text{nucleus} \rightarrow \mu^- + \pi^i + X^i. \quad (1)$$

A basic condition for coherent scattering requires the wavelength of the incident particle or the wavelength of the momentum transferred to the target to be large enough so that the entire region within the

wavelength contributes to the amplitude. This situation is difficult to realize in neutrino reactions because the radius of the nucleus sets the scale

$$R_{\text{nucleus}} \approx 2 \text{ fm} \approx \frac{1}{100 \text{ MeV}} \quad (2)$$

and it is fulfilled either at very low neutrino energy where the cross sections are small or low momentum transfers  $|t| \lesssim 0.10 \text{ GeV}^2$  where the phase space is limited. In the latter case it is also necessary to define the particles and the method for controlling the momentum transfer, so that we know that the events originate from coherent scattering.

Several cases of coherent neutrino scattering have been discussed in articles [9]–[10] but only the reaction in eq. (1) has been observed experimentally. The main reason is that the cross-sections are very small.

A first case of coherent scattering occurs when the momentum transfer between the

incident neutrino and the scattered lepton is small. This corresponds to the parallel configuration of the leptons. At  $Q^2 = 0$ , the PCAC hypothesis allows one to derive the contribution of the axial current to the cross section [14]:

$$\left. \frac{d\sigma}{d\nu dQ^2 dk_T^2} \right|_{Q^2=0} = \frac{G_F^2 E' f_\pi^2}{2\pi^2 E \nu} \frac{d\sigma_{el}^{\pi N}}{dk_T^2} \quad (3)$$

The extension to non-zero  $Q^2$  is given by other mesons, like  $A_1$  or  $\rho\pi$  pairs [14].

A second case of coherent scattering occurs when the wavelength of the momentum transferred to the target nucleus is large enough. This is satisfied when the 4-momentum transfer squared to the nucleus is small. We shall denote the momentum transfer by  $t$  and for  $|t| < 0.10 \text{ GeV}^2$  a peak has been observed for reaction (1) in several experiments, which is interpreted as the coherent scattering from the nucleus. In the zero-recoil approximation

$$t = (q - p_\pi)^2 = - \left[ \sum_{\mu, \pi} (E_i - p_i^\parallel) \right]^2 - \left[ \sum_{\mu, \pi} p_i^\perp \right]^2 \quad (4)$$

where the right-hand side depends on the transverse and parallel momentum components of the muon and the pion, both of which are detectable in the experiments [13].

An additional requirement for coherent scattering demands the wave function of the nucleus to be the same before and after the interaction. This puts restrictions on the intermediate mesons interacting with the nucleons. The scattering on the nucleus should not change charge, spin, isospin or other quantum numbers. Since the isospin operator,  $\tau_3$ , has eigenvalues with opposite sign for proton and neutron, the contribution of the isovector

intermediate mesons is proportional to difference of number of protons and neutrons and therefore negligible for most nuclei. Consequently, in order for proton and neutron contributions to add up the intermediate mesons must be isoscalars.

Diagrams which are allowed are shown in figure 1.

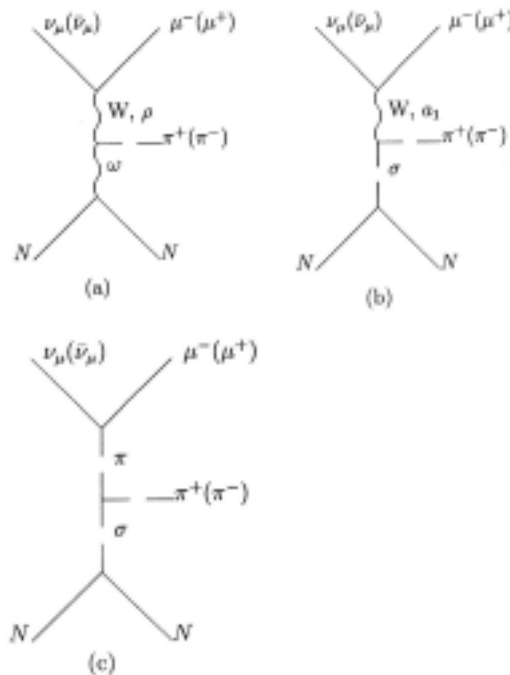


Figure 1. Leading channels contributing to coherent single pion neutrino production.

According to these diagrams intermediate vector boson is replaced with the  $\rho$  and the  $A_1$  mesons and the pion. The remaining part of the diagrams is computed as the scattering of hadronic states. Piketty and Stodolsky [12] estimated the production of  $\pi$ ,  $\rho$ ,  $A_1$ -mesons using meson-dominance, suggesting that the vector

current is replaced by the  $\rho$ -meson and the axial current by  $A_1$  and other mesons. Rein and Sehgal [13] developed a model with intermediate mesons, introducing a form factor for the nucleus in order to describe coherence. The last active group in this field is Belkov and Kopeliovich [14] who suggest that a summation over intermediate meson states is more accurate. These suggestions are appealing but it is still hard to compute them accurately [15]. We shall describe a calculation along these lines, which relies on the available data and estimates the coherent cross-section at lower and higher energies.

## 2. Effective Couplings

The effective Lagrangian for the low-energy weak interaction of a charged vector meson is [16]

$$\mathcal{L}_\rho = -\frac{g_W}{2} \frac{f_\rho}{2} V_{ud} W_{\mu\nu} \rho^{\mu\nu} \quad (5)$$

with  $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$  and  $\rho^{\mu\nu} = \partial^\mu \rho^\nu - \partial^\nu \rho^\mu$ . Whenever the  $\rho$  is on the mass-shell the Lagrangian becomes

$$\mathcal{L}_\rho = -\frac{g_W}{2} V_{ud} f_\rho m_\rho^2 W_\mu \rho^\mu. \quad (6)$$

In this equations  $g_W$  is the SU(2) coupling constant and  $V_{ud} = \cos(\theta_c)$  with  $\theta_c$  the Cabibbo angle.

Similarly the effective interaction of a charged axial meson on the mass shell is given by

$$\mathcal{L}_A = \frac{g_W}{2} V_{ud} f_A m_A^2 W_\mu A_1^\mu. \quad (7)$$

The constants  $f_\rho$  and  $f_{A_1}$  are coupling constants of the respective vector mesons to the  $W$ -boson and must be determined by experiments. The decays of the  $\tau$ -lepton provide this opportunity. Combining with

the Standard Model Lagrangian we easily obtain Lagrangian of effective interaction of the charged current with the  $\rho$  meson:

$$\mathcal{L}_{eff} = G_F f_\rho m_\rho^2 V_{ud} \bar{e} \gamma^\mu (1 - \gamma^5) \nu \rho_\mu \quad (8)$$

and there is a similar formula for the  $A_1$ -meson.

The width of the process  $\tau \rightarrow \nu_\tau + \rho$  is [16]

$$\Gamma(\tau \rightarrow \nu + \rho) = (G_F V_{ud} f_\rho)^2 \frac{m_\rho^2}{8\pi m_\tau^3} (m_\tau^2 - m_\rho^2)^2 (m_\tau^2 + 2m_\rho^2). \quad (9)$$

This gives  $f_\rho \approx 0.16$ . Since chiral symmetry is broken, relation  $f_a = f_\rho$  is modified and analysis of experimental data [16] gives  $f_a \approx 0.8 \cdot f_\rho$ .

The next coupling refers to the decay  $A_1 \rightarrow \pi + \sigma$  with the effective coupling

$$g_1^{a_1 \sigma \pi} \sigma a_{1\mu} \partial^\mu \pi + g_2^{a_1 \sigma \pi} a_1^{\mu\nu} (\partial_\mu \pi \partial_\nu \sigma - \partial_\nu \pi \partial_\mu \sigma). \quad (10)$$

The total width of the  $A_1$  is poorly known (being very wide) and the branching ratios are not determined. For that reason values of  $g_1^{a_1 \sigma \pi}$  and  $g_2^{a_1 \sigma \pi}$  were determined in [17] from theoretical considerations based on extended Nambu–Jona-Lasinio model.

The amplitudes for the various diagrams are written following standard Feynman rules. They also involve the couplings of isoscalar mesons to the nucleus for which the contributions of protons and neutrons add up. When the momentum transfer to the nucleus is large, the scattering is incoherent. For small momentum transfers  $|t| < 0.10 \text{ GeV}^2$  the whole nucleus participates and contributes coherently. This aspect is included phenomenologically by introducing a factor  $F(t) = e^{-b|t|}$  with  $b$  being determined experimentally.

The experiments distinguish two categories of events: events with and without

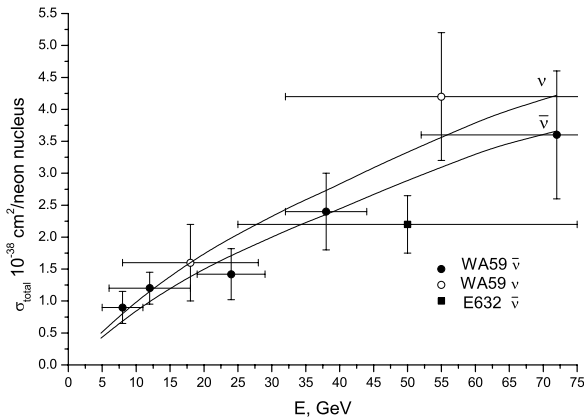


Figure 2. Total cross section of coherent single pion neutrino and antineutrino production.

stubs. Events with stubs are incoherent since the nucleus breaks up – they have no special characteristics. For events without stubs, the experiments observed a large peak at  $|t| < 0.10 \text{ GeV}^2$ . Many experiments attempt to determine  $b$  but they reported a large range of values. The experimental groups also report [7,8] the energy dependence of the coherent pion production shown in fig. 2.

We use the sum of the diagrams described above to produce the curves presented in fig. 2 and obtained the value  $b = 52 \text{ GeV}^{-2}$  for a neon nucleus. We also computed the differential cross section shown in fig. 3.

At  $t = 0$  the  $\rho$ -exchange graph vanishes whereas  $A1$ -exchange graph is finite. With increase of  $|t|$  the differential cross section  $d\sigma/d|t|$  corresponding to the  $\rho$ -exchange graph grows faster than that corresponding to the  $A1$ -exchange. Thus diagram in fig. 1(a) substantially contributes to the total cross section. We

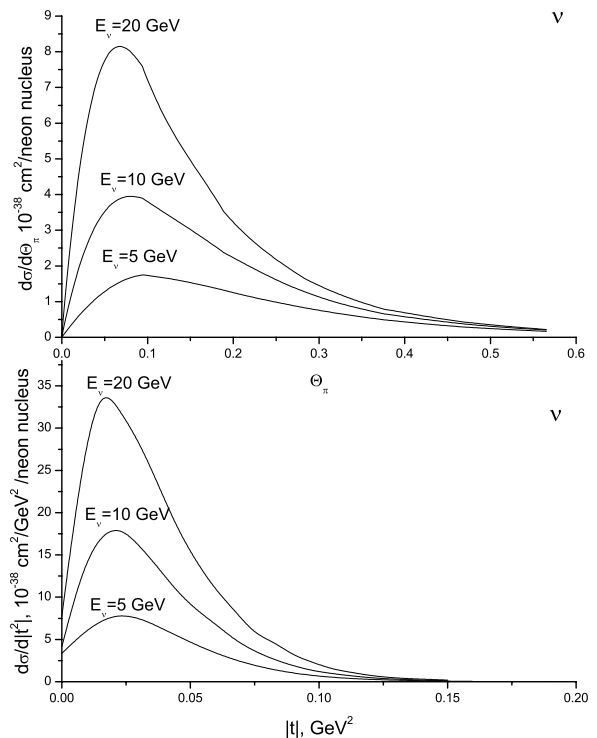


Figure 3. Differential cross sections  $d\sigma/d\theta_\pi$  and  $d\sigma/d|t|$ .

wish to note here, that in our calculations we take both longitudinal and transversal polarizations of the gauge bosons into account.

The cross section peaks at low values of  $t$  and  $\theta$  as expected. The differential cross section falls off with increasing  $|t|$  which is a consequence of the nucleus' form factor. The value of  $b$  is much larger than typical values of diffractive scattering, where  $b \sim 3 - 5 \text{ GeV}^{-2}$ , which is a strong indication that it reflects the particle density within the nucleus.

### 3. Numerical Results

The scattering of neutrinos through charged current receives contributions mainly from the  $A_1$  and  $\rho$  intermediate states. Contribution of diagram in Fig. 1(c) is proportional to the lepton mass and therefore negligible.

The difference between neutrino and antineutrino cross sections is also determined by the interference between the diagrams 1(a) and 1(b) and is relatively small.

The integrated cross sections for  $CC$  and  $NC$  coherent scattering are depicted in fig. 4.

The cross-section per Oxygen nucleus at  $E_\nu = 2$  GeV is  $0.16 \times 10^{-38}$  cm<sup>2</sup> and for antineutrinos  $0.13 \times 10^{-38}$  cm<sup>2</sup>. The cross-section for resonance production at the same energy per Oxygen nucleus is  $\sim 5 \times 10^{-38}$  cm<sup>2</sup>. Thus coherent scattering is  $\sim 3\%$  of the charged current resonance production.

Similar calculations were performed for the scattering of neutral currents on an Oxygen target. The cross-sections are smaller and are shown in fig. 4. Again in the case of neutral currents the coherent production of pions is 3% of resonance production. The two numerical estimates for coherent scattering add a small contribution to the neutrino oscillation data at small values of  $|t|$  and agree with the values introduced in the analysis of the data [18].

### 4. Summary and Outlook

Coherent production of pions by neutrinos has been observed in several experiments. The events have a characteristic  $t$ -dependence which suggests the scattering from the entire nucleus. In addition

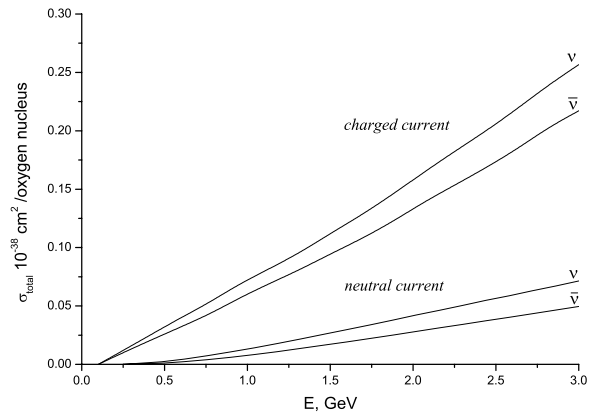


Figure 4. Total cross section for CC and NC coherent single pion antineutrino and neutrino production.

to the  $t$ -dependence coherent scattering must show characteristic dependence

- (i) on the momentum transfer between the leptons,  $Q^2$ ,
- (ii) an azimuthal dependence
 
$$d\sigma = C_1 + C_2 \cos \phi + C_3 \cos 2\phi$$
 with  $C_1, C_2, C_3$  functions of momenta etc. independent of  $\phi$ , and
- (iii) a dependence on the atomic number of the nucleus  $A$ , which has not been determined yet.

The cross sections at various neutrino energies are correlated (see figs. 2 and 4) and it will be a challenge to observe and determine properties of the effect at lower energies in the new generation of neutrino experiments.

A closely related process is [19] – [21]

$$\nu + e^- \rightarrow e^- + \gamma + X_1 . \quad (11)$$

This is a weak process with the pion being replaced by the emission of a photon and

it can be calculated accurately. The cross-section is expected to be very small [19] – [21].

Finally, another interesting process is

$$a + N \rightarrow \gamma + X_2 \quad (12)$$

where  $a$  is the field for an axion. Coherent scattering in this reaction is very important because it significantly enhances the chances for observing axions coming from Sun or another extraterrestrial source.

## 5. Acknowledgement

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