

## Neutrino-induced nuclear excitations

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We present an improved, compared to that of Belusevic and Rein, theoretical value of the cross section for the neutrino-induced nuclear excitation of iron. This result is based on a measurement of the photoabsorption cross section on the same nucleus, which can be related to the transverse part of the neutrino cross section via the conserved vector current hypothesis. The longitudinal part is related to the pion absorption cross section through the partial conservation of the axial-vector current, and thus reflects the spontaneous breaking of chiral symmetry. A general formula for the excitation cross section is derived, which is valid for both low and high incident neutrino energies. When caused by a weak neutral current, this process may play an important role in core-collapse supernovae. It can also be detected using low-temperature techniques with the purpose of cosmological and weak-interaction studies. A new estimate of the cross sections for neutrino-induced nonscaling processes described by Belusevic and Rein is discussed in the context of two experiments using iron targets, but at very different beam energies.

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An incident neutrino can excite the target nucleus, which subsequently deexcites without much measurable fragmentation. At high energies the value of the excitation cross section per nucleon is comparable to that for quasielastic scattering of neutrinos on nucleons, whereas at low energies it is appreciably larger. This contribution has been previously estimated [1] for an iron nucleus by relating the neutrino cross section to known electromagnetic and pion-induced cross sections via the conserved vector current (CVC) and partially conserved axial-vector current (PCAC) hypotheses [2]. However, the earlier estimate was not very accurate because data for neighboring nuclei were used to obtain the value of the photoabsorption cross section on iron. Since then a measurement [3,4] of the photoabsorption cross section on  $^{56}\text{Fe}$  has been brought to our attention [5], enabling us to improve considerably the accuracy of the prediction. In this paper, as opposed to Ref. [1], a general formula for the excitation cross section is derived, which is valid for both low and high incident neutrino energies.

The cross section (per nucleon) for neutrino scattering off a target  $A$  of mass  $m$  reads [2]

$$\frac{d^2\sigma}{dxdy} = \frac{G^2 E^2}{4\pi^2} \frac{y}{(1 + Ey/2mx)} \frac{\Phi_A}{N_A} \times \left\{ \left( 1 - y + \frac{y^2}{2} + \frac{xy m}{2E} \right) \sigma_t + \left( 1 - y - \frac{xy m}{2E} \right) \sigma_l + \sigma_i \right\}, \quad (1)$$

where  $\sigma_l$  denotes the longitudinal and  $\sigma_t = (\sigma_+ + \sigma_-)/2$  the transverse cross section for the scattering of the intermediate vector boson with  $A$ ;  $\Phi_A$  is the corresponding flux factor ( $\Phi_A = 4m\sqrt{\nu^2 - q^2}$ ) and

$$\sigma_i = \left( 1 - \frac{y}{2} \right) \sqrt{y^2 + \frac{2mxy}{E}} (\sigma_+ - \sigma_-) \quad (2)$$

is the vector-axial-vector interference term. In the above

expressions  $E$  is the incident neutrino energy,  $G$  the Fermi coupling constant,  $N_A$  the number of nucleons, and  $q^2$  the four-momentum transfer squared; Bjorken variables  $x$  and  $y$  are defined as  $x \equiv -q^2/2m\nu$  and  $y \equiv \nu/E$ , where  $\nu$  is the energy transfer. The cross section (1) was derived assuming locality, Lorentz and  $CP$  invariance, and the  $V - A$  structure of the current.

There is no general prescription how to calculate  $\sigma_i$ . However, its contribution

$$\frac{d^2\sigma_i}{dxdy} = \frac{2G^2 E^2 m^2}{\pi^2} xy^2 \left( 1 - \frac{y}{2} \right) \frac{\sigma_{\pm}}{N_A} \quad (3)$$

( $\sigma_{\pm} \equiv \sigma_+ - \sigma_-$ ) is much smaller than that of  $\sigma_t$ , as can be seen by integrating (3) over  $x$  (from 0 to  $\leq 1$ ) and  $y$  (from 0 to  $\leq m_\pi/E$ ) and comparing the result with expression (1) below; consequently it will be neglected in what follows. As mentioned above,  $\sigma_t$  and  $\sigma_l$  can be related, via CVC and PCAC, to corresponding cross sections for the scattering of virtual (labeled with an asterisk) photons and (massless) pions on  $A$ :

$$\sigma_t = \text{const} \times \sigma_{\gamma_i^*}, \quad \sigma_l = \text{const} \times \sigma_{\gamma_i^*} + \sigma_l^{\text{PCAC}}, \quad (4)$$

where

$$\text{const} \equiv \frac{C_V^2 + C_A^2}{4\pi\alpha} \quad (5)$$

( $C_V$  is the vector and  $C_A$  the axial-vector coupling constant) and

$$\sigma_l^{\text{PCAC}} = \frac{f_\pi^2 C_A^2}{2mExy} \sigma_{\pi^*} \quad (6)$$

( $f_\pi$  is the pion decay constant and  $\sigma_{\pi^*}$  the pion absorption cross section). In the limit  $q^2 \rightarrow 0$ ,  $\sigma_{\gamma_i^*}$  vanishes and  $\sigma_{\gamma_i^*} \approx \sigma_\gamma$ ,  $\sigma_{\pi^*} \approx \sigma_\pi$ .

A few remarks are in order here concerning this formalism: The CVC hypothesis finds its justification in the electroweak theory, where the charged weak current

and the electromagnetic current belong to the same isotopic triplet. In contrast with electroproduction,  $\sigma_l$  does not vanish as  $q^2 \rightarrow 0$ , since the weak hadronic current is not conserved [see expressions (4) and (6) above].

The transverse vector and axial-vector (CVC) contribution can be written as

$$\frac{d^2\sigma_{CVC}}{dx dy} = (C_V^2 + C_A^2) \frac{G^2 E^2 m^2}{2\pi^3 \alpha} xy \left(1 + \frac{2mx}{Ey}\right)^{-1/2} \times \left(1 - y + y^2 + \frac{xy m}{2E}\right) \frac{\sigma_\gamma(y)}{N_A}, \quad (7)$$

where we take  $\sigma_\gamma$  to be the photoabsorption cross section in the region of the giant dipole resonance. The data [3,4] suggest that  $\sigma_\gamma^{Fe}(y)$  can be parametrized by a Gaussian distribution

$$\sigma_\gamma(E_\gamma) = \sigma_\gamma(\nu) \approx \sigma_0 \exp\left[-\left(\frac{\nu - \nu_0}{a}\right)^2\right], \quad (8)$$

where  $\nu_0 \approx 18.5$  MeV and  $a \approx 3.5$  MeV. The normalization factor  $\sigma_0$  is related to the integrated cross section

$$\sigma_\gamma = 2 \int_0^\infty \sigma_\gamma(\nu) d\nu = a\sqrt{\pi}\sigma_0 \quad (9)$$

(the upper limit of the integral can be extended to infinity since the Gaussian drops off rapidly). After integrating (7) over  $x$  from 0 to  $1 - \nu_1/\nu_2$  (where, according to Refs. [3,4],  $\nu_1 \approx 12$  MeV and  $\nu_2 \approx 24$  MeV) we obtain

$$\frac{d\sigma_{CVC}}{dy} = (C_V^2 + C_A^2) \frac{G^2 E^{5/2} m^{3/2}}{12\pi^3 \alpha} y^{3/2} \times \left(1 - y + \frac{y^2}{2} + \frac{3my}{20E}\right) \frac{\sigma_\gamma(y)}{N_A}. \quad (10)$$

Inserting (8) into (10) and integrating the latter results in

$$\sigma_{CVC}^{excit} = (C_V^2 + C_A^2) \frac{G^2}{12\pi^3 \alpha} m^{3/2} \nu_0^{3/2} \left[1 + \frac{3m\nu_0}{20E^2}\right] \frac{\sigma_\gamma}{N_A}. \quad (11)$$

From (1), (4), and (6) the PCAC contribution is given by

$$\frac{d\sigma_{PCAC}}{dx dy} = \frac{G^2 f_\pi^2 C_A^2}{\pi^2} Em \left(1 + \frac{2mx}{Ey}\right)^{-1/2} \times \left(1 - y - \frac{mxy}{2E}\right) \frac{\sigma_\pi(y)}{N_A}. \quad (12)$$

Now,

$$\frac{d\sigma_{PCAC}}{dy} = \frac{\sqrt{2} G^2 f_\pi^2 C_A^2}{\pi^2} m^{1/2} E^{3/2} \left[1 - \frac{m}{6E} y\right] y^{1/2} \frac{\sigma_\pi(y)}{N_A} \quad (13)$$

and

$$\sigma_{PCAC}^{excit} = \frac{2\sqrt{2} G^2 f_\pi^2 C_A^2}{3 \pi^2} m^{1/2} \nu_{\max}^{3/2} \left[1 - \frac{m\nu_{\max}}{10E^2}\right] \frac{\sigma_\pi}{N_A} \quad (14)$$

where  $\nu_{\max}$  is the upper limit of the integral  $\int d\nu (d\sigma_{PCAC}/d\nu)$ , and setting  $\sigma_\pi(\nu) \approx \text{const}$ .

At neutrino energies above a few GeV, the second term inside the brackets in both (11) and (14) can be neglected, with the result that the excitation cross section  $\sigma^{excit} = \sigma_{CVC}^{excit} + \sigma_{PCAC}^{excit}$  becomes energy independent.

Let us denote by  $\sigma(\gamma, n)$  the photoneutron, and by  $\sigma(\gamma, p)$  the photoproton cross sections (they pertain to photodisintegration of atomic nuclei in the region of the giant dipole resonance with neutron and proton emission, respectively). From the available data [3,4] we obtain

$$\sigma_\gamma^{56Fe} = \sigma^{56Fe}(\gamma, Xn) + \sigma^{56Fe}(\gamma, p) \approx 0.7 \text{ mb GeV}. \quad (15)$$

Using this value, and the measured [6] pion absorption cross section,  $\sigma_\pi^{Fe} \approx 380$  mb at  $0.02 \text{ GeV} \leq \nu \leq 0.1 \text{ GeV}$ , we have evaluated  $\sigma^{excit}$  for the iron nucleus according to (11) and (14):

$$\sigma_{CVC}^{excit} \approx 1.4 \times 10^{-39} \text{ cm}^2/\text{nucleon} \quad (16)$$

and

$$\sigma_{PCAC}^{excit} \approx (0.32 \pm 0.16) \times 10^{-39} \text{ cm}^2/\text{nucleon} \quad (17)$$

for energies exceeding a few GeV,  $\nu_{\max} = 100$  MeV and  $f_{\pi^+} = 0.93m_\pi$ ; we also set  $C_V = C_A = 1$  for charged-current interactions. The error in (17) reflects the uncertainty in the actual value of  $\nu_{\max}$ . Note that the measured photoabsorption cross section for  $^{56}\text{Fe}$  is somewhat smaller than those for neighboring nuclei, which are in the region 0.9 – 1.0 mb GeV.

Table I shows a new estimate of the cross sections for the exclusive neutrino processes at energy transfers  $\nu \leq 1.67$  GeV (corresponding to invariant final state masses less than  $2 \text{ GeV}/c^2$ ), which were described in Refs. [1,7]. There has been one published measurement of the differential cross section  $d\sigma/d\nu$  in this region for high energy (50 and 130 GeV) neutrino interactions on iron nuclei [8]; it agrees to within 12% with the present calculation (see Ref. [1] for a discussion of that measurement in terms of the neutrino-induced exclusive processes shown in Table I). The total exclusive cross section at  $\nu \leq 1.67$  GeV is energy independent for  $E \geq 20$  GeV (apart from the inverse muon decay component), and thus can be used for relative normalization of the neutrino flux at high energies, where it is often difficult to monitor it ex-

TABLE I. Exclusive neutrino cross sections at  $E = 50$  GeV.

Process	Cross section/nucleon (cm <sup>2</sup> )
Resonance production	$\sigma^{\text{res}} = 0.75 \times 10^{-38}$
Quasielastic scattering	$\sigma^{\text{QE}} = 0.42 \times 10^{-38}$
Inverse muon decay	$\sigma^{\text{IMD}} = 0.27 \times 10^{-39}$
Coherent $\pi$ production ( $^{56}\text{Fe}$ )	$\sigma^{\text{coh}} = 1.0 \times 10^{-39}$
Nuclear excitation ( $^{56}\text{Fe}$ )	$\sigma_{CVC}^{\text{excit}} = 1.4 \times 10^{-39}$
	$\sigma_{PCAC}^{\text{excit}} = (0.32 \pm 0.16) \times 10^{-39}$
Total	$\sigma^{\text{excl}} = 1.47 \times 10^{-38}$

perimentally. It can also serve as a basis for studying possible new physics in this kinematic domain.

According to expressions (11) and (14), the excitation cross section increases at  $E \leq 1$  GeV. A precise measurement of the differential cross section  $d\sigma/d\nu$  in low energy neutrino interactions on heavy nuclei would thus present a sensitive test of this formalism: Note that below 1 GeV the quasielastic neutrino-nucleon cross section decreases very fast with decreasing energy (and is suppressed due to the Pauli exclusion principle in case of heavy nuclei), and that the coherent meson production is negligible; also, the resonance production cross section is 2–3 times smaller than at high energies (see Refs. [1,7,9] regarding nuclear effects in exclusive neutrino interactions and energy dependence of their cross sections). Consequently, the nuclear excitation should counterbalance a strong decrease, expected due to nuclear effects, in the quasielastic cross section at very low momentum transfers. This was indeed observed in an experiment using an iron target and low energy (about 1 GeV) neutrino beams [10]. As shown in Refs. [9,10], calculations using the Fermi gas model, and nuclear shell model wave functions for iron, yield quasielastic differential cross sections 3–4 standard deviations smaller than the measured values at very low momentum transfers. Combining either of the above model calculations with our estimate of the nuclear excitation cross section (for an incident neutrino energy equal the weighted average of the neutrino spectrum [10]), an agreement to within 13% was found between theory and experiment. In this context, it is gratifying that a high statistics counter experiment using a target with a low atomic number [11] did not observe the effect reported in Refs. [8,10].

In what follows we consider neutrino-induced nuclear excitation as a neutral current process ( $\nu + A \rightarrow \nu + A^*$ ) at low incident neutrino energies. In the limit  $E \approx$  a few hundred MeV, our formalism breaks down as far as the PCAC contribution is concerned. In this case the excitation cross section is given by

$$\sigma^{\text{excit}} \approx \frac{G^2}{160\pi^3\alpha} m^{5/2} \nu_0^{5/2} \frac{\sigma_\gamma}{E^2 N_A} \quad (18)$$

setting  $C_V = C_A = \frac{1}{2}$  for weak neutral currents in expression (11). Here  $E \geq 24$  MeV, if one is to include the entire giant dipole resonance. For a 25 MeV neutrino and an iron nucleus, for example, (18) yields

$$\sigma_{\text{Fe}}^{\text{excit}}(E = 25 \text{ MeV}) \approx 7 \times 10^{-38} \text{ cm}^2/\text{nucleon}, \quad (19)$$

which is considerably larger than the cross section for elastic neutrino-nucleus scattering [12].

The neutrino-induced nuclear excitation could play an important role in core-collapse (type II) supernovae (for a recent review of supernova mechanisms see, e.g., Ref. [13]). According to theory, about 99% of the gravitational energy released by the core collapse is radiated away by neutrinos of all flavors; only a fraction of a percent is transferred to the outer regions of the star causing their expulsion on a truly cosmic scale. The actual link between the core collapse and the mantle ejection is still not well understood [14]. It is quite plausible to assume that the supernova physics may crucially depend on the energy deposition associated with a particular neutrino interaction with matter, like the one described in this paper. Therefore, it is important to include all relevant neutrino processes while modeling core-collapse supernovae, as pointed out in Ref. [14].

Finally, we would like to mention that the recent advent of cryogenic particle detectors [15] enables a great improvement in the detection of low-energy neutrinos, with applications in cosmology and weak-interaction physics. A neutrino process which has a large cross section at low energies, and also deposits a good fraction of the incident neutrino energy, would play an important role in such studies.

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