ОБЪЕДИНЕННЫЙ
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ДУБНА

8/IX-75

E2 - 8936

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Submitted to ЯФ

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A number of experiments have established the existence of events believed to be induoed by incident $\nu_\mu (\bar{\nu}_\mu)$ interacting with nucleons without the emission of a muon [1]. There seems to be evidence for neutral currents.

Existing experimental data do not permit one to make a unique conclusion about the nature of neutral ourrents [2]. The study of this new phenomena is of great importance for the theory of weak interactions. Thus, it is necessary to investigate neutral currents both at high and at low energies. The importance of studying neutral current effects at low energies is connected also with the fact that the nature of the outgoing lepton is unknown. In particular, one does not exclude a possible mass of the outgoing particle in the range from 0 to 500 MeV [19]. Meson factories give the unique possibility to investigate neutral current effects at low ($\leqslant$ 100 MeV) energies.

A possible method of investigating weak neutral currents in excitation of nuclear levels by neutrinos was discussed in the paper [3] long before neutral currents had been discovered.

Recently a number of authors have discussed possible nuclear effects due to the presence of neutral weak currents [4-8].

In paper [5] excitation of nuclear giant dipole states by neutrinos due to the neutral currents was considered but only a vector-current isovector transition was involved. Thus, the lower limit of the cross section of such processes was estimated for a number of heavy and medium nuclei.

In the present paper more detailed calculations are performed to find the cross section of the neutrinoexcitation of giant dipole resonance of the well studied nuclei ^{12}C and ^{16}O due to the neutral currents.

We assume that interaction between neutrinos and neutral hadronic current has the form, arising in the simplest variant of the Weinberg theory [9,10]:

$$H_0 = \frac{G}{\sqrt{2}} \sum_{\ell = e,\mu} (\bar{\nu}_\ell \gamma_\mu (1+\gamma_5) \nu_\ell) \mathcal{J}_\mu^z, \quad (1)$$

where

$$\mathcal{J}_\mu^z = \mathcal{J}_\mu^3 - 2\sin^2\theta_W \mathcal{J}_\mu^{em}.$$

Here $\mathcal{J}_\mu^{em}$ is the operator of electromagnetic current of hadrons, $\mathcal{J}_\mu^3$ is the third component of V-A hadronic current, $\sin^2\theta_W$ is the parameter in the Weinberg theory and $G = 10^{-5} M_p^{-2}$ is the constant of weak interactions.

Hamiltonian (1) is consistent with experimental data [1] (CERN) and $\sin^2\theta_W$ equals 0.3–0.4.

We consider the processes

$$\nu(\bar{\nu}) + A \to \nu'(\bar{\nu}') + A^*, \quad (2)$$

where A^* is the nucleus A in an excited state.

To obtain the effective Hamiltonian which describes the interaction between neutrino and nucleus, the following assumptions are made:

a) Interaction between neutrinos and nucleus is determined by the idependent contribution of the individual nucleons.

b) All constants of the weak interactions for the nucleons in the nucleus are those of the free nucleons.

c) The motion of the nucleons in the nucleus can be treated nonrelativistically.

Taking into account a) and b), the matrix element of the process (2) has the form

$$\langle f|\hat{H}|i\rangle = -\frac{G}{\sqrt{2}} \ell_\mu \langle f| \sum_j e^{-i\vec{q}\vec{x}_j} \mathcal{J}_{\mu,j}^z |i\rangle, \quad (3)$$

where $\ell_\mu = \bar{u}(k')\gamma_\mu(1+\gamma_5)u(k)$ (k and k' are the four-vectors of the initial and final neutrino) and $\mathcal{J}_\mu^z$ is determined by the matrix element of the single-nucleon current.

Neglecting the second class currents, omitting all terms in q_μ in the matrix element of the single-nucleon current (because they give zero contribution to the cross section of process (2)), and taking into account c), we have:

$$\langle \bar{p}'\lambda'\rho'| \mathcal{J}_\mu^z |\bar{p}\lambda\rho\rangle = \xi_{\rho'}^+ \chi_{\lambda'}^+ [M_\mu] \chi_\lambda \xi_\rho, \quad (4)$$

where χ_λ and ξ_ρ are the two-component Pauli spinors and isospinors, $M_\mu = (\vec{M}, iM_0)$, where

$$\vec{M} = F_A \vec{\sigma} - (F_1 + 2MF_2)\, i\vec{\sigma} \times \frac{\vec{q}}{2M} ,$$
$$M_0 = F_1 . \tag{5}$$

For the form-factors F_1, F_2, F_A we have $F_i(q^2) = C_i F_i'(q^2)$, where $i = 1, 2, A$ (assuming that all form-factors have the same q^2 dependence) and $C_i = \frac{1}{2}(C_i^S + \tau_3 C_i^V)$, symbols S and V denote isoscalar and isovector parts respectively.

In the Weinberg model

$$C_1^S = -2\sin^2\theta_W \qquad\qquad C_1^V = 1 - 2\sin^2\theta_W$$
$$C_A^S = 0 \quad (6) \qquad\qquad C_A^V = \frac{1}{2} g_A = \frac{1}{2}(-1,2) \quad (7)$$
$$2MC_2^S = -2\sin^2\theta_W (\mu_p + \mu_n) \qquad\qquad 2MC_2^V = (1 - 2\sin^2\theta_W)(\mu_p - \mu_n) .$$

From CVC

$$F_1'(q^2) = F_p(q^2) ,$$

where $F_p(q^2)$ is the well known [11] proton charge form factor, for which we shall take

$$F_p(q^2) = \left(1 + \frac{q^2}{M_1^2}\right)^{-2} \qquad M_1 = 840 \text{ Mev} . \tag{8}$$

The axial form factor $F_A(q^2)$ may be assumed to be the same, that is consistent with the last experimental data [12].

Using (3) -(8) and relating the nuclear matrix element of the axial isovector current to the nuclear matrix element of the isovector current [13], we obtain the differential cross section for neutrino (antineutrino) excitation of closed-shell nuclei. (Since we are working in the framework of the generalized Goldhaber-Teller and Weinberg models, the contribution to the cross section from the T=0 states is much smaller in comparison with the T==1 states because of the smallness of $\left[\frac{\mu_p + \mu_n}{\mu_p - \mu_n}\right]^2 = \left(\frac{0.88}{4.7}\right)^2 \approx 0.035$)

$$\left(\frac{d\sigma}{d\bar{q}^2}\right)_{\nu/\bar{\nu}} = \frac{G^2 k_0'}{2\pi k_0} [m]^2 F_p(q^2) \cdot \Big\{ A \cdot \Big[C_1^{V\,2} \frac{(\bar{q}^2 - \delta^2)^2}{\bar{q}^4} + C_A^{V\,2} \frac{\delta^2}{\bar{q}^2} \Big] +$$
$$+ 2\Big[C_A^{V\,2} + \frac{\bar{q}^2}{4M^2} (C_1^V + 2MC_2^V)^2 \Big] \cdot \Big[\frac{\bar{q}^2 - \delta^2}{2\bar{q}^2} \cdot A + B \Big] \mp \tag{9}$$
$$\mp \frac{2C_A^V}{M} (C_1^V + 2MC_2^V) \cdot B^{1/2} \cdot \big[(\bar{q}^2 - \delta^2) \cdot A + \bar{q}^2 \cdot B \big]^{1/2} \Big\}$$

$$A = \frac{(k_0 + k_0')^2 - \bar{q}^2}{4k_0 k_0'} ; \qquad B = \frac{\bar{q}^2 - \delta^2}{4k_0 k_0'} ,$$

where

$$|m|^2 = \sum_{M_f} \left| \langle J_f M_f | \sum_{j=1}^{A} \tau_3(j) e^{-i\bar{q}\bar{x}_j} | 0 \rangle \right|^2$$

is the isovector nuclear matrix element , $\bar{q} = \bar{k} - \bar{k}'$ and excitation energy $\delta = k_0 - k_0'$.

Using the Goldhaber-Teller model of the "giant dipole" nuclear collective oscillations [13,14] we have

$$|m|^2 = 8\pi \left| \langle 1^- | \hat{M}^{v}_{1M} | 0 \rangle \right|^2 = \frac{A}{4M_p\delta} |\bar{q}|^2 \left[F_0(\bar{q}) \right]^2, \tag{10}$$

where $F_0(\bar{q})$ is the ground state elastic form factor of the nucleus, which can be taken in the form [15] x)

$$F_0(\bar{q}) = Z \left(1 + \frac{\bar{q}^2}{M_0^2} \right)^{-2}, \tag{11}$$

where $M_0 = 0.725\, M_p A^{-1/3} = 680\, A^{-1/3}\ (Mev)$.

To calculate the differential cross section for inelastic neutrino scattering off the clossed-shell nuclei, leading to excitation of $0^-, 1^-, 2^-$ spin-isospin states and 1^- (GT) state, we use the generalized Goldhaber-Teller model [13,14]

x) Expression (11) for $F_0(\bar{q})$ is consistent with the experimental data for electroexcitation of giant dipole resonance[16].

$$\frac{d\sigma}{d\bar{q}^2}^{1^-(GT)} = \frac{G^2 k_0'}{2\pi k_0} \left[C_1^{v\,2} \frac{(\bar{q}^2-\delta^2)^2}{\bar{q}^4} \cdot A \right] \cdot [m]^2 \cdot \left(F_p(q^2) \right)^2$$

$$\left(\frac{d\sigma}{d\bar{q}^2} \right)^{1^-(s.s)}_{\nu/\bar{\nu}} = \frac{G^2 k_0'}{2\pi k_0} \Big\{ \left[C_A^{v\,2} + \frac{\bar{q}^2}{4M^2} (C_1^v + 2MC_2^v)^2 \right] \cdot \left[\frac{\bar{q}^2-\delta^2}{2\bar{q}^2} \cdot A + B \right] \mp$$

$$\mp B^{1/2} \cdot \left[(\bar{q}^2-\delta^2) \cdot A + \bar{q}^2 \cdot B \right]^{1/2} \cdot \frac{C_A^v}{M_p} (C_1^v + 2MC_2^v) \Big\} [m]^2 \cdot \left(F_p(q^2) \right)^2 \tag{12}$$

$$\frac{d\sigma}{d\bar{q}^2}^{0^-(s.s)} = \frac{G^2 k_0'}{2\pi k_0} \left[1/3\, C_A^{v\,2} \cdot \frac{\delta^2}{\bar{q}^2} \cdot A \right] [m]^2 \cdot \left(F_p(q^2) \right)^2$$

$$\left(\frac{d\sigma}{d\bar{q}^2} \right)^{2^-(s.s)}_{\nu/\bar{\nu}} = \frac{G^2 k_0'}{2\pi k_0} \Big\{ \frac{2}{3} C_A^{v\,2} \frac{\delta^2}{\bar{q}^2} \cdot A + \left[C_A^{v\,2} + \frac{\bar{q}^2}{4M^2} (C_1^v + 2MC_2^v)^2 \right] \cdot \left[\frac{\bar{q}^2-\delta^2}{2\bar{q}^2} \cdot A + B \right] \mp$$

$$\mp \frac{C_A^v}{M} (C_1^v + 2MC_2^v) \cdot B^{1/2} \left[(\bar{q}^2-\delta^2) \cdot A + q^2 \cdot B \right]^{1/2} \Big\} [m]^2 \left(F_p(q^2) \right)^2.$$

We have integrated eq. (9) and (12) over $\bar{q}^2$, because the emitted neutrino is unobservable.

Since the collective states, which are excited in closed-shell nuclei by electron scattering [17] , in muon capture [18] and in neutrino reactions [14] , are components of the [15] - dimensional SU(4) supermultiplet of giant resonances the same states will also be excited in the processes (2) . Therefore we have taken energies δ of the collective states, which the model does not provide, from electroexcitation data [16] .

The results are presented for the reactions .

$$\nu(\bar{\nu}) + {}^{12}C \rightarrow \nu'(\bar{\nu}') + {}^{12}C^*$$

$$\nu(\bar{\nu}) + {}^{16}O \rightarrow \nu'(\bar{\nu}') + {}^{16}O^*$$

in the form of integrated over $\bar{q}^2$ cross sections versus the neutrino energy (fig.1). In figure 2 the total cross sections for neutrino and antineutrino excitation are plotted against k_o for different values of $\sin^2\theta_W$: 0.34;0.45;0.6 .

As is clear from the figure, when $\sin^2\theta_W$ varies from 0.34 to 0.6, the cross section for neutrinoexcitation increases while the cross section for antineutrinoexcitation decreases. Thus, the cross seotions for neutrino and antineutrinoexoitation of giant dipole resonance are strongly dependent on $\sin^2\theta_W$.

Using the total widths of emitted particles (neutrons and protons) of the collective nuclear states ^{16} , in figure 3 we present excitation curves for the collective levels in inelastic neutrino scattering due to the neutral currents. Figure 3 refers to ^{12}C. for various initial energies k_o and corresponsing intervals of the momentum transfers and shows the ohange of the relative strength of the states with momentum transfer.

The results, which have been obtained by means of the simplest variant of the Weinberg model and the generalized Goldhaber-Teller model are capable to give a semi-quantitative description of the gross features of the giant resonance excitation by neutral currents.

The obtained values of the cross sections ($\sigma \sim 10^{-40}$ cm^2) testify to experimental possibility of studying the neutral current effects in neutrinoexcitation of the giant resonances in nuclei.

We are grateful to Dr.S.M.Bilenky for the statement of the problem, for unceasing interest in the work and for a number of critical remarks. We would like to thank Dr.R.A.Eramjan for many valuable discussions as well as V.V.Barov for the help in numerical calculations.

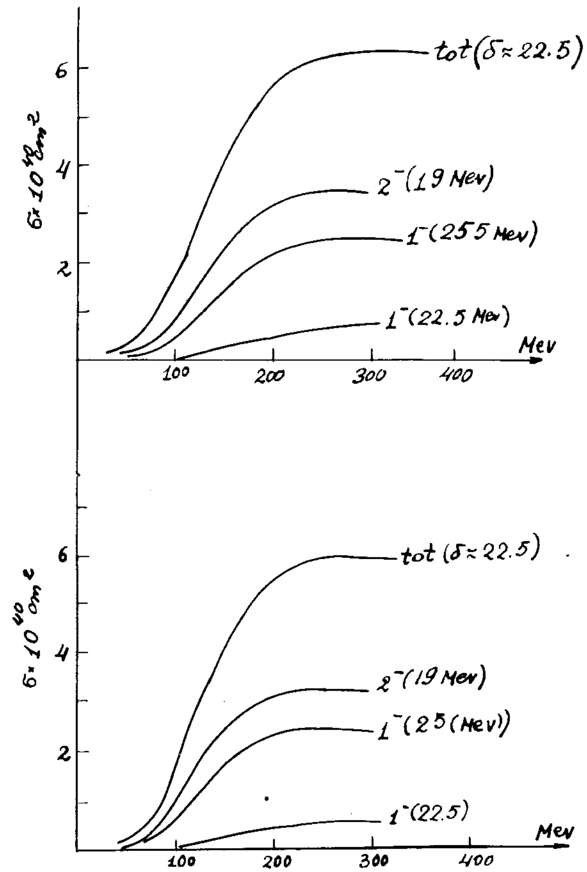

Fig.1

The cross section of the neutrinoexoitation of the giant dipole resonance in ^{12}C and ^{16}O (bottom) due to the neutral ourrents as a function of the primary energy.

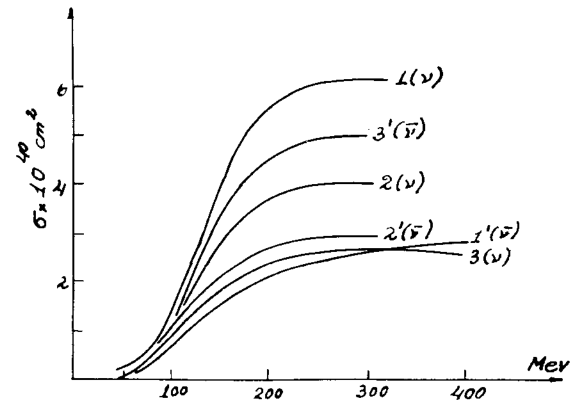

Fig.2

The dependence of the integrated over $\bar{q}^2$ cross section $\sigma_{\bar{\nu}}^{\nu}$ on the parameter $\sin^2\theta_W$ 0.34 (curves 1 and 1′), 0.45 (curves 2 and 2′), 0.6 (curves 3 and 3′).

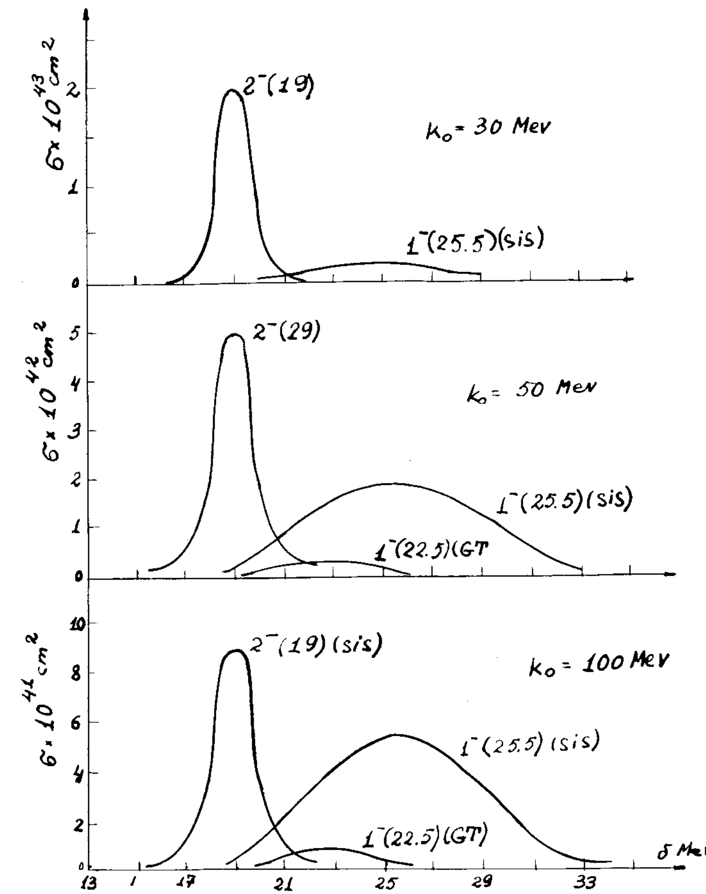

Fig.3

Neutrinoexcitation cross section of giant resonances by neutral currents in ^{12}C for various primary energies.

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Received by Publishing Department
on Jine 3, 1975.