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INVESTIGATION OF THE NEUTRAL CURRENTS IN THE PROCESSES OF THE NEUTRINO SCATTERING ON ATOMIC NUCLEI

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At present the obtained experimental data give evidence on existence of a direct interaction of the muonic neutrino with the nucleons without muon production /1/. To elucidate the nature of this interaction it is necessary to determine its isotopic structure and relation between vector and axial parts of the hadron current*.

In the popular Salam-Ward /4/ and Weinberg /5/ models a quite definite relation between V and A-currents with isospin 0 and 1 is predicted (in particular, the absence of an isoscalar A-interaction). In the scheme which attempts to explain muonless neutrino scattering by an anomalously large electromagnetic neutrino radius /6,7/, A-variant is absent whereas the isotopical structure of the V-variant is similar to the electromagnetic current structure. There are also schemes which predict another structure of the hadron current /8,9/. The scheme /9/ predicts, for example, the existence of the isoscalar A-current. Therefore it seems reasonable not to confine oneself hardly to the framework of any scheme in the experimental investigation.

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*Strictly speaking we can limit ourselves to V and A-currents only, if we suppose that muonless processes are induced by the longitudinal neutrino without change of their chirality. From the phenomenological point of view we cannot exclude, for example, an interaction of the type $\nu_\mu N \to \tilde{\nu}_e N$ (or $\nu_\mu N \to \tilde{\nu}_e N$)) in which the neutrino chirality is charged. Such reactions are not forbidden by the lepton number conservation in the scheme of Konopinski-Mahmoud /2/ and Zeldovich /3/. In this case the four-fermion interaction should have the form of a superposition of S, P and T-variants. The presence of such variants should change, for example, the recoil proton spectrum in the elastic νN-interaction at high energy, as compared to V and A variants.

The main information on the nature of the weak interaction is known to be obtained at first in the nuclear beta-decay investigations. As the levels of light nuclei have the definite angular momentum, parity and isospin, the study of the nuclear level excitations in the process $\nu Z \to \nu Z^*$ can give an important information on the nature of the neutral weak interaction.

The possibility of the nuclear level excitation by the neutral currents by the reactor antineutrino was discussed in paper /10/ (in particular, for ^7Li nucleus). Papers /11-12/ discussed the giant resonance excitation and nuclear fission processes induced by the electromagnetic neutrino radius and the neutral currents at the energies of mesonic factories. Recently reactions of the nuclear level excitation in the Weinberg model were discussed in the paper /13/.

In the present paper we analyze the reactions of the nuclear level excitation by the neutrino of low and intermediate energies with a view to determine the isotopic structure of the neutral current and relations between vector and axial vector coupling constants.

The amplitude of the reaction $\nu Z \to \nu Z^*$ is

$M = \frac{G}{\sqrt{2}} \ell_\alpha H^+_\alpha$, where ℓ_α is the lepton neutral current, $\ell_\alpha = \bar{\nu}_1 \gamma_\alpha (1 \pm \gamma_5) \nu_0$. The sign plus (minus) corresponds to the neutrino (antineutrino) scattering. We take the nucleon current operator J_α in the matrix element $H_\alpha = \int \prod_i d^3 r_i \, \psi^+_1 \Sigma \gamma_{0,k} J_{\alpha,k} e^{i\vec{q}\vec{r}_k} \psi_0$ in the form of a combination of V and A -currents

$$J_\alpha = f_V \gamma_\alpha - f_M \frac{\sigma_{\alpha\beta} q_\beta}{2m} + f_A \gamma_\alpha \gamma_5 \qquad (1)$$

$q = q_0 - q_1$, q_0 and q_1 are the momenta of the initial and final neutrino; ψ_0 and ψ_1 are the wave functions of the initial and final nuclear states; summing runs over all the nucleons in the nucleus. Each form factor f_V, f_M and f_A is a sum of the isoscalar and isovector parts.

For example, $f_V = (f^0_V + f^1_V \tau_3)/2$. Index "0" corresponds to the isoscalar and index "1" to the isovector parts of the interaction. We neglect the contributions of isotensor parts and second class currents. In the Weinberg model

$$f^0_V = -2\sin^2\theta_W, \qquad f^1_V = 1 - 2\sin^2\theta_W$$

$$f^0_A = 0, \qquad f^1_A = g_A$$

$$f^0_M = -2\sin^2\theta_W(\mu_p + \mu_n), \qquad f^1_M = (1 - 2\sin^2\theta_W)(\mu_p - \mu_n),$$

where θ_W is the Weinberg angle, μ_p and μ_n are the proton and neutron anomalous magnetic moments. Note that the contribution of weak magnetism term in the isoscalar interaction is smaller by one order of magnitude as compared with the isovector one. The renormalization of the isovector constants due to the strong interactions is the same as for the charged current, i.e., $f^1_A = g_A = 1{,}24$ (In the models where a bare isoscalar axial current is present, which is a member of SU_3-octet, the renormalized by the strong interaction constant f^0_A can be expressed via the F and D couplings, that gives $f^0_A \simeq 0{,}3(f^0_A)_{bare}$ in the simple three-quark model).

The differential cross section for the neutrino scattering with the excitation of a nucleus has the form

$$\frac{d\sigma}{d\Omega} = \frac{G^2 \omega_1}{4\pi^2 \omega_0} \{ 2\,\mathrm{Re}[(q_0 H)(q_1 H)^* - \frac{1}{2}(q_0 q_1)(HH^*)] \mp \mp \mathrm{Im}(\epsilon_{\alpha\beta\rho\mu} H^\alpha H^{*\beta} q_0^\rho q_1^\mu) \}, \qquad (2)$$

ω_0 and ω_1 are the energies of the initial and final neutrino.

It is convenient to single out explicitly the time and space parts of the four-vector matrix element H_α. Then the cross section takes the form

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2}\,\omega_1^2\{(1+\cos\theta)\,|H_0|^2 + (1-\cos\theta)\,|\vec H|^2 + \tag{3}$$

$$+\,2\,\mathrm{Re}[(\vec n_0\vec H)(\vec n_1\vec H) - (\vec n_0 + \vec n_1)\,\vec H_0\,\vec H^*\,] \mp$$

$$\mp\,\mathrm{Im}\,[\,2\vec H H_0^*\,(\vec n_0\times\vec n_1) + (\vec n_0 - \vec n_1)\,(\vec H\times\vec H^*)]\,\},$$

where

$$\vec n_0 = \vec q_0/\omega_0, \quad \vec n_1 = \vec q_1/\omega_1, \quad k = |\vec q|, \quad \cos\theta = (\vec q_0\vec q_1)/(\omega_0 - \omega_1).$$

Omitting the relativistic terms and neglecting the retardation ($\exp(iqr) \simeq 1$), we find that the allowed transitions at low energies of the neutrino can only come due to the axial currents. The scattering cross section for the allowed transition is /10/

$$\sigma = \frac{G^2}{\pi}\,\omega_1^2\,|\overline{<\frac{1}{2}\,(f_A + f_A^1\,\tau_3)\,\vec\sigma>}|^2. \tag{4}$$

The bar means summing and averaging over the final and initial nuclear orientations.

1. To elucidate the isotopical structure of the axial current, the allowed transitions in light nuclei with the even number of nucleons are the most suitable. In such nuclei it is possible to choose in the pure form the isoscalar part of the axial current, if it exists, in the transitions $T_0 = 0 \to T_1 = 0$. As an example we discuss two such cases which are of real interest

$$^{12}C(J^\pi = 0^+,\ T = 0 \to J^\pi = 1^+,\ T = 0;\ E = 12{,}71\ \mathrm{MeV}),$$

$$^{14}N(J^\pi = 1^+,\ T = 0 \to J^\pi = 2^+,\ T = 0;\ E = 7{,}03\ \mathrm{MeV}),$$

The nuclear matrix element in expression (4) can be determined from the experimental data on corresponding M1-transition rate. Using the experimental data /14/ we obtain that for the transition in ^{14}N the matrix element is large and equal to

$$|\overline{<\vec\sigma>}|^2 = 4.40 \pm 0.64.$$

As to the case of ^{12}C such an information does not exist. The calculation in the framework of the shell model with an intermediate coupling gives the following value

$$|\overline{<\vec\sigma>}|^2 = 2.82$$

which is somewhat smaller, than in ^{14}N.

2. The isovector part of the axial current can be chosen in the pure form in the transitions

$$^6Li(1^+,\ 0 \to 0^+,\ 1;\ E = 3{,}56\ \mathrm{MeV}),$$

$$^{12}C(0^+,\ 0 \to 1^+,\ 1;\ E = 15{,}11\ \mathrm{MeV}).$$

3. At high energies ($\omega R \sim 1$), where R is the nuclear radius, the vector part of the current gives the contribution in all the mentioned transitions. The typical result is shown in Fig. 1 for the transition $1^+,\ 0 \to 2^+,\ 0$ in ^{14}N. The scattering cross section for neutrino and antineutrino is a sum of the three terms $\Lambda\sigma_A$, $\Lambda\sigma_V$ and $\Lambda\sigma_{int}$. The first one corresponds to the contribution of the axial current, second one to the vector current, and the last one to the interference between them.

The expressions for all quantities are given in Appendix. In Fig. 1 the quantities $\Lambda\sigma_V$, $\Lambda\sigma_{int}$ and σ_ν are given. The cross sections for neutrino and antineutrino scattering and the quantity $\Lambda\sigma_A$ are almost equal to each other because of smallness of the isoscalar weak magnetism constant. (The calculation is made with all matrix elements, listed in Appendix. The constants f_A^0 and f_V^0 are set to equal to 1).

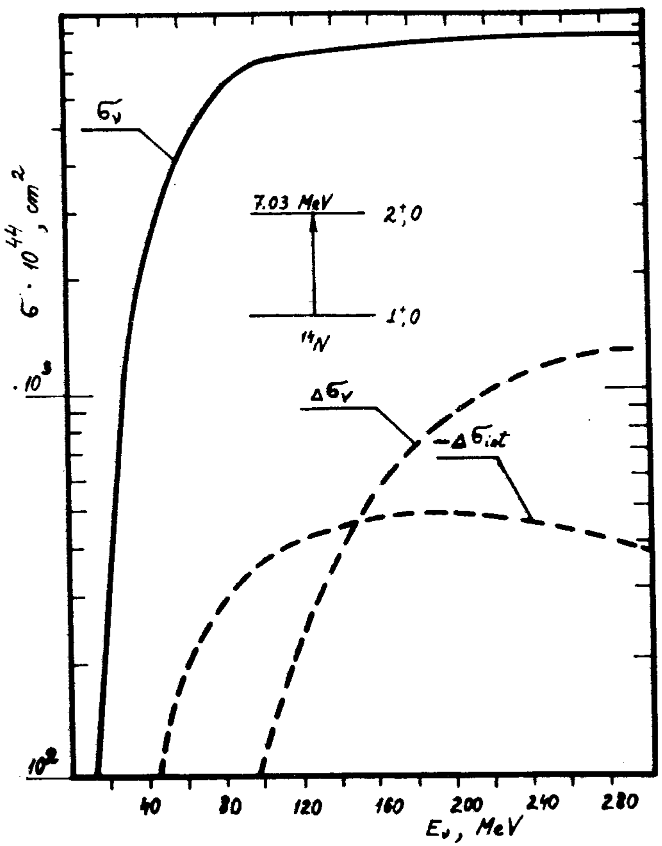

Fig. 1. The energy dependence of quantities $\Delta\sigma_V$, $\Delta\sigma_{int}$ and σ_ν for the transition $1^+, 0 \to 2^-, 0$ ($\Delta E = 7.03$ MeV) in ^{14}N. The constants f^0_V and f^0_A are equal to 1.

4. In the case of the odd nuclei levels excitation the isoscalar and isovector currents interfere. Therefore, if the presence of both the isovector and the isoscalar axial currents is established, then the investigation of the transitions in the odd nuclei will permit to determine the relative sign of these currents. It is necessary to have in mind that in the odd nuclei the excited levels lie low enough and they can be excited by the neutrino from reactors. The most interesting are the following transitions

$$^7Li(3/2^-, 1/2 \to 1/2^-, 1/2; \; E = 0{,}478 \text{ MeV}),$$

$$^{23}Na(3/2^+, 1/2 \to 5/2^+, 1/2; \; E = 0{,}439 \text{ MeV}).$$

The matrix elements for these transitions * can be directly obtained from the data on the beta-decay of its analogous states

$$\overline{|\langle \tau_3 \vec{\sigma} \rangle|^2_{^7Li}} = 1.16$$

and

$$\overline{|\langle \tau_3 \vec{\sigma} \rangle|^2_{^{23}Na}} = 0.13.$$

The calculations in the framework of the shell model with an intermediate coupling give for ^7Li the equality of the matrix elements $|\langle\vec{\sigma}\rangle|^2$ and $|\langle\tau_3\vec{\sigma}\rangle|^2$ entering Eq. (4). In the general case (for ^{23}Na in particular) these matrix elements are not equal to each other. Thus comparing the data on the excitation of the mentioned levels in ^7Li and ^{23}Na by reactor neutrinos it appears to be possible in principle to determine a relative sign and values of isoscalar and isovector axial constants.

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*In paper /10/ we quote the value $\frac{2J_i + 1}{2J_f + 1} |\langle\vec{\sigma}\rangle|^2$, which is two times larger than the value $|\langle\vec{\sigma}\rangle|^2$, cited in the present paper.

A possible effect of the isoscalar axial current on neutrino cross section ^{7}Li is shown in Fig. 2.

The transitions induced by the vector current can take place due to the relativistic (velocity) terms and retardation. The energy of the neutrino grows, the retarded terms become dominating. Due to these terms the cross section increases sharply with the energy and then comes to the plateau at the neutrino energy $\omega \sim 1/R$.

If the velocity terms are neglected the quantities H_0 and H in formula (3) take the form

$$H_0 = f_V \int 1 - \frac{1}{2m} f_A \vec{\sigma}\, \vec{q} \; ,$$

$$\vec{H} = - f_A \int \vec{\sigma} + \frac{\vec{q}}{2m} f_V \int 1 - i \frac{1}{2m} (f_V + f_M) \int \vec{q} \times \vec{\sigma} \; , \tag{5}$$

where

$$\int a \equiv \int d^3 r \, (\psi_1^*, \Sigma \exp(i \vec{q} \vec{r})\, a, \psi_0) \, .$$

After summing and averaging over the nuclear orientations we obtain the following expression for the excitation cross section

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} \omega_1^2 \{ (1 + \cos\theta) \, |\overline{f_V \int 1}|^2 + (1 - \cos\theta) \, |\overline{f_A \int \vec{\sigma}}|^2 +$$

$$+ \overline{2 \mathrm{Re} [(f_A \int \vec{n}_0 \vec{\sigma}) (f_A \int \vec{n}_1 \vec{\sigma})^*]} -$$

$$- \frac{1}{m} \mathrm{Re} [((\vec{q}_0 + \vec{q}_1) f_A \int \vec{\sigma}) ((f_V + f_M) \int \vec{\sigma})^* (\vec{n}_1 \times \vec{n}_0)] -$$

$$- \frac{1}{m} \vec{q} (\vec{n}_0 + \vec{n}_1) \mathrm{Re} [|f_V \int 1|^2 + |f_A \int \vec{\sigma}|^2] \mp \tag{6}$$

$$\mp \frac{1}{m} (\vec{n}_0 - \vec{n}_1) \mathrm{Re} [\vec{q} [(f_A \int \vec{\sigma}) ((f_V + f_M) \int \vec{\sigma})^*] -$$

$$- (f_A \int \vec{\sigma}) ((f_V + f_M) \int \vec{q} \vec{\sigma})^*] .$$

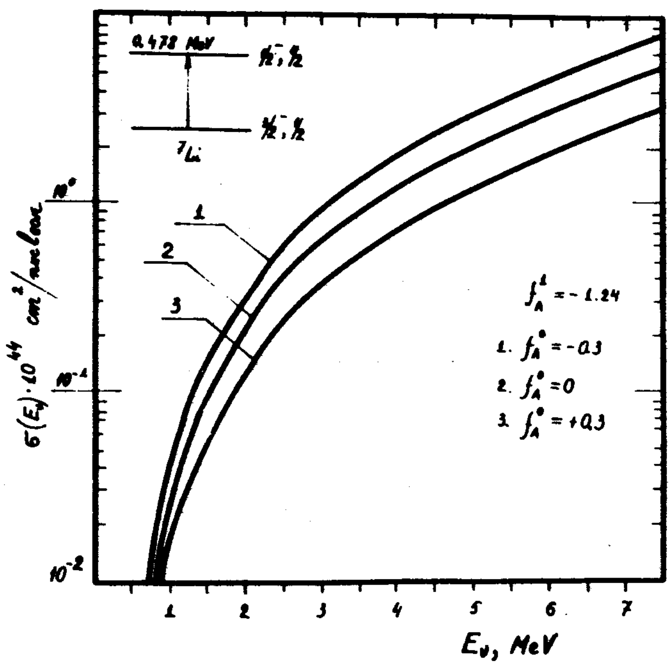

Fig. 2. The energy dependence of neutrino cross section in the transition $3/2^- \to 1/2^-$, , $\Delta E = 0.478$ MeV in ^{7}Li. The different curves correspond to the different contribution of the isoscalar axial current.

In the general case both the axial and the vector currents give a contribution to the transitions. Transitions $0^+, 0 \to 0^+, 0$ are the exception. However, they have the strength of the second forbidden one. Such a transition comes only due to the vector part of the hadron current, and, for example, takes place in the nuclei ^{12}C ($E = 7.65$ MeV), and ^{16}O ($E = 6.05$ MeV).

1) The most interest presents the level $(0^+, 0)$ in ^{16}O which has the single and very specific decay channel - the electromagnetic $E0$- transition. For such a case the expression for the cross section is as follows:

$$\frac{d\sigma\,(0^+, 0 \to 0^+, 0)}{d\Omega} = \frac{G^2}{4\pi^2}\,\omega_1^2\, f_V^2 (1 + \cos\theta) \times \tag{7}$$

$$\times \left(\frac{q^2}{q^2 + (\Delta E)^2}\right)^2 (000)^2 ,$$

where ΔE is the excitation energy and (000) is the nuclear matrix element (we use the notation accepted in the theory of muon capture /15/; the corresponding matrix elements are defined in Appendix).

$$(000) = \frac{1}{2} \langle 0_f^+ \mid j_0(kr) \mid 0_i^+ \rangle$$

In the limit $kr \ll 1$ this matrix element equals

$$(000) \simeq \frac{1}{12} k^2 \langle 0_f^+ \mid r^2 \mid 0_i^+ \rangle$$

and can be directly related to the rate of $E0$-transition. As a result one has /16/ for ^{16}O

$$\langle 0_f^+ \mid r^2 \mid 0_i^+ \rangle = (3.66 \pm 0.55)\ \text{fermi}^2$$

and the cross section at $\omega_1 = 100$ MeV for $f_V^0 = 1$ will be equal to $2 \cdot 10^{-42}$ cm ^{2} .

2) The transitions $0^+ \to 0^-$ are due to pure axial current and therefore can be used for determination of its strength. As an example we consider the transition $0^+, 0 \to 0^-, 0$ ($\Delta E = 10.95$ MeV) in ^{16}O. The corresponding cross section is given in Fig. 3. Again, the constant f_V^0 is chosen to be equal to 1.

The transition $0^+, 0 \to 2^-, 0$ practically is also due to the axial current. As follows from the expressions given in Appendix the contributions of the vector matrix elements are much more smaller than of the axial ones. Therefore, one can neglect them. As a result the cross sections for neutrino and antineutrino scattering become equal to each other. It is interesting to mention that the cross section for the transition $0^+, 0 \to 2^-, 0$ in ^{16}O is large and equals to about 10^{-41} cm ^{2} at neutrino energy of 50 MeV. The energy dependence of $0^+, 0 \to 2^-, 0$ cross section in ^{16}O is shown in Fig. 3.

If there is no isoscalar A-current (as, for example, in the Weinberg model) then the transitions $T_0 = 0 \to T_1 = 0$ come due to the pure vector variant. But the vector current cannot be revealed in the allowed transition. Therefore let us consider the first-forbidden ones. As an example, we can indicate the transitions which can have a real interest

$^{12}C(0^+, 0 \to 1^-, 0;$ $E = 10,84$ MeV)

$^{14}N(1^+, 0 \to 0^-, 0;$ $E = 4,69$ MeV)

$^{14}N(1^+, 0 \to 2^-, 0;$ $E = 5,11$ MeV)

$^{16}O(0^+, 0 \to 1^-, 0;$ $E = 7,1$ MeV)

$^{16}O(0^+, 0 \to 1^-, 0;$ $E = 9,58$ MeV)

The excited state $1^-, 0$ ($\Delta E = 10.84$ MeV in ^{12}C and ($\Delta E = 9.58$ MeV) in ^{16}O decays mainly

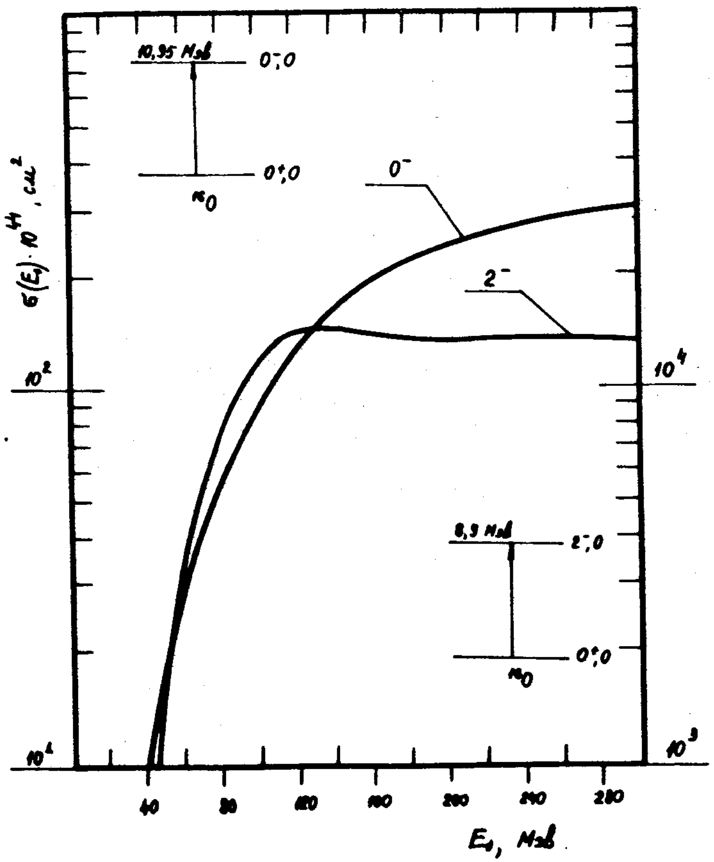

Fig. 3. The energy dependence of neutrino cross section in the transitions $0^+, 0 \to 0^-, 0$, $\Delta E = 10.95$ MeV and $0^+, 0 \to 2^-, 0$, $\Delta E = 8.9$ MeV. in ^{16}O. In both cases $f_A^0 = 1$. The right-hand scale relates to the transition $0^+, 0 \to 2^-, 0$.

by emission of three α -particles with definite energy. The other levels decay by emission of a γ -quantum to the ground state of the target nucleus.

If the Weinberg model is correct, the cross section for these transitions is proportional to $\sin^4\theta_W$. If an isoscalar A -current does exist, relative sign of the constants f_A and f_V can be determined by measuring the residual of the neutrino and antineutrino scattering cross section.

In the approximation of formula (6) in the high energy limit when $\omega_1 \gg \Delta E$, we have

$$\frac{d\sigma}{d\Omega}(\nu) - \frac{d\sigma}{d\Omega}(\tilde{\nu}) = \frac{G^2}{4\pi^2}\omega_0^2 \frac{2\omega_0}{m} \cdot$$

$$\{2(1-\cos\theta)(f_A \int \vec{\sigma})((f_V + f_M)\int \vec{\sigma})^* - (f_A \int \vec{n}\vec{\sigma})((f_V + f_M)\int \vec{n}\vec{\sigma})^*\}.$$

The results of the cross section calculations for transition in ^{16}O are shown in Fig. 4. Again we present the results for $\Delta\sigma_A$, $\Delta\sigma_V$, $\Delta\sigma_{int}$, σ_ν and $\sigma_{\tilde{\nu}}$.

Conventional (dipole approximation) four-momentum transfer dependence of the form factors was used.

When f_A^0 is changed into $(-f_A^0)$ the expression for the neutrino cross section transforms into the corresponding expression for antineutrino and vice versa. Thus, if $\sigma_\nu > \sigma_{\tilde{\nu}}$ then $f_A^0 > 0$, what means that relative sign of vector and axial currents is negative.

If one of these isoscalar (axial or vector) currents does not exist, the neutrino and antineutrino scattering cross sections become equal to each other. However, the energy dependence and absolute value of the cross section in both cases are different (see Fig. 4). This makes it possible to distinguish the interaction variant.

Unlike the allowed transitions, in case of the first forbidden ones we cannot simply relate the matrix elements to the experimental data. Therefore, the matrix elements were calculated in the shell model with the wave functions from paper /17/. In this case the accuracy of the

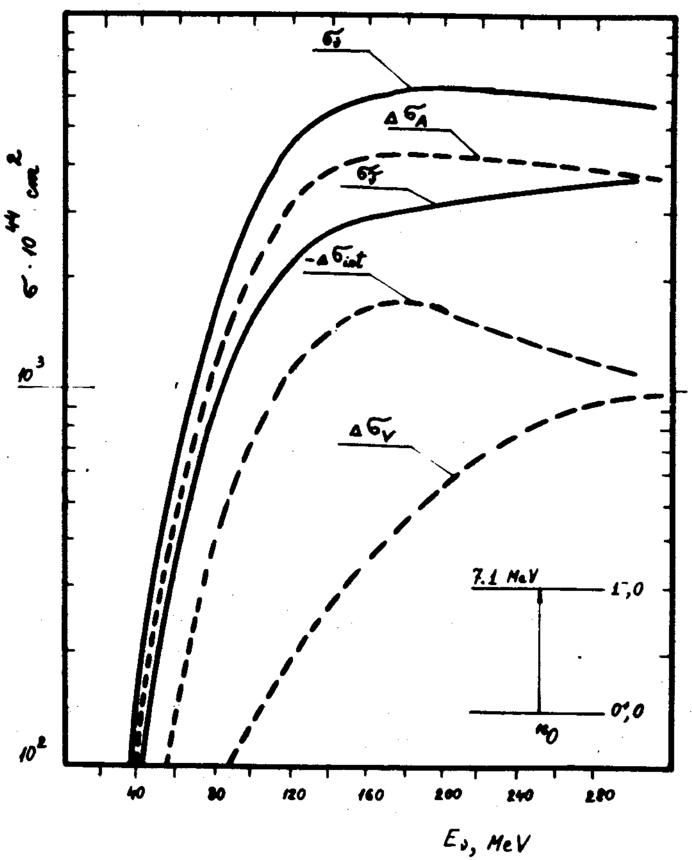

Fig. 4. The energy dependence of quantities $\Delta\sigma_V$, $\Delta\sigma_A$, $\Delta\sigma_{int}$, σ_ν and $\sigma_{\tilde{\nu}}$ for the transition $0^+,0 \to 1^-,0$ $\Delta E = 7.1$ MeV in ^{16}O. The constants f_V^0 and f_A^0 equal to 1.

absolute value of the cross section is lower than in the allowed transitions, but the qualitative behaviour of the cross section is well described. The detailed analysis of the wave function structure for these states, similar to the analysis which was made in the muon capture case /18/, will permit to determine precisely absolute values of the cross sections as well.

4) The value of the interference effect for the transitions with $\Delta T = 1$ in ^{12}C and ^{6}Li in the Weinberg model can be seen from the calculations of paper /13/.

We do not consider the effects of the asymmetry and polarization of the γ-quanta from de-excitation of the nuclei and the effects with a polarized target, because they cannot be practically observed in the nearest future.

The considered class of the experiments on the measurement of the nuclear excitation cross sections appears to be real at the mesonic factories and the impulse reactors with the lithium convertor. The impulse character of the neutrino beam and relatively high energy of the transitions permit to decrease the background from the natural and cosmical radioactivity.

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Appendix

1. Definition of the scattering cross section.
2. Definition of quantities B, C and D for some partial translations.
3. Definition of the nuclear matrix elements.

$$1. \quad \frac{d\sigma_\pm}{d\Omega} = \Delta\sigma_V + \Delta\sigma_A \mp \Delta\sigma_{int} \quad ;$$

$$\Delta\sigma_{V,A} = \frac{G^2}{4\pi^2}\,\omega_1^2\,\frac{2J_f+1}{2J_i+1}\,\{(1+\cos\theta)\,B_{V,A} +$$

$$+\frac{3}{2}[(1-\frac{1}{3}\cos\theta)-\frac{1}{3}\frac{(\Delta E)^2}{q^2+(\Delta E)^2}(1+\cos\theta)]C_{V,A}\};$$

$$\Delta\sigma_{int} = \frac{G^2}{4\pi^2}\omega_1^2\frac{2J_f+1}{2J_i+1}(1-\cos\theta)\frac{\omega_0+\omega_1}{k}D;$$

$$\omega_1=\omega_0-\Delta E; \qquad q^2=k^2-(\Delta E)^2;$$

$$k=\sqrt{\omega_0^2+\omega_1^2-2\omega_0\omega_1\cos\theta}\ .$$

2. a) $0^+\to 0^-$

$$B_V=C=D=0;$$

$$B_A=\{\frac{f_A}{M}(000p)+(\frac{k}{2M}-\frac{\Delta E}{k})f_A(110)\}^2.$$

b) $0^+\to 1^-$

$$B_V=\{f_V[1-(\frac{\Delta E}{k})^2](011)\}^2; \quad B_A=0;$$

$$C_V=\{\frac{f_V}{M}[-\sqrt{\frac{1}{3}}(121p)+\sqrt{\frac{2}{3}}(101p)]-(f_V+f_M)\frac{k}{2M}(111)\}^2;$$

$$C_A=[f_A(111)]^2;$$

$$D=-2f_A(111)\cdot\{\frac{f_V}{M}[-\sqrt{\frac{1}{3}}(121p)+\sqrt{\frac{2}{3}}(101p)]+$$

$$+(f_V+f_M)\frac{k}{2M}(111)\}.$$

c) $0^+\to 2^-$

$$B_V=0;$$

$$B_A=\{\frac{f_A}{M}(022p)+(\frac{k}{2M}-\frac{\Delta E}{k})f_A[\sqrt{\frac{3}{5}}(132)+\sqrt{\frac{2}{5}}(112)]\}^2;$$

$$C_V=\{\frac{f_V}{M}(122p)+(f_V+f_M)\frac{k}{2M}[-\sqrt{\frac{2}{5}}(132)+\sqrt{\frac{3}{5}}(112)]\}^2;$$

$$C_A=\{f_A[-\sqrt{\frac{2}{5}}(132)+\sqrt{\frac{3}{5}}(112)]\}^2;$$

$$D=2f_A[-\sqrt{\frac{2}{5}}(132)+\sqrt{\frac{3}{5}}(112)]\cdot\{\frac{f_V}{M}(122p)+$$

$$+(f_V+f_M)\frac{k}{2M}[-\sqrt{\frac{2}{5}}(132)+\sqrt{\frac{3}{5}}(112)]\}.$$

d) $0^+\to 1^+$

$$B_V=0;$$

$$B_A=\{\frac{f_A}{M}(011p)+(\frac{k}{2M}-\frac{\Delta E}{k})^2 f_A[\sqrt{\frac{2}{3}}(121)+\sqrt{\frac{1}{3}}(101)]\}^2;$$

$$C_V = \{ \frac{f_V}{M} (111p) + (f_V + f_M) \frac{k}{2M} [-\sqrt{\frac{1}{3}} (121) + \sqrt{\frac{2}{3}} (101)] \} \quad ;$$

$$C_A = \{ f_A [-\sqrt{\frac{1}{3}} (121) + \sqrt{\frac{2}{3}} (101)] \}^2 \quad ;$$

$$D = 2 f_A [-\sqrt{\frac{1}{3}} (121) + \sqrt{\frac{2}{3}} (101)] \times$$

$$\times [\frac{f_V}{M} (111p) + (f_V + f_M) \frac{k}{2M} [-\sqrt{\frac{1}{3}} (121) + \sqrt{\frac{2}{3}} (101)] \} .$$

3. $(kwu) = \langle J_i \, M_i \, uM : J_f \, M_f \rangle^{-1} \times$

$$\times \langle J_f M_f | \frac{1}{2} (1+\tau_3) \Sigma \sqrt{4\pi} \, j_w(kr) \langle k\mu \, wm : uM \rangle Y_{wm}(\hat{r}) \, S_{k\mu} | J_i \, M_i \rangle$$

$$S_{k\mu} = \begin{cases} 1 , & k = 0 . \\ \sigma_{1\mu} , & k = 1 . \end{cases}$$

$$(0uup) = \langle J_i \, M_i \, uM : J_f \, M_f \rangle \times$$

$$\times \langle J_f M_f | \frac{1}{2} (1+\tau_3) \sqrt{4\pi} \, j_u(kr) \, Y_{uM}(\hat{r}) \, (\vec{\sigma} \, \vec{\nabla} \,) | J_i \, M_i \rangle$$

$$(1wup) = \langle J_i \, M_i \, uM : J_f \, M_f \rangle \times$$

$$\times \langle J_f M_f | \frac{1}{2} (1+\tau_3) \sqrt{4\pi} \, j_w(kr) \, \Sigma \langle 1\mu \, wm : uM \rangle Y_{wm}(\hat{r}) \nabla_{1\mu} | J_i \, M_i \rangle$$

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