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Review Article

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What Neutrino Reaction Has a Large Cross-Section?

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Abstract

All reactions that are currently used to detect neutrinos are endothermic (more precisely, endo-energy). They occur at the expense of the energy of neutrino that initiates them. These reactions are characterized by a very small cross-section, which is close in magnitude to the 10^{-20} barn.

Beta decay is an exo-thermal (more precisely, exo-energetic) reaction. Currently, it seems that the entire physical community believes that the beta decay phenomenon occurs completely by accident.

However, recent experiments with reactor neutrinos [1, 2] have shown that their flux makes an additional contribution to the beta decay rate. Since beta decay is an exo-energetic reaction, neutrinos catalyze beta-active nuclei without losing own energy (or with a small loss of it). The cross-section of this process is much larger than the cross-section of the endo-energetic interaction of neutrinos with matter. Experimental measurements show that the cross section of reactor neutrinos with ^{63}Ni nuclei is close to 1 barn.

Keywords: Neutrino, Beta Decay, Reverse Beta Decay Cross Section

Introduction

Neutrinos are fundamental neutral stable particles and unique because of their extremely high penetrating power. Finding out their mysterious nature seems to be one of the main tasks of modern elementary particle physics.

The main reactions, with the help of which it is possible to register rare acts of interaction of neutrinos with matter, are usually called reverse beta decay reactions. These reactions were first considered by X. Bethe and R. Peierls in 1934. These reactions are endo-energetic, since they come at the expense of the neutrino energy. Measurements show that reactions of this type are characterized by a very small cross-section, which has a value close to 10^{-20} barn.

Another class of reaction is exo-energetic one, they go with the release of energy. These include nuclear decay reactions. The question of the nature of nuclear decay arose immediately after the discovery of this phenomenon. In the first decades of the last century, this question was repeatedly arose at discussions between the creators of quantum mechanics, led by N. Bohr, and the proponents of determinism in physics, led by A. Einstein. It seems that the power and beauty of mathematical arguments of quantum mechanics have won over the majority of the physical community to the side of anti-determinists. At present, almost all physicists consider the phenomenon of beta decay to be purely accidental.

However, at the turn of the new millennium, professor E. Falkenberg in the article <<Radioactive Decay Caused by Neutrinos? >> provided experimental evidence that solar neutrinos actually affect beta decay [3]. This result was later confirmed by other researchers.

Recent experiments with reactor neutrinos have shown that their flux also increases the decay rate in the isolated beta source [1, 2]. The controlled conditions of this experiment allow to conclude that beta decays under normal conditions (in the absence of reactor neutrinos) are caused by the influence of the cosmic neutrino flux and, thus, beta decay is not a random phenomenon, but a causal one, as suggested by A. Einstein.

At the same time, the effect of the neutrino flux on beta decay is unusually large and is characterized by a cross section close to 1 bar. In order to detail the mechanism of the effect of neutrinos on beta decay, it is necessary to consider in detail the model of the neutron, the neutrino, and the beta decay process itself.

The Electron-Proton Model of Neutron

Modern particle physics consider usually protons and neutrons as independent elementary particles united in a common group of nucleons.

Quark theory explains their internal structure by various combinations of the fundamental lower-level quarks u and d. Replacing just one of these quarks explains an important property of the neutron - its transformation into proton. However, other properties of neutrons and protons, such as the ratio of their masses or magnetic moments, the quark theory, introducing the fundamental quarks of the lower level, cannot explain.

In the last century, just after it was established that protons and neutrons play equivalent roles inside nuclei, the physical community was inclined to believe that neutron can be considered a fundamental particle, just like proton.

It should be noted that there were attempts to consider the neutron as a composite particle constructed from a proton and an electron, but since at that electron was considered non-relativistic, these attempts ended in failure [4].

It turns out theoretical consideration can explain the existence of a composite corpuscle that has neutron properties, if to consider a unification of proton with relativistic electron [5-8].

Such the electron-proton model of a neutron allows to calculate all its basic properties: magnetic moment, mass, spin, existence of excited states. The process of neutron-to-proton conversion, which the quark model aims to explain, does not require a complex interpretation. However, this model allows to calculate the neutron decay energy.

In addition, the electron-proton model of neutron makes it possible to explain the nature of nuclear forces, which according to this model are the standard effect of quantum mechanics. This makes it possible to exclude gluons, mesons, and the strong interaction from consideration (at least for case of light nuclei) [6, 7].

In addition, the electron-proton model makes it possible to show that the neutron has excited states, which are currently classified as elementary particles with their own special quark composition [8].

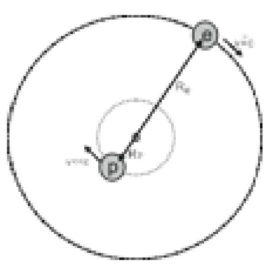

Figure 1: A system consisting of a proton and a heavy (relativistic) electron, revolving around a common center of mass.

The Energy of the Relativistic Electron + Proton Interaction

To describe a neutron structure in the electron-proton model, consider a composite particle in which an electron with a rest mass of m_e and a charge of −e rotates around the proton along a circle of radius R_e at a speed of $v \sim c$ (Figure (1)).

Since we will be looking for a stable orbit for a relativistic electron, it is necessary to take into account the relativistic effect of its mass growth:

$$m_e^* = \gamma m_e, \tag{1}$$

where the relativistic factor

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \tag{2}$$

and $\beta = v/c$

Since the electron has a large mass m_e^* due to the relativistic effect, we cannot consider the proton at rest. The proton will rotate around a common center of mass with a heavy electron.

Let us introduce a parameter that characterizes the ratio of a relativistic electron mass to a relativistic proton mass:

$$\vartheta = \frac{\gamma m_e}{M_p/\sqrt{1-\beta_p^2}}. \tag{3}$$

The condition of momentum equality gives $\beta_p = \vartheta$. Therefore, the radii of the orbits of the electron and proton can be written as:

$$R_e = \frac{R_{ep}}{1+\vartheta}, \qquad R_p = \frac{R_{ep}\vartheta}{1+\vartheta}. \tag{4}$$

Where $R_{ep} = R_e + R_p$.

The relativistic factor that characterizes the electron in this case is equal to

$$\gamma = \frac{\vartheta}{\sqrt{1-\vartheta^2}}\frac{M_p}{m_e}. \tag{5}$$

Since a proton moves in a circle, the magnetic field applied to it, according to Larmor's theorem, is determined by its gyromagnetic ratio. This field orients the magnetic moment of the proton perpendicular to the plane of rotation. As a result, the rotation of the electron due to the interaction with the magnetic moment of the proton should occur in the plane of the "equator" of the proton.

Quantization of a Stable Orbit

It can be assumed that, just as in the formation of a stable orbit in a Bohr hydrogen atom, the orbit of a relativistic electron in our case will be stable if the de Broglie wavelength λ_{dB} is equal to the circumference of the electron ring $2\pi R_e$, i.e., the condition is met:

$$2\pi R_e = \lambda_{dB}. \tag{6}$$

and

$$\lambda_{dB} = \frac{2\pi\hbar}{\gamma m_e c}. \tag{7}$$

That is, in accordance with this assumption, the stability condition of the electron orbit takes the form:

$$\frac{r_c}{R_e} = \frac{\vartheta}{\sqrt{1-\vartheta^2}}\frac{M_p}{m_e} = \gamma \tag{8}$$

Where $r_c = h / m_e c$ is the Compton radius.

Kinetic Energy of the Relativistic Electron + Proton System

For a relativistic electron, the kinetic energy can be written as:

$$\mathcal{E}^e_{kin} = (\gamma - 1) \cdot m_e c^2 \tag{9}$$

Since the electron is ultrarelativistic (γ >>1)

$$\mathcal{E}^e_{kin} \approx \gamma \cdot m_e c^2 \tag{10}$$

In this case, the centrifugal force acting on the electron:

$$\mathcal{F}_1 = \gamma m_e [\omega[\omega, R_e]] = \frac{\gamma m_e c^2}{R_e} \tag{11}$$

The kinetic energy of the proton in this case is equal to:

$$\mathcal{E}^p_{kin} = \left(\frac{1}{\sqrt{1-\vartheta^2}} - 1 \right) \cdot M_p c^2 \tag{12}$$

Coulomb Interaction in the Relativistic Electron + Proton System Given the relativism of the electron, the energy of its Coulomb attraction to the proton is written as [9], §24.

$$\mathcal{E}_C = -\gamma \frac{e^2}{R_{ep}} = -\gamma \frac{\alpha r_c}{R_e(1+\vartheta)} m_e c^2. \tag{13}$$

Where $\alpha = e^2 / hc$ is the ne structure constant.

As a result, the Coulomb attraction force acting between these particles is equal to

$$\mathcal{F}_2 = -\gamma \frac{e^2}{R^2_{ep}} = -\gamma \frac{\alpha}{(1+\vartheta)^2} \frac{r_c}{R_e} \frac{m_e c^2}{R_e}. \tag{14}$$

Magnetic Interaction of a Rotating Relativistic Electron with A Proton

The Magnetic Energy of the Electron Current Ring: The magnetic energy of the rotating electron creates an additional contribution to the kinetic energy of the system.

This energy is associated with a force that tends to break the current electron ring, and depends on the magnitude of the magnetic flux in the ring Φ and the current that creates it J:

$$\mathcal{E}_\Phi = \frac{\Phi J}{2}. \tag{15}$$

Due to the fact that the motion of the electron in the orbit is quantized, the resulting magnetic flux that permeates the ring of radius R_e must be equal to the quantum of the magnetic flux Φ_0:

$$\Phi = \Phi_0 = \frac{2\pi \hbar c}{e}. \tag{16}$$

Since by definition the magnetic flux in a current ring is the current strength J_0 per the area of the ring S_0:

$$\mu_0 = J_0 \cdot S_0 \tag{17}$$

we have

$$\mathcal{E}_{\Phi_e} = \frac{e^2}{R_e} \frac{1}{2\alpha} \frac{r}{R_e} = \frac{1}{2n} \frac{\vartheta}{\sqrt{1-\vartheta^2}} \cdot M_p c^2. \tag{18}$$

The force tending to break the current ring is equal to

$$\mathcal{F}_3 = \frac{\gamma}{2} \frac{m_e c^2}{R_e}. \tag{19}$$

The rotation of the proton leads to the creation of additional magnetic energy, which has a much smaller value:

$$\mathcal{E}_{\Phi_p} = \frac{\sqrt{2} \cdot \vartheta^2}{\sqrt{1-\vartheta^2}} \cdot M_p c^2. \tag{20}$$

The force associated with this rotation is applied to the proton and does not directly affect the equilibrium orbit of the electron.

Interaction of an Electron with the Magnetic Field of a Proton
In this case, the proton has two magnetic moments - its own magnetic moment

$$\mu_p = \frac{\xi e \hbar}{2 M_p c} \tag{21}$$

and orbital moment, which occurs due to the fact that the proton rotates in an orbit of radius R_p:

$$\mu_{0p} = \frac{e \vartheta R_p}{2} \tag{22}$$

Therefore, the interaction energy of the rotating electron with the magnetic field of the proton will be composed of two components:

$$\mathcal{E}_\mu = \pm \frac{\gamma e}{2 R_e^2} \left(\mu_{0_p} - \mu_p \right). \tag{23}$$

In order for the energy of the system to be less, the magnetic moments μ_p and $\mu 0_p$ must be directed opposite, i.e. in the brackets of this equality between the magnetic moments there must be a minus. But the contribution of the energy of this interaction can be either positive or negative. It depends on the direction of rotation of the electron relative to the orientation of the magnetic moment of the proton. Therefore, in the future, when solving these equations, it will be necessary to take into account both options with different signs.

The force that will act on the rotating electron can be written as:

$$\begin{aligned} \mathcal{F}_4 &= \pm \gamma e \beta \left(\frac{\mu_{0_p}}{R_e^3} - \frac{\mu_p}{R_{ep}^3} \right) = \\ &= \pm \gamma e \left(\frac{\mu_{0_p}}{R_e^3} - \frac{\mu_p}{R_e^3 (1+\vartheta)^3} \right) = \\ &= \pm \gamma \frac{m_e c^2}{R_e} \left(\frac{\vartheta^2}{2} - \frac{\xi}{(1+\vartheta)^3} \frac{\vartheta}{2\sqrt{1-\vartheta^2}} \right) \frac{\vartheta}{2\sqrt{1-\vartheta^2}} \alpha \frac{M_p}{m_e}. \end{aligned} \tag{24}$$

Where ξ ≈ 2.79 is the proton magnetic moment expressed in Bohr magnetons.

The magnetic moment of the electron is not included in the consideration because, as will be shown below, the moment of the generalized momentum (spin) of the electron orbit is zero and there is no direction in the system for the selected orientation of the electron magnetic moment.

Equilibrium Orbit of Electron

The equilibrium condition of the electron orbit has the form:

$$\sum_{i=1}^{4} \mathcal{F}_i = 0. \tag{25}$$

Summing up the equalities Equation (11), Equation (19), Equation (14), and Equation (24) after simplifying transformations taking into account Equation (8), we get:

$$1+\frac{1}{2}-\left(\frac{\vartheta}{\sqrt{1-\vartheta^2}}\frac{\alpha M_p}{m_e}\right)\left[\frac{1}{(1+\vartheta)^2}\right]- \quad (26)$$
$$-\left(\frac{\vartheta}{\sqrt{1-\vartheta^2}}\frac{\alpha M_p}{m_e}\right)\left[\frac{\vartheta^2}{2}-\frac{\xi}{2(1+\vartheta)^3}\frac{\vartheta}{\sqrt{1-\vartheta^2}}\right]=0.$$

As a result, the solution of this equation is obtained

$$\vartheta = 0.1991. \quad (27)$$

Table 1: Comparison of the calculated value of the neutron magnetic moment with the measured value.

ϑ	μ_0	μ_c	measurement data	Ref.
0.1991	-4.727	-1. 9367	μ_{no}=-1:9130427 ± 0:0000005	[10]

The Magnetic Moment of the Particle

The magnetic moment of the particle consists of the own magnetic moment of proton and magnetic moments of orbital currents of particles.

Total magnetic moment generated by circular currents

$$\mu_0=-\frac{e\beta_e R_e}{2}+\frac{e\beta_p R_p}{2}=\frac{eR_{ep}}{2}\frac{(1-\vartheta^2)}{(1+\vartheta)}=\frac{eR_{ep}}{2}(1-\vartheta). \quad (28)$$

If we express this moment in the Bohr magnetons μ_B, we get

$$\xi_0=\frac{\mu_0}{\mu_B}=-\frac{(1-\vartheta^2)\sqrt{1-\vartheta^2}}{\vartheta}. \quad (29)$$

Thus, the magnetic moment of the electron orbit:

$$\mu_0=\left[-\frac{(1-\vartheta^2)\sqrt{1-\vartheta^2}}{\vartheta}\right]. \quad (30)$$

Summing it with the magnetic moment of the proton, we get

$$\mu_c=\left[-\frac{(1-\vartheta^2)\sqrt{1-\vartheta^2}}{\vartheta}+2.79\right]. \quad (31)$$

Neutron mass

The mass of a composite particle is determined by the sum of the rest masses of the particles, their relativistic kinetic energy, and the mass defect resulting from the presence of the potential energy of their internal interaction. Let's calculate these contributions.

Kinetic energy of the electron and proton

Summing the equalities (10), (12), (18), (20) we get

$$\mathcal{E}(kin)=\frac{\vartheta}{\sqrt{1-\vartheta^2}}\left[1+\left(\frac{1}{\sqrt{1-\vartheta^2}}-1\right)\frac{\sqrt{1-\vartheta^2}}{\vartheta}+\left(\frac{1}{2}+\sqrt{2}\vartheta\right)\right]\cdot M_pc^2 \quad (32)$$

Table 2: Comparison of the calculated value of neutron mass with the measurement data.

$\frac{\mathcal{E}_{kin}}{c^2}$	$\frac{\mathcal{E}_{pot}}{c^2}$	M_{calc} Eq.(34)	measurement data	$\Delta=\frac{M_{exp}-M_{calc}}{M_{exp}}$
$702m_e$	$700m_e$	$1839m_e$	$M_{n0}=1837m_e$	0.001

Potential Energy the Energy of the Electron and Proton

Summing up the equalities (13) and (23) we get

$$\mathcal{E}(pot)=\frac{\alpha M_p}{m_e}\left[\frac{1}{1+\vartheta}-\frac{\vartheta^2}{2}\left(1-\frac{1}{(1+\vartheta)^3}\cdot\frac{\xi}{\vartheta\sqrt{1-\vartheta^2}}\right)\right]\left(\frac{\vartheta}{\sqrt{1-\vartheta^2}}\right)^2\cdot M_pc^2. \quad (33)$$

Neutron Mass

The total mass of proton and electron is equal to:

$$\mathcal{E}^{e+p}=m_e+M_p+\frac{\mathcal{E}(kin)}{c^2}-\frac{\mathcal{E}(pot)}{c^2}=$$
$$=m_e+M_p+$$
$$+\frac{\vartheta}{\sqrt{1-\vartheta^2}}\left[1+\left(\frac{1}{\sqrt{1-\vartheta^2}}-1\right)\frac{\sqrt{1-\vartheta^2}}{\vartheta}+\left(\frac{1}{2}+\sqrt{2}\vartheta\right)\right]\cdot M_p-$$
$$-\frac{\alpha M_p}{m_e}\left[\frac{1}{1+\vartheta}-\frac{\vartheta^2}{2}\left(1-\frac{1}{(1+\vartheta)^3}\cdot\frac{\xi}{\vartheta\sqrt{1-\vartheta^2}}\right)\right]\left(\frac{\vartheta}{\sqrt{1-\vartheta^2}}\right)^2\cdot M_p \quad (34)$$

The results of the calculations are shown in the table (2).
The sum of kinetic and potential energy obtained in this way is in satisfactory agreement with the amount of energy released during neutron decay

Particle spin

The centrifugal force F_1 (Equation11), acting on a rotating particle, can be expressed in terms of its kinetic energy:

$$F_1=\gamma m\left[\omega[\omega,r]\right]=rotE_{(kin)}. \quad (35)$$

Since in the relativistic case, the vector potential takes the form [9], §24:

$$A=\gamma\left(A'+\beta\varphi'\right), \quad (36)$$

the force that acts on the charge of a relativistically rapidly rotating particle can be represented as:

$$F_e=\gamma e\cdot rotA, \quad (37)$$

and as a result, taking into account the equality (31), we obtain a condition for the generalized momentum of the particle

$$P_0=\gamma mc+\gamma\frac{e}{c}A=0. \quad (38)$$

Thus, in the case under consideration, the moment of the generalized momentum of rotating particles

$$S_0=[R_e,P_0]=0. \quad (39)$$

For this reason, the total spin of the particles in question is 1/2, since it is created by the spin of the proton. A detailed calculation of the neutron spin is considered in [6, 7].

Discussion

There is an important difference between the Bohr atom, which is constructed from proton with non-relativistic electron, and neutron, in which a stationary level is formed for relativistic electron. In the Bohr atom, stable electron shells are formed due to the Coulomb interaction of electron and proton. At the same time, the magnetic forces between them play a small role, manifesting themselves in the hyperfine splitting of the spectral lines. The electron-proton model of the neutron suggests that in this case, the magnetic forces play a primary role. The electron orbit in this case turns out to be flat and the field that forms it has a very large value:

$$H \approx \frac{\mu_p}{R_e^3} \approx 10^{16} Oe. \qquad (40)$$

Electromagnetic Neutrino Model

Magnetic Dipole Radiation in Maxwell's Theory

Let us consider the description of the radiation of electromagnetic waves by a magnetic dipole in a vacuum, which is given by Maxwell's theory. For simplicity, we will assume that electric charges and currents, electric dipoles and quadrupoles are absent. Let the only source of electromagnetic fields in the subsequent consideration be the time-varying magnetic dipole moment **m**(t).

According to the Maxwell equations, the electromagnetic field in this case can be represented by its vector potential [9].

$$\mathbf{A}(R,t) = \frac{[\dot{\mathbf{m}}(\mathbf{t}^*) \times \mathbf{n}]}{cR}, \qquad (41)$$

(to account for the delay of the electromagnetic signal, the retarded time $t^* = t - R/c$ is entered here).

By definition, in the absence of free charges (i.e., when $\varphi = 0$)

$$\mathbf{E}(R,t) = -\frac{1}{c}\frac{d\mathbf{A}(R,t)}{dt^*} = -\frac{1}{c^2 R}[\ddot{\mathbf{m}}(t^*) \times \mathbf{n}]. \qquad (42)$$

The magnetic field in a wave created by a magnetic dipole (assuming $\varphi = 0$) by definition ([9], Equation 46.4)

$$\mathbf{H}(R,t) = rot\mathbf{A}(R,t) = \left[\nabla \times \frac{[\dot{\mathbf{m}}(\mathbf{t}^*) \times \mathbf{n}]}{cR}\right] = \frac{1}{c}\left[\nabla \times [\dot{\mathbf{m}}(t^*) \times \mathbf{n}] \cdot \frac{1}{R}\right] \qquad (43)$$

In general, the rotor of the function F, which depends on the parameter ξ, can be written as:

$$[\nabla \times \mathbf{F}(\xi)] = \left[grad\ \xi \times \frac{d\mathbf{F}}{d\xi}\right]. \qquad (44)$$

Therefore, since grad $t^* = \nabla(t - R/c) = -n/c$, we get

$$rot\ \dot{\mathbf{m}}(t^*) = \left[grad\ t^* \times \frac{d\dot{\mathbf{m}}(t^*)}{dt^*}\right] = -\frac{1}{c}[\mathbf{n} \times \ddot{\mathbf{m}}(t^*)]. \qquad (45)$$

The second term obtained by differentiating the equation (43) has the form

$$\frac{1}{c}\left[\nabla\frac{1}{R} \times [\dot{\mathbf{m}}(t^*) \times \mathbf{n}]\right] = \frac{1}{cR^2}[\mathbf{n} \times [\dot{\mathbf{m}}(t^*) \times \mathbf{n}]] \qquad (46)$$

Finally, we get that the magnetic field in the electromagnetic wave

$$\mathbf{H}(R,t) = -\frac{1}{c^2 R}[\mathbf{n} \times [\ddot{\mathbf{m}}(t^*) \times \mathbf{n}]] + \frac{1}{cR^2}[\mathbf{n} \times [\dot{\mathbf{m}}(t^*) \times \mathbf{n}]] \qquad (47)$$

Thus, according to Maxwell's theory, electromagnetic waves excited in vacuum by a magnetic dipole must have an electric field component determined by equality (42) and a magnetic component with intensity (47) having the corresponding orientation [10].

In this case, two options are possible, since two types of waves are possible.

Photons

This option is explored in all courses of electrodynamics. It is realized in the case when the magnetic dipole performs a motion described by a differentiable function of time. I.e., the motion of the magnetic dipole is described by a function that has the first two time derivatives. A typical example of such a motion is the harmonic oscillation of the dipole **m(*t*) = m •** *sin ωt*, for which both the E and H fields exist, since $\dot{\mathbf{m}}(t) \neq \mathbf{0}$ and $\ddot{\mathbf{m}}(t) \neq \mathbf{0}$.

The same solution is found for problems where the oscillations of the magnetic moment are described by more complex formulas, if the spectrum of these oscillations can be decomposed into harmonic components.

For harmonic oscillations at a considerable distance from the oscillating dipole, the second term in the formula (47), which depends on $\dot{\mathbf{m}}$, is λ/R times smaller than the first term. (Here λ is the length of the generated wave, R is the distance from the dipole). Therefore, it can be ignored.

As a result, we get that in this case the fields E and H (equations (42) and (47)) in an electromagnetic wave are equal to each other and are only rotated relative to each other by 90° degrees.

Magnetic Excitation of the Ether

Another solution to the equation (42) and (47) is obtained if m is a discontinuous
function. In this case, $\dot{\mathbf{m}} \neq 0$, but $\ddot{\mathbf{m}} = 0$, and hence a purely magnetic wave is formed, in which $\boldsymbol{H} \neq 0$, but $\boldsymbol{E} = 0$.

More precisely, this vacuum excitation should be classified as a kind of particle, since it is characterized by a very short time interval.

An example of the radiation of such a particle is β-decay, in which a free electron carrying a large magnetic moment arises relativistically quickly.

Another example is the transformation of a π-meson into a μ-meson. The π-meson does not have a magnetic moment, but the μ-meson does.

To estimate the duration of the magnetic burst that occurs when the π-meson turns into a μ-meson, we can use the uncertainty relation:

$$\tau_m \approx \frac{\hbar}{(M_\pi - M_\mu)c^2} \approx 10^{-23} sec, \qquad (48)$$

at the same time, its spatial extent:

$$\lambda_m \approx c\tau_m \approx 10^{-12} cm. \qquad (49)$$

The magnetic burst propagating in the ether when the muon turns into an electron will be even shorter.

The magnitude of the magnetic field strength carried by a magnetic photon can be estimated if its energy is known $\mathcal{E}$. **At** $\mathcal{E} \approx$ **1*MeV***

$$H_m \approx \sqrt{\frac{8\pi\mathcal{E}}{\lambda_m^3}} \approx 10^{15} Oe. \qquad (50)$$

It is reasonable to consider such a short magnetic burst in time and space as a particle.

The unusual property that such a particle **V** must possess arises from the absence of magnetic monopoles in nature. The fact is that ordinary photons with an electrical component are scattered and absorbed in a substance due to the presence of electrons in it. In the absence of magnetic monopoles, a magnetic particle of low energy should interact extremely weakly with matter and its free path in the medium should be about two dozen orders of magnitude longer than that of an ordinary photon [11].

Thus, Maxwell's equations say that the escape of a free electron at beta decay should generate a magnetic excitation in a vacuum, similar to a photon, but weakly interacting with matter.

This and other factors, such as the presence of an antiparticle and a spin equal to 1/2, suggest that these particles are identical to neutrinos [12].

Two Types of Reaction Involving Neutrinos

Reactions Due to The Energy of Neutrinos

H.Bethe and R. Peierls in 1934 proposed to use the so-called reverse beta decay reaction for neutrino detection, the possibility of which follows from the Fermi theory:

$$\overline{\nu} + p \rightarrow e^{+} + n \qquad (51)$$

This is an endo-thermal (more precisely, endo energetical) reaction, which is due to the energy of the neutrino that initiates it. This energy must be sufficient to cover the mass defect that exists between its products. Thus, the reaction Equation (51) experimentally realized by F. Reines and C. Cowan is possible at an antineutrino energy greater than 1.8 Mev, which corresponds to the excess of the total mass of the neutron and positron over the proton mass.

The same reactions that require the absorption of a high-energy neutrino for their implementation include the Bruno Pontecorvo reaction:

$$\nu +^{37}_{17} Cl \rightarrow^{37}_{18} Ar + e^{-}. \qquad (52)$$

According to the measurements of F. Reines and C. Cowan, the cross-section of reaction Equation (51)

$$\sigma \approx 6 \cdot 10^{-20} barn. \qquad (53)$$

Another approach to detecting neutrinos is based on their inelastic scattering by electrons. With this scattering, the neutrino gives its energy to electrons, which, accelerating, create bursts of Cherenkov radiation. The cross-section of this reaction is approximately the same as that of the reverse beta decay reactions.

Beta Decay

The phenomenon of beta decay is conveniently analyzed by the example of neutron decay. Neutron decay is an exo-energetical reaction. Since the mass of the neutron is greater than the sum of the rest masses of proton and electron, this reaction releases energy corresponding to the mass difference of its products. Therefore, taking into account that it must go under the influence of the neutrino that initiates it, it can be represented as:

$$\nu + n \rightarrow p^{+} + e^{-} + \overline{\nu} + \nu. \qquad (54)$$

Due to the fact that the neutrino causing this reaction is scattered on the neutron without energy transfer and flies away unnoticed, our instruments register this reaction in a shortened form:

$$n \rightarrow p^{+} + e^{-} + \overline{\nu}. \qquad (55)$$

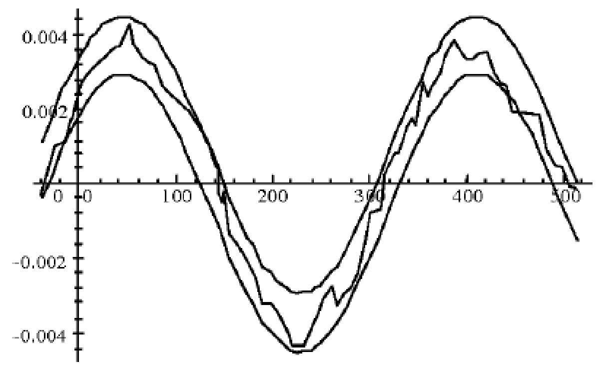

Figure 2: Modulation of the beta decay rate by the solar neutrino flux, discovered by E. Falkenberg [3].

The nature of beta decay was the subject of multi-year discussion among physicists at the beginning of the last century. The creators of quantum mechanics considered this decay to be purely random and explained it by the phenomenon of quantum tunneling. The determinists, led by A. Einstein, strongly objected to this point of view. Over time, the anti-determinist view prevailed. In our time, this point of view is the dominant one. However, back in the 30s of the last century, N. Tesla wrote that beta decay could be explained by the influence of a stream of certain particles that do not register devices.

Later, neutrinos were discovered, and at the turn of the new millennium, professor E. Falkenberg in the article <<Radioactive Decay Caused by Neutrinos?>> provided experimental evidence that the solar neutrino flux actually affects beta decay [3].

A few years later, a group of American researchers confirmed the presence of this effect on a number of other beta-active isotopes [13].

According to their data, solar neutrinos change the rate of beta decay, modulating it to a depth of about 0.4% with a period equal to a year (Figure (2)).

Cosmic Neutrino Flux

The solar neutrino flux is fairly accurately determined from the total luminosity of the Sun. On the surface of the Earth it is considered to be equal

$$\Phi_{\odot} \approx 6 \cdot 10^{10} \frac{\nu}{cm^2 \cdot s}. \qquad (56)$$

Taking into account the results of the Falkenberg's measurement we can calculate the total flux of cosmic neutrinos in our laboratories:

$$\Phi_\star = \frac{6 \cdot 10^{10}}{4 \cdot 10^{-3}} = 1.5 \cdot 10^{13} \frac{\nu}{cm^2 \cdot s} \qquad (57)$$

Experiment with Reactor Neutrinos

The experiment with reactor neutrinos was performed in Dubna (Russia) at the IBR-2 reactor [1]. This reactor operates in pulsed mode, repeating its flashes every 200 ms. At the same time, it develops an average power of 1.6 MW. It means it happens about

$$F_{IBR} = 5 \cdot 10^{16} \qquad (58)$$

acts of plutonium fission in its active zone for a second. Measurements on a pulsed reactor allow the use of the accumulation mode. In this mode, the measurement results obtained during the time between the reactor flares are superimposed on each other. Due to this, a synchronous accumulation of the useful signal occurs. When the accumulation time is equal to a day, the sensitivity of such measurements increases by several orders of magnitude.

However, in this case, only a small part of the entire spectrum of reactor neutrinos is cut out. The results are summarized only for those neutrinos that are emitted by short-lived fission fragments with a half-life of less than 200 ms.

In our experiments, the rate of beta decays was measured in a source ^{63}Ni protected from the penetration of reactor radiation and located at the distance of about R = 20m from the reactor core [1].

This source was small in size compared to the flat scintillator, which recorded the radiation of the source. Therefore, we can assume that the measuring system recorded all beta electrons that flew out of the source at an angle almost equal to 2π. The rest of electrons that flew into the other hemisphere were not registered and thus fell out of consideration for all calibrations and measurements.

Given the fact that the ^{63}Ni nucleus has a long half-life, ($\tau_{1/2}(Ni) = 3 \cdot 10^9$ sec) the decay rate (number of decays per second) can be written as

$$\mathfrak{n}_\star = \frac{dN_{Ni}}{dt} = N_{Ni} \cdot \frac{de^{-\frac{t}{\tau}}}{dt} = \frac{N_{Ni}}{\tau}. \qquad (59)$$

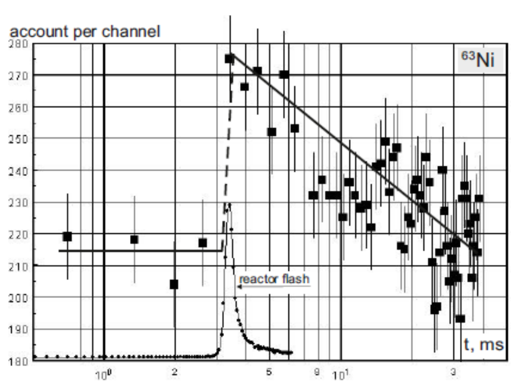

Figure 3: The result of the accumulating registration of beta-electrons emitted by ^{63}Ni. Measurement time is 1 day.

The level of amplitude discrimination close to the boundary energy was chosen experimentally.

On abscissa: time in ms in the logarithmic scale [1].

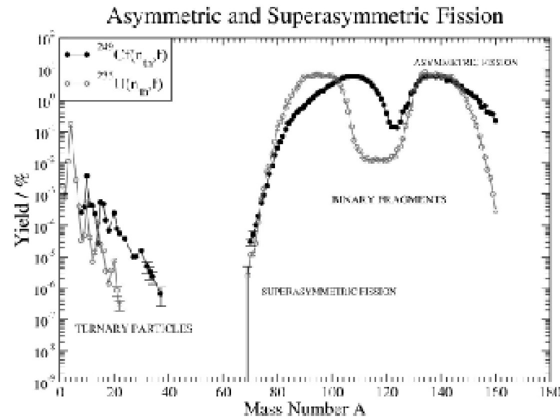

Figure 4: Probability of formation of fission fragments of nuclear fuel depending on their mass number [14].

The measurements showed that the number of recorded decays per second was approximately equal to

$$\mathfrak{n}_\star \approx 5 \cdot 10^5 \qquad (60)$$

Therefore, the total number of beta-active nuclei ^{63}Ni in the source (excluding those that decay into the upper hemisphere):

$$N_{Ni} = \mathfrak{n}_\star \cdot \tau_{1/2}(Ni) \approx 1.5 \cdot 10^{15} \qquad (61)$$

The result of measuring the effect of reactor neutrinos generated by a pulsed reactor on an isolated source ^{63}Ni is shown in Figure3. From these measurements, it can be seen that the increase in the count induced by the reactor pulse decreases with a time constant of about 20 ms. Based on the data given in the reference book, we can conclude that this is the result of the influence of neutrinos born in the core due to the beta decay of two fission fragments - ^{12}B and ^{13}B, the half-life of which is 20.3ms and 18.6ms, respectively [15]. Other fragments with half-lives of less than 200ms do not appear to form in appreciable quantities.

The probability of the formation of ^{12}B and ^{13}B isotopes as a result of plutonium fission is quite small. According to, this probability is approximately $w \approx 10^{-4}$ for each isotope, so that the total flux of neutrinos passing through the measuring unit [14].

$$\Phi_r = \frac{F_{IBR} \cdot 2 \cdot w}{4\pi R^2} = \frac{5 \cdot 10^{16} \cdot 2 \cdot 10^{-4}}{4\pi \cdot 2000^2} \approx 2 \cdot 10^5 \frac{\nu}{cm^2 s}. \qquad (62)$$

As a result of the impact of reactor neutrinos, the number of beta-decaying electrons per second should increase by

$$\mathfrak{n}_r' = \sigma \cdot N_{Ni} \cdot \Phi_r \qquad (63)$$

In this case, the cosmic neutrino flux should cause

$$\mathfrak{n}_\star' = \sigma \cdot N_{Ni} \cdot \Phi_\star. \qquad (64)$$

recorded decays per second.

Thus, based on the ratio of the fluxes of reactor neutrinos to cosmic ones, we can estimate the efficiency of our reactor against the background of cosmic neutrinos:

$$Y_{es} = \frac{\mathfrak{n}_r^{'}}{\mathfrak{n}_\star^{'}} = \frac{\Phi_r}{\Phi_\star} \approx 1.3 \cdot 10^{-8} \quad (65)$$

Summing up the data obtained during the measurements by channel (see Figure (3)) and subtracting the background level, we get, that for all the time of measurements ($\tau\Sigma = 1$ day), the impact of reactor neutrinos led to 800 additional decays. That is, the counting rate per second averaged

$$\mathfrak{n}_r = \frac{800}{86400} \approx 9 \cdot 10^{-3} \quad (66)$$

Taking into account Equation (60), we obtain the measured value of the efficiency of the reactor neutrino flux

$$Y_{meas} = \frac{\mathfrak{n}_r}{\mathfrak{n}_\star} = \frac{9 \cdot 10^{-3}}{5 \cdot 10^5} \approx 1.9 \cdot 10^{-8}. \quad (67)$$

Thus, the estimation of the parameter of reactor efficiency Y_{es} (Equation (65)) is quite satisfactorily consistent with the measurement data.

Cross Section of Neutrino Influence on the Beta decay

The cross section that characterizes the decay of nuclei Equation (64) caused by the action of the cosmic neutrino flux can be represented as

$$\sigma = \frac{\mathfrak{n}_\star^{'}}{\Phi_\star N_{Ni}} \quad (68)$$

Given Equation (61), we get

$$\sigma = \frac{1}{\Phi_\star \tau_{1/2}} = \frac{1}{1.5 \cdot 10^{13} \cdot \tau_{1/2}} cm^2. \quad (69)$$

For ^{63}Ni, this cross section is equal to

$$\sigma(^{63}Ni) \approx \frac{1}{1.5 \cdot 10^{13} \cdot 3 \cdot 10^9} \approx 2 \cdot 10^{-23} cm^2 \quad (70)$$

Nuclei with a shorter half-life have an even larger cross-section of interaction with neutrinos.
This unusually large cross-section value compared to the cross-sections of other reactions involving neutrinos should not be puzzling.

All commonly used methods for detecting neutrinos are based on the reactions of reverse beta decay or the excitation of a Cherenkov radiation pulse. In all such cases, the reaction products are registered, which were formed due to the endo-energetic process, which is due to the absorption of neutrino energy.

For beta decay, there is no need to absorb additional energy. The neutron, according to the electron-proton model (chapter (2)), exists in a stable state due to electromagnetic forces that do not carry degradation processes. However, unlike the Bohr atom, whose stable state is formed due to the Coulomb interaction, magnetic forces play a major role in the formation of the stable state of the neutron.

Neutrino, as a magnetic gamma-quantum (see the chapter (3)) carries a very short burst of a very strong magnetic field Equation (50). In the elastic collision of neutron with neutrino, the latter does not need to spend its energy on the neutron destruction. Since the mass of neutron is greater than the sum of the rest masses of proton and electron, there is no need to transfer energy to such an energetically unstable particle to break up. It is enough to make a disturbance in its equilibrium state, affecting it with a magnetic field. Naturally, the cross-section of such a reaction must correspond in order of magnitude to other electromagnetic processes.

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