Scientific session of the Division of General Physics and Astronomy of the Academy of Sciences of the USSR (28 February 1990)

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The scientific session of the Division of General Physics and Astronomy of the USSR Academy of Sciences was held on 28 February 1990 at the USSR Academy of Sciences S. I. Vavilov Institute of Physics Problems. The following reports were presented:

1. L. B. Leinson, V. N. Oraevskiĭ, V. B. Semikoz, Ya. A. Smorodinskiĭ. Electrodynamics of the neutrino in solid media.

2. V. V. Nesterov, A. A. Ovchinnikov, A. M. Cherepashchuk, E. K. Sheffer. Problems of space astrometry. Project LOMONOSOV.

A summary of the reports is given below.

L. B. Leinson, V. N. Oraevskibı, V. B. Semikoz, Ya. A. Smorodinskibı. *Electrodynamics of the neutrino in solid media.* In the standard model of electro-weak interactions, vacuum electromagnetic characteristics of the neutrino, the RMS electromagnetic radius $\langle r_\nu^2\rangle^{1/2}$ and the anomalous magnetic moment $\Delta\nu_{\rm vac}$, require the interaction of the neutrino with the vacuum of vector Z- and W-bosons and leptons.

Due to these characteristics the neutrino, as the neutron, interacts with photons, electrons, etc. In other words, a consideration of the radiation corrections to the weak interaction, which are calculated in a one-loop approximation, make it possible to calculate the electromagnetic structure of the neutrino in vacuum.

References 1–11 studied the electromagnetic properties of the neutrino in dispersive media, which differ greatly from vacuum media.

The polarization of dispersive media by weak forces is significantly stronger than the polarization of vacuum media $(\varepsilon_{\rm vac}-1)$, which is close to zero and for reasonable values of transmitted momenta $|q^2|\ll M_{\rm W}^2$, where $M_{\rm W}$ is the mass of the W-boson, has the character of small radiation corrections. In a medium, polarization $|\varepsilon_{\rm med}-1|$ may be comparable to and even larger than unity, and this determines the value of the relatively large additional electromagnetic interaction, which is comparable with the known Born contribution.

Due to the polarization of such a medium by weak forces (the moving neutrino), in the neighborhood of the "trajectory" of the neutrino, a small-scale inhomogeneity of electron concentration is generated (of the order of the Debye radius in plasma $r_{\rm D}$), which changes the character and value of the electromagnetic interaction of the neutrino with matter.

We note that most authors generalizing vacuum electro-weak models for the case of a medium examine a homogeneous medium or a medium with a slow, adiabatically changing density, without considering its spatial and temporal dispersion. In these conditions, the medium suppresses, for example, the electrodynamic interaction of intrinsic vacuum dipole moments of the neutrino with the magnetic field, which has no effect whatsoever on the value of the electrodynamic moments of the neutrino.

Conversely, in the case of dispersive media, the electromagnetic interaction of the neutrino with particles of the medium intensifies as the density of matter increases, and, in contrast to radiation corrections in vacuum, significantly changes the value of the corresponding cross section of weak interaction in the standard model.

For example, the cross section of elastic scattering of a massless neutrino on a spinless nucleus in plasma[11]

$$\frac{d\sigma}{d\Omega}=\frac{G_{\rm F}^2E^2(1+\cos\theta)}{16\pi^2}\times\left[Z(1-4\xi)-N+\frac{(1+4\xi)Z}{1+(kr_{\rm D})^2}\right]^2, \qquad (1)$$

in addition to the known Born contribution of neutral currents, which depends on the number of protons Z and the number of neutrons N in the nucleus, contains an additional term, which disappears in vacuum $(r_{\rm D}\to\infty)$. Here $k=2E\sin(\theta/2)$ is the transmitted momentum. The additional contribution is of a polarization origin and when one ignores neutral currents, leads to the Mott-Rutherford formula for scattering by a screened Coulomb center $(Z_e/r)\exp(-r/r_{\rm D})$ of the neutrino with the "induced electric charge"[5]

$$e_\nu^{\rm ind}=\frac{G_{\rm F}(1+4\xi)}{4\pi\alpha\cdot\sqrt{2}r_{\rm D}^2}e \qquad (\xi=0.25), \qquad (2)$$

where ξ is a parameter of the standard model (from experiment, $\xi\sim0.23$); $G_{\rm F}$ is the Fermi constant, $e^2=\alpha=137^{-1}$, e is the charge of the electron (all in the system $\hbar=c=1$).

The induced electric charge (2) owes its origin to the weak attraction of electrons to the neutrino. The inhomogeneity of the electron concentration is the charge (2) which is compensated by the charge of ions at a distance of the order of $r_{\rm D}$. The opposite sign of the amplitude of scattering for the antineutrino leads to the repulsion of electrons and a change in the sign of (2).

Despite the small value of the charge $e_\nu^{\rm ind}/e\sim10^{-16}$ (Sun, metal), $\sim10^{-8}$ (collapser), the effect of the additional term on the cross section (1) is significant in the range of small neutrino energies.

For energies $E\sim r_{\rm D}^{-1}$ ($\sim$keV in metal, $\sim$3.5 MeV for a density of $\rho\sim10^{12}$ g/cm^3 in a collapser) the cross section for the scattering of the electron neutrinos by nuclei decreases, due to collective interaction, by a factor of a value comparable to the Born value, not taking into account the polarization of the medium by weak forces.

A consequence of the propagation (after the neutrino) of the longitudinal perturbation of the electron concentration is the polarization emission $\nu\to\nu+\gamma_l$ of longitudinal plasmons in an isotropic medium[6] by a moving neutrino. The presence of a mass, in contrast to the decays of hypothetical heavy neutrinos in vacuum $\nu_{\rm H}\to\nu_{\rm L}+\gamma$, is not assumed here.

The presence of pseudovector currents, which are responsible for the nonconservation of parity in weak interactions, leads to a new axial function of linear response, which supplements the known polarization tensor of statistical quantum electrodynamics.[9] If one examines the interaction of the neutrino with a weak static and homogeneous external magnetic field, the presence of an axial response function leads to the appearance of an induced magnetic moment of the neutrino

$$\mu_\nu^{\rm ind} = \frac{e_\nu^{\rm ind}}{2m_e}\frac{2}{1+4\xi}, \qquad (3)$$

where $e_\nu^{\rm ind}$ is the charge (2), m_e is the mass of real electrons of the polarized medium, which form a circular current $\mathbf{j}$ around the spin of the neutrino, creating a magnetic moment $\mu_\nu^{\rm ind} = (1/2)[\mathbf{rj}]\int d^3r$ with the value of (3).

In the old *V–A* model of Feynman and Gell-Mann (1957), where there are no neutral currents ($\xi = 0.25$), the magnetic moment (3) has a canonical form; however, it does not depend on the mass of the neutrino m_ν.

In ferromagnetics the analog of the magnetic moment (3) generated from the same pseudovector current of electrons reaches a large value,[12] $\mu_\nu^{\rm ind} = -2\sqrt{2}G_{\rm F}m_e^2\mu_{\rm B}/4\pi\alpha$ of the order of $10^{-10}\mu_{\rm B}$, where $\mu_{\rm B}$ is the Bohr magneton. In a collapser, in the ultrarelativistic degenerated electron gas, $\mu_\nu^{\rm ind}$ (3) also reaches a large value $\sim 10^{-10}\mu_{\rm B}$ without drawing on the hypothesis of right-handed currents.

In the standard model, the induced magnetic moment does not lead to a change in the helicity of the neutrino in the external magnetic field or in scattering by charged particles, in contrast to the vacuum magnetic moment.

However, the addition of a small admixture of right-handed currents to the weak interaction in a dispersive medium leads to the appearance of an effective magnetic moment of the neutrino, which is proportional to the medium density and the electric charge (2) or the moment (3), but which now leads to a change in the helicity even when one ignores the vacuum magnetic moment.

The inclusion of right-handed currents immediately leads to the appearance in a homogeneous medium of a finite neutrino mass proportional to the density of matter:[13]

$$m_\nu^{\rm eff} = \frac{G_{\rm F}(\varepsilon^2-1)m_e}{\sqrt{2}}\int (f_0^e + f_0^{\bar e})\frac{d^3p}{\varepsilon_{\rm p}}, \qquad (4)$$

which has the necessary transformation properties and determines the spectrum of neutrinos in matter, similar to the mass of an electron in a crystal; here $f_0^{(\bar e,\bar e)}$ are the Lorentz-invariant equilibrium functions of the distribution of electrons and positrons. We stress that in this same model of Pati and Salam with the mixing of the left and right *W*-bosons ($W_1 = W_{\rm L}\cos\zeta + W_{\rm R}\sin\zeta, \zeta$ is the mixing angle) the vacuum mass of the neutrino is uncertain due to the need to renormalize. Despite the smallness of the effective mass ($m_\nu^{\rm eff} \sim 2\cdot 10^{-3}$ eV) for a density $\rho \sim 10^{14}$ g/cm^3, the appearance of two states of helicity is of fundamental importance for a neutrino which is massless in vacuum.

In this same model with right-handed currents, the interaction of a neutrino with a cloud of real electrons around an ion (in elastic scattering of a neutrino by an ion in a plasma) leads to a more effective change in the helicity of the neutrino than when one considers its interaction with an ion through the vacuum magnetic moment.[14]

The latter effect, which was examined for the simple case of an isotropic dispersive medium, may be noticeable for a neutrino in a dense medium, where the de Broglie wavelength of the neutrino $\lambda \sim E^{-1}$ exceeds the average distance between particles of the medium (a collapser with $\langle E\rangle \sim 10$ MeV, $p_{\rm Fe} \sim 30$ MeV ($\rho \sim 10^{12}$ g/cm^3)).

For media such as the Sun, the approximation of an isotropic medium (magnetic field $\mathbf{B}_0 = 0$) is clearly insufficient for the collective effects to lead to a noticeable change in the helicity of the neutrino or the cross sections of its interaction with matter. Here, apparently, one needs further development of the proposed approach for the case of the magnetically active plasma of the Sun.

Among other results, we also note the calculation in the standard model (without right-handed currents) of the anapole moment of the Dirac and Majorana neutrino in a medium. In particular, in ferromagnetics the value of the induced anapole moment, which depends on the magnetic permeability $(1-\mu^{-1}\sim 1)$, is at least $\alpha^{-1} = 137$ times greater than the expected vacuum value.[15]

In this same model the Bogolyubov method was used to deduce the relativistic kinetic equations for charged leptons and neutrinos.[16] The important role of the contribution of the self-consistent field, which is dependent on charge (2), to the equation of neutrino transport was noted.

All the dependences of the electromagnetic interactions of neutrinos with a dispersive medium through an induced electric charge (2) or magnetic moment (3) are of an indirect character in the sense that electromagnetic form factors of the neutrino are introduced directly into observed values (cross section, energy losses), and these form factors depend on the functions of linear response of the medium to weak interaction. Normalizations of these form factors, that is, of their value, are multipole electromagnetic moments of the neutrino in the medium,[17] which are useful for qualitative understanding of the interaction of the neutrino with the dispersive medium, and the use of known analogies for behavior of common charged particles in these media.

Depending on the parameters of the medium (density, temperature), the charge (2), magnetic moment (3), etc., are not such universal characteristics as, for example, the charge of the electron, but they correctly reflect the physics of electromagnetic phenomena for the neutrino in a dispersive medium, which is noticeably different in its consequences from the results of the interaction of vacuum electromagnetic characteristics of the neutrino with electromagnetic fields in the same medium.

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