accordance with the law $e^{-\mu t}\delta(E_0 - E)$, then $\bar{s}$, t and y are related by

$$-\lambda_1'(\bar{s})\,[t - 1/(\lambda_1(\bar{s}) + \mu)] = y, \tag{8}$$

where μ is the coefficient of absorption of the component that generates the primary electrons or photons. The integral energy spectrum of the electrons has the form

$$N_p(E_0, E, t) = \frac{H_1(\bar{s})}{\bar{s}} \exp\left\{y\bar{s} + \lambda_1(\bar{s})\,t - \ln[\lambda_1(\bar{s}) + \mu]\right\} \times \left[2\pi\left\{\lambda_1''(\bar{s})\,t - \frac{\lambda_1''(\bar{s})\,[\lambda_1(\bar{s}) + \mu] - \lambda_1''^2(\bar{s})}{[\lambda_1(\bar{s}) + \mu]^2}\right\}\right]^{-1/2}. \tag{9}$$

It can be shown that in the case of continuous generation in depth, the quantities s, t, y, and x in three-dimensional theory are related by

$$-\lambda_1'(s)\,[t - 1/(\lambda_1(s) + \mu)] = y + \ln x. \tag{10}$$

We used the foregoing method to calculate the following functions: the laterial distribution function of electrons and photons with energy greater than E (approximation A) at $\bar{s}$ = 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, and 1.6 for various values of the ratio $E_0/E = 10^6, 10^4, 10^3, 10^2$ and 10; the functions of lateral distribution of electrons with energy E > 0 (approximation B) for $\bar{s}$ = 0.6, 0.8, 1.0, 1.2, 1.4, 1.6 and for values of the ratio $E_0/\beta = 10^6, 10^4, 10^3, 10^2$ and 10. We also calculated the equilibrium functions of angular and lateral distributions of electrons for several values of the parameters.

---

*The condition $E_0 = \infty$ is used here only for calculating the function $f_p^\infty(x, s)$.

---

[1] S. Z. Belen'kiĭ, Лавинные процессы в космических лучах (Cascade Processes in Cosmic Rays), Gostekhizdat, 1948.

[2] V. V. Guzhavin and I. P. Ivanenko, Dokl. Akad. Nauk SSSR **115**, 1089 (1957), Soviet Phys.-Doklady **2**, 407 (1958).

[3] L. Eyges, Phys. Rev. **74**, 1801 (1948).

[4] S. Z. Belen'kiĭ and I. P. Ivanenko, Usp. Fiz. Nauk **69**, 591 (1959), Soviet Phys.-Uspekhi **2**, 912 (1960).

Translated by J. G. Adashko
134

ON THE PRODUCTION OF AN ELECTRON-POSITRON PAIR BY A NEUTRINO IN THE FIELD OF A NUCLEUS

A. M. BADALYAN and CHOU KUANG-CHAO

Submitted to JETP editor November 26, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **38**, 664-665 (February, 1960)

PRESENT experimental possibilities have allowed a rather close approach to a measurement of the cross section for scattering of a neutrino by an electron.[1] This process is a very important one for testing the theory of the universal weak interaction.

In the laboratory system, in which the electron is at rest, and for incident neutrino energy $\omega_1 \gg m$, the cross section for scattering of a neutrino by an electron is

$$\sigma_1 = (g^2/3\pi)\, m\omega_1, \tag{1}$$

i.e., a linear function of ω_1.

There is another process, $\nu + Z \to \nu + Z + e^+ + e^-$, for which the laboratory system coincides with the center-of-mass system. On one hand, it could be expected that the cross section for this process would be smaller than that for scattering, since it contains the factor $(Ze^2)^2$, and the phase volume gives an additional numerical factor $(2\pi)^{-2}$. On the other hand, the phase volume is proportional to ω_1^8, since there are three particles in the final state.

This process is described by two second-order diagrams. The calculation of the contributions of the two diagrams to the cross section leads to extremely cumbersome formulas. We shall, however, get the right order of magnitude for the total cross section if we confine ourselves to the contribution of one diagram. The differential cross section for the process then has the form

$$d\sigma_2 = \frac{16g^2(Ze^2)^2}{\omega_1\omega_2\varepsilon_+\varepsilon_-} \frac{d\mathbf{p}_- d\mathbf{p}_+ d\mathbf{k}_2}{q^4(2\pi)^8} \frac{(k_1k_2)}{m^2 - f^2} \times \left[2\varepsilon_+\varepsilon_- - (p_+p_-) + 2fp_+ \frac{2\varepsilon_-^2 + m^2 - (fp_-)}{m^2 - f^2}\right] \times \delta(\omega_1 - \omega_2 - \varepsilon_+ - \varepsilon_-), \tag{2}$$

where

$$f = k_1 - k_2 - p_+, \qquad q = k_1 - k_2 - p_+ - p_-.$$

Here k_1, k_2, p_+, and p_- are four-vectors that refer respectively to the neutrino in its initial and final states and to the positron and electron; ω_1, ω_2, ϵ_+, and ϵ_- are the corresponding energies.

For high energies of all the particles involved in the process the differential cross section $d\sigma_2$ has a sharp maximum near the direction of the momentum of the incident neutrino. All of the emerging particles are concentrated in a narrow cone around this direction, with angular aperture $\vartheta \approx m/\omega_1$. This follows from the fact that the denominator of the expression (2) contains the factor

$$[\omega_1\omega_2(1-\cos\vartheta_{12}) + \omega_1\varepsilon_+(1-v_+\cos\vartheta_{1+}) - \omega_2\varepsilon_+(1-v_+\cos\vartheta_{2+})]$$

(ϑ_{ik} is the angle between the momenta of the i-th and k-th particles, and v_+ is the velocity of the positron), together with the fact that the effective recoil momentum of the nucleus is $q \sim m$.

The reduction of the "effective" solid angle sharply lowers the degree of the energy dependence of the total cross section. Apart from terms of second order in m/ω_1 the total cross section is

$$\sigma_2 = \frac{8g^2(Ze^2)^2\omega_1^2}{3(2\pi)^3}\alpha\left(\ln\frac{\omega_1}{m}-\beta\right), \qquad \omega_1 \gg m, \qquad (3)$$

where $\alpha, \beta \sim 1$; $1 < \beta < 2$. Comparison of Eqs. (1) and (3) shows that for $Z/137 \approx 1/2$ the cross section σ_2 becomes comparable with σ_1 only for incident neutrino energy $\omega_1 \approx 10$ Mev. It is only at energies higher than this that the process of production of an electron-positron pair may become observable.

The writers express their gratitude to Ya. A. Smorodinskiĭ for his interest in this work and for a discussion of the results.

[1] C. L. Cowan, Jr. and F. Reines, Phys. Rev. **107**, 528 (1957).

Translated by W. H. Furry
135

INSTABILITY IN A SEMICONDUCTOR AMPLIFIER WITH NEGATIVE EFFECTIVE CARRIER MASS

A. L. ZAKHAROV

Submitted to JETP editor December 8, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **38**, 665-667 (February, 1960)

KRÖMER has shown[1] that a crystal of germanium or silicon, of the p type, in which there exists a strong field in the [100] direction ("longitudinal" direction), will have in any direction perpendicular to the [100] ("transverse directions") a negative conductivity. The use of this negative conductivity for amplification and generation is precisely the idea of the new semiconductor instrument proposed by Krömer, the NEMAG (negative effective mass amplifier and generator).

This device differs from diodes with negative conductivity (for example, tunnel or parametric) in that its negative conductivity is specific. This circumstance leads to an unstable operating state of the device, as can be seen from the following consideration. Assume that in a certain microvolume, the thermal fluctuations of the hole concentrations result in an accumulation of a small positive charge. Then the field produced by this charge causes in the surrounding medium a current flowing not from the charge (as in the case of positive specific conductivity) but to the charge (more accurately, to the [100] line, passing through the charge). The charge will start increasing exponentially with a time constant called the time of dielectric relaxation ($\tau = |\epsilon\rho|$ where ϵ is the dielectric constant and ρ the negative specific resistivity of the semiconductor) and this process will slow down and cease only when a transverse field E_t is produced strong enough to make the conductivity in it positive (a negative conductivity is observed only at sufficiently small transverse fields).

An analogous process leads to the formation of a negative charge (region where the concentration of the holes is less than the concentration of the charged impurity centers — acceptors), if the initial fluctuation reduces the concentration of the holes compared with the equilibrium value.

In the stationary state the charge is arranged around the [100] axis with a density that decreases with the distance from this axis. The state with negative conductivity (weak transverse field) is retained only in a thin cylinder about this axis, and the finite thickness of the cylinder is determined only by the diffusion loss of holes, and amounts to a fraction of a micron (of the order or less than kT/eE_t). Such cylinders are attracted to each other when their charges are of the same polarity, and are repelled when they are different, and consequently, as can be shown, the distances between the cylinders in the state of stable equilibrium are of the same order as or greater than the thickness of the crystal in the transverse direction. But this thickness is always much greater than the thickness of the cylinder and furthermore the lineary density of the charge in the cylinder is negligible (on the order of $kT/2$); therefore the contribution of the cylinders to the total con-