ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

D-577

ON HIGH ENERGY NEUTRINO PHYSICS

Дубна 1960

D–577

ON HIGH ENERGY NEUTRINO PHYSICS *

* Reports on JINR seminars (1957–1960).

C O N T E N T S

ON HIGH ENERGY NEUTRINO PHYSICS

M. A. Markov

A new branch of physics-high energy neutrino physics - is likely to appear in the nearest future. At present a discussion of experimental possibilities of observation of varions reactions with high energy neutrino seems already be very essential.

Possible experimental results, which will be spoken about below, are not excluded to be able to play a decisive part when constructing future theory of elementary particles .

As is known, weak four- fermion interactions lead to cross-sections of reactions with a square energy dependence (in the center of mass system of colliding particles).

$$\sigma \sim E_i^2 . \qquad (1)$$

From the point of view of the recent formalism, the cross-section (1) is correct up to the energy 10^{11} eV in the center of mass system, as the perturbation theory, with whose help the cross-section (1) is obtained, is valid up to the lengths

$$\ell = \sqrt{\frac{G}{\hbar c}} \sim 0,6 . 10^{-16} cm. \qquad (2)$$

where G - characteristic constant of weak interactions.

The question arises - how far does the square increase of the weak interaction cross-sections in real effects[1/2] proceed with the energy ? In other words, are of any physical meaning in the real space for example lengths of the order of the characteristic lengths of weak four-fermion interactions; or does the universal length of the larger dimension (as is required by strong interactions) exist, which cuts off the weak interaction cross-sections earlier than the limit established here by the application of the perturbation theory.

Unfortunately, energies 10^{11} eV in the center of mass system at least in the nearest years will not be accessible for experimentalists (i.e. counter beams with the energy 10^{11} eV), therefore the questions put should be answeered in some indirect way.

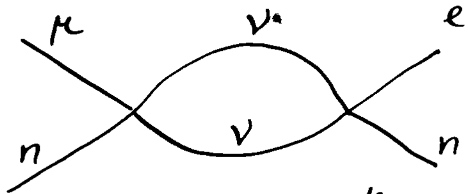
One of such indirect ways is connected with consideration of high effects of the perturbation theory of weak interactions, which in intermediate states allows whatever large momenta.

A number of the like effects was theoretically analysed (Pontecorvo[3], Asanov, Valuev[4] and Ioffe[5]) with the supposition that the momenta of the intermediate states are cut off for such $K_{max} < K$

of the ultimate $\quad = 10^3\, M_N$, which gives the maximum value of the considered effect being not contradictory to experimental data.

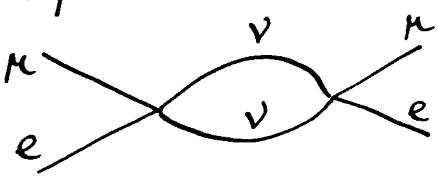
These effects are of the type

1. $\mu^+ + n \to n + e^+$



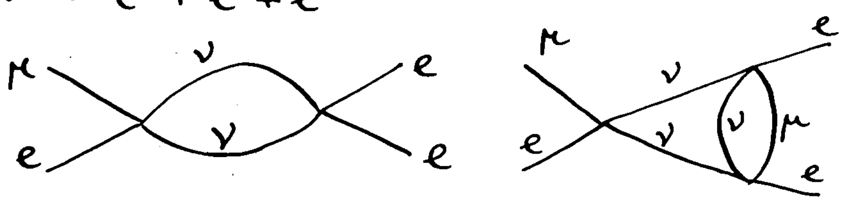
$\kappa_{max} < 200\, M_N$

2 $\mu^+ + e^- \to e^+ + \mu^-$



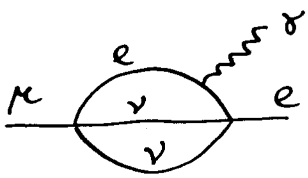
$$\frac{w(\mu^+ e^- \to \mu^- e^+)}{w(\mu \to e \nu \tilde{\nu})} \sim 10^{-5}$$

3 $\mu^+ \to e^+ + e^- + e^+$



$\kappa_{max} < 400\, M_N$

4 $\mu \to e + \gamma$



$K_{max} < 50\, M_N$

The immediate conclusion from the given estimations rather proves that the momenta are cut off in the intermediate states by some factor which effect for smaller momenta than those for which the perturbation theory could be suspected as not applied.

Analysing these results, lepton-baryon effects should separated from lepton-lepton effects.

Lepton—Barion Interactions

The point of view becomes lately very probable that four-fermion interactions with the participation of baryons for example for the vector variant ("weak" electrodynamics) are cut off by the same Hofstadter form-factor, i.e. on the lengths

$$\ell \geqslant \frac{\hbar}{M_N c} \sim 2.10^{-14}\ cm.$$

It is naturally to suppose that the total interaction ($V-A$) is cut off by the same form-factor, though the last statement is a new hypothesis.

For these suppositions the effects of the type 1 are small and agree with the experiment.

For the neutrino of energy ~ 1 BeV the cross-sections of effects of the type

$$\nu + p \rightarrow \begin{matrix} n+\mu \\ n+e \end{matrix} \qquad (3)$$

become of the order of $10^{-38}\ cm^2$. As to higher energies the further increase of the cross-section with the energy (1) is essentially modified by the form-factor6/. The application of the extrapolation of Hofstadter form-factor (which is actually not quite lawful) in the region of such large momenta leads to the constant cross-section $10^{-38} cm^2$ for large energy values.

Lepton-Lepton Interactions

For lepton-lepton interactions of the type

$$\nu + e \rightarrow \mu + \nu \qquad (4)$$

the expression for the cross-section in the center of mass system has the same form (1). Considerations as to the limitation of the energy increase of the cross-sections of the four-fermion lepton-baryon interactions are rather reasonable, but the limitation of lepton-lepton interactions by the characteristic nucleon, or pion lengths may be considered at present from the point of view of common theoretical ideas as little probable.

There is a different situation for example with the non-linear theory of Heisenberg type.

The question arises: how do really lepton-lepton interactions behave with the energy ?

Cross-section (1) in the laboratory coordinate system becomes of the form:

$$\sigma \sim m E_\nu . \qquad (5)$$

Consequently, cross-sections for (νe) interactions for the given neutrino energy are 10^3 times smaller than the corresponding cross-sections of the neutrino-nucleon interactions. The last circumstance makes at present meaningless the attempt of detection of direct (νe) $\to$ ($\mu \nu$) interaction with the most powerful modern accelerators.

But there are effects of neutrino interaction on 'bound' electrons, which conserve higher energy dependence of the cross-section at high energies and in the laboratory coordinate system.

We gave an example of such effect /6/, namely-neutrino ν in the field of a nucleus Z scattering, produces the pair $e^-\mu^+$, e^-e^+, $\mu^+\mu^-$, μ^-e^+ i.e. the effect of the form

$$\nu + Z \to Z + e^- + e^+ + \nu' \qquad (6)$$

Chou Kuang-chao (Dubna) estimated this effect and obtained the cross-section in the form:

$$\sigma = \frac{8G^2(Ze^2)^2}{3(2\pi)^3} E_\nu^2 \ln \frac{E_\nu}{m} . \qquad (7)$$

In case of effect (νe) (νe) for $Z = 80$ and taking into account the screening of the Coulomb field of a nucleus by the shell electrons

$$\sigma_{\nu e} \sim 7.10^{-40} E_\nu^2 \qquad (8)$$

here E_ν is expressed in BeV.

At neutrino energies $E_\nu \sim 5.10^9$ eV cross-section (8) for $\sigma_{\nu e}$ already compared with the expected according to (3) value of the maximum cross-section * $\sigma_{\nu p}$

---

* As at little collision parameters the Hofstadter formfactor is unknown, the cross-section $\sigma_{\nu e}$ may drop quicker with neutrino energy /6/ and at energy $E_\nu \sim$ 10 BeV for example, may be that $\sigma_{\nu e} > \sigma_{\nu p}$ on lead detector.

$$\sigma_{e\nu} \approx 2.10^{-38} cm^2 \geqslant \sigma_{\nu p} \sim 10^{-38} cm^2 \qquad (9)$$

and for $E_\nu = 10$ BeV

$$\sigma_{e\nu} \sim 10^{-37} cm^2 .$$

Approximately (till the diferences in screening effects) the like cross-sections in the region of the same energies are obtained for the effects with the production of pairs $\mu^+\mu^-$, μ^+e^- for neutrino scattering on the Coulomb center.

Theoretical consideration of lepton-lepton effects of the type 3.4 seems also to indicate that lepton-lepton interactions should be also cut off on the momenta, which are smaller than critical ones.

Such types of effects are in the most detailed and consistent manner considered by B.I.Ioffe[5]

The decay

$$\mu \rightarrow e + \gamma \qquad (10)$$

proves to be most critical, as according to the existing experimental upper limit for this effect

$$\frac{w(e+\gamma)}{w(e+\nu+\tilde{\nu})} \leq 2.10^{-6}$$

the critical momentum should be chosen

$$K_{max} < 50\ M_N .$$

With further increase of the upper limit accuracy for the effect $\mu \rightarrow e+\gamma$ probability the value K_{max} may become still closer to the baryon mass value.

Certainly, statement of the fact of such universality in cut off of all weak interactions on one length, close to that of pion or baryon, should be itself fundamentally for the theory of elementary particles.

Unfortunately, the results of the preceeding analysis of the effects of weak lepton-lepton interactions are greatly ambiguous even if mathematical apparatus of the theory of weak interactions to momenta 300 Bev is considered correct.

If the hypothesis is accepted that two kinds of neutrinoes (ν_μ and ν_e)[1/8/] exist, the possibility of different effects of the considered type is substantially limited.

One of the natural mechanisms able of cutting of the weak interaction cross-sections on the lengths close to those of baryons, would be the mechanism with the idea of intermediate vector meson with the mass close to that of baryon.

Intermediate Boson

From dimension considerations the crude estimation for the cross-section of vector meson production from neutrino in the Coulomb nuclear field Z is given by the expression*

$$\sigma \sim \alpha \left(\frac{Z}{137}\right)^2 G_V \qquad (11)$$

where $G_V = \ell^2$ constant of weak interaction, expressed in terms of the characteristic length ($\ell \sim 0.5 \cdot 10^{-16}$ cm). For $Z \sim 10$ the cross-section (11) may be expected:

$$\sim 10^{-35} - 10^{-36} \text{ cm}^2. \qquad (12)$$

And if the considered charged vector boson weakly interacts with nucleons and pions, the more probable process of vector meson production is the pair production from photon in the Coulomb nuclear field.

The cross-section of such process[9/] is given in the form**

$$d\sigma = \left(\frac{e^2}{mc^2}\right)^2 \alpha Z^2 d\varepsilon \left(\frac{E_0}{Mc^2 Z^{1/3}} \frac{\pi}{40} \left(2 - 2\varepsilon + \varepsilon^2\right)\right), \qquad (13)$$

---

* First indications to this effect seems to belong to Ponteoorvo and Ryndin. Kiev Conferenoe, 1959.

** Here, as in (11), corrections are necessary, as the production of particles pairs with such large mass takes place with the impact parameters $\hbar/Mc \sim 10^{-14}$ cm and thus in the region of relatively small energies ε the cross-section may be realized less, e.g. $\sim Z$ but not $\sim Z^2$.

where εE_0 energy of the produced positive meson, α -fine structure constant, Z -nuclear charge. For $E \sim 4$ BeV, $\sigma \sim 10^{-31} cm^2$.

ν_μ and ν_e - neutrinoes

The neutrino creating from the pion decay $\pi \rightarrow \mu + \nu$ is usually asepted of the same nature as that creating for example, from the neutron decay

$$n \rightarrow p + \nu + e.$$

This hypothesis is not still experimentally proved.

It is worth noting, that in case of difference of ν_μ and ν_e - neutrinoes, the effects of the type $\mu \rightarrow e + \gamma$ could be prohibited and the question on the value of the critical momentum of weak interactions would be left open.

Thus, the problems, settled above and connected with the character of weak interactions should be solved in the following turn:

1. Intermediate meson
2. ν_μ and ν_e neutrinoes
3. Existence of interactions of the type $(\nu e)(\nu e)$
4. The value of the critical momentum of weak interactions -a/ for neutrino-baryon, b/ neutrino-lepton interaction.

In this aspect experimental possibilities were considered both of the operating accelerators and cosmic rays.

Possibilities of Accelerators

Estimations of neutrino fluxes in accelerators, based on the statistic theory (Barashenkov, Hsieng Ding-chang, Dubna) give per one proton collision in the target ($E_p = 10^{10}$ eV) 1.10^{-8} neutrino/cm^2 with $E_\nu > 1$ BeV at the distance of 50 meters from the target. These values are related to the angle 0°. For neutrino with $E_\nu > 2$ BeV the neutrino flux density under the same conditions is 10 times smaller.

1. Intermediate Meson

Assuming the cross-section of production of the vector meson with the mass, equal to that of nucleon, for $E_\nu > 2$ BeV being equal to 10^{-35} cm^2, and assuming the accelerated proton flux 10^{11}/sec, 1 event per 1 day* takes place in the detector target of the volume of 1 m^3 and $\xi > 10$. Due to fast decay of the vector meson to $\mu + \nu$, $e + \nu$ these events will be detected as μ - meson and electron production from neutral primary component of the beam.

Under these conditions:

$$E_\mu \sim E_\nu \sim 0{,}5 \text{ BeV}.$$

with the distribution close to the isotropic one. Barashenkov and Hsieng Ding-chang estimated photon beams for bevatrons (preprint, Dubna).

Per one proton-nucleon collision of protons with $E_i \sim 10^{10}$ MeV at the distance of 50 meters from the target γ - quantum flux appears of about 10^{-6} $\frac{\text{quanta}}{(\text{cm})^2}$ with the energy able to give a pair of charged particles with the mass equal to that of a nucleon.

According to experimental data of the CERN accelerator (report made by Adams) at the distance of 100 meters from the target at the intensity 10^{11} protons per pulse 1 5 cm^{-2} photons are produced with the energy ~ 11 BeV.

Under the same conditions the photon flux with $E_\gamma \sim 5$ Bev attains $2 \cdot 10^{-3}$cm^{-2} per pulse.

The last value gives about 2 events per 1 hour for the production of the vector meson pair in the lead plate 1 cm thick and with the surface of 10^2 cm^2.

The production of the pairs of vector mesons fastly decaying into $e\nu$ and $\mu\nu$ means in reality another mechanism for the production of pairs $e^+\mu^-$, $\mu^+\mu^-$.

The last $\mu^+\mu^-$ with much larger cross-section will be produced in the same photon beam.

But the characteristic properties of the considered effects may be used. For μ -mesons and electrons, produced from the decay of vector mesons of not too great velocities a great probability will be characteristic for the momenta directed to the second semi-sphere (large angles), the

---

* Not taking into account the magnetic focusing of pion beam.

energy of μ, e - decay being $E_{\mu e} \geqslant 0.5$ BeV.

Pairs of $\mu^+\mu^-$-mesons, resulting from direct photoproduction will be localized in small angles $\sim \frac{\mu}{E_\gamma}$.

The selection of pairs $\mu + e$ with $E_{\mu e} \gtrsim 0.5$ BeV at large angles would be still more critical.

These properties of the considered effect are not excluded to be decisive for this experiment.

It is worth emphasize, that the application of photon beams with modern proton accelerators is becoming or with further increase of intensities will become expedient. Proton-antiproton pairs will be produced approximately with the same cross-section* (13).

An essential property of the production of charged particle pairs from photon is, that the cross-section for the production of even such particles as Ξ^- -hyperons is almost the same, like that for the production of nucleon pairs.

In this sense the search of possible, according to Gell-Mann systematic, particles Z^+, Ω^- hyperons and $\vartheta^\pm$ -mesons and even multiply charged particles is expedient in the photon beam.

$\nu_\mu - \nu_e$ problem

Basing on the previous estimations and having the accelerated proton flux 10^{11} /sec, we may expect at the distance of 50 meters from the target the neutrino flux with $E_\nu > 1$ BeV, $\sim 10^3$ cm^{-2}.

Using in the target 1/10 of the number of primary protons, in 1 m^3 of heavy detector 1/4 of event per one day takes place, i.e. the events of the type:

$$\nu + p \rightarrow \begin{matrix} n + \mu^+ \\ n + e^+ \end{matrix}$$

(without magnetic focusing).

---

* More exactly:

$$d\sigma_p = \left(\frac{e^2}{M_p c^2}\right)^2 \alpha Z^2 d\varepsilon \, \frac{16}{3}\left(\frac{3}{4} - \varepsilon(1-\varepsilon)\right).$$

Neutrino-Lepton Interactions

On the basis of the consideration of the effect ($\nu + Z$) and the increase of this effect with the energy (9) it would be of use to try to detect the effect of neutrino-lepton interactions at neutrino energies $>$ 5 BeV.

The cross-section at $E_\nu = 3$ Bev reaches those expected for neutrino-nucleon interaction, and at $E_\nu \sim 30$ Bev reaches those on lead (10^{-36} cm^2). Then the cross section may even become greater than for neutrino-nucleon interaction , if the last decreases with neutrino energy. Thus, it is expedient to investigate the neutrino-lepton interactions, making use the features of effect into consideration : a) Z - dependence, b) creation of characteristic pairs of ($\mu + e$) kind, c) E_ν-dependence. In this way the detection of neutrino-electron interactions in principle is the problem of the highest energy accelerators. Note that rational technical suggestion for characteristic μe pairs detection could make this experiment expedient on bevatrons with intensity* $10^{12} - 10^{13}$ particles per one sec. The last experiment would become essentially simpler if $\nu_\mu \neq \nu_e$.

It is worth emphasize that the considered events should be identified in the presence of cosmic rays background, which gives on the Earth surface 10^{-2} mesons cm^{-2}/sec with $E_\mu > 10^9$ eV and 10^{-4} neutrons cm^{-2} sec^{-1} approximately with the same energy ($\sim$ 1 BeV).

Here the positive factor is the duration of the pulse in the machine 10^{-3} sec.

It is important to note that the absolute number of the decayed mesons (i.e. the neutrino number) increases with the increase of the distance from the accelerator target, but due to the geometry factor the neutrino flux density decreases (it reaches its maximum immediately near the target[10]).

Even for the parallel pion beam the density of the decay neutrino beam has at some distance from the target the maximum value, and then decreases because of the disturbance in the decay act of the

---

* Of order of one $\mu^- e^+ (or\ e^+ e^-)$ event per one day: the number of neutrinoes decreases. fast with increasing of E_ν.

parallelizm of the primary beam of π -mesons, transforming into neutrino beam[11].

All the previous estimations were given without corrections for the possible magnetic focusing of pion beam.

This factor may increase the previous estimations by more than one order, that could increase the number of corresponding counts under the same condition for the proton flux 10^{11}/sec.

1) Intermediate meson - 1 count per an hour .

2) $\nu + n \rightarrow \begin{matrix} p+\mu \\ p+e \end{matrix}$ 5-10 events per one day .

3) $\nu + Z \rightarrow Z + \mu^- + e^+ + \nu$, ~ 1 event per one month .

References

1. M.A. Markov, Hyperonen und K-mesonen, Verlag der Wissenschaften, Berlin, 1960, S. 292.
2. D.I. Blokhintsev, Nuovo Cimento, Ser. X, Vol. 9, 925 (1958); Usp.Phys.Nauk, 62, 381 (1957).
3. B. Pontecorvo, JETP, 33, 549 (1957).
4. R. Asanov and B. Valuev, Preprint JINR.577, Dubna, 1960.
5. B.L. Ioffe, JETP, 38, 1608 (1960); Thesis for a Doctor's degree.
6. I.M. Zheleznykh 'On interaction of high energy neutrinoes in cosmic rays with a substance', Diploma, MSU, 1958.
7. N. Cabibbo and R. Gatto, Nuovo Cimento, XY, 305 (1960).
8. B. Pontecorvo, JETP, 37, 1751 (1959); Kiev Conference on High Energy Physics, 1959.
9. V. Pauli, Relativistic theory of elementary particles.
10. D.G. Fakirov, 'On possibility of investigation with accelerators of high energy neutrinoes with a substance', MSU, 1958. 'On the spacial distribution of the neutrino beam generated by high energy nucleon collisions', Ann. de L'Univ. de Sofia, Fac. de Sci.Phys. Math. v. 53, ℓ.2 (phys) 1958/1959.
11. I. Polubarinov, Preprint JINR, Dubna, 1960.

ON HIGH ENERGY NEUTRINO PHYSICS IN COSMIC RAYS

I.M. Zheleznykh[x] and M.A. Markov

The preliminary disoussion of different estimations in general detected effects from neutrinoes in cosmic rays was given by us in the previous paper[xx].

The given paper contains the further corrections of estimations and the development of the problem on the whole.

Let us consider, firstly, the neutrino flux creating from the deoays of $\pi^{\pm}$-mesons produced in the Earth atmosphere from primary cosmic protons (i.e. the neutrinoes of Earth origin). The energy speotrum of cosmic neutrinoes (i.e. neutrinoes, coming to the Earth from the Universe) is unknown at the present time. And even here some considerations of quantitative oharacter are possible. Thus, the oonsidered below first estimations of effects, caused by high energy neutrinoes of the Earth origin are the lowest ones.

For the decay

$$\pi \rightarrow \mu + \nu \qquad (I)$$

in the rest system of π-meson the energy of deoayed neutrino

$$E_{\nu} = \frac{M_{\pi}^2 - M_{\mu}^2}{2 M_{\pi}} \sim 0,23\, M_{\pi} \qquad (2)$$

$$E_{\mu} \sim 3,3\, E_{\nu} \,. \qquad (3)$$

---

x) Physical Institute of the U.S.S.R. Academy of Sciences.

xx) I.M. Zheleznykh. "On interaotion of high energy neutrinoes in oosmic rays with substance". Diploma, Mosoow City Univ., 1958.

Further, we assume, that at an average in the laboratory system the energy of the corresponding neutrino and μ -meson is connected by the same ratio (3).

The neutrino energy spectrum was reduced over the corresponding μ -mesons energy spectrum. In the paper[x)] the experimental μ -mesons energy spectrum at two hundred feet above the sea level is given up to the μ -meson energy $\sim 10^{12}$ eV.

In different intervals the neutrino energy spectrum was approximated in the following way.

In the regions: 1-3 BeV $f(E_\nu) = 1{,}5.10^{-3} \frac{dE_\nu}{E_\nu^{1,4}}$

$$\text{3-30 BeV} \quad = 5{,}3.10^{-3} \frac{dE_\nu}{E_\nu^{2,5}} \qquad (4)$$

$$\text{30-100 BeV} \quad = 5{,}7.10^{-2} \frac{dE_\nu}{E_\nu^{3,2}}$$

The isotropy of neutrino flux and small value of the neutrino interaction cross-section allow to suggest the experiment deep under the ground, separating reactions from neutrinoes, coming from the low semi-sphere, i.e. passing all the Earth.

It is essential to note, that such an organization of the experiment, in principle, can completely exclude the cosmic-ray background. Charged particles do not pass through the Earth and small-probable back reflections of μ -mesons may be apparently separated using corresponding registrating schemes. In case of the experiment with accelerators the cosmic-ray background makes a problem for recent intensities of accelerated particles.

In the underground experiment the relative smallness of the background allows to use large detector masses, that compensates to some extent the smallness of cosmic neutrino fluxes.

Note, that the background due to the natural radioactivity in the ground may be avoided, using detectors with the threshold of the energy release detection, e.g. 0,5 BeV.

---

x) F. Ashton. "Nature," 185, 4710, p. 364.

1. Neutrino-Nucleon Interaction

In the limits of existing experimental facts and theoretical ideas the following reactions may be supposed:

$$
\begin{aligned}
&a) \quad \nu_\mu + n \rightarrow p + \mu^-(e^-) \\
&b) \quad \tilde{\nu}_\mu + p \rightarrow n + \mu^+(e^+) \\
&c) \quad \tilde{\nu}_\mu + n \rightarrow \Sigma^- + \mu^+(e^+) \\
&d) \quad \tilde{\nu}_\mu + p \rightarrow \Sigma^0 + \mu^+(e^+) \\
&e) \quad \tilde{\nu}_\mu + p \rightarrow \Lambda^0 + \mu^+(e^+)
\end{aligned}
\tag{5}
$$

If ν_μ and ν_e are the same, both the production of e and μ -mesons are possible.

The cross-section of the interaction ν with nucleons, may be, cut off for exchange momenta, corresponding to nucleon dimensions and then the cross-section for $E_\nu \gtrsim 1$ BeV is $\sim 0{,}8 \cdot 10^{-38}$ cm^2. For anti-neutrino the cross-section for $E_{\tilde{\nu}} = 1$ BeV is approximately three times smaller.

By integration (4) we get the total neutrino and anti-neutrino flux with the energies, larger than 1 BeV, that gives $S(E_\nu > 1\,\mathrm{Bev}) \cong 4 \cdot 10^{-3}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{ster}^{-1}$. The number of events per 1 sec. in 100 m^3 of the water is

$$
N = (\sigma_\nu + 4\sigma_{\tilde{\nu}}) \cdot 2\pi \frac{S}{2} \cdot N_{Avog.}\, \rho \cdot V \sim 1{,}3 \cdot 10^{-2}\ \mathrm{day}^{-1}
\tag{6}
$$

or one case per 75 days. If electrons are also produced, 1 event per 40 days in 10^3 m^3 of water takes place.

Not only produced in detector μ -mesons but from adjacent layers of the ground are detected. The effect is strengthened due to the proportionality paths of μ -mesons to the first degree of the energy. For electrons it is much weaker. For neutrino-nucleon interaction the contribution from adjacent layers is of the same order, as the effect in the detector (i.e. one $\begin{smallmatrix}\nu \rightarrow \mu \\ \nu \rightarrow e\end{smallmatrix}$ even per 20 days).

If the interaction in case (5) is not cut off at nucleon wave length, the number of detected events is 5 times greater.

II. Production of Lepton and Baryon Pairs of Particles

Lepton-Lepton Interaction

The following effects are possible, when neutrino produces a pair of leptons in the nuclear field:

$$\begin{aligned} \nu_\mu + Z &\to \mu^- + e^+ + \nu_e' + Z' \\ \tilde{\nu}_\mu + Z &\to \mu^+ + e^- + \tilde{\nu}_e' + Z' \\ \nu_\mu + Z &\to \mu^+ + \mu^- + \nu_\mu' + Z' \\ \tilde{\nu}_\mu + Z &\to \mu^+ + \mu^- + \tilde{\nu}_\mu' + Z'. \end{aligned} \tag{7}$$

If ν_μ and ν_e are the same, the following processes will be added:

$$\begin{aligned} \nu + Z &\to e^+ + e^- + \nu' + Z' \\ \tilde{\nu} + Z &\to e^+ + e^- + \tilde{\nu}' + Z'. \end{aligned} \tag{8}$$

Since small momenta of nuclear recoil in (7) and (8) are essential, the cross-section does not depend on formfactor. The cross-section of such processes is supposed[x)]

$$\sigma = \frac{8 g^2 Z^2}{3 (2\pi)^3 137^2} E^2 \ln \frac{E}{m}. \tag{9}$$

According to Chou Kuang-chao the account of screening changes the logarithm only For the cross-section, corresponding to (8) $\ln \frac{E}{m}$ is changed to $\ln \frac{183}{Z^{1/3}}$ =3,35 on lead in the region of energies we are concerned with.

For production of μ -mesons the minimum momentum of recoil is μ^2 times larger. Therefore, in our case for reactions with production of two or one μ -meson the screeening is not essential.

---

x) Chou Kuang-chao (Dubna).

For (8) $\sigma = 7{,}2.10^{-40} E^2$ (on lead, E in BeV). (10)

For (7) in lead

$$\sigma = 1{,}9.10^{-40} E^2 \ln 10E$$

in "ground" $(Z = 10,\ A = 20)$

$$\sigma = 2{,}8.10^{-42} E^2 \ln 10E. \qquad (11)$$

In case of reactions (8) the neutrino flux gives 1 event per 6000 days in 100 m^3 of lead.

Reactions (7) are of greater interest. Since the path of μ -mesons with the energy up to 100 BeV is proportional to E , this circumstance leads to the resulting effect increasing as $E^3 \ln 10E$, instead of $E^2 \ln 10E$.

Thus, the flux of μ -mesons from "the pillow" (adjacent layers of the ground) becomes more essential here, than their production in detector itself.

The energy distribution of three leptons produced in reaction, is unknown. We shall suppose for estimations, that at an average we get 1/3 of initial neutrino energy per one lepton.

Then the path of μ -mesons in the ground will be equal to $\frac{2}{3} 10^2 E_\nu$ (cm) (E_ν in BeV) (we suppose, that in 100 cm of the ground 0,5 BeV is lost). It should be taken into account, that the effective path depends on the angle

$$R_{eff} = \frac{2}{3} 10^2 E_\nu \cdot \cos\theta. \qquad (12)$$

The number of mesons (N), passing through the surface S , taking into account the fact, that in reactions (7) the flux ν and $\tilde{\nu}$ gives 3 μ -mesons:

$$N = 3\pi \frac{N_{Avog.}\,\rho}{A} \cdot \frac{2}{3} 10^2 S \sigma_0 \int_1^{300} f(E) E^3 \ln 10E \, dE. \qquad (13)$$

For the ground $\rho = 2$, $A = 20$, $\sigma_0 = 2{,}8.10^{-42}\ cm^2$, $f(E)$ is taken from (4).

If $S = 10^7\ cm^2$, $N = 3{,}6.10^{-8}\ sec^{-1}$, i.e. 1 case per 300 days.

For (8) $\sigma = 7{,}2.10^{-40} E^2$ (on lead, E in BeV). (10)

For (7) in lead

$$\sigma = 1{,}9.10^{-40} E^2 \ln 10E$$

in "ground" $(Z = 10,\ A = 20)$

$$\sigma = 2{,}8.10^{-42} E^2 \ln 10E. \tag{11}$$

In case of reactions (8) the neutrino flux gives 1 event per 6000 days in 100 m^3 of lead.

Reactions (7) are of greater interest. Since the path of μ -mesons with the energy up to 100 BeV is proportional to E , this circumstance leads to the resulting effect increasing as $E^3 \ln 10E$, instead of $E^2 \ln 10E$.

Thus, the flux of μ -mesons from "the pillow" (adjacent layers of the ground) becomes more essential here, than their production in detector itself.

The energy distribution of three leptons produced in reaction, is unknown. We shall suppose for estimations, that at an average we get 1/3 of initial neutrino energy per one lepton.

Then the path of μ -mesons in the ground will be equal to $\frac{2}{3} 10^2 E_\nu$ (cm) (E_ν in BeV) (we suppose, that in 100 cm of the ground 0,5 BeV is lost). It should be taken into account, that the effective path depends on the angle

$$R_{eff} = \frac{2}{3} 10^2 E_\nu \cdot \cos\theta. \tag{12}$$

The number of mesons (N), passing through the surface S , taking into account the fact, that in reactions (7) the flux ν and $\tilde{\nu}$ gives 3 μ -mesons:

$$N = 3\pi \frac{N_{Avog.}\rho}{A} \cdot \frac{2}{3} 10^2 S \sigma_0 \int_1^{300} f(E) E^3 \ln 10E \, dE. \tag{13}$$

For the ground $\rho = 2$, $A = 20$, $\sigma_0 = 2{,}8.10^{-42}$ cm², $f(E)$ is taken from (4).

If $S = 10^7$ cm², $N = 3{,}6.10^{-8}$ sec⁻¹ , i.e. 1 case per 300 days.

In lead ores the flux of μ -mesons, and hence, the number of detected events is 7 times greater, in iron ores - 2,5 times and becomes correspondingly one event per 40 days and one event per 100 days. These estimations give only the lowest limit of the effect.

In these estimations the contribution from neutrinoes with the energy $>$ 300 BeV was not taken into account, as μ -mesons from these neutrinoes averagely have the path, increasing more slowly than E. Here, the contribution of neutrinoes from μ -meson decays was not taken into account.

Further, more careful calculation of the cross-section, than in (2) where only one matrix element was taken into account is required, that will several times increase the effect.

The following reactions may in principle, take place in the field of nucleus:

$$
\begin{aligned}
\tilde{\nu} + Z &\rightarrow n + \tilde{p} + \mu^{+}(e^{+}) + Z' \\
\nu + Z &\rightarrow p + \tilde{n} + \mu^{-}(e^{-}) + Z' \\
\tilde{\nu} + Z &\rightarrow \Sigma^{-} + \tilde{n} + \mu^{+}(e^{+}) + Z' \\
\tilde{\nu} + Z &\rightarrow \Sigma^{0} + \tilde{p} + \mu^{+}(e^{+}) + Z' \\
\tilde{\nu} + Z &\rightarrow \Lambda^{0} + \tilde{p} + \mu^{+}(e^{+}) + Z'
\end{aligned}
\tag{14}
$$

that also increases the number of detected events.

If scattering ν on baryons exists, reactions with production of baryon pairs are also possible, e.g.

$$
\begin{aligned}
\nu(\tilde{\nu}) + Z &\rightarrow \Lambda^{0} + \tilde{\Lambda}^{0} + \nu'(\tilde{\nu}') + Z' \\
\nu(\tilde{\nu}) + Z &\rightarrow p^{+} + \tilde{p}^{+} + \nu'(\tilde{\nu}') + Z'
\end{aligned}
\tag{15}
$$

etc.

The last remarks testify to the fact, that cross-sections, given above, may be equal to one order lower than the real ones, that would correspondingly give 1 case for the ground per 30 days, for iron ores per 10 days and lead ones - per four days.

III. Heavy Meson

There may exist a heavy meson, which with very little life-time decays into:

$$M^{\pm} \to \mu^{\pm} + \nu(\tilde{\nu}) \tag{16}$$

or

$$M^{\pm} \to e^{\pm} + \nu(\tilde{\nu}).$$

Then reactions also exist:

$$\begin{aligned} \nu + Z &\to M^{+} + \mu^{-}(e^{-}) + Z' \to \mu^{+} + \mu^{-}(e^{-}) + \nu' + Z' \\ \tilde{\nu} + Z &\to M^{-} + \mu^{+}(e^{+}) + Z' \to \mu^{-} + \mu^{+}(e^{+}) + \tilde{\nu}' + Z'. \end{aligned} \tag{17}$$

These reactions are of the first order over the weak interaction constant g. For the part of effect, being due to Z^2- dependence, the cross-section is given by expression (18)[x)]

$$\sigma = \frac{1}{6\pi\sqrt{2}} \frac{Z^2}{137^2} G \left(\ln \frac{2E_\nu q_0}{M^2}\right)^3 , \tag{18}$$

$$E_\nu \gg \frac{M^2}{2q_0} \sim 2 \text{ BeV}.$$

For $Z = 10$

$$\sigma = 10^{-36}\left(\ln \frac{E_\nu}{2}\right)^3 \ (\text{cm}^2). \tag{19}$$

The contribution into the cross-section (18) is given by the region of impact parameter from nucleon radius to the radius, corresponding to minimum recoil momentum $\frac{2E_\nu}{M^2}$.

---

x) T.D. Lee, C.N. Yang. Phys.Rev.Lett., 4, 307 (1960).

μ -meson flux from "the pillow" ($E_\nu > 10$ BeV)

$$N = 3\sigma_0 \pi \frac{N_{Avog.} \rho}{A} \frac{2}{3} 10^2 S \int_{10}^{300} f(E) E \left(\ln \frac{E}{2}\right)^3 dE. \qquad (20)$$

For $S = 10^7$, two meson per 1 day.

IV. The Estimations for Neutrino Fluxes from Cosmic Space

With the isotropy of sources and isotropic cosmic rays distribution in Galaxy neutrino flux on the Earth must be fully determined by the flux of produced in atmosphere neutrinoes, since in this case, the probability of meson production in the interstellar space, where density is 10^{-24} gr.cm^{-3}, is extremely small.

But apparently, observations testify in favour of the theory of production of cosmic particles in the shells of supernew and new stars[x)]. According to radio-astronomical data there are many relativistic electrons in expanding shells of these stars.

In Crab-like nebula the electron energy in the expanding shell is estimated as ($3 \cdot 10^{50} - 10^{53}$) BeV, and the spectrum of electrons decreases as $\frac{1}{E} \div \frac{1}{E^{1.5}}$. If these electrons were produced as the result of nuclear collisions, we get 3 neutrinoes approximately of the same energy per each electron. According to estimations from maximum data (and also, supposing, that electrons were stored for 300 years, $R = 5 \cdot 10^{21}$ cm, $E_{max} = 10^3$ BeV) we obtain, that neutrino flux on the Earth has the spectrum $f(E) = 3 \cdot 10^{-5} \frac{1}{E}$ cm^{-2}, where E is expressed in BeV.

Then for reactions (7), taking into account (13), we obtain, that through 1000 m^3 of the ground the flux of 1 μ -meson per two days will be.

In conclusion it is necessary to emphasize, that a ground layer, which is equivalent to $\sim$10 km of water, absorbs completely all the kinds of penetrating radiation, except

---

x) V.L. Ginzburg, Usp. Fiz. Nauk, 1953, 1957.

R e f e r e n c e s

B. Pontecorvo, JETP, 37, 1751 (1959), and IX International Conf. on High Energy Physics, Kiev, 1959.

M. Schwartz, Phys. Rev. Lett., 4, 306 (1960).

T.D. Lee, C.N. Yang, Phys. Rev. Lett., 4, 307 (1960).

N. Cabibbo, R. Gatto, Nuovo Cimento 15, 304 (1960).

M.A. Markow, Hyperonen und K-Mesonen, Verlag der Wissenschaften, Berlin, 1960.

B. Pontecorvo, R. Ryndin. IX International Conf. on High Energy Physics. Discussion after Alikhanov's report. See also R. Marshak's report.

B. Pontecorvo, JETP, 36, 1615 (1959).
G.M. Gandelman, V.S. Pinaev, JETP, 37, 1072 (1959).
Hong-Yee Chin, preprint, Institute for Advanced Study, Princeton, 1960.

ELECTRON AND MUON NEUTRINOS *

B. Pontecorvo

The cross section for β -particle production in the collision of free neutrinos with nuclei was first evaluated in 1934 by Bethe and Pierls [1]. As is well-known the cross section for 1 MeV neutrinos was expected to be 10^{-44} cm^2. Because of this for a long time the effects induced by free neutrinos were considered unobservable. Later on it was shown [2,3] that experimenting with free neutrinos was a real possibility and only recently some experiments were performed in which free antineutrinos from reactors were used. These experiments, in fact, showed that free neutrino effects are observable and, thus demonstrated the 'reality' of neutrinos [4]. They proved also the two-component nature [4] of neutrinos and indicated that the neutrino and the antineutrino are different particles. [5].

The purpose of this paper is to emphasize the possibility of solving new problems of neutrino physics by investigating some effects induced by free neutrinos which have not yet been discussed. Such experiments may appear to be unfeasible at present, but the discussion of their planning seems to be not more premature than was at its time the discussion of experiments with antineutrinos from reactors.

Mainly attention will be drawn to the possibility of answering the question whether the neutrinos emitted in the $\pi\to\mu$ -decay (ν_μ) and the neutrinos emitted in the β -decay (ν_e) are identical particles.

REACTIONS INDUCED BY NEUTRINOS

All the known slow processes are, apparently, due to the interaction between the following fermion pairs:

$$\begin{matrix} (e^+\nu_e), & (\mu^+\nu_\mu), & (p\tilde{n}), & (p\tilde{\Lambda}) \\ (e^-\tilde{\nu}_e), & (\mu^-\tilde{\nu}_\mu), & (\tilde{p}n), & (\tilde{p}\Lambda) \end{matrix} \qquad (1)$$

Any pair of particles may interact with the same pair or with another one; according to the Markov-Sakata-Okun[6] scheme, strange particles other than Λ -hyperons are not included in the composition of the 'strange' pair. In terms of the universal interaction theory [7,8] this scheme implies that the current J^+ entering into the weak interaction Lagrangian consists of four terms

$$J^+ = J^{e^+\nu_e} + J^{\mu^+\nu_\mu} + J^{\tilde{n}p} + J^{\tilde{\Lambda}p} \qquad (2)$$

each of which corresponds to the above-mentioned pairs.

Some processes induced by free neutrinos, if the Markov-Sakata-Okun scheme and the universal interaction theory are assumed to be valid, are listed below (Table 1).

* JETP 37, 1751 /1959/

The question whether ν_e and ν_μ are identical particles is open and will be discussed in the next Section. There are no reasons for asserting that ν_e and ν_μ are identical particles. Therefore, in the Table and in the different terms of the lepton current it was written $e^+\nu_e$, $\mu^+\nu_\mu$ and not $e^+\nu$, $\mu^+\nu$ as is usually accepted.

Table I.

SOME REACTIONS INDUCED BY FREE NEUTRINOS ON REAL TARGETS

NN	Reaction	Note
1.	$\tilde{\nu}_e + p \to e^+ + n$	In investigating this process [4] free neutral leptons were first observed. The experiment supported the two-component nature of the neutrino.
2.	$\tilde{\nu}_e + Cl^{37} \to A^{37} + e^-$ 2,3,5	The non-observability of this process [5] proved that ν_e and $\tilde{\nu}_e$ are not identical particles.
3.	$\nu_e + Cl^{37} \to A^{37} + e^-$	The investigation of this process might be of interest in astrophysics, particularly, for measuring the neutrino flux from the sun.(9)
4.	$\nu_e + A \to \pi^+ + e^- + A$ $\tilde{\nu}_e + A \to \pi^- + e^+ + A$	Inverse π-e -decay in the field of a nucleus. Note that ν_e produce π^+ -mesons, $\tilde{\nu}_e$ -produce π^- -mesons.
5.	$\tilde{\nu}_e + e^- \to \pi^- + \pi^0$	
6.	$\tilde{\nu}_e + p \to \Lambda + e^+$ $\tilde{\nu}_e + A \to$ hyperfragments $+ e^+$	Only $\tilde{\nu}$ (but not ν) may produce strange particles.
7.	$\tilde{\nu}_e + n \to \Sigma^- + e^+$	This process may occur only in nuclei.

8. $\nu_e + A \to K^+ + e^- + A$ $\tilde{\nu}_e + A \to K^- + e^+ + A$	See 4.
9. $\tilde{\nu}_e + e^- \to K^- + K^0$	See 5.
10. $\tilde{\nu}_e + e^- \to \tilde{\nu}_e + e^-$ $\nu_e + e^- \to \nu_e + e^-$	Scattering of neutrinos by electrons, predicted by the universal theory of weak interactions (8).
$\nu_e + A \to \nu_e + e^+ + e^- + A$ $\tilde{\nu}_e + A \to \tilde{\nu}_e + e^+ + e^- + A$	Creation of a e^+e^- -pair in the field of a nucleus. [10] This is the inverse process of the lepton bremsstrahlung by electrons described in [11].
12. $\tilde{\nu}_e + e^- \to \tilde{\nu}_\mu + \mu^-$ $\nu_e + e^- \to \nu_\mu + \mu^-$	Inverse μ -decay. Forbidden, if $\nu_e \neq \nu_\mu$
13. $\tilde{\nu}_e + A \to \tilde{\nu}_\mu + e^+ + \mu^- + A$ $\nu_e + A \to \nu_\mu + e^- + \mu^+ + A$	Formation of a μ-e -pair in the field of a nucleus.
14. $\tilde{\nu}_\mu + p \to \mu^+ + n$ $\tilde{\nu}_\mu + p \to e^+ + n$	Inverse μ -capture. Forbidden, if $\nu_e \neq \nu_\mu$
15. $\nu_\mu + A \to \pi^+ + \mu^- + A$ $\tilde{\nu}_\mu + A \to \pi^- + \mu^+ + A$	Inverse π-μ -decay in the field of a nucleus.
16. $\tilde{\nu}_\mu + p \to \Lambda + \mu^+$ $\tilde{\nu}_\mu + p \to \Lambda + e^+$ $\tilde{\nu}_\mu + A \to \mu^+ +$ hyperfragment	Forbidden, if $\nu_e \neq \nu_\mu$

17.	$\nu_\mu + A \rightarrow \mu^- + K^+ + A$ $\tilde{\nu}_\mu + A \rightarrow \mu^+ + K^- + A$	
18.	$\nu_\mu + A \rightarrow \nu_\mu + \mu^+ + \mu^- + A$ $\tilde{\nu}_\mu + A \rightarrow \tilde{\nu}_\mu + \mu^+ + \mu^- + A$	Scattering of neutrinos by μ -mesons in the field of a nucleus.
19.	$\nu_\mu + e^- \rightarrow \nu_e + \mu^-$ $\tilde{\nu}_\mu + e^- \rightarrow \tilde{\nu}_e + \mu^-$	Inverse μ -decay. Forbidden, if $\nu_e \neq \nu_\mu$
20.	$\nu_\mu + A \rightarrow A + \mu^- + e^+ + \nu_e$ $\tilde{\nu}_\mu + A \rightarrow A + \mu^+ + e^- + \tilde{\nu}_e$	Formation of a $\mu - e$ pair in the field of a nucleus.
21.	$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$	If $\nu_e \neq \nu_\mu$, the reaction is possible only as a second order process.

Among the processes enumerated above, only the reactions 1, 2, 3, 10 had been previously discussed in the literature. For the most of the processes listed above we limit ourselves to the remarks made in the Table. Only some processes, which are related to the problem of the distinction between ν_μ and ν_e particles, are discussed in detail below.

ARE ν_e AND ν_μ IDENTICAL PARTICLES?

The upper limit of the mass of neutral leptons emitted in the μ decay, the magnitude of Michel's parameter ρ and theoretical considerations show that neutral leptons in the μ -decay have a mass equal or close to 0 and are not identical. Because of this, the μ- decay is usually described as follows: $\mu \rightarrow e + \nu + \tilde{\nu}$

It is easy to see, however, that experimental and theoretical data require only that the two neutral leptons in the μ -decay should be not identical, but do not require that they should be necessarily a particle and an antiparticle. The possibility has already been discussed [12] that there exist two pairs of neutrinos. At first sight the question of the existence of two types of neutrinos – an electron neutrino (ν_e) and a muon neutrino (ν_μ) may be considered as an irrelevant and unnecessary complication. There are reasons, however, which make attractive the hypothesis that the electron and muon neutrinos are distinct particles. The absence in nature of some processes of the type $\mu \to 3e$, $\mu^- + p \to e^- + p$ etc. indicates that only pairs involving one charged and one neutral particle (see 1 and 2) may contribute to the currents entering into the weak interaction Lagrangian. The existence of only 'charged' currents might be naturally explained [8] if in nature there would exist a charged vector boson β coupled with different fermions by an 'intermediate intensity' interaction. The well-known weak interaction processes in this case would be due to an interaction of the second order with respect to the 'intermediate interaction' constant. As is shown in Ref. [13], the nonlocality of the $\mu - e$ decay related to the existance of the intermidiate vector boson would require a transition rate for the decay $\mu \to e + \gamma$ which contradicts the experimental data [14] .

It can be easily seen, however, that even if there exists a β -meson the probability of the process $\mu \to e + \gamma$ would be zero*, (that is entirely consistent with the experimental data), if the electron and muon neutrinos were different particles. Thus, the fact that the current in the Lagrangian of weak interaction is 'charged' would be very well explainable in terms of the intermidiate boson assumption only if ν_e is different from ν_μ .

Besides this reason, as it seems, the existence of two different types of neutrinos, which are not able to annihilate**, is attractive from the point of view of the symmetry and the classification of particles and might help to understand the difference in the nature of muons and electrons.

It follows from what has been said that experimental data on the question whether or not ν_e and ν_μ are identical particles would be of great interest. One possibility to get information on this point would consist in measuring the spirality of the μ -meson. If in nature there is only one neutrino - antineutrino pair the $V-A$ -interaction requires a positive spirality of a μ^- -meson. If in the experiment the μ^- -spirality turned out to be negative, there would be a strong evidence in favour of the existence of two types of neutrinos : the μ^+ decay, in this case, might be described by the scheme $\mu^+ \to e^+ + \nu_e + \nu_\mu$.

---

* *Even if there is no β meson the process $\mu \to e + \gamma$ is possible in higher order approximations of the perturbation theory, if there is only one type of neutrino -antineutrino pairs, while it is absolutely forbidden if $\nu_e \neq \nu_\mu$.*

** *Note that if ν_μ and ν_e are different particles the muonium system $(\mu^+ e^-)$ cannot go over into the antimuonium system ($\mu^- e^+$) in any approximation.*

The experiment [16] shows, however, that the spirality of a μ^- -meson is likely to be positive, as expected. Therefore, the problem whether there are two types of neutral lepton pairs in nature is open. The positive spirality of a μ^- -meson indicates, however, that if in nature there are really two neutrino-antineutrino pairs the weak interaction must be described just as in (1), and the decay of a μ^+ -meson must follow the scheme $\mu^+ \to e^+ + \nu_e + \tilde{\nu}_\mu$ Here, as usual, ν_e is defined as the particle emitted together with a positron in β -decay. Its spirality, determined experimentally, is negative[17] (the $\tilde{\nu}_e$ spirality is, of course, positive). As for ν_μ and $\tilde{\nu}_\mu$, these particles are difined as having negative and positive spirality. Thus, the decay of a π^+ -meson follows the scheme $\pi^+ \to \mu^+ + \nu_\mu$. These notations were used in the Table of the previous paragraph.

To clear up the question whether ν_e and ν_μ are different particles there remains one possibility which is discussed in the next paragraph.

DISCUSSION OF AN EXPERIMENTAL ARRANGEMENT WHICH, IN PRINCIPLE, IS APT TO ANSWER THE QUESTION AS TO WHETHER ν_e AND ν_μ ARE IDENTICAL

The method which is suggested below is essentially analogous to that used in deciding whether a neutrino and an antineutrino (in our definition ν_e and $\tilde{\nu}_e$) are identical particles [2,5] or whether K^0 and $\tilde{K}^0$ -mesons are identical particles [18]. In these cases the non-identity of particles and antiparticles has been proved experimentally by the non-observability of some transitions, the matrix elements of which differ from 0 only if particles and antiparticles are identical. For example, the absence of the process $\tilde{\nu}_e + Cl^{37} \to A^{37} + e^-$ proves that ν_e and $\tilde{\nu}_e$ are not identical since the process $\nu_e + Cl^{37} \to A^{37} + e^-$ must, undoubtedly , occurs.

In our case we are not concerned with the problem already solved of the non-identity of neutrinos and antineutrinos, but with that of the possible non-identity of ν_e and ν_μ (or of $\tilde{\nu}_e$ and $\tilde{\nu}_\mu$).

To solve this problem it is suggested to test experimentally whether a beam of $\tilde{\nu}_\mu$ is able to induce transitions which may be, undoubtedly, induced by $\tilde{\nu}_e$ -particles. From an experimental point of view a beam of muon neutrinos is more attractive than an electron -neutrino beam for the following reasons. Usual intensive sources of electron neutrinos are radioactive isotopes. The latter ones by their nature are not capable of emitting neutrinos of high energies. On the contrary, muon neutrinos are obtained, naturally, with high energy.

On the one hand, it is of interest to use antineutrino of very high energy, say $\gtrsim$100 MeV, since the cross section for the processes induced by these particles rapidly increases with energy. On the other hand, at very high energies the intensity of muon neutrino generation decreases due to a relativistic lengthening of the pion lifetimes. Therefore, we discuss here the arrangement of an experiment with $\tilde{\nu}_\mu$ of energy of $<$ 100 MeV.

Consider for example the reactions (see the Table I)

$$\tilde{\nu}_\mu + p \rightarrow \mu^+ + n \qquad (a)$$

$$\tilde{\nu}_\mu + p \rightarrow e^+ + n \qquad (b)$$

Reaction (b), if ν_e and ν_μ are identical particles, was successfully observed by Reines and Cowan [4]; if $\nu_e \neq \nu_\mu$, (b) is not observable. The reaction (a) is a threshold reaction and is unobservable at energies $<$ 100 MeV. The problem consists in determining the cross section for the reaction (b). In the energy range where the neutron from the reaction (b) may be detected with a good efficiency inside a large scintillation counter containing cadmium, Reines's and Cowan's method is quite suitable. When an event induced by the reaction (b) takes place, two impulses will appear in the scintillation counter one. One of these corresponds to the positron energy release (the neutron gets a small share of energy) and the second, which is delayed with respect to the first impulse corresponds to the photon energy released in the neutron capture by cadmium. To detect the reaction (b) a scintillation counter of the Reines and Cowan type may be bombarded by a beam of muon antineutrinos which because of their energy are not capable of inducing the reaction (a). Such $\tilde{\nu}_\mu$ beam must have a negligible small contamination of electron antineutrinos, which might induce the 'trivial' reaction $\tilde{\nu}_e + p \rightarrow e^+ + n$.

In order to clear up the experimental conditions, we consider the production of neutral leptons of different types in an accelerator of protons, say, a 700 MeV accelerator.

The radioelements which are produced in the target and in other parts of the accelerator are sources of ν_e, and to a less extent, $\tilde{\nu}_e$ with a low energy ($\lesssim$ 10 MeV). These electron neutrinos do not give a dangerous background, since:

a) their energy is small, and, essentially, they can be easily discriminated by analyzing the corresponding pulses from the scintillator;

b) the cross section for the reaction $\tilde{\nu}_e + p \rightarrow n + e^+$ is proportional to the square of the incident antineutrino energy, and, thus, it is relatively small at low energies. Pions of both signs will be produced in the accelerator target. They will generate neutral leptons as follows:

1\. 1) $\pi^+ \rightarrow \mu^+ + \nu_\mu$ 2) $\mu^+ \rightarrow e^+ + \nu_e + \tilde{\nu}_\mu$

3) $\pi^- \rightarrow \mu^- + \tilde{\nu}_\mu$ 4) $\mu^- \rightarrow e^- + \tilde{\nu}_e + \nu_\mu$

5) μ^- + nucleus $\rightarrow \nu_\mu$

Contaminations of ν_e and ν_μ in the beams are not harmful, since it is already known that neutrinos (both ν_μ and ν_e) cannot induce the reaction under consideration. It is easy to see that the 'harmful' contamination of $\tilde{\nu}_e$ appears only from the decay (4) of μ^- -mesons. However, μ^- -mesons stopping in matter of high atomic number (it is not difficult to make it impossible for mesons to stop in light materials) do not practically undergo a μ^- -decay. As far as

a μ^- -decay in flight is concerned, it may be neglected, since the decay mean free path of μ mesons is measured in hundreds of meters whereas it is reasonable to place the detector of the reaction (b) at a distance of ~10 meters from the target.
Thus, it is possible to obtain a beam of $\tilde{\nu}_\mu$ -particles, which practically has no contamination of $\tilde{\nu}_e$. The $\tilde{\nu}_\mu$ from reaction (2), (originating from stopped μ^+ -mesons), have a mean energy of $\sim$ 35 MeV, whereas $\tilde{\nu}_\mu$ from reaction (3) may have considerably greater energy (decay in flight), but their intensity will be in general small.
The number of $\tilde{\nu}_\mu$ produced in reaction (2) may be close to that of the π^+ produced in the target. Therefore, the number of $\tilde{\nu}_\mu$ generated in modern phasotrons may attain the value 10^{12}/sec. Models of new accelerators are being discussed now in which the intensity of the accelerated protons may be increased as much as by three orders of magnitude. Thus, one may hope that in the near future a flux ϕ of 10^8 $\tilde{\nu}_\mu$/cm^2 sec. at a distance of 10 m from the target may become real. The cross section for the process (b) was estimated by the perturbation theory and turned out to be 2.10^{-41} cm^2, if $\nu_e = \nu_\mu$ for $\tilde{\nu}_\mu$ of energy of 35 MeV If we make use of a scintillation counter of the Reines and Cowan's type (1-2 tons), the number of events is equal to ~1 per hour ($\phi \sim 10^8$ / cm^2 sec), if the detection efficiency is unity and if $\nu_e = \nu_\mu$.

As Reines and Cowan[4] showed recently, the efficiency may exceed 0.5. The recording of events under consideration is less difficult technically than in Reines and Cowan's experiment, as the energy of the emitted $\tilde{\nu}_\mu$ -particles is large. Thus, the reality of the experiment depends upon the magnitude of the background, which is very difficult to evaluate a priori. . One may only note that unfortunately, the ratio signal to background must be considerably less than in Reines and Cowan's experiment. It is of interest to note that $\tilde{\nu}_\mu$ from reaction (2), in contrast to the neutrons emitted in the target, are emitted isotropically. This makes it possible to decrease the difficulties which are due to the accelerator background; the detector of $\tilde{\nu}_\mu$ must be placed at an angle $\gtrsim$ 90° with respect to the direction of the protons incident on the target.

Summarizing one may say that experiments planned to test the identity of ν_e and ν_μ, though very difficult, must be seriously thought over when new intense accelerators are being designed. In particular, the problem of radiation shielding in such experiments must be considered at a very early stage of the accelerator's design.

In conclusion the author considers it his pleasant duty to thank Chou Huang Chao, L.B. Okun, and J.A. Smorodinsky for numerous discussions.

REFERENCES

H.A. Bethe and R. Pierls Nature 133, 532, 1934.

B. Pontecorvo Report PD–205, 1946.

L.W. Alvarez Report URCL–328, 1949.

F. Reines and C.L. Cowan Phys.Rev. 98, 492, 1953; F. Reines and C.L. Cowan Phys.Rev. 113, 273, 1959.

R. Davis Phys.Rev. 86, 976, 1952, Bull.Am.Phys.Soc. Washington meeting, 1959.

S. Sakata Progr. Theor. Phys. 16, 686, 1946. M.A. Markov, VI Rochester Conf.High Energy Physics, 1956. L.B. Okun JETP, 34, 469, 1958.

E.C.G. Sudarshan, R.E. Marshak Proceedings of the Padua-Venice conference on mesons and newly discovered particles, 1957.

R.P. Feynman, M. Gell-Mann Phys.Rev. 109, 193, 1958.

See e.g. A.G.W. Cameron Annual review of nuclear science, 1958, p. 306.

Recently this process was investigated theoretically by J.A. Smorodinsky.

B. Pontecorvo JETP 36, 1615, 1959.

See, e.g., S. Onsda and J.C. Pati Phys.Rev. Letters, 2, 125, 1959.

G. Feinberg Phys.Rev. 110, 1482, 1958. R.P. Feynmann, M. Gell-Mann, Proceedings of the 8th conference on high energy physics, Geneva, 1958.

See, e.g., Berley, J. Lee, M. Bardon Phys.Rev. Letters, 2, 357, 1959.

B. Pontecorvo, JETP, 549, 1957.

W.A. Love, S. Marder, I. Nadelhaft, R.T. Siegel, A.E. Taylor Phys.Rev. Letters, 2, 107, 1959.

M. Goldhaber, L. Grodzins, A.W. Sungar Phys.Rev. 109, 1015, 1958.

M.P. Balandin, B.D. Balashov, V.A. Zhukov, B.Pontecorvo, G.I. Selivanov JETP, 29, 265, 1955.

This paper was received by Publishing Department on June 29, 1959.

ON THE INTERMEDIATE BOSON IN WEAK INTERACTIONS

B. Pontecorvo, R.M. Ryndin

The question as to whether weak interactions processes are mediated through a vector B-boson has already been raised[1]. The small probability of the process $\mu \to e + \gamma$ can hardly be conciliated with the intermediate boson assumption if in nature there exists only one type of neutrino-antineutrino pairs[2]. However, if "electron" (ν_e) and "muon" (ν_μ) neutrinoes are different particles, there are no arguments against this assumption. Even more, it can be said that the existence of the B-boson would practically prove that muon and electron neutrinoes are different particles.

According to Lee and Yang[3], the non-locality of the μ -decay connected with the B-boson affects the Michel parameter and the μ -decay rate. However, the accuracy of the measurements is entirely insufficient to determine possible limits on the B-meson mass. Below are discussed some consequences of the B-particle assumption.

If there exists a B-meson, all the known weak interaction processes will be of the second order in the constant g_B coupling the B-meson field with various fermion pairs. The Fermi constant G $\left(G \simeq \frac{10^{-5}}{M^2}, \hbar = c = 1, M-\right.$ nucleon mass) is then a phenomenological constant: $G \sim g_B^2/m_B^2$ (m_B is the B-meson mass). Assuming, e.g. $m_B \sim M$, we get $g_B^2 \sim 10^{-5}$, which is only thousand times less than e^2 . It is hardly possible to get some information on the existence of the B-meson by studying ordinary weak interaction processes in which virtual B-mesons are involved. Consequently we turn our attention to the processes involving the production of <u>real</u> B-mesons.

It is clear that B-mesons will decay, in particular, as follows:

$$B \to \mu + \nu \;, \quad B \to e + \nu \;, \quad B \to \pi + \pi \;.$$

---

x) This paper was reported at the IX Conference on High Energy Physics, Kiev, 1959. (See discussion after the report of Alikhanov and also the report of Marshak).

The decay rate of the B-meson is of the order of $10^{18}\,sec^{-1}$. As the mean life is relatively short, the collisions in which real B-mesons are generated will simulate stars with apparent production of muons and electrons, although these leptons are emitted with a characteristic time uncomparably greater than the collision time. Therefore, the B-particle existence implies that processes apparently accompanied by lepton emission become relatively probable when the collision energy in the c.m.s. is greater than the B-meson mass: in high-energy stars there will be emitted muons and electrons with a probability only five or six orders of magnitude smaller than the emission probability of pions, a fact which might help to prove experimentally the B-particle existence. Putting aside the processes of B-meson production by strong interacting particles and B-meson photoproduction processes (the cross-section of which contains a factor $g_B^2 e^2$), we will consider some processes of first or zero orders in g_B, especially attractive from the experimental point of view.

1. "Electromagnetic" production of B-meson pairs:

$$\gamma + A \rightarrow B^+ + B^- + A$$
$$\pi + A \rightarrow B^+ + B^- + A$$

The cross-sections contain the factors $Z^2 e^6$ and $Z^2 e^4 g_\pi^2$ respectively.

2. The production of a B-meson by neutrinoes in the field of a nucleus:

$$\nu + A \rightarrow \begin{cases} B + e + A \\ B + \mu + A \end{cases}.$$

Clearly the processes 2 are the only first order processes in g_B, which may be induced by neutrinoes. The probability of such processes is relatively suppressed because of the large value of m_B. Dimension arguments suggest that the cross-section for neutrino induced processes 2 is $\sim Z^2 g_B^2 e^4 m_B^{-2}$. At neutrino energies of a few BeV the cross-section for B-meson production in collisions with lead nuclei attains a value $\sim 10^{-34}$ cm^2, which is quite a reasonable value from the point of view of people wishing to plan experiments on the subject. Events of B-meson production will simulate, for example, the generation of electron, muon and μe pairs. In the experiment an attempt must be undertaken to observe (let us say with a xenon bubble chamber or by means of electronic methods) individual events induced by very hard neutral radiation from an accelerator, under such conditions of shielding, that effects produced by other neutral radiation either are negligible or can be evaluated.

Eventually it may be noted that quite a part from the possibility of parity non-conservation in strong interactions, the real production of B-mesons with their subsequent disintegration into pions will simulate parity non-conservation in strong interactions at high energies (in $\sim 10^{-5}$ of the total number of events).

The authors are grateful to J.B. Zeldovich and Chou Kuang-chao for useful discussions.

References

1). R.P. Feynman, M.G. Gell-Mann, Phys. Rev., 109, 193, (1958).

2). G. Feinberg, Phys. Rev., 110, 1482, (1958).

3). T.D. Lee and C.N. Yang, Phys. Rev., 108, 1611, (1957).

EXPERIMENTS WITH NEUTRINOS EMITTED BY MESONS

B. Pontecorvo

Recently there were widely discussed the possibilities of using beams of high energy neutrinos emitted by mesons to get information on weak interactions.[1,2,3,4,5]

In the papers[3,4] it has been shown that the form-factors related to the presence of strong interacting particles suppress the increase with energy of the cross-sections for reactions of the type $\tilde{\nu} + p \rightarrow e^+ + n$ at neutrino energies $\sim$ 1 BeV.

In the discussion of experiments with high energy neutrino ($\gtrsim$ 1 BeV) the problem as to whether there exists the intermediate vector B-meson has a special place, since the corresponding experiments may turn out to be feasible within a relatively short time. R.M. Ryndin and the author[6], and Lee and Yang[3], as a matter of fact, have shown that a B-boson with a mass of a few nucleon masses can be discovered in reactions of the type $\nu + Z \rightarrow B + \mu(e) + Z$, the cross-section of which is much greater than the cross-section characterizing the reactions induced by neutrinos in the case of local interaction. In[1], it was pointed out that $\tilde{\nu}_\mu$ of relatively low energy emitted by stopping μ^+- mesons may be used in order to decide whether muon (ν_μ) and electron (ν_e) neutrinos are identical particles.

Below additional arguments are given on neutrino of intermediate energy ($<$ 300MeV) which may be useful in planning experiments with neutrino beams and in designing accelerators meant for performing such experiments.

Apart from the B-meson problem and the problem of the energy dependence of the cross-sections for weak processes, the solution of which clearly demands neutrinos with very high energy, the main qualitative questions in neutrino physics are the following ones:

1. Are ν_e and ν_μ identical particles?

2. Does neutrino scattering by leptons occur as a first order process in the weak interaction constant?

From an experimental point of view, the neutrinos with intermediate energy have definite advantages in connection with the above-mentioned problems: not only their intensity (for a number of reasons) can exceed very much the intensity of very high energy neutrinos, but they can easily be obtained with very well defined energy, a circumstance allowing a kinematic interpretation of neutrino induced events.

Monochromatic sources of neutrinos may be obtained by stopping π^+, K^+ and μ^- in matter, as follows:[x)]

Neutrino source	Neutrino energy (MeV)
$\pi^+ \to \mu^+ + \nu_\mu$	29,8
$K^+ \to \mu^+ + \nu_\mu$	235,7
$\mu^- + A \to \nu_\mu + \ldots$	$\sim$ 100

It is to be noted that monochromatic ν_μ, rather than $\tilde{\nu}_\mu$ are obtained when a $\lesssim$ 1 BeV proton beam is being stopped in a block of heavy material. The moderation in the same block of the produced mesons permits, according to the Table, to obtain a spatially well localized monochromatic neutrino source. These lines of monochromatic neutrinos are, of course, accompanied by a background of a continuous spectrum, especially ν_e and $\tilde{\nu}_\mu$ from μ^+-meson decay[1)].

For example, to test whether ν_e and ν_μ are identical particles, it is possible to measure the cross-sections for the reaction $\nu_\mu + C^{12} \to e^- + N^{12}$. The energy of the electrons emitted by incident monoenergetic neutrino is known, the time at which the electrons are emitted must coincide with the time at which the neutrino is absorbed (today's electronics allows to make use of the time characteristics of the accelerator, including the cyclotron with a spatial variation of the magnetic field). Besides, it is necessary to record delayed positrons from N^{12} decay. Such an experiment can be performed with large magnetic bubble chambers or with electronic methods of registration. The counting rate is comparable with the rate expected in the experiment suggested in[(1)].

---

x) The possibility of using a K-capture radioelement as a strong source of low energy ($E_\nu \sim 1$ MeV), monochromatic neutrinos, is beyond the scope of the present note. Such a possibility is attractive from the point of view of performing experiments on $(\nu_e e)$ scattering under conditions in which the kinematics of the events can be analysed. Here we wish to mention also the possibility that the answer to the question as to whether there is the $(\nu_e e)$ scattering process might be given by astrophysics.[7)]

References

1. B. Pontecorvo, JETP, 37, 1751 (1959), and IX International Conf. on High Energy Physics, Kiev, 1959.
2. M. Schwartz, Phys. Rev. Lett., 4, 306 (1960).
3. T.D. Lee, C.N. Yang, Phys. Rev. Lett., 4, 307 (1960).
4. N. Cabibbo, R. Gatto, Nuovo Cimento 15, 304 (1960).
5. M.A. Markow, Hyperonen und K-Mesonen, Verlag der Wissenschaften, Berlin, 1960.
6. B. Pontecorvo, R. Ryndin. IX International Conf. on High Energy Physics. Discussion after Alikhanov's report. See also R. Marshak's report.
7. B. Pontecorvo, JETP, 36, 1615 (1959).
   G.M. Gandelman, V.S. Pinaev, JETP, 37, 1072 (1959).
   Hong-Yee Chin, preprint, Institute for Advanced Study, Princeton, 1960.

MESONIUM AND ANTIMESONIUM[x)]

B. Pontecorvo

Gell-Mann and Pais[1] first pointed out the interesting consequence of the fact that K^o and $\tilde{K}^o$ particles are not identical[2]. The possibility of $K^o \to \tilde{K}^o$ transitions induced by weak interactions makes it necessary to consider neutral K mesons as a mixture of particles of different (combined)[3] parity (K_1^o and K_2^o).

We discuss here the problem as to whether there exist other "mixed" neutral particles (not necessarily "elementary" ones) which are not identical to the corresponding antiparticles and for which particle $\rightleftarrows$ antiparticle transitions are not strictly forbidden.

The number of possible mixed neutral systems are strongly limited by conservation laws for the number of baryons and light fermions (conservation of nuclear[4] and neutrino[5] charges). According to the first law mixed particles cannot exist among baryons (for instance, neutron, hydrogen atom) and due to the second law such particles cannot exist among systems of light particles with only one fermion (e.g., neutrino, π^+e^- and π^-e^+ systems...).

From this it apparently follows that mesonium defined as the bound system (μ^+e^-) is the only mixed particle of interest existing (in addition to the K^o meson) among already well-known systems. Antimesonium, that is the system (μ^-e^+), obviously differs from mesonium; in addition mesonium $\to$ antimesonium transitions not only are not forbidden by any known law but, what is more, they must take place due to known interactions.

Indeed, transitions

$$(\mu^+e^-) \to (\nu+\tilde{\nu}) \to (\mu^-e^+) \qquad (1)$$

x) JETP, 33, 549 (1957).

are induced by the same interaction which is responsible for the μ-meson decay. Incidentally the probability $1/\theta$ of real decay processes

$$(\mu^+ e^-) \rightarrow \nu + \tilde{\nu} + 106{,}1\,\text{MeV} \tag{2}$$

which can be easily estimated taking into account the dimensions of mesonium, turns out to be equal to 10^{-4} $\sec^{-1}$, that is about 10^{10} times less than the decay probability $1/\tau$ of the μ meson. For this reason it is practically impossible to observe the (non trivial) absence of an electron track at the point where a μ^+-meson comes to rest, which would be connected with the process (2).

As for the mesonium → antimesonium transition, its characteristic time $\frac{\hbar}{c^2 \Delta m}$ is determined by the mass difference Δm between the symmetrical (ψ mesonium + ψ antimesonium) and the antisymmetrical (ψ mesonium − ψ antimesonium) systems. The value Δm is proportional to the first power of the matrix element responsible for the mesonium → antimesonium transformation and that is why Δm is proportional to the square of the coupling constant when such transformation is due to two successive transitions as in (1).

Thus, the time characterizing the transformation (1) is of the same order of magnitude as θ, that is about 10^{10} times larger than the life-time of μ-meson ($\tau = 2\times10^{-6}$ sec), which in fact determines also the rate of the mesonium decay. If we assume, however, that the mesonium → antimesonium transformation is due to the direct interaction ($\mu^+ e^-$) ($\mu^- e^+$), the time T characterizing this transformation turns out to be considerably smaller than θ. Indeed, in this case the mass difference $\Delta m'$ between the symmetrical and antisymmetrical systems ($\Delta m' = \frac{2M}{c^2}$, where M is the matrix element) is proportional to the first power[7] of the coupling constant g.

Consequently, we have

$$T \sim \frac{\hbar}{c^2 \Delta m'} \sim \frac{\hbar}{2g/\pi r^3}$$

where r is the mesonium radius. If we suppose that the direct interaction ($\mu^+ e^-$) ($\mu^- e^+$) has an intensity comparable with the intensity of all the other known weak interactions, g is about 3.10^{-49} erg.cm^3, and T is found to be $\sim 5.10^{-4}$ sec, that is only ~ 300 times larger than τ. Under such circumstances it seems at first glance that the process of mesonium → antimesonium transformation can be easily observed, for instance, by detecting a "fast" negative electron from a μ^+-meson coming to rest

$$(\mu^+e^-) \to (\mu^-e^+) \to e^-_{fast} + \nu + \tilde{\nu} + e^+.$$

Unfortunately, however, the mesonium $\to$ antimesonium transformation in presence of matter is impossible: on account of the electrical asymmetry of nucleons the masses of mesonium and antimesonium are no more equal under such conditions. Besides, it is necessary to note that the probability of fast negative electron emission from mesonium (in vacuum) is proportional to $\left(\frac{\tau}{T}\right)^2$ and not to $\frac{\tau}{T}$. Indeed, if $\mathcal{E}_{\mu^+}(t)$ and $\mathcal{E}_{\mu^-}(t)$ are the probabilities that (in vacuum) mesonium or antimesonium are found at the time t when at $t = 0$ there is one "atom" of mesonium, then

$$\mathcal{E}_{\mu^+}(t) \sim \frac{1}{2} e^{-t/\tau}\left(1+\cos\frac{t}{T}\right)$$
$$\mathcal{E}_{\mu^-}(t) \sim \frac{1}{2} e^{-t/\tau}\left(1-\cos\frac{t}{T}\right)$$

where the life-times of the symmetrical and antisymmetrical systems are assumed to be identical and equal to the μ-meson life-time. Under such initial conditions the probability of emission of a fast positive or negative electron in the decay process is found to be

$$P(e^+) \sim \int_0^\infty \frac{\mathcal{E}_{\mu^+}(t)}{\tau}\,dt \sim \frac{1}{2}\left(1+\frac{T^2}{T^2+\tau^2}\right) \sim 1$$
$$P(e^-) \sim \int_0^\infty \frac{\mathcal{E}_{\mu^-}(t)}{\tau}\,dt \sim \frac{1}{2}\left(1-\frac{T^2}{T^2+\tau^2}\right) \sim \frac{1}{2}\left(\frac{\tau}{T}\right)^2$$

respectively.

If in nature there existed other weakly interacting charged particles with a very long life-time it is possible that effects analogous to those discussed here might be observed. The life-time of the particles with mass about 500 m_e recently discovered by Alikhanyan and others (JETP, 31, 955, (1956)), has not yet been determined; only its lower limit (5×10^{-9} sec) is known.

Above it was supposed that neutrino charge is conserved. This means that scattering cannot convert a neutrino into an antineutrino in any approximation. The law of conservation of neutrino charge is not yet definitely established: it is only established experimentally that neutrino and antineutrino are not identical particles[8].

If the theory of two component neutrino[9] was not valid (which is hardly probable at present) and if the conservation law for neutrino charge took no place, neutrino → antineutrino transitions in vacuum would be in principle possible. Even in this case, just as in the case where it is supposed that to every would correspond an antiworld, the number of neutrino and antineutrino in the universe would be the same.

The author is grateful to Ya.B. Zeldovich, L.B. Okun and I.G. Ivanter for critical remarks and interesting discussion.

References

1. M. Gell-Mann, A. Pais, Phys. Rev., 97, 1387 (1955).
   A. Pais, O. Piccioni, Phys. Rev., 100, 1487 (1955).
2. See, for instance, M. Balandin, B. Balashov, V. Zhukov, B. Pontecorvo, G. Selivanov, JETP, 29, 265 (1955).
3. L. Landau, JETP, 32, 405 (1957).
4. Ya. Zeldovich, DAN, USSR, 86, 505 (1952).
5. Ya. Zeldovich, DAN USSR, 91, 1317 (1953).
   E. Konopinski, H. Mahmond, Phys. Rev., 92, 1045 (1953).
6. See, for instance, Ya. Zeldovich, JETP, 30, 1168 (1956).
7. Detailed consideration of a case of a first order $K^0 \to \tilde{K}^0$ transition is given in the paper of L. Okun and B. Pontecorvo, JETP (in press).
8. R. Davis, Bull. Am. Phys. Soc. Washington meeting, 1956,
   M. Awschalom, Phys. Rev., 101, 1041 (1956).
9. L. Landau, JETP, 32, 407 (1957).
   T. Lee, C. Yang, Phys. Rev. (in press).

UNIVERSAL FERMI INTERACTION AND ASTROPHYSICS[x)]

B. Pontecorvo

The hypothesis of a deep analogy between various slow decay processes (both leptons[1]) and non-leptons[2])) found recently a briliant formulation in the universal interaction (vector and axial-veotor) theory of Sudarshan-Marshak[3]) and Feynman-Gell-Mann[4]). According to this theory scattering of neutrino by electrons is described as a process of first order in the weak interaction constant[4,5]). Experimental evidence on this process would be extremely desirable. However, direct detection of the scattering by electrons of reactor antineutrino (that is, detection of the ionization produced by antineutrino, not connected with inverse β processes) seems at present quite hard, although in principle the possibility of such experiment should not be excluded.

In the present note we wish to point out that the existence of a first order νe interaction could have macroscopic consequences. Such interaction implies that positron-electron annihilation can result in the emission of a neutrino-antineutrino pair*. Consequently in electromagnetic processes it is possible that a $\nu\tilde{\nu}$ pair, through the virtual production of a e^+e^- pair, is emitted instead of a photon. This general fundamental connection between electromagnetic and lepton processes is a direct consequence of the universal Fermi interaction.

Of course the emission of $\nu\tilde{\nu}$ pairs is extremely unlikely in comparison with the emission of photons. However, the tremendous penetrating power of neutrino suggests that effects connected with the electron-neutrino interaction might exist in big bodies at high temperature T. Let us consider the process of electron bremstrahlung with emission either of a photon or $\nu\tilde{\nu}$ pair in a collision of an electron with a neucleus A with charge Z:

$$e + A \longrightarrow e + A + \gamma \quad \text{(photon bremstrahlung)}$$

$$e + A \longrightarrow e + A + \nu + \tilde{\nu} \quad \text{(lepton bremstrahlung)}$$

Let α indicate the ratio of the probabilities W_γ and $W_{\nu\tilde{\nu}}$ that in a deflection of an electron with energy E by a nucleus a photon or a $\nu\tilde{\nu}$ pair is emitted. Dimension arguments suggest that:

---

* In particular ortopositronium annihilation with emission of a $\nu\tilde{\nu}$ pair is about 10^{15} times less probable than annihilation into three photons. Parapositronium cannot undergo annihilation with emission of a $\nu\tilde{\nu}$ pair, if neutrinos are longitudinal.

x) JETP, 36, 1615 (1959).

$$\alpha = \frac{W_\gamma}{W_{\nu\tilde{\nu}}} \approx \frac{(e^2Z/\hbar c)^2 \; e^2/\hbar c}{(e^2Z/\hbar c)^2 \; G^2 (E/mc^2)^4}$$

where $G = \frac{m^2 c}{\hbar^3} g$ is the dimentionless weak interaction constant, $g = 1.4 \times 10^{-49} \, cm^3 erg$ is the Fermi constant and m is the electron mass.

Clearly α is enormously big at any temperature which may be encountered in astrophysics. However, because of the difference in penetrating power of photons and neutrinos, the radiation in space of a given energy (let us say $\sim kT$) in form of photons by stars occurs eventually as a result of a colossal number of photon bremstrahlung processes. Such number is incomparably larger than the number (~1) of lepton bremstrahlung processes in which in form of neutrinos the same energy $\sim kT$ is emitted. Consequently at some stage in the star evolution it may well be that the energies radiated in space in form of neutrinos and photons become comparable in spite of the extraordinary small value of $W_{\nu\tilde{\nu}}/W_\gamma$, characterizing an elementary act.

It should be noted that the dimensions of the Fermi constant imply a very rapid increase with temperature of the relative probability of lepton bremstrahlung. In addition the photon mean free path decreases with increasing Z, a fact which increases the weight of neutrino processes in the energy balance at high Z.

All these considerations suggest that the process might become important at a star evolution stage when the star temperature and average Z are considerably larger than the corresponding solar values. It is not difficult to see that the lepton bremstrahlung mechanism practically does not play any role in the energy balance of the Sun.

$(kT \sim 1 \, keV, \; Z \sim 1)$.

The mechanism of neutrino emission by stars suggested above is connected with the first order neutrino-electron interaction and fundamentally differs from the "Urka-process" suggested by Gamow and Shoenberg[6] which is connected with nuclear (direct and inverse) β -processes. Lepton bremstrahlung of electrons is a thresholdless process while the "Urka-process" has a definite threshold.

Recently Gandelman and Pinaev[7] investigated quantitatively the astrophysics effects connected with the mechanism of lepton bremstrahlung suggested above. They showed that in the region of temperature $kT \gtrsim 10 \, keV$ and ~~pressures~~ densities $\gtrsim 10^5 \, gr/cm^3$ the energy radiated by stars in form of neutrino is larger than that radiated in form of photons (Z ≈ 20).

In conclusion I am happy to thank Ya.B. Zeldovich, D.A. Frank-Kamenezky and L.B.Okun for critical remarks and support.

Literature

1. B. Ponteoorvo, Phys.Rev. 72, 246, 1947
   G. Puppi, Nuovo Cim. 5, 505, 1948
   O. Klein, Nature 161, 897, 1948
   T.D. Lee, M. Resenbluth, C.N. Yang, Phys.Rev. 75, 905, 1949
   J. Tiomno, J.A. Wheeler, Rev.Modern Physics, 21, 144, 1949
2. N. Dallaporta, Nuovo Cim. I, 962, 1955
   G. Costa, N. Dallaporta, Nuovo Cim. 2, 519, 1955
   B. Ponteoorvo "Hyperons, K-mesons and universal Fermi interaction" Report of the Institute of Nuclear Problems, 1955.
   M. Gell-Mann, Proceedings of the Sixth Rochester Conference on high energy physics, 1956.
3. E.C.G. Sudarshan, R.E. Marshak, Proceedings of the Padua-Venice conference on mesons and newly discovered particles, 1957.
4. R.P. Feynman, M. Gell-Mann, Phys.Rev. 109, 193, 1958
5. V.M. Shehter JETP 34, 257, 1958
6. G. Gamow, M. Schoenberg, Phys.Rev. 59, 539, 1941.
7. G.M. Gandelman, V.S. Pinaev, private communication.

Received by Publishing Department on April 2, 1958.

WHEN DOES WEAK INTERACTION BECOME STRONG?x)

D. Blokhintsev

The concept of strong interaction[I] was considered in my paper "On Non-Local and Non-Linear Field Theories" which was published in the second issue of "Usp. Fiz. Nauk" for 1957. Strong interaction was understood there as such when during the collisions of the particles their energy is concentrated mainly in the interaction energy but not in their proper kinetic one.

A set of examples was considered on the basis of this criterion and, in particular, the electromagnetic interactions of electrons. But weak interaction of electrons with the participation of μ -mesons and neutrinos was not considered.

It appears that this interaction may become strong in the sense defined above.

The proof of this assertion is given below. This letter therefore, is a contribution to the chapter of my paper, devoted to strong interaction physics.

Let us consider the process of the interaction between neutrino and electron with the electron transformation into μ -meson.

$$\nu + e \rightarrow \mu + \nu'. \tag{I}$$

This is an original "combinational" scattering of neutrinos on an electron.

The energy density by the order of magnitude, in this case is equal to:

$$W = g^* \bar{\psi}_e \psi_\mu \bar{\psi}_\nu \psi_\nu' \tag{2}$$

where g^* is Fermi constant, and $\psi_e , \psi_\mu , \psi_\nu$ are the wave functions of electron, μ -meson and neutrino, respectively.

The magnitude g^* may be written in the form:

$$\frac{g^*}{\hbar c} = \Lambda_0^2 \tag{3}$$

where Λ_0 - a certain length of the order of $\sim 10^{-16}$ cm.

---

x) Usp. Fiz. Nauk, U.S.S.R., LXII, 381, (1957).

(It was I.S. Shapiro who noticed the possible magnitude of this length in connection with the non-conservation of parity. [2])

For instance, the kinetic energy density for electrons is

$$\mathcal{E}_e \doteq \overline{\Psi}_e D \Psi_e \tag{4}$$

where $D = c\vec{\alpha}\vec{p} + \beta mc^2$ is Dirac Hamiltonian.

Therefore, the order of the magnitude

$$\overline{\Psi}_e \Psi_e \cong \frac{\mathcal{E}_e \ell}{\hbar c} \tag{5}$$

where ℓ - the characteristic scale of space region which determines the magnitudes of the gradients so that

$$\frac{1}{c}\frac{\partial}{\partial t}, \ \frac{\partial}{\partial x} \cong \frac{1}{\ell} .$$

Thus, the order of the magnitude W is

$$W = \frac{g^* \ell^2}{\hbar c^2} \mathcal{E}_e^{\frac{1}{2}} \mathcal{E}_\mu^{\frac{1}{2}} \mathcal{E}_\nu . \tag{6}$$

Assuming $\mathcal{E}_e = \alpha \mathcal{E}, \ \mathcal{E}_\mu = \beta \mathcal{E}, \ \mathcal{E}_\nu = \gamma \mathcal{E},$
where $\mathcal{E}$ - the total energy density, we find:

$$\mathcal{E} \cong \mathcal{E}(\alpha+\beta+\gamma) + \frac{g^* \ell^2}{\hbar^2 c^2} \mathcal{E}^2 \alpha^{\frac{1}{2}} \beta^{\frac{1}{2}} \gamma . \tag{7}$$

In accordance with the definition, the interaction will be strong, if

$$\alpha+\beta+\gamma \ll 1 \quad (\alpha, \beta, \gamma > 0)$$

$$W = \frac{g^* \ell^2}{\hbar^2 c^2} \mathcal{E}^2 \alpha^{1/2} \beta^{1/2} \gamma \cong \mathcal{E}$$

i.e.

$$\mathcal{E} > \frac{\hbar^2 c^2}{g^* \ell^2} = \frac{\hbar c}{\Lambda_0^2 \ell^2} = \mathcal{E}_{crit} . \tag{8}$$

Now let us consider the neutrino package falling on the electron (in the system of the electron and neutrino centre of gravity), with the characteristic wave length $\lambdabar$ and with diametric dimensions $a > \lambdabar$. In this case the energy density $\mathcal{E}$ is

$$\mathcal{E} = \frac{\hbar\omega}{\lambdabar a^2} = \frac{\hbar c}{\lambdabar^2 a^2} \quad (9)$$

Further $\ell \cong \lambdabar$. The condition (8) gives now $a^2 < \Lambda_0^2$; since $a > \lambdabar$, strong interaction of electron and neutrino occurs if

$$\lambdabar < \Lambda_0 . \quad (10)$$

The direct calculation shows that the cross-section for the considered process $\nu + e \rightarrow \mu + \nu'$ by the order of the magnitude is equal to:

$$\sigma \cong \Lambda_0^2 \frac{\Lambda_0^2}{\lambdabar^2} \quad (11)$$

probably becomes greater $\pi \lambdabar^2$ if $\lambdabar < \Lambda_0$. In this connection it can be expected that at the wave lengths of the order of Λ_0 some other effects may occur, which will change essentially the electromagnetic interaction of electrons.

Namely at small distances there arises an interaction between electrons which will lead to mutual electron scattering by means of the following process: at first one of the electrons emits a pair of neutrinos (or neutrino and antineutrino) and transforms into μ -meson. The second electron absorbs these neutrinos and also transforms into another μ -meson. Then this meson emits neutrinos, which are absrobed by the first meson. As a result two scattered electrons arise.

These very processes lead to electron charge spreading, i.e. to the arising of electron "form factor."

This "form factor" will essentially change both the Compton effect on the electron at high energies of photons and the electromagnetic interaction of electrons.

The origin of such a spreading can be easily seen from the fact that besides direct absorption and emission of real or virtual photons by an electron it is also possible their absorption and emission by μ -meson arising in the temporary electron dissociation into μ -meson and a pair of neutrinos.

The situation is analogous to the arising of π -meson cloud around the nucleons. This analogy is, however, incomplete as in the case of π -meson cloud its scales are determined by the Compton length of π -meson, and in the case of electron it is the length Λ_0 which is essential but not the Compton length of μ -meson.

The effects mentioned here are also essential at the wave lengths of real or virtual photons, close to Λ_0 .

In conclusion one more remark about the role of the weak interaction of the mode $p \rightleftharpoons n + e^+ + \nu$ in nucleon collisions. As it was underlined in my paper this interaction fails to become strong at any energies.

At the same time it was assumed that the nucleon energy in the centre of gravity system is distributed in the ellipsoid volume $V \simeq \ell_0^3 \sqrt{\frac{Mc^2}{E}}$, where ℓ_0 - Compton length of π -mesons ($\hbar/\mu c$) or, may be that of nucleons ($\hbar/Mc$), E - nucleon energy in the laboratory coordinate system.

If we assume that the nucleon energy may be concentrated on any small region, then at the lengths of the nucleon waves $\lambda\!\!\!^{-} < \Lambda^0$ (in the centre of gravity system) the weak interaction will become essential.

We can show it by the considerations similar to those given above for neutrino and electron. It can be seen also directly from Tamm-Ivanenko theory of pair β -forces [3].

The expression for the potential of these forces states:

$$V = \frac{1}{(2\pi)^3} \frac{g^{*2}}{\hbar c R^5} = \frac{1}{(2\pi)^3} \left(\frac{\Lambda_0}{R}\right)^5 \frac{\hbar c}{\Lambda_0} \tag{12}$$

where R - the distance between nucleons.

If $R < \Lambda_0$ then $V = \frac{\hbar c}{\Lambda_0} \gg Mc^2$.

And the nucleon is assumed to be point. Thus the estimation of the magnitudes of weak interactions in nucleon collisions depends essentially on the reliability of the assumption that the proper nucleon energy at rest is distributed in the volume not less than $(\hbar/Mc)^3$. The theory of meson generation in the energetic nucleon collisions confirms this last assumption [4] .

References

1. D.I. Blokhintsev, Usp.Fiz.Nauk, 61, 137 (1957).
2. I.S. Shapiro, Usp.Fiz.Nauk, 61, 313 (1957).
3. I.E. Tamm, D.D. Ivanenko, Nature, 133, 981 (1934).
4. S.Z. Belenky, L.D. Landau, Usp.Fiz.Nauk, 56, 309 (1955).

D. I. Blohinčev
1958, Settembre
Il Nuovo Cimento
Serie X, Vol. 9, pag. 925-929

On a Possible Limit of Applicability of Quantum Electrodynamics.

D. I. Blohinčev
Joint Institute for Nuclear Research. Laboratory for Theoretical Physics - Moscow

(ricevuto il 17 Marzo 1958)

Summary. — In the present note the processes competing with the electromagnetic ones at high energies are considered. It is shown that such processes may be those involving the four-fermion interactions.

1. - Introduction.

It has been shown (1) that the application of the modern renormalization method in quantum electrodynamics leads to a difficulty of principle, *i.e.*, to the vanishing of the renormalized charge. Although the absolute proof of this conclusion was argued (2), none the less, the presence of the principle difficulties in the energy region E determined by the condition $\alpha \ln(E/mc^2) \sim 1$ $(\alpha = e^2/\hbar c)$ appears to be rather convincing. The space scale $l_0 \sim (\hbar/mc) \cdot \exp[-3\pi/\alpha]$ corresponding to this energy is far beyond the limits of the gravitational radius of the electron as it was first pointed out in (3). The extreme energy itself is enormously high $(E_0 \sim mc^2 \cdot \exp[3\pi/\alpha])$.

(1) L. D. Landau, A. A. Abrikosov and I. M. Halatnikov: *Dokl. Akad. Nauk SSSR*, **95**, 1177 (1954).
(2) N. N. Bogoljubov and D. V. Širkov: *Introduction to Quantum Field Theory* oscow, 1957), pp. 355-356.
(3) M M. A. Markov: *Žu. Èxper. Teor. Fiz.*, **17**, 661 (1947).

It can be expected, therefore, that the limits of applicability of modern electrodynamics will be revealed much earlier, *e.g.*, due to a possible change of space-time structure in space-time regions which are small but still considerably greater than l_0.

There is, however, another possibility of limiting the significance of quantum electrodynamics which is more accessible to theoretical analysis.

Together with the purely electrodynamic interactions of photons, electrons and positrons there occur the processes involving mesons and nucleons. They may be induced in a purely electrodynamic way, *e.g.*, by photon interaction with an electron.

If it would turn out that the contribution of these non-electromagnetic processes exceed that of the electromagnetic ones then it would not be possible to consider pure electrodynamics without essentially involving other types of interactions. In particular, from a certain energy $E_{\text{кр}}$ the expansion in a series $e^2/\hbar c$ would become not reasonable.

We will show that such a competing interaction may be the weak four-fermion Fermi interaction.

The validity of this interaction in the high energy region is not experimentally checked and different theoretical doubts on the applicability of this interaction for the energies $E \gg mc^2$ may arise.

However, we shall start from the assumption about the applicability of this interaction up to very high energies and consider the conclusions resulting from this assumption.

The physical property of the pure fermion interactions is that their matrix elements do not decrease with the increase of the energy of the fermions involved in the process, while the matrix elements of the processes involving bosons (photons, π and K-mesons) decrease while the boson energy increases. It can be accounted for the fact that the boson field falls as $K^{-\frac{1}{2}}$ with increasing boson energy as follows:

$$\Phi_K = \sqrt{\frac{h}{2K}} \exp[iKx] b_K^+ + \text{conj}.$$

where K is the boson momentum, b_K^+ is the operator of the boson production; while the fermion field is constant with increasing fermion energy:

$$\psi_K \sim u_K \exp[iKx] a_K^+ + \text{conj}.,$$

where u_K is the spinor amplitude, a_K is the operator of fermion production.

We shall show further that due to this property the fermion interactions become essential in the electromagnetic processes much earlier than the energy reaches the logarithmic limit $E \sim mc^2 \exp[3\pi/\alpha]$.

2. - Fermion-electromagnetic interaction.

Let us consider the interaction process of a photon (K) with an electron (e) leading to the production of a μ-meson (μ) and two neutrinos ($\nu, \tilde{\nu}$):

(1) $$K + e \to \mu + \nu + \tilde{\nu}\,.$$

Such a process will be described by the interaction Lagrangian

(2) $$W = eW_e + eW_\mu + gW_{e\mu\nu}\,,$$

where $eW_e = (I_e A)$ is the electron interaction (I_e is the electron current) with the electromagnetic field (A is the vector potential), eW_μ has the same meaning for a meson. Finally, $gW_{e\mu\nu}$ is the four-fermion interaction of an electron, a μ-meson and a neutrino:

$$g = hcA_0^2 \simeq 10^{-49}\ \text{erg}\cdot\text{cm}^3$$

is the Fermi constant, $A_0 = 6\cdot 10^{-17}\ \text{cm}^4$, whereas

$$W_{e\mu\nu} = (\bar{\psi}_e O_1 \psi_\mu)(\bar{\psi}_\nu O_2 \psi_\nu) + \text{conj.}$$

Here ψ_e, ψ_μ, ψ_ν are the spinor electron, meson and neutrino fields, respectively; O_1 and O_2 are certain spinor operators.

The total effective cross-section for the process (1) is:

(3) $$\sigma_\mu = \frac{2\pi}{hc}\int |W_{af}|^2 \frac{P_\nu^2\, dP_\nu\, d\Omega_\nu \tilde{P}_\nu'^2\, d\tilde{P}_\nu'\, d\tilde{\Omega}_\nu'}{(2\pi h)^6\, dE_f}\,,$$

where W_{af} is the matrix element from the interaction energy (2) for process (1) P_ν, $\tilde{P}_\nu$ are neutrino and antineutrino momenta, E_f is energy of the finite state.

The structure of this matrix element W_{af} is such that in the first non-vanishing approximation it is equal to

(4) $$W_{af} = eg\sum_j \left\{\frac{(a|We|c)(c|We\mu\nu\ f)}{E_0 - E} - \frac{(a|We\mu\nu\ c)(c|W\mu\ f)}{E_0 - E_c'}\right\}\,,$$

where E_0 is the energy of the initial state, and E_c is the intermediate state energy. In the system of the center of gravity of a photon and electron $E_0 - E_c \sim hcK$ (K is the photon wave vector),

$$(a|W_e|c) \sim K^{-\frac{1}{2}}\,, \qquad (c|W_\mu|f) \sim K^{\frac{1}{2}}$$

272

Therefore, $|W_{af}|^2 \sim egK^{-3}$. The weight factor in (3) is proportional to K^5 Thus, the total cross-section is as follows

$$\sigma_\mu \cong \alpha \Lambda_\upsilon^4 K^2 \cdot F \,, \tag{5}$$

where F is a factor of order 1, which weakly depends on K (*).

Just in a similar manner one may consider the collision of two electrons and their simultaneous conversion into two mesons, in accordance with the scheme

$$e' + e'' \rightarrow \mu' + \mu'' \,. \tag{1'}$$

The differential cross-section (in the center of mass system) for this process will be

$$d\sigma_{\mu\mu} \cong \Lambda_\upsilon^8 q^4 P^2 F \cdot d\Omega \,, \tag{6}$$

where q is the momentum transfer and P is the initial electron momentum, both measured in reciprocal lengths.

On the other hand, the cross-sections of purely electromagnetic processes are equal to

$$\sigma_c = \frac{1}{2} \pi \alpha^2 \frac{1}{K^2} \left(\ln \frac{4K^2}{K_c^2} + \frac{1}{2} \right) \tag{7}$$

for the Compton effect,

$$d\sigma_{ee} = \alpha^2 \frac{P^2}{q^4} \, d\Omega \tag{8}$$

for electron elastic collision,

$$\sigma_P = \frac{28}{9} \alpha^3 \frac{1}{K^2} \left(\ln \frac{4K^2}{K_c^2} - 3.5 \right) \tag{9}$$

for pair production (here $K_c = (mc/\hbar)$, $\alpha = (e^2/\hbar c)$) and

$$\sigma_\gamma = 4\alpha^3 \frac{1}{K_c^2} \left| \ln \frac{4}{K_c^2} - 3.5 \right| \tag{10}$$

for the bremsstrahlung in the electron collision.

(*) These qualitative conclusions are supported by more detailed calculations made by Dr. M. Mayer (Rumania). The author is very grateful to him.

The comparison of these cross-sections with those of mixed processes (1) and (1′) shows that

(11) $\sigma_\mu > \sigma_e$ with $K \gtrsim \alpha^{1/4} \Lambda_0^{-1}$

(12) $\sigma_\mu > \sigma_p$ with $K \lesssim \alpha^{\frac{1}{2}} \Lambda_0^{-1}$,

(13) $d\sigma_{\mu\mu} > d\sigma_{ee}$ with $q \gtrsim \alpha^{\frac{1}{2}} \frac{1}{\Lambda_0}$,

(14) $\sigma_{\mu\mu} > \sigma_\gamma$ with $q \sim p \gtrsim \alpha^{1/2} (K_c \Lambda_0)^{-1/3} \Lambda_0^{-1}$

Here the factors ~ 1 are omitted (*).

We see from these inequalities that if four-fermion interactions may be considered applicable in the energy range $K > 1/\Lambda_0$, the processes with neutrinos and μ-meson production are more intensive than the purely electromagnetic processes. The corresponding photon and electron energy in the system of center of gravity should be greater than $(\hbar c/\Lambda_0) \sim$ 250 GeV.

This is a great energy but, nevertheless, it is much lower than the logarithmic one.

It should be noted that the production of nucleon and meson pairs will play a considerably smaller role, since their production cross-section will be $(m/M)^2$ times less than that of electron-positron pairs.

The processes involving the production of neutrinos and boson mesons will be essential later, due to the above-mentioned difference in the behaviour of the boson and fermion matrix elements.

Thus, the fermion interaction may be the one which restricts the region of applicability of electrodynamics by a scale $> \Lambda_0$. For smaller scales and, consequently, for energies above $\hbar c/\Lambda_0$ it is not reasonable at all to study electrodynamics without considering the processes involving both μ-mesons and neutrinos and the Fermi constant g, together with $e^2/\hbar c$.

(*) Note that pair production in this energy range is the main electromagnetic process.

RIASSUNTO (*)

Si considerano nella presente nota i processi che alle alte energie competono con quello elettromagnetico. Si dimostra che tali processi possono essere quelli che interessano le interazioni fra quadrifermioni.

(*) *Traduzione a cura della Redazione.*

THE PHOTO-PRODUCTION OF $\nu-\tilde{\nu}$ PAIRS ON ELECTRONS

I. Ciulli, S. Ciulli, J. Fischer and Wang Yong.

Two years ago Professor D.I. Blokhintsev suggested that at very high energies the weak interactions could become comparable with the electromagnetic interactions. [1]. Among the processes he considered, the photo-production of $\nu-\tilde{\nu}$ pairs on electrons ($\gamma + e \to \nu + \tilde{\nu} + \mu$) has a larger cross-section than others, and he estimated roughly that it could be comparable with the Compton-effect at 250 BeV. We calculated in detail the expression for the cross-section of the above mentioned process, and obtained a value which confirms his estimations.

The interaction Hamiltonian has the following form:

$$H_i = ie(\bar{\psi}_e A \psi_e) + ie(\bar{\psi}_\mu A \psi_\mu) + \tag{I}$$
$$+ f(\bar{\psi}_e \gamma_\alpha [1+\gamma_5] \psi_\mu)(\bar{\psi}_\nu \gamma_\alpha [1+\gamma_5] \psi_\nu) + f(\bar{\psi}_\mu \gamma_\alpha [1+\gamma_5] \psi_e)(\bar{\psi}_\nu \gamma_\alpha [1+\gamma_5] \psi_\nu).$$

and we took into account the two diagrams of lowest order, which are similar to the lowest order diagrams of the Compton-effect.

After averaging over the initial polarizations and summing over the final ones with neglecting the quadratic terms in m_μ and m_e, we got the following expression for the total cross-section

$$\sigma_\mu = \frac{1}{v} \frac{e^2 f^2}{(2\pi)^5} \frac{8}{\omega \varepsilon_e} \int \frac{d^3 p_\mu \, d^3 p_\nu \, d^3 p_{\tilde{\nu}}}{\varepsilon_\mu \, \varepsilon_\nu \, \varepsilon_{\tilde{\nu}}} \delta^4 (p_e + k - p_\mu - p_\nu - p_{\tilde{\nu}}) \times$$
$$\times \left[- \frac{(kp_e)(p_{\tilde{\nu}} k)(p_\nu p_\mu)}{[(p_e+k)^2 + m_e^2]^2} - \frac{(k p_\mu)(p_{\tilde{\nu}} p_e)(p_\nu k)}{[(p_\mu - k)^2 + m_\mu^2]^2} + \right. \tag{2}$$
$$+ \frac{1}{[(p_e+k)^2 + m_e^2] \cdot [(p_\mu - k)^2 + m_\mu^2]} \Big\{ [2(p_e p_\mu) - (p_e k) + (p_\mu k)](p_{\tilde{\nu}} p_e)(p_\nu p_\mu) +$$
$$\left. + (p_e p_\mu)(p_{\tilde{\nu}} k)(p_\nu p_\mu) - (p_e p_\mu)(p_{\tilde{\nu}} p_e)(p_\nu k) + (k p_\mu)(p_{\tilde{\nu}} p_e)(p_\nu p_e) - (k p_e)(p_{\tilde{\nu}} p_\mu)(p_\nu p_\mu) \Big\} \right]$$

This expression was integrated in the center of mass system and the following extreme relativistic approximations were taken:

$$\mathcal{E}_e = \omega = \frac{E}{2}, \quad \mathcal{E}_\mu = |\vec{p}_\mu|, \quad \mathcal{E}_\mu^{max.} = \frac{E}{2}, \quad v = 2$$

(where E is the total energy of the system).

The final expression of the extreme relativistic cross-section is

$$\sigma_\mu = \frac{e^2 f^2}{4\pi^3}\,\omega^2\left(\ln\frac{2\omega}{m_\mu} - 0.7014\right) \tag{3}$$

where ω is the energy of the γ-quanta in the center of mass system.

Using the well-known expression for the cross-section of the Compton-effect in the center of mass system σ_c, we found the condition for $\sigma_\mu > \sigma_c$ as being

$$\frac{e^2 f^2}{4\pi^3}\,\omega^2 \geqslant \pi r_0^2 \frac{m_e^2}{\omega^2} \tag{4}$$

and thus, the cross-section of the $\nu - \tilde{\nu}$ pair photo-production on electrons becomes equal to that of the Compton-effect for an energy of the incident γ-quanta $\omega = 243$ Bev.

We wish to express our thanks to Professor D.I. Blokhintsev for the helpful discussions.

Reference

[1]. D.I. Blokhintsev, Nuovo Cim., 9, 925 (1958). See also the work of M.A. Markov.

Translated by authors.

ON THE GENERATION OF FAST NEUTRINO BEAMS

V.S. Barashenkov, Hsien Ding-chang

Many physicists are lately attracted by the possibility of experiments with the high energy neutrinos[1]. These experiments give a fine opportunity to investigate many important properties of weak interactions. In particular, it is possible to test experimentally whether weak interactions really become strong ones at high energies[2].

Intensive neutrino beams of high energies may be generated with large proton accelerators such as the synchrophasotron in Dubna and the 30-BeV accelerator in Geneva. In this case neutrinos appear when charged pions produced at fast nucleon collisions (see Fig. 1) decay. The energy spectrum and angular distribution of such neutrinos may be calculated if the spectrum and angular distribution of the pions produced in $\mathcal{N}-\mathcal{N}$ -collisions are known. In the general case the problem is rather complicated, especially if the finite dimensions of the neutrino detector are taken into account (compare[3]). However, the calculations are considerably simplified if only fast neutrino, outgoing at small angles in the direction of the primary accelerated proton beams are considered. In this case the emergence angle of neutrinos θ_ν is little differing from the angle at which the decaying pion was moving: $\theta_\nu \simeq \theta$ (see Fig. 1).

Further on we shall consider the neutrinoes with the energies $E_\nu > 1$ BeV and the angles θ_ν of the order of several degrees. As in the planned experiments the neutrino detector with the square of the transverse cross-section $S_D \sim 1\ m^2$ is to be placed at a distance of some tens of metres from the target 1), such approximation seems to be quite sufficient at present.

If $W_\pi(p,\theta)$ is the momentum distribution of the outgoing charged pions in the direction θ from the primary proton beam, the corresponding energy spectrum of the neutrinos at distance of L from the target, where the pions are generated, has the

1) Remind that due to the relativistic contraction of time fast pions will decay only at great distances from the target.

form

$$W_\nu (E, \theta, L) = a \int W_\pi (p, \theta) \left\{ 1 - \exp\left(-\frac{L}{\ell}\frac{m}{p}\right) \right\} \frac{dp}{p} . \qquad (I)$$

Here $a = m^2 / (m^2 - \mu^2)$; m - is the pion mass; μ - is the muon mass. If L is given in metres, so $\ell = \tau c \cdot 10^{-2} = 7.68$; τ - is the life-time of the charged pion.

Expression (I) differs from the corresponding expression for the γ-quanta, produced at neutral pion decay[4,5] only by the exponential term and the value of the ooefficient a.

The calculated values of the neutrino spectra for the angle $\theta = 0^0$ are in Fig. 2 in the logarithmic scale. The calculations showed that at small angles the neutrino spectra very weakly depend on the angle. For example the values of the neutrino spectra for an angle $\theta = 3^0$ are only 5 per cent smaller than the corresponding values for $\theta = 0^0$. It is also seen from Fig. 3 where the flux of all neutrino with energies $E >$ 1 BeV and $E >$ 2 BeV for the angles $\theta = 0^0$ and $\theta = 3^0$ are given.

$$W_\nu^{(1)} (\theta, L) = \int_{E>1} W_\nu (E, \theta, L)\, dE ,$$

$$W_\nu^{(2)} (\theta, L) = \int_{E>2} W_\nu (E, \theta, L)\, dE .$$

In Fig. 2 and 3 the spectra W_ν and fluxes $W_\nu^{(i)}$ are given, which are calculated from the spectra of the charged pions created in one single act of inelastic nucleon-nucleon collision in the target

$$\int W_\nu (E, \theta, L)\, d\theta\, dE = n$$

where n = 2, 3 - the mean number of charged pions, generating in one single act of inelastic N-N-collision at the energy of 10 BeV[5,6]. The values of function $W_\pi (p, \theta)$ are calculated as in paper[5] according to the statistic theory of multiple production.

It is seen from Fig. 3 that the neutrino flux per unit solid angle $W_\nu^{(1)}(\theta, L)$ increases rapidly as the distance from the target increases. Table 1 gives the limit values for $L = \infty$.

However, with the increase of L the solid angle of the neutrino detector $\Omega_D = S_D/L^2$ decreases rapidly. Therefore the number of neutrino registered by the detector decreases as the distance between the detector and the target increase:

at distance $L = 30$ м, 11×10^{-8} neutrinos pass through 1 cm^2 of the detector area in one single act of inelastic nucleon-nucleon collision, at distance L = 50 m and 100 m $0,6x10^{-8}$ and $0,27x10^{-8}$ neutrinos correspondingly.

These figures might be very useful for various estimations when planning experiments with the synchrophasotron of the Joint Institute.

Concluding we thank M.A. Markov for numerous discussions and valuable advice. We also thank R. Asanov and I. Polubarinov for discussion and critical remarks.

T a b l e I

$\theta \backslash W_\nu^{(i)}(\theta; \infty)$	$W_\nu^{(1)}$	$W_\nu^{(2)}$
0^o	1,5	0,18
3^o	1,4	0,16

References

1. M.A. Markov, "Hyperonen und K-mesonen" Verlag der Wissenschaften, Berlin, 1960.
T.D. Lee, C.N. Yang, "Theoretical discussions on possible high energy neutrino experiments," preprint, 1960.
N. Cabibbo, R. Gatto, Nuovo Cimento, 15, 304 (1960).
B. Pontecorvo, IX Annual International Conference on High Energy Physics, Kiev, 1959.
2. D.I. Blokhintsev, JETP, 35, 257 (1958); UFN, 62, 381 (1957).
H. Nagai, D. Ito, "Anomalous Creation of π -mesons Originating in the Weak Interactions," preprint, Physics Institute, Hokkaido University, 1960.
3. I.V. Polubarinov, Interaction of neutrinoes produced by the parallel monochromatic beam of π -mesons, (to be published).
4. R.M. Sternheimer, Phys.Rev., 99, 277 (1955).
5. V.S. Barashenkov, Hsien Ding-change, Atomnaya Energiya (in print); preprint of the JINR P-512, 1960.
6. V.S. Barashenkov, Nuovo Cimento, 14, 656 (1959).

Translated by V.N. Orel.

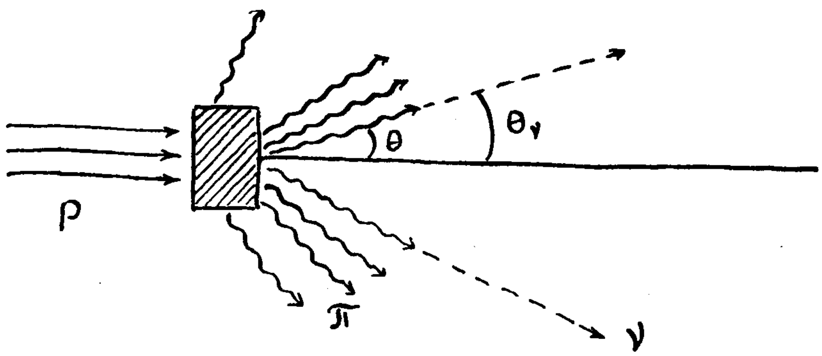


Fig. 1.

Neutrino beam produced at the decay of charged pions, generated by fast protons.

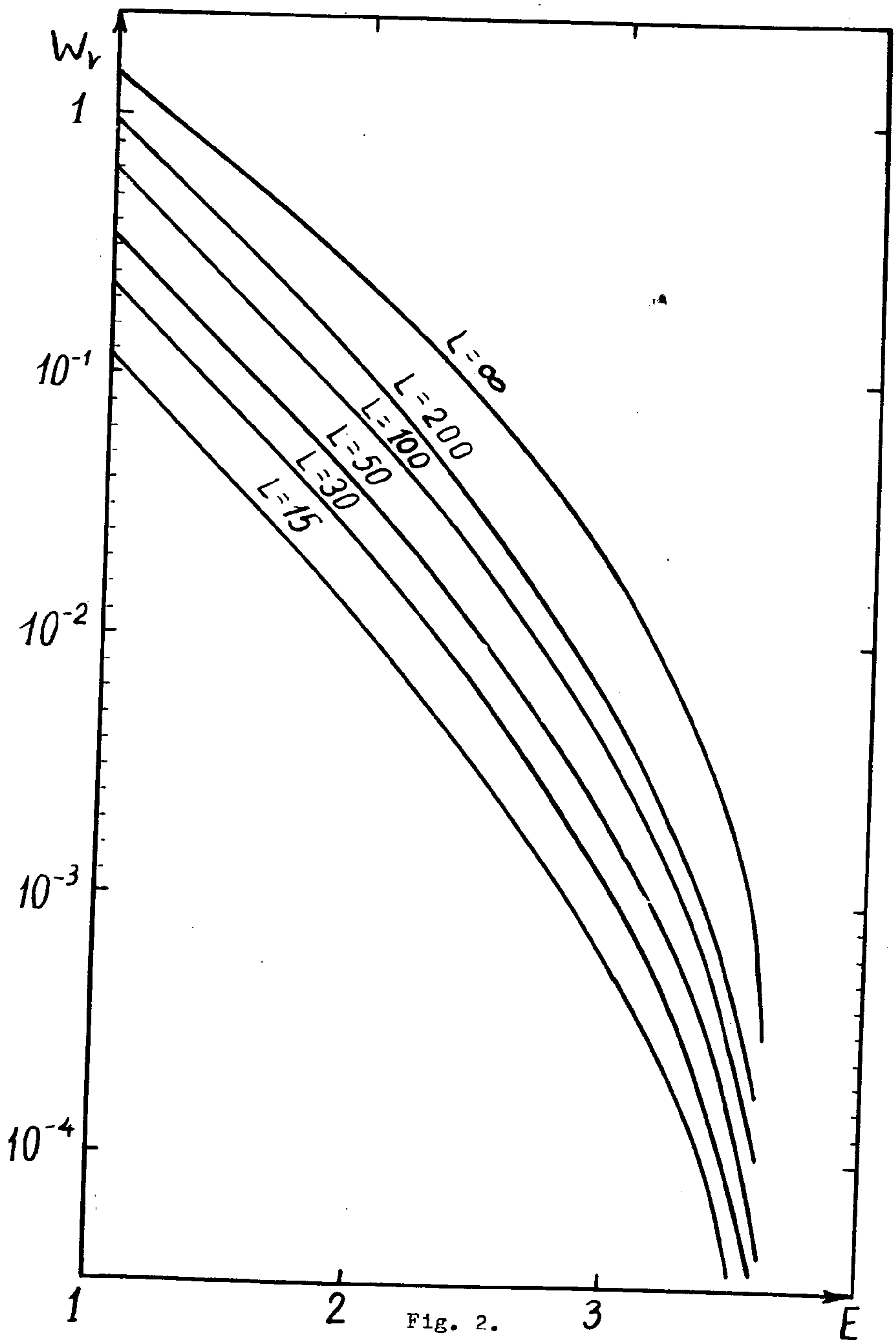


Fig. 2.

Energy distribution of the neutrino at different distances from the target L at angle $\theta=0^0$ from the primary proton beam. (Logarithmic scale). L is given in metres; neutrino energy in BeV. The laboratory coordinate system.

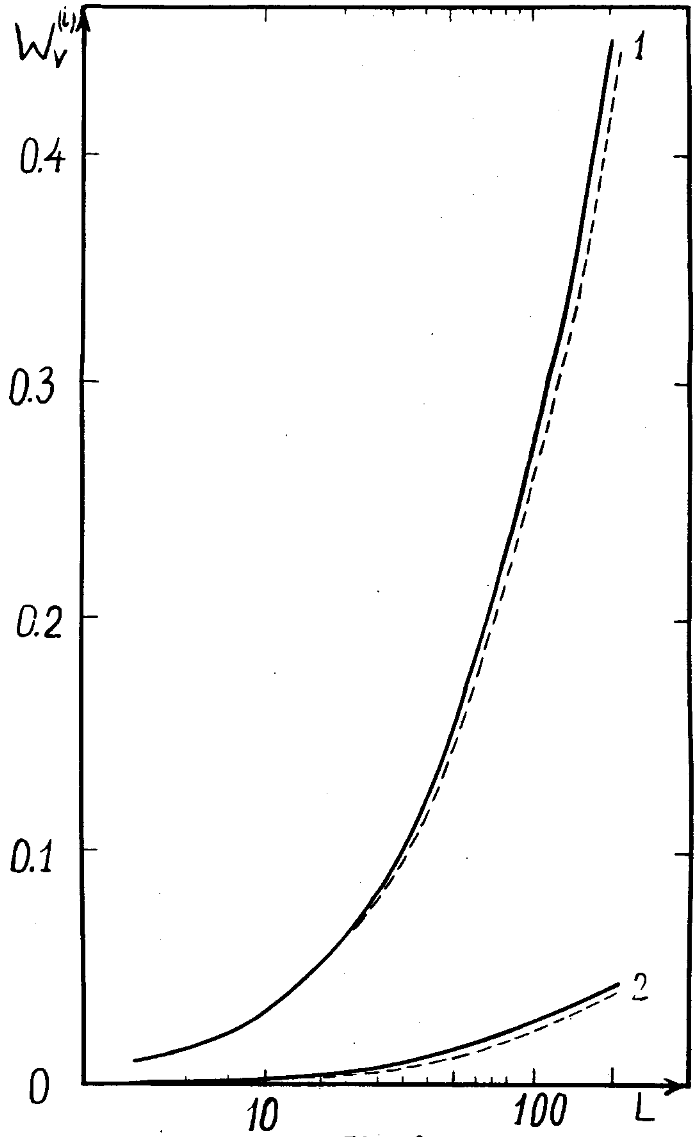


Fig. 3.

$W^{(1)} \equiv W_\nu^{(1)}(\theta, L)$ - neutrino fluxes with the energy $E >$ 1 BeV at different distances from the target L at angles $\theta = 0^\circ$. (full curve) and $\theta = 3^\circ$ (dashed curve) from the primary proton beam.

$W^{(2)}$ is the same for the neutrino with the energy $E > 2$ BeV. L is given in metres (logarithmic scale), the flux values $W^{(i)}$ are given calculating on the unit of a solid angle. The laboratory coordinate system.

INTERACTION OF NEUTRINOES PRODUCED BY PARALLEL MONOCHROMATIC BEAM OF π-MESONS

I.V. Polubarinov

1. Introduction. The possibilities of experiment with high energy neutrinoes[1,2] from the decay of pions, generated with the high energy accelerators are estimated.

The estimations suppose magnetic focusing of the decaying pions into the parallel monochromatic beam. The neutrino detector of the volume V (0,52 or 9,9 m^3) is placed on the beam axis. It is supposed that the shielding of the thickness ξ_1 absorbing pions (as well as all other particles but neutrinoes) is placed before the neutrino detector and that the pion beam is abrupting just on the board of the shielding (see Fig. 1 and 4).

In Section 2 and 3 necessary for estimations most simple expressions for the probability of the pion decay and the cross-sections of the interaction ν and $\tilde{\nu}$ with nucleons and electrons are collected. In Section 4 and 5 the general expression is derived for the number of the neutrino interaction acts in the volume element from the decay of the arbitrary pion beam.

Numerical calculations are made in Section 6 for the case of the infinitely thin pion beam and numbers of the antineutrino interaction acts in 24 hours are obtained depending on the distance ξ_2 between the pion source and the detector for the shielding of different thickness ξ_1 (see Fig. 2 and 3). The pion energy is taken equal to ε_π = 4,2 BeV. The curves are normalized on the intensity of the negative pions $10^8 \frac{\text{mesons}}{\text{sec}}$. On the collision of the 10-BeV proton with the nucleon with the production of pions $\sim$ 0,05 of the negative pion is produced in the energy interval 3.7 - 5.1 BeV ($\bar{\varepsilon}_\pi$ = 4,2 BeV). Thus the given flux of negative pions of these energies appears from the flux of $\sim 2.10^{10} \frac{\text{proton}}{\text{sec}}$, when 0,1 part of it is absorbed in the target with the pion production.

The maximum in the curves appears due to the increase of the number of acts with the increase of the used part of the pion beam and the decrease of their number at large distances where the angle between the pion direction and the direction of the neutrino outgoing affects.

In Section 7 estimation is made for the case of the pion wide beam.

These calculations were carried out on the proposition of Prof. M.A. Markov and represent the 1959 report.

2. <u>The pion decay</u>. At pion decay $\pi \to \mu + \nu$ neutrinoes of the energy

$$\varepsilon_\nu = \frac{m_\pi^2 - m_\mu^2}{2(\varepsilon_\pi - p_\pi \cos\theta)} \qquad /\hbar = c = 1/ \qquad (I)$$

are produced. Here m_π and m_μ are the rest masses of the pion and μ-meson; ε_π and p_π are the pion energy and the momentum; θ is the angle between the primary direction of the pion and the direction of the neutrino outgoing.

The probability per unit of time of the decay of the pion with the momentum $\vec{p}_\pi$ provided that the outgoing neutrino has the momentum in ($\vec{p}_\nu$, $\vec{p}_\nu + d\vec{p}_\nu$) equals ($\hbar = c = 1$).

$$dw(\vec{p}_\pi, \vec{p}_\nu) = f(\vec{p}_\pi, \vec{p}_\nu)\, d\vec{p}_\nu = \frac{m_\pi^2\, d\vec{p}_\nu}{\pi \tau(\varepsilon_\pi)(m_\pi^2 - m_\mu^2)\varepsilon_\nu}\, \delta\left[(p_\pi - p_\nu)^2 + m_\mu^2\right] \qquad (2)$$

where p_π and p_ν - are the 4-momenta of the pion and neutrino $/p_\pi^2 = -m_\pi^2,\ p_\nu^2 = 0/$ $\tau(\varepsilon_\pi)$ is the life-time of the pion with the energy ε_π . It results from this expression that the ratio of the number of the pion decays with the outgoing of neutrinoes of the energy exceeding some ε_0 to the number of all decays is equal to

$$u = \frac{\varepsilon^\nu_{max} - \varepsilon_0}{\varepsilon^\nu_{max} - \varepsilon^\nu_{min}} \qquad \varepsilon^\nu_{min} \leq \varepsilon_0 \leq \varepsilon^\nu_{max} \qquad (3)$$

ε_π BeV	1	2	3	4	5	6	7	8	9	10
$\varepsilon^\nu_{min} = \frac{m_\pi^2 - m_\mu^2}{2(\varepsilon_\pi + p_\pi)}$	2,1 MeV									
$\varepsilon^\nu_{max} = \frac{m_\pi^2 - m_\mu^2}{2(\varepsilon_\pi - p_\pi)}$	0,43 BeV	0,86 BeV	1,28 BeV	1,71 BeV	2,14 BeV	2,57 BeV	3,00 BeV	3,42 BeV	3,86 BeV	4,28 BeV

3. Interaction of neutrinoes and antineutrinoes with nucleons and electrons.

If

$$\mathcal{L}(x) = \frac{g}{\sqrt{2}} \left(\bar{p}(x)\gamma_\mu(1+\gamma_5)n(x)\right)\left(\bar{e}(x)\gamma_\mu(1+\gamma_5)\nu(x)\right) + h.c. \tag{4}$$

$$g = 1,41 \text{ erg.cm}^3$$

is taken as the Lagrangian of the β-interaction then for all possible (in the first order) processes of interaction of neutrinoes and antineutrinoes with nucleons and electrons

$$\nu + n \rightarrow e + p \tag{5}$$

$$\tilde{\nu} + p \rightarrow \tilde{e} + n \tag{6}$$

$$\tilde{\nu} + e \rightarrow n + \tilde{p} \tag{7}$$

we obtain the following cross-sections:

$$\sigma_{\nu+n\rightarrow e+p} = \frac{g^2}{4\pi\hbar^4} \cdot \frac{M^4c^4}{\varepsilon_n\varepsilon_\nu\beta_0} \sqrt{1 - \frac{2(m_p^2+m_e^2)}{M^2} + \frac{(m_p^2-m_e^2)^2}{M^4}} \left(1 - \frac{m_n^2+m_\nu^2}{M^2}\right)\left(1 - \frac{m_p^2+m_e^2}{M^2}\right) \tag{8}$$

$$\sigma_{\tilde{\nu}+p\to\tilde{e}+n}=\frac{g^2}{12\pi\hbar^4}\cdot\frac{M^4c^4}{\varepsilon_p\varepsilon_{\tilde{\nu}}\beta_0}\sqrt{1-\frac{2(m_n^2+m_{\tilde{e}}^2)}{M^2}+\frac{(m_n^2-m_{\tilde{e}}^2)^2}{M^4}}\,\cdot$$

$$\cdot\left\{1-\frac{m_n^2+m_p^2+m_{\tilde{\nu}}^2+m_{\tilde{e}}^2}{2M^2}-\frac{(m_n^2-m_{\tilde{e}}^2)^2+(m_p^2-m_{\tilde{\nu}}^2)^2-2(m_n^2+m_{\tilde{e}}^2)(m_p^2+m_{\tilde{\nu}}^2)}{2M^4}-\right.$$

$$\left.-\frac{(m_n^2+m_{\tilde{e}}^2)(m_p^2-m_{\tilde{\nu}}^2)^2+(m_p^2+m_{\tilde{\nu}}^2)(m_n^2-m_{\tilde{e}}^2)}{2M^6}+\frac{(m_n^2-m_{\tilde{e}}^2)^2(m_p^2-m_{\tilde{\nu}}^2)^2}{M^8}\right\} \qquad (9)$$

$$\sigma_{\tilde{\nu}+e\to n+\tilde{p}}=\frac{g^2}{12\pi\hbar^4}\cdot\frac{M^4c^4}{\varepsilon_e\varepsilon_{\tilde{\nu}}\beta_0}\sqrt{1-\frac{2(m_n^2+m_{\tilde{p}}^2)}{M^2}+\frac{(m_n^2-m_{\tilde{p}}^2)^2}{M^4}}\,\cdot$$

$$\cdot\left\{1-\frac{m_n^2+m_{\tilde{p}}^2+m_{\tilde{\nu}}^2+m_e^2}{2M^2}-\frac{(m_n^2-m_{\tilde{p}}^2)^2+(m_e^2-m_{\tilde{\nu}}^2)^2-2(m_n^2+m_{\tilde{p}}^2)(m_e^2+m_{\tilde{\nu}}^2)}{2M^4}-\right.$$

$$\left.-\frac{(m_n^2+m_{\tilde{p}}^2)(m_e^2-m_{\tilde{\nu}}^2)^2+(m_e^2+m_{\tilde{\nu}}^2)(m_n^2-m_{\tilde{p}}^2)^2}{2M^6}+\frac{(m_n^2-m_{\tilde{p}}^2)^2(m_e^2-m_{\tilde{\nu}}^2)^2}{M^8}\right\} \qquad (10)$$

These cross-sections are written in the arbitrary unit system and the arbitrary of reference frame.

β_0 is the relative velocity of colliding particles divided by the velocity of light; masses m and energies ε are marked by indexes indicating to what particles they are related. M is the mass of system being expressed in terms of the energies and momenta of colliding particles 1 (ν or $\tilde{\nu}$) and 2 (n, p or e) according to the expression

$$M^2=(\varepsilon_1+\varepsilon_2)^2/c^4-(\vec{p}_1+\vec{p}_2)^2/c^2$$

In the coordinate system where particle 2 rests and the neutrino or antineutrino have momentum p_1 $\qquad M^2=m_2^2+2m_2p_1/c$

If interaction

$$\mathcal{L}(x)=\frac{g}{\sqrt{2}}\left(\bar{e}(x)\gamma_\mu(1+\gamma_5)\nu(x)\right)\left(\bar{\nu}(x)\gamma_\mu(1+\gamma_5)e(x)\right) \qquad (11)$$

is taking place, the following processes will be possible

$$\nu + e \to \nu + e$$
$$\tilde{\nu} + e \to \tilde{\nu} + e$$

the cross-sections for which are:

$$\sigma_{\nu+e\to\nu+e} = \frac{g^2}{4\pi\hbar^4}\cdot\frac{M^4c^4}{\varepsilon_e\varepsilon_\nu\beta_0}\sqrt{1-\frac{2(m_\nu^2+m_e^2)}{M^2}+\frac{(m_\nu^2-m_e^2)^2}{M^4}}\left(1-\frac{m_e^2+m_\nu^2}{M^2}\right)^2 \tag{12}$$

$$\sigma_{\tilde{\nu}+e\to\tilde{\nu}+e} = \frac{g^2}{12\pi\hbar^4}\cdot\frac{M^4c^4}{\varepsilon_e\varepsilon_{\tilde{\nu}}\beta_0}\sqrt{1-\frac{2(m_e^2+m_{\tilde{\nu}}^2)}{M^2}+\frac{(m_e^2-m_{\tilde{\nu}}^2)^2}{M^4}}\,\cdot$$

$$\cdot\left\{1-\frac{m_e^2+m_{\tilde{\nu}}^2}{M^2}+\frac{4m_e^2m_{\tilde{\nu}}^2}{M^4}-\frac{(m_e^2+m_{\tilde{\nu}}^2)(m_e^2-m_{\tilde{\nu}}^2)^2}{M^6}+\frac{(m_e^2-m_{\tilde{\nu}}^2)^4}{M^8}\right\} \tag{13}$$

The meaning of the symbols is like that as above. For the energy $\varepsilon_\nu \gtrsim 1$ BeV

$$\sigma_{\tilde{\nu}+p\to\tilde{e}+n} \approx \frac{g^2}{3\pi\hbar^4c}m_p p_{\tilde{\nu}} = 4{,}8\cdot 10^{-39}\,\frac{p_{\tilde{\nu}}}{m_pc}\quad cm^2 \tag{14}$$

and the other cross-sections are expressed in terms of this cross-section in the following way:

$$\begin{aligned}
&\sigma_{\nu+n\to e+p} \approx 3\,\sigma_{\tilde{\nu}+p\to n+\tilde{e}}\\
&\sigma_{\tilde{\nu}+e\to n+\tilde{p}} \approx \frac{m_e}{m_p}\,\sigma_{\tilde{\nu}+p\to n+\tilde{e}}\\
&\sigma_{\nu+e\to\nu+e} \approx 3\frac{m_e}{m_p}\,\sigma_{\tilde{\nu}+p\to n+\tilde{e}}\\
&\sigma_{\tilde{\nu}+e\to\tilde{\nu}+e} \approx \frac{m_e}{m_p}\,\sigma_{\tilde{\nu}+p\to n+\tilde{e}}
\end{aligned} \tag{15}$$

4. <u>Expression of the neutrino phase density in terms of the phase density of pions producing them.</u> If $\rho_\pi(\vec{x},\vec{p}_\pi)$ is the pion phase density so that $\rho_\pi(\vec{x},\vec{p}_\pi)\,d\vec{x}\,d\vec{p}_\pi$ mesons are in the phase space $(\vec{x},\vec{x}+d\vec{x};\,\vec{p}_\pi,\vec{p}_\pi+d\vec{p}_\pi)$, and $dw(\vec{p}_\pi,\vec{p}_\nu)=f(\vec{p}_\pi,\vec{p}_\nu)\,d\vec{p}_\nu$ is the probability per unit of time of the decay of the pion with the momentum $\vec{p}_\pi$ provided that the outgoing neutrino has the momentum in $(\vec{p}_\nu,\vec{p}_\nu+d\vec{p}_\nu)$ then

$$\int d\vec{p}_\pi \, \rho_\pi(\vec{x},\vec{p}_\pi) \, f(\vec{p}_\pi,\vec{p}_\nu) \, d\vec{x} \, d\vec{p}_\nu \tag{16}$$

neutrino is outgoing per unit of time from the volume $(\vec{x}, \vec{x}+d\vec{x})$ with the momentum in $(\vec{p}_\nu, \vec{p}_\nu+d\vec{p}_\nu)$. Only those neutrinoes will hit point $\vec{y}$ from point $\vec{x}$ which have

$$\frac{\vec{p}_\nu}{|\vec{p}_\nu|} = \frac{\vec{y}-\vec{x}}{|\vec{y}-\vec{x}|} \tag{17}$$

We have $d\vec{p}_\nu = p_\nu^2 \, dp_\nu \, d\Omega$ in the spherical coordinate system with the origin in $\vec{x}$. If v_ν is the velocity of neutrino, $|\vec{y}-\vec{x}|^2 v_\nu \, d\Omega$ is the volume which is occupied by all neutrinoes ingoing into $d\Omega$ per unit of time. Therefore in volume $(\vec{y}, \vec{y}+d\vec{y})$ will be

$$\frac{\int d\vec{p}_\pi \, \rho_\pi(\vec{x},\vec{p}_\pi) \, f(\vec{p}_\pi,\vec{p}_\nu) \, d\vec{x} \, d\vec{p}_\nu \, d\vec{y}}{(\vec{y}-\vec{x})^2 v_\nu \, d\Omega} = \frac{\int d\vec{p}_\pi \, \rho_\pi(\vec{x},\vec{p}_\pi) \, f\left(\vec{p}_\pi, p_\nu \frac{\vec{y}-\vec{x}}{|\vec{y}-\vec{x}|}\right) d\vec{x} \, p_\nu^2 \, dp_\nu \, d\vec{y}}{(\vec{y}-\vec{x})^2 \, v_\nu}$$

neutrinoes with the momentum in the interval (p_ν , $p_\nu+dp_\nu$) supplied by the volume ($\vec{x}, \vec{x}+d\vec{x}$) or

$$\rho_\nu(\vec{y},p_\nu) \, d\vec{y} \, dp_\nu = \int \frac{d\vec{x}}{(\vec{y}-\vec{x})^2} \int d\vec{p}_\pi \, \rho_\pi(\vec{x},\vec{p}_\pi) \, f\left(\vec{p}_\pi, p_\nu \frac{\vec{y}-\vec{x}}{|\vec{y}-\vec{x}|}\right) \frac{p_\nu^2 \, dp_\nu}{v_\nu} \, d\vec{y} \tag{18}$$

neutrinoes supplied by the whole space.

Consequently in the phase space $(\vec{y}, \vec{y}+d\vec{y} \, ; \vec{p}_\nu, \vec{p}_\nu+d\vec{p}_\nu)$ will be

$$\rho_\nu(\vec{y},\vec{p}_\nu) \, d\vec{y} \, d\vec{p}_\nu = \int \frac{d\vec{x}}{(\vec{y}-\vec{x})^2} \int d\vec{p}_\pi \, \rho_\pi(\vec{x},\vec{p}_\pi) \, f(\vec{p}_\pi,\vec{p}_\nu) \, \delta\left(\frac{\vec{p}_\nu}{|\vec{p}_\nu|} - \frac{\vec{y}-\vec{x}}{|\vec{y}-\vec{x}|}\right) \frac{d\vec{p}_\nu \, d\vec{y}}{v_\nu}$$

neutrinoes. Here $\delta\left(\frac{\vec{p}_\nu}{|\vec{p}_\nu|} - \frac{\vec{y}-\vec{x}}{|\vec{y}-\vec{x}|}\right)$ – two-dimensional δ -function taking into account (17) and having the property

$$\int d\Omega_{\vec{p}} \, \delta\left(\frac{\vec{p}}{|\vec{p}|} - \frac{\vec{y}-\vec{x}}{|\vec{y}-\vec{x}|}\right) = 1$$

Thus the neutrino phase density is equal to

$$\rho_\nu(\vec{y},\vec{p}_\nu) = \int \frac{d\vec{x}}{(\vec{y}-\vec{x})^2} \int d\vec{p}_\pi \, \rho_\pi(\vec{x},\vec{p}_\pi) \, f(\vec{p}_\pi,\vec{p}_\nu) \, \delta\left(\frac{\vec{p}_\nu}{|\vec{p}_\nu|} - \frac{\vec{y}-\vec{x}}{|\vec{y}-\vec{x}|}\right) \frac{1}{v_\nu} . \tag{19}$$

5. The number of events $\tilde{\nu}+p \rightarrow n+\tilde{e}$ per unit of time caused by antineutrinoes from pion decay in volume $(\vec{y}, \vec{y}+d\vec{y})$ is evidently equal to

$$n(\vec{y})d\vec{y} = \rho_p \int dp_\nu \, \sigma(p_\nu) v_0(p_\nu) \rho_\nu(\vec{y}, p_\nu) \, d\vec{y} \tag{20}$$

where ρ_p is the proton density; $\sigma(p_\nu)$ - is a cross-section of the interaction of the neutrino with the momentum p_ν with a proton, $v_0(p_\nu)$ - is a relative velocity $\tilde{\nu}$ - proton, $\rho_\nu(\vec{y}, p_\nu)$ - is the integrated respect to the directions of $\tilde{\nu}$ phase density, i.e. (18).

By setting (18) into (20) we have

$$n(\vec{y})\, d\vec{y} = \rho_p \int dp_\nu \, \sigma(p_\nu) \frac{v_0(p_\nu)}{v_\nu} p_\nu^2 \int \frac{d\vec{x}}{(\vec{y}-\vec{x})^2} \int d\vec{p}_\pi \, \rho_\pi(\vec{x},\vec{p}_\pi) \, f\left(\vec{p}_\pi, p_\nu \frac{\vec{y}-\vec{x}}{|\vec{y}-\vec{x}|}\right) d\vec{y} \tag{21}$$

6. Linear monochromatic beam of pions. The beam of decaying pions moving along z -axis has the phase density.

$$\rho_\pi(\vec{x},\vec{k}) = \frac{I}{v_\pi} \delta(\vec{p}_\pi - \vec{k}) \, \delta(x) \delta(y) \, e^{-\frac{z}{v_\pi \tau(\varepsilon_\pi)}} \tag{22}$$

where $\vec{x} = \{x,y,z\}$, I - is the linear flux of pions through point $z = 0$, $\vec{p}_\pi$ and v_π their momentum and velocity. The detector will be taken in the form of a sphere of radius a with the centre on the beam axis in point z_a (Fig. 1). The pion beam will be considered to begin and abrupt at distances ξ_2 and ξ_1 from z_a, respectively.

Substituting $\rho_\pi(\vec{x},\vec{k})$ and $f(\vec{p}_\pi,\vec{p}_\nu)$ in (21) by their expression (22) and (2), respectively, integrating respect to $\vec{y}$ (over the sphere volume) and respect to p_ν and substituting $\sigma(p_\nu)$ by approximate expression (14) we obtain the number of events (7) per unit of time in the sphere volume equal to

$$n(V_{sphere}) = \frac{2I\rho_p m_\pi^2}{v_\pi \tau(\varepsilon_\pi)(m_\pi^2-m_\mu^2)p_\pi}\int \frac{dp_\nu}{v_\nu}\sigma(p_\nu)v_0(p_\nu)\theta\left[4p_\nu^2p_\pi^2-(m_\pi^2-m_\mu^2-2p_\nu\varepsilon_\pi)^2\right]\int_{\xi_1}^{\xi_2} d\xi\, e^{-\frac{z_a-\xi}{v_\pi\tau(\varepsilon_\pi)}}\sqrt{a^2-\xi^2\sin^2\psi} =$$

$$= \frac{I\rho_p(m_\pi^2-m_\mu^2)g^2}{12\pi v_\pi \tau(\varepsilon_\pi)\hbar^4}\cdot\frac{m_p}{m_\pi}\cdot e^{-\frac{z_a}{v_\pi\tau(\varepsilon_\pi)}}\int_{\xi_1}^{\xi_2} d\xi\, e^{\frac{\xi}{v_\pi\tau(\varepsilon_\pi)}}\cdot\frac{\xi}{1+\frac{p_\pi^2}{m_\pi^2c^2}\cdot\frac{a^2}{\xi^2}}\cdot$$

$$\cdot\left\{\left[1+\frac{a^2}{\xi^2}\frac{(\varepsilon_\pi+p_\pi c)p_\pi}{m_\pi^2c^3}\right]\frac{a}{\xi}\,\frac{\varepsilon_\pi+p_\pi c}{m_\pi c^2}-\frac{1-\frac{a^2}{\xi^2}}{\sqrt{1+\frac{p_\pi^2}{m_\pi^2c^2}\cdot\frac{a^2}{\xi^2}}}\,\mathrm{arch}\frac{1+\frac{a^2}{\xi^2}\frac{(\varepsilon_\pi+p_\pi c)p_\pi}{m_\pi^2c^3}}{\sqrt{1-\frac{a^2}{\xi^2}}}\right\} \quad (23)$$

where $\cos\psi = \dfrac{2\varepsilon_\pi\varepsilon_\nu - m_\pi^2 + m_\mu^2}{2p_\pi\varepsilon_\nu}$.

The results of calculations according to this expression are represented in Fig. 2 and 3. It was supposed that the linear flux of negative pions is equal to $I = 10^8\ \frac{\text{meson}}{\text{sec}}$ their mean energy ε_π = 4,2 BeV, a = 0,5 m or 1,33 m (the sphere volume 0,52 m^3 or 9,9 m^3); $\rho_p = 1{,}2\times10^{24}\ \frac{\text{proton}}{\text{cm}^3}$. $\tilde{\nu}$ of low energies, detected for ξ_1 = 0,5 m, are interacting with a smaller cross-section than that given by (14). Therefore the curve for ξ_1 = 0,5 m in Fig. 2 gives excessive values.

7. Wide parallel beam of pions. In case of wide parallel monochromatic beam of decaying pions

$$\rho_\pi(\vec{x},\vec{k}) = \begin{cases} \frac{J}{v_\pi}\delta(\vec{k}-\vec{p}_\pi)\, e^{-\frac{(\vec{p}_\pi\vec{x})}{p_\pi v_\pi\tau(\varepsilon_\pi)}} & \text{inside } V_\pi \\ 0 & \text{outside } V_\pi \end{cases} \quad (24)$$

where J is the initial flux per unit of surface, V_π is the cylindrical region of radius b with the axis, parallel to $\vec{p}_\pi$ (Fig. 4). The detector will be taken in the form of an infinitely thin (of thickness dl) disc with radius a . The disc and beam axes coincide.

Substituting $\rho_\pi(\vec{x},\vec{k})$ and $f(\vec{p}_\pi,\vec{p}_\nu)$ in (21) by the expressions (24) and (2), respectively, integrating respect to $\vec{y}$ (over the disc volume) and the azimuth and the distance from axis of $\vec{x}$, we obtain

$$n(V_{disc}) = \frac{J \rho_p m_\pi^2 dl}{v_\pi \tau(\varepsilon_\pi)(m_\pi^2 - m_\mu^2) p_\pi} \int dp_\nu \sigma(p_\nu) \frac{v_0(p_\nu)}{v_\nu \cos\psi} e^{-\frac{z_a}{v_\pi \tau(\varepsilon_\pi)}} \cdot$$

$$\cdot \int_{\xi_1}^{\xi_2} d\xi \, e^{\frac{\xi}{v_\pi \tau(\varepsilon_\pi)}} \Big\{ \left[\theta(b-a)\pi a^2 + \theta(a-b)\pi b^2\right] \theta(|a-b| - \xi \, tg\psi) +$$

$$+ \theta(a+b-\xi \, tg\psi)\theta(\xi \, tg\psi - |a-b|)\Big[b^2 \arccos \frac{b^2 + \xi^2 tg^2\psi - a^2}{2b\xi \, tg\psi} + a^2 \arccos \frac{a^2 + \xi^2 tg^2\psi - b^2}{2a\xi \, tg\psi} -$$

$$- \frac{1}{2}\sqrt{4a^2b^2 - (a^2+b^2-\xi^2 tg^2\psi)^2}\,\Big]\Big\} \qquad (25)$$

If $a = b = 0{,}5$ m and as before $I = J\pi a^2 = 10^8 \frac{\pi^- \text{-meson}}{\text{sec}}$, $\varepsilon_\pi = 4{,}2$ BeV, the detector volume $V_{disc} = 0{,}52 \text{ m}^3$, $\rho_p = 1{,}2 \cdot 10^{24} \frac{\text{proton}}{\text{cm}^3}$, the last expression and expression (9) for $\xi_1 = 25$ m and $\xi_2 = z_a = 50$ m give $n = 0{,}075 \frac{\text{event}}{24 \text{ hours}}$.

I express my gratitude to Prof. M.A. Markov for the suggestion of the problem and continual attention.

References

1. M.A. Markow, Hyperonen und K-Mesonen, Verlag der Wissenschaften, Berlin, 1960.
2. D.G. Fakirov, On possibility of investigation of high-energy neutrino interaction with matter with accelerators, Thesis, Physical Faculty MGU, 1958.
3. V.S. Barashenkov and V.M. Maltsev, Central and peripheral collisions between fast nucleons, 11. Preprint of JINR, P-433, Dubna, 1959.

Translated by V.N. Orel.

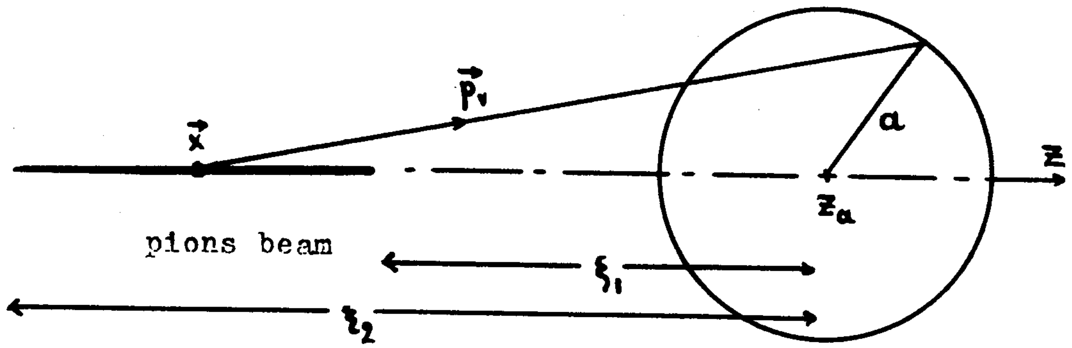
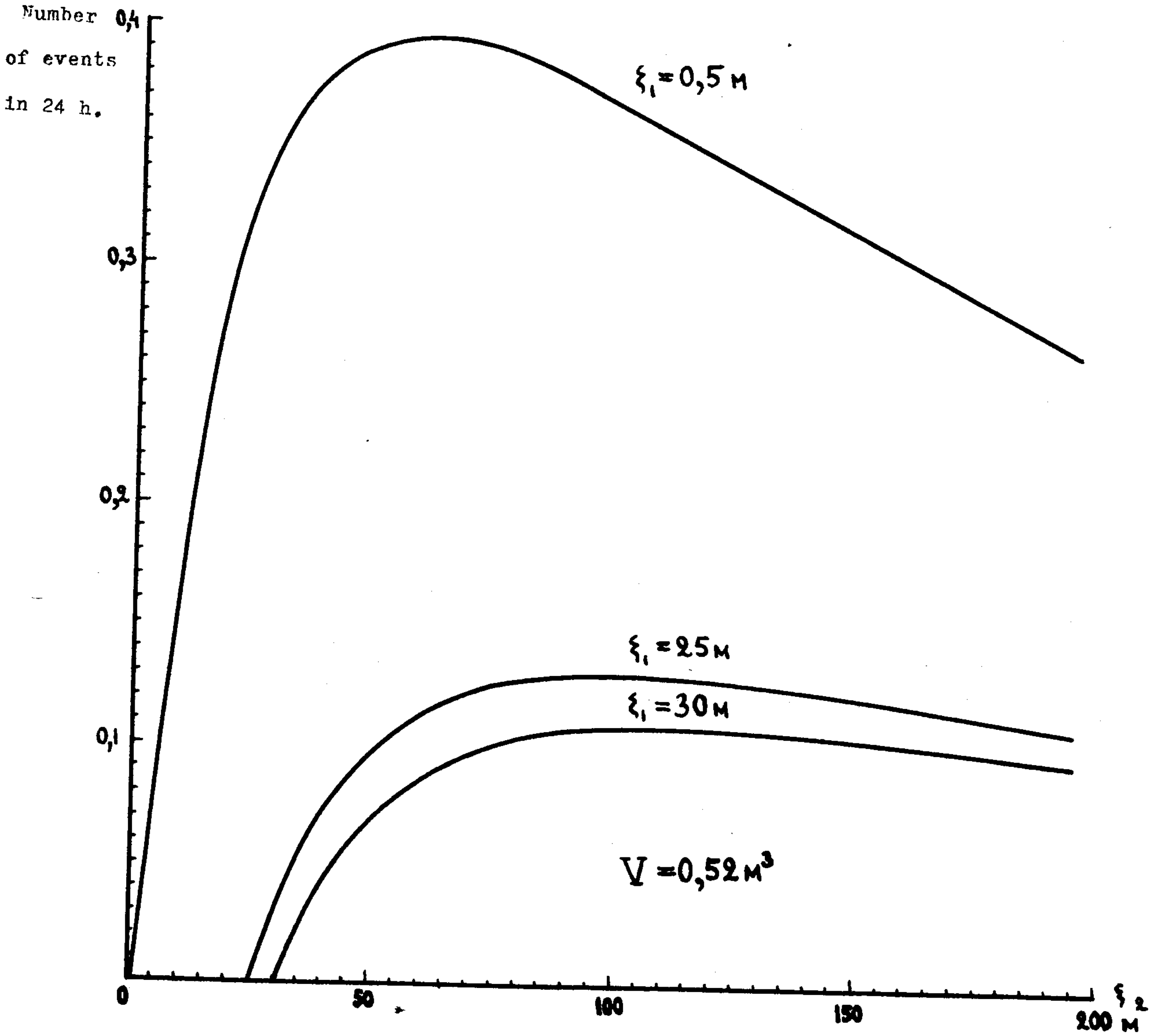


Fig. 1.



Number of events in 24 h.
0,4
0,3
0,2
0,1
0
50
100
150
200 M
ξ2
ξ1 = 0,5 M
ξ1 = 25 M
ξ1 = 30 M
V = 0,52 M3

Fig. 2.

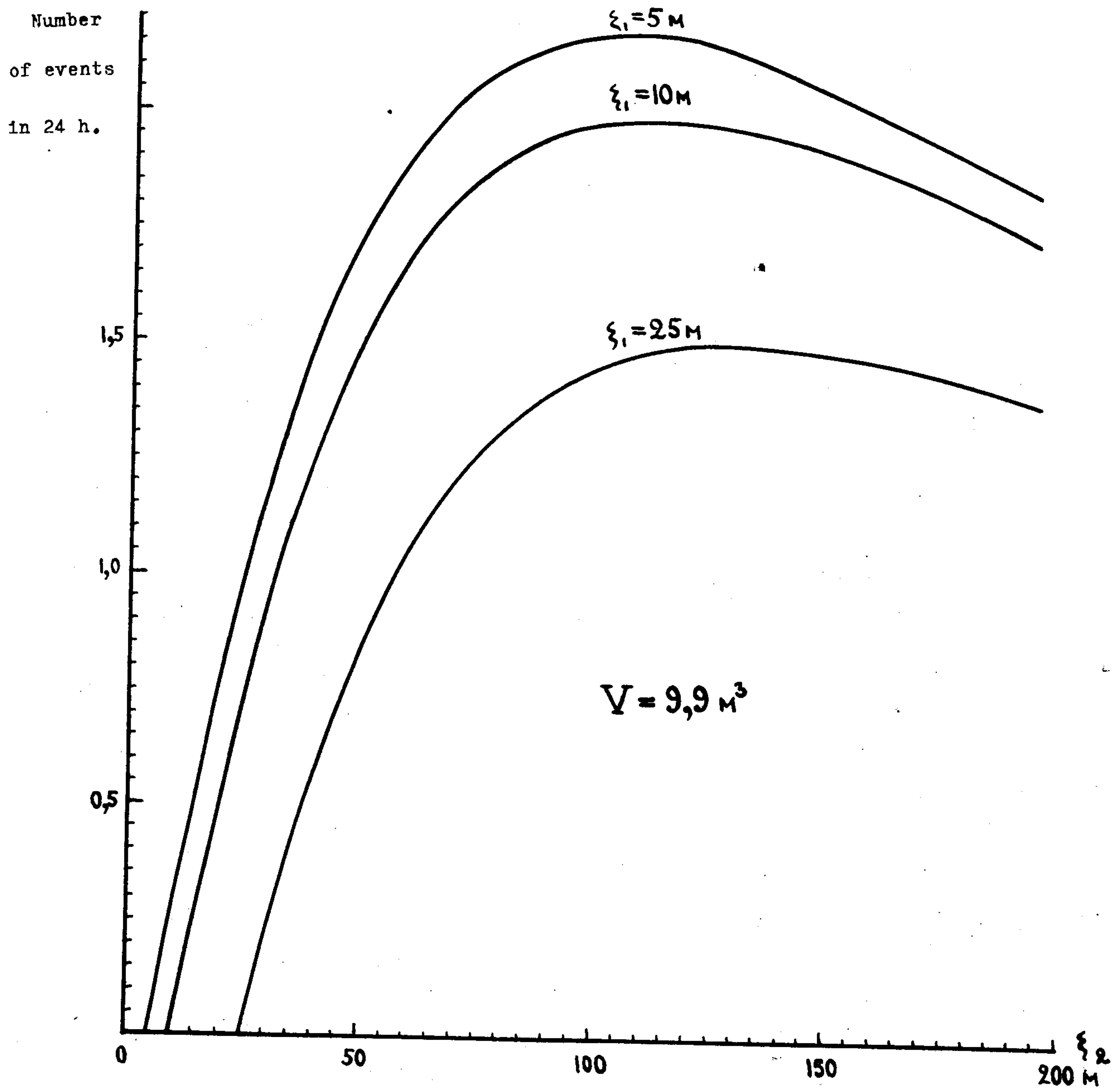

Number
of events
in 24 h.
$\xi_1=5$ м
$\xi_1=10$ м
$\xi_1=25$ м
1,5
1,0
0,5
0
50
100
150
200 м
ξ_2
$V = 9{,}9$ м^3

Fig. 3.

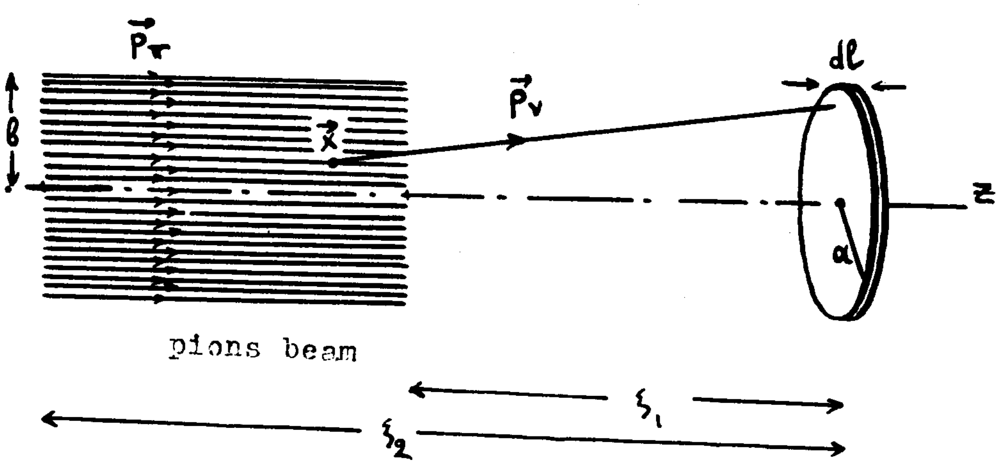


Fig. 4.

ON THE ROLE OF HIGH APPROXIMATIONS FOR WEAK FOUR-FERMION INTERACTIONS

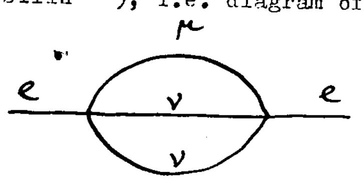
R.A. Asanov, B.N. Valuev

The applicability limit of the recent weak interactions theory on the basis of the analysis of different high effects over the interaction constant is discussed below.[1]

The quantitative estimations of these effects depend on the cut off the corresponding divergent integrals. The comparison with the experiment gives upper limits for the cut off momentum.

As it is known, weak interactions are well described in the first approximation of the perturbation theory over the constant G. It is explained by the smallness of the constant G, or, more exactly, by the smallness of dimensionless expansion parameter $Gk^2/(2\pi)^2$, here k - is the maximal virtual momentum ("cut off momentum").

The use of highly non-satisfactory "cut off" technique was for the present inevitable, as the four-fermion interaction theory is not renormalized in its present form. For the momenta $k \ll 1000\, m_N$, say, for $k \sim m_\pi$ or $k \sim m_N$, the smallness of the expansion parameter is provided. However, if only β -decay lengths $\sim 10^{-16}$ cm. are essential, the situation may change. The simplest indication on the length value 10^{-16} cm may be already obtained from the dimension considerations of the constant G, which requires the introduction of some length into the theory (the combination value $\sqrt{G_\beta/\hbar c}$ has the order of 10^{-16} cm). Then, some characteristic length may be obtained considering the correction to the proper electron mass on the account of the four-fermion interaction (V.P. Silin[2]), i.e. diagram of the form



that gives an addition in the scalar variant

$$\frac{\Delta m_e}{m_e} \cong G^2 k^4 \ln \frac{k}{m_e} ,$$

from where the electron "radius" ($r \sim \frac{1}{K}$, where K corresponds to $\left|\frac{\Delta m}{m}\right| \sim 1$), is due to such interaction, is also equal to $\sim 10^{-16}$ cm.

Let us note for comparison, that other lengths (excluding nucleon ones), which could appear in the theory, for instance, connected with the gravitational[3] or electrodynamical forces, have, apparently, much smaller value. In fact, the gravitational electron "radius" has the value of the order of 10^{-55} cm, and the electron "radius," is due to the electrodynamical forces, i.e. to the addition to the proper electron energy

$$\frac{\Delta m_e}{m_e} = \frac{3\alpha}{2\pi}\left(\ln\frac{k}{m_e} + \frac{1}{4}\right)$$

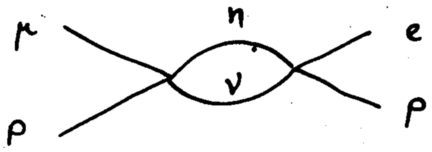
(Weisskopf[4])

has even smaller value $\sim 10^{-140}$ cm.

Thus, if the lengths $\ell \sim (10^{-16} \div 10^{-17})$ cm (and corresponding momenta $k \sim \frac{1}{\ell} \sim 1000\ m_N$) are really essential for weak interactions, the expansion parameter of the perturbation theory becomes close to the unit $\frac{Gk^2}{(2\pi)^2} \sim 1$ and it is clear, that in this case the high approximations cannot be negligible.

We shall try to consider, to what consequences such a situation would lead for low energy processes, using rough estimations over the value order, without taking into account the matrix structure of interaction. (Let us note, that account of high approximations does not lead to a change of the variant in the effective Hamiltonian for β -decay[5]). Note, that the conception $\frac{Gk^2}{(2\pi)^2} \sim 1$ could be attractive for the theory of universal Fermi interaction in the sense, that it would decrease the number of phenomenological Hamiltonians, explaining the interaction of all the currents j_α [6] between each other. At first, we shall accept, that only one kind of neutrino exists.

The possibility of investigation of the processes with the participation of strong interacting particles in the sense, which we are interested in, is apparently excluded as the result of the existence of the electromagnetic (Hofstadter[7]) nucleon formfactor, which will lead to the virtual momentum cut off at sufficiently low value ($\sim m_N/3$). In a case of absence of this formfactor the account of the second approximation, for $k \sim 1000\, m_N$, would give μ -meson transformation into the electron, for instance, on the proton, as the result of interaction of the form



The estimation of the second approximation gives

$$\frac{\sigma_{II}(\mu^- p \to e^- p)}{\sigma_I(\mu^- p \to n\tilde{\nu})} \approx \frac{G^2 k^4}{16\pi^4} \sim 1$$

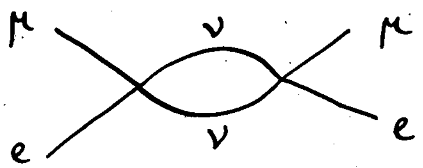
for $k \sim 1000\, m_N$,

while the experiment for this ratio gives

$$\frac{\sigma_{II}}{\sigma_I} \leqslant 5.10^{-4}$$ [8] .

Consequently, the experiment would already require the restriction by cut off momentum of the order of $k \leq 200\, m_N$, however, the "cut off" surely takes place even lower, because of the existence of Hofstadter formfactor.

Therefore, we shall take the processes with the participation of the particles μ, ν, e and photons only, which don't take part in strong interactions. The process of charge-exchange of muonium into antimuonium



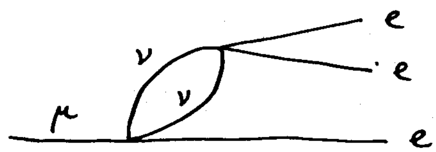
$$\mu^- \to e^- + \nu + \tilde{\nu}$$

with the following μ^- -meson decay was considered by B.M. Pontecorvo[9] . The estimations given by him correspond to the fact, that for the momentum $k_{max} \sim 10^3 m_N$ the probability of this process, relating to the probability of μ^+ -meson decay, which in general must determine the life-time of the primary system, is equal to

$$\frac{w\,(\mu^+e^- \to \mu^-e^+,\ \mu^- \to e^-\nu\tilde{\nu})}{w\,(\mu \to e\nu\tilde{\nu})} \sim 10^{-5}$$

that is apparently accessible to the experiment. In case of cut off $K \sim m_N$, this ratio is many orders smaller than ($\sim 10^{-20}$). It may be shown, that the prohibition of the transition $\mu^+e^- \to \mu^-e^+$, which could appear because of muonium and antimuonium mass difference in substance does not take place in fact. Thus, the experiment on the observation of muonium-charge-exchange is quite possible.

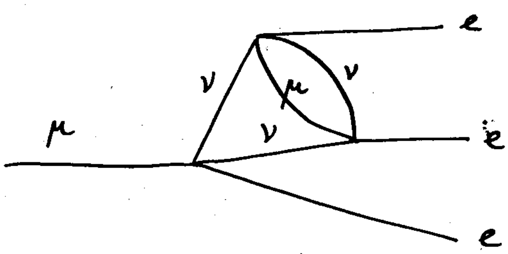
Let us consider the $\mu \to 3e$ decay process with the help of weak interactions. In the lowest approximation the diagram has the form



the estimation of the contribution of such a diagram gives:

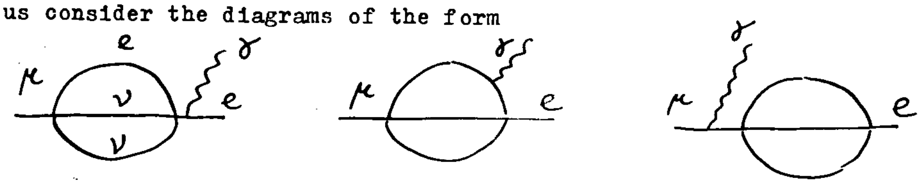
$$\frac{w(\mu \to 3e)}{w(\mu \to e\nu\tilde{\nu})} \approx \frac{G^2 K^4}{16\,\pi^4}$$

that for $K \sim 10^3 m_N$ is equal to ~ 1, being in an evident contradiction with the experiment. The experiment gives for this ratio the value: $\leqslant 4.10^{-6}$ [10] and it should be necessary to take $K_{max} \leqslant 60\, m_N$ for non-contradiction with the experiment. Note, that we supposed the existence of $(\bar{e}\nu)(\bar{\nu}e)$ interaction. However, diagrams with the participation of "real" vertices only are possible, for instance:



For $k \sim 10^3 m_N$ such diagrams also lead to the probabilities, exceeding those experimentally observed, but in this case k_{max} in formulae is of a higher degree.

Let us consider the diagrams of the form



leading to $\mu \rightarrow e + \gamma$ decay. The estimation of such diagrams gives for the probability of process $\mu \rightarrow e + \gamma$

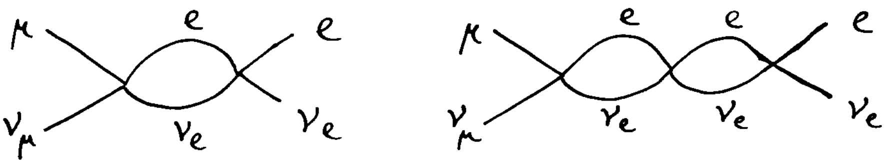
$$w \sim \frac{\alpha}{(4\pi)^4} (G\mu^2)^2 \left(\frac{Gk^2}{4\pi^2}\right)^2 \mu ,$$

here $\alpha = \frac{1}{137}$, μ is μ-meson mass. It is known experimentally, that $w_{\mu e \gamma} \leqslant 1\, sec^{-1}$ [11]. We get the estimation from here

$$k_{max} \lesssim 160\, m_N .$$

Thus it could seem that the experiment for the present doesn't confirm the supposition of the possibility of large intermediate momenta existence in weak interactions. It should be noted, however, that processes of the type $\mu^+ e^- \rightarrow \mu^- e^+$, $\mu \rightarrow 3e$, $\mu \rightarrow e + \gamma$ can be strictly prohibited for the other reasons, but not for the smallness of intermediate momentum. It would be enough for this, for instance, the existence of two kinds of neutrinoes ν_e and ν_μ each of them interacting together with electron or muon only[12]. In this case all the considered diagrams would be prohibited (except the proper energy diagrams of electron and muon). In the scheme of Feynman and Gell-Mann such processes are prohibited with the help of phenomenological prohibition at neutral currents of phenomenological prohibition at neutral currents j_α. As to the existence of two kinds of neutrinoes ν_e and ν_μ, such possibility in fact exists till now, and it is necessary to have special experiments to confirm the identity and non-identity of these kinds of neutrinoes. (In detail see B.M. Pontecorvo[13]).

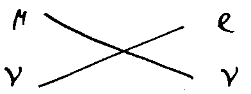
Let us take now the processes, in which the role of high approximations could influence even in the case of existence of two different kinds of neutrinoes ν_e and ν_μ. J. Smorodinsky's remark[14] may be essential for clearing out the role of high approximations in weak interactions. It is the following: the vector constant determined from O^{14}, and the constant, determined from decay $\mu \to e\nu\tilde{\nu}$ are known to be rather different from each other [6] (when electromagnetical corrections are introduced, this difference still more increases [16]). At the same time, as it was marked by Smorodinsky, the account of high approximations could influence the diference of effective constant. In fact, if the role of high approximation in the process $n \to p + e + \tilde{\nu}$ is apparently small, as the result of presence of strong interacting particles (that excludes the possibility of high intermediate momenta) in $\mu \to e\nu\tilde{\nu}$-decay they would surely play the role:

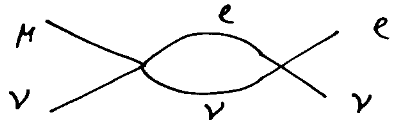


etc.

and it is essential, that the situation takes place not depending on the fact if two (muon and electron) or one kind of neutrinoes exist. Hence it follows, that μ -meson life-time observed experimentally, may differ from the time, which is computed theoretically in the first approximation with the use of constant G_V, determined from O^{14} decay. Let us estimate, what restriction this difference between τ_{exp} and τ_{theor} may put over the intermediate momentum, if to suppose that it is completely obliged to high approximations. Let us suppose, that the probability of the process $\mu \to e\nu\tilde{\nu}$ is determined only by the sum of two diagrams of the first and second orders, i.e.

$$w_{exp} = w_{I+II}$$

I 

II 

Then, supposing $G_{\mu e} = G_{ee}$

$$\frac{w_{I+II}}{w_I} = \left| 1 + G_{ee}\frac{k^2}{4\pi^2} \right|^2 = 1 + 2\cos\varphi \frac{|G|k^2}{4\pi^2} + \frac{|G|^2 k^4}{16\pi^4}$$

Using data $\frac{1}{w_{exp}} = 2,20 \cdot 10^{-6}$ sec. [15]

and $\frac{1}{w_{theor}} = \frac{1}{w_I} = 2,33 \cdot 10^{-6}$ sec. [16]

we must obtain

$$\frac{w_{I+II}}{w_I} = 1 + 0,06.$$

We shall obtain the hardest restriction for the maximal cut off momentum, if the phase G_{ee} is equal to zero, i.e. $\cos\varphi = 1$. Then $\frac{Gk^2}{4\pi^2} \lesssim 0,06$, hence $k_{max} \lesssim 300\, m_N$. For any other values of the phase φ, the estimation is less hard. However, the estimation is rather rough, neither higher approximations nor electromagnetical corrections are not taken into account here. Besides, the value τ_{theor} cannot be considered much reliable, as electromagnetical corrections to the vector constant 0[14], with the help of which the corrections to τ_{theor} are introduced, are obtained in the lowest approximation and when cut off is used, and therefore, they cannot be considered as absolutely certain [16] [17].

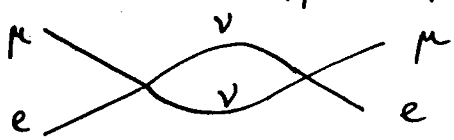
Resuming, we may say, that the analysis of the problem of existence of high momentum k_{max} by considering low-energy processes depends first of all on the difference or identity of muon and electron neutrinoes. Besides, the situation may change if the interaction between currents j_α is realised with the help of intermediate vector mesons [12] field; the hypothesis on their existence cannot be apparently rejected for the present.

The authors express their sincere gratitude to Prof. Markov for the settling of the problem and permanent courtesy.

Addition

In the recent paper by B.L. Ioffe [18] effects of high approximations for weak interactions were considered in more detail.

Restrictions on the cut off momentum, obtained in this paper rather differ from our estimations. These differences are caused by the fact, that some graphs, according to B.L. Ioffe, give a small contribution, while they are essential in our estimations. For instance, in case of a typical graph $(\mu^+e^- \rightarrow \mu^-e^+)$



it turns out, that this graph does not give the term $\sim k^2_{max}$.

We would like to note, that this result is not unconditional. In fact, the term $\sim k^2$ disappears, if to introduce the cut off in such a way, as in the case of photon proper energy in the electrodynamics, i.e. with the conservation of gauge invariance of the theory. But VA-theory in general has no such a property of symmetry, analogical to the gauge invariance in electrodynamics. (Even the condition $\partial V_\mu / \partial x_\mu = 0$ is not proved yet).

The above mentioned graph, taken separately, assumes such a symmetry approximately (i.e. for terms $\sim k^2$), but requirements to the introduction of cut off must include, generally speaking, only the conservation of symmetries, characteristic for all the theory on the whole.

We are thankful to B.L..Ioffe for discussion of this point.

References

1. M.A. Markow. Hyperonen und K-Mesonen, Verlag der Wissenschaften, Berlin, 1960.
2. V.P. Silin, JETP, 21, 462 (1951).
3. M.A. Markov, JETP, 17, 849 (1947).
4. V. Weisskopf, Phys.Rev., 56, 72 (1939).
5. B.N. Valuev, JETP, 36, 1578 (1959).
6. R. Feynman, M. Gell-Mann, Phys. Rev., 109, 193 (1958).
7. R. Hofstadter, Ann. Rev. Nucl. Sci., 7, 231 (1957).
8. S. Lokanathan, J. Steinberger, Phys. Rev., 100, 1490 (1955).
9. B.M. Pontecorvo, JETP, 33, 549 (1957).
10. R. Crittenden, W. Walker, I. Ballam
    IX International Conference on High Energy Physics, Kiev, 1959.
11. D. Berley, J. Lee, M. Bardon, Phys. Rev. Lett., 2, 357 (1958).
    T.O. Keefe, M. Rigby, J. Wormald, Proc. Phys. Soc., 73, 951 (1959).
    J. Ashkin, T. Fazzini, G. Fidecaro, N.H. Lipman, A.W. Merrison, H. Paul
    Nuovo Cimento, 14, 1266 (1959).
12. J. Schwinger, Ann. of Phys., 2, 407 (1957).
13. B.M. Pontecorvo, JETP, 37, 1751 (1959).
14. J.A. Smorodinsky, private information.
15. J. Fischer, B. Leontic, A. Lundby, R. Meunier, J.P. Stroot,
    Phys. Rev. Lett, 3, 349 (1959).
16. S.M. Berman, Phys. Rev., 112, 267 (1958).
17. J.A. Smorodinsky, Ho Tso-hsiu, JETP, 38, 1007 (1960).
18. B.L. Ioffe, JETP, 38, 1608 (1960).

Translated by O.M. Ivanova