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INCONSISTENCY BETWEEN THE THEORETICAL AND EXPERIMENTAL DELTA-SHOWER FREQUENCIES AT HIGH ENERGIES

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Experimental data on the frequency of high-energy δ-electron production are tabulated. Calculation of the frequency of small underground ionization bursts is carried out. All the data point to a contradiction between theory and experiment at energies $\geq 5 \times 10^8$ ev.

A hypothesis that the finite dimensions of the structure of the electric charge may manifest themselves in electromagnetic interactions at very high energies has been proposed and substantiated in a series of articles.[1] In connection with this, we have studied the currently available experimental data on δ-electron production by cosmic-ray μ-mesons in order to find out whether a systematic inconsistency exists between the experiment and the predictions of the present-day theory which assumes an elementary electric point charge.

The results of interest to us, obtained in experiments in which the energy of δ-electrons was directly measured, are given in Table I. The theoretically expected number of δ-electrons is given in the second column, the experimentally obtained number and the purely statistical error of the measurement in the third. In addition, the probability P_i of deviation of the experimental result from the theory (estimated by means of the error integral) is given in the fourth column of the table.

TABLE I. Summary of experimental data

Energy of secondary particles (Mev)	N_{theor}	$N_{\text{exp.}}$	P_i
Walker[2] δ-process			
Series A: $E_\delta \geqslant 100$	25	39 ± 6.3	0.04
$E_\delta \geqslant 200$	10.3	17 ± 4.1	0.10
Series B: $E_\delta \geqslant 100$	22.3	27 ± 5.2	0.35
$E_\delta \geqslant 200$	9.7	14 ± 3.8	0.25
Kannagara et al[3] δ-process			
$E_\delta \geqslant 100$	22.5*	27.5 ± 5.2	0.35
$E_\delta \geqslant 200$	10*	14 ± 3.8	0.28
Pair production: $E_{2\gamma} \geqslant 100$	16	23 ± 4.8	0.23
$E_{2\gamma} \geqslant 200$	8.5	18.5 ± 4.3	0.03
Trident production: $E_3 \geqslant 140$	10	16.2 ± 4.0	0.13

* Theoretical curve renormalized to the number of δ-electrons with energies between 100 and 300 Mev.

It can be seen that deviations of ~ 50 percent (towards higher values) exist both in the work of Walker[2] carried out at sea level with a cloud chamber and in that of Kannagara et al.,[3] who used photographic emulsions at the depth of 60 meters water equivalent (m.w.e.). If we also take into the account that the same situation exists for the processes of pair and trident production[3] we can maintain that either a systematic discrepancy exists between the theoretical and experimental results or that a highly improbable chance coherence of the results of several experiments has occurred.

A numerical-graphical computation of the frequency of ionization chamber bursts at the depth of 60 m.w.e. in the conditions of the experiment of George and Trent[4] was carried out by us in view of the conclusion reached by the authors about an agreement of theory and experiment, contradicting the data of Table I. The computation was carried out following formula (31.2) of Belen'kii's book.[5] The transition effect for electron-photon cascades developing in lead before attaining their maximum and then passing through the 12 mm thick aluminum walls of the ionization chamber, which decreases the number of particles in a shower by a factor of 2.5, was taken into account.

The vertical differential spectrum of μ-mesons at the depth of 60 m.w.e. was taken, following Refs. 3, 4, and 6, in the form

$$S(W)\,dW = 2 \cdot 10^{17} (W + 1.3 \cdot 10^{10})^{-3}\,dW \text{ particles/cm}^2 \cdot \text{sec} \cdot \text{sterad} \cdot \text{ev}.$$

Normalization of the spectrum was carried out according to the data of Owen and Wilson[7] at the point

$W = 10^{10}$ ev accounting for ionization losses (from sea level to the given depth) amounting to 1.4×10^{10} ev. Angular distribution of μ-mesons was assumed as $\sim \cos^2 \theta$.[6,8] The assumed normalization and angular distribution yield a total flux of μ-mesons smaller by ~ 15% than the value accepted in Refs. 3 and 9. Only the processes of production of δ-electrons and radiative photons were taken into the account in the calculation, and the cross-sections for these processes, following Rossi,[10] were taken for μ-mesons with mass $M = 209$ and spin $^1/_2$. The process of direct electron pair production by μ-mesons was disregarded; its contribution was found to be negligible (cf. Ref. 11). The intermediate result of the calcuations, in the form of δ-electron and radiative-photon spectra, is given in Table II.

The final theoretical result for the frequency of ionization bursts produced by showers with the number of particles in a burst $n \geq 20$, in the conditions of Ref. 4, is $B = 0.14$ bursts/hour, while the experiment yields the value $B = 0.54$ bursts/hour. The calculation shows that δ-electrons and radiative photons yield similar contributions to the frequency of bursts, the energy of these primaries being $\geq 4.5 \times 10^9$ ev. The contribution of nuclear disintegrations induced by μ-mesons is not greater than 0.01 bursts/hour, according to George and Trent's[4] and our estimates. The discrepancy between our theoretical result and that of Ref. 4 is mainly due to our accounting for the transition effect: since this effect decreases the number of particles in a shower by a factor of 2.5 and since the slope of the experimental curve of ionization-burst frequency vs. the number of particles in a burst has a power exponent 1.6 ± 0.2, the results will differ by $(2.5)^{1.6} \approx 4.3$

If we calculate, according to formula (29.21) and Table XVII of Belen'kii's book and with normalization of the μ-meson spectrum following Owen and Wilson,[7] the frequency of ionization bursts with number of particles $n \geq 25$ ($E_\delta \geq 2 \times 10^9$ ev) in the conditions of Ref. 12 where the frequency of bursts was measured at sea level in a spherical chamber shielded with lead, we shall obtain an analogous discrepancy between the theory and experiment: $B_{\text{theor}} = 17$ bursts/hour, $B_{\text{exp}} = 4-5$ bursts/hour. Further theoretical and experimental investigations are necessary to disclose the causes of this systematic inconsistency between the theoretical frequency of δ-showers and the experimental results at $E_\delta \gtrsim 10^9$ ev.

TABLE II. Calculated vertical differential spectrum of δ-electrons and radiative photons produced by μ-mesons in lead at the depth of 60 m.w.e. (57° N) (particles/cm^2·sec·sterad·ev)

E_δ, E_γ(eV)	N_γ	N_δ
10^8	$2,8\cdot10^{-16}$	$1,50\cdot10^{-14}$
$5\cdot10^8$	$4,0\cdot10^{-17}$	$4,4\cdot10^{-16}$
10^9	$1,6\cdot10^{-17}$	$8,60\cdot10^{-17}$
$4\cdot10^9$	$2,1\cdot10^{-18}$	$2,57\cdot10^{-18}$
10^{10}	$4,5\cdot10^{-19}$	$2.2\cdot10^{-19}$
$3\cdot10^{10}$	$4,5\cdot10^{-20}$	$8,0\cdot10^{-21}$
$6\cdot10^{11}$	$8,5\cdot10^{-21}$	$7,9\cdot10^{-22}$
10^{11}	$2,4\cdot10^{-21}$	$1,3\cdot10^{-22}$

It is interesting to note the following: δ-electrons of ~ 1 Bev are efficiently produced by μ-mesons of ~ 10 Bev. The estimate of the minimum impact parameter r between an electron and a μ-meson of ~ 10 Bev in a head-on collision yields

$$e^2/r = \sqrt{2m_e c^2 E_{\mu^-}}, \quad r \approx 1.4\cdot10^{-15} \text{ cm}.$$

It follows that the cross-section for the production of δ-electrons of ~ 1 Bev is roughly $\pi r^2 \approx 6 \times 10^{-30}$ cm^2. At energies ≥ 4.5 Bev the experiment yields a cross-section a few times larger (see above) than that predicted by theory and does not contradict the assumption that the value of the cross-section remains constant above ~ 1 Bev. The μ-meson—nucleon interaction cross section is of the same value (cf. Ref. 9) which, as it was shown by Fowler,[13] is also larger than the theoretical. It is possible that the finite structure of the electric charge, of dimension $\sim 10^{-15}$ cm, manifests itself in the numerical equality of both cross-sections and their common discrepancy with the theoretical values, the cross-sections reaching in both cases their minimal "geometrical" value[13] determined by the new forces of such a structure.

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NONLINEAR MESON FIELD EQUATIONS

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All possible variants of pseudoscalar mesodynamics with third-order self-action are considered. Asymptotic expressions are obtained for the nonrelativistic potentials of point nucleons. Studies are also made of the solutions of the resulting nonlinear equations that correspond to plane waves, and of the question of the definite character of the energy density.

THE introduction of nonrenormalizable nonlinear equations into the quantum field theory seems to be the only promising way of overcoming a number of difficulties in the present mesodynamics and meson theory of nuclear forces. The different values of the coupling constant $g^2/\hbar c$ obtained from various experiments on the interaction of nucleons give a quite definite indication that the interaction of nucleons is a nonlinear one, and that the value of the coupling constant is always an effective value depending on the nature of the experiment. Also it is hardly possible to give a convincing explanation of the fact of the saturation of nuclear forces outside the framework of a nonlinear theory.

In the present paper we consider nonlinearities in the equations of the meson field in the form of terms of third order with respect to φ. Out of all possible forms of such self-action, that of the type $\lambda\varphi^3$, and the associated Schiff equation[1 — 3]

$$(\Box^2 - k_0^2 - \lambda\varphi^2)\,\varphi = 0.$$

have been studied in more or less detail.

Here consideration is given to all possible variants of pseudoscalar mesodynamics with third-order self-action. Asymptotic expressions are obtained for the nonrelativistic potentials of point nucleons for the various types of self-action. They all show the presence of movable singularities for a definite sign of λ. The conditions for saturation are examined in connection with the sign of λ. Studies are also made of the wave solutions of the nonlinear equations that correspond to plane waves, and of the question of the definiteness of the energy density.

1. GENERAL RELATIONS

The initial assumptions adopted are as follows:

(1) General covariance of all equations in the four-dimensional space; (2) conservation of energy and momentum in the free field; (3) the possibility of the passage to the limit $k_0 \to 0$ for arbitrary nonlinearities without the appearance of additional divergences.