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SCALING DESCRIPTION OF ELECTROMAGNETIC CASCADES PRODUCED BY HIGH ENERGY GAMMA QUANTA IN DENSE AMORPHOUS MEDIA[2]

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I. INTRODUCTION

A gamma quantum (or, shortly, a photon) of high energy (i.e. $E_\gamma > 100$ MeV) passing through dense enough medium creates an electron-positron pair and, next, the produced particles emit photons, either of them of sufficiently high energy, initiating this way the process of electromagnetic cascade (or a shower). The analytical approach to the description of this process [1] is valid at very high energies of primary photons (or electrons and positrons) and for light media only (in particular, for air and water). On the other hand, the computer simulation of electromagnetic cascades [2] which has proved to be quite successful gives fragmentary numerical information about this process and requires, as a rule, a lot of time of big computers. So, the problem still exists to describe the main characteristics of the phenomenon under discussion in the concise form of simple formulas suitable for different practical applications [3]. Such a problem is to be solved in the quite satisfactory way using the 180 liter Xenon Bubble Chamber (XeBC) [4] as a shower detector. In this work we briefly report the results of the analysis of longitudinal and transverse distributions of ionization loss as well as their fluctuations in electromagnetic cascades produced in liquid xenon by gamma -quanta of energy E_γ = 200-3500 MeV. The former experimental material has been obtained from the pictures of the XeBC exposed to the beam of π^- mesons with the momentum of 3.5 GeV/c.

II. EXPERIMENT

The 180 liter XeBC of the ITEP (Moscow), the pictures of which have been used for the purpose of this work, permits to analyse in detail every single event of a cascade registered on the pictures and at the same

time it has very large dimensions in radiation lengths (10x11x25) allowing to study electromagnetic cascades up to about 4 GeV of primary photon energy. So, for all events of cascades selected in the pictures and satisfying the appropriate criteria, summary plane projection ranges of shower electrons and positrons (later: electrons), $\Delta\Sigma r(E_\gamma,t,p)/\Delta t\Delta p$, were measured in the picture plane using a grid of the cell size in radiation lengths: $\Delta t = 0.6$ along the shower axis and $\Delta p = 0.3$ in its perpendicular direction. As has been shown [3] these ranges are proportional to the relevant ionization loss of cascade electrons $\Delta\Sigma E(E_\gamma,t,p)/\Delta t\Delta p$ to an accuracy of ~3 % . The total number 908 of selected and measured events was devided into 22 intervals of energy E_γ in such a way that relative widths of these intervals $\Delta E_\gamma/E_\gamma$ are approximately equal to 0.1 which roughly corresponds to the precision of the determination of gamma quanta energy in the XeBC. Therefore, having the measured values $\Delta\Sigma E(E_\gamma,t,p)/\Delta t\Delta p$ one can easily obtain the longitudinal distribution (or profile) of ionization loss in cascades as a sum $f_t(t/E_\gamma) = \Sigma[\Delta\Sigma E(E_\gamma,t,p)/\Delta t\Delta p]\Delta p$ and, similarly, the transverse distribution in the picture plane $f_p(p/t,E_\gamma) = \Sigma[\Delta\Sigma E(E_\gamma,t,p)/\Delta t\Delta p]\Delta t$. Next, the experimental distributions have been fitted to the simplest analytical functions convenient for practical applications.

III. LONGITUDINAL PROFILE

Fig.1 shows six among 22 analysed longitudinal distributions of ionization loss in electromagnetic cascades created in liquid xenon by gamma quanta of energy E_γ. If the average cascade depth $\bar{t}(E_\gamma)$ is taken as a scaling depth parameter then these distributions coincide within experimental errors, at least at $E_\gamma \geq 500$ MeV, as demonstrated in Fig.2. So, the conclusion may be drawn that the longitudinal shower profile displays a clear scaling with the energy E_γ and therefore it may be represented as some universal form while the energy and material dependence is contained in the parameter $\bar{t}(E_\gamma)$. The distribution averaged over the energy interval 500-3500 MeV and normalized to unity is depicted in Fig.3 together with the fitting function

$$F_1(x) = a_1 x^{a_2} \exp(-a_3 x) \qquad (1)$$

shown as a solid line. Here $x = t/\bar{t}(E_\gamma)$ and $a_1 = 83.1 \pm 3.4$, $a_2 = 1.65$

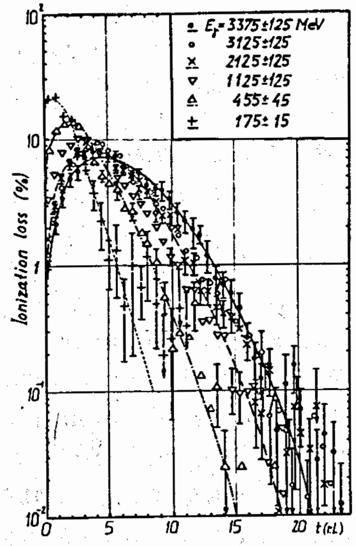

Fig.1. Longitudinal distribution of average ionization loss in e.m.cascades produced by gamma quanta of energy E_γ in liquid xenon.

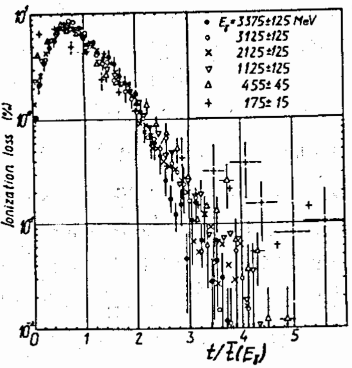

Fig.2. Same as fig.1 but as a function of the ratio $t/\bar{t}(E_\gamma)$ of the depth t and the average shower depth $t(E_\gamma)$.

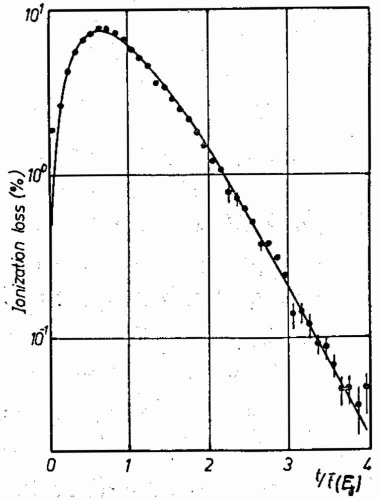

Fig.3. Same as fig.2 but averaged over the range of E_γ = 500–3500 MeV.

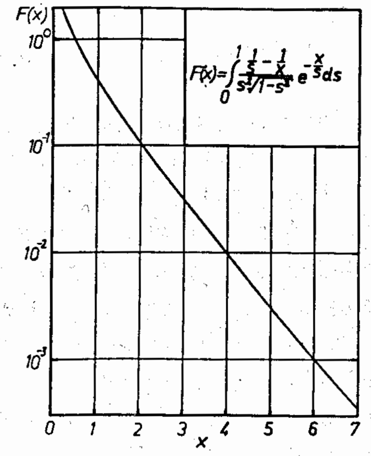

Fig.4. Radial dependence of the density of cascade electron ionization loss.

+/- 0.03 and a_3 = 2.62 +/- 0.03 at χ^2_{35} = 35.8 when $x \gtrsim 0.15$. The energy dependence of $t(E_\gamma)$ is fitted to the linear function of $\ln E_\gamma$:

$$\bar{t}(E_\gamma) = a_t + b_t \ln E_\gamma, \qquad (2)$$

where a_t = - 4.84+/-0.09 rad.length and b_t = 1.32+/-0.03 (E_γ is in MeV).

III. TRANSVERSE PROFILE

The similar way in principle, but much more complicated as above, has been used to describe the transverse shower profile. We summarize here the results only. So, taking into account the evident condition of the axial symmetry of ionization loss, i.e. its symmetric, on the average, deposition around the cascade axis, one can express the radial distribution $F_r(r/t,E_\gamma)$ of average ionization loss in electromagnetic cascades by means of some universal again function

$$F(x) = \int_0^1 \left(\frac{1}{s} - \frac{1}{x}\right) s^{-2} \frac{\exp(-x/s)}{\sqrt{1-s^2}} ds \qquad (3)$$

as follows [3]:

$$F_r(r/t, E_\gamma) = [\pi p^2(t, E_\gamma)]^{-1} F(x), \qquad (4)$$

where $x = r/p(t,E_\gamma)$ and the average width of a cascade at its depth t

$$p(t, E_\gamma) = \alpha + \beta(E_\gamma) t \qquad (5)$$

contains all information about the energy and material dependence. The values α and β are described in [3]. The universal function of radial distribution of ionization loss in electromagnetic cascades is displayed in Fig.4.

IV. FLUCTUATIONS

It turned out that both the longitudinal and transverse fluctuations of ionization loss of shower electrons are to be presented in the form of simple formulas when expressed by the following dimensionless parameters: the standard deviation $\sigma_A^{(t)}$ of a part A of total ionization loss at the shower depth, at which on the average the part A of this loss was released, and the similar quantity characterizing transverse fluctuations. We have found that [3]:

$$\sigma_A^{(t)} = A[\sqrt{\alpha_t^2 + \beta_t(\gamma_t - A)} - \alpha_t], \qquad (6)$$

where α_t = 0.038 +/- 0.001, β_t = 0.166 +/- 0.005 and γ_t = 1.01 +/- 0.01. Moreover, the part A obeys the normal distribution with the mean value $\bar{A}$, at least at $\bar{A} \gtrsim 0.5$.

Transverse fluctuations also display scaling-like behaviour when expressed by means of similar as above standard deviation [3].

V. CONCLUDING REMARKS

Our investigation has shown that the electromagnetic cascade initiated in amorphous medium by high energy photons reveals interesting and practically useful scaling properties allowing to describe its main characteristics in the form of simple formulas, in which one can single out some general features of the phenomenon itself given by certain universal functions, and the scaling parameters containing the energy and material dependence. Such a representation does not follows, of course, neither from a concrete kind of interaction (e.g. electromagnetic or nuclear), nor from any properties of a material used (if amorphous and homogenius) but it seems most probably to be a consequence of the multiparticle nature of the phenomenon under consideration and, therefore, the vanishing correlations between constituent elementary acts of interaction. If so, then other many-particle processes occurring within macroscopic volumes should admit such a representation, too. Indeed, the first attempts to analyse in this way the characteristics of high energy electronuclear cascade developing in heavy materials provided promissing results [5]. The aforesaid suggests that this approach may also be fruitful in the case of penetration of high energy ions into solids.

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