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SCALING STRUCTURE OF ELECTROMAGNETIC CASCADES IN DENSE AMORPHOUS MEDIA

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I. INTRODUCTION

The ionization energy deposition profile of electromagnetic cascades (or showers) produced by high energy gamma quanta or electrons in dense amorphous materials is of special interest from the practical point of view. In particular, the longitudinal deposition, also called a longitudinal cascade profile (LP), measured in the form of average ionization energy losses, is the most often experimentally studied characteristic of the phenomenon. At the same time it is the simplest one among all basic shower features for experimental determination and reveals useful scaling property when the shower depth is expressed in units of average shower depth (ASD) depending linearly on energy of a primary particle initiating the shower, as well as on parameters of material in which the cascade is released [1]. The similar property of the LP has been established using another scaling parameter, too [2].

In the present work we analyse the experimental data concerning the LP of cascades induced in liquid xenon by gamma quanta (or photons) of energy range from 100 to 3375 MeV [1] and the cascades created by electrons of energy from 2 GeV to 512 GeV [3,4,8] in lead, and from 4 GeV to 49 GeV in tungsten [5]. The main purpose of this study is to investigate the similarity of these distributions and to search for a relevant scaling factor. Analysed are as well the energy and material dependence of ASD which is very important gauge parameter of cascades. Another urgent problem concerns the dependence of LPs on cut-off energy of cascade electrons because in different experiments and Monte Carlo calculations this parameter is often assumed to have different values [1,3,4].

II. SCALING BEHAVIOUR OF LONGITUDINAL SHOWER PROFILES

It was found that the LP of showers produced by gamma quanta of energy $E\gamma$ from the interval ~500 - 3350 MeV in liquid xenon do not differ from each other within experimental errors of several percent if the shower depth t is expressed not simply in unit of radiation length (r.l.) but in terms of dimension-less parameter $x = t/\langle t(E\gamma)\rangle$ [1], where $\langle t(E\gamma)\rangle$ is the ASR at energy $E\gamma$ of primary photons.

The longitudinal shower profiles have also been studied in beams of electrons of energy up to 512 GeV in lead (E_e = 2 - 15 and 512 GeV [2]), and up to 49 GeV in tungsten (E_e = 4 - 49 GeV [4]). From the analogous analysis of the experimental data one can draw the similar as above conclusion: the LPs as a function of dimension-less cascade depth do not reveal the dependence on primary particle energy E to an average accuracy of about several percent [6].

III. ENERGY DEPENDENCE OF AVERAGE SHOWER DEPTH

The energy dependence of the ASD for electromagnetic cascades created by gamma quanta in liquid xenon and electrons in lead and tungsten is shown in Figs.1-3, respectively. The former experimental data have been taken from [3,4]. Straight lines on these figures represent the approximation function of the form:

$$\langle t(E_\gamma)\rangle = a_t + b_t{}^* \ln E_\gamma \qquad (1)$$

for liquid xenon, where a_t=-4.8 ± 0.1, b_t=1.32 ± 0.03, and for lead and tungsten

$$\langle t(E)\rangle = a_t + b_t{}^* \ln E, \qquad (2)$$

where a_t = -1.5 ± 0.5, b_t = 1.01 ± 0.03 (for lead [3,4]), and a_t = 8.4 ± 0.5, b_t = 0.45 ± 0.17 (for tungsten [5]). In all cases the ASD is in r.l. and the energy is expressed in MeV.

Note that the linear dependence of the form (1) and (2) also follows from the approximation B of cascade theory [7].

IV. MATERIAL DEPENDENCE OF AVERAGE SHOWER DEPTH

The slope parameter b_t in formulas (2) and (3) contains information about the medium in which a cascade is induced. Because the process of energy loss of cascade electrons (and positrons) in electromagnetic showers is mainly due to their interaction with electrons of the medium, the concentration of medium electrons ρZ or its relative value $\rho Z/A$ (where ρ is a density of the material, Z and A are its atomic and mass numbers) should be taken as the most appropriate parameter describing the material dependence of the ASD. The results of examination of the dependence of the parameter b_t on ρZ and $\rho Z/A$ are depicted in figs. 5 and 6 respectively. One can see that the parameter b_t (and consequently the ASR) significantly decrease with increasing the value both of the medium electrons concentration ρZ and its relative value $\rho Z/A$ as well.

V. CUT-OFF ENERGY DEPENDENCE OF LONGITUDINAL SHOWER PROFILES

Since in different experiments (and computer simulations) different values of cut-off energy E_c are admitted (usually from ~1 to ~7 MeV), it is interesting to study the corresponding dependence of longitudinal ionization loss distributions in electromagnetic showers. The results of comparison of two sets of experimental data are shown in the Fig.7. The former experimental results for showers generated in lead by electrons of energy E = 6 GeV have been obtained for from [3,8].

The solid lines represent the approximating function:

$$F_t(t|E_c) = a_1 t^{a_2} \exp(-a_3 t) \qquad (3)$$

where the fitted parameters a_1, a_2 and a_3 corresponding to two different values of the cut-off energy E_c are given in Table 1 together with relevant values of χ^2/n test statistics.

Table 1

a_1	a_2	a_3	χ^2/n	E_c (MeV)	ref.
7.19±0.36	**2.33±0.55**	**0.462±0.08**	**16.0/8**	**7.4**	**[2]**
1.83±0.18	**2.86±0.94**	**0.424±0.01**	**2.0/8**	**1.5**	**[7]**

In both cases we have set the relative errors of experimental data [2,7] to be ~10 %.

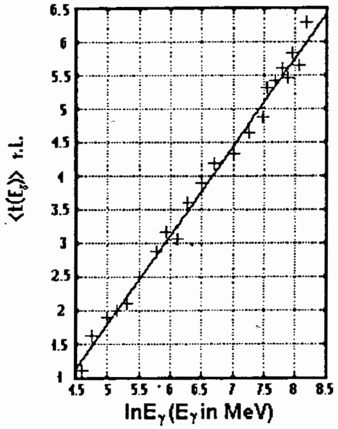

Fig.1. Average shower depth of cascades produced in liquid xenon by gamma quanta of energy E_γ [1].

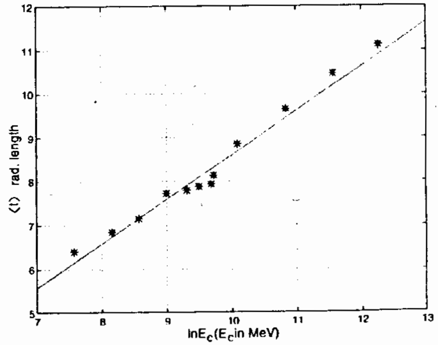

Fig.2. Same as in Fig.1 but for electrons in lead [3,4].

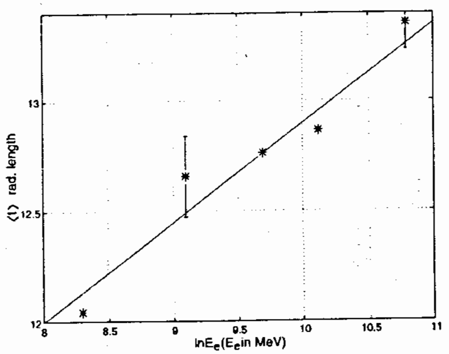

Fig.3. Same as in Fig.1 but for electrons in tungsten [5].

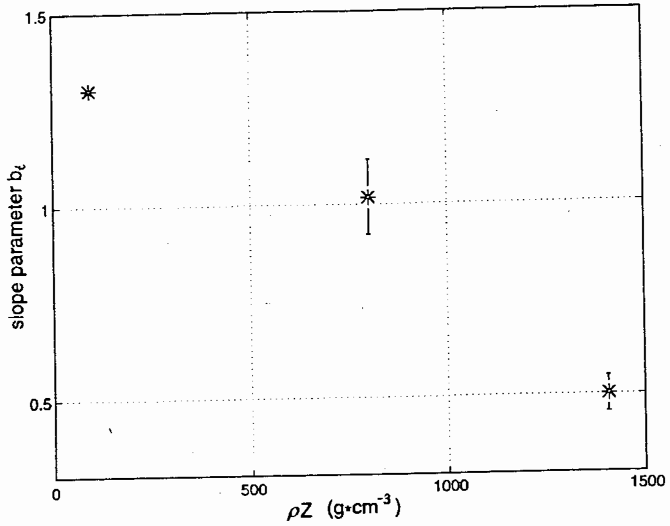

Fig.4. Dependence of the slope parameter b_t of the formula (4) on the electron density of shower absorber ρZ.

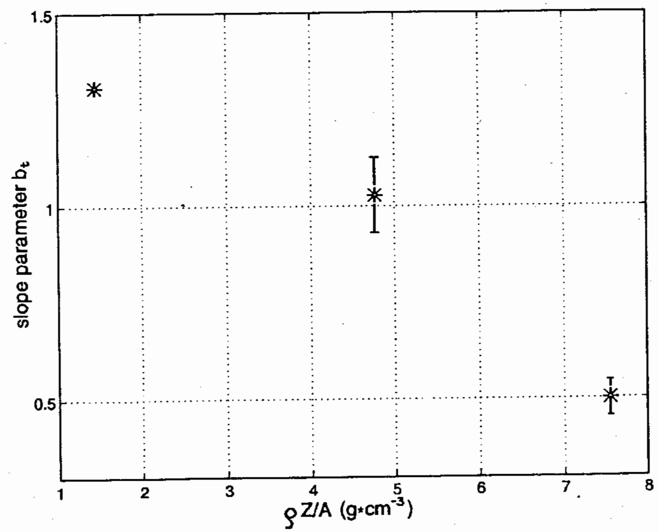

Fig.5. Same as Fig.4 but as a function of the relative electron density ρZ/A.

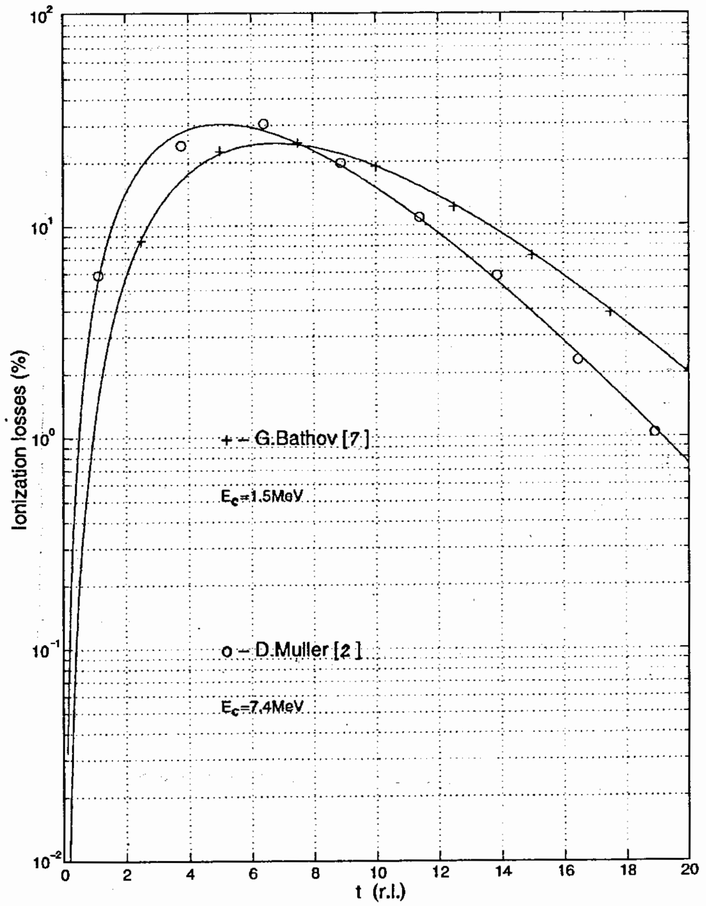

Fig.6. Longitudinal distribution of average ionization loss in showers produced by electrons with energy of E=6GeV in lead at two different values of cut-off energy of cascade electrons [2,7].

VI. CONCLUSIONS.

The analysis of the experimental results concerning the longitudinal profiles of electromagnetic cascades produced in lead, tungsten and liquid xenon shows that:

- the average shower depth <t(E)> is a good enough scaling parameter for longitudinal shower profiles in wide range of energy of cascade initiating particle in different materials. This parameter makes these profiles energy independent to an accuracy of about several percent,
- the scaling parameter <t(E)> significantly decrease with decreasing the relative electron density of the material in which the shower is developed,
- the longitudinal profiles of showers induced by electrons of the same energy in the same material remarkably depend on the cut-off energy E_c , i.e. the showers observed at higher values of E_c vanish much quicker inside the same material,
- further investigations of both the scaling parameter and cut-off energy dependence of longitudinal shower profiles need more experimental data about showers generated in different media by primary particles within wide energy interval and registered at different cut-off energies E_c as well as the relevant results of Monte Carlo simulation of such process to improve the noticed profile dependencies. Collecting data for these purposes using the EGS4 code system [9] is in progress.

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