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Three techniques for measuring electrons in the range of high (10^{11} – 10^{13} eV) energies by a single instrument

N. Grigorov and E. Tolstaya

Skobeltsyn Institute of Nuclear Physics, Moscow State University 119899, Moscow, Russia

Abstract . The possibility of using a thick ionization calorimeter for measuring high energy electrons using three different techniques is discussed. The three techniques are: 1) proton rejection to the level of 10^{-5} ; 2) measuring of electron imitations by protons with further account; 3) a technique, eliminating the impact of electron imitations by protons.

1 Introduction

The difficulty in measuring electrons with energies ~1 TeV is caused by two circumstances.

The first difficulty is caused by the low flux of such electrons. Thus, the electron flux with $E_e \geq 1$ TeV is equal to ~2.5 10^{-5} $m^{-2}s^{-1}sr^{-1}$. Therefore, for measuring such electrons large area instruments and prolonged exposures outside the atmosphere are required.

The second difficulty is due to the fact, that the flux of protons with energies $E \geq 1$ TeV exceeds the electron flux of the same energy by a factor of ~2000. (see Table 1.) The protons with $E > 1$ TeV, interact with the instrument material, producing γ-quants, which can be recorded by the instrument as high energy electrons. In other words the protons can imitate electrons.

If the instrument does not distinguish between these imitations and electrons, it will record the sum $N = N_e + N_{im}$, where N_e is the number of electrons, and N_{im} is the number of electron imitations. At $N_{im} \geq N_e$ there will be an overestimated number of electrons. Therefore, the second difficulty is to ensure $N_{im} << N_e$.

In order to distinguish between electrons and imitations, the instrument should provide information on those parameters of the cascade which are typical for electron cascades. These parameters are the following:

1). The electron cascade begins in the first 2÷4 cascade lengths of the material.

2). The electron shower has one maximum at the depth of t_m cascade lengths , where $t_m = \ln(E/E_{cr})$, where E_{cr} is the critical energy.

3). The number of particles in the cascade maximum N_m is unambiguously connected with the electron energy.

$$N_m = \eta \frac{E/E_{cr}}{\sqrt{\ln(E/E_{cr})}} = \eta \frac{s}{\sqrt{\ln s}}, \text{ where } s = \int_0^\infty N(t)dt$$

4). The electron cascade has limited length in matter. At the depth of 18÷22 cascade lengths after maximum the number of particles $N(t) \leq 0.01 N_m$. Hence, the full length of the electron cascade can be estimated as $t_m + (18 \div 22$ casc. lengths). (18 cascade lengths correspond to E =10^9 eV; 22 cascade lengths correspond to E =10^{13} eV.)

5). The dependence $N(t)$ for an electron cascade is accurately described by the cascade theory and if the experimental dependence $N(t)$ does not coincide with the calculated one, then the primary particle, which induced the shower is not an electron.

All the considerations which will follow concern an instrument which is a sufficiently thick ionization calorimeter (IC).

The IC has two lead plates each of them ~2 cascade lengths thick, in which the electron cascades initiate.

2 The techniques for calculating the number of electron imitations by protons

We can calculate the number of proton interactions, imitating primary electrons with energies ε , $\varepsilon + d\varepsilon$ in an

Correspondence to: E.Tolstaya (katya@srdlan.npi.msu.su)

instrument with geometry factor Γ during exposure time T. If $J_p(E_0)dE_0$ is the intensity of protons with energy E_0, E_0+dE_0 and they interact in a layer of Δt cascade lengths thick, transferring the energy of $\varepsilon, \varepsilon+d\varepsilon$ ($\varepsilon=\sum E_\gamma$) to the electron-photon component, then the number of such interactions will be equal to :

$$N(\varepsilon)d\varepsilon=\int_0^\infty j_p(E_0)\Gamma\mathrm{T}\frac{\Delta t}{\lambda_p}f(E_0,\varepsilon)d\varepsilon dE_0$$

$$=\Gamma\mathrm{T}\frac{\Delta t}{\lambda_p}J_p(\varepsilon)<K_\gamma^{\beta-1}>d\varepsilon$$

where λ_p is the proton mean free path for inelastic interactions, $f(E_0,\varepsilon)d\varepsilon$ is the probability for a proton with energy E_0 to transfer the energy of $\sum E_\gamma=\varepsilon$, $\varepsilon+d\varepsilon$, to the electron component in one interaction; $K_\gamma=\varepsilon/E_0$, and β is the proton spectrum index.

$N(\varepsilon)$ is not the number of electron imitations, but the number of cascades with energy $\varepsilon,\varepsilon+d\varepsilon$, beginning in a Δt layer. From these cascades we need to chose the ones with cascade length l not more than t_m+22 cascade lengths. Let us assume that their fraction is P_1. Apart from that, from the cascades which have the lengths $l\le t_m$+22 we need to select those which have $N(t)$ corresponding to the cascade curve from an electron with energy ε. Let us assume their fraction to be P_2. Then $N(\varepsilon)P_1P_2d\varepsilon=N_{im}(\varepsilon)d\varepsilon$ will be the fraction of cascades, imitating electrons with energy $\varepsilon,\varepsilon+d\varepsilon$. Hence, $N_{im}(\varepsilon)=J_p(\varepsilon)\Gamma\mathrm{T}\frac{\Delta t}{\lambda_p}\cdot\left\langle K_\gamma^{\beta-1}\right\rangle P_1P_2$.

We can estimate the values in this expression. In lead $\lambda_p=$ 195 g/cm^2=30 cascade lengths, Δt =4 cascade lengths. For β=3.0 we obtain $\left\langle K_\gamma^{\beta-1}\right\rangle\approx 6\cdot10^{-2}$. Hence, $\frac{\Delta t}{\lambda_p}\left\langle K_\gamma^{\beta-1}\right\rangle$=$8\cdot10^{-3}$.

The value P_1 was estimated according to the following experimental fact. We considered 79 cascades, induced by a proton with E >2 TeV in the ionization calorimeter of the 'Sokol' instrument. In these cascades only one had at the distance of 32 cascade lengths from its beginning the number of particles $N(t)=0.03N_m$. The other 78 cascades at this depth had $N(t)>>0.03N_m$. From these data it follows, that $P_1\approx 1/79\approx 1.3\cdot10^{-2}$, Therefore,

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$$N_{im}(\varepsilon)d\varepsilon\le J_p(\varepsilon)d\varepsilon\Gamma\mathrm{T}\cdot8\cdot10^{-3}\cdot1.3\cdot10^{-2}P_2=10^{-4}\Gamma\mathrm{T}J_p(\varepsilon)P_2d\varepsilon$$

The number of galactic electrons with energy $\varepsilon,\varepsilon+d\varepsilon$, for the same measurement conditions $N_e(\varepsilon)d\varepsilon$ will be equal to: $N_e(\varepsilon)d\varepsilon=\Gamma\mathrm{T}J_e(\varepsilon)d\varepsilon$. If in the energy range $E>1$ TeV the spectral indices of protons β_p and electrons β_e are the same, then $J_e(\varepsilon)=J_p(\varepsilon)/2\cdot10^3$, i.e. $N_e(\varepsilon)d\varepsilon=5\cdot10^{-4}J_p(\varepsilon)\Gamma\mathrm{T}d\varepsilon$, and

$$\frac{N_{im}(\varepsilon)}{N_e(\varepsilon)}=\frac{10^{-4}J_p(\varepsilon)\Gamma\mathrm{T}P_2}{5\cdot10^{-4}J_p(\varepsilon)\Gamma\mathrm{T}}=\frac{1}{5}P_2.$$

The value of P_2 is difficult to estimate, since the notion 'correspondence of the cascade curve $N(t)$ to the electron cascade' is rather uncertain : due to experimental errors this notion will inevitably be subjective. Therefore, we accepted the following approach. For an electron-induced cascade we can introduce the coefficient $\eta_e=\frac{N_m\sqrt{\ln s}}{s}=const$ (if the cascade develops in lead, then $\eta_e=0.27$).

If the cascade is induced by a proton with total energy $\sum E_\gamma$, then for such a cascade $\eta_p>\eta_e$ for electron energies $E_e=\sum E_\gamma$. Therefore, for an experimental cascade, induced by a proton (i.e. a group of γ-quants) we determine η_p and compare this value with η_e. It turned out, that at $\eta_p/\eta_e\ge1.10$ the cascade induced by the sum of γ- quants, unconditionally differs from the electron cascade (Fig.1. shows the electron (curve 1) and proton (curve 2) induced cascades for different values of η_p/η_e.)

For the considered 42 proton interaction events, obtained via computer simulation of $E_p=$ 10 TeV interactions with lead nuclei *, only in 6 cases $\eta_p/\eta_e\le1.10$. Therefore, the value P_2 can be estimated as 6/42≈0.14. Therefore, $\frac{N_{im}}{N_e}\cong\frac{0.14}{5}\approx3\cdot10^{-2}$.

A thick IC permits to use a different technique for separating electrons and protons, which is also suitable in

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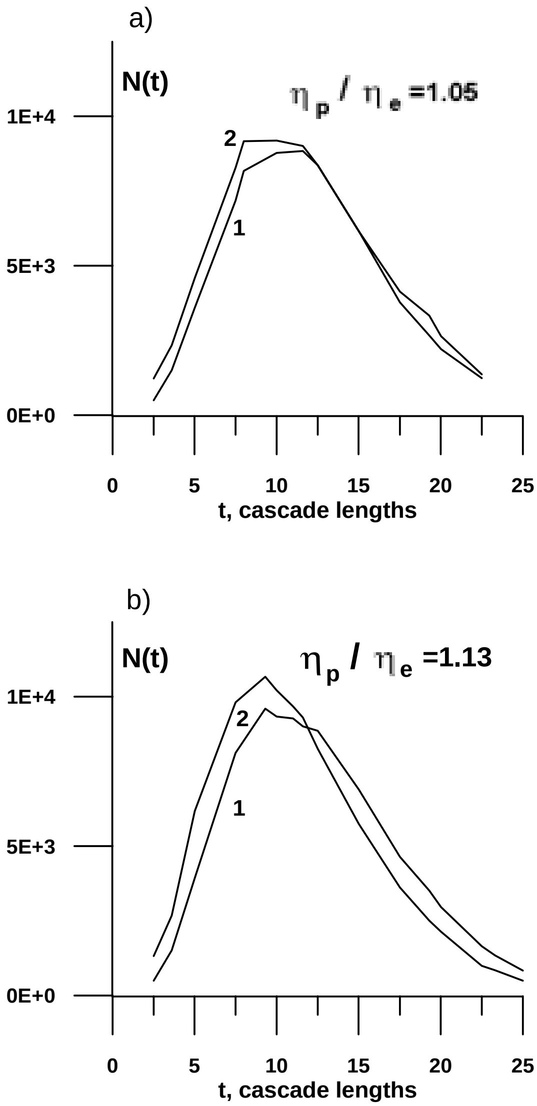

Fig.1. Comparison of cascade curves in lead : 1- induced by one electron with $E_e \approx$ 1 TeV, and 2 induced by several γ -quants (a proton) with $\sum E_\gamma = E_e$ for different values of η_p / η_e. =1.05 - panel a) and η_p / η_e =1.13 - panel b).

the case when $N_{im} \geq N_e$. In this technique all the cascades, induced by primary particles with Z =1 and satisfying criteria '2' and '4' are selected. For these cascades we plot the distribution of the number of cascades $N(x)$, starting in the ionization calorimeter at the depth of $x \geq 5$ cascade lengths. Obviously, all these events, starting at the depth of $x > 5$ cascade lengths are imitations. Their distribution should have the form $N_{im}(t) = ce^{-t/\lambda_p}$, where λ_p is the mean free path for proton inelastic interactions (in cascade lengths) in the IC. If we normalize the 'c' coefficient in such a way, that $N_{im}(t)$ is the number of imitations in the layer $\Delta t = 4$ cascade lengths at the depth of t, then the obtained dependence $N_{im}(t)$, extrapolated to t =0, gives the number of electron imitations in two lead plates, located at the IC boundary.

In reality N_0 cascades, which satisfy the selection criteria originate in these two lead plates, since all electron cascades satisfy the imposed criterea and all of them originate in the two lead plates. Therefore, $N_0 = N_e + N_{im}$ and $N_e = N_0 - N_{im}$. The value of $N_{im}(t=0)$ is known, N_0 has been measured, thus we can determine N_e. The statistical error of the number of electrons, determined in this way will be:

$$\sigma(N_e) = \sqrt{N_0 + N_{im}(t=0)} = \\ = \sqrt{N_e + 2N_{im}(t=0)} = \sqrt{N_e} \cdot \sqrt{1 + 2N_{im} / N_e}.$$

This technique gives N_e which does not depend on the value of N_{im}. Only the error of N_e will grow with increasing N_{im}.

It is obvious, that both techniques should give the same number of electrons $N_e(\varepsilon)$, if $N_{im} << N_e$.

A third approach is also possible, we will consider it below. First of all the cascades, satisfying points '2' and '4' are selected. We will denote as N_1 and N_2 the number of cascades beginning in the first and second lead plates, respectively. Both N_1 and N_2 are the sum of purely electron cascades N_1^e and N_2^e and imitations N_{1im} and N_{2im}, i.e. $N_1 = N_1^e + N_{1im}$ and $N_2 = N_2^e + N_{2im}$. Note, that $N_{2im} = N_{1im} e^{-\Delta t/\lambda_p} = \gamma N_{1im}$, where Δt is the lead plate thickness. Therefore, $\gamma N_1 - N_2 = \gamma N_1^e + \gamma N_{1im} - N_2^e - N_{2im} = \gamma N_1^e - N_2^e$. Denoting, $N_2^e / N_1^e = \nu$, and noting, that $N^e = N_1^e + N_2^e$ we obtain, that $N^e = (\gamma N_1 - N_2)(1+\nu)/(\gamma - \nu)$.

This expression does not contain any imitations, only two calculated coefficients γ and ν are used. Therefore, there are three techniques for separating electrons in a thick IC.

Conclusions

Thus, we have discussed how a thick ionization calorimeter can be used for measuring high energy electrons; the three possible approaches are 1) proton rejection to the level of 10^{-5} ; 2) measuring of electron imitations by protons with further account; 3) a technique, eliminating the impact of electron imitations by protons.