Abstract

For the high energy electromagnetic showers the thickness dependence of a) the development of electron and positron components, b) the difference between the secondary electron and positron numbers, c) the charge asymmetry of high energy electromagnetic showers, as well as d) the spectral distributions of the components at the shower maxima for various energies of primary particle energies, 1 - 1000 GeV were investigated employing GEANT Monte Carlo simulation package. Using these simulation results it is discussed the possibility of observation and study of the charge asymmetry with the help of a magnetic spectrometer which is important for the current and future experiments on the detection of radiowaves produced by high energy neutrinos.

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I.Introduction

At present all the elementary electromagnetic processes taking place when high energy electrons and photons pass through the matter are well known. Therefore, the formulation of the correct theory for high energy electromagnetic showers (EMS) is possible in principle. However, due to mathematical difficulties the construction of the EMS theory...
is realized in various approximations, and almost always the study of the EMS theory and comparison with the experimental data are carried out with the help of Monte Carlo simulations using the existing codes as EGS, GEANT [1] and others developed at SLAC, CERN and other laboratories. In all the available EMS codes the "fate" of electrons and photons is followed down to certain lowest energies, cut energies, in order to escape very large program complication and computation times. Usually these cut energies are less than 1 MeV. In some cases as in the study of biological processes and some processes considered below when high density energy depositions, say, by δ- or Compton electrons are essential one should lower these threshold energies. Nevertheless, there is a satisfactory agreement between the experimental observations and Monte Carlo simulation results on EMS, and one can use the the laters to study some processes which are not observed and studied yet.

In 1961 G. Askarian [2] predicted an excess of electrons over positrons in high energy EMS due to positron annihilation in flight, Compton and δ- electrons and estimated the intensity of coherent Cherenkov and transition radiation radiowaves produced by this moving negative charge excess. The estimates carried out in [2] neglecting the contribution of Compton-, δ- and not mentioned in [2] photo-electrons show that the number of electrons in EMS can exceed the number of positrons by more than 10 % at energies higher than hundreds MeV. The more accurate calculations (see [3] and references therein) of such electron surplus with the help Monte Carlo simulations confirm the predictions of [2]. In the latest calculations [3] it has been shown that the following processes give main contribution in the production of the EMS charge excess: Compton scattering (50-60 %), Bhaba scattering (30-35 %), positron annihilation in flight (5-20 %), and their contribution depends weakly on the primary particle energy and relatively strongly on the component energy. Due to the low cross section the number of MeV photons is larger than the combined number of electrons and positrons in EMS, and Compton effect gives the largest part of the excess in MeV energy region. However, at present there is no direct experimental results on the EMS charge excess, while the existing indirect data (see below) are ambiguous and need correct interpretation.

In the work [2] it has been also estimated and shown that the intensity of the coher-
ent Cherenkov radiation radiowaves produced by this moving negative charge excess is sufficient to be used for detection of high energy EMS on the earth and moon. Following [2] it was suggested [4] to use this radiowave production for the underground detection of high energy neutrinos in the salt mines, while the mechanisms of radiowave production has been considered in details by the authors of the work [5] assuming various time and space distributions of the charge excess. After these and later theoretical and experimental investigations carried out in sixties devoted to EMS charge excess and radiowave production (see, [6]) many works have been published by the cosmic ray physicists because the method promised to be very convinient for the very high energy neutrino astrophysics and neutrino oscillation problems.

Despite the achievements in this field after more than 35 years of theoretical and experimental investigations and many interesting projects under construction (see [7] and Proceedings of last International Cosmic Ray Conferences), the technique of detection of EMS with the help on radio antennas has not yet been proven and difficulties are anticipated [8]. In this connection it seems reasonable to study experimentally the various characteristics of the EMS charge excess and of the coherent Cherenkov as well as transition radiation produced by the available high energy electron beams at various accelerators.

When this paper was ready for submitting an electronic preprint [9] has appeared in which the authors in addition to the existing experimental studies devoted to the far infrared and submillimeter coherent Cherenkov and transition radiation have investigated the polarization, angular, coherence and other properties of the same radiations in GHz radio region using 15.2 MeV electron bunches. The authors conclude that it is necessary to carry out more accurate measurement for various applications.

Taking into account the above said, the actuality of the problem and the available contemporary computational possibilities in this work we study the processes connected with the charge excess at primary energies 0.5 - 256 GeV with the help of the GEANT code package. It is shown the possibility of the observation and experimental study of this processes at YerPhI, SPS, CERN, and FERMILAB.
II. Results of Simulations

We have chosen GEANT [1] to carry out the necessary Monte Carlo simulations on EMS for two reasons. First, long term practice indicates that GEANT handles in a proper way. Second, GEANT is designed to simulate the geometry of the experimental setup, which is essential for our purpose. The agreement between our calculations and published results, in particular, on the depth dependence at higher energies, witnesses the correctness of our calculations. Calculations have been performed for various kinetic energy cuts for electrons and photons, \( T_{\text{cut}} = T_{\text{cut}}^e = E_{\gamma_{\text{cut}}} \) from \( T_{\text{cut}} = 50 \text{keV} \) up to \( T = 12 \text{MeV} \) and when the primary particles were photons (the results for electrons do not differ significantly from those for photons) with total number \( N_{\gamma} \) and various primary photon energies \( E_{\gamma} \) from 0.5 GeV up to 1000 GeV. Each element of the calculation array with fixed \( E_{\gamma} \) and \( E_{\text{cut}} \) contains information on a) the dependence of the electron and positron numbers \( N_{e^-}, e^+ \) upon the depth \( t \) in radiation length units; b) the dependence of the excess \( \nu = N_{e^-} - N_{e^+} \) on \( t \); c) the dependence of the charge asymmetry \( A = (N_{e^-} - N_{e^+})/(N_{e^-} + N_{e^+}) \) on \( t \) and d) the energy spectrum of the electrons at the depth where the maximum of the charge excess for the given parameters takes place, \( t = t_{\text{max}} \).

All the calculations presented in this work have been carried out for BGO because it is a diamagnetic insulator, has a small radiation length unit (useful properties for radiowave detection), has sufficient scintillation yield which can be useful in some cases and is available. Fig.1 shows the information of one array element when \( E_{\gamma} = 128 \text{ GeV} \) and \( T_{\text{cut}} = 0.4 \text{ MeV} \). As it is seen from Fig.1 a the showering behaviors for electrons and positrons are similar, but they differ significantly in magnitudes. The behavior of the excess t-dependence (see Fig.1b) reminds the usual behavior of shower curves with tails of the form \( \exp(-\alpha t) \) and its more intense part around the maxima can be approximated roughly by the symmetric function \( \sim \exp(-\omega_0 \tau^2) \) where \( \tau = t - t_{\text{max}} \) and \( \alpha \) and \( \omega_0 \) are constants as it is suggested in [5] to calculate the radiation intensity. As it follows from Fig.1c for the given \( E_{\text{cut}} = 0.4 \text{ MeV} \) the asymmetry exceeds the value given in [2,3] because of the contribution of low energy electrons produced due to Compton effect. However, as it will be shown below for energies of the electron component higher than few MeV the asymmetry becomes less than it is predicted in [2,3]. The results given in Fig.1d
show that indeed one can measure the asymmetry, and such measurement is easier for lower energies of electrons and positrons. As it is seen from Fig.2 the charge asymmetry virtually disappears above 20 MeV.

Using many such simulation results as ones presented in Fig.1 one can reveal the characteristic properties of the EMS charge asymmetry necessary for the future employment. In Fig.3 a and b it is given the dependence of the charge excess on $E_\gamma$ (for fixed $E_{\text{cut}}$) and $E_{\text{cut}}$ (for fixed $E_\gamma$), respectively. $\nu$ increases almost linearly with the increase of $E_\gamma$ and decreases with the decrease of $E_{\text{cut}}$. In Fig.4 a and b it is given the dependence of the charge asymmetry on $E_\gamma$ (for fixed $E_{\text{cut}}$) and $E_{\text{cut}}$ (for fixed $E_\gamma$), respectively. It is seen that $A$ almost does not depend on $E_\gamma$, decreases with the decrease of $E_{\text{cut}}$ and almost vanishes when $E_{\text{cut}} > 10$ MeV. Therefore, it is advantageous to study the charge asymmetry at possible higher primary particle energies and lower cut energies.

As expected the calculations show that at the shower maxima the contributions from various processes resulting in charge excess depend on the component energy, and in the energy region below few MeV where the number of the electrons and the charge asymmetry are larger the proportion of the contribution from various processes coincides with that given in [3] for higher energies, $E \geq 1$ TeV.

III. Asymmetry Measurement Using Magnetic Spectrometers

Various characteristics of EMS have been investigated experimentally for a wide energy region of electrons and photons from 50 MeV up to few TeV with accelerator and cosmic ray particles using various methods and detectors. The authors of the work [10] used streamer chambers. In all these works the measurements have been carried out for secondary particle energies not less than 1 MeV. This is not because the corresponding Monte Carlo calculations of that time were available for $E_{\text{cut}} > 1$ MeV, but because the applied methods did not allow to decrease further the energies of the detected secondary particles because of larger energy measurement errors due to multiple scattering.

The use of streamer chambers in magnetic field with insulator layers (BGO) in which the EMS are developed seems more suitable for the EMS charge excess investigations because they give the possibility to carry out the measurements at various depths simul-
taneously. With low Z gas filling and magnetic fields $B = 0.03$ T the expected accuracy for the energy measurements are about 16, 14, 7 and less than 5 % for electron energies 0.075, 0.15, 0.3 and 1.0 MeV, respectively. The use of streamer as well as time projection chambers is connected with technical difficulties, and it will be much easier to perform such studies with the help of low energy magnetic pair spectrometers.

It will be convinient to carry out such an experiment with the arrangement NA59, SPS, CERN (see Fig.6 of [11]) proposed for other purpose and which will be ready in spring 1999. Since as it has been mentioned above the charge excess characteristics do not depend whether the primary particles are electron or photons, the 150-180 GeV electrons of the H2 beamline or the gamma quanta produced by these electrons must be focused (The beam angular and energy spread are not important, while its cross section radius must be decreased to 1-2 cm, since the Mollie radius for BGO is 2.4 cm) on 5-15 cm thick BGO slabs replacing the berillium target in the experiment NA59, and the pair spectrometer magnet with $B.l = 0.52$ Tm ($l$ is the length of the magnetic field) must be replaced with a weak magnet with $B.dl = 0.0033$ Tm. Such weak fields and few meter distance provide the deflection of particles with energies higher than few MeV under angles greater than the angles under which the particles leave the BGO radiator and detect them at transversal distances larger than few Moller radius. The higher energy components do not touch the sensitive parts of the detectors downstream the magnet. The energy of the photons in the region 96-144 GeV is determined by the tagging system. The energy of the negative and positive shower particles coming out from BGO is measured with the help of two or three drift chambers. Since there are no polarization measurements the charge excess measurements at some depth will be much easier than the shower measurements on the arrangement NA43 [12] using polarized photon beams. Again the multiple scattering in various thin windows alowes to determine the charge for secondary particle energies higher than few MeV. Since the primary electron beam intensity is $4.10^5 min^{-1}$ and the expected number of photons with energies 96-144 GeV will be only less by one order, the measurement time at one depth estimated with the above given curves is about 1 and 10 hours in the cases of primary electrons and photons, respectively.
Though the number of shower components is much lower at GeV energies (see Fig. 2a), nevertheless, EMS charge excess measurements are also possible at such energies using the ejected electron and photon beams, say, at Yerevan Synchrotron because of their higher intensity, about $10^9$ electrons or photons per second.

IV. Discussion

In this work it is reported the results of the Monte Carlo simulations on the negative charge excess and differential energy spectra of secondary particles in EMS taking into account all the processes in the primary particle energy interval $1-256$ GeV. For the energy region of the shower components below few MeV (above ten MeVs) the presented results predict much larger (smaller) excess than the estimates [2,3]. Nevertheless, as it has been shown in this work this charge excess can be measured with the low intensity, but high energy ($\geq 100$ GeV) electron and photon beams at SPS, CERN and Fermilab or using the high intensity but relatively low energy ($\geq 1$ GeV) beams at YerPhI. At present since the expected intensities of the atmospheric EMS coherent radiation of very high energy particles in the radio diapason is higher, than the intensity of the EMS transition radiation in the clouds [13] and the sensitivity threshold of antennas, the formers are detected unambiguously in coincidence with other extended shower detectors. However many problems concerning the correct mechanisms of radio wave production, spectral and angular distribution etc. remain unsolved before wide application in very high energy neutrino astrophysics. The results of the excess measurements proposed in this work can shed light on the problems of EMS radiowave detection in dense (ice or salt) and air media.
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Figure Captions

Fig.1. Characteristic charge excess dependences in BGO for primary photons when $E_\gamma = 128$ GeV and $E_{\text{cut}} = 0.4$ MeV. a) Shower curves separately for secondary electrons (solid histograms) and positrons (dashed histogram); b) Dependence of the excess $\nu = N_{e^-} - N_{e^+}$ upon t (in radiation length units); c) Dependence of the asymmetry $A = (N_{e^-} - N_{e^+})/(N_{e^-} + N_{e^+})$ upon depth, and d) Differential spectrum of the electrons at the maximum of the charge excess (100 events are simulated).

Fig.2. The dependence of the charge asymmetry on the energy of electrons and positrons at the shower maximum in the energy intervals a)1-10 MeV and b)10-50 MeV.

Fig.3. The dependence of the charge excess on a) $E_{\text{cut}}$ for the fixed $E_\gamma = 128$ GeV and on b) $E_\gamma$ for the fixed $E_{\text{cut}} = 0.4$ MeV.

Fig.4. The dependence of the charge asymmetry on a) $E_{\text{cut}}$ for the fixed $E_\gamma = 128$ GeV and on b) $E_\gamma$ for the fixed $E_{\text{cut}} = 0.4$ MeV.
Figure 1:
Figure 2: [Graphs showing energy distribution of $e^+$ and $e^-$ at $t_{\text{max}}$.]
Figure 3:

Figure 4: