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SIMULATION OF ELECTROMAGNETIC SHOWERS IN SALT PERFORMED WITH GEANT4*

A. SAFTOIU[1,2], O. SIMA[2], I. LAZANU[2], A. BADESCU[3], I.M. BRANCUS[1], O. FRATU[3], S.V. HALUNGA[3], G. TOMA[1], B. MITRICA[1]

[1] "Horia Hulubei" National Institute for Physics and Nuclear Engineering, P.O. Box MG-6, 077125 Bucharest-Magurele, Romania, E-mail: alexandra.saftoiu@nipne.ro
[2]Faculty of Physics, University of Bucharest, Bd. M. Kogalniceanu, no 36-46, Bucharest
[3] Faculty of Electronics, "Politehnica" University of Bucharest, Bd. Iuliu Maniu, no 1-3, Bucharest

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Abstract. In the larger context of detection of high energy cosmic particles using the radio signal generated by the charge excess in showers developing in a dense medium (the Askar'yan effect) we have developed and analyzed a series of simulations of electromagnetic showers. The chosen material was rock salt, one of the three media proposed for the study of this effect. Influence of the medium's composition and geometry on the shower's profiles and charge excess was investigated. For the simulations we have used GEANT4.9, a C++-based tool for geometry and tracking of particles.

Key words: GEANT4, electromagnetic shower, salt, simulation.

1. INTRODUCTION

In recent years, interest on the detection of very high energy cosmic rays has increased due to the fact that new technologies now provide fast acquisition of very large amount of data and communication between detectors is not a problem anymore [1]. Very high energy cosmic rays are still a mistery for physicists because of their unknown origin, acceleration mechanisms and propagation.

Of all the cosmic particles incoming at Earth neutrinos are of a special interest because, due to the fact that they only interact weakly, they are neither deflected nor much absorbed and, therefore, they can point back to their origin unimpeded and can traverse immense distances. Their observation is important because it will provide valuable information on the astrophysical processes involved in their generation and also will test our understanding of the particle physics at energies not available in man made accelerators.

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One method of detection involves the Askar'yan effect, presented in section 2, that has been predicted since the '60s but not tested until recently [2, 3].

The first step in calculating the signal induced by a high energy particle in a medium is simulating and studying the shower development in material, procedure which will be explained in section 3. The results of simulations of electromagnetic electron-induced showers will be presented in sections 4 and 5.

2. THE ASKAR'YAN EFFECT

In 1961 and 1965, G. Askar'yan [4, 5], came up with the idea that high energy particles, both charged and neutrinos, could be detected by means of registering the coherent radio emission from showers developing in dense media. Cosmic rays interacting with a medium generate showers that have electromagnetic and/or hadronic components. All charged particles in the shower moving with a speed greater than the speed of light in the medium will emit Cerenkov radiation. Emission from negative charges, *e.g.* electrons will cancel out with emission from the same number of positive charges, *e.g.* positrons, but if the number of negative charges is larger, there will be a net signal. Therefore, it is the charge excess that is relevant for this effect and not the total number of particles.

For a dense medium the shower dimension will be small, in the order of a few meters up to tens of meters, and, thus, the radiation in the low frequencies will add coherently, while the higher frequencies will not propagate. The energy in a coherent emission scales with the square of the charge excess in the shower which is itself proportional to the energy of the incident particle. For sufficiently high primary energy, PeVs, the Cerenkov pulse in the radio domain will be detectable. Askaryan himself proposed 3 media suitable for the study of the effect he envisioned: ice, salt and sand [6]. All these would be the active medium for detectors at ground level or underground.

For the present study we are investigating salt as the medium for the shower generation, and in comparison with other studies for salt [7] we will also consider the effect of impurities uniformly distributed in the volume.

Salt is a dielectric radio transparent media suitable for this type of detection. The salt deposit at Slanic, Romania, has presented interest for physicist and studies in the rock itself have been done in the fields of dosimetry [8], and astroparticles [9].

3. GEANT4 SIMULATION

In the larger context of the Askar'yan effect presented above we have developed a series of simulations of electromagnetic showers in salt to test the generation of the charge excess responsible for the radio emission and the influence of changes in the medium on the shower parametrization and profiles. In future studies the output of this work will be used for the simulation of the emission and propagation of the radio signal.

High energy primary charge particles and gammas cannot penetrate the atmosphere without generating extensive air showers and thus producing secondaries with lower energies.

The neutrino, due to its small cross-section can pass even through the whole planet, but due to inefficient calculation we will not consider it as the generator particle for the shower simulation. The primary interaction of the neutrino may be simulated outside the shower code [10, 11]. From this primary neutrino interaction leptons result and carry away most of the energy, in a charged-current (CC) interaction, or hadrons, from a neutral-current (NC) interaction [12].

In this study we will restrict to the electron as incident particle. The muon and tau leptons are special cases and will be treated elsewhere.

For a 100 GeV electron incident on salt most of the hadrons generated are neutrons which don't even contribute to the generation of radio signal and the total number of charged hadrons is ≈1% while for a 100 GeV muon-initiated shower the number of hadrons is of the order of 10^{-4} %.

Thus, most of the particles being gammas and leptons, a lepton initiated shower may be treated as a pure electromagnetic shower, in which only electromagnetic processes take place.

For the simulations we have employed GEANT4, version 9.3, a geometry and tracking tool, based on C++ [13]. Other simulation codes that could serve this purpose are EGS [13], the code developed by Zas, Halzen and Stanev [14] designed especially for generation of showers in medium and computation of the radio emission, and FLUKA [15], as used in [16]. We have employed GEANT4, and not any of the other two codes, because it is a tool generally known and used because of its reliability, up-to-date, covers all the physical processes, provides information on all the generated tracks/particles and offers the possibility to implement various compositions/geometries for the medium.

The definition of the problem in GEANT4 involves setting the particles, processes, material, volume properties and geometry.

3.1. CONSISTENCY CHECK

In order to check the accuracy of our GEANT4simulation we have performed simulations in iron (X_0 = 1.757 cm radiation length, 21.68 MeV critical energy for electrons and 21.00 MeV critical energy for positrons, from PDG [17]) for comparison with other results.

The longitudinal profiles obtained by us and the corresponding profiles from [17] obtained with EGS4 and, another GEANT4 simulation and the ZHS code [14], can be seen in Fig. 1.

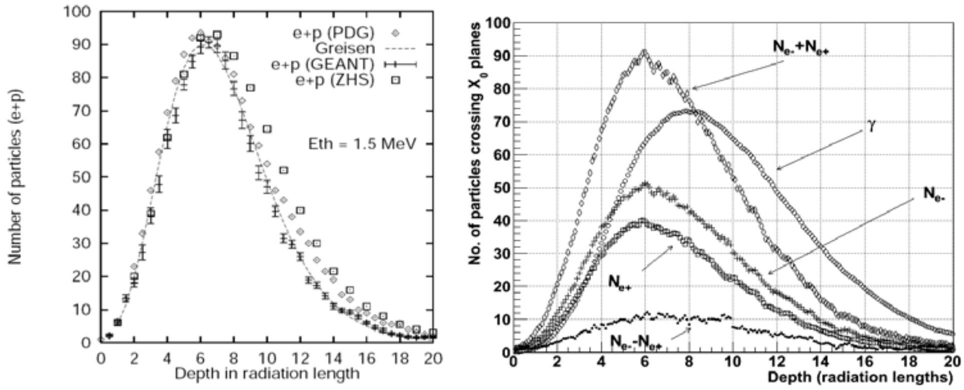

Fig. 1 – Longitudinal profiles of total number of charged particles, electrons plus positrons and difference between the number of electrons and positrons, averaged over 50 electron generated showers in iron at 30 primary energy, simulated using GEANT4 (left panel); PDG [17] profile for charged particles (right panel). The photons profile is scaled so that the area below the curve is equal to the area below the charged particles curve. Threshold energy is 1.5 MeV in both cases.

4. RESULTS. SIMULATION IN PURE SALT

The properties for the pure salt employed in these simulations have been taken from Particle Data Group [17], 2.17 g/cm^3 – density, 10.09 cm – radiation length, 44.97 MeV – critical energy for electrons, 65.7^o – Cerenkov angle and the energy threshold for the generation of Cerenkov radiation is 49.7 keV. *Unless stated otherwise the energy threshold for the generation of Cerenkov radiation is also the energy cut, below which particles are not further propagated into the medium*, in order to save time and computing resources.

4.1. LONGITUDINAL PROFILES AND GREISEN PARAMETRIZATION

The longitudinal profile represents the development of the shower along the shower axis in the depth of the material. This profile is influenced by the physics that takes place there and by the properties of the material.

For an electromagnetic shower the longitudinal profile can be parametrized by the Greisen formula. The Greisen equation, [18], describes the integral distribution $\Pi(t, E_0/E_C)$, the average number of particles in a shower as a function of shower depth, t, given the energy of the primary particle, E_0, and the critical energy, E_C.

Given that the height and the maximum of a distribution described by a Greisen function may vary also as a function of threshold energy, E_{th}, a form of the Greisen equation, modified by Hillas [19], is employed. The average number of electrons is given by:

$$\bar{N}_e\left(E_0, E_{th}, t\right) = A_e\left(E_{th}\right)\frac{0.31}{\sqrt{y}}\exp\left[t_1\left(1 - 1.5\ln s_1\right)\right], \quad (1)$$

where $y = \ln(E_0/E_C)$, t_1 is the modified depth, $t_1 = t + a_e(E_{th})$ and s_1 is the shower age, $s_1 = 3t_1/(t_1 + 2y)$. A_e, and a_e are threshold energy dependent parameters.

The shower maximum occurs at $X_{max} = X_0 \ln(E_0/E_C)$.

We performed simulations for 100, 500 GeV and 1 TeV electrons incident on pure salt. Shower longitudinal profiles were calculated by adding the number of particles of a given type, with energy above the Cerenkov threshold in the medium, crossing planes of fixed depths. Individual profiles were then averaged and the result is shown in Fig. 2.

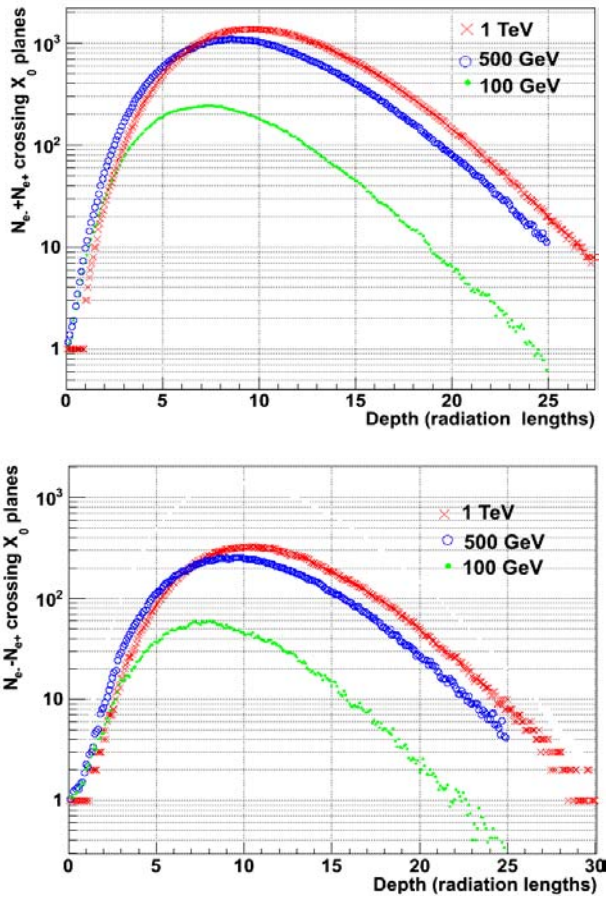

Fig. 2 – Longitudinal profiles of total number of charged particles, electrons plus positrons (upper panel), and difference between the number of electrons and positrons (lower panel), logarithmic scale, averaged over 50 electron generated showers in pure salt, at 100 GeV, 500 GeV and 1 TeV primary energy, simulated using GEANT4. Threshold energy 49.7 keV.

The profiles were fit using the modified Greisen equation (1). Parameters of this fit are listed in Table 1. It can be observed that the showers extend over maximum 25 radiation lengths which means ~2.5 meters depth in the material (1 radiation length = 10.09 cm). This is due to the high density of the material.

Table 1

Fit parameters for the modified form of the Greisen equation for 100, 500 GeV and 1 TeV electron initiated showers

Primary energy	$A_e(E_{th})$	$a_e(E_{th})$
100 GeV	0.97 ± 5e-4	0.51 ± 3e-3
500 GeV	0.96 ± 1.1e-4	0.61 ± 6.5e-4
1 TeV	0.62 ± 4.5e-5	0.32 ±4e-4

4.2. CHARGE EXCESS, ENERGY DISTRIBUTION AND TRACK LENGTH

As the shower develops, a net negative charge excess will appear because of processes such as the Compton scattering ($\gamma + e^-_{atom} \rightarrow \gamma + e^-$), which incorporates electrons to the shower, Bhabha ($e^+ + e^-_{atom} \rightarrow e^+ + e^-$) and Moller ($e^- + e^-_{atom} \rightarrow e^- + e^-$) scatterings and annihilation of positrons, [13].

The charge excess can be quantified as a percentage of the total number of charged particles as:

$$\Delta Q = \frac{N_{el} - N_{pos}}{N_{el} + N_{pos}}. \tag{2}$$

Figure 3 shows the charge excess for 100, 500 GeV and 1 TeV electron initiated showers. It can be seen that at the shower maximum it reaches ~21% and increases up to ~35% as the shower evolves. The excess, being induced by the medium, does not change with incident energy.

Another aspect important for the generation of the radio signal by the charge excess is the energy of the secondary particles involved. The depth distribution of the difference between electrons and positrons for a 100 GeV, 500 GeV and 1 TeV electron initiated shower in pure salt can be seen in Fig. 4 separated into 3 energy intervals: $E < 5$ MeV, $E < 50$ MeV and $E < E_0$ GeV, for a single shower with the energy threshold set to the minimum energy for the generation of Cerenkov radiation (49 keV). It can be observed that the major contribution to the charge excess comes from the low energy electrons and positrons. This happens because in this dense material electrons loose energy quickly, which means that the overall development of the shower will be short.

The amplitude of the emitted signal is proportional to the track length, i.e. the longer a particle exists and has a velocity greater than the velocity of light in the medium the more radiation it will generate which will then add up coherently to give a stronger signal. The total track length for all particles, total track length projected on the shower axis and the weighted track length (the difference of track lengths for electrons and positrons projected onto the shower axis) are listed in Table 2. As it was obvious from the longitudinal profiles Fig. 2, the total track length for particles that will contribute to the Cherenkov emission increases. Also the projected and weighted track lengths increase because the shower profile exhibits the same type of features, only the amplitude and extension in the material change.

Table 2

Track lengths for 100, 500 GeV and 1 TeV electron initiated showers

Quantity (m)	100 GeV	500 GeV	1 TeV
total track length for charged particles	268.61	1320.37	1738.44
total projected charged track length	195.50	957.71	1260.95
weighted track length	45.21	218.84	288.99

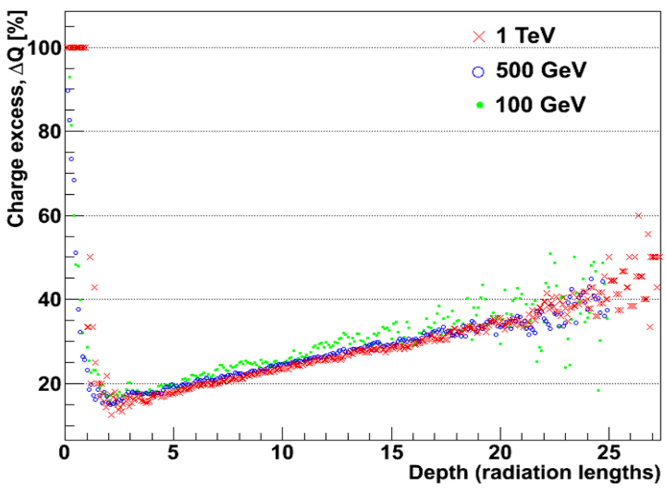

Fig. 3 – Charged excess, averaged over 50 electron generated showers in pure salt, 100 GeV, 500 GeV and 1 TeV primary energy.

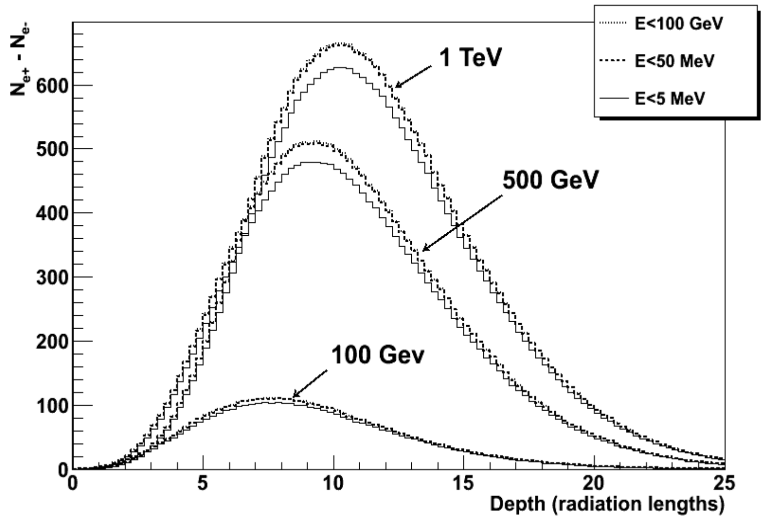

Fig. 4 – Depth distribution of the difference between the number of electrons and positrons, separated into 3 energy intervals: E < 5M eV, E < 50M eV and $E < E_0$ (100 GeV, 500 GeV or 1 TeV), averaged over 50 showers.

5. RESULTS. SIMULATION CONTINUOUS VOLUME OF IMPURE SALT

In order to establish how the presence of impurities in the bulk volume may influence the results, both qualitatively and quantitatively, we have performed simulations in pure salt plus a fraction of impurity uniformly distributed, $CaCO_3$, one of the most common components in soil. The chemical elements in the volume are uniformly distributed. We have considered 3 cases:

– 3% fraction of mass $CaCO_3$ impurity (X_0 =9.903 cm, ρ = 2.218 g/cm^3),

– 15% fraction of mass $CaCO_3$ impurity (X_0 =9.694 cm, ρ = 2.290 g/cm^3),

– 30% fraction of mass $CaCO_3$ impurity (X_0 = 9.539 cm, ρ = 2.359 g/cm^3).

It can be observed in Fig. 5 that the total number of particles tends to decrease as the concentration increases and the shower's maximum is reached sooner than in the case of pure salt, with ~10 cm or ~1 radiation length. This trend is also true for the track length which shortens as the concentration of the impurity increases, Table 3.

But the difference between number of electrons and positrons remains roughly the same, which will cause the charge excess, ΔQ, to increase slightly, ~ 1%, Fig. 6.

It seems that, from the point of view of the shower generation, as long as the bulk volume is uniformly unpurified with $CaCO_3$, which increases the total density, the development of the charge excess will not be much influenced.

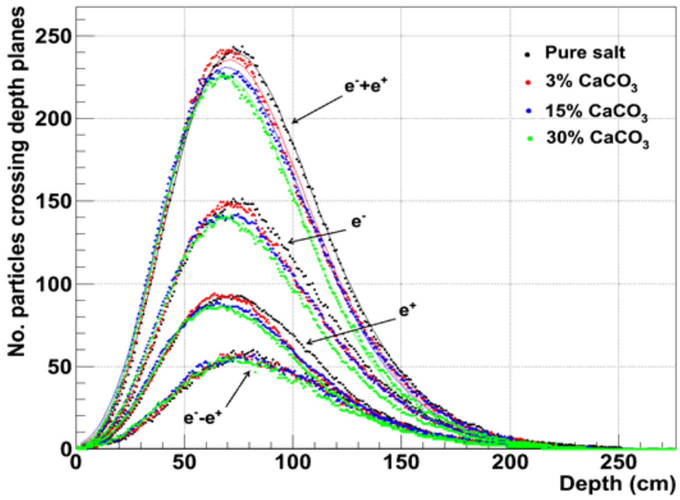

Fig. 5 – Longitudinal profiles of Ne− , Ne+ , Ne− + Ne+ and Ne− − Ne+ averaged over 50 electron generated showers in bulk volume of pure salt and salt plus 3%, 15% and 30% $CaCO_3$ impurities, 100 GeV primary energy.

Table 3

Track lengths for 100 GeV electron initiated shower in unpurified salt

Amount of impurity	3%	15%	30%
total track length for charged particles (m)	262.93	253.65	245.28
total projected charged track length (m)	190.76	185.11	179.96
weighted track length (m)	44.11	43.82	42.53

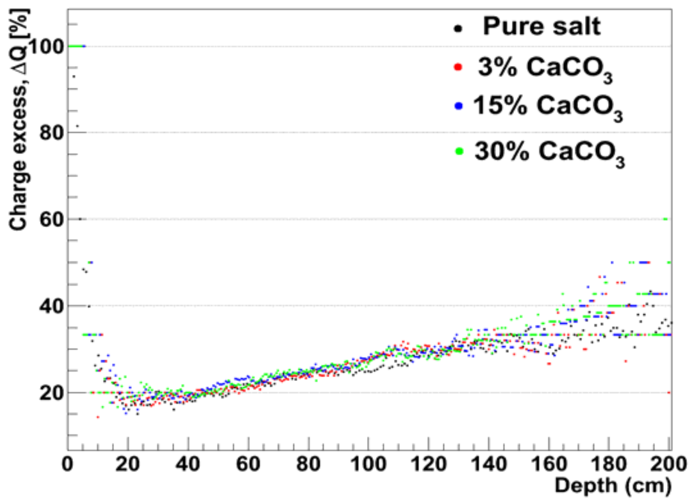

Fig. 6 – The charge excess vs. depth in radiation lengths, averaged over 50 electron generated showers in pure and unpurified salt, 3% and 15% impurity, 100 GeV primary energy.

6. CONCLUSIONS AND FUTURE ASPECTS

The first step in detecting high energy particles, especially neutrinos, by registering the radio signal, is the understanding of shower development in the material. Once the information from all the particles, or the parametrization of the charge excess, is known the emission can be computed and the propagation to observer simulated.

We have obtained correct simulations for electromagnetic electron-induced showers in pure salt using the GEANT4 toolkit, in the energy range 100 GeV to 1 TeV. GEANT4 provides detailed information for each particle in the shower which will be needed for the track-by-track approach in the calculation of the radio pulse. Longitudinal profiles are parametrized with the Greisen formula which makes them easy to use in the following phase of the calculation of the radio pulse in the 1-dimensional approximation approach [7].

We have also investigated the effects of impurities on the generation of electromagnetic showers and development of the charge excess in showers initiated by electrons. $CaCO_3$ impurities, which increase the overall density of the material, determine a decrease in the number of particles at the shower maximum of ~10% and a decrease of the depth of the maximum with ~1 radiation length. The charge excess for a 100 GeV electron initiated shower does not increase significantly when the impurity concentration increases.

In the future we will investigate hadron induced showers considering both electromagnetic and hadronic components and a more realistic volume geometry will be implemented, i.e. layers of salt with different impurities.

Also the radio emission will be calculated based on the output of these simulations in two different ways: computing the emission from each separate particle and then adding up all the contributions or using the parametrization of the longitudinal profile of the charge excess as an approximation for a 1-dimensional shower, as in [7]. This is why it is imperative to be sure than simulations are correct and realistic.

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