Shower Simulation Input for Fluorescence Yield Measurements

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Abstract

The CORSIKA simulation code has been adapted for an extensive study of the energy release of shower particles during the cascade development. The contributions to the energy deposit from different particle species and energies as well as the typical particle densities are investigated. The dominant contribution stems from electrons and positrons from sub-MeV up to a few hundred MeV, with typical distances between particles exceeding 1 mm for 10 EeV showers. Special care is taken of particles falling below the simulation energy threshold which contribute around 10% to the total deposition.

1. Introduction

For the primary energy determination of extensive air showers observed by fluorescence telescopes, it is generally assumed that the yield of fluorescence photons is locally proportional to the energy release in air. This has been justified to some extent by fluorescence yield measurements [5]. Different approaches, some of them at accelerator facilities, are underway to further check the validity of this assumption and to improve our knowledge about this quantity [4]. To give a guideline for the preparation of such experiments, it is investigated which particle types and energies contribute to the energy release in air showers and which are the typical particle separations in the region of main fluorescence production.

2. Calculation of the Energy Release

Shower simulations for proton, iron and photon primaries at energies of 10^{18}-10^{20} eV have been performed with the CORSIKA code [2]. The electromagnetic interactions are treated in CORSIKA within the EGS4 code [7] which has been upgraded to allow simulations at the highest energies [3]. More details about CORSIKA features at the highest energies are given in [6,8].

The energy release is determined following the concept of "restricted stopping power" [1]: The energy loss to particles below the simulation energy threshold is treated as continuous process whereas production of particles above the

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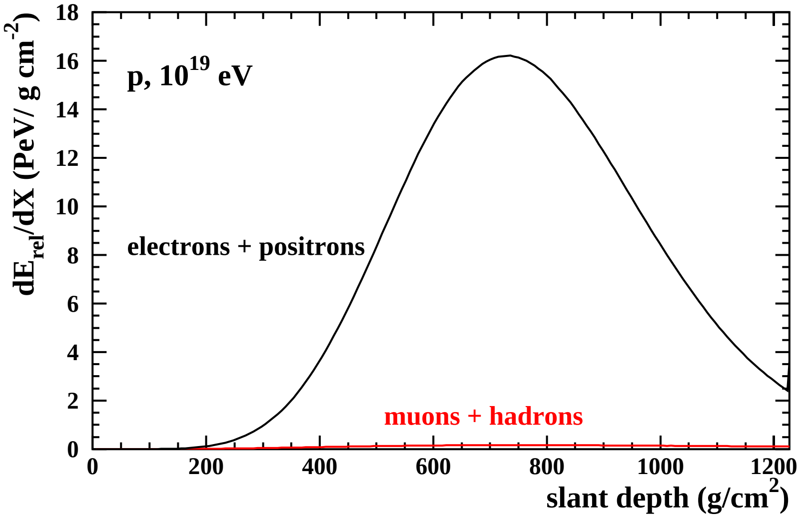

Fig. 1. Longitudinal energy release of different shower components.

threshold is simulated explicitely. In case of a particle directly produced below or reaching the threshold, a *releasable energy* is defined and written to an output table which consists at least of the kinetic energy plus some species-dependent part. The latter effectively takes processes such as future annihilation or decay into account. In case of positrons, annihilation quanta are produced for further tracking. A detailed description is given in [9].

3. Results

In Fig. 1, the longitudinal development of individual contributions to the energy release is shown. As the main shower features relevant for this analysis turn out to dependent only modestly on the considered primary particle and energy, only results for proton showers of 10^{19} eV are plotted (for others see [9]). As expected, the main energy release is provided by electrons and positrons, the most numerous particles (photons contribute indirectly via production of charged particles). Around shower maximum, less than 2-3% are provided by muons and hadrons. Thus, electromagnetic particles should be the main target for the study of energy release.

In Fig. 2, the energy spectrum of electrons and positrons at shower maximum (which is of most interest for fluorescence observations) is given. Particles with energies below 1 GeV dominate the energy release. A large portion stems from energies slightly below the critical energy of electrons in air ($\simeq$84 MeV), with a tail towards small energies. While at higher kinetic energies ($E_{\mathrm{kin}} > 300$ MeV) electrons and positrons contribute about equally to the energy release, at lower energies only electrons survive due to the positron annihilation. The annihilation

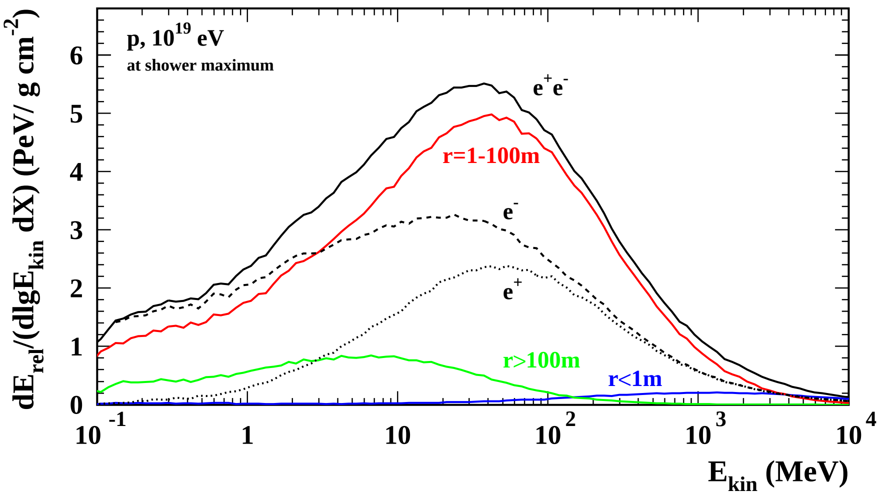

Fig. 2. Contribution to the energy release per matter traversed in shower direction as a function of the kinetic particle energy. Simulation for primary proton, 10^{19} eV, at shower maximum. The sum of $e^{\pm}$ and their individual distributions are shown. Additionally, the total contribution has been divided in three different distance ranges from the shower axis as indicated.

Table 1. Estimates for the contribution of different ranges in $e^{\pm}$ kinetic energies to the electromagnetic energy deposit. Uncertainty of the values is about ±2 (in %).

Energy in MeV	< 0.1	0.1-1	1-10	10-100	100-1000	>1000
Contribution in %	10	12	23	35	17	3

photons will eventually transfer the energy by Compton scattering to electrons. As a guideline, in Table 1 the contribution to the electromagnetic energy deposit for different energy ranges is estimated. The value for $E_{\rm kin} < 0.1$ MeV is given by the releasable energy of the particles below threshold.

The spectral shape mainly reflects the particle energy spectrum [8]. Especially the contributions of the lower energies are more pronounced, however. This is due firstly to the increased specific energy loss (Bethe-Bloch formula), and secondly to a larger average path length through the considered layer, since at lower energies the dispersion of particle angles is increasing.

The range of mainly contributing energies is to a good approximation quite independent of the primary particle type (including primary photons), primary energy, and shower age. For instance, at earlier development stages the spectrum is only slightly shifted to higher electron energies. This result may be understood, since the particle energy spectrum is known to show a small, but in this context only minor dependence on primary type and shower age [8].

Also indicated in Fig. 2 are contributions from different lateral distance ranges. Most of the energy is released in the distance range of 1−100 m. The fraction provided by particles with less than 1 m distance to the shower axis is quite small: Though the densities are largest here, the absolute particle number is comparatively small. A correlation of the average particle energy with distance to the shower axis reveals that the contributions are shifted towards higher E_{kin} values for the smaller distances. More detailed analyses [9] show that the main energy release occurs at core distances of $\simeq$30 m, implying typical particle separations exceeding 1 mm for 10 EeV showers (scaling with the inverse primary energy). With respect to the ionization region around the particles, this is a large separation resulting in a relatively "undisturbed" de-excitation of the air molecules. Thus, high-density particle bunches should be avoided in fluorescence yield measurements as the fluorescence yield might be obtained in conditions not typical for air showers.

4. Conclusion

The energy release in air showers has been studied with respect to currently planned fluorescence yield measurements. Most relevant is the determination of the yield for electrons and positrons with energies in the range from sub-MeV up to a few hundred MeV. The typical particle separation is relatively large with 1 mm or more for 10 EeV showers at shower distances which mainly contribute to the energy release and thus, presumably, to the fluorescence light. For shower calculations, the energy release provided by CORSIKA can be transformed to fluorescence light based on existing and upcoming fluorescence yield measurements.

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