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Current status of the AIRES air shower simulation system

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A report on the progress achieved in the development of the AIRES air shower simulation system is presented. The AIRES algorithms are briefly described and a series of results coming from the simulations are analyzed, focusing on comparisons with experimental data, and analysis of hadronic model dependences of observables.

1. Introduction

When an ultra high energy astroparticle interacts with an atom of the Earth's atmosphere, it produces a shower of secondary particles that continue interacting and generating more secondary particles that can eventually hit the Earth's surface. The study of the characteristics of such air showers initiated by ultra high energy cosmic rays is of central importance. This is due to the fact that presently such primary particles cannot be detected directly; instead, they must be studied from different measurements of the air showers they produce.

Due to the complexity of the processes that take place during the development of an air shower, detailed studies of its characteristics are commonly made with the help of numerical simulations. The simulating algorithms must take into account all the processes that significantly affect the behavior of the shower. This includes electrodynamic interactions, hadronic collisions, photonuclear processes, particle decays, scattering, etc.

The **AIRES system**[1] [1] is a set of programs to simulate air showers. AIRES has been successfully used to study several characteristics of the showers, including comparisons between interaction models and/or experimental data, impact on the response of detection instruments, etc.

In all the studies performed using AIRES, the results obtained present a good agreement with experimental data or simulated data coming from other sources. As an important example, it is worth mentioning that an AIRES simulation of atmospheric muon flux, reported in detail at reference [3], was found to present a very good agreement with experimental measures corresponding to the CAPRICE98 experiment.

More recently, we have used AIRES to estimate the influence of diffractive processes in the final shower observables [4], and to study in detail the characteristics of showers initiated by photons in connection with cosmic ray composition analysis at the highest energies [5].

The aim of this paper is to describe the relevant characteristics of the AIRES program, stressing on the most recent developments, and discuss briefly the strategy for future developments.

2. Characteristics of AIRES

The AIRES simulation system provides a comfortable environment for performing realistic simulations taking advantage of present day computer technology.

Table 1 summarizes the main characteristics of the particle propagating engine of AIRES.

The set of particles that are fully propagated by AIRES include the most commonly observed ones, together with other less numerous but capable of producing indirectly a non negligible impact on the final shower

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[1] **AIRES** is an acronym for **AIR**-shower **E**xtended **S**imulations.

Table 1. Main characteristics of the AIRES air shower simulation system.

MAIN CHARACTERISTICS OF AIRES	
Propagated particles	Gammas. Leptons: $e^{\pm}$, $\mu^{\pm}$. Mesons: π^0, $\pi^{\pm}$; η, $K^0_{L,S}$, $K^{\pm}$. Baryons: p, $\bar{p}$, n, $\bar{n}$, Λ, Σ^0, $\Sigma^{\pm}$, Ξ^0, Ξ^-, Ω^-. Nuclei up to $Z = 36$. Neutrinos are generated (in decays) and accounted for their number and energy, but not propagated.
Primary particles	All propagated particles can be injected as primary particles. Multiple and/or "exotic" primaries can be injected using the *special primary* feature (see text).
Primary energy range	From 800 MeV to 1 ZeV (10^{21} eV).
Geometry and environment	Incidence angles from vertical to horizontal showers. The Earth's curvature is taken into account for all inclinations. Realistic atmosphere (Linsley model).
Propagation (general)	Medium energy losses (ionization). Scattering of all charged particles. Geomagnetic deflections.
Propagation: ***Electrons and gammas***	Photoelectric and Compton effects. Bremsstrahlung and e^+e^- pair production. Emission of knock-on electrons. Positron annihilation. LPM effect, and dielectric suppression. Photonuclear reactions.
Propagation: ***Muons***	Bremsstrahlung and muonic pair production. Emission of knock-on electrons. Decay.
Propagation: ***Hadrons and nuclei***	Hadronic collisions using the EHSA (low energy) and QGSJET or SIBYLL (high energy). Hadronic cross sections are evaluated from fits to experimental data (low energy), or to QGSJET or SIBYLL predictions (high energy). Emission of knock-on electrons. Decay of unstable hadrons.
Statistical sampling	Particles are sampled by means of the Hillas thinning algorithm [2], extended to allow control of maximum weights. A full propagation option (thinning disabled) is also available.
Main observables	Longit. development of all particles recorded in up to 510 observing levels. Energy deposited in the atmosphere, at every observing level. Number and energy of low energy particles, at every observing level. Lateral, energy and time distributions at ground level. Detailed list of particles reaching ground, and/or crossing predetermined observing levels.

observables. All these particles can be injected as shower primaries. It is also possible to initiate showers produced by “special” primaries. This useful feature of AIRES, explained in detail elsewhere [1] allows to dynamically call a user-defined module that generates the primary (or primaries) that starts the shower, thus extending the set of primary particles beyond the standard ones that are recognized by the propagating engine. As an example of such an external module, we can mention the MaGICS module to process gamma preshowers in the magnetosphere [5].

The interactions indicated in table 1 represent, for the case of air showers, the most important ones from the probabilistic point of view. Particle decays and electromagnetic interactions are simulated using built-in procedures that have been developed on the basis of tested and commonly accepted theoretical formulations.

It is worth mentioning that at present our knowledge of the hadronic interactions is by far more incomplete than in the case of the electromagnetic ones. To process such interactions, it is necessary to rely on a given model, that is always based on phenomenology. Additionally, in an air shower, the energy spectrum of the hadrons undergoing inelastic collisions spans regions where there are no experimental data available, where the only alternative is to use the extrapolations provided by the available models.

In AIRES the hadronic collisions are processed by means of two models, depending on the energy of the projectile: For collisions with energy less than $\approx$ 100 GeV, an extension of the Hillas Splitting Algorithm (EHSA) [6] is used, while for higher energies it is possible to select between QGSJET [7] and SIBYLL [8].

3. Massive production of simulations

The particular needs of complex studies based in simulations, that require generating very large sets of simulated showers, have been considered in detail during the last years, and a series of developments have been performed to better adapt AIRES to these kind of tasks. We consider that it is important to briefly summarize such technical features in this work, for details see [1].

The software developments performed to improve heavy production tasks can be separated into two categories, namely, developments of the simulation system itself, and developments of complementary software.

In the first category we can mention: (i) Production of special output files to ease automated processing of simulations. (ii) Extension of the AIRES IDL input directive set to support more complex input instructions, like interactions with the operating system and conditional execution of directives, for example.

On the other hand, the second category of complementary software includes: (i) An auxiliary program, Aires-Merge, that can merge output files coming from different simulations in a single file. (ii) SRManager, a complete system for massive fully automatic parallel processing of shower simulations.

With the aid of such developments it has been possible to generate very large sets of simulated showers (more than 50,000 top quality showers simulated in the last three years), that are, to the best of our knowledge, the largest shower libraries build up to now.

Most of those shower libraries have been used within the Auger Collaboration to perform many studies based on simulations [9].

We would like to mention also that during the last months we have simulated a series of air showers initiated by photon primaries, taking into account the possibility of gamma conversion in the magnetosphere. Some of those showers are used for a composition reanalysis of AGASA data presented separately [5], and showing that the thinning level could affect substantially the results.

4. Final remarks

We have presented an update of the main features of the AIRES system for air shower simulations, stressing on the recent developments than can be summarized as follows:

1. Extended recognized particle set to sigma, xi and omega baryons, to permit proper treatment of low energy hadronic model output.
2. Developed an external module for gamma preshowering.
3. Special developments for massive production.

All these features are included in the present version of AIRES (2.8.0). We are presently working on the release of a new public version of AIRES that will contain some additional improvements. The current status of the AIRES system can always be checked at the AIRES Web page:
www.fisica.unlp.edu.ar/auger/aires.

Acknowledgments

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