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Muon imaging: Principles, technologies and applications

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ABSTRACT

During the last 15 years muon-based imaging, or *muography*, has experienced an impressive development and has found applications in many different fields requiring penetrating probes. Structures of very different sizes and densities can be imaged thanks to the various implementations it offers: either in absorption/transmission or in deviation modes, not to mention the muon metrology for monitoring. The goal of this paper is to give an overview of the main principles of the muography, as well as the technologies employed nowadays and its current and potential applications. Considering the amount of studies dedicated to muography and the number of projects conducted in the last decade, this review focuses on the fields which are the most representative of the muography capabilities.

1. Introduction

The variety of radiations and particles offers nowadays numerous possibilities in imaging. The choice of the source depends on many parameters, in particular the nature of the object and its thickness. If several options exist below typically one meter, like X-rays or neutrons, deeper structures require very high energy and/or penetration capabilities which are often out of reach of artificial sources. For such cases, a particularly penetrating probe is offered by cosmic muons naturally produced in the atmosphere. Thanks to their high energy and large mass, they can indeed cross up to several hundreds of meters of rocks before being absorbed. Their potential for imaging has been known for decades, but the recent progress on particle detection driven by high energy physics has opened the door to a vast range of applications, resulting in a growing interest for this technique.

The next section is dedicated to the origin of these muons and to the principles of the different types of muography. The performance requirements as well as the most common detection techniques are described in Section 3, before reviewing some flagship applications in Section 4.

2. Cosmic rays and muography

2.1. Cosmic rays and muons

2.1.1. Primary particles

The extraterrestrial origin of this ionizing flux was conclusively discovered in 1912 with measurements under the sea and at high altitude [1,2]. It took another few years to understand that the primary particles are charged, in particular through the measurements by Compton of the latitude effect [3] as well as the East–West effect predicted by Rossi [4–6]. Today we know that this particle flux, unfortunately called cosmic rays,[1] is composed of about 90% of protons and 9% of alphas, the rest being essentially electrons and some small fractions of heavier ions up to Fe. Though the solar wind gives a small contribution at low energy, most of the cosmic rays are produced outside the solar system, in particular in supernovae and in Active Galactic Nuclei (AGN). The intensity of cosmic ray nucleons shows a strong energy dependence approximately given by:

$$I_N(E) \approx 1.8 \times 10^4 \left(\frac{E}{\mathrm{GeV}}\right)^{\alpha} \frac{\mathrm{nucleons}}{\mathrm{m}^2\ \mathrm{s\ sr\ GeV}}, \tag{1}$$

with $\alpha = 2.7$ at energies below a few hundreds of TeV. In addition to the variations of the solar wind component, the intensity of the low energy part of the spectrum depends on the sun magnetic deflection and is thus anti-correlated with the solar activity (11-year cycle).

2.1.2. Decays in the atmosphere

When entering the Earth atmosphere, the primary particles interact with the atoms producing copious quantities of baryons and mesons. These particles can either reinteract or decay depending on their lifetime. In particular charged mesons may decay into muons, electrons

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[1] This expression originates from Millikan, who was convinced that primary particles were photons.

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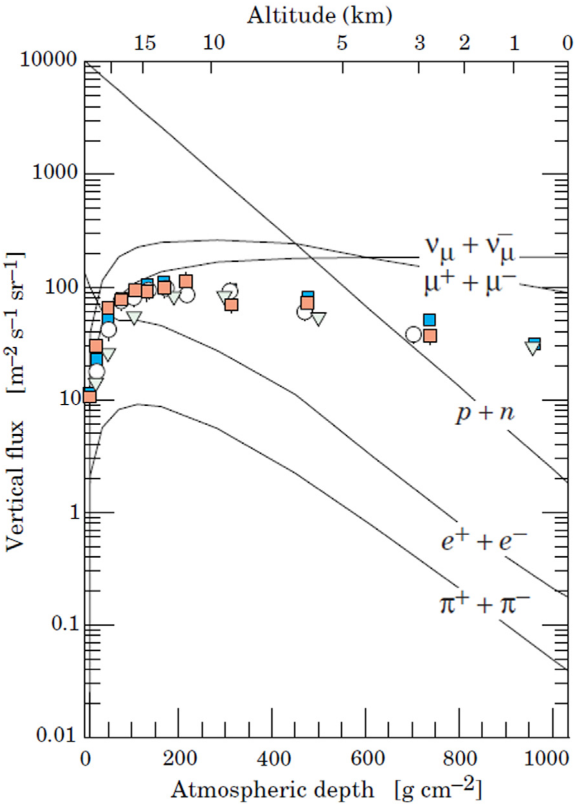

Fig. 1. Vertical fluxes of particles (except photons) originating from the cosmic rays as a function of the depth in the atmosphere, from [7]. Points are measurements for negative muons above 1 GeV.

and neutrinos, while neutral mesons quickly decay into photons. This cascade of reactions leads to the formation of a shower with a spatial extension reaching several hundreds of meters or more depending on the energy of the primary. The vertical flux of particles as a function of the atmospheric depth is shown in Fig. 1.

The two main sources of muon production correspond to the decay of charged pions and kaons:

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \qquad K^- \rightarrow \mu^- + \bar{\nu}_\mu, \tag{2}$$

with branching ratios of 99.99 and 63.5% respectively. It is worth mentioning that the decay into electron, which should be favored because of its lighter mass, is in this particular case strongly suppressed by an helicity effect, see *e.g.* [8].

In addition to this favorable production modes, muons have a significantly higher probability to survive the atmosphere crossing, benefitting from the combination of two effects:

- A longer mean lifetime (≈2.2 μs) compared to other unstable particles like mesons. Because of their high energy and the time dilatation from special relativity, this lifetime translates into a long mean decay length L in air given by L (km) = 6200×E (TeV).
- A large mass compared to electrons ($m_\mu \approx 207\ m_e$). The energy loss by Bremsstrahlung being proportional to $1/m^2$, it yields a value 40,000 smaller for muons compared to electrons at a given energy. The ionization and excitation therefore dominate the muon energy loss up to energies of the order of 500 GeV.

2.1.3. *Flux at the sea level*

As can be inferred from Fig. 1, the muon flux dominates by more than one order of magnitude the flux of other particles at the sea level. It yields approximately 70 /(m^2 s sr) on the vertical axis, with a rough $\cos^2(\theta)$ dependence where θ is the angle to this axis. When θ increases, the larger muon path in the atmosphere favors the decay of low energy muons, resulting in a higher mean energy. A semi-empirical estimate of the mean flux at the sea level for high energy muons ($E > 100$ GeV$/\cos\theta$) is given by:

$$\frac{dN}{dEd\Omega} = \frac{0.14E^{-2.7}}{\text{cm}^2\ \text{s sr GeV}} \times \left(\frac{1}{1 + \frac{1.1 \times E\cos\theta}{115\ \text{GeV}}} + \frac{0.054}{1 + \frac{1.1 \times E\cos\theta}{850\ \text{GeV}}} \right) \tag{3}$$

which shows the separate contributions from pions and kaons to the muon yield. At lower energies, the non-negligible muon decay probability as well as several atmospheric and solar effects complicate the determination of a mean muon flux, but systematic measurements and some parametrizations are available, see *e.g.* [9,10] respectively.

Though quite stable, the muon flux can be affected both in space and in time by several effects of different origins [11]:

- the altitude: as seen in Fig. 1, the muon flux increases above the sea level, essentially because of low energy muons which did not have time to decay;
- the latitude: the flux is lower close to the equator because of the shielding Earth's magnetic field;
- the solar activity (see previous section);
- the atmospheric pressure (short-time effect): a higher pressure in the lower part of the atmosphere results in a reduced flux, as the enhanced quantity of air absorbs low energy muons;
- the upper atmosphere temperature (seasonal effect): during summer, the increase of the upper atmosphere temperature enhances the mean free path of pions and kaons and therefore their probability to decay into muons [12].

Several simulation tools are nowadays available to study the precise development of cosmic showers in the atmosphere, like CORSIKA [13], and to efficiently propagate cosmic muons in thick matter, like MUSIC [14,15] or TIERRAS [16].

2.2. *Muon imaging*

As any other charged particles, muons interact with atoms of the matter they cross, resulting in a loss of energy and a change of direction (multiple scattering). These two effects underlie two different kinds of muon imaging as described in the next sections.

2.2.1. *Transmission and absorption muography*

Because of the energy loss, a muon has only a certain probability P to cross a given amount of material. If the mean energy loss (ionization, excitation and radiative) is large (resp. small) compared to the initial muon energy, P is very close to 0 (resp. 1).[2] The general equations for the mean energy loss (Bethe–Bloch and Bremsstrahlung) show that for a thin layer dx of material with density ρ, it primarily depends on the product $\rho \times dx$. At first order, the fraction of muons crossing (or non crossing) a material is therefore determined by the integrated density over the path length $\int \rho(x)dx$, a quantity called *opacity*. The experimental measurements of this fraction in different directions through an object from a given point of view (the position of the muon detector) then gives access to a cartography of the opacity, integrated along these directions. In the usual case where the thickness is actually known, the mean density is then obtained. This technique is commonly referred as *transmission* or *absorption* muography by analogy with the photography, though the term *absorption* is actually misleading.[3] Though one or the other term is usually employed in a generic way, it should be emphasized

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[2] The exact calculation of P is difficult, as it depends on the fluctuations around the mean energy loss, but it can be estimated through a simulation.

[3] Indeed, muons either decay (μ^+ and μ^-) or are captured (μ^-) by the material.

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