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Charm in cosmic rays (The long-flying component of EAS cores)

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Abstract

Experimental data on cosmic ray cascades with enlarged attenuation lengths (Tien–Shan effect) are presented and analyzed in terms of charm hadroproduction. The very first estimates of charm hadroproduction cross sections from experimental data at high energies are confirmed and compared with recent accelerator results.

Keywords: Charm; Production cross-section; Cosmic rays; Extensive air showers; High energy interactions

1. Introduction and brief overview

Charm was found in cosmic rays in 1971 by Niu et al. [1] (no such name was ascribed to it at that time). The creation of charm particles provoked in 1975 to relate them [2] to the long-flying component of the cores of extensive air showers (EAS) observed a couple of years before [3,4] and named as the Tien–Shan effect. This idea was however abandoned for several years because no precise data on properties of charm hadrons existed. Let us note that the similar elongation of the cascades observed at Aragatz installation in Caucauses with rather low statistics was analyzed in late 1970s in [5] but the resulting estimates of particle parameters (mass about 10 GeV and lifetime 10^{-10} s) were misleading.

Open charm measurements in accelerator experiments date back to late 1970s when D and $\bar{D}$ mesons were first detected. In earlier 1980s, the leading effect in Λ_c production was declared by experimentalists [6,7] and supported by theorists [8]. The small inelasticity coefficient for Λ_c was also advocated [8,9]. The spectra of D-mesons were considered to be much softer than those of Λ_c [7,10]. The charm hadroproduction cross sections measured at energies $\sqrt{s} < 20$ GeV were quite small (less or about 10 μb). It looked improbable that they increase fast with energy even though first calculations in the quark-gluon strings model showed [11] that they can become as large as 0.1–1 mb at energies exceeding $\sqrt{s} = 100$ GeV. Smaller values were however obtained in [12].

Meantime, masses and lifetimes of charm particles were measured more and more accurately. In parallel, the more precise data about the long-flying component of the EAS cores were obtained [13]. The specific structure in the energy dependence of the attenuation length of cascades observed in the hadron calorimeter [14,15] revived the idea about charm production responsible for these peculiar features [16]. The starting impact was related with long lifetimes of charm particles. Both analytical and computer calculations with kinetic equations [17] and Monte-Carlo simulations of cascades in the calorimeter [18–20] were attempted. They lead to the conclusion [16,18,21] that the charm production cross section can be as large as 1.4–2.8 mb at the laboratory energy $E_L = 10$–20 TeV ($\sqrt{s} = 140$–200 GeV) and about 3–5 mb at $E_L \approx 100$ TeV ($\sqrt{s} \approx 450$ GeV). These estimates were the earliest values for the charm hadroproduction cross sections obtained from experimental results at very high energies. The cosmic ray data obtained with lead and X-ray emulsion detectors also showed the existence of the long-flying cascades [22]. Later it was concluded [23,24] that they support a large

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charm cross section at $\sqrt{s} = 300$ GeV. These values of the charm hadroproduction cross section were considered as being extremely large and almost unrealistic until recent experiments at RHIC energy $\sqrt{s} = 200$ GeV claimed (see, e.g., [25]) that this cross section per nucleon in *pp* and *d*-Au collisions is $1.4 \pm 0.2 \pm 0.4$ mb according to STAR collaboration [26,27] and $0.92 \pm 0.15 \pm 0.54$ mb according to PHENIX collaboration [28]. The same collaborations extracted the same cross sections from Au–Au collisions at $\sqrt{s} = 200$ GeV and give the following numbers: $1.11 \pm 0.08 \pm 0.42$ mb for STAR [29] and $0.622 \pm 0.057 \pm 0.160$ mb for PHENIX. The compilation of both accelerator and cosmic ray data on charm hadroproduction cross section at various energies is demonstrated in Fig. 1.

The difference by a factor about 1.5–2 between the two collaborations at RHIC is related to problems in extracting the cross section values. They are obtained from a finite number of measured *D* mesons in a particular decay channels by using many correction factors. Especially important are the extrapolations to the full phase space because of undetected forward region and the role of other numerous unmeasured charm hadrons. Let us stress here that namely forward region is crucial in cosmic ray experiments.

The situation with QCD calculations is also not clear yet even though there has been a great deal of improvement over last 10–15 years. In 1990s they predicted rather low values of these cross sections (tens microbarns) with a very mild increase with energy. Recent results taking into account higher order (NLO) perturbative corrections [30,31] give larger values about 0.25 mb with uncertainty up to 0.4 mb and improve the situation. They are however still lower by a factor 5–6 than STAR data. The quark-gluon strings model is in a better position (see, e.g., [32,33]) predicting larger cross sections about 1 mb. The heavy quark production was also considered in the semi-hard QCD approach [34].

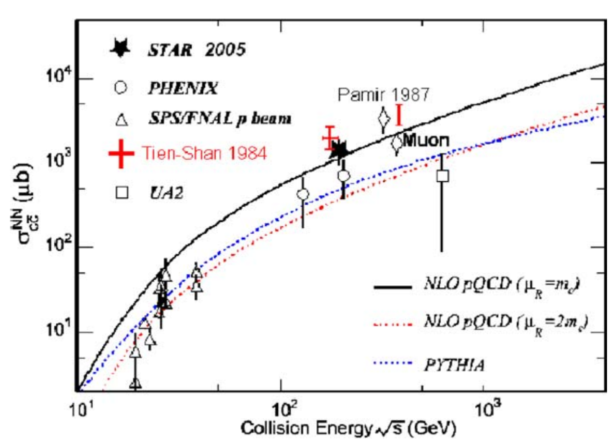

Fig. 1. The compilation of the charm hadroproduction cross sections at different energies from accelerator and cosmic ray data. This is the modification of Fig. 4 in [26] (see also Fig. 1 in [25]) with Tien–Shan results added. The highest energy point at 100 TeV shows the limits for the extrapolated according to Eq. (11) total charm cross section which provide satisfactory fits for the attenuation length behaviour in Fig. 8. The cross at 10–20 TeV corresponds to values obtained by interpolation between these limits and low energy data. Pamir and Muon points are the cosmic ray data from [22–24].

In view of this intriguing and rapidly evolving situation we decided to reanalyze previous cosmic ray data and compare with results obtained during last years.

Let us mention that the charm particle production is also important for muon studies, both underground and in gamma-astronomy [35,36].

2. Qualitative expectations

Before discussing the experimental installation in detail, we would like to explain the physics of the phenomenon and present the qualitative expectations which gave rise to the idea about the role of charm particles. EAS cores consist of beams of high energy hadrons. These hadrons interact actively when they pass through the dense matter of the calorimeter. Most interactions give rise to abundant pion production. These pions create new pions in inelastic collisions. The hadronic shower is developed with the typical attenuation length in lead about 600–700 g/cm^2. In some events the charm particles are however produced. Their decay lengths are of the order of tens or hundreds μm at comparatively low energies. Thus the low energy charm particles decay within the main shower and nothing special happens. The decay length is proportional to the γ-factor. Therefore, high energy charm particles are able to penetrate to larger depths in the calorimeter. If they carry large portion of initial energy, then the shower elongates and the attenuation length increases. However, at a somewhat higher energy it can happen that a produced charm particle passes through the whole calorimeter without decay. Its energy is no more detected in the calorimeter. The attenuation length should come back to its standard values. Thus one would expect to observe a maximum in the energy dependence of the attenuation length.

Let us advertize in Fig. 2 the final result of the Tien–Shan experiment where the observed energy dependence of the attenuation length of hadronic showers in EAS cores is plotted. This anticipates its detailed discussion below. The upper and lower experimental points correspond to two classes of cascades separated according to special methods among the available amount of data.

We will interpret the upper points as typical for long-flying cascades with decaying high energy particles because they are obtained from samples enriched by such particles as advocated below. With three peaks in it, one is tempted to ascribe this plot to $D^{\pm}$, D^0 and Λ_c. The decay length l_i for any species i is given by

$$l_i = c\tau_i\gamma_i = c\tau_i\frac{E_i}{m_i}, \tag{1}$$

where τ_i is its lifetime, γ_i is the γ-factor, E_i, m_i are its energy and mass. If the interaction with production of a charm particle took place in the upper part of the calorimeter, then the attenuation length would return to its standard