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Energy dependence of charm production cross section at high energies

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Charm production cross-sections estimated from data obtained in the "Pamir" and other cosmic ray experiments are compared with accelerator data. The strong increase of the charm production cross-section with energy, essential for the explanation of cosmic ray data, is analyzed from a theoretical point of view.

1. INTRODUCTION

During the last decade fixed-target studies of heavy-flavour production have provided a wealth of data about charm. Total cross-sections, single inclusive distributions and quark and antiquark correlations have been measured in proton- and pion-induced reactions up to a laboratory energy of 1 TeV. Perturbative QCD is in this case at its very limit of applicability, because the charm mass is close to the typical hadron scales. Thus, non-perturbative effects will very likely play an important role [1]. The overall conclusion of these studies is that the qualitative and quantitative features of the experimental distributions are properly described by the theory, but many open problems remain unsolved in this field [1]. Theoretical predictions for charm production cross-section, $\sigma_{c\bar{c}}$, at high energies are very uncertain because they depend on the heavy quark mass, the contribution of next-to-leading order corrections (NLO), parton structure functions at small x, and the scale factor μ^2. However, the energy dependence of $\sigma_{c\bar{c}}$ is very important for cosmic ray physics. The rapidly progressing neutrino astrophysics needs, for an interpretation of their data, a knowledge of atmospheric neutrino and muon fluxes, which at high energy depend strongly on the contribution of so called "prompt" muons and neutrinos, originating in the atmosphere from charmed particle decays.

In the late 80s three cosmic ray experiments reported a significant indication that $\sigma_{c\bar{c}}$ is large at several tens of TeV. At the Tian-Shan ionization calorimeter [2] the energy absorption path, revealed in the calorimeter by EAS core hadrons, was found to increase abruptly for total hadron energies of about 40 TeV. To explain the observed effect, the authors proposed a hypothesis that the excess in the ionization is caused by particles, which decay deep in the calorimeter. Ionization induced by high energy hadrons in a calorimeter depends strongly on low-energy processes difficult to account for. Furthermore the composition and spectrum of EAS core hadrons makes the quantitative evaluation of charm production cross-sections exceedingly difficult. In view of these facts the Pamir Collaboration started to expose the deep lead X-ray emulsion chambers (XEC) [3] in order to study the absorption of single hadrons in lead. Contrary to calorimetry methods, hadrons detected in XEC are not distorted by group arrival of particles due to the high spatial resolution of X-ray films (300 μm). Moreover only electromagnetic cascades with high energy threshold (6 TeV), induced by hadrons in successive interactions in the chamber, are detected in XEC. The results obtained confirmed the conclusion on a probable large value of charm cross-section ($\sigma_{c\bar{c}}^{pp} = 1.5 \pm 1\ mb$) at a laboratory energy of about 75 TeV [3].

The "Muon" experiment [4] observed a hardening of the spectrum of electromagnetic cascades for single muons arriving at azimuthal angles $\theta < 60°$ and at energies beyond 10 TeV, whereas the spectra of muons at larger angles were described by a power law with a fixed index. This behaviour of the muon spectra can be described qualitatively by the contribution of "prompt" muons. The total cross-section need-

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ed to explain this hardening was estimated to be ($\sigma_{c\bar{c}}^{pp} = 1.7 \pm 1\ mb$) at a laboratory energy near 100 TeV. The reliability of the rapid increase of the charm production cross-section with energy is analyzed comparing the charm production cross-section, estimated from cosmic ray data, accelerator data and theoretical predictions.

2. PAMIR EXPERIMENTAL DATA ON $c\bar{c}$ PRODUCTION

Atmospheric hadrons (mostly nucleons and pions) passing through the 110 cm deep chamber can successively interact with lead nuclei and produce electromagnetic cascades, detected by X-ray films, if their energy E_γ^h exceeds the threshold 6 TeV. The t-distribution of the cascade starting points in the chambers is mostly sensitive to hadron cross-sections and the inelasticity coefficient, K [3]. But if charmed particles are produced, due to the large decay length, they can penetrate deeper in the chamber, comparable to the total depth of the chamber, and hence should be observed as excess cascades at large chamber depths.

The total area of the exposed chambers was 30.5 m^2. 900 cascades induced by hadrons with $E_\gamma^h > 6.3$ TeV were selected. The measured absorption length, L, obtained in the interval $22 - 78 c.u.$ is $L = 212 \pm 19\, g/cm^2$ and agrees with results obtained in an experiment using a 40 cm XEC and with calculations. However, at depths t > 78 c.u. L is found to be 310± 36 g/cm^2, which is significantly larger. The excess of cascades at a depth > 80 c.u. is about 30%. A number of methodical effects which could result in incorrect measurements of the hadron absorption path in lead were studied in detail [3]. It could be shown that, within the accurcy of this experiment, excess cascades do not differ from usual cascades induced by hadrons.

The hadron absorption was calculated up to 110 cm of lead in the framework of two simulation codes which both describe accelerator well: MQ [8], based on the quark gluon string model [6] and AQM, based on the additive quark model [7]. Both codes take into account the energy distributions of particles, procedures of detection and selection of events, the composition of hadrons incident upon the chamber and so on. The absorption obtained was strictly exponential over the entire range of the absorber depths, with an expected absorption path in lead of $L = 215 \pm$ 10 g/cm^2.

For a detailed analysis of the charm hypothesis responsible for excess cascades, the modified program MQ [8] was used for calculations of nuclear-electromagnetic cascades in air and lead taking charm production into account. The inclusive spectra of various types of charmed particles in the MQ model compared with recent experimental data were well reproduced in the framework of the MQ generator [8]. When simulating the experiment the relative production cross-section of $c\bar{c}$-pair $\delta_c = \frac{\sigma_c^{hPb}}{\sigma_{in}^{hPb}}$ was varied. The effect of the absorption curve bending similar to the experimental one can only be observed for a very large relative cross-section $\delta_c = 0.5 \pm 0.1$. The calculated value of L varies from 220 ± 8 g/cm^2 in the depth interval 10-80 c.u., to 276±12 g/cm^2 for 80-190 c.u. that is close to the values obtained in our experiment. Calculations show that the effective production energy at which charm particles produce excess cascades deep in the chamber is, on average, 75 TeV, with a mean value x_F for these particles of 0.4. Hence the Pamir experiment can only give information about charm production cross-sections in the region of large x_F. Estimates of the total charm production cross-section are difficult. But in order to compare our data with that of other experiments, the estimated value of the charm production cross-section over the entire x_F range was calculated and compared to the cross-section in pp collisions under the assumption that $\sigma_{c\bar{c}}^{pA} = \sigma_{c\bar{c}}^{pp} A^{1 \pm 0.04}$. We obtain $\sigma_{c\bar{c}}^{pp} = 3.3 \pm 0.7 \pm 0.8\ mb$. The first error is associated with the accuracy of the relative cross-section, δ_c, and the second one, with the uncertainty of the extrpolation from a lead to a proton target.

The program MQ enabled simulation of the muon spectrum [9]. To describe the vertical muon spectra measured in the experiment "Muon"[4] $\sigma_{c\bar{c}}^{pp} \geq 2.5$ mb/nucleon should be assumed, which agrees with our estimates using the hadron absorption curve and is slightly larger than estimated earlier [5].

3. COMPARISON WITH THEORY

We present the energy dependence of $\sigma_{c\bar{c}}$ in Fig.1. In the low energy region the charm producton cross-section, $\sigma_{c\bar{c}}$ in $pp-$ and $\pi p-$interactions from fixed-target accelerator experiments [1] were used. In the high energy region the estimates of charm cross-section obtained from the "Pamir" [8] and "Muon" experiments [5] are shown together with a measurement at $\sqrt{S} = 630 GeV$ in the collider experiment UA2 [10]. In the low energy region $\sigma_{c\bar{c}}$ grows rapidly is well reproduced by QCD calculations [1] taking into account next-to-leading order corrections. The default value of the charm mass in [1] is M_c=1.5 GeV, and the default choice for the factorization scale μ_F and renormalization scale μ_R are $2M_c$ and M_c correspondingly. Even in the low energy range the uncertainty in the calculation is an order of magnitude. If the energy dependence is estimated using accelerator data at GeV energies and cosmic ray data in the TeV region $\sigma_{c\bar{c}}$ will increase as $\sim E^{0.80}$, over three orders of magnitude in energy. The inelastic cross section in this region increases slowly. To analyze how realistic is this assumption, we have considered the theoretical predictions [11], where the charm particle production cross-section was calculated in the framework of QCD up to the high energies as a function of different parameters: NLO corrections, the structure functions $G(x, \mu^2)$, the scale factor μ^2. At small $\mu^2 \sim M_c^2$, where the best agreement with experiment is attained, the contribution of NLO corrections enhances the cross section by a factor of 2 at GeV energies and increases significantly with energy. Furthermore the energy increase of the cross-section was shown to depend strongly on the behavior of the structure function in the region of small x_F which define the contribution of gluons to the interaction cross-section at superhigh energies. Fig.1 shows the above mentioned calculations for two sets of the structure functions: the Duck-Ouens (D02) [13], Gluck-Reyi-Vogt (GRV1) [12] at $\mu^2 = 4$ Gev^2. One can see, that an increase of the charm production cross-section assumpting GRV1 structure functions is almost linear with energy. It is explained by the power law behaviour of the structure functions at $xG(x \to 0) \sim x^{-(0.33-0.4)}$. For D02, where $xG(x \to 0) \sim Const$, the predicted increase in the cross section is significantly weaker. Moreover one can see that even GRV1 does not predict the cross-section value 3 mb at 75 TeV, which is necessary for explaining cosmic ray results. Predictions of the quark-gluon string model, QGSM, from the same paper [11] also contradict the obtained cross section value. Herein it should be noted that in most theoretical calculations for RHIC or LHC, authors as a rule predict slower energy dependence of charm production. But choosing the free parameters of calculations they are based on the experimental point UA2, which in principal is in contradiction to cosmic ray points. But collider measurements are sensitive only to central region of charm production. Conversely the cosmic ray data is sensitive only to large values of x_F.

4. DISCUSSION

Summarizing the above consideration, one can state that in spite of the latest achievements of heavy quark physics it is not clear whether the results of the two cosmic ray experiments [3] and [4] can be explained by the production of charm particles. But a rapid growth of $c\bar{c}$ cross-sections does not seem too fantastic. To clarify the nature of excess cascades in the Pamir experiment, a special experiment with X-ray emulsion chambers with large air gap [15] was suggested for direct measurement of the charm production cross section. Unfortunately there are no other cosmic ray experiments sensitive to charm production. Numerous experiments, where the muon spectra at sea level are reconstructed using the muon absorption curve in the ground, give significantly smaller estimates for the charm production cross-section than in the "Muon"experiment. More likely this difference is associated with the principal impossibility to measure high energy muons with small angles, because such installations should be located very deep underground.

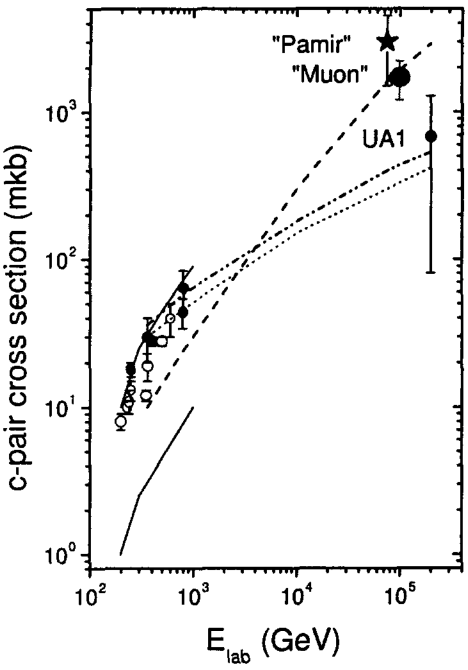

Figure 1. The charm production cross-section measured at accelerators in pp-reactions (small black circles), in πp-reactions (small open circles), and estimated in the cosmic ray experiments "Pamir" (big star) and "Muon" (big full circle). Theoretical predictions for low energy range from [1] (solid lines for upper and lower limits), for high energies from [11] for QCD NLO calculation with two sets of structure functions GRV1 [13] (dashed line) and D02 [12] (dotted line). Predictions of the quark-gluon string model QGSM [11] are shown by dot-dot-dashed line.

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