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CROSS SECTION FOR PRODUCTION OF CHARMED PARTICLES IN pN-INTERACTIONS AT 70 GeV IN PROTON BEAM DUMP EXPERIMENT AT IHEP–JINR NEUTRINO DETECTOR*

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Introduction

Results of processing the data of the proton beam-dump experiment at the IHEP-JINR neutrino detector by different methods in order to isolate a signal from "direct" neutrinos (from decay of charmed particles) and to estimate the cross section for production of charmed particles in pN collisions at 70 GeV were given in [1-3]. The results of these investigations were represented as estimates of upper limits for the cross section.

In the present paper we report an averaged cross section derived from four independent measurements [1, 3] and discuss both total cross sections and differential distributions in variables $p_{\perp}^2$ and X_F compared with the QCD-based calculations [4-6].

Total cross section for charm production in pN interactions at 70 GeV

The experimental lay-out is shown in Fig.1. Iron target with effective densities $\rho_1 = \rho_{Fe}$ and $\rho_2 = \frac{1}{2}\rho_{Fe}$ were used in the measurements. The experimental lay-out is described in more detail in [1-3].

The result of four measurements are given in Table 1. In [1] cross sections were derived from the number of charged current interactions of electron neutrinos and antineutrinos recorded in the detector: $\overset{(\sim)}{\nu_e} + N \rightarrow e^{\mp} + X$.

In [3] cross sections were derived from the number of incoming "equilibrium" μ^+ -mesons arising from interaction of muon antineutrinos in the last 16 metres of iron shield installed directly in front of the detector.

Two methods were used to derive the cross section:

- linear extrapolation of the number of interacted neutrinos as a function of $\frac{1}{\rho}$ to the infinitely dense target;
- subtraction of the neutrino interaction background from normal sources (decays of π - and K - mesons).

Averaged over four measurements, the total cross section for production of charmed particles in pN collisions at 70 GeV is

$$\sigma_{C\bar{C}}(pN \to C\bar{C}X) = (0.9 \; {}^{+1.1}_{-0.9})\mu b/nucleon$$

The upper limit for the cross section is $2.7\mu b/nucleon$ at the 90% confidence level. The cross section for production of charmed particle on iron nuclei was supposed to be linearly dependent on the atomic weight:

$$\sigma_{C\bar{C}}(pFe) \sim A^{\alpha} \cdot \sigma_{C\bar{C}}(pN) \qquad \alpha = 1.$$

Comparison with other experiments and theoretical calculations

Figure 2 shows the experimental data on total cross sections for production of charmed particles in NN interactions and those calculated with the charmed quark mass $m_c = 1.5GeV$ [4, 5] up to α_s^3, where α_s is the running strong interaction constant. The upper curve is derived with the dimensional parameter of gluon momentum scale in QCD $\mu_R = 1GeV$, the lower one with $\mu_R = 3GeV$ [5].

Consideration of the next-to-leading approximation of the QCD perturbation theory resulted in the 3 times larger cross section as compared with the leading approximation and allowed agreement between the calculations and experimental data at $m_c = 1.5GeV$, which is the value following from the mass spectrum of J/Ψ -particles.

As is evident from the figure, our cross section value obtained at 70 GeV ($\sqrt{S} = 11.46GeV$) agrees (within the experimental and theoretical uncertainties) with the cross section values calculated within perturbative QCD in the next-to-leading approximation (up to α_s^3) and lies well below the results of the BIS–2 experiment ($\sqrt{S} = 10.5GeV$) [7].

The experimental cross section for production of D-mesons in the NA–32 experiment [8] at 200 GeV ($\sqrt{S} = 19.6GeV$) is $\sigma_{C\bar{C}} = 1.5 \pm 0.7\mu b/nucleon$, being also well below the estimates of the charm production cross section in the BIS–2 experiment [7].

Table 1: Cross section for charm production in pN interactions at 70 GeV

Authors	Type of interaction of "direct" neutrinos	Target	Method	Number of interactions of "direct" neutrinos per 10^{18} protons	Cross section $\mu b/nucleon$
J.Blumlein et.all [1]	$\overset{(\sim)}{\nu}_e + N \to e^{\mp} + X$	$Al+CH_2$ 40t	Extrapolation	16.2 ± 12.3	4.8 ± 3.8
J.Blumlein et.all [1]	$\overset{(\sim)}{\nu}_e + N \to e^{\mp} + X$	$Al+CH_2$ 40t	Subtraction	-1.5 ± 5.1	-0.5 ± 1.7
L.Barabash et.all [3]	$\tilde{\nu}_\mu + N \to \mu^+ + X$	Fe $\sim 1000t$	Extrapolation	19 ± 46	1.3 ± 3.2
L.Barabash et.all [3]	$\tilde{\nu}_\mu + N \to \mu^+ + X$	Fe $\sim 1000t$	Subtraction	28 ± 30	1.9 ± 2.0

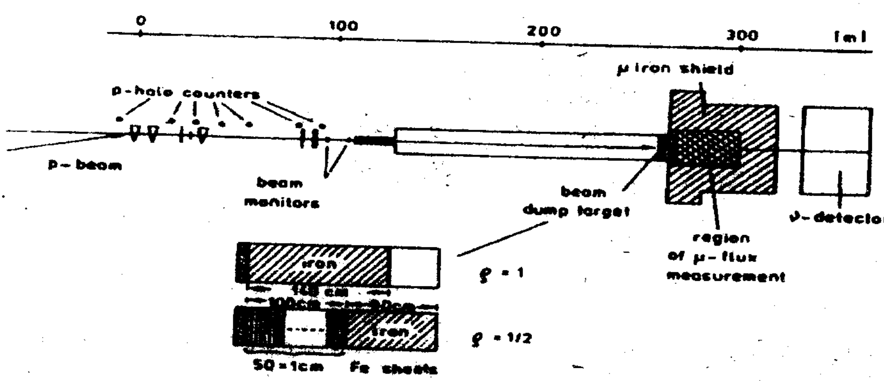

Figure 1: Lay-out of the experiment with full absorption of the proton beam from the accelerator U-70 (Protvino).

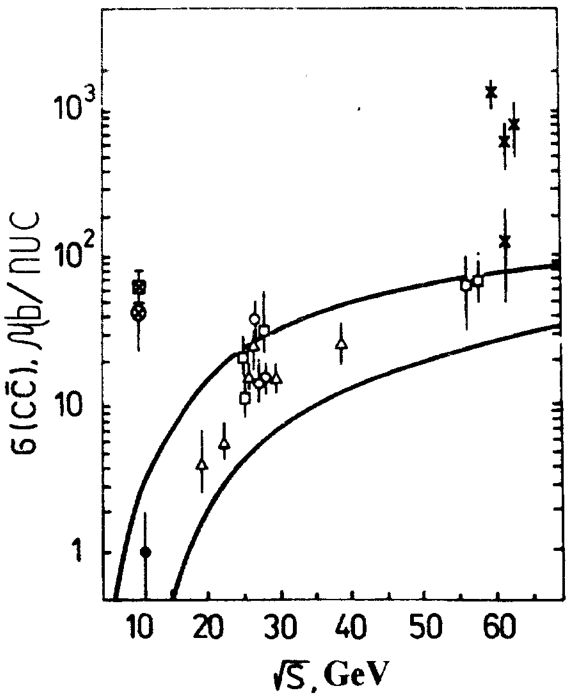

Figure 2: Experimental and calculated [4, 5] total cross section for production of charmed particles in NN interactions.

Differential cross sections for charm production in pN collisions

Estimation of the total cross section for production of charmed particles in the beam dump experiment depends on the type of the differential cross section we use.

In [1] they used a semi-empirical approximation of the differential cross section:

$$\frac{d^2\sigma}{dX_F dp_\perp} \simeq (1 - |X_F|)^n \cdot e^{-bp_\perp^2} \qquad (1)$$

where $X_F = p_{||}^*/p_{max}^*$.

The parameter n depends on the type of particles divided into fragments or produced and increases with increasing energy. At $X_F \to 1$ it can be estimated the quark counting rules [10,11]. For production of charmed particles in NN interactions its values are n=1 for Λ_c, n=5 for D^+ and D^0, n=3 for D^0, and n=4 for D^-. In [1] n=4 was chosen for D^0 and D^- mesons at 70 GeV, the parameter b was chosen to be 1.

In [3] the differential cross section was parametrized by the formula

$$\frac{d^3\sigma}{dx_+ dx_- dp_\perp} \simeq [(1 - x_+)(1 - x_-)]^n \cdot e^{-2.5p_\perp} \qquad (2)$$

where $x_\pm = \frac{E^* \pm p_{||}^*}{\sqrt{S}}$ and, according to the model [9], n was taken to be 1.5, 6.5, 3.5, 3.5 for Λ_c, D^+, D^0, D^- and D^0 respectively.

In (1) and (2) E and $p_\perp$ are the energy and transverse momentum of the charmed particle, E^* and $p_{||}^*$ are the energy and longitudinal momentum of the charmed particle in the c.m.s., S is the energy squared of colliding nucleons in the c.m.s.

Expressions (1) and (2) are close in the sense that if $X_F \to 1$, $(1 - x_+)(1 - x_-) \to (1 - |X_F|)$. Yet, parametrization (2) is preferable as it does not distinguish between the longitudinal and transverse components of the charmed particle momentum. A histogram in Fig.3 shows the distribution $\frac{d\sigma}{dX_F}$ for charmed antiquark production calculated at our request by S.Frixione on the basis of [6] for the energy

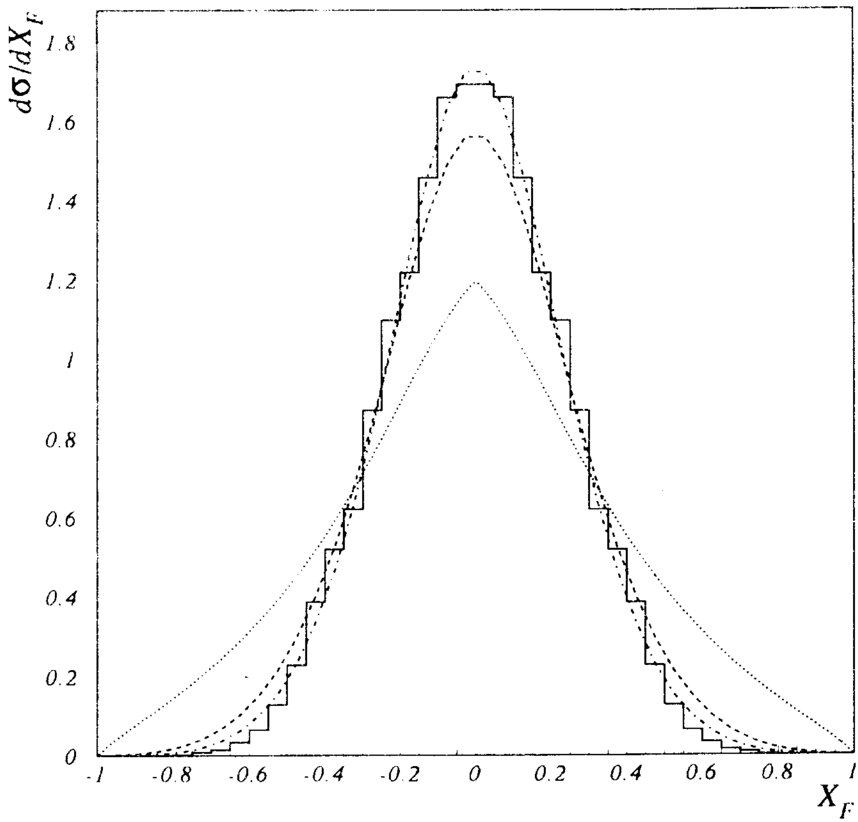

Figure 3: Distribution over the relative longitudinal momentum: $X_F = p^*_{||}/p^*_{max}$ The solid histogram is S.Frixione's calculation for the charmed anti-quark on the basis of [6]. The dashed curve is parametrization (2) with n = 3.5 for D^- -mesons. The dot-dashed curve is parametrization (2) with n = 4.5. The dotted curve is the BIS-2 result for D^- -mesons. All distributions are normalized to a unit area.

($\sqrt{S} = 11.46 GeV$). The histogram is best described by parametrization (2) at n=4.5 (dot-dashed curve). In our paper [3] parametrization (2) at n=3.5 was used to describe the distribution of D^- –mesons over X_F (dashed curve). A smaller n for D^- –mesons as compared with antiquarks can be naturally explained by the hadronization effect.

The experiment BIS-2 [7] yielded the data on the differential cross section for production of D^- and $\bar{D}^0$ mesons at the average energy $\sqrt{S} = 10.5 GeV$. There they used parametrization (1) and obtained $n = 1.1 \pm 0.6$, $b = 1.2 \pm 1.1$ for D^- mesons and $n = 1.1 \pm 0.6$, $b = 1.2 \pm 1.1$ for D^0 mesons. The distribution $\frac{d\sigma}{dX_F}$ obtained with the spectrometer BIS-2 for D^- mesons is shown by points in Fig.3. The distribution is seen to contradict both the QCD calculations and parametrization (2) used in our paper. The total cross sections $\sigma_{D^-}(X_F > 0.5) = 4.7 \pm 1.8 \mu b/nucleon$ and $\sigma_{\bar{D}^0}(X_F > 0.5) = 3.3 \pm 1.3 \mu b/nucleon$ are much overestimated. The sum of total cross sections for production of D^- and $\bar{D}^0$ mesons evaluated from our experimental data on the basis of distribution (2) is $\sigma_{C\bar{C}}(X_F > 0.5) = (2.8 \pm 3.4) \times 10^{-2} \mu b/nucleon$, i.e. more than two orders of magnitude below the values obtained in the BIS – 2 experiment.

That n is chosen correctly at 70 GeV is indirectly proved by the experimental data obtained at higher energies. For example, at 200, 370 and 400 GeV n is equal to $5.5\,^{+2.1}_{-1.8}$ [8], 6.0 ± 0.3 [12] and 4.9 ± 0.5 [13] respectively and only slightly depends on energy.

To describe differential cross sections by the transverse momentum in parametrization (1), we took b=1. Parametrization (2) $\frac{d\sigma}{dp_\perp} \simeq e^{-bp_\perp}$ yields the same description of the coefficient values at $p_\perp$: $b = 2.5$. The values of b given in Table 2 of [6] show that experimental data up to 400 GeV are well described by parametrization (1) at $b \simeq 1$.

In [6] differential cross sections for hadroproduction of charm calculated up to α_s^3 are compared with available experimental data in the proton energy interval from 200 to 800 GeV. The comparison showed that nonperturbative effects must included to describe differential distributions over the relative longitudinal momentum X_F and the transverse momentum $p_\perp^2$.

To distributions over the relative longitudinal momentum X_F, these effects must be simulated by a random distribution over the longitudinal momentum of colliding protons with allowance made for the final state interaction of the C quark in the form of a function of the Peterson fragmentation [14].

For theoretical description of distributions over the transverse momentum of charmed particles, the average transverse momentum $\langle K_\perp^2 \rangle = 2GeV^2$ of incident partons was introduced.

The parameter b, characterizing the distribution over $p_\perp^2$ in the parametrization $\frac{d\sigma}{dp_\perp^2} = \alpha C \cdot exp(-bp_\perp^2)$, was found to be very sensitive to the upper limit in $p_\perp^2$. This is because at large $p_\perp^2$ the cross section drops by a power law rather than exponentially. In the entire $p_\perp^2$ region the experimental data are well described by the formula

$$\frac{d\sigma}{dp_\perp^2} \simeq \left(\frac{C}{bm_c^2 + p_\perp^2}\right)^\beta$$

Yet, at $p_\perp^2 < 3GeV^2$ one can use exponential parametrization.

Conclusion

1. The total cross section for production of charmed particles at proton energy 70 GeV is $\sigma_{C\bar{C}} = (0.9 \,^{+1.1}_{-0.9})\mu b/nucleon$ on the assumption that the cross section on iron nuclei linearly depends on the atomic weight. This value agrees with the upper cross section limits obtained in the proton beam dump experiment at the accelerator U-70 [15,16]. Like most data for other energies, the cross section obtained at 70 GeV is in good agreement with the theoretical values calculated up to a in perturbative QCD with the charmed quark mass $m_c = 1.5GeV$ and the dimensional scale parameter $\mu_R = 1.5GeV$.

   Exceptions are the results of experiments at relatively low energies with the spectrometer BIS 2 ($\sqrt{S} = 10.5GeV$) [7] on the accelerator U 70 and at high energies with the ISR at CERN [17].

2. Parametrizations (1) and (2) were used to describe differential cross sections at proton energy 70 GeV over the relative longitudinal momentum X_F and transverse momentum $p_\perp^2$. In parametrization (1) over the longitudinal momentum X_F an average value n = 4 was taken for production of D mesons and D mesons, in parametrization (2) n was taken to be 6.5 for D-mesons and 3.5 for D mesons. At higher energies experimental values of n increase, being 4.9 ± 0.5 at E = 400 GeV and 8.6 ± 2.0 at E = 800 GeV.

   The parameter b was taken to be 1 in parametrization (1). Parametrization (2) $\frac{d\sigma}{dp_\perp} = e^{-2.5 p_\perp}$ yields similar description at the value of the coefficient at $p_\perp$ b=2.5.

   At $p_\perp^2 < 3GeV^2$ the exponential dependence describes the experimental data well. At high energies and the upper boundary of the region for $p_\perp^2 > 3GeV^2$ the cross section drops rather by the power law [6].

3. Analysis of the data for higher energies from 200 to 800 GeV [6] showed that nonperturbative effects should be taken into account to describe differential cross sections. At lower proton energies similar effects are even more probable both in differential and in total cross sections. More precise data for energies close to the charm production threshold will help to determine parameters in calculation of cross sections within perturbative QCD and the size of nonperturbative effects.

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Сечение образования очарованных частиц в pN-взаимодействиях при 70 ГэВ по результатам протонного beam-dump эксперимента на нейтринном детекторе ИФВЭ-ОИЯИ

Определено сечение образования очарованных частиц в протон-нуклонных взаимодействиях при энергии 70 ГэВ, усредненное по результатам четырех независимых измерений в протонном beam-dump эксперименте на нейтринном детекторе ИФВЭ-ОИЯИ. Величина полного сечения равна $0{,}9^{+1,1}_{-0,9}$ мкбн/нуклон и находится в согласии с теоретическими расчетами, выполненными на основе пертурбативной КХД с точностью до α_s^3 при массе очарованного кварка m_c = 1,5 ГэВ и размерном параметре шкалы μ_R = 1,5 ГэВ. Использованная в работе форма дифференциальных сечений в зависимости от X_F и $p_\perp^2$ находится в качественном согласии с результатами теоретических расчетов. Величина полного и дифференциального сечения в области $X_F > 0{,}5$ противоречит результатам, полученным на установке БИС-2, и основанном на них утверждении об аномально большом сечении образования очарованных частиц в нуклон-нуклонных столкновениях в околопороговой области энергий.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Cross Section for Production of Charmed Particles in pN-Interactions at 70 GeV in Proton Beam Dump Experiment at IHEP-JINR Neutrino Detector

The cross section for production of charmed particles in proton-nucleon interactions at 70 GeV is determined by averaging over the results of four independent measurements in the proton beam dump experiment with the IHEP-JINR neutrino detector. The total cross sections is $0.9^{+1.1}_{-0.9}$ μb/nucleon, which agrees with the calculations in perturbative QCD up to α_s^3 at the charmed quark mass m_c = 1.5 GeV and dimensional scale parameter μ_R = 1.5 GeV. The shape of differential cross sections vs X_F and $p_\perp^2$, used in the paper, is in qualitative agreement with the calculations. The values of the total and differential cross sections in the region $X_F > 0.5$ contradicts the results obtained with the set-up BIS-2 and to the statement, based on these results, that there is an anomalously large cross section for production of charmed particles in nucleon-nucleon collisions in the near-threshold energy region.

The investigation has been performed at the Laboratory of Nuclear Problem, JINR.

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Бунятов С.А., Нефедов Ю.А. E1-95-398

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