Charm production nearby threshold in pA-interactions at 70 GeV

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The results of the SERP-E-184 experiment at the U-70 accelerator (IHEP, Protvino) are presented. Interactions of the 70 GeV proton beam with C, Si and Pb targets were studied to detect decays of charmed $D^0$, $D^+$, $D^-$ mesons and $\Lambda_c^+$ baryon near their production threshold. Measurements of lifetimes and masses are shown a good agreement with PDG data. The inclusive cross sections of charm production and their A-dependencies were obtained. The yields of these particles are compared with the theoretical predictions and the data of other experiments. The measured cross section of the total open charm production ($\sigma_{tot}(c\bar{c}) = 7.1 \pm 2.3\text{(stat)} \pm 1.4\text{(syst)} \mu\text{b/nucleon}$) at the collision c.m. energy $\sqrt{s} = 11.8$ GeV is well above the QCD model predictions. The contributions of different species of charmed particles to the total cross section of the open charm production in proton-nucleus interactions vary with energy.
1. Monte Carlo simulation and selection of events with the charmed particles

The SERP-E-184 experiment "Investigation of mechanisms of the production of charmed particles in pA-interactions at 70 GeV and their decays" at the U-70 accelerator (IHEP, Protvino) was carried out at the SVD-2 (Spectrometer with Vertex Detector) setup [1]. This setup was constructed to study the charmed particles production in pp- and pA-interactions by the SVD collaboration including IHEP (Protvino), JINR (Dubna) and SINP MSU (Moscow). The main elements of the setup are the high-precision micro-strip vertex detector (MSVD) with an active target (AT) and a magnetic spectrometer. The AT contains 5 silicon detectors each 300-µm thickness and 1-mm pitch strips, a Pb-plate (220 µm thick) and a C-plate (500 µm thick), placed as Si-Si-Pb-Si-C-Si-Si. The tracking part of MSVD consists of 10 Si-detectors: four XY pair and one XYUV quadruplet, U and V are the oblique planes. The angular acceptance of MSVD is ±250 mrad. The spectrometer features allow one to get the effective mass resolution of \( \sigma = 4.4 \text{ MeV}/c^2 \) for \( K^0 \) and 1.6 MeV/c^2 for \( \Lambda^0 \) masses.

Monte Carlo (MC) events were obtained with FRITIOF separately for interactions on C, Si, and Pb with the charm production. Decays of unstable particles happened later within GEANT code. Certain decay modes were imposed for charmed particles (\( D^0 \rightarrow K^-\pi^+ \), \( \bar{D}^0 \rightarrow K^+\pi^- \), \( D^+ \rightarrow K^-\pi^+\pi^+ \), \( D^- \rightarrow K^+\pi^-\pi^- \), \( \Lambda_c^+ \rightarrow pK^-\pi^+ \)). GEANT3.21 package was used to simulate registration of pA-interactions. We analysed the simulated events in order to work out the selection criteria [2] for \( D^0 \rightarrow K^-\pi^+ \) and \( \bar{D}^0 \rightarrow K^+\pi^- \). The effective mass spectra of the \( K\pi \) system after applying of all criteria were fitted by the sum of the straight line and the Gaussian function. It gives 1861 ± 7 MeV/c^2 for \( D^0 / \bar{D}^0 \) mass and the signal-to-noise ratio of \((51\pm17)/(38\pm13)\). The detection efficiency of \( (D^0 / \bar{D}^0) \) particles with taking into account of the efficiency of visual inspection is equal to \( \varepsilon(D^0 / \bar{D}^0) = 0.036 \).

For reconstruction of the charged charmed mesons, we analysed the \( K\pi\pi \)-systems: \( D^+ \rightarrow K^-\pi^+\pi^+ \), \( D^- \rightarrow K^+\pi^-\pi^- \). The charged charmed mesons were found by analysing of the events with a three-prong secondary vertexes (the selection procedure is described in [3]). After parametrisation of the spectrum as sum of the Gaussian function and polynomial we were got 15.5 ± 5.6 (15.0 ± 4.7) signal events from \( D^+ / \bar{D}^+ \) meson decay over the background of 16.6 ± 6.0 (8.7 ± 2.7) events. Also, the mass of \( D^+ \): \( M(D^+) = 1874 \pm 5 \text{ MeV}/c^2 \) (PDG − 1869.6), \( \varepsilon(D^+) = 0.014 \) (efficiency of a signal extraction); the mass of \( D^- \): \( M(D^-) = 1864 \pm 8 \text{ MeV}/c^2 \), \( \varepsilon(D^-) = 0.008 \).

The charmed \( \Lambda_c^+ \)-baryon was analysed with the three-prong decay \( \Lambda_c^+ \rightarrow pK^-\pi^+ \). Application of all the selection criteria [4] resulted in the effective mass spectrum with the signal-to-noise ratio: \((21.6 \pm 6.0)/(16.4 \pm 4)\) and mass \( M(\Lambda_c^+) = 2287 \pm 4 \text{ MeV}/c^2 \) (PDG − 2286.5), \( \varepsilon(\Lambda_c^+) = 0.011 \).

2. Cross sections for charmed particle production and their A-dependence

We have calculated inclusive cross sections for charmed particle \( i(i = D^0, \bar{D}^0, D^\pm \) or \( \Lambda_c^+ \)) using the relation:

\[
N_s(i) = (N_0 \sigma(i) A^0_t/(\sigma_{pp} A^{0.7})) (B(i) \varepsilon(i)) K_{it} \text{ or } ln(N_s(i)/C(i)) = \alpha \times ln(A) + ln\sigma(i),
\]

where \( C(i) = [N_0/(\sigma_{pp} A^{0.7})] \times [(B(i) \times \varepsilon(i))/K_{it}] \), \( N_s(i) \) determines the number of events in the signal for the \( i \)-charmed particle produced in the given target, \( N_0 \) — the number of inelastic interactions in this target, \( \sigma(i) \) — the cross section for charmed particle production at a single nucleon of the
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**Figure 1:** (a) the A-dependence of cross sections for the charmed particles production in pA-interactions; the \( \alpha \)-parameter as a function of (b) \( x_F \) and (c) \( p_T^2 \) for \( (D^0/\bar{D}^0) \) particle, the lines describe MC events (FRITIOF); (d) relative yields of charmed particles: \( \bullet - D^0, \circ - \bar{D}^0, \blacksquare - D^+, \square - \bar{D}^+, \blacktriangle - \Lambda_c^+ \) [2, 3, 4], the theoretical curves (with designation of a particle) are taken from [6].

The total cross section of the charmed particle production in pp at 70 GeV/c is estimated as

\[ \sigma_{tot}(c\bar{c}) = 7.1 \pm 2.3 \text{ (stat)} \pm 1.4 \text{ (syst)} \mu b/\text{nucleon} \]

**3. Conclusion**

Our basic results of study of the charmed particle production are careful measurements of...
**Figure 2:** Left panel: $\sigma_{\text{tot}}(c\bar{c})$ in $pA$-interactions. Extrapolation is solid line. Experiments: $\circ$ – SVD-2, $\square$ – SCAT bubble chamber, $\Delta$ – BIS-2 spectrometer [6], other lines are taken from various models (see refs. in [4]). Right panel: $\sigma(\Lambda_c^\pm)$ at $x_F > 0$, where $\blacksquare$ – world data, $X$ – the result of our experiment, lines - the model predictions based on QCD [5].

- $\sigma_{\text{tot}}(c\bar{c}) = 7.1 \pm 2.3$ (stat) $\pm 1.4$ (syst) $\mu$b/nucleon at c.m. energy $\sqrt{s} = 11.8$ GeV that is much above the QCD model predictions (Fig. 2, the left panel);
- the contributions of $\sigma(i)$, where $i = D^0, \bar{D}^0, D^+, D^-$ and $\Lambda_c^\pm$ into the total cross section $\sigma(c\bar{c})$ vary at lower collision energies (Fig. 1, d);
- the cross section for $\Lambda_c^\pm$ production at $\sqrt{s} > 30$ GeV contradicts $\sigma(c\bar{c})$ for the open charm production cross section (Fig. 2, the right panel). $\sigma(\Lambda_c^\pm)$ are extraordinarily large in this area.

**References**

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