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ELEMENTARY PARTICLES AND FIELDS
Experiment

# Detection of the Production and Decays of Neutral Charmed Mesons in Proton–Nucleus Interactions at 70 GeV with the SVD-2 Facility

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**(on behalf of the SVD-2 Collaboration[1)])**

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**Abstract**—The results of processing the data of the SERP-E-184 experiment that studied mechanisms of the production of charmed particles in proton–nucleus interactions at 70 GeV and their decays are reported. The data were obtained in irradiating the SVD-2 active target consisting of carbon, silicon, and lead plates with a proton beam of energy 70 GeV. A signal from the two-body decay of neutral charmed mesons $D^0$ and $\check{D}^0$ is separated. The signal-to-background ratio is $(51 \pm 17)/(38 \pm 13)$. A detailed simulation of relevant processes on the basis of the FRITIOF and GEANT codes made it possible to find meson-detection efficiencies and to evaluate the charm-production cross section at this energy: $\sigma(c\hat{c}) = 7.1 \pm 2.4(\text{stat.}) \pm\ 1.4(\text{syst.})\ \mu\text{b/nucleon}$.

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## INTRODUCTION

At the present time, about ten experiments devoted to studying open-charm production in proton–nucleus ($pA$) interactions are under way. However, the number of events involving open-charm production that were obtained in $pA$ interactions over the past 20 years is well exceeded by the statistics of electron-beam experiments, where the main properties of charmed particles (mass, decay branching ratios, etc.) have been studied. Meanwhile, data from $pA$ experiments are important for studying the dynamics of charmed-quark production in nucleon–nucleon collisions and hadronization mechanisms for product charmed quarks and for verifying existing theoretical models. It is of great interest to find experimentally the cross section for the production of charmed particles at energies in the vicinity of the threshold for their production. This task was fulfilled in the E-184 experiment at the SVD-2 facility.

Table 1 [1] lists the main $pA$ charm-production experiments and their results. These experiments were performed at proton energies ranging from 250 to 920 GeV. We selected the experiments where measurements were performed in the forward hemisphere in the c.m. frame (Feynman variable $x_{\text{F}} > -0.1$), this corresponding the potential of the E-184 experiment. In these experiments, the dependence of the cross section on the atomic weight of the target nuclei is linear: $\sigma(pA) = \sigma(pN) \cdot A$. In Table 1, the notation $N(D^0)$ and $N(D^+)$ is used for the total sum of particle and antiparticle events, while the notation $\sigma(D^0)$ and $\sigma(D^+)$ is used for the sum of the particle- and antiparticle-production cross sections.

Figure 1 shows dependence of the cross section for $D^0$-meson production on the c.m. energy. The curve was obtained by parametrizing the data in the form of a power-law function as

$$\sigma(\sqrt{s}) = P1 \cdot (\sqrt{s})^{P2}.$$

Upon extrapolating it to the region of the E-184 energy, $\sqrt{s} = 11.8$ GeV, we obtain

$$\sigma(D^0 + \check{D}^0) = 4.3 \pm 2.3\ \mu\text{b/nucleon}.$$

Taking the particle yield from the experimental data in [1],

$$\text{Yield}\ (D^0 + \check{D}^0) = 48.7/49.6/2 = 0.49,$$

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**Table 1.** Experimental data on the cross section for $D$ meson production in proton–nucleus interactions

| Experiment | Target | Beam energy, GeV | $\sqrt{s}$, GeV | $N(D^0)$ | $\sigma(D^0)$, $\mu$b/nucleon | $N(D^+)$ | $\sigma(D^+)$, $\mu$b/nucleon |
|---|---|---|---|---|---|---|---|
| E769 | Be, Al, Cu, W | 250 | 22.4 | 136 | $12.0 \pm 3.8$ | 159 | $6.6 \pm 1.4$ |
| NA16 | $H_2$ | 360 | 26.8 | 5 | $20.4 \pm 16.0$ | 10 | $10.6 \pm 4.8$ |
| NA27 | $H_2$ | 400 | 28.3 | 98 | $18.3 \pm 2.5$ | 119 | $11.9 \pm 1.5$ |
| E743 | $H_2$ | 800 | 40.0 | 10 | $22.0 \pm 14.0$ | 46 | $26.0 \pm 10.0$ |
| E653 | Emulsion | 800 | 40.0 | 108 | $39.0 \pm 15.0$ | 18 | $31.0 \pm 22.0$ |
| HERA-B | C, Ti, W | 920 | 43.0 | 175 | $48.7 \pm 10.6$ | 130 | $20.2 \pm 4.9$ |

we obtain an estimate of the expected cross section for the production of $c\hat{c}$ pairs at our energy; that is

$$\sigma(c\hat{c}, \sqrt{s} = 11.8 \text{ GeV}) \approx 4.5 \pm 2.5\ \mu\text{b/nucleon}.$$

Knowing the cross section for inelastic proton–proton ($pp$) interaction ($\sigma_{\text{in}}(pp) = 31.44$ mb at 70 GeV/$c$ [2]) and relying on the experimental fact that the cross section for the production of $c\hat{c}$ pairs in nucleon–nucleus interactions depends linearly on the atomic weight of the target nuclei (while the "ordinary" inelastic cross section is proportional to $A^{0.7}$), one can evaluate the number of all charm production events expected in the E-184 experiment for the statistics of 52 million inelastic events of $pA$ interactions. Table 2 presents the experimental number of events in various target materials and the number of expected charm-production events calculated by the formula

$$N(c\hat{c}) = N_0(\sigma(c\hat{c}) \cdot A)/(\sigma_{\text{in}}(pp) \cdot A^{0.7}),$$

where $N_0$ is the number of events in a target whose atomic weight is $A$, and $\sigma(c\hat{c})$ is taken to be 1 $\mu$b.

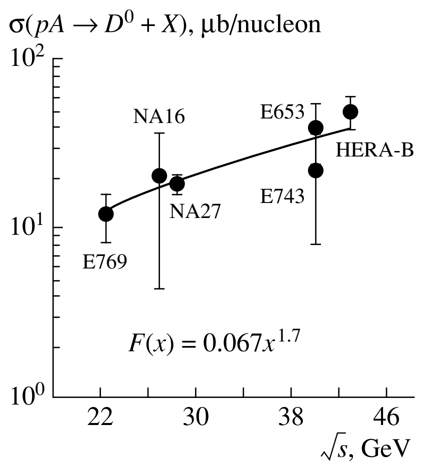


**Fig. 1.** Experimental data on the cross section for $D^0$-meson production in proton–nucleus interactions.

Knowing particle yields and branching ratios, one can evaluate the number of events for specific modes of charmed-particle decays. Table 3 presents the number of expected events for $\sigma(c\hat{c}) = 1.0\ \mu$b.

A detailed description of the SVD-2 facility can be found in [4]. A thorough simulation of processes arising in the interaction of protons with carbon, silicon, and lead nuclei on the basis of the FRITIOF7.02 code [5] and processes accompanying the detection of products of these interactions in the SVD-2 detectors on the basis of the GEANT3.21 code [6] permitted evaluating the efficiencies of all stages through which events pass in the data-processing system [7]. After that, 52 million events were processed according to all of the procedures, and mass spectra were obtained for the $K\pi$ two-particle system, where a signal from the decay of neutral $D$ mesons was selected. The subsequent analysis of the signals in question was followed by the evaluation of the background, by the derivation of the number of events involving the decay of neutral $D$ mesons, and by the use of this number in estimating the cross section for charm production in the near-threshold energy region.

## SIMULATION OF DETECTION OF $V^0$ EVENTS IN THE VERTEX DETECTOR

The FRITIOF7.02 code was used to simulate $pA$ interactions at 70 GeV. These interactions were simulated in the FRITIOF generator with allowance for the Fermi motion of nucleons, the deformation of the target nucleus, and multiple rescattering. The Woods–Saxon potential

$$\rho(r) = \rho(0)/\left(1 + \exp\left(\frac{r - r(0)\sqrt[3]{A}}{c}\right)\right),$$

whose parameters were set to $r(0) = 1.16(1 - 1.16A^{-2/3})$ fm and $c \approx 0.5$ fm, was used to simulate the distribution of nucleons in the nucleus.

**Table 2.** Number of expected events corresponding to the charm-production cross section of $\sigma(c\hat{c}) = 1\ \mu$b

| Material | Thickness, $\mu$m | Number of interact., % | $A$ | $A^{0.7}$ | $N_0$, $10^6$ | $N(c\hat{c})$ (events) |
|---|---|---|---|---|---|---|
| C | 540 | 21 | 12 | 5.7 | 10.92 | 732 |
| Si | $300 \times 5 = 1500$ | 55 | 28 | 10.3 | 28.60 | 2472 |
| Pb | 270 | 24 | 207 | 41.8 | 12.48 | 1966 |
| Total | | 100 | | | 52.00 | 5170 |

**Table 3.** Number of expected events involving the decays of $D^0$ mesons

| Decay | Branching ratio [3] | Carbon | | Silicon | | Lead | | Total number of events |
|---|---|---|---|---|---|---|---|---|
| | | Yield | Number of events | Yield | Number of events | Yield | Number of events | |
| $D^0 \to K^-\pi^+$ | 0.038 | 0.488 | 14 | 0.497 | 47 | 0.527 | 39 | 100 |
| $\check{D}^0 \to K^+\pi^-$ | 0.038 | 0.590 | 16 | 0.585 | 55 | 0.578 | 43 | 114 |
| Total | | | 30 | | 102 | | 82 | 214 |

The production of quark–antiquark pairs in the selected "minibias" events was simulated within the dipole cascade model, and the hadronization processes were described by the Lund scheme with the fragmentation function $f(z) \propto z^{-1}(1-z)^a \exp(-bm_t^2/z)$. The parameters of this function were set to $a = 0.18$ and $b = 0.34$ GeV$^{-2}$ in accordance with the results of the $e^+e^-$ experiments OPAL [8] and CLEO [9], where the parameters were adjusted by the measured spectra of $D$ and $D^*$ mesons. For all other parameters, the default values of the FRITIOF7.02 code were used.

The detection of particles in the SVD-2 facility was simulated by using the GEANT3.21 code. The geometry of the sensitive elements and passive structures of the facility was simulated in accordance with respective drawings, real metrological measurements, and the adjustment of the detector arrangement with the aid of straight-line tracks. The values of the magnetic-field strength were given by the measured map [10] used for the processing of experimental data.

The coordinates of the vertex of $pA$ interaction in the active target (AT) were simulated in the following way:

(i) The probability for the interaction in a given AT plate was calculated with allowance for its thickness and the nuclear length of the target material. The sum of the probabilities for the interaction of a proton with each of seven plates was normalized to unity, the experimental trigger conditions being taken into account. The number of the plate where the interaction occurred was found by using a random-number generator uniform in the interval [0, 1].

(ii) The longitudinal coordinate $Z$ was specified by the position of the AT plate center and the shift simulated uniformly over the thickness of the plate being considered.

(iii) The transverse coordinates $(X, Y)$ of the interaction point were specified by the beam profile obtained from the experimental data.

The kinematics of particles at the interaction vertex was determined by the data obtained on the basis of the FRITIOF7.02 code with allowance for the AT material. In our case, three files with interactions on carbon, silicon, and lead for the simulation of charm-production events and three files for background events were used in GEANT. These files did not contain decay products for unstable particles because their decay occurred directly as the GEANT code was running. A certain decay mode was specified for charmed mesons. When the particle being considered passed through the vertex detector (VD) [4], one took into account the charge spreading over the strips and introduced noise in each channel according to experimental data, and an amplitude cutoff (similar to the cutoff in the data-acquisition system). In the formation of hits in the magnetic spectrometer (MS), one took into account the actuation efficiencies obtained experimentally for the proportional wire chambers.

The system for processing data of the E-184 experiment includes the following procedures: filtration of VD data and selection of events where the

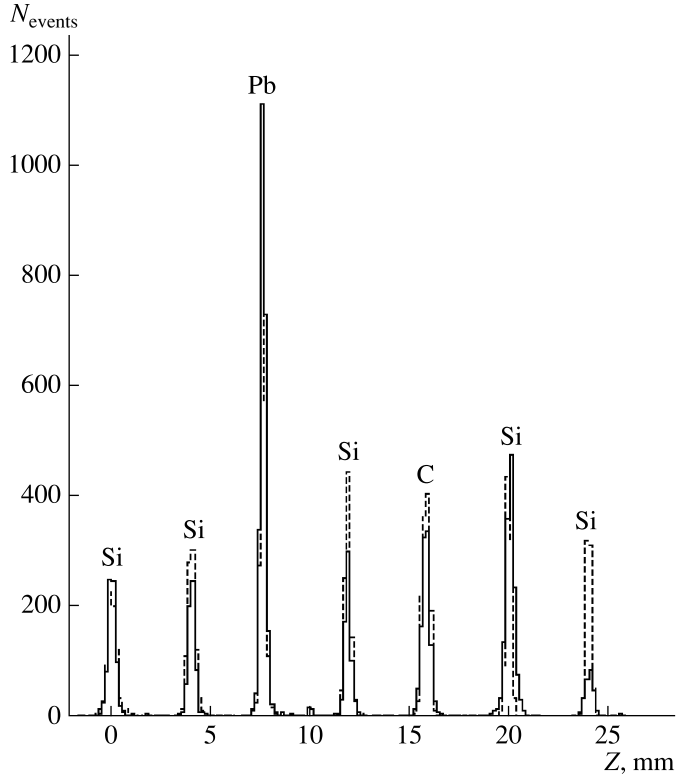


**Fig. 2.** $Z$ coordinate of the interaction vertex along the beam for (solid curve) experimental events and (dashed curve) Monte Carlo events.

secondary vertex was near the interaction point and which are candidates for charm-production events (for this purpose, use was made of the method of an analysis in the space of track parameters $\{a, b\}$ [11]); a geometric reconstruction of events in the MS and a determination of the momentum of charged particles; and an analysis of events, including a kinematic analysis.

Figure 2 shows distributions in the $Z$ coordinate of the primary vertex. The number of interactions in each AT plate depends on the target material. One can also see that the reconstruction efficiency for the primary vertex is different for different plates, and this must be taken into account in the data analysis. In general, the probabilities for the reconstruction of the primary vertex in each plate for experimental data and events simulated by the Monte Carlo method agree.

Figure 3 shows the multiplicity and momentum distributions of charged particles after processing E-184 data and Monte Carlo events. A comparison of these distributions leads to the conclusion that the FRITIOF code describes reasonably well the mechanism of $pA$ interaction. The discrepancies in the multiplicity distributions, especially for the carbon target, can be due to the effect of the trigger conditions and the difference in the data-processing efficiency for the experimental and Monte Carlo events.

## DETECTION OF $K_S^0$ MESONS

An important objective of the E-184 experiment was to evaluate the cross section for the production of neutral charmed mesons at near-threshold energies. For this purpose, it is necessary to know the efficiencies of all data-processing procedures. The detection of $K_S^0$ mesons in the VD becomes some kind of a reference procedure because the kaon-production cross section is known, and it is many times larger than the cross section for the production of charmed particles.

To attain the above objective, 540 000 $pA$-interaction events featuring 124 000 kaons were simulated by using the FRITIOF code. These events were fed into the GEANT code, and an output file was obtained with the data to which the following selection criteria were applied: (i) the number of charged tracks is larger than 3; (ii) the distance between the primary vertex and the $K_S^0$ vertex is larger than 0.5 mm; (iii) the $Z$ coordinate of $K_S^0$ is smaller than 35 mm; and (iv) the tracks from $K_S^0$ decay must be within the last VD plane. Of 85 000 kaons decaying via the $K_S^0 \to \pi^+\pi^-$ mode, only 2674 (3%) meet the above conditions. This information is available only for MC events, in which case it is exactly known whether there is a $K_S^0$ meson in the

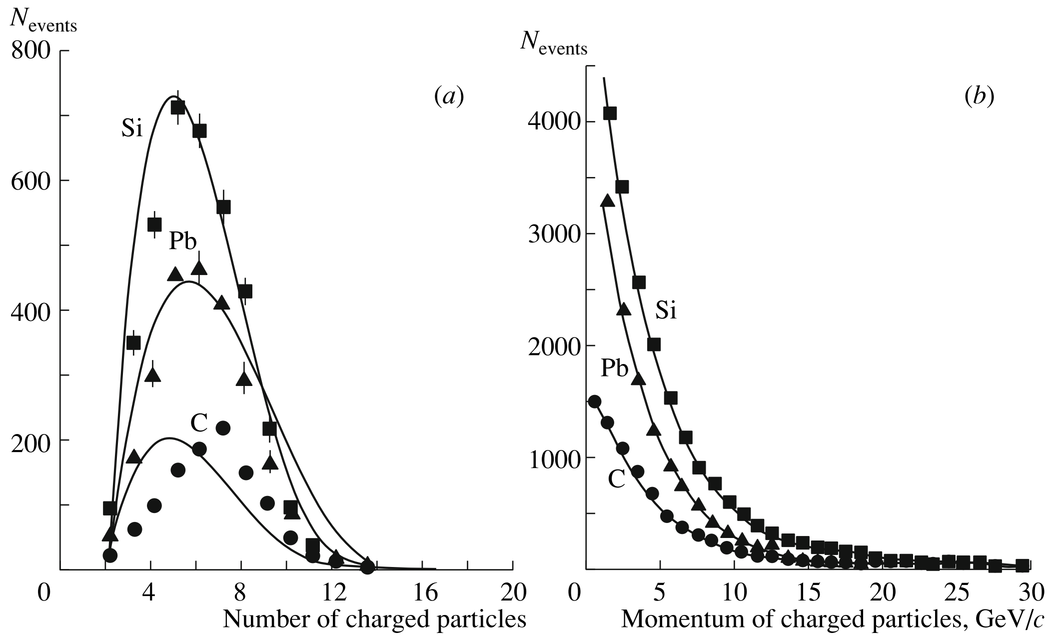


**Fig. 3.** Predictions of the FRITIOF code (solid curves) and experimental data for carbon (closed circes), silicon (closed boxes), and lead (closed triangles) targets: (*a*) multiplicity distribution of charged particles at the primary vertex and (*b*) momentum distribution of charged particles.

event being considered. After that, a fast filter code selects events featuring a $V^0$ vertex on the basis of the VD data alone. To reduce the background from spurious $V^0$, the filtration employs a system of selection criteria based on the parameters of the tracks lying in the $XZ$ and $YZ$ views and forming $V^0$ with allowance for their errors. The criteria are as follows:

A track from $V^0$ must have an inpact parameter with respect to the primary vertex, $b/\sigma_b > 2$, where $b$ is the parameter of the straight line $X = aZ + b$ describing this track and $\sigma_b$ is the error in it.

Two tracks from $V^0$ intersect at one spatial point in space, $\chi^2 < 4$ [11].

The $V^0$ vertex is separated from the primary vertex, $(Z_2 - Z_1)/\sqrt{(\sigma_1^2 + \sigma_2^2)} > 3$.

The $V^0$ vertex satisfies the modified Armenteros–Podolansky criterion [7].

After fitting a Lorentz function to the signal and a second-degree polynomial to the background, the resulting number of $K_S^0$ proved to be $317 \pm 19$. Thus, the detection efficiency for events involving the decay $K_S^0 \to \pi^+\pi^-$ was estimated at $317/85\,000 = 0.0036$.

In order compare the results of the simulation with experimental data, 1 115 091 experimental events involving interactions in the AT were processed by using the same procedures. The effective-mass spectrum of the $\pi^+\pi^-$ system shows a signal from $K_S^0$ decay (Fig. 4). From an analysis of the signal, we find the following: the $K_S^0$ mass is 498.6 MeV, the FWHM value is $\Gamma = 12$ MeV, and the number of events in the signal is $222 \pm 20$. The simulated and experimental momentum and Feynman variable ($x_{\text{F}}$) distributions of reconstructed $K_S^0$ in the signal band of the mass spectrum after leveling out the histograms with respect to the number of entries are compared in Fig. 5.

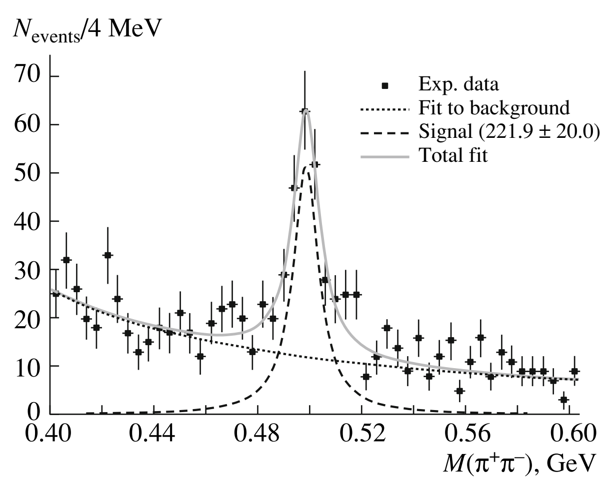


**Fig. 4.** Effective-mass spectrum of the $\pi^+\pi^-$ system for experimental events.

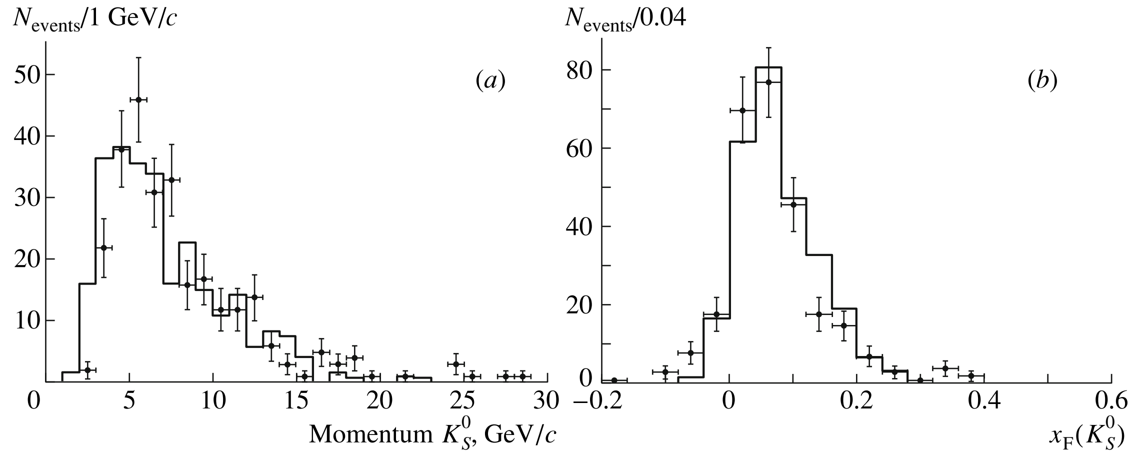


**Fig. 5.** Distributions of reconstructed $K_S^0$ with respect to the (*a*) momentum and (*b*) Feynman variable $x_F$ for (histograms) Monte Carlo and (points) experimental events.

## SIMULATION OF THE DETECTION OF NEUTRAL *D* MESONS

The two-body decay channel $D^0(\check{D}^0) \to K\pi$, whose branching ratio is 3.8%, was chosen for evaluating the detection efficiency in the simulation. One hundred thousand charm-production events were simulated by using the FRITIOF code. After that, the events were processed on the basis of the GEANT code, where charmed mesons decayed through a preset channel. The data-processing procedures were analogous to those for the separation of a $K_S^0$ signal.

The simulation yielded the following evaluated efficiencies for the procedures of the reconstruction of events involving the decays of neutral charmed mesons:

$\boldsymbol{D^0 \to K^-\pi^+}$. The number of $D^0$ mesons is 51 133, which agrees with the $D^0$ yield. The number of events meeting the conditions used for $K_S^0$ [(i) the number of charged tracks is larger than 3, (ii) the distance between the primary vertex and the $D^0$ vertex is larger than 0.5 mm, (iii) the $Z$ coordinate of $D^0$ is smaller than 35 mm, and (iv) the tracks from $D^0$ decay must lie within the last VD plane] was 27 967. After the geometric reconstruction and the analysis of the mass spectrum, the $D^0$ signal was $3683 \pm 60$ events (Fig. 6*a*). The detection efficiency for $D^0$-decay events is 7.2%. After constructing fits to the signal and the background, we have the $D^0$ mass of 1864 MeV (the world-average value is 1865 MeV) and the FWHM value of $\Gamma = 33$ MeV.

$\boldsymbol{\check{D}^0 \to K^+\pi^-}$. The number of $\check{D}^0$ mesons is 58 454, which agrees with the $\check{D}^0$ yield. The number of events after the application of the selection criteria (see above) is 13 160. After the geometric reconstruction and an analysis of the mass spectrum, the $\check{D}^0$ signal is $1588 \pm 40$ events (Fig. 7*a*). The detection efficiency for $\check{D}^0$-meson decay events is 2.7%. After constructing fits to the signal and the background, we have the $\check{D}^0$ mass of 1866 MeV and the FWHM value of $\Gamma = 36$ MeV.

## SEPARATION OF EVENTS INVOLVING THE DECAY OF NEUTRAL *D* MESONS

In simulating charm-production events, we optimized criteria for the selection of events involving neutral-particle decay in the vicinity of the interaction vertex, which are candidates for events involving the decay of neutral $D$ mesons ($D^0 \to K\pi$). The main selection criteria are the following:

(i) The distance between the primary vertex and the $V^0$ vertex must be larger than 0.5 mm.

(ii) The decay tracks of the $V^0$ particle must have an impact parameter with respect to the primary vertex, and the $V^0$ track must “aim” at it.

(iii) The effective mass of the $K\pi$ system must not deviate from the world-average value of the $D^0$ mass (1.865 GeV) by more than 0.5 GeV.

(iv) The momentum of the $K\pi$ system must be higher than 10 GeV/$c$.

(v) As follows from an analysis of the Armenteros–Podolansky criterion and the condition for the suppression of the background from the decay of neutral kaons and $\Lambda^0$ hyperons (Fig. 8), the transverse momentum of the decay particle with respect to the direction of motion of the $K\pi$ system must be higher than 0.3 GeV/$c$.

(vi) Of two hypotheses ($K^-\pi^+$ and $K^+\pi^-$), one selects that for which the effective mass value is closer to the world-average value of the $D^0$-meson mass.

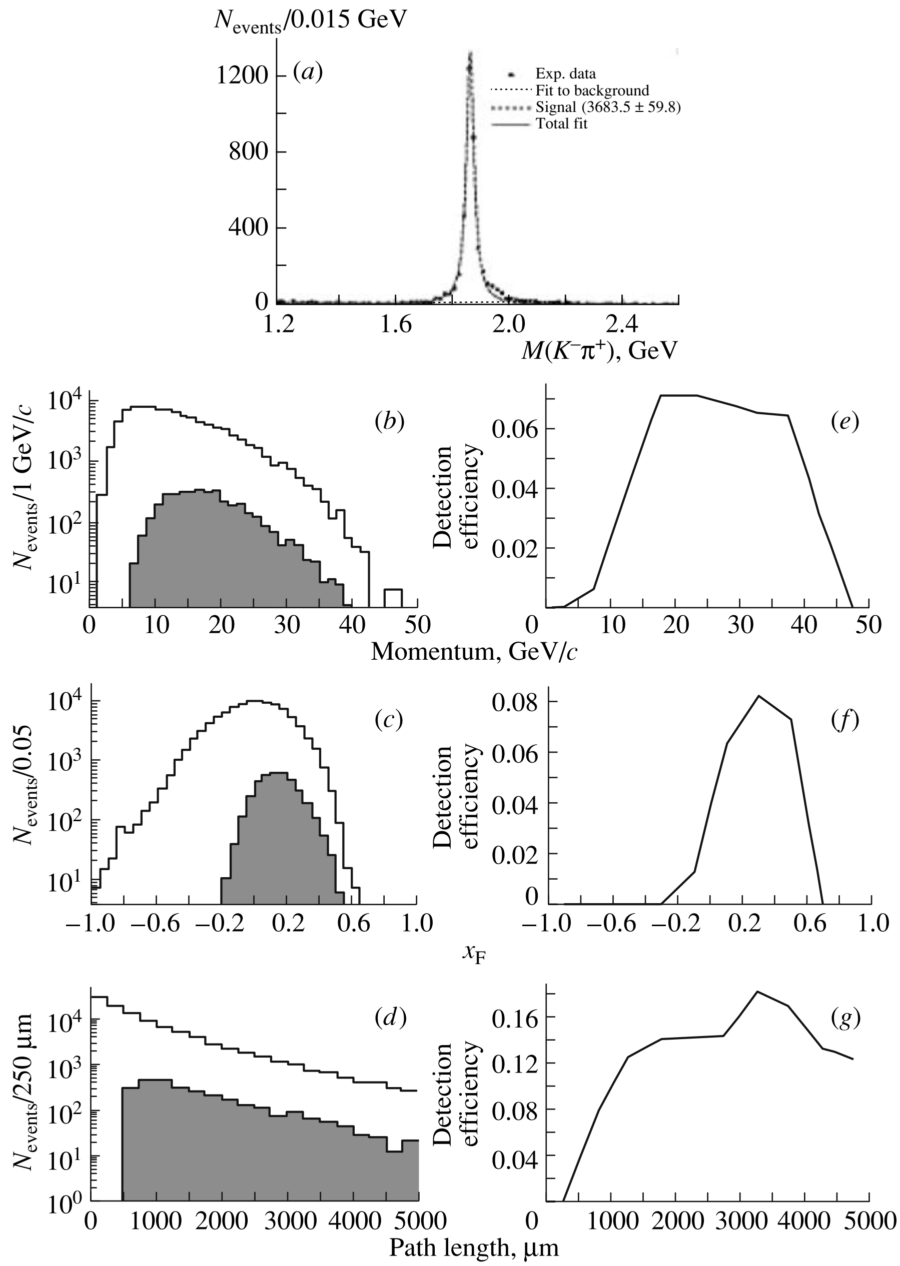


**Fig. 6.** ($a$) Effective-mass, ($b$) momentum, ($c$) Feynman variable ($x_{\mathrm{F}}$), and ($d$) path-length spectra of the $K^-\pi^+$ system for (open histograms) all and (filled histograms) reconstructed $D^0$; detection efficiency for $D^0$ as a function of ($e$) the momentum, ($f$) $x_{\mathrm{F}}$, and ($g$) path length.

It was found that the main source of background is inaccurate knowledge of the spatial location of the facility's detecting elements and the presence of spurious $V^0$, whose tracks belong to the primary vertex but have large angular errors. This is particularly important for high-multiplicity events. Therefore, a visual inspection by physicist (physical scanning) was introduced at the last data-treatment stage. A specially developed graphical package made it possible to display in detail the VD region with marking of the actuated elements (strips) and constructed tracks. On the basis of the results of physical scanning, events where tracks from $V^0$ could "aim" at the primary vertex or where there were tracks that were not geometrically reconstructed in the MS, but which could probably belong to $V^0$ being considered, were eliminated from further consideration. Figure 9 shows an example of the shape that an event featuring a two-prong secondary vertex can have in physical scanning.

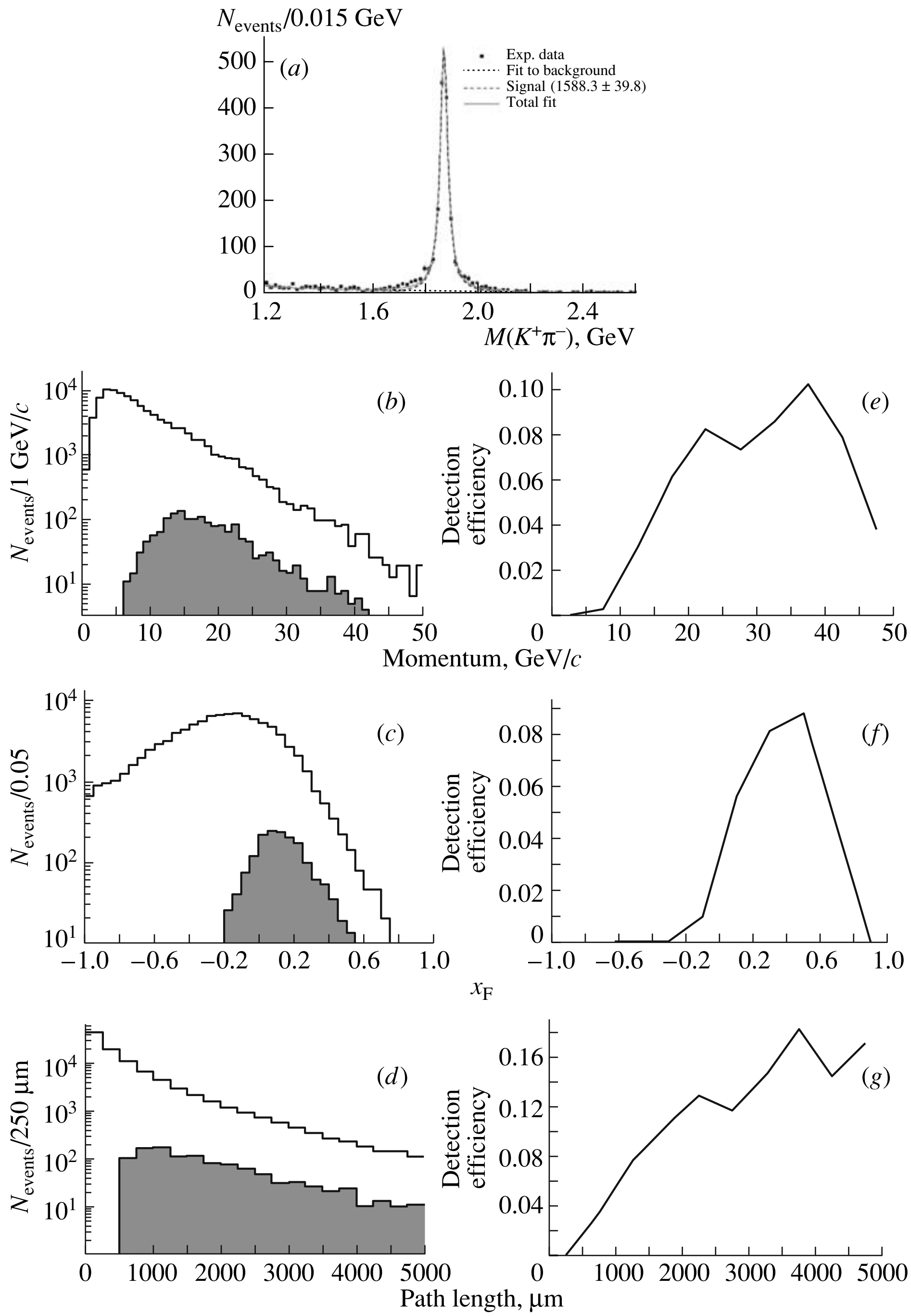


**Fig. 7.** As in Fig. 6, but for the $K^+\pi^-$ system.

Figure 10 shows the effective-mass spectra of the $K\pi$ system after the application of the selection criteria and after physical scanning. Since the statistics are low, the spectra for the $K^-\pi^+$ and $K^+\pi^-$ systems are combined into one spectrum. The mass range where physical scanning was performed was 1.7–2.0 GeV. The change in the number of events at the peak after the scanning was negligible, but the background decreased markedly. The approximation of the data by a straight line and a Gaussian curve after the physical scanning yields the $D^0$ mass of 1861 MeV and the value of $\sigma = 21$ MeV for the standard deviation of the distribution. The signal-to-background ratio is $(51 \pm 17)/(38 \pm 13)$.

In order to test the correctness of the event-selection criteria, the distributions of the $K\pi$ system

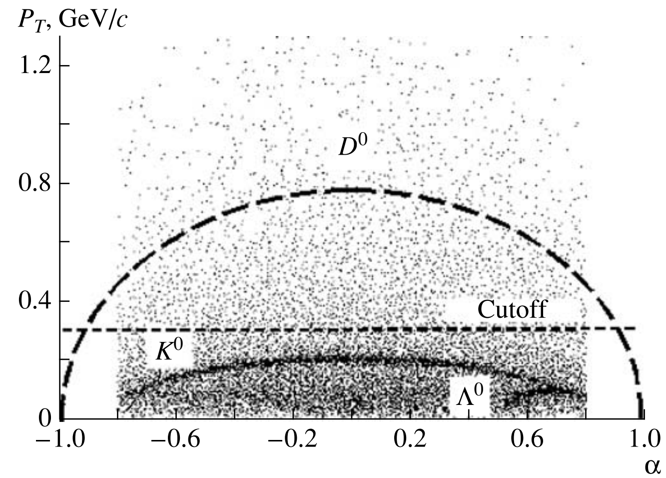


**Fig. 8.** Armenteros–Podolansky plot for $K^0$, $\Lambda^0$, and $D^0$; $\alpha = (P_L^+ - P_L^-)/(P_L^+ + P_L^-)$.

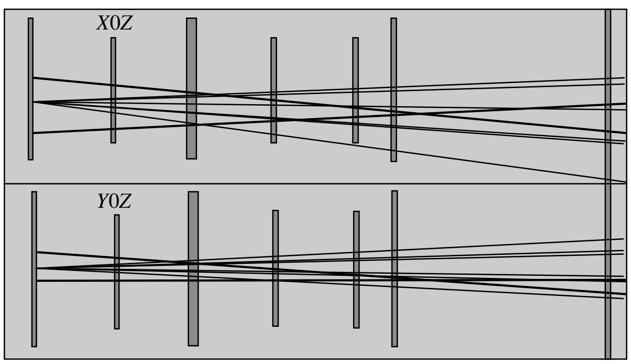


**Fig. 9.** Example of an event with a magnified image of tracks in the region of the active target.

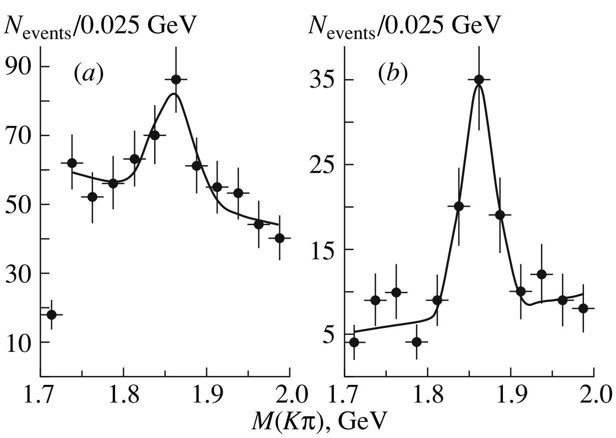


**Fig. 10.** Effective-mass spectra of the $K\pi$ system ($a$) before and ($b$) after physical scanning.

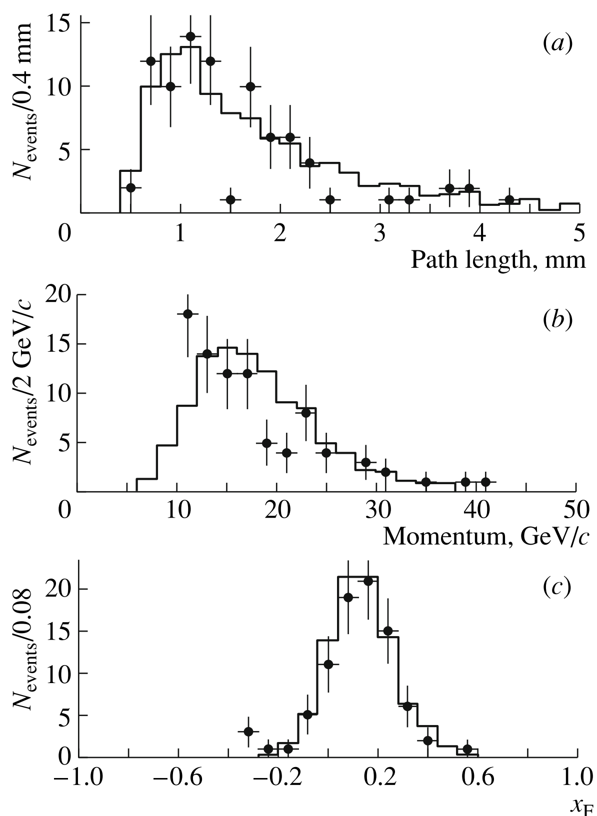


**Fig. 11.** ($a$) Path-length, ($b$) momentum, and ($c$) Feynman variable ($x_F$) distributions of the $K\pi$ system for (histograms) Monte Carlo and (points) experimental events.

in the path length in the mass region $M_D \pm 3\sigma$, the momentum, and the Feynman variable ($x_F$) were compared with the corresponding distributions obtained for the simulated events (see Fig. 11). Figure 11 shows that the measured properties of the $K\pi$ decay systems selected in the experiment agree with the properties of the simulated $D^0$ mesons.

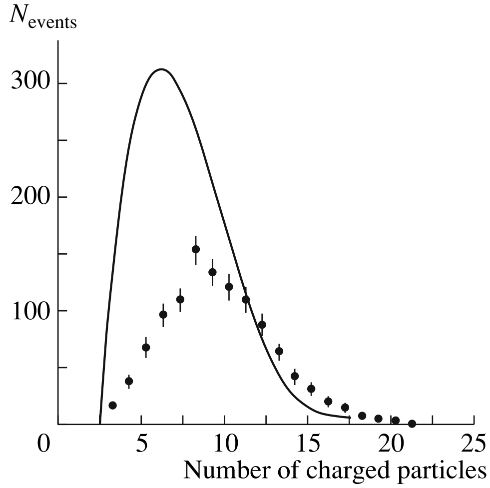


**Fig. 12.** Multiplicity distributions of charged particles at the primary vertex for (points) experimental and (solid curve) simulated events.

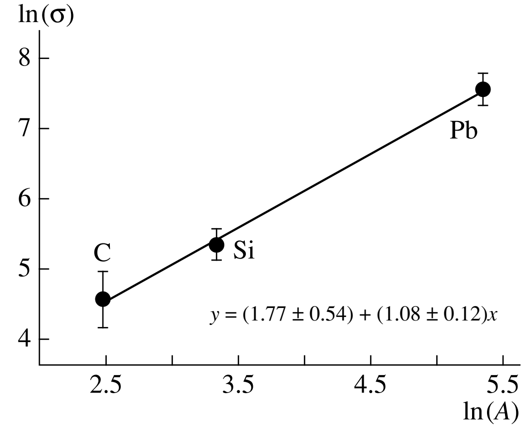


**Fig. 13.** Dependence of the charm-production cross section on the atomic weight $A$.

## EVALUATION OF THE CHARM-PRODUCTION CROSS SECTION

In order to evaluate the charm-production cross section, it is necessary to know not only the number of events in the signal and total statistics but also estimates of the triggering coefficient and the efficiencies of all data processing procedures. The triggering coefficient (that is, the degree of suppression of inelastic-event detection in the data-taking run) was evaluated from a comparison of the multiplicity distributions of charged tracks in the VD for experimental and simulated inelastic events. An analysis of these distributions in Fig. 12 yields the value of $K_{\text{trigg}} = 0.51$.

A comparison of the results of data treatment for simulated $K_S^0$ and experimental events showed that the efficiency of this procedure is slightly lower for experimental data. This also applies to all detected $V^0$. The instrumental factor ($K_{\text{app}}$) for the $D$ mesons found can be evaluated from the results obtained by separating a $K_S^0$ signal. We know the experimental values of the $K_S^0$-production cross section at our energy in $pp$ interactions ($\sigma = 3430$ $\mu$b) and the exponent $\alpha$ in the $A$ dependence of the cross section for $pA$ interactions ($\alpha = 0.78$) [12]. The detection efficiency for Monte Carlo events involving the decay of $K_S^0$ mesons is 0.36% (see above), and the number of $K_S^0 \to \pi^+\pi^-$ decays, whose branching ratio is 0.692 [3], must be

$$N(K_S^0) = 52 \times 10^6 \times (3.43/31.44)(A^{0.78}/A^{0.7}) \times 0.692 \times 0.0036 = 19\,200,$$

because the average atomic weight of the target nuclei is $A = 68$. The $K_S^0$ signal separated in our statistics involves 12 000 decays. Thus, we have $K_{\text{app}} = 19\,200/12\,000 = 1.6$.

An attempt was made to calculate the charm-production cross section from the number of separated decays of neutral $D$ mesons by two methods, individually for each target material.

**Method 1.** The predictions for the number of events involving the decay of neutral $D$ mesons on the basis of experimental statistics without allowance for $K_{\text{trigg}}$ and $\sigma(c\hat{c}) = 1$ $\mu$b (Table 3) yield $N_{\text{pred}} = 30(\text{C}) + 102(\text{Si}) + 82(\text{Pb}) = 214$ events. The number of these events separated at the efficiency of $\varepsilon = 0.036$ is $N_{\text{reg}} = 7(\text{C}) + 22(\text{Si}) + 22(\text{Pb}) = 51$. On the basis of the relation

$$\sigma(c\hat{c}) = K_{\text{app}}(N_{\text{reg}}/\varepsilon)/(N_{\text{pred}}/K_{\text{trigg}}),$$

we estimate the charm-production cross section for the different targets at

$$\sigma(c\hat{c}) = 5.3(\text{C}),\ \ 4.9(\text{Si}),\ \ 6.1(\text{Pb})\ \mu\text{b/nucleon}.$$

The weighted mean over these nuclei is $\sigma(c\hat{c}) = 5.5$ $\mu$b/nucleon.

**Method 2.** The formula for calculating the cross section for the production of neutral $D$ mesons can be written in the form

$$\sigma(D^0)_{\text{nucl}} = K_{\text{app}} N_{\text{reg}}(D)/(\text{Br} \cdot \varepsilon L_{\text{int}}),$$

where the branching ratio Br for the decay $D^0 \to K\pi$ is 0.038 and the integrated luminosity $L_{\text{int}}$ with allowance for all possible losses was calculated in [13] to be $2.3 \times 10^{33}$ cm$^{-2}$. In order to find the integrated luminosity for each target material, we multiply it by the coefficient from Table 2. Since this luminosity corresponds to the events on nuclei, its value must be divided by $A^{0.7}$, which corresponds to the $A$ dependence of the cross section for inelastic interactions (background). For each material, we then obtain

$$\sigma(D^0)_{\mathrm{nucl}} = 96.5(\mathrm{C}),\ \ 209.5(\mathrm{Si}),\ \ 1949.0(\mathrm{Pb})\ \mu\mathrm{b}.$$

The values obtained for the cross section show the dependence on the target-nucleus atomic weight ($A$ dependence) where the exponent is $\alpha = 1.08 \pm 0.12$ (Fig. 13). This agrees with the behavior of the cross sections for charm production on nuclei.

In order to compare these values with the cross sections obtained above (by method 1) and with data from other experiments, we must take into account the $A$ dependence of the charm-production cross section ($\alpha = 1.0$) according to data of other experiments. We then obtain

$$\sigma(D^0) = \sigma(D^0)_{\mathrm{nucl}}/A = 8.0(\mathrm{C}),\ \ 7.5(\mathrm{Si}),$$
$$9.4(\mathrm{Pb})\ \mu\mathrm{b/nucleon}.$$

In order to find $\sigma(c\hat{c})$, it is necessary to divide it by the fraction of events involving neutral $D$ mesons, which is 49% according to the measurements in the experiment reported in [1], and by two because we consider the sum $(D^0 + \check{D}^0)$. For the charm-production cross section, we then have

$$\sigma(c\hat{c}) = \sigma(D^0)/0.49/2 = 8.2(\mathrm{C}),\ \ 7.6(\mathrm{Si}),$$
$$9.6(\mathrm{Pb})\ \mu\mathrm{b/nucleon}.$$

The weighted mean over these nuclei is $\sigma(c\hat{c}) = 8.7\ \mu\mathrm{b/nucleon}$.

Averaging over the two methods yields the value

$$\sigma(c\hat{c}) = 7.1\ \mu\mathrm{b/nucleon}.$$

The error in this cross-section value is due to statistics of the signal from the decay of neutral $D$ mesons and the uncertainties in calculating the coefficients and efficiencies. We have (a) an uncertainty of 34% in the number of events in constructing a fit to the signal in the effective-mass spectrum (Fig. 10), (b) an uncertainty of 3% in the detection efficiency [7], (c) an uncertainty of 6% in the triggering coefficient (see Fig. 12), and (d) an uncertainty of about 11% in the instrumental factor [7].

## CONCLUSIONS

A detailed simulation of processes in the SVD-2 facility and an analysis of data on the decay of neutral $D$ mesons made it possible to evaluate the cross section for charm production in $pA$ interactions at the near-threshold energy of 70 GeV. The result is

$$\sigma(c\hat{c}) = 7.1 \pm 2.4(\mathrm{stat.}) \pm 1.4(\mathrm{syst.})\ \mu\mathrm{b/nucleon}.$$

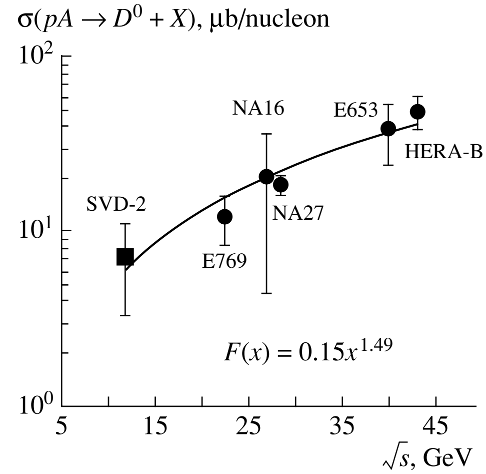


**Fig. 14.** Dependence of the cross section for production of $D^0$ mesons in $pA$ interactions on the c.m. energy with allowance for the results of our present experiment.

Figure 14 shows the dependence of the cross section for the production of $D^0$ mesons in $pA$ interactions on the c.m. energy with allowance for the results of our present experiment. It is worth mentioning that an attempt at evaluating the charm-production cross section at the near-threshold energy was made more than 20 years ago in an experiment at the BIS-2 facility (Institute for High Energy Physics), where a carbon target was irradiated with 40- to 70-GeV neutrons [14]. In the kinematical region $x_{\mathrm{F}} > 0.5$, the measured cross section for the production of $D^0$ mesons turned out to be much larger than the theoretical predictions—namely, $\sigma(D^0) = 28 \pm 14\ \mu\mathrm{b/nucleus}$. The cross section obtained in the present experiment is also larger than theoretical estimates, and this requires a more thorough investigation into the problem. The present study is important because there are still no reliable data on the cross section for charm production in $pA$ interactions at near-threshold energies, but such data are necessary for verifying theoretical models used to describe these processes.

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