Search for the Process $e^+e^- \to D^*(2007)^0$ with the CMD-3 Detector

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Received May 13, 2020; revised May 13, 2020; accepted May 13, 2020

Abstract—Searches for the process of electron–positron ($e^+e^-$) annihilation to the $D^*(2007)^0$ meson were performed by means of the CMD-3 detector at the VEPP-2000 $e^+e^-$ collider. In the data analysis, use was made of two dominant modes of $D^0\pi^0$-meson decay to $D^0\pi^0$ and $D^0\gamma$, where $D^0$ was reconstructed in the $K^{\pm}\pi^\mp\pi^+\pi^-$ channel. By employing a 3.7 pb$^{-1}$ data sample accumulated at the c.m. energy of $E_{cm} = 2006.62$ MeV, an upper bound of $B(D^0 \to e^+e^-) < 1.7 \times 10^{-6}$ on the decay branching ratio was obtained at a 90% confidence level.

DOI: 10.1134/S1063778820060277

1. INTRODUCTION

$e^+e^- \to D^0$ is highly sensitive to new-physics effects. An upper limit of $B(D^0 \to e^+e^-) \sim (0.1-5) \times 10^{-10}$ on the decay branching ratio in the Standard Model is much smaller than the respective limits

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in some extended theories. In the FCNC (flavor-changing (weak) neutral current) model, for example, $B(D^0 \to e^+e^-) < 2.5 \times 10^{-11}$. This and other models are considered in [1].

In the present article, we describe the procedure used in searches for the process $e^+e^- \to D^0$ by means of the CMD-3 detector. We sought this process in the following decay channels: $D^0 \to D^0\pi^0$ ($B_{D^0\to D^0\pi^0} = 64.7 \pm 0.9\%$) and $D^0 \to D^0\gamma$ ($B_{D^0\to D^0\gamma} = 35.3 \pm 0.9\%$) [2]. The $D^0$ meson was reconstructed by employing the decay process $D^0 \to K^+\pi^-\pi^+\pi^-$ ($B_{D^0\to K^+\pi^-\pi^+\pi^-} = 8.11 \pm 0.15\%$), which we chose because of a low background level (see below).

2. CMD-3 DETECTOR

The cryogenic magnetic detector (CMD-3) [3] is positioned in one of the electron–positron collision regions of the VEPP-2000 collider [4]. For the determination of the coordinates, angles, and momenta of charged particles to be possible, the collision region houses a tracker consisting of a drift chamber (DC) formed by a hexagonal system of 1218 cells and a two-layer cylindrical proportional chamber with information readout from anodes and cathodes (of the Z chamber). On the basis of the amplitudes from the DC wires, the ionization loss ($dE/dx$) of charged particles is determined to a precision of $\sigma_{dE/dx} \approx 11-14\%$. In the present analysis, $dE/dx$ is used to separate kaons from pions. The tracking system is within a superconductor solenoid generating a field of strength 1.3 T. In order to detect photons and to measure their energy, two calorimeters, an endcap and a cylindrical one, are used in the detector. The
endcap calorimeter is manufactured on the basis of BGO(13.4X₀) crystals. The cylindrical calorimeter consists of two parts. Its inner part is formed by a set of in-line cylindrical ionization chambers employing liquid xenon (5.4X₀). The outer part of the calorimeter is based on CsI(8.1X₀) crystals combined into blocks in the form of eight octants. A time-of-flight system on the basis of scintillation counters with a time resolution of about 1 ns is placed between the LXe and CsI calorimeters. A muon system consisting of 46 scintillation counters is arranged at the outer surface of the magnetic guide.

In order to determine the event-detection efficiency, the CMD-3 detector is simulated on the basis of the GEANT4 code package [5]. The simulated events are processed by the same code package as that used for the experimental events. Initial-state radiation is taken into account according to [6]. The background is estimated by employing the MHG2000 multihadron generator [7].

The present analysis relies on an integrated luminosity of 3.7 pb⁻¹ accumulated by the CMD-3 detector at an energy close to the D*⁺-meson mass of m_D*⁺ = 2006.85 ± 0.05 MeV/c² [2]. In the course of data acquisition, the beam energy was measured by means of inverse Compton scattering [8, 9]. The average energy in the system was E_{av.}^c.m. = 2006.632 ± 0.008 MeV, the energy spread in one beam being σ_E_{av.} = 0.954 ± 0.053 MeV.

3. EVENT SELECTION

Candidates for events of the process being studied have four charged tracks. The method used here to separate kaons from pions for events having four tracks was described in detail elsewhere [10]. On the basis of approximating the two-dimensional distribution of dE/dx versus the momentum, the probability-density function f_{K/π}(p,dE/dx_{DC}) is constructed. The likelihood function is taken in the form

\[ L_{Kπππ} = \log \left( \prod_i f_i(p,dE/dx_{DC}) / \prod_i f_i(p,dE/dx_{DC}) + f_K(p,dE/dx_{DC}) \right), \]

where α_i is the type of particle with subscript i (i = 1, . . . , 4). It is assumed that three particles are pions and one particle is a kaon. At the maximum value of the likelihood function, the attribution of the track being considered to a specific particle type is the most probable. Figure 1a shows the value of L_{Kπππ} for the simulation of the process D*⁺ → D⁰π⁺π⁻.

The total energy of the system is determined as

\[ E_{tot} = \sum_{i=1}^{4} \sqrt{p_i^2 + m_{π}^2} - 2E_{beam}. \]

The distribution of E_{tot} versus the absolute value of the total momentum of the system, P_{tot}, is shown in Fig. 1b. The light-gray, black, and dark-gray points represent, respectively, experimental data, results of our simulation of the process D*⁺ → D⁰π⁺π⁻, and results of our simulation of the process D*⁺ → D⁰γ. Since the reconstruction of neutral particles is not used in the present analysis to improve the detection efficiency, the total energy of detected particles differs from the doubled beam energy by about 140 MeV. The absolute value of the total momentum of detected particles is close to zero for events of the process D*⁺ → D⁰π⁺π⁻ and differs substantially from zero for the final state of the process D*⁺ → D⁰γ; therefore, the physical background is different for these two channels.

The following selection criteria are used in the present analysis:

- |E_{tot}-141.6| < 40 MeV,
- |P_{tot}-46| < 50 MeV/c

for D*⁺ → D⁰π⁺π⁻ and

- |E_{tot}-136.6| < 40 MeV,
- |P_{tot}-138.6| < 50 MeV/c

for D*⁺ → D⁰γ.

After imposing these selection criteria, the detection efficiency for the process under study becomes approximately 25%, which is close to the acceptance of the drift camera for events involving four charged particles.

According to the results of the simulation, the processes \( e^+e^- → π^+π^-π^+π^- \), \( K^+K^-π^+π^- \), \( π^+π^-π^+π^-π^0 \), \( π^+π^-π^+π^-π^0 \), \( π^+π^-π^+π^-π^0 \), \( K_S^0K^+π^-π^0 \), and \( K_S^0K^+π^-π^0 \) are the main background processes. In order to suppress the physical background involving \( K_S^0 \) mesons in the final state, the following condition is imposed on the dipion invariant mass: \(|M_{π^+π^-}-498|>15 \text{ MeV/c}^2 \). The distribution of \( M_{π^+π^-} \) for the \( K_S^0K^+π^-π^0 \) and \( K_S^0K^+π^-π^0 \) channels is shown in Fig. 2a. The condition on \( M_{π^+π^-} \) reduces further the detection efficiency by approximately 3%.

The following conditions on the likelihood functions are also used to suppress the physical background:

- \( L_{Kπππ} > -0.3 \) (this condition is intended for suppressing all background events and is shown in Fig. 1a by a dashed line);
Fig. 1. (a) Value of $L_{K\pi\pi\pi}$ for simulated events of the process $D^{*0} \rightarrow D^0\pi^0$; (b) $E_{\text{tot}}$ as a function of $P_{\text{tot}}$. The light-gray, black, and dark-gray points on display represent, respectively, experimental data, results of our simulation of the process $D^{*0} \rightarrow D^0\pi^0$, and results of our simulation of the process $D^{*0} \rightarrow D^0\gamma$.

Fig. 2. (a) Dipion invariant mass $M_{\pi^+\pi^-}$ for the $K^0_S K^\pm \pi^\mp$ and $K^0_S K^\pm \pi^\mp \pi^0$ channels; (b) cross section for the process $e^+e^- \rightarrow D^{*0} \rightarrow D^0\pi^0$ in a resonance form (dashed black line) and analogous cross section calculated with allowance for initial-state radiation (solid gray line).

- $L_{KK\pi\pi} < -3$ (this condition is intended for suppressing events of the $K^+ K^- \pi^+ \pi^-$ process);
- $L_{\pi\pi\pi\pi} < -3$ (this condition is intended for suppressing events of the $\pi^+ \pi^- \pi^+ \pi^-$ process).

These conditions reduce additionally the detection efficiency by approximately 10%.

4. CALCULATION OF THE UPPER LIMIT

In the narrow-resonance approximation, the cross section for the process $e^+e^- \rightarrow D^{*0} \rightarrow D^0\pi^0$ can be represented in a standard form as

$$\sigma(E) = \frac{12\pi}{m^{2}_{D^{*0}}} \mathcal{B}_{D^{*0} \rightarrow e^+e^-} \frac{m^{2}_{D^{*0}} \Gamma_{D^{*0}}}{(m^{2}_{D^{*0}} - E^2)^2 + E^2 \Gamma^2_{D^{*0}}},$$

(1)

where $\Gamma_{D^{*0}}$ is the $D^{*0}$-meson width calculated on the basis of the $D^{*+}$-meson width and found to be $\Gamma_{D^{*0}} = 60$ keV [1].

The integrated cross section is calculated with allowance for the Gaussian distribution in the energy of electrons and positrons in the beam with a spread $\sigma_{E_{\text{c.m.}}}$ and with allowance for initial-state radiation[6].
As a result, we obtain
\[
\sigma_{\text{int}} = \int_{E_{\text{beam}}}^{E_{\text{beam}}} dE \int_0^1 \frac{1}{\sqrt{2\pi}\sigma_{E_{\text{c.m.}}}} dE \times e^{-\frac{(E_{\text{av.c.m.}} - E)^2}{2\sigma^2_{E_{\text{c.m.}}}}} \cdot F(x, E) \cdot \sigma(E(1-x))dx .
\]

(2)

where \( L_{\text{int}} = 3701 \text{nb} \cdot \text{bn}^{-1} \) is the integrated luminosity, \( \epsilon_{D^* \to D^0\pi^0} = 13.4\% \) and \( \epsilon_{D^* \to D^0\gamma} = 13.2\% \) are the event-detection efficiencies, and \( C = 62769 \) is a calculated dimensionless constant.

In order to evaluate the number of background events, we used the data obtained below the threshold for the \( D^0 \) meson production and collected at c.m. energies in the range of \( E_{\text{c.m.}} = 1900-2000 \) MeV. All event-selection procedures were performed for them.

We selected two events that could be candidates for the \( D^0\gamma \) intermediate state, estimating the respective background at 1.2 ± 0.5, and one event for the \( D^0\pi^0 \) channel, estimating the background at 1.5 ± 0.7. As a result, we measured an upper limit for the first time and, within the Bayesian approach, found that \( B(D^* \to e^+e^-) < 1.7 \times 10^{-6} \) at a confidence level of 90%.

FUNDING

This work was supported in part by the Russian Foundation for Basic Research (project no. 20-52-00008). The application of the multihadron generator constituted its part supported by the Ministry of Science and Higher Education of Russian Federation (Agreement no. 14.W03.31.0026).

A comparison of the resonance cross sections calculated without and with allowance for initial-state radiation is illustrated in Fig. 2b.

The branching ratio for the decay \( D^* \to e^+e^- \) can be calculated by the formula

\[
\mathcal{B} = \frac{N}{L_{\text{int}} \cdot \epsilon_{D^* \to f} \cdot \mathcal{B}_{D^* \to f} \cdot \mathcal{B}_{D^0 \to K^+\pi^+\pi^-\pi^-} \cdot C}.
\]

(3)

where \( L_{\text{int}} = 3701 \text{nb} \cdot \text{bn}^{-1} \) is the integrated luminosity, \( \epsilon_{D^* \to D^0\pi^0} = 13.4\% \) and \( \epsilon_{D^* \to D^0\gamma} = 13.2\% \) are the event-detection efficiencies, and \( C = 62769 \) is a calculated dimensionless constant.

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