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Measurement of D^0 and D^+ meson masses with the KEDR detector

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The masses of the neutral and charged D mesons have been measured with the KEDR detector at the VEPP-4M electron–positron collider:

$$M_{D^0} = 1865.30 \pm 0.33 \pm 0.23\ \text{MeV},$$

$$M_{D^+} = 1869.53 \pm 0.49 \pm 0.20\ \text{MeV}.$$

1. Introduction

Neutral and charged D mesons are the ground states in the family of open charm mesons. Measurement of their masses provides a mass scale for the heavier excited states. In addition, a precise measurement of the D^0 meson mass should help to understand the nature of the narrow $X(3872)$ state [1–4], which, according to some models, is a bound state of D^0 and D^{*0} mesons [5] and has a mass very close to the sum of the D^0 and D^{*0} meson masses. Presently, the world-average D^0 mass value [6] ($M_{D^0} = 1864.84 \pm 0.17$ MeV) is dominated by the CLEO measurement $M_{D^0} = 1864.847 \pm 0.150(\text{stat}) \pm 0.095(\text{syst})$ MeV [7], which uses the decay $D^0 \to \phi K^0_S$. Other D meson mass measurements are much less precise. These measurements were carried out long ago in the MARK-II experiment at the SPEAR e^+e^- collider [8], and by the ACCMOR Collaboration in a fixed-target experiment [9]. Both measurements are dominated by the systematic uncertainty, which in the case of MARK-II is related to beam en-

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ergy calibration. In addition, the mass of the D^+ is constrained by the D^0 mass and a mass difference $M_{D^+} - M_{D^0}$ much more precisely than directly measured: the world-average D^+ mass is $M_{D^+} = 1869.62 \pm 0.20$ MeV, while the direct measurements yield $M_{D^+} = 1869.5 \pm 0.5$ MeV.

As both D^0 and D^+ mass values are based on a single measurement, the cross-check involving a method different from the one used at CLEO is essential. This Letter describes a measurement which has been performed with the KEDR detector at the VEPP-4M e^+e^- collider using the decay $\psi(3770) \to D\overline{D}$.

2. Experimental facility

The electron–positron accelerator complex VEPP-4M [10] designed for high-energy physics experiments in the center-of-mass (CM) energy range from 2 to 12 GeV is currently running in the ψ family region. The collider consists of two half-rings, an experimental section where the KEDR detector is installed, and a straight section, which includes an RF cavity and injection system. The circumference of the VEPP-4M ring is 366 m. The luminosity at the J/ψ in an operation mode with 2 by 2 bunches reaches $\mathcal{L} = 10^{30}\ \text{cm}^{-2}\,\text{s}^{-1}$.

Precise measurement of beam energy can be performed at VEPP-4M using the resonant depolarization method [11]. The method is based on the measurement of the spin precession frequency of the polarized beam, which depends on its energy. Using resonant depolarization, the precision of the beam energy measurement reached in the KEDR experiment is $\simeq 10$ keV [12].

The KEDR detector [13] includes a tracking system consisting of a vertex detector and a drift chamber, a particle identification (PID) system of aerogel Cherenkov counters and scintillation time-of-flight counters, and an electromagnetic calorimeter based on liquid krypton (in the barrel part) and CsI crystals (endcap part). The superconducting solenoid provides a longitudinal magnetic field of 0.6 T. A muon system is installed inside the magnet yoke. The detector also includes a high-resolution tagging system for studies of two-photon processes. The online luminosity measurement is performed with sampling calorimeters which detect photons from the process of single brehmsstrahlung.

Charged tracks are reconstructed in the drift chamber (DC) and vertex detector (VD). DC [14] has a cylindrical shape of 1100 mm length, an outer radius of 535 mm and is filled with pure dimethyl ether. DC cells form seven concentric layers: four axial layers and three stereo-layers to measure track coordinates along the beam axis. The coordinate resolution averaged over drift length is 100 μm. VD [15] is installed between the vacuum chamber and DC and increases a solid angle accessible to the tracking system to 98%. VD consists of 312 cylindrical drift tubes aligned in 6 layers. It is filled with an $\text{Ar} + 30\%\ \text{CO}_2$ gas mixture and has a coordinate resolution of 250 μm. The momentum resolution of the tracking system is $\sigma_p/p = 2\% \oplus (4\% \times p\ [\text{GeV}])$.

Scintillation counters of the time-of-flight system (TOF) are used in a fast charged trigger and for identification of the charged particles by their flight time. The TOF system consists of 32 plastic scintillation counters in the barrel part and in each of the endcaps. The flight time resolution is about 350 ps, which corresponds to π/K separation at the level of more than two standard deviations for momenta up to 650 MeV.

Aerogel Cherenkov counters (ACC) [16] are used for particle identification in the momentum region not covered by the TOF system and ionizations measurements in DC. ACC uses aerogel with the refractive index of 1.05 and wavelength shifters for light collection. This allows one to identify π and K mesons in the momentum range of 0.6 to 1.5 GeV. The system design includes 160 counters in the endcap and barrel parts, each arranged in two layers. During data taking only one layer of ACC was installed, and it was not used because of insufficient efficiency.

The barrel part of the electromagnetic calorimeter is a liquid krypton ionization detector [17]. The calorimeter provides an energy resolution of 3.0% at the energy of 1.8 GeV and a spatial resolution of 0.6–1.0 mm for charged particles and photons. The endcap part of the calorimeter is based on 1536 CsI(Na) scintillation crystals [18] with an energy resolution of 3.5% at 1.8 GeV, and a spatial resolution of 8 mm.

The muon system [19] is used to identify muons by their flight path in the dense medium of the magnetic yoke. It consists of three layers of streamer tubes with 74% solid angle coverage, the total number of channels is 544. The average longitudinal resolution is 3.5 cm, and the detection efficiency for the most of the covered angles is 99%.

Trigger of the KEDR detector consists of two levels: primary (PT) and secondary (ST). Both PT and ST operate at the hardware level. PT uses signals from TOF counters and both calorimeters as inputs, the typical rate is 5–10 kHz. ST uses signals from VD, DC and muon system in addition to systems listed above, and the rate is 50–150 Hz.

3. Measurement method

Measurement of D meson masses is performed using the near-threshold $e^+e^- \to D\overline{D}$ production with full reconstruction of one of the D mesons. Neutral D mesons are reconstructed in the $K^-\pi^+$ final state, charged D mesons are reconstructed in the $K^-\pi^+\pi^+$ final state (charge-conjugate states are implied throughout this Letter). To increase a data sample, the collider is operated at the peak of the $\psi(3770)$ resonance. The production cross sections at this energy are $\sigma(D^0\overline{D}^0) = 3.66 \pm 0.03 \pm 0.06$ nb and $\sigma(D^+D^-) = 2.91 \pm 0.03 \pm 0.05$ nb [20].

The invariant mass of the D meson can be calculated as

$$M_{\text{bc}} \simeq \sqrt{E_{\text{beam}}^2 - \left(\sum_i \vec{p}_i\right)^2}, \tag{1}$$

(so-called *beam-constrained mass*), where E_{beam} is the average energy of colliding beams, $\vec{p}_i$ are the momenta of the D decay products. The mass calculated this way is determined more precisely than in the case when the D energy is obtained from the energies of the decay products. The precision of M_D measurement in one event is

$$\sigma_{M_D}^2 \simeq \sigma_W^2/4 + \left(\frac{p_D}{M_D}\right)^2 \sigma_p^2 \simeq \sigma_W^2/4 + 0.02\sigma_p^2, \tag{2}$$

where σ_W is the CM energy spread. The contribution of the momentum resolution is suppressed significantly due to small D momentum ($p_D \simeq 260$ MeV).

In addition to M_{bc}, D mesons are effectively selected by the CM energy difference

$$\Delta E = \sum_i \sqrt{M_i^2 + p_i^2} - E_{\text{beam}}, \tag{3}$$

where M_i and p_i are the masses and momenta of the D decay products. The signal events should satisfy a condition $\Delta E \simeq 0$. In our analysis, we select a relatively wide region of M_{bc} and ΔE close to $M_{\text{bc}} \sim M_D$ and $\Delta E \sim 0$ (specifically, $M_{\text{bc}} > 1700$ MeV, $|\Delta E| < 300$ MeV); then a fit of the event density is performed with D mass as one of the parameters, with the background contribution taken into account. The background in our analysis comes from the random combinations of tracks of the continuum process