Measurement of the absolute branching fraction of $D_s^\pm (2317) \rightarrow \pi^0 D_s$
The process $e^+e^- \rightarrow D_{s0}^{*+}(2317)^- + c.c.$ is observed for the first time with the data sample of 567 pb$^{-1}$ collected with the BESIII detector operating at the BEPCII collider at a center-of-mass energy $\sqrt{s} = 4.6$ GeV. The statistical significance of the $D_{s0}^{*+}(2317)^-$ signal is 5.8$\sigma$ and the mass is measured to be $(2318.3 \pm 1.2 \pm 1.2)$ MeV/c$^2$. The absolute branching fraction $B(D_{s0}^{*+}(2317)^- \rightarrow \pi^0 D_s^{\pm})$ is measured as $1.00^{+0.00}_{-0.14} \pm 0.14$ for the first time. The uncertainties are statistical and systematic, respectively.

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The $D_{s0}^{*+}(2317)^-$ meson was first observed at the BABAR experiment via its decay to $\pi^0 D_s^- [1, 2]$; it was subsequently confirmed at the CLEO [3] and Belle [4] experiments. The $D_{s0}^{*+}(2317)^-$ meson is suggested to be the $P$-wave $\bar{c}s$ state.
with spin-parity $J^P = 0^+$. However, the measured mass $(2317.7 \pm 0.6) \text{ MeV}/c^2$ [5] is at least 150 MeV/$c^2$ lower than the calculations of a potential model [6] and lattice QCD [7] for such a state. As the $D_{s0}^*(2317)^-$ is 45 MeV/$c^2$ below the $DK$ threshold, it has been proposed as a good candidate for a $DK$ molecule [8], a $c\bar{s}q\bar{q}$ tetraquark state [9], or a mixture of a $c\bar{s}$ meson and a $c\bar{s}q\bar{q}$ tetraquark [10].

The $D_{s0}^*(2317)^-$ is extremely narrow, and the upper limit on its width is 3.8 MeV at the 95% confidence level (C.L.) [11]. The only known decay is the isospin-violating mode $\pi^0D_s^-$, and no branching fraction or partial width of this mode has been measured. Theoretical calculations give different values for the partial decay width $\Gamma(D_{s0}^*(2317)^- \to \pi^0D_s^-)$ based on different assumptions [12–15]. The partial width $\Gamma(D_{s0}^*(2317)^- \to \pi^0D_s^-)$ is around 30 keV or even less as a few keV if the $D_{s0}^*(2317)^-$ is a pure $c\bar{s}$ state, while it can be enhanced by a hundred keV or even larger in the molecule picture due to the contribution of meson loops. Therefore, the partial decay width or the branching fraction is a key quantity to identify the nature of the $D_{s0}^*(2317)^-$.

In this Letter, we present first observation of $e^+e^- \to D_s^{*+}D_{s0}^*(2317)^- + c.c.$ and the first measurement of the absolute branching fraction of $D_{s0}^*(2317)^- \to \pi^0D_s^-$. Throughout the text, the inclusion of the charge conjugate mode is implied unless otherwise stated. The data sample, which corresponds to an integrated luminosity of 567 pb$^{-1}$ [16], is collected at a center-of-mass (c.m.) energy of 4.6 GeV [17] with the BESIII detector [18] operating at the BEPCII collider [19]. In this analysis, a $D_s^{*+}$ is reconstructed via its $\gamma D_s^+$ decay with $D_s^+$ decaying to $K^+K^−\pi^+$, and its recoil mass spectrum is examined to search for a $D_{s0}^*(2317)^-$ signal. The $D_s^{*+}$ tagged sample is further divided into two subcategories, one with a tagged $\pi^0$ and the other with no tagged $\pi^0$. By using the numbers of signal events in these two categories, the absolute branching fraction of $D_{s0}^*(2317)^- \to \pi^0D_s^-$ is determined.

In order to determine the detection efficiency and to optimize the selection criteria, the GEANT4-based [20] Monte Carlo (MC) simulation software BOOST [21], which includes the geometric description of the detector and detector responses, is used to simulate $e^+e^- \to D_s^{*+}D_{s0}^*(2317)^-$ at $\sqrt{s} = 4.6 \text{ GeV}$ with $D_{s0}^*(2317)^- \to \gamma D_s^+$ and $D_s^{*+} \to K^+K^-\pi^+$, and $D_{s0}^*(2317)^- \to \pi^0D_s^-$ or $\gamma D_s^-$. The $D_s^+$ and $D_s^-$ are set to decay inclusively. The $JP$ of $D_{s0}^*(2317)^-$ is $0^-$, so it is in relative $S$-wave to the $D_s^{*+}$, and they are generated uniformly in phase space. The initial state radiation (ISR) is simulated with KKMCS [22] using a calculation with a precision better than 0.2%. The final state radiation (FSR) effects associated with charged particles is handled with PHOTOS [23]. To study the possible backgrounds, an inclusive MC sample with an integrated luminosity equivalent to data is generated. All the known charmonium transitions, hadronic decays and open charm channels are modeled with EVTGEN [24, 25] incorporating the branching fractions taken from the Particle Data Group [5], while the QED processes and the unknown charmonium decays are generated with BABAYAGA [26] and LUNDCHARM [27], respectively.

To reconstruct $D_{s0}^*(2317)^-$, the $\gamma D_s^+$ channel is used with $D_s^+$ decaying to $K^+K^-\pi^+$. Events with at least three charged track candidates and at least one photon candidate are selected. For each charged track candidate, the polar angle $\theta$ in the multi-layer drift chamber (MDC) must satisfy $|\cos(\theta)| < 0.93$, and the distance of the closest approach to the $e^+e^-$ interaction point is required to be less than 10 cm along the beam direction and less than 1 cm in the plane perpendicular to the beam. Particle identification (PID), which uses both the information from time of flight (TOF) and the specific energy loss ($dE/dx$), is performed to separate kaons and pions. The photon candidates are selected from showers in the electromagnetic calorimeter (EMC) with deposited energy greater than 25 MeV in the barrel ($|\cos(\theta)| < 0.8$), or greater than 50 MeV in the end-cap regions ($0.86 < |\cos(\theta)| < 0.92$). To eliminate showers produced by charged tracks, the photon candidate must be separated by at least 20 degrees from any charged track. The time for the shower measured by the EMC from the start of this event is restricted to be less than 700 ns to suppress electronic noise and energy depositions unrelated to the event.

All combinations are required to have the invariant masses of $K^+K^-\pi^+$ and $\gamma K^+K^-\pi^+$ within $\Delta M_{K^+K^-\pi^+} \equiv |M(K^+K^-\pi^+)-m_{D_s^+}| < 16 \text{ MeV}/c^2$ and $\Delta M_{\gamma K^+K^-\pi^+} \equiv |M(\gamma K^+K^-\pi^+)-m_{D_s^+}| < 11 \text{ MeV}/c^2$, where $M$($\gamma K^+K^-\pi^+$) is the invariant mass of the $(\gamma)K^+K^-\pi^+$ system and $m_{D_s^+}/D_s^+$ is the nominal mass of $D_s^{*+}/D_s^+$ [5]. A two-constraint (2C) kinematic fit is performed on the surviving events with the mass constraints of $D_s$ and $D_s^{*+}$ to obtain a better recoil mass resolution and to suppress backgrounds. The $\chi^2_{2C}$ from the kinematic fit is required to be less than 14. All successful combinations in each event are kept for further study.

After the previously described selection criteria, the recoil mass distribution of $D_s^{*+}$ is shown in Fig. 1 where a $D_{s0}^*(2317)^-$ signal can be observed. The events in the sidebands of $D_{s0}^*$ and $D_s^{*+}$ in the sample before the kinematic fit are checked and no signal of $D_{s0}^*(2317)^-$ is observed. The inclusive MC sample, which does not include production of the $D_{s0}^*(2317)^-$, matches well with the background from data. In the inclusive MC sample, the remaining events are non-$D_{s0}^*$ events around the $D_{s0}^*(2317)^-$ peak, including non-$D_s^{*+}$ events and mis-combined $\gamma D_s^{*+}$ events, where the $\gamma$ or $D_s^{*+}$ could come from other decay modes of $D_s^{*+}$. For the fit with a real $D_s^{*+}$, such as $e^+e^- \to D_s^{*+}D_s^{-}$ or $D_s^{*+}D_s^-$, the recoil mass of $D_s^{*+}$ is far away from the $D_{s0}^*(2317)^-$ peak and has no influence in this analysis. In general, none of the known backgrounds can form a peak in the signal region. On the other hand, the technique to measure the absolute branching fraction $B(D_{s0}^*(2317)^- \to \pi^0D_s^-)$ avoids the influence of the unknown three-body processes $\gamma D_s^* D_{s0}^*(2317)^-$ and $\pi^0D_s^* D_{s0}^*(2317)^-$ even if they exist.
since they have an identical $D_{s0}^*(2317)^-$ compared to the signal process $D_{s+}^0 D_{s0}^*(2317)^-$. The process $e^+e^- \rightarrow D_{s+}^0 D_{s0}^*(2317)^- \rightarrow D_{s+}^0 \pi^0 D_s^-$ is studied via a further $\pi^0$ reconstruction with two photons from the remaining showers in the EMC and $D_s^-$ as missing particle. If there are more than two photons, all combinations of $\gamma \pi^0 D_s^+$ are subject to a 4C kinematic fit with mass constraints on the $D_{s+}^0$, $D_{s+}^0$, $\pi^0$ candidates and a missing $D_s^-$, requiring the $\chi^2_{4C}$ to be less than 36.

The requirements on $\Delta M_{K^+ K^- \pi^0}$, $\Delta M_{\pi^0 K^+ K^-}$, $\chi^2_{4C}$ and $\chi^2_{3C}$ are optimized with MC samples to obtain the best statistical precision of $B(D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-)$. The $D_{s+}^0 D_{s0}^*(2317)^-$ signal is generated by assuming $B(D_{s0}^*(2317)^- \rightarrow \pi^0 D_{s}^-) = 0.9$ and $B(D_{s0}^*(2317)^- \rightarrow \gamma D_{s0}^-) = 0.1$ and normalized according to the number of signal events from data. The background is taken from a toy MC sample generated by fitting the recoil mass distribution of $D_{s+}^0$ from data. The MC samples are analyzed with the same procedure as for data to obtain the branching fraction $B(D_{s0}^*(2317)^- \rightarrow \pi^0 D_{s}^-)$. The requirements yielding the smallest relative statistical uncertainty are used in this analysis.

The $e^+e^- \rightarrow D_{s+}^0 D_{s0}^*(2317)^-$ events are divided into two subcategories: “$\pi^0$-tag succeeded” if at least one $\pi^0$ is tagged and the event passed the 4C kinematic fit, and “$\pi^0$-tag failed” for the other events. The recoil mass distributions of the $D_{s+}^0$ from the 2C kinematic fit of these two subcategories are shown in Fig. 2. These distributions are fitted simultaneously to measure the branching fraction of $D_{s0}^*(2317)^- \rightarrow \pi^0 D_{s}^-$. The real $D_{s0}^*(2317)^- \rightarrow \pi^0 D_{s}^-$ signal events could be categorized into both subsamples since the detection efficiency for $\pi^0$ is 43.4%. On the other hand, potential background events, such as $D_{s0}^*(2317)^- \rightarrow \gamma D_{s0}^-$ or other decay channels, could be reconstructed in the “$\pi^0$-tag succeeded” sample too. Therefore, the number of $D_{s0}^*(2317)^-$ signal events in the “$\pi^0$-tag succeeded” subsample, $N_0$, is expressed as

$$N_0 = N_{tot}/\epsilon_{tot} \cdot B \cdot \epsilon_{sig} + N_{tot}/\epsilon_{tot} \cdot (1-B) \cdot \epsilon_{bkg}, \quad (1)$$

where the first and the second terms represent the contributions from $D_{s0}^*(2317)^- \rightarrow \pi^0 D_{s}^-$ (with a branching fraction of $B$) and from the other $D_{s0}^*(2317)^-$ decay mode (with a branching fraction of $1-B$), respectively. Here the other decay mode means the potential peaking background mode $D_{s0}^*(2317)^- \rightarrow \gamma D_{s0}^-$, which is expected to be the dominant mode besides $\pi^0 D_{s}^-$, and any other decay modes are considered in the systematic uncertainty. The $N_{tot}$ is the number of $D_{s0}^*(2317)^-$ signal events in the full sample (the sum of “$\pi^0$-tag succeeded” and “$\pi^0$-tag failed” events), $\epsilon_{tot}$ is the corresponding detection efficiency for the reconstructed $D_{s+}^0$, $N_{tot}/\epsilon_{tot}$ is the number of produced $D_{s+}^0$ events in the $D_{s0}^*(2317)^-$ events, $\epsilon_{sig}$ is the detection efficiency for $D_{s0}^*(2317)^- \rightarrow \pi^0 D_{s}^-$ events being reconstructed in the “$\pi^0$-tag succeeded” sample including the branching fraction of $\pi^0 \rightarrow \gamma\gamma$ [3], and $\epsilon_{bkg}$ is the efficiency for non-$D_{s0}^*(2317)^- \rightarrow \pi^0 D_{s}^-$ events to be reconstructed in the “$\pi^0$-tag succeeded” sample. The efficiencies $\epsilon_{tot}$, $\epsilon_{sig}$ and $\epsilon_{bkg}$ are obtained from MC simulations, and are 40.0%, 17.2%, and 5.8%, respectively.

From Eq. (1), we derive the absolute branching fraction $B(D_{s0}^*(2317)^- \rightarrow \pi^0 D_{s}^-)$ as

$$B = \frac{N_0 - N_{tot}/\epsilon_{tot} \cdot \epsilon_{bkg}}{N_{tot}/\epsilon_{tot} \cdot (\epsilon_{sig} - \epsilon_{bkg})}, \quad (2)$$

where the branching fraction $B$ and $N_{tot}$ are the free parameters in a simultaneous fit to the recoil mass distributions of the $D_{s+}^0$ in Fig. 2 and $N_0$ is calculated using Eq. (1).
The shape for the $D^*_s(2317)^-$ signal is described with a Crystal Ball function [28] convolved with a Gaussian function, while the background is parameterized with a linear function. The parameters of the Crystal Ball function except for the mass are fixed to the values from a fit to the MC simulated $D^+D^*_0(2317)^-$ sample, in which the $D^*_0(2317)^-$ is simulated with zero width. The Gaussian function is used to describe the data-MC difference in mass resolution, and the standard deviation is taken from a control sample of $e^+e^- \rightarrow D^+_sD^-_s$ at 4.6 GeV. By reconstructing the $D^+_s$ from the process $e^+e^- \rightarrow D^+_sD^-_s$, it is found that the recoiling $D^+_s$ signal shape in MC simulation needs to be smeared by a Gaussian with the standard deviation of 0.9 MeV/c² in order to match the data. The standard deviation of the Gaussian function in the fit to the $D^*_0(2317)^-$ signal is fixed to this value.

From the simultaneous fit, the total number of $D^*_0(2317)^-$ signal events is $115 \pm 21$, and the number of $D^*_0(2317)^-$ events in the "$\pi^0$ tag-success" subsample is $46.8 \pm 9.4$. The latter event yield is found to be 49.3 with a constraint that the branching fraction is no larger than one. Using Eq. (2), the absolute branching fraction of $D^*_0(2317)^- \rightarrow \pi^0 D^-_s$ is measured to be $1.00^{+0.06}_{-0.14}$, with a constraint that the branching fraction cannot be larger than one. The statistical uncertainty, 0.14, is estimated by covering 68.3% confidence level from the likelihood distribution of the branching fraction. By comparing the difference of the log-likelihood with and without the $D^*_0(2317)^-$ signal in the fit and considering the change of the number of degrees of freedom, the statistical significance of the $D^*_0(2317)^-$ signal is estimated as 5.8σ. The mass of $D^*_0(2317)^-$ is measured to be $(2318.3 \pm 1.2)$ MeV/c².

The $J^P$ of $D^*_0(2317)$ is $0^+$, so both the $D^+_sD^*_0(2317)^-$ and the $\pi^0 D^-_s$ systems are expected to be in a relative S-wave, and the angular distributions are expected to be flat. We define the signal region of $D^*_0(2317)^-$ as $[2.31, 2.33]$ GeV/c², and the sideband regions as $[2.28, 2.30]$ and $[2.34, 2.36]$ GeV/c² to estimate the contribution of background. Figure 3 shows the angular distributions of $D^*_0(2317)^-$ in the $e^+e^-$ c.m. system and of $\pi^0$ in the $D^*_0(2317)^-$ c.m. system. Both distributions are flat as expected, and can be modeled by the MC simulations.

For the branching fraction measurement, many sources of systematic uncertainties cancel since the branching fraction is determined by the relative signal yields in the two subsamples. The main systematic uncertainties come from $\pi^0$ reconstruction, the used signal and background shapes, $\pi^0 D^-_s$ selections, possible width of $D^*_0(2317)^-$, and potential peaking backgrounds.

The uncertainty on $\pi^0 D^-_s$ selection, we perform a kinematic fit, which could cause a systematic bias in the efficiency between data and MC simulation. To study this difference, we correct the helix parameters of the charged tracks in MC simulation [29], the difference in $\chi^2$ distribution between data and MC simulation becomes negligible small according to other studies [30]. We take half of the difference in the ratio of detection efficiencies $\epsilon_{\text{sig}}$ and $\epsilon_{\text{tot}}$ between MC simulations with and without this correction as systematic uncertainty (3.1%). The nominal result is based on the corrected MC simulation.

The width of $D^*_0(2317)$ is unknown and cannot be measured in this analysis due to limited statistics. In the nominal fit, we use the shape from MC simulation of $D^*_0(2317)^-$ with zero width to describe the signal. The upper limit on the width of $D^*_0(2317)^-$ is estimated as 3.8 MeV at 95% C.L. from previous experiments [3]. In an alternative fit, we change the width of $D^*_0(2317)^-$ to 3.8 MeV and use the same Gaussian function to convolve the shape from MC simulation, and take the difference in the branching fraction, 5.3%, as systematic uncertainty.

In Eq. (2), the peaking background is considered, and the result of the fit shows that its contribution is negligible. For the signal mode, $D^*_0(2317)^- \rightarrow \pi^0 D^-_s$, the tagged $\pi^0$ could also come from $D^-_s$. This kind of events is regarded as signal, and its contribution is included in the definition of the efficiency, which is estimated from the MC simulation of $e^+e^- \rightarrow D^+_sD^*_0(2317)^- \rightarrow D^+_s\pi^0 D^-_s$ with $D^-_s$ decaying to all possible modes. All peaking backgrounds come from other decay modes of $D^*_0(2317)^-$. To study the possible contribution conservatively, we simulate the potential peaking backgrounds, $D^*_0(2317)^- \rightarrow \gamma D^-_s$, $\gamma\gamma D^-_s$ and $\pi^+\pi^- D^-_s$ exclusively. The upper limits on the ratio $\Gamma(\gamma D^-_s)/\Gamma(\pi^0 D^-_s)$, $\Gamma(\gamma\gamma D^-_s)/\Gamma(\pi^0 D^-_s)$, and $\Gamma(\pi^+\pi^- D^-_s)/\Gamma(\pi^0 D^-_s)$, are esti-
mated as 0.059, 0.18, and 0.006 [5]. The total systematic uncertainty in $B(D^\ast_{s0}(2317)^- \rightarrow \pi^0 D_s^\ast)$ is conservatively estimated to be 8.5%.

All the above systematic uncertainties are listed in Table I. Assuming all of them are independent and adding them in quadrature, we estimate a total systematic uncertainty of 13.8% in the branching fraction.

| Source                        | Uncertainty (%) |
|-------------------------------|-----------------|
| $\pi^0$ reconstruction        | 0.7             |
| Signal shape                  | 5.0             |
| Background shape              | 7.4             |
| $\pi^0 D_s^\ast$ selections  | 3.1             |
| Width of $D^\ast_{s0}(2317)^-$ | 5.3             |
| Peaking backgrounds           | 8.5             |
| **Total**                     | **13.8**        |

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