Study of the Decay and Production Properties of $D_{s1}(2536)$ and $D_{s2}^*(2573)$

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The $e^+e^- \to D_s^+ D_{s1}(2536)^-$ and $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$ processes are studied using data samples collected with the BESIII detector at center-of-mass energies from 4.530 to 4.946 GeV. The absolute branching fractions of $D_{s1}(2536)^- \to \bar{D}^{*0} K^-$ and $D_{s2}^*(2573)^- \to \bar{D}^0 K^-$ are measured for the first time to be $(35.9 \pm 4.8 \pm 3.5)\%$ and $(37.4 \pm 3.1 \pm 4.6)\%$, respectively. The $e^+e^- \to D_s^+ D_{s1}(2536)^-$ and $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$ cross sections are measured, and a resonant structure at around 4.6 GeV with a width of 50 MeV is observed in both processes with a statistical significance of 7.2σ and 15σ, respectively. The state is observed for the first time in $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$ and could be the $Y(4626)$ found by the Belle oration in the $D_s^+ D_{s1}(2536)^-$ final state, since they have similar masses and widths. There is also evidence for a structure at around 4.75 GeV in both processes.

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The D_s mesons are bound states of $c\bar{s}$ quarks. Four P-wave $c\bar{s}$ states with $J^P = 0^+$ (D_{s0}^*), 1^+ (D_{s1}), 1^+ (D_{s1}'), and 2^+ (D_{s2}^*) are predicted in the conventional quark model [1], and the four experimentally observed states $D_{s0}^*(2317)$, $D_{s1}(2460)$, $D_{s1}(2536)$, and $D_{s2}^*(2573)$ are assigned to them, respectively. Recently, authors of Ref. [2] developed a coupled-channel framework which considers the quark-pair-creation mechanism and $D^{(*)}K$ interactions to investigate the inner structures of these states. The framework explains the lower measured masses of $D_{s0}^*(2317)$ [3] and $D_{s1}(2460)$ [4] compared with those predicted by the conventional quark model and infers that $(98.2^{+0.1}_{-0.2})\%$ and $(95.9^{+1.0}_{-1.5})\%$ of the contents of the $D_{s1}(2536)$ and $D_{s2}^*(2573)$, respectively, are bare $c\bar{s}$ cores [2]. At the heavy quark limit, authors of Refs. [1,5] predict the decays of not only the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ but also the $D_{s1}(2536)$ and $D_{s2}^*(2573)$. Absolute branching fractions for $D_{s1}(2536)$ and $D_{s2}^*(2573)$, which are essential in understanding the inner structure of these strange-charmed states, have never been measured before [6].

Effective field theory [7–9] and quantum chromodynamics–inspired potential models [10–13] predict six vector charmonium states with masses between 4.0 and 4.8 GeV$/c^2$: $\psi(3^3S_1)$, $\psi(2^3D_1)$, $\psi(4^3S_1)$, $\psi(3^3D_1)$, $\psi(5^3S_1)$, and $\psi(4^3D_1)$. The first three states are usually assigned as $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$, respectively. The unclassified $\psi(3^3D_1)$, $\psi(5^3S_1)$, and $\psi(4^3D_1)$ states are expected to have masses above 4.45 GeV$/c^2$. However, the $Y(4500)$ [14], $Y(4660)$ [15], $Y(4710)$ [16], and $Y(4790)$ [17] are observed in this mass region, which makes the assignment of these states very uncertain. The $Y(4660)$ is observed through initial state radiation (ISR) in $e^+e^- \to \pi^+\pi^-\psi(2S)$ [15], and the $\pi^+\pi^-$ invariant mass tends to accumulate at the nominal mass of $f_0(980)$, which has an $s\bar{s}$ component [15]; the $Y(4500)$ and $Y(4710)$ are observed in $e^+e^- \to K^+K^-J/\psi$ [14,16] and the $Y(4790)$ in $e^+e^- \to D_s^{*+}D_s^{*-}$ [17], where K and D_s^* have s components also. These measurements indicate that these four states have both $s\bar{s}$ and $c\bar{c}$ components and may decay into a strange-charmed meson pair. Therefore, the search for possible Y states in $c\bar{s}$ and $\bar{c}s$ meson pairs provides an opportunity to investigate these unclassified Y states. Evidence for $Y(4626)$ in $e^+e^- \to D_s^+ D_{s1}(2536)^-$ (charge conjugated processes and particles are always implied in the following) [18] and evidence for a $Y(4620)$ state in $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$ [19] are reported by the Belle collaboration in ISR processes with large uncertainties. Improved measurements at BESIII and other experiments are needed to draw more solid conclusions on these states.

In this Letter, the $e^+e^- \to D_s^+ D_{s1}(2536)^-$ and $D_s^+ D_{s2}^*(2573)^-$ processes are investigated with $D_{s1}(2536)^-$ and $D_{s2}^*(2573)^-$ decaying both inclusively (inclusive analysis) and to $\bar{D}^{*0}K^-$ and $\bar{D}^0K^-$ (exclusive analysis). The absolute branching fractions of $D_{s1}(2536)^- \to \bar{D}^{*0}K^-$ and $D_{s2}^*(2573)^- \to \bar{D}^0K^-$ are measured by comparing the cross sections of inclusive and exclusive processes, and possible Y states are searched for in the exclusive cross sections.

The BESIII detector is described in detail in Refs. [20,21]. The experimental data samples used in this

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Letter are taken at center-of-mass energies ($\sqrt{s}$) ranging from 4.530 to 4.946 GeV with 15 energy points [22,23] corresponding in total to an integrated luminosity of 6.60 fb^{-1} [23,24]; the details of the data samples are shown in Supplemental Material [25]. Since the cross sections of some background processes are not measured for data samples with $\sqrt{s} < 4.6$ GeV and $\sqrt{s} > 4.7$ GeV, only six data samples with $4.6 \leq \sqrt{s} < 4.74$ GeV (excluding $\sqrt{s} = 4.610$ GeV due to low statistics) are used for the absolute branching fraction measurements. Cross sections of the exclusive processes at all energy points are measured. Simulated samples, which are used to estimate the background and to determine the detection efficiencies and ISR correction factors, are produced with GEANT4-based [31] Monte Carlo (MC) software, which includes the geometric description of the BESIII detector and its response.

The $e^+e^- \to D_s^+ D_{s1}(2536)^-$ process is simulated with the ANGSAM model [32,33], using an angular distribution described by $1 + \alpha\cos^2\theta$, where θ is the polar angle of D_s^+ in the e^+e^- rest frame and $\alpha = -0.65 \pm 0.22$ is measured in this work. The simulation of the kinematic of $D_{s1}(2536)^- \to \bar{D}^{*0}K^-$ decay accounts for the spin of particles in initial and final states, as implemented in EvtGen with VVS_PWAVE model [32,33], and the fraction of S wave and D wave is fixed according to the Belle measurement [34]. The $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$ process is generated via D wave with $D_{s2}^*(2573)^-$ decaying to $\bar{D}^0K^-$ via D wave. The $D_s^+ \to K^-K^+\pi^+$ decay is simulated with the D_Dalitz model [32,33,35], and the $K_S^0 \to \pi^+\pi^-$ and $D_s^+ \to K_S^0 K^+$ decays are simulated with a phase space model [32,33]. Beam energy spread and ISR are considered with the generator KKMC [36,37].

In the inclusive measurement, a D_s^+ is reconstructed with the decay of $D_s^+ \to K^-K^+\pi^+$. The selection criteria for charged tracks are described in Ref. [38]. The tracks used to reconstruct D_s^+ are required to originate from a common vertex, and the χ^2 of the vertex fit (χ^2_{VF}) [39] is required to satisfy $\chi^2_{\mathrm{VF}} < 100$. Only decays containing the intermediate states ϕ or $\bar{K}^{*0}$ in $D_s^+ \to K^-K^+\pi^+$ are used to select D_s^+ candidates. The invariant masses of K^+K^- [$M(K^+K^-)$] or $K^-\pi^+$ [$M(K^-\pi^+)$] are required to satisfy $1.004 < M(K^+K^-) < 1.034\ \mathrm{GeV}/c^2$ with a helicity angle of K^+ in the K^+K^- helicity frame satisfying $|\cos\theta_{K^+/K^+K^-}| > 0.4$, or $0.832 < M(K^-\pi^+) < 0.928\,\mathrm{GeV}/c^2$ with $|\cos\theta_{\pi^+/K^-\pi^+}| > 0.52$. The invariant mass of $K^-K^+\pi^+$ [$M(K^-K^+\pi^+)$] is constrained to the known D_s^+ mass $m_{D_s^+}$ [6] using a one-constraint kinematic fit to improve the resolution of the D_s^+ recoiling mass, $RM(D_s^+)$, defined as $RM(D_s^+)^2 = [p(e^+e^-) - p(D_s^+)]2$, where $p(e^+e^-)$ and $p(D_s^+)$ are the four-momenta of the initial e^+e^- system and the D_s^+, respectively.

The yields of $D_{s1}(2536)^-$ and $D_{s2}^*(2573)^-$ events are determined by a two-dimensional (2D) extended unbinned likelihood fit to $M(K^-K^+\pi^+)$ versus $RM(D_s^+)$. Distributions of $RM(D_s^+)$ versus $M(K^-K^+\pi^+)$ from data and the projection of the 2D fit in $RM(D_s^+)$ at $\sqrt{s} = 4.680$ GeV are shown for illustration in Figs. 1(a) and 1(b), respectively. The details of the fit methods in inclusive and exclusive measurements and numerical results of the cross section calculation are described in Supplemental Material [25]. The cross sections for the processes $e^+e^- \to D_s^+ D_{s1}(2536)^-$ and $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$ (labeled with index $i = 1$ and 2, respectively) for the jth value of $\sqrt{s}$ are calculated with

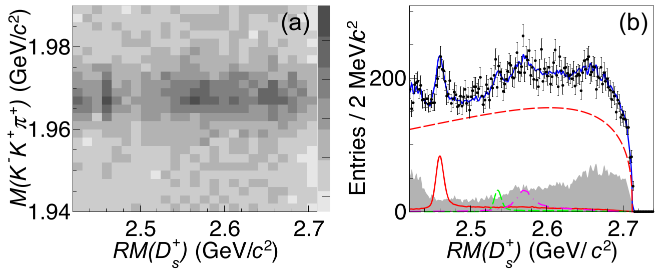

FIG. 1. Distribution of (a) $RM(D_s^+)$ versus $M(K^-K^+\pi^+)$ from data and (b) projection of the 2D fit in $RM(D_s^+)$ in the inclusive analysis at $\sqrt{s} = 4.680$ GeV. Here, the dots with error bars are data, the gray histogram is background from processes involving an excited D_s or D meson, the red dashed line is an ARGUS function [40], the blue solid line is the total fit, and the red solid, green dashed, and purple dash-dotted lines are MC shapes of $D_{s1}(2460)^-$, $D_{s1}(2536)^-$, and $D_{s2}^*(2573)^-$ signals, respectively.

$$\sigma_{i,j}^{\mathrm{inc}} = \frac{N_{i,j}^{\mathrm{inc}}}{\frac{1}{|1-\Pi|^2}_j (1+\delta)_{i,j} \epsilon_{i,j}^{\mathrm{inc}} \mathcal{B}_{K^-K^+\pi^+} \mathcal{L}_j}, \tag{1}$$

where $\mathcal{B}_{K^-K^+\pi^+}$ is the branching fraction of $D_s^+ \to K^-K^+\pi^+$ [6], $N_{i,j}^{\mathrm{inc}}$ is the number of signal events obtained from the 2D fit, $(1+\delta)_{i,j}$ is the ISR correction factor obtained from MC simulation, and $\epsilon_{i,j}^{\mathrm{inc}}$ is the detection efficiency in the inclusive cross section measurement; $(1/|1-\Pi|^2)_j$ and $\mathcal{L}_j$ are the vacuum polarization factor and integrated luminosity, respectively.

In the exclusive measurement, a D_s^+ is reconstructed with the decay of $D_s^+ \to K^-K^+\pi^+$ or $D_s^+ \to K_S^0(\to \pi^+\pi^-)K^+$ and a K^- is selected from the charged tracks not forming the D_s^+ in order to be able to consider the recoiling mass $D_s^+K^-$, $RM(D_s^+K^-)$. The selection criteria for K_S^0 are described in Refs. [38,39]. The tracks used to reconstruct D_s^+, including K_S^0 pseudo-candidate from a secondary vertex fit [39], are also required to originate from a common vertex with $\chi^2_{\mathrm{VF}} < 100$. In addition to the selection criteria used in the inclusive analysis, the invariant mass of $K^-K^+\pi^+$ or $K_S^0K^+$ [$M(K_S^0K^+)$] must satisfy $|M(K^-K^+\pi^+/K_S^0K^+) - m_{D_s^+}| < 8\,\mathrm{MeV}/c^2$. To select $D_{s2}^*(2573)^- \to \bar{D}^0K^-$ and $D_{s1}(2536)^- \to \bar{D}^{*0}K^-$,

$RM(D_s^+K^-)$ must satisfy the following requirements: (a) for the $e^+e^- \to D_s^+D_{s1}(2536)^-$ process, $|RM(D_s^+K^-) - m_{\bar{D}^{*0}}|$ should be less than 9 MeV$/c^2$ for $D_s^+ \to K^-K^+\pi^+$ and 7 MeV$/c^2$ for $D_s^+ \to K_S^0K^+$; (b) for the $e^+e^- \to D_s^+D_{s2}^*(2573)^-$ process, $|RM(D_s^+K^-) - m_{\bar{D}^0}|$ should be less than 11 MeV$/c^2$ for $D_s^+ \to K^-K^+\pi^+$ and 9 MeV$/c^2$ for $D_s^+ \to K_S^0K^+$. Here, $m_{\bar{D}^{*0}}$ and $m_{\bar{D}^0}$ are the known $\bar{D}^{*0}$ and $\bar{D}^0$ masses, respectively [6]. For the selected entries, $M(K^-K^+\pi^+/K_S^0K^+)$ are constrained to $m_{D_s^+}$, $RM(D_s^+K^-)$ is constrained to $m_{\bar{D}^0}$ or $m_{\bar{D}^{*0}}$, and the total four-momenta is constrained to that of the initial e^+e^- system via a kinematic fit.

For data samples with $\sqrt{s} \geq 4.6$ GeV, the yields of $D_{s1}(2536)^-$ and $D_{s2}^*(2573)^-$ events are determined by extended unbinned likelihood fits to the corresponding $RM(D_s^+)$ distributions, while for data samples with $\sqrt{s} < 4.6$ GeV, due to the low number of events, the counting method described in Refs. [41,42] is used. The fit results of $RM(D_s^+)$ for $D_{s1}(2536)^-$ and $D_{s2}^*(2573)^-$ at $\sqrt{s} = 4.680$ GeV are shown in Figs. 2(a) and 2(b), respectively. The cross sections are calculated with

$$\sigma_{i,j}^{\rm exc} = \frac{N_{i,j}^{\rm exc}}{\frac{1}{|1-\Pi|^2}_j(1+\delta)_{i,j}(\epsilon\mathcal{B})_{i,j}\mathcal{L}_j}, \qquad (2)$$

where $N_{i,j}^{\rm exc}$ is the number of signal events obtained from the fit and $(\epsilon\mathcal{B})_{i,j} = (\epsilon^{\rm exc}_{K^-K^+\pi^+,i,j}\mathcal{B}_{K^-K^+\pi^+} + \epsilon^{\rm exc}_{K_S^0K^+,i,j}\mathcal{B}_{K_S^0K^+})$. Here, $\mathcal{B}_{K_S^0K^+} = \mathcal{B}(D_s^+ \to K_S^0K^+)\mathcal{B}(K_S^0 \to \pi^+\pi^-)$ [6] is the product of the branching fractions of $D_s^+ \to K_S^0K^+$ and $K_S^0 \to \pi^+\pi^-$, $\epsilon^{\rm exc}_{K^-K^+\pi^+,i,j}$ and $\epsilon^{\rm exc}_{K_S^0K^+,i,j}$ are the detection efficiencies for the signal processes with $D_s^+ \to K^-K^+\pi^+$ and $D_s^+ \to K_S^0(\to \pi^+\pi^-)K^+$, respectively. The measured cross sections of $e^+e^- \to D_s^+D_{s1}(2536)^-$ and $e^+e^- \to D_s^+D_{s2}^*(2573)^-$ with the inclusive and exclusive methods are shown in Figs. 3(a) and 3(b), respectively.

Using the data at the six energy points with both inclusive and exclusive cross sections measured, we determine the absolute branching fractions of the $D_{s1}(2536)^- \to \bar{D}^{*0}K^-$ and $D_{s2}^*(2573)^- \to \bar{D}^0K^-$ with a likelihood fit that maximizes the likelihood function

$$L_i(\sigma_{i,j}^{\rm inc}, \delta_{i,j}^{\rm inc}, \sigma_{i,j}^{\rm exc}, \delta_{i,j}^{\rm exc}; \sigma_{i,j}, \mathcal{B}_i) = \prod_{j=1}^{6} L_{i,j}^{\rm inc}(\sigma_{i,j}^{\rm inc}, \delta_{i,j}^{\rm inc}; \sigma_{i,j}) L_{i,j}^{\rm exc}(\sigma_{i,j}^{\rm exc}, \delta_{i,j}^{\rm exc}; \sigma_{i,j}, \mathcal{B}_i), \qquad (3)$$

where $\delta_{i,j}^{\rm inc}$ and $\delta_{i,j}^{\rm exc}$ are the statistical uncertainties of the measured inclusive and exclusive cross sections, respectively; $\sigma_{i,j}$ is the actual cross section of $e^+e^- \to D_s^+D_{s1}(2536)^-$ or $e^+e^- \to D_s^+D_{s2}^*(2573)^-$; and $\mathcal{B}_i$ is the absolute branching fraction of $D_{s1}(2536)^- \to \bar{D}^{*0}K^-$ ($i = 1$) or $D_{s2}^*(2573)^- \to \bar{D}^0K^-$ ($i = 2$). Since the significances, calculated by comparing changes of likelihood value of fits with and without the corresponding component and accounting for Δndf, where ndf is the number of degree of freedom, for $e^+e^- \to D_s^+D_{s1}(2536)^-$ ($e^+e^- \to D_s^+D_{s2}^*(2573)^-$) at $\sqrt{s} = 4.66$ (4.66 and 4.7) GeV in both inclusive and exclusive measurements are less than 5σ, $L_{i,j}^{\rm inc,exc}$ at that energy point is a normalized likelihood as a function of $\sigma_{i,j}^{\rm inc,exc}$ which is obtained from the signal yield fits. The likelihoods $L_{i,j}^{\rm inc,exc}$ for the other samples with sufficiently high statistics are approximated as a Gaussian function, and details are described in Supplemental Material [25]. Figures 4(a) and 4(b) show the fit results of the absolute branching fractions, which are $(35.9 \pm 4.8)\%$ and $(37.4 \pm 3.1)\%$ for $\mathcal{B}(D_{s1}(2536)^- \to \bar{D}^{*0}K^-)$ and $\mathcal{B}(D_{s2}^*(2573)^- \to \bar{D}^0K^-)$, respectively.

To study the resonance structures in the $e^+e^- \to D_s^+D_{s1}(2536)^-$ and $e^+e^- \to D_s^+D_{s2}^*(2573)^-$ processes, least-χ^2 fits to the measured cross sections are performed. The cross sections are described with the coherent sum of two Breit-Wigner (BW) functions with mass-independent width, as shown in Eq. (4),

$$\sigma(\sqrt{s}) = |BW_0(\sqrt{s}) + BW_1(\sqrt{s})e^{i\phi}|^2. \qquad (4)$$

We find two solutions in $e^+e^- \to D_s^+D_{s1}(2536)^-$ with $\chi^2/\text{ndf} = 4.0/8$, they have the same masses and widths but differ in the relative phase of the two BW functions [one of them is shown in Fig. 3(a)], and only one solution in $e^+e^- \to D_s^+D_{s2}^*(2573)^-$ with $\chi^2/\text{ndf} = 6.2/7$ [shown in Fig. 3(b)]. The mass and width for BW_0 in $e^+e^- \to D_s^+D_{s1}(2536)^-$ are $(4584 \pm 14 \pm 80)$ MeV$/c^2$ and $(57 \pm 12 \pm 219)$ MeV, respectively, those in $e^+e^- \to D_s^+D_{s2}^*(2573)^-$ are $(4603.1 \pm 3.9 \pm 0.8)$ MeV$/c^2$ and $(45.2 \pm 5.7 \pm 0.7)$ MeV, respectively; the mass and width for BW_1 in $e^+e^- \to D_s^+D_{s1}(2536)^-$ are $(4749.9 \pm 8.2 \pm 5.5)$ MeV$/c^2$ and $(24.9 \pm 8.0 \pm 1.0)$ MeV, respectively, those in $e^+e^- \to D_s^+D_{s2}^*(2573)^-$ are $(4720 \pm 13 \pm 2)$ MeV$/c^2$ and $(50 \pm 12 \pm 1)$ MeV, respectively, where

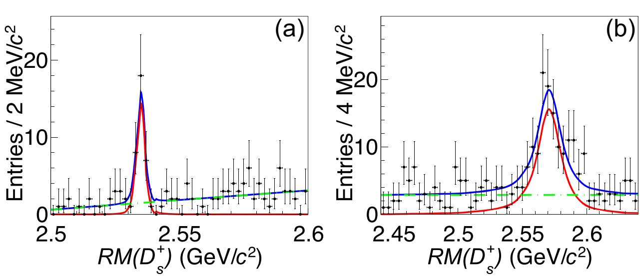

FIG. 2. Fit results of $RM(D_s^+)$ for (a) $D_{s1}(2536)^-$ and (b) $D_{s2}^*(2573)^-$ in the exclusive analysis at $\sqrt{s} = 4.680$ GeV. Here, the dots with error bars are data, the blue solid, red solid, and green dashed lines are the total fit, signal shape, and background shape, respectively.

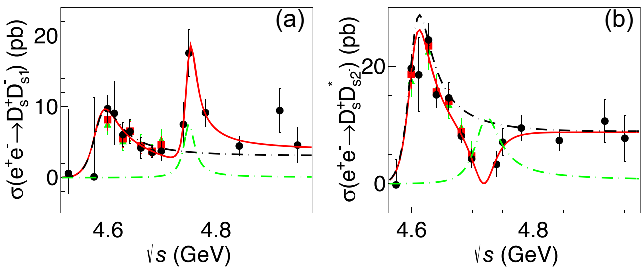

FIG. 3. Cross sections of (a) $e^+e^- \to D_s^+ D_{s1}(2536)^-$ with $D_{s1}(2536)^- \to \bar{D}^{*0}K^-$ and (b) $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$ with $D_{s2}^*(2573)^- \to \bar{D}^0 K^-$. The black dots, red squares, and green triangles with error bars are measured exclusive cross sections, inclusive cross section from likelihood fit multiplied by the absolute branching fraction, and measured inclusive cross section multiplied by the absolute branching fraction, respectively. The red solid, black dashed, and green dashed lines are results of total fit, BW_0, and BW_1, respectively. The uncertainties are statistical only. A larger format of plots can be found in Supplemental Material [25].

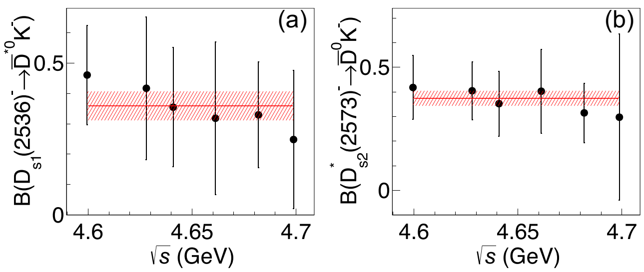

FIG. 4. The absolute branching fractions of (a) $D_{s1}(2536)^- \to \bar{D}^{*0}K^-$ and (b) $D_{s2}^*(2573)^- \to \bar{D}^0 K^-$. The black dots with error bars are absolute branching fractions calculated at each $\sqrt{s}$, where $\mathcal{B}_{i,j} = \sigma_{i,j}^{\rm exc}/\sigma_{i,j}^{\rm inc}$. The red lines represent results calculated by the maximum likelihood fit. The uncertainties are statistical only and are shown with the red shaded bands.

the first uncertainties are statistical and the second systematic. The phase ϕ between the two BW functions is $(0.4 \pm 0.4 \pm 1.1)$ rad for the fit shown in Fig. 3(a) and $(-1.5 \pm 0.2 \pm 0.0)$ rad for the other fit solution, while it is $(-1.7 \pm 0.3 \pm 0.0)$ rad for the fit result shown in Fig. 3(b). The fit details and systematic uncertainty estimations are described in supplemental material [25]. By comparing $\Delta\chi^2$ of the fits with and without the corresponding component and accounting for Δndf, the significance is determined. The statistical significances of BW_0 and BW_1 are 7.2σ and 4.3σ, respectively, in $e^+e^- \to D_s^+ D_{s1}(2536)^-$, and 15σ and 2.7σ, respectively, in $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$. Continuum contributions are also tested, but the significances are less than 1σ in both processes.

The systematic uncertainties for the measurements of absolute branching fractions related to fits, including signal and background descriptions and fit ranges in the fits of inclusive and exclusive analyses, are described in Supplemental Material [25]. The other systematic uncertainties are introduced below.

The systematic uncertainties from the mass window requirement of $M(D_s^+)$ $[RM(D_s^+K^-)]$ are estimated by comparing the efficiency difference between data and MC simulation [43] as 3.4% and 5.5% (4.3% and 4.3%), for $D_{s1}(2536)^- \to \bar{D}^{*0}K^-$ and $D_{s2}^*(2573)^- \to \bar{D}^0K^-$, respectively.

The systematic uncertainties from tracking (particle identification, PID) efficiencies for $K^\pm$ and π^+ from D_s^+ are taken as 0.5% (0.5%) and 0.2% (0.4%), respectively [17]. The systematic uncertainty from K_S^0 reconstruction is assigned as 2.3% [44]. Most of these uncertainties cancel in the D_s^+ reconstruction as they appear in both inclusive and exclusive processes. Only those uncertainties not common between the two are considered, and the systematic uncertainties from $D_s^+ \to K^-K^+\pi^+$ and $D_s^+ \to K_S^0 K^+$ are added according to their branching fractions. Since the momentum of the bachelor K^- that does not come from D_s^+ decays in the exclusive analysis is very low, the systematic uncertainties of this K^- are estimated with a control sample of $J/\psi \to pK^-\Lambda$ [45] as 1.2% and 0.0% for $D_{s1}(2536)^- \to \bar{D}^{*0}K^-$ and $D_{s2}^*(2573)^- \to \bar{D}^0K^-$, respectively.

The uncertainties of $\mathcal{B}(D_s^+ \to K^-K^+\pi^+)$ and $\mathcal{B}(D_s^+ \to K_S^0K^+)$ are 1.9% and 2.4% [6], respectively. The systematic uncertainty from $\mathcal{B}(D_s^+ \to K^-K^+\pi^+)$ cancels out in the calculation of the absolute branching fractions but does not cancel in the exclusive cross section measurements.

The fractions of the S wave and D wave of the $D_{s1}(2536)^- \to \bar{D}^{*0}K^-$ decay are changed by 1 standard deviation [34], and the systematic uncertainty is estimated by the maximum change at $\sqrt{s} = 4.680$ GeV on the exclusive cross section as 0.2%.

The total systematic uncertainties are 9.7% and 12.4% for the two processes, respectively, by assuming all sources to be independent and summing them in quadrature.

Most systematic uncertainty estimations for the exclusive cross section measurements are the same as those described for the absolute branching fraction measurements, including the mass window requirements, $\mathcal{B}(D_s^+ \to K^-K^+\pi^+)$ and $\mathcal{B}(D_s^+ \to K_S^0K^+)$, the fraction of the S wave and D wave in the $D_{s1}(2536)^- \to \bar{D}^{*0}K^-$ decay, and tracking and PID efficiencies, where 1.9% is assigned for tracks from D_s^+ for both processes. Systematic uncertainties related to the fit, including the fit range and background shape, are described in Supplemental Material [25]. Additional sources of systematic uncertainties unique to the exclusive cross section measurement are described below.

The angular distribution of $e^+e^- \to D_s^+ D_{s1}(2536)^-$ is described by $1 + \alpha\cos^2\theta$ with the AngSam model. To estimate the systematic uncertainty from this model, α is changed by 1 standard deviation and the maximum change at $\sqrt{s} = 4.680$ GeV is taken as the uncertainty of 3.3%.

TABLE I. Systematic uncertainties (%) in the cross sections for $e^+e^- \to D_s^+ D_{s1}(2536)^-$. The source marked with "*" are from fit procedure. Exact value for $\sqrt{s}$ is shown in Supplemental Material [25].

$\sqrt{s}$ (GeV)	4.600	4.610	4.620	4.640	4.660	4.680	4.700	4.740	4.750	4.780	4.840	4.914	4.946
Background shape [exc: $RM(D_s^+)$]*	4.7	3.6	9.2	6.1	5.9	0.4	0.6	0.4	8.1	6.0	6.8	8.2	13.4
Tracking PID (K^- not from D_s^+)	1.7	1.5	1.4	1.6	1.3	1.2	1.1	0.9	0.9	0.8	0.8	0.8	0.8
ISR	1.4	3.5	3.6	1.9	2.2	1.7	2.0	3.2	1.1	1.0	0.9	0.4	2.3
Independent on $\sqrt{s}$	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
Total	9.2	9.2	12.5	10.1	10.0	7.9	8.0	8.3	11.2	9.8	10.3	11.2	15.6

TABLE II. Same as Table I for $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$.

$\sqrt{s}$ (GeV)	4.600	4.610	4.620	4.640	4.660	4.680	4.700	4.740	4.750	4.780	4.840	4.914	4.946
Background shape (exc: $RM(D_s^+)$)*	3.0	6.5	5.4	13.4	5.5	8.8	7.0	2.5	4.1	7.2	13.0	46.3	25.8
Tracking PID (K^- not from D_s^+)	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.0	0.1	0.1
ISR	1.0	2.7	1.1	1.3	0.8	1.2	2.9	5.3	2.5	0.7	0.6	0.6	1.6
Independent on $\sqrt{s}$	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9
Total	8.5	10.6	9.7	15.6	9.7	11.9	11.0	9.9	9.3	10.7	15.2	47.0	27.0

The ISR correction factor and efficiency of the signal process depend on the input cross section in KKMC. We sample the input cross section 500 times at each $\sqrt{s}$ according to its statistical uncertainty, and take the ratio of the standard deviation and the mean value of $\epsilon(1+\delta)$ as the systematic uncertainty. The uncertainty from the luminosity measurement is 1% [23,24].

The systematic uncertainties are shown in Tables I and II. The systematic uncertainties of the data sample at $\sqrt{s} = 4.600$ GeV are assigned to those of the data samples at $\sqrt{s} = 4.530$ and 4.575 GeV because of low statistics.

In summary, we measure for the first time the absolute branching fractions of $D_{s1}(2536)^- \to \bar{D}^{*0}K^-$ and $D_{s2}^*(2573)^- \to \bar{D}^0 K^-$ as $(35.9 \pm 4.8 \pm 3.5)\%$ and $(37.4 \pm 3.1 \pm 4.6)\%$, respectively, where the first uncertainties are statistical and the second systematic. Our measurements will stimulate discussions on the nature of the four strange-charmed states. The exclusive cross sections of $e^+e^- \to D_s^+ D_{s1}(2536)^-$ with $D_{s1}(2536)^- \to \bar{D}^{*0}K^-$ and $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$ with $D_{s2}^*(2573)^- \to \bar{D}^0 K^-$ are also reported in this Letter. A resonant structure at around 4.6 GeV is observed for the first time in $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$, which is consistent with the evidence for the $Y(4620)$ with the same final state reported by the Belle collaboration [19]. A clear enhancement at around 4.6 GeV is also observed in $e^+e^- \to D_s^+ D_{s1}(2536)^-$, which could be the $Y(4626)$ state observed by the Belle collaboration [18] in the same final state. Our data may indicate that the same state at around 4.6 GeV decays into both $D_s^+ D_{s1}(2536)^-$ and $D_s^+ D_{s2}^*(2573)^-$ final states. Evidence for a peaking activity at around 4.75 GeV is observed, which may be the $Y(4710)$ or $Y(4790)$ reported earlier by the BESIII experiment [16,17].

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