Very recently the LHCb Collaboration has released a new observation of an excess around 2.86 GeV in the $\bar{B}^0 K^-$ invariant mass spectrum of $\bar{B}^0 \to \bar{B}^0 K^\ast$, which can be an admixture of spin-1 and spin-3 resonances corresponding to $D_{sJ}(2860)$ and $D_{sJ}^{*}(2860)$, respectively. As indicated by LHCb, it is the first time to identify a spin-3 resonance. In addition, $D_{sJ}^{*}(2573)$ also appears in the the $\bar{B}^0 K^-$ invariant mass spectrum.

Before this observation, a charmed-strange state $D_{sJ}(2860)$ was reported by BaBar in the $D K$ channel \cite{2}, where the mass and width are $m = 2856.6 \pm 1.5 \pm 5.0$ MeV and $\Gamma = 47 \pm 7 \pm 10$ MeV \cite{2}, respectively, which was later confirmed by BaBar in the $D^* K$ channel \cite{4}. The $D_{sJ}(2860)$ has stimulated extensive discussions on its underlying structure. In Ref. \cite{5}, $D_{sJ}(2860)$ is suggested as a $1^{2}D_{1}$ $c\bar{s}$ meson. This explanation was also supported by study of the Regge phenomenology \cite{6}, constituent quark model \cite{7} and mass loaded flux tube model \cite{8}. The ratio $\Gamma(D_{sJ}(2860) \to D^* K)/\Gamma(D_{sJ}(2860) \to D K)$ was calculated to be 0.36 \cite{12} by the effective Lagrangian method. However, the calculation by the QPC model shows that such a ratio is about 0.8 \cite{11}, which is close to the experimental value $1.10 \pm 0.15 \pm 0.19$ \cite{4}. Thus, $J^{P} = 3^{-}$ assignment to $D_{sJ}(2860)$ is a possible explanation. In addition, $D_{sJ}(2860)$ as a mixture of charmed-strange states was given in Refs. \cite{7,8,11}. $D_{sJ}(2860)$ could be a partner of $D_{sJ}(2710)$, where both $D_{sJ}(2860)$ and $D_{sJ}(2710)$ are a mixture of $2^{3}S_{1}$ and $1^{3}D_{1}$ $c\bar{s}$ states. By introducing such a mixing mechanism, the obtained ratio of $D^* K/D K$ for $D_{sJ}(2860)$ and $D_{sJ}(2710)$ \cite{11} is consistent with the experimental data \cite{2}. Reference \cite{12} indicates that there exist two overlapping resonances (radially excited $J^{P} = 0^{+}$ and $J^{P} = 2^{+}$ $c\bar{s}$ states) at 2.86 GeV. Besides the above explanations under the conventional charmed-strange meson framework, $D_{sJ}(2860)$ was explained as a multiquark exotic state \cite{13}.

Briefly reviewing the research status of $D_{sJ}(2860)$, we notice that more theoretical and experimental efforts on $D_{sJ}(2860)$ are still necessary to clarify the properties of $D_{sJ}(2860)$. It is obvious that the recent precise measurement of LHCb \cite{1,2} provides us a good chance to identify higher radial excitations in the charmed-strange meson family. The resonance parameters of the newly observed $D_{sJ}^{*}(2860)$ and $D_{sJ}^{*}(2860)$ by LHCb include \cite{1,2}:

\begin{align}
    m_{D_{sJ}^{*}(2860)} &= 2859 \pm 12 \pm 6 \pm 23 \text{ MeV}, \\
    \Gamma_{D_{sJ}^{*}(2860)} &= 159 \pm 23 \pm 27 \pm 72 \text{ MeV}, \\
    m_{D_{sJ}^{*}(2860)} &= 2860.5 \pm 2.6 \pm 2.5 \pm 6.0 \text{ MeV}, \\
    \Gamma_{D_{sJ}^{*}(2860)} &= 53 \pm 7 \pm 4 \pm 6 \text{ MeV},
\end{align}

where the errors are due to statistical one, experimentally systematic effects and model variations \cite{1,2}, respectively.

At present, there are good candidates for the 1S and 1P states in the charmed-strange meson family (see Particle Data Group for more details \cite{14}). Thus, two newly observed $D_{sJ}^{*}(2860)$ and $D_{sJ}^{*}(2860)$ can be categorized into the 1D charmed-strange states when considering their spin quantum numbers and masses. Before observation of these two resonances, there were several theoretical predictions \cite{15-18} of the mass spectrum of the 1D charmed-strange meson family, which are collected into Table I. Comparing the experimental data of $D_{sJ}^{*}(2860)$ and $D_{sJ}^{*}(2860)$ with the theoretical results, we notice that the masses of $D_{sJ}^{*}(2860)$ and $D_{sJ}^{*}(2860)$ are comparable with the corresponding theoretical predictions, which further supports that it is reasonable to assign $D_{sJ}^{*}(2860)$ and $D_{sJ}^{*}(2860)$ as the 1D states of the charmed-strange meson family.

Although both the mass spectrum analysis and the measurement of the spin quantum number support $D_{sJ}^{*}(2860)$ and $D_{sJ}^{*}(2860)$ as the 1D states, we still need to carry out a further test of this assignment through study of their decay behaviors. This study can provide more detailed information on the partial decay widths, which is valuable for future experimental investigation of $D_{sJ}^{*}(2860)$ and $D_{sJ}^{*}(2860)$. In addition, there exist four 1D states in the charmed-strange meson family. At
present, the spin partners of $D_s^*(2860)$ and $D_{s1}^*(2860)$ are still missing in experiment. Thus, we also predict the properties of two missing $1D$ states in this work.

Among all properties of these $1D$ states, their two-body Okubo-Zweig-Iizuka (OZI) allowed strong decays are the most important and typical properties. Hence, in the following we mainly focus on the study of their OZI-allowed strong decays. For the $1D$ states studied in this work, their allowed decay channels are listed in Table II. Among four $1D$ states in the charmed-strange meson family, there are two $J^P = 2^−$ states, which is a mixture of $1^1D_2$ and $1^3D_2$ states, i.e.,

$$\begin{pmatrix} 1D(2^-) \\ 1D′(2^-) \end{pmatrix} = \begin{pmatrix} \cos \theta_{1D} & \sin \theta_{1D} \\ -\sin \theta_{1D} & \cos \theta_{1D} \end{pmatrix} \begin{pmatrix} 1^1D_2 \\ 1^3D_2 \end{pmatrix},$$

(5)

where $\theta_{1D}$ is a mixing angle. Here, we take the conclusion based on the heavy quark limit, which gives the general mixing angle between $1^1L_1$ and $1^3L_1$ to be $\theta_L = \arctan(\sqrt{L}/(L + T))$, i.e., $\theta_{1D} = 39^\circ$ [19].

In the following, we apply the quark pair creation (QPC) model [20–26] to describe the OZI allowed two-body strong decays shown in Table III where the QPC model was extensively adopted to study the strong decay of hadrons [3, 27–37]. In the QPC model, we introduce the transition operation describing creation of quark and antiquark pair from the vacuum, where the details can be found in Refs. [20–26]. Then, the helicity amplitudes $M_{M_i,S_i,L_i,R}^k(K)$ of the OZI-allowed strong decay channels in Table III are calculated, which is the main task of the whole calculation, where the harmonic oscillator wave function $\Psi_{n_L,n_T}(R,K)$ is adopted to obtain the spatial integral in the transition matrix element. The parameters involved in the QPC model are the $R$ values and the strength $\gamma$ of the QPC from the vacuum. Here, the parameter $R$ in the harmonic oscillator wave function is obtained by reproducing the realistic root mean square radius. In Table III we list the $R$ values adopted in our calculation. The strength of $q\bar{q}$ is taken as $\gamma = 6.3$ while the strength of $s\bar{s}$ satisfies $\gamma_s = \gamma/\sqrt{3}$ [28]. In addition, the constituent quark masses for charm, up/down, and strange quarks are 1.60 GeV, 0.33 GeV, and 0.55 GeV, respectively [38].

| Channels | $D_{s1}^*(2860)$ | $1D(2^-)$ | $1D′(2^-)$ |
|----------|-----------------|-----------|-----------|
| $DK$     | o               | o         | o         |
| $D^*K$   | o               | o         | o         |
| $D_s\eta$| o               | o         | o         |
| $D_s'\eta$| o             | o         | o         |
| $DK^*$   | o               | o         | o         |
| $D_s(2400)\eta$ | o     | o | o |
| $D_s'(2317)\eta$ | o         | o         | o         |

TABLE II: The two-body OZI allowed decay modes of 1D charmed-strange mesons. Here, we use symbols, $o$ and $–$, to mark the OZI-allowed and -forbidden decay modes, respectively. $D_{s1}^*(2860)$ and $D_{s1}^*(2860)$ are $1^1D_s$ and $1^3D_s$ states, respectively.

| States | R mass | States | R mass |
|--------|--------|--------|--------|
| $D$    | 2.33   | 1677   | 2.70   | 2008   |
| $D_s$  | 1.92   | 1684   | 2.22   | 2112   |
| $K$    | 2.17   | 494    | 3.13   | 896    |

TABLE III: The $R$ values (in unit of GeV$^{-1}$) [35] and masses (in unit of MeV) [14] of the mesons involved in present calculation.

With the above preparation, we obtain the total and partial decay widths of $D_{s1}^*(2860)$, $D_{s1}^*(2860)$ and their spin partners, and comparison with the experimental data [1–2]. As shown in Table III the $R$ value of the $P$-wave charmed-strange meson is about 2.7 Gv$^{-1}$. For the $D$-wave state, the $R$ value is estimated to be around 3.00 GeV$^{-1}$ [38]. In present calculation, we varies the $R$ value for the $D$-wave charmed-strange meson from 2.4 to 3.6 GeV$^{-1}$. In Fig. I we present the $R$ dependence of the total and partial decay widths of $D_{s1}(2860)$ and $D_{s1}^*(2860)$.

$D_{s1}(2860)$: The total width of $D_{s1}(2860)$ as the $1^3D_1$ state is given in Fig. I where the total width is obtained as 128 $\sim$ 177 MeV corresponding the selected $R$ range, which is consistent with the experimental width of $D_{s1}(2860)$ ($\Gamma = 159 \pm 23 \pm 27 \pm 72$ MeV [1–2]). The information of the partial decay widths depicted in Fig. I also shows that $DK$ is dominant decay mode of the $1^3D_1$ charm strange meson, which explains why $D_{s1}(2860)$ was experimentally observed in its $DK$ decay channel [1–2]). In addition, our study also indicates that the $D^*K$ and $DK^*$ channels are also important for the $1^3D_1$ state, which have partial widths $35 \sim 44$ MeV and $24 \sim 40$ MeV, respectively. The $D_s\eta$ and $D_s'\eta$ channels have partial decay widths with several MeV, which is far smaller than the partial decay widths of the $DK$ and $D^*K$ channels.

Besides providing the partial decay widths, we also predict
several typical ratios, i.e.,
\[
\begin{align*}
\frac{\Gamma(D_{s1}(2860) \rightarrow D^*K)}{\Gamma(D_{s1}(2860) \rightarrow DK)} &= 0.46 \sim 0.70, \\
\frac{\Gamma(D_{s1}(2860) \rightarrow D^*K^*)}{\Gamma(D_{s1}(2860) \rightarrow DK)} &= 0.25 \sim 0.85, \\
\frac{\Gamma(D_{s1}(2860) \rightarrow D_{s1}K)}{\Gamma(D_{s1}(2860) \rightarrow D_{s1}K)} &= 0.10 \sim 0.14,
\end{align*}
\]
which can be further tested in the coming experimental measurements.

The above results show that \(D_{s1}(2860)\) can be a good candidate for the \(1^3D_1\) charmed-strange meson.

\(D_{s1}(2860)\): The two-body OZI-allowed decay behavior of \(D_{s1}(2860)\) as the \(1^3D_1\) charmed-strange meson is presented in the right panel of Fig. 1, where the obtained total width can reach up to 42 \sim 60 \text{ MeV}, which overlaps with the LHCb’s data (53 \pm 7 \pm 4 \pm 6 \text{ MeV} [1, 2]). This fact further reflects that \(D_{s1}(2860)\) is suitable for the \(1^3D_1\) charmed-strange meson. Similar to \(D_{s1}(2860)\), the \(DK\) channel is also the dominant decay mode of \(D_{s1}(2860)\), where the partial decay width of \(D_{s1}(2860) \rightarrow DK\) is 25 \sim 30 \text{ MeV} in the selected \(R\) value range. Additionally, we also calculate the partial decay width of \(D_{s1}(2860) \rightarrow D^*K\) and \(D_{s1}(2860) \rightarrow DK^*\), which are 14 \sim 24 \text{ MeV} and 0.9 \sim 2.5 \text{ MeV}, respectively. The partial decay widths for \(D_{s1}K\) and \(D_{s1}K^*\) channel are of order of 0.1 MeV. The corresponding typical ratios for \(D_{s1}(2860)\) are
\[
\begin{align*}
\frac{\Gamma(D_{s1}(2860) \rightarrow D^*K)}{\Gamma(D_{s1}(2860) \rightarrow DK)} &= 0.55 \sim 0.80, \\
\frac{\Gamma(D_{s1}(2860) \rightarrow D^*K^*)}{\Gamma(D_{s1}(2860) \rightarrow DK)} &= 0.03 \sim 0.09, \\
\frac{\Gamma(D_{s1}(2860) \rightarrow D_{s1}K)}{\Gamma(D_{s1}(2860) \rightarrow D_{s1}K)} &= 0.018 \sim 0.020,
\end{align*}
\]
which can be tested in future experiment.

\(1D(2^-)\) and \(1D'(2^-)\): In the following, we discuss the decay behaviors of two missing \(1D\) states in the present experiment, which is crucial to the experimental search for the \(1D(2^-)\) and \(1D'(2^-)\) states.

We present the \(R\) value dependence of the total and partial decay widths of the two experimentally missing \(2^-\) states in Fig. 2. Since these two \(1D\) states have not yet been seen in experiment, we take the mass range 2850 \sim 2950 \text{ MeV}, which covers the theoretically predicted masses of the \(1D(2^-)\) and \(1D'(2^-)\) states from different groups listed in Table II to discuss the decay behaviors of the \(1D(2^-)\) and \(1D'(2^-)\) states.

As for the \(1D(2^-)\) state, the estimated total decay width varies from 90 \text{ MeV} to 190 \text{ MeV}, which is due to the uncertainty of the predicted mass of the \(1D(2^-)\) state and the \(R\) value dependence as mentioned above. If the mass of the \(1D(2^-)\) state can be constrained by future experiment, the uncertainty of the total width for the \(1D(2^-)\) state can be reduced. In any case, our study indicates that the \(1D(2^-)\) state has a broad width.

Additionally, as shown in Fig. 2 the \(1D(2^-)\) state can dominantly decay into \(D^*K\), where \(\mathcal{B}(1D(2^-) \rightarrow D^*K) = (77 \sim 87)\%\), and \(DK\) and \(D_{s1}K\) are its main decay modes. Comparing \(D^*K\) and \(D_{s1}K\) with each other, \(D_{s1}K\) is the subordinate decay channel. Hence, we suggest experimental search for the \(1D(2^-)\) state firstly via the \(D^*K\) channel.

We also obtain two typical ratios, i.e.,
\[
\begin{align*}
\frac{\Gamma(1D(2^-) \rightarrow DK^*)}{\Gamma(1D(2^-) \rightarrow D^*K)} &= 0.11 \sim 0.36 \\
\frac{\Gamma(1D(2^-) \rightarrow D_{s1}K)}{\Gamma(1D(2^-) \rightarrow D^*K)} &= 0.11 \sim 0.18,
\end{align*}
\]
which can be accessible at experiment.

As for the \(1D'(2^-)\) state, we predict its total decay width \((80 \sim 240) \text{ MeV}\), which shows that the \(1D'(2^-)\) state is also a broad resonance, where \(DK^*\) is its dominant decay mode with a branching ratio \(\mathcal{B}(1D'(2^-) \rightarrow DK^*) = (0.64 \sim 0.73)\%\). Its main decay mode includes \(D^*K\), while \(1D' \rightarrow D_{s1}K\) and \(1D' \rightarrow D_{s1}(2400)K\) have small partial decay widths.
the above information, two typical ratios are listed as below

$$\frac{\Gamma(1D'(2^-) \to D^* K)}{\Gamma(1D'(2^-) \to D^* \eta)} = 0.36 \sim 0.53, \quad (14)$$

$$\frac{\Gamma(1D'(2^-) \to D' \eta)}{\Gamma(1D'(2^-) \to D' K^*)} = 0.004 \sim 0.013. \quad (15)$$

It should be noticed that the threshold of $D'_{s0}(2317)\eta$ is 2865 MeV and two 1D charmed-strange mesons with $J^P = 2^-$ decaying into $D'_{s0}(2317)\eta$ occur via $D-$wave. Thus, $1D(2^-)/1D'(2^-) \to D'_{s0}(2317)\eta$ is suppressed, which is supported by our calculation since the corresponding partial decay widths are of the order of a few KeV for $1D(2^-) \to D'_{s0}\eta$ and of the order of 0.1 KeV for $1D'(2^-) \to D'_{s0}\eta$.

**Summary:** With the observation of two charmed-strange resonances $D_{s1}(2860)$ and $D_{s3}(2860)$, which was recently announced by the LHCb Collaboration [1,2], the observed charmed-strange states become more and more abundant. In this work, we have carried out the study of the observed $D_{s1}(2860)$ and $D_{s3}(2860)$, which indicates that $D_{s1}(2860)$ and $D_{s3}(2860)$ can be well categorized as $1^3D_1$ and $1^3D_3$ states in the charmed-strange meson family since the experimental widths of $D_{s1}(2860)$ and $D_{s3}(2860)$ can be reproduced by the corresponding calculated total widths of the $1^3D_1$ and $1^3D_3$ states. In addition, the result of their partial decay widths shows that the $DK$ decay mode is dominant both for $1^3D_1$ and $1^3D_3$ states, which naturally explains why $D_{s1}(2860)$ and $D_{s3}(2860)$ were first observed in the $DK$ channel. If $D_{s1}(2860)$ and $D_{s3}(2860)$ are the $1^3D_1$ and $1^3D_3$ states, respectively, our study also indicates that the $D^*K$ and $DK^*$ channels are the main decay mode of $D_{s1}(2860)$ and $D_{s3}(2860)$, respectively. Thus, we suggest for future experiment to search for $D_{s1}(2860)$ and $D_{s3}(2860)$ in these main decay channels, which can not only test our prediction presented in this work but also provide more information of the properties of $D_{s1}(2860)$ and $D_{s3}(2860)$.

As the spin partners of $D_{s1}(2860)$ and $D_{s3}(2860)$, two 1D charmed-strange mesons with $J^P = 2^-$ are still missing in experiment. Thus, in this work we also predict the decay behaviors of these two missing 1D charmed-strange mesons. Our calculation by the QPC model shows that both $1D(2^-)$ and $1D'(2^-)$ states have very broad widths. For the $1D(2^-)$ and $1D'(2^-)$ states, their dominant decay mode is $D^*K$ and $DK^*$, respectively. In addition, $DK^*$ and $D'K^*$ are also the important decay modes of the $1D(2^-)$ and $1D'(2^-)$ states, respectively. This investigation provides valuable information when further experimentally exploring these two missing 1D charmed-strange mesons.

In summary, the observed $D_{s1}(2860)$ and $D_{s3}(2860)$ provide us a good opportunity to establish higher states in the charmed-strange meson family. The following experimental and theoretical efforts are still necessary to reveal the underlying properties of $D_{s1}(2860)$ and $D_{s3}(2860)$. Furthermore, it is a challenging research topic for future experiment to hunt the two predicted missing 1D charmed-strange mesons with $J^P = 2^-$.  

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In present work, we do not consider the mixture between the $2S_1$ and $1D_1$ states, which can be discussed in future work.