# Unveiling the Nature of the Tetraquark Candidate $Z_c(3900)$

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One of the most important subjects in hadron physics is to establish the existence of exotic hadrons different from the standard quark-antiquark mesons and three-quark baryons. Such exotic candidates include the pentaquark candidates $P_c(4380)$ and $P_c(4450)$ observed by the LHCb Collaboration [1] and the tetraquark state $Z_c(3900)$ reported by the BESIII [2] and the Belle [3] Collaborations. The $Z_c(3900)$, in particular, is observed as a peak in $\pi J/\psi$ and $\bar{D}D^*$ invariant masses of $e^+e^- \rightarrow Y(4260) \rightarrow \pi\pi J/\psi$ and $\pi\bar{D}D^*$ reactions.

Various phenomenological attempts [4] have been made to understand the nature of $Z_c(3900)$ as a compact tetraquark and a s-wave hadronic molecule as well as a threshold cusp when opening the $\bar{D}D^*$ threshold. However, no conclusive result has been achieved due to the lack of information about the coupled-channel interaction relevant to $Z_c(3900)$. (See Fig. 1 for the level structure.)

In this circumstance, the first principle lattice QCD calculations with explicit channel couplings is the most desirable method to determine the structure of $Z_c(3900)$. The HAL QCD Collaboration [5] extracts the s-wave diagonal and off-diagonal potentials among the $\pi J/\psi$, $\rho\eta_c$ and $\bar{D}D^*$ channels by the so-called coupled-channel HAL QCD method [6]. The key quantity in the HAL QCD method is the Nambu-Bethe-Salpeter (NBS) wave functions, which are faithful to the QCD S-matrix, and thus we are able to calculate any scattering observables directly based on QCD using the extracted coupled-channel potential from the NBS wave functions.

It has been found that the resulting diagonal elements of the s-wave coupled-channel potential are all weak. This indicates that $Z_c(3900)$ is not a state associated with a hadronic molecule. Also, the off-diagonal $\pi J/\psi$-$\rho\eta_c$ potential is weak. This is a consequence of the heavy quark spin symmetry. On the other hand, the off-diagonal elements of the $\pi J/\psi$-$\bar{D}D^*$ and the $\rho\eta_c$-$\bar{D}D^*$ are found to be strong.

With the above coupled-channel potential, we have calculated the scattering amplitudes in two-body $\pi J/\psi$, $\rho\eta_c$ and $\bar{D}D^*$ channels by solving the Lippmann-Schwinger equation. In two-body amplitudes, the peak appears around the $\bar{D}D^*$ threshold. We also have examined the complex pole of the amplitudes to understand whether the peak structure is associated with a conventional resonance or not. The result of the pole position is shown in Fig. 2. The pole is far below the $\bar{D}D^*$ threshold and has a large imaginary part; thus, the pole does not contribute to the amplitudes. In addition to the above analyses of the two-body scatterings, we have investigated Y(4260) decay and compared it with the experiments. As shown in Fig. 3, the peak observed in the experiments is well reproduced. Therefore we conclude that the $Z_c(3900)$ is not a conventional resonance but a threshold cusp when opening the $\bar{D}D^*$ threshold [7].

In summary, thanks to the coupled-channel HAL QCD method, it turns out that $Z_c(3900)$ is not a conventional resonance but a threshold cusp just opening the $\bar{D}D^*$ threshold assisted by the strong $\pi J/\psi$-$\bar{D}D^*$ coupling: the pole position is far below the $\bar{D}D^*$ threshold, and the Y(4260) decay is well reproduced. The novel method developed in this study paves the way to understand the nature of exotic hadron candidates directly based on QCD. Some interesting future targets include $P_c$'s, X(3872) and $Z_c(4430)$.

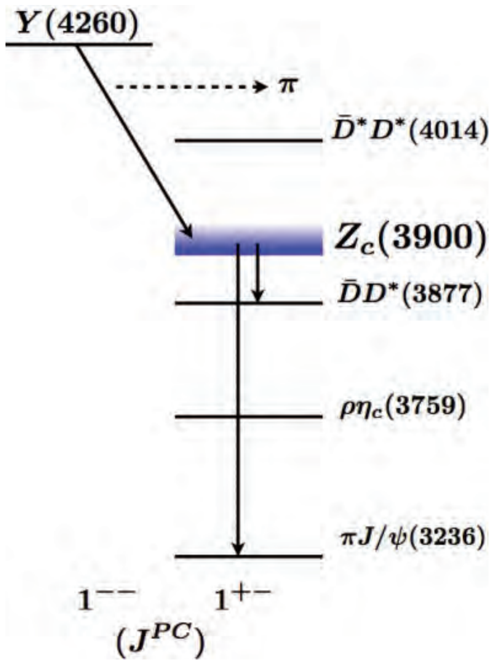


**Fig. 1:** Decay scheme of the $Z_c(3900)$ and the relevant two-meson threshold energy.

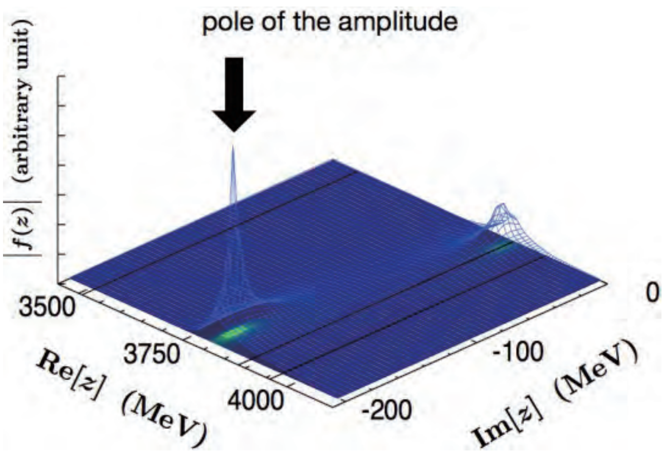


**Fig. 2:** The pole of the amplitude on the complex energy plane.

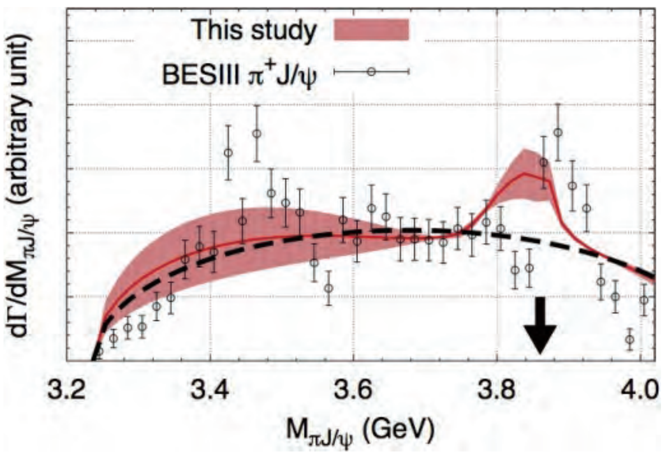


**Fig. 3:** The $\pi J/\psi$ invariant mass spectrum of the Y(4260) decay. The statistical error of the simulation is included in the shaded area. The dashed curve represents the invariant mass spectrum, when the off-diagonal potential is switched off.

**Acknowledgements:** This work is supported in part by MEXT as a "Priority Issue on Post-K computer" (Elucidation of the Fundamental Laws and Evolution of the Universe) and SPIRE (Strategic Program for Innovative REsearch).

### *References*


[1] R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 115, 072001 (2015).
[2] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 110, 252001 (2013).
[3] Z.Q. Liu et al. (Belle Collaboration), Phys. Rev. Lett. 110, 252002 (2013).
[4] M. B. Voloshin, Phys. Rev. D 87, 091501 (2013); D. Y. Chen, X. Liu and T. Matsuki, Phys. Rev. D 88, 036008 (2013).
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[6] N. Ishii, S. Aoki and T. Hatsuda, Phys. Rev. Lett. 99, 022001 (2007); S. Aoki et al. (HAL QCD Collaboration), PTEP 2012, 01A105 (2012).
[7] Y. Ikeda et al. (HAL QCD Collaboration), Phys. Rev. Lett. 117, 242001 (2016).


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