EXOTIC QUARKONIUM SPECTROSCOPY: 
X(3872), Z_b(10610), AND Z_b(10650) IN NON-RELATIVISTIC EFFECTIVE THEORY

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This talk summarizes recent developments in quarkonium spectroscopy. I comment on the relation between the Z_b(10610) and Z_b(10650) and recently observed Z_c(3900) and Z_c(4025) states. Then I discuss a number of calculations using non-relativistic effective field theory for the X(3872), Z_b(10610), and Z_b(10650), under the assumption that these are shallow molecular bound states of charm or bottom mesons.

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1. Recent Experimental Developments

The last decade has seen an explosive growth in the field of heavy quarkonium spectroscopy. Below the threshold for open charm and open bottom, the spectrum and transitions of experimentally observed heavy quarkonium states are well-described by the conventional quark model. Beginning in 2003 with the discovery of the X(3872) experiments around the world have been discovering many states above the open charm and open bottom thresholds which are not explained by the non-relativistic quark model. One of the most exciting developments in the last couple of years has been the discovery of manifestly exotic bottomonia, Z_b(10610) and Z_b(10650) (denoted Z_b and Z'_b, respectively, below), as well as manifestly exotic charmonia, Z_c(3900) and Z_c(4025).

The Z_b and Z'_b were discovered in the three-body decays Υ(5S) → Υ(nS)π^+π^−, n = 1, 2, and 3, and Υ(5S) → h_b(mP)π^+π^−, m = 1, 2, where they were seen as resonances in Υ(nS)π^± and h_b(nS)π^±. More recently, neutral partners of the Z_b and Z'_b have also been observed. These states have isospin-1 and in some cases electric charge, therefore they are quite clearly not conventional b̅b mesons. Since the Z_b and Z'_b lie within a few MeV of the B B^* and B^* B^* thresholds, respectively, it is tempting to speculate they are molecular in character. The molecular hypothesis makes an interesting prediction for the spin structure of these states. Assuming these are S-wave molecular states, then writing the quark model wave functions in
a basis of states in which the heavy $b\bar{b}$ have definite total spin, $S_{bb}$, one finds that the $Z_b$ and $Z'_b$ are equal mixtures of $S_{bb}^S = 0$ and $S_{bb}^S = 1$. This is consistent with the fact that $Z_b$ and $Z'_b$ couple with approximately equal strength to final states with $\Upsilon(nS)(S_{bb}^S = 1)$ and $h_c(mP)(S_{bb}^S = 0)$. Furthermore, the wave functions of the $Z_b$ and $Z'_b$ are orthogonal, i.e., the relative phase of the $S_{bb}^S = 0$ and $S_{bb}^S = 1$ components has the opposite sign in the $Z_b$ and $Z'_b$. A consequence of this is that if one examines the $\Upsilon(nS)\pi$ and $h_c(mP)\pi$ invariant mass distribution between the two resonances, one expects destructive interference for $\Upsilon(nS)\pi^+\pi^-$ and constructive interference for $h_c(mP)\pi^+\pi^-$. This qualitative expectation is in agreement with the observed invariant mass distributions, and is strong evidence for the proposed heavy quark spin structure.

The $Z_c(3900)$ is seen in $e^+e^- \rightarrow \Upsilon(4260) \rightarrow J/\psi\pi^+\pi^-$ and appears as a pronounced peak in the $J/\psi\pi^\pm$ spectrum. It is noteworthy that this is the first manifestly exotic state that has been observed by three different experiments. The $Z_c(4025)$ has been seen by the BESIII experiment in $e^+e^- \rightarrow (D^*\bar{D}^*)^{\pm}\pi^\pm$ and in $e^+e^- \rightarrow h_c\pi^+\pi^-$. In the latter process it appears as a resonance in $h_c\pi^\pm$. The central values of the widths of the states extracted from these two measurements differ by a factor of three, so it is far from clear that these are the same state. Various interpretations of the $Z_c(3900)$ have been put forward. Some authors regard it as a charm meson molecule and hence the charm analog of the $Z_b$ and $Z'_b$. Other possibilities include various kinds of tetraquarks: diquarkonium, hadrocharmonium and Born-Oppenheimer (B-O) tetraquark. These tetraquark models differ in how the quarks pair in the state. For example, in diquarkonium the quarks (antiquarks) pair into antitriplets (triplets) of $SU(3)$, which are then combined into a color-singlet. In hadrocharmonium, the heavy charm and anticharm quarks are bound into a compact color-singlet configuration with the light quark and antiquark surrounding them. In the B-O tetraquark, the heavy quark and antiquark are separated in a color-octet state. The light quark and antiquark play the role that an excited gluon plays in a hybrid meson and are also in a color-octet state. Most of these models predict $J^P = 1^+$ quantum numbers for the $Z_c(3900)$, the notable exception being the B-O tetraquark, which predicts $J^P = 1^-$. A recent BESIII measurement of the angular distributions in $e^+e^- \rightarrow (D^*\bar{D}^*)^{\pm}\pi^\pm$ favors $J^P = 1^+$ and disfavors $J^P = 0^-$ or $1^-$, casting doubt on the B-O tetraquark interpretation.

Though it is tempting to identify the $Z_c(3900)$ as the charm analog of $Z_b$, there are important differences. The mass is roughly 20 MeV above the $DD^*$ threshold so the $Z_c(3900)$ is much farther away from its threshold than the $Z_b$. Also the $Z_c(3900)$ couples strongly only to $J/\psi\pi^\pm$ and has not been observed in $e^+e^- \rightarrow h_c\pi^+\pi^-$. Furthermore, the $Z_c(4025)$ has only been seen decaying to $h_c\pi^\pm$ and not $J/\psi\pi^\pm$. So the heavy quark spin structures of the $Z_c(3900)$ and $Z_c(4025)$ appear to be quite different than those of the $Z_b$ and $Z'_b$. Perhaps this could be attributed to large violations of heavy quark spin symmetry. In addition to measuring the $J^P$ quantum numbers, measurement of relative rates to para- and ortho-charmonium, measure-
ments of rates to $D\bar{D}^*$ final states, and searches for partner states predicted in
tetraquark models should shed light on the nature of the $Z_c(3900)$ and $Z_c(4025)$.

2. $X(3872)$, $Z_b$ and $Z_b'$ in Non-Relativistic Effective Theory

The $X(3872)$ was discovered as a resonance in $J/\psi\pi^+\pi^-$, and has also been observed
to decay to $J/\psi\pi^+\pi^-\pi^0$, $J/\psi\gamma$, $D^0\bar{D}^0\pi^0$, and $D^0\bar{D}^0\gamma$. It is very narrow: $\Gamma_X < 1.2$ MeV. A recent LHCb analysis of angular distributions in $X(3872) \rightarrow J/\psi\pi^+\pi^-$ conclusively determines the $X(3872)$ quantum numbers to be $J^{PC} = 1^{++}$ which means it couples to $D\bar{D}^*$ in an $S$-wave. The roughly equal rates for $X(3872) \rightarrow J/\psi\pi^+\pi^-\pi^0$ and $X(3872) \rightarrow J/\psi\pi^+\pi^-\pi^0$ suggest it is a state of mixed isospin-1 and isospin-0. Finally, the $X(3872)$ lies extremely close to the $D^0\bar{D}^*0$ threshold: $m_{X(3872)} - m_{D^0} - m_{D^*0} = -0.17 \pm 0.26$ MeV. These facts taken together strongly suggest that the $X(3872)$ is a very shallow bound state of $D^0\bar{D}^*0 + c.c.$. The tiny binding energy implies that the typical separation of the $D^0$ and $\bar{D}^*$ in the $X(3872)$ is of order several fermi, which is much larger than the range of the interaction binding the charmed mesons. In such a situation, the long-distance part of the wave function of the $D\bar{D}^*$ is known from quantum mechanics, and one can exploit effective range theory (ERT) to compute long-distance properties of the $X(3872)$ in terms of the binding energy and known properties of the charmed mesons.

XEFT is a low energy effective field theory (EFT) of nonrelativistic charm mesons and pions that can be used to systematically analyze the properties of the $X(3872)$. For processes such as $X(3872) \rightarrow D^0\bar{D}^*0$ that are dominated by long distance scales, XEFT reproduces the results of ERT at leading order. These calculations can be improved by including range corrections, higher dimension operators, and pion exchange. Pion exchange was shown to give negligibly small corrections to $X(3872) \rightarrow D^0\bar{D}^*\pi^0$. Predictions for other universal processes include $D^+\bar{D}^*0 \rightarrow X(3872)\pi^+$ and $D^{(*)}X(3872) \rightarrow D^{(*)}X(3872)$ scattering. XEFT can also be used to study decays to quarkonia, such as $X(3872) \rightarrow \chi_{cJ}\pi$ where relative rates for final states with different $J$ can be predicted, and the radiative decays $X(3872) \rightarrow \psi(2S)\gamma$, $\psi(4040)$, $X(3872)\gamma$, and $\psi(4160)$, $X(3872)\gamma$. In the XEFT approach to these decays, the decay rate is written as, for example,

$$\Gamma[X(3872) \rightarrow \psi(2s)\gamma] = |\psi_{DD}(0)|^2 \times \sigma[D^0\bar{D}^*0 + c.c. \rightarrow \psi(2S)\gamma],$$

where $|\psi_{DD}(0)|^2$ is an XEFT matrix element that can be interpreted as the wave function of the charm mesons at the origin squared, and the cross section $\sigma[D^0\bar{D}^*0 + c.c. \rightarrow \psi(2S)\gamma]$ is calculated at tree level in heavy hadron chiral perturbation theory. In this approach, there are two distinct types of diagrams contributing to $D^0\bar{D}^*0 + c.c. \rightarrow \psi(2S)\gamma$: a) diagrams with a virtual meson exchange, and b) short-distance contributions coming from contact interactions. See Fig. 1 of Ref. 25 for examples of these diagrams. The relative importance of these two mechanisms depends on an unknown coupling constant, and angular distributions in the decays can discriminate between these two mechanisms. It is impossible to
compute absolute rates because $|\psi_{DD}(0)|^2$ as well as coupling constants in the EFT are unknown. An alternative approach \cite{27} is to add explicit fields for the quarkonium and the $X(3872)$ and compute the decay rate from a triangle diagram with heavy mesons in the loop that couple to the $X(3872)$, the quarkonium, and the photon. The triangle diagram is finite, so if possible contact interactions \cite{28} are neglected and if various hadronic couplings are known, then this model is predictive. The radiative decays of $1^{--}$ quarkonia to $X(3872)$ were considered in this approach \cite{27}, and an enhanced rate for $Y(4260) \rightarrow X(3872)\gamma$ was predicted, under the assumption the $Y(4260)$ is a $D_1-D$ molecule. Recently, BESIII \cite{29} has observed $e^+e^- \rightarrow X(3872)\gamma$ for the first time at the center-of-mass energies 4.229 GeV and 4.260 GeV, but not at 4.009 GeV and 4.360 GeV. It seems likely that the $X(3872)$ is being produced in the radiative decay of the $Y(4260)$ but the experiment cannot rule out continuum production with current data. All calculations in XEFT so far neglect the contribution of charged $D$ mesons. However, model calculations \cite{30} show loops with charged $D$ mesons can be quite important. In the future, XEFT calculations will have to be performed that include explicit charged charmed mesons.

An effective theory similar to XEFT can be applied to the $Z_b$ and $Z'_b$ \cite{31,32,33}. Voloshin \cite{34} has argued that heavy quark spin symmetry predicts partners of the $Z_b$ and $Z'_b$ which have yet to be observed, and makes heavy quark symmetry predictions for the spectroscopy of these states as well as for their transitions. EFT can be used to reproduce these results, obtain new heavy quark symmetry predictions, and do explicit calculations of the two-body decays of the $Z_b$ and $Z'_b$ and their heavy quark symmetry partners \cite{31,33}. Recently, the Belle experiment \cite{35} has obtained further evidence for the $Z_b$ and $Z'_b$ in the three-body decays $\Upsilon(5S) \rightarrow [B^{(*)}\bar{B}^{(*)}]^{\pm}\pi^{\mp}$ and this data has been analyzed using EFT \cite{32}. This analysis shows quite clearly that resumming to all orders the final state interactions of the $B$ mesons is necessary to produce line shapes that are consistent with the data. When more data is available, one may hope that such an analysis will make it possible to extract some parameters of the $Z_b$ and $Z'_b$ mesons.

3. Conclusions

It is an exciting time for hadronic physics as $e^+e^-$ collider experiments continue to discover quarkonia states with novel properties. EFTs incorporating heavy quark and chiral symmetries should be applicable to these states, especially when they are molecular in character. Many early applications of XEFT to $X(3872)$ focused on calculating universal properties or decays to quarkonium that are difficult to access experimentally. But in the past year, EFT calculations of $Z_b$ and $Z'_b$ properties and $1^{--}$ radiative decays to $X(3872)$ have become directly relevant to recent experimental results. Hopefully, new experimental results and calculations will allow for more serious tests of EFT and gain insight into the nature of the new states.
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References

1. Belle Collaboration (S. K. Choi et al.), Phys. Rev. Lett. 91, 262001 (2003).
2. CDF Collaboration (D. Acosta et al.), Phys. Rev. Lett. 93, 072001 (2004).
3. D0 Collaboration (V. M. Abazov et al.), Phys. Rev. Lett. 93, 162002 (2004).
4. BaBar Collaboration (B. Aubert et al.), Phys. Rev. D 71, 071103 (2005).
5. N. Brambilla, et al., Eur. Phys. J. C 71, 1534 (2011).
6. Belle Collaboration (A. Bondar et al.), Phys. Rev. Lett. 108, 122001 (2012).
7. BESIII Collaboration (M. Ablikim et al.), Phys. Rev. Lett. 110, 252001 (2013).
8. Belle Collaboration (Z. Q. Liu et al.), Phys. Rev. Lett. 110, 252002 (2013).
9. T. Xiao, S. Dobbs, A. Tomaradze and K. K. Seth, Phys. Lett. B 727, 363 (2013).
10. BESIII Collaboration (M. Ablikim et al.), arXiv:1308.2760 [hep-ex].
11. BESIII Collaboration (M. Ablikim et al.), [arXiv:1309.1896 [hep-ex]].
12. Belle Collaboration (I. Adachi et al.), [arXiv:1207.4345 [hep-ex]].
13. A. E. Bondar, A. Garmash, A. I. Milstein, R. Mizuk and M. B. Voloshin, Phys. Rev. D 84, 054010 (2011).
14. Q. Wang, C. Hanhart and Q. Zhao, Phys. Rev. Lett. 111, 132003 (2013).
15. L. Maiani, V. Riquer, F. Faccini, F. Piccinini, A. Pilloni and A. D. Polosa, Phys. Rev. D 87, 111102 (2013).
16. M. B. Voloshin, Phys. Rev. D 87, 091501 (2013).
17. E. Braaten, [arXiv:1305.0905 [hep-ph]].
18. BESIII Collaboration (M. Ablikim et al.), [arXiv:1310.1163 [hep-ex]].
19. LHCb Collaboration (R. Aaij et al.), Phys. Rev. Lett. 110, 222001 (2013).
20. S. Fleming, M. Kusunoki, T. Mehen and U. van Kolck, Phys. Rev. D 76, 034006 (2007).
21. E. Braaten, H. -W. Hammer and T. Mehen, Phys. Rev. D 82, 034018 (2010).
22. D. L. Canham, H. -W. Hammer and R. P. Springer, Phys. Rev. D 80, 014009 (2009).
23. S. Fleming and T. Mehen, Phys. Rev. D 78, 094019 (2008).
24. S. Fleming and T. Mehen, Phys. Rev. D 85, 014016 (2012).
25. T. Mehen and R. Springer, Phys. Rev. D 83, 094009 (2011).
26. A. Margaryan and R. P. Springer, Phys. Rev. D 88, 014017 (2013).
27. F. -K. Guo, C. Hanhart, U. -G. Meiner, Q. Wang and Q. Zhao, Phys. Rev. D 85, 034006 (2012).
28. T. Mehen and D. -L. Yang, Phys. Rev. D 85, 034002 (2012).
29. BESIII Collaboration (M. Ablikim et al.), [arXiv:1310.4101 [hep-ex]].
30. F. Aceti, R. Molina and E. Oset, Phys. Rev. D 86, 113007 (2012).
31. T. Mehen and J. W. Powell, Phys. Rev. D 84, 114013 (2011).
32. T. Mehen and J. Powell, Phys. Rev. D 88, 034017 (2013).
33. M. Cleven, Q. Wang, F. -K. Guo, C. Hanhart, U. -G. Meissner and Q. Zhao, [arXiv:1301.6461 [hep-ph]].
34. M. B. Voloshin, Phys. Rev. D 84, 031502 (2011).
35. I. Adachi et al. [Belle Collaboration], [arXiv:1209.6450 [hep-ex]].