Hadron-hadron spectroscopy

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Abstract

Discoveries of many narrow states near meson-meson (e.g. $X(3872)$, $Z_c^{\pm,0}$ and $Z_b^{\pm,0}$) and meson-baryon ($P_c^{\pm}$) thresholds among heavy-quark hadrons hint at the importance of hadron-hadron interactions beyond nuclear structures. Such interactions can possibly create deuteron-like bound ("molecular") or virtual states. Proximity of hadron-hadron thresholds can also impact conventional $q\bar{q}$ meson and qqq baryon spectra and their properties. Coupled-channel cusps or triangle diagrams can lead to mass structures without poles in reaction amplitude. There is a rich literature on these subjects, yet little consensus on how to interpret the observations and what to expect in the future. By collaboration of theorists and experimentalists active in this field, we propose to study key measurements, which can be performed at experimental facilities in the next decade, and which are likely to advance our understanding of hadronic structures near hadron-hadron thresholds.

Nucleon-nucleon forces create nuclei, which in a nutshell are multiquark states, in which groups of three light quarks are nearly confined into separate baryons, with the residual

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strong forces between them leading to loosely bound states. The simplest of them, the deuteron, has one stable bound state 2.2 MeV below the sum of masses of proton and neutron. Aligning spins of the nucleons differently leads to a virtual state, which is only 0.06 MeV below the pn threshold, and which produces observable effects in neutron-proton scattering. Hypernuclei with strangeness also exist. It has been a long-standing question if mesons participate in creation of similar multiquark structures when paired up with a baryon (in the form of a pentaquark: $qqqq\bar{q}$) or a meson (in the form of a tetraquark $qq\bar{q}\bar{q}$).

Puzzling properties of $f_0(980)$ or $\Lambda(1405)$, with masses near the $K\bar{K}$ and $N\bar{K}$ thresholds, respectively, led to the suggestion that these states contain molecular components. These resonances have widths of the order of tens of MeV [1]. The much narrower (width of the order of a couple of MeV or less) and, thus, dramatic $X(3872)$ (aka $\chi_{c1}(3872)$) state, was discovered by the Belle experiment right at the $D^0\bar{D}^{*0}$ threshold [2]. Even after nearly 2000 citations of the $X(3872)$ discovery paper, phenomenological disputes over the internal structure of this state continue: is it a $D^0\bar{D}^{*0}$ molecule, with a large radius, or a small conventional, $\chi_{c1}(2P)$ charmonium state, or maybe another type of a bound state, like a compact tetraquark, with all quarks confined together by direct color interactions? Discoveries by the Belle and BESIII experiments of relatively narrow isovector Z_b [3] and Z_c [4, 5] states, near $B^{(*)}\bar{B}^*$ and $D^{(*)}\bar{D}^*$ thresholds, respectively, gave more credence to the importance of meson-meson interactions, without any confusion from ordinary bottomonium or charmonium states. However, whether these are truly loosely-bound molecular states or more complicated manifestations of hadron-hadron interactions is less clear, with alternative compact-state explanations offered as well. The recent observation by the LHCb experiment of three narrow (widths below tens of MeV) hidden-charm pentaquarks, P_c^+, having masses close to the $\Sigma_c^+\bar{D}^{(*)0}$ thresholds [6], also points to loose hadron-hadron binding. More examples of the impact of hadron-hadron thresholds on mesons (e.g., $D_{s0}^*(2317)^\pm$ and $D_{s1}(2460)$ below the $D^{(*)}K$ threshold) or baryons (e.g., $\Lambda_c(2940)$ below the pD^* threshold) exist.

To settle theoretical disputes over the exact nature of these states, better measurements of their properties, as well as discovery of more threshold states, will be crucial. The Belle II and LHCb upgrade programs will reach new domains of sensitivity. ATLAS and CMS will operate at world-record pp luminosities. The BESIII program will continue. The next generation of tau-charm factories are also under consideration. Photoproduction at JLab and EIC, production studies in high-multiplicity pp, pA, and AA collision programs, or in $p\bar{p}$ annihilation at the charm threshold (PANDA), may also shed light into the nature of some of these states. In a collaborative effort between theorists and experimentalists, we propose to study which future measurements will be most effective in advancing our understanding of the role of hadron-hadron interactions on conventional and exotic-hadron spectra, and how they complement each other. As a part of the effort, advanced data analysis techniques, the status of phenomenological models, and of lattice QCD calculations relevant to this problem, will be surveyed [7].

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