PRODUCTION OF EXOTIC HADRONS AND PERSPECTIVES FOR HEAVY-ION COLLISIONS*

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The recently discovered abundance of heavy hadrons with more than three valence quarks remains poorly understood. Measurements of these exotic hadrons and their interactions with the QCD medium provide a new avenue to investigate their properties. Additionally, the production of hadrons with more than three quarks presents new testing grounds for models of particle transport and coalescence in hadron collisions. These proceedings will explore new data on exotic hadrons, various models of their properties, and give an outlook on future measurements in heavy-ion collisions.

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1. Introduction

The quark model of hadron structure forms one of the foundations of our understanding of matter in the universe [1, 2]. This model explains the mesons and baryons in terms of two or three constituent quarks q and antiquarks $\bar{q}$. In addition to these familiar conventional particles, the model also predicts that exotic hadrons made of four, five, or more quarks are allowed. However, until recently, unambiguous identification of these tetra- and pentaquark states has remained elusive.

In order to identify exotic states, one must first understand the expected spectrum of conventional mesons and baryons. The mass of bound states of heavy quarks can be calculated with remarkable precision. Due to their large mass, the charmonium and bottomonium states can be effectively modeled as non-relativistic systems described by the Schrodinger equation with the Cornell QCD potential [3]. This approach yields a rich spectrum of $c\bar{c}$ and $b\bar{b}$ states, with calculated masses that agree with measured values within less than 1%.

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This consistency between theory and experiment was shaken in 2003, when the Belle experiment discovered the unexpected "charmonium-like" $X(3872)$ resonance in the invariant mass spectrum of $J/\psi\pi^+\pi^-$ originating from the decays of B hadrons [4]. Potential models which successfully predict the $c\bar{c}$ spectrum show that no charmonium states near the measured mass of 3872 MeV with compatible quantum numbers $J^{PC} = 1^{++}$ are expected to exist [5]. The inability to reconcile the observed properties of the $X(3872)$ resonance with any expected $c\bar{c}$ states led to speculation that a multiquark state, consisting of at least two light quarks and a $c\bar{c}$ pair ($c\bar{c}q\bar{q}$), had been found.

The $X(3872)$ discovery, and the subsequent lack of a clear interpretation, led to a renewed interest in heavy-quark spectroscopy. This flurry of activity has resulted in the discovery of more than 60 new hadrons at the Large Hadron Collider (LHC), see Fig. 1. These include conventional quarkonia, heavy quark baryons and mesons, and more poorly understood exotic states. The exotic hadrons are known collectively as the XYZ states, and include particles with $c\bar{c}$ and $b\bar{b}$ pairs, some of which are neutral, and some which carry an electric charge. In the charm sector, there are more exotic states than conventional expected charmonium states above the $D\bar{D}$ threshold, and analogous exotic bottomonium states are expected to exist.

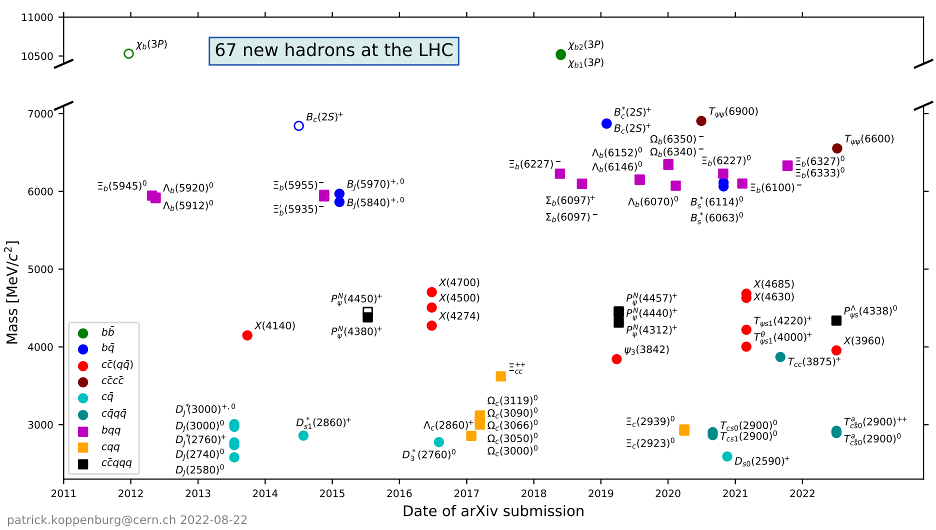

Fig. 1. New hadrons discovered at the Large Hadron Collider [6].

Despite a large amount of theoretical and experimental work, there is no consensus on the structure of any of the observed exotics. Many models have been proposed which attempt to explain various exotics states (see [7] for a review), but they can be roughly sorted into two categories: compact *versus* molecular. Compact tetra- or pentaquarks are tightly bound multiquark states, with radii of ~ 1 fm that are typical of many conventional hadrons. Molecules are bound states of conventional hadrons that interact through light meson exchange, similar to how protons and neutrons are bound inside of nuclei. These are weakly bound extended states, with radii that can be on the order of ~ 5 fm or more, depending on the binding energy. Given a large number of exotic states, and their widely varying properties, it is likely that some may fall into the compact category while others are molecular.

2. Exotic hadrons in medium

Many of the XYZ particles have only been observed as intermediate states in the decay products of B hadrons. Experiments at "B factories", such as BaBar and Belle [8, 9] have given many of the first observations of these particles. At those facilities, e^+e^- collisions are typically tuned to the $\Upsilon(4\mathrm{S})$ resonance, which decays to a pair of B mesons with a branching fraction of $\sim 100\%$, providing large data samples. Experiments at the Tevatron and the LHC hadron colliders have also focused on measuring these states in B decays. Due to the low backgrounds, this is an efficient method for discovery of particles, and measurements of some of their properties in vacuum.

Heavy-ion collisions provide a unique opportunity to study the properties of the XYZ states in extreme conditions that cannot be produced in e^+e^- collisions or studied through B decays in vacuum. For guidance, we consider existing data on conventional quarkonium states, which have been studied extensively in proton–nucleus and nucleus–nucleus collisions. Measurements of charmonium production in pA collisions [10–13] showed that the $\psi(2S)$ is suppressed more than the more strongly bound J/ψ in rapidity regions where a relatively large number of charged particles are produced. As the effects governing heavy-quark production and transport through the nucleus are similar for states with the same quark content, the mechanism for the suppression of excited states is expected to occur in the late stages of the collision, after the $Q\bar{Q}$ pair has hadronized into a final state. Models incorporating final-state effects, such as breakup via interactions with co-moving hadrons, are able to describe the relative suppression of excited quarkonium states in pA collisions [14, 15]. If the $X(3872)$ or other exotics have a small binding energy and large radius, similar effects could also disrupt their formation, via interactions with other particles produced in the underlying event [16].

The first study of potential breakup effects on $X(3872)$ in small systems has been carried out by the LHCb Collaboration [17]. These measurements studied the relative rate of $X(3872)$ production as compared to the conventional charmonium state $\psi(2S)$, as a function of event multiplicity. The ratio of prompt cross sections $\sigma_{X(3872)}/\sigma_{\psi(2S)}$ is found to decrease with multiplicity, while non-prompt production shows no significant multiplicity dependence, see Fig. 2. This data is compared to co-mover interaction models, where the promptly produced $X(3872)$ and $\psi(2S)$ can be disrupted via interactions with other particles produced in the event. One model calculates the breakup cross section based on the radii of compact and molecular $X(3872)$, and finds the data to be consistent with expectations of a compact state [18]. Another model, however, calculates the breakup cross section of the molecule in terms of pion scattering on the individual hadrons which make up the molecule, and is also consistent with the data [19].

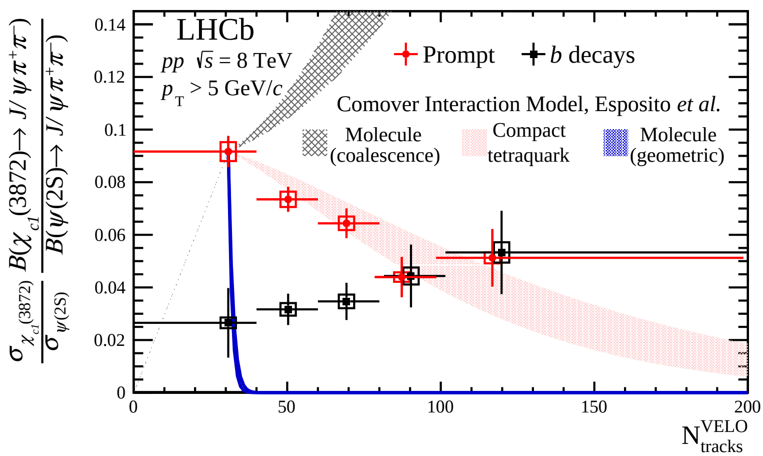

Fig. 2. The ratio of $X(3872)$ to $\psi(2S)$ cross sections *versus* multiplicity in pp collisions, as measured by the LHCb [17].

The $\sigma_{X(3872)}/\sigma_{\psi(2S)}$ ratio has recently been measured in pPb collisions by the LHCb experiment [20]. As shown in Fig. 3, a moderate increase in the ratio is found relative to multiplicity-integrated pp collisions, although uncertainties on the pPb data are large. As previously discussed, it has been measured that $\psi(2S)$ production is suppressed in pPb collisions, which would drive the ratio up even if there were no effects on the $X(3872)$. Another possibility is increased $X(3872)$ production, which was predicted to happen due to an enhanced rate of double parton scattering in pPb [21], which has since been observed [22].

In nucleus+nucleus collisions at RHIC and the LHC, a relatively large volume of quark–gluon plasma is formed, providing an abundant source of deconfined quarks that can potentially coalesce and freeze out into exotic states. Competing with this production mechanism is color screening, which is expected to suppress the production of bound heavy-quark states. The production and suppression of these states in heavy-ion collisions are sensitive to fundamental properties of the quark–gluon plasma such as temperature, density, and baryon chemical potential. The first measurements of an exotic hadron in heavy-ion collisions was done by the CMS Collaboration [23]. This measurement, shown in Fig. 3, displays a dramatic enhancement of the $\sigma_{X(3872)}/\sigma_{\psi(2S)}$ ratio by a factor of ~ 10 as compared to pp collisions. However, significant uncertainties on this data preclude drawing firm conclusions. The combination of data across pp, pPb, and PbPb does seem to indicate that the exotic $X(3872)$ behaves differently in medium than the conventional state $\psi(2S)$.

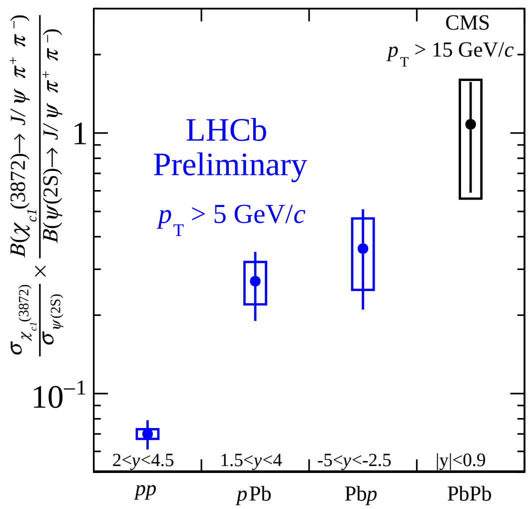

Fig. 3. The ratio of $X(3872)$ to $\psi(2S)$ cross sections in various collision systems, as measured by the LHCb [20] and CMS [23].

In response to this data, multiple models of $X(3872)$ production and transport in quark–gluon plasma have been developed. The statistical hadronization model predicts that $X(3872)$ production is strongly enhanced to values equivalent to $\sim 1\%$ of the J/ψ cross section [24]. A model using AMPT to simulate the coalescence of $X(3872)$ predicts that a molecular $X(3872)$ will be enhanced much more than a compact state [25], while a recent transport calculation expects the opposite [26]. Additional data is required to more fully constrain these models.

3. Outlook

An ideal detector for an exotic hadron heavy-ion program has the following requirements:

— Hadron breakup and formation through recombination are both dependent on interactions among bulk particles created in hadron–hadron collisions. These effects are therefore expected to be most prominent at low $p_{\rm T}$, where particle production is concentrated. To observe these effects, the experimental apparatus must have the capability to measure heavy-quark states at low $p_{\rm T}$, ideally down to $p_{\rm T} = 0$, in order to examine the phase space of interest.

— The decay chains of many observed exotics have multiple hadrons in the final state, and give decay topologies that are significantly more complicated than the dimuon decays that are typically used to study charmonia and bottomonia in heavy-ion collisions (*e.g.*, $X(3872) \to J/\psi\pi^+\pi^-$ and $P_c^+ \to J/\psi p^+$). Reconstruction of particles with multiple hadrons in the final state can lead to large combinatorial backgrounds in heavy-ion collisions. To minimize this, detection systems must be capable of identifying pions, kaons, protons, and muons in order to exclude as many irrelevant particles as possible when constructing invariant mass spectra. Therefore, the experimental apparatus must have full particle identification capabilities over a wide range of transverse momentum.

— In order to distinguish exotics that are promptly produced at the primary collision vertex (where they will be subject to effects from the dense QCD environment) from non-prompt production via B-decays (which occur in vacuum), the detector must be able to clearly identify B hadrons via their displaced decay vertices. Precise vertex measurements are also required to separate multiple collision vertices that may occur in a single-beam crossing, and aid in measurements of the track multiplicity to characterize the event associated with each vertex. Therefore, the apparatus must have precision vertexing capability.

— Exotic production is a relatively rare process in hadron collisions. As an example, the rate of prompt $X(3872)$ production relative to prompt $\psi(2S)$ production as measured in the $J/\psi\pi^+\pi^-$ channel is $\sim 10\%$ in pp collisions at 8 TeV. Therefore, the detector must sample a relatively high luminosity across the full centrality range in order to produce statistically meaningful results.

While all four of the major LHC experiments each meet some of these criteria, none currently meet them all. However, a series of ambitious upgrades are underway at ALICE, ATLAS, CMS, and LHCb, [27–30] which will greatly enhance the capabilities for exotic hadron measurements in future runs at the LHC.

4. Summary

The study of exotic hadrons is a highly active field of QCD. Very recently the first measurements of $X(3872)$ in pA and AA collisions have become accessible, giving us the first information on exotics in a dense hadronic medium. While current experimental uncertainties are large, the ongoing upgrade program at the LHC gives strong possibilities for greatly improved measurements in future runs.

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