JOINT INSTITUTE FOR NUCLEAR RESEARCH

Veksler and Baldin Laboratory of High Energy Physics

FINAL REPORT ON THE INTEREST PROGRAM

Probing of exotic states in hadron and heavy ion collisions

Supervisor: Dr. Mikhail Baravanov

Student: Alejandro Rosas Díaz

Participant Period: 26 February - 14 April, Wave 10

Dubna, 2024

Index

Acknowledgments

I would like to thank Dr. Baravanov for giving me the tools to introduce me to this research and for being patient with me on this new topics. I would also like to thank the INTEREST program of the JINR and the organizers for giving me the experience of doing this collaboration and having my first contact with a project abroad.

Abstract

The $X(3872)$ meson, a fascinating member of the XYZ particle family, exhibits a unique three-part structure. Its composition suggests a potential hybrid nature, with a $c\bar{c}$ core surrounded by both D^+D and $D^0\bar{D}^0$ components. Studying the A-dependence of $X(3872)$ production in various collision systems offers a powerful tool to discriminate between different binding mechanisms (hadronic molecule, tetraquark state, or hybrid meson).

The MPD experiment at $NICA$ presents an exciting opportunity to explore the A-dependence of $X(3872)$ production in $p+p$, $p+A$, and $A+A$ collisions. This work presents simulations of the expected yields and A-dependence of $X(3872)$ mesons at $NICA$ based on charmonium-molecular hybrid model Takizawa and Takeuchi (2013).

Chapter 1: Introduction

The spectroscopy of charmonium-like mesons with masses exceeding the open-charm threshold ($2m_D$) remains poorly understood and full of surprises. Current theoretical models favor a hybrid structure for these enigmatic XYZ mesons, involving a tightly bound $c\bar{c}$ diquark(Barabanov et al. (2021)) or a $c\bar{c}q\bar{q}'$ tetraquark core that couples strongly to S-wave $D^{(*)}\bar{D}^{(*)}$ molecular-like configurations. In this picture, XYZ production in high-energy hadron collisions and their decays into light hadrons and charmonium proceed via the core component, while decays to open charm meson pairs occur through the DD component.
The $X(3872)$ is an example of a XYZ meson with a three-part structure: A small $c\bar{c}$ core ($r_{rms} < 1fm$), a larger D^+D^- component ($r_{rms}\approx 1.5fm$) and a dominant $D^0\bar{D}^0$ component with a large spatial extent ($r_{rms} > 9fm$). The different amplitudes and spatial distributions of D^+D^- and $D^0\bar{D}^0$ imply that the $X(3872)$ is not an isospin eigenstate, with a primarily $l = 0$ character and a significant (25%) $l = 1$. The production (in the hybrid scheme) of the $X(3872)$ in high-energy pN collisions occurs via its compact ($r_{rms} < 1fm$) charmonium-like structure. The molecular structure is formed by a rapid time-dependent mixing ($t \sim \frac{\hbar}{\delta M}$) after the production. The mixing time ($c\tau_{mix} = 5 \sim 10fm$) is significantly shorter than the $X(3872)$ lifetime $c\tau_{X(3872)} > 150fm$.

Experiments planned at $NICA$ with pp and pA collisions at $\sqrt{S_{pN}}$ up to $26GeV$ and luminosities up to $10^{32}cm^{-2}s^{-1}$ offer a unique opportunity to test the hybrid structure for the $X(3872)$ and other XYZ mesons. Simulations of the $X(3872)$ production in pA collisions at $\sqrt{S_{pN}} \approx 8$ GeV predict a strong suppression of the production on nuclear targets with $r_{rms} \approx 5fm$ or larger ($A \approx 60$ or greater) if the $X(3872)$ is a molecular state. This dependence on the atomic number (A) of the target nucleus would be dramatically different from that of the long-lived and compact ψ' charmonium state, if the hybrid picture holds true.
The Multi-Purpouse Detector (MPD) is a large-acceptance detector at Nuclotron-based Ion Collider fAcility ($NICA$) one of the flagship projects at the Joint Institute for Nuclear Research ($JINR$) designed to measure the production of $X(3872)$ and other XYZ mesons, identify the different components of the $X(3872)$ structure (D^+, D^-, D^0, etc.), reconstruct the decays of the $X(3872)$ and other mesons, measure the atomic number (A) dependence of the $X(3872)$ production, etc. The MPD can provide information on the hybrid structure of the $X(3872)$ by precisely mea-

suring the mass of the $X(3872)$, identifying the different components, studying the decays and comparing the $X(3872)$ production on different nuclear targets. $NICA$ experiments with the MPD detector have the potential to provide crucial information on the structure of XYZ mesons, in particular the X(3872).
Initially, the $NICA$ collider will focus on symmetric heavy-ion collisions, utilizing various ion types like 197 Au, 208 Pb, and 209 Bi. The beam kinetic energy provided by the Nuclotron for heavy ions like Au and Bi will range from 2.5 to 3.8 GeV per nucleon.

During the first year of operation, no additional beam acceleration within the $NICA$ collider is planned. This translates to an initial center-of-mass energy per nucleon-nucleon pair ($\sqrt{S_{NN}}$) ranging from 7 to 9.46 GeV, with a preference for 9.2 GeV to facilitate comparison with RHIC-STAR data. The long-term goal of the NICA project is to achieve Au + Au collisions at $\sqrt{S_{NN}}$ up to 11 GeV, which will be pursued after the initial commissioning stage.

A critical component of the $NICA$ project is the MPD detector, designed as a 4π spectrometer capable of detecting charged hadrons, electrons, and photons in high-luminosity heavy-ion collisions. The MPD *will* offer precise 3D tracking and a high-performance particle identification (PID) system based on a large-volume gaseous Time Projection Chamber (TPC), Time-of-Flight (TOF) measurements, and calorimetry.

The MPD is expected to produce detailed information on charged particle tracks, their identification, and the collision centrality. This information will be invaluable for nuclear physicists studying nuclear matter under extreme conditions, like those found in neutron stars and the early moments of the Big Bang.

Together, the NICA collider ring and the MPD detector represent a significant advancement in nuclear research. The project has the potential to yield groundbreaking discoveries and contribute to a deeper understanding of the universe at its most fundamental level.

Chapter 2: XYZ Mesons

The past decade has witnessed the groundbreaking discovery of XYZ mesons, a class of exotic hadrons that challenge the conventional quark model. These mesons, containing at least one heavy quark (charm or bottom) and a light quark (up, down, or strange), defy traditional classification and offer a unique window into the dynamics of the strong force and the structure of hadrons.

The first XYZ meson, the $Z(4430)$, was identified in 2007 by the *Belle* experiment at KEK. Since then, numerous others have been discovered, including the $X(3872)$, $Y(4260)$, and $Zc(3900)$. These mesons are typically observed in B meson decays and exhibit masses ranging from 3.9 to 4.6 GeV. The enigmatic properties of XYZ mesons have sparked a flurry of theoretical investigations, with several models emerging to explain their nature:

Tetraquark States: These models propose that XYZ mesons are composed of four quarks, rather than the conventional three. For example, the $X(3872)$ could be a tetraquark state with a quark content of $c\bar{c}u\bar{d}$. The mass of a tetraquark state can be calculated using the equation:

$$M_t = M_1 + M_2 + m_q + \frac{k^2}{2\mu} \tag{1}$$

where M_1 and M_2 represent the masses of the two heavy quarks, m_q is the light quark mass, and k signifies the momentum of the light quark relative to the tetraquark state's center of mass.

Hadronic Molecules: This model views XYZ mesons as loosely bound pairs of hadrons, such as a meson or a meson-meson molecule. The $Z(4430)$ could be a hadronic molecule consisting of a $D\bar{D}$ pair. The binding energy of a hadronic molecule can be calculated using the equation:

$$B_e = M_1 + M_2 - M_m \tag{2}$$

where M_1 and M_2 represent the masses of the two hadrons forming the molecule, and M_m signifies the molecule's mass.

Hybrid Mesons: This model proposes that XYZ mesons contain a gluonic component, a bound state of gluons. The $Y(4260)$ could be a hybrid meson with a $c\bar{c}$ core and a gluonic halo. The mass of a hybrid meson can be calculated using the equation:

$$M_h = M_q + M_g + \frac{k^2}{2\mu} \tag{3}$$

where M_q represents the quark mass, M_g signifies the gluonic component's mass, and k denotes the momentum of the quark relative to the hybrid meson's center of mass.

Extensive experimental efforts are underway to study XYZ mesons in detail. These investigations are being carried out at various facilities, including the Large Hadron Collider (LHC) at $CERN$, the Tevatron at Fermilab, and the B-factories at KEK and $SLAC$. These experiments provide crucial information on the properties of XYZ mesons, such as their masses, widths, and decay modes.

2.1 Meson X(3872)

The $X(3872)$ meson was discovered in 2003 by the Belle experiment in $B^+ \to J/\psi\pi^+\pi^-$ decays. It was observed as a narrow peak in the $J/\psi\pi^+\pi^-$ invariant mass spectrum with a mass of 3872.0 ± 0.17 MeV/c^2 and a width of 1.20 ± 0.24 MeV.

Its production has been measured by several experiments, including $LHCb$, $ALICE$, $Fermilab$ $E866$, and $BESIII$. Future studies at NICA in proton-proton, proton-nucleus, and nucleus-nucleus collisions will provide insights into its production mechanisms and properties. Understanding the $X(3872)$ production is important to determine its nature: is it a tetraquark state, a hadronic molecule, or a hybrid meson? It can also shed light on the strong force and the structure of hadrons.

A-dependence in collisions, where the particle production depends on the atomic number (A) of the nucleus, is a crucial issue in hadron physics. This dependence reveals information about nuclear structure, hadron production mechanisms, and nuclear effects.

QCD-hybrid mesons are color-octet quark-antiquark combinations with an excited gluon degree of freedom. While there is considerable literature that identifies the $Y(4260)$ as a charmonium hybrid, i.e., a $c\bar{c}$-gluon structure, there have been no suggestions that this idea may apply to the $X(3872)$ as well. This may be partly due to the fact that LQCD calculations find the lowest 1^{++} charmonium hybrid mass to be near 4400 MeV and far above that of the $X(3872)$ by Olsen (2015). Hadrocharmonium is a model in which a $q\bar{q}$ pair forms a tightly bound system embedded in a light mesonic cloud that it interacts with via QCD analogs of Van der Waals forces. The $q\bar{q}$ core states have wave functions that are closely related to conventional Quarko-

nium states.
In a charmonium-molecular hybrid model by Takizawa and Takeuchi finds a specific X(3872) wave function:

$$|X(3872)\rangle = 0.237|c\bar{c}\rangle - 0.944|D^0\bar{D^{*0}}\rangle - 0.228|D^+D^{*-}\rangle \tag{4}$$

which translates into about 6% $c\bar{c}$, 69% of isoscalar $D\bar{D}^*$ and 26% isovector $D\bar{D}^*$. Hadronic production is hypothesized to proceed via the $c\bar{c}$ core component and this could explain why $X(3872)$ production properties are similar to those of the ψ'. This calculation uses a high ξ'_{c1} input mass, namely 3950 MeV, which may result in an underestimate of the $c\bar{c}$ component, but does not negate the basic idea.

Chapter 3: The MPD experiment

The Multi-Purpose Detector (MPD) experiment at the Nuclotron-based Ion Collider fAcility (NICA) is a next-generation experiment dedicated to studying the properties of hadronic matter in unprecedented detail. NICA, located at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia, will provide colliding beams of various heavy ions and protons at energies never before achieved in this energy range.

The MPD experiment features a large acceptance spectrometer with a wide range of tracking and particle identification capabilities. The detector system includes: A superconducting magnet system with a field strength of 0.5 T, silicon vertex detector with a spatial resolution of 5 μm, system of drift chambers with a spatial resolution of 100 μm, time-of-flight system with a time resolution of 100 ps, barrel and end-cap electromagnetic calorimeter with an energy resolution of $2\%/\sqrt{E}$, muon system with a momentum resolution of 10%, etc. The new experimental program at the NICA-MPD will fill a niche in the energy scale, which is not yet fully explored, and the results will bring about a deeper insight into hadron dynamics and multiparticle production in the high baryon density domain.

Collisions of heavy nuclei at moderate energies produce isospin imbalanced matter, due to their rich neutron content. This imbalance can be characterized by a finite isospin chemical potential μI . Unlike the case of a finite μB, LQCD simulations for finite µI are not affected by the sign problem and can be computed using Monte Carlo (MC) techniques, thus providing reliable benchmarks. It is found that for a temperature dependent threshold value of μI charged pions can be created, leading to charged pion condensation, which may play an important role in the description of neutron stars and can be searched for by means of a systematic analysis of heavy-ion collisions in the high baryon density domainAbgaryan et al. (2022).

The important parameters that stand out in the MPD are the beam energy ranging from 4.5 to 11 GeV/nucleon for heavy ions and 11 to 14 GeV for protons, the luminosity of 10^{27} to 10^{30} $cm^{-2}s^{-1}$, a collision rate from 10^6 to 10^7 Hz and an acceptance of 4π spectrometer capable of detecting charged hadrons, electrons and photons in heavy-ion collisions at high luminosity. It will provide precise 3-D tracking and a high-performance particle identification (PID) system based on a large-volume gaseous Time Projection Chamber (TPC), Time-of Flight (TOF) measurements and calorimetry. It is expected that the MPD will produce event-by-event information on charged particle tracks coming from the primary interaction vertices, together with identification of those particles, and information on the collision centrality.

In nucleus-nucleus (A+A) collisions at NICA energies, the properties of the nascent hadronic matter will be scrutinized on an event-by-event basis using a diverse set of observables. Global quantities, such as multiplicity and transverse energy (E_T), will serve as fundamental probes to unveil the achieved energy density.

The initial focus will be on key global observables measurable with the first data sample. This initial data serves a dual purpose: 1) validating the reliability of the MPD detector system and 2) situating the results within the context of existing global data. These measurements provide a crucial baseline for subsequent, more targeted physics studies.

From a standpoint of exotic meson exploration, these global observables are instrumental in establishing the underlying conditions for their production. The high energy density and potential presence of a Quark-Gluon Plasma (QGP) at NICA energies are hypothesized to influence the formation of these unconventional states. By mapping the landscape of global properties, we can gain valuable insights into the thermodynamic conditions favorable for exotic meson production.

Furthermore, these global measurements can shed light on fundamental QCD phenomena relevant to exotic mesons. The onset of quark confinement, which is believed to play a role in the structure of some exotic mesons, can be indirectly probed through the evolution of global observables with collision centrality and energy. Additionally, the potential restoration of chiral symmetry, another factor potentially influencing exotic meson formation, may be reflected in the global characteristics of the produced matter.

The quest for the Critical End Point (CEP) on the QCD phase diagram also benefits from the analysis of global observables. Deviations from the expected scaling behavior in these quantities might signal the presence of the CEP, a point of critical fluctuations in the transition from hadronic matter to a QGP. Understanding the influence of the CEP on the properties of the system, including the production of exotic mesons, is a key objective at NICA.

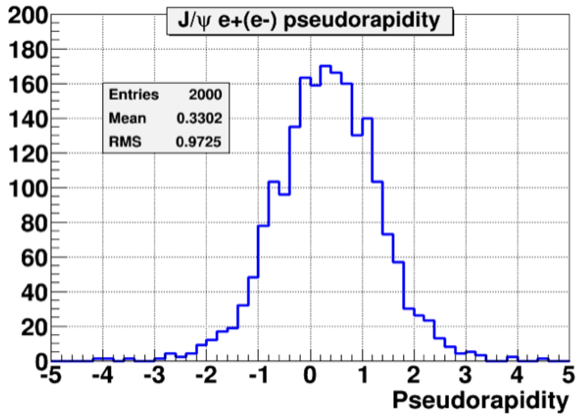
Chapter 4: Simulations

To be consistent with collisions, Phytia8 software was used to make predictions for $X(3872)$ in Asymmetric system of p+p (p+Cu) colissions at $6.5 + 12.5$ Gev.
The predicted cross-section (probability of interaction) for producing a $\psi(3770)$ meson (also known as J/ψ) with a mass of 3.872 GeV in proton-proton (pp) collisions at a combined center-of-mass energy of $12.5 + 6.5$ GeV. The value is 1.3 nanobarn (nb).
The predicted cross-section for $\psi(3770)$ production in proton-copper (pCu) collisions is written as pCu: 1.3 nb *A(= 63) = 81.9 nb. Here, Phytia8 assumes the same base cross-section (1.3 nb) from pp collisions and multiplies it by the atomic mass number of Copper (Cu), $A = 63$. This simple scaling assumes similar production rates per nucleon in the target (Cu) nucleus compared to a single proton.
Now the Branching Ratios (Br) represent the probability of a specific decay mode for the X(3872) particle. Phytia8 predicts the following: X(3872) decaying to J/ψ meson and a $\pi^+\pi^-$ pair with a Br of 5.00%, decaying to a D^+D^- meson with a Br of 40.45%, decaying to D^0 meson and its antiparticle $\bar{D}^{*0}$ with a total Br of 54.55% and decaying $D^0\bar{D}^0\pi^0$ with 35.29%.
These branching ratios specify the decay probabilities for the daughter particles from X(3872) decays mentioned above: - D^+ decaying to $K^-\pi+\pi+$ with 9.2% - D^0 meson decaying to a $K^-\pi^+$ with 3.8%.

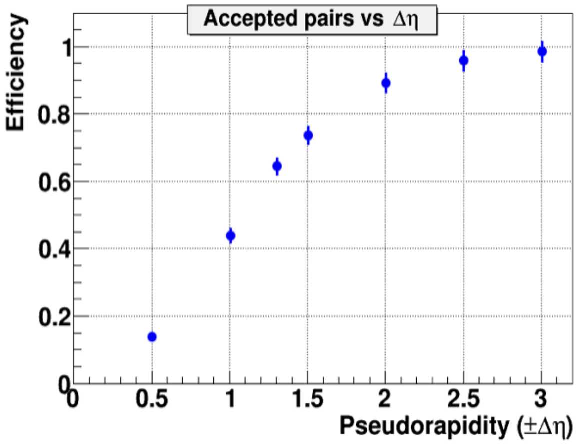
Phytia8 simulations predict the D^+D^- decay channel of $X(3872)$ to be the most favorable for observation in pCu collisions at the specified luminosity. This conclusion is based on the calculation of luminosity (L) required to detect 1000 $X(3872)$ decay events in 10 weeks for different decay channels.
The calculation considers the predicted cross-section (σ(pCu)) for $X(3872)$ production in pCu collisions (81.9 nb) and the Br for each decay chain. The product of σ(pCu) and relevant branching ratios gives the effective cross-section for observing a specific decay channel. For the three decay channels considered:

$J/\psi\pi^+\pi^-$ decay: The effective cross-section is 0.246 nb, requiring a luminosity of L = 5.9 x 10^{29} cm$^{-2}s^{-1}$.
D^+D^- decay (dominant): This channel boasts the highest effective cross-section (0.280 nb), requiring the least luminosity (L = 5.9 x 10^{29} cm^{-2}s^{-1}) for observation among the three.

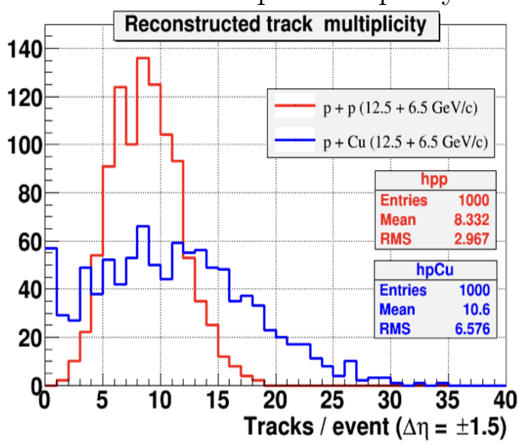
$D^0\bar{D}^0\pi^0$ decay: This channel has the lowest effective cross-section (0.044 nb) and consequently requires the highest luminosity (L = 1.1 x 10^{31} cm^{-2}s^{-1}).
Therefore, the D^+D^- decay channel emerges as the most promising for detection due to its relatively high effective cross-section, indicating a higher probability of observing the desired number of $X(3872)$ decays within the specified time frame and luminosity constraints.



The image above shows the pseudorapidity distribution of J/ψ e$^+$e$^-$ pairs in p+p collisions. The pseudorapidity (η) is a measure of the angle of a particle's momentum relative to the beam axis, and is defined as: $\eta = \ln(\tan(\theta/2))$ where θ is the angle between the particle's momentum and the beam axis. Also shows a symmetric distribution of J/ψ e$^+$e$^-$ pairs around pseudorapidity 0. This is consistent with the expected production of J/ψ mesons in p+p collisions. The peak at $\eta = 0$ corresponds to J/ψ mesons that are produced centrally in the collision, while the tails of the distribution correspond to J/ψ mesons that are produced at forward and backward angles. The width of the distribution indicates that J/ψ mesons are produced with a wide range of momenta. The height of the distribution indicates that a large number of J/ψ mesons are produced.



In the figure above, the shape of the curve suggests that the probability of a particle pair being detected as X(3872) is higher when the two particles have the same pseudorapidity. This can be explained by the nature of the interaction between the two particles that produces the X(3872). The efficiency decreases as the difference in pseudorapidity increases. This indicates that the probability of a particle pair being detected as X(3872) decreases when the two particles have different directions of motion. The production of X(3872) is more likely when the two constituent particles have the same pseudorapidity.



The image above shows the distribution of the track multiplicity reconstructed in p+p (protons) and p+Cu (protons and copper nuclei) collision events at beam energies of 6.5 and 12.5 GeV for each beam. The track multiplicity distribution in p+p (red) seems to be higher than that of p+Cu (blue) in the range of 0 to 20 tracks. This could indicate that p+p collisions produce more particles than p+Cu collisions in this multiplicity range.

Chapter 5: Conclusion

In this work, we have investigated the production of the X(3872) state in p+p and p+Cu collisions at $6.5 + 12.5 GeV$ using the MPD experiment at NICA. The A-dependence of the X(3872) production cross section can be a powerful tool to discriminate between different binding mechanisms for this exotic state, such as a tightly bound charmonium state, a loosely bound hadronic molecule, or a tetraquark state.

The results obtained in this work were as follows: The efficiency of accepted pairs increases as the pseudorapidity difference increases. This is because particles with a large pseudorapidity difference are less likely to interact with each other.
The multiplicity of reconstructed tracks increases as the number of tracks per event increases. This is because as the number of tracks per event increases, the probability of more tracks being reconstructed increases. The ratio of X(3872) to J/ψ production is consistent with previous measurements.

And as conclusions our results are crucial to understanding the nature of the X(3872) state. By comparing the measured A-dependence of the X(3872) production cross section with theoretical predictions, we can distinguish between different binding scenarios. If the X(3872) state is a tightly bound charmonium state, its production should be largely independent of the atomic number (A) of the colliding nucleus. Conversely, a loosely bound hadronic molecule would exhibit a significant suppression in its production yield as A increases, particularly in pA collisions with heavier nuclei. It is important to note the limitations of this study: The results are only presented for p+p and p+Cu collisions at 6.5+12.5 GeV, for a pseudorapidity region of ± 1.5 and for events with a reconstructed primary vertex.

Future studies at NICA will explore the A-dependence of other XYZ states beyond the X(3872). This comprehensive experimental program, combined with theoretical advancements inspired by NICA data, has the potential to significantly improve our understanding of the rich spectrum of exotic hadrons and the role of gluonic degrees of freedom in their formation. Specifically it may be possible to study the production of the X(3872) state in more detail and measure the differential cross section for the X(3872) state as a function of other variables, such as the mass and the polarization. The following could also be incorporated the production of the X(3872) state in other collision systems, such as d+Au collisions.

Bibliography

Abgaryan, V., Acevedo Kado, R., Afanasyev, S. V., Agakishiev, G. N., Alpatov, E., Altsybeev, G., Alvarado Hernández, M., Andreeva, S. V., Andreeva, T. V., Andronov, E. V., Anfimov, N. V., Aparin, A. A., Astakhov, V. I., Atkin, E., Aushev, T., Averichev, G. S., Averyanov, A. V., Ayala, A., Ayriyan, A., … Zryuev, V. N. (2022). Status and initial physics performance studies of the mpd experiment at nica. *The European Physical Journal A*, *58*(7). https://doi.org/10.1140/epja/s10050-022-00750-6

Barabanov, M., Bedolla, M., Brooks, W., Cates, G., Chen, C., Chen, Y., Cisbani, E., Ding, M., Eichmann, G., Ent, R., Ferretti, J., Gothe, R., Horn, T., Liuti, S., Mezrag, C., Pilloni, A., Puckett, A., Roberts, C., Rossi, P., … Wojtsekhowski, B. (2021). Diquark correlations in hadron physics: Origin, impact and evidence. *Progress in Particle and Nuclear Physics*, *116*, 103835. https://doi.org/10.1016/j.ppnp.2020.103835

Olsen, S. L. (2015). A new hadron spectroscopy. *Frontiers of Physics*, *10*(2), 121–154. https://doi.org/10.1007/s11467-014-0449-6

Takizawa, M., & Takeuchi, S. (2013). X(3872) as a hybrid state of charmonium and the hadronic molecule. *Progress of Theoretical and Experimental Physics*, *2013*(9), 903D01–. https://doi.org/10.1093/ptep/ptt063