Exotic Hadrons: A Subatomic Bestiary

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Introduction

Particle physicists study unfamiliar forms of matter – matter that hasn't commonly existed in the cosmos since fractions of a second after the universe began. It has allowed scientists to dive down into an ever-decreasing set of size scales, from molecules, to atoms, to protons and neutrons, and even to quarks. The world of quarks can be a confusing one, but over the past couple decades, it has gotten even more complicated. Using powerful particle accelerators researchers have begun to create and study a truly new form of matter, one in which quarks are combined in unusual ways and one which will teach us some interesting new things about the strong nuclear force.

The subatomic world has often been called a zoo[1], inhabited by a confusing array of particles, each with a dizzying collection of different properties: mass, spin, charge, lifetime, production and decay modes, just to name a few. The subatomic particles that are most ubiquitous in matter are the proton, neutron, and electron; indeed, from 1895 to 1935, these were the only known subatomic constituents of matter. The early subatomic zoo was more like a barnyard, filled with relatively familiar particles.

However, beginning in 1936, that all changed. That year, Carl Anderson and his student Seth Neddermeyer discovered the muon[2,3]. The muon was found in collisions caused by cosmic rays, and it has a mass of about ten percent that of a proton. It was the first subatomic particle that plays no role in the makeup of ordinary matter, leading quantum pioneer I.I. Rabi when he learned of the particle's existence to exclaim, "Who ordered that?" Anderson and Neddermeyer are shown with their detector in Fig. 1. A decade later, another group discovered what are now called pions[2,4], also generated in collisions between cosmic rays and matter. Pions have a mass about fifteen percent that of a proton.

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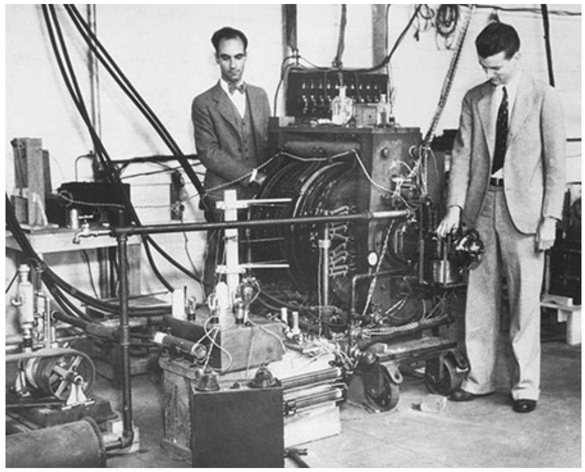

Figure 1: Carl Anderson (left) and Seth Neddermeyer (right) with the cloud chamber detector in which they discovered both antimatter and the muon. This photo was taken in September 1933. (From CSU Archives.) **[end caption]**

By the 1950s, scientists had begun to use particle accelerators to transform energy into unknown subatomic particles. Rather than braving the temperatures of high mountain peaks to get access to more cosmic rays so they could search for something new, researchers could now wander down to their department's basement, flip a switch, and create new particles while sipping their morning coffee.

With particle accelerators, particle discoveries became relatively easy. Scientists would accelerate protons (usually) or s (occasionally) to high energy and slam them into stationary targets. Exploiting Einstein's most famous equation, $E = mc^2$, researchers would transform the beam energy into unstable particles that would decay in the blink of an eye. These particles are not common in nature; all of them decay in far less than a second. Indeed, we now know that these particles were last common in the universe only in the very first moments of the Big Bang.

By the early 1960s, hundreds of new particles had been discovered, with exotic names, pions, kaons, Deltas, Sigmas, to name just a few. The full story of figuring out how to organize all of them is beyond the scope of this review. It can be found in Refs. 1 and 2. Of relevance to this article are two classes of particles that are now called mesons and baryons. At the time, mesons were believed to have a mass in the range of 10 – 50% that of a proton, while baryons were particles with masses in the range of 100 – 200% that of a proton. (This was as of the early 1960s. Subsequent discoveries have found particles outside these ranges and led to a revision in the meaning of these names.) There is another class of particles, called leptons and of which the electron and muon are examples, which are not the core topic of this article.

Quark theory

It was in 1964 when an explanatory theory describing the patterns seen in mesons and baryons was invented.[1,2,5] Where scientists once knew of over a hundred mesons and baryons that defied explanation (i.e., the “zoo”), all of them can now be explained as combinations of smaller particles inside them called “quarks,” named after an obscure line in James Joyce’s *Finnegan’s Wake.* Together, the quark-containing baryons and mesons are called “hadrons.” Hadrons are influenced by the strong nuclear force.

In the original quark proposal, three quark variants existed, with the names: up (u), down (d), and strange (s). Up quarks have an electric charge $q = +2/3$ that of a proton, while the down and strange quark have a charge of $q = -1/3$. Both matter and antimatter quarks exist, and the antimatter quarks $(\bar{u}, \bar{d}, \bar{s})$ have an electric charge opposite of their matter counterparts. Figure 2 shows the known quarks.

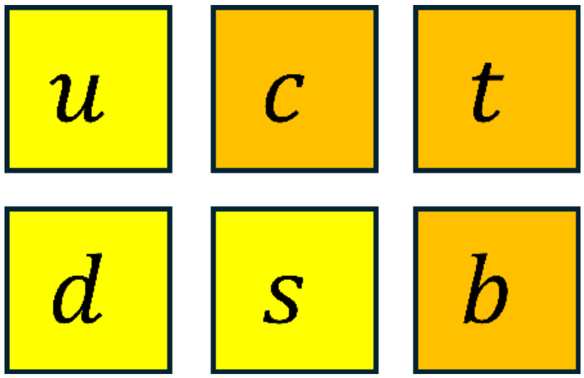

Figure 2: Six different types of quarks are now known. The up, down, and strange quarks were part of the original proposal. The other quarks were discovered later: (charm, 1974, $q = +2/3$), (bottom, 1977, $q = -1/3$), (top, 1995, $q = +2/3$)[1,2]. **[end caption]**

In quark theory, mesons consist of one matter quark and one antimatter quark, while baryons consist of three quarks. Antimatter baryons consist of three antimatter quarks. Figure 3 shows the quark content of typical baryons and mesons.

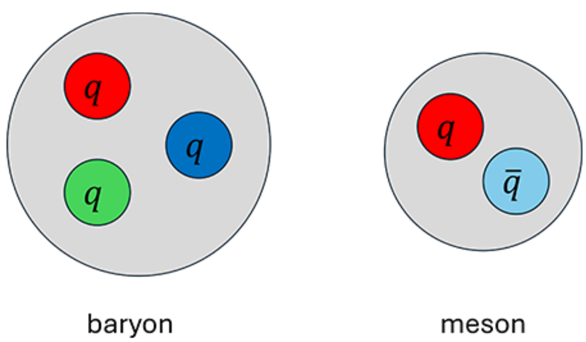

Figure 3: In the simplest version of quark theory, heavy baryons consist of three quarks, while mesons consist of a quark/antimatter-quark pair. The line over the symbol denotes antimatter. **[end caption]**

Using this theory, it is possible to construct the quark content of all of the known mesons and baryons. A sampling is shown in Table 1.

Table 1: A sampling of mesons and baryons and their quark content. For the neutral pion and kaon, the quark content is given as a difference, indicating that the meson is a quantum mechanical admixture of the two states. There are many other quark combinations not given here. **[end caption]**

Mesons				Baryons			
Particle	Symbol	Charge	Quark Content	Particle	Symbol	Charge	Quark Content
Neutral pion	π^0	0	$u\bar{u} - d\bar{d}$	Proton	p^+	+	uud
Positive pion	π^+	+	$u\bar{d}$	Neutron	n	0	udd
Negative pion	π^-	-	$d\bar{u}$	Lambda	Λ	0	uds
Neutral kaon	K^0	0	$d\bar{s} - s\bar{d}$				
Positive kaon	K^+	+	$u\bar{s}$				
Negative kaon	K^-	-	$s\bar{u}$				
Charmonium	J/ψ	0	$c\bar{c}$				
Bottomium/Upsilon	Υ	0	$b\bar{b}$				

Exotic particles

The theory of mesons and baryons as sketched out in the previous section is relatively well known and can be found in both textbooks and books about particle physics written for the general public.[1,2] However, what is less generally known is that these are not the only configurations predicted by the theory.

For instance, in Gell-mann's 1964 paper,[5] he noted that his model also permitted the existence of what are now called tetraquarks ($qq\bar{q}\bar{q}$, two quarks and two antimatter quarks), pentaquarks ($qqqq\bar{q}$, four quarks and an antimatter quark), hexaquarks ($qqqqqq$, six quarks), and so on. The problem is that for a long time, no examples of these sorts of exotic quark matter had been observed.

However, over the past few decades, several experiments have observed particles that are candidates for all of these types of exotic matter. The field is still new and there remains considerable controversy for many of the observations. In the following section, I will give a selection of the various reports that have been announced over the last twenty years.

Prior to discussing some of the experimental evidence for these particles, there is a fundamental question that must be considered when analyzing data. You see, there are two distinct possible variants of all versions of this exotic form of quark matter, which depend crucially on the configuration of quarks and antimatter quarks. It is possible that all of the quarks and antiquarks could be thought of as existing in a single, tightly bound, state; but it is also possible that they might consist in a more loosely bound configuration of baryons and mesons.

Take, for example, the hexaquark, consisting of six quarks. At some level, a deuteron, which is the bound state of a proton and neutron (each containing three quarks), can be thought of as a type of hexaquark. However, a "true" hexaquark would consist of all six quarks intermingled together in a configuration that is similar to the manner in which quarks are found inside individual protons and neutrons. In contrast, the deuteron should be thought of as a dibaryon. This ambiguity is true of all of the various exotic forms of quark matter. Figure 4 illustrates the various possibilities.

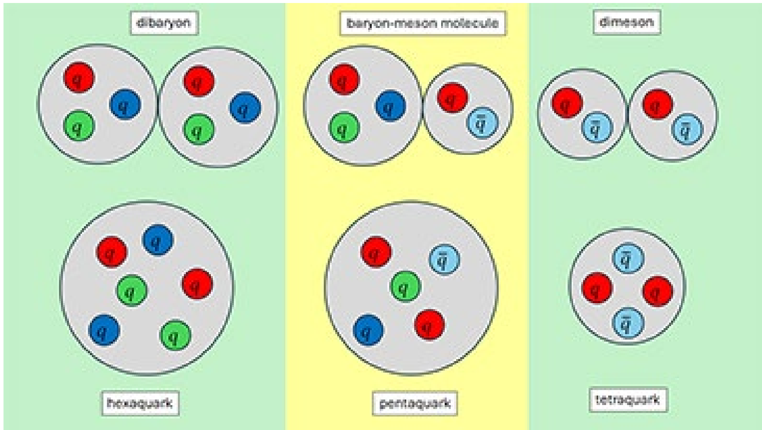

Figure 4: Exotic matter could consist of bound states of baryons and mesons (top) or a new form of matter which combines the quarks and antiquarks into a single container (bottom). **[end caption]**

The question of whether the recently observed examples of exotic quark matter are of the tightly or loosely bound forms remains an open question; indeed, it is both possible and likely that both forms exist.

Observations

While many unsuccessful searches for exotic hadrons were performed over the decades, probably the first one that can be called a reliable sighting occurred nearly 40 years after quarks were proposed. The Belle experiment[6] ran from 1999 to 2010. It was conducted at the KEKB accelerator in Japan, and it recorded the collisions of electrons and positrons. The energy of the collisions was tuned to copiously produce what are called $\Upsilon(4S)$ mesons (pronounced “upsilon-4S”). The $\Upsilon(4S)$ is a meson consisting of a bottom quark and antimatter bottom quark. The “4S” indicates that the quark/antiquark is in an excited state, roughly analogous to the 4S state of hydrogen. The goal of the experiment was to study a specific category of decays of the meson, in order to search for differences in the decay properties of matter vs. antimatter.

While the primary goal of the experiment was to search for matter/antimatter asymmetries, many other studies were performed. These studies include both the properties of known particles, as well as searches for unknown ones.

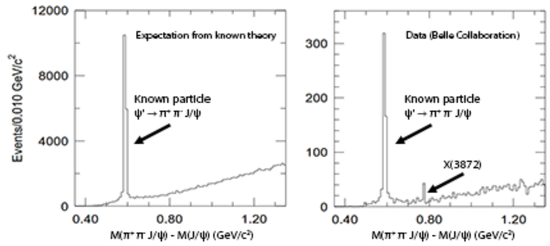

Figure 5: The first evidence for the existence of the $\mathrm{X}(3872)$ tetraquark. The x-axis is the invariant mass of three particles ($\pi^+\pi^-J/\psi$), minus the mass of the J/ψ meson. (This variable is intended to show the mass difference between the ψ' and J/ψ mesons, which was of interest in the reference from which the figure was drawn, but is not here. For this article, this choice is a historical curiosity.) The data (right) shows an additional peak compared to theoretical expectations (left). (Figure heavily adapted from Ref. 9.) **[end caption]**

The $\Upsilon(4S)$ decays approximately half of the time into a pair of B^+B^- mesons[7]. $B^\pm$ mesons are themselves unstable and decay in a myriad of ways. One such decay is the very complicated $B^\pm \to K^\pm\pi^+\pi^-J/\psi$ decay[8]. All of this is pretty standard, if a bit complicated, particle physics. The interesting thing arose when researchers did some studies intended to ensure that they were seeing what they expected. Specifically, they were verifying that they could see a certain known decay of charged B mesons, $B^\pm \to K^\pm\psi'$, with the subsequent decay $\psi' \to \pi^+\pi^-J/\psi$. The basic idea is that they should see a clear signal of the existence of a ψ' meson[10]. If they saw that, it would give them confidence that they were doing everything correctly.

So, the researchers constructed a distribution of a variable defined by the invariant mass spectrum of three particles, $\pi^+\pi^-J/\psi$, minus the mass of the J/ψ meson, under the assumption that these three daughter particles originated from the decay of a single parent particle. The expected result should include a sharp peak for events in which a ψ' meson is created, along with a continuum distribution arising from events in which these three particles do not originate from a single parent particle. Both theory and data showed the expected features; however, the data showed a second peak from an unexpected particle with a mass of 3872 MeV/c^2, now called the $\mathrm{X}(3872)$. The data is shown in Fig. 5.

After significant investigation into the nature of the $\mathrm{X}(3872)$ particle (e.g., spin, parity, charge, etc.), scientists ruled out the possibility that it is an ordinary meson or baryon and have concluded that it is a tetraquark with quark content $(u\bar{u}c\bar{c})$, however it remains unclear whether it is a di-meson or a true tetraquark. In the intervening years, this particle has been confirmed by many experiments[11].

The search for pentaquarks was much more difficult. While several experiments claimed in the mid-2000s to have found a pentaquark called a Θ^+, with a quark content of $(uudd\bar{s})$, subsequent experiments failed to confirm its existence[12].

It was only in 2015 when the LHCb collaboration[13] at CERN announced[14] the first compelling evidence for two pentaquarks, named $P_c^+(4380)$ and $P_c^+(4450)$, where the number denotes the particle's mass in units of MeV/c^2. Both pentaquark candidates are thought to have a quark content of $(uudc\bar{c})$, and were found in the decays of heavy baryons containing bottom quarks (Λ_b^0 baryons, with a quark content of (udb)). Figure 6 shows the clear signal of these particles. The LHCb experiment has subsequently discovered several other pentaquark states.[15]

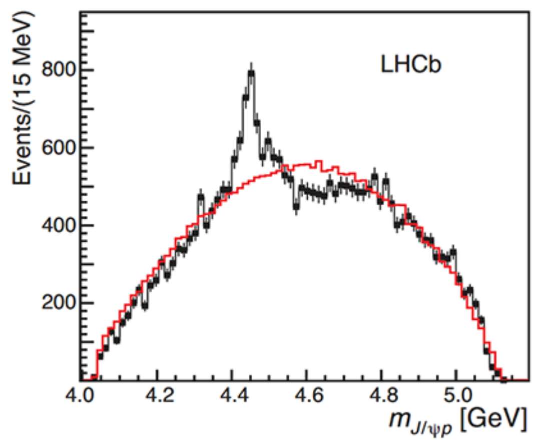

Figure 6: First compelling evidence for the existence of pentaquarks. The red curve shows the expected invariant mass distribution of combinations of J/ψ mesons and protons, while the black curve shows data. The peak near 4.5 GeV is readily apparent. More careful study has shown that this feature actually consists of two peaks, each with a slightly different mass. In addition to the difference in mass of these two particles, they have different spin and parity J^P, i.e., ($P_c^+(4380), J^P = 3/2^-$) and ($P_c^+(4450), J^P = 5/2^+$). (Figure heavily adapted from Ref. 14.) **[end caption]**

Searches for hexaquarks have been less successful. While some might call the deuteron a hexaquark, searches for other hexaquarks have produced results that are not universally accepted. An example of an experimental result that has not been confirmed can be found in Ref. 16.

What took so long?

Given the relative simplicity by which baryons and mesons were observed, why did it take so long to find these more exotic forms of quark matter? Surely, examples of tetraquarks and pentaquarks have long been contained in the data samples of the past half a century?

The answer is actually quite interesting. It boils down to a mix of the strength of the known fundamental forces and the effects of the Heisenberg Uncertainty Principle.

The astute reader might have noticed that the examples of exotic matter that have been offered here all contain heavier quarks, or are created in events in which heavy quarks play a role (e.g., charm and bottom). This isn't an accident.

At distance and energy scales typical of particle physics interactions, the strong force is of order 100,000x stronger than the weak force, which means that processes governed by the weak force happen more quickly. This implies that the lifetimes of hadrons that can governed by strong force interactions are typically quite short, of order 10^{-23} seconds or so.[17] A limitation of strong force decays is that the strong nuclear force cannot change the identity of an isolated quark. For example, a bottom quark could emit a gluon (the carrier of the strong force), but it would remain a bottom quark.

In contrast, interactions involving the weak nuclear force are weaker and therefore they take longer to occur. Weak force interactions typically take of order 10^{-16} – 10^{-12} seconds, although some can take even longer. This longer lifetime is a crucial feature of successful tetraquark and pentaquark searches. In addition, the weak nuclear force is unique in that it can change the identity of isolated quarks. For example, through the emission of a weak force particle called the W boson,[1,2] a bottom quark can change into a charm quark (e.g., $b^{-1/3} \rightarrow c^{+2/3} + W^{-}$).

The disparity in the lifetimes of particles that decay via the strong vs. weak nuclear force becomes relevant when one includes the Heisenberg Uncertainty Principle, specifically the form that relates time and energy ($\Delta E \Delta t \geq \hbar/_2$), where $\hbar = 6.6 \times 10^{-16}$ eV s is the reduced Planck constant. If we consider the lifetime of a particle to be of order the uncertainty of time for which it exists, we see that particles with very short lifetimes have a poorly determined energy, while ones with long lifetimes will have a comparably smaller range of energies. Using Einstein's $E = mc^2$, we see that long-lived particles have a unique and relatively well-defined mass, while short-lived particles have a much broader range.

The vast majority of the particles of the subatomic zoo last for tiny fractions of a second, which means that they cannot be directly seen in detectors. Instead, one looks for their longer-lived decay products and uses kinematics to determine the mass of the parent particle.[18] The difficulty is that you usually cannot know *a priori* which of the particles observed in any particular event have a common parent. Accordingly, you create a mass distribution of possible pairs, most of which are not related. The result is a continuum spectrum. However, some of the pairs do have a common origin, which leads to a peak in the mass spectrum. When you look at the distribution of all pairs, you will see a continuum with a superimposed peak. Figure 7 shows the basic idea.

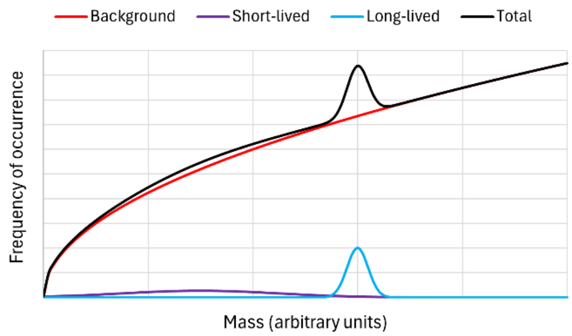

Figure 7: Representative mass spectrum. A short-lived particle (purple) creates a broad peak, while a long-lived one (light blue) creates a narrow one. When these peaks are added to a continuum (red), the result (black) clearly shows the long-lived particle, but finding the short-lived one is much more difficult. **[end caption]**

Since a short-lived particle results in a broad peak in a mass spectrum, it is more difficult to find. In contrast, a long-lived particle is relatively easy to observe.

All of this is a way of demonstrating why the observed tetraquarks and pentaquarks all contain heavier quarks. They are simply easier to find (c.f., Figs. 5 and 6). There must exist examples of these forms of exotic matter consisting of only the lighter quarks (up, down, and strange), but it is difficult to find them from continuum studies.

It is these longer lives that will also tell us something about whether these observed tetra- and pentaquarks are truly new or simply bound states of known baryons and mesons.

For example, the pentaquarks discussed previously ($P_c^+(4380)$ and $P_c^+(4450)$), are thought to likely be a bound meson/baryon state. The quark content of these particles is $(uudc\bar{c})$, and they are observed by their decay into a proton (uud) and a J/ψ meson $(c\bar{c})$. If these pentaquarks were just a bound state of the proton and J/ψ, they would decay quickly, as the binding energy would be quite low. In addition, given that in this configuration the $(c\bar{c})$ of the J/ψ would be in close proximity, the two could annihilate relatively quickly, converting into a photon, which would then convert into a muon and antimatter muon. Finally, if these particles were true pentaquarks, the quantum mechanical wave functions of the charm and anticharm quarks would be in proximity, again leading to a quick decay.

However, if these pentaquarks were, for example, a bound state of a baryon called a Σ_c^+ (quark content udc) and a meson like a D^0 (quark content $u\bar{c}$), this would account for the long lifetime. Given that the charm quark and antiquark are in different particles, their quantum mechanical wave function will not overlap a lot, which will suppress their mutual annihilation. Figure 8 illustrates the expected configuration.

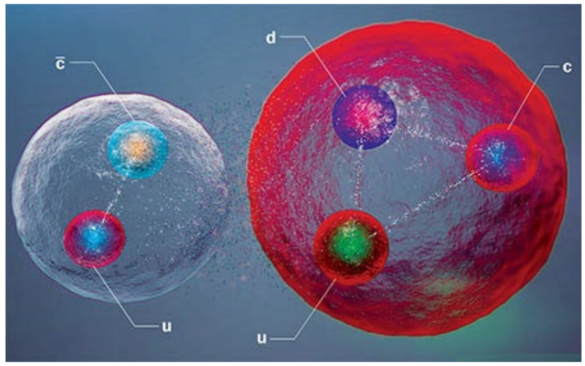

Figure 8: The recently found pentaquarks $P_c^+(4380)$ and $P_c^+(4450)$ are thought to most likely be a bound state, like that of a Σ_c^+ baryon (quark content udc) and a D^0 meson (quark content $u\bar{c}$). This configuration keeps the charm quark and antiquark away from one another, extending the life of this exotic state. Figure from Ref. 19. (Credit: D. Dominguez) **[end caption]**

The story of exotic quark matter continues to unfold. Researchers are constantly finding new candidates of tetraquarks and pentaquarks, each with their own myriad properties of mass, charge, spin, parity, and more. The question of whether these particles are bound states of baryons and mesons, or truly new forms of matter (or sometimes a quantum mechanical mix of both), has not yet been determined. Data taken at the Large Hadron Collider is only just now beginning to answer these questions and we can expect our understanding to improve over the next several years.

A deeper and more technical dive into this interesting topic can be found in Refs. 19 and 20.

References

[1] C. Schwarz, *A Tour of the Subatomic Zoo: a guide to particle physics*, IOP Concise Physics, Bristol, 2017.
[2] R. Crease and C. Mann, *The Second Creation: Makers of the Revolution in Twentieth-Century Physics*, Rutgers University Press, Rutgers, 1996; D. Lincoln, *Understanding the Universe: From Quarks to the Cosmos*, World Scientific Publishing, Singapore, 2012.
[3] S. Neddermeyer and C. Anderson, *Note on the Nature of Cosmic-Ray Particles*, Phys Rev. **51**, 884, 1937.
[4] C.M.G Lattes, H. Muirhead, G.P.S. Occhialini, C.F. Powell, *Processes Involving Charged Mesons*, Nature, Volume 159, Issue 4047, pp. 694-697, 1947.
[5] M. Gell-mann, *A Schematic Model of Baryons and Mesons*, Phys. Lett. 8 (3) 214-215 (1964); G. Zweig, *An SU(3) Model for Strong Interaction Symmetry and its Breaking,* CERN-TH-401, (1964); G. Zweig, *An SU(3) Model for Strong Interaction Symmetry and its Breaking: II*, CERN-TH-412, (1964).
[6] K. Abe et al. (Belle Collab.), *The Belle Detector*, Nucl. Instrum. Meth. A, 479 (2002), pg. 117-232.

[7] A B^+ consists of an up quark and a bottom antiquark, while a B^- consists of an up antiquark and a bottom quark.

[8] The quark content of these mesons are: $(K^+, u\bar{s})$, $(K^-, s\bar{u})$, $(\pi^+, u\bar{d})$, $(\pi^-, d\bar{u})$, and $(J/\psi, c\bar{c})$. The J/ψ meson, discovered in 1974, was the first particle discovered containing a quark type beyond the up, down, and strange quarks of the initial proposal. The peculiar name comes from the fact that it was discovered simultaneously by two groups, one of whom wanted to call it the J particle, while the other wanted to call it the ψ. For more of that story, see Refs. 1 and 2.

[9] Choi, S.-K., et al (Belle Collab.), *Observation of a Narrow Charmoniumlike State in Exclusive $B^\pm \to K^\pm\pi^+\pi^- J/\psi$ Decays,* PRL **91** (26): 262001 (2003).

[10] The ψ' meson has the same quark content as the J/ψ meson (e.g. $c\bar{c}$) but with the quarks in an excited state.

[11] A. Esposito, A. Pilloni and A. D. Polosa, *Multiquark Resonances,* Phys. Rept. 668, 1 (2017); F.-K. Guo et al., *Hadronic Molecules,* Rev. Mod. Phys. 90, 1, 015004 (2018).

[12] W.-M. Yao et al (Particle Data Group), *Review of particle physics*: Θ^+, Journal of Physics G. **33** (1): 1–1232 (2006).

[13] I. Belyaev et al, *The history of LHCB*, The European Physical Journal, H. 46 (1) (2021).

[14] R. Aaij et al. (LHCb collaboration), *Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays*, PRL 115 (7): 072001 (2015).

[15] R.L. Workman et al. (Particle Data Group), *Pentaquarks*, Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update.

[16] P. Adlarson et al., *Evidence for a New Resonance from Polarized Neutron-Proton Scattering*, PRL 112 202301 (2014).

[17] The lifetime of strong force interactions is governed by the range of the strong force ($d \approx 10^{-15}$m) and the fact that quarks move at near light speed within interactions ($v \approx 10^8$ m/s). Combine and you get ($t = d/v \approx 10^{-23}$ s).

[18] If a short-lived particle X decays into two particles A and B (e.g., $X \to A + B$), you can use measure the energy and momentum of the decay products, e.g., $(E_A, \vec{p}_A)$, and energy conservation to determine the energy and momentum of the parent, e.g. $E_X = E_A + E_B$. One can then use Einstein's full kinematic equation, $E^2 = (pc)^2 + (mc^2)^2$, to determine the invariant mass of the parent particle.

[19] M. Karliner and J. Rosner, *Inside pentaquarks and tetraquarks*, CERN Courier, vol. 64, pp 33-36 (November/December 2024); https://cerncourier.com/a/inside-pentaquarks-and-tetraquarks/

[20] P. Koppenburg and M. Pappagallo, *A Bestiary of Exotic Hadrons*, CERN Courier, vol. 64, pp 26-32 (November/December 2024); https://cerncourier.com/wp-content/uploads/2024/12/CERNCourier2024NovDec-digitaledition.pdf