Delta Baryons, Isospin, and the Need for a New Mendeleev

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Mendeleev's pragmatic table approach to capturing patterns in the chemical elements allowed it to endure even after quantum theory uncovered the simplicity that created those patterns. While predictively powerful, the Standard Model's early extensive use of mathematical symmetries likely added a level of noise that to this day is hiding, rather than clarifying, the deeper foundations of physics.

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I. THE CURIOUSLY CONSISTENT DELTA BARYONS

In early 2012, I asked a question [1] in a popular physics forum about the masses of the four spin $^3/_2$ Delta (Δ) baryons. Their designations are Δ^-, Δ^0, Δ^+, Δ^{++}, with the superscripts multiples (or sometimes fractions) the +1 charge of a proton. I wondered why these four baryons have nearly identical masses and lifetimes despite containing all four possible mixes of three up (u) and down (d) quarks. In the analysis [2] that became this paper, I found the comparison of Δ^- to Δ^{++} particularly striking since Δ^- contains three $d^{-1/3}$ down quarks while Δ^{++} has three $u^{+2/3}$ up quarks. Since the nominal "rest mass" [1] of a down quark is about half that of an up quark, the most naïve model is that Δ^- should be about half as heavy as Δ^{++}, or at the very least wildly divergent in mass. Yet to within a fraction of a percent, the masses of Δ^{++} and Δ^- are almost identical. That is… odd! It is also quite fascinating since it says that there must be some manner of "gears and wheels" working behind the scenes to keep all the Delta masses so closely similar.

While flying a one-woman ultralight airplane, a fast-developing fog bank enveloped her, causing her to lose her bearing. She soon found herself in a dangerous cityscape with huge buildings looming out of the fog, often just tens of feet away from her. Desperate to get her bearings, she sees a man on top of one such building and yells out to him, "Where am I?" The man on top of the building yells back, "You're in an airplane!" She immediately realized where she was, got her bearings back, and landed safely.

But how did she know? It was simple logic. Since the response to her question was precisely correct yet explained nothing, the building from which it emanated had to be the well-known headquarters of a vast personal computer software corporation known for giving only such answers in response to customer requests for help.

In the case of the delta baryons, the well-stated and quite mainstream answer I got back was that Delta baryons have similar masses due to isospin symmetry. Isospin symmetry is also responsible for why protons and neutrons have similar masses since they are also triplets of up and down quarks, just with spins that add up to ½ instead of $^3/_2$. The isospin symmetry is part of a broader set of symmetries called Lie groups (pronounced "Lee"). Lie groups have a lot to do with how things rotate in spaces with more than three dimensions.

So what's wrong with that? After all, I not only got an answer but one that was mathematically precise and directly related to both a historical prediction of new particles and a deeper understanding of the strong or color force. How can I possibly be disappointed by an answer that has had so much success at predicting and helping to verify new particles and concepts?

Easy: It didn't answer my question. I asked why these remarkable coincidences of mass exist – that is, what are the underlying "gears and wheels" that enable the masses of these particles with very different charges and very different constituent particles nonetheless to have almost

[1] To be honest, rest mass is a delightfully fictitious concept for quarks. A quark can only exist if bound to one, two, or possibly more other quarks via the strong force, creating an orbital-like bonding that ensures quarks are constantly in motion. What, then, does "rest mass" mean for a particle that can never rest?

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identical masses. The answer given by Lie groups boils down to saying that the particles are "symmetric" under certain rotation-like operations – think of Wheel of Fortune with the similar but numerically different wedges – and that in the case of the delta baryons, the symmetry is "almost exact," meaning there is very little difference in their masses after you rotate in different electrical charges. That, in turn, is the same as saying "by selecting different mixes of quarks."

II. TAUTOLOGIES VERSUS SYMMETRIES

The problem is that such an answer is ultimately tautological. It is a re-assertion of the premises of the original question, played back in a complicated mathematical form that makes it sound like an answer without really giving any new insight to the mass question. The most fundamental reason the delta particles are all known to have the same mass is that experimentally, they all have about the same mass. No one predicted that – it just happened. The similarity of the masses of these particles then guided theorists to deduce, correctly, that the four delta baryons (and other groups of other particles) are closely related in some more profound way. That latter part worked out well, and in time it helped lead to some of the most fundamental ideas in the Standard Model.

Nonetheless, while these ideas suggest that something deeper keeps the masses the same, they do not address at any deep level what those mechanisms are. One could argue it the other way around, for example. If there had been no data to constrain it, the quark model *by itself* would more likely have predicted that particles made entirely of either up or down quarks probably should have significantly different masses – a more strongly broken symmetry – than is seen in the four delta baryons. Given that the information learned about the delta baryons played a significant role in the formulation of the Standard Model, that's a bit ironic.

III. FUNDAMENTAL VERSUS COINCIDENTAL SYMMETRIES

A bit more pointedly: Despite their predictive power when used carefully, mathematical symmetries and concepts such as group theory are a great way to muddle things up royally if you are not careful in how you use them. If you are not careful, you can use group theory to transform understandable, straightforward relationships into multidimensional beasts whose notations are so cryptic that it requires years of training just to read them. It can also make *coincidental* symmetries look more important than they are. By a "coincidental" symmetry, I mean one that may be more a reflection of how you are doing your experiments than of nature itself.

An excellent example of a coincidental symmetry that nonetheless played a significant role in forming the Standard Model is the property of *strangeness*. The label reflects the fact that this property messed up a lot of early predictions in particle physics. We now know that strangeness is just a measure of how many strange quarks are in a particle and that a strange quark is not much more than an overweight twin of the very common down quark. As it turns out, every fundamental point-like particle has three versions whose only difference is mass. For example, the electron also has a next-heavier version of itself called a muon.

Early experimenters and theorists did not know any of this, however. Early particle colliders were energetic enough to create many strange quarks since strange quarks are the lightest of the following two generations of fatter, higher-mass quark variations. Because these strange quarks are identical except in mass to down quarks, they could slip in and replace down quarks for any particle where a down quark would have been. This ability to one-for-one substitute strange quarks for down quarks considerably expanded the range of possible particles, and in doing so, it also created a series of apparent symmetries based around the property "strangeness." Adding strangeness allowed theorists to predict new families of particles in much the same way that discovering columns of similar elements enabled Mendeleev to predict new elements and closely related compounds.

Now it's important to point out that not only were these symmetries correct, but they also were beneficial for predicting some critical new particles, in particular the Omega baryon, Ω^{-1}. This baryon has one negative charge and is composed entirely of down-like strange quarks, and is nothing more than the strange-quark analog to the all-down-quarks Δ^{-} particle I mentioned earlier.

So, once again: If these symmetries proved so effective, why should I complain about them at all?

The reason is that they resulted in a false assumption that you can still see in older books and works on particle physics. The assumption is that strangeness is a property on an equal par with "up-ness" and "down-ness." That is simply wrong. In a society composed of thin people, it is like declaring that the first overweight man ever encountered a new gender distinct from males and females. While the obese man adds more weight to dances, he still plays the same role as his slenderer counterparts.

Given that there are a total of four such fat quarks (strange, charm, bottom, top), there is no fundamental reason for distinguishing strange any more than charm, bottom, or top. The deeper symmetry must involve all six quark types and fully recognize the archetypical roles of the up and down quark, with the other four being just mass variants of these two. The symmetries found early on, such as the incomplete $^{3}/_{2}$ spin baryon decuplet that led to the prediction of the Ω^{-1} baryon, were valid but incomplete, reflecting the limits of the particle colliders of the time as much as they reflected the symmetries of matter itself.

The example of misclassifying strangeness shows how premature assignment of a mathematical symmetry can complicate, rather than clarify, the actual physics. Every such assignment is, to some degree, a leap of faith that *assumes* the full range of mathematical symmetries applies to actual physics. Such leaps of faith sometimes work out beautifully, such as in Dirac's predictions of the anti-electron. However, in other cases, they are wrong and only create confusion.

One way to lessen the risk is to use methods that seem less impressive from a precision perspective but more honest in terms of uncertainty in the data. Such less-precise descriptive methods look more like recipes or construction models than symmetries, with both triplets of quark for hadrons and ball-and-stick for organic molecules being examples. Such less precise models can be surprisingly powerful for making non-mathematical predictions about what is or is not possible and for gaining insights of a different type from those of equations.

IV. MENDELEEV AND GROUP THEORY

If you've read this far and are still wondering why I mentioned Mendeleev, the creator of chemistry's periodic table, in my title, here's why: The periodic chemistry table is full of partial symmetries, some of which are not much different from the symmetries of particle physics.

For example, Group 1 of the periodic table — the elements H, Li, Na, K, Rb, Cs, Fr — form a symmetry group in the sense that *usually*, one can substitute for another in compounds such as salts without changing the results much. The symmetries of the periodic table are incomplete since some distinguishing properties are inevitable. However, at the chemistry level, such symmetries can be so good that it is difficult to isolate elements from each other. Zirconium and hafnium are perhaps the best examples of chemical indistinguishability between elements with radically different atomic masses. Masses always break the symmetries of the periodic table groups since, at the nuclear level, the elements are all distinct. Isotopes — elements with the same numbers of protons but different numbers of neutrons — are arguably even better examples of chemical symmetries since, with one exception, none of the distinct isotopes of an element are distinguishable chemically. (The exception is deuterium or heavy hydrogen, which differs enough from hydrogen to be fatal if ingested in large quantities.)

Mendeleev knew nothing or next to nothing about group theory and did not attempt to group elements using such concepts. Instead, he constructed tables and tried to get elements with similar chemical properties to line up. Early particle physicists used similar grouping techniques based on optical properties to create singlets, doublets, triplets, octets, and decuplets.

Mendeleev never took his work much beyond the table level. His table-form framework captured similarities and documented trends but otherwise left it to later generations to decipher the inner gears and wheels behind those trends.

In retrospect, that was probably a good thing. By organizing the data while adding as few assumptions and additional structure as possible, Mendeleev produced a product ripe for later developments when the theory of atoms and quantum mechanics emerged. The needed theoretical ideas did not yet exist in Mendeleev's time, and in the case of quantum theory, they proved to be so bizarre that no amount of earlier speculation would have helped. The simplicity and lack of added assumptions made Mendeleev's table thus likely made the later emergence of quantum-based chemistry easier, not harder.

But here's an interesting question: What if Mendeleev had been an expert in group theory and had insisted on expressing the patterns he uncovered in terms of higher-dimensional groups and matrix operations?

He certainly could have done so, but the result would have been far more complicated and challenging for other chemists to follow. While it would have been more integrated mathematically, it would also necessarily have contained many perplexing assumptions and mysterious constants to account for inconsistencies that, even to this day, are not fully explainable with quantum theory. Using techniques such as matrices would have made it inaccessible even to most college graduates. It certainly would not have been presentable to students in elementary schools, as is Mendeleev's actual periodic table is. On the other hand, it would have been an impressive construct to those who had the time to learn it.

So my question is this: If Mendeleev had created a much more mathematical group-theory-based periodic table in some alternative history, would that table have helped or hurt the eventual emergence of quantum chemical theory a few decades later?

Most likely, it would have slowed progress. Compared to Mendeleev's humbler table-based work, the risk of introducing subtle assumptions by overextending patterns — the "strangeness effect" to use an actual example — would have distracted researchers to follow too many bogus leads that were fare more features of the model than of the actual data. A good term for this is *theory noise*.

V. THEORY NOISE

Recognizing the existence and risks of theory noise is essential since a theory is a form of communication. A noisy theory can be technically correct, yet in practice, it consumes everyone's always-finite intellectual time with ideas and concepts not relevant to the underlying message or predictions of the theory. Theory noise includes needless redundancy, in which a single underlying idea ends up replicated and distorted into forms whose underlying commonality is no longer easy to discern.

Forced fitting of symmetries is one way that theory noise can arise. Breaking a symmetry in ways that do not fully reflect underlying data is one way this can occur. When this happens, the result can be a theory that distracts people away from the actual causes of the underlying regularity. For example, the regularities of the Group 1 chemical elements did not receive a precise explanation until decades later, when new theories of atomic structure and quantum behavior were able to explain cycles of the periodic table in terms of the unusual stability of doublets and octets of electrons. If Mendeleev had made premature assignments of group symmetries to describe Group 1 and other periodic table symmetries, he would have created theory noise.

When a theory has a high noise-to-content ratio, it becomes difficult to comprehend, and even adept users may have trouble pushing it forward. The noise begins to define the model, and users spend so much time dealing with that noise that they have few intellectual resources or options for new, innovative ideas. Even worse, theory noise clouds perception and makes it harder to cross-link commonalities within the model. The identification of such commonalities is typically one of the critical steps in making significant new theoretical progress.

A noisy theory is like a wall made of warped glass tiles. The tiles present viewers with many different images of the reality on the other side but at the same time provide no real insight into the rhyme or reason behind why the wall-generated images are slightly different. Viewers spend most of their deciphering the warping effects created by the wall instead of focusing on the other side.

VI. THE MENDELEEVIAN CHALLENGE

So three cheers for Mendeleev! He stuck to simplicity even as he worked to unravel one of the greatest mysteries of similarity and difference in all of scientific history.

While there's no doubt the Standard Model has done remarkably well at capturing known particle physics, there is a separate question that to be addressed: Does the Standard Model convey its theoretical reality in a way that is simple, straightforward, minimally redundant, and sufficiently fundamental? Or is it a noisy theory?

Just this week, a physicist who once worked at CERN noted to me that "the Standard Model describes everything and explains nothing." Also, despite the phenomenal successes of the Standard Model at predicting particles, for almost forty years, particle theory has languished in a desert free of new predictive insights. Ironically, it was the very experimental success of the Standard Model that helped create this desert. Sadly, the lack of predictive challenges caused far too many theorists to focus instead on empty philosophies, ideas that lack any real connection with experimentally predictive physics or traditional scientific criteria of theoretical success.

VII. TRANSFORMING THE STANDARD MODEL

Another possibility is that even though the Standard Model is technically brilliant and all-inclusive, it is also very noisy. While to this day, they retain the same simple format, the modern version of Mendeleev's is rich with details and explanations beyond anything Mendeleev could have imagined, provided decades later by quantum theory. Quantum theory now explains with considerable specificity how complex patterns such as octets of element columns emerge from the elements.

While some may claim it, no such simplification of the Standard Model ever occurred. Patterns as simple as why there are four fundamental archetypes of fermions — neutrinos, down quarks, up quarks, and electrons — have never been explained, at least not in a way with which everyone agrees. That's deeply ironic since both the Period Table and the current Standard Model show clear signs of the presence of deeper gears and wheels whose churnings produce such partial patterns and unexplained constants. One sign of how bad the situation has become is the number of papers that abandon all hope of simple explanations, preferring instead to invoke infinite numbers of universes and "selection" of the one that happens to have the Standard Model particles and particle charges.

A more palatable possibility is that the Standard Model crystallized too quickly, locking in so much theory noise and redundancy that further insight became difficult. A new generation of physicists and mathematicians needs to reexamine the Standard Model with an eye for finding genuine simplicity in existing patterns. Perhaps some new Mendeleev can peer deeper at data that has existed for decades. Just as deciphering the structure of DNA rested as much on pulling on a couple of tiny and seemingly minor clues in the DNA data as it did on overall data, the Standard Model very likely still had the critical clues to greater simplicity hidden in plain sight. Someone needs to start looking for those threads and yanking them hard.

[1] T. Bollinger, "Similar masses and lifetimes of the Δ baryons." Physics Stack Exchange, 2012-02-14. https://physics.stackexchange.com/questions/20999/similar-masses-and-lifetimes-of-the-delta-baryons (Accessed 2021-11-12)

[2] T. Bollinger, "Delta Baryons, Isospin, and the Need for a New Mendeleev." terrybollinger.com, 2012-02-18. https://terrybollinger.com/physics_essays/bollinger_20120218_mendeleev_and_group_theory.pdf (Accessed 2021-11-12) https://tarxiv.org/tao.2012-02-14.ob1.pdf (Accessed 2021-11-13)