Genies in Physics: The Magic of Locking Phenomenal Forces into Itty-Bitty Spaces

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Figure 1. *Unleased, the electric force would obliterate the universe. Tightly bottled, it enables the magic of chemistry.*

Despite the immense power of gravity in everyday life and physics, you've likely heard science teachers and professors comment on how much weaker gravity is than the other forces of physics, such as the pull of oppositely charged electric bodies. Our intuition based on everyday experiences tells us otherwise since, for example, it's easy to think of examples where static electricity can barely keep a balloon glued to the wall in the face of the unrelenting pull of Earth's gravity. The idea that such a weak electric-charge attraction force could, for example, suspend our entire bodies against the pull of gravity seems unlikely or even silly.

Appearances can be deceiving since the number of electrons needed to hold a balloon to the ceiling is insignificant compared to the number of atoms in a balloon. Is there a better way to compare the strengths of gravity and electric charge, which more fairly captures the power of the electric force?

Nobel Laureate Richard Feynman once made just such a comparison [1][2]:

> *[6:06] ... The protons and the electrons ... form the most intimate possible mixture because of this enormous [electric] force. ... So fine and so perfectly are these terrific forces balanced that ... [if a particular individual is] 10 meters away [from me], there's practically no electrical force. ... [But] if we each had an excess of 1% more minus charges than plus charges, then we would repel each other by an incredible force. How great? Enough force to lift the Empire State Building? No! Mt.*

> *Everest? No! [It is] enough force to lift a weight equal to the mass ... of another entire Earth standing next to [our] Earth. So incredible is this that I made the calculation four times, hoping, thinking, "I must have made a mistake in the decimal point," and I hoped that somebody would check me and find out that it really is only the Empire State Building. [8:02]*

Phenomenal Cosmic Powers

Now imagine extending Feynman's thought problem of a 1% excess of electrons to the entire cosmos. What would happen?

In such a universe, *every* rock, bolder, or volume of gas about your size would repulse *every* nearby rock or volume with the same planet-pushing force of Feynman's example. Even worse, that's for the optimistic case of these chunks being a good-size room away from each other. This force *quadruples* every time you cut that distance in half, meaning the person at the back of the room would get pushed away from Feynman with *four times the pull of two Earth-sized planets* almost touching. The closer you get, the worse this repulsion becomes.

Even best friends don't hug in this 1%-excess-charge universe. Of course, hugging someone assumes you could remain intact long enough to come up with the idea — which you would not since your body would repel its parts far more enthusiastically than anything as far away as the other side of a room. You and everything around would explode with mind-boggling enthusiasm, dwarfing anything conceivable in our universe. A nuclear explosion in this universe would, at most, become a negligible smudge of disturbance in the ongoing dissipation of the Earth.

Things only get worse for objects the size of stars. The idea that a star-sized collection of 1% excess matter could be held together by *gravity* — assuming such a trivial force could be detected — is absurd. This 1% excess electrons universe has only one outcome: Instant demolition and vaporization of *everything*, leaving nothing but a plasma of particles expanding at a speed vanishing close to that of light.

This example is the true comparison of the power of electric charge to gravity. It is power so phenomenal that gravity becomes less than a wisp of smoke. Fully unleased — or even just *1% unleashed* — it becomes an instantly overwhelming power that obliterates every trace of the universe we know.

Itty-Bitty Living Spaces

But why does this *not* happen?

If the electric force is a genie that, if unleashed, is unbelievably more powerful than gravity or any other everyday force of pull or cohesion, how do we survive its presence? Why do we not end up as nothing more than snails crossing an incredibly busy and deadly highway of random fluctuations of electric forces of various scales?

We see just a trace of this power in phenomena such as lightning. For those fortunate enough to be on the path of the 2024 total eclipse in North America, you have a memory of a far more powerful example of the power of the electromagnetic force: Those two or three red dots you saw around the edge of the sun. Each of those was a loop of electromagnetic forces many times larger than Earth, ripping matter and energy away from the immense gravity of the sun as if it was nothing at all, suspending it in space for months at a time, and ejecting parts of it across space to sometimes collide with Earth and give us spectacular northern lights.

All of these are nothing but the tiniest whispers of far deeper forces. As Feynman suggests, the genie of electric repulsion fails to impact our world much because most of it is trapped incredibly fine mixing of opposite charges that *almost* fully cancel. On Earth, this traps and locks the electric force into the tiniest of vessels: atoms.

The Surreal Magic of Atoms

Atoms! You know they are tiny, but they are far more magical than you may realize. The first point to consider is how effectively these tiny lamp-like containers keep the electric genie from destroying everything on Earth. Sure, it leaks out here and there to give us lightning and other spectacular effects, but those are shadows of shadows, incredibly dim images of the true forces inside every atom.

Atoms work because, for every electron that would rip the universe apart, they provide exactly one proton that is every bit as powerful as the electron but also *fully cancels* that electron. Within any given atom, the immense force of these two opposed electric genies results in an unending battle that would utterly and fully obliterate any object or bond in our larger world exposed to similar forces. Both positive and negative charges fight for release, but both want that release at the expense of the other. The result is an eternal stalemate — an almost-total bottling of *both* genies. Each would like to destroy the cosmos, yet instead, both end up *protecting* the cosmos.

Another magical mystery of atoms is this: *Why* does our universe contain almost exactly one such proton lamp for each otherwise phenomenally destructive electron?

You might be surprised to hear that the fully honest answer is that *no one knows*. You may have heard that charges come in pairs, so that, for example, you can take one very energetic photon — a gamma ray — and sometimes split it into two particles: the ordinary electron and an *antimatter* version of that electron — a particle called a positron that has precise the same charge as a proton. Problem solved! One can only create charges in balanced pairs, so the universe has an exact balance of the two.

Not so fast! The problem is simple: A positron *is not a proton*. A universe of nothing but electrons and positrons would not look like ours and would turn back into a universe of gamma rays almost instantly. That's because when an electron and a positron form an atom, the atom almost instantly destroys itself and reverts to a couple of gamma rays.

(Incidentally, these atoms built of electrons and positrons are observed fleetingly in both nature and laboratories. Technically, they form the lightest of all possible elements, *positronium*, though it is not a name seen often in Periodic Tables. However, since positronium endures far longer than many short-lived radioactive elements at the heavy end of the periodic table and has a curiously hydrogen-like electron shell, it deserves more attention as an element than it receives.)

Protons as Magic Lamps

Thus, the mystery is not why our universe keeps positive and negative charges in balance. After all, every physics reaction we know of creates them in pairs. The utterly baffling question is this: *How* did half of that charge end up not on positrons but these bizarre, incredibly heavy beasts called protons, which serve as the magic lamps that keep the negatively-charged genie of electrons forever captured but never annihilated? Where do these complicated proton constructions come from? Why do they exist at all?

The phrase "never annihilated" is important. Magic lamps don't *annihilate* genies. They *confine* genies. An annihilated genie is no longer a threat but also loses the ability to do *anything* interesting. It is a dead genie.

The case for the electric genie is similar. The more obvious case of a *positronium* lamp quickly *annihilates* the electron-charge genie, taking its power entirely out of the picture and replacing it with a boring universe of nothing but intense light. The bizarre and immensely more complicated construct of a *proton* lamp does not and, in nearly every case, *cannot* entirely remove the electron from the picture. Proton lamps only *contain* the power of negative charge within an atomically tiny space. It remains incredibly intense and bent on escape, looking for ways to unleash its power. Protons are the confining lamps that keep Feynman's scenario from happening.

The Bizarre Mystery of Almost-Annihilation

Here's a mystery for you: If the lamp in the tale of Aladdin is nothing but a mundane object, how can it contain the cosmic power of a genie? There is more to that lamp than meets the eye!

A similar statement holds for proton lamps: How in the world does a proton manage to confine the charge of an electron without *quite* annihilating it? How can these magic lamps — better known as hydrogen atoms — endure literally for the universe's lifespan "getting hungry" and simply eating the electron genie, returning to some more photon-like state?

It's a bit worse than the nice simplicity of a uniform "no eating allowed" policy. You may have noticed earlier that I said that proton lamps *almost* always never eat their electron genies. If you watched the eclipse of 2024, you used glasses to gaze at proof that this is not always true: The light of the sun. Deep in the sun, pressures and other far more complicated processes *occasionally* allow a proton lamp to eat its electron genie. The result lacks a significant electric charge, but it is also a particle so remarkably similar to the proton that it used to be called a *symmetry* of the proton. We call it a *neutron*, and its formation enables the nuclear fusion that powers the sun.

The question, then, is not *whether* proton lamps sometimes eat their electron genies — they do — by why, in most cases, they do *not*.

The answer goes back to the issue of needing zero balances — the same one that drives electrons and positrons to annihilate each other to produce true elimination of both charge genies. Protons have one net unit of the same electric charge as positrons *when viewed from a distance*. However, they do it piecemeal up close, combining and partially canceling special charges from *three* particles. These particles, called *quarks*, have their stubborn idea of how to get the bank account balance back to zero. Each is happy *only* if it can meet an exact antiparticle equivalent of itself. The electron cannot provide that, so the entire lamp-and-genie system enters a ferocious standoff that *mostly* cancels electric charge but cannot annihilate the individual particles.

However, the greatest mystery of the proton-and-electron lamp-and-genie system is what happens when arguments about balancing checkbooks block mutual annihilation. At this point, the rules of quantum mechanics emerge. At the scale of proton lamps, the confining behavior of quantum mechanics exhibits itself in a deep fashion that only great minds and young children can understand well: skip ropes! Fig. 2 shows how this curious quantum mechanical version of extreme confinement works in atoms with multiple protons.

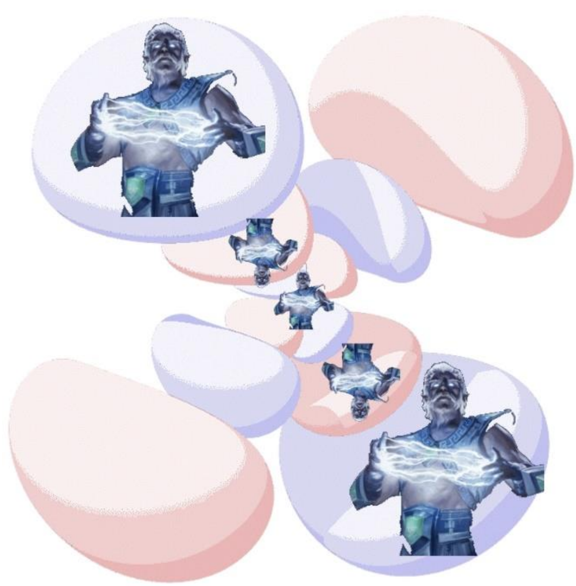

Figure 2. *The proton "lamps" of atomic nuclei lock up the power of electrons within incredibly tiny lobes.*

Fig. 3 gives the skip-rope interpretation of how quantum confinement produces such oddly shaped genie cages. Unable to resolve their charge-annihilation quandary, the massive proton lamp and lightweight electron genie begin a dance with each other. Each tries to get as close to full annihilation of both of their charges as possible but is blocked not only by the inability of quarks to cancel all properties of electrons fully but by other electron genies performing their dances on what can become an extremely crowded dance floor.

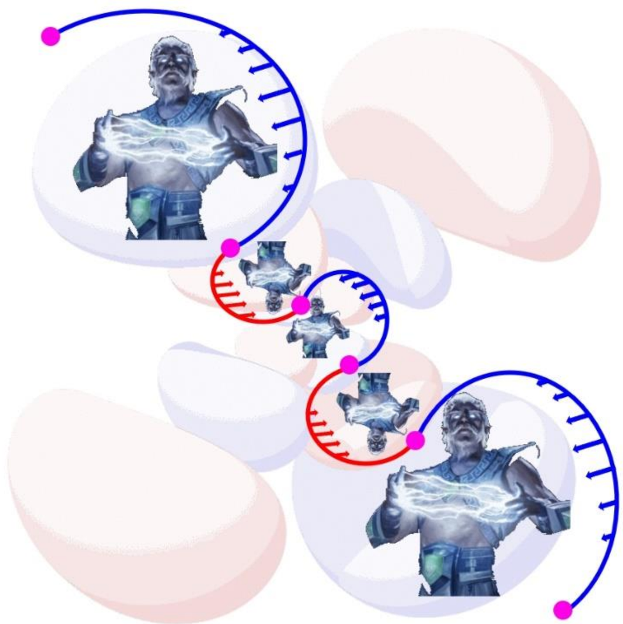

Figure 3. *While more complex in full computational form, confinement always has a skip-rope component.*

To calculate such results with any precision, one must use the same equations that produced the images of these lovely orbital lobes in the first place. However, it's easy to miss the simplicity of what is going on, which bears a remarkable resemblance mathematically to nothing more than a vibrating string, albeit one wrapped around in odd ways within the "bent box" of positive charge that is the nucleus. Mathematically, this string forms loops not that different from those seen in a long, flexible cord dangling from your fingers. The electron genie's powerful charge is then captured remarkably literally within the boundaries this abstract form of vibration marked out. In this case, the blue and red lobes represent regions in which the positions of the rope — the "phases" of the rope — are precisely opposite. The purple dots are regions where even the genie's power cannot reach between them. Even in an entity as small as an atom, the tremendous field of the charge cannot penetrate these points. The splitting effect of these "null points" causes the charge genie to appear in multiple images or charge regions.

Vibrating Strings in Still Deeper Places

The presence of skip-rope-like confinement in particle physics doesn't end with electrons.

Do you recall those quarks I mentioned inside protons and neutrons, the particles whose charges add up to those of an electron but whose "bank accounts" contain other quantities that cannot be satisfied by canceling themselves out with an electron?

Quarks have their version of the lamp-and-genie lamp model that binds them together, but in a far more symmetric fashion than heavy protons and light electrons. Their unique charges form *flux tubes* that are not just "similar" to the rope model I showed in Fig. 3 but, for all practical purposes, *are* vibrating ropes — actually, a bit more like stretchy rubber bands — that connect the quarks and engage in various types of vibrations closely akin to those of dangling cords and violin strings.

Figuring this out was no trivial matter since, like any good science project, it began with enormous quantities of data first collected by particle accelerators in the 1960s. There was no reason at that time to suspect anything that small would or could have quantized vibrations akin to the one or more loops of a skip rope. After much examination of both the data and the models of that time, in particular, Richard Feynman's then-new Quantum Electrodynamics (QED) model [3], physicist Leonard Susskind was the first to realize that this massive set of data theory largely boiled down to the remarkably simple statement that the math of such internal binding resembles that of rubber bands and skip ropes, suitably translated into mathematical phase spaces [4].

Professor Susskind should have won (and still should win) a Nobel Prize for this enormously important, profoundly non-obvious, and deeply data-driven 1969 insight. He did not due mostly to a quirk of history: He recognized the existence of such string vibrations *before* either quarks or flux tubes were known definitively to exist. Yet it was Susskind, rather than the Nobel Laureates who developed quark and color force models, who first figured out that the forces inside protons behaved in a stretchy, linear fashion utterly unlike the rapid fadeout of the electric or gravity forces — and he did so before anyone figured out that these forces exist! These stringlike confinement dynamics pop up persistently — though often less blatantly, as in the warped case of electron orbitals — whenever the issue of force confinement and "taming" of otherwise unimaginably powerful forces comes up in physics.

Confinement Creates Complexity

Finally, the confinement and almost-but-not-quite annihilation of electron genies do much more than allow flimsy gravity and weakly bound objects like planets and stars to exist. As shown by the dance of ropes in Fig. 3, near cancellation creates *complexity* in how atoms behave. As it tries and fails to escape its lamp, the electron genie's power creates extraordinarily complicated shapes and orientations of where its charges end up. These charges are also dynamic and seek to interact with other nearby atoms to increase the electric charge's range.

At small scales, these attempts to escape the lamp lead to such critical effects as atomic bonding in which an electron can, at least, extend its cage over two or more atoms, providing a bit more confinement relief. The breakout attempts can get quite clever and extend over scales far large than molecules, as anyone who has ever received a shock from touching some bit of metal can attest to. The concept of conduction bands is little more than the immense power of the electric force spreading itself out into our everyday realm. It is always moderated, of course, but it also creates incredibly useful effects for those who understand how the genie works.

Thus, as scarily powerful as these genies are, when we have the lamps to keep them in check, they become the foundation not just for our world to exist but for us to learn how to tickle these forces correctly to make our modern world possible. Be thankful for powerful forces in tiny places!

References

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