1/137: The Number That Holds the Secrets of the Universe

Fine structure constant

The Number That Holds the Secrets of the Universe

The number 1/137, also known as the fine structure constant (α), is a fundamental constant in physics that measures the strength of the electromagnetic interaction between charged particles. It is a dimensionless number that does not depend on the measurement system used, making it a pure number that exists independently of our measurement systems. The fine structure constant is crucial in various areas of physics, including relativity, electromagnetism, and quantum mechanics, and it plays a key role in determining how atoms form and interact with each other. The constant has intrigued physicists since its discovery in the 19th century, and it remains a subject of fascination and study for those interested in the mysteries of the universe.

1. **The fine-structure constant, denoted by α, is a fundamental physical constant approximately equal to 1137** 1371 **that quantifies the strength of electromagnetic interactions between elementary charged particles.**

   Definition and Value

   The fine-structure constant (α) is a dimensionless quantity that plays a crucial role in quantum electrodynamics (QED). Its approximate numerical value is:

   α≈0.0072973525693α≈0.0072973525693

   This value implies that its reciprocal is about 137.035999177, which is often rounded to 137.

   Significance in Physics

   1. **Electromagnetic Interaction**: The fine-structure constant characterizes the strength of the electromagnetic force that governs interactions between charged particles, such as electrons

and protons. It is essential for understanding atomic structure and the behavior of light and matter.

2. **Quantum Mechanics**: α emerges in various equations and theories within quantum mechanics, influencing phenomena such as the splitting of spectral lines in atoms, which is known as fine structure.
3. **Dimensionless Nature**: Unlike many physical constants that depend on the units used (like the speed of light), α is dimensionless, making it a pure number that is universal across different systems of measurement.
4. **Mystery and Fascination**: The value of 11371371 has intrigued physicists for decades, leading to various theories and speculations about its significance in the universe. Richard Feynman famously referred to it as a "magic number" that holds deep implications for the nature of reality.

Historical Context

The fine-structure constant was introduced by physicist Arnold Sommerfeld in 1916 as part of his work extending the Bohr model of the atom. It was used to explain the observed fine structure in the spectral lines of hydrogen. Despite its importance, the reason for its specific value remains one of the unsolved mysteries in physics, with ongoing research aimed at measuring it with greater precision.

In summary, the fine-structure constant α is a fundamental aspect of our understanding of the physical universe, influencing everything from atomic interactions to the very fabric of quantum mechanics. Its approximate value of 11371371 continues to inspire curiosity and investigation among scientists.

The strange number 1/137 shows up everywhere in physics. What does it mean?

Does it have a deeper significance — or is it just a number?

KEY TAKEAWAYS

- The *fine structure constant*, a number that emerges from theories of quantum mechanics, is measured in laboratory experiments to be roughly 1/137.
- This slightly coincidental number is a perennial source of excitement.
- While its meaning holds some intrigue, the greatest mystery surrounding this number is why it so fascinates physicists.

Popular science coverage of theoretical physics frequently fantasizes over the fraction 1/137. PBS Space Time mused about it for 20 minutes. *NewScientist* hyperbolically called it "the answer to life, the universe, and everything." Numerologists, including religious ones, have been inspired by the number.

To be fair, science popularizers and numerologists alike are taking their cues from eccentric physicists. Various 20th century quantum theoreticians made bold guesses, claims, and rambling metaphysical speculations about 1/137. Among them are Nobel Prize winners like Wolfgang Pauli, Paul Dirac, and Richard Feynman. Who are we mere mortals to disagree with these giants?

Geniuses are sometimes wrong. Feynman was an egotist who would do anything for attention and thought that brushing his teeth was a superstition. Pauli dabbled in parapsychology, alchemy, and numerology with Carl Jung. Maybe the mysterious 1/137 — which is known as the *fine structure constant* — falls into this camp?

It's not really 137

Let’s start with what the value of the fine structure constant (α) actually is. According to NIST, the best measurement of the number is 0.0072973525693 — give or take 0.0000000000011. When you take its reciprocal (1 divided by that number), the result is about 137 (specifically, 137.035999084, again according to NIST).

Thus, the numerological significance of 137 has lost some of its shimmer. The actual number is 137.04 (rounded). It’s not 137. If your grocery bill came out to be $137.04, would you shriek with excitement because it was almost 137? Probably not, yet that’s what some physicists and science popularizers are doing here. It’s also not clear what’s so exciting about 137. It is a prime number, so that’s sort of cool — but there are a lot of those (an infinite number, actually). Besides, other numbers are arguably cooler; the number 6 is probably the coolest.

α appears everywhere

The non-numerological nature of α is far more interesting. It is a natural ratio that pops up in sophisticated (and less sophisticated) models of atoms, electrons, and photons. Perhaps most interestingly, the number has no associated units, so it’s not dependent upon our arbitrary systems of measurement.

You’re already familiar with “unit-less” numbers. Pi (π), which is ~3.14 and represents the ratio of a circle’s circumference to its diameter, also has no units. It’s not 3.14 meters or 3.14 inches or 3.14 hamburgers. It’s just 3.14. α is like that. And just like π, α shows up in a variety of physics equations.

But here’s the bottom line: Like π, α is simply a fact of life, a number to be plugged into a formula to calculate an answer, like calculating light emission from an atom. The number itself comes from the need to calibrate the mathematics behind quantum mechanics to match experimental observations. In the same way that a map needs a scale factor to translate inches on the paper (or screen) to miles on the ground, mathematical physics theories need scaling numbers to match data.

Some physicists and science enthusiasts are hunting for a deeper meaning, but there isn’t one. However, to search for meaning is a fundamentally human endeavor, and weird numbers tempt us into doing just that. This may be best demonstrated by something called the *Eddington Number*.

The Eddington Number

Brilliant astrophysicist Sir Arthur Eddington famously developed a theory, founded upon multiplying the inverse of α (which he believed to be exactly 136) by 2^{256}. He described its results in this way:

“I believe there are 15747724136275002577605653961181555468044717914527116709366231425076185631031296 protons in the Universe, and the same number of electrons.”

This physical constant was dubbed the Eddington Number, N_E. According to fellow genius Subrahmanyan Chandrasekhar, Eddington was so smart that he calculated N_E by hand on paper during a voyage across the Atlantic. Later astronomers re-checked with a computer, and Eddington got it exactly right. That is to say, he got the calculation right; of course, no one knows how many protons are actually in the Universe. Whatever the true number of protons may be, it's a good bet that it isn't determined by multiplying arbitrarily "beautiful" numbers.

Math isn't magic

This sort of mysticism for strange numbers is the product of attempting to ascribe meaning to mathematics, as if math itself was the underlying fundamental reality of existence. But it isn't. True, math is extremely effective at describing the Universe, in part because much of it was literally invented to do so. Math has always had irascible champions who see it as a pure and abstract art, even though most of its historical development was motivated by the need to calculate a "good enough" answer to some important problem.

This isn't to say that math isn't awe-inspiring or beautiful. It absolutely can be. Mathematician Dr. Francis Su describes the spiritual experience of grasping eternal truths, like those he finds in both math and religion. But trying to find meaning behind specific numbers is a fruitless endeavor. There is no deeper meaning to 1/137, just as there is no deeper meaning to 3.14.

The Enigma of 137: Science's Most Magical Number

By: Patrick J. Kiger & Austin Henderson |

From physics, mathematics and science to mysticism, occultism, the Kabbalah and the Torah, the number 137 may just be the most magical and important number in the universe.

In the vast realm of numbers, some stand out with an allure that captivates both scientists and spiritualists alike. One such number, which has been the subject of intrigue for decades, is the seemingly ordinary three-digit number: **137**.

Contents

The Allure of 137

For many, the number 137 is more than just a numerical value. It's a bridge between the tangible world of science and the intangible realm of mysticism.

"137 continues to fire the imagination of everyone from scientists and mystics to occultists and people from the far-flung edges of society," states Arthur I. Miller, an emeritus professor of history and philosophy of science at University College London. His book, 137: Jung, Pauli and the Pursuit of a Scientific Obsession, delves deep into this fascination.

The Fine-structure Constant: A Cosmic Clue

To the world of physics, 137 is synonymous with the fine structure constant. This constant, represented as approximately 1/137.03599913, gauges the strength of the electromagnetic force, according to the National Institute of Standards and Technology. This force governs how charged elementary particles, like electrons, interact with light's photons.

The National Institute of Standards and Technology describes the fine-structure constant as one of the universe's key physical constants. Michael Brooks, in a New Scientist article, explains, "This immutable number determines how stars burn, how chemistry happens and even whether atoms exist at all."

In this video, British physicist Laurence Eaves explains that if the fine structure constant was a different value, "physics, chemistry, biochemistry would be totally different – and we might not be around to talk about it."

In December 2020, the journal Nature reported a breakthrough. A group led by Saïda Guellati-Khélifa at the Kastler Brossel Laboratory in Paris reported the most precise measurement of the fine-structure constant. Their findings, which were almost three times more precise than the previous best measurement in 2018, showcased the constant’s value to the 11th decimal place.

The Metaphysical Significance of 137

Beyond its scientific importance, 137 has been seen as a number with deeper, metaphysical implications. English astrophysicist Arthur Eddington, a pivotal figure in validating Einstein's General Theory of Relativity, viewed 137 as a number with spiritual ramifications. He believed that perhaps the mysteries of the universe could be unraveled through numbers, with 137 being a key.

The intersection of quantum theory and relativity, explored by quantum physics pioneer Wolfgang Pauli with the help of Carl Jung, also highlighted the significance of 137. This number's allure was so profound that in 1936, Nature published an article titled "The Mysterious Number 137."

137 in Mysticism and Religion

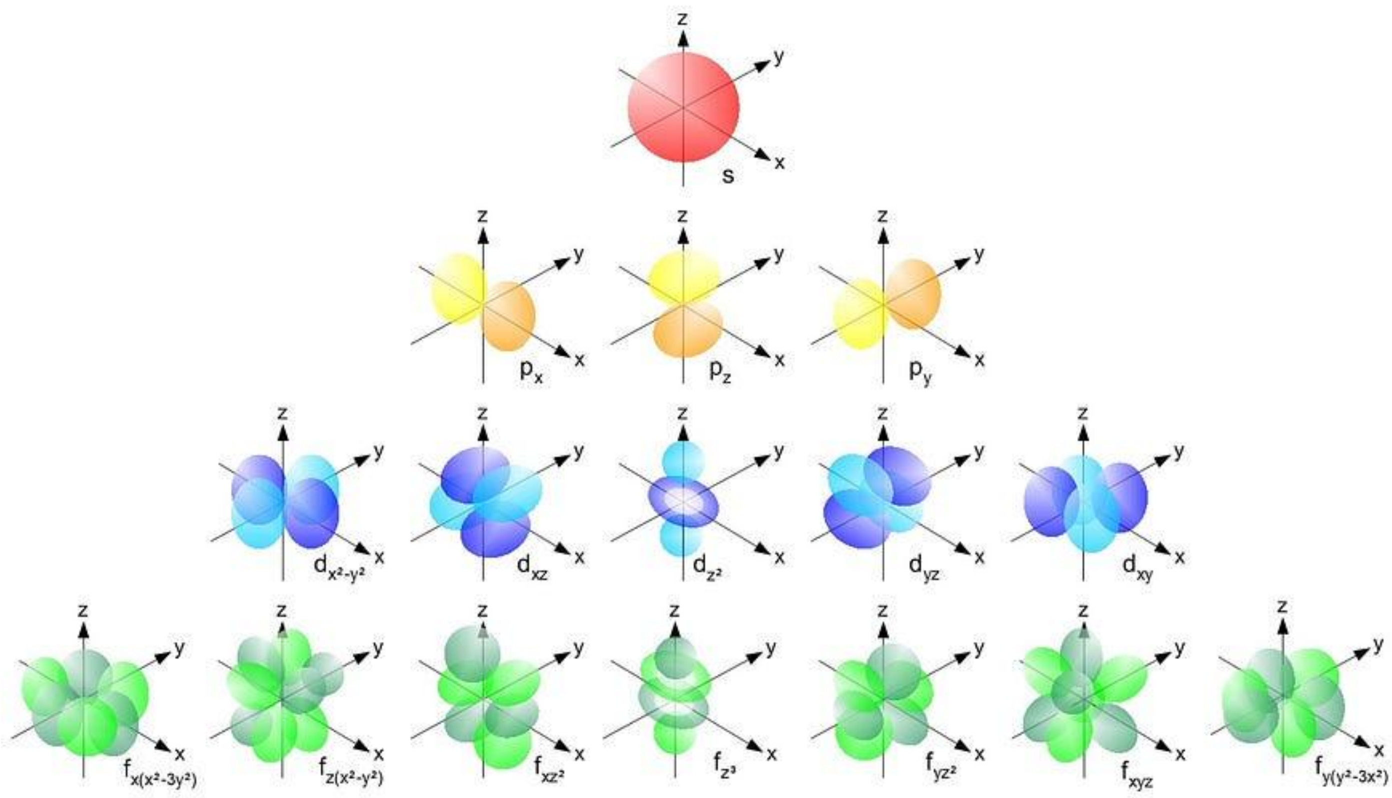
The number 137 doesn't just resonate with scientists. It holds significance in the Kabbalah, a form of Jewish mysticism. As this article by Billy Phillips from Kabbalahstudent.com details, the number frequently appears in the Torah, marking the lifespan of figures like Ishmael and Levi. The Kabbalists' concept of connecting with light, or achieving enlightenment, mirrors the fine-structure constant's relationship to light in physics.

Recommended Reading

For those looking to dive deeper into the mystery of 137, consider adding the book "137: Jung, Pauli and the Pursuit of a Scientific Obsession" to your library. It offers a comprehensive exploration of this enigmatic number's history and significance.

The Everlasting Enigma

The number 137, whether viewed through the lens of science or spirituality, remains one of the greatest mysteries of our time. Its dual significance in both realms makes it an important number that continues to intrigue good theoretical physicists and spiritualists alike.

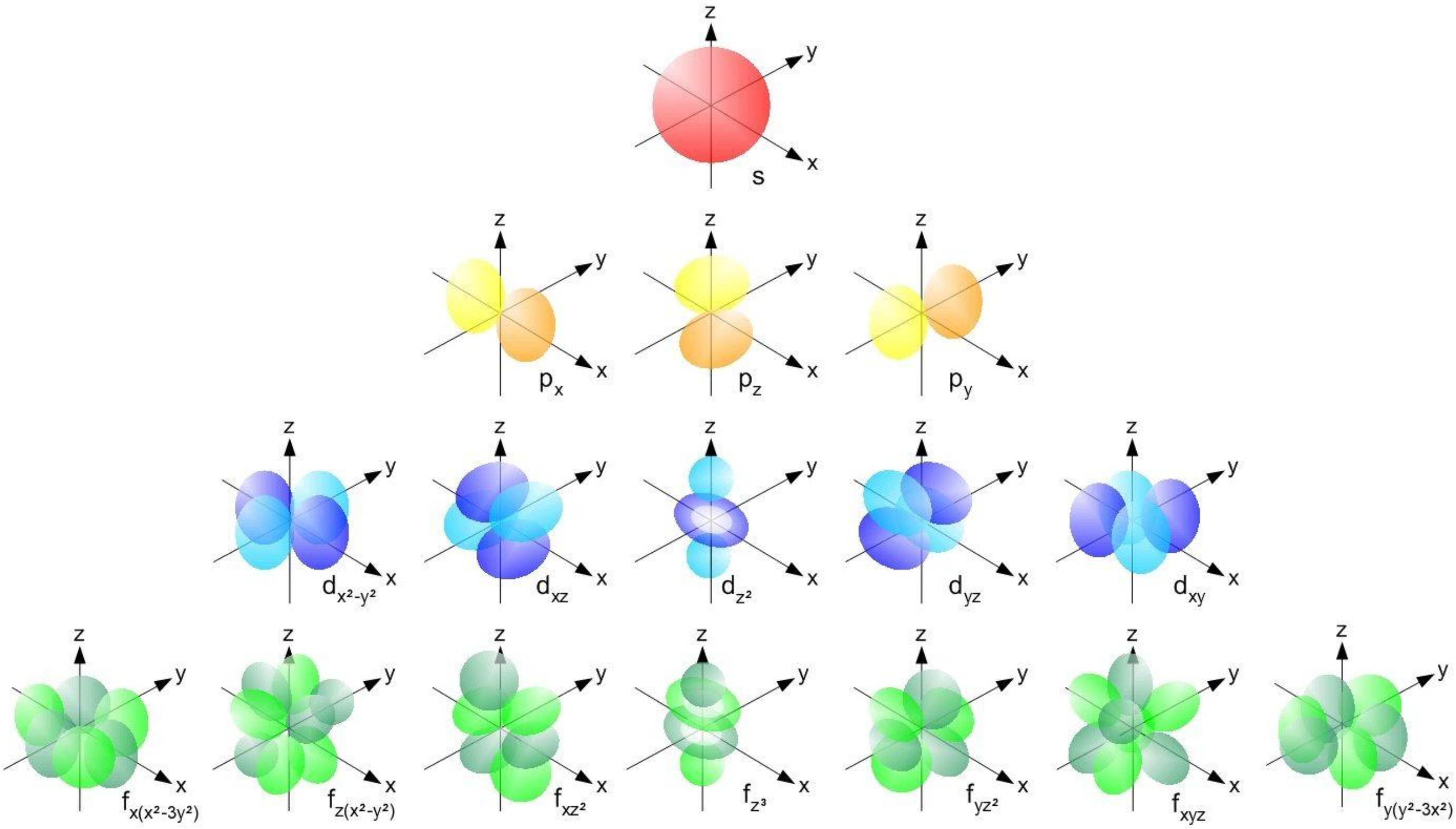


Each s orbital (red), each of the p orbitals (yellow), the d orbitals (blue) and the f orbitals (green) can contain only two electrons apiece: one spin up and one spin down in each one. The effects of spin, of moving close to the speed of light, and of the inherently fluctuating nature of the quantum fields that permeate the Universe are all responsible for the fine structure that matter exhibits. (Credit: LibreTexts Library/UC Davis)

Why the number “1/137” appears everywhere in nature

Why the number “1/137” appears everywhere in nature

One of the fundamental constants of nature, the fine-structure constant, determines so much about our Universe. Here’s why it matters.



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KEY TAKEAWAYS

- When we think of fundamental constants, we often think of things like the speed of light, the strength of the force of gravity, or the electric charge of the electron.
- Those constants, however, are all dimensionful; they depend on the units we choose to measure the Universe. An alternative is to use dimensionless constants: pure numbers, alone, with no units at all.
- When we do, we run into a completely fascinating one: the fine-structure constant, which represents the strength of the electromagnetic force. Here’s why it, and the number 1/137, matters.

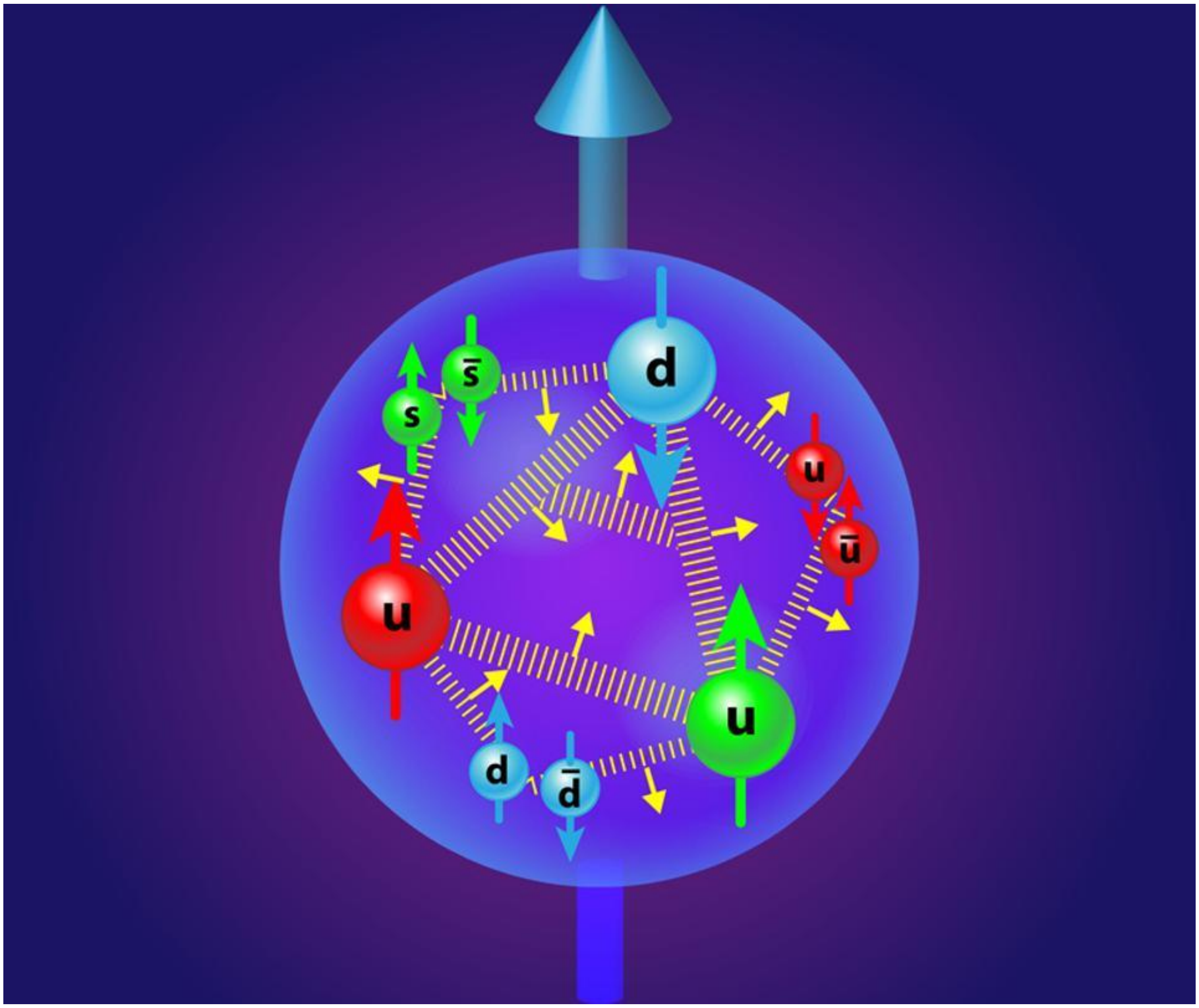
There's an enormous existential question that we've wondered about ever since we first realized that the Universe does, in fact, obey physical laws at all: why is our Universe the precise way it is, rather than any other way we could've imagined? There are only three things that make it so:

- the laws of nature themselves,
- the fundamental constants governing reality,
- and the initial conditions that our Universe was born with.

If our Universe had different laws of nature, then all bets would be off; the cosmos would have been vastly different in almost any way you can fathom. Protons might decay, fundamental quantities like particle masses might not be constant, and the strengths of any fundamental forces might joltingly change at any moment.

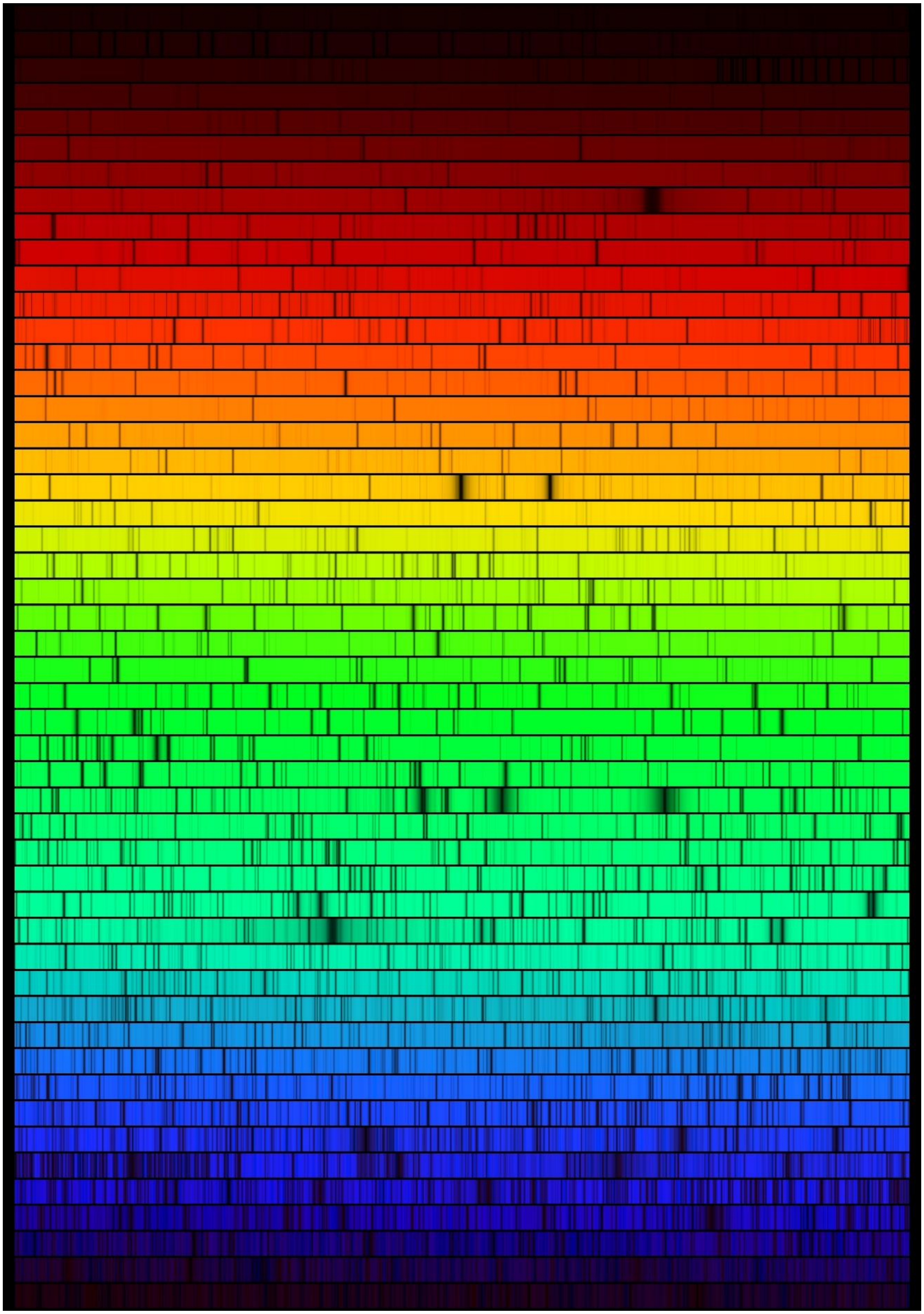
If only the initial conditions of our Universe were different, the way the cosmic story unfolded would be the same in terms of broad strokes, but the details would differ between that hypothetical Universe and our own. But for the fundamental constants, some changes would be profound, while others would be barely noticeable. In our own Universe, the constants have the explicit values they do, and that specific combination yields the life-friendly cosmos we inhabit. One of those fundamental constants is known as the fine structure constant, and its approximate value (1/137) appears in calculations that matter for a whole host of phenomena, on subatomic and cosmic levels both.

Our story begins with the simple building blocks of matter that make up the Universe: the fundamental particles of the Standard Model.



The proton's structure, modeled along with its attendant fields, show how even though it's made out of point-like quarks and gluons, it has a finite, substantial size which arises from the interplay of the quantum forces and fields inside it. The proton, itself, is a composite, not fundamental, quantum particle. The quarks and gluons inside it, though, along with the electrons that orbit atomic nuclei, are believed to be truly fundamental and indivisible.

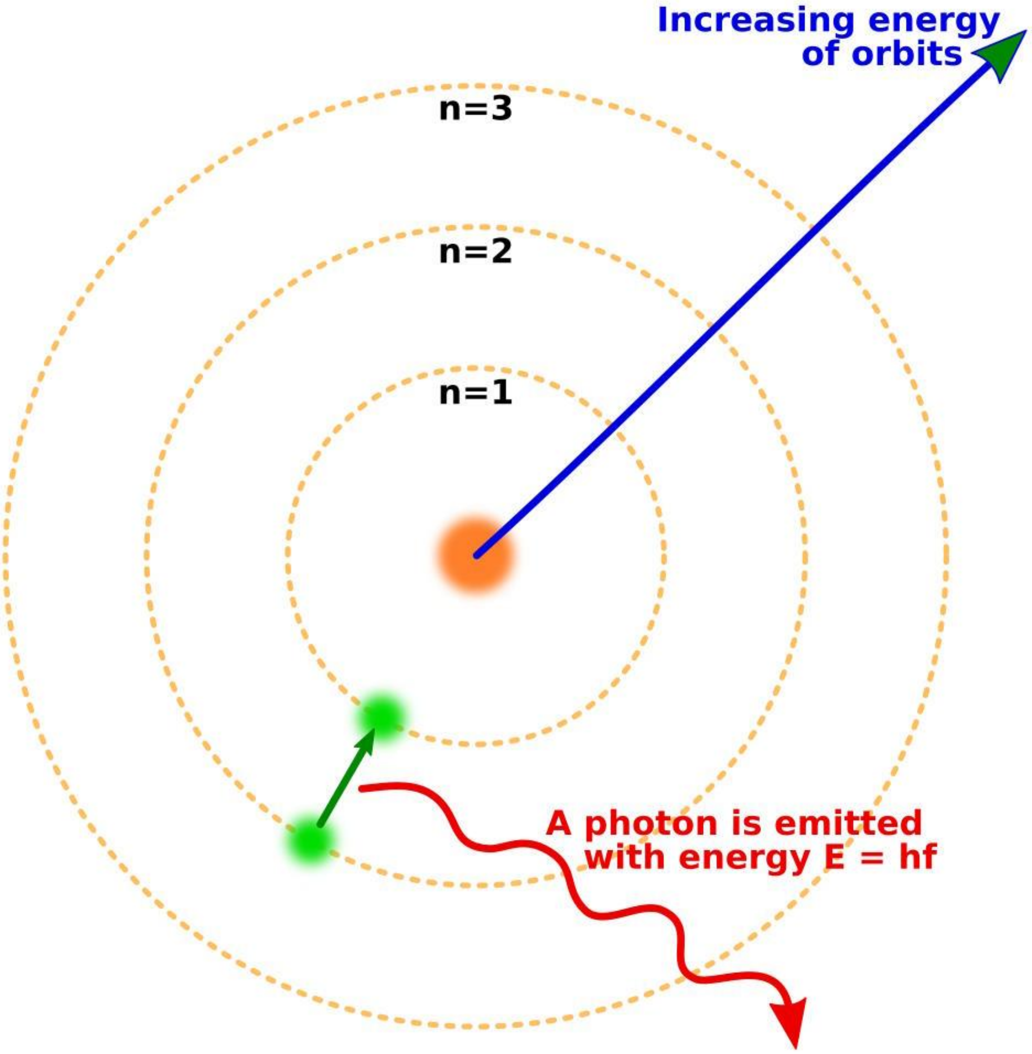
Our Universe, if we break it down into its smallest constituent parts, is made up of the particles of the Standard Model. Quarks and gluons, two types of these particles, bind together to form bound states like the proton and neutron, which themselves bind together into atomic nuclei. Electrons, another type of fundamental particle, are the lightest of the charged leptons. When electrons and atomic nuclei bind together, they form atoms: the building blocks of the normal matter that makes up everything in our day-to-day experience. Before humans even recognized how atoms were structured, we had determined many of their properties. In the 19th century, we discovered that the electric charge of the nucleus determined an atom's chemical properties, and found out that every atom had its own unique spectrum of lines that it could emit and absorb. Experimentally, the evidence for a discrete, quantum Universe was known long before theorists put it all together.



The visible light spectrum of the Sun, which helps us understand not only its temperature and ionization, but the abundances of the elements present. The long, thick lines are hydrogen and *helium, but every other line is from a heavy element. Many of the absorption lines shown here are very close to one another, showing evidence of fine structure, which can split two degenerate energy levels into closely-spaced but distinct ones.*

In 1912, Niels Bohr proposed his now-famous model of the atom, where the electrons orbited around the atomic nucleus like planets orbited the Sun. The big difference between Bohr's model and our Solar System, though, was that there were only certain particular states that were allowed for the atom, whereas planets could orbit with any combination of speed and radius that led to a stable orbit.

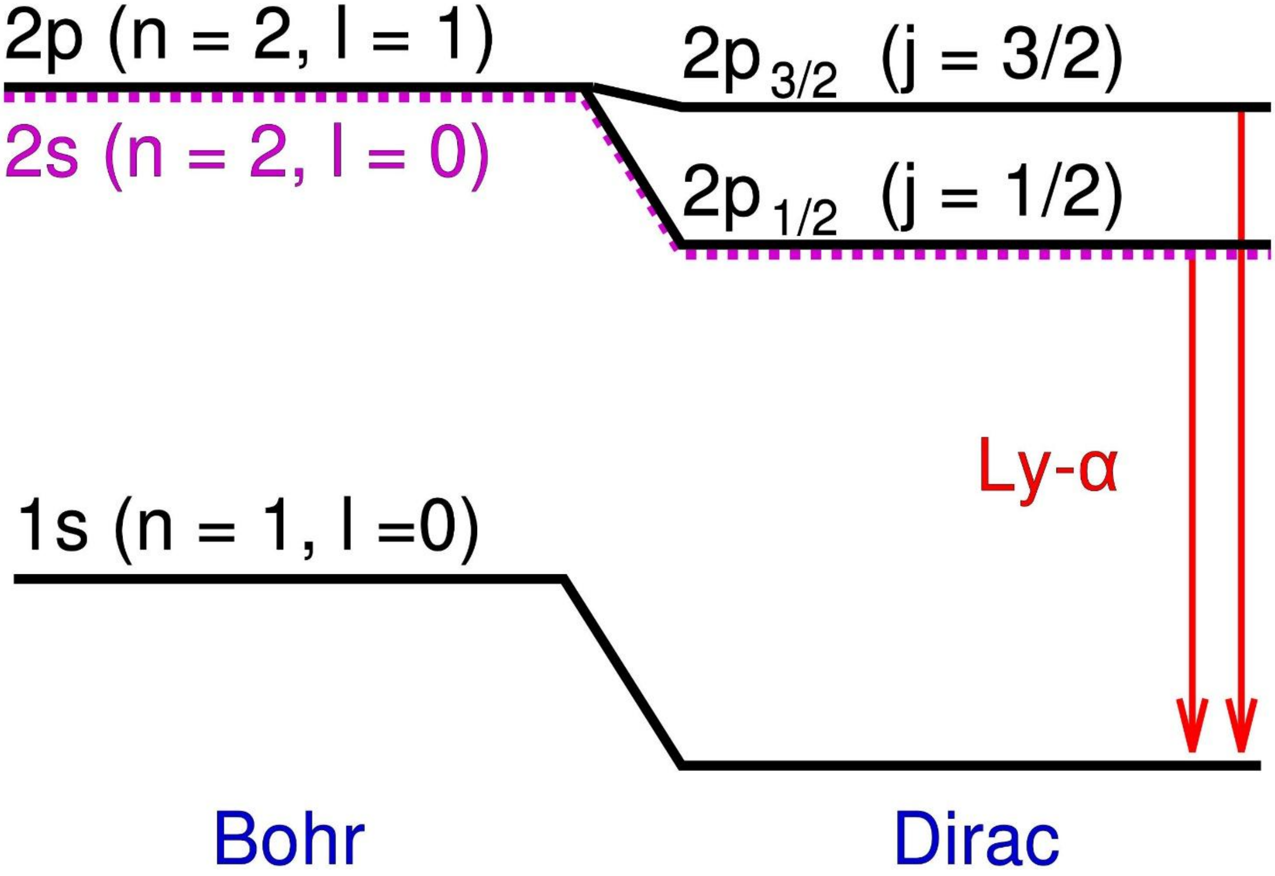
Bohr recognized that the electron and nucleus were both very small, had opposite charges, and knew that the nucleus had practically all of the mass. His groundbreaking contribution was understanding that electrons can only occupy certain energy levels, which he termed "atomic orbitals." The electron can orbit the nucleus only with particular properties, leading to the absorption and emission lines characteristic to each individual atom.



When free electrons recombine with hydrogen nuclei, the electrons cascade down the energy levels, emitting photons as they go. In order for stable, neutral atoms to form in the early Universe, they have to reach the ground state without producing a potentially ionizing, ultraviolet photon. The Bohr model of the atom provides the coarse (or rough, or gross) structure of the energy levels, but this already was insufficient to describe what had been seen decades prior.

This model, as brilliant and clever as it is, immediately failed to reproduce the decades-old experimental results from the 19th century. All the way back in 1887, Michelson and Morely had determined the atomic emission and absorption properties of hydrogen, and they didn't quite match the predictions of the Bohr atom.

The same scientists who determined that there was no difference in the speed of light whether it moved with, against, or perpendicular to the motion of the Earth had also measured the spectral lines of hydrogen more precisely than anyone ever before. While the Bohr model came close, Michelson and Morely's results demonstrated small shifts and extra energy states that departed slightly but significantly from Bohr's predictions. In particular, there were some energy levels that appeared to split into two, whereas Bohr's model only predicted one.

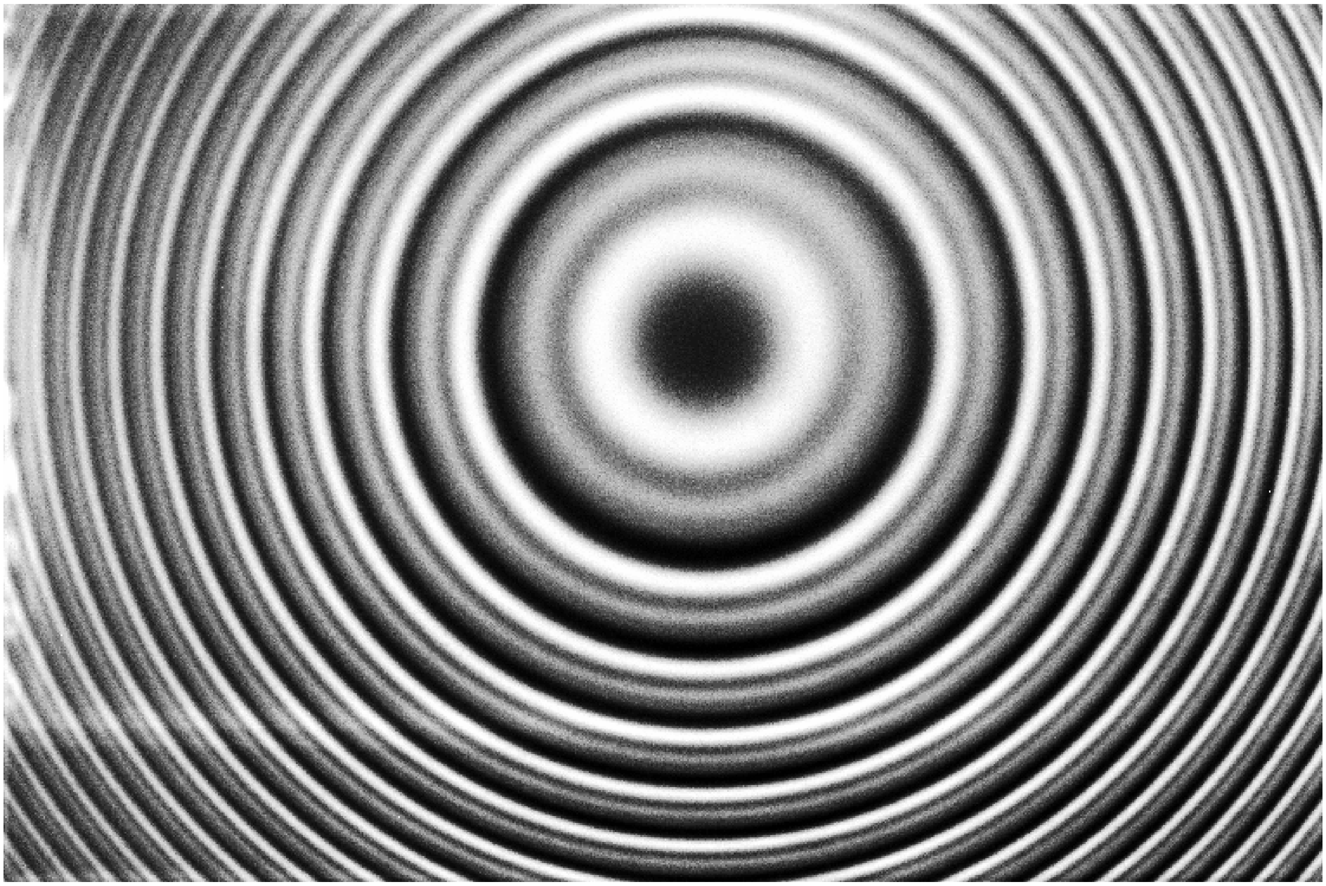


In the Bohr model of the hydrogen atom, only the orbiting angular momentum of the point-like electron contributes to the energy levels. Adding in relativistic effects and spin effects not only

causes a shift in these energy levels, but causes degenerate levels to split into multiple states, revealing the fine structure of matter atop the coarse structure predicted by Bohr.
Credit: Tobix10/Wikimedia Commons

Those additional energy levels, which were very close to one another and also close to Bohr's predictions, were the first evidence of what we now call the fine structure of atoms. Bohr's model, which simplistically modeled electrons as charged, spinless particles orbiting the nucleus at speeds much lower than the speed of light, successfully explained the coarse structure of atoms, but not this additional fine structure.

That would require another advance, which came in 1916 when physicist Arnold Sommerfeld had a realization. If you modeled a hydrogen atom as Bohr did, but took the ratio of a ground-state electron's velocity and compared it to the speed of light, you'd get a very specific value, which Sommerfeld called α: the fine structure constant. This constant, once folded into Bohr's equations properly, was able to precisely account for the energy difference between the coarse and fine structure predictions.

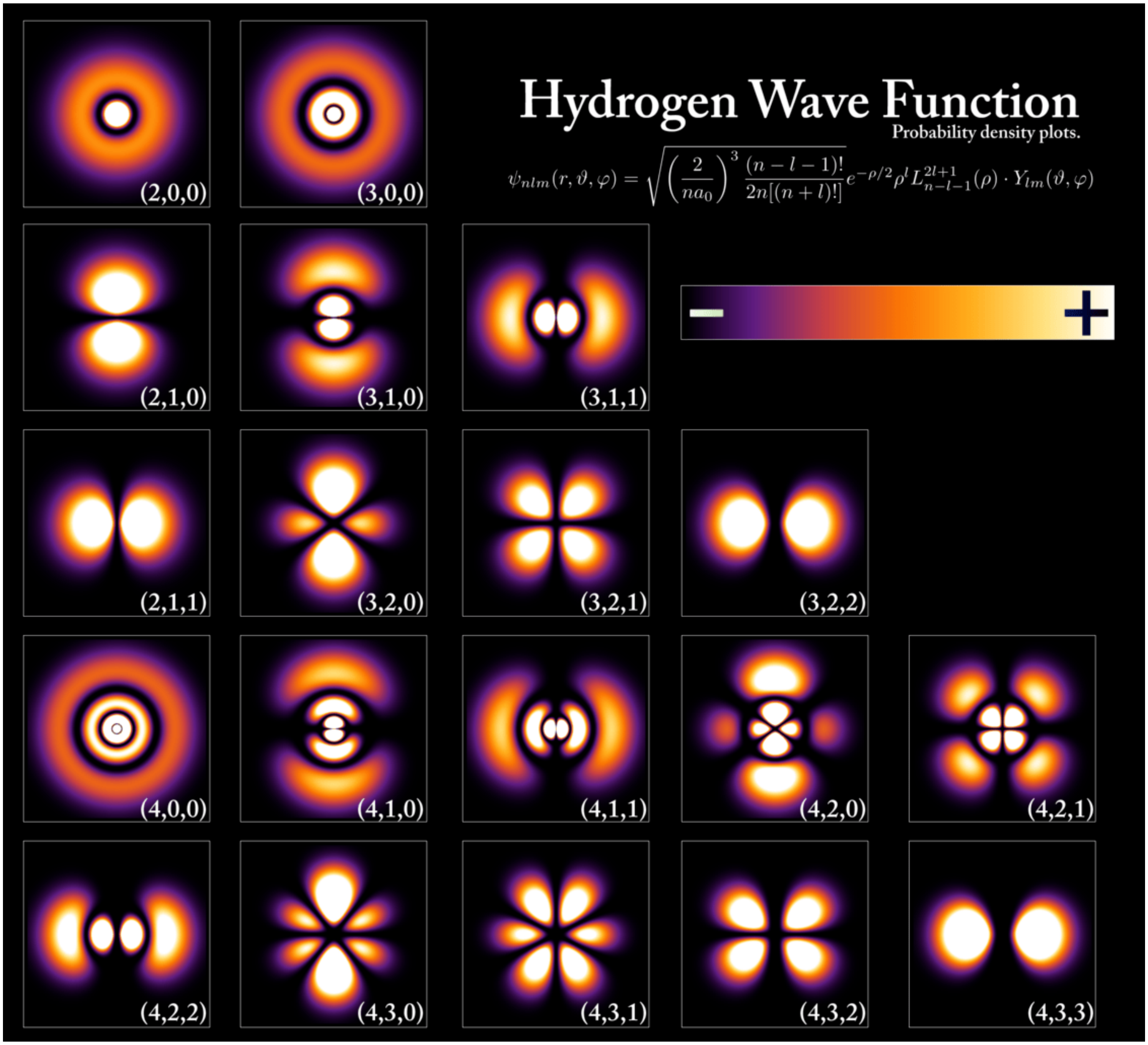


A supercooled deuterium source, as shown here, doesn't simply show discrete levels, but fringes that go atop of the standard constructive/destructive interference pattern. This additional fringe effect is a consequence of the fine structure of matter.

In terms of the other constants known at the time, $\alpha = e^2/(4\pi\varepsilon_0)\hbar c$, where:

- e is the electron's charge,
- ε_0 is the electromagnetic constant for the permittivity of free space,
- $\hbar$ is Planck's constant,
- and c is the speed of light.

Unlike these other constants, which have units associated with them, α is a truly dimensionless constant, which means it is simply a pure number, with no units associated with it at all. While the speed of light might be different if you measure it in meters per second, feet per year, miles per hour, or any other unit, α always has the same value. For this reason, it's considered to be one of the fundamental constants that describes our Universe.



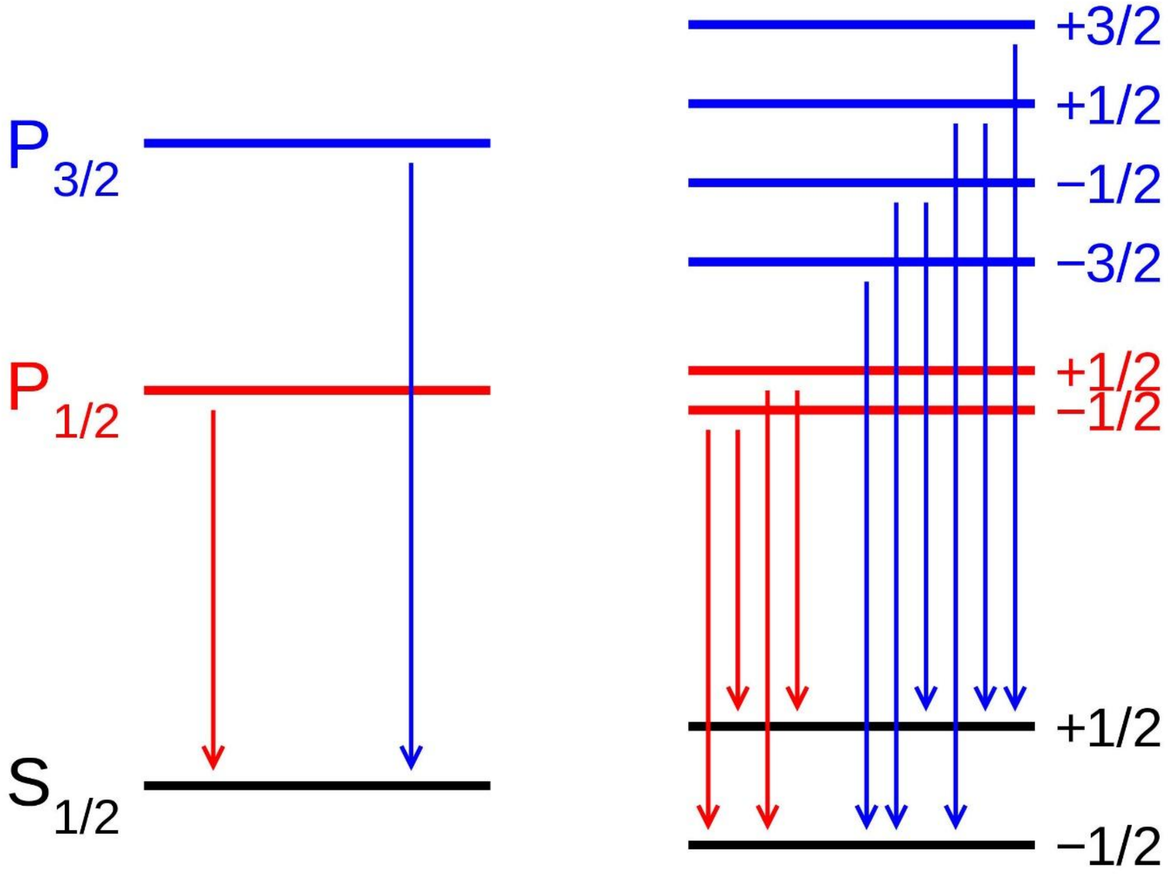
The energy levels and electron wavefunctions that correspond to different states within a hydrogen atom, although the configurations are extremely similar for all atoms. The energy levels are quantized in multiples of Planck's constant, but the sizes of the orbitals and atoms are determined by the ground-state energy and the electron's mass. Additional effects may be subtle, but shift the energy levels in measurable, quantifiable fashions.

Credit: PoorLeno/Wikimedia Commons

An atom's energy levels cannot be accounted for properly without including these fine structure effects, a fact which resurfaced a decade after Bohr when the Schrödinger equation came onto the scene. Just as the Bohr model failed to reproduce the hydrogen atom's energy levels properly, so did the Schrödinger equation. It was quickly discovered that there were three reasons for this.

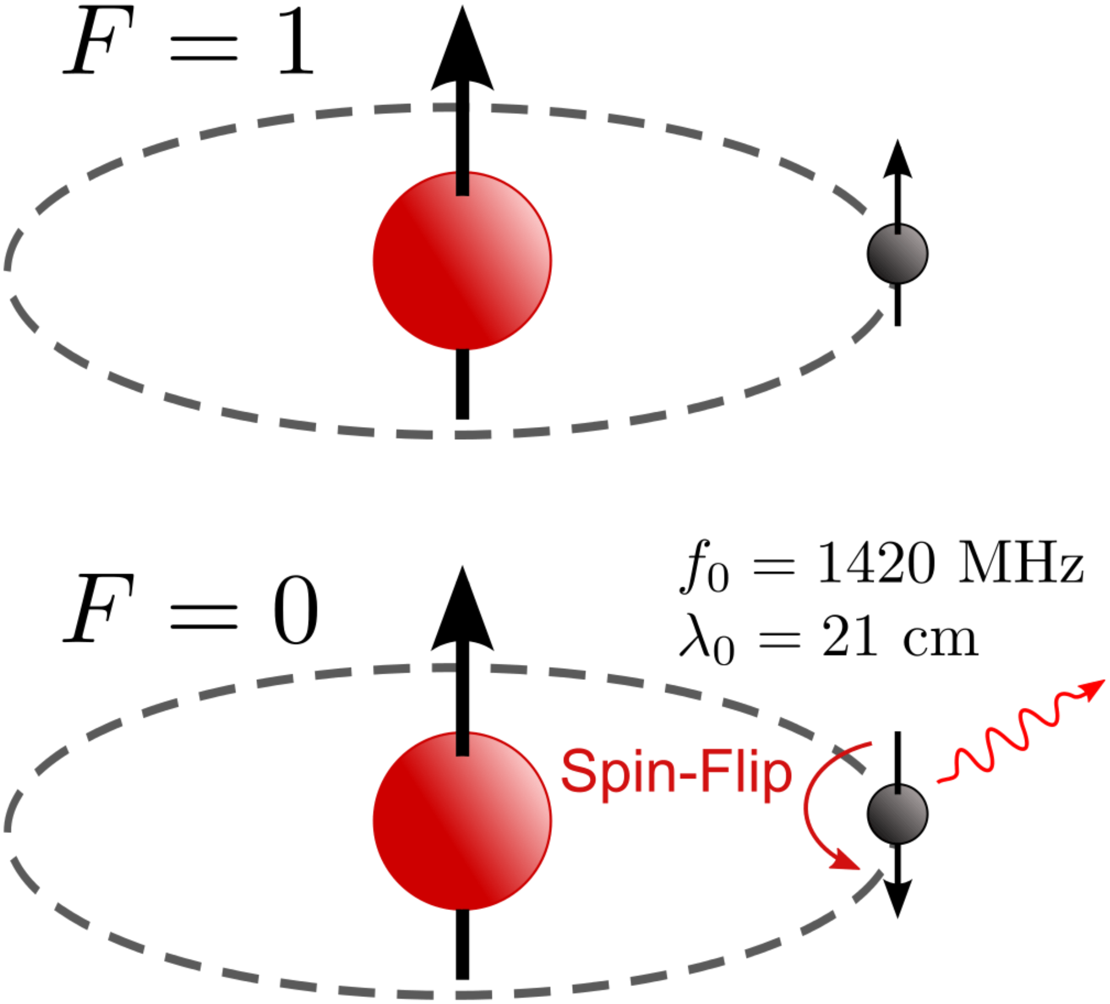
1. The Schrödinger equation is fundamentally non-relativistic, but electrons and other quantum particles can move close to the speed of light, and that effect must be included.
2. Electrons don't simply orbit atoms, but they also have an intrinsic angular momentum inherent to them: spin, with a value of $\hbar/2$, that can either be aligned or anti-aligned with the rest of the atom's angular momentum.
3. Electrons also exhibit an inherent set of quantum fluctuations to their motion, known as zitterbewegung; this also contributes to the fine structure of atoms.

When you include all of these effects, you can successfully reproduce both the gross and fine structure of matter.



In the absence of a magnetic field, the energy levels of various states within an atomic orbital are identical (L). If a magnetic field is applied, however (R), the states split according to the Zeeman effect. Here we see the Zeeman splitting of a P-S doublet transition. Other types of splitting occur owing to spin-orbit interactions, relativistic effects, and interactions with the nuclear spin, leading to the fine and hyperfine structure of matter.
Credit: Evgeny at English Wikipedia

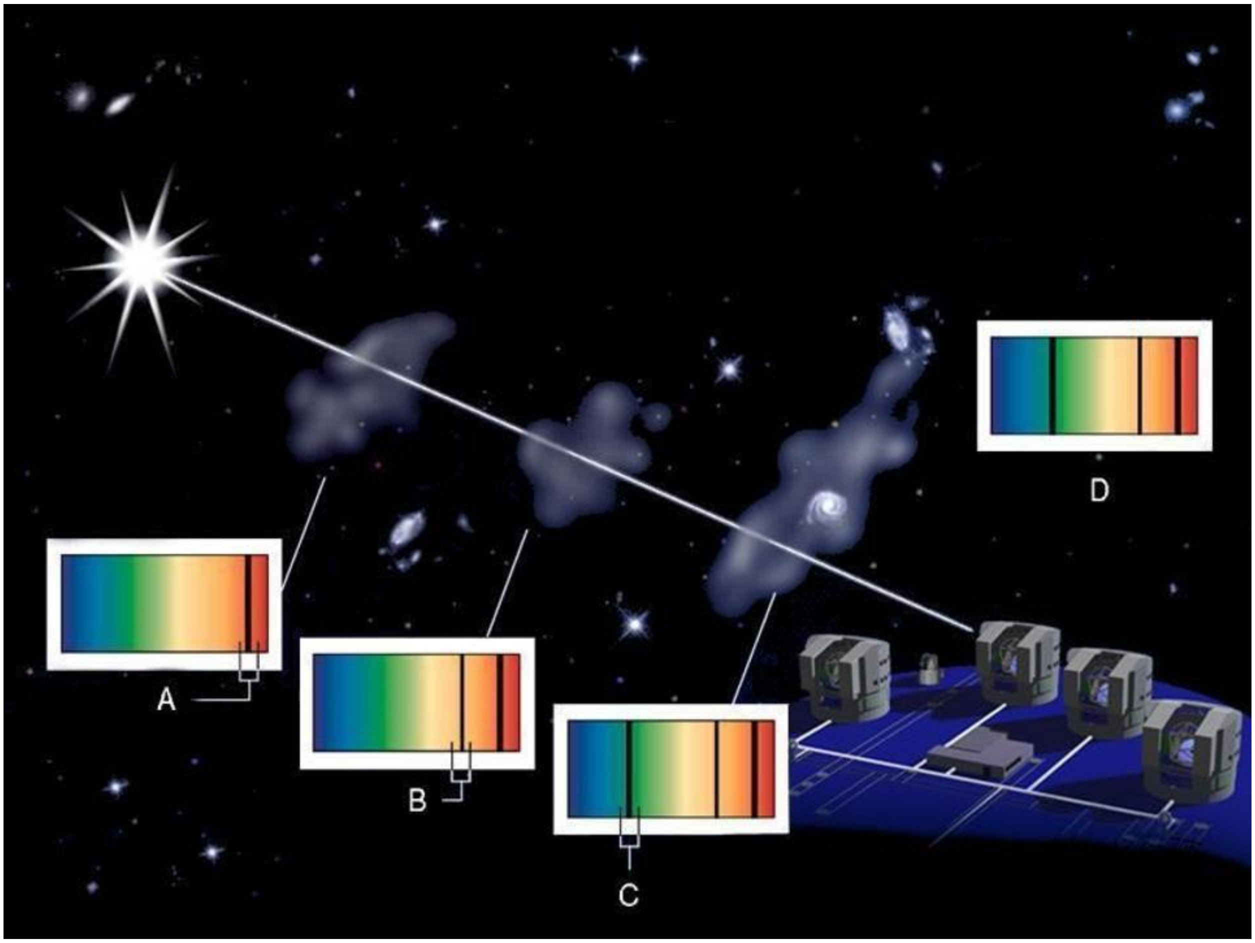
The reason these corrections are so small is because the value of the fine structure constant, α, is also very small. According to our best modern measurements, the value of α = 0.007297352569, where only the last digit is uncertain. This is very close to being an exact number: α = 1/137. It was once considered possible that this exact figure could be accounted for somehow, but better theoretical and experimental research has demonstrated that the relation is inexact, and that α = 1/137.0359991, where again only the last digit is uncertain.



The 21-centimeter hydrogen line comes about when a hydrogen atom containing a proton/electron combination with aligned spins (top) flips to have anti-aligned spins (bottom), emitting one particular photon of a very characteristic wavelength. The opposite-spin configuration in the n=1 energy level represents the ground state of hydrogen, but its zero-point-energy is a finite, non-zero value. This transition is part of the hyperfine structure of matter, going even beyond the fine structure we more commonly experience.

Credit: Tiltec/Wikimedia Commons

Even including all of these effects, though, doesn't get you everything about atoms. Not only is there the coarse structure (from electrons orbiting a nucleus) and fine structure (from relativistic effects, the electron's spin, and the electron's quantum fluctuations), but there's hyperfine structure: the interaction of the electron with the nuclear spin. The spin-flip transition of the hydrogen atom, for example, is the narrowest spectral line known in physics, and it's due to this hyperfine effect that goes beyond even fine structure.

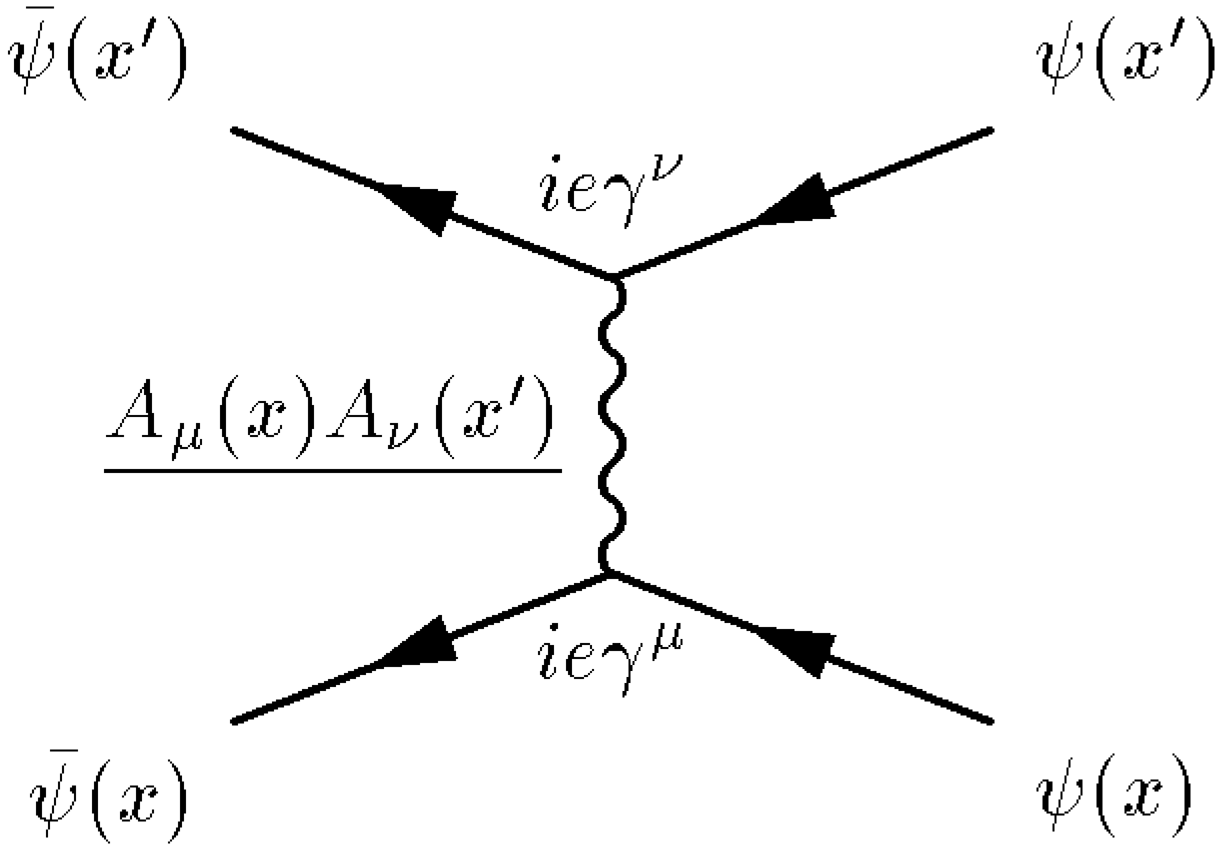


The light from ultra-distant quasars provide cosmic laboratories for measuring not only the gas clouds they encounter along the way, but for the intergalactic medium that contains warm-and-hot plasmas outside of clusters, galaxies, and filaments. Because the exact properties of the emission or absorption lines are dependent on the fine structure constant, this is one of the top methods for probing the Universe for time or spatial variations in the fine structure constant.

Credit: Ed Janssen/ESO

But the fine structure constant, α, is of tremendous interest to physics. Some have investigated whether it might not be perfectly constant. Various measurements have indicated, at various points in our scientific history, that α might either vary with time or from location to location in the Universe. Measurements of the spectral lines of hydrogen and deuterium, in some cases, have indicated that perhaps α changes by ~0.0001% through space or time.

These initial results, however, have failed to hold up to independent verification, and are treated as dubious by the greater physics community. If we did ever robustly observe such variation, it would teach us that something that we observe to be unchanging in the Universe—like the electron charge, Planck's constant, or the speed of light—might actually not be a constant through space or time.

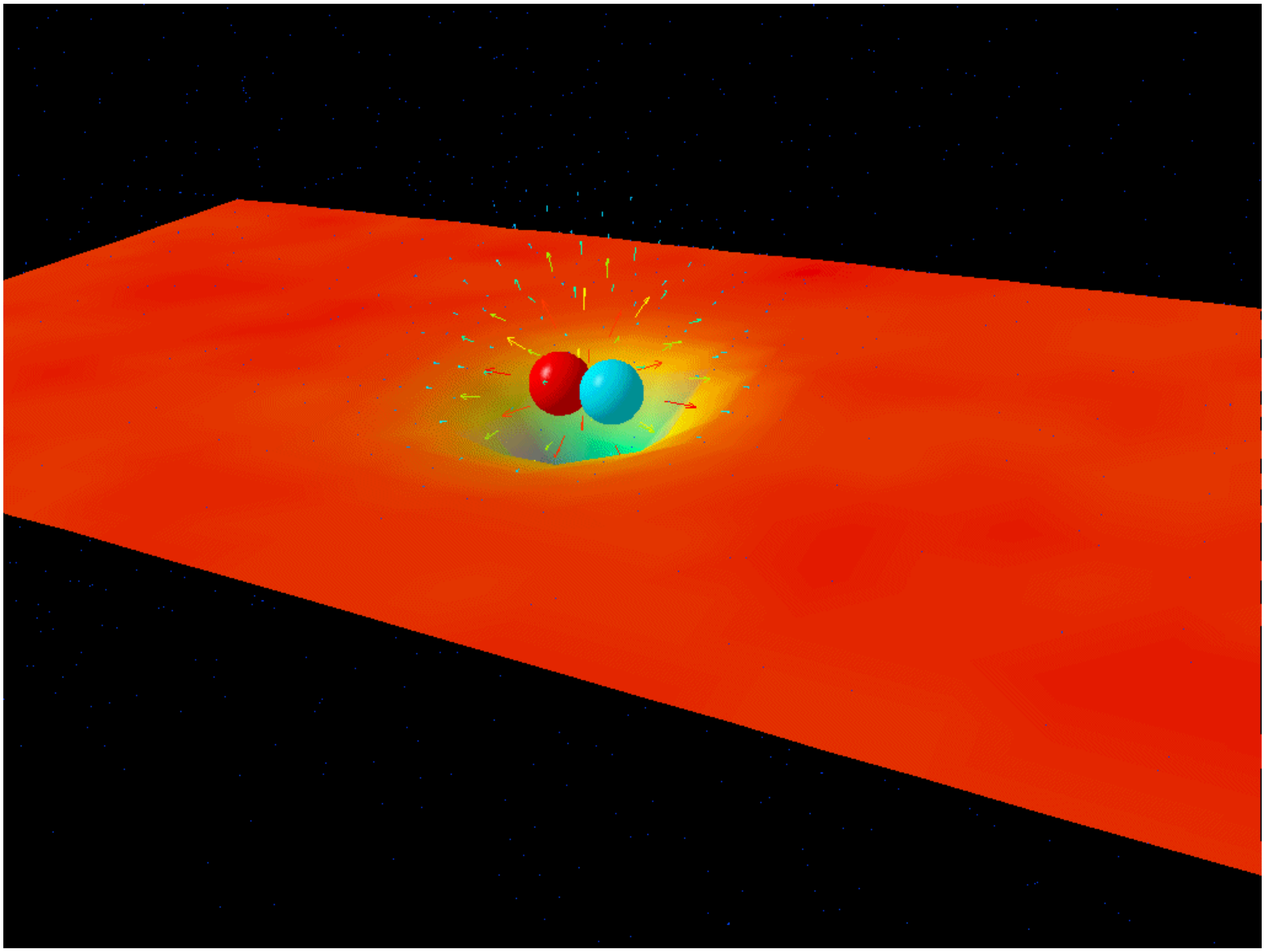


A Feynman diagram representing electron-electron scattering, which requires summing over all the possible histories of the particle-particle interactions. The idea that a positron is an electron moving backward in time grew out of the collaboration between Feynman and Wheeler, but the strength of the scattering interaction is energy-dependent and is governed by the fine structure constant describing the electromagnetic interactions.
Credit: Dmitri Federov/Wikimedia Commons

A different type of variation, though, has actually been reproduced: α changes as a function of the energy conditions under which you perform your experiments.

Let's think about why this must be so by imagining a different way of looking at the fine structure of the Universe: take two electrons and hold them a specific distance apart from one another. The fine structure constant, α, can be thought of as the ratio between the energy needed to overcome the electrostatic repulsion driving these electrons apart and the energy of a single photon whose wavelength is 2π multiplied by the separation between those electrons.

In a quantum Universe, though, there are always particle-antiparticle pairs (or quantum fluctuations) that populate even completely empty space. At higher energies, this changes the strength of the electrostatic repulsion between two electrons.

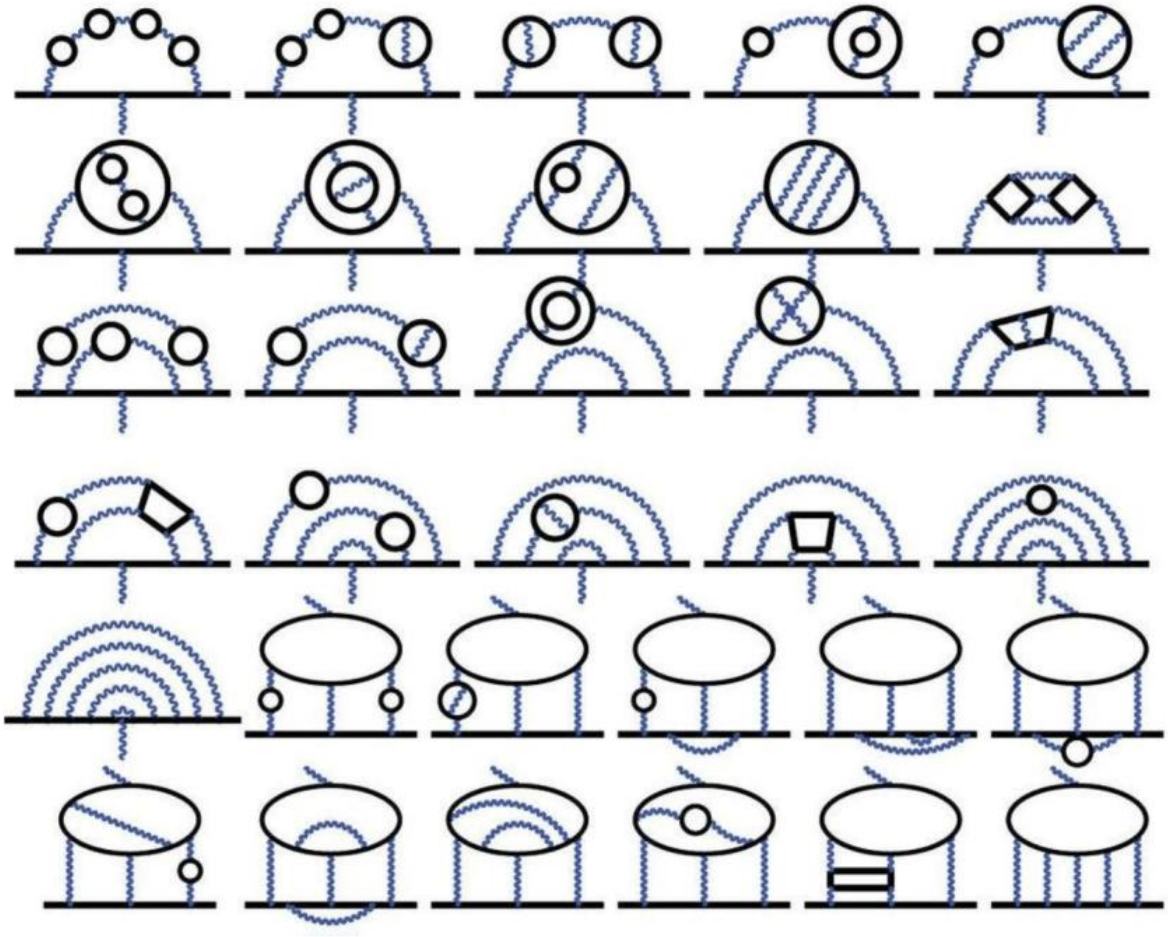


A visualization of QCD illustrates how particle/antiparticle pairs pop out of the quantum vacuum for very small amounts of time as a consequence of Heisenberg uncertainty. The quantum vacuum is interesting because it demands that empty space itself isn't so empty, but is filled with all the particles, antiparticles and fields in various states that are demanded by the quantum field theory that describes our Universe.

Credit: Derek B. Leinweber

The reason why is actually straightforward: the lightest charged particles in the Standard Model are electrons and positrons, and at low energies, the virtual contributions from electron-positron pairs are the only quantum effects that matter in terms of the strength of the electrostatic force. But at higher energies, it not only becomes easier to make electron-positron pairs, giving you a larger contribution, but you start getting additional contributions from heavier particle-antiparticle combinations.

At the (mundane) low energies we have in our Universe today, α is approximately 1/137. But at the electroweak scale, where you find the heaviest particles like the W, Z, Higgs boson and top quark, α is somewhat greater: more like 1/128. Effectively, owing to these quantum contributions, it's as though the electron's charge increases in strength.



Through a herculean effort on the part of theoretical physicists, the muon magnetic moment has been calculated up to five-loop order. The theoretical uncertainties are now at the level of just one part in two billion. This is a tremendous achievement that can only be made in the context of quantum field theory, and is heavily reliant on the fine structure constant and its applications.

The fine structure constant, α, also plays a major role in one of the most important experiments going on in modern physics today: the effort to measure the intrinsic magnetic moment of fundamental particles. For a point particle like the electron or muon, there are only a few things that determine its magnetic moment:

1. the electric charge of the particle (which it's directly proportional to),
2. the spin of the particle (which it's directly proportional to),

3. the mass of the particle (which it’s inversely proportional to),
4. and a constant, known as *g*, which is a purely quantum mechanical effect.

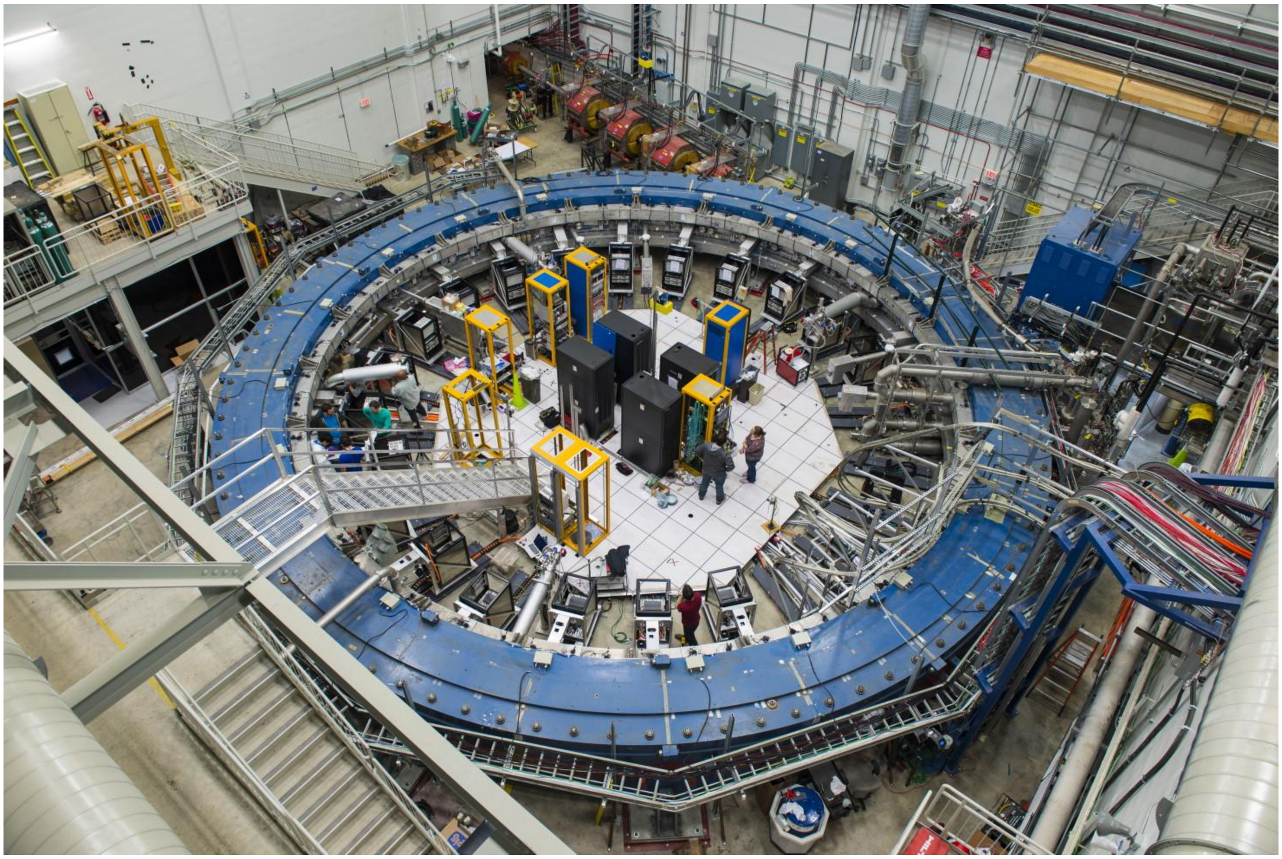
While the first three are exquisitely known, *g* is only known to a little better than one part per billion. That might sound like a supremely good measurement, but we’re attempting to measure it to an even greater precision for a very good reason.

This is the headstone of Julian Seymour Schwinger at Mt Auburn Cemetery in Cambridge, MA. The formula is for the correction to “g/2” as he first calculated in 1948. He regarded it as his finest result.

Back in 1930, we thought that *g* would be 2, exactly, as derived by Dirac. But that ignores the quantum exchange of particles (or the contribution of loop diagrams), which only begins to show up in quantum field theory. The first-order correction was derived by Julian Schwinger in 1948, who states that $g = 2 + \alpha/\pi$. As of today, we've computed all the contributions to 5th order, meaning we know all of the (α/π) terms, plus the $(\alpha/\pi)^2$, $(\alpha/\pi)^3$, $(\alpha/\pi)^4$, and $(\alpha/\pi)^5$ terms.

We can measure g experimentally and calculate it theoretically, and what we find, very curiously, is that the match between the two is very close, but not perfect. The differences between g from experiment and theory are very, very small: 0.0000000052, with an uncertainty of around ±0.0000000010: a 5.2-sigma difference. However, a second theoretical method yields a much smaller difference, suggesting that there may be some difficulty on the theory side; the experiments will certainly decide.

If there's a true difference, we may be on the verge of new, beyond-the-Standard-Model physics; if not, we will learn something about our theoretical assumptions instead.



The Muon g-2 electromagnet at Fermilab, ready to receive a beam of muon particles. This experiment began in 2017 and continues to take data, having reduced the uncertainties in the experimental values significantly. Theoretically, we can compute the expected value perturbatively, through summing Feynman diagrams, getting a value that disagrees with the experimental results. The non-perturbative calculations, via Lattice QCD, seem to agree, however, deepening the puzzle of the muon's anomalous magnetic moment.

When we do our best to measure the Universe—to greater precisions, at higher energies, under extraordinary pressures, at lower temperatures, etc.—we often find details that are intricate, rich, and puzzling. It's not the devil that's in those details, though, but rather that's where the deepest secrets of reality lie.

The particles in our Universe aren't just points that attract, repel, and bind together with one another; they interact through every subtle means that the laws of nature permit. As we reach greater precisions in our measurements, we start uncovering these subtle effects, including intricacies to the structure of matter that are easy to miss at low precisions. Fine structure is a vital part of that, but learning where even our best predictions of fine structure break down might be where the next great revolution in particle physics comes from. Doing the right experiment is the only way we'll ever know.

Why Is 137 The Most Baffling Number In Physics? Universe Secret Revealed

Why Is 137 The Most Baffling Number In Physics? Uncovering The Universe's Hidden Code

Have you ever wondered if a single number could hold the key to understanding our entire universe? Welcome to the fascinating world of the fine structure constant—a number so peculiar yet so fundamental that it has bewildered the greatest minds in physics for generations. At FreeAstroScience.com, we're thrilled to take you on this journey through one of science's most enduring mysteries. Stay with us until the end as we unravel how this seemingly ordinary number shapes everything from the atoms in your body to the stars in distant galaxies!

What Actually Is the Fine Structure Constant?

The fine structure constant—often represented by the Greek letter α (alpha)—is approximately equal to 1/137.035999... It's not exactly 137, but close enough that physicists often refer to it simply as "137" in casual conversation.

But what makes this number truly special? Unlike most constants in physics, the fine structure constant has no units or dimensions. It's a pure number that exists independently of our measurement systems—whether you use meters or miles, seconds or hours, the fine structure constant remains unchanged .

As physicist Richard Feynman once described it, the fine structure constant is "a magic number that comes to us with no understanding" . This number characterizes the strength of the electromagnetic interaction between elementary charged particles. In simpler terms, it tells us how strongly electrons and photons interact with each other .

According to Arnold Sommerfeld, who first introduced this constant, α represents the ratio between the speed of an electron in the innermost orbit of a hydrogen atom and the speed of light . This seemingly simple relationship appears throughout quantum physics in numerous ways.

Why Should We Care About This Mysterious Number?

The Building Block of Everything We Know

The fine structure constant doesn't just appear in obscure physics equations—it fundamentally shapes our physical reality. Here's why this matters:

Would life exist with a different value? If the fine structure constant were slightly different—say 1/138 instead of 1/137.036...—stars wouldn't be able to create carbon, and life as we know it would be impossible . It's precisely because this number has the value it does that atoms can form, chemicals can bond, and we can exist to ponder these questions.

It connects fundamental forces: The fine structure constant relates three essential domains of physics: electromagnetism (through the electron's charge), relativity (through the speed of light), and quantum mechanics (through Planck's constant) . It serves as a bridge between these foundational theories.

The Obsession With 137 Throughout History

The Tormented Geniuses

The mystery of 137 has captivated some of the greatest scientific minds throughout history. Wolfgang Pauli, the brilliant quantum physicist, developed such an obsession with this number that a strange coincidence occurred at the end of his life—he died in room 137 of a Zurich hospital .

Richard Feynman, Nobel Prize winner and one of the most celebrated physicists of the 20th century, famously stated: "It has been a mystery ever since it was discovered more than fifty years ago, and all good theoretical physicists put this number up on their wall and worry about it" .

Paul Dirac, another Nobel laureate, considered the origin of this number "the most fundamental unsolved problem of physics" .

How Precisely Do We Know This Number?

In 2020, an extraordinary achievement occurred in the world of physics. A team led by Saïda Guellati-Khélifa at the Kastler Brossel Laboratory in Paris reported the most precise measurement of the fine structure constant to date, determining its value to the 11th decimal place: $\alpha = 1/137.035999206$.

This measurement was nearly three times more precise than the previous best measurement from 2018. To achieve this precision, researchers had to account for factors as subtle as Earth's rotation and gravity . They cooled rubidium atoms almost to absolute zero, then measured how strongly these atoms recoil when absorbing a photon of light.

Why go to such extreme lengths to measure a single number? Because any discrepancy between measurements could point to new physics beyond our current understanding—potentially revealing particles or effects not accounted for in our standard equations .

Why Does This Number Have This Specific Value?

The Greatest Unsolved Mystery

Here's where we reach the heart of the mystery: despite knowing the value of the fine structure constant with extraordinary precision, we have no theoretical explanation for why it has this specific value .

In the early 20th century, some physicists believed the constant had a value of precisely 1/137, and they engaged in numerology to explain its origins. Today, we know it's approximately 1/137.036, but we're no closer to understanding its fundamental origin .

As Leon Lederman, another Nobel Prize winner, clearly stated: "The most surprising thing about it? It has no dimensions. It has no units, it's a pure number. And until we understand where it comes from, quantum mechanics will remain incomplete" .

Is There A Deeper Meaning?

Some physicists suggest that the fine structure constant might be a key to discovering the elusive "Theory of Everything"—a unified theory that would bring together all fundamental forces of the universe . Others believe that understanding its origin might bridge the gap between quantum mechanics and the theory of relativity .

What if the constant isn't actually constant? Some controversial research hints that the fine structure constant might vary slightly across different regions of the universe or over cosmic time scales If true, this would fundamentally change our understanding of physics.

Eric Cornell, a Nobel Prize-winning physicist, compared the fine structure constant to the golden ratio in architecture: "In the physics of low-energy matter — atoms, molecules, chemistry, biology — there's always a ratio" of bigger things to smaller things, and "those ratios tend to be powers of the fine-structure constant" .

Could This Number Be Our Universal Language?

Interestingly, if we were to communicate with intelligent extraterrestrials, the fine structure constant could serve as a perfect universal language. Since it's dimensionless and doesn't depend on human-invented units, any advanced civilization would recognize this number and understand its significance .

As Paul M. Sutter, an astrophysicist, explains: "If you were to meet an alien from a distant star system, you'd have a pretty hard time communicating the value of the speed of light... But the fine structure constant? You could just spit it out, and they would understand it" .

What Does This Mean For Our Understanding Of The Universe?

The mystery of the fine structure constant reminds us that despite our technological and scientific progress, fundamental questions about our universe remain unanswered. We can measure this number with astonishing precision, yet we cannot explain why it has the value it does.

Perhaps the most profound implication is how finely tuned our universe appears to be. The fact that small changes to this constant would render life impossible suggests either incredible cosmic luck or deeper principles we haven't yet uncovered.

Conclusion: The Enduring Enigma

The fine structure constant (1/137) stands as one of the most fascinating mysteries in modern physics. This dimensionless number shapes our physical reality in countless ways, from determining how atoms form to enabling the chemical reactions that make life possible. Yet despite our ability to measure it with extraordinary precision, its fundamental origin remains unknown.

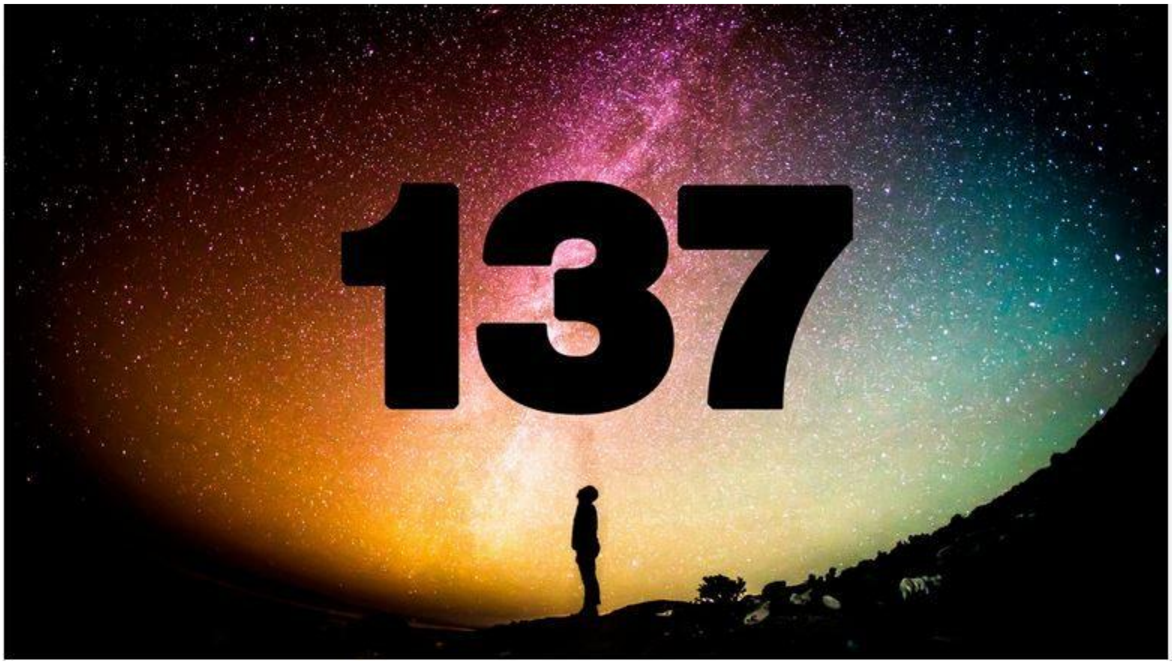
As we continue exploring the deepest questions about our universe at FreeAstroScience.com, the mystery of 137 reminds us that some of the most profound insights might come not from the largest cosmic structures or the most energetic particle collisions, but from contemplating the meaning of a single number that appears throughout nature.

The next time you look at the night sky or wonder about the atoms that make up your body, remember that all of it—the stars, the planets, the chemical elements, and life itself—exists as it does because of this enigmatic number that continues to challenge our understanding of reality.

What do you think about this mysterious number? Do you believe we'll ever fully understand its origins? Share your thoughts and join us at FreeAstroScience.com for more fascinating explorations of the uni

Fine structure constant - Why the number 137 is one of the greatest mysteries in physics

Famous physicists like Richard Feynman think 137 holds the answers to the Universe.



- The **fine structure constant** has mystified scientists since the 1800s.
- The number **1/137** might hold the clues to the Grand Unified Theory.
- Relativity, electromagnetism and quantum mechanics are unified by the number.

Does the Universe around us have a fundamental structure that can be glimpsed through special numbers?

The brilliant physicist **Richard Feynman** (1918-1988) famously thought so, saying there is a number that all theoretical physicists of worth should "worry about". **He called it "one of the greatest damn mysteries of physics: a magic number that comes to us with no understanding by man".**

That magic number, called the **fine structure constant**, is a fundamental constant, with a value which nearly equals **1/137**. Or 1/137.03599913, to be precise. It is denoted by the Greek letter **alpha - α.**

What's special about alpha is that it's regarded as the best example of a **pure number,** one that doesn't need units. It actually combines three of nature's fundamental constants - the speed of light, the electric charge carried by one electron, and the Planck's constant, as explains physicist and astrobiologist **Paul Davies** to *Cosmos magazine.* Appearing at the intersection of such key areas of physics as relativity, electromagnetism and quantum mechanics is what gives 1/137 its allure.

Physicist **Laurence Eaves,** a professor at the University of Nottingham, thinks the number 137 would be the one you'd signal to the aliens to indicate that we have some measure of mastery over our planet and understand quantum mechanics. The aliens would know the number as well, especially if they developed advanced sciences.

The number preoccupied other great physicists as well, including the Nobel Prize winning **Wolfgang Pauli** (1900-1958) who was obsessed with it his whole life.
"When I die my first question to the Devil will be: What is the meaning of the fine structure constant?" Pauli joked.
Pauli also referred to the fine structure constant during his Nobel lecture on December 13th, 1946 in Stockholm, saying a theory was necessary that would determine the constant's value and "thus explain the atomistic structure of electricity, which is such an essential quality of all atomic sources of electric fields actually occurring in nature."

One use of this curious number is to measure the interaction of charged particles like electrons with electromagnetic fields. Alpha determines how fast an excited atom can emit a photon. It also affects the details of the light emitted by atoms. Scientists have been able to observe a pattern of shifts of light coming from atoms called "fine structure" (giving the constant its name). This "fine structure" has been seen in sunlight and the light coming from other stars.

The constant figures in other situations, making physicists wonder why. Why does nature insist on this number? It has appeared in various calculations in physics since the 1880s, spurring numerous attempts to come up with a Grand Unified Theory that would incorporate the constant since. So far no single explanation took hold. Recent research also introduced the possibility that the constant has actually increased over the last six billion years, even though slightly.

If you'd like to know the math behind fine structure constant more specifically, the way you arrive at alpha is by putting the 3 constants h,c, and e together in the equation --

$$\begin{aligned} \alpha_{SI} &= \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c} \approx \frac{1}{137} \\ \alpha_{CGS} &= \frac{e^2}{\hbar c} \approx \frac{1}{137} \end{aligned}$$

© Big Think

As the units c, e, and h cancel each other out, the "pure" number of 137.03599913 is left behind. For historical reasons, says Professor Davies, the inverse of the equation is used 2πe2/hc = 1/137.03599913. If you're wondering what is the precise value of that fraction - it's **0.007297351.**

The secret of the universe is 1/137

What did **Paul Dirac** describe as "the most fundamental problem of physics?". What did **Richard Feynman** call " a magic number that comes to us with no understanding?" The answer is the **Fine Structure Constant** or α- constant, which works out at close to 1/137 (see below)

Today we've got a piece of really good, clear science journalism for you by **Natalie Wolchover** of *Quanta* magazine. * For over a hundred years now physicists working over a whole range of advanced problems- light, electromagnetism, the structure of matter, you name it, keep finding that the calculations keep coming back to this strange, mysterious and recurring number. Because its so important, the race is on to measure it more and more precisely. Good science journalism makes the work of really clever people easy for us ordinary mortals. Natalie takes us lightly through a tour de force of work by scientist **Saida Guellati-Khélifa** and her team,who have fine-tuned it down to 1/137.035999206, with an uncertainty of 0.000000011. Was that about what you were expecting? Natalie has the first link, but we've posted another, just in case you want to dig deeper.* *Passé* Criswell, we predict: with all these new forces and theories turning up, the world of physics is in for an exciting ride in the next decade.

#finestructureconstant #physics #quantumphysics #universe #speedof light #time #space #measurement

Physicists Nail Down the ‘Magic Number’ That Shapes the Universe

A team in Paris has made the most precise measurement yet of the fine-structure constant, killing hopes for a new force of nature.

The fine-structure constant was introduced in 1916 to quantify the tiny gap between two lines in the spectrum of colors emitted by certain atoms. The closely spaced frequencies are seen here through a Fabry-Pérot interferometer.

Introduction

As fundamental constants go, the speed of light, c, enjoys all the fame, yet c’s numerical value says nothing about nature; it differs depending on whether it’s measured in meters per second or miles per hour. The fine-structure constant, by contrast, has no dimensions or units. It’s a pure number that shapes the universe to an astonishing degree — “a magic number that comes to us with no understanding,” as Richard Feynman described it. Paul Dirac considered the origin of the number “the most fundamental unsolved problem of physics.”

Numerically, the fine-structure constant, denoted by the Greek letter α (alpha), comes very close to the ratio 1/137. It commonly appears in formulas governing light and matter. “It’s like in architecture, there’s the golden ratio,” said Eric Cornell(opens a new tab), a Nobel Prize-winning physicist at the University of Colorado, Boulder and the National Institute of Standards and Technology. “In the physics of low-energy matter — atoms, molecules, chemistry, biology — there’s always a ratio” of bigger things to smaller things, he said. “Those ratios tend to be powers of the fine-structure constant.”

The constant is everywhere because it characterizes the strength of the electromagnetic force affecting charged particles such as electrons and protons. “In our everyday world, everything is either gravity or electromagnetism. And that’s why alpha is so important,” said Holger Müller(opens a new tab), a physicist at the University of California, Berkeley. Because 1/137 is small, electromagnetism is weak; as a consequence, charged particles form airy atoms whose electrons orbit at a distance and easily hop away, enabling chemical bonds. On the other hand, the constant is also just big enough: Physicists have argued that if it were something like 1/138, stars would not be able to create carbon, and life as we know it wouldn’t exist.

Physicists have more or less given up on a century-old obsession over where alpha's particular value comes from; they now acknowledge that the fundamental constants could be random, decided in cosmic dice rolls during the universe's birth. But a new goal has taken over.

Physicists want to measure the fine-structure constant as precisely as possible. Because it's so ubiquitous, measuring it precisely allows them to test their theory of the interrelationships between elementary particles — the majestic set of equations known as the Standard Model of particle physics. Any discrepancy between ultra-precise measurements of related quantities could point to novel particles or effects not accounted for by the standard equations. Cornell calls these kinds of precision measurements a third way of experimentally discovering the fundamental workings of the universe, along with particle colliders and telescopes.

Today, in a new paper in the journal *Nature*(opens a new tab), a team of four physicists led by Saïda Guellati-Khélifa(opens a new tab) at the Kastler Brossel Laboratory in Paris reported the most precise measurement yet of the fine-structure constant. The team measured the constant's value to the 11th decimal place, reporting that $\alpha = 1/137.035999206$.
With a margin of error of just 81 parts per trillion, the new measurement is nearly three times more precise than the previous best measurement(opens a new tab) in 2018 by Müller's group at Berkeley, the main competition. (Guellati-Khélifa made the most precise measurement before Müller's in 2011.) Müller said of his rival's new measurement of alpha, "A factor of three is a big deal. Let's not be shy about calling this a big accomplishment."

Guellati-Khélifa has been improving her experiment for the past 22 years. She gauges the fine-structure constant by measuring how strongly rubidium atoms recoil when they absorb a photon. (Müller does the same with cesium atoms.) The recoil velocity reveals how heavy rubidium atoms are — the hardest factor to gauge in a simple formula for the fine-structure constant. "It's always the least accurate measurement that's the bottleneck, so any improvement in that leads to an improvement in the fine-structure constant," Müller explained.

The Paris experimenters begin by cooling the rubidium atoms almost to absolute zero, then dropping them in a vacuum chamber. As the cloud of atoms falls, the researchers use laser pulses to put the atoms in a quantum superposition of two states — kicked by a photon and not kicked. The two possible versions of each atom travel on separate trajectories until more laser pulses bring the halves of the superposition back together. The more an atom recoils when kicked by light, the more out of phase it is with the unkicked version of itself. The researchers measure this difference to reveal the atoms' recoil velocity. "From the recoil velocity, we extract the mass of the atom, and the mass of the atom is directly involved in the determination of the fine-structure constant," Guellati-Khélifa said.

In such precise experiments, every detail matters. Table 1 of the new paper is an "error budget" listing 16 sources of error and uncertainty that affect the final measurement. These include gravity and the Coriolis force created by Earth's rotation — both painstakingly quantified and compensated for. Much of the error budget comes from foibles of the laser, which the researchers have spent years perfecting.

> I love building shiny nice machines. And I love applying them to something important.
>
> Holger Müller

For Guellati-Khélifa, the hardest part is knowing when to stop and publish. She and her team stopped the week of February 17, 2020, just as the coronavirus was gaining a foothold in France. Asked whether deciding to publish is like an artist deciding that a painting is finished, Guellati-Khélifa said, "Exactly. Exactly. Exactly."

Surprisingly, her new measurement differs from Müller's 2018 result in the tenth digit, a bigger discrepancy than the margin of error of either measurement. This means — barring some fundamental difference between rubidium and cesium — that one or both of the measurements has an unaccounted-for error. The Paris group's measurement is the more precise, so it takes precedence for now, but both groups will improve their setups and try again.

Though the two measurements differ, they closely match the value of alpha inferred from precise measurements of the electron's g-factor, a constant related to its magnetic moment, or the torque that the electron experiences in a magnetic field. "You can connect the fine-structure constant to the g-factor with a hell of a lot of math," said Cornell. "If there are any physical effects missing from the equations [of the Standard Model], we would be getting the answer wrong."

Instead, the measurements match beautifully, largely ruling out some proposals for new particles. The agreement between the best *g*-factor measurements and Müller's 2018 measurement was hailed as the Standard Model's greatest triumph. Guellati-Khélifa's new result is an even better match. "It's the most precise agreement between theory and experiment," she said.

And yet she and Müller have both set about making further improvements. The Berkeley team has switched to a new laser with a broader beam (allowing it to strike their cloud of cesium atoms more evenly), while the Paris team plans to replace their vacuum chamber, among other things.

What kind of person puts such a vast effort into such scant improvements? Guellati-Khélifa named three traits: "You have to be rigorous, passionate and honest with yourself." Müller said in response to the same question, "I think it's exciting because I love building shiny nice machines. And I love applying them to something important." He noted that no one can single-handedly build a high-energy collider like Europe's Large Hadron Collider. But by constructing an ultra-precise instrument rather than a super-energetic one, Müller said, "you can do measurements relevant to fundamental physics, but with three or four people."

***Correction:** December 4, 2020*
The original version of this article incorrectly reported the newly measured value of alpha as 1/137.03599920611; the correct number is 1/137.035999206, with an uncertainty of 0.000000011. In an article about the "nailing down" of the constant's value, we regret the error.

The Secret Code of the Universe: A Remarkable Way of Measuring the Fine Structure Constant

BY VIENNA UNIVERSITY OF TECHNOLOGYJANUARY 15, 2023

A light source (left) sends a beam of light through a special material, which changes the direction of polarization — by an angle that is given by the fine structure constant. Credit: Tatiana Lysenko / TU Wien

The fine structure constant is a fundamental constant of nature and its measurement is crucial in physics. Recently, researchers at TU Wien have discovered a unique way of measuring it.

The value of one over 137, also known as the fine structure constant, is considered a crucial number in physics. It plays a significant role in atomic and particle physics.

While traditionally the fine structure constant is measured indirectly through calculations and measurements of other physical quantities, researchers at TU Wien have developed an experiment that allows for the direct measurement of the fine structure constant in the form of an angle.

1/137 — the Secret Code of the Universe

The fine structure constant describes the strength of the electromagnetic interaction. It indicates how strongly charged particles such as electrons react to electromagnetic fields. If the fine structure constant had a different value, our universe would look completely different — atoms would have a different size, so all chemistry would work differently, and nuclear fusion in the stars would be completely different as well.

A much-discussed question is whether the fine structure constant is actually constant, or whether it could possibly have changed its value a little over billions of years.

Direct Measurements Instead of Calculations

“Most important physical constants have a specific unit — for example, the speed of light, which can be given in the unit of meters per second,” says Professor Andrei Pimenov from the Institute of Solid State Physics at TU Wien. “It’s different with the fine structure constant. It has no unit, it is simply a number – it is dimensionless.”

But usually, when the fine structure is measured, various quantities with different physical units have to be measured, and then the value of the fine structure constant is inferred from these results. “In our experiment, on the other hand, the fine structure constant itself becomes directly visible,” says Andrei Pimenov.

A Thin Film That Rotates the Light

A laser beam is polarized linearly — the light oscillates exactly in the vertical direction. Then the beam hits a layer of a special material that is only a few nanometers thick. This material has the property of changing the polarization direction of the light.

“A material rotating the polarization of a laser beam is, by itself, nothing unusual. Different materials can do this; the thicker the material layer, the more the polarization of the laser is rotated. But we are dealing with a completely different effect here,” explains Andrei Pimenov. “In our case, the polarization is not rotated continuously — it jumps.”

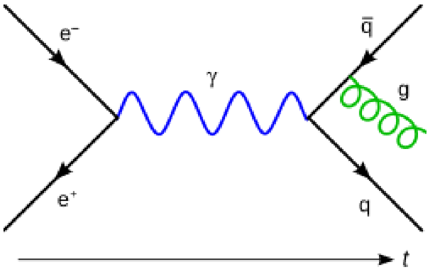
When passing through the thin film, the polarization direction of the light performs a quantum jump. After passing through, the light wave oscillates in a different direction than before. And when the size of this jump is calculated, an astonishing result appears: the quantum of this angular change is exactly the fine structure constant.

“We thus have direct access to something quite unusual: a quantum of rotation,” says Andrei Pimenov. “The fine structure constant becomes immediately visible as an angle.”Reference: “Universal rotation gauge via quantum anomalous Hall effect” by Alexey Shuvaev, Lei Pan, Lixuan Tai, Peng Zhang, Kang L. Wang and Andrei Pimenov, 7 November 2022, *Applied Physics Letters*.
DOI: 10.1063/5.0105159

Fine-structure constant

Value of α
0.0072973525643(11)
Value of α^{-1}
137.035999177(21)

Quantum field theory



Feynman diagram

In physics, the **fine-structure constant**, also known as the **Sommerfeld constant**, commonly denoted by α (the Greek letter *alpha*), is a fundamental physical constant that quantifies the strength of the electromagnetic interaction between elementary charged particles.

It is a dimensionless quantity (dimensionless physical constant), independent of the system of units used, which is related to the strength of the coupling of an elementary charge *e* with the electromagnetic field, by the formula $4\pi\varepsilon_0\hbar c\alpha = e^2$. Its numerical value is approximately 0.0072973525643 ≈ 1/137.035999177, with a relative uncertainty of 1.6×10^{-10}.[1]

The constant was named by Arnold Sommerfeld, who introduced it in 1916[2] when extending the Bohr model of the atom. α quantified the gap in the fine structure of the spectral lines of the hydrogen atom, which had been measured precisely by Michelson and Morley in 1887.[a]

Why the constant should have this value is not understood,[3] but there are a number of ways to measure its value.

Definition

In terms of other physical constants, α may be defined as:[4] where

- e is the elementary charge ($1.602176634\times10^{-19}$ C[5]);
- h is the Planck constant (6.62607015×10^{-34} J⋅Hz^{-1}[6]);
- $\hbar$ is the reduced Planck constant, $\hbar = h/2\pi$ ($1.054571817...\times10^{-34}$ J⋅s[7])
- c is the speed of light (299792458 m⋅s^{-1}[8]);
- ε_0 is the electric constant ($8.8541878188(14)\times10^{-12}$ F⋅m^{-1}[9]).

Since the 2019 revision of the SI, the only quantity in this list that does not have an exact value in SI units is the electric constant (vacuum permittivity).

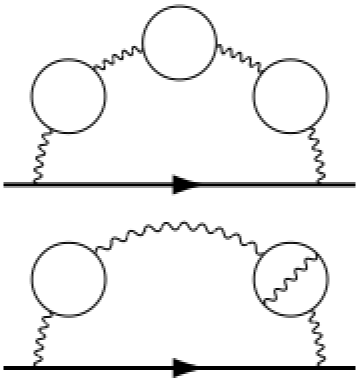
Alternative systems of units

The electrostatic CGS system implicitly sets $4\pi\varepsilon_0 = 1$, as commonly found in older physics literature, where the expression of the fine-structure constant becomes

A nondimensionalised system commonly used in high energy physics sets $\varepsilon_0 = c = \hbar = 1$, where the expression for the fine-structure constant becomes[10] As such, the fine-structure constant is chiefly a quantity determining (or determined by) the elementary charge: $e = \sqrt{4\pi\alpha} \approx 0.30282212$ in terms of such a natural unit of charge.

In the system of atomic units, which sets $e = \hbar = 4\pi\varepsilon_0 = 1$, the expression for the fine-structure constant becomes

Measurement



Eighth-order Feynman diagrams on electron self-interaction. The arrowed horizontal line represents the electron, the wavy lines are virtual photons, and the circles are virtual electron–positron pairs.

The CODATA recommended value of α is[1]

$\alpha = e^2/4\pi\varepsilon_0\hbar c$ = 0.0072973525643(11).

This has a relative standard uncertainty of 1.6×10^{-10}.[1]

This value for α gives the following value for the vacuum magnetic permeability (magnetic constant): $\mu_0 = 4\pi \times 0.99999999987(16) \times 10^{-7}\ \mathrm{H{\cdot}m^{-1}}$, with the mean differing from the old defined value by only 0.13 parts per billion, 0.8 times the standard uncertainty (0.16 parts per billion) of its recommended measured value.

Historically, the value of the reciprocal of the fine-structure constant is often given. The CODATA recommended value is [11]

$1/\alpha = 137.035999177(21)$.

While the value of α can be determined from estimates of the constants that appear in any of its definitions, the theory of quantum electrodynamics (QED) provides a way to measure α directly using the quantum Hall effect or the anomalous magnetic moment of the electron.[12] Other methods include the A.C. Josephson effect and photon recoil in atom interferometry.[13] There is general agreement for the value of α, as measured by these different methods. The preferred methods in 2019 are measurements of electron anomalous magnetic moments and of photon recoil in atom interferometry.[13] The theory of QED predicts a relationship between the dimensionless magnetic moment of the electron and the fine-structure constant α (the magnetic moment of the electron is also referred to as the electron g-factor g_e). One of the most precise values of α obtained experimentally (as of 2023) is based on a measurement of g_e using a one-electron so-called "quantum cyclotron" apparatus,[12] together with a calculation via the theory of QED that involved 12672 tenth-order Feynman diagrams:[14]

$1/\alpha = 137.035999166(15)$.

This measurement of α has a relative standard uncertainty of 1.1×10^{-10}. This value and uncertainty are about the same as the latest experimental results.[15]

Further refinement of the experimental value was published by the end of 2020, giving the value

$1/\alpha = 137.035999206(11)$,

with a relative accuracy of 8.1×10^{-11}, which has a significant discrepancy from the previous experimental value.[16]

Physical interpretations

The fine-structure constant, α, has several physical interpretations. α is:

- The ratio of two energies:
    i. the energy needed to overcome the electrostatic repulsion between two electrons a distance of d apart, and

ii. the energy of a single photon of wavelength $\lambda = 2\pi d$ (or of angular wavelength d; see *Planck relation*):

- The ratio of the velocity of the electron in the first circular orbit of the Bohr model of the atom, which is $1/4\pi\varepsilon_0 e^2/\hbar$, to the speed of light in vacuum, c.[17] This is Sommerfeld's original physical interpretation. Then the square of α is the ratio between the Hartree energy (27.2 eV = twice the Rydberg energy = approximately twice its ionization energy) and the electron rest energy (511 keV).

- is the ratio of the potential energy of the electron in the first circular orbit of the Bohr model of the atom and the energy $m_e c^2$ equivalent to the mass of an electron. Using the virial theorem in the Bohr model of the atom which means that Essentially this ratio follows from the electron's velocity being .
- The two ratios of three characteristic lengths: the classical electron radius r_e, the reduced Compton wavelength of the electron $\bar{\lambda}_e$, and the Bohr radius a_0: $r_e = \alpha\bar{\lambda}_e = \alpha^2 a_0$.
- In quantum electrodynamics, α is directly related to the coupling constant determining the strength of the interaction between electrons and photons.[18] The theory does not predict its value. Therefore, α must be determined experimentally. In fact, α is one of the empirical parameters in the Standard Model of particle physics, whose value is not determined within the Standard Model.
- In the electroweak theory unifying the weak interaction with electromagnetism, α is absorbed into two other coupling constants associated with the electroweak gauge fields. In this theory, the electromagnetic interaction is treated as a mixture of interactions associated with the electroweak fields. The strength of the electromagnetic interaction varies with the strength of the energy field.
- In the fields of electrical engineering and solid-state physics, the fine-structure constant is one fourth the product of the characteristic impedance of free space, and the conductance quantum, : The optical conductivity of graphene for visible frequencies is theoretically given by $\pi/4G_0$, and as a result its light absorption and transmission properties can be expressed in terms of the fine-structure constant alone.[19] The absorption value for normal-incident light on graphene in vacuum would then be given by $\pi\alpha/(1 + \pi\alpha/2)^2$ or 2.24%, and the transmission by $1/(1 + \pi\alpha/2)^2$ or 97.75% (experimentally observed to be between 97.6% and 97.8%). The reflection would then be given by $\pi^2\alpha^2/4(1 + \pi\alpha/2)^2$.

- The fine-structure constant gives the maximum positive charge of an atomic nucleus that will allow a stable electron-orbit around it within the Bohr model (element feynmanium).[20] For an electron orbiting an atomic nucleus with atomic number Z the relation is $mv^2/r = 1/4\pi\varepsilon_0\ Ze^2/r^2$. The Heisenberg uncertainty principle momentum/position uncertainty relationship of such an electron is just $mvr = \hbar$. The relativistic limiting value for v is c, and so the limiting value for Z is the reciprocal of the fine-structure constant, 137.[21]

When perturbation theory is applied to quantum electrodynamics, the resulting perturbative expansions for physical results are expressed as sets of power series in α. Because α is much less than one, higher powers of α are soon unimportant, making the perturbation theory practical in this case. On the other hand, the large value of the corresponding factors in quantum chromodynamics makes calculations involving the strong nuclear force extremely difficult.

Variation with energy scale

In quantum electrodynamics, the more thorough quantum field theory underlying the electromagnetic coupling, the renormalization group dictates how the strength of the electromagnetic interaction grows logarithmically as the relevant energy scale increases. The value of the fine-structure constant α is linked to the observed value of this coupling associated with the energy scale of the electron mass: the electron's mass gives a lower bound for this energy scale, because it (and the positron) is the lightest charged object whose quantum loops can contribute to the running. Therefore, $1/137.03600$ is the asymptotic value of the fine-structure constant at zero energy. At higher energies, such as the scale of the Z boson, about 90 GeV, one instead measures an *effective* $\alpha \approx 1/127$.[22]

As the energy scale increases, the strength of the electromagnetic interaction in the Standard Model approaches that of the other two fundamental interactions, a feature important for grand unification theories. If quantum electrodynamics were an exact theory, the fine-structure constant would actually diverge at an energy known as the Landau pole – this fact undermines the consistency of quantum electrodynamics beyond perturbative expansions.

History

Based on the precise measurement of the hydrogen atom spectrum by Michelson and Morley in 1887,[b] Arnold Sommerfeld extended the Bohr model to include elliptical orbits and relativistic dependence of mass on velocity. He introduced a term for the fine-structure constant in 1916.[c] The first physical interpretation of the fine-structure constant α was as the ratio of the velocity of the electron in the first circular orbit of the relativistic Bohr atom to the speed of light in the vacuum.[26] Equivalently, it was the quotient between the minimum angular momentum allowed by relativity for a closed orbit, and the minimum angular momentum allowed for it by quantum mechanics. It appears naturally in Sommerfeld's analysis, and determines the size of the splitting or fine-structure of the hydrogenic spectral lines. This constant was not seen as significant until Paul Dirac's linear relativistic wave equation in 1928, which gave the exact fine structure formula.[27]:407

With the development of quantum electrodynamics (QED) the significance of α has broadened from a spectroscopic phenomenon to a general coupling constant for the electromagnetic field, determining the strength of the interaction between electrons and photons. The term $\alpha/2\pi$ is engraved on the tombstone of one of the pioneers of QED, Julian Schwinger, referring to his calculation of the anomalous magnetic dipole moment.

History of measurements

Successive values determined for the fine-structure constant[28][d]

Date	α	$1/\alpha$	Sources
1969 Jul	0.007297351(11)	137.03602(21)	CODATA 1969
1973	0.0072973461(81)	137.03612(15)	CODATA 1973
1987 Jan	0.00729735308(33)	137.0359895(61)	CODATA 1986
1998	0.007297352582(27)	137.03599883(51)	Kinoshita
2000 Apr	0.007297352533(27)	137.03599976(50)	CODATA 1998
2002	0.007297352568(24)	137.03599911(46)	CODATA 2002
2007 Jul	0.0072973525700(52)	137.035999070(98)	Gabrielse (2007)
2008 Jun	0.0072973525376(50)	137.035999679(94)	CODATA 2006
2008 Jul	0.0072973525692(27)	137.035999084(51)	Gabrielse (2008), Hanneke (2008)

2010 Dec	0.0072973525717(48)	137.035999037(91)	Bouchendira (2010)
2011 Jun	0.0072973525698(24)	137.035999074(44)	CODATA 2010
2015 Jun	0.0072973525664(17)	137.035999139(31)	CODATA 2014
2017 Jul	0.0072973525657(18)	137.035999150(33)	Aoyama *et al.* (2017)[29]
2018 Dec	0.0072973525713(14)	137.035999046(27)	Parker, Yu, *et al.* (2018)[30]
2019 May	0.0072973525693(11)	137.035999084(21)	CODATA 2018
2020 Dec	0.0072973525628(6)	137.035999206(11)	Morel *et al.* (2020)[16]
2022 Dec	0.0072973525643(11)	137.035999206(21)	CODATA 2022
2023 Feb	0.0072973525649(8)	137.035999166(15)	Fan *et al.* (2023)[12][e]

The CODATA values in the above table are computed by averaging other measurements; they are not independent experiments.

Potential variation over time

Further information: Time-variation of fundamental constants

Physicists have pondered whether the fine-structure constant is in fact constant, or whether its value differs by location and over time. A varying α has been proposed as a way of solving problems in cosmology and astrophysics.[31][32][33][34] String theory and other proposals for going beyond the Standard Model of particle physics have led to theoretical interest in whether the accepted physical constants (not just α) actually vary.

In the experiments below, $\Delta\alpha$ represents the change in α over time, which can be computed by $\alpha_{\text{prev}} - \alpha_{\text{now}}$. If the fine-structure constant really is a constant, then any

experiment should show that or as close to zero as experiment can measure. Any value far away from zero would indicate that α does change over time. So far, most experimental data is consistent with α being constant, up to 10 digits of accuracy.

Past rate of change

The first experimenters to test whether the fine-structure constant might actually vary examined the spectral lines of distant astronomical objects and the products of radioactive decay in the Oklo natural nuclear fission reactor. Their findings were consistent with no variation in the fine-structure constant between these two vastly separated locations and times.[35][36][37][38][39][40]

Improved technology at the dawn of the 21st century made it possible to probe the value of α at much larger distances and to a much greater accuracy. In 1999, a team led by John K. Webb of the University of New South Wales claimed the first detection of a variation in α.[41][42][43][44] Using the Keck telescopes and a data set of 128 quasars at redshifts $0.5 < z < 3$, Webb *et al.* found that their spectra were consistent with a slight increase in α over the last 10–12 billion years. Specifically, they

found that

In other words, they measured the value to be somewhere between −0.0000047 and −0.0000067. This is a very small value, but the error bars do not actually include zero. This result either indicates that α is not constant or that there is experimental error unaccounted for.

In 2004, a smaller study of 23 absorption systems by Chand *et al.*, using the Very Large

Telescope, found no measurable variation:[45][46]

However, in 2007 simple flaws were identified in the analysis method of Chand *et al.*, discrediting those results.[47][48]

King *et al.* have used Markov chain Monte Carlo methods to investigate the algorithm used by the UNSW group to determine $\Delta\alpha/\alpha$ from the quasar spectra, and have found that the algorithm appears to produce correct uncertainties and maximum likelihood estimates for $\Delta\alpha/\alpha$ for particular models.[49] This suggests that the statistical uncertainties and best estimate for $\Delta\alpha/\alpha$ stated by Webb *et al.* and Murphy *et al.* are robust.

Lamoreaux and Torgerson analyzed data from the Oklo natural nuclear fission reactor in 2004, and concluded that α has changed in the past 2 billion years by 45 parts per billion. They claimed that this finding was "probably accurate to within 20%". Accuracy is dependent on estimates of impurities and temperature in the natural reactor. These conclusions have yet to be verified.[50][51][52][53]

In 2007, Khatri and Wandelt of the University of Illinois at Urbana-Champaign realized that the 21 cm hyperfine transition in neutral hydrogen of the early universe leaves a unique absorption line imprint in the cosmic microwave background radiation.[54] They proposed using this effect to measure the value of α during the epoch before the formation of the first stars. In principle, this technique provides enough information to measure a variation of 1 part in 10^9 (4 orders of magnitude better than the current quasar constraints). However, the constraint which can be placed on α is strongly dependent upon effective integration time, going as $1/\sqrt{t}$. The European LOFAR radio telescope would only be able to constrain $\Delta\alpha/\alpha$ to about 0.3%.[54] The collecting area required to constrain $\Delta\alpha/\alpha$ to the current level of quasar constraints is on the order of 100 square kilometers, which is economically impracticable at present.

Present rate of change

In 2008, Rosenband *et al.*[55] used the frequency ratio of Al^+ and Hg^+ in single-ion optical atomic clocks to place a very stringent constraint on the present-time temporal variation of α, namely $\Delta\alpha/\alpha = (-1.6 \pm 2.3) \times 10^{-17}$ per year. A present day null constraint on the time variation of alpha does not necessarily rule out time variation in the past. Indeed, some theories[56] that predict a variable fine-structure constant also predict that the value of the fine-structure constant should become practically fixed in its value once the universe enters its current dark energy-dominated epoch.

Spatial variation – Australian dipole

Researchers from Australia have said they had identified a variation of the fine-structure constant across the observable universe.[57][58][59][60][61][62]

These results have not been replicated by other researchers. In September and October 2010, after released research by Webb *et al.*, physicists C. Orzel and S.M. Carroll separately suggested various approaches of how Webb's observations may be wrong. Orzel argues[63] that the study may contain wrong data due to subtle differences in the two telescopes.[64] Carroll takes an altogether different approach: he looks at the fine-structure constant as a scalar field and claims that if the telescopes are correct and the fine-structure constant varies smoothly over the universe, then the scalar field must have a very small mass. However, previous research has shown that the mass is not likely to be extremely small. Both of these scientists' early criticisms point to the fact that different techniques are needed to confirm or contradict the results, a conclusion Webb, *et al.*, previously stated in their study.[60]

Other research finds no meaningful variation in the fine structure constant.[65][66]

Anthropic explanation

The anthropic principle provides an argument as to the reason the fine-structure constant has the value it does: stable matter, and therefore life and intelligent beings, could not exist if its value were very different. For instance, if modern grand unified theories are correct, then α needs to be between around 1/180 and 1/85 to have proton decay to be slow enough for life to be possible.[67]

Numerological explanations

As a dimensionless constant which does not seem to be directly related to any mathematical constant, the fine-structure constant has long fascinated physicists.

Arthur Eddington argued that the value could be "obtained by pure deduction" and he related it to the Eddington number, his estimate of the number of protons in the universe.[68] This led him in 1929 to conjecture that the reciprocal of the fine-structure constant was not approximately but precisely the integer 137.[69] By the 1940s experimental values for $1/\alpha$ deviated sufficiently from 137 to refute Eddington's arguments.[27]
Physicist Wolfgang Pauli commented on the appearance of certain numbers in physics, including the fine-structure constant, which he also noted approximates reciprocal of the prime number 137.[70] This constant so intrigued him that he collaborated with psychoanalyst Carl Jung in a quest to understand its significance.[71] Similarly, Max Born believed that if the value of α differed, the universe would degenerate, and thus that $\alpha = 1/137$ is a law of nature.[72][f]

Richard Feynman, one of the originators and early developers of the theory of quantum electrodynamics (QED), referred to the fine-structure constant in these terms:

There is a most profound and beautiful question associated with the observed coupling constant, e – the amplitude for a real electron to emit or absorb a real photon. It is a simple number that has been experimentally determined to be close to 0.08542455. (My physicist friends won't recognize this number, because they like to remember it as the inverse of its square: about 137.03597 with an uncertainty of about 2 in the last decimal place. It has been a mystery ever since it was discovered more than fifty years ago, and all good theoretical physicists put this number up on their wall and worry about it.)

Immediately you would like to know where this number for a coupling comes from: is it related to pi or perhaps to the base of natural logarithms? Nobody knows. It's one of the greatest damn mysteries of physics: a magic number that comes to us with no understanding by humans. You might say the "hand of God" wrote that number, and "we don't know how He pushed His pencil." We know what kind of a dance to do experimentally to measure this number very accurately, but we don't know what kind of dance to do on the computer to make this number come out – without putting it in secretly!

—R. P. Feynman[3]

Conversely, statistician I. J. Good argued that a numerological explanation would only be acceptable if it could be based on a good theory that is not yet known but "exists" in the sense of a Platonic Ideal.[g]

Attempts to find a mathematical basis for this dimensionless constant have continued up to the present time. However, no numerological explanation has ever been accepted by the physics community.

In the late 20th century, multiple physicists, including Stephen Hawking in his 1988 book *A Brief History of Time*, began exploring the idea of a multiverse, and the fine-structure constant was one of several universal constants that suggested the idea of a fine-tuned universe.[74]

Quotes

For historical reasons, α is known as the fine structure constant. Unfortunately, this name conveys a false impression. We have seen that the charge of an electron is not strictly constant but varies with distance because of quantum effects; hence α must be regarded as a variable, too. The value 1/137 is the asymptotic value of α shown in Fig. 1.5a.[75]

—Francis Halzen and Alan Martin (1984)[76]

The mystery about α is actually a double mystery: The first mystery – the origin of its numerical value $\alpha \approx 1/137$ – has been recognized and discussed for decades. The second mystery – the range of its domain – is generally unrecognized.

—M.H. MacGregor (2007)[77]

When I die my first question to the Devil will be: What is the meaning of the fine structure constant?

—Wolfgang Pauli [78]

Footnotes

1. In quantum electrodynamics, α is proportional to the square of the coupling constant for a charged particle to the electromagnetic field. There are analogous coupling constants that give the interaction strength of the nuclear strong force and the nuclear weak force.
2. "Among other substances [that were] tried in the preliminary experiments, were thallium, lithium, and hydrogen. ... It may be noted, that in [the] case of the red hydrogen line, the interference phenomena disappeared at about 15,000 wave-lengths, and again at about 45,000 wave-lengths: So that the red hydrogen line must be a double line with the components about one-sixtieth as distant as the sodium lines."[24](p430)
3. *"Wir fügen den Bohrschen Gleichungen (46) und (47) die charakteristische Konstante unserer Feinstrukturen* (49) $\alpha = 2\pi e^2/ch$ *hinzu, die zugleich mit der Kenntnis des Wasserstoffdubletts oder des Heliumtripletts in §10 oder irgend einer analogen Struktur bekannt ist."*

   (We add, to Bohr's equations (46) and (47), the characteristic constant of our fine structures (49) $\alpha = 2\pi e^2/ch$ which is known at once from knowledge of the hydrogen doublet or the helium triplet in §10 or any analogous structure.)[25](p91)
4. Numbers in parentheses (e.g. the "(11)" appearing at the end of the value "137.035999206(11)") give its standard uncertainty referred to the least significant preceding digit.
5. This is not an experimentally measured value; instead it is a value determined *by the current theory* from an experimentally determined value of the electron magnetic moment.

6. "If alpha were bigger than it really is, we should not be able to distinguish matter from ether [the vacuum, nothingness], and our task to disentangle the natural laws would be hopelessly difficult. The fact however that alpha has just its value 1/137 is certainly no chance but itself a law of nature. It is clear that the explanation of this number must be the central problem of natural philosophy." – Max Born[72]
7. "There have been a few examples of numerology that have led to theories that transformed society: See the mention of Kirchhoff and Balmer in Good (1962) p. 316 ... and one can well include Kepler on account of his third law. It would be fair enough to say that numerology was the origin of the theories of electromagnetism, quantum mechanics, gravitation. ... So I intend no disparagement when I describe a formula as numerological. When a numerological formula is proposed, then we may ask whether it is correct. ... I think an appropriate definition of correctness is that the formula has a good explanation, in a Platonic sense, that is, the explanation could be based on a good theory that is not yet known but 'exists' in the universe of possible reasonable ideas." — I. J. Good (1990)[73]