


# In constant search of 'alpha'

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ON A hefty aluminium table in a Harvard University basement sits the biggest atom in the world. The culmination of 20 years' work, it looks like two oil drums stacked on top of one another, sprouting wires and tubing out the top. The drums contain powerful superconducting magnets, charged metal plates and special refrigerators - all to do a job usually accomplished by the nucleus of a hydrogen atom. "God would be ashamed if he made an apparatus this big," says Harvard physicist Gerald Gabrielse, the device's creator. "He did it with just the proton."

The point of this "home-made atom" is to confine an electron and trick it into behaving as if it were in a real atom. By precisely controlling the electron's movements, Gabrielse can probe the innermost workings of electromagnetism, the force that shapes much of our everyday world and binds us together. It's not just about fridge magnets, radio waves and television: electromagnetism is responsible for virtually everything we see and feel, from the redness of roses to the toughness of diamonds.

One pure number dictates the strength of this force. The number - known as alpha, the fine-structure constant - is one of nature's most precisely known quantities and one of the fundamental determinants of the universe's behaviour.

"Everywhere you have electromagnetic interactions, in principle you can measure alpha," says Andrzej Czarnecki of the University of Alberta in Edmonton, Canada. "The number of digits we can get characterises how well we understand the system. There's a great race between different areas of physics to get alpha to the most decimal places." There's a good reason for doing this, too, because measuring alpha even more precisely could lead to the discovery of new physical laws and phenomena.

## Flying colours

Following years of progress in refining their estimates for alpha, researchers hit a roadblock, and they have been stuck there for nearly 20 years. Now Gabrielse and his colleagues have made the breakthrough. By combining measurements from their home-made atom with the latest theoretical developments, they have calculated the most precise value yet for alpha. Combined with other measurements of alpha, this new value could challenge our understanding of how light and matter interact on the quantum level - one of the great pillars of modern physics.

Alpha first popped up in 1915 in a theory that explained the colours of light emitted by excited atoms, as in fireworks and burning stars. Early versions of quantum physics described why each element shines with a few characteristic colours. The German physicist Arnold Sommerfeld explained why this atomic light has "fine structure", in which each band of light splits into two or more subtle bands. In this model, alpha was thought to represent the ratio of an electron's velocity in an atom to the



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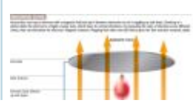
How QED works



speed of light.


Enlarge image
Measuring alpha

Throughout the 1930s, some researchers thought the numerical value of alpha might be a simple fraction, 1/137. It didn't turn out that way, and since then physicists have striven to add more decimal places to alpha's value. They have no clue why alpha has this particular value; all they can do is measure it.

By the 1940s, alpha had taken on a starring role in the development of a quantum theory of electromagnetism. Quantum electrodynamics, or QED, explained how matter interacts with light and put a quantum face on familiar phenomena like light-bending lenses and iron-attracting magnets. In the theory, alpha determines the strength of particle interactions. Its most important effect is on how tightly atoms hold on to their electrons. "If alpha changed tomorrow, all the atoms in the world would suddenly change their size," Gabrielse says. That would alter chemical reactions and probably prevent the existence of life as we know it.

> “If the quantum theory of light and matter is wrong, that would be fantastic”

If most quantum physics seems weird, QED is weirder. At its heart lie numerous strange quantum phenomena, one of the most bizarre being "virtual" particles. Because of the uncertainty principle, a virtual particle can pop briefly into existence, borrowing energy from empty space, only to disappear like a ghost an instant later. Virtual particles are crucial to QED's predictions and provide a quantum-level mechanism for how electromagnetic fields work. The exact value of alpha is intimately tied to the behaviour of these virtual particles, so spooling out more decimal places of alpha can test whether QED continues to match experimental results.

To calculate the effects that virtual particles have on, say, an electron, physicists work out how many ways an electron can get from point A to point B (see Diagram). One route is a straight line, another a wiggly path. There are also other more convoluted possibilities: as an electron cruises along, it can spit out a virtual photon, only to reabsorb it an instant later. Or the electron can spit out two, three or more virtual photons - and each of these can do a pirouette, transforming into an electron and a positron. Like a magician's assistant who gets sawn into pieces and then reassembled, the virtual particles recombine with the original electron.

Keeping pace with improving experiments, theorists are continually updating QED to capture more permutations of the virtual photons. This takes time: there are an infinite number of possibilities, and extending the calculations to encompass each additional virtual photon and its transformations requires exponentially more equations to be solved. Toichiro Kinoshita of Cornell University in Ithaca, New York, who has led many of the efforts to push quantum electrodynamics further, and his collaborator Makiko Nio of the Theoretical Physics Laboratory in Wako, Japan, recently completed a new level of calculations (*Physical Review D*, vol 73, 013003). It took years to set up computers to crunch through the 891 equations involved, which they solved approximately. Undaunted, the researchers have started on the next level, which will require solving more than 12,000 equations.

All the experimental results so far have matched QED's predictions, making it arguably the best-tested theory in all of physics. In fact, QED paved the way for the standard model of particle physics, a hugely successful conglomeration of theories that explain the quantum workings of all the fundamental forces except gravity.

Historically, though, QED's success was a surprise. "It was just patched together out of bits and pieces, in order to explain some experiments," says Freeman Dyson, one of the theory's architects, now at the Institute for Advanced Study in Princeton, New Jersey. "We didn't expect it to last," he adds. "Every time there was a new experiment, we all expected that the theory would be proved wrong in some interesting way. Instead, each experiment still agrees with the theory. That's sort of a disappointment."

Because QED has been so robust, pushing the theory has not led to any new physics. Six decades later, researchers are pushing their experiments further to see if QED will break. If there is a discrepancy, it could signal the existence of particles never before seen, or it could force physicists to give up their cherished assumption that electrons are point particles with no size or structure.

There could also be bigger repercussions. If QED ever failed to mesh with experiments, physicists could suddenly find themselves looking for a way to fix the theory, and the standard model too. "There is no wiggle room if theory and experiment disagree," Kinoshita says. Some fundamental aspect of QED - quantum mechanics, say, or special relativity - might have to be modified. "If quantum electrodynamics is wrong, that would be a fantastic discovery," says Gabrielse. "The stakes are really high here."

That's where Gabrielse's home-made replica of the hydrogen atom comes in. Like the real thing, it features a lone electron that can inhabit various quantum energy states. Gabrielse's device uses meticulously tuned electric and magnetic fields to trap the electron in a sugar-cube-sized space (see Diagram). The greatest challenge is keeping the electron in a given energy state, as any fluttering between states would lead to fuzziness in the measurements. Specially designed refrigerators cool it to within 0.1 degrees of absolute zero so it will stay in its lowest energy level indefinitely, and a near-perfect vacuum gets rid of particles the electron could bump into.

Gabrielse's team measured a quantum property of the electron called its magnetic moment, which makes it act as if it contains a tiny bar magnet. The magnetic moment dictates the strength and direction of the electron's response to a magnetic field, and through QED it is directly related to alpha. They found that if they shot a photon into the trap they could spur the electron to perform quantum leaps into higher energy levels. Gabrielse's contraption employs electrodes to measure the state of the electron, making it wiggle up and down. It resonates at different rates depending on its quantum state, so measuring these vibrations is a bit like listening to a guitar's notes to figure out where the player is pressing the strings. Comparing the electron's vibration rates across its different states gives a read-out of the magnetic moment.

Early versions of quantum theory predicted that the electron's magnetic moment would have a value of exactly 2, but in QED, the virtual particles - governed by alpha - subtly tweak the value of the electron's magnetic moment. In Gabrielse's experiment, the electron's magnetic moment weighed in at 2.00231930436170. This measurement has improved the value of the electron's magnetic moment to a precision of one part per trillion - six times better than previous results (*Physical Review Letters*, vol 97, 030801). "It's tough to measure anything this well," says Barry Taylor of the US National Institute of Standards and Technology in Gaithersburg, Maryland. "I'm very impressed."

Taking their new measurement, Gabrielse and his colleagues plugged it into the latest QED theory to get a new value for alpha: 1/137.035999710. They honed down the fine-structure constant's uncertainty by a factor of 5, the first improvement in precision since 1987 (*Physical Review Letters*, vol 97, 030802). This brings its exactitude to better than one part per billion, the equivalent of measuring the distance from New York to San Francisco with flea-sized precision. "It's irresistible to see how precisely we can pin down these quantities," says Gabrielse.

**Twitchy atoms**

Meanwhile, researchers have been looking out for another, equally precise way to obtain the value of alpha, only this time doing it without reference to quantum electrodynamics. Comparing this measurement with Gabrielse's, which does use QED, will put the theory to its toughest test yet.

The best hope for this seems to come from atomic recoil experiments. Here, physicists measure the tiny twitches of atoms when they kick back after emitting a photon. By measuring the twitches and the colour of the light that comes out, researchers can derive a value of alpha that is independent of QED. Two groups - one led by François Biraben at the Ecole Normale Supérieure in Paris, France, and another by Carol Tanner at the University of Notre Dame in Indiana - have recently reported precise measurements of alpha (*Physical Review Letters*, vol 96, 033001, and *Physical Review A*, vol 73, 032504).

So, for the first time in 20 years there is a method to measure alpha that could eventually compete with techniques based on the electron's magnetic moment. For now, Gabrielse's magnetic-moment method gives a value of alpha that is about 10 times as precise as Biraben's and Tanner's. If improved, however, the latter approach will set the stage for the ultimate test of QED's accuracy. "This atomic recoil method is coming to the rescue, potentially," says Czarnecki.

Will QED survive intact? "It has worked so remarkably well for a number of years that it has made it into all of our textbooks as if it's the gospel truth," Gabrielse says. "Most of us would be surprised if it breaks down, just because we've failed to make it break down after trying so hard." He adds, "We're in a rut, for very good reason, in using these field theories. They have been wildly successful. But it seems to me sort of part of the human experience to always ask, 'Is that the whole story? Or is there something more to it?'"

Call it the romance of the next decimal place: physicists never know what new phenomena may be lurking just around the corner.

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### Is alpha changing?

Recent studies suggest that the fine-structure constant, alpha, might not be constant, but may have changed over billions of years (*New Scientist*, 3 July 2004, p 6). If confirmed, that would suggest the ground rules of physics are shifting under our feet. While measurements of alpha are homing in on its value today, we can get an idea of what alpha was in the past by looking at ancient processes.

Distant stars, whose light has travelled for billions of years before reaching Earth, could reveal the value of alpha long ago. Researchers look at the characteristic wavelengths of light emitted by the elements in these stars, similar to measurements that introduced alpha in the first place. A natural nuclear reactor in west Africa could also reveal whether alpha has changed in the past 2 billion years. At Oklo, in Gabon, enough uranium naturally clumped together to start a nuclear reaction. Alpha affects the rate of this reaction and thus determined which radioactive isotopes are left there today.

Both types of studies have yielded mixed results. For now, it seems, most physicists think the fine-structure constant is still just that - constant.