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Why Do Physicists Want A 'Nuclear Clock'?

It didn’t generate much excitement in mass media, but there was one physics story last week that made me sit up and say “Hey, cool!,” namely the confirmation that a particular energy state in the nucleus of thorium actually exists (there’s also a news story in Nature, but that’s paywalled because Nature). This might not sound especially exciting, but it’s a step on the road to a “nuclear clock” in thorium that might improve on state-of-the-art atomic clocks by an order of magnitude or more. And that would be pretty cool, for reasons that I’ll attempt to explain here.

The core idea is just an upgrade of the existing definition of time. The second is currently defined as 9,192,631,770 oscillations of the light absorbed and emitted as electrons in cesium atoms move between two particular energy levels. Every cesium atom in the universe is identical to every other, with exactly the same energy levels, which means they can serve as perfect time references to set the frequency of a microwave source.

The particular choice of cesium as the standard is fundamentally arbitrary and driven by historical convenience– to get the best possible measurement, you want a fairly heavy atom (so they’re not moving very fast and thus don’t have a big Doppler shift) and a frequency that’s fairly high but not too high to convert to an electronic time signal, and when the standard was set in 1967, cesium happened to be a good choice. And thanks to the steady march of technology, state-of-the-art atomic clocks match the cesium transition with an uncertainty of a few parts in 1016– speaking somewhat loosely, that means that one second according to the microwave source is 1.0000000000000000+/-0.0000000000000001 seconds according to the cesium atoms themselves.

That’s pretty impressive all by itself, but laser technology has come a long, long way since 1967, and it’s now possible to make atomic clocks using frequencies 100,000 times greater than the microwaves used in cesium. Better yet, thanks to the development of laser frequency combs, those high frequencies can be connected to easy-to-work-with radio frequencies in the lab. These “Optical clocks” (PDF) can be much more precise than microwave ones, operating at a level of a few parts in 1018. In particular, “optical lattice clocks” that hold a few thousand atoms stationary in a trap made from carefully tuned lasers, greatly exceed the performance of the best cesium clocks, and Hidetoshi Katori’s group in Japan has shown they can compare clocks based on different atoms with an uncertainty in the 18th decimal place. That’s a bit like measuring the distance from the Earth to the Moon to within the width of an atom.

The thorium measurement published last week is part of an attempt to do even better by changing to a “nuclear clock.” Both microwave and optical clocks are based on the light emitted as the electrons orbiting an atom change places, but a nuclear clock would be based on the light emitted as protons and neutrons inside the nucleus rearrange themselves. Most of the time, this involves frequencies well into the x-ray and gamma-ray regions of the spectrum, which are really difficlt to work with, but calculations suggest that there should be a transition between two states of the nucleus of thorium-229 corresponding to an ultraviolet laser not too much more extreme than the ones used in some existing optical clocks. This is a tempting target for clock physicists, because the nucleus of an atom is shielded by the orbiting electrons, and thus much less sensitive to a lot of the external perturbations that limit the performance of current optical clocks. Theoretical proposals suggest that a nuclear clock based on trapped thorium ions might be a factor of 10 better than the best optical clocks.

Of course, this is all theory so far, as nobody has ever used lasers to drive a transition between nuclear states before. And the energy-level calculations are difficult enough that it's hard to even know where to look– you can get a sense of the difficulty by noting that a 2003 paper proposing the clock refers to a transition energy of 3.5eV but ten years later it's up to 7.6eV. Lots of searching has failed to turn anything up, and last week's experiment is the first to show that the state needed for the clock even exists, using the electrons emitted when the nucleus drops to a lower energy to prove that there's a transition somewhere between 6.3 and 18.3eV. Which throws the ball back into the laser physicists' court.

Now, from the outside, this whole business might seem kind of absurd. After all, the precision of cesium clocks is already much better than most people need– roughly analogous to measuring the height of a person to within the diameter of an atomic nucleus. Given that, it might not be clear why physicists would bother with optical lattice clocks, let alone the massive effort needed to make a nuclear clock.

So, why bother? It turns out that there are some very cool things you can do with improved clocks.

1) Navigation. The headline application for atomic time has long been the Global Positioning System. Navigation with GPS is based on a network of atomic clocks on satellites, each broadcasting the time according to its onboard clock. The difference between the times picked up from different satellites tells a receiver how long light took to travel from each satellite, which in turn gives the distance to that satellite and locates the receiver on the surface of the Earth.

There are a bunch of factors that limit GPS performance beyond the clocks themselves, but better, more robust clocks are never a Bad Thing. And the Navy has a strong interest in submarine navigation techniques that don't involve surfacing to check the GPS signal, most of which would also benefit from better clocks. Which is why people working on clock physics get a good deal of funding from various military agencies.

2) Geodesy. One of my favorite atomic clock experiments is a demonstration of relativity done in Dave Wineland's group some years back, where they measured the gravitational effect of lifting one of their test clocks up by about a foot. You can imagine turning this around, though, and using the known physics of relativity to measure elevations by changes in the "ticking" of identical atomic clocks. And while I can't find a paper mentioning it (yet), there's an abstract for a talk at next week's DAMOP conference by Hidetoshi Katori that mentions using optical lattice clocks to measure the elevation difference between two labs near Tokyo to within 5cm. This sort of "relativistic geodesy" has some cool applications in things like measuring local variations in density caused by stuff underground. In parallel with the general improvements in clocks, there's also a lot of cool recent work on connecting large networks of clocks, so this is a subfield to keep an eye on.

3) Fundamental Physics. Physicists often talk about “fundamental constants” that measure the relative strengths of known interactions (electromagnetism, the strong and weak nuclear forces, and gravity). These don’t necessarily have to be constant in time or space, though, and some attempts to tie all these forces together into a coherent whole allow them to change over time. A lot of effort has gone into looking to see whether these constants had different values in the distant past, using things like an ancient “natural nuclear reactor” and spectra of distant objects. Some observations of distant quasars seem to show a spatial variation (dubbed the “Australian dipole” after the location of the group who did the measurements), with the strength of the electromagnetic force appearing weaker in the past in one part of the sky, and stronger in the other. This remains somewhat controversial– I expressed skepticism in 2010, and there are still papers being published arguing about it.

The scale of the changes people talk about are exceedingly small– several parts per million over a few billion years– but they turn out to be just within reach of atomic clock comparisons. The states used to make atomic clocks in different types of atoms shift in different ways as the fundamental constants change, so if you compare two clocks based on different atoms over an extended period, you can put a limit on how rapidly the fundamental constants are changing today. With a sufficiently sensitive clock– right around the level projected for the thorium nuclear clock– you might even be able to test the “Australian dipole,” as the Sun’s orbit is carrying it from one region toward the other.

So, while it’s vanishingly unlikely that improvements in clock technology will turn up in a wristwatch or even on your phone, there are lots of good physics reasons to want to push to more and more precise clocks. Up to and including the development of a “nuclear clock,” and last week’s result is a good (if early and tentative) step in that direction.

Chad Orzel is a physics professor, pop-science author, and blogger. His latest book is Eureka: Discovering Your Inner Scientist (Basic Books, 2014).

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