Resolving the gravitational redshift across a millimetre-scale atomic sample

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Gravity warps time. This is not a metaphor — it’s physics. Place one clock on the floor and another on a table, and the table clock genuinely runs faster, because it is at a slightly higher gravitational potential. The effect is real, measurable, and has been confirmed at a range of scales, from airplane flights to skyscraper heights. But Tobias Bothwell, Jun Ye, and their colleagues at JILA just measured this effect across a distance smaller than the width of a pencil eraser — less than one millimeter. They took one atomic cloud, split it in two, and read gravity's fingerprint pixel by pixel across its length.

This achievement begins with a number: the gravitational redshift at Earth's surface corresponds to a fractional frequency gradient of negative 1.09 times ten to the minus nineteenth per millimeter. In simpler terms, raising a clock by one millimeter changes its tick rate by roughly one part in ten quintillion. This is an almost incomprehensibly small number — and yet, the strontium optical lattice clock that Bothwell and his team built is sensitive enough to measure it.

The instrument works by trapping around one hundred thousand atoms of strontium-87 in a one-dimensional optical lattice — a standing wave of laser light that holds the atoms in place like beads on a string. The lattice forms inside an in-vacuum cavity with a mode waist of 260 micrometers and a mirror spacing of about fifteen centimeters. Atoms are cooled to temperatures near 100 nanokelvin, loaded into the lattice, and then interrogated on strontium’s ultranarrow clock transition: the jump between the ground state and an excited state at 698 nanometers, ticking at around 429 terahertz. That high frequency provides the clock's extraordinary precision — more oscillations per second mean more ticks to count and a finer ruler.

A key design choice was to run the lattice at what the team calls a magic trap depth — a specific operating point where two types of collisional frequency shifts, from atoms on the same lattice site and from atoms on neighboring sites, cancel each other out. Operating at this magic depth reduced collisional frequency shifts by more than three orders of magnitude compared to their previous work. The lattice's large waist and shallow operational depth of 12 recoil energies also reduced atomic density, which is crucial because denser atom clouds produce larger collision-induced frequency errors. These engineering decisions compound: each one removes a source of noise, and together they allow the clock to achieve a fractional frequency instability of 3.1 times ten to the minus eighteenth per second for a single region — among the best ever demonstrated.

Now, here is what makes this experiment distinct from any previous clock comparison. The team did not build two separate clocks and move one up. Instead, they used a single elongated cloud of strontium atoms — oriented along the direction of gravity — and read out its clock frequency with spatial resolution, pixel by pixel, using an electron-multiplying charge-coupled device camera. The effective pixel size was calibrated to 6.04 micrometers, with an imaging resolution of about 6 micrometers and no measurable correlations between neighboring pixels. Every time the clock ran, the camera produced a one-dimensional frequency map of the cloud. The top of the cloud and the bottom were ticking at different rates — and the team could see it directly.

The gravitational redshift they were pursuing follows from a simple relation: the fractional change in a clock's frequency equals the local gravitational acceleration multiplied by the vertical separation, divided by the speed of light squared. Tiny acceleration, tiny separation, enormous divisor. The predicted gradient in their lab was negative 1.09 times ten to the minus nineteenth per millimeter. What they measured, after processing fourteen measurements collected over ten days, was a raw weighted mean slope of negative 1.00 plus or minus 0.12 times ten to the minus nineteenth per millimeter. This was already consistent with the prediction. However, that raw number had to be earned.

Fighting for every digit of precision is where the real work of this paper resides. Two systematic effects loomed largest. First, the lattice light itself. The laser that traps the atoms also perturbs their clock transition through what is known as an AC Stark shift. Any spatial variation in the laser intensity could mimic a gravitational gradient. The team characterized the residual lattice light shift by modulating between two different trap depths, finding a detuning from the scalar magic frequency of 7.4 plus or minus 0.6 megahertz. After evaluation, they bounded the re-

sidual differential lattice light shift to a fractional gradient of about negative 5 times ten to the minus twenty-first per millimeter — approximately fifty times smaller than the gravitational signal.

Second, atomic density. More atoms in a given region means more collisions, which shifts the clock frequency in a density-dependent way. Instead of applying a single global correction, Bothwell and colleagues measured density-dependent shifts at every individual pixel using the camera counts as a proxy for local atom number. The average density shift coefficient during the main data run was negative 2.43 times ten to the minus eighth hertz per camera count. At a shallower trap depth of 8 recoil energies, where this effect was much worse, they measured a spurious gradient of negative 1.08 times ten to the minus eighteenth per millimeter — a factor of ten larger than the gravitational signal they were seeking. This comparison vividly illustrates why the magic trap depth mattered so much: without it, the density shift would have entirely buried the signal. After applying per-pixel density corrections, they bounded the residual uncertainty from this effect to 1.7 times ten to the minus twentieth per millimeter.

Additional corrections addressed second-order Zeeman shifts — frequency perturbations from magnetic fields, which varied across the cloud at a measured gradient of about negative 7.0 times ten to the minus twentieth per millimeter, corresponding to a field gradient of 0.291 milligauss per millimeter — as well as black body radiation gradients, DC Stark effects, and pixel calibration uncertainties. Each of these was evaluated and subtracted. The final corrected fractional frequency gradient from the ten-day campaign was negative 9.8 plus or minus 2.3 times ten to the minus twentieth per millimeter. The predicted value from general relativity is negative 1.09 times ten to the minus nineteenth. This indicates agreement within the stated uncertainties.

As a complementary check, the team binned the camera pixels into two larger uncorrelated regions — effectively treating the top and bottom halves of the cloud as two independent clocks — and conducted a synchronous comparison for 92 hours. This method achieves a fractional frequency uncertainty between the two regions of 7.6 times ten to the minus twenty-first, representing an improvement in measurement uncertainty by more than a factor of ten relative to previous benchmarks. The corrected gradient from this comparison was negative 1.28 plus or minus 0.27 times ten to the minus nineteenth per millimeter, again fully consistent with the general relativistic prediction.

The coherence times achieved here are also noteworthy. Ramsey spectroscopy — a technique where atoms are prepared, allowed to evolve freely, then interrogated —

yielded an exponential contrast decay time of 36.5 seconds, implying a quality factor of 3.6 times ten to the sixteenth. The atoms oscillate for over half a minute before they lose track of each other. At optical frequencies, this translates to an extraordinary number of perfectly correlated oscillations, enabling the clock to achieve uncertainties in the twenties decimal places of fractional frequency.

What Bothwell and colleagues demonstrated is that the instruments we now have do not just measure general relativity — they are integrating general relativity as a feature of their own internal physics. The gravitational redshift is no longer merely something to test against the universe; it is now something to correct for inside the laboratory, within a single sample of atoms. The paper notes that leading clocks are already positioned to enable local geodetic surveys — using tick rates to map height differences — at the sub-centimeter level, and that future satellite-based comparisons could advance terrestrial redshift tests orders of magnitude further.

A cloud of atoms, less than one millimeter tall, ticking in a laser trap, with gravity written across it in parts per ten quintillion per millimeter. That is what a clock looks like when it runs out of things to ignore.

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