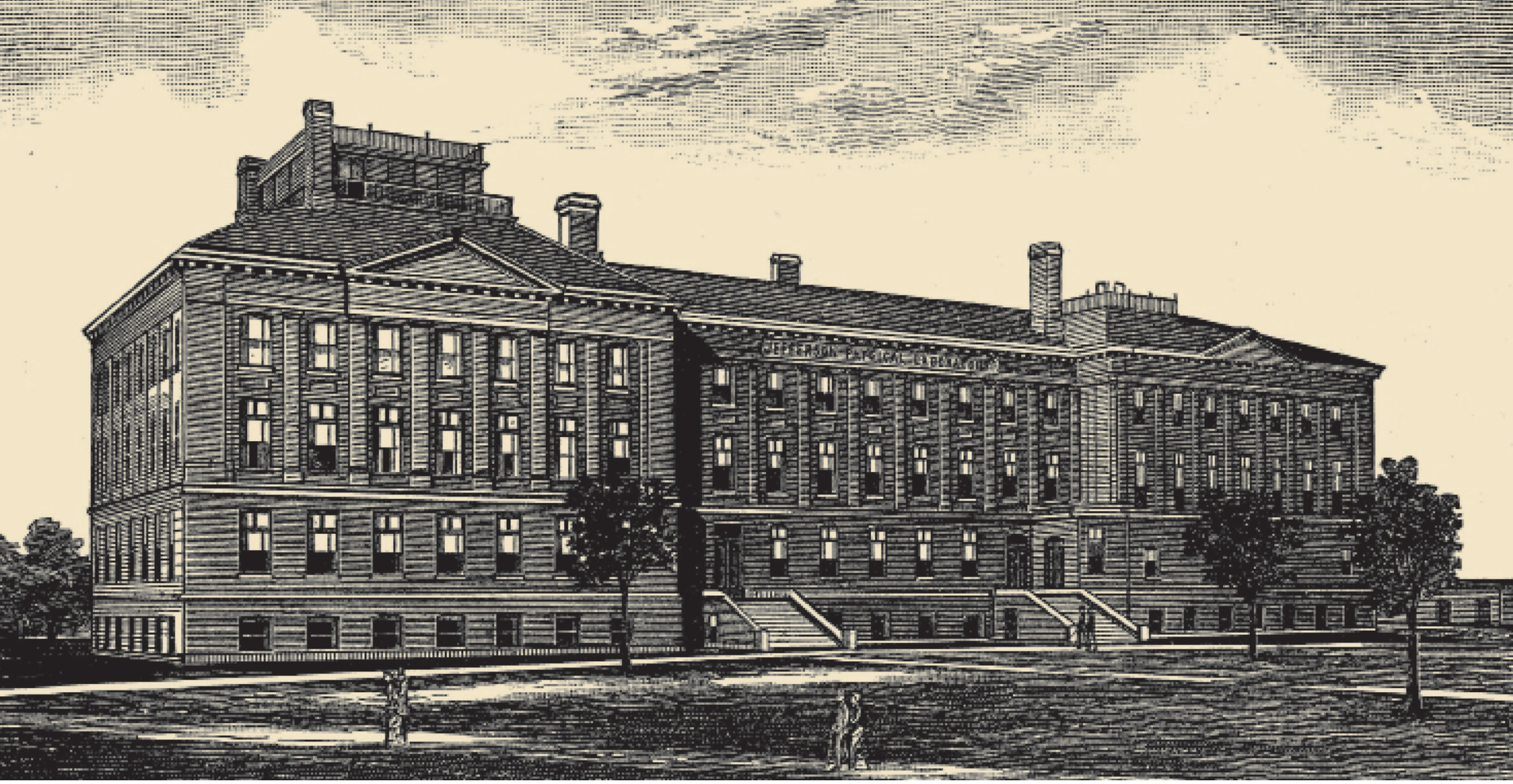

TESTING EINSTEIN'S PREDICTION:

The Pound–Rebka Experiment

by Paul Horowitz

Monday, January 24th, 1960: Robert Pound was worried. The previous night's data – the first with the fully configured experimental setup – had seemed to agree with Einstein's prediction, made a half century earlier, the only one of the famous three[1] that had stubbornly resisted experimental confirmation. But, having worked through the night, the exhausted professor and his student Glen Rebka realized, with chagrin, that the more recent measurements were wandering, that "something not under our control seemed to be interfering with the system, and we had no idea what it could be."[2]

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[1] These are (1) the precession of the perihelion of Mercury, which deviates from the classical prediction by about 8% (43 arc-sec per century); (2) the bending of light in a gravitational field; and (3) the shift of color of light as it moves toward or away from a gravitating body. The first of these was known when Einstein formulated his theory of general relativity. The second (1.75 arc-sec deflection of starlight grazing the sun) was first tested during a solar eclipse on May 29, 1919, with subsequently improved observations in the decades following; it is responsible for the phenomenon of "gravitational lensing." The third prediction—the "gravitational red shift"—was long considered beyond the possibility of laboratory measurement, amounting to only one part in 10^{16} per meter of height.

[2] As related in Pound's delightful account "Weighing Photons, I," *Phys. perspect.* 2, 224—268 (2000).

Setbacks like this are the stuff of experimental science; understanding experimental flaws, and overcoming them, gives joy to scientists.

But Pound was scheduled to give an invited talk one week later, at the annual American Physical Society meeting in New York, at which he hoped to report on this brave experiment. And, as luck would have it, a competing group from England had rushed in with a post-deadline talk to report their experiment's preliminary results. The image of the dispassionate scientist overlooks the reality of human ambitions.

The Gravitational Red Shift

Rewind fifty years: Einstein contributes a lengthy review article titled "On the Relativity Principle and the Conclusions Drawn from It,"[3] in which he reviews his theory of (special) Relativity, but with an added section introduced this way: "A further question suggesting itself is whether the principle of relativity is limited to nonaccelerated moving systems. I added to the present paper a fifth part that contains a novel consideration, based on the principle of relativity, on acceleration and gravitation."

His "novel consideration" begins with the bold assumption of "the complete physical equivalence of a gravitational field and a corresponding acceleration of the reference system." This is helpful, he tells us, because "it permits the replacement of a homogeneous gravitational field by a uniformly accelerated reference system, the latter case being to some extent accessible to theoretical treatment."

If you're OK with this "Equivalence Principle," the rest is clear sailing: imagine a photon of frequency f falling through a height h on Earth; it arrives $t=h/c$ seconds later. Now, following Einstein's recipe, replace gravity with a rocket with acceleration a equal to g. During the photon's time of flight the rocket acquires velocity $v=gt=gh/c$, which causes a first-order (classical) fractional Doppler shift of v/c; i.e., the frequency of the received photon is $f'=f(1+gh/c^2)$.

That's the gravitational red shift.[4] It's a really small effect, just 3.5×10^{-14} for a photon scaling the Eiffel Tower. Such precision

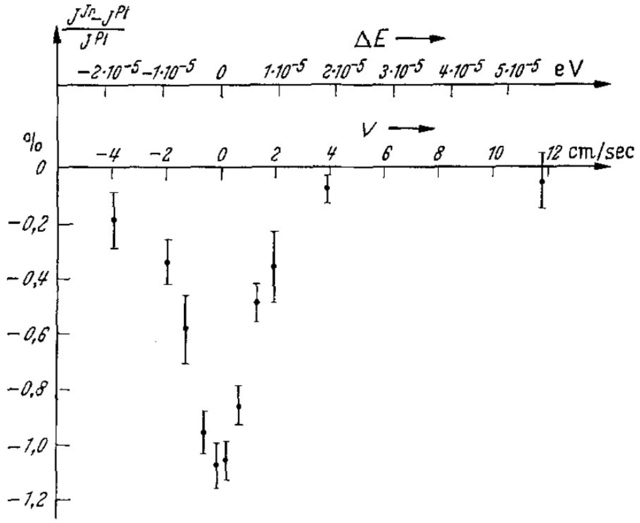

Fig. 2. Intensitätsdifferenz der hinter dem Resonanzabsorber (Iridium) und einem Vergleichsabsorber (Platin) gemessenen Gammastrahlung des 129 keV-Überganges in Ir^{191}, als Funktion der Relativgeschwindigkeit v der Quelle gegenüber dem Absorber, bei einer Temperatur der Quelle und des Absorbers von 88° K. $\Delta E = (v/c)\,E_0$ bezeichnet die Energieverschiebung der 129 keV-Gammaquanten

Figure 1: Graph of absorption versus source velocity, as published in Mössbauer's discovery paper.

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[3] *Jahrbuch der Radioaktivität und Elektronik*, 4, 411-462 (1907).

[4] Nicely derived in A. Einstein, "On the Influence of Gravitation on the Propagation of Light," *Annalen der Physik,* 35, 898-908 (1911). English translation found at https://einsteinpapers.press.princeton.edu/vol3-trans/393. Interestingly, in that paper he used only the equivalence principle (i.e., gravity vs. acceleration), which gives the correct result for the redshift, but only half the correct result for starlight deflection. He corrected this error in a 1915 paper.

Figure 2: Pound (center) speaking with J. B. H. Kuper via his cavity-stabilized X-band (10GHz) klystron oscillators, stable enough for frequency-modulated audio communication. Henry Torrey (of the NMR-discovery trio, see the 2019 Physics Newsletter) stands mute at the right. (Photo from "Five Years at the Radiation Laboratory," M.I.T., 1946).

was considered beyond the realm of possibility – so Einstein calculated instead the reddening of a solar photon,[5] getting $f'=f(1-2\times 10^{-6})$.

Astronomical attempts to measure solar redshifts were generally unsuccessful, owing to large offsets, line broadening, and Doppler shifts caused by turbulent motion of the emitting regions, along with the effects of pressure and temperature.

As far as the possibility of a terrestrial (laboratory) measurement, the best frequency standards were inadequate by many orders of magnitude. As late as 1955, for example, the first atomic beam apparatus (an "atomic clock") was built by Zacharias; it had a short-term stability of a part in 10^9, some five to six orders of magnitude poorer than required to measure, even approximately, the redshift from a structure as tall as the Eiffel Tower.

And thus things stood until 1958.

Enter Rudolf Mössbauer

In a surprising paper,[6] the German physicist Mössbauer reported a sharply defined resonant absorption of gamma rays, emitted by nuclei in the excited state of iridium-191, by a foil of the same isotope. Resonant absorption was a well-known phenomenon in optical spectroscopy (where photon energies are around an electron-volt), but at gamma-ray energies (129keV in this case) the recoil of the emitting nucleus reduces the gamma energy (Doppler effect); and the analogous effect in an absorbing atom further separates the lines. The newly-discovered "Mössbauer Effect" circumvented this resonance shift by transferring the recoil momentum to the atomic lattice as a whole, thus the term "recoilless resonant scattering." Figure 1 reproduces Mössbauer's measured absorption versus imposed velocity of the emitter, thus tracing out the resonance width; the resonance is sharp, with a full-width to half-maximum of about 10^{-10}.

In the fall of 1959, Pound's student Glen Rebka learned of Mössbauer's work, and proposed a program of measurements of possible hyperfine structure. Pound had other ideas – he (along with colleagues like Zacharias at M.I.T.) had been pondering the use of stable atomic clocks to test Einstein's redshift (Zacharias was thinking of a pair of clocks, on a Swiss mountain and valley; but his cesium-beam clocks were not yet good enough). The quest for stable oscillators had been a persistent theme in Pound's career: during his wartime radar work at M.I.T. he had developed a cavity-stabilized klystron that allowed FM communication at audio frequencies (see Figure 2); and around this time he devised an NMR-stabilized oscillator. [7]

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[5] For the general case of nonuniform gravitational field, substitute the gravitational potential difference for gh.

[6] R. L. Mössbauer, "Kernresonanzabsorption von Gammastrahlung in Ir^{191}," *Die Naturwissenschaften*, 45, 538-39 (1958).

[7] "R. V. Pound and R. Freeman, "Frequency Control of an Oscillator by Nuclear Magnetic Resonance," *Rev. Sci. Ins.*, 31, 2, 96-102 (1960).

So Pound wanted to exploit the resonance of unprecedented sharpness to test the last unconfirmed prediction of Einstein. Here we let him tell the story:

> *When I saw Glen that morning, I described what I had read [about using masers to test General Relativity] and again expressed the feeling that one ought to be able to use this new gamma-ray resonance for such tests. As we talked we suddenly realized a test of the "gravitational red shift" couldn't be simpler, and I think Glen saw it first. By simply separating the source of the gamma rays from the resonant absorber by a vertical path, the gravitational potential difference… should lead to a measurable displacement of the resonance.*

The Experiment

Were that "it couldn't be simpler"! Consider this: exploiting the full height of Jefferson Laboratory's isolated tower (Figure 3, an architectural feature incorporated seventy five years earlier in anticipation of sensitive physical measurements), the magnitude of the redshift would be just 2×10^{-15}, so you'd need precision of a part in 10^{16} to measure it with just modest confidence. That's six orders of magnitude smaller than Mössbauer's measured resonance in iridium!

Pound and Rebka quickly identified the stable isotope Fe^{57} as a better candidate than Mössbauer's cryogenic iridium – the lifetime of its Co^{57} parent was nearly a thousand times longer (0.1μs, versus 0.14ns), thus promising a far narrower (lifetime-limited) resonance; and its gamma energy was an order of magnitude lower (14.4keV, versus 129keV), favorable for improving the fraction of recoilless decays (by depositing more of the recoil energy in the lowest phonon mode, i.e., motion of the lattice as a whole). With luck it could be even used at room temperature.

The duo set to work, and, with help from M.I.T. nuclear physicist Lee Grodzins, they obtained a few millicuries of isotopically pure Co^{57} and a suitable scintillator detector. Glen learned to roll thin foils of iron absorber, and to electroplate the precious cobalt onto an iron substrate, followed by annealing to diffuse it into the lattice. Initial measurements showed a satisfyingly narrow and deep resonance – a line width of a part in 10^{12} (somewhat larger than theoretically possible) and a recoilless fraction of 80%. And this did not require Mössbauer's cryogenic environment – it was done at room temperature.

The way was now clear to attempt to measure Einstein's effect. Pound and Rebka published their Fe^{57} results,[8] with the comment "We are now confident that we can perform the gravitational experiment inside the laboratory using this γ-ray from Fe^{57}."

The Hard Work

Confidence is one thing. Designing, building, debugging, and properly interpreting the results is quite another – and there are many ways to do an experiment wrong. The successful execution of the Pound-Rebka experiment is a textbook example of experimental brilliance and attention to detail. Particularly so since their measured Fe^{57} resonance width was

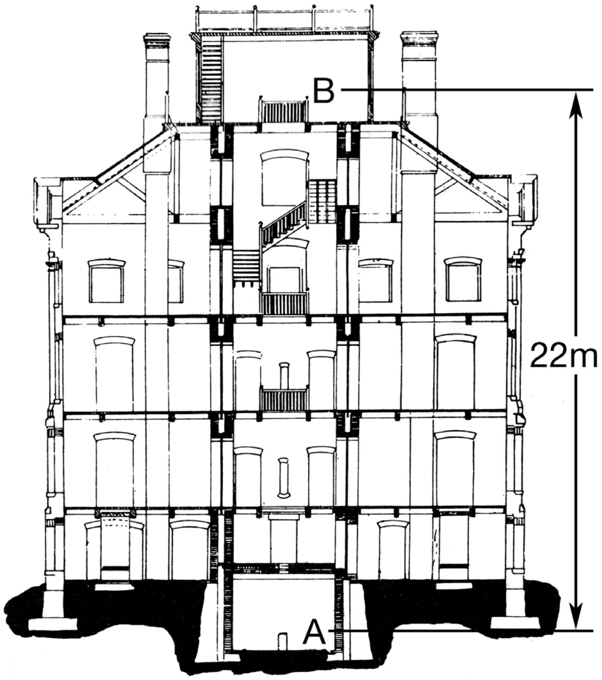

Figure 3: Cutaway diagram of Jefferson Laboratory, showing the approximate location of source/detector pairs (A and B) used in the redshift experiment. The top level is currently a penthouse "thinkatorium" for the 4th-floor theory group. The sub-basement had been the target area for the ball-dropping experiments of Edwin Hall (of Hall-Effect fame), and subsequently became Wallace Sabine's original reverberation chamber. Sabine was asked by the President and Fellows of Harvard College to fix the poor acoustics of the new Fogg Lecture Hall. He determined, through an exhaustive set of acoustic measurements, the ideal reverberation time for concert halls (he was the acoustical consultant for Boston's exemplary Symphony Hall) and for lecture halls. The Fogg reverberated for about 5.5~seconds, about six times longer than optimal. Sabine is generally credited with founding the field of architectural acoustics; the unit of absorption is the Sabin. (Figure from Rebka thesis, 1961)

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[8] R. V. Pound and G. A. Rebka, Jr., "Resonant absorption of the 14.4-keV γ from 0.10-μs Fe^{57}, *Phys. Rev. Lett.,* 3, 12, 554-56 (1959).

10^{-12} – a hundred times better than that of Mössbauer's discovery paper, and the narrowest resonance by far, at the time – but the predicted redshift up or down the 22m Jefferson tower was just 2 parts in 10^{15}. Measuring a shift that's 500 times smaller than the line width (and doing it to, say, 10%) is asking for trouble. And this experiment delivered trouble, on both shores of the Atlantic.

The best way to measure a small shift is by "slope detection" (Figure 4) – deliberately offsetting the resonance (via an imposed velocity's Doppler shift) to compare the absorption near the inflection points. Pound and Rebka experimented with both magnetic and piezoelectric transducers, choosing the latter, which oscillated the radioactive source at 50Hz with a peak velocity of ~1μm/s. The frequency was chosen to stay below mechanical resonances, but high enough to stay clear of "*1/f*" noise and system drifts. The detected gammas were gated to a set of pulse counters, according to the phase of the oscillatory motion, performing "synchronous detection" of the resonance line offset.

But we're only beginning – this was just the inner layer of what could be described as a nested set of three synchronous detectors. Next was a hydraulic piston that imposed a precise back-and-forth calibration velocity (±0.634μm/s – just a wavelength of light per second, enough to produce a Doppler shift approximately equal to the predicted redshift), with a 10-minute-long periodicity.

What could possibly go wrong? Plenty: there was no assurance that the source and absorber did not suffer from a congenital resonance offset. It would take an offset of only 0.2% of the line width to completely wipe out the predicted redshift signal. To address this possibility, the entire experiment was periodically inverted: the source (with its own "monitor" channel) and detector, along with their accoutrements, were carried up and down the winding staircases. Figure 5 shows the experimental hookup as published in Rebka's thesis.

Tuning It Up

It's a long slog from conception to fully working experiment, filled with sleepless nights. There's space enough here only to hint at the many tasks that had to be mastered – for example finding and preparing sources of isotopically enriched iron (Fe^{57} comprises only ~2% of natural iron) and of the Co^{57} parent isotope with substantial activity; arranging a hexagonal array of thin-crystal scintillation detectors and matching their sensitivities; boring a 2-foot hole through floors and ceilings and filling the resulting 22m path with a helium bag (because in air the gammas would be absorbed in just a few feet); building the (vacuum-tube!) electronics to do the modulation, switching, phasing, and signal routing; rigging up and calibrating the hydraulic motion system; and so on. Figure 6 is a photograph of Pound at the helm, illustrating a portion of the experiment's complexity.

The Troubles

With the bugs shaken out by mid-January, and encouraging initial results with round-trip (i.e., accounting for system inversions) redshifts in the ballpark, Pound and Rebka expected to have preliminary experimental confirmation of Einstein's prediction ready to report a week later at the New York meeting. But by the 24th (when this narrative began) the expected improvement from the statistics of additional runs was not in sight; quite the opposite – some runs produced wildly varying results. Something was wrong.

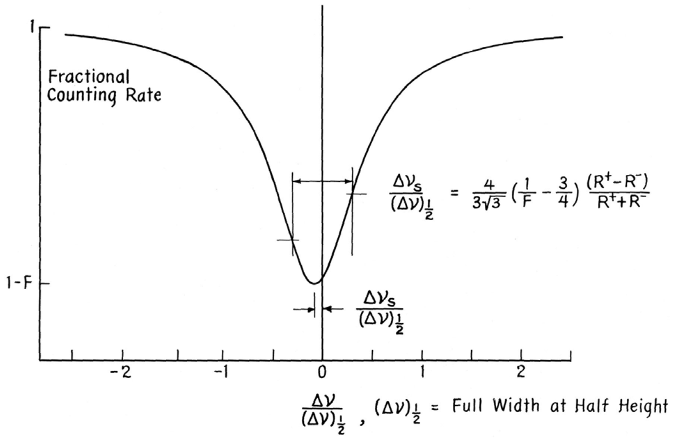

Figure 4: By tallying the difference of count rates at the inflection points of the Lorentzian, "slope detection" permits accurate measurement of the shift of maximum absorption. For clarity the offset is exaggerated in this figure -- the predicted redshift for the Jefferson Laboratory tower is about 1/10 of the width of the inked line in this figure. (Figure from Rebka thesis, 1961)

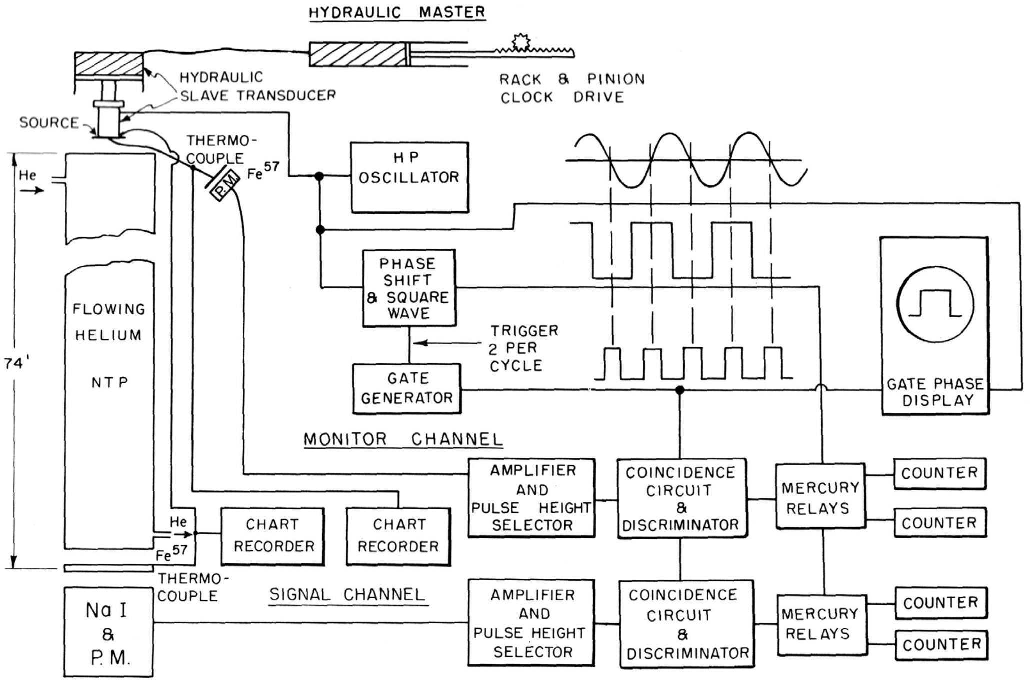

Figure 5: Block diagram of the Pound-Rebka gravitational redshift experiment. One can think of this as a hierarchy of three nested synchronous detectors: 50Hz sinewave piezo modulation for line-splitting "slope detection," on top of slow hydraulic up/down triangle motion of 10~minutes' duration, all within a top/bottom periodic inversion on a timescale of days. (Figure from Rebka thesis, 1961)

Being an extraordinarily careful experimenter, Pound, when he gave his APS talk a week later (demonstrating successful use of Fe^{57} and its narrow linewidth in the experiment), declined to report any conclusion about the redshift. The Harwell group from the U.K. also spoke, saying that more data was needed, but making the claim (from their preliminary data) that the chance of there being no redshift was less than one in sixty. For reasons that will become evident, their claim was without any foundation.

As sometimes happens, it's the opportunity of explaining something to a student that clears one's mental fog. Here's Pound's account of a chance encounter that unlocked the mystery:

> *One day, as frequently happened, an undergraduate student wandered into the room where the data was coming in and which I was evaluating, and he asked about how the experiment worked. I proceeded to tell him about it and explained how, in the Mössbauer effect, in spite of the presence of large thermally-excited vibrations, there is no Doppler broadening because, over the time of emission, the net displacement, and so the average thermal velocity along a given direction of emission or absorption, vanishes. I added, "of course the mean-squared velocity doesn't vanish." I then added, "my word, what about the second-order (special-relativistic) Doppler effect?" I quickly jotted some numbers down for a quantity estimating* v^2/c^2*, at room temperature, which would be of the order of* kT/Mc^2*, where* k *is Boltzmann's constant,* T *the absolute temperature, and* M *the atomic mass… No wonder we had instability, when this thermal effect of a* one-degree temperature change *should shift the frequency as much as the* whole effect *we sought.*

In a remarkable convergence, a certain Brian Josephson at the University of Cambridge, hearing about the redshift experiments at Harwell and at Harvard, independently discovered this temperature effect (and by a quite different calculation), which he sent for publication in *Physical Review Letters*.[9]

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[9] B. D. Josephson, "Temperature-dependent Shift of γ rays Emitted by a Solid," *Phys. Rev. Lett.* 4, 7, 341-42 (1960). Pound put in a transatlantic telephone call to Josephson (a big deal, in those days), but was told by the Porter at Trinity College that undergraduates were not allowed to receive telephone calls.

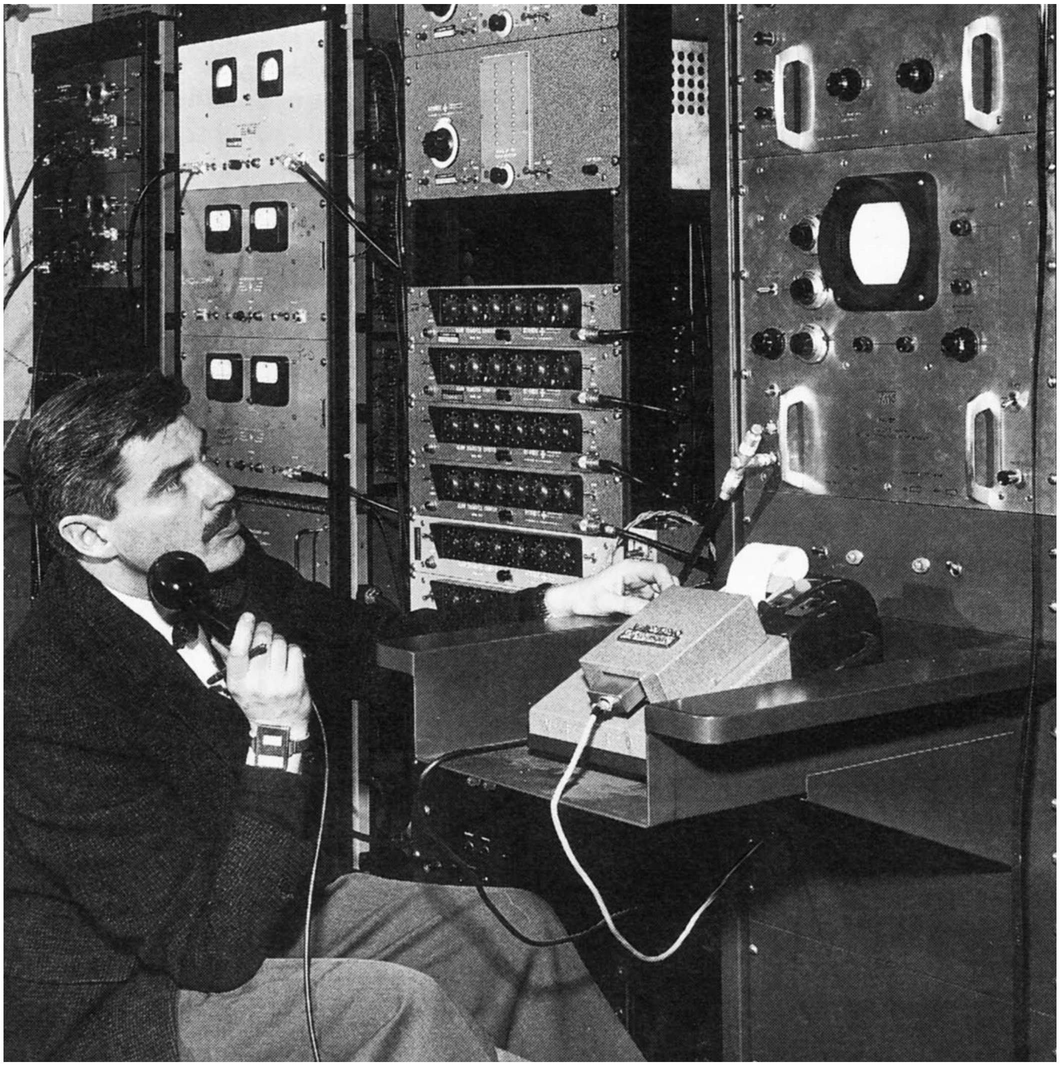

Figure 6: Pound at the 2nd-floor control area. Equipment in 1960 was large and slow: the two rack-mounted units above the printer comprise a 100-channel vacuum-tube pulse-height analyzer; the rack to its left houses a set of 6-decade "glow-transfer counters" that can run as fast as… 20kHz!; they are preceded by the two decades counters above, which can handle 1MHz. Farther to the left are power supplies and single-channel discriminators. (Photo: Harvard News Office)

Clear Sailing

As Pound relates in his "Weighing Photons" memoir, "This discovery was clearly the answer to our problem with the gravitational experiment, and looking at the data we had accumulated earlier, we now could see why there seemed to be almost a periodicity of two days or so in the shifts. Our penthouse temperature… was very closely coupled to the variable New England weather… It also seemed to us that the ignorance of the importance of this factor by the Harwell group rendered any conclusion based on the one-way measurement questionable."

With the installation of thermocouples at both ends, the temperature effect was removed from further measurements, and, after a month of data accumulation, the duo was able to report[10] that:

> *The shift observed agrees with* -4.92×10^{-15}*, the predicted gravitational shift for this 'two-way' height difference. Expressed in this unit, the result is*
> $(\Delta\nu)_{obs} / (\Delta\nu)_{theor} = +1.05 \pm 0.10$
> *where the plus sign indicated that the frequency increases in falling, as expected.*

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[10] R. V. Pound and G. A. Rebka, Jr., "Apparent Weight of Photons," *Phys. Rev. Lett.*, 4, 7, 337-41 (1960).

A contemporaneous page from Pound's notebook is reproduced in Figure 8, where the excitement of the normally placid professor is evident in the red-lined box.

Epilogue

In the years following, Joe Snider joined the experiment, modified in important ways to reduce systematic uncertainties and thus enhance the accuracy. In a pair of publications[11] they reported "the result of the experiments on the full two-way baseline $2h$ of 44.96m is 0.9994±0.0084 times the value of $2gh/c^2$."

And with that, Einstein's gravitational redshift was confirmed to an accuracy of 1%.

In subsequent years the redshift was measured in other ways. In 1981 a group in Helsinki used the Mössbauer effect in Zn^{67} (half-life of 78 hours, fractional line width of 10^{15}, 600 times narrower than that of Fe^{57}) in a 1m-path cryogenic experiment, demonstrating the shift versus angle with 5% accuracy. And in 1976 a hydrogen maser (invented by Ramsey, Goldenberg, and Kleppner at Harvard[12]) was flown in a rocket to an altitude of 10,000km, in an experiment led by Robert Vessot at the Harvard-Smithsonian Astrophysical Observatory (and to which Pound made an essential contribution that eliminated errors from differential ionospheric delays of the transponder signals). Continuous tracking of the transmitted signal, combined with precise trajectory data, confirmed the redshift to an accuracy of 0.007%.[13]

Recent experiments exploiting the stability of strontium optical-lattice clocks have confirmed the Einstein redshift to comparable precision (10^{-4}) over a *terrestrial* path[14] of 450m (the Tokyo Skytree), and, in a stunning demonstration of the precision of such lattice clocks, the redshift over a mere one *millimeter* has been measured[15] to some 20%. It seems incontrovertible that Einstein got it right.[16]

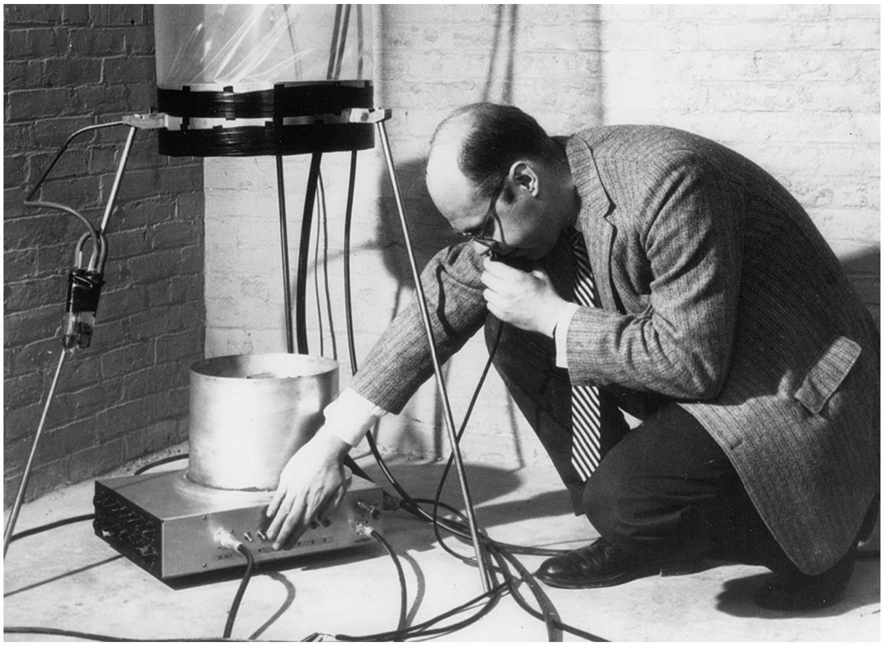

Figure 7: Pound's student Glen Rebka adjusting the scintillator array in the Sabine sub-basement of Jefferson Lab

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[11] R. V. Pound and J. L. Snider, "Effect of Gravity on Nuclear Resonance," *Phys. Rev. Lett.*, 13, 539-40 (1964); R. V. Pound and J. L. Snider, "Effect of Gravity on Gamma Radiation," *Phys. Rev.*, 140, B788-B803 (1965).

[12] "H. M. Goldenberg, D. Kleppner, and N.F. Ramsey, "Atomic Hydrogen Maser," *Phys. Rev. Lett.*, 5, 361-62 (1960).

[13] R.C. Vessot et al., "Test of Relativistic Gravitation with a Space-Borne Hydrogen Maser," *Phys. Rev. Lett.*, 45, 2081-84 (1980).

[14] Takamoto et al., *Nat. Photonics* 14, 411 (2020).

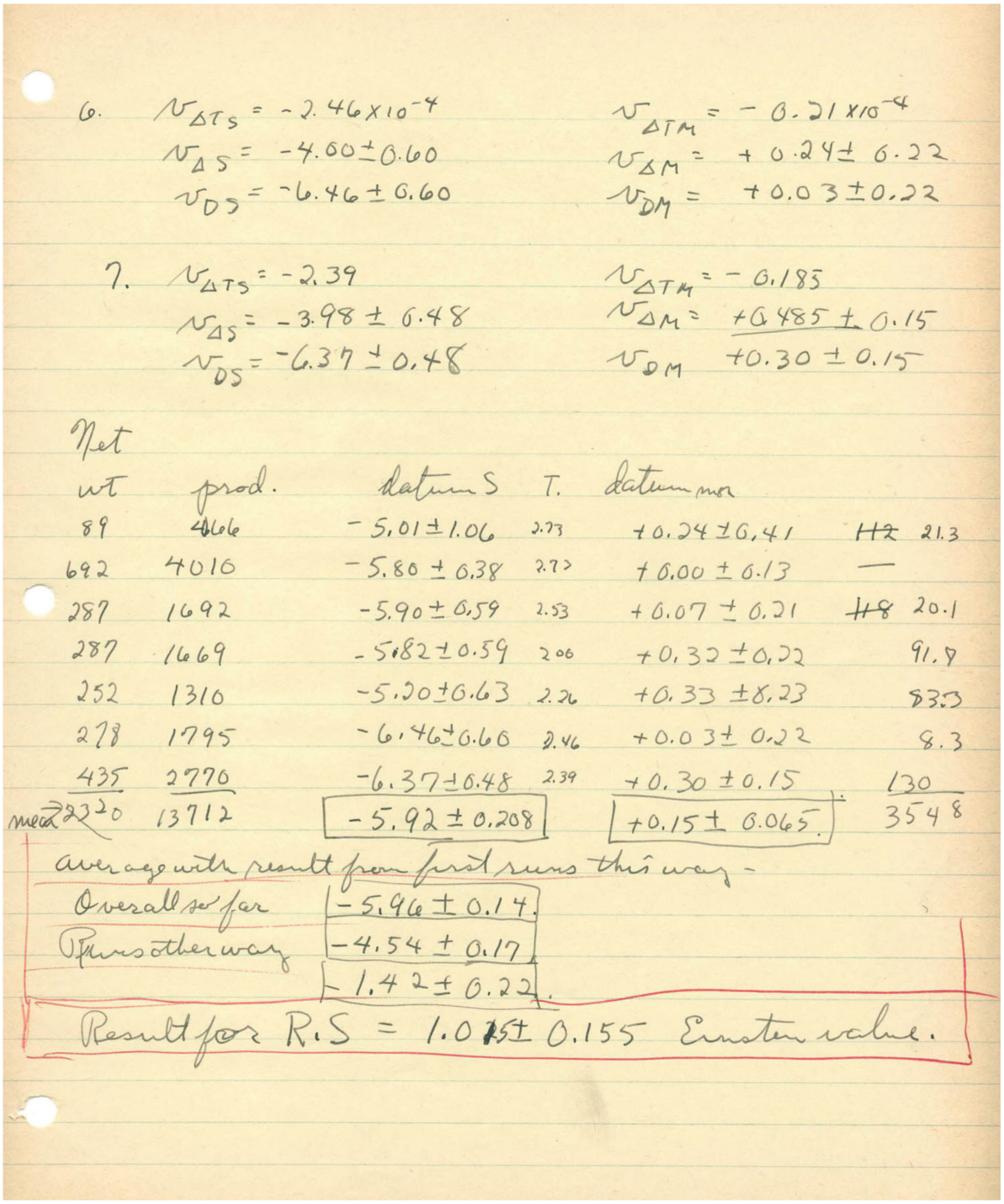
[15] Bothwell et al., arXiv:2109.12238 (2021).

[16] And to whom is indebted the global positioning system (GPS), whose operation requires appropriate corrections.

SOURCES AND REFERENCES

In addition to the references cited in the text and footnotes, the following were used in the preparation of this short history:

- G.A. Rebka, "Gravitational Shift of Frequency," Ph.D. thesis, Harvard University (1961);
- E.H. Hall, "Do Falling Bodies Move South?" *Phys. Rev.*, 17, 3, 179-90 (1903);
- Oral Histories at the American Institute of Physics (Niels Bohr Library and Archive);
- R.V. Pound's laboratory notebook 1959-60;
- helpful comments by Pound advisee Bill Vetterling, whose Ph.D. thesis was "Techniques for Improved Gravitational Red-Shift Measurements";
- and many delightful conversations with Robert Pound, my Ph.D. advisor.



6. $\nu_{\Delta TS} = -2.46 \times 10^{-4}$ $\nu_{\Delta TM} = -0.21 \times 10^{-4}$
$\nu_{\Delta S} = -4.00 \pm 0.60$ $\nu_{\Delta M} = +0.24 \pm 0.22$
$\nu_{DS} = -6.46 \pm 0.60$ $\nu_{DM} = +0.03 \pm 0.22$

7. $\nu_{\Delta TS} = -2.39$ $\nu_{\Delta TM} = -0.185$
$\nu_{\Delta S} = -3.98 \pm 0.48$ $\nu_{\Delta M} = +0.485 \pm 0.15$
$\nu_{DS} = -6.37 \pm 0.48$ ν_{DM} $+0.30 \pm 0.15$

Net wt	prod.	datum S	T.	datum mor		
89	4666	-5.01 ± 1.06	2.73	$+0.24 \pm 0.41$	~~H2~~	21.3
692	4010	-5.80 ± 0.38	2.72	$+0.00 \pm 0.13$	—	
287	1692	-5.90 ± 0.59	2.53	$+0.07 \pm 0.21$	~~H8~~	20.1
287	1669	-5.82 ± 0.59	2.06	$+0.32 \pm 0.22$		91.8
252	1310	-5.20 ± 0.63	2.26	$+0.33 \pm 0.23$		83.3
278	1795	-6.46 ± 0.60	2.46	$+0.03 \pm 0.22$		8.3
435	2770	-6.37 ± 0.48	2.39	$+0.30 \pm 0.15$		130
mean 2320	13712	$\boxed{-5.92 \pm 0.208}$		$\boxed{+0.15 \pm 0.065}$		3548

average with result from first runs this way –

Overall so far $\boxed{-5.96 \pm 0.14}$
Runs other way $\boxed{-4.54 \pm 0.17}$
$\boxed{-1.42 \pm 0.22}$

Result for R.S = 1.015 ± 0.155 Einstein value.

Figure 8: A page from Pound's notebook, with the first results of the temperature-controlled experiment. The bottom line summarizes (with barely concealed excitement): "Result for Red Shift = 1.015±0.155 [of the] Einstein value."