The Pound and Rebka experiment.

Anirbit

October 21, 2008

Dreams and Reality

Removing sources of extranneous frequency shifts

The mechanics and the electronics of the experiment

It begins where it ends

Miles to go before *you* sleep...

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The aim of the experiment

For various reasons (**NOT** necessarily coming from General Relativity) theoretical physicists had started believing that gravitational force affects energy of the photon and hence there was a pressing need to experimentally test this apparently non-intuitive prediction.

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Rebka was a graduate student under Pound at the Harvard University.

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References

- "Apparent Weight of Photons" by Pound and Rebka on 1^{st} *April* 1960PRL
- Lectures by Mester "Experimental Tests of General Relativity"
- "The Mossbauer Effect" review paper by A.F.Boyle and H.E.Hoyle
- "Weighing Photons, I by R. V. Pound, " Physics in Perspective 2, 224 (2000)
- "Weighing Photons, IIR. V. Pound", Physics in Perspective 3, 4 (2001)

Thanks

I would also thank Prof.Arnab for the references and Arnab Sen (senior DTP student) and Prof.Vikram for helpful disucssions

A rough idea of the magnitude $\longrightarrow$ of the effect

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So that kind of number that they were trying to measure is of the order of 10^{-15}!

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So the probe has a natural "spread" that is a fractional FWHM of $\frac{\Gamma}{E} = 10^{-12}$

The constraints

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  A free recoil will cause a spread of about 10^5 **times the natural width**

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From these numbers it is obvious that Pound and Rebka have to do everything they can to reduce the effect of the recoil and thermal motion.

From constraints to creativity...

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Energy is trivially conserved in the process but momentum conservation is the subtlety.

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Hence giving a sharp emission frequency limited predominantly by the energy uncertainity and the thermal vibration.

Further the **stiffness of the crystal** causes the **energy levels of the emitter to be far spaced** and that also reduces the broadening by **suppressing the transition probabilities**.

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These arguments shows that we have an **upper bound** of order of $100Kev$ for the gamma photons to show Mossbauer Effect.

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Getting a great Mossbauer Effect was an important aspect where Pound and Rebka won over their competitors by carefully annealing the source so that the emitter (0.4 curie of 270 day Co^{57}) diffuses to a distance of 3×10^{-5} cm into a 0.005 $inch$ of iron disk.

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Other sources of frequency shifts and their removal

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Other sources of frequency shifts and their removal

- The energy of the emitted gamma photons is sensitive to temperature. A difference of $0.6^{\circ}C$ can swamp out the gravitational effect.

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  This effect was elimated by **exchanging the source and the absorber** many times during the experiment.

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These two effects were not considered by the previous experimenters like Cranshaw and hence through they did similar experiments their data was not convincing that the shift was coming completely due to gravitational effect.

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These gamma photons can be absorbed by air.

So they kept a constant flow of He through the Mylar Bag at the rate of $30 liters/hr$.

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This method of measurement increased the sensitivity and removed errors due to background shifts of the modulation.

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There were 2 such circuits and alternately in each quater cyle of the source the signal was fed into it. The difference in counts was a measure of the assymmetry and hence of the frequency shift due to gravitation.

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Their Results

Pound and Rebka found the frequency shift as $\frac{1}{2}(5.13 \pm 0.51) \times 10^{-15}$ good to 10%.

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Pound and Snider later improved this to an uncertainity of 1% (PRL 13 539(1964))

Final reflections

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  Both of these experiments pushed the limits of precision and resolution of measurement of length and time.
- We should note that the time difference between the discovery of Mossbauer Effect and its miraculous use to test gravity-photon interaction is only 2-years!

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I see here a lesson to learn in terms of research that we must always be aware of the current frontiers and...

The chief enemy of creativity is good sense. Picasso