How OPERA measures the speed of neutrinos

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Neutrinos are produced by an accelerator at CERN (near Geneva Switzerland), travel 730 km through the Earth in 2.4 ms and are detected by the Oscillation Project with Emulsion-tRacking Apparatus (OPERA) in Gran Sasso (Southern Italy).

OPERA measures times it take for the neutrinos to travel the 730 km from CERN to Gran Sasso and finds they arrive 60 ns **earlier** than if they were traveling at the speed of light.

Measuring a velocity

$$v = \frac{\text{distance}}{\text{time}} = \frac{d}{t}$$

For light: v = c = 299,792,458 m/s.

Exactly

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Whaa...?

Officially¹, 1 meter is the distance travelled by light in $1/299,792,458^{th}$ of a second.

1 second is 9,192,631,770 periods of the radiation from the transition between the $6S^{1/2}(F = 4)$ and $6S^{1/2}(F = 3)$ hyperfine levels of ¹³³Cs.

¹http://www.bipm.org/en/si/si_brochure/chapter2/2-1/second_html \equiv = $\circ \circ \circ \circ$

Making neutrinos I



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Making neutrinos II

$p + Cu \rightarrow \pi + K + \dots \rightarrow \nu + \mu + \dots \rightarrow \nu + \nu + e + \dots$



Trip from Geneva to Gran Sasso - 730 km in 2.4 ms





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Detecting neutrinos



Result

$$v = \frac{d}{t}$$
 and $\Delta v = v \sqrt{\left(\frac{\Delta d}{d}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$

OPERA measured

$$d = 730,534.61 \pm 0.20 \text{ m}, (0.2 \text{ ppm})$$

$$t = 2,436,740 \pm 10 \text{ ns}, (4 \text{ ppm})$$

which gives

 $v = 299,799,983 \pm 1,199 \text{ m/s}$ c = 299,792,458 m/s $v - c = 7,525 \pm 1,199 \text{ m/s}$ $\frac{v - c}{c} = 24.8 \pm 4.1 \text{ ppm}$

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What could it be?

I do not know. This result is receiving extraordinary scrutiny by physicists. Keep in mind:

- 1. The uncertainty is dominated by the time measurement.
- 2. Protons come out of the accelerator in bunches over about 1 $\mu {\rm s}$
- 3. Neutrinos are produced along the beam dump over more than 1 km (300 ns flight time)
- 4. The result depends critically on knowing how particles are distributed in items 2 and 3.
- 5. The paper and supporting documentation are very well written and thorough (think about this for Junior Lab).
- The OPERA collaboration has been very good about answering questions and engaging with those of us trying to understand what is going on.

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I predict we are going to learn something very interesting.