Testing Einstein’s special relativity with clocks moving near the speed of light

Making our way (really slowly) to the Planck scale

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The very smallest and the very largest: From the Planck scale to the cosmos
The very smallest and the very largest:
From the Planck scale to the cosmos

Cosmology and particle physics increasingly connected
Evolution of the universe

Big Bang

With big telescopes can look into the past — up to a point.

Development of Galaxies, Planets, etc.

Dark Energy Accelerated Expansion

Inflation

Quantum Fluctuations

First Stars: about 400 million yrs.

Big Bang Expansion: 13.7 billion years

http://discoverycenter.dk/content/cosmology-and-astro-particle-physics
To understand the large, we must understand the small — but how small?

How do we probe smaller and smaller distances?

Heisenberg uncertainty principle:

$$\Delta x \approx \frac{h}{\Delta p}$$

Need larger and larger momenta (and energy)
The fundamental forces of nature
They have very different strength — and it changes!

- Standard Model
- Grand Unification Theory of Everything

http://nrumiano.free.fr/Ecosmo/cg_standard.html

- strong (nuclear) force
- electromagnetic force
- electroweak force
- gravity

limit of the accelerators

higher energy and smaller size

Standard Model

Grand Unification

Theory of Everything
Can we infer what is here?

Planck scale
$10^{-35}$ m

$10^{-44}$ s

10

$10^{-44}$ s

$10^{-35}$ m

$10^{27}$ K

$10^{14}$ GeV

Accessible to particle physics

$\ell_P = \sqrt{\frac{\hbar G}{c^3}}$
How can we probe the Planck scale without going there?

• Planck scale physics has ramifications at lower energies
• Make very precise measurements at low energy and hope to find a glimpse

The approach of our experiment:
• All 4 fundamental forces (or interactions) are intimately connected to certain symmetries, and their violation can be probed
Violations of “Lorentz Symmetry”
The framework underlying Special Relativity

The velocities we experience in daily life are so low that the theory of special relativity plays no role

Example: the addition of velocities

\[ v_{\text{train}} = 200 \text{ km/h} \]
\[ v_{\text{passenger}} = 5 \text{ km/h} \]
\[ v_{\text{total}} = 205 \text{ km/h} \]
Very different at ‘high’ velocities

Gedankenexperiment: Enterprise travels at $v = c/2 = 150\,000\,\text{km/sec}$ towards Klingon ship and fires photon torpedo

At what speed do the Klingons see the photon torpedo approach?

450\,000\,\text{km/sec} \,? 

No, with 300\,000\,\text{km/sec} \,!
The central principle of the theory of special relativity (SR):

The speed of light does **not** depend on the motion of the source or the observer and its value in vacuum is **always**

\[ c = 299\ 792.458 \text{ km/sec} \]

From this principle, all laws of SR can be derived
Relativity on one slide

\[ l = \frac{l_0}{\gamma}, \quad d = d_0 \]

Lorentz contraction

\[ \tau = \tau_0 \gamma \]

time dilation

\[ \gamma = \frac{1}{\sqrt{1 - (v/c)^2}} \]
A fascinating manifestation of the theory of special relativity is the phenomenon of time dilation.

i.e. the fact, that moving clocks tick more slowly.

There is no absolute time!
The round-trip time for light is the ‘tick’ of this clock.
$t = 2.5 \text{ nsec}$

Diagram showing a mirror reflecting a light pulse at a distance of 3 meters from a flash lamp and photo detector.
$t = 5.0 \text{ nsec}$

- Mirror
- Flash lamp and photo detector
- 3 m
$t = 7.5 \text{ nsec}$

- Mirror
- Flash lamp and photo detector
- Distance: 3m
t=10.0 nsec

mirror

3m

flash lamp and photo detector
$t=10.5 \text{ nsec}$

- Mirror
- 3m
- Flash lamp and photo detector
$t = 12.5 \text{ nsec}$
$t = 15.0 \text{ nsec}$
t = 17.5 nsec

mirror

3m

flash lamp and photo detector
t=20.0 nsec

mirror

3m

flash lamp and
photo detector

klick
time from start \((t=0)\) to the click \((t_{\text{click}})\): \(2L/c\)
$t=0$

$v = 0.75 \, c$  
(225 000 km/sec)
t=2.5 nsec
t=7.5 nsec
t=10.0 nsec
t=12.5 nsec
t=17.5 nsec
t=22.5 nsec
t=25.0 nsec
(ct'/2)^2 = (ct/2)^2 + (vt'/2)^2

from experiment with car at rest we know:
L = ct_{click}/2
\[(ct' / 2)^2 = (ct / 2)^2 + (vt' / 2)^2\]

Solve for \(t'\):

\[t' = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \cdot t\]

i.e. for an observer moving with respect to the clock, it ticks more slowly, by the time dilation factor

\[\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}\]
The size of the effect:

<table>
<thead>
<tr>
<th>km/sec</th>
<th>time dilation</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.000 000 000 14</td>
</tr>
<tr>
<td>150 000</td>
<td>1.15</td>
</tr>
<tr>
<td>225 000</td>
<td>1.51</td>
</tr>
<tr>
<td>almost 300 000</td>
<td>180 000</td>
</tr>
</tbody>
</table>

space craft
0.5 c
0.75 c
electrons in the storage ring LEP at CERN at 90 Gev
Tests with "real" (macroscopic) clocks

Atomic clocks in a plane (1970)

after 60 hour flight:
53 nsec
difference to clock on ground

accurate tests of SR need much faster clocks
Atomic and subatomic particles as clocks

Quantum mechanics: energy levels in atoms are discrete (Bohr model)

\[ E = h\nu \]

Frequency \( \nu \) of excitations of atomic levels are our most accurate clocks
The MPI-K Accelerator Facility

- $^7\text{Li}^+$
- Tandem + 6.65 MV
- ($\sim10\%$ in $^3\text{S}_1$)

- Electron Cooler
- TSR
- 15 m

- $^7\text{Li}^+$
- $E = 13.3$ MeV
- $v = 19\,000$ km/sec
- $\beta = v/c = 0.064$
- Storage Time $t_{1/2} = 50$ sec
- Stored particles $\sim 10^8$

(ion beam diameter (FWHM) $\sim 600\mu m$
beam divergence (FWHM) $< 100\mu$rad
after 5 sec of cooling)
The Doppler Effect

Basic phenomenon: the frequency of sound (and other waves) changes depending on relative motion of the source and observer.

Everyday example: the pitch of a siren rises and then falls again as an emergency vehicle approaches you and then speeds away.

Sign of the effect: relative motion towards each other: \( f \) increases

away from each other: \( f \) decreases.
The new TSR dual-boost experiment

- Dye laser 565 nm
- Dye laser 585 nm
- Cs frequency standard
- Nd:YAG laser 532 nm
- Ar ion laser 514 nm

Electron cooler

- PMT 1
- PMT 2: $v = 0.064 c$
- PMT 3: $v = 0.030 c$
Most important part: checking all the systematic effects and are often unexpected ...

They can kill you ...
Most important part: checking all the systematic effects

They can kill you ...
Test of relativistic time dilation with fast optical atomic clocks at different velocities

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confirm Special Relativity at the 10 ppb level

Time dilation is one of the most fascinating aspects of special relativity as it abolishes the notion of absolute time. It was first observed experimentally by Ives and Stilwell in 1938 using the Doppler effect. Here we report on a method, based on fast optical atomic clocks with large, but different Lorentz boosts, that tests relativistic time dilation with unprecedented precision. The approach combines ion storage and cooling with optical frequency counting using a frequency comb. $^7$Li$^+$ ions are prepared at 6.4% and 3.0% of the speed of light in a storage ring, and their time is read with an accuracy of $2 \times 10^{-10}$ using laser saturation spectroscopy. The comparison of the Doppler shifts yields a time dilation measurement represented by a Mansouri–Sexl parameter $|\hat{\alpha}| \leq 8.4 \times 10^{-8}$, consistent with special relativity. This constrains the existence of a preferred cosmological reference frame and CPT- and Lorentz-violating ‘new’ physics beyond the standard model.
... in just seven years...
How many idiots does it take to confirm an idiocy like RT?

qbit  View profile  ★★★★★ (5 users) More options  Aug 24, 12:52 am

A team of 14 (!) people have done an experiment and have published their earth-shaking (sic :-) result on exactly one (yes 1 (!), i.e. a single) page, titled: "Experimental Test of Special Relativity" by G. Saatho, S. Karpuk, S. Reinhardt, U. Eisenbarth, I. Hoog, G. Huber, S. Krohn, R. Mu-noz-Horta, J. Lassen, D. Schwalme, M. Weidemüller, A. Wolf, S. Wricke and G. Gwinner


I strongly doubt the correctness of this experiment!

Whoever believes that paper can IMO be only an idiot!

Unbelievable! It was even accepted by Phys. Rev. Lett. 91, 190403 (2003) !!!

How is such an idiocy possible????????

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Physikalische 'Wahrheiten' direkt aus der Volksverarschungsanstalt!

—I strongly doubt the correctness of this experiment!

How can someone who has never even studied calculus be fit to make such a qualification?
2007/11/11

It's a century late, but Einstein's still on time

"After two hours, I looked at my watch," a reviewer of Wagnerian opera is said to have written. "I found that 17 minutes had gone by."
What’s next? Li$^+$ in the ESR at $\beta=0.34$
What’s next?

- at ESR (GSI, Darmstadt) much higher velocities attainable (> 30% c), can expect \( \alpha_{ESR} < 8 \times 10^{-9} \)

but ...
The drive to uncover nature’s secrets is what propelled physics professor Gerald Gwinner to slog through data generated by particle accelerators for 15 years. He and his colleagues imagined a better way to confirm Albert Einstein’s time-dilation theory, carefully planned a visionary experiment, and now they are basking in results that are “nearly five times better than our old result and 50 to 100 times better than any other method used by other people to measure relativistic time dilation.”

**Two new studies: Verifying Einstein’s time-dilation theory, and understanding whale testicles**

**SEPTEMBER 24, 2014 —** University of Manitoba researchers constantly find insights into nature’s
Is all this useful for something?

During the last decade, the global positioning system (GPS) has become almost a household item. Due to the altitude and speed of the GPS satellites, general and special relativity have to be taken into account. Otherwise, position readout errors of up to 1 km would accumulate during a day (bad for yachting and smart bombs)!
Can we understand why Lorentz invariance could break down?

- Idea: Planck length \((10^{-35} \text{ m})\) is a universal, smallest length in the universe
- Space-time is discrete at these length scales
- Lorentz contraction cannot be valid here, as Planck length is same in all inertial frames

\[ \ell_P = \sqrt{\frac{\hbar G}{c^3}} \]
Or: In a cosmological picture

- Special relativity
  \[\uparrow\]
  all inertial frames are equivalent

- SR violated
  \[\rightarrow\]
  preferred frame in the universe
Thank you!

Winnipeg ("where all atoms are ultracold")