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Modern Optical Tests of Special Relativity

»The speed of light is finite and does not depend on the motion of either source or observer«. This is the fundamental statement underlying Albert Einstein's theory of Special Relativity. First formulated early in the 20th century, this theory now is one of the cornerstones of our scientific understanding of the world and tightly woven into the fabric of modern physical theories. It also has become more and more relevant for daily life – timekeeping using modern atomic clocks and navigation using the global positioning system are just two examples. Due to this outstanding role, it always has been of prime importance to experimentally verify the validity of the underlying theory. Optical tests, as presented here, are especially well suited for this task.

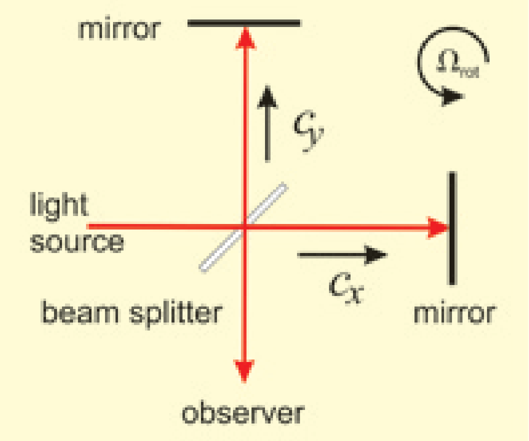

Fig. 2
Basic principle of the classical Michelson-Morley experiments.

Experimental tests of the Special Theory of Relativity (SR) and the fundamental principles it is based upon have a long and fascinating history that spans the whole period of modern physics, starting with the famous Michelson-Morley (MM) test of the isotropy of light propagation (see Fig. 1) that even predated the creation of Special Relativity. Over time, the accuracy of such experiments has improved by orders of magnitude due to use of new concepts and technologies, most notably lasers and atomic clocks, as soon as they became available. They all strive to either validate the theoretical predictions or, more interestingly, to find first discrepancies pointing at tiny violations. That such important violations might indeed occur, is in fact suggested by several approaches (string theory, loop gravity, ...) attempting to unify the forces of nature in a common theory – one of the outstanding open challenges of modern physics [1].

Michelson-Morley Experiments – Old and New

Michelson-Morley experiments search for directional dependence of the speed of light »*c*«, which would violate the abovementioned fundamental principles and »Lorentz-Invariance«. In the classical version of the experiment (Fig. 2) [2], first performed in 1881 by Albert Michelson at the Astrophysical Institute in Potsdam, a beam of light is split by a partially reflecting mirror into two partial beams propagating along two orthogonal arms of the apparatus. Reflected at the end of those arms, the returning beams are recombined at the partially reflecting mirror and can show interference – depending on the difference in propagation delay the detected light intensity will either be amplified or attenuated.

If now the apparatus is turned, a potential directional dependence of the speed of light would manifest itself as a angel-dependent change in the detected intensity. Following the »ether theory« prevalent at the time of the original Michelson experiment, according to which light propagates in an unspecified »ether« as sound does in air, such a directional dependence was indeed expected – that it was not observed startled Michelson as well as the whole scientific community. After a much improved version of the experiment (set up together with Edward Morley in Cleveland Ohio) confirmed the null-result in 1887, the »ether« hypothesis was clearly disproved and only the development of the theory of Special Relativity by Einstein finally resolved the resulting enigma.

Modern versions of the Michelson-Morley experiment are more sensitive than the original version by a factor of a million, or more. Such enormous improvements are made possible by the use of advanced Laser systems and optical resonators, in which the light is confined between two highly reflecting mirrors separated by a distance L (Fig. 3). For $L = 3$ cm and a mirror reflectivity of 99,997 %, the enclosed light thus travels more than 1 km during ~30000 round-trips before once again leaving the resonator. If one now by a suitable electronic circuitry adjusts the laser frequency f such that a standing light wave with an integer number m of wavelengths will form inside the resonator, it will be given by the resonance condition $f = mc/(2L)$. As this obviously depends on the speed of light c, any variation of c would be mirrored by a corresponding modulation of the frequency f – which is highly desirable, as frequencies among all physical quantities are those which can be measured with the highest precision. Thus, a Michelson-Morley measurement can be performed by monitoring the laser frequency while rotating the apparatus.

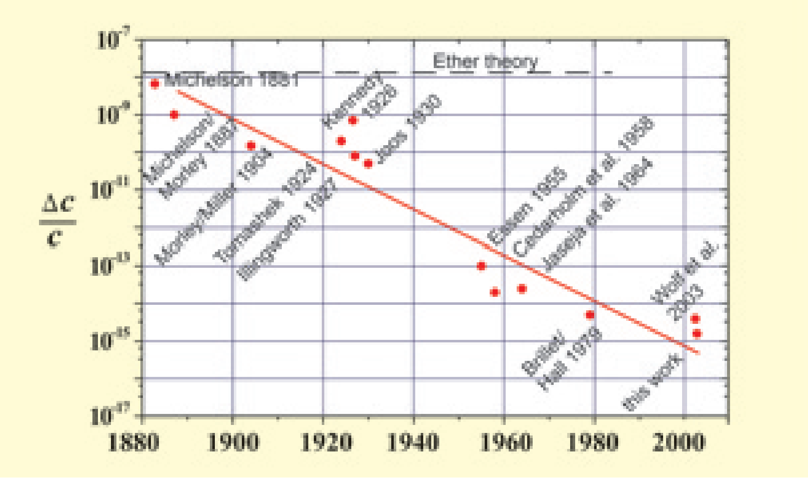

Fig. 1
Accuracy of tests of the isotropy of electromagnetic wave propagation. Δc / c is the accuracy of measuring the speed of light anisotropy. Experiments until 1930 were performed using optical interferometers, later experiments using electromagnetic cavities. The dotted line gives the amount of anisotropy expected from naive »ether theories«.

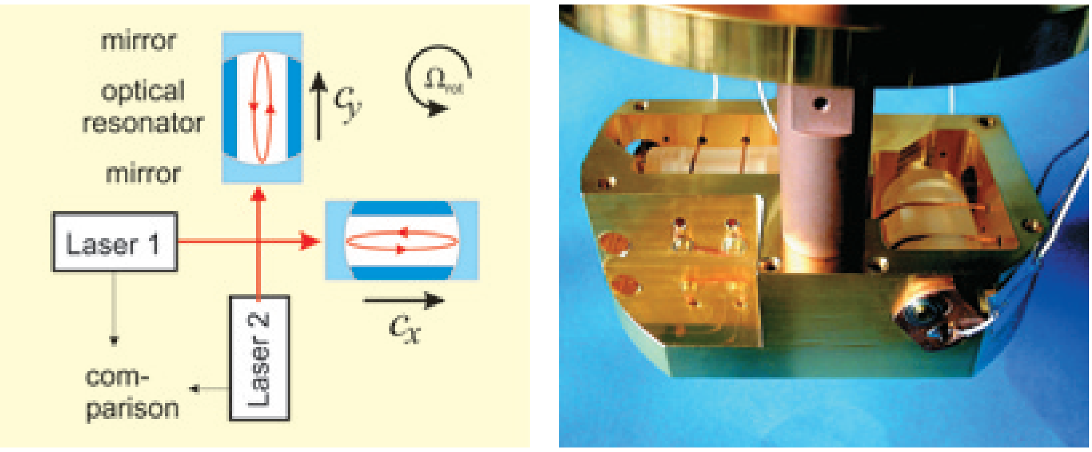

Fig. 3
Modern Michelson-Morley experiment using two orthogonal cryogenic optical resonators.
Left: Basic principle of a modern Michelson-Morley experiment, that compares the frequencies of two lasers, stabilized to orthogonaly oriented optical resonators.
Right: Sapphire resonators as implemented in our experiment. The two resonators are placed inside a copper mount, which is attached to a liquid helium reservoir at T = 4.2 K inside a cryostat.

This method only works, though, if the length of the optical resonator stays sufficiently constant. In our group we achieve this by using resonators fabricated from ultrapure crystalline sapphire and operated at the temperature of liquid Helium (4.2 K). Under these conditions they exhibit an extremely low thermal expansion coefficient and show no indication of the ageing related shrinking processes affecting resonators operated at room temperature. For the Michelson-Morley experiment (see Fig 3) we use two such resonators, mounted orthogonally and each resonantly excited by corresponding laser system (Nd:YAG lasers operating at 1064 nm wavelength). For the search for an anisotropy of the speed of light, we then analyze the beat signal of the two lasers (i.e., their frequency difference) measured by a fast photodetector as function of the angular orientation. The excellent long-term resonator stability allows us to rely solely on Earth's rotation for changing the orientation (resulting signal period ~12 hours), while previous experiments had no choice but to use a potentially noisy turn-table to rotate the laboratory setup.

In a year long measurement campaign we acquired more than 199 data sets of more then 12 hours in length, and thus suitable for analysis. From this, we extracted a new limit of $\Delta c / c < 3\text{x}10^{-15}$ for a possible anisotropy of the speed of light [3, 4] – an about 3-fold improvement compared to the best previous experiments.

Präzisionstests der Speziellen Relativitätstheorie
Aktiv frequenzstabilisierte Laser, wie sie in unserer Arbeitsgruppe unter anderem auf der Basis besonders stabiler optischer Resonatoren aufgebaut werden, erreichen relative Genauigkeiten von bis zu 1 Teil in 10^{-15}. Diese hochgenauen »Uhren« ermöglichen es, Präzisionsmessungen an den Grenzen der bekannten Physik durchzuführen. Im Fokus unserer Arbeit stehen dabei seit einigen Jahren Tests der Grundlagen der speziellen Relativitätstheorie. Kleinste Verletzungen der der speziellen Relativitätstheorie zugrunde liegenden Lorentzinvarianz werden gegenwärtig in verschiedenen Ansätzen zur Schaffung einer großen vereinheitlichten Theorie aller Naturkräfte einschließlich der Gravitation diskutiert. Die bei uns durchgeführten Messungen stellen dabei einen der wenigen experimentellen Prüfsteine auf diesem Gebiet dar.

Kennedy-Thorndike Experiments – Testing the Relativity Principle

The second basic principle of Special Relativity – the independence of the speed of light from the velocity of source and observer – today is not nearly as well tested as the isotropy of light propagation. Thus, if one strives to perform a *complete* test of special relativity, then progress in corresponding experiments, which were first performed by Roy Kennedy and Edward Thorndike in the 1930's [5], are of special relevance. In such Kennedy-Thorndike experiments, one searches for a variation of the speed of light as a function of the laboratory velocity (see Fig. 4). In modern versions of the experiment, one detects a potential variation of the speed of light by measuring the frequency of a laser stabilized to an optical resonator (and thus directly dependent on *c)* relative to the frequency of an optical atomic- or molecular clock (which does not directly depend on *c*, see Fig 4a). In our own setup, the optical clock was a second laser, whose frequency was stabilized relative to an electronic transition between quantum-mechanical eigenstates in molecular iodine.

For our Kennedy-Thorndike measurement the remarkable long-term stability of the cryogenic optical resonators was even more important than for the Michelson-

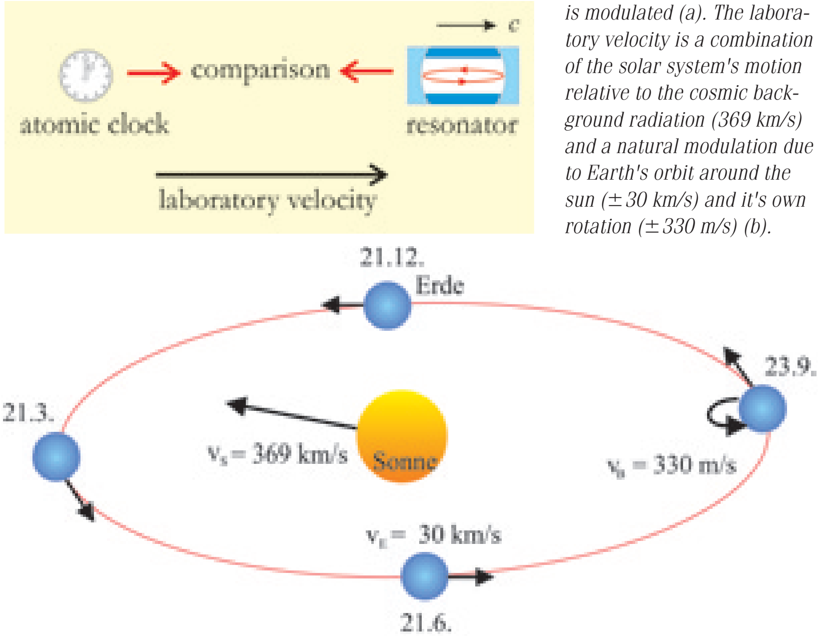

Fig. 4
Basic principle of modern Kennedy-Thorndike experiments. The frequency of a laser stabilized to an optical resonator is compared to an optical atomic clock while the velocity of the laboratory is modulated (a). The laboratory velocity is a combination of the solar system's motion relative to the cosmic background radiation (369 km/s) and a natural modulation due to Earth's orbit around the sun (± 30 km/s) and it's own rotation (± 330 m/s) (b).

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Morley experiment, as during a 190 day long measurement it allowed us to directly search for an effect due to the *yearly* change of the velocity due to Earth's orbit around the sun (± 30 km/s). Previous experiments, in contrast, were forced by the high drift rates of room-temperature resonators to use only the *daily* modulation due to Earths's rotation – and thus a 100-fold smaller potential effect. The analysis of our data shows that even though the laboratory velocity changed by 60 km/s over the measurement period, the speed of light varied by no more than $\Delta c / c < 6\text{x}10^{-12}$ (corresponding to 0,0018 m/s) [6]. Compared to previous experiments this again results in a 3-fold improvement in the test for velocity independence, and thus the complete theory.

The Future

Both types of experiments presented here will be improved substantially in the near future, with increases in sensitivity by factors of 100–1000. In the case of the Kennedy-Thorndike experiment, this can be achieved by the use of the newly developed optical frequency-combs (Fig. 4) [7] to combine the outstanding properties of cryogenic optical resonators and the very best clocks (microwave *or* optical) available at the time. For the Michelson-Morley experiment, big gains are possible from the use of a new generation of optical resonators in a setup which is actively rotated on a high performance air-bearing turntable at an optimized rate. Looking further into the future, the ultimate performance for tests of Special (and General) Relativity will be possible in the context of specially designed satellite mission, such as OPTIS (Fig. 5) [8].

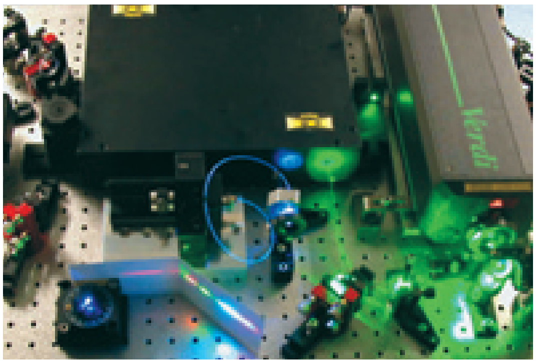

Fig. 5
Optical frequency comb for the absolute measurement and comparison of optical frequencies. Based on a femtosecond laser and a microstructured optical fiber.

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Fig. 6
OPTIS. This proposed mission would place an ensemble of ultrastable optical cavities, lasers, an atomic clock and an optical frequency comb generator on a drag free satellite in a highly elliptical orbit around Earth. The scientific goals would include a test of the isotropy of light propagation (Michelson-Morley experiment), a test of the independence of the speed of light from the velocity of the laboratory (Kennedy-Thorndike experiment), and a test of the equality of the Gravitational Red Shift for an atomic clock and an optical clock.