PTB news
Metrology
Technology
Services
Cooperation
09.2

Collisions in optical lattice clocks under control

Optical atomic clocks have attained an accuracy and stability which is already superior to the primary atomic clocks today. However, these clocks are very elaborate laboratory set-ups which are not yet suitable for special applications, for example in space. In PTB it has now been shown that such a high accuracy (one order of magnitude better than with current fountain clocks) can also be attained by means of an optical lattice clock with a much simpler design.

Optical clocks use very narrow absorption lines as a reference to stabilise an optical frequency. As the movement of the atoms leads to very large frequency shifts through the Doppler effect, in the best of these clocks the atoms are slowed down to a hundredth of the speed of a pedestrian in a first preparation step with the aid of laser cooling. In a lattice clock a further step then follows in which the atoms are held in potential wells. These are created through the intensive light field of a laser. Several tens of thousands of strontium atoms are trapped in this so-called optical lattice. The movement of the atoms is thus limited to the fraction of an optical wavelength, so that shifts through the Doppler effect can be ignored.

A few hundred atoms which can disturb each other are trapped in each potential well. If the isotope strontium-87 – a fermion – is used, two of these particles do not come close to each other at very low temperatures due to the Pauli principle. As this isotope can only be cooled relatively complicatedly with laser light and, moreover, only has a natural abundance of 7 %, it is not so well suited for simple, transportable clocks or even for clocks suitable for space.

The isotope strontium-88 with over 80 % natural abundance, which is also easier to cool, is, however, a boson. That means that even at the lowest temperatures many collisions between the atoms occur. They can lead to losses and to a shift and broadening of the reference line. How strongly these collisions influence the accuracy of the clock was, however, not known previously. In an experiment at PTB, these influences have now been measured in detail for the first time.

The results of the investigation have shown how the optical lattice has to be dimensioned and how many atoms may be stored in it to operate a very accurate lattice clock also with strontium-88. A clock is now being built on this basis which is more compact and more transportable than the previous lattice clocks.

The gravitational red shift of the earth, amounting to a height difference of 10^{-16} per meter on its surface, is being discussed as a possible first use for the precise determination of the height over the geoid.

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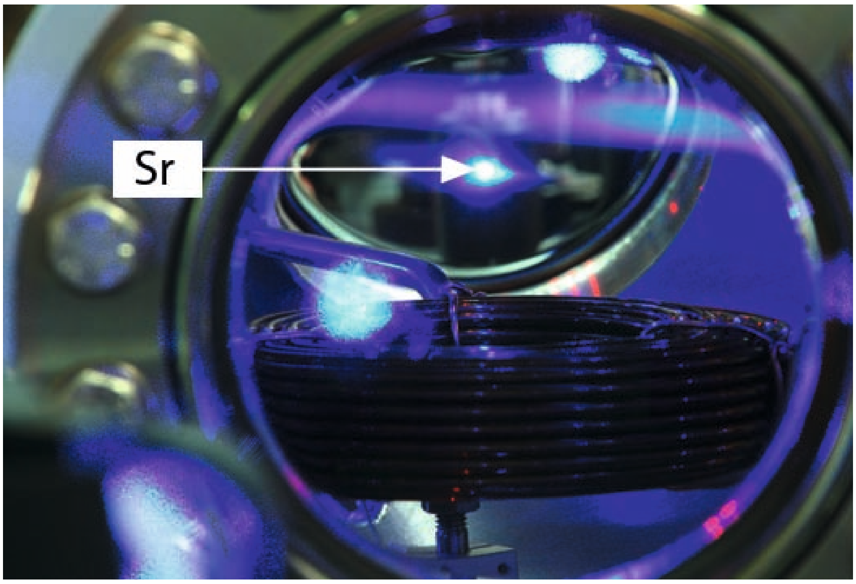

View into the ultrahigh vacuum chamber in which strontium atoms are cooled and stored. In the upper third of the window, the blue fluorescent light of a cloud of cold strontium atoms (Sr) is to be seen.

Taking the „gene ferry“ to the site of operation

In a novel method of treatment, repair genes are targeted to a diseased organ. To this end, health professionals use so-called vectors or „gene ferries“, which are developed, for example, on the basis of viruses. They load them with therapeutic genes and magnetic nanoparticles and navigate them through the body with the aid of an external magnetic field. Now it has become possible, with magnetic relaxometry – a detection method developed at PTB – to validate the efficiency of the magnetic navigation, accurate to the picogram per cell.

Magnetic nanoparticles today are often used as a contrast medium in magnetic resonance imaging, thus in diagnostics. However, they could also be helpful for purposes of treatment. A novel approach here is the gene transfer with the aid of magnetic nanoparticles. Health professionals send therapeutic genes on their way through the blood stream so that they can, for example, repair tissue damage in arteries. Often, modified viruses, which transfer genetic material into foreign cells

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Taking the „gene ferry“ to the site of operation *(continued from page 1)*

anyway, serve as the carrier. In order to transfer the therapeutic genes, the „gene ferry“ must stay at the cell long enough for the genes to penetrate its wall. For this purpose, magnetic nanoparticles are linked to the viral vectors. With the aid of an applied magnetic field, pharmacologists navigate the „gene ferry“ with its cargo to the desired site and detain it there until the therapeutic genes have been transferred.

With the magnetic relaxometry method developed at PTB it was possible for the first time to accurately determine under clinically relevant test conditions the amount of magnetic nanoparticles with their gene material that was absorbed by the cells at the target site. The method is based on the SQUID precision measurement technique and enables measurements in the range of a few picograms (billionth of a milligram) per cell. By measuring with several SQUID sensors simultaneously, the magnetic nanoparticles can be accurately localized to a few millimeters. It was demonstrated that the magnetic navigation drastically increases the efficiency of the treatment or even makes it possible in the first place.

The tests are a part of a research project under the management of the University of Bonn, in which in addition to PTB also the Technical and the Ludwig Maximilian Universities of Munich are involved. It is focused mainly on the heart circulation system, with the aim of navigating therapeutic agents more accurately in order to avoid side effects. The project has been funded by the German Research Foundation with approx. two million euros.

The results suggest that magnetic relaxometry is suited to control the efficiency of the gene and cell transfers also in vivo, i.e. directly on the patient.

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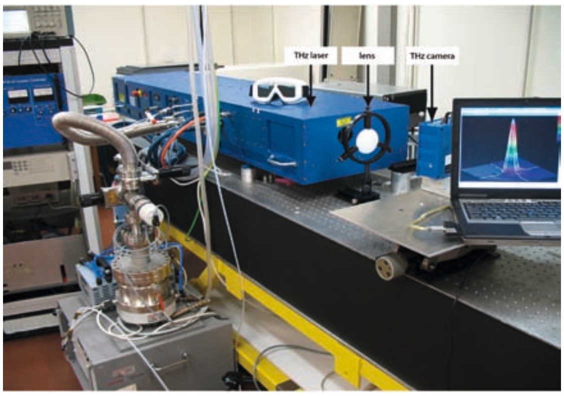
Radiometry with terahertz lasers

For the first time, the radiant power of a quantum cascade laser in the THz range has been absolutely determined with PTB's cryogenic radiometer. This is an important step towards the secure and efficient use of terahertz waves. Because promising applications in material testing, safety engineering, biomedicine and communications technology will become possible only if the power of the terahertz waves is accurately known.

For the use of terahertz technologies, a further development of radiometry in the terahertz spectral range is necessary, as this range has so far been only insufficiently covered by the methods of electrical and optical power measurements of electromagnetic radiation. PTB is taking the first steps in this direction together with the department for terahertz and infrared sensors of the DLR (German Aerospace Center). Within the scope of the cooperation it was recently possible for the first time to measure the radiant power of a quantum cascade laser of the DLR at 2.5 THz with a PTB cryogenic radiometer primary standard, in such a way that it is traceable to the International System of Units (SI). The precisely determined stable radiant power of the quantum cascade laser then enabled the determination of the spectral responsitivity of a terahertz detector and the corresponding uncertainty budget.

The analysis of the measurement conditions to determine the measurement uncertainty has shown that the laser-aided method for detector calibration, well established in optical radiometry, leads to very small uncertainties of a few percent even in the case of the wavelengths of terahertz lasers, which are more than two orders of magnitude larger.

At present, PTB is setting up a new measuring facility for the characterisation and calibration of detectors with laser radiation in the terahertz spectral range for manufacturers and commercial users. The core instrument is a molecular gas laser pumped with a frequency-stabilised CO_2 laser. The system generates coherent radiation at frequencies of molecular rotational lines adjustable in the range from approximately 1 THz to 7 THz. This frequency range is four times larger than the entire visible spectrum. Thus PTB is taking a first big wavelength step to bridge the metrological gap between high-frequency electronics and infrared optics at long wavelengths.



The molecular gas laser is the core instrument of PTB's new THz measurement set-up. The screen displays the beam profile of the laser at 1.9 THz, measured with a pyroelectric terahertz camera in the focus of a lens.

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Insight into the immune system

By means of nuclear magnetic resonance on ^{129}Xe atoms, scientists from PTB have managed to spectroscopically demonstrate the bond of a pathogenic germ to a protein which is important for the immune system. This bond is of essential importance for the immune reactions of the body. This work opens up new research fields on the development of magnetic resonance imaging and spectroscopy methodology for immunology.

The immune system continuously checks the operation of somatic cells and organises protection against the permanent attacks of exogenous and toxic substances. In a first step, the invading exogenous antigens (bacteria, viruses, parasites, or their fragments) have to be bound by a certain protein complex designated as „MHC" (major histocompatibility complex class II). This is the precondition for the harmful intruders to be detected by T cells and destroyed during a subsequent immune reaction.

The formation of the complex of antigen and MHC has been investigated at PTB by means of nuclear magnetic resonance measurements on ^{129}Xe atoms. Since xenon, a noble gas, can hardly be responsive to any other bonds, it is bound to the antigen, in the present case a fragment of the influenza virus (haemagglutinin; the figure shows HA peptides), by means of a molecular cage and of a so-called linker. Unhindered by its new appendix, the virus fragment then binds to the MHC protein in an aqueous solution. This complex formation can be demonstrated by means of nuclear magnetic resonance. It is possible to observe the binding of antigen to MHC at concentrations as low as 5 µmol/l. By exploiting the exchange process of xenon atoms between the molecular cage and the solution, the complex formation can even be detected at nano molar concentrations – an important requirement for observing the antigen binding by MHC in cell cultures or natural tissues.

This work was successfully carried out in collaboration with the Leibniz-Institut für Molekulare Pharmakologie (FMP) and the Max-Delbrück-Centrum für Molekulare Medizin (MDC) in Berlin. The methodology used is to be still further improved and is to support physicians, e.g., in finding the causes of an autoimmune disease.

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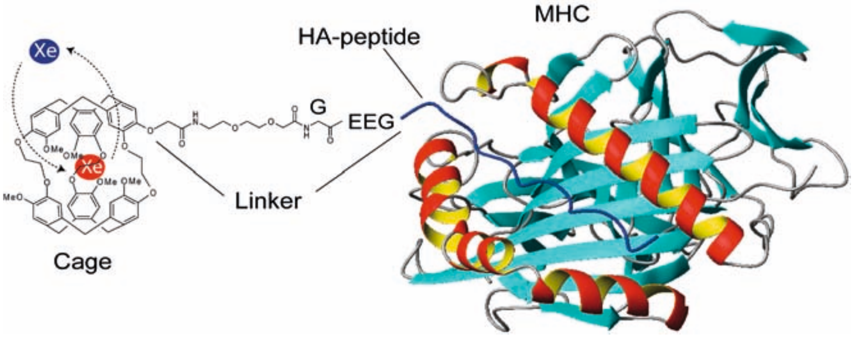

Xenon atoms permanently move between the solution and the molecular cage (Cage) which is coupled to the HA peptide via a linker (polyethylene glycol and quadripeptide GEEG). This construction can bind to an MHC so that NMR spectroscopy makes it possible to differentiate between three forms: free xenon, xenon in the cage without an MHC bond, and xenon in the cage with an MHC bond.

QUEST Institute at PTB

The Excellence Cluster QUEST (Centre for Quantum Engineering and Space-Time Research), founded in November 2007 in cooperation with PTB, has grown in the form of a QUEST Institute at PTB. Thus, the unique measuring facilities of PTB can contribute even more to the already very successful cooperation in which six institutes of the Leibniz University Hannover, the Laser Centre Hannover, the Gravitational Wave Detector GEO600 in Ruthe, the Max Planck Institute for Gravitational Physics (Albert Einstein Institute/AEI) as well as the Centre of Applied Space Technology and Microgravitation (Zentrum für Angewandte Raumfahrttechnologie und Mikrogravitation (ZARM)), Bremen, are involved.

One of the major scientific goals of the institute is the development of an ultra-accurate clock based on a single aluminium atom with an expected measurement uncertainty of only 10^{-18}.

As a result, researchers will be able to pursue the question of whether the fundamental constants of physics, as for example the fine structure constant, change in space or time. This has been predicted by modern theories of physics, such as, for instance, the String Theory. In its start-up phase, the new QUEST Institute at PTB is being financed by the German Research Foundation (DFG). After this period of funding, the professorship will be permanently continued by PTB and BMWi.

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New silicon load cells

At PTB, the technology of conventional strain gauge load cells has been further developed, also for high-precision weighing. The new load cell made of monocrystalline silicon (instead of metal) with sputtered-on (instead of glued) thin-film strain gauges shows a significantly improved time and hysteresis behaviour, as well as a better reproducibility.

With an annual turnover of 500 million euros, weighing technology makes up a large share of the market in Germany. A large part of this annual turnover is achieved with conventional load cells for low to medium precision. These load cells are made of metallic mechanical springs with glued strain gauges. The sensor which was further developed by PTB works according to the same principle. Its spring bellow, however, is made of silicon instead of metal. Since, under the influence of a load, monocrystalline silicon deforms ideal-elastically, the time-dependency and hysteresis of such a spring bellow is negligible. The application of the strain gauge by means of the thin-film method leads to a more direct connection with the spring bellow than in the case of the conventional glueing method. Thus, also time-dependencies occurring during the transmission of the strain from the spring bellow to the strain gauge could be significantly reduced, and the reproducibility of the strain measurement was clearly increased.

These fundamental advantages were confirmed by investigations on the load- and time-dependency behaviour on five of these new load cells at temperatures from 10 °C to 40 °C. Compared to those of conventional load cells, the characteristic curves of the silicon load cells achieve values which are better by more than one order of magnitude with regard to hysteresis, zero-point behaviour and reproducibility. The non-linearity is comparable to that of conventional load cells.

In order to evaluate the application range of the new load cells, the measured data were analysed on the basis of the OIML International Recommendation on the testing of load cells for applications subject to legal verification. The silicon load cells which were analysed by means of creeping and correctness tests achieve more than 30,000 intervals for applications subject to legal verification and are, thus, suitable also for precision weighing operations such as, for example, in the case of laboratory balances.

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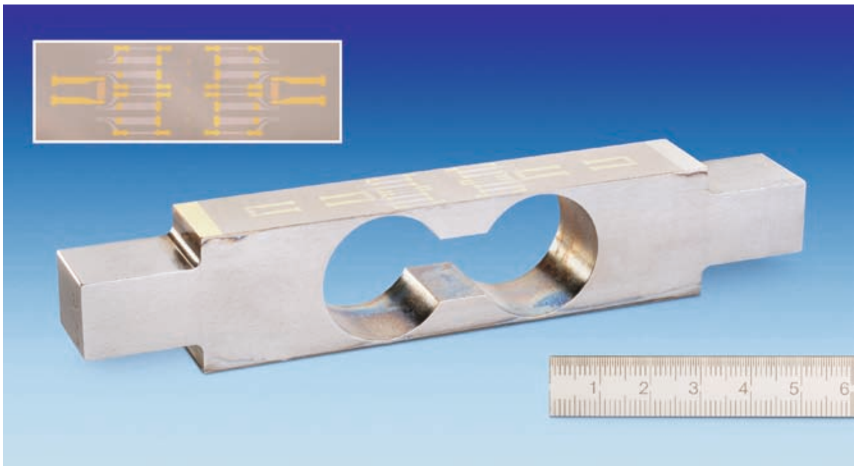

Silicon load cell with sputtered-on thin-film strain gauges

EU supports future metrological research

The EU supports the European Metrology Research Programme (EMRP) in Europe with 200 million euros and thus bears half of the costs estimated at 400 million euros, over a period of seven years. It is the aim of EMRP to further develop the scientific-technical metrology infrastructure in Europe – for the greatest possible benefit of all who have to rely on accurate and reliable measurements. The contents of the programme, which in Germany is borne, above all, by PTB, are oriented both towards pressing social and scientific questions, such as the energy supply, environment, safety and health, as also towards the further development of metrology. Within the scope of EMRP, each European country will no longer define its scientific projects on its own. Research institutes from 22 states much rather want to concentrate all their existing strength in future on joint projects and create the freedom to find solutions to current research work.

Last year already, 21 joint projects, from nanotechnology and cancer treatment, to highly accurate length measurements, and to the redefinition of the kilogram, were launched within the scope of an ERANET-plus promotion – as a test run for the much more comprehensive EMRP. EMRP is coordinated by EURAMET e.V., the joint umbrella organisation of the metrology institutes in Europe.

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