MILLIHERTZ-LINEWIDTH LASERS

A sharper laser

A new approach to lasers that promises optical emission with a spectral linewidth of just 1 mHz could lead to even more accurate and stable atomic clocks.

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Optical radiation from trapped atoms can produce laser emission with unprecedented spectral purity and coherence properties — surpassing the linewidth of current lasers, which is limited by the Brownian motion of the optical reference cavity. Writing in *Physical Review Letters*, Dominic Meiser and co-workers[1] show that this idea has the potential to improve the stability of optical lattice clocks by two orders of magnitude.

During recent years, there has been a dramatic improvement in the accuracy of clocks. This progress has mainly been due to atomic-clock technology switching from microwave to optical reference transitions and has led to clocks that tick 10^{15} times per second. Ions or neutral atoms can now also be held undisturbed for periods of several seconds and cooled close to their quantum ground states of motion; therefore, shifts and broadening due to the Doppler effect or from the finite interaction time no longer limit the resolved linewidth.

This progress in the manipulation of absorbers and the control of their motion makes accessible a host of new optical transitions for use as references in atomic clocks. For example, in neutral alkaline-earth-like atoms, transitions with a natural linewidth in the milli- to microhertz range are available, and in a single Yb^+ ion the upper state of the clock transition has a lifetime of about six years, corresponding to a nanohertz linewidth[2]. To profit fully from these extremely narrow and mostly undisturbed reference transitions, a high-quality laser that serves as a local oscillator must be incorporated into the optical clock, the frequency of which is steered towards the centre of the clock transition by periodical interrogation of the atoms. However, the development of the necessary lasers has not kept pace with the potential of the atomic absorbers. Laser linewidths remain in the neighbourhood of 1 Hz (equivalent to a fractional instability of around 10^{-15}), very similar to the best results observed ten years ago[3].

Conventional lasers, such as diode lasers or solid-state lasers, suffer from technical and environmental noise that broadens their linewidths to tens of kilohertz. To make these suitable for interrogation of narrow atomic transitions, electronic servo loops are used to tame the noisy lasers by forcing their frequencies (or wavelengths) to precisely fit the length of a Fabry–Pérot reference resonator. Thus, the laser wavelength (and frequency) is directly linked to the macroscopic spacing between the mirrors, which is usually around 10 cm. Any disturbance that changes the cavity directly affects the stability of the laser frequency. Therefore, the cavities are isolated from all environmental noise, such as acoustic, seismic and temperature fluctuations. Even with perfect isolation from the environment, however, thermally excited fluctuations of the length of the resonators remain. This Brownian motion of the mirrors, their coatings and the cavity spacer material typically limits the frequency stability of state-of-the-art lasers to a 1 Hz linewidth and to a coherence time of a fraction of a second[4]. There have been several proposals on how to reduce this Brownian noise: apart from the brute-force approach of cooling the cavity to cryogenic temperatures, novel mirrors and other geometries have also been discussed.

Meiser *et al.*[1] present a new solution to the problem that actually reverses the traditional set-up (Fig. 1). Instead of first narrowing the laser radiation with the help of a cavity to interrogate the atoms, in the new approach the atoms themselves emit narrowband optical radiation at the frequency of the optical-clock transition. To avoid any broadening of the emission by atomic motion, about one million atoms are held in an optical lattice nearly at the motional quantum ground state, by a method similar to that nowadays used in optical-lattice clocks.

To obtain a powerful signal, another trick is used. If spontaneously emitted radiation is used, only a vanishingly small amount of power can be extracted because it is spread over the full 4π solid angle. Therefore, Meiser and colleagues proposed to build a high-finesse cavity around the atomic ensemble. Then, as in a laser, induced emission forces the output into a narrow spatial region and ensures very high coherence of the radiation. The authors have

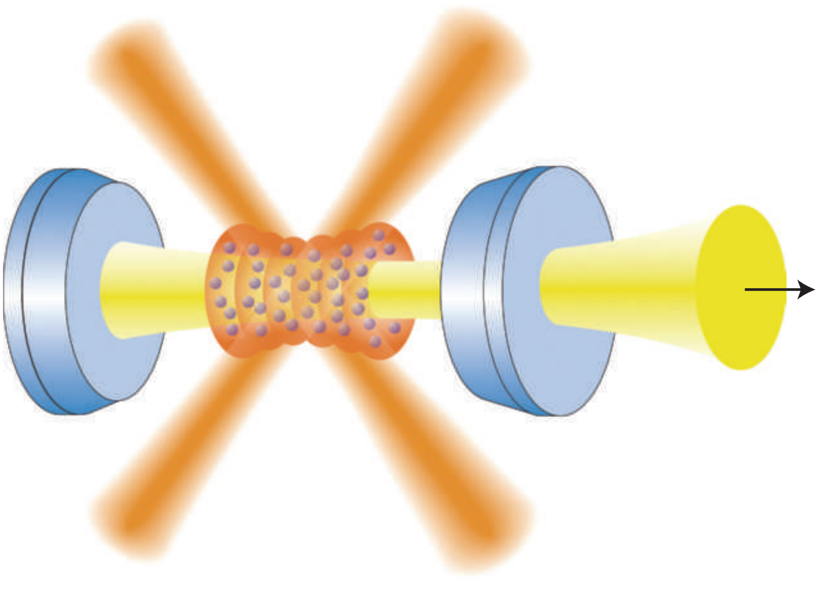

Figure 1 | Using atoms trapped at separate sites of an optical lattice (brown) as an active medium between two highly reflecting mirrors (blue), Meiser *et al.*[1] propose an active laser source that can deliver radiation with a millihertz linewidth.

estimated that up to 10^{-12} W of output power in a linewidth of a few millihertz is emitted from this novel laser, enough to be amplified and used in applications.

The natural linewidth of the atomic transition that is used to produce radiation in this set-up is much less than the linewidth of the cavity. In this sense, rather than to a common laser, the set-up better corresponds to a maser[5] — the workhorse of frequency metrology where, for example, hydrogen atoms are made to emit narrow-linewidth microwave radiation at 1.4 GHz into a microwave cavity. In the hydrogen maser, a continuous flux of excited atoms replenishes the system with energy lost to emission. In the proposal of Meiser and colleagues[1], this energy is supplied by a rather slow excitation of the atoms by an additional laser field that pumps the trapped atoms back to the excited level of the laser transition. This approach has the benefit that length fluctuations of the cavity have only a minor effect on the frequency of the emitted radiation.

The proposal is a new approach to the next generation of ultrastable lasers. There are still some open questions: the set-up is experimentally quite demanding, as the atoms have to be held within a small volume defined by the cavity; technical noise might broaden the line; and the back-action of the photon recoil on the cavity and laser fields has so far not been taken into account. Hopefully, an experimental realization will soon show how well these issues can be handled in practice: the race is now on against cryogenic cavities, new materials and other optical designs.

Unquestionably, highly stable lasers will lead to high-stability clocks and enable the further exploitation of atomic reference lines, with a projected stability in lattice clocks of less than 10^{-16} within a one-second averaging time. The ability to compare different clocks leads to improved limits on the possible drift of fundamental constants in physics, and on tests of local position invariance. The effect of gravity on clocks will then become easily visible (a difference in height of only 1 cm leads to a general-relativistic time dilation of 10^{-18}), making possible fascinating new applications for clocks. ❐

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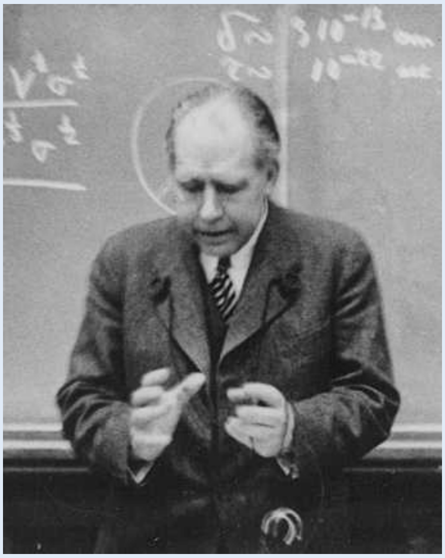
HISTORY OF QUANTUM THEORY

The short version

"Quantum mechanics is a difficult theory, the history of which is even more difficult." Such is not the conclusion, but the starting point of a study by Olivier Darrigol, in which he sets out to give a simplified account of the complex history of quantum mechanics, and its early history in particular (*Studies in History and Philosophy of Modern Physics* **40,** 151–166; 2009). His "simplified genesis", Darrigol hopes, might serve both physicists and philosophers as a more direct approach to the foundations of quantum theory.

Darrigol considers the period from Max Planck's quantum hypothesis to the first complete mathematical formalism of quantum mechanics, Paul Dirac's transformation theory. During that time, spanning the first quarter of the last century, a number of great minds left their mark, as they investigated a broad spectrum of physical phenomena. Different schools emerged, in terms both of geographical location and of approach, and by the middle of the 1920s, two distinct formulations of quantum mechanics had emerged: matrix mechanics (developed in Germany by Werner Heisenberg, Max Born and Pascual Jordan, and by Dirac in England) and Erwin Schrödinger's wave mechanics.

Darrigol takes these two branches — their formal equivalence was established eventually — as the backbone of his 'simplified history'. He starts the story of matrix mechanics with the failure of classical electrodynamics to describe black-body radiation, leading to the work of Niels Bohr (pictured) on the model of atomic structure and the correspondence principle, and, in what Darrigol says may be regarded as a "necessary consequence" — Heisenberg's quantum mechanics. The developments that eventually led to wave mechanics, on the other hand, he traces back to Einstein's light-quantum hypothesis and its extension to matter waves, by Louis de Broglie.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Although this overall structure of Darrigol's 'brief history' might be, in itself, not surprising, it is in the selection of key contributions that he chooses to take a new path, so as to construct a coherent sequence of achievements where each step follows as a consequence of previous ones (anything but an easy task in the face of the multilayered history of the field). Also, convoluted derivations are replaced with shorter, more direct reasoning. This approach, Darrigol admits, does leave out important developments, and, in a sense, provides the kind of "linear, great-men accounts" which, in principle, should be avoided in historical writing. But in the light of the already existing large body of work covering the history of quantum mechanics, priority is given to a short and clear account that highlights conceptual connections and key features of quantum theory, in a way that facilitates capturing its foundations, as well as the philosophical stance of some of its fathers. A fuller history, Darrigol argues, would not alter much the basic constructive steps in his simplified genesis, or help to understand why quantum mechanics was born.

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