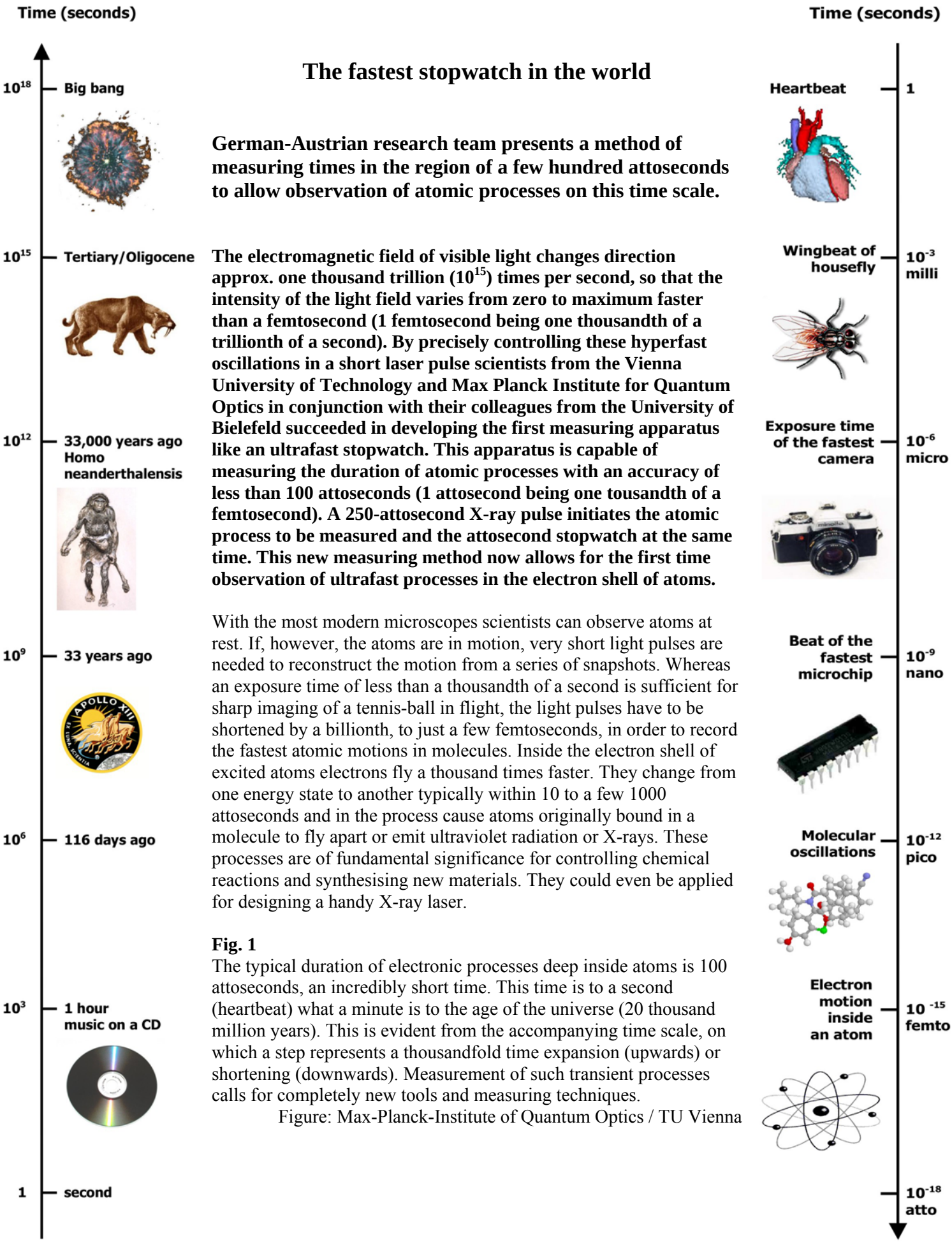
The fastest stopwatch in the world

German-Austrian research team presents a method of measuring times in the region of a few hundred attoseconds to allow observation of atomic processes on this time scale.

The electromagnetic field of visible light changes direction approx. one thousand trillion (10^{15}) times per second, so that the intensity of the light field varies from zero to maximum faster than a femtosecond (1 femtosecond being one thousandth of a trillionth of a second). By precisely controlling these hyperfast oscillations in a short laser pulse scientists from the Vienna University of Technology and Max Planck Institute for Quantum Optics in conjunction with their colleagues from the University of Bielefeld succeeded in developing the first measuring apparatus like an ultrafast stopwatch. This apparatus is capable of measuring the duration of atomic processes with an accuracy of less than 100 attoseconds (1 attosecond being one tousandth of a femtosecond). A 250-attosecond X-ray pulse initiates the atomic process to be measured and the attosecond stopwatch at the same time. This new measuring method now allows for the first time observation of ultrafast processes in the electron shell of atoms.

With the most modern microscopes scientists can observe atoms at rest. If, however, the atoms are in motion, very short light pulses are needed to reconstruct the motion from a series of snapshots. Whereas an exposure time of less than a thousandth of a second is sufficient for sharp imaging of a tennis-ball in flight, the light pulses have to be shortened by a billionth, to just a few femtoseconds, in order to record the fastest atomic motions in molecules. Inside the electron shell of excited atoms electrons fly a thousand times faster. They change from one energy state to another typically within 10 to a few 1000 attoseconds and in the process cause atoms originally bound in a molecule to fly apart or emit ultraviolet radiation or X-rays. These processes are of fundamental significance for controlling chemical reactions and synthesising new materials. They could even be applied for designing a handy X-ray laser.

Fig. 1
The typical duration of electronic processes deep inside atoms is 100 attoseconds, an incredibly short time. This time is to a second (heartbeat) what a minute is to the age of the universe (20 thousand million years). This is evident from the accompanying time scale, on which a step represents a thousandfold time expansion (upwards) or shortening (downwards). Measurement of such transient processes calls for completely new tools and measuring techniques.
Figure: Max-Planck-Institute of Quantum Optics / TU Vienna



First the microscopic process to be investigated - and simultaneously the stopwatch - has to be initiated. In order to set the interior of an atom in motion, energy has to be imparted to it. The start of the process must be defined more exactly than the duration of the process, and so energy input has to happen in a flash - within a fraction of a femtosecond. If atoms at rest are to be set in motion, the input energy has to overcome the binding of the electrons to the atomic nucleus. For this purpose the Vienna-Munich-Bielefeld research team uses X-ray flashes lasting 250 attoseconds, the shortest pulses in the world at present. The attosecond flash excites the electron shell of the irradiated atoms. Many of the electrons set in motion thereby acquire such a high energy that they are released from their atomic binding and go independent. The duration and evolution of this electron emission afford direct information on the evolution of excitation and relaxation processes inside the interior of the atom.

The German-Austrian research team has now developed the first method for measuring these processes. This involved reverting to a well-known concept, streak imaging. Till recently this method was used exclusively for measuring the duration of short light flashes. (Fig. 2).

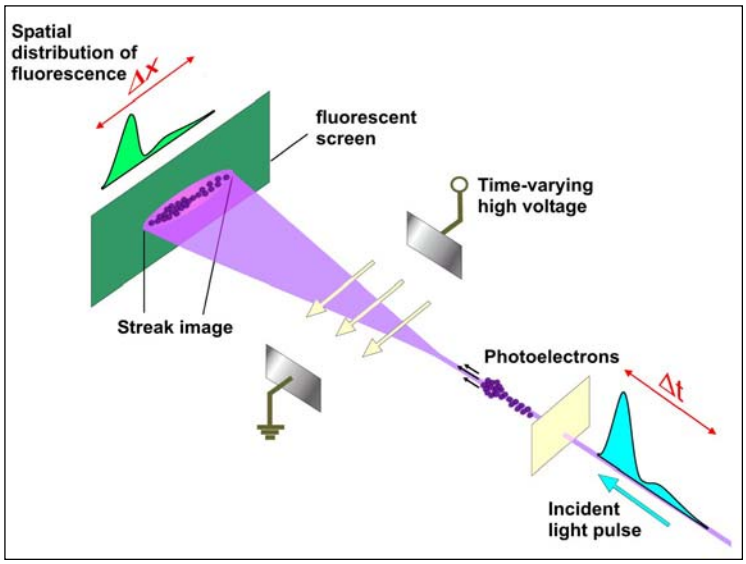


Fig. 2:
Conventional streak camera: In its lifetime the light flash ejects electrons from a metal plate which are then accelerated with a static electric field to a fluorescent screen (see "streak camera" illustration). Before they hit the screen, they are deflected aside with another field increasing linearly with time. The temporally varying deflection "streaks" the point of impact of the electrons on the screen. The spatial width of this "streak image" (Δx) is directly proportional to the duration of the electron emission, i.e. the duration of the light flash (Δt). The faster the deflecting field varies, the shorter are the pulses that can be recorded. The most modern streak cameras attain a resolution in the region of 100 femtoseconds.
Figure: Max-Planck-Institute of Quantum Optics / TU Vienna

The novelty of the new method is that deflection of the electrons is done with a light field - varying millions of times faster - that imparts its effect in space and time immediately on release of the electrons (Fig. 3). For this purpose the attosecond X-ray flash irradiating the atoms is supplemented with an intense laser light pulse comprising just a few oscillations. In this manner the successively emitted electrons are detected separately again, but this time not spatially on a screen but alongside one another *on the energy scale*. The width ΔE and shape of the measured energy distribution of the electrons reflect the duration and evolution of the electron emission, just as their spatial distribution in conventional streak imaging. In this case, however, "deflection" occurs within half a light period, which opens the way to measurement in the attosecond region.

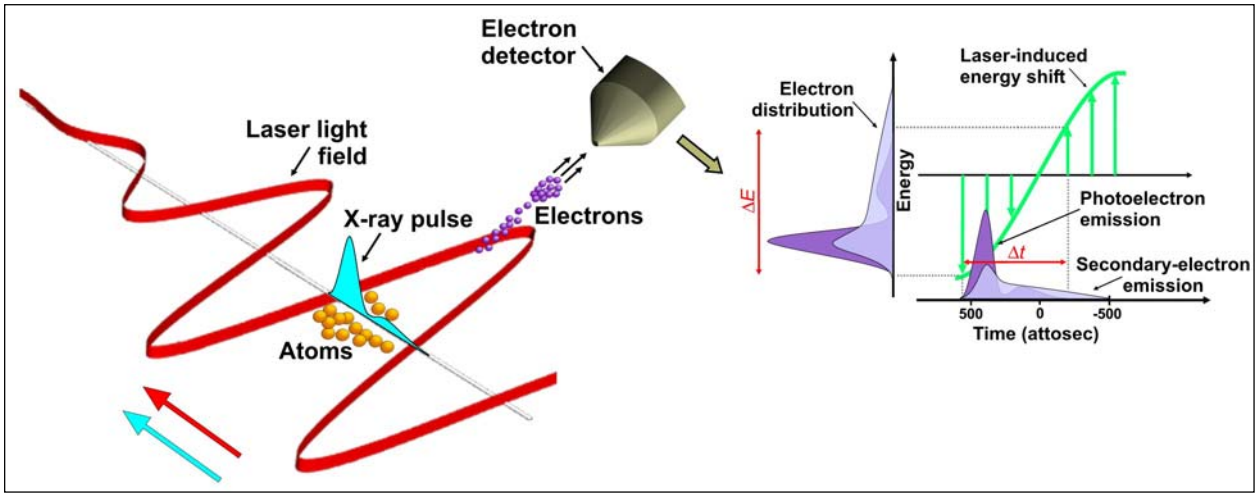


Fig. 3:
Light-field-controlled streak camera: The red and the blue curves represent, respectively, the evolutions of the electric field of the laser light and the intensity of the attosecond x-ray flash. The latter excites the atoms, which then emit electrons. The electrons ejected in the direction of the electric field of the laser light pulse simultaneously beamed in are detected. They undergo - depending on the time of their emission within half the oscillation period of the laser light a change of velocity: in the case illustrated the electrons emitted first are decelerated, while those released on termination of the X-ray flash are accelerated.
Figure: Max-Planck-Institute of Quantum Optics / TU Vienna

In order to implement this concept of a light-field-controlled streak camera successfully in practice, two conditions have to be satisfied: i) the oscillations of the "deflecting" light field have to be precisely controlled and ii) the exciting X-ray flash has to be synchronised to these oscillations with attosecond precision. The required intense laser pulses consisting of just a few oscillations and having a controlled waveform were demonstrated by the research team a year ago for the first time in the world.[2] The controlled light waveforms opened the way to generating single attosecond X-ray pulses reproducibly from laser pulse to laser pulse by controlled excitation of gigantic oscillations of the electron shell in atoms. The excited atoms emit - like tiny antennas - an X-ray flash perfectly synchronised to the exciting laser field.

In the latest experiment the attosecond flash and the light wave generating it are beamed into a group of atoms to excite them and "deflect" (i.e. accelerate or decelerate) the emitted electrons, respecitvely, thus meeting both of the conditions stated above. The evolution of the emission of the electrons directly ejected by the X-ray flash, photoelectrons as they are called, reflects the evolution of the exciting X-ray flash, while the evolution of the emission of so-called secondary or Auger electrons affords direct information on the relaxation processes occurring in the electronic shell in the wake of the flash-like excitation. By measuring the emission time of the photoelectrons by the new streak method the German-Austrian research team was able to determine an X-ray flash time of 250 attoseconds. These are the shortest pulses ever reported and also the shortest timespan measured hitherto. When the method is applied to secondary electrons, the new device allows direct measurement of the evolution of processes inside the electron shell of atoms with a resolution of approx. 100 attoseconds.

Observation of the motion of electrons deep inside atoms and molecules is thus now within easy reach. For the first time there is now a chance of presenting experimental answers to questions of effective, collective X-ray emission from atoms (X-ray laser) or of creation and destruction of chemical bonds (control of chemical reactions).

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This work was sponsored by the Fonds zur Förderung der wissenschaftlichen Forschung (Austria), the Deutsche Forschungsgemeinschaft and the Volkswagenstiftung (Germany) and by the European Union's Human Potential Programme.

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