Atomic clock

A device that uses an internal resonance frequency of atoms (or molecules) to measure the passage of time. The terms atomic clock and atomic frequency standard are often used interchangeably. A frequency standard generates pulses at regular intervals. A frequency standard can be made into a clock by the addition of an electronic counter, which records the number of pulses. *See also: Digital counter*

Basic principles. Most methods of timekeeping rely on counting some periodic event, such as the rotation of the Earth, the motion of a pendulum in a grandfather clock, or the vibrations of a quartz crystal in a watch. An atomic clock relies on counting periodic events determined by the difference of two different energy states of an atom. According to quantum mechanics, the internal energy of an atom can assume only certain discrete values. A transition between two energy states with energies E_1 and E_2 may be accompanied by the absorption or emission of a photon (particle of electromagnetic radiation). The frequency ν of this radiation is given by the equation below,

$$h\nu = |E_2 - E_1|$$

where h is Planck's constant. A basic advantage of atomic clocks is that the frequency-determining elements, atoms of a particular isotope, are the same everywhere. Thus, atomic clocks constructed and operated independently will measure the same time interval, that is, the length of time between two events. In order for the two clocks to agree on the time, they must be synchronized at some earlier time. *See also: Atomic structure and spectra; Energy level (quantum mechanics); Quantum mechanics*

An atomic frequency standard can be either active or passive. An active standard uses as a reference the electromagnetic radiation emitted by atoms as they decay from a higher energy state to a lower energy state. An example is a self-oscillating maser. A passive standard attempts to match the frequency of an electronic oscillator or laser to the resonant frequency of the atoms by means of a feedback circuit. The cesium atomic beam and the rubidium gas cell are examples of passive standards. Either kind of standard requires some kind of frequency synthesis to produce an output near a convenient frequency, such as 5 MHz, that is proportional to the atomic resonance frequency. *See also: Feedback circuit; Laser; Maser; Oscillator*

Two different gages of the quality of a clock are accuracy and stability. The accuracy of a frequency standard is defined in terms of the deviation of its frequency from an ideal standard. In practice, it might be defined in terms of the frequency differences measured between independently constructed and operated standards of the same type. Improving the accuracy depends on understanding and controlling all the parameters that might cause the frequency to shift. The stability of a frequency standard is defined in terms of the constancy of its average frequency from one interval of time to the next. For many frequency standards, the stability initially improves with increasing measurement time but eventually gets worse. That is, a more precise measurement of the frequency can be made by averaging together successive measurements, until some imperfection in the apparatus causes the frequency to change. The stability increases with increased Q (resonance frequency divided by the width of the resonance) and with increased measurement signal-to-noise ratio. *See also: Q (electricity); Signal-to-noise ratio*

Common types. The three most commonly used types of atomic clock are the cesium atomic beam, the hydrogen maser, and the rubidium gas cell. The cesium clock has high accuracy and good long-term stability. The hydrogen maser has the best stability for periods of up to a few hours. The rubidium cell is the least expensive and most compact and also has good short-term stability.

Cesium atomic-beam clock. This clock (Fig. 1) uses a 9193-MHz transition between two hyperfine energy states of the cesium-133 atom. Both the atomic nucleus and the outermost electron have magnetic moments; that is, they are like small magnets, with a north and a south pole. The two hyperfine energy states differ in the relative orientations of these magnetic moments. The cesium atoms travel in a collimated beam through an evacuated region. Atoms in the different hyperfine states are deflected into different trajectories by a nonuniform magnetic field. Atoms in one of the two states are made to pass through a microwave cavity, where they are exposed to radiation near their resonance frequency. The resonant radiation may cause the atom to make a transition from one state to the other; if that happens, the atom is deflected by a second, nonuniform magnetic field onto a detector. *See also: Electron spin; Hyperfine structure; Magnetic moment; Molecular beams; Nuclear moments*

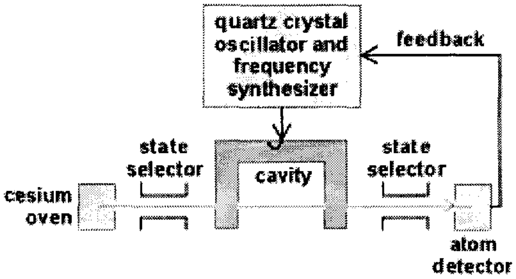

Fig. 1 Cesium atomic-beam clock. (*After G. Kamas, ed., Time and Frequency Users' Manual, NBS Tech. Note 695, 1977*)

The Q of the resonance is over 10^8 for some laboratory standards and somewhat less for the smaller standards that are commercially available. Cesium atomic beams, including variants such as optically pumped atomic beams and atomic fountains, are the most accurate of all atomic clocks. The best models have an error of only a few parts in 10^{15}, or about 1 s in 10^7 years. For this reason, cesium has become the basis of the international definition of the second: the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine states of the ground state of the cesium-133 atom. The cesium clock is especially well suited for applications such as timekeeping, where absolute accuracy without recalibration is necessary. Measurements from many cesium clocks throughout the world are averaged together to define an international time scale that is uniform to parts in 10^{14}, or about 1 microsecond in a year. *See also: Atomic time; Dynamical Time; Physical measurement*

Hydrogen maser. This instrument (Fig. 2) is based on the hyperfine transition of atomic hydrogen, which has a frequency of 1420 MHz. Atoms in the higher hyperfine energy state are selected by a focusing magnetic field, so that they enter an evacuated storage bulb inside a microwave cavity. The atoms bounce off the poly(tetrafluoroethylene)-coated walls for about 1 s before they are induced to make a transition to the lower hyperfine state by a process called stimulated emission. The stimulated emission from many atoms creates a self-sustaining microwave oscillation.

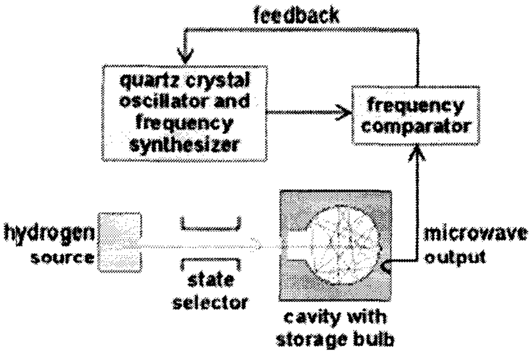

Fig. 2 Hydrogen maser. (*After G. Kamas, ed., Time and Frequency Users' Manual, NBS Tech. Note 695, 1977*)

The resonance Q is about 10^9. The best hydrogen masers have a stability of about 1 part in 10^{15} for averaging periods of 10^4 s. Over longer periods of time, the frequency drifts, primarily because of changes of the cavity tuning. Collisions with the walls cause the frequency to be shifted by about 1 part in 10^{11} relative to that of a free atom, but the magnitude of the shift varies from one device to another. This shift limits the accuracy of the hydrogen maser to about 1 part in 10^{12}.

The hydrogen maser can also be operated as a passive device, with improved long-term stability, due to the addition of automatic cavity tuning. The short-term stability is worse than that for an active maser.

Rubidium gas cell. This device (Fig. 3) is based on the 6835-MHz hyperfine transition of rubidium-87. The rubidium atoms are contained in a glass cell together with a buffer gas, such as argon, that prevents them from migrating to the cell walls. A method called optical pumping is used to prepare the atoms in one hyperfine state. Filtered light from a rubidium resonance lamp is absorbed by atoms in one of the two hyperfine states, causing them to be excited to a higher state, from which they quickly decay to the other hyperfine state. If the atoms are then subjected to microwave radiation at the hyperfine transition frequency, they are induced to make transitions back to the other hyperfine state. They can then absorb light again from the lamp; this results in a detectable decrease in the light transmitted through the cell.

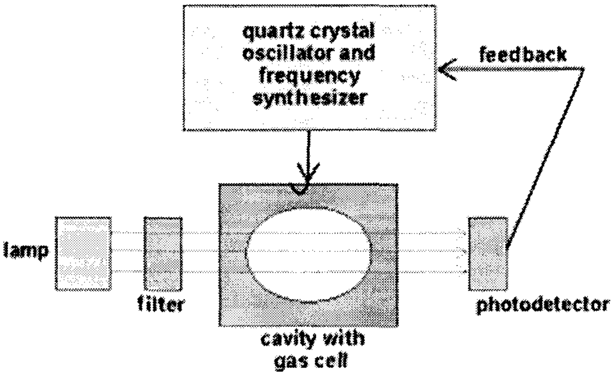

Fig. 3 Rubidium gas cell. (*After G. Kamas, ed., Time and Frequency Users' Manual, NBS Tech. Note 695, 1977*)

The Q is only about 10^7, but the short-term stability is quite good, reaching 1 part in 10^{13} for averaging times of 1 day. After longer periods, changes in the buffer gas pressure and the lamp cause the frequency to drift. The accuracy is not better than 1 part in 10^{10}. Rubidium standards are used in applications that do not require the accuracy of a cesium standard.

Experimental types. Many other kinds of atomic clocks, such as thallium atomic beams and ammonia and rubidium masers, have been demonstrated in the laboratory. The first atomic clock, constructed at the National Bureau of Standards in 1949, was based on a 24-GHz transition in the ammonia molecule.

Some laboratories have tried to improve the cesium atomic-beam clock by replacing the magnetic state selection with laser optical pumping and fluorescence detection. Improved performance is expected because of increased signal-to-noise ratio and a more uniform magnetic field. One such standard, called NIST-7, is in operation at the U.S. National Institute of Standards and Technology and is the primary frequency standard for the United States. Other laboratories have studied atomic-beam standards based on magnesium, calcium, or methane, which have frequencies higher than that of cesium.

Atomic frequency standards can also be based on optical transitions. One of the best-developed optical frequency standards is the 3.39-micrometer (88-THz) helium-neon laser, stabilized to a transition in the methane molecule. Frequency synthesis chains have been built to link the optical frequency to radio frequencies.

Ion traps, which confine ions in a vacuum by electric and magnetic fields (Fig. 4), have been studied for use in atomic clocks. They provide a benign environment for the ions while still allowing a long measurement time. Clocks based on buffergas-cooled, optically pumped mercury-199 or ytterbium-171 ions have been built and show good stability. Values of Q as high as 1.5×10^{13} have been observed on the ytterbium-171 hyperfine transition. Other trapped ion standards make use of laser cooling to reduce frequency errors due to Doppler shifts. Laser cooling is a method by which resonant light pressure is used to damp the motion of atoms. A clock based on laser-cooled mercury-199 ions has demonstrated an accuracy close to that of the best cesium clocks. It might be possible to observe extremely high values of Q on optical transitions of trapped ions. An optical transition has been observed in a single, trapped mercury ion with a Q of about 10^{13}, and it should be possible to increase this Q by a factor of 100. An optical frequency standard based on such an ion might be capable of an accuracy of 1 part in 10^{18}. *See also: Laser cooling; Particle trap*

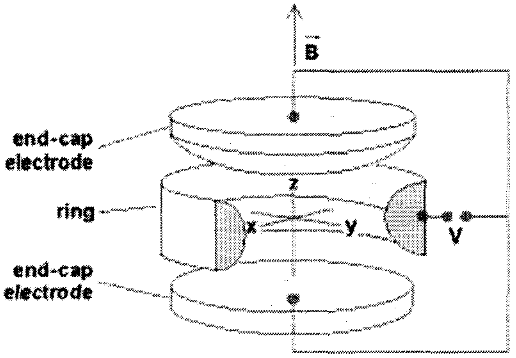

Fig. 4 Electrodes used to create the confining electric potential for a Penning ion trap or a Paul ion trap. An electric potential V, which is static for a Penning trap and oscillating for a Paul trap, is applied between the ring electrode and the end-cap electrodes. The Penning trap requires a uniform magnetic field B. *(After F. J. Rogers and H. E. Dewitt, eds., Strongly Coupled Plasma Physics, Plenum, 1987)*

The atomic fountain is another method of using laser-cooled atoms in a frequency standard. In this method, neutral atoms, such as cesium, are laser cooled and state selected and then launched upward on a ballistic trajectory. The atoms pass through a microwave cavity, as in the atomic-beam method. They are moving slowly enough that they fall back down through the cavity a second time, after which they are detected by laser-induced fluorescence. The general principles are the same as in an atomic-beam standard, but greater precision is possible because the flight time of an atom through the apparatus is longer. Clocks based on cesium atomic fountains are in operation at several laboratories. One, at the Laboratoire Primaire du Temps et des Fréquences in Paris has an accuracy of a few parts in 10^{15}, currently the best in the world.

Applications. Atomic clocks are used in applications for which less expensive alternatives, such as quartz oscillators, do not provide adequate performance. The use of atomic clocks in maintaining a uniform international time scale has already been mentioned; other applications are described below. *See also: Quartz clock*

Navigation. The Global Positioning System is a satellite-based system that enables a user with a suitable radio receiver to determine position within about 10 m (33 ft). The satellites send out accurately timed radio pulses, from which the user's receiver can calculate its location and time. The satellites and the ground stations, but not the users, need atomic clocks (usually cesium clocks). *See also: Satellite navigation systems*

Communications. Various digital communications systems require precise synchronization of transmitters and receivers in a network. Some systems use time-division multiplexing, in which many channels of information are sent over the same line by sequentially allotting a small time slot to each channel. Timing is very critical when there are several sources of information with their own clocks. The primary timing is provided by cesium clocks. *See also: Electrical communications; Multiplexing and multiple access; Pulse modulation*

Radio astronomy. Very long-baseline interferometry is a technique that allows two or more widely separated radio telescopes to achieve very high angular resolution by correlation of their signals. The system has the resolution that a single telescope would have if its aperture were equal to the distance between the telescopes. This can be thousands of miles. The stable timing needed to correlate the signals is provided by hydrogen masers. *See also: Radio astronomy; Radio telescope*

Space exploration. Navigation of space probes by Doppler tracking requires very stable local oscillators, derived from atomic frequency standards. Doppler tracking relies on determining the velocity of the spacecraft by measuring the frequency shift of a signal after it has been echoed to the Earth by a transponder on the spacecraft. Stable local oscillators are also needed for studies of planetary atmospheres and rings by fluctuations of the radio signals transmitted through them. *See also: Space navigation and guidance*

Fundamental science. According to A. Einstein's special and general theories of relativity, a moving clock runs slower than a stationary one, and a clock on the Earth's surface runs slower than one far from the Earth. These predictions were verified to high accuracy by an experiment in which a hydrogen maser was launched in a rocket to an altitude of 10,000 km (6000 mi). *See also: Clock paradox; Relativity; Time*

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