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Nobel Prize in Physics 1989

Norman F. Ramsey

Hans G. Dehmelt

Wolfgang Paul

The Nobel Prize in Physics 1989 was divided, one half awarded to Norman F. Ramsey *"for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks"*, the other half jointly to Hans G. Dehmelt and Wolfgang Paul *"for the development of the ion trap technique"*.

Information about winners:

half to Professor **Norman F. Ramsey**, Harvard University, Cambridge, MA, USA, **for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks**, and one half jointly to Professor **Hans G. Dehmelt**, University of Washington, Seattle, USA, and Professor Dr **Wolfgang Paul**, University of Bonn, Federal Republic of Germany.

RESEARCH INFORMATION:

The work of the Laureates in Physics has led to a dramatic development in the field of atomic precision spectroscopy in recent years. The resonance method of Professor **Norman F. Ramsey**, Harvard University, USA, using separated oscillatory fields forms the basis of the *cesium atomic clock*, which is our present time standard. Professor Dr **Wolfgang Paul**, University of Bonn, Federal Republic of Germany and Professor **Hans G.**

Dehmelt, University of Washington, USA, have introduced and developed the *ion trap technique* which has made it possible to study a single electron or a single ion with extreme precision. Ramsey and co-workers have also developed the *hydrogen maser*, which is at present our most stable source of electromagnetic radiation. The methods have been used in testing fundamental physical principles such as quantum electrodynamics (QED) and the general theory of relativity. Another application is in space communication and for measuring continental drift. The techniques have reached an unprecedented level of precision, and the development does not yet seem to have culminated.

Background information

According to quantum physics a free atom can have certain energy levels only. An atom at an energy level other than the lowest state will spontaneously decay to a lower state after some time, normally by emitting electromagnetic radiation such as light. The radiation emitted has a characteristic frequency or wavelength which depends on the energy difference between the two levels, and this is the basis of the appearance of optical spectra that have been studied for more than a century. From the measured wavelengths one can get information on the level structure of the atom, and this was long our main source of information regarding atomic structure.

An important step towards higher precision was taken in 1937 by I.I. Rabi at Columbia University, when he introduced the *Atomic-beam-magneticresonance method (ABMR)*. Rabi used the fact that a transition between levels in the atom can be induced by means of characteristic radiation, as first proposed by Albert Einstein. This is also the basis for other resonance methods developed later, such as nuclear magnetic resonance (NMR).

In the Rabi ABMR method, a beam of atoms passes through a homogeneous magnetic field with a superimposed oscillating electromagnetic field. The latter can induce the desired transitions if the frequency is right. The time the atoms spend in the oscillating field determines the width of the resonance line: the longer the time, the narrower the line - provided that the magnetic field is sufficiently homogeneous. The homogeneity is a serious problem, however, and new techniques had to be invented to increase precision.

The accomplishments of the Laureates

In 1949 **Norman F. Ramsey** modified the Rabi atomic-beam-magnetic-resonance method by introducing two separated oscillatory fields. An interference pattern then appears, with a sharpness that depends on the distance between the two oscillatory fields but is independent of the degree of homogeneity of the magnetic field between them. This made it possible to increase the accuracy of the ABMR method appreciably. Later Ramsey showed that more than two oscillatory fields can be used, and that these can be separated in time rather than in space. This had important implications for future development.

An important application of the Ramsey method is the *cesium atomic clock*, which is our present time standard. Transitions between two very closely spaced levels (hyperfine levels) in the cesium atom are here observed. The accuracy of such a clock is today about 1:10^{13} i.e. one part in ten thousand billion. Since 1967 one second has been defined as the time during which the cesium atom makes exactly 9,192,631,770 oscillations.

The possibility of observing a single atom or ion - a long-felt dream of a spectroscopist - has recently been realised largely thanks to the work of the Physics Laureates. There are three stages in this development:

- to "trap" the atoms or ions
- to "cool" them to a low temperature
- to increase sensitivity so that a single atom or ion can be observed.

The first experiments on trapping atoms and ions were made in the laboratory of

Wolfgang Paul in Bonn in the 1950s. Paul showed that it was possible to focus atoms in a beam by using a six-pole magnetic field. Together with his collaborator H. Steinwedel he showed that ions with different masses could be separated by a four-pole electrical field with a radio-frequency field superimposed. This was developed into a standard method for mass separation, now widely used. The "Paul trap" now used in ion-trap spectroscopy is a further development of this mass filter. Another kind of ion trap, the "Penning trap", also used for this purpose, was developed simultaneously in Paul s laboratory and by **Hans Dehmelt** and his co-workers in Seattle, Washington.

Dehmelt and his co-workers used ion-trap spectroscopy mainly to study electrons. According to relativistic quantum mechanics, the electronic g-factor - essentially the ratio of magnetic and angular momentums - is exactly equal to two. In the 1940s a deviation of about 0.1% from this value was discovered. This deviation was shortly afterwards attributed to effects of quantum electrodynamics (QED), i.e. interaction with the surrounding radiation field. Improved methods developed particularly at the University of Michigan later led to more accurate determinations of this anomaly, but the most important development has more recently taken place in Dehmelt s laboratory in Seattle.

In 1973 Dehmelt succeeded for the first time in observing a single electron in a trap, and two years later he introduced a method for "cooling" the electron - two inventions which improved accuracy considerably. The g-factor anomaly has now been determined by Dehmelt and his co-workers with an accuracy of a few parts in a billion, and this, together with corresponding theoretical calculations, constitutes one of the most critical tests we have of QED.

Later in the 1970s Dehmelt succeeded together with P. Toschek in Heidelberg in observing a single ion in a trap. This opened the way to a new kind of spectroscopy, *single-ion spectroscopy*, which has been further refined and applied particularly at the National Institute of Standards and Technology (NIST, previously NBS) in Boulder, Colorado. Using the Ramsey method with separated oscillatory fields, a stability has been achieved which exceeds even that of the cesium clock.

Another method of storing and studying atoms has been developed by Ramsey together with D. Kleppner and others. This is the hydrogen maser. Atoms of hydrogen in an excited state are fed into a cavity, which can be brought to self-oscillation if properly tuned. The line width is determined by the average time the atoms spend in the cavity, which is about one second. The walls of the cavity are covered with teflon to reduce the effect of wall collisions. The hydrogen maser was first used to study the hyperfine structure of hydrogen with extreme precision. The instrument has a considerably higher stability than the cesium clock for short and intermediate times (hours-days) but its absolute accuracy is inferior. It has therefore been used mainly as a secondary standard, and for measurements of frequency shifts where extreme precision is needed. One example is measurement of continental drift using Very Long Base Line Interferometry (VLBI), where the signals from a radio star are compared from two radio telescopes on different continents. Another application is the verification of the "gravitational red shift". This is the effect of gravitation on electromagnetic radiation predicted by the general theory of relativity. By comparing the frequencies of one rocket-borne and one earth-bound hydrogen maser, the predictions of the theory have been verified to one part in 10,000.

The hydrogen-maser technique has in recent years been improved considerably. By cooling the instrument to below 1 K (one degree above absolute zero), the walls of the cavity can be covered with superfluid helium. This drastically reduces the disturbing collisions with the walls, with a corresponding increase in stability and reproducibility. An impressive stability of 10e18 (one part in one billion billion) seems realistic.

A frequency stability of the same order might also be possible with the ion-trap technique. The method is based on an idea of Dehmelt in observing what is termed the *quantum jump* in a single ion in a trap. Laser radiation corresponding to two different transitions is used - one to a strong transition and one to a very weak one. The former is used for detecting the latter, which is very narrow and cannot be observed directly.

The realisation of methods of the extreme precision that now seems possible opens completely new opportunities for testing fundamental principles in quantum physics, gravitation theory and other branches of basic physics.

For more details please visit:

http://www.nobelprize.org/nobel_prizes/physics/laureates/1989/press.html