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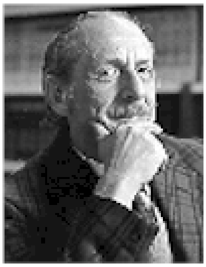

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EUGENE GARFIELD
INSTITUTE FOR SCIENTIFIC INFORMATION®
3501 MARKET ST PHILADELPHIA, PA 19104

Of Atomic Clocks, Ion Traps, and Quantum Leaps: The 1989 Nobel Prize in Physics Is Awarded to Norman F. Ramsey, Wolfgang Paul, and Hans G. Dehmelt

Number 35 August 27, 1990

The 1989 Nobel Prize in physics was awarded to Norman F. Ramsey, Hans G. Dehmelt, and Wolfgang Paul for their pathfinding efforts in the measurement of the behavior and characteristics of atomic particles. Their work has improved the accuracy of time measurement to unprecedented levels. Scientists can now quantify, with high precision, theories central to science. The techniques used by the laureates are described. Biographical information and citation analysis of their papers are also provided. Although most of the papers date from over 20 years ago, their impact is still evident today.

The 1989 Nobel Prize in physics was awarded to Norman F. Ramsey, Harvard University, Cambridge, Massachusetts; Hans G. Dehmelt, University of Washington, Seattle; and Wolfgang Paul, University of Bonn, Federal Republic of Germany (FRG). The prize recognized their studies performed in the late 1940s and 1950s that led to the precise measurements of electrically charged particles. The research of all three scientists, who did their studies independently, revolves around the laws of quantum mechanics, which describe how atoms absorb and discharge energy. According to the Royal Swedish Academy of Sciences awards committee, the laureates' work was important "for the development of atomic precision spectroscopy."[1]

Atomic spectroscopy is "the technique of producing spectra via streams of atoms, analyzing their constituent wavelengths, and using them for chemical analysis or the determination of energy levels and molecular structure."[2] One of the 1989 physics prizewinners went one step further in his efforts by examining individual particles, and recording characteristics of these in exacting fashion, through the use of instrumentation and techniques the laureates invented. Their work has enabled high-precision tests of several theories central to science, including general relativity and quantum electrodynamics (QED).

Norman F. Ramsey and the Measurement of Time

One-half of the 1989 physics prize went to Ramsey for work started in the late 1940s. The Nobel awards committee cited Ramsey's "invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks."[1] Ramsey commented on the time span of his heralded work: "It is true that the separated oscillatory fields method was invented in the late 1940s, but the work that established its usefulness and importance was carried out subsequently and is continuing. Likewise, the hydrogen maser work was not even started until after the 1940s."[3]

His work provided the basis for modern cesium atomic clocks, which set the international time standard and are used in many applications requiring precise measurements of time—that is, fractions of time that are many orders less than one second. These applications include digital communications, satellite navigation, and measurements of the creep of the continents across the ocean floor.

Norman F. Ramsey

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Hans G. Dehmelt

Ramsey was born in Washington, DC, on August 27, 1915, and attended Columbia University, New York, where he earned his AB and MA. He also earned BA (1937), MA (1941), and DSc (1954) degrees from the University of Cambridge, UK. In 1940 he received a PhD in physics at Columbia. During the 1940s, he held positions at the University of Illinois, Urbana; the Massachusetts Institute of Technology Radiation Laboratory, Cambridge; and Columbia. During World War II, Ramsey was a consultant to the US National Defense Research Committee (1940-1945), an expert consultant to the US secretary of war (1942-1945), and a group leader and associate division head at the Los Alamos Scientific Laboratory, New Mexico. He also was deputy for scientific and technical matters for "Project A," which coordinated all activities concerned with the first use of nuclear weapons.[4]

After the war Ramsey was executive secretary of the group of scientists who established the Brookhaven National Laboratory, Upton, New York. He was the first chairman of its physics department (1946-1947). From there, Ramsey went to Harvard, where he was an associate professor from 1947 to 1950 and a full professor from 1950 onwards; he was named Higgins professor of physics in 1966. Ramsey continued to serve as a consultant to government, being a science adviser to NATO (1958-1959) and a member of the general advisory committee of the US Atomic Energy Commission (1960-1972). In 1989 he was cochairman of a federal committee to investigate the practical significance of cold fusion.

Ramsey's awards include the Presidential Order of Merit (1950) for his work on radar, the Ernest Orlando Lawrence Memorial Award of the US Department of Energy (1960), the Davisson-Germer Prize of the American Physical Society (1974), the Columbia Award for Excellence in Science (1980), and the National Medal of Science (1988). He was elected to the American Academy of Arts and Sciences (AAAS) in 1950 and to the US National Academy of Sciences (NAS) in 1952.

The Separated Oscillatory Fields Method

Following two years of postgraduate studies at the University of Cambridge, Ramsey went to work at Columbia in the summer of 1937 with Isidor I. Rabi. The two were beginning to perform research in the field of nuclear magnetic resonance (NMR) spectroscopy. This was a new and powerful method of determining molecular structure where not only the presence of a nucleus can be revealed, but also the atomic nucleus's interactions with nearby nuclei.[5] Ramsey recalled the remarks he included in Columbia's *A Tribute to Professor I.I. Rabi*, published in 1970:

> The first advice I received from Rabi in 1937 when I applied to him to begin my research was that I should not go into the field of molecular beams since the interesting problems amenable to that technique had already been solved and there was little future in the field. I have often wondered how I...had the temerity to disregard this bit of advice from the master. However, I am grateful that I did since the advice was given only a few months before Rabi's great invention of the molecular beam resonance method.[6]

Rabi received the 1944 Nobel Prize in physics for this technique, in which a beam of atoms is passed through both a uniform magnetic field and a single oscillatory magnetic field. The oscillating magnetic field induces the atom to jump from one energy level to another if the frequency of the field matches one of the atom's electron orbital levels.[7]

Ramsey eventually left Rabi's laboratory to work on the war effort. By 1949 he had moved to Harvard, where he became interested in improving the accuracy of the Rabi method. In so doing, he invented the method of separated oscillatory fields.

Ramsey's method involves first passing a beam of molecules or atoms through an electric or magnetic field, which allows particles in a specific quantum state to pass through.[8] Then, a radio frequency (microwave) field is applied to the beam at two separate places a few meters apart. This induces the particle to move to another energy level. A second electric or magnetic field then selectively routes those particles that have made the transition to a detector. (In the Rabi method, the magnetic field is only applied at one site.)

The two fields cycle at the same frequency and are in phase, producing a very finely tuned interference pattern band. As a result the method enables scientists to make a finer, more accurate examination of the structure of particles that make it to the detector.[8]

Ramsey's 1949 and 1950 *Physical Review* papers that describe this procedure are entitled "A new molecular beam magnetic resonance method,"[9] and "A molecular beam resonance method with separated oscillating

Figure 1: Year-by-year distribution of citations to the most-cited works of Norman F. Ramsey, Wolfgang Paul, and Hans G. Dehmelt.

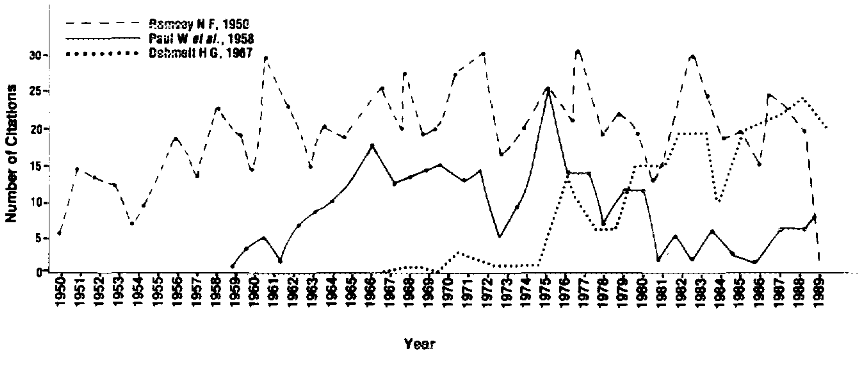


Table 1: Norman F. Ramsey's 10 most-cited papers, based on the *SCI®*, 1945-1989.

Citations	Bibliographic Data
729	**Ramsey N F.** Magnetic shielding of nuclei in molecules. *Phys. Rev.* 78:699-703, 1950.
489	**Ramsey N F.** Electron coupled interactions between nuclear spins in molecules. *Phys. Rev.* 91:303-7, 1953.
302	**Ramsey N F.** Chemical effects in nuclear magnetic resonance and in diamagnetic susceptibility. *Phys. Rev.* 86:243-6, 1952.
158	**Ramsey N F & Purcell E M.** Interactions between nuclear spins in molecules. *Phys. Rev.* 85:143-4, 1952.
157	**Kleppner D, Goldenberg H M & Ramsey N F.** Theory of the hydrogen maser. *Phys. Rev.* 126:603-15, 1962.
136	**Ramsey N F.** Letter to editor. (The internal diamagnetic field correction in measurements of the proton magnetic moment.) *Phys. Rev.* 77:567, 1950.
109	**Dress W B, Miller P D, Pendlebury J M, Perrin P & Ramsey N F.** Search for an electric dipole moment of the neutron. *Phys. Rev. D—Part. Fields* 15:9-21, 1977.
108	**Chan L H, Chen K W, Dunning J R, Ramsey N F, Walker J K & Wilson W.** Nucleon form factors and their interpretation. *Phys. Rev.* 141:1298-307, 1966.
98	**Ramsey N F.** Thermodynamics and statistical mechanics at negative absolute temperatures. *Phys. Rev.* 103:20-8, 1956.
93	**Ramsey N F.** Dependence of magnetic shielding of nuclei upon molecular orientation. *Phys. Rev.* 83:540-1, 1951.

fields."[10] A review article on the method has also been written.[11] A large number of papers by Ramsey, his students, and many others have been based on these three papers.

Ramsey has contributed to many different research fields in physics, as is illustrated by the fact that his most-cited paper, entitled "Magnetic shielding of nuclei in molecules,"[12] which has received over 700 citations through 1989, is quite independent of the work for which he received the Nobel Prize. While the magnetic shielding paper is 40 years old, it has received, on average, about 15 citations annually for the last 5 years, indicating continuing impact in the field of physics. Figure 1 is a depiction of year-by-year citations to Ramsey's and the other 1989 Nobel physics laureates' most-cited works.

I recall the elation we felt when, in 1984, Ramsey sent us a manuscript containing his commentary on this *Citation Classic®*. In it, Ramsey commented on the significance of his method:

> The primary reason that the paper has become one of the most cited is that it provides the fundamental theoretical basis for all later work on nuclear magnetic shielding and on the chemical shifts of NMRs that have made NMR such a powerful tool for analysis in chemistry, physics, and biology.[13]

Table 1 lists 10 publications by Ramsey that were cited at least 90 times through 1989. Ramsey has authored over 350 publications.

The Hydrogen Maser and Atomic Timekeeping

Ramsey employed an approach similar to his separated oscillatory fields technique to develop the hydrogen maser with Harvard colleagues Daniel Kleppner and H. Mark Goldenberg.[14] (Maser is an acronym for *m*icrowave *a*mplification by *s*timulated *e*mission of *r*adiation.) In a hydrogen atom, the electron and proton have magnetic spins that are either opposed or aligned so two discrete energy levels are available. In the maser a magnetic field selects hydrogen atoms at the higher energy level. These are passed through a field tuned to the transition frequency between the two levels, which causes all the atoms to flip their spins to the lower energy level, exactly in phase. When this occurs, the atoms discharge highly coherent microwave radiation at a specific and precise frequency.[8]

The hydrogen maser's accuracy has been used to precisely measure the speed and direction of a wide range of items—ranging from the inches-per-year movement of continental drift to the several tens of miles-per-second speed of the *Voyager II* spacecraft during its recent successful encounter with Neptune.[15]

Ramsey's separated fields method has been used to measure the oscillatory cycles of the nuclei of cesium atoms, the basis for world timekeeping. The cesium atomic clock is basically a maser combined with a cycle counter. In 1967 timekeepers from around the world met at the International Time Bureau, Sèvres, France, and agreed to make the atomic second the primary time standard. The second has been defined as the time for 9,192,631,770 cycles of the cesium atom to occur.[16] The accuracy of the cesium clock is astounding—the clock will err by less than one second in three million years. But physicists are still searching for even more precise measurement. The inventions of Paul and Dehmelt are considered important steps in this direction.

The Search for the Definitive Atomic Particle Measurement: Wolfgang Paul and Hans G. Dehmelt

The other half of the physics prize went to Dehmelt and Paul "for the development of the ion trap technique...which has made it possible to study a single electron or single ion with extreme precision."[1] Ion-trapping techniques to elucidate the structure of atomic particles are an alternative to the expensive high-energy particle accelerators. Metaphorically, accelerators are akin to using a sledgehammer on a watch and examining the fragments to figure how the instrument works. Ion trapping, in contrast, is like deducing what is going on inside the watch by measuring the subtle vibrations of its casing. For some kinds of determinations, data from trapping techniques are superior to those from accelerators.[17]

Paul was honored for his pioneering work in the early 1950s on trapping atoms and ions and for his inventions called the "Paul trap" (the first ion trap invented) and the "Penning trap" (codiscovered independently by both Paul and Dehmelt). The Penning trap is so called after the Penning ion discharge that forms part of the ion-sputter pump of the trapping equipment.[15](A photograph of Paul was unavailable as we went to press.)

Dehmelt's Nobel citation also recognized his successful isolation of both individual electrons and ions for long periods of time, ranging from hours to months. The achievement was made by a method that "cooled" the particles (slowing their spin to nearly a standstill) for an accurate assessment of their properties. Dehmelt's efforts have led to a new field of study called single-ion spectroscopy.

Wolfgang Paul: Ion-Trap Pioneer

Paul was born in Lorenzkirch, Germany, on August 10, 1913. He grew up in Munich and was educated at the Technical Universities of Munich and Berlin, Germany. He studied both atomic and nuclear physics with Hans Kopfermann and earned his PhD in 1939. Paul then followed his thesis adviser to the Universities of Kiel and Göttingen, Germany, where he was appointed to an assistant professorship. In 1952 Paul was named a professor at the University of Bonn and the director of its Physics Institute. His active interests were wide-ranging: high-resolution spectroscopy (together with Kopfermann, he was the first to observe the Lambshift with optical methods), mass spectroscopy, molecular beam physics, high-energy electron physics, and radiobiology. After working with a 6 MeV Betatron in Göttingen, Paul started high-energy physics in Germany by building a strong focusing 500 MeV electron-synchrotron in Bonn in 1953, followed by a 2.5 GeV accelerator.[15]

Paul has played a leadership role in a number of other European institutions. He has been both director of the nuclear physics division at the European Organization for Nuclear Research (CERN), Geneva, Switzerland, and executive director of the German Electron Synchrotron (DESY), Hamburg, FRG, as well as being chairman for some years of the scientific policy committee in both institutions. In the same functions, he served at the nuclear energy facility in Jülich, FRG. Closer to home his interest in education and research led him to serve on various governmental planning committees. For the past 10 years, Paul has been president of the Alexander von Humboldt Foundation, which fosters the international exchange of scientists.[18]

Even though Paul remains at Bonn as an emeritus professor, he has not stopped working on physics experiments. One of his recent efforts involved experiments with a neutron storage ring, carried out in Grenoble, France, in close relevance to the previously mentioned experiment of Ramsey.[18]

Paul's honors and awards include membership in the Leopoldina German Academy of Research and the Natural Sciences, Halle/Salle, German Democratic Republic, and in the German Academy of Sciences for the cities of Dusseldorf, Heidelberg, and Göttingen, FRG; the Distinguished Merit Award of the Arts and Sciences, Vice Chancellor for the Sciences, FRG; the Robert Wichard Pohl Prize of the German Physical Society, FRG; and the Gold Medal of the Czechoslovakian Academy of Sciences, Prague. Paul has also been awarded doctorates by the University of Uppsala, Sweden, and the Technical University of Aachen, FRG.

Paul's prizewinning work began in the 1950s when, together with Helmuth Friedburg and Hans Gerd Bennewitz, University of Bonn, he designed electric and magnetic quadrupole and sextupole fields as lenses to focus atomic and molecular beams and to separate particles with different orientations of their dipole moments (the angle of the magnetic field given off by the particle) or in different quantum states. Such fields found application with the ammonia and hydrogen maser by Charles H. Townes, then at Columbia, and Ramsey, respectively.[18]

Together with Helmuth Steinwedel, University of Würzburg, FRG, Paul found that ions with different masses could be guided and separated by a quadrupole microwave field with a direct current field superimposed. This configuration is widely used today as a mass spectrometer. The three-dimensional version of such a device, now known as a Paul trap, was developed by Paul with the late Erhardt Fischer and Otto Osberghaus, University of Freiburg, to confine ions in a small region. In such a trap, a microwave field is applied between the end caps and a ring-shaped electrode at the center. The fields create hyperbolic potentials in which the motion of the ions is harmonic to the first order. At the very center of the trap, the ion inhabits a virtually field-free region. Ions can live in a trap for more than a month.[18]

Since 1973 Paul and his students have concentrated on confining neutral particles in magnetic traps by means of their magnetic moment. Together with colleagues U. Trinks, Munich Technical University, and K.-J. Kügler, University of Bonn, Paul succeeded in the construction of a superconducting storage ring for very slow neutrons in analogy to rings for charged particles.[19] Last year this instrument enabled Paul with his younger colleagues (including his two sons) to determine a new value for the neutron lifetime, observing the stored neutrons for more than one hour.[20] As the neutrons are elastically bound to the symmetry plan of the magnetic field, Paul and his colleagues were able to measure the weight of the neutrons by measuring the downward shift of their orbit as a function of the restoring magnetic force.[18]

In his Nobel lecture, Paul commented on the importance and impact of observing individual particles on measurements in physics:

> [T]he possibility to observe individual trapped particles opens up a new quality in atomic measurements. Until a few years ago, all measurements were performed on

Table 2: Papers by Hans G. Dehmelt and Wolfgang Paul with more than 50 citations identified in the *SCI®*, 1945-1989.

Citations	Bibliographic Data
280	**Paul W, Reinhard H P & von Zahn U.** Das elektrische Massenfilter als Massenspektrometer und Isotropentrenner (The electric mass filter mass spectrometer and isotope separator). *Z. Phys.* 152:143-82, 1958.
247	**Dehmelt H G.** Radiofrequency spectroscopy of stored ions. I: storage. *Advan. Atom. Mol. Phys.* 3:53-72, 1967.
169	**Dehmelt H G.** Slow spin relaxation of optically polarized sodium atoms. *Phys. Rev.* 105:1487-9, 1957.
156	**Dehmelt H G.** Radiofrequency spectroscopy of stored ions. II: spectroscopy. *Advan. Atom. Mol. Phys.* 5:109-54, 1969.
141	**Dehmelt H G.** Spin resonance of free electrons polarized by exchange collisions. *Phys. Rev.* 109:381-5, 1958.
114	**Dehmelt H G & Krüger H.** Quadrupol-Resonanzfrequenzen von Cl- und Br-Kernen in Kristallinem Dichloräthylen und Methylbromid (Quadrupole resonance frequencies of Cl and Br nuclei in crystalline dichloroethylene and methylbromide). *Z. Phys.* 129:401-15, 1951.
107	**Dehmelt H G.** Letter to editor. (Modulation of a light beam by precessing absorbing atoms.) *Phys. Rev.* 105:1924-5, 1957.
109	**Paul W & Raether M.** Das elektrische Massenfilter (The electrical mass filter). *Z. Phys.* 140:262-73, 1955.
95	**Bennewitz H G, Kramer K H, Paul W & Toennies J P.** Messung der Anisotropie des van der Waals-potentials durch Streuung von Molekülen in definiertem Quantenzustand (Measurement of the anisotropy of the van der Waals potentials by dispersion of molecules into defined quantum states). *Z. Phys.* 177:84-110, 1964.
88	**Dehmelt H G & Krüger H.** Kernquadrupolfrequenzen in festem Dichloräthylen (Nuclear quadrupole frequencies in solid dichloroethylene). *Naturwissenschaften* 37:111-2, 1950.
85	**Van Dyck R S, Schwinberg P B & Dehmelt H G.** Precise measurements of axial, magnetron, cyclotron, and spin-cyclotron-beat frequencies on an isolated 1-meV electron. *Phys. Rev. Lett.* 38:310-4, 1977.
81	**Bennewitz H G, Paul W & Schlier C.** Fokussierung polarer Moleküle (Focusing of polar molecules). *Z. Phys.* 141:6-15, 1955.
79	**Hulpke E, Paul E & Paul W.** Bestimmung von Oszillatorenstärken durch Lebensdauermessungen der ersten angeregten Niveaus für die Elemente Ba, Sr, Ca, In und Na (Determination of oscillator strengths through measurements of the lifetimes of the first excited states of the elements Ba, Sr, Ca, In and Na). *Z. Phys.* 177:257-68, 1964.
68	**Dehmelt H G & Walls F L.** "Bolometric" technique for the rf spectroscopy of stored ions. *Phys. Rev. Lett.* 21:127-31, 1968.

> an ensemble of particles. Therefore the measured value...is a value averaged over many particles. Tacitly one assumes that all atoms show exactly the same statistical behaviour if one attributes the result to the single atom. On a trapped single atom, however, one can observe its interaction with a radiation field and its own statistical behaviour alone.[21]

Paul has published 90 papers to date. Table 2 lists his five most-cited publications. It is noteworthy that all were published in German. This may account in part for their lower citation impact when compared to Dehmelt's nine most-cited publications (also listed in Table 2), most of which are in English. In a recent essay on language use in science,[22] it was shown that German-language publications in the 1984 *Science Citation Index®* had a five-year impact of 0.64, compared to 3.74 for English-language articles. However, this generalization needs to be examined in greater detail. Delayed recognition may be involved.[23,24]

Paul's most-cited work is a 1958 article published in *Zeitschrift für Physik*, which describes his ion trap.[25] This is ranked 35th among the top 50 papers for this journal. As Figure 1 shows, the citations of this pathfinding paper on the Paul trap gradually increased in the first 10 years or so, but peaked in 1975.

Hans G. Dehmelt: Atoms At Rest; Quantum Leaps

Dehmelt was born on September 9, 1922, in Görlitz, Germany. He studied physics at Breslau Technical University, Silesia, in

1943-1944. In 1946 he took up studies at the University of Göttingen, where in 1950 he was awarded a doctoral degree in physics summa cum laude.

In 1952 Dehmelt traveled to the US for postdoctoral work at Duke University, Durham, North Carolina. In 1955 he joined the faculty of the University of Washington, where he became a full professor in 1961. He became a US citizen in the same year.

Dehmelt's awards include the Davisson-Germer Prize of the American Physical Society (1970); the Alexander von Humboldt Prize of Ruprecht Karl University, Heidelberg (1974); the International Society of Magnetic Resonance Basic Research Award (1980); and the Count Rumford Prize of AAAS (1985). Dehmelt was elected to AAAS in 1977 and to NAS in 1978. He is a member of Sigma Xi and a Fellow of the American Physical Society.

Spectroscopy Achievements

As a graduate student during the early 1950s, Dehmelt codiscovered, with Hubert Krüger, University of Göttingen, the technique of nuclear electric quadrupole resonance, which has become an important adjunct to NMR in the study of solids.[26] In studies undertaken after arriving in the US, he originated the optical absorption technique of monitoring atomic orientation. He also succeeded in lining up the spins of a sample of free electrons, using a magnetic field technique that included a vapor of optically oriented sodium atoms. From the resulting spin exchange collisions between sodium atoms and the free electrons, Dehmelt was able to measure the spin magnetic moment of the free electrons.[27]

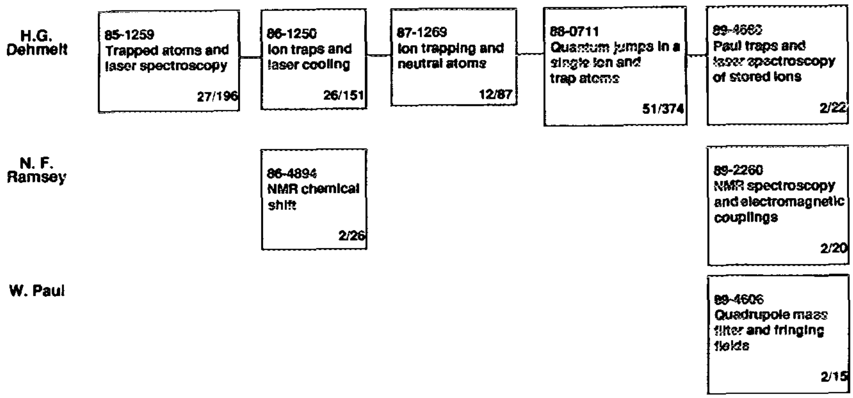
In the early and mid-1960s, Dehmelt and his colleagues succeeded in making precision measurements of two important ions of helium and molecular hydrogen by confining the ions in radio-frequency quadrupole traps. This allowed the rotational and spin couplings of the hydrogen ion to be measured for the first time.[28] The measurements demonstrated the potential for using ion-trap techniques for a variety of experiments and have found a number of applications, including the development of precision frequency standards for telecommunications.

Perhaps Dehmelt's greatest research efforts were achieved in the past two decades. In 1973, by using a Penning trap, Dehmelt became the first to isolate a single electron for observation.[29] Dehmelt and his colleagues used the Penning trap in another ground-breaking procedure when they measured an electron's magnetic moment to an accuracy of four parts in a trillion, the most precise measurement of that quantity at the time. Scientists subsequently used the measurement to test theoretical predictions of QED.[15]

In 1975 Dehmelt devised a method for "cooling" or reducing the energy level of the trapped electrons and ions, which further improved the accuracy of measurements.[30] For the atomic ions, this was done via a laser, which is tuned to a frequency slightly below that of one of the energy-level transitions of the target atoms or ions. The particles in the trap that are moving towards the laser absorb photons from the laser and reemit them at a slightly higher frequency. The energy difference is taken from the particles' motion, with the result that the atoms gradually slow down, or "cool." The technique is so successful that Dehmelt has been able to cool a magnesium ion to just a few thousandths of a degree above absolute zero—nearly the theoretical limit.[30] Dehmelt's work has enabled scientists to see for the first time an individual atom at rest in free space.[31]

Quantum theory postulates that energy is not a continuous quantity but comes in units, or quanta. Thus, atoms do not slide imperceptibly from one energy state to the next but instead make quantum leaps between energy levels. In 1986 Dehmelt and his colleagues became the first scientists to witness a quantum leap.[32] When an atom decays from high to lower energy states, it emits

Figure 2: Historiograph of research fronts that include papers by Hans G. Dehmelt, Norman F. Ramsey, and Wolfgang Paul as core documents. The number of core/citing papers is given at the bottom of each box.



the excess energy in the form of electromagnetic radiation, which can also appear as a photon, a quantum of light. When this radiation is emitted, it has a characteristic wavelength, or frequency, based on the difference between the two energy states. The quantum leaps (from upper states, living as long as 100 seconds) may produce extremely regular waves of electromagnetic radiation, which can be counted.[33] Dehmelt has published over 150 papers to date.

It is interesting to note that his most-cited work, "Radiofrequency spectroscopy of stored ions. I: storage,"[34] appears to exhibit the delayed recognition phenomenon.[23,24] This can be seen in Figure 1. For seven years, the paper was cited five or less times annually. However, in 1976 the paper seems to have made a quantum leap to a higher citation energy level, followed by a fairly steady increase in citations over the following 12 years. Even with the initial low citation rate, the paper has averaged nearly 20 explicit references annually.

Dehmelt has some thoughts as to why his paper experienced the delayed recognition phenomenon:

> When I published my proposal to do high resolution spectroscopy on an individual trapped atomic ion in 1973, people simply did not believe that this could be done now, even though we had already demonstrated the isolation of an individual electron. In fact, the gentlemen at one of the military agencies which had been supporting my group for years alleged that I was *non compos mentis*, and shortly afterwards cut off their support. [One must remember that] such highly influential theoreticians like [Wolfgang] Pauli and [Niels] Bohr had widely asserted in the 1930s that it was principally impossible to measure such a "purely quantum mechanical phenomenon" as the spin magnetic moment of a free electron via changes in its classical trajectory, which I also had proposed to do. According to the well-known Earnshaw's theorem, trapping of a charged particle in a static field is impossible.[35]

ISI Research Fronts, 1985-1989, on Ion Spectroscopy Indicate Laureates' Centrality to Field

Figure 2 is a historiograph of ISI® research fronts on ion trapping and related subjects from 1985 through 1989. A research front (specialty) is formed by the connections made by scientists in their referencing patterns. Using a method called co-citation clustering, it is possible to order automatically the scientific literature into bibliographically distinct and intellectually coherent groupings. Articles that are frequently cited together by current papers constitute the "core" of the specialty. The research front, in part, is composed of current citing articles and is named from phrases co-occurring in the titles of these citing papers. Figure 2 is a graphic display of the continuity of various lines of research over the years, as core papers continue to be cited together. The historiograph shows these linkages between fronts.

It is interesting to note that the most-cited works of all three laureates are core papers in several research fronts. Dehmelt's most-cited publication on "Radiofrequency spectroscopy of stored ions..."[34] has consistently been core to a series of research fronts since 1985. Two other publications by Dehmelt[36,37] also appear as core works in research front #86-1250, "Ion traps and laser cooling."

Research Fronts, 1970-1976, Reflect Ramsey's Core Research

Ramsey's most-cited paper[12] is core to fronts in 1971, 1973, 1975, and 1976. More recently, it appears in two 1980s specialties that deal with NMR: #86-4894, "NMR chemical shift," and #89-2260, "NMR spectroscopy and electromagnetic couplings." Several of Ramsey's other highly cited works also appear: his second most-cited work, "Electron coupled interactions between nuclear spins in molecules,"[38] is a core publication in research fronts for 1970 and 1973, while his third most-cited work, "Chemical effects in nuclear magnetic resonance and in diamagnetic susceptibility,"[39] appears in a 1970 research front. One further publication by Ramsey, a book entitled *Molecular Beams*,[40] appears as a core work to a 1978 research front.

Paul's most-cited work[25] appears as one of two core papers in research front #89-4606, "Quadrupole mass filter and fringing fields." The fact that Paul's classic papers were published in the 1950s and 1960s and in German might explain why his works do not appear in more current research-front specialties.

Conclusion: Measuring the Pulse of the Universe

Today's high-precision clocks work by sensing the vibration of a moving beam of atoms. But eventually, with refined methodologies using ion traps, the oscillations of a single atom will be able to be measured. This might provide a phenomenal timepiece—losing just one second in 10 billion years—an accuracy equal to the lifespan of stars similar to our sun.[41]

The atom has proven to be a more bountiful scientific adventure than was first realized in 1895 when Sir Joseph John Thompson, University of Cambridge, first discovered the electron. In the conclusion of his Nobel lecture, Dehmelt said: "I should like to cite a line from William Blake, 'To see a world in a grain of sand—' and allude to a conceivable parallel—to see worlds in an electron—."[42]

* * * * *

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