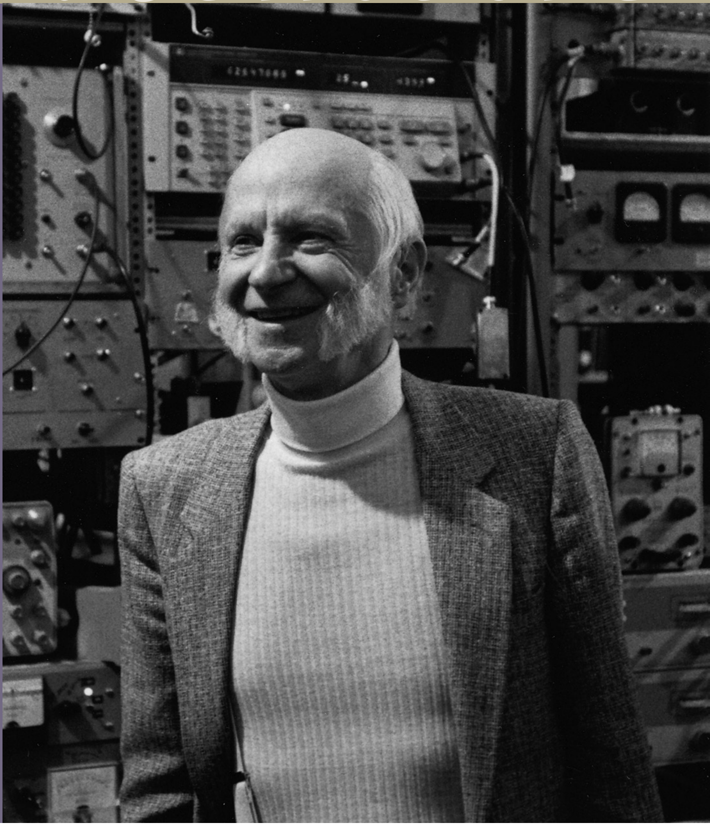
Hans G. Dehmelt

1922–2017

BIOGRAPHICAL *Memoirs*



A Biographical Memoir by
D. J. Wineland

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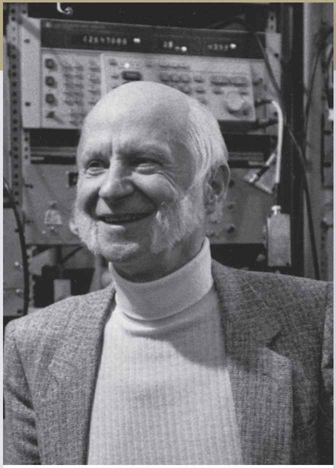
HANS GEORG **DEHMELT**

September 9, 1922–March 7, 2017

Elected to the NAS, 1978



Hans Dehmelt

By D. J. Wineland

Hans Georg Dehmelt was a leading figure in high-resolution spectroscopy experiments on simple systems—including isolated electrons and atomic and molecular ions—that led to some of the most precise tests of quantum mechanics ever performed.

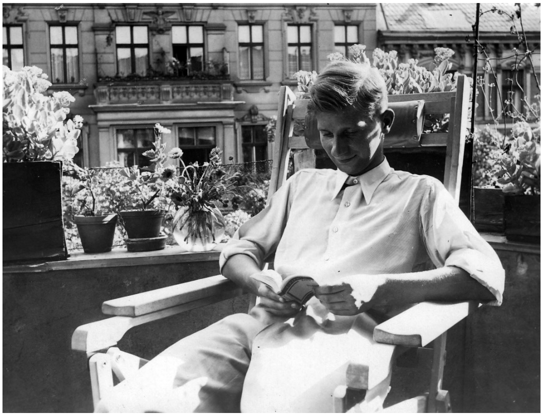
After serving in World War II, Hans completed his graduate studies at Göttingen University, Germany, where he received his Ph.D. in 1950 and worked as a postdoctoral fellow until 1952. Moving to the United States, Hans was a postdoctoral fellow at Duke University from 1952 to 1955 and then took a faculty position at the University of Washington in Seattle, where he was based until his retirement in 2002. It was at Washington that Hans carried out his most celebrated experiments in measuring the magnetic properties of the electron and its antiparticle.

Hans was born in 1922, in Görlitz, Germany, to Georg and Asta Dehmelt, but grew up in Berlin during the 1930s. Georg had studied law at the University of Berlin, served as an artillery officer in World War I, and during the Depression worked in real estate to support the family, which included Hans's sister Brigitte and brother Bernard.

As a young boy, Hans played with erector sets, and at the age of 10 he began building and playing with radios, thereby developing skills that would figure in his later experiments as a physicist. At eleven, Hans's mother enrolled him in Gymnasium zum Grauen Kloster, Berlin's oldest Latin school, which, as Hans liked to point out, Otto von Bismarck had also attended. Hans's performance on a rigorous entrance exam earned him a scholarship to Kloster, although, as he later recalled, he was more interested in his radio projects. These efforts adversely affected his coursework, but they also stimulated his interest in physics. Eventually he would take physics classes, which he took more seriously, at Kloster; to prepare for them, he consumed texts that he had borrowed from the public library. This is how, for example, he first learned about the basic structure of atoms. Meanwhile, Hans showed little interest in school sports; he and a few of his classmates preferred intellectual discussions.

After graduating from Kloster in the spring of 1940, Hans was drafted into the German military. First serving in an anti-aircraft artillery unit, he was later sent to relieve the troops at Stalingrad and considered himself quite lucky not to have been encircled by the Russians. He was sent back to Germany in 1943 to study physics in an army program at the University of Breslau, but in 1944 was assigned to the Western Front during the Battle of the Bulge, where he was captured. After spending a year in an American POW camp in France, Hans was released in early 1946.

He returned to his study of physics by enrolling at the University of Göttingen, where he attended lectures by some of Germany's most famous physicists, including Hans Kopfermann and Werner Heisenberg. He supported himself by repairing prewar radios and bartering with them. Hans recounted that he especially enjoyed a laboratory class at Göttingen in which he could repeat many of the seminal physics experiments of the 20th century, including the Frank-Hertz experiment, the Millikan oil-drop experiment, and magnetron and plasma experiments. This class was taught by Wolfgang Paul, who would later share the 1989 Nobel Prize with Hans (and Norman F. Ramsey).



Berlin, 1943.

In the Kopfermann Institute at Göttingen, Hans completed a Diplom-Arbeit (masters thesis) on the photographic effect from protons. He then did doctoral thesis work on nuclear magnetic resonance (NMR), which included the first demonstrations of nuclear electric quadrupole resonance, under his adviser Hubert Krüger. It was during this period that Hans married Irmgard Lassow, and they had a son (Gerd). The couple later divorced when Hans moved to the United States.

In the early 1950s, Hans joined Walter Gordy's microwave spectroscopy group at Duke University as a postdoctoral research associate. There he advised a graduate student,

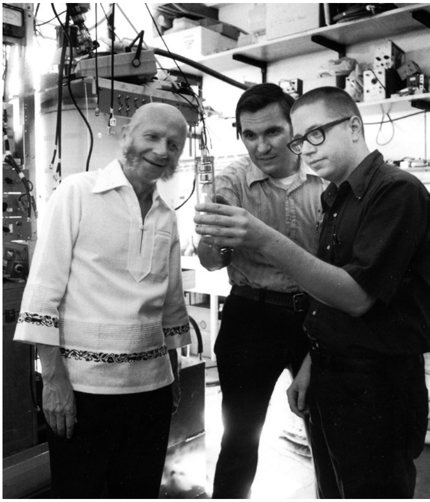
Duke University, 1954.

Hugh Robinson, on a new nuclear quadrupole resonance experiment and contributed to an NMR cryogenic experiment on ^{3}He/^{4}He mixtures. Also, while Hans had tried, without success, at Göttingen to observe paramagnetic resonance in free atoms, he was eventually successful at Duke. During this time, Hans took a visiting assistant professor position at the University of Washington, where he conducted his own research and advised students of Edwin Uehling during Uehling's sabbatical. It was at Washington that Hans developed a technique wherein the angular momentum of atoms could be partially aligned by electron impact. Changes in the angular momentum due to magnetic resonance could then be observed by angular-momentum-dependent optical absorption or angular-momentum-dependent electron-impact ionization.

In 1958, Hans reported the observation of spin resonance of free electrons through angular-momentum exchange with optically pumped sodium atoms, both being contained in a cell with an inert gas to suppress diffusion. In the introduction to his paper on this work, he pointed out the importance of precise measurements of the electron magnetic moment (each electron behaves like a tiny magnet), given its deviation from the value provided by the Dirac theory (i.e., the Bohr magneton). This deviation is usually expressed in terms of the ratio of electron moment to the Bohr magneton, 1 + a, where a is called the "anomaly."

Hans's work at that time appeared to mark the beginning of a quest that he pursued throughout most of his career—a precise measurement of the electron's magnetism. During that period, Hans also continued optical pumping experiments; he patented several of the associated techniques, which were bought by private companies.

For more precise electron moment measurements, Hans explored the use of a Penning ion gauge, basically a "trap" for charged particles. The device resulted from experiments, initiated by his graduate student Fred Walls, to confine ensembles of electrons in a Penning trap that used a combination of uniform magnetic field and a superposed electric quadrupole potential, which made the electrons' motion along the magnetic field direction highly harmonic. In this way, the harmonic motion of an ensemble of electrons could be coupled to a tuned circuit whose resistance would cool the electrons' temperature to that of the circuit. Conversely, currents induced by the electrons in the tuned circuit would also provide a measure of the electrons' temperature, acting as a bolometer.



With Robert Van Dyck, Paul Schwinberg, and the famous electron trap (ca. 1980).

The electrons' cyclotron frequency was determined by applying microwaves to the sample; when the microwave frequency matched the cyclotron frequency the sample would heat and the increased thermal currents, could be subsequently detected through the tuned circuit. The spin resonance frequency could be detected indirectly by first applying a high-power uniform microwave field near the spin flip frequency, which made the spin temperature very high. Then an inhomogeneous oscillating magnetic field was applied. When tuned to a frequency equal to the difference between spin and cyclotron frequencies, that magnetic field would cause an exchange of energy between the spins and cyclotron motion, resulting in a slight increase in the cyclotron temperature, which could be observed bolometrically. This difference frequency, in conjunction with the measured cyclotron frequency, could provide a direct measurement of the anomaly. Results using this bolometric method were reported by Fred Walls and Talbert Stein in 1973.

In parallel with the electron experiments, Hans initiated ion spectroscopy experiments using the RF "Paul ion trap" developed by his former professor Wolfgang Paul. This device employed inhomogeneous oscillating electric fields, which provided "ponderomotive" forces to achieve the trapping. For atomic ions, the Paul ion trap had certain advantages relative to the Penning trap.

As a graduate student with Norman Ramsey (1965–1970), I was working on hydrogen masers and their use as accurate atomic clocks based on their ground-state hyperfine transition frequency. During that time, I read about the Paul trap experiments of Hans and his University of Washington colleagues Norval Fortson, Fouad Major, and Hans Schuessler. The trapping of ions at high vacuum presented some nice advantages for precision spectroscopy and clocks—including the near-elimination of first-order Doppler shifts and the relatively small frequency shifts of the ions from background collisions—precisely because of those very high vacuums. Using a Paul trap, this Washington group had made high-resolution measurements of the hyperfine structure of $^3He^+$. One challenge these researchers encountered was that detection of hyperfine structures by optical-pumping/double-resonance was (and still is) not feasible because of the very short wavelengths required.

But in a heroic (to my mind) set of experiments, they accomplished state preparation of polarized $^3He^+$ through charge exchange with a polarized Cs beam that passed through the ions. Detection of $^3He^+$ hyperfine transitions was achieved through a charge-transfer process($^3He^+ + Cs \rightarrow {}^3He + Cs^+$) that depended on the internal state of $^3He^+$; subsequent detection of the depleted $^3He^+$ ion number was then made by observing the ions' number-dependent induced currents in the trap's electrodes. This experiment attained an impressive fractional imprecision of about 1 part in 10^9, suggesting the potential of trapped-ion spectroscopy for use in future atomic clocks. In related experiments by Hans's first postdoctoral research associate Charles Richardson and graduate student Keith Jefferts, state-dependent photodissociation of H_2^+, followed by detecting changes in the number of H_2^+ ions, was used to detect Zeeman transitions in the hyperfine states of H_2^+ for the first time.

Hans had certain eccentricities, which he seemed to enjoy. Charles Richardson wrote:

> *He drove a 1962 Lincoln Continental convertible, the nearest thing to a barge that Detroit produced. He was a striking figure, with his bald head and mutton-chop whiskers, motoring with the top down. At a meeting in Berkeley, Norman Ramsey was giving a talk and he turned to the subject of transitions. He noted in particular that Dehmelt's hair had transitioned from the top of his head to his jowls. Whereupon the top of that head turned bright pink.*

I was a postdoc in Hans's group starting in the fall of 1970. I had been attracted by their high-resolution spectroscopy experiments on $^3He^+$, but when I arrived Hans was more focused on measurements of the electron magnetic moment. I thus became familiar with the apparatus that Fred Walls had constructed, but in discussions with Hans it became clear that systematic perturbations inherent in an ensemble of trapped electrons would prevent reaching the highest-precision measurements. Therefore, along with Hans's student Philip Ekstrom, we undertook an experiment to isolate single trapped electrons.

The method was relatively straightforward: the harmonic motion of a small ensemble of electrons was driven with a resonant electric field and detected by observing induced currents in the trap electrodes. With a critical drive level, one of the electrons would occasionally have enough energy to strike one of the trap electrodes and be absorbed, causing the induced current to take an observable step downward. By calibrating these steps, the current for a single oscillating electron could be determined (a "mono-electron oscillator," as Hans liked to call it). I left the group before the single-electron magnetic moment measurements (described below) were made, but while I was still there, Hans and I came up with a scheme (concurrently with a proposal by Theodor Hänsch and Arthur Schawlow) for laser cooling of atoms.

In working as a postdoc with Hans, I became very impressed with his ability to reduce seemingly complicated problems to simple ones. He had a knack for mixing just the right proportions of classical and quantum physics into straightforward models for understanding the key ideas at play. This process often involved mapping the problem onto a harmonic oscillator (a ubiquitous player in physics); he often cast the oscillator in terms of a resonant electrical circuit, harking back to his early radio days, when tuned circuits were used as frequency filters. I also remember that he often used to say, "The apparatus is the scratchpad of the experimentalist," meaning that by varying enough parameters in an experiment, the observed results would root out the basic physics. In fact, I think it was this experimentation, combined with his deep understanding through simple models, that made Hans so successful.

As the electron experiments progressed, Hans and Philip Ekstrom proposed a new scheme—called the "continuous Stern-Gerlach effect"—to measure an electron spin flip. In this procedure, the addition of a small static quadratic component to the otherwise uniform magnetic field (often referred to as a magnetic bottle) caused the frequency of the electron's harmonic motion to depend on its spin direction along the magnetic field (as well as on the state of its quantized cyclotron motion). By averaging over the thermal fluctuations of the cyclotron quantum states, the average frequency of the electron's harmonic motion could be used to determine the electron's spin state. One of the electron's modes of motion, called the magnetron motion, must be actively controlled. It's amplitude relative to the center of the trap can be minimized by a process analogous to laser cooling. In 1976, the Washington group incorporated this technique and were able to measure all three mode frequencies of a single electron. Hans coined the term "geonium" to describe the apparatus—that is, a single electron that is bound to the earth through the trap.

These experiments, carried out by Hans's colleague Robert Van Dyck and graduate student Paul Schwinberg, also measured the electron magnetic moment anomaly with an inaccuracy of 5 parts per million—and several months later, with an unprecedented inaccuracy of 0.2 ppm. After this work was further improved in a series of experiments, in 1987 the group reported an anomaly inaccuracy of just 0.004 ppm. In this experiment, they could also trap single positrons (the electron's antiparticle) by reversing the relative signs of the electric potentials on the trap electrodes. They reached the same level of uncertainty and showed that the electron and positron magnetic moments agreed to a level of 2 parts in one trillion, yielding the most accurate demonstration of charged particle-antiparticle symmetry.

Van Dyck wrote:

> *Hans Dehmelt is well remembered for having proposed that it was possible to isolate a single elementary electron and to measure its magnetism. He was also fond of reminding us that a few very wise and prominent physicists said this was impossible. Not only did we succeed, even well beyond our own expectations, but this work produced the highest level of agreement at that time between any research measurement and the theory that predicted the given result.*

After Gerald Gabrielse, one of Hans's former postdocs, moved to Harvard, he made several additional improvements in the group's measurement techniques, thus enabling his own group to measure the anomaly with an uncertainty of only about 3 parts in 10^{10}—or equivalently, to determine the magnetic moment of the electron in terms of the Bohr magneton to 3 parts in 10^{13}. Amazingly, theorists have been able to calculate the magnetic moment to comparable precision. The theoretical value depends on the "fine structure constant" α, which represents the strength of electromagnetic forces. When theory and experiment are combined, a value of α can now (at this writing) be derived with an uncertainly of around 2.4×10^{-10}. In fact, values of α can be independently derived from entirely different physics experiments; the two values agree at the few-parts-in-10^{10} level. The agreement between theory (using the independently determined value of α and the measured value of the electron magnetic moment provides the most precise test of the "standard model" of quantum physics—at a level of around 1 part per trillion.

In 1973, Hans wrote a brief description (in a paper presented to the American Physical Society) of a proposed experiment involving high-resolution optical spectroscopy of a single atomic ion (a "mono-ion oscillator"). His paper set ion-trapping groups thinking about this possibility, and many have since incorporated his basic ideas. Ironically, Hans wrote at the time he received the Nobel Prize,

> *This proposal infuriated one of the agencies funding our research to the degree that they terminated their support almost immediately. I was rescued by a prize from the Humboldt Foundation and an invitation by Gisbert zu Putlitz to initiate the proposed laser spectroscopy project at his institute at the Universität Heidelberg.*

In 1975, Hans expanded his discussion of single-ion optical spectroscopy and described a very sensitive way to detect transitions from an atom's ground state to an excited level. In principle, one can detect such transitions by observing the photons that are scattered from the atom. But for very high-resolution optical spectroscopy, the excited-state lifetime can be very long (many seconds in some cases). That fact, coupled with the inability to capture all the scattered photons, would lead to very inefficient detection. Hans suggested employing a second transition from the ground state to an excited state that would decay very rapidly, enabling photon scattering (fluorescence) at a very high rate.

Therefore, starting from the ground state, one laser beam would be applied for a certain duration to excite the high-resolution transition. Then another laser beam would be applied to the second transition, tuned to resonance. If the first beam excited the atom, application of the second beam would lead to no fluorescence. If the first beam did not excite the atom, then the second beam would generate fluorescence. Thus the absorption (or non-absorption) of a single photon on the first transition would be signaled by the absence or presence of millions of scattered photons on the second—a huge amplification in detection efficiency. This technique, which Hans called "electron-shelving amplification"—because the optically active electron is "shelved" in the excited state of the first transition—has become a mainstay of the large majority of ion trap (and neutral atom) spectroscopy experiments.

During Hans's sabbatical at Heidelberg, he worked in Peter Toschek's laboratory with research associate Werner Neuhauser and grad student Martin Hohenstatt on a project to demonstrate laser cooling. The group in fact was able to demonstrate laser cooling of barium ions at the same time as a group at NIST, working with magnesium ions. Subsequently, the Heidelberg group isolated a single barium ion, and photographs they took of this result brought Hans closer to realizing his goal of a "single atomic system at rest in free space." In this dramatic experiment, the barium ion fluoresced in the visible (blue) part of the spectrum, and one could see it with the aid of a simple magnifier. It looked much like a faint blue star.

The electron-shelving technique described above makes intuitive sense, but in the early 1980s, there was some controversy among theorists as to what one would see if both lasers were applied simultaneously. Some people thought that sudden jumps in fluorescence from the second laser would still be seen, while others thought there would be a smooth reduction in this fluorescence as the intensity of the first laser beam was increased. Although the controversy seemed to have been resolved before the first experiments (in favor of the "quantum jumps"), it was still interesting to demonstrate the jumps in the lab.

The experiments on single barium ions in Hans's lab were carried out in 1986 by postdoc Warren Nagourney and student Jon Sandberg. Laser cooling and fluorescence light were accomplished by simultaneously driving the ${}^2S_{1/2} \longleftrightarrow {}^2P_{1/2}$ and ${}^2D_{3/2} \longleftrightarrow {}^2P_{1/2}$ optical transitions. During this process, fluorescence photons were emitted from the ions at a rate up to about 10^8 per second, easily verifying the fluorescence even though only a small fraction of these photons could be detected. Subsequently, light from a filtered discharge lamp, which produced an incoherent source of light, was applied to the ion. This light would cause transitions from the ${}^2S_{1/2}$ ground-state level to the ${}^2P_{3/2}$ level, which would then quickly decay to the ${}^2D_{5/2}$ state. When this reaction occurred, fluorescence from the laser-driven transitions would suddenly disappear—and only reappear when the ion radiatively decayed from the ${}^2D_{5/2}$ state back to the ${}^2S_{1/2}$ ground state. This would take about 30 seconds, so the jumps were clearly and dramatically observed. At about the same time, Peter Toschek's group (which had moved to Hamburg) carried out similar experiments on barium ions and Jim Bergquist's group at the National Institute of Standards and Technology (NIST) observed the jumps with mercury ions.

As an aside, we note that Hans could be a caustic critic at times. But he could also criticize in an amusing way. In our NIST quantum-jump experiments, the sudden cessation of fluorescence from the second transition was caused by the ion decaying to another excited level; from there, it would decay to the ground state, either directly or through another excited state. By simply observing the statistics of the no-fluorescence durations, all three excited-level lifetimes needed to describe this process could be extracted. We thought that this experiment, led by Wayne Itano and Jim Bergquist, was an interesting extension of quantum jumps, and we submitted a paper on it to *Physical Review Letters*

(PRL) in 1987. One of our reviewers was clearly Hans; from other correspondence we had had with him, his particular dot-matrix printer was unmistakable as well as his writing style. In part, he wrote, "This paper essentially is a worthwhile study of a small wart on the pretty face of the shelved-electron amplifier scheme." He concluded, "While this may not be a great discovery, the work is, in my opinion, up to the average level of papers in *PRL*," apparently taking a bit of a jab at *PRL* as well. We had a great laugh over these comments, and of course we were happy that he gave his recommendation for *PRL* to publish the work.

With colleagues Warren Nagourney, Nan Yu, and student Gary Janik, Hans continued to exploit the shelved electron amplifier scheme for high-resolution spectroscopy in barium ions. He and Nagourney also proposed the use of aluminum ions for an optical clock, which has since been successfully used by the NIST ion-clock group to reach very high precisions.

At the time of Hans's retirement in 2002, the University of Washington held a festschrift to honor him, and produced a tribute titled "*An Isolated Atomic Particle at Rest in Free Space*" edited by E. Norval Fortson, Ernest Henley, and Warren Nagourney and published in 2006 by Alpha Science International Ltd, (Oxford, England), which included written versions of the festschrift's presentations.

In the late 1990s, Hans shifted his focus from physics to health and nutrition. This was not a sudden transition. Even in the early '70s, Hans would give his students and postdocs small books on these topics; one of his favorites at time was the benefits of eating fruits and nuts, and in particular he seemed to settle on an unprocessed mixture of frugivore and herbivore diets—his so-called "chimp diet." He also favored caloric restriction, having cited the many benefits of undereating and having argued that our ancient ancestors lived and survived because of very similar practices.

Hans had several other interests outside physics; he practiced yoga, was an avid dancer, and attended many classical music and ballet performances. His second wife, Diana Dundore, a medical doctor in Seattle, wrote:


Yoga, 1988.

Dancing with Diana, 1987.

I met him in the '80s at a ballet party, when he asked me to dance. No one was dancing, as there was just a little combo playing some background music. But things like that never bothered Hans. (He loved to dance.) Such was my introduction to Hans, who basically fascinated me with his nonconformity and interesting ideas; he was probably the best-educated man I had ever met. And we had a lot of common interests: ballet, opera, classical music, science, history, walks in nature, and of course dancing. Although I initially had reservations about life with an older man, eventually I concluded that we worked amazingly well together. Hans adhered to Joseph Campbell's philosophy of 'follow your bliss,' and he often quoted Eleanor Roosevelt's saying that 'The purpose of life is to live it.' We married in 1989; when he won the Nobel Prize, he called me in the middle of the night to propose.

ACKNOWLEDGMENTS

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