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# ROBERT VIVIAN POUND
# 1919–2010

*A Biographical Memoir by*

NICOLAAS BLOEMBERGEN



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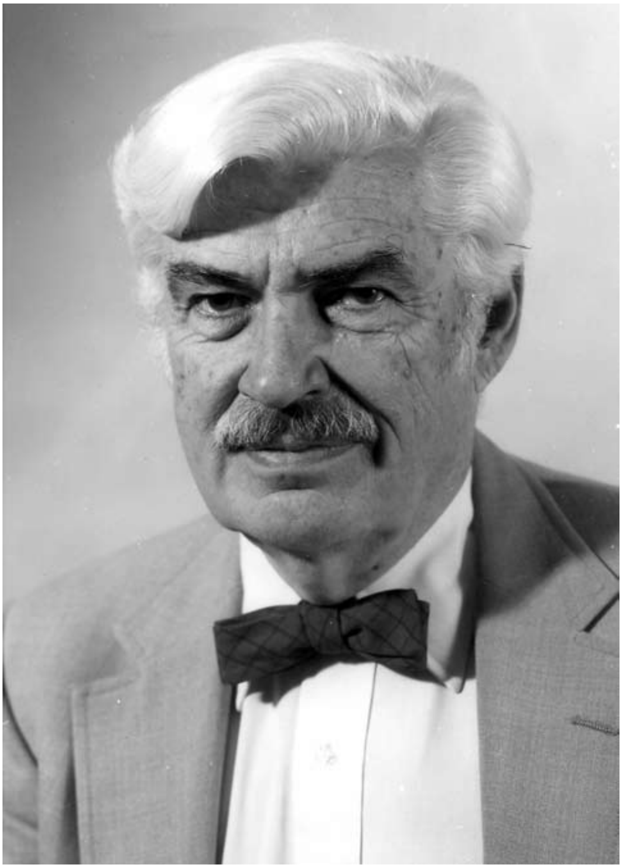

Robert V. Pound

# ROBERT VIVIAN POUND

*May 16, 1919—April 12, 2010*

BY NICOLAAS BLOEMBERGEN

SYNOPSIS

Robert Vivian Pound was born on May 16, 1919, in Ridgeway, Ontario, Canada. He obtained a B.A. degree from the University of Buffalo in 1940. At the age of 28 he became a member of the physics faculty at Harvard University without having obtained any graduate degree.

He retired as the Mallinckrodt Professor of Physics in 1989. He died at age 90 on April 12, 2010, in Belmont, Massachusetts.

The detection of nuclear magnetic resonance (NMR) spectra in condensed matter systems and the utilization of these spectra to determine the properties of the systems in which the nuclei are embedded have made NMR one of the most widely used analytical tools throughout the sciences. One application, magnetic resonance imaging (MRI), is used in every medical facility. Robert Vivian Pound, a creative and resourceful "hands-on" experimenter, was a co-discoverer of this tool, and he and his students made major contributions to the development of its many ubiquitous applications over the past half century.

Pound is best known for another remarkable experiment – the demonstration and measurement of the frequency shift of a gamma-ray photon as it moves up or down in the earth's gravitational potential – a shift that provides laboratory proof of the "equivalence principle" in Einstein's theory of general relativity.

His accomplishments have been recognized by numerous national and international awards and honors. This memoir describes some aspects of the life of this remarkable scientist and my interactions with him.

## THE EARLY YEARS, 1919 – 1946

Robert Vivian Pound was born in 1919 in Ridgeway, Ontario, Canada. His father moved the family in 1923 to Buffalo, New York, to assume the post of Professor of Mathematics at the University of Buffalo. Bob attended grade and high school in Buffalo, but this education made no significant mark on his development. Bob independently pursued his interest in radio already at the age of eight, and at the age of twelve he operated a ham radio. He wanted to learn more about the physics background and was not content with just being an "electronics-whiz-kid." He enrolled in the Electrical Engineering Department of the University of Buffalo in 1937 and earned some pocket money by assisting Professor Grant Hector by building an electronic circuit to measure the acoustic reverberation time in a lecture hall as a function of the size of the audience. This device was demonstrated at a meeting of the New York State Section of the American Physical Society. Pound finished his undergraduate studies in seven, rather than the usual eight, semesters and obtained his B.A. degree in December 1940. His professor suggested that he continue graduate studies at Columbia University in NYC, but Pound thought he could have more of an impact by participating directly in industrial radio research which was growing rapidly because of rising war threats in the United States.

In early 1941 Bob married a fellow student from the University of Buffalo. Her name was Betty Anderson, and she encouraged him to accept a laboratory job with the Submarine Signal Corporation on Atlantic Avenue in Boston. Bob arrived there in February 1941. “I was happy to have the opportunity to contribute to the technical side of the anticipated war effort and, thereby, to be less likely to become an ineffective foot soldier.” This is a direct quote from notes Bob wrote in 1985 about his participation in the discovery of NMR. Not long thereafter a key event for his further scientific development occurred. The newly established MIT Radiation Laboratory allowed three technicians from the Submarine Signal Corporation to attend lectures on microwave technology given by Dr. W. W. Hansen. These lectures made it clear to Bob that he should try to transfer, but transfer required approval of the Selective Service System. In April 1942 Bob officially became a staff member of the MIT Radiation Laboratory. There he met many of his future Harvard colleagues including professors J. Curry Street, Edward M. Purcell and Ken T. Bainbridge. The value of the combination of Bob’s intellectual powers and his “hands-on” laboratory expertise was recognized when he was promoted to group leader of the section working on microwave mixers. These devices are essential in the detection of radar signals. When the experimental work on microwave radars was terminated in December 1945, a group of selected researchers was asked to stay on for another six months to write a permanent record of the MIT Radiation Laboratory accomplishments. Bob Pound wrote volume 16 of the MIT Radiation Laboratory Series, called *Microwave Mixers*, published by McGraw Hill in New York City in 1948. Bob’s Harvard colleagues had already proposed him as a candidate for the Society of Fellows at Harvard University and he had been appointed as a Junior Fellow for a three year term starting in July 1945. He had then requested and been granted a one year leave of absence to finish his work on microwave mixers.

During the final year of the MIT Radiation Laboratory, discussion groups had already been formed of professors returning to academia in 1946. They addressed the question, what kind of research could be done with the new developments in radio and microwave technology.

Robert V. Pound had such discussions with Edward M. Purcell and Henry C. Torrey. They decided to attempt to detect NMR in condensed matter. NMR had been extensively studied in molecular beams at Columbia University, and I. I. Rabi had been awarded the 1944 Nobel Prize in Physics for this work. In December 1945 Purcell, Torrey and Pound succeeded in detecting the resonance of proton spins in paraffin at a frequency of 30 MHz in a magnetic field of about 7000 gauss. Pound had designed a 30 MHz resonator consisting of a section of capacitatively loaded coaxial transmission line. On the outside it looked like a brass cylindrical box about 10 cm high and 20 cm in diameter. The space between the inner and outer conductor was filled with paraffin. The resonator was placed in the gap of a large magnet which Professor J. C. Street had been using for cosmic ray research. The magnet was located in a wooden shed outside the Lyman Laboratory of Physics at Harvard University.

They communicated their results in a letter to the *Physical Review* in January 1946. Another letter appeared two weeks later from a group at Stanford University, consisting of F. Bloch, W. W. Hansen and M. C. Packard. The Stanford group called the phenomenon “Nuclear Induction.” Bloch had also worked in Cambridge, Massachusetts, during World War II, but in a group concerned with radar countermeasures that had been located at Harvard University. Purcell and Bloch met each other for the first time at the meeting of the American Physical Society, held in Boston in April 1946. They decided that their results were concerned with the same physical phenomenon of NMR. As group leaders, they jointly received the Nobel Prize for Physics in 1952.

I arrived in the United States in February 1946 and was accepted by Ed Purcell as his first graduate student. My first task was to fill the cavity with a muddy mixture of mineral oil and calcium fluoride powder. I witnessed the second experiment of Purcell, Torrey and Pound, in which they demonstrated both the proton and $F^{19}$ magnetic resonance. Pound was in charge of the electronics and Purcell managed the current in the electromagnet close to its maximum permissible value. Professor Torrey had provided theoretical background and information about earlier unsuccessful attempts by Professor C. J. Gorter in the Netherlands. He returned to his position of Physics Professor at Rutgers University in New Jersey soon thereafter.

### THE HARVARD YEARS, 1946-2010

While Bob Pound and Ed Purcell were still writing full time at the MIT Radiation Laboratory, I was building a lock-in amplifier and a low-frequency power amplifier to drive the modulation coils for the smaller electromagnet, built in 1905 by the Société Génévoise. It was available for the NMR experiments in a basement room of the Lyman Laboratory of Physics at Harvard University. I also built a radio frequency (RF) bridge with RF coils and tunable capacitors to replace the large 30 MHz resonator used in the first experiment. Our cylindrical samples now were smaller, about 2 mm in diameter and 10 mm long. They fitted inside an RF coil of seven turns which was placed in the magnet gap. The pole pieces of the electromagnet left a gap 2 cm wide, and about 20 cm in diameter. The current for the magnet was derived from a pack of truck batteries with a home-built rheostat of manganin tape in series. This equipment worked well enough that the NMR signal in water could be shown to I. I. Rabi, when he visited Ed Purcell at the time of the April 1946 meeting of the American Physical Society held in Boston.

We measured the width of the $F^{19}$ resonance in a single crystal of calcium fluoride. It followed the Van Vleck theory for dipolar broadening due to neighboring $F^{19}$ nuclear spins in a static simple cubic lattice.

It was obvious that the line width in liquid samples was narrower. When I mentioned to Bob Pound that I observed different widths on different runs, he immediately used his "hands-on" approach and systematically moved our RF coil with sample throughout the available magnet gap. It turned out that the "sweet" spot with the least inhomogeneity was located near the top edge of the gap. There the line width in liquids was about 0.1 gauss for our samples. This observation led to the idea of "motional narrowing" of dipolar interaction between nuclei undergoing Brownian motion. Ed Purcell, Bob Pound, and I had many discussions in the evenings in the basement room of the Lyman Laboratory in the fall of 1946. We used our index fingers, up or down, to denote the spin states $| +\frac{1}{2} >$ and $| -\frac{1}{2} >$ of the proton spins and pictured flip-flop, flip-flip and flop-flop processes induced by the dipolar interaction between moving nuclear spins. An experiment in hydrogen gas led to the concept of "pressure narrowing." Results were communicated at the American Physical Society meeting in January 1947 in New York City and in letters to the *Physical Review* in December 1946 and to *Nature* in 1947. A complete account was presented in the *Physical Review* in 1948 by N. Bloembergen, E. M. Purcell and R. V. Pound. It became one of the most cited papers in condensed matter physics and is often referred to as BPP. It describes the basic physics of relaxation effects in NMR.

The sharp resonances in fluids are the basis for molecular structure determination in chemistry and biology and for the medical imaging technique known as MRI. The contrast and resolution obtainable in MRI is based on differences in $T_1$ and $T_2$ (the characteristic times respectively for decay of the magnitude and rate of precession of magnetization) of bodily fluids in various tissues. Four medical experts—D. W. Robbie, E. A. Moore, M. J. Graves and M. R. Prince—wrote a book entitled *MRI, from Picture to Proton* published by Cambridge University Press, in 2003. They describe the medical pictures first and then trace history backwards to the basic physics of NMR.

Already in 1947 Bob had left the BPP triumvirate to pursue another device for measuring NMR. He constructed a tunable radiofrequency marginal oscillator. The resonance could be probed by changing the frequency rather than the magnetic field, as the output level of the oscillator would change at resonance. The device is described in an issue of the *Review of Scientific Instruments* in 1950 in a paper co-authored with W. D. Knight, who had independently worked at the University of California in Berkeley on a similar design. The device became known as the "Pound box" and was used in many NMR laboratories, including my own, during the fifties and sixties. In 1950 Bob wrote a comprehensive paper on quadrupolar interactions in crystals, based on results obtained with the "Pound box."

When Bob Pound's term in the Society of Fellows ended in July 1948, he was appointed to an assistant professorship in the Harvard Physics Department. He became a Harvard faculty member without ever having obtained a Ph.D. degree, nor a master's degree for that matter. Clearly, his book on microwave mixers was of higher caliber than most Ph.D. theses. He became a tenured professor of physics a few years later.

In 1951 Bob obtained a nuclear spin system with a negative temperature, where the magnetization is antiparallel to the magnetic field. It was accomplished in a lithium fluoride crystal by switching the magnetic field instantaneously, i.e. in a time much shorter than $T_2$ from +10 gauss to -10 gauss. When the external field $H_0$ is smaller than the internal dipolar field, the behavior of the nuclear spin systems is determined by the Hamiltonian of the nuclear dipolar interactions. Changes in the nuclear spin systems then occur at a rate of the dipole-dipole relaxation time $T_2$, which in the crystal used is on the order of microseconds. If the external field $H_0$ is reversed in such a manner that the time period when it is smaller than the dipolar field is less than $T_2$, the state of the nuclear spin system is not changed. Thus the nuclear spin magnetization becomes antiparallel to $H_0$ after such a sudden reversal. It can be described by a negative spin temperature. It takes a spin-lattice relaxation time $T_1$ on the order of seconds or minutes for the crystal used, to revert to thermal equilibrium at the positive crystal lattice temperature. There is thus plenty of time to observe this relaxation in the NMR signal, provided the external field $H_0$ is kept large compared to the internal dipolar fields after the sudden reversal. It is a rather unique manifestation of instantaneous and adiabatic changes in the external parameter $H_{0.}$ In the inverted or negative temperature state, the absorption is negative, and the signal shows stimulated emission. A joint paper by E. M. Purcell and R. V. Pound in the *Physical Review* (1951) describes the negative temperature situation. This result is an important forerunner of maser action developed in the mid-fifties at microwave frequencies. Pumping schemes were then developed to obtain inverted population or negative temperature situations in the steady state.

In the fifties Pound co-authored a paper with Anatole Abragam from Paris who spent the year 1952 at Harvard.

Abragam later wrote the NMR bible *Principles of Nuclear Magnetism* Oxford University Press 1960 and a second edition appeared in 1983. I also enjoyed co-authoring a 1954 paper with Bob on "Radiation Damping in Nuclear Magnetic Resonance."

Pound's most spectacular experiment was the verification in a laboratory setting, of the equivalence principle in Einstein's theory of general relativity. It was carried out in 1959 and 1960. Bob had the insight and experimental skill to use the Mössbauer effect to measure the shift in frequency of a gamma ray, as it moved up or down in the gravitational potential of the earth. The fractional shift in frequency over a height differential of 23 meters is only $2.3 \times 10^{-15}$. The Mössbauer effect of the $Fe^{57}$ isotope involves a 14.4 kev gamma ray with a life time of about $10^{-7}$ seconds. The expected gravitational shift is about 0.1% of the line width. It is detected by reference to the Doppler shift of a slow moving $Fe^{57}$emitter or absorber. Pound knew that the Jefferson Laboratory contained a vertical shaft extending from a tower on the roof to a basement room. More than a century ago, Professor E. Hall had used the shaft, which provided a 23 meter height differential, to detect a Coriolis-type force. Bob performed the critical experiments with a graduate student, Glen A. Rebka, Jr., who went on to become a Professor of Physics at the University of Wyoming. Pound and Rebka published four short papers in *Physical Review Letters* in 1959 and 1960. They demonstrated the necessity of treating the thermal motion of $Fe^{57}$ nuclei accurately. Differences in the second order Doppler shift for an absorber and emitter whose temperatures differed by a degree produce a shift as large as the general relativistic effect. At the time there was a fierce competition with another group, working at the Harwell Atomic Energy Research Establishment in England, which, it emerged, had failed to recognize and account for the second-order Doppler effect in their contemporaneous experiments.

Pound published his own extensive memoir about "Weighing photons" in 2000 and 2001. This historic account contains correspondence with Professor Mössbauer and many others. The Royal Astronomical Society in London awarded Pound the Eddington Medal in 1965 in recognition of this experiment. He was also elected to the National Academy of Sciences in 1961 and to the Academie des Sciences in Paris as correspondant in 1975 and "Associé étranger" in 1978. In 1990, he was awarded the National Medal of Science by the President of the United States.

He served as chairman of the Harvard Physics department and kept an active interest in matters of physics education. He did not agree with the Harvard policy of the Core Curriculum that required a certain distribution of courses. He felt that the bright students admitted to Harvard should be allowed to choose their own courses as he had done himself in his formative years.

Bob spent his sabbatical leaves with colleagues in the USA and abroad. He spent time in Paris with Anatole Abragam, in Oxford with Brebis Bleaney and in The Netherlands, with H. de Waard. He served for many years as a trustee of Associated Universities, Inc., which ran the Brookhaven National Laboratory on Long Island, and runs the National Radio Astronomical Observatories. He retired as Mallinckrodt Professor Emeritus from Harvard in 1989, at the then mandatory age of 70.

On the personal side I remember him as a modest and helpful person. I learned a lot from him in my early years at Harvard. I liked his "hands-on" attitude, to solve the daily "annoyances" and "contretemps" of laboratory work, which occur both in electronic and mechanical problems. He told his students "sometimes you just have to whack it."

He was usually dressed as an English gentleman with a jacket, bowtie and a neat moustache. His contact with colleagues, students and service personnel was always correct, often cordial and intellectually stimulating. Yet both he and his wife Betty treasured their privacy.

He loved British motor cars. In the forties he had a small Hillman Minx. Forty years later, Bob told the story of its demise at an after-dinner talk in Tallahassee, Florida. The occasion was the retirement of Professor E. R. Andrew. Bob and I knew him when he was a post-doc at Harvard in 1948. He is known in NMR for his method of "magic angle" spinning to obtain narrower resonances in solids. Bob and Betty had set out on a transcontinental trip in 1949 in their Hillman Minx. It gave up the ghost on a steep slope in the Rocky Mountains. In the seventies Bob and I served on a scientific advisory committee for the United Technologies Research Center in East Harvard, Connecticut. Bob gave me a ride to the meeting in his luxurious Jaguar. He tried in vain to convince me of the advantage that this vehicle boasted two separate gas tanks.

Bob had to spend the last years of his life in a nursing home in Belmont, Massachusetts. He suffered a series of strokes. The immediate cause of his death on April 12, 2010 was pneumonia. He is survived by his wife Betty, their son John and two grandchildren.

I am indebted to his colleague Professor Paul Horowitz at Harvard, who was also one of Pound's graduate students. He wrote an obituary for R. V. Pound in *Physics Today*, published September 12, 2010, and supplied much additional information for this memoir. I also acknowledge helpful comments of another Harvard colleague, Paul C. Martin.

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