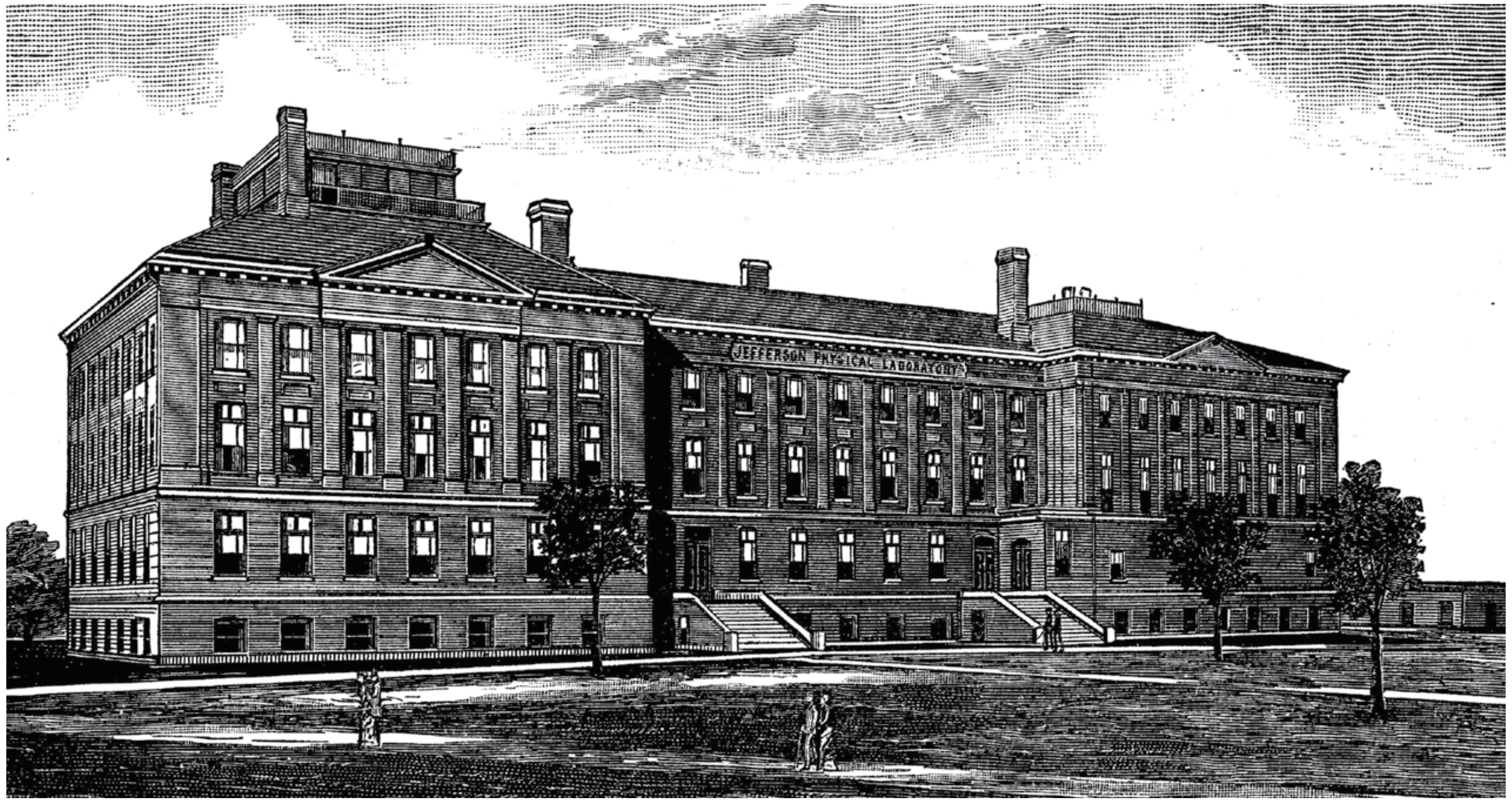

FOCUS

Nuclear Magnetic Resonance: Lyman Laboratory, December 1945

by Paul Horowitz

Seventy five years ago, in the chilly "cosmic-ray shed" that extended from the first floor of Lyman Laboratory, three physicists observed, for the first time, the gentle resonance of protons in a paraffin sample. Thus was born nuclear magnetic resonance (NMR), the basis of the astonishingly successful contemporary tool of medical MRI. The story of NMR is rich with human ingenuity, chance encounters, and good luck.[1] Some of us had the wonderful good fortune to study with two of those, who generously shared their memories; and much of the history has been captured in the oral history archives of the American Institute of Physics[2].

It was December 15, 1945 — exactly four months after Japan's capitulation in the war in the Pacific — and Robert Pound, Edward Purcell, and Henry Torrey had been seeking the elusive resonance since the idea came up in a happenstance lunch while the three were wrapping up their work at the MIT Radiation Lab (the wartime radar project, energized by the British invention of the powerful cavity magnetron). Purcell asked, "Why couldn't one do the Rabi-type of proton resonance in solids?" The resonance frequency in a given magnetic field was known from Rabi's work with molecular beams at Columbia University, but the amount of time for the nuclear spins to equilibrate (what we now call "the spin-lattice relaxation time," T_1) was anyone's guess. Their best guess was a few hours, during which the sample had to sit, undisturbed, in the magnetic field. As Pound described it, "Ed agreed to come in around seven in the morning on Saturday and turn the magnet on and let it cook until we would come in."

They spent the rest of the day (as in the days before) in fruitless pursuit, slowly varying the magnet current through the expected value. But late in the day Pound suggested, in desperation, "why don't we just turn the magnet all the way up?" And as we came down through 80 amperes it went bump. There it was." They had expected it at 73 amperes, and had earlier swept nearly plus and minus 10 percent. They hadn't miscalculated, they simply had not realized that the magnet was close to saturation; as Pound eloquently put it, "we were only off 2% in the calibration, which is pretty good for that kind of system [flip-coil plus galvanometer], but it took 15% more current to get that 2% more field." Amusingly, their estimate of the relaxation was considerably more in error: as Purcell put it, "in the final time when the experiment was successful, I had been over here ... it must have been all day, nursing the magnet generator along so as to keep the field on for many hours, that being in our view a possible prerequisite for seeing the resonances. Now, it turned out later that in paraffin the relaxation time is actually 10^{-4} seconds. So I had the magnet on exactly 10^8 times longer than necessary!"

The field moved quickly after that: within a month Felix Bloch[3], William Hansen, and Martin Packard at Stanford University, not knowing of the Harvard work, succeeded in their NMR; and in Cambridge the arrival of Nicolaas Bloembergen advanced the theoretical underpinnings of NMR, most famously with their 34-page 1948 *Phys. Rev.* paper, "Relaxation Effects in Nuclear Magnetic Resonance Absorption" (one of the most-cited articles in physics, ever), familiarly known as "BPP" (Bloembergen, Pound, and Purcell). The "BPP Theory" addressed the effects of molecular motions in the NMR relaxation time and resonance width.

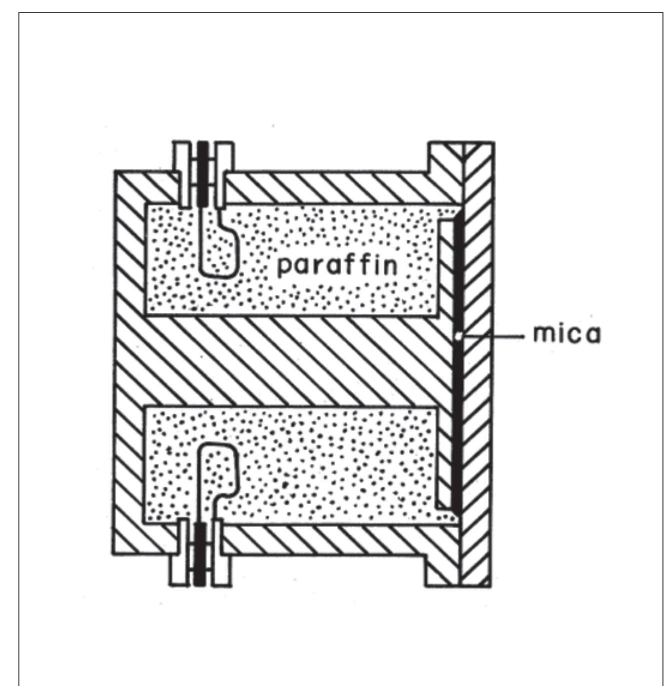

Fig. 1. NMR was first seen in this resonant cavity, filled with paraffin obtained from the First National Store on Purcell's way to work. (leftover wax in original box courtesy of Pound)

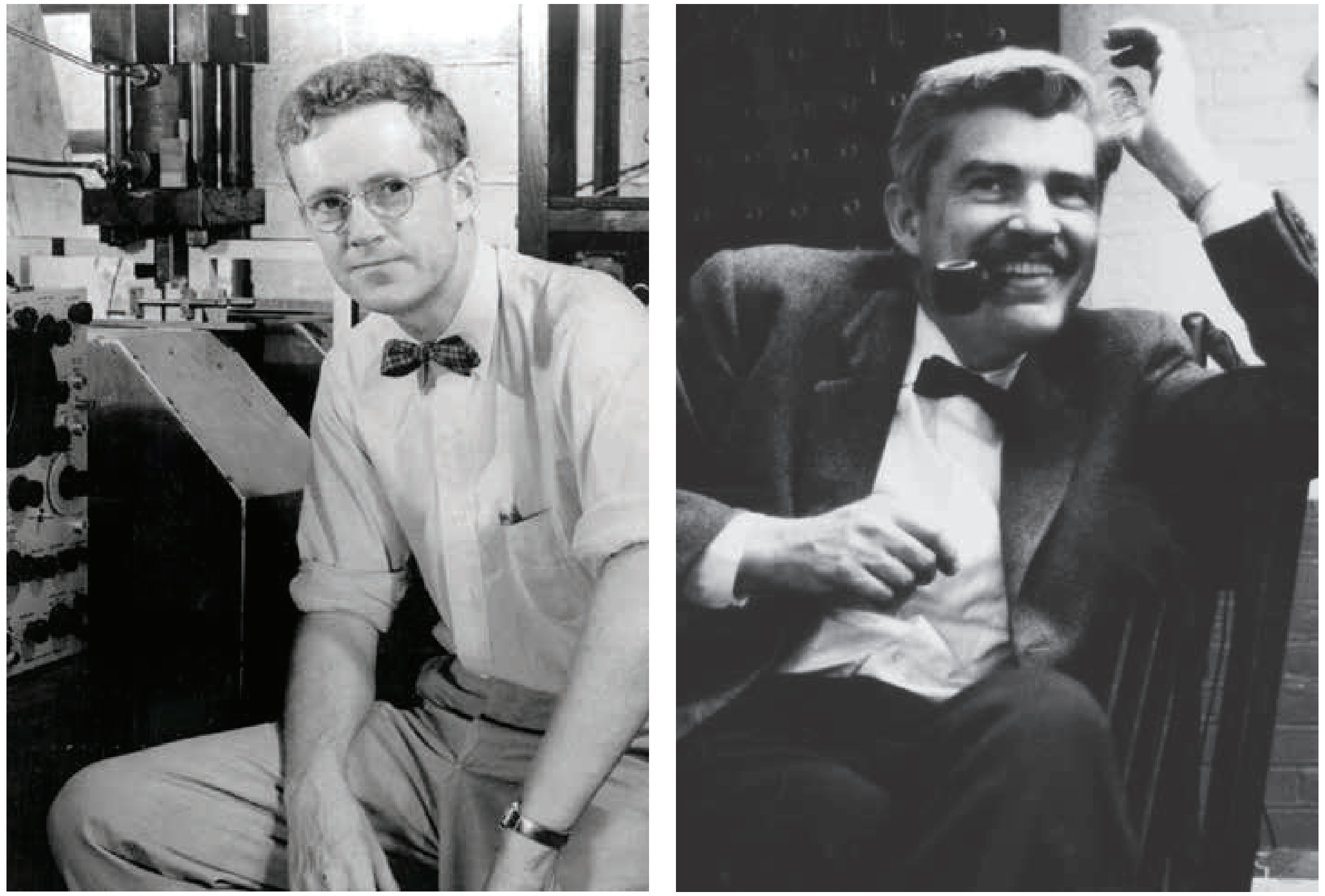

Fig. 2. Purcell (sleeves rolled up) and Pound (with pipe), in their labs, both with their characteristic bowties.

We like to think of the NMR as a Harvard Physics discovery; but it could have been an MIT discovery, Purcell remarked, were it not for the fact that "I tried to borrow a magnet down at MIT and did not succeed. That's why we had to come back and do it here. We would have done it down there if somebody had given us [a magnet]." And MIT might have another claim, because the discovery was made while they were moonlighting from their official employment at MIT (documenting their microwave technology in the legendary 28-volume "Rad Lab Series"[4]). In fact, much of the apparatus was leftover radar gear. Happily, it was Curry Street's cosmic-ray magnet[5] that was available, and the rest is history (as was the elevation of Pound and Purcell to professorships in our department).

NMR matured rapidly — with improved resolution it became a standard tool of analytical chemistry and structural biology, revealing the local molecular environments through "chemical shifts." But perhaps the application with the most impact was the development, beginning in the 1970s, of MRI[6]. This remarkable non-ionizing medical diagnostic tool produces stunning three-dimensional images, enhanced by contrast mechanisms that exploit proton density and differences in relaxation times to reveal subtle details of soft tissue. More than a billion scans have been performed, and it is no exaggeration to say that more than a million lives have been saved by MRI.

Quite apart from the satisfaction that the discoverers must have felt from these practical applications of NMR, the discovery itself was something very special. As Purcell put it in his 1952 Nobel lecture, "I have not yet lost a feeling of wonder, and of delight, that this delicate motion should reside in all the ordinary things around us, revealing itself only to him who looks for it. I remember, in the winter of our first experiments, just seven years ago, looking on snow with new eyes. There the snow lay around my doorstep — great heaps of protons quietly precessing in the Earth's magnetic field. To see the world for a moment as something rich and strange is the private reward of many a discovery."

With Thanks:

The author wishes to thank the Harvard University Archives, the Collection of Historical Scientific Instruments, Gerald Holton, Peter Galison, and Marina Werbeloff for assistance. On a personal note, I am forever grateful for the education I received in the footsteps of Bob Pound and Ed Purcell. Their contribution to human welfare was brought home to me memorably this year, as I succumbed to a bout of severe spinal stenosis (vividly imaged by Figure 3's MRI, which informed a successful surgical intervention). It was an honor to know these fine gentlemen.

References:

1. Oddly, though, not a single photograph of the experiment seems to exist — a stunning contrast with our over-photographed world of today.

2. https://www.aip.org/history-programs/niels-bohr-library/oral-histories. All quotations are from these transcripts unless noted otherwise.

3. Bloch and Purcell, respective leaders of the two groups, shared the 1952 Nobel Prize in Physics. Bloch invited the Harvard group to join in a patent, but Purcell declined, evidently feeling that fundamental discoveries in physics should be openly shared. The Stanford group filed their patent application on December 23, 1946, one day short of a year after the Harvard group's paper had been received at *The Physical Review*.

4. Prefaced with "The tremendous research and development effort that went into the development of radar and related techniques during World War II resulted not only in hundreds of radar sets for military (and some for possible peacetime) use, but also in a great body of information and new techniques in the electronics and high-frequency fields. Because this basic material may be of great value to science and engineering, it seemed most important to publish it as soon as security permitted." It is undisputable that their work with radiofrequency and microwave techniques contributed greatly to their ability to build the necessary NMR apparatus. As Pound relates, "[the choice of paraffin] was automatic for us, and there were two reasons. One is ... that it had all those protons; the other is because we were much involved in microwave spectroscopy, so we knew that paraffin had about the lowest electromagnetic absorption by ordinary dielectric laws, of anything going, you see. Paraffin was an extremely good dielectric, as we call it." Following this "swords into plowshares" thread a bit further, a good case can be made that the wartime radar project spawned the post-war inventions of the transistor, molecular spectroscopy, and the maser/laser; see, for example, Robert Buderi's *The Invention That Changed The World* (Touchstone, 1996) and Peter Galison's *Image and Logic* (Univ. of Chicago, 1997); Chapter 4 of the latter is titled "Laboratory War: Radar Philosophy and the Los Alamos Man," while the former follows the MIT Rad Lab radar project's influence on post-war science and technology.

5. The same magnet used in Street and Stevenson's 1937 confirmation of Anderson and Neddermeyer's observation of the muon (J.C. Street and E.C. Stevenson, "New Evidence for the Existence of a Particle of Mass Intermediate Between the Proton and Electron," *Phys. Rev.*, 52, 9, 1003).

6. Unanticipated even by NMR's inventors: in the Foreword to *Magnetic Resonance Imaging* (Partain et al., Saunders, 1988) Purcell wrote "NMR imaging is so powerful, so general, and at the same time so gentle a diagnostic procedure that it is likely to become part of most people's experience. That seems obvious now, even to an antiquated NMR expert like myself who did not foresee it."

Fig. 3. MRI is good for finding bad things like this in your spine.