Purcell's role in the discovery of nuclear magnetic resonance: Contingency versus inevitability

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An account of the discovery of NMR at Harvard in 1945 is presented. It is based on an interview with one of the main participants, E. M. Purcell, and focuses on his role in the discovery. The account also puts the discovery in the context of Purcell's previous experiences, particularly his wartime work at the MIT Radiation Laboratory.

I. INTRODUCTION AND BACKGROUND ON THE PHYSICS OF NMR

In the winter of 1945, Edward M. Purcell, Robert V. Pound, and Henry C. Torrey discovered nuclear magnetic resonance (NMR) at Harvard. About a month after their discovery Felix Bloch, William Hansen, and Martin Packard independently discovered NMR at Stanford. NMR was to have far-reaching physical, chemical, and medical applications and to earn Purcell and Bloch Nobel Prizes.

Here an account of the NMR discovery is presented which is based on an interview with Purcell[1] and which focuses on his particular role in the discovery. It is not meant to be definitive, and other accounts of the discovery of NMR have been published, particularly by Rigden.[2]

Immediately before the 1945 discovery, Purcell worked at the MIT Radiation Laboratory in a wartime radar development project. Although NMR and radar are distinct in terms of physics, Purcell's wartime experiences are intimately related to his peacetime discovery. So after the account of the discovery is presented, three particular ways the Rad Lab influenced Purcell will be described. Throughout the discussion, particular care will be taken to show how, on one hand, the discovery fits seemingly inevitably into Purcell's personal and career development while, on the other hand, it was contingent on particular "lucky" events.

Before beginning an account of the NMR discovery, it is worthwhile summarizing some of the physics underlying NMR.[3,4] A proton has intrinsic angular momentum, or spin, about an axis and a magnetic moment associated with this spin. When it is placed in a magnetic field, a component of the spin points either parallel or antiparallel to the magnetic field with magnitude $h/4\pi$. These two spin orientations form a two-level system: i.e., a system that has two states and a definite energy difference, or splitting, between them. Here, the antiparallel orientation has the higher energy. Photons with the same energy as the splitting, which are said to be at the resonance frequency of the system, can cause transitions between the states. The resonance frequency, in turn, depends on the strength of the magnetic field and lies in the radio-frequency region of the spectrum (about 30 MHz) in a relatively strong magnetic field (about 7000 G).

When a bulk sample of protons is first put into a magnetic field, it is expected to have an equal population of parallel and antiparallel spins. Radio waves at the resonance frequency would then be expected to have an equal chance of causing energy absorbing transitions (from a lower to a higher state) as energy emitting transitions. However, after a certain time, called the relaxation time, the sample of protons will attain thermal equilibrium with respect to the magnetic field.[3] At equilibrium, there will be a difference in population between the two orientations. As more protons will have the lower-energy parallel orientation, a radio signal at the resonance frequency will cause more upward transitions and, in net, be absorbed.

II. AN ACCOUNT OF THE DISCOVERY OF NMR AT HARVARD

During World War II, Purcell, Pound, and Torrey were members of the MIT Radiation Laboratory, henceforth referred to as the Rad Lab, where they worked developing better radar for the military. Their war work was primarily of an "engineering" nature: Purcell became an expert on microwave circuits; Pound, an authority on microwave mixers; and Torrey, a specialist on crystals. However, all three were physicists by inclination and training and wanted to resume "pure" scientific research as soon as the war ended.

Shortly after the end of the war in August 1945, Purcell, Pound, and Torrey got together at a restaurant on Massachusetts Avenue in Cambridge for lunch. The Rad Lab was closing, and Purcell, Pound, and Torrey remained there only to contribute reports to a 28 volume series on the advances made during the war.[5] It was a hot summer day and their discussion turned to possible areas of postwar research. Purcell brought up the idea of using a magnetic field to split the energy levels of a hydrogen nucleus (i.e., a proton) and using a resonance frequency of a radio signal to measure the nuclear magnetic moment of a proton. His scheme hinged on being able to detect the absorption of the radio signal at resonance. Torrey was skeptical, for he thought that the difference in population between the two energy levels would be so small that the energy absorbed from a normal radio signal would be minuscule. That night Torrey went home and did some calculations, which showed that the signal could perhaps be detected after all. The next day he came into Purcell's office and told him the news. Soon afterwards Purcell enlisted Pound and Torrey in the project, and all three set out to detect the absorption.

The first order of business was to assemble the apparatus necessary to carry out the experiment. In particular, they needed to get a magnet strong enough to split the energy levels. Purcell initially wanted to used the one in the MIT cyclotron, but the MIT authorities were not too enthusiastic about this. Their frugal attitude was quite a change from the generosity of the Rad Lab administrators during the war. Purcell then managed to persuade J. Curry Street to let him use the magnet with which Street had discovered the muon in 1937 at Harvard.[6] From Harvard, Purcell, Pound, and Torrey also obtained a signal generator from the psychoacoustic lab.[7] From MIT, they procured a metal cavity from the Rad Lab workshops, filled it with two pounds of paraffin (850 cm^3), purchased at a First National grocery store, and put the cavity between the poles of Street's magnet.[1,8] The hydrogen atoms in the paraffin provided a supply of protons, and Street's magnet created the energy difference between the parallel and antiparallel spin orientations. All Purcell, Pound, and Torrey needed now was radio waves at the resonance frequency.

To obtain these waves, they connected the cavity to a circuit driven by a radio-frequency signal generator. The circuit, called a bridge circuit, was especially sensitive to small changes in signal intensity. Their apparatus was now complete, and the three began to look for the absorption. Their first attempts to detect the signal failed, but they continued their work and concentrated on two aspects of their procedure and apparatus. First, they kept the paraffin in the magnetic field for longer and longer times. They were worried that the relaxation for the protons in the paraffin was very long, more than 1 h, and in some trials they kept the paraffin in the field for up to 10 h.[2] Second, they tried to improve the uniformity of the magnetic field. Protons in different regions of a nonuniform field have their energy levels split slightly differently and consequently have different absorption frequencies. Improving the uniformity of the field makes the signal absorption narrower and more prominent.

In the midst of this work to detect the absorption signal, Purcell, Pound, and Torrey heard of the work on the same project that C. J. Gorter had carried out in Leiden in 1942.[9] Because of restrictions on communications resulting from the war, it was fairly difficult to obtain Gorter's paper, and they had to settle for reading it on microfilm. Gorter's results were disheartening, for he had tried an experiment similar to that of Purcell, Pound, and Torrey and could not detect an absorption. However, the three felt that by keeping the paraffin in the magnetic field for a very long time and by making the field very uniform, they could overcome Gorter's difficulties. Continuing their trials, they varied the magnetic field by adjusting the current flowing into the magnet with a rheostat. They assumed that the magnetic field was proportional to the current, and based on this assumption, they sent radio signals of a constant frequency into the cavity and varied the magnet current to get resonance.

Yet, they still were not able to detect the signal after many trials with their modified apparatus. In Purcell's words: "We were about ready to give up...But we said...Before we turn off let's go clear up to the top. So we cranked the rheostat up to the maximum possible current and looked down [at the meter]. And by God, the needle went like that [At this point Purcell makes a wave-like gesture with his finger.]"[1] It so happened that the currents they were using were large enough to saturate the iron magnet, and this saturation invalidated their assumption about the proportionality between the current and the magnetic field intensity. The resonance occurred just beyond the range of magnet currents they had been looking at. Purcell, Pound, and Torrey repeated the experiment a number of times and discovered to their surprise that the anticipated proton relaxation time of a few hours was, in fact, much shorter. Later measurements placed its value at a few milliseconds.

With this result and the measurement of the magnetic moment of the proton, Purcell, Pound, and Torrey wrote up their findings sent them to the *Physical Review*.[8] Their paper was received on the day before Christmas 1945, about a month before Bloch, Packard, and Hansen's paper, reporting similar findings.[10]

III. INEVITABILITY VERSUS CONTINGENCY

Reflecting on the experiment, Purcell describes it as a novel synthesis of sure principles that produced the anticipated outcome. "The ingredients [of the experiment] are the law of physics, well-established things: the proton has a magnetic moment; I put on a magnetic field and the energy is so and so; I put on an oscillating field at the right frequency and it absorbs. Each one of these, by that time, was a well-established law of physics. If I put them all together, and if I haven't forgotten anything, it has got to do what the laws tell it to do...If it had not worked, that would have been a real discovery!"[1] The confidence that Purcell exudes about the laws of physics gives a sort of inevitability to the outcome of his experiment. This inevitability should be tempered by considering the many contingencies that were present in the preceding account of the experiment.[11]

In changing one's perspective from the five-month course of the discovery to the many years of Purcell's career, the same tension between contingency and inevitability reappears. Looking at some of the details of Purcell's life, one is immediately impressed with the seemingly inevitable progress of his career. He was born in 1912 in Taylorville, a small town in Illinois. As a youth in Taylorville and Mattoon, Illinois he did not have any "role models" of physicists to emulate. Nevertheless, as an undergraduate engineering major at Purdue University, he became interested in physics,[1] and through the kindness of K. Lark-Horovitz, the newly arrived chairman of the Purdue physics department, he was able to study modern physics in an independent laboratory course. If fact, as a college senior, he participated in experimental research in electron diffraction, which had only been discovered 5 years earlier by Davisson and Germer at Bell Labs.[7,12] Once he had committed himself to physics, he soon made significant contributions. His work at the Radiation Laboratory led to his coauthorship of a 1948 book on microwave circuitry.[13] His discovery of NMR in 1945 with Pound and Torrey was soon followed by many papers unraveling the intricacies of the relaxation effects and applying the technique to study molecular structure.[14] In 1951 he became involved in radio astronomy and found the 21 cm line in the galactic spectrum with Harold I. Ewen.[15] And in 1965 he condensed much of his expertise in electricity and magnetism into a classic textbook.[16] As he made these contributions to physics, he progressed through a sequence of academic positions and awards: a fellowship to Germany after graduating from Purdue in 1933, a physics doctorate from Harvard in 1938, head of the Fundamental Developments Division of the Radiation Laboratory during the war, Professor of Physics at Harvard in 1949, Nobel Laureate in 1952, University Professor in 1960, Member of the President's Science Advisory Committee in the 1960's, and recipient of the Oersted Medal for Physics Education in 1968.

Surveying these details of Purcell's career one cannot help noticing the seeming inevitability with which he ascended from modest rural upbringings to become one of the most eminent members of the natural-sciences community. However, a closer look at his life reveals the essential contingency in the sequence of events. In particular, his codiscovery of NMR in the winter of 1945 was closely connected with his previous experiences at the MIT Radiation Laboratory. The aspects of the Rad Lab that had the greatest influence on Purcell can be grouped into three categories: Rabi and his associates, the technical achievements made at the Rad Lab, and the problems there that forced Purcell to learn about two-level systems.

IV. RABI'S INFLUENCE ON PURCELL

At the Rad Lab, Purcell was in charge of group 41: Fundamental Developments. His direct superior was Isidor I. Rabi, the associate director for scientific research at the laboratory.[17,18] When he came to the Rad Lab, Rabi was already a well-established scientist. In fact, in 1944 during his stay at the Rad Lab he won the Nobel Prize for work he had done before the war.

Rabi's work was an outgrowth of the original Stern–Gerlach molecular beam experiments. The first Stern–Gerlach experiment was done in 1922.[4,19] It consisted of sending a collimated beam of silver atoms through an inhomogeneous magnetic field. According to the classical physics of Maxwell, the beam should be smeared out as the silver atoms are pushed towards or away from the region of high field in proportion to how aligned their magnet moments are with the field. However, in the Stern–Gerlach experiment the beam splits into two distinct parts. This splitting demonstrated that the magnet moment (and consequently the angular moment) of an atom is quantized. Later, by relating the degree of the beam splitting to the magnetic field strength and the velocity of particles in the beam, Stern extended this work to measure magnetic moments.

Rabi visited Stern's lab in 1927 and left with vivid memories of the elegant simplicity of the Stern–Gerlach experiment.[19] There were, however, many aspects of Stern's apparatus that were hard to control and lead to imprecise results. For instance, it was hard to measure the magnitude of the inhomogeneous field, and the split beams were always smeared out because of the Maxwellian velocity distribution of the molecules in the original, collimated beam. In the 1930s Rabi began doing molecular beam experiments similar to Stern's in his laboratory at Columbia University, and over the course of the decade Rabi improved the Stern setup in three stages.[4,19,20] First, to the original inhomogeneous magnetic field (the A field) he added another inhomogeneous magnetic field (the B field) directed in the opposite direction. The molecular beam would transverse the B field after the A field, and the B field reversed the splitting caused by the A field and focused the beam back through a slit. Second, Rabi introduced a third field, the T field, between A and B fields. The T field was spatially distributed in such a way that to a moving molecule it appeared to be rotating. This "rotating field" would sometimes flip the spin of the molecule, and when this happened the molecule would not be refocused through the slit by the B field, so when applied to the whole beam, the T field could change the number of molecules going through the slit.

In 1938 Rabi introduced his most important innovation. He replaced the T field by a radio-frequency oscillating magnetic field superimposed on a constant magnetic field (the C field).[19] When the oscillating field is at the proper frequency—i.e., the resonance frequency—it induces transitions between the states with magnetic moments parallel and antiparallel to the constant C field. By measuring the resonance frequency field Rabi and his co-workers could determine precisely the magnitude of the proton magnetic moment. This final method is called the magnetic-resonance method. It is the link between Stern's original experiments in the twenties and Purcell's work in forties. Viewed in this historical perspective, it is evident that Purcell, Pound, and Torrey's codiscovery of NMR was an outgrowth of Rabi's work. It is also evident how incredibly simple and elegant their experiment really was: they drastically simplified Rabi's apparatus by removing the unnecessary A and B fields and generalized it to allow for motionless samples not in a molecular beam.

When we came to the Rad Lab in January of 1941, Purcell "had no idea about this [work that Rabi had done],"[21] but over the next 4 years he frequently came in contact with Rabi and even accompanied him on a trip to England.[7] Moreover, many of Rabi's co-workers at Columbia, such as Sidney Millman, Norman Ramsey, and Jerrold Zacharias were at the Rad Lab.[7] Henry Torrey, in fact, received his doctorate working with Rabi. According to Purcell, "In the course of knocking around with these people, I had learned enough about what they had done in molecular beams to begin thinking about what we can do in the way of resonance."[7] It is thus apparent that Purcell's contacts with Rabi and the Columbia molecular beam people were partly responsible for his interest in NMR and the 1945 experiment. However, Purcell's ideas were not Rabi's. In fact, when Torrey told Rabi the plans for the 1945 experiment, Rabi scoffed at the setup and predicted that it would fail.[1]

Like Rabi, Bloch, the leader of the Stanford group that codiscovered NMR also spent his war years in Cambridge. He worked on radar countermeasures in the Harvard physics building within meters of Purcell's postwar office and lived in North Cambridge within a few blocks of Purcell's home. Yet Bloch only met Purcell once, at a party celebrating Rabi's Nobel Prize in 1944. This is especially ironic considering that Bloch knew Rabi as well as Purcell.[2,7] Thus by a twist of fate, two possible collaborators never got to know each other despite geographic proximity, common friends, and obviously common interests.

V. THE TECHNICAL PROGRESS MADE AT THE RAD LAB

A second factor that greatly influenced Purcell was the technical progress made with microwaves at the Rad Lab. The expertise he gained there proved to be a valuable source of ideas for the NMR experiment. At the beginning of World War II in their Chain Home early warning stations, the English employed radar sets that operated with wavelengths around 1300 cm and produced 200 kW pulses for 1.5 ms.[22] In early 1940 John T. Randall and Henry A. Boot invented the cavity magnetron while they were working in Oliphant's laboratory in Birmingham.[22] The cavity magnetron was a revolutionary source of microwaves. It could generate 1 ms pulses with a power of 10 kW at a wavelength of 10 cm. The Tizard Mission of September 1940 brought the cavity magnetron to American, and this invention to a great degree lead to the creation of the Rad Lab that fall.[17] Working in and on the roof of building 4 at MIT, Rad Lab physicists worked throughout the war to make the microwave radar based on the cavity magnetron more accurate and sensitive. To increase its resolution, they steadily decreased the microwave wavelengths used from the 10 cm S band to the 3 cm X band and finally to the 1 cm K band. To increase its sensitivity, they boosted the power of the magnetron and built very sensitive mixers and amplifiers to detect weak signals. By the end of the war their radars could send out megawatt pulses and detect echoes of only 10^{-13} W.

After the war the technical progress made in manipulating microwaves paid off rich dividends in such research areas as microwave spectroscopy. However, since NMR takes place in the radio-frequency range of the spectrum, which was fairly well developed in the 1930s, it did not benefit directly from the Rad Lab advances in the microwave region. Nevertheless, it is still possible to identify two major effects of the Rad Lab work on Purcell's NMR experiments. The first and most direct effect was the greater understanding of the relationship between signal and noise. At the Rad Lab, George Uhlenbeck and Jim Lawson did much of this work,[7] developing techniques to extract extremely weak signals from the background noise. In the interview Purcell underscored the importance of these techniques, "One of the most useful things we learned at the Rad Lab was the idea of signal to noise and how to calculate it."[21] Furthermore, he noted that Pound's "crucial contribution" to the 1945 discovery was his knowledge of amplifier noise.[1,7]

Second, on a more nebulous, but still important, level, Purcell's war work at the Rad Lab gave him such a great facility with microwaves that he could not help applying them to his 1945 NMR work. For instance, recollecting the design of his apparatus, he said, "Designing the thing as a big resonant cavity was really a heritage from our microwave past. But we were not working at microwave frequencies, but at 30 MHz. It was just the point of view of coming from microwaves where everything was metal cavities and tubes."[1] Purcell, Pound, and Torrey elected, moreover, to center their work around 30 MHz because narrow bandwidth amplifiers at this frequency were readily available at the Rad Lab.[2]

VI. THE *K*-BAND CATASTROPHE AT THE RAD LAB

The third, and perhaps most important, experience Purcell had at the Rad Lab that had an impact on his NMR experiment was the *K*-band catastrophe. The scientists at the Rad Lab would often test their equipment by observing various buildings in Boston and Cambridge using radar mounted on the roof of an MIT building. Popular targets were initially the dome of the Christian Science Center, on the other side of the Charles River from MIT, and later a water tower, some 10 km away.[21] When sufficient progress had been made on the 3 cm *X*-band units, it was decided to switch to a shorter *K*-band wavelength. Purcell "well remember[ed] the meeting at Columbia" that the attended where the decision was made to standardize the *K*-band wavelength at 1.25 cm.[1] After the standardization, they rapidly made progress on the *K*-band components, but for no apparent reason they were able to detect less and less. Even more surprising, the sensitivity and range of their new *K*-band equipment varied from day to day. The explanation of this apparent paradox, which is credited to J. H. Van Vleck, was the onset of spring. It so happens that a transition between two rotational energy levels of the water molecule leads to an absorption maximum at 1.28 cm, so the water vapor in the air produced the deterioration of the *K*-band signal.

Purcell had briefly considered a simple two-level system in 1937 in his first paper on cooling by adiabatic demagnetization,[23] but the immediacy and importance of the *K*-band catastrophe required Purcell to understand two-level systems much more deeply. "The water vapor absorption caused us to think a great deal about two-level systems...I never thought much about them before...[Now] we had to think about them and calculate their absorption per mile of path."[1] On numerous occasions Purcell mentioned that the water vapor absorption was a direct source for his ideas about the two-level system he investigated in 1945.[1,21] In fact, clear thinking about two-level systems runs through two other significant experiments that Purcell did: the investigation of spin systems at negative temperatures and the observations of the 21 cm line in galactic spectrum.[15,24]

It is apparent that the *K*-band "catastrophe" at the Rad Lab had an impact on Purcell's career. In fact, it is possible that the experience was so evocative that it lead Purcell to conceive of NMR in a way that was contrary to his usual style of thinking. Purcell has a very visual style of thinking. He explains, "When I lie in my bed designing an experiment I can practically see the edges of the thing I'm going to design in the shop. I see it as a mechanical drawing...I don't think I ever had an idea that I couldn't visualize."[1] In consonance with his enjoyment of thinking visually, Purcell likes to draw, is very well known for his illustrations in his textbooks, and is very attracted to modern geometric chemistry: "Chemistry became geometry around 1933 with Pauling's book about the nature of the chemical bond...The whole three-dimensionality of the thing and the absolutely dominant role of geometric shape in the molecules and their function was not known when I was in college. I think I would have become a chemist if it had been known."[1] Incidentally, Purcell notes that there are different styles of visual thinking and distinguishes between thinking about clearly defined mechanical drawings, which he does easily, and pondering irregular objects like a complex molecule, when he is not as proficient at.[1] In contrast to his facility with visual imagery, Purcell in the 1930s and 1940s was not as comfortable with the formal style of quantum-molecules: "I had a [college] course in quantum mechanics but it really wasn't a working tool. It had to become that in those years."[1] A two-level system is one of these unvisualizable quantum-mechanical entities that Purcell would perhaps have preferred to deal with visually.

In fact, the two-level system in Rabi's molecular-beam experiments and Purcell's 1945 NMR experiment can be conceived of in an equivalent, but extremely visual way.[2,3] Bloch's conception of NMR centered on the picture of a classical magnetic dipole. In a constant magnetic field, a dipole experiences a torque and precesses about the field direction with a constant frequency, usually called the Larmor frequency. If a rotating constant field or, equivalently, a stationary oscillating field is now applied perpendicularly to the constant magnetic field, the dipole will precess around it too. For most rotating-field frequencies, these two precessions interfere with each other and combine to produce a complicated motion. However, when the rotating field revolves with a frequency equal to the Larmor frequency, the two precessions reinforce each other and produce a graceful corkscrew motion. Furthermore, at this resonant frequency, the magnetic dipoles, following the corkscrew, flip at a maximum rate (compared to other frequencies) between parallel and antiparallel orientations to the constant magnetic field. Thus at the Larmor frequency, maximum power is absorbed from the applied rotating field. The Larmor frequency is identical to the resonance frequency that Purcell, Pound, and Torrey searched for in 1945. Moreover, Ehrenfest's theorem, which exhibits the equality between the classical equations of motion and the quantum-mechanical expectation value, shows that both Bloch's visual picture of the dipole precession and Purcell's conception of a two-level system are equivalent.[3]

Not only can the NMR experiment be understood in visual as well as formal terms, but both Bloch's precession picture and Purcell's quantum-mechanical two-level system share common roots in Rabi's molecular beam work in the 1930s. Purcell and Bloch even cite the same 1938 paper by Rabi in their first papers on NMR.[2] In these citations, Purcell focuses on Rabi's statements about transitions between levels, and Bloch concentrates on statements about changes in dipole orientation. Eventually, Purcell adopted the dipole-precession picture with a certain fondness. "There were so many things for which the precessing model was neat. We all had to adopt it. The two level absorption was just part of the story."[1] He often used the precessing picture for explanatory purposes—for example, in his 1948 article in *Science*, his Nobel lecture, and his electricity and magnetism text.[12,16,25] A striking image from his Nobel lecture, in fact, makes use of the precessing picture: "There the snow lay on my doorstop—great heaps of protons quietly precessing in the earth's magnetic field."[12] It should also be noted, however, that Purcell continued to use the two-level approach, as in his negative-temperature experiment.[1] Judging by Purcell's fondness for visual description, by the close connection between the precession picture and two-level systems, and by Purcell's eventual embrace of the visual way of understanding NMR, one can speculate that he would naturally have employed the precession picture at the onset, in his 1945 experiment, if his experience during the K-band catastrophe had not forcefully channeled his thoughts towards two-level systems. Thus the essential contingency of events again manifests itself in the way a chance event, the K-band catastrophe, steered Purcell's thought.

VII. CONCLUSION

Purcell, Pound, and Torrey's discovery of NMR in 1945 can be examined at a variety of different scales. First of all, it can be seen as a detail within the context of Purcell's life. From this perspective, it fits into the orderly development of Purcell's career, like a character into a well-spelled word, and it takes on an inevitable, almost uninteresting character. Alternatively, one can look closer and view the discovery in the context of Purcell's prior work at the Rad Lab. From this vantage point, an element of contingency appears, for Purcell's post-war work is strongly dependent on three aspects of his experience at the Rad Lab: his enlightening association with Rabi, the helpful technical progress made at the Rad Lab, and the mentally stimulating K-band catastrophe. If any of these three aspects had been different or absent, Purcell's post-war work probably would not have followed the same path. Finally, one can look even closer at the discovery and observe the actual events that constituted it. Further contingencies appear at this level. Suppose, for instance, that Purcell, Pound, and Torrey had not made that one last try with the maximum possible magnet current. It is this constant interplay between a seemingly inevitable destiny and many contingent events that makes a discovery such as this so interesting and worthy of study.

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[1] Interview of Purcell by the author at Purcell's home in Cambridge on 23 April 1987. Except where otherwise indicated the amount of the NMR discovery in Sec. II is based on this interview.

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Relation between equations in the international, electrostatic, electromagnetic, Gaussian, and Heaviside–Lorentz systems

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A brief description of the method of suppression and restoration of constants is given. The method is then applied to the constants in the basic equations of electromagnetism in the international system and shown to permit passage back and forth between it and the electrostatic and electromagnetic systems, but not between it and the Gaussian and Heaviside–Lorentz systems. Introduction of an added dimension of magnetic charge is then shown to lead to a new system, designated the universal system, containing an additional constant. The method of suppression and restoration of constants is then applied to the constants in the universal system and shown to permit passage back and forth between it and the international, electrostatic, electromagnetic, Gaussian, and Heaviside–Lorentz systems. Simple rules for effecting conversions between the above six systems are provided in appendices. The above methodology is shown not only to facilitate conversions but also to explain the fundamental relationships between the different systems.

I. INTRODUCTION

When an equation describing some general relation in electromagnetic theory is converted between the international (SI), electrostatic (ESU), electromagnetic (EMU), Gaussian (G), and Heaviside–Lorentz (HL) systems (see Appendix A), the structure of the equation remains unchanged, but there are variations in the constants and dimensional properties of the equation that have been the source of considerable theoretical confusion and conflict. In the present paper we show that judicious application of the method of suppression and restoration of constants not only explains these variations but provides a simple method for converting equations from one to another of the above systems.

In Sec. II, the method of suppression and restoration of constants is introduced. In Sec. III, the basic equations of electromagnetism in the international system are summarized. In Sec. IV, we show that the technique of suppression and restoration of constants applied to the constants in the international system allows one to pass back and forth between it and the electrostatic and electromagnetic systems, but not between it and the Gaussian or Heaviside–Lorentz systems. In Sec. V, we show that introduction of an additional dimension of magnetic charge leads to a new system of equations, which we designate the universal system, containing an additional constant. In Sec. VI, we show that the technique of suppression and restoration of constants applied to the constants in the universal system allows one to pass back and forth between it and the international, electrostatic, electromagnetic, Gaussian, and Heaviside–Lorentz systems. Specific and detailed rules for effecting conversions between the above six systems are provided in appendices.

Our approach to the above problem contains features in common with approaches taken by a number of other authors, but the complete synthesis as far as we are aware is unique. The method of suppression and restoration of constants, which is the keystone in the present paper, has been discussed by us in several earlier papers.[1,2] The method is basically an application of the Buckingham pi theorem,[3] which has been dealt with in this journal by Parkinson,[4] Evans,[5] and Remillard.[6] Use of the method of suppression and restoration of constants for converting equations from one system to another has been proposed by Leroy,[7] but he considers only the case of conversion from the Gaussian system to the international system, and as noted in Sec. IV his use of the method is inconsistent with our theoretical development. Berreman[8] and Trigg[9] discuss generalized systems similar to our universal system that can be specialized to the international, electrostatic, electromagnetic, Gaussian, or Heaviside–Lorentz system, but they do not generate these generalized systems or consider methods for the inverse conversion from one of the latter five systems to a generalized system. Venkates,[10] Gelman,[11] and Smith[12] present elegant theoretical treatments of the relations between the different systems, and also derive methods for conversion of equations from one to another of the systems; but their theoretical developments and methods of conversion are not as simple and straightforward as ours. Weibel[13] and Page[14] show how one can generate conversion factors relating corresponding quantities in different systems, and Spees,[15] Matthews,[16] and