Paul Forman

Researching Rabi's Relics: Using the Electron to Determine Nuclear Moments Before Magnetic Resonance, 1927–37.

Through the last two decades of his life I. I. Rabi had insisted that nothing remained of the apparatus employed in his molecular beam researches prior to the Second World War: 'It's all gone.'[1] When, however, following his death in January, 1988, Rabi's papers and effects were removed from his office at Columbia University, three pieces of 'hardware' came to light and were donated to the Smithsonian Institution's National Museum of American History (Figure 1).

Figure 1. Three molecular beam deflecting magnets as received from the estate of I. I. Rabi early in 1989 (National Museum of American History accession no. 1996.0331). The two bars, of length two feet and five feet, precisely, are of non-magnetic aluminum alloy. Each carries, embedded in one side, a pair of thin copper tubes. The object at lower right is a C-shaped (annular), ferric magnet, formed of two opposed halves, here hinged together and partially opened. These three magnets will be denominated, respectively, the 'Millman' magnet, the 'Manley' magnet, and the 'indium' magnet. In use, the bars were rotated 180° from their orientations in this photograph (see Figure 3). The hinge on the 'indium' magnet is attached at the 'bottom' of the magnet, whose gap, in use, was vertical at top (see Figure 4).

All three of these objects are molecular beam deflecting magnets employed in measurements of angular momenta and magnetic moments of atomic nuclei, measurements carried out under Rabi's direction at Columbia over the five years 1933–37. The technique employed in those measurements, devised by Rabi and Gregory Breit in 1930/31,[2] was an ingenious modification of that first introduced by Otto Stern in 1921 (Figure 2).

In a lengthy paper being published in sequential parts in *Annals of Science*, I report an investigation—in which the assistance of Roger Sherman, Museum Specialist in the Electricity and Modern Physics

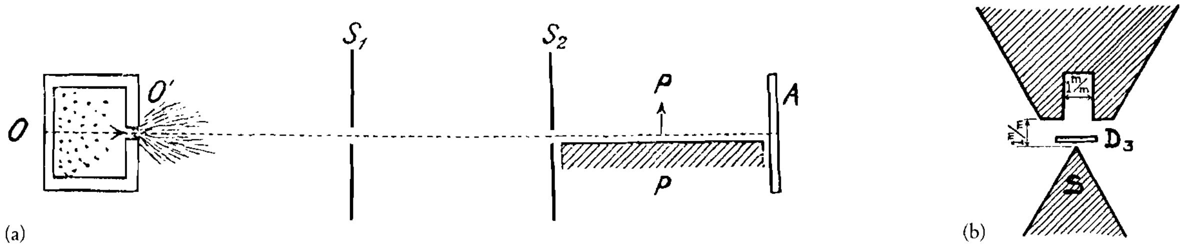


Figure 2. Schematic drawings of the Stern-Gerlach experiment. At left (Figure 2a) the substance to be investigated is vaporized in the oven, O. Evaporated atoms (or molecules) emerge into an evacuated chamber at O', and are formed into a ribbon-like beam by the slits, S_1, S_2, whose long dimensions are perpendicular to the paper. The beam so formed is then deflected by the action of an inhomogeneous magnetic field, between the pole pieces PP, upon the magnetic moments (electronic and/or nuclear) of the atoms. Finally, the atoms strike and adhere to the arrester plate, A. The separations between the traces left in the presence and in the absence of the inhomogeneous magnetic field are a measure of the strength of the magnetic moments borne by the atoms. At right (Figure 2b) is a transverse section through the pole pieces, showing the configuration Stern and Gerlach employed to maximize the magnetic field and its gradient—and hence to maximize the deflection of the atoms. Figures reproduced from: Walther Gerlach, 'Über die Richtungsquantelung im Magnetfeld II. Experimentelle Untersuchungen über das Verhalten normaler Atome unter magnetischer Kraftwirkung,' Annalen der Physik 76 (1925), Figure 1 on p. 164; Gerlach, 'Der experimentelle Nachweis der Richtungsquantelung im Magnetfeld und das magnetische Moment des Silberatoms,' Physica 2 (1922), Figure 2 on p. 123.

Collections, has been essential—aiming to describe and identify those three objects and to explicate them as historical artefacts within Rabi's developing program of research.[3]

Making use of the documentary resources available, especially Rabi's manuscripts, correspondence, and projection slides deposited at the Library of Congress, I provide in that longer paper a detailed, critical account of Rabi's route into molecular beam research, and of the first decade of his work with that technique. I point out Rabi's early commitment to the field of magnetism, highlight the extent of his indebtedness to Otto Stern's pioneering efforts toward molecular beam measurements of nuclear moments, and, especially, make evident the coherence of the research program for determination of nuclear moments by the 'Breit-Rabi method' that Rabi pursued from 1930 to 1937, i.e., prior to his implementation of the justly famous magnetic resonance method. Here in this brief paper I scant biographical and institutional circumstances and offer a very condensed account of that research program and the roles of these objects within it.

Born Israel Isaac in 1898 in a small town in Galicia—born to poor, little educated, deeply religious parents in this proverbially impoverished Polish province of the Austro-Hungarian Empire—Isidor Isaac Rabi spent his childhood and youth in immigrant neighborhoods of New York City. A voracious reader, exceptionally bright and broadly gifted intellectually, Rabi was long uncertain of his vocation, but found his way by age 30 into 'the purest kind of pure science.'[4] Such, for Rabi, was the technique of molecular beams, as he found it practiced by Stern at Hamburg University. From 1928 Rabi took this as his own field of research, applying it more and more exclusively to the measurement of the spins and magnetic moments of atomic nuclei. A decade of significant conceptual and instrumental advances, advances with which the artefacts here in question are closely associated, was then quite overshadowed by that further improvement in the technique—the magnetic resonance method—that Rabi and Co. began to employ late in 1937. And 'magnetic resonance' so increased the sensitivity and precision of the molecular beam method as largely to obliterate all earlier advances from scientific memory.[5] But for Rabi himself those earlier researches—and the magnets he had designed for them—remained an important part of his own sense of accomplishment and of his place in the history of science.[6]

Rabi was not wrong so to regard himself and these artefacts. In the late 1920s nuclear physics was becoming widely recognized as the 'new frontier' of physical research, and in the early 1930s American physicists, more than those of any other nation, began turning their research efforts in this direction. Over the six years 1932–1937, in which Rabi's pre-magnetic-resonance researches were appearing in the *Physical Review*, nuclear physics was springing from under 10% to over 30% of the papers published in that journal.[7] Thus Rabi, a bit of a Rutherford, was on the crest of a wave that he himself was helping to create. Moreover, what he contributed to the making of that nuclear physics wave was in some respects unique. Nuclear moments—i.e., a nucleus's 'spin' (angular momentum) and its magnetic moment—were among the very few parameters then regarded as necessary to define a nucleus as a quantum-physical system. While optical spectroscopists, through their analyses of hyperfine structure, provided most of the experimental data on nuclear moments, Rabi and only Rabi was providing confirmation and supplementation of that data by an independent technique, the Breit-Rabi method.[8] Those pre-magnetic resonance experiments were imaginatively conceived, skillfully performed, knowledgably analyzed—and technically demanding. Experimentalists so able and successful as Ernest Lawrence listened 'almost with reverence' to Rabi's account of them.[9]

Measuring nuclear magnetic moments was a desideratum that Rabi's principal mentors had earlier emphasized: Ralph Kronig, with whom Rabi studied and collaborated at Columbia University, January 1926 to June 1927; Wolfgang Pauli and Otto Stern, at Hamburg University, October 1927 to December 1928.[10] The question took on great importance through the acceptance early in 1926 of the concept of electron spin—the attribution to every electron of an intrinsic angular momentum of magnitude exactly half that possessed by an electron circulating in the lowest orbit of a Bohr atom, and, along with that 'spin', the attribution of an intrinsic magnetic moment exactly equal to that which an electron circulating in a lowest Bohr orbit would produce electrodynamically: $\mu_B = eh/4\pi m_e c$, the 'Bohr magneton'. (Here e is the electron's charge, m_e its mass, $h/4\pi$ its intrinsic angular momentum, and c the velocity of light.) Since, until neutrons came to the rescue in 1932, atomic nuclei were thought to be composed of protons and electrons, the attribution to electrons of this atomic size magnetic moment, roughly a thousand times greater than that which atomic nuclei had been thought to possess, presented atomic physicists with a perplexing problem.[11]

This issue was further sharpened with Dirac's publication early in 1928 of an equation that, applied to a particle of the electron's charge and mass, 'produced' exactly the previously attributed intrinsic angular momentum and magnetic moment. With the success of Dirac's equation, it came to be widely accepted in the early 1930s that the proton was describable by the same equation, with appropriate charge and mass—leading to the conclusion that the magnitude of the proton's intrinsic magnetic moment, the 'nuclear magneton', must be exactly $\mu_B(m_e/m_p)$, where m_e and m_p are the masses of the electron and the proton, standing in the ratio of 1 to 1850.[12]

Measurement of the magnetic moment of a nucleus was Stern's cynosure, the particular goal towards which his refinements of the molecular beam technique had pointed from the early 1920s to the early 1930s.[13] The implication of an atom-size nuclear magnetic moment, however perplexing, was enticing to the experimenter. When Rabi, itinerant postdoc in Europe, committed himself to a year's work in Stern's laboratory late in 1927, he was paired with Stern's other American postdoctoral fellow, John B. Taylor. This very skilled experimentalist, to whose example and instruction Rabi would be greatly beholden, was then, at Stern's behest, searching for the large nuclear magnetic moment implied by the spinning electron.[14]

Through the strong support of George B. Pegram, the perpetual head of Columbia's physics department and occupant of various higher administrative positions in the university, in the autumn of 1929 Rabi came back to Columbia as faculty member. Although research funds at Columbia were not especially ample, Pegram ensured that Rabi always had an exceptionally large share of them, as well as an exceptionally large share of the time of the Physics Department's exceptionally well-equipped machine shop. Moreover, in the enormous, 14-storey, physics building that Columbia had completed as Rabi was completing his doctoral research in 1926, there was ample space through the 1930s for Rabi's ever-expanding research group.[15]

Rabi's return to Columbia in the summer of 1929 coincided with Gregory Breit's arrival in New York to begin teaching at New York University—indeed, to take, at twice Rabi's salary, intellectual leadership of physics at NYU. Breit was Rabi's age, but was his senior in every professional sense, having been precocious rather than backward in finding his way into theoretical physics. Industrious and learned, he already had a huge record of publication, and he did much of his work in close collaboration with experimentalists. His particular concern at this time and on through the early 1930s was the calculation of nuclear magnetic moments and of hyperfine splittings, and comparison of the results with spectroscopic observations.[16]

Soon after their simultaneous arrivals, Rabi and Breit initiated a joint Columbia-NYU seminar in theoretical physics. Thus it was inevitable that Breit and Rabi would come to discuss the problem of atomic beam measurement of nuclear magnetic moments. Rabi was well aware of the difficulties of such measurements after his year in Stern's laboratory: they required a precise 'mapping' of the magnetic field and its gradient in that extremely narrow channel through which the beam passed between the poles of the magnet (Figure 2), while the very smallness of nuclear magnetic moments required the highest possible gradients, and hence the narrowest possible channels. The prospects for such measurements, and especially for such as could compete with those by optical spectroscopists studying hyperfine structures, would not have looked good to Rabi—and all the less good as he well knew that his own strength lay in conceptual tricks, not in refined, precise experimental technique.

Though it was presumably here, with *magnetic* moments, that Breit and Rabi's cogitations over molecular beam measurements of nuclear moments began, it was to *mechanical* moments that they led. Contrary to what is usually stated, the remarkable conceptual trick upon which they came was not a method for measuring nuclear magnetic moments. Rather, the essence of the Breit-Rabi method, clearly stated in the title of their paper,[17] was to ignore the extremely difficult task of quantitatively measuring nuclear magnetic moment, and concentrate rather upon the far less demanding, merely semi-quantitative task of evaluating the integer, or half-integer, quantum number determining the angular momentum (mechanical moment, 'spin') of a nucleus.

Breit and Rabi pointed out that under certain experimental conditions the relatively large electronic magnetic moment of an atom could serve as a 'handle' on the angular momentum vector of the nucleus. The condition therefor was that the magnetic fields used to deflect the atoms must remain so weak as not to disrupt the coupling between the angular momentum of the nucleus and the angular momentum of the extranuclear electron cloud.

The criterion developed by Breit and Rabi for the maintenance of this coupling was that the ratio $g\mu_B H/\Delta W$ be much less than 1. Here H is the applied magnetic field; μ_B is, as before, the Bohr magneton; g is a known number, generally between one and two, characterizing the way in which the angular momenta of the extra-nuclear electrons are themselves coupled together in the particular atomic state considered; and ΔW is the width of the hyperfine structure in the optical spectrum of the atom (expressed in energy units, $h\Delta\nu$). Physically, this denominator ΔW is the energy of the (undetermined) nuclear magnetic moment, μ_I, in the magnetic field produced by the extranuclear electron cloud, H_J, while the numerator $g\mu_B H$ is the energy of that cloud in the applied magnetic field H. And the requirement that the former be much greater than the latter is equivalent to requiring that the torque exerted by the external magnetic field on the electron cloud be much less than that exerted by the electron cloud on the nucleus, i.e., that the mechanical coupling between the angular momentum of the nucleus and that of the electron cloud not be disrupted by the applied magnetic field.

Breit and Rabi pointed out that the preservation of this coupling results in the splitting of the atomic beam into a multiplicity of beamlets whose intensities and separations are not greatly different and whose number, $(2J+1)(2I+1)$, yields the number of quantum units of nuclear angular momentum. (Here J is the known angular momentum quantum number of the extra-nuclear electrons, and I is the unknown number of quantum units of angular momentum of the nucleus.) When the condition for maintenance of this coupling was fulfilled, evaluating nuclear spin would merely require determining with certainty the number of 'beamlets' into which the primary beam was split in the magnetic field. No precise knowledge of the strength or gradient of the field and no quantitative measurement of the deflection of the 'beamlets' was required.

This concept, and with it the limitation to the determination of nuclear spin, had obvious appeal, but its implementation was by no means unproblematic. In particular, the condition for the application of the Breit-Rabi method was abandonment of the strong magnetic fields (and field gradients) that had always been employed in magnetic deflection experiments, for the greater the field and gradient, the greater the beam deflection, and hence the greater the sensitivity and precision of the experiment. Now, weak fields had to suffice.

Early in 1931 Rabi began to build up a molecular beam apparatus 'on an American scale' (as Rabi wrote Stern) to demonstrate the practicability of the Breit-Rabi method. In order to achieve perceptible separations of the 'beamlets' with the weak magnetic fields and field gradients required by the Breit-Rabi method, Rabi's design provided a beam path of almost 40 cm, twice the lengths Stern had used. Otherwise, however, the apparatus was a rather crude replica of John Taylor's Hamburg apparatus. The results that Rabi reported at the end of 1931 could be construed as evidence for the existence of nuclear spin only with some good will. For an evaluation of that spin his results were entirely insufficient.[18]

Rabi's only hope for doing better was to find collaborators gifted for experimental work. Late in 1931 he got one in graduate student Victor William ('Bill') Cohen, and in the autumn of 1932 he was able to hire a postdoctoral research assistant, Carl Frische—for one year only.

Thereafter the number of skilled experimental collaborators—students and, especially, postdocs—grew steadily: Sidney Millman, Jerome Kellogg, Jerrold Zacharias, John Manley, ...[19]

Meanwhile, back in Hamburg, through 1932 and during the first half of 1933—until forced to emigrate in summer 1933—Stern used his high-gradient technique in several very difficult experiments on hydrogen molecules and deuterium molecules in order to measure the intrinsic magnetic moment of the proton to within 10% and make a rough estimate of the magnetic moment of the neutron. He found that μ_p was not the the nuclear magneton, $\mu_B(m_e/m_p)$, that physicists, following Dirac's 1928 theory of the electron, confidently expected it to be, but some $2^1/_2$ times this value.[20]

Stern's result being, without question, the most important relating to nuclear moments that had yet come to light, it cried out for confirmation by a different method. The Breit-Rabi 'indirect' method was an alternative—the only alternative—but only if Rabi could extend it from determination of nuclear spin to measurement of nuclear magnetic moment. This was indeed possible in the case of hydrogen atoms, because for one-electron atoms, and only those, it was possible to calculate numerically, exactly, the magnetic field H_J produced at the nucleus by the 'electron cloud'. To take advantage of this possibility, however, more was required from a Breit-Rabi experiment, namely, just what was required in a traditional Stern-Gerlach experiment: precise knowledge of the deflections produced and of the strength and the gradient of the magnetic field producing them.

Rabi's whole prior career was based on circumventing field gradient measurements, and he was not disposed to accept the necessity of such now—especially now, where the weak fields employed in the Breit-Rabi method tended rather to increase the significance of measurement uncertainties. The alternative to measuring was calculating: to produce a magnetic field by a means that permitted an accurate and precise calculation of its strength and gradient. Such were the fields produced by electric currents in the absence of ferromagnetic materials. Fields so produced could never be very strong, and therefore had not previously been employed in atomic beam magnetic deflection experiments. But the very point of the Breit-Rabi method was to remain in a regime of weak fields.

Rabi found that two parallel 'wires' (in practice, copper tubes) with electric current flowing in them in opposite directions (and water as coolant flowing through them) produced a magnetic field that was nearly constant in planes parallel to the plane through the two wires (center lines of the copper tubes). And as the magnetic field was constant in such planes, so also was its gradient. In these planes the ribbon-like atomic beam would lie, and all atoms within the beam thus would be subject to the same deflecting field. This allowed still broader ribbons, and consequently higher beam intensities, than had ever been possible with the wedge-and-groove Stern Gerlach magnets. With such a deflecting magnet—this first was only 15 cm long—Rabi and collaborators determined the proton magnetic moment in the spring of 1934, confirming the anomaly, and indeed finding it even larger than had Stern.[21]

Late in 1933 Rabi designed and had Columbia's skilled machinists construct for doctoral student Sidney Millman—who was gearing up to follow up Cohen's wedge-and-groove measurements on alkalis—a 61.5 cm long version of the '2-wire' magnet (Figure 3). This, with great certainty, is the 2-foot magnet here denominated the 'Millman' magnet.

Having found that the 2-wire scheme worked so well, Rabi naturally wanted to see whether the uniformity of the magnetic field and the strength of its gradient could be improved by more complicated configurations of parallel wires. The most obvious refinement was the addition of a second pair of parallel wires, their centers forming a square with those of the first pair, but powered independently. This indeed is the design of our 2-foot magnet (the 'Millman' magnet). Occasionally, but only occasionally, employing the second pair of wires, Millman was able to gain some advantage in his experiments on potassium-39.[22]

Millman's magnet continued in service in Rabi's laboratory, first in experiments by Marvin Fox, Millman's understudy, on the nuclear

Figure 3. The 'Millman' and the 'Manley' magnets as depicted in publications from Rabi's laboratory: Figs 3a and 3b, 'Millman' magnet in 1935 and in 1937;[22, 23] *Figure 3c, 'Manley' magnet in 1936.*[24]

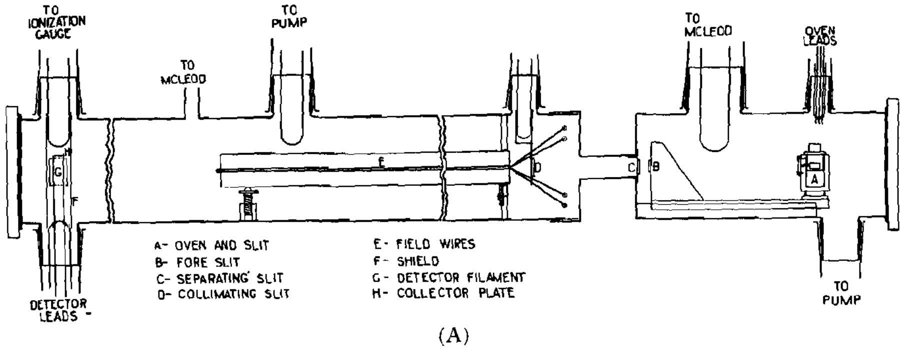
In Figure 3a the 'Millman' magnet, marked 'E', appears at the center of the apparatus. The four copper tubes ('FIELD WIRES'), separated only by thin sheet of micas, lie against each other, embedded in the face of the aluminum alloy bar ('field block'). Here, as also in Figs 3b and 3c, as indeed was then standard in magnetic deflection experiments, the ribbon-like beam is vertical (stands on edge), and passes from oven 'A' to detector 'G' just 'in front' of the field wires. That there were originally two sets of field wires is clearly indicated by the two pairs of lines diverging from the right end of the field block to either side of the collimating slit 'D'.

In Figure 3b the 'Millman' magnet, marked 'B', has been reused by Torrey in a rather more complicated experiment.[23] *Here the orientation of the magnet is unchanged, but the oven and detector positions are switched. Thus the collimator slit 'D', with its brass frame bolted to the duralumin field block, is now at the 'trailing', not the 'leading' end of the magnet. Here only two field wires are shown at the right end of the magnet, indicating the desuetude, if not already the removal, of the second pair of tubes by 1937.*

Figure 3c shows the apparatus, essentially similar to that of Figure 3a, in which the lengthy 'Manley' magnet, marked 'D', was first used. Here the two pairs of tubes feeding into the field block at its center are clearly indicated as tubes rather than schematically as wires.

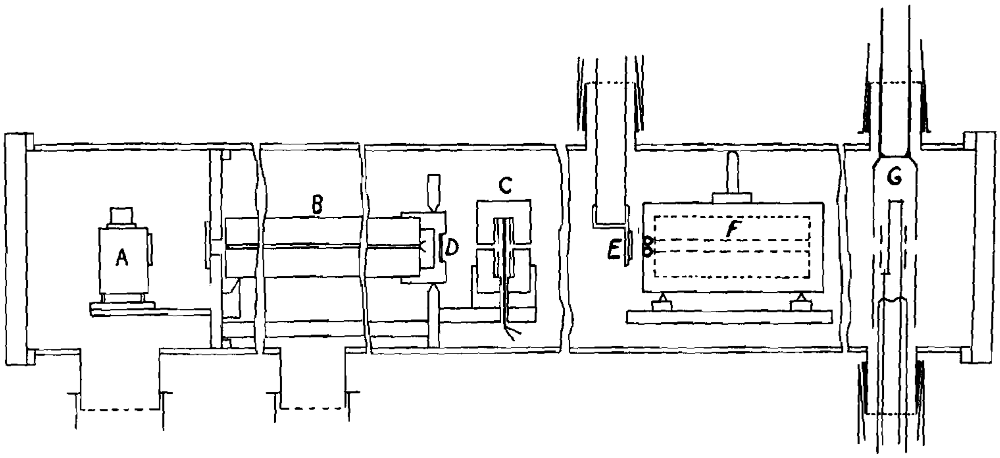
All three drawings depict, in progressively increasing detail, a contact ionization detector 'G'. Developed by John B. Taylor in 1928, the year Rabi shared his Hamburg laboratory, this was the first electronic detector of molecular or atomic beams, as also the first highly sensitive and truely quantitative detector. It was indispensable for all of Rabi's experiments at Columbia employing alkali atoms, i.e., the overwhelming majority of his experiments. At its center is a fine tungsten wire parallel to the plane of the beam and translatable perpendicular to that plane. The tungsten wire is held at a high temperature and at a moderate positive potential, and is surrounded by a cylindrical cage connected through a sensitive galvanometer to a negative potential. Alkali atoms, on striking the hot tungsten, surrender their one, loosely bound, valence electron to it, and are then repelled to the surrounding cage. The current through the galvanameter so produced is thus a precise measure of the atom flux at the position of the wire.

SIDNEY MILLMAN



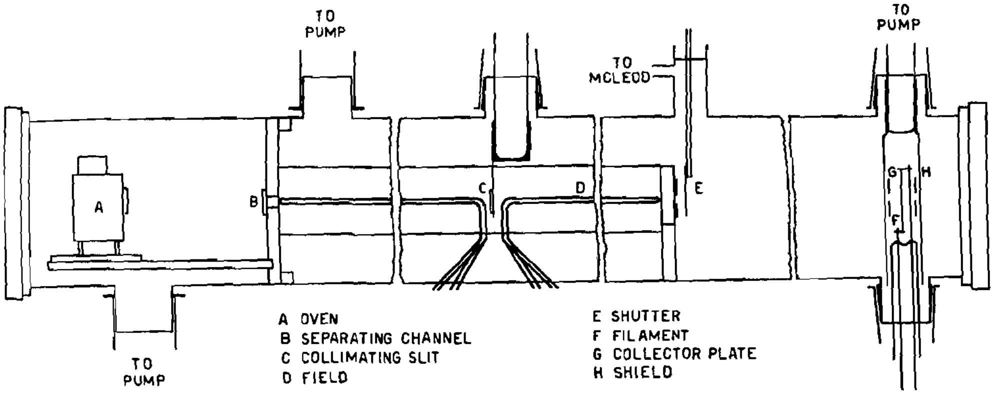
(a)

MAGNETIC MOMENT OF POTASSIUM NUCLEUS



(b)

J. H. MANLEY



(c)

moments of potassium-41, and then by graduate student Henry Torrey, 1936–37, in an experiment to determine the sign of the potassium-39 nuclear magnetic moment, i.e. whether the magnetic moment is directed parallel or anti-parallel to the nuclear spin. It appears that the form in which the 'Millman' magnet has come down to us is that in which it was left by Torrey, with his brass frame bearing an adjustable-slit attached to its right end.[23]

John Manley, with a doctorate from the University of Michigan, arrived at Columbia late in the summer of 1934 to take up a sub-faculty position as Instructor. Looking about to see who had interesting research in progress, he came to Rabi, who really had little competition in that regard. Manley's background included a B.S. in 'engineering physics', and perhaps for that reason Rabi set him to work on an atomic beam apparatus (Figure 3) that made Rabi's original 'American scale' Breit-Rabi apparatus appear Lilliputian. The nucleus in question was, once again, potassium 41, which because of its very small nuclear magnetic moment and low abundance, had resisted Millman's and Fox's (and Rabi's) efforts to determine its spin with certainty. And when Manley had succeeded well there, Rabi had him proceed to lithium 6 and 7 with the same apparatus.[24]

The apparatus (Figure 3c), more than two meters long, contained a deflecting magnet of length 153 cm, that is, again with considerable certainty, our 5-foot 'Manley' magnet. Although constructed so that the tubes in each half of the bar are fed separately at its center, it was operated integrally—two feeds being provided only to reduce electrical resistance and facilitate cooling. Further, although the published schematic drawing of the apparatus shows it to have been constructed as a '4-wire' magnet, as indeed ours is, neither Manley, nor John Gorham who used it after him, reported having used it otherwise than as a 2-wire magnet.

The Breit-Rabi method was a brilliantly direct method for the determination of nuclear spin, but it was an only indirect, and in most cases insufficient, method for measurement of nuclear magnetic moment. Stern took hydrogen molecules with zero electronic angular momentum and zero electronic magnetic moment, and operated directly upon their very small nuclear magnetic moment, μ_p, by means of highly inhomogeneous magnetic fields. Consequently, the deflections that he measured were (with appropriate corrections) direct measures of μ_p. Rabi, on the contrary, required atoms with non-zero electronic magnetic moment, for it was that thousand-times larger electronic magnetic moment upon which the Breit-Rabi method relied to get observable deflections with weak magnetic fields. And he could put a number on the nuclear magnetic moment, μ_I, only when theory could provide him with an estimate of H_I, the magnetic field at the nucleus due to the electron cloud.[25]

Only for hydrogen (i.e., one-electron atoms) could theory provide a precise H_I, and only for the alkalis (i.e., atoms with only one valence electron) could it provide even an approximate value. Such a situation is never entirely congenial to the experimentalist, and it was especially uncomfortable in the mid-1930s as optical hyperfine spectroscopy was producing very different values of μ_I, depending upon which hyperfine structure—i.e., which electronic state—was used to evaluate μ_I.[26] Since Rabi was limited to the evaluation of μ_I in just one state—the ground state—and that only where theory had an H_J to give him, he was hard pressed to make any very strong claim for his number.

It was thus the 'logical conclusion' of the Breit-Rabi method to extend it in such a way as to wrest from it a direct measurement of μ_I. Indeed, the possibility had been implicit in the Breit-Rabi calculation all along, had it not treated μ_I as negligibly small compared with μ_B (i.e., compared with μ_J, the electronic magnetic moment). In 1936 Rabi reconsidered the calculation from that point of view, and found that carrying μ_I through implied a more complicated beam splitting. In the mode of Breit-Rabi measurement introduced in 1934—the so-called 'zero moment' method—treating μ_I/μ_J as small but non-negligible implied that the peaks in detector current were actually narrow doublets. (In the 'zero moment' method, rather than mapping the pattern of beamlets at a fixed magnetic field, the detector was fixed at the position of the undeflected beam, and the 'pattern' was swept over the detector by gradually increasing the current through the magnet.) The small difference in magnetic field ΔH separating these two maxima in detector current is proportional to H and to μ_I/μ_J.

If the Breit-Rabi technique could be made sensitive enough to make this fine structure perceptible, μ_I would be obtained free of that factor for which Rabi was dependant upon theoretical calculation, as also free of the assumptions about the physical nature of the interaction between the magnetic moment of the nucleus and the extranuclear electrons on which the hyperfine structure determinations depended. With such a measurement Rabi would have obtained the 'absolute nuclear moment.'[27] To carry this through, Rabi needed a nucleus with a large magnetic moment in an atom with small (but non-zero) μ_J and a readily detachable valence electron (so as to behave like an alkali atom in a contact-ionization detector).

Rabi fixed on indium. Its large nuclear magnetic moment assured the satisfaction of the Breit-Rabi coupling condition at relatively high magnetic fields—10,000 gauss. Such fields, however, were larger than could be obtained without the aid of iron. Rabi therefore designed an iron-core magnet with pole faces that would reproduce the field of a 2-wire magnet. The requisite geometry of the pole cross-section proved exceptionally simple: semicircles. A magnet one meter long of Armco iron, accurately milled with poles of approximately 3 mm (1/8 inch) radius of curvature (corresponding to two parallel wires 1/4 inch apart), wound with four turns of copper tubing, was fabricated under hand and eye of

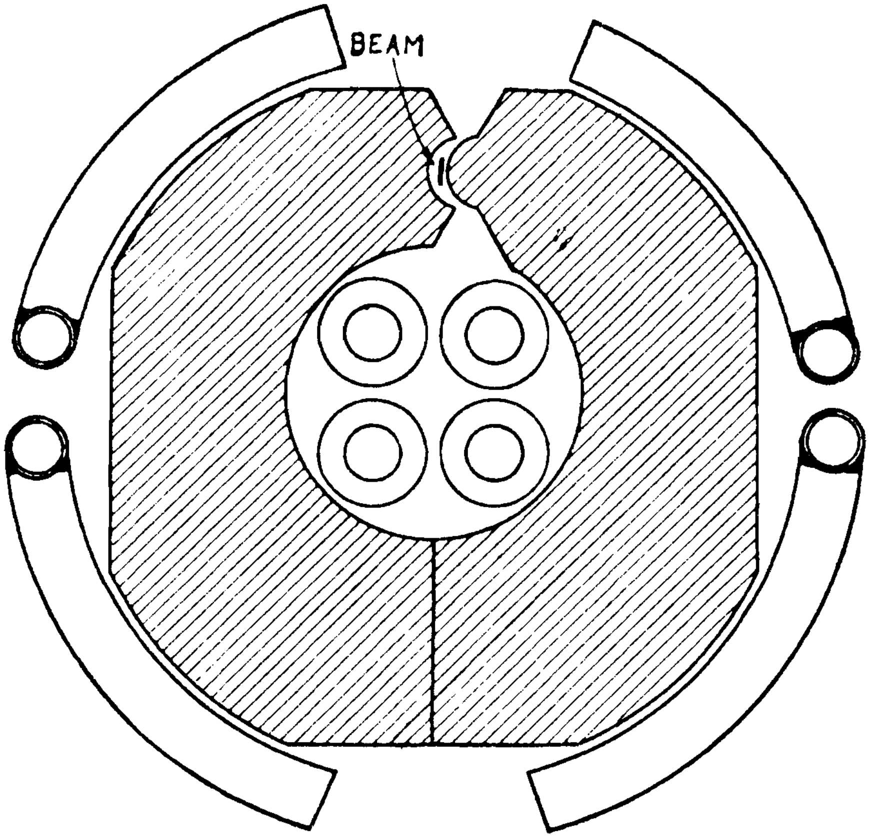


Figure 4. The 'indium' magnet. Figure 4a is 'Cross section of magnet and windings' as depicted in Rabi and collaborators' report on their 1937 experiments.[27] *The iron portion of the magnet is shown hatched. The copper windings take the form of thick-walled tubes, running the full meter length of the magnet from end to end within the central hole, and outside the magnet body have the form of segments of hollow copper cylinders (with cooling water carried in thin-walled copper tubes soldered to them). As Rabi et al. state the drawing to be '2/3 full size,' the 17 mm diameter of the central hole as there depicted corresponds closely to the 1 inch measured diameter of the central hole of our 'indium' magnet. (Thus Rabi's drawing is here reproduced '1½ full size'.)*

the Department's chief mechanician, Sam Cooey. The apparatus was otherwise essentially similar to that in Fig. 3c.

It is my surmise that the third of our artefacts, the iron magnet with central hole of 1-inch diameter, and of 'length' 1-inch, was sliced off that original 1-meter long magnet as souvenir paperweight—the hinge being then added to hold the two halves together while displaying the finely machined pole faces.[28]

In a series of very difficult experiments, together with Sidney Millman and Jerrold Zacharias, in the summer of 1937 ('the indium summer' Zacharias punned) Rabi carried through this 'absolute' measurement. It was indeed a tour de force, the capstone of the Breit-Rabi research program. Further in this direction it was hardly possible to proceed. In September Cornelius Gorter visited Columbia and urged Rabi to try magnetic resonance.[29] Rabi was ready.

Notes

1. I. I. Rabi, Julian S. Schwinger, Norman F. Ramsey, Sidney Millman, and Jerrold Zacharias, with Jack S. Goldstein, moderator, 'Reminiscences of the thirties,' recollections and discussions videotaped at Brandeis University, 16 March 1984, transcript, 57pp., and videotapes in Zacharias Papers, MIT Archives, on p. 51 of the transcript.

2. Gregory Breit and I. I. Rabi, 'Measurement of Nuclear Spin,' *Physical Review* 38 (1931), 2082–83 .
3. Paul Forman, 'Molecular Beam Measurements of Nuclear Moments before Magnetic Resonance: I. I. Rabi and Deflecting Magnets to 1938. Part I,' *Annals of Science* 55 (1998), 111–160. Parts II and III to appear in future.
4. Rabi to F. K. Richtmyer, 22 January 1929, draft (Library of Congress, Rabi Papers, box 7, folder 7).
5. The most complete collection of references to pre-World War II molecular beam research is W. H. Bessey and O. C. Simpson, 'Recent Work in Molecular Beams,' *Chemical Reviews* 30 (1942), 239–279. For the magnetic resonance technique, as also for valuable discussions and references on earlier techniques: Norman F. Ramsey, *Molecular Beams* (Oxford, 1956; reprinted 1990).
6. This circumstance is clearly 'illustrated' in photographs taken of Rabi at about the time he was himself giving up active research work—photographs, reproduced in the introduction to the *Annals of Science* paper cited above (note 3), in which Rabi chose to have himself shown holding one or another of these artefacts. Even decades later when Rabi had long forgotten the existence of these artefacts buried in the clutter of his office, *this* remained the work that he wanted to talk about when he had the ear of a historian of physics. Thus in 1984 S.S. Schweber sought to interview Rabi about the work at Columbia after World War II bearing upon quantum electrodynamics. Rabi, however, turned and returned the interview to his pre-magnetic-resonance experiments and their fundamental importance. Rabi, interview, 1984 February 13, by S.S. Schweber, transcript, 25pp., in Niels Bohr Library, American Institute of Physics.
7. Papers and data of Angelo Baracca and collaborators as cited and reproduced in Forman, '"Swords into Ploughshares": Breaking New Ground with Radar Hardware and Technique in Physical Research after World War II,' *Reviews of Modern Physics* 67 (1995), 397–455, on pp. 420–21. J. L. Heilbron and R. W. Seidel, *Lawrence and his Laboratory: A History* ... (Berkeley, 1989).
8. Forman, '"Swords into Ploughshares"....,' p. 405. Rabi's technique—the Breit-Rabi method—was really only *semi*-independent. Only in the 1937 experiment employing the 'indium' magnet did Rabi & Co. succeed in a measurement of nuclear magnetic moment that did not depend upon elaborate and sometimes uncertain theoretical calculations. Alone and of itself, all that a Breit-Rabi experiment can provide is a rough, rather qualitative, estimate of the magnitude of the magnetic moment of the nucleus, based on observation of the range of applied magnetic field strengths in which decoupling of the electronic from the nuclear angular momentum is first produced.
9. K.K. Darrow to Rabi, from San Francisco, 6 August 1936 (Library of Congress, Rabi Papers, box 2, fldr 11). Rabi had presented his work at the Cornell Symposium on Nuclear Physics early in July, and had lectured at the Ann Arbor Summer School during the last two weeks of July.
10. Kronig, 'Spinning Electrons and the Structure of Spectra,' *Nature* 117 (1926), 550. Rabi, 'Spinning Electrons,' *Nature* 118 (1926), 228. Forman, 'Molecular Beam Measurements ... Part I,' pp. 137, 142–43. Pauli left Hamburg for Zurich in spring 1928, where Rabi rejoined him early in 1929.
11. Roger H. Stuewer, 'The Nuclear Electron Hypothesis,' in William R. Shea (ed.), *Otto Hahn and the Rise of Nuclear Physics* (Dordrecht, 1983), pp. 19–67.
12. Forman, 'Molecular Beam Measurements ... Part I,' p. 145; Helge S. Kragh, *Dirac: A Scientific Biography* (Cambridge, 1990).
13. Stern, 'Zur Methode der Molekularstrahlen,' *Zeitschrift für Physik* 39 (1926), 759–60. Stern himself was the first to introduce the concept of a 'nuclear magneton,' pointing out that general arguments implied thar if the atomic nucleus is a dynamical system containing proton-mass particles with electron-size charges and with angular momenta quantized in the same units as that of the extra-nuclear electrons, then the magnetic moments of nuclei should be roughly two thousand times smaller than those of atoms, i.e., should be of the order of $\mu_B(m_e/m_p)$.
14. John B. Taylor, 'Das magnetische Moment des Lithiumatoms,' *Zeitschrift für Physik* 52 (1928), 846–52. Forman, 'Molecular Beam Measurements ... Part I,' p. 127–9, 144–58.
15. Columbia University, *The New Physics Laboratories of Columbia University in the City of New York*, 1927 (Privately printed: New York, 1927). L. A. Embrey, 'George Braxton Pegram,' National Academy of Sciences of the USA, *Biographical Memoirs* 41 (1970), 357–407. I. I. Rabi, 42 interviews for the Columbia University Oral History Research Office, 1983–85, by Chauncey Olinger, 1102pp. continuously paginated transcript, on pp. 233–34, et passim.
16. John Archibald Wheeler with Kenneth Ford, *Geons, Black Holes, and Quantum Foam: A Life in Physics* (New York, 1998), Chapter 5 ('I Try My Wings [with Breit]'), pp. 103–123. D. A. Bromley and V. W. Hughes (eds.), *Facets of Physics* [Breit Festschrift] (New York, 1970).
17. Breit and Rabi, 'Measurement...' op. cit., note 2.
18. I. I. Rabi, 'The Nuclear Spin of Caesium by the Method of Molecular Beams,' *Physical Review* 39

(1932), 864. This is a 200-word abstract of a paper presented at the American Physical Society meeting New Orleans, 29–30 December 1931. Details of the development of concept and apparatus are to be found in Rabi's letters to Stern, 3 June 1931 and 18 January 1932, in University of California, Berkeley, Bancroft Library, Stern Papers, carton 1, folder: Rabi.

19. John S. Rigden, *Rabi: Scientist and Citizen* (New York, 1987). Jack S. Goldstein, *A Different Sort of Time: The Life of Jerrold R. Zacharias, Scientist, Engineer, Educator* (Cambridge MA, 1992). Victor W. Cohen, untitled recollections sent to Lucy Hayner, 27 July 1956, 5pp. rypescript, in Columbia University Rare Book and Manuscript Library, George B. Pegram papers, box 3, folder: Cohen.
20. Announced in I. Estermann, R. Frisch and O. Stern, 'Magnetic Moment of the Proton,' *Nature* 132 (1933), 169–70, with details provided in the *Zeitschrift für Physik.*
21. Rabi, Kellogg and Zacharias, 'The Magnetic Moment of the Proton,' *Physical Review* 46 (1934), 157–63.
22. Sidney Millman, 'On the Nuclear Spins and Magnetic Moments of the Principal Isotopes of Potassium,' *Physical Review* 47 (1935), fig. 2 on p. 742; Millman, 'Recollections of a Rabi Student of the Early Years in the Molecular Beam Laboratory,' *Transactions of the New York Academy of Sciences* 38 (1977), 87–105.
23. Henry Cutler Torrey, 'The Sign of the Magnetic Moment of the K^{39} Nucleus,' *Physical Review* 51 (1937), fig. 2 on p. 503.
24. J. H. Manley, 'The Nuclear Spin and Magnetic Moment of Potassium (41),' *Physical Review* 49 (1936), fig. 1 on p. 922; Manley and Millman, 'The Nuclear Spin and Magnetic Moment of Li^6,' *Physical Review* 51 (1937), 19–21; John E. Gorham, 'The Signs of the Nuclear Magnetic Moments of Li^6 and K^{41},' *Physical Review* 53 (1938), 563–67.
25. Marvin Fox and I. I. Rabi, 'On the Nuclear Moments of Lithium, Potassium, and Sodium,' *Physical Review* 48 (1935), 747.
26. H. A. Bethe and R. F. Bacher, 'Nucleat Physics,' *Reviews of Modern Physics* 8 (1936), 206–225, reprinted in Hans A. Bethe, et al., *Basic Bethe: Seminal Articles on Nuclear Physics,* 1936–1937 (New York, 1986).
27. S. Millman, I. I. Rabi, and J. R. Zacharias, 'Absolute Nuclear Moment of Indium 115,' *Physical Review* 53 (1938), 331; S. Millman, I. I. Rabi, and J. R. Zacharias, 'On the Nuclear Moments of Indium,' *Physical Review* 53 (1938), 384–91.
28. The stated lengths and gap dimensions of the deflecting magnets used in Rabi's early post-World-War-II molecular beam magnetic resonance experiments on hydrogen—John E. Nafe and Edward B. Nelson, 'The Hyperfine Structure of Hydrogen and Deuterium,' *Physical Review* 73 (1948), 722–3—togethet with the reference there directly back to the description of the magnet used in Rabi and collaborators's 1937 Breit-Rabi method experiments on indium (op. cit., note 27), suggest that the original indium magnet was cut into shorter lengths for these early (and urgent) postwar experiments, and that Rabi's souvenir was a by-product of this process.

    It is worth noting that the problem of identifying our 'indium' magnet with certainty is greatly aggravated by the circumstance that this basic design, devised for indium in 1937, was then adopted for the several magnets constructed in subsequent years for experiments employing the magnetic resonance technique. Indeed, the iron emulation of the two-wire field by semi-circular pole faces became *the* standard magnet design during the following two decades in which the molecular beam technique spread from two or three centers to two ot three hundred.
29. I. I. Rabi, J. R. Zacharias, S. Millman, and P. Kusch, 'A New Method of Measuring Nuclear Magnetic Moment,' *Physical Review* 53 (1938), 318. C. J. Gorter, 'Bad Luck in Attempts to Make Scientific Discoveries,' *Physics Today* (January 1967), 76–81.