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I. I. RABI

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A Biographical Memoir by

NORMAN F. RAMSEY

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SOME SCIENTISTS MAKE their greatest contribution through their own personal research, while others are best remembered for their general wisdom and their influence on others. A few, including Rabi, excel in both respects. His own discoveries, which led to his Nobel Prize in 1944, are of great importance, including the invention of the molecular beam magnetic resonance method, which he and his associates used to measure magnetic moments and electric quadrupole moments of many atomic nuclei and to show the existence of a previously unsuspected tensor force between the neutron and the proton. But Rabi's influence extended far beyond his own laboratory. He was a creative scientist, an innovative statesman, and a philosopher. Proposals first made by Rabi have led to many of the most successful ventures in national and international cooperation in science.

THE EARLY YEARS

Rabi was born on July 29, 1898, in Rymanow, a small town in Galicia, a province in the northeast of the Austro-Hungarian empire. His parents were Orthodox Jews who gave their son the name Israel Isaac Rabi. Soon after Rabi was born, his father moved to New York City and within a few months had earned enough money for his wife and son to join him on the Lower East Side of Manhattan. At home the young Rabi was called "Izzy," but when his mother gave this name at the time he was first enrolled in public school, the name was recorded as Isidor and the error was never corrected. Throughout most of Rabi's professional life he was known as I. I. Rabi except to his closest friends, who called him either Rabi or Rab. The Rabi home was in a Jewish ghetto in the Manhattan slums. Rabi's education began in Hebrew school at age three. His father worked in a sweatshop making women's clothes by day, and at night he operated a small but unsuccessful grocery store that was tended by Rabi's mother during the day.

When Rabi was nine his parents moved to the Brownsville section of Brooklyn, which was crowded but still somewhat rural. Rabi attended New York public schools but did not find school inspiring. Rabi's fascinating childhood and early education have been well described by Jeremy Bernstein[1] and John Rigden.[2] Rabi was an avid reader and gained much of his education and interest in science through books borrowed from the public library. He was for several years particularly interested in books on socialism, science, radio and technology. His first scientific paper, written while he was still in elementary school, was on the design of a radio condenser and was published in Hugo Gernsback's *Modern Electronics.* In 1916, after graduating from the Manual Training High School in Brooklyn, Rabi entered Cornell University, starting in electrical engineering but graduating in the field of chemistry. After three years of uninteresting jobs, he returned to Cornell to do graduate work in chemistry, moving a year later to Columbia University and to physics. At Columbia, Rabi did his doctoral research on magnetic susceptibility with A. P. Wills, but, characteristically, it was on a subject of Rabi's own choosing and with a novel technique which greatly simplified the experiments. The day after he sent in his doctoral thesis, he married Helen Newmark, who remained his lifelong companion and became the mother of his two daughters, Nancy Lictenstein and Margaret Beels.

The Rabis soon went on a traveling fellowship to Europe, where he worked intermittently with Sommerfeld, Heisenberg, Bohr, and Pauli. The Stern-Gerlach experiment demonstrating the reality of space quantizations had earlier sparked Rabi's keen interest in quantum mechanics and so, while working in Hamburg with Pauli, Rabi became a frequent visitor to Stern's molecular beam laboratory. During one of these visits Rabi suggested a new form of deflecting magnetic field; Stern in characteristic fashion invited Rabi to work on it in his laboratory, and Rabi in an equally characteristic fashion accepted. Rabi's work in Stern's laboratory was decisive in turning his interest toward molecular beam research.

RESEARCH AND TEACHING AT COLUMBIA

Rabi returned from Europe to join the faculty at Columbia University and to begin atomic beam research in his own laboratory. In 1931 he and Gregory Breit developed the important Breit-Rabi formula, which showed how the magnetic energy of an atom and its effective magnetic moment vary with the strength of the external magnetic field. These changes occur because the atomic configuration varies from the electron angular momentum being primarily coupled to the nucleus at a low external field to being principally coupled to the external magnetic field at a high field.

Utilizing the Breit-Rabi formula and an atomic beam apparatus which deflected the atomic magnetic moments with inhomogeneous magnetic fields, Rabi, V. Cohen, and others[3] were able to determine the strengths of the electron-nucleus interaction and the magnitudes of nuclear spins and magnetic moments. Rabi further improved the precision of the measurements by noting from the Breit-Rabi formula that the effective magnetic moments are zero at certain magnetic fields, which give marked identifiable rises in the intensity of the undeflected atoms passing through an inhomogeneous field. Since the strengths of the fields giving zero moments depended on the hyperfine interactions and nuclear spins, Rabi, Fox, and other students and associates determined a number of hyperfine interactions by measuring the zero moment magnetic fields. Although the zero moment method did not work for atoms with nuclear spin 1/2, Rabi devised an alternative refocusing technique which did.

Rabi also showed that the molecular beam deflection method could be adapted to measurements of the signs of nuclear magnetic moments by determining which transitions occurred when atoms went through a region of space in which the directions of the magnetic fields were successively reversed.[3]

Rabi developed the theory of such transitions in his important paper entitled "Space Quantization in a Gyrating Magnetic Field" (1937). In this paper Rabi assumed for simplicity, that the applied field changed its direction ("gyrated") at a fixed frequency. As a result, this paper provides the theoretical basis for all subsequent magnetic resonance experiments.

Rabi initially applied his theory to fields which changed only in space rather than in time. A few months after the publication of that paper, following a visit by C. J. Gorter, Rabi directed the major efforts of his laboratory toward the development of the molecular beam magnetic resonance method with the magnetic fields oscillating in time. As shown in Figure 1, a molecular beam was deflected by

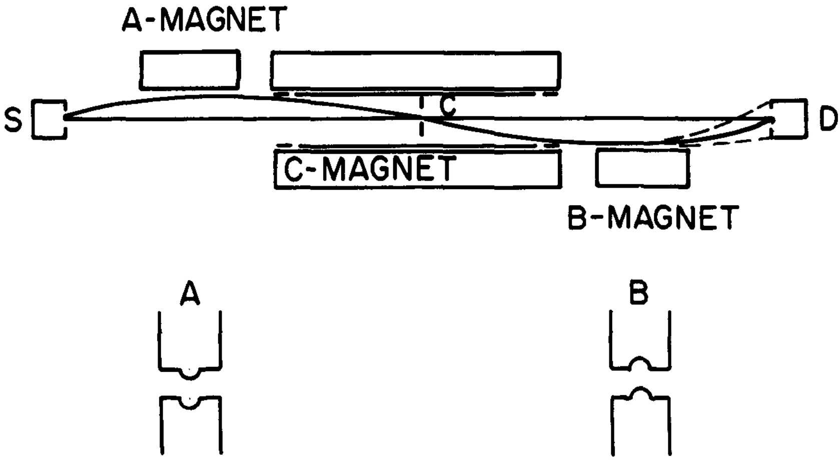

FIGURE 1

one inhomogeneous magnetic field and refocused by a similar field. In passing between the two fields, the molecules were subjected to a weak oscillatory magnetic field at frequency ν. When ν equaled the Bohr frequency $\nu_0 = (W_f - W_i)/h$, transitions could take place with a consequent refocusing failure and a reduction in beam intensity. By measuring the beam intensity as a function of frequency, one could thereby determine the spacing of the molecular energy levels.

The first successful molecular beam magnetic resonance experiment was that of Rabi, S. Millman, P. Kusch, and J. R. Zacharias in 1938, which determined the nuclear magnetic movement of Li. Soon thereafter, J. M. B. Kellogg, Rabi, N. F. Ramsey, and Zacharias applied the method to molecular hydrogen and discovered a multiplicity of resonance lines, whose separation arose from the magnetic interactions of the nuclear moments with each other and with the magnetic field caused by the rotation of the molecule. They found that the separations of the resonances for D_2 were much greater than could be attributed to such magnetic interactions but could be fitted by assuming that the deuteron had a nuclear electric quadrupole moment, i.e., had an ellipsoidal shape like an American football rather than a spherical shape; an ellipsoidal shape would result from the existence of a previously unsuspected tensor force between the neutron and proton.

In subsequent years Rabi, with his students and associates, successfully applied the beam resonance method to single atoms as well as to polyatomic molecules and in such experiments measured numerous nuclear spins, nuclear and atomic magnetic moments, atomic hyperfine interactions, and nuclear quadrupole moments. The Rabi laboratory at Columbia was a major research center providing new physics data, new ideas, and outstanding and creative young scientists who later went on to establish their own research programs in a variety of fields. Although most of Rabi's graduate students were experimentalists, some, including Julian Schwinger, were theorists.

WORLD WAR II

World War II interrupted the molecular beam research at Columbia University from 1940 to 1945, when Rabi was actively involved with the development of microwave radar at MIT. There Rabi was a major source of new research ideas and an influential advisor to his research associates. He headed the magnetron group at the MIT Radiation Laboratory and later became deputy director. He was particularly active in developing shorter wavelengths, first from 10 centimeters to 3 centimeters at MIT; later he initiated the establishment of the Columbia Radiation Laboratory, which pioneered in the development of 1-centimeter-wavelength radar.

Rabi originated the plans for the writing of the twenty-eight-volume Radiation Laboratory Series, which for many years was the major reference for microwave and electronic technology. Rabi also served as an influential consultant to J. Robert Oppenheimer, director of the Los Alamos nuclear research laboratory.

Shortly before the end of the war, in his 1945 Richtmeyer Lecture, Rabi discussed the possible use of an atomic beam magnetic resonance apparatus as the control element of an accurate clock. The *New York Times* report on this lecture is the first published account of atomic clocks, which have now become so accurate that they are the basis of the international definition of the second.

RETURN TO COLUMBIA

Following the end of the war, Rabi, Ramsey, and Kusch returned to Columbia to reestablish the molecular beam laboratory. Nierenberg and Ramsey rebuilt an old apparatus and measured the radiofrequency spectra of a number of alkali halides. Rabi, with his students J. Nafe and E. Nelson, successfully applied the magnetic resonance method to atomic hydrogen and discovered that the hyperfine separation due to the interaction of the magnetic moment of the proton with the electron was slightly different from the theoretical expectation from the Dirac quantum theory; this result was the first indication that the magnetic moment of the electron was different from the expected Dirac value, an observation later confirmed at Columbia by Kusch's direct measurements of the electron magnetic moment. These observed anomalies were the principal stimuli to the development of relativistic quantum electrodynamics, the first successful quantum field theory.

Another important molecular beam development was the adaptation by Rabi and his student H. Hughes of the resonance method to electric deflecting and oscillating fields. With subsequent improvements by Rabi, J. Trischka,

V. Hughes, and others,[3] the electric resonance method has been used for many precise measurements of the spin-dependent internal interactions within molecules in specific rotational states.

Most of Rabi's experiments were with molecular beams, but he also participated with W. Havens and J. Rainwater in a neutron-electron scattering experiment which provided the first experimental evidence for the neutron-electron interaction.

Rabi's classroom lectures were often chaotic, but he was a stimulating teacher who made his students think. He was an inspiring supervisor of Ph.D. students whose research experiments were innovative and fundamental. Rabi and his wife Helen were personally very helpful to his students and associates, most of whom remained lifelong friends. Rabi gave his students freedom and independence while maintaining high standards for the research. The influence of Rabi has been extended by his students, such as Zacharias, Ramsey, Nierenberg, Schwinger, and Hughes, who in turn have had a number of excellent students; many of the scientists now active in physics can trace their scientific ancestry back to Rabi or his former students.

Rabi not only contributed innovative new resonance techniques to the field of atomic physics but imparted to his students and associates high standards for both the quality and the interest of the research. His lifelong interest in scientific taste and standards is illustrated by his last publication, written just a few weeks before he died. In paying tribute to Wolfgang Pauli and Otto Stern, Rabi wrote:

> From Stern and Pauli I learned what physics should be. For me it was not a matter of more knowledge. I learned a lot of physics as a graduate student. Rather it was the development of taste and insight; it was the development of standards to guide research, a feeling for what was good and what is not

so good. Stern had this quality of taste in physics and he had it to the highest degree. As far as I know, Stern never devoted himself to a minor question.

For a number of years Rabi was a highly effective chairman of the Columbia Physics Department; his critical and stimulating presence was clearly responsible for much of that department's greatness.

Although Rabi was not directly involved in physics experiments after 1960, he retained an active and critical interest in the field and was a regular and stimulating participant in atomic physics meetings and seminars until a few months before he died from cancer on January 11, 1988, at the age of eighty-nine.

SCIENTIST STATESMAN

Rabi's influence extended far beyond his own and his students' research through his membership on important committees, his presidency of the American Physical Society, his many public lectures, and his innovative proposals for new means of cooperation among institutions and nations. Discussions late in 1945 between Rabi and Oppenheimer led to the Acheson-Lillienthal-Baruch plan proposed by the United States for the international control of atomic energy. One of Rabi's greatest disappointments was that this forward-looking plan, after initial favorable consideration, was never adopted by the United Nations.

Rabi was a member of the AEC General Advisory Committee and joined with Enrico Fermi in writing a strong memorandum supporting the controversial GAC recommendation against a crash program for the development of a hydrogen bomb. Later, Rabi became chairman of the GAC and an eloquent defender of Oppenheimer in the AEC hearings that culminated in the removal of Oppenheimer's security clearance.

Rabi and Ramsey initiated the first proposals for Brookhaven National Laboratory and were early strong proponents for the construction of the Cosmotron. Later, with the model of Brookhaven in mind, Rabi pioneered in advocating the European collaboration that led to CERN. Rabi was the initiator of the International Conferences on the Peaceful Uses of Atomic Energy and a principal speaker at them.

Through his friendship with President Eisenhower, Rabi was largely responsible for the establishment in 1957 of the President's Science Advisory Committee and the Office of Special Assistant to the President for Science and Technology. For many years Rabi was the U.S. representative to the NATO Science Committee, where he effectively advocated the establishment of the highly successful NATO-supported Summer Schools and Fellowship program.

Rabi was the recipient of many honorary degrees and awards, including election to the National Academy of Sciences in 1940, the Japan Academy in 1950, and the French Legion of Honor in 1956. He received the 1944 Nobel Prize, the 1948 U.S. Medal for Merit, Britain's 1948 King's Medal, the 1964 Priestley Memorial Award, the 1967 Niels Bohr International Gold Medal, the 1967 Atoms for Peace Award, the 1982 Oersted Medal of the American Association of Physics Teachers, the 1985 Roosevelt Four Freedoms Medal, the 1985 Public Welfare Medal of the National Academy of Sciences, and the 1986 Vannevar Bush Award of the National Science Foundation.

Rabi's carefully prepared public lectures were stimulating and presented fresh points of view, as illustrated by his words at the Fourth International Conference on the Peaceful Uses of Atomic Energy:

> Real peace is more than the absence of violent war. To fulfill human expectations peace must be a condition which permits the release of the

latent creative energies of all the people to the end of enhancing and elevating the quality of human life on this globe.

NOTES

1. Jeremy Bernstein, "Profiles: Physicist," *The New Yorker* (October 13 and 20, 1975).

2. J. Rigden, *Rabi: Scientist and Citizen* (New York: Basic Books, 1987).

3. N. F. Ramsey, *Molecular Beams* (Oxford: Oxford University Press, 1956, 1985).

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