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JERROLD R. ZACHARIAS

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A Biographical Memoir by
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BY NORMAN F. RAMSEY

JERROLD ZACHARIAS MADE important, creative, and lasting contributions to physics, national defense, and education. He participated in the first molecular beam magnetic resonance experiments; he measured nuclear magnetic moments and electric quadrupole moments of various nuclei, including the proton and deuteron; he confirmed the anomalous hyperfine separation in atomic hydrogen; and he developed the first commercial atomic clocks. During World War II, he developed radar systems at MIT and nuclear weapons at Los Alamos. In the years following the war he initiated and led important national defense studies. As a result of his deep concerns about science education in the United States, he initiated numerous fruitful studies to improve it. He established the Physical Sciences Study Committee (PSSC), which not only made successful recommendations but also stimulated the production of movies and textbooks. The PSSC became a model for similar educational reforms in mathematics and most other sciences.

EARLY YEARS

Jerrold Zacharias was born on January 23, 1905, in Jacksonville, Florida. His father, Isadore, was a lawyer with interests in real estate, and his mother was a talented violinist. His childhood and education are well described in an excellent biography by Jack S. Goldstein.[1] Jerrold had little interest in music, while his sister, Dorothea, and his adopted brother, Beryl Rubenstein, were talented musicians. Their musical mother was consequently less interested in Jerrold, who found real companionship in his nurse, Anna Liza Johnson, who later cared for Jerrold's children in New York City.

Jerrold's interest in physics began at age four with a fascination with his grandfather's automobile and continued into his teens with interests in photography, crystal set radio, and the Tom Swift books. Although he received excellent grades in high school, including his first physics course, Jerrold later complained that he did not learn much.

Soon after graduation from high school, his family moved to Riverside Drive in New York City, where Jerrold entered Columbia as an engineering student. By his sophomore year, he found physics challenged him more than engineering, so he changed to a major in mathematics with a minor in physics. Jerrold did well as an undergraduate but later described himself as having been a fraternity playboy with a generous allowance, a raccoon coat, and a Packard touring car. In 1925 as a Columbia undergraduate, Jerrold, on a blind date, met Leona Hurwitz, a delightful, serious biology major at Barnard. They married two years later. Leona remained his lifelong companion and became the mother of Susan and Johanna.

After graduating, Jerrold entered Columbia graduate school and began research with Shirley Quimby in solid state physics, a barely recognized research field at that time. Quimby suggested the problem of measuring the stress-strain relationship (Young's modulus) and internal friction in crystals of nickel by studying their vibrations. Zacharias discovered an unexpected diminution of internal friction of the crystals at the Curie temperature, where their magnetic properties also change dramatically.

RESEARCH AT COLUMBIA

Jerrold Zacharias completed his thesis research in 1931—the middle of the great depression, when few jobs were available. He succeeded in obtaining an appointment as a tutor at Hunter College at a salary of $2,000 per year and with a heavy teaching schedule.

Zacharias was an excellent teacher but was eager to return to experimental research as well, so, in addition to his Hunter teaching duties, he soon arranged to work with I. I. Rabi of Columbia University. He spent his free evenings and weekends in Rabi's atomic beam laboratory as an unpaid research associate. Rabi had invented an atomic beam method for measuring the magnetic moments of nuclei by their interaction with the magnetic moment of the electron, which affected how the atom would be deflected by an inhomogeneous magnetic field. With his first graduate student, Victor Cohen, Rabi was applying this method to the measurement of the nuclear magnetic moments of sodium and cesium. Zacharias was especially interested in simpler fundamental atoms, so he joined with Rabi and Jerome M. B. Kellogg, a young Columbia instructor newly arrived from Iowa, on the more difficult task of measuring the nuclear magnetic moments of hydrogen and deuterium. They confirmed Otto Stern's earlier observation that the magnetic moment of the proton was much larger than the theoretically expected value of one nuclear magneton. These observations provided the first indications that the proton had a complex internal structure. Later Zacharias and his associates improved their results by using the new zero moment method and then further modified their apparatus to measure the signs of the proton and deuteron magnetic moments.

In the summer of 1937, Zacharias, S. Millman, P. Kusch, and Rabi measured the magnetic moments of indium and gallium and found a small contribution to the deflection patterns from the thermally excited higher energy states. By studying these contributions they could also measure the nuclear quadrupole moments of these nuclei. With characteristic humor, Jerrold described this period of research as indium summer. I had the good fortune to join the Columbia atomic beam laboratory at this time and to work on this experiment as an apprentice. It was a great experience and I learned much, ranging from apparatus design and vacuum techniques to data analysis and theoretical principles. Although Jerrold had not yet acquired his fame in science education, he was a talented teacher. He taught me one particularly memorable lesson. I had just given what seemed to be a highly successful colloquium and Jerrold asked me to hand him my third slide. Instead of the expected question about its contents, he dramatically broke the slide over the edge of the lecture table and said, "Don't ever again show a slide that cannot be read from the back of the room"—a painful lesson I have never forgotten.

In 1937 Jerrold was appointed assistant professor at Hunter College and Leona obtained her Ph.D. and an appointment as instructor at the Columbia College of Physicians and Surgeons.

Also in 1937 the research at Columbia was revolutionized by Rabi's invention of the magnetic resonance method. The first successful experiment with this method was by Rabi, Millman, Kusch, and Zacharias. This experiment was the forerunner of many different kinds of resonance experiments, including nuclear magnetic resonance and paramagnetic resonance. The first resonance experiment was soon followed by the experiments of Kellogg, Rabi, Ramsey, and Zacharias, which not only obtained accurate values for the proton and deuteron magnetic moments but also discovered the electric quadrupole moment of the deuteron, which in turn showed the existence of a new kind of force—a tensor force—between the proton and neutron.

Zacharias then turned his attention to measuring the magnetic moment of ^{40}K, since some theorists had predicted that its unusually long lifetime might be associated with a large nuclear magnetic moment. The measurement was successful though difficult because only one atom in 10,000 of natural potassium is ^{40}K. In 1940 Jerrold and I were invited to give talks on our magnetic and electric dipole moment measurements at a meeting of the American Physical Society in Seattle, Washington, so Jerrold drove my new wife and me cross country to Seattle and then back to Glacier Park where we were joined by Leona. The trip was scientifically and scenically exciting but politically distressing since the Nazis were moving through France almost as rapidly as we moved across the United States. It appeared that the war would soon be upon us.

THE WAR YEARS

Our fears soon proved to be valid; within the next four months Zacharias, Rabi, and I had moved to the MIT Radiation Laboratory, where we worked on microwave radar.

Zacharias's first task at MIT was to establish a lab on the MIT roof and build a radar system there capable of detecting distant objects. His success led to his being asked by the Navy to install a radar set on a destroyer. When this was successfully completed, Zacharias became the Radiation Laboratory representative at the Bell Telephone Laboratories in Whippany, New Jersey, during the development of a production model for the MIT 10-cm night fighter radar.

He then went to England to adapt the Oboe blind bombing system from long wavelengths to microwaves. He returned to the Radiation Laboratory to head the Transmitter Components Division, and in the spring of 1945 he accepted the offer of a full professorship at MIT while remaining on leave to continue his radar research.

Zacharias left MIT to go to Los Alamos a few months before the end of the war to head the Ordnance Engineering Division, a position vacated by Captain (later Admiral) W. S. Parsons, who had left for the Pacific island of Tinian. That division later became the Z division, which evolved into the Sandia National Laboratories.

NUCLEAR SCIENCE, ATOMIC BEAMS, AND ATOMIC CLOCKS

At the war's end Jerrold Zacharias returned to MIT as professor of Physics and director of the newly established Laboratory for Nuclear Science and Engineering. He quickly arranged for financial support from the newly established Office of Naval Research and organized a strong research staff, including B. Rossi, J. G. Trump, M. Deutsch, R. J. Van deGraff, R. D. Evans, I. A. Getting, V. F. Weisskopf, M. Benedict, and C. D. Coryell. Zacharias was also an MIT representative on the Initiatory University Group and later the Associated Universities, Inc. (AUI), which established Brookhaven National Laboratory.

Zacharias and his associates established a vigorous and effective atomic beam research laboratory. They independently confirmed that the experimental value of the atomic hydrogen hyperfine structure disagreed with the theoretical value, a disagreement that stimulated the development of relativistic quantum electrodynamics. They measured a number of nuclear spins and magnetic moments and for the first time detected a nuclear magnetic octupole moment.

Zacharias at this time became interested in developing atomic clocks and pursued two versions concurrently. One was a cesium atomic beam clock using my separated oscillatory field method,[2] well engineered for reliability and commercial applications, including a source and vacuum system that could be operated for years rather than hours. He cooperated with the National Company in developing a commercial clock known as the Atomichron. The availability of this highly successful cesium atomic beam clock contributed greatly to the adoption of atomic time and to the international definition of the second as 9,192,631,770 oscillations of the cesium atom.

His other version had the potential for much greater accuracy but the risk of total failure. A very slow beam of atomic cesium was directed upward and allowed to fall as a fountain, with separated oscillatory field excitation on the way up and down. The half second required for the roundtrip in the fountain was approximately fifty times greater than that for an atom to traverse the oscillatory field region of a conventional atomic beam apparatus, so the resonance width, by the Heisenberg uncertainty principle, would be fifty times narrower with correspondingly increased clock accuracy. Despite valiant efforts by Zacharias and his associates, the fountain experiment failed because the numbers of ultra-slow atoms in the beam were far below theoretical predictions, probably due to scattering in the nonequilibrium region between the slits. It is of interest to note that thirty years later, in 1989, Steven Chu[3] succeeded in making an atomic fountain by using the new laser cooling techniques to produce ultra-slow atoms. The atomic fountain with laser cooling is now one of the most promising prospects for increasing the accuracy of clocks and frequency standards.

DEFENSE STUDIES

As the Cold War intensified in the late 1940s, Zacharias became involved in defense studies. The first of these was Project Lexington, commissioned by the Atomic Energy Commission in 1948 to study the feasibility of nuclear-powered aircraft. Although deputy director of the study, Zacharias was frustrated by its being limited to the narrow question of the feasibility of nuclear-powered aircraft to the exclusion of the broader questions of their practicality and desirability. He learned from this experience that later studies that he organized or directed must have broadly defined missions.

For the Navy he directed Project Hartwell, on the threat by Soviet submarines. At his insistence the mission was so broadly defined that the title of the final report was *A Report on the Security of Overseas Transport.* The conclusions included recommendations for a new high-speed merchant fleet and modernization of port and cargo facilities as well as recommendations for submarine detection.

In 1951 Zacharias served as associate director of Project Charles, which was established to make recommendations on the air defense of the North American continent. The project recommended tests of an experimental system of radars coupled through high-speed digital computers and the establishment of a new laboratory (Lincoln Laboratory) to continue research on this problem. Jerrold later directed a 1952 Lincoln Laboratory study of air defense that recommended establishment of the DEW (distant early warning) line, a chain of huge radars stretched across the Arctic and coupled to high-speed computers to detect approaching missiles. In 1955 Zacharias directed Project Lamp Light to study fleet and air defense.

Many years later, during the Vietnam War, Zacharias directed one more Department of Defense study, this time on means for preventing the infiltration of men and materials across the demilitarized zone between North and South Vietnam. The study recommended an electronic barrier as an alternative to air bombardment.

EDUCATION REFORM

In 1955, at the age of fifty and after ten years of service, Zacharias retired as director of MIT's Laboratory for Nuclear Science, and a year later he terminated his atomic beam research to devote himself to his newest interest—education reform, especially in the sciences. He deeply believed that the United States would suffer in the future from the inadequacy of its science education and that "in order to save our democracy, we've got to educate the people who vote."

Although his initial plans emphasized the development of a series of educational physics films, he approached the problems of education in the same broad manner that had been so successful in his defense studies. With the support of the National Science Foundation, he assembled a brilliant array of individuals, including research physicists, teachers, scholars, writers, and motion picture directors, to form the Physical Sciences Study Committee (PSSC). The committee agreed that an entirely new approach to physics education was required, including new textbooks, laboratory kits to provide firsthand experience with simple apparatus, films, supplementary reading materials, and teacher training. The U.S. public reaction to the spectacular success of the Russian Sputnik in 1957 added urgency to the PSSC project. Talented new recruits joined the PSSC, which subsequently was well supported by the NSF and private organizations such as the Alfred P. Sloan Foundation.

Nearly sixty films were eventually produced by the PSSC, with scientists rather than actors and with emphasis on fundamental principles and on holding student interest. A textbook was written and widely adopted, along with teaching aids and new laboratory materials, including simple but informative experiments for schools with low budgets. Since good teachers are essential to the success of such a program, special summer institutes for teacher training were established.

The PSSC influence extended far beyond the teaching of high school physics in the United States. In universities, physics courses were improved to meet the changed knowledge and expectations of entering students with PSSC experience. The PSSC also served as a model for similar studies and curriculum changes in mathematics and other sciences. The PSSC was followed with great interest abroad, and its textbooks were translated into more than twelve languages.

Zacharias also became interested in elementary school science problems and established Educational Services, Inc. (ESI), under which a study was initiated to develop a science program for elementary schools. Eventually, this had a large impact on American education. His meetings and discussions about the problems of science education in Africa led to the African nations cooperating to establish a Science Education Program for Africa (SEPA).

Zacharias's educational interests were not limited to science. He also encourageed ESI to establish the influential Social Studies Curriculum Program and the Negro College Program.

A triple bypass coronary operation in 1977 only slowed Zacharias as he continued to push for education reform. At the same time, his deep concerns about the threat of nuclear war led him to coauthor a thoughtful essay titled *Common*

Sense and Nuclear Peace. He died from coronary artery disease on July 16, 1986, at the age of eighty-one.

HONORS AND AWARDS

Jerrold Zacharias received many honors and awards, including election to the National Academy of Sciences in 1957 and to the American Academy of Arts and Sciences. He was a fellow of the American Physical Society, American Association for the Advancement of Science, and the Institute of Electrical and Electronic Engineers. He was an institute professor at MIT and a member of the American Association of Physics Teachers (AAPT) and the President's Science Advisory Committee. The U.S. government awarded him the President's Certificate of Merit and the Department of Defense Certificate of Appreciation, its highest civilian honor. He received the AAPT's Oersted Medal for his contributions to teaching, the National Teachers Association Citation for Distinguished Service to Science Education, and the I. I. Rabi Award "for technical excellence and outstanding contributions in the fields relating to atomic and molecular frequency standards." Zacharias also received honorary degrees from Tufts University, Oklahoma City University, St. Lawrence University, Lincoln University, and Brandeis University.

SCIENCE, DEFENSE, AND EDUCATION

Science, national defense, and education were all greatly changed by Jerrold Zacharias. His work on the first molecular beam magnetic resonance experiments led the way for later magnetic resonance techniques, such as nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI). He and his associates measured numerous nuclear spins and magnetic moments and discovered the quadrupole moment of the deuteron, which implied the existence of a new kind of nuclear force. His development of the first commercial atomic cesium beam clock eventually led to the international adoption of the atomic cesium oscillations as the definition of the second.

Zacharias's wartime work on radar increased the reliability, versatility, and effectiveness of radar. The studies he initiated during the cold war contributed importantly to national defense.

The teaching of physics in many elementary and secondary schools was greatly changed by studies, such as PSSC, initiated by Zacharias and by new movies, classroom materials, and teacher training programs. The success of these programs in turn stimulated similar education reforms in other sciences and in other countries.

In his scientific research his development of atomic clocks, and his defense and educational projects, Jerrold Zacharias was not deterred by formidable obstacles. He attacked formidable problems with enthusiasm and determination. His positive and constructive attitude is well characterized by the remark of I. I. Rabi: "Dr. Zacharias is a man who, if he were to discuss the weather, would finish not by just talking about it, but he would be doing something about it."

NOTES

1. J. S. Goldstein. *A Different Sort of Time: The Life of Jerrold R. Zacharias.* Cambridge, Mass.: MIT Press, 1992. This excellent biography is the source of much of my information about Zacharias's full and varied life and provides a much fuller account than can be presented in a brief memoir.

2. N. F. Ramsey. Molecular beam resonance method with separated oscillatory fields. *Phys. Rev.* 78(1950):695.

3. M. Kasevich, E. Riis, S. Chu, and R. S. DeVoe. RF spectroscopy in an atomic fountain. *Phys. Rev. Letters* (1989):612.

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