NATIONAL ACADEMY OF SCIENCES

ARTHUR SCHAWLOW
1921–1999

A Biographical Memoir by

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Biographical Memoirs, VOLUME 83

PUBLISHED 2003 BY
THE NATIONAL ACADEMIES PRESS
WASHINGTON, D.C.

Arthur L. Schawlow

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May 5, 1921–April 28, 1999

BY STEVEN CHU AND CHARLES H. TOWNES

ARTHUR SCHAWLOW, the J. G. Jackson and C. J. Wood Professor of Physics at Stanford University and coinventor of the laser, contributed to many aspects of nuclear, atomic, and molecular physics. He was awarded the 1981 Nobel Prize in physics for "contributions to the development of laser spectroscopy." His early work included examination of the shapes, radial charge distributions, and moments of nuclei, the first microwave spectroscopy of a free radical, and coauthoring a widely used text on microwave spectroscopy. After the laser invention he introduced many innovative techniques for very-high-precision spectroscopic measurements, including new types of two-step spectroscopy of molecules. With Theodor Hänsch, Schawlow proposed the idea of laser cooling atoms in a vapor to extremely low temperatures. This new field has progressed to the point where atoms can be cooled to temperatures of less than 10^{-6} degrees above absolute zero, and where new states of matter have been created. (David Wineland and Hans Dehmelt proposed a closely related idea in the same year.) His work has had far-reaching effects—in physics, chemistry, biology, medicine, communications, and many other aspects of modern technology.

In addition to receiving the Nobel Prize Arthur Schawlow was elected a member of the National Academy of Sciences and was accorded many additional awards and honors, including the National Medal of Science in 1991. He was one of two people who had the distinction of serving as both president of the American Physical Society and president of the Optical Society of America. He was also chairman of the Physics Division of the American Association for the Advancement of Science.

Arthur L. Schawlow was born in Mount Vernon, New York, on May 5, 1921. His mother, Helen Mason, was from Canada and his father, Arthur Schawlow, was an emigrant from Latvia. They moved to Toronto, Canada, when Arthur the son was only three years old, and he was brought up there, though remaining a U.S. citizen. As a youngster Arthur enjoyed the famous *Book of Knowledge*, read about engineering and science, liked to tinker, was intrigued by radio, and built radio receivers. His intellectual skills were notable, resulting in completion of high school at the age of 16, and receipt of a scholarship in science at the University of Toronto. The latter was important because his family had no excess funds, and it steered him toward physics rather than engineering, which he had been seriously considering.

Arthur very much enjoyed jazz music, and while at Toronto he played the clarinet in the Delta Jazz Band, which he helped to organize. This and his engineering interests led him to record and collect jazz records, an avocation he continued during his entire career. This resulted in an extensive jazz record collection that is now in the Stanford University archives.

After earning his undergraduate degree Arthur continued in graduate school at the University of Toronto. His graduate work was interrupted during World War II. After receiving a master's degree in physics he took a job at Research Enterprises building radar equipment for several years. Toward the end of the war he began work on his Ph.D. at Toronto with Professor Malcolm Crawford, a spectroscopist of high standards who was particularly interested in examining nuclear properties. Working with him, Arthur developed a good understanding of electron interactions with nuclei in atoms, and published what he felt was one of his most important papers, on the determination of nuclear size from hyperfine structure. This interest was to show up again when he took a postdoctoral position with me (C.H.T.) at Columbia University.

In the 1950s I (C.H.T.) was in the physics department at Columbia University and fortunately had been given money for a postdoctoral fellowship by the Carbide and Carbon Corporation because Helmut ("Hap") Schulz, a creative, blind theoretical chemist there, thought my work on microwave spectroscopy of molecules might lead to work with infrared radiation and its effect on chemical reactions. The University of Toronto was outstanding in spectroscopy, and I knew professors there, such as Harry Welsh, who told me that Arthur Schawlow would be a good person for this postdoctoral position and would probably be interested. Several faculty members recommended him very highly, and I was glad that he accepted the position and joined me at Columbia University in the fall of 1949. His work at Columbia made it clear to me that he was unusually capable and had remarkable intuition and insight. I would have liked to have seen him in a permanent academic position at Columbia, but another event, though a happy one, unfortunately made this impractical.

My younger sister, Aurelia Townes, had come to New York to study voice and for a time lived in our apartment near Columbia. Arthur has often said that the very best thing that happened to him in New York was that he met

Aurelia; the first meeting being when my wife, Frances, made a point of inviting him to dinner and introducing the two of them. They were married in 1951, and I was delighted. We continued to work together at Columbia, both on research and on writing the book *Microwave Spectroscopy*. I would have wanted our collaboration to continue, with him on the Columbia faculty, however I was moving into the chairmanship of the physics department at Columbia, and potential claims of nepotism made it impractical for me to be instrumental in putting my new brother-in-law on the faculty. He accepted a position at Bell Telephone Laboratories in late 1951 and left Columbia.

The Schawlows had three children, Arthur Jr., Helen, and Edith. The family was religious, and Aurelia sang and conducted the choir at their church. Their two daughters, now Helen Johnson and Edith Dwan, have families and are in Wisconsin and California, respectively. Arthur Jr. introduced a difficult and challenging problem into the family, one on which Arthur Sr. and his wife, Aurelia, worked tirelessly and hopefully. Arthur Jr. was autistic, with very little speech ability. Part of the reason the Schawlows accepted a position at Stanford was that Professor Robert Hofstadter there also had an autistic child and they, the Shawlows and Hofstadters, hoped to help each other find solutions to the problem.

After his early years Arthur Jr. was put in a special center for autistic individuals, and later Arthur Sr. put together an institution to care for autistic individuals in Paradise, California. This was named the Arthur Schawlow Center in 1999 shortly before Arthur Sr.'s death. Both parents worked intensively toward finding ways for communicating with autistic individuals. One somewhat controversial method on which Arthur Sr. did research and became well known was for the autistic individual to spell words with a small handheld machine. Arthur and Aurelia wrote a chapter in a book *Integrating Moderate and Severely Handicapped Learners* under the title "Our Son: The Endless Search for Help." The two parents spent many weekends at the center in Paradise, and in 1991 Aurelia Schawlow died as a result of an automobile accident during the long drive from Stanford to see her son at the center. The Arthur Schawlow Center continues to give important service to individuals with autism or related problems and their families.

In 1961 Arthur left Bell Laboratories to join the faculty at Stanford University, where he remained until he retired to emeritus status in 1996. During this time he embarked on his remarkable career developing laser spectroscopy.

In addition to being an eminent scientist, Arthur was an entertaining lecturer and beloved mentor. He was a jovial and friendly person who enjoyed his own jokes so much that he would burst out laughing as he came to the punch lines. He attracted a large group of students and postdocs who affectionately called him "the boss." While his brilliant insight produced many striking and incisive experiments, and yielded new phenomena and high-precision instruments, his guiding maxim for experimental physics was "keep it simple."

Arthur showered fatherly advice and maxims to the point where "the sayings of Art Schawlow" became known beyond Stanford's physics department. To a young scientist intimidated by information overload he would say, "To do successful research, you don't need to know everything, you just need to know one thing that isn't known." Art felt that one of the hallmarks of a successful scientist was a driving need "to find the answer" and toward this goal "anything worth doing is worth doing twice, the first time quick and dirty and the second time the best way you can." Having been infected with his charm and vision, many of his flock have gone on to make their own significant contributions in science.

Arthur's wit and humor became renown. Recognizing that a scientist does his best work on the back of an envelope, he had envelopes with two backs made. They could be bought from Double Think, Inc., a division of Nocturnal Aviation, Art Schawlow Proprietor. The company's motto: "We fly by night." Art was chairing a session of an optical pumping conference in 1959 when Gordon Gould presented a paper entitled "The LASER, Light Amplification by Stimulated Emission of Radiation," thus introducing the acronym that was to soon replace the "optical maser." At the end of the paper Chairman Schawlow could not resist a comment. As Don Nelson of Bell Laboratories recalls, "Beginning with mock solemnity and ending in belly-shaking laughter, Art opined that the laser was likely to be most used as an oscillator and so should be named 'light oscillation by stimulated emission of radiation,' or the LOSER."[1] Once he gave a physics colloquium at Stanford entitled "Is Spectroscopy Dead?" He began the talk by defining at great length what he meant by "spectroscopy." After this long introduction his colleague at Stanford, Felix Bloch, asked him to define "dead." After a thoughtful pause Art answered, "Dead is when the chemists take over the subject." Art could say this and make the chemists laugh.

For Art, physics was fun and he made it more fun for the rest of us. While president of the Optical Society of America, Art initiated a "turvy-topsy" contest seeking the inverse of a topsy-turvy picture. A turvy-topsy slide was one that can never be presented correct side up. Four prizes were offered: first prize, $10; second prize, a copy of Schawlow's latest paper; third prize, copies of Schawlow's two latest papers; honorable mention, a choice of bumper stickers reading "Optics is Light Work," "Spectroscopists Have

Seen the Light," "Light Headed? Stop Eating Photons," or "Photons are Phorever."

Even Schawlow's amusing jokes and demonstrations have turned into profound contributions. Guided by his postulate that "anything will lase if you hit it hard enough," he and Ted Hänsch strove to create the first "edible laser" made out of Jell-O dessert. Working with two flavors per day, they marched through all 12 flavors of Knox-brand Jell-O. Unfortunately, none of the gelatin desserts showed lasing action, and Art retreated back to his office, where he ate each of the failures! Eventually he and Ted spiked the Jell-O with sodium fluorescein, a known laser dye, and immediately saw lasing action.[2] The news of the almost-edible laser spread rapidly and was eventually published in the *IEEE Journal of Quantum Electronics* in 1971. This experiment stimulated an experiment done by Herwig Kogelnik and Charles Shank at Bell Laboratories, where they irradiated a gelatin film with the interference pattern of two laser beams, making the first distributed feedback laser. This type of laser is now widely used in long-distance optical fiber communications.

His well-known demonstration during which he broke a blue Mickey Mouse balloon inside a clear outer balloon with a portable laser (in the shape of a ray gun, of course!) showed us that a beam of light could reach inside an object without puncturing the outer layers resurfaced when lasers were used to repair detached retinas. In a more recent embodiment the concept was used as an application of "optical tweezers," an optical trap fashioned out of a single focused laser beam. This trap, which was invented to hold onto atoms and micron-size particles, has also been used to reach inside a living cell and manipulate an organelle or chromosomes without damaging the cell or nucleus membrane. Similar optical tweezers have been used to manipulate a single molecule of DNA and pull against the force of a myosin molecule found in muscle tissue tugging on an actin filament.

Schawlow had many productive students and associates. I (C.H.T.) was delighted with our association at Columbia University. The last paper we ever published together was "Infrared and Optical Masers,"[3] which initiated the laser development. At Stanford University he attracted many excellent students and postdoctoral fellows. Perhaps his closest long-term associate was Theodore Hänsch, who with him did much innovative work on high-precision spectroscopy.

Professor Schawlow died of leukemia on April 28, 1999, very close to what would have been his seventy-eighth birthday. He spent his last few months in a wheel chair, gracefully accepting the expected outcome and welcoming the visits of friends and family. Appropriately, the memorial service, which celebrated his remarkable life, included happy music by the Magnolia Jazz Band.

Arthur Schawlow was not just admired, he was cherished by those who knew him. He was a great scientist of remarkable modesty, a supportive teacher, a gentle leader, and a caring human being.

Arthur Schawlow's thesis research, in close collaboration with Professor Malcolm Crawford, led him into high-resolution spectroscopy and study of nuclear characteristics by atomic spectroscopy. His student work produced seven publications, mostly on nuclear spins and magnetic movements. They included an important paper on electric field distribution within nuclei. After he came to Columbia University to work with me (C.H.T.) on a postdoctoral fellowship his interest and ideas about nuclei continued. This resulted in measurements and interpretation of nuclear quadrupole moments and a publication concerning the effect of nuclear charge distribution on X-ray fine structure. At Columbia he also was deeply involved with microwave spectroscopy of molecules, and with some of my students found the first microwave spectrum of a free radical, OH. This initial measurement was critically important in the later search for and discovery of OH in interstellar gas clouds by Allen Barrett, who was one of my students at that time. This was the first molecular microwave radiation found in interstellar clouds. It helped open up an important series of discoveries of interstellar molecules and molecular masers, OH itself producing many powerful masers. I was also pleased that Arthur agreed to coauthor with me the book on *Microwave Spectroscopy*, published in 1955 by McGraw-Hill. His work on it began at Columbia University but continued nights and weekends after he moved to the Bell Laboratories in 1951.

At Bell Laboratories Arthur initially worked on superconductivity, collaborating with others there, including Berndt Matthias, Harold W. Lewis, and George Devlin. As a consultant at Bell Laboratories I visited him there on occasion, and one day in the fall of 1957 I mentioned my ideas about making optical and infrared masers (later to be called lasers), and found he had also become interested in this possibility. We put our ideas and efforts together and Art came up with the idea of using two parallel mirrors as a way of obtaining a single mode of oscillation. I thought this idea might have somehow come from his early work at Toronto University on Fabry-Perot interferometers, but he always dismissed that as unlikely. After all, I had myself worked with Fabry-Perot systems but somehow missed the idea. Because we felt optical and infrared masers clearly should be patented, and I decided to interpret my own ideas as belonging to Bell Laboratories, from then on we kept the laser idea as a proprietary secret until a patent was prepared in mid-1958. After this our manuscript on the subject could be circulated and it was published in late 1958.

Publication of the paper on “Infrared and Optical Masers”[3] stimulated a number of efforts to build them. The first International Quantum Electronics Conference, held in the fall of 1959, was humming with ideas of possible optical transitions that might lead to the realization of the first laser. Art, along with colleagues Frank Varsani, Dar Wood, Al Clogston, Stanley Geshwind, and Robert Collins at Bell Laboratories, were exploring the optical properties of ruby ($Al_2O_3{:}Cr^{3+}$) and were thinking that this material could be a potential candidate for a laser. Art’s studies of the properties of the narrow R_1 and R_2 resonance lines in ruby[4] generated significant interest, but he eventually rejected the R lines as a potential lasing candidate at the Quantum Electronics Conference.[5] Art was skeptical that a good lasing transition could terminate in the ground state, and suggested instead the near-neighbor pair lines in ruby he had also been studying as a means of obtaining a 4-level system.[6]

In this case Art’s intuition proved wrong. The following year Theodore Maiman used a flash lamp to excite a lightly doped “pink” ruby crystal and achieved laser action on the R_1 resonance line. Shortly afterward Art and his colleagues were able to demonstrate lasing on his candidate pair lines with more highly doped ruby using the same type of a flash lamp used by Maiman in his landmark experiment. Art later remarked, “I thought I was being clever, but I outsmarted myself.”[7]

Art and his Bell Laboratories colleagues continued to explore narrow resonance impurity lines in solids and how these lines were affected by strain, magnetic fields, temperature, and other perturbations. In 1961 he accepted a professorship at Stanford, where he continued these pioneering studies with his graduate students and postdoctoral fellows. His young colleagues included Roger Macfarland, William Yen, Linn Mollenauer, and Frank Imbush, who went on to become leaders in solid-state spectroscopy in their own right. Other Art Schawlow students, including John Emmett, John Holzrichter, and Jeff Paisner, became experts in high-energy pulsed lasers, eventually rising to positions of high responsibility at Lawrence Livermore National Laboratory. Warren Moos, a postdoc during these years, went on to Johns Hopkins University to become a leader in astrophysics spectroscopy.

In the spring of 1970 Theodor Hänsch arrived at Stanford, having just finished his graduate studies with Peter Toschek. He recalls, "Walking down the hallway of the second floor of the Varian physics building, a futuristic poster on one of the doors caught my eye. It showed an enormous laser gun blasting at some attacking rockets in the sky. The caption in bold letters read "The incredible laser." In smaller letters below someone had written, "For credible lasers, see inside."[8]

Ted Hänsch and, independently, Christian Bordé invented Doppler-free saturation spectroscopy, based in part on the spectral hole-burning effect (the "Lamb dip") discovered by Roger Macfarlane, William Bennett, and Willis Lamb. With Art's support, encouragement, and council Ted initiated a remarkable series of experiments in which narrow atomic and molecular lines could be observed without the inhomogeneous broadening due to the Doppler effect. Using a prism-tuned, single-mode argon ion laser, Ted, Marc Levenson, and Art resolved the hyperfine lines of molecular iodine. With a pulsed dye laser that Ted built they were liberated from working with absorption lines that accidentally overlapped the narrow tuning range of existing lasers. Ted, Issa Shahin, and Art were able to measure the Doppler-free spectra of the sodium D lines.[9] Upon seeing the sodium spectra taken the night before, Art immediately urged, "You have to do the same with the red Balmer-α line of atomic hydrogen."

Within a few weeks the same team recorded the saturation spectra of the red Balmer line of atomic hydrogen.[10] This quick and dirty experiment with atomic hydrogen was to initiate an experimental program that is continuing today after three decades and seven orders of magnitude of spectacular improvement. In addition to Shahin, other students and postdoctoral fellows that further refined this measurement in these early days included Munir Nayfeh, Siu Au Lee, Stephen Curry, Carl Wieman, John Goldsmith, and Erhard Weber.

During this enormously productive period Art introduced molecular-state labeling, in which a laser is used to preferentially pump molecules out of a specific occupied molecular level. Absorption lines from the labeled level as measured using a second broadband laser were then weakened, as observed by Mark Kaminsky, R. Thomas Hawkins, and Frank Kowalski.[11] Following the invention of polarization spectroscopy by Carl Wieman and Ted Hänsch, Art and his students used polarized light to label specific angular momentum states.[12-15] These methods enabled Art and his associates to greatly simplify and then give assignment to the forest of absorption lines in molecular spectra.

Other advances during this time included the two-photon Doppler-free spectroscopy of sodium using a CW dye laser with Ted Hänsch et al.,[16] near-resonant enhancement of two-photon spectra with Sune Svanberg et al.,[17] observation of quantum beats with Serge Haroche and Jeff Paisner,[18] and Doppler-free opto-galvanic spectroscopy with James Lawler, Allister Ferguson et al.,[19-20] and polarization intermodulation spectroscopy with Ted Hänsch et al.[21] Also during this time William Fairbank, Jr., and Gary Klauminzer studied the excited-state absorption spectra of ruby, emerald, and MgO:Cr^{3+},[22] and Fairbank demonstrated that it was possible to use resonance fluorescence to detect a single atom in a laser beam.[23]

In 1981 Arthur Schawlow was named co-winner of the Nobel Prize for his many contributions to the development of laser spectroscopy. In his Nobel lecture "Spectroscopy in a New Light" he listed 21 of his most significant papers out of the 168 papers he had coauthored. Conspicuously absent from this list is a two-page paper published in *Optics Communications* in 1975 entitled "Cooling of Gases by Laser Radiation."[24]

In their paper Ted and Art outlined a proposal to cool atoms by surrounding the atoms with light from all sides, realizing that the atoms would lose kinetic energy by preferentially scattering laser light opposing the motion of the atoms due to the Doppler effect. They made a rough estimate of the final temperature by assuming that the initial Doppler width of the absorption line could be reduced to the natural line width of the scattering transition. In the case of magnesium they estimated that atoms in the vapor phase could be cooled to temperatures of ~0.24 K.

Their idea was demonstrated by Leo Hollberg, John Bjorkholm, Alex Cable, Art Ashkin, and myself (S.C.) 10 years after their publication. In our initial experiments sodium atoms were cooled to temperatures of ~0.24 thousandths of a degree above absolute zero. Progress in this field developed rapidly and by the year 2000 billions of atoms could be laser cooled to temperatures as low as 300 nanokelvin at densities greater than 10^{13} atoms/cm^3. Further cooling by evaporation in magnetic or optical traps has led to the formation of new states of matter: Bose condensates in a dilute gas and degenerate Fermi gases.

The field of laser cooling and trapping of atoms was recognized with a Nobel Prize in 1997 in recognition of the revolutionary impact of this work on atomic physics, laser spectroscopy, and metrology. And in 2001 on the one-hundredth anniversary of the first Nobel Prize, a Nobel Prize was given to researchers who used laser cooling and atom trapping methods to achieve Bose condensation of a dilute alkali gas.

In 1987 Arthur Schawlow succeeded in convincing me (S.C.) to leave Bell Laboratories and join the faculty at Stanford University. Soon after arriving I settled into the enjoyable routine of retreating often into his office to unwind and discuss what was happening in my laboratory, with physics at large, and life in general. During one of these conversations I asked Art why he did not even *mention* his seminal laser cooling paper in his 1981 Nobel lecture. He shrugged in his characteristically modest and self-effacing way, "In 1981 how was I to know it was going to become important?"

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