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LEONARD MANDEL
1927–2001

A Biographical Memoir by

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LEONARD MANDEL

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LEONARD MANDEL WAS the Lee DuBridge Professor of Physics and Optics at the University of Rochester: masterful scientist, exemplary teacher, generous colleague, and beloved family man. He is widely credited with being one of the founding fathers of the field of quantum optics, which sprung from the marriage of quantum mechanics and optics in the 1960s into one of the most exciting areas in modern science. He made seminal contributions to experimental and theoretical problems of optical coherence, laser physics, and quantum optics, including laser phase transitions, locality violations in optics, tests of quantum mechanics, and nonclassical states of light. A central theme of his research was a continuing quest to explore and elucidate the quantum character of light by way of insightful theoretical analyses and a set of pioneering experiments that have become landmarks in the field. He deepened our understanding of quantum mechanics in important and lasting ways through ingenious experiments that provided convincing demonstrations and precise tests of many of the most counterintuitive aspects of the quantum nature of light. Rarely has any one individual so intimately investigated and so dramatically advanced our understanding of the quantum mechanical nature of light.

Although Leonard began his research career in cosmic-ray physics in the late 1940s, he soon developed an interest in light and how it was measured. Using his knowledge of particle detectors to advantage and intrigued by the 1956 experiment of H. Hanbury Brown and R. Q. Twiss, he early on made important contributions to the field of photon-correlation spectroscopy, in which correlations between counts in independent photodetectors yield information about the source of light (e.g., about the diameters of stars). He then went on to make some of the earliest measurements of interference between independent lasers.

These experiments raised the hackles of some physicists at least in part because of Nobel Laureate Paul Dirac's often quoted statement that "photons only interfere with themselves," suggesting that photons from independent sources do not interfere. In fact these experiments demonstrate something deeper, namely the existence of higher order correlations of the radiation field that were not yet thought of when Dirac made his statement. Over the course of his career Leonard devised ingenious experiments to explore the quantum statistics of light and thereby to advance profoundly our understanding of its quantum character.

In 1977 Leonard's quest led to the pioneering demonstration of the manifestly quantum, or "nonclassical," nature of light by way of the first observation of photon antibunching, here for the fluorescent light from a single atom. These measurements are widely regarded as having ushered in a new era in quantum optics involving nonclassical effects. Moreover, the same techniques are now employed as a definite test to identify individual quantum emitters in diverse physical systems and to characterize nonclassical light for various applications, including for secure quantum communication schemes.

In the early 1980s Leonard initiated what would become a landmark set of experiments involving pairs of photons produced by the fission of a pump photon in the process of parametric down conversion, including the creation of a localized one-photon state. He developed new experimental tools based upon parametric down conversion to produce seminal and striking experimental proofs of some of the most unsettling aspects of basic quantum mechanics. Leonard showed that Dirac's well-known statement about single-photon interference must be modified to assert that "in fourth order interference, a pair of photons interferes only with the pair itself." In a classic experiment with photon pairs in 1995 he demonstrated with brilliant clarity a central tenet of quantum mechanics, namely, that there is no physical reality for elemental quantum processes in the absence of a measurement. Leonard's ability to identify critical issues and make their consequences manifest are evidenced in many other important contributions to both classical and quantum optics.

Mandel was honored by his peers, receiving awards that included the Frederic Ives and the Max Born medals of the Optical Society of America, the Thomas Young Medal of the British Institute of Physics, and the Marconi Medal of the Italian Research Council. He was elected to the New York Academy of Sciences and to the American Academy of Arts and Sciences. Shortly after his death he was posthumously elected to the National Academy of Sciences.

EARLY LIFE

Leonard Mandel was born in Berlin on May 9, 1927, the only child of Naftali and Rosa Mandel. Naftali had grown up in Poland, but his parents sent him to Berlin when he was 16 because of their concern that he would be killed if conscripted into the Russian army. From a penniless beginning and with the help of a stranger, Naftali was ultimately able to start a successful business of his own. Leonard's mother, Rosa, led a very different life. She was one of 12 siblings and grew up in a close-knit family. Of the 12 children in her family, only Rosa, three of her sisters, two brothers, and their families survived the Holocaust. Of his siblings, only Naftali survived.

In his early life in Berlin, Leonard was able to stay focused on his studies and excel in school, despite the violent anti-Semitism he was beginning to experience. He was deemed a gifted violinist but realized at a young age that his life's interests lay elsewhere, although he did continue to play for pleasure throughout his life. Leonard's family was pursued by the Gestapo; however, with the help of Rosa's sister, who was already in England, they escaped to London, leaving most of their belongings behind. While his parents struggled to rebuild their life, Leonard lived in a hostel with other Jewish refugee children who were evacuated to Bedford for safety when the war started. Some years later, Leonard and his parents moved to Llangollen in North Wales. It was here that he had his first physics lessons. He had never encountered a subject that excited him so much, and he knew right away that he wanted physics to be part of his life. He showed exceptional aptitude, winning the science prize and prompting his physics teacher to write on his report card, "Surely this boy is a genius." The family returned to London, only to be greeted by Flying Bombs and V-2s, and spent their nights sleeping on a subway platform. Back in London, Leonard attended the William Ellis School, a distinguished boy's grammar school, where he excelled academically and also became the most honored student in the school (as the head boy).

Because he had such an outstanding school record, his teachers strongly supported his decision to apply for a Cambridge scholarship and fully expected him to get one, but he was turned down. He was not eligible for several other scholarships because he was not British born. It was then that his physics teacher, Miss Shavelson, to whom he was forever grateful, suggested that he apply to Birkbeck College, University of London, where he could become financially independent by working during the day and taking classes during the evening. Leonard was accepted as a student and also employed as a lab assistant in the physics department. In two years he earned his B.Sc. in mathematics and physics, graduating with first-class honors in 1947. In only one year more (rather than the usual two), he obtained a B.Sc. special in physics, also with first-class honors. He then joined the Cosmic Ray Group of E. Paul George to work toward his Ph.D., having previously assisted in building equipment for this group.

Leonard's graduate studies were in the field of cosmic-ray physics, which required him to construct and transport delicate particle detectors to an observatory at the Jungfraujoch high in the Swiss Alps. In the Alps he not only enjoyed working but also relished the opportunity to ski and to climb mountain ridges alone. On one of these escapades across a glacier, he surely would have been lost for good sliding toward a precipice were it not for his trusty penknife, which is a story his own students would hear told matter-of-factly in years to come. Leonard completed his Ph.D. in only three years, graduating from Birkbeck in 1951 with a thesis titled "Interactions of Non-Ionizing Cosmic Ray Particles." He was always grateful to Paul George for giving him the freedom to work on his own ideas in his own way. Throughout his own career Leonard enabled his students by entrusting them with the same faith and confidence in their abilities that George had shown in him.

After obtaining his doctoral degree, Leonard joined the Research Laboratories of Imperial Chemical Industries Ltd. in Welwyn Garden City, where he was appointed technical officer and published his first paper.[1] Even in this earliest paper it is possible to glimpse the origins of what would become a lifelong interest in stochastic processes in the paper's discussion of limitations to measurement accuracy due to noise from Geiger tubes. After a few years at ICI, Leonard decided to return to academia but had a hard time convincing colleges that he was willing to take a large cut in salary to do so. He was very pleased when he was offered a lectureship in the Physics Department at Imperial College, where he moved in 1955, later becoming a senior lecturer.

While a graduate student at Birkbeck College, Leonard met his future wife, Jeanne. She was a physics undergraduate student who had heard that he was the best student advisor around, and who then learned first-hand that this was true. In her own words, "His answers to my questions were so clear and simply explained that I was left wondering why I had ever thought there was a problem." Jeanne later worked as lecturer demonstrator and printed all the photographs for Leonard's doctoral thesis, where she experienced first-hand his perfectionist nature.

Leonard and Jeanne were married in 1953. Their courtship was cemented through parallel academic interests and similar hobbies. They excelled at playing doubles in table tennis, enjoyed ice skating together, and did very well in ballroom dancing. Their daughter, Karen Rose, was born in 1956, followed by a son, Barry Paul, in 1959.

During the years at Imperial College, Leonard began what would become a lifelong association with Emil Wolf, who by then had moved from the University of Manchester in England to the University of Rochester in New York. Jeanne relates the story of Emil and Leonard working at the Mandel home on a joint paper late into the night to finish before Emil's departure back to Rochester. Emil explained how much easier the collaboration would be if only Leonard would move to the United States. He continued to press his case, and in 1960 and again in 1963 the Mandel family spent a few months in Rochester. During these visits, Leonard realized that here he would be much freer to pursue his own lines of research. In 1964 Leonard was offered a professorship in the Department of Physics at the University of Rochester, where it was hoped that his appointment would strengthen a new research group in the rapidly developing field of optical coherence. It was a difficult decision for the family to leave England for the United States, but in 1964 Leonard left Imperial College to become professor of physics at the University of Rochester, where he remained until his death in 2001.

PROFESSIONAL HISTORY

Although Leonard's initial research had been in nuclear physics, his interest in optical coherence was stimulated by the Brown-Twiss experiment in 1956. Leonard's entrance into the debate about the appropriate theoretical description of this experiment were classic papers in 1958-1959 in which the so-called "Mandel formula" for photoelectric counting made its first appearance.[2] This work first, and firmly, established the relationship between the classical statistical properties of incident radiation and the emitted photoelectrons. It has become a mainstay of photon-counting measurements.

Soon after his move to the University of Rochester, Leonard and his student R. Pfleegor reported in 1967 a now famous experiment involving interference at the single photon level.[3] More precisely, two beams derived from independent lasers were attenuated to a level such that the average interval between photon emissions was very long compared with the transit time through the apparatus. Even though each photon was absorbed at the detector long before the next one was emitted, interference fringes were nonetheless recorded. Leonard concluded that it is better "to associate the interference with the detection process itself, in the sense that the localization of a photon at the detector makes it intrinsically uncertain from which of two sources it came." In an ingenious extension of the Brown-Twiss experiment, Leonard employed a detection scheme exploiting interference of fourth-order in the amplitudes of the relevant fields, as opposed to the more familiar second-order interference (e.g., as in a Michelson interferometer) that would have been absent here. Over the next three decades, Leonard continued to refine fourth-order interferometry into an extremely powerful tool for investigations of the quantum character of light, so much so that it is now a standard technique employed by groups worldwide.

The growth of quantum optics was triggered and sustained by the invention of the laser. With the hindsight of history, it may be surprising that there was considerable controversy about the quantum statistical properties of the laser and other light sources in which Leonard and his colleagues George Sudarshan and Emil Wolf were actively involved.[4,5] Perhaps spurred by this debate, Leonard and his students F. Davidson, D. Meltzer, and others were among the first to carry out basic experiments to elucidate the coherence properties of the laser in the transition from incoherent to coherent emission around threshold.[6,7,8] Carried forward by several successive generations of graduate students, these early studies of the light from a single-mode laser grew over the ensuing decades into diverse investigations of more complex laser behavior, including mode correlation and competition in ring lasers, and optical bistability and first-order phase transitions in dye lasers.[7,8]

Although quantum theories are sufficient to understand the laser and general optical interactions, it is nonetheless the case that the statistical properties of optical fields can be described almost without exception in terms of so-called semiclassical theories in which the material system is quantized but the field is treated classically. Since the earliest days of quantum optics, much attention has thus been directed to finding physical processes that generate nonclassical fields and to identifying unique experimental signatures. Through diverse theoretical analyses, Leonard played a vital role in this effort, including the prediction that the fluorescent light from a single atom would exhibit "photon antibunching,"[9] which is a manifestly quantum effect derived independently by H. J. Carmichael and D. F. Walls. Leonard and his students H. J. Kimble and M. Dagenais carried out an experiment to investigate this effect, and in 1977 succeeded in making the first observation of photon antibunching.[10] Subsequently, R. Short and he made the first measurements of another nonclassical effect, namely sub-Poissonian photon statistics, again in the setting of single-atom resonance fluorescence.[11]

The observation of photon antibunching by Leonard and his students is widely regarded as having initiated a new era in quantum optics. Beyond being simply a matter of semantics, such nonclassical fields are required to achieve measurement precision beyond the standard quantum limits, and more generally form the basis for advances in quantum information science related to quantum computation and communication.

In further investigation of nonclassical light, Leonard recognized in the early 1980s the tremendous potential associated with the process of parametric down conversion, in which a single pump photon is split into a pair of "daughter" photons. His insight came in large measure from his own theoretical investigations, including work on configuration-space wave functions for photons[12] and on two-photon interference.[13] Over the next two decades, Leonard and his students would achieve a dazzling set of experimental advances related to nonclassical states of light, to two-photon interference, and to quantum entanglement, which he has reviewed.[14] This work continued to advance and refine the theme of fourth-order interference that Leonard had previously employed but now with pairs of photons.

In his early work on parametric down conversion, Leonard and his students S. R. Friberg and C. K. Hong first demonstrated the nonclassical character of the down conversion process[15] and were thereby able to achieve a localized one-photon state.[16] They further made the first demonstration of quantum cryptography with correlated pairs of photons.[17] With Hong and Z. Y. Ou, he introduced what is known today as the Hong-Ou-Mandel interferometer.[18] In an ingenious experiment with Ou, Leonard utilized polarization entanglement for photon pairs produced in down conversion to achieve a violation of Bell's inequality (i.e., local realism).[19] In work with Ou, L. J. Wang, and X. Y. Zou, he systematically explored other aspects of quantum entanglement, including phase memory due to entanglement with the vacuum,[20] frequency entanglement to produce spatial quantum beating,[21] and phase entanglement to achieve nonlocal interference in separated photon channels.[22]

With these advances, Leonard played a pioneering role in laying the foundations for modern research in quantum optics and quantum information science, including for Bell-state detection to enable diverse tasks, such as quantum teleportation of the polarization state of single photons. The realization of quantum computation by way of linear optics and photon detection incorporates the Hong-Ou-Mandel interferometer as a ubiquitous element.

Throughout the 1990s Leonard continued a prodigious output of remarkable experiments to advance our understanding of quantum measurement, of nonclassical field states, and of nonlocal effects. In 1991 Leonard and his students L. J. Wang and X. Y. Zou reported what has since been referred to as a “mind-boggling” experiment involving interference from the superposition of fields from two different but coherent parametric processes.[23] In this experiment the mere *possibility* of making a measurement was shown to destroy an interference pattern, even if this possibility went unrealized and absent any external “disturbance.” Following the theory of M. O. Scully in 1982, Leonard realized that this experiment could also be interpreted as a realization of a “quantum eraser,” in which information contained in one photon, or the erasure of this information, could change the way we viewed another photon.[24] In another experiment Leonard and his students D. Branning and J. Torgerson and research associate C. Monken made a striking demonstration of one of the most unsettling aspects of the quantum realm, namely, that there is no physical reality in the absence of a measurement.[25]

Regrettably, it has not been possible in this biography to offer more than these few glimpses into the set of topics encompassed by Leonard’s remarkable career.[7,8] We might just mention that in addition to the study of nonclassical fields, he was also deeply interested in the question of quantum phase for the electromagnetic field and, together with his students A. Fougeres and J. W. Noh, developed an operationally based theory and carried out extensive experiments to test this and other competing theories.[26] Leonard’s ability to identify critical issues and make their consequences manifest are evidenced in many important contributions, including his fundamental analysis of photon cloning[27] and his work on cross-spectral purity, concerning a criterion ensuring that the spectrum of light remains unchanged on superposition in an interference experiment.[7] With his last student, A. Kuzmich, and his colleague N. Bigelow he initiated a new line of research related to nonclassical states for a collection of atomic spins, which led to one of the first demonstrations of "spin squeezing,"[28] thereby helping to initiate what is by now a very active area of research worldwide.

Leonard supervised the thesis research of 39 students, many of whom subsequently became leading figures in diverse areas of science and technology. He earned the lifelong respect of his students for his detailed and conscientious stewardship of their scientific development. Research problems were chosen to fit a particular student's capabilities with an eye toward improvement with each experience. Most often twice per day he made the rounds of his laboratories to interact with each of his students, with help ranging from optical alignment to electronic design to theoretical calculations. Not wanting to interrupt a student at work, he would sometimes quietly approach in his soft-soled shoes to view the activity at hand, leading to more than a few startled heart skips. In response to a student's query ("Can you see a signal yet?") as some component of an apparatus was being aligned, would come his distinctively British reply, "Not a sausage!" Once when the need arose to regulate the water cooling for an oil diffusion pump, he arrived the next morning with a flow switch commandeered from a washing machine at home, which did indeed solve the problem.

Notes with calculations or designs given to him were promptly returned with extensive annotations (corrections of grammar as well as physics), most often the following morning. At least one student carried these exchanges over the Queen's English forward into later life by sending Leonard a letter with a dangling participle hidden in the text only to receive a prompt reply with the postscript, "I found it!"

In addition to his work at the frontiers of physics, Leonard established a reputation as an excellent teacher at all levels of the university curriculum. He had a special interest in neophyte science students and developed the first course at the University of Rochester for nonscience majors, which he taught regularly for 20 years. In 1992 he received the university's Faculty Award for Graduate Teaching.

Leonard published about 300 papers, was the coauthor with Emil Wolf of a comprehensive book of more than 1,100 pages entitled *Optical Coherence and Quantum Optics,*[7] and was the coeditor of several conference proceedings. In 1980 his paper on coherence properties of optical fields coauthored with E. Wolf in 1965 was designated a Citation Classic by the Institute of Scientific Publications.[5] In 1988 the paper was listed as one of the 100 most cited articles published in the *Review of Modern Physics* since 1955. Beyond the many top awards that he received, during the period 1966-1995 he was one of the main organizers of the Rochester Conferences on Coherence and Quantum Optics.

An account of Leonard's career and of his scientific contributions and the enumeration of the many honors he received is only a part of the story. What it does not bring out is that Leonard was a scientist with a warm personality, humility, and compassion and with a delightful sense of humor. He enjoyed a happy family life with Jeanne, a ballet teacher and with whom he shared the love for ballet, and with their two children, Karen and Barry. He had a warm and close relationship with his children and four grandchildren, always finding time to become actively involved in their lives. He was never too busy to help with homework, teach table tennis, go to concerts and sports events, or simply to sit down and discuss anything that interested them. He only gave advice when asked. They all remember the many family dinners when he would think of a problem and, with a twinkle in his eyes, give it to them and then listen as they came up with some interesting but sometimes unlikely solutions.

All who were fortunate to have been associated with Leonard Mandel will always remember him with deep affection and utmost respect. His example as mentor, colleague, and friend will vividly continue to shape our own lives. His career provides a standard for accomplishment and integrity that exemplifies the best of a noble profession. He is greatly missed.

THE AUTHORS ARE grateful to the Mandel family for sharing many insights into Leonard's life. H.J.K. acknowledges the contributions of Emil Wolf, who coauthored an obituary, which appeared in the August 2001 issue of *Physics Today,* as well as the contributors to the symposium honoring Mandel,[8] upon which some parts of this article are based.

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