

PERSPECTIVE

About Roy Glauber

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Abstract

We recount the life, work, and legacy of the theoretical physicist Roy Glauber (1925–2018). Admitted to Harvard at age 16, called upon to participate in the Manhattan Project at age eighteen, and appointed to the Harvard Physics faculty at age 29, Glauber is credited with seminal contributions to three separate fields of physics: nuclear scattering, statistical physics, and foundational work in quantum optics, which earned him the 2005 Nobel Prize in Physics. Over decades, Glauber was also a dedicated teacher of high-school, college, and graduate students. His pedagogical gifts are reflected in his lucid papers that read as if they were written yesterday.

Key points

- perspective on the life, work, and legacy of the 2005 Physics Nobel laureate Roy Glauber (1925–2018)
- impact of Glauber's contributions on large swaths of physics, from nuclear to optical to condensed matter
- Glauber's work in quantum optics has nurtured burgeoning areas of quantum science and engineering

KEYWORDS

coherent states, Glauber approximation, Glauber dynamics, Manhattan Project, nuclear scattering, quantum optics, Roy Glauber

INTRODUCTION

Roy Jay Glauber was widely respected in the world of physics for his seminal work in three separate research areas: nuclear scattering (Glauber Approximation), statistical physics (Glauber Dynamics), and quantum optics, a field he created. For his foundational work in quantum optics, he was recognized by the 2005 Nobel Prize in Physics (one-half of the share).

This Perspective on the life, work, and legacy of Roy Glauber is structured as follows: this section is devoted to his life and career; the second section presents a technical summary of Glauber's major contributions to physics; the third section is dedicated to Glauber's

teaching and writing; and finally, the fourth section summarizes the impact of Glauber's discoveries.

Roy was born on September 1, 1925 into an unconventional family (much of the biographical information that follows was adapted from Ref. [1]). When he reached 2 years of age, his parents abandoned their tiny apartment in Manhattan and moved into a company-owned automobile, see Figure 1. Roy's father was a traveling salesman who went from farm to farm in the Midwest. At night, the family usually slept in a room rented from a farmer and advertised by a road sign "Tourists-Vacancy." Roy's mother, trained as an elementary school teacher, was determined to make the nomadic life as instructive as possible for her (then) only child: she would visit with him fire and

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FIGURE 1 Roy, age 5, standing on the bumper of the company car used by his father, 1930. Reproduced with permission from Valerie Glauber Fleishman and Jeffrey Glauber.

police stations, courtrooms, and even lockups—introducing Roy to civics, as he would later comment with glee.

Their itinerant life “with no two successive nights in the same house”¹ came to an end with the birth of Roy’s sister, Jacqueline, in 1931 and the need to send Roy to school. The family settled in New York, where it continued moving but only between apartments that the parents had been renting in the city’s different boroughs. Most of the schools Roy went to were uninspiring to him until the family moved to Upper Manhattan and Roy started attending at age 12 the ninth grade of a public school there. Not only were the math and science classes a “redemption” of Roy’s previous experiences,¹ but the gift of an astronomy book and a visit to the Hayden Planetarium converted Roy into a science enthusiast. The dexterity he cultivated while pursuing his earlier interests in painting and sculpture was quickly redirected to building scientific instruments, among them a reflecting telescope or a device to reveal polarization-by-reflection phenomena. The American Institute of the City of New York gave him the opportunity to give his first scientific talk—a 10-min presentation on the forthcoming 200-inch telescope at Mount Palomar. Roy was still only 12 then.

In 1938, the Bronx High School of Science opened, just in time for Roy to enroll as a freshman. The teachers were excellent—as were the schoolmates; the future Nobel laureates and eventual Harvard colleagues, Sheldon Glashow and Steven Weinberg, would also attend “Bronx Science.” As Roy would put it, “We seemed to have the depression years to thank for [the excellent teachers] ... seeing no future in continuing their studies, [they] had taken refuge in positions with the school system.”¹ By that time, Roy had a scientific mentor, Dorothy Bennett, an assistant lecturer at the Hayden Planetarium who wit-



FIGURE 2 Roy Glauber presenting his reflecting 6-inch telescope (left) with a diffraction grating spectroscope (center) at the Science Congress in New York, 1940. Reproduced with permission from Valerie Glauber Fleishman and Jeffrey Glauber.

nessed Roy’s talk on the Mount Palomar telescope. She introduced him to the Junior Astronomy Club that deepened Roy’s passion for building optical instruments. His 6-inch reflecting telescope fashioned with a diffraction grating as a dispersion element, see Figure 2, won acclaim and was exhibited at the New York World’s Fair of 1939 and 1940. In 1941, Roy gave an invited talk about the photographs (of planets, planetary nebulae, double stars, and clusters) taken with his telescope at a conference of the New York Electrical Society entitled “To-morrow’s Scientists.”

At the same time, Roy experienced a turning point in his relation to mathematics: on the suggestion of his math teacher, he taught himself elementary calculus in his sophomore year and by the time he graduated from “Bronx Science,” he had mastered enough to be able to skip several math courses in college.

The college was Harvard and Roy became a freshman there in 1941 at age 16. Roy would not have applied to Harvard had there not been encouragement from an acquaintance (a Harvard alumnus) who recognized—as Harvard’s admissions officers would—that Harvard was the right place for Roy. Roy was admitted to several other colleges but only Harvard offered him a full scholarship (Harvard Club scholarship). Glauber: “College was for [Roy’s Harvard classmates] primarily a social experience, overlaid by a burden of course work. For me, on the other hand, having skipped a couple of grades along the way, and some two years younger than most of my classmates, it was the other way around. I enjoyed a few social contacts, but worked hard at my studies, finding them demanding at times, but on the whole well planned and satisfying.”¹

Roy’s freshman year at Harvard was punctuated by the Japanese attack on Pearl Harbor on December 7, 1941 and America’s entry into

World War Two, both in Europe and the Pacific, the next day. The mobilization of American resources required many faculty to depart for war work; the remaining compressed their courses—not only because of the depletion of their ranks but also to accelerate the education of the students before they would be drafted for military service. For instance, the four-semester physics course that Roy registered for was packed into a single semester. The university also changed its looks and habits. As Glauber observed, “Harvard’s dining halls were transformed into the cafeteria mess-halls that they have been ever since.”¹ No more waiters ... Soon, Harvard Physics announced that its graduate courses would be given for the last time “for the duration.” This galvanized Glauber to absorb most of their material by the time he turned 18, the recently lowered draft age. He registered via the National Roster of Scientific Personnel for military service and was recruited, in October 1943—at age eighteen—for the Manhattan Project. He arrived at the Los Alamos laboratory a few months after it had been launched and worked alongside luminaries such as John von Neumann, Hans Bethe, Richard Feynman, and, of course, Robert Oppenheimer, the director of the Los Alamos Laboratory.

During his time in Los Alamos (1943–46) as one of the youngest staff scientists of the Manhattan Project, Glauber worked on neutron diffusion, key to finding the critical mass of fissionable nuclei. This work was done within the group of Robert Serber, “the intellectual midwife at the birth of the atomic bomb,”² and is summarized in three lengthy secret papers, still partly classified. Among the unclassified results are analytic solutions to the generalized Milne equation for diffusion found by Glauber.³

In 2016, at the meeting of Nobel laureates at Lindau, Germany, Glauber delivered the following comment about the product of the Manhattan Project⁴: “Nobody thought of that weapon as anything that we needed in order to deal with Japan. The people who were there were almost entirely concerned with the German threat – and, of course, the German threat no longer existed when the bomb was used. But once the bomb was brought into existence, it became the property of the military people. And while there were several scientists on Advisory Committees advising the military, it was they who made the decision about the use of the bomb and I don’t think many people at Los Alamos would have been sympathetic, frankly.” When subsequently asked at Lindau whether he believed that atomic weapons should be reduced and ideally abolished, Glauber answered: “Absolute zero is the only thing, I think, that makes any sense.”⁵

Upon returning from Los Alamos to Harvard in 1946 to finish college, Glauber wasted no time and took, still as an undergraduate, the remaining physics graduate courses required. Among them, Julian Schwinger’s class proved formative for Glauber, who noted: “[Schwinger’s] knowledge and his incredibly informative lecturing style [impressed me so much] that I felt he was unique among teachers and would be the ideal thesis advisor as well.” Although Glauber became friendly with Schwinger, whom he had gotten to know already at Los Alamos, he had to work on his thesis essentially by himself as Schwinger was overcommitted. Figure 3 shows Glauber during this period. The solitary work on his thesis, *The relativistic theory of meson fields* (Harvard, 1949), shaped Glauber’s perspectives and helped him develop

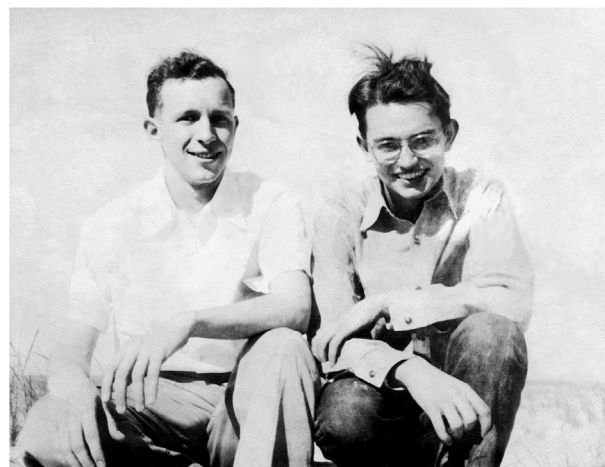


FIGURE 3 Roy Glauber (left) with his fellow graduate student and lifelong friend Charles Slichter attending the annual “beach party” of Harvard’s Physics Department in 1947. Courtesy of the Department of Physics, University of Illinois at Urbana-Champaign and AIP Emilio Segrè Visual Archives.

skills that would come to bear on his later work in quantum optics. For his postdoctoral stay (1950–51), Glauber was invited to Princeton’s Institute for Advanced Study by Robert Oppenheimer, its director since 1947. This stay was interrupted by several months spent with Wolfgang Pauli at the ETH Zurich and followed by a lectureship at Caltech in 1951–1952. Glauber returned to Harvard in late 1952 as a lecturer, was appointed an Assistant Professor in 1954, an Associate Professor in 1956, and a Professor of Physics in 1962, at age 37. In 1976, he received the Mallinckrodt Professorship of Physics at Harvard.

Among Glauber’s students at Harvard were Paul Martin, Irwin Shapiro (the very first), and (Ariel) Charles Zemach. Thomas von Foerster, Maciej Lewenstein, Benjamin Mollow, and Per Osland were Glauber’s postdoctoral affiliates.

The roster of Glauber’s senior collaborators includes Kevin Cahill (Université de Paris XI, Orsay), Ignacio Cirac (Max-Planck-Institut für Quantenoptik, Garching), Fritz Haake (Universität Duisburg-Essen), Gerd Leuchs (Max-Planck-Institut für die Physik des Lichts), Maciej Lewenstein (Institut de Ciències Fotòniques, Barcelona), Vladimir Man’ko (Universität Ulm), Arkadiusz Orłowski (Polish Academy of Sciences, Warsaw), Sudakhar Prasad (University of New Mexico), Wolfgang Schleich (Universität Ulm), Marlan Scully (Texas A & M University), Urban Titulaer (Rijksuniversiteit Utrecht), Jorge Velasco (University of Valencia), Dan Walls (University of Waikato, New Zealand), and Herbert Walther (Max-Planck-Institut für Quantenoptik, Garching)—some of whom he would frequently visit.

There were at least three colleagues who worked in parallel with Glauber but did not collaborate with him directly: Gert Molière (Max-Planck-Institut für Physik, Göttingen), a nuclear scattering theorist, and Leonard Mandel (University of Rochester) and Ennackal (George) Sudarshan (University of Texas at Austin), who worked in quantum optics, the former also experimentally.

Glauber was a Fellow of the American Physical Society (1972), the Optical Society of America (1985), the National Academy of Sciences

(1988), and a Foreign Member of the Royal Society (1997). He served on the National Advisory Board of the Center for Arms Control and Non-Proliferation of the Council for a Livable World.

Glauber received many honors for his research, including the Albert A. Michelson Medal from the Franklin Institute, Philadelphia (1985), the Max Born Award from the Optical Society of America (1985), the Alexander von Humboldt Research Award (1989), the Dannie Heineman Prize for Mathematical Physics from the American Physical Society (1996), Medalla de Oro of the Consejo Superior de Investigaciones Científicas (in 2008)—apart from the 2005 Nobel Prize in Physics.

Roy Glauber died on December 26, 2018 in Newton, Massachusetts. He was 93 years old.

ROY GLAUBER'S RESEARCH

Scattering

Throughout the intervening 13 years following his PhD, Glauber worked on scattering, mainly nuclear. His interest was, however, triggered during his 1-year stint at Caltech by the puzzling interpretations of electron diffraction data on the structure of gaseous molecules and crystals by the group of Linus Pauling. Glauber recognized that the puzzle could be solved by revising the inadequate first-order Born approximation for electron scattering by ascribing a phase to the scattering amplitude.^{6,7} Pondering the mutually exclusive validity ranges of the Born and semiclassical (WKB) approximations, Glauber found an approximation for high-energy collisions that held in the intermediate range as well.⁸

For scattering at collision velocity v by a potential of magnitude V and range a , the Born and WKB approximations are valid in the limits $\frac{Va}{\hbar v} \ll 1$ and $\frac{Va}{\hbar v} \gg 1$, respectively. For collision energy E large enough that $\frac{V}{E} \ll 1$ and $ka \gg 1$, with $k \equiv 2\pi/\lambda$ the wavenumber, $\lambda = h/\sqrt{2Em}$ de Broglie wavelength, and m the reduced mass, Glauber realized that there will be little backward scattering and that the 1D forward scattering wave function could be written in the form

$$\psi(x) = \exp(ikx)\varphi(x) \quad (1)$$

with $\varphi(x)$ a slowly-varying function over (the small) λ . Plugging in the wavefunction of Equation 1 into the corresponding Schrödinger equation yields

$$\left(\frac{d^2}{dx^2} + 2ik\frac{d}{dx}\right)\varphi(x) = \frac{2m}{\hbar^2}V(x)\varphi(x). \quad (2)$$

At this point, Glauber introduced the approximation proper, namely, dropping the second derivative, $\frac{d^2}{dx^2}$, as this had little effect on the slowly varying $\varphi(x)$. Equation 2 then had a solution for the boundary condition $\varphi(-\infty) = 1$ (no back scattering) of the form

$$\varphi(x) = \exp\left(-\frac{i}{\hbar v} \int_{-\infty}^x V(x)dx\right). \quad (3)$$

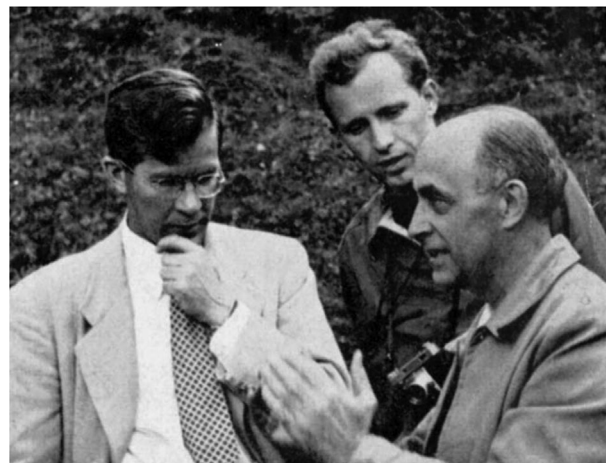


FIGURE 4 At Summer School in Les Houches in 1954, where Don Hughes (left) spoke on neutron physics, Enrico Fermi (right) on pion scattering, and Glauber (center) on collision theory. Reproduced with permission from Valerie Glauber Fleishman and Jeffrey Glauber.

Substitution of Equation 3 into Equation 1 gives the generic form of the scattering wavefunction within the *Glauber Approximation*.

The Glauber Approximation is a good approximation to the scattering problem not only under the conditions $\frac{V}{E} \ll 1$ and $ka \gg 1$ but also for *any* value of the key parameter $\frac{Va}{\hbar v}$, proportional to the product $\frac{V}{E}ka$, as no restriction has been placed on this parameter in deriving Equation 3.

A generalization to 3D and a combination with the eikonal (optical) approximation yielded the Glauber scattering amplitude for axially symmetric potentials in the form

$$f(\theta) = \frac{k}{i} \int_0^\infty J_0(kb\theta) \{\exp[i\chi(b)] - 1\} b db \quad (4)$$

with J_0 the zeroth-order Bessel function of the first kind, θ the scattering angle, b the impact parameter, and $\chi(b)$ the deflection function.

Apart from being “ready-to-use,” Equation 4 revealed a connection to optics, namely, diffraction by a transparent obstacle.⁹ The Glauber Approximation further proved capable of treating both elastic and inelastic scattering by axially nonsymmetric potentials as well as multiple scattering by many-body (composite-nucleus) targets. In his voluminous 1959 review of the Glauber Approximation,⁸ p. 315, Roy pointed out similarities between his work and that of Gert Molière from the period 1947–1952.^{10–13}

Roy took advantage of the Glauber Approximation in about two dozen papers that cover nucleon–nucleon, nucleon–nucleus, and nucleus–nucleus collisions. Figures 4 and 5 show Glauber in this phase of his career. Another topic Glauber tackled, together with Paul Martin, in the 1950s was radiative capture of orbital electrons by nuclei.^{14,15} During his sabbatical at CERN in 1967, Glauber would “gravitate back,” as he put it, “to high-energy collision theory, since experiments had begun to reveal many of the results [his] diffractive multiple scattering

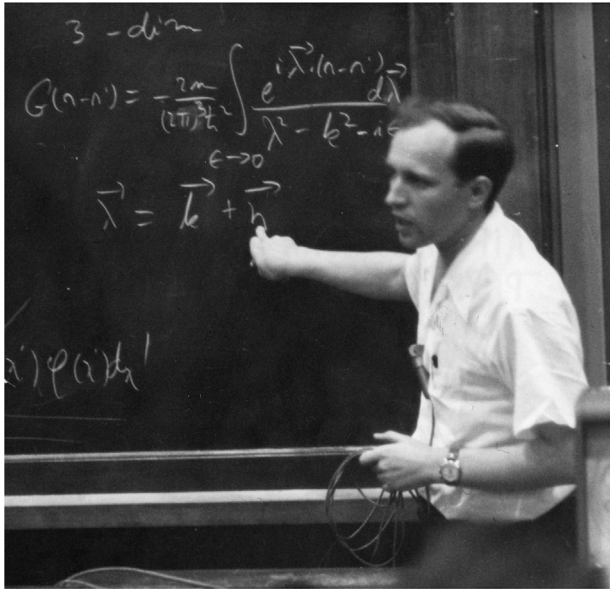


FIGURE 5 Roy Glauber lecturing on scattering theory, circa 1958. Courtesy AIP Emilio Segrè Visual Archives, Physics Today Collection.

theory had predicted.¹ Comprehensive reviews of Glauber's work on nuclear scattering appeared in 2007¹⁶ and 2020.¹⁷

Quantum optics

In a follow-up to his thesis work on meson fields, Roy Glauber investigated the radiation of photons by classical electric currents and found in 1951 that the photons thus produced obey the Poisson statistics, that is, are statistically independent of one another.¹⁸ He was thus well prepared to enter the fray when discussions unfolded about the then puzzling Hanbury Brown-Twiss effect in 1954–57^{19–24} and the workings of the laser, such as its helium–neon variety, in 1961.²⁵ Indeed, in 1963, his *annus mirabilis*, Glauber wrote a series of seminal papers on the quantum theory of optical coherence that resolved these puzzles and launched quantum optics.^{26–28} Key ingredients to his quantum theory of the optical field were the interlinked notions of coherence and the correlation function. Glauber thus disproved the widespread belief that quantization of the radiation field was irrelevant to optics. As he put it: “quantum theory ... has had only a fraction of the influence upon optics that optics has historically had upon quantum theory.”²⁹ However, once detection of individual photons became possible, optical phenomena—gleaned up to that point from ordinary light intensities—could no longer be explained by classical optics.

In laying the foundations of quantum optics, Glauber introduced the notion of an ideal photon detector. This has an infinitesimal (i.e., atomic) size and a photoabsorption probability that is independent of the frequency of the optical field. The detector measures the probability, $G^{(1)}(x, x)$, per unit time that a photon will be detected at a space-time point x . This probability is given by the expectation value of the product of the field operator, $E(x)$, with its complex conjugate, $E^*(x)$, that is,

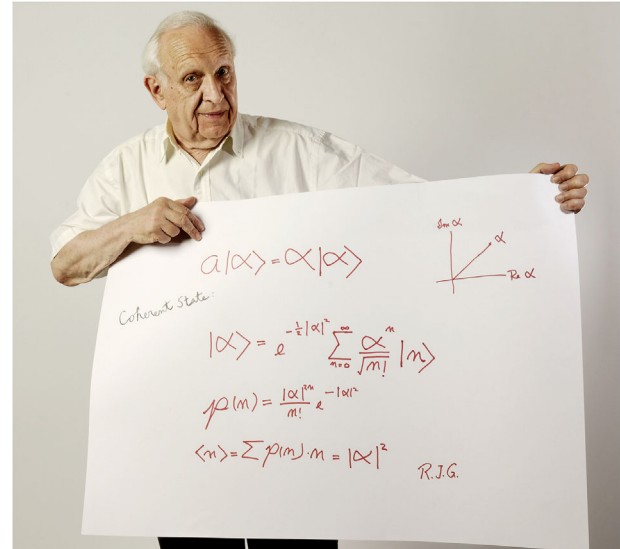


FIGURE 6 Roy Glauber displaying a poster with the gist of his theory of optical coherence in his own handwriting. Courtesy of Science Photo Library/Volker Steger, 2006.

$G^{(1)}(x, x) = \langle E(x)E^*(x) \rangle$.²⁹ In contrast, a classical “square-law detector” measures the square of the real field vector.

With this notion of the probability of detecting a photon at space-time point x , Glauber could tackle the question of what happens when two ideal photon detectors are trained at two different space-time points, x_1 and x_2 , of an optical field, which amounts to measuring the photon coincidence—or correlation—at the two space-time points. In his analysis of photon correlations, Glauber realized that the optical field operators taken at different space-time points do not commute with one another. This fundamental difference with respect to a classical optical field proved key in defining—and treating—the correlation functions for the optical field. We note that the optical field operators do not commute only if the space-time points are in the light cone of one another. If they are not, for instance, if the space-time points correspond to the same times but different locations, the optical field operators do commute, cf. Ref. [30], Sec. 10.8.

In Glauber's theory of optical coherence, an optical field exhibits a coherence of order ℓ if the correlation function, $G^{(\ell)}$, factorizes into a product of ℓ first-order correlations $G^{(1)}$ throughout the spatiotemporal extent of the field (i.e., for all values of x).³¹ In other words, if a field possesses an ℓ th-order coherence, the rate at which a j -coincidence (with $j \leq \ell$) is observed by the ideal photon counters reduces to a product of the j detection rates of the individual counters. In particular, for the Hanbury Brown–Twiss effect, the second-order correlation function, $G^{(2)}(x_1, x_2, x_2, x_1)$, already contains, apart from a product of two first-order correlation functions, $G^{(1)}(x_1, x_1)$ and $G^{(1)}(x_2, x_2)$, a cross term, $G^{(1)}(x_1, x_2)$, and therefore, does not factorize. In contrast, for coherent light, $G^{(2)}(x_1, x_2, x_2, x_1) = G^{(1)}(x_1, x_1)G^{(1)}(x_2, x_2)$ and the probability of detecting photons at space-time points $x_1 = \{r_1, t_1\}$ and $x_2 = \{r_2, t_2\}$ simultaneously remains constant for all values of $t_2 - t_1$.

In general, coherent states of the optical field display no correlations at all. Correlations only appear if the optical field is made

up of superpositions of coherent states or of incoherent states. The coherence conditions restrict the randomness of an optical field rather than its bandwidth, which can be reduced dramatically for ordinary light sources by filtering and collimation. The monochromaticity of optical sources has thus no bearing on whether they exhibit second-order or higher-order coherences. Optical fields with the same spectral distributions may exhibit quite different photon correlations that reflect amplitude and phase relations among the field's quantum states.

A fully coherent field—whose complete set of correlation functions $G^{(l)}$ factorizes—has the remarkable property that annihilating (or creating) a photon of such a field leaves the field unchanged. This is only possible if the number of photons in the field is indefinite. By taking advantage of the correspondence between the annihilation, a , and creation, a^\dagger , field operators of a given propagation mode of the optical field and the lowering and raising operators of a harmonic oscillator, Glauber was able to show that the coherent states are the eigenstates $|\alpha\rangle$ of the annihilation operator a with complex eigenvalues α ,

$$|\alpha\rangle = \exp\left(-\frac{1}{2}|\alpha|^2\right) \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle, \quad (5)$$

where $|n\rangle$ is a photon number (Fock) state with n quanta. The probability $P(n)$ of detecting n photons in a coherent state is given by the squared moduli of the coefficients of the Fock states $|n\rangle$, that is,

$$P(n) = |\langle n|\alpha\rangle|^2 = \frac{|\alpha|^{2n} \exp(-|\alpha|^2)}{n!}. \quad (6)$$

By taking into account that the mean number of photons $\langle n \rangle \equiv \langle n|a^\dagger a|n\rangle$ in a coherent state is given by $\langle n \rangle = |\alpha|^2$ (a relationship that “connects the particle and the wave view,”²⁹ that is, amplitude and the number of photons), $P(n)$ can be recast as

$$P(n) = \frac{\langle n \rangle^n \exp(-\langle n \rangle)}{n!}, \quad (7)$$

which is recognized as the (sought-after) Poisson distribution, see also Figures 6 and 7.

Glauber showed that coherent states are neither orthogonal nor linearly independent. However, any coherent state can be expanded in terms of all the other coherent states.

Finally, Glauber showed that the probability density of a coherent state is a nonspreading Gaussian wave packet whose center oscillates in a harmonic potential (all terms in the expansion are in phase). It is a wave packet with minimal uncertainty, such as the one found by Schrödinger in 1926³³ when he analyzed the transition from quantum to classical mechanics for the case of the harmonic oscillator. Indeed, a coherent state is as classical as the uncertainty principle allows. Coherent states of the optical field are often referred to as *Glauber States*.

In 1963, Roy Glauber³⁴ and, independently, George Sudarshan³⁵ introduced the P (phase-space) representation that makes it possible to express the density operator in terms of diagonal coherent states. Unlike the above Gaussian Q (coordinate) distribution, the correspond-



FIGURE 7 A “chamber” rendition by one of us (B.F. in collaboration with Adam Hoffmeister) of Roy Glauber’s quip that he uttered upon sighting a school of fish in Lake Como³²: “They obey the Poisson statistics!”

ing P -distribution of a coherent state is a delta function (Ref. 36, p. 338). Glauber made use of the P -representation in the late 1960s in his analysis of parametric amplification and in evaluating the correlations between different mode amplitudes.^{37,38}

In 1987, Glauber and coworkers launched cavity quantum electrodynamics (QED) in the optical regime. Apart from demonstrating dynamical suppression of spontaneous emission, this work³⁹ inspired a slew of studies on the entanglement between atoms or ions and cavity modes that culminated in the realization of Schrödinger’s cat.^{40,41}

Glauber also showed, *en passant*, that Dirac’s 1930 dictum that had confused generations of physicists, “Each photon [in the Michelson interferometer] interferes only with itself. Interference between two different photons never occurs,” (Ref. 42, p. 15) was wrong.⁴³ As Glauber noted in his Nobel Lecture²⁹: “It is not the photons that interfere physically, it is their probability amplitudes that interfere – and probability amplitudes can be defined equally well for arbitrary numbers of photons.”

Glauber’s work in quantum optics, described in nearly 60 publications, is extolled in the citation for his Nobel Prize in Physics, which was awarded “for his contribution to the quantum theory of optical coherence.”⁴⁴ This was in the centennial year of Einstein’s 1905 discovery of light quanta.* See also Figure 8.

After the Nobel Prize, Roy Glauber made contributions to the understanding of the statistical properties of systems of ultracold atoms—both bosonic and fermionic. Especially the P -representation

* In 1926, G.N. Lewis would coin the term photon for the quantum of light, cf. Ref. 45.



FIGURE 8 Roy Glauber with his daughter Valerie and son Jeffrey at the Nobel festivities in Stockholm, 2005. Reproduced with permission from Valerie Glauber Fleishman and Jeffrey Glauber.

of the density operator proved its worth for evaluating correlation functions for such systems, see, for instance, Ref. [46].

Glauber dynamics

A third research area that “claims” Glauber’s name is statistical/condensed-matter physics. A single paper that Glauber wrote in 1963, *Time-dependent statistics of the Ising model*,⁴⁷ secured his place in the statistical physics Pantheon. The paper is oftentimes referred to informally as *Glauber Dynamics*. The paper has been cited formally almost as often as Glauber’s founding paper of quantum optics, *Quantum theory of optical coherence*.²⁶

Conceived as a model of ferromagnetism in 1925,⁴⁸ the Ising model consists of a 1D chain of spins in contact with a heat reservoir or subject to a magnetic field. Glauber Dynamics is a model of how the spin configurations of the Ising model depend on time⁴⁹ as well as the basis of a particular model of dynamic critical phenomena in higher dimensions.⁵⁰ “Motivated more by the desire for simplicity, than for generality,”⁴⁷ Glauber set up a system of master equations for the expectation values of the spins and of pairs of spins and assumed a particular dependence of the rates at which the spins flip as a result of their interactions with their next neighbors. He then analyzed the time dependence of the Markoff process of the evolution of the spins for the case of a closed chain (a ring) and succeeded not only in obtaining explicitly the time dependence of the expectation values of the individual spins but also of the products (correlations) of pairs of spins. This allowed him to show how the spins of the Ising model reach thermal

equilibrium—as given by the generalized Maxwell-Boltzmann distribution. Moreover, Glauber was able to treat analytically the influence of a uniform, time-varying magnetic field on the ring. In particular, Glauber’s solution exhibits the tendency of any spin to surround itself with a “polarization cloud.”

Apart from the master-equation formulation of the spin dynamics, Glauber offered an alternative method for treating the Glauber Dynamics of a system of N spins that was based on what is now called the *stochastic matrix*.⁵¹ He was able to construct the 2^N eigenvectors of the stochastic matrix M and to show that they are the many-body states of the spin system. Glauber was also able to find the corresponding eigenvalues. The gap between the eigenvalue of a given many-body state and the ground state is inversely proportional to the relaxation time needed for that state to reach thermal equilibrium. Glauber Dynamics was extended to higher dimensions via computer simulation (Metropolis Monte Carlo algorithm^{52,53}).

In recent years, Glauber Dynamics has been used to simulate ergodic local Markov processes obeying detailed balance, such as those that furnish representations of quantum many-body states based on their local entanglement structure. Among these representations are tensor networks^{54–56} that make use of entanglement to reduce the exponential scaling of the dimension of the Hilbert space with the number of particles comprising a many-body system to a polynomial one. The projected entangled pair state representation of quantum states on two-dimensional lattices has been shown to entail states with critical and topological properties⁵⁷ that can serve as computational resources for the solution of NP-hard problems.⁵⁸

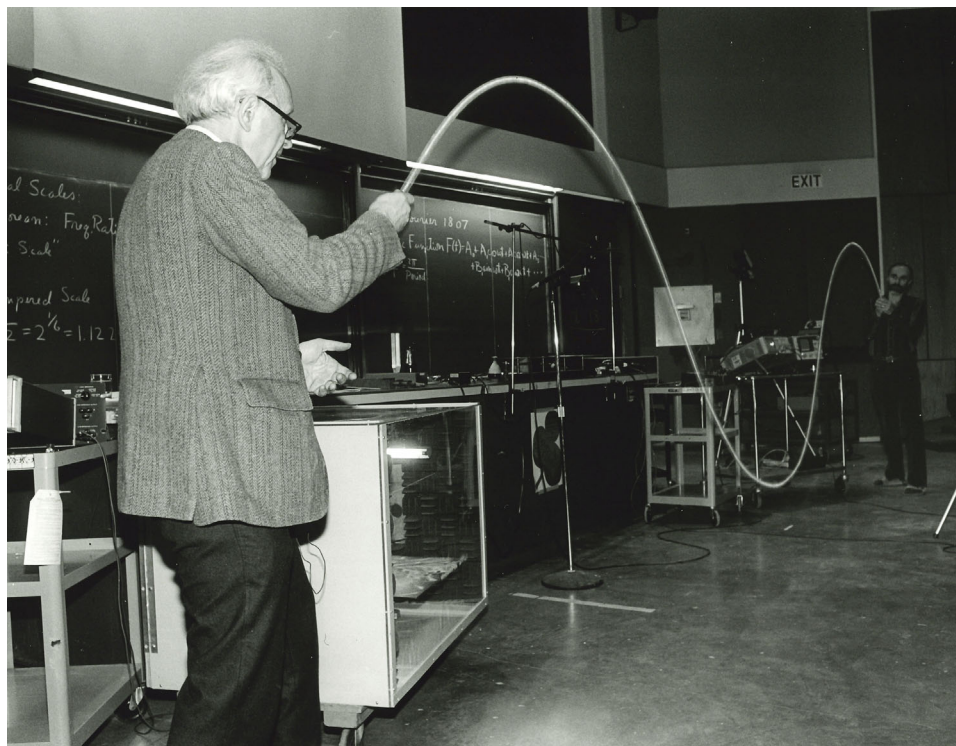


FIGURE 9 Roy Glauber demonstrating a sine curve to high-school students—and some of their teachers—at Harvard Extension School. Photo: Laura Wulf. Published by Harvard Gazette on April 28, 1989. Reprinted by permission of Harvard University Archives, UAV 605.295.8 Box 6.

ROY GLAUBER'S PERSONALITY AS REFLECTED IN HIS TEACHING AND WRITING

In the opening to his biographical note for the Nobel Foundation,¹ Roy Glauber asked: “What is it that makes a dedicated scientist out of a kid with an everyday background? Is it the ungovernable forces that seem to shape all our lives, or is it the development of our own curiosity and tastes that tips the balance of randomness? I’ve always been puzzled by those questions and can’t claim to have found serious answers.”

At Harvard, in 1955, Roy Glauber gave a course on electromagnetism. It was the first time that Roy, then an assistant professor, gave this course. He would never bring any lecture notes to class but worked out the mathematics on the blackboard. Fellow graduate students in Roy’s class—among them Sheldon Glashow—confirmed that Roy came with no lecture notes because he wanted to outdo his mentor, Julian Schwinger. Julian would arrive in class with a stack of 4-inch \times 6-inch cards about five inches thick. He would plunk them on the desk but never even glance at them, as he unreeled a dazzling lecture. Roy, along with the math details, always offered heuristic insights and, unlike Schwinger’s, his lectures were quite comprehensible.

Roy had not required his students to do much homework. However, we (D.H. and D.K.) do remember that in the Spring term of his electromagnetism course, in May 1956, Roy did not ask for a final exam but instead to write a paper pertinent to the course. D.H.: “I chose to write *On Collision and Saturation Broadening of Microwave Lines*. It was 22 pages long. Roy returned my paper marked A⁺ but didn’t add a comment.”

Remarkably, on Saturdays or Thursday evenings, Roy taught a large class of high school students at the Harvard Extension School. He did that for many years, perhaps 15. In good years, this tuition-free course attracted over 200 high-school students as well as more than a dozen high-school teachers. As part of the course, he would demonstrate a host of experiments, see Figure 9. Some used toy trains, other times he entered riding on a scooter.

Also, Roy took part in the annual IgNobel festivals held in Harvard’s Sanders Theatre. For about 30 years, he would push a large broom to clear away the cascade of paper airplanes that landed on stage.

Within the physics community, Roy brought forth his research beautifully in lectures and papers. The latter read like textbooks. Marlan Scully noted about Glauber’s coauthored papers³²: “Roy was rarely persuaded that a manuscript was ready until he had thoroughly vetted it for rigor and clarity, a process that could take months.”

Here is how trying—but also rewarding—was the experience of working with Roy for Maciej Lewenstein⁵⁹: “Glauber taught me that results are important, but how you present them is even more so. In 1987, I started to write a paper on quantum optics in dielectric media with Glauber. The paper⁶⁰ was published 4 years later because every sentence in the paper was changed, optimized, changed again; a process that occurred several times. At the time, it wasn’t an enjoyable experience for me, but looking back it was invaluable. The paper ... has become a reference paper in the community because it is so precisely and beautifully written.”

ROY GLAUBER'S LEGACY

Roy Glauber's contributions to nuclear scattering, statistical physics, and, especially, quantum optics—his brainchild—created a legacy that permeates contemporary physics.

His concept of optical coherence has provided a framework for describing light⁶¹ and has fueled a quantum renaissance.⁶² His work has been crucial to observing the violation of Bell's inequalities^{63,64} as well as to advancing quantum information science,^{65,66} quantum measurement,⁶⁷ photon entanglement,⁶⁸ and teleportation.⁶⁹

The impact of quantum optics is far-reaching. To cite two examples: The detection of gravitational waves relied on squeezed states of light,^{70–72} a concept that emerged from quantum optics. Teleportation is being used for secure communications.^{73,74} Moreover, Glauber's coherent states have been recently invoked in condensed-matter physics to describe lattice vibrations and their interactions with charge carriers.⁷⁵

Roy Glauber's contributions could be compared to fine threads that are spun into a tapestry of quantum optics that has nurtured burgeoning areas of quantum science and engineering around the world. It is difficult to see these threads because they are everywhere.

AUTHOR CONTRIBUTIONS

Bretislav Friedrich: Conceptualization (equal), investigation (equal), project administration (equal), writing - original draft (equal), writing - review and editing (equal). Daniel Kleppner: Investigation (supporting), writing - review and editing (supporting). Dudley Herschbach: Investigation (supporting), writing - review and editing (supporting).

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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The authors confirm that they have followed the ethical policies of the journal.

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