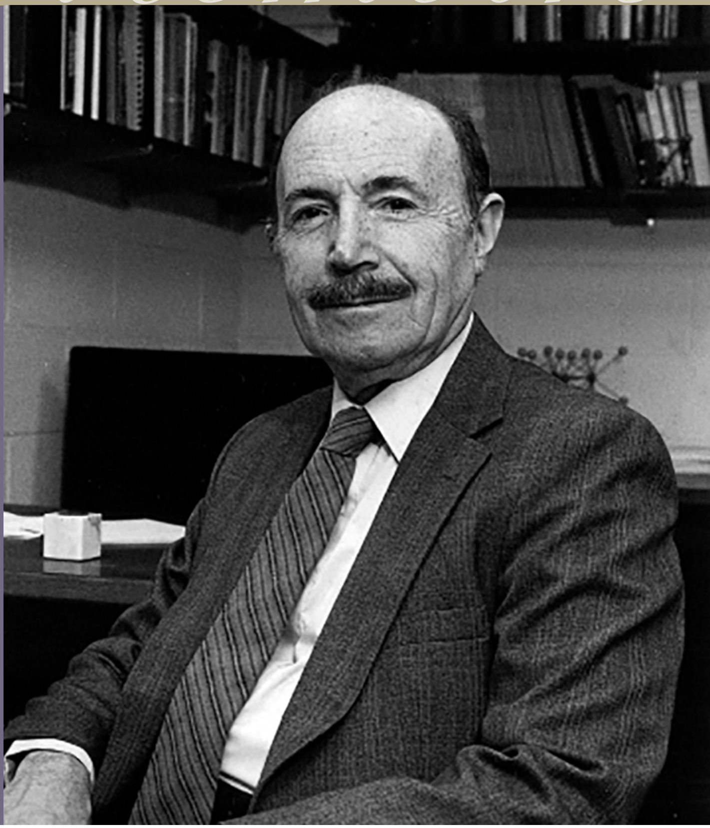
Elias Burstein

1917–2017

BIOGRAPHICAL *Memoirs*



A Biographical Memoir by
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NATIONAL ACADEMY OF SCIENCES

ELIAS **BURSTEIN**

September 30, 1917–June 17, 2017

Elected to the NAS, 1979

*By James M. Kikkawa,
Eugene Mele, Aron Pinczuk,
Erio Tosatti,
and Arjun G. Yodh*

Elias Burstein was an American physicist whose work in condensed-matter science spanned nearly seven decades. Known in particular for his pioneering fundamental research in the optical physics of solids, Eli was highly regarded as well for his organization of meetings, conferences, and symposia that brought together scientists from around the world, and for his mentoring of numerous younger physicists.[1]

Born in Brooklyn, New York, Eli earned a B.A. degree in chemistry from Brooklyn College in 1938 and an M.A. in chemistry from the University of Kansas in 1941. Over the next two years he took graduate courses in chemistry and physics at MIT, but his doctoral studies were interrupted by World War II. In 1944 Eli worked on war-related projects in MIT's Physics Department, and in 1945 he joined the U.S. Naval Research Laboratory (NRL) in Washington, DC, as a member of the physics section of its crystal branch.

Eli served as head of the crystal branch from 1948 to1958. A noteworthy achievement during that time occurred in 1954, when he interpreted an apparent shift of the optical absorption edge in semiconductors as a manifestation of the Pauli principle. This phenomenon, which he concluded was due to a "band-filling effect" from free-electron populations in the semiconductor, became widely known as the "Burstein-Moss shift." In 1958, Eli became head of the NRL's semiconductor branch.

Earlier, during 1946–1948, he took graduate courses in physics at Catholic University, but for the remainder of his career Eli never formally earned a Ph.D. degree. Nevertheless, his numerous accomplishments as an innovative scientist, his long service as an inspiring teacher, and his extensive record of mentoring of younger scientists were recognized by four honorary doctorates.

1 https://en.wikipedia.org/wiki/Elias_Burstein

In 1958, Eli joined the physics department of the University of Pennsylvania, where he was based for the rest of his career. In 1960, he led the efforts to establish the Laboratory for the Research on the Structure of Matter (LRSM) at Penn, and to this day the LRSM continues to be one of the university's main centers for interdisciplinary materials research. In 1982, he succeeded Nobel-prize winner J. R. Schrieffer as Mary Amanda Wood Professor of Physics. Eli formally retired in 1988, but he remained active at Penn until his death at the age of 99.

Among his many honors, Eli was elected to the National Academy of Sciences (1979), he received the John Price Wetherill Medal of the Franklin Institute (1979), and he was awarded the Frank Isakson Prize of the American Physical Society (1986). In 2004, at a conference at the prestigious International Centre of Theoretical Physics in Trieste (Italy), Eli was hailed as "one of the founders of studies of optical and quantum effects in solids." That same year, at the Symposium on the 50th Anniversary of Cyclotron Resonance (held at the 27th International Conference on the Physics of Semiconductors), Eli and three other scientists—M. L. Cohen, G. Dresselhaus, and B. Lax—were acknowledged by their colleagues as the founders of the field of cyclotron resonance.

Research at the U.S. Naval Research Laboratory

Eli's pioneering research at NRL established him as one of the pillars of the then-nascent field of semiconductor optics. His research played key roles in connecting measured optical properties with vibrational properties, with electron-band structures, and with electron interactions in diamond and in semiconductor crystals such as Si, Ge, and InSb.

In 1950, Eli reported measurements of infrared optical-absorption spectra of diamond, silicon, and germanium. These data were more fully interpreted in a paper he published with Mel Lax in 1955; the researchers interpreted the intrinsic infrared optical absorption in terms of second-order electric moments, and the extrinsic component was assigned to an electric moment induced by impurities. Eli's further semiconductor work elucidated basic infrared properties, including— in terms of electrical and mechanical anharmonicity—long-wavelength lattice vibrations' mechanisms of second-order infrared absorption.

From 1953 to 1956, Eli and his collaborators studied, at liquid-helium temperature, the infrared photoconductivity due to ionization of impurities in Si and Ge; they observed novel effects, such as impact ionization of impurity states in high electric fields. Such studies of impurity photoconductivity enabled applications in the design and construction of infrared detectors with responses in the far-infrared regions. In other research, Eli and colleagues reported low-temperature absorption spectra, resulting from excited states of shallow impurities in Si, and they detected deviations from existing theoretical models. It was mentioned above, in passing, that in 1954 Eli explained an "anomalous shift"—of the interband optical-absorption edge of InSb toward higher energies—in terms of the Burstein-Moss shift. This phenomenon is a consequence of the combined impact of wave-vector conservation in optical transitions and of the Pauli exclusion principle, which causes the fundamental absorption of a semiconductor to shift to higher energy due to the presence of free carrier populations from impurity dopants.

Eli's attention later turned to magneto-optics studies of semiconductors. This research was made possible by NRL's access to a Bitter magnet whose magnetic fields that could reach 6 Tesla (60,000 Gauss). While cyclotron resonance microwave absorption in silicon and germanium had already been reported, much of the focus of Eli's magneto-optics research was on indium antimonide. Given the smaller effective mass of electrons in indium antimonide, the cyclotron frequencies are typically in the far infrared. In 1956, Eli and his collaborators reported the first observation of infrared cyclotron resonance at room temperature. Eli's later work in this area involved studies of interband optical absorption mediated by Landau levels, which he understood have large density of states with a significant signature in optical spectra. The results of this novel fundamental magneto-optics research were reported in a set of papers published in 1957–1959.

Research at the University of Pennsylvania

In his research with students and other collaborators, Eli explored a broad set of research topics at Penn in semiconductors, insulators, metals, and superconductors, all of which contributed to the understanding of the of solid-state materials' optical behavior. His experimental methods included de Haas–van Alphen effect, Azbel-Kaner cyclotron resonance, magneto-acoustic resonance, and tunneling between superconductors.

Eli had a long-standing interest in selection rules that apply to optical infrared absorption and Raman scattering. He was partial in particular to studying the breaking of symmetry-related selection rules by application of externally controllable electric fields or strains. A major success of these efforts was the observation in 1966 of electric-field-induced infrared absorption in diamond.

In the early 1960s, Eli recognized the potential of the laser for studies of Raman scattering in solids. Because high-performance spectrometers required for laser Raman scattering from crystals were not available at the time, he launched a project for building an instrument of novel design—a computer-controlled spectrometer—and in the summer of 1966 Eli and his colleagues put it to work.

In fact, access to this spectrometer enabled Eli's group to do pathbreaking research on Raman scattering. Their early work led to the discovery of Raman scattering intensities by optical phonons in opaque semiconductors such as InSb; when these materials were probed with visible laser light, they broke the conventional selection rules for Raman scattering. This Raman effect, first reported in 1968, resulted from the breakdown of selection rules caused by resonance excitation and by the presence of space-charge electric fields at the surface of the semiconductors. The resonance enhancements in the light-scattering intensities were due to the overlap of photon energies with interband transitions at energy levels above the fundamental absorption gap. Eli and his colleagues used this method to probe surface space-charge layers of InSb, InAs, PbTe, and SnTe, and also to determine the dependence of surface electric fields on surface orientation.

By using laser photon energies above the fundamental absorption gap of n-type GaAs (photon energies were in resonance with the $E_0+\Delta_0$ interband optical gap), the researchers reported in 1971 that they had observed resonance inelastic light-scattering by single-particle electronic excitations in a semiconductor electron gas. Crucially, the optical interband transitions participating in the resonance enhancements needed to involve the states of the electron gas. They later used the insights on inelastic light-scattering processes from the GaAs experiments in a proposal, formulated in 1976, that resonant inelastic light-scattering methods could successfully probe the electron excitations of two-dimensional electron systems at semiconductor inversion layers and quantum wells. Eli and his collaborators formulated a description of LO phonon modes that coupled to elementary excitations modes of two-dimensional plasmas.

The Burstein team reported theoretical formulations of Raman scattering processes by surface polaritons at semiconductor surfaces and interfaces, including determinations of conditions for the observation of modes, and they highlighted the intriguing property that the Raman scattering cross-section for backscattering is orders of magnitude smaller than for forward scattering. They also reported Raman scattering by "soft" optical phonons in $BaTiO_3$; they had used measurements of phonon-polaritons in $BaTiO_3$ (in forward Raman scattering) in a novel determination of the low-frequency dielectric constant of this benchmark ferroelectric crystal.

In addition, the researchers carried out theoretical and experimental research on the nonlinear optical responses of noble metal surfaces. These studies were based on three-wave mixing and second-harmonic generation. Resonant three-wave mixing was interpreted in terms of three-step electronic processes that involved discrete intrinsic surface states and continuum states modified by the presence of a surface.

In the latter part of his extended career, Eli and collaborators discovered that fullerene C_{60} molecules ("buckyballs"), when in close proximity to a smooth metal surface, exhibit channels of optical emission (luminescence)—a singlet exciton fluorescence and a triplet exciton phosphorescence—that normally are forbidden. The researchers interpreted this metal-induced fluorescence as arising from the lowering of the molecular symmetry. They attributed the metal-induced phosphorescence to two mechanisms: a mixing of singlet and triplet exciton states of the molecules by the spin-orbit interaction with the metal atoms; and the mixing of singlet and triplet excitons by a virtual hopping of electrons between the excited molecules and the metal. Both were new mechanisms for turning on the phosphorescence of the molecules in close proximity to a smooth metal surface.

Impact on condensed-matter physics groups at Penn

Through the recruitment and mentoring of young faculty, Eli helped Penn expand and develop its condensed-matter physics research group into one of the most eminent in the country. Notable faculty recruits in the 1958–1980 period included Robert Schrieffer (1972 Nobel Prize in Physics), Douglas Scalapino, Alan Heeger (2000 Nobel Prize in Chemistry), Ward Plummer, Tom Lubensky, Torgny Gustafsson, Eric Siggia, and Steven Louie. This group's strength was further enhanced by regular extended visits to Penn by some of Eli's closest collaborators, including Stig Lundqvist (Chalmers) and Doug Mills (Irvine). The focus of activity during this period was on new spectroscopies of metals, semiconductors, superconductors, and their interfaces. The work established Penn as a major player at an exceptionally fertile time in the development of these fields. One byproduct of these collaborations was the influential 1969 review volume, *Tunneling Phenomena in Solids*, coauthored by Lundqvist and Burstein. But perhaps the most enduring legacy of Eli's work during this period was the initiative to establish an interdisciplinary center for the study of materials, Penn's Laboratory for Research on the Structure of Matter.

Founding father of the Laboratory for Research on the Structure of Matter

Early on, decades before it became popular, Eli recognized the value of interdisciplinary collaboration, and he applied it to materials research. In 1960, together with Professors Norman Hixon (Chemical Engineering), Robert Hughes (Chemistry), and Robert

Madden (Metallurgical Engineering), Eli submitted a programmatic proposal to the U.S. Advanced Research Projects Agency (ARPA) for coordinated materials research; ARPA was a pioneering entity in that it sought to cross the traditional lines that divided disciplines. Thus the proposed program aimed to integrate faculty and students working in key materials fields, including solid state physics, structural chemistry, inorganic and organic chemistry, ceramics, metallurgy, electrical engineering of solid state devices, and chemical engineering. The proposal featured interdisciplinary contact via research, seminars, courses, shared experimental equipment and facilities, and, notably, a new building to host a “Laboratory for Research on the Structure of Matter” (LRSM); Eli had insisted that the title of the center include “matter,” and he envisioned the new building as helping to create a fertile environment for researchers from different fields to work side by side. In 1960, ARPA selected the University of Pennsylvania, Cornell University, and Northwestern University to establish the first academic interdisciplinary laboratories for research and training in materials science. The LRSM was born.

Five years later, Penn’s LRSM building was realized in a centrally located structure of some 100,000 sq. ft., with about two-thirds of its cost borne by ARPA. Eli’s vision for cross-disciplinary interactions was reflected in the LRSM’s mission statement: “Offices … will be located together in the facility, regardless of the academic department to which the staff members belong. This deliberate policy will increase interdisciplinary contacts and cooperation.” Eli often commented that the graduate students benefited even more than faculty from these arrangements, and that the resulting interactions were a vital part of their training. In 1965, he secured funding for, and then supervised, a high-field magnet lab at the LRSM, with Bitter magnets supporting 10, 12, and 14 Tesla continuous operation.[2] In keeping with Eli’s philosophy that science was truly a global joint effort, the Penn Magnet Lab was open to users from outside universities.

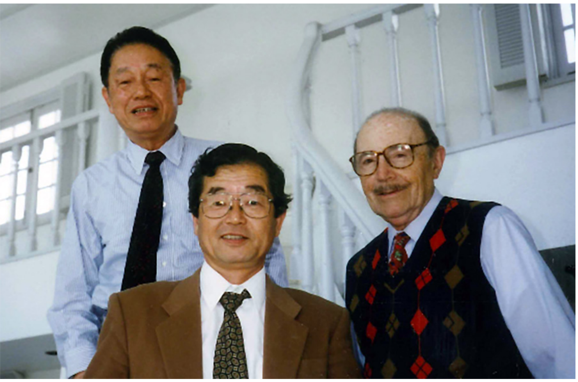
The LRSM community at the University of Pennsylvania turned out to be vibrant, which resulted in a “virtuous cycle”—it helped to stimulate investment in faculty across many disciplines who had interests in materials. Meanwhile, the LRSM nurtured numerous excellent students and postdocs. And LRSM research thrived, yielding scientific breakthroughs, such as the Nobel Prize-winning discovery of conducting polymers, that relied heavily on collaboration. The LRSM has sustained its programs too; it has garnered continuous support for almost 60 years, from ARPA until 1972 and since then from the National Science Foundation.

2 Penn Magnet Lab, *Physics Today* 18(6):74 (1965).

Eli remained deeply engaged with the LRSM throughout his life. He was a major player in many of its evolving interdisciplinary research groups, especially in connection with optical spectroscopies, magnetism, and surface science. He also worked to bring relevant speakers to campus and ensure that their seminars or colloquia would take place in LRSM venues. For example, even after he became emeritus professor, Eli started a new lecture series, "Frontiers of Materials Science," that brought a spectacular array of scientists and engineers to the LRSM. Finally, for more than two decades, the LRSM has hosted annual "Burstein Lectures," which are now a fixture at Penn for hosting thoughtful and energetic visiting lecturers. Very often, Eli and his wife Rena joined in the lecture festivities, even as recently as February 2017.

International activities

Eli was a widely loved physicist who had a remarkable number of international friends and connections, many of whom he and Rena visited frequently over at least half a century. In some instances, those relationships evolved naturally from within Eli's lab. He mentored several Japanese graduate students, for example, and among them, Yasuji Sawada and Sukekatsu Ushioda established themselves in the Japanese academic world, forming a link between Eli and Japan that began at Sendai University and then flourished. Eli also became friends with Leo Esaki (Nobel Prize, 1973) while Leo was at IBM, and Eli would visit him often, thereby further strengthening Penn's connection to that country. Over the years, Eli persistently stimulated dialogue between Japanese and American researchers, typically in the form of symposia, proceedings, and published works.



Left to Right: Leo Esaki, Sukekatsu Ushioda, Elias Burstein.

Eli also formed transatlantic friendships. He was close to Stig Lundqvist of Chalmers University in Sweden, having met Stig when Eli held a visiting professorship there in 1981. Eli and Stig worked together tirelessly on the editorial board of *Solid State Communications* (for which Eli was the founding editor); and, starting in 1984, they organized a series of Adriatico Research Conferences on the Frontiers of Condensed

Matter Physics at the International Centre for Theoretical Physics (ICTP) in Trieste. With Franco Bassani, Eli organized in 1971 a Varenna School on the "atomic structure and properties of solids." Eli sought to use these venues to promote young scientists. Among those at the Varenna School was Bassani's former student Erio Tosatti, who formed an enduring friendship with Eli. Eli also brought to Italy some of his other students, including Aron Pinczuk, who helped design and run the ICTP Adriatico Conferences after 1995.

Eli and Rena Burstein at the banquet of the Adriatico Research Conference on Advancing Frontiers of Optical and Quantum Effects in Condensed Matter that honored Eli in 2004.

In 2004, Eli was honored by the Adriatico Research Conference on Advancing Frontiers of Optical and Quantum Effects in Condensed Matter. The program noted that Eli was "a founding father of optical and quantum effects in solids, and a staunch friend and believer of ICTP and its role in the international science scene." Indeed, Eli had a fundamental influence on ICTP, not only through the conferences he organized there but also through his participation in its "Condensed Matter Advisory Committee," an international body of advisors. Among Eli's contributions in that capacity, he guided ICTP's evolution from a pure volunteer organization to one with approximately 30 permanent staff scientists.

Left to right: Erio Tosatti, Rena Burstein, Elias Burstein, and Stig Lundqvist.

Family

Eli and Rena Burstein married on September 19, 1943, and they had three daughters (Joanna, Sandra, and Miriam) and two grandchildren (Susanna and Graham Mitro). To many individuals who knew the family well, Rena was an inseparable and cherished part of their relationship with Eli. Together, the Bursteins traveled to conferences and welcomed students and colleagues into their homes in Narberth, PA, and Eagles Mere, PA. Often, visiting professors were invited to stay in the Burstein home for weeks at a time. Graduate students fondly recall discussing physics on Sunday mornings there, or driving in the family car to the Bursteins' country home in Eagles Mere.

During those drives, physics was not the only topic on the agenda. In a memoir for Eli's 90th birthday, one student wrote "I entertained the family with my singing from the back seat of Eli's station wagon, my repertoire ranging from ancient Japanese folksongs and Gregorian chants to arias from western operas. Even the girls did not utter unkind words."

Whatever the venue, the warmth that the Bursteins showed to others could indeed be disarming. In many ways, the manner in which the Bursteins connected their personal and professional lives was a reflection of Eli's core belief that great things happen when people with different perspectives are brought together.

A common scene for the Bursteins, co-mingling family, friends, and colleagues. Eli and Rena Burstein (center) with daughter Miriam (right) and Joanna and husband Gary Mitro (left), surrounded by students, colleagues, and friends.

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CAREER MILESTONES AND HONORS

Eli Burstein was a member of the Physics Section of the Crystal Branch at the U.S. Naval Research Laboratory (1945–1958), head of that branch (1948–1958), and thereafter head of the Semiconductors Branch (early 1958).

Later in 1958, Burstein was appointed professor of physics at the University of Pennsylvania, and in 1982 he succeeded Nobel Laureate John Robert Schrieffer as Mary Amanda Wood Professor of Physics. He retired as a member of the standing faculty in 1988, but he remained active as Mary Amanda Wood Professor Emeritus.

Burstein held visiting professorships at the University of California, Irvine (1967–1968), at the Hebrew University in Israel (1974), and at the University of Parma in Italy (1974). He also was the Fiftieth Anniversary Jubilee Visiting Professor at Chalmers University of Technology in Gothenburg, Sweden (1981); and Miller Visiting Research Professor in the Department of Physics at the University of California, Berkeley (1996).

Among his numerous professional roles, Burstein was a member of the Solid State Sciences Committee of the National Academy of Sciences' National Research Council (1971–1980) and served as its chairman (1976–1978). Starting in 1995, he was a member of the Arts and Sciences Committee of the Franklin Institute.

AWARDS

Gold Medal of the Brooklyn College Chemistry Department (1938) for "outstanding record as an undergraduate student in chemistry."

Annual Award of the Washington Academy of Sciences (1957) "in recognition of his distinguished study of impurity levels and effective mass in semiconductors" (awarded to persons under 40 years of age).

Alumni Award of Honor of Brooklyn College (1960) "for major experimental achievements as a solid-state physicist."

Election to the National Academy of Sciences (1979) "in recognition of outstanding contributions in condensed-matter physics and, in particular, his pioneering studies of optical properties of semiconductors."

The John Price Wetherill Medal of the Franklin Institute (1979) "in recognition of the outstanding contributions to the science of optical properties of solids and its application to photoconductive technology."

Guggenheim Foundation Fellowship (1980).

The Frank Isakson Prize of the American Physical Society (1986) "for his pioneering work on the optical properties of semiconductors and insulators, particularly extrinsic photoconductivity, the anomalous band-edge optical absorption shift (Burstein shift), magneto-optical effects in semiconductors, and infrared and Raman processes."

Von Humboldt U.S. Senior Scientist Award (1988–1990,1991–1992).

Honorary Doctor of Technology degree from Chalmers University of Technology in Gothenburg, Sweden (1981).

Honorary Doctor of Science degrees from Brooklyn College (1985), Brooklyn, NY; Emory University, Atlanta, GA (1994); and Ohio State University, Columbus, OH (1999).

Fellow of the American Physical Society (1965), the Optical Society of America (1965), and the American Association for the Advancement of Science (2002).

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