Isadore Rudnick (1917-1997): Acoustics in the Service of Physics

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"I don't consider myself an acoustician. I am a physicist who uses acoustical techniques and tools to understand physical systems."

In the opinion of most physicists, Isadore Rudnick (**Figure 1**) was the world's greatest physical acoustician during the second half of the 20th century. His enormous potential was obvious early in his career; he was the fourth recipient of the Acoustical Society of America (ASA) Biennial Award (now the Lindsay Award) in 1948 that is presented to a member of the ASA who is younger than 35 years.

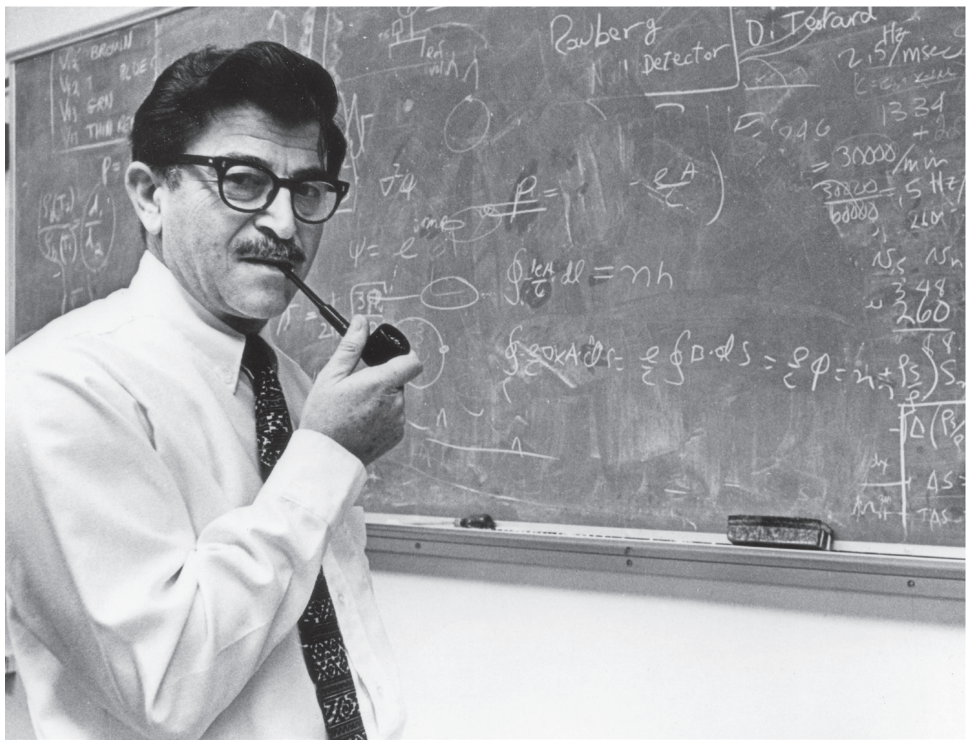


Figure 1. *Professor Rudnick in front of his blackboard, circa 1960.*

Izzy (as he was known to everyone except his graduate students) was an undergraduate student in the University of California (UC), Berkeley Physics Department when "Dick" Bolt (cofounder of Bolt, Beranek and Newman) was a teaching assistant there. Bolt said having Izzy in the class made his job as the grader for the course easy; all he had to do was assign Izzy's problem set solutions full credit and then use Izzy's solutions as an answer key to grade the other submissions.

Izzy's contributions to physical acoustics were recognized by his receiving the ASA's first Silver Medal in Physical Acoustics in 1975 and the Society's Gold Medal in 1982.

He received similar recognition for his contributions to low-temperature physics, receiving the Fritz London Award in 1982 followed by his election to the National

Academy of Sciences in 1983. Although none of the discoveries made in Izzy's lab were recognized by a Nobel Prize in Physics, the 2016 prize, awarded to Kosterlitz, Thouless, and Haldane, recognized Izzy's contribution that was made through acoustic measurements near absolute zero and established the universality of the two-dimensional topological phase transition during the superfluid transition in atomically thin films of superfluid helium (He II).

This article reviews some of Izzy's landmark contributions to both classical acoustics and to the understanding of the behavior of superconductors and quantum fluids, but more importantly, it will attempt to document the career of a great physicist during a period of unprecedented change as physics transitioned from the late 19th century triumphs of classical analysis, epitomized by Lord Rayleigh's *Theory of Sound* (Strutt, 1896) to ongoing attempts to unravel the implications introduced by the emergence of quantum mechanics.

"Talkies" Were His Path to Acoustics

Born in New York City, Izzy moved with his family to Los Angeles at an early age. He became interested in physics while he was an undergraduate student at UC, Berkeley during the depression. To cover his living expenses, he worked as a lab assistant to a physics PhD student, about whom he commented, "The guy was working on his PhD. I was appalled that this guy, who I really had such a high opinion of, couldn't find a job. He did get a job with the USA group that studied weather where he translated French books on the weather into English. That's all he could find. I decided right then that somehow I'm going to find a way to get a decent job. I was talking to Moshe Kadish [a friend from high school] about it, and he said he heard that down in Los Angeles, people were making money by [improving the audio quality of] movies that have voices on them. They called them 'talkies.'"

During a trip to Los Angeles, Izzy wrangled an appointment to speak with Vern Knudsen, a physics professor at UC, Los Angeles (UCLA) and consultant to the film industry in Hollywood. Knudsen was designing "sound stages" and reducing the noise made by cameras at that time. Izzy believed he did not impress Knudsen "because I didn't have such a hot record. I had to go back to Berkeley for another semester. I did that, and then I got straight As." Ultimately, he transferred from UC, Berkeley to UCLA where he received his BS (1938) and MS (1940) in physics followed by a PhD thesis under Knudsen's supervision (1944).

The Classical Era

After wartime research at Duke as a postdoc, Izzy took a junior faculty position at Pennsylvania State College (now University) in 1945 and then returned to UCLA in 1948, where he served as a professor of physics for 39 years, producing 32 PhD students and hosting postdoctoral fellows and visiting international scholars.

Before his return to UCLA, Izzy had already significantly advanced our understanding of classical acoustics in several areas. These included atmospheric sound propagation through turbulence and along a porous boundary. He also demonstrated the application of the reciprocity technique for free-field calibration of condenser microphones to frequencies as high as 100 kHz and studied the attenuation of sound in soil, which earned him the moniker "Dr. Mudnick."

Also notable were studies of nonlinear distortion and the effects of high-amplitude sound that were enabled, in part, by the development with Clayton Allen[1] of a special type of siren that was the most powerful man-made sound source at the time. That source was shown to produce "whiter whites" through ultrasonic laundry.

Izzy was asked by the US Navy to measure the sound levels on the flight decks of aircraft carriers. The Navy was worried that the introduction of jet aircraft could cause significant hearing damage. Izzy's measurements confirmed this hypothesis, but the sailors were unwilling to wear hearing protectors because they felt it conflicted with their *macho* self-image. Apparently, Izzy was as good a psychologist as he was a physicist. He wrote an article for the ship's newspaper pointing out that in addition to hearing loss, high-intensity sound exposure was also suspected to cause impotence. The next day, it was observed that all of the crew on the flight deck were wearing hearing protectors (presumably over their ears).

At UCLA, his investigations of high-amplitude sound continued with studies of acoustically induced streaming (with Herman Medwin), attenuation of repeated shock waves, and harmonic distortion produced in the throats of horn-coupled loudspeakers. Izzy encountered R. W. Leonard, who was also on UCLA's physics faculty and was interested in the attenuation of sound due to relaxation processes. "He [Bob Leonard] had a real talent for building experiments just the

[1] *Readers who want to go beyond this biography of Dr. Rudnick and read the original research papers from his lab can find all of the citations, by the investigators mentioned in the article, at http://acousticstoday.org/rudnick-references/. In addition, the actual articles can be found on a CD of Dr. Rudnick's* Collected Works *(Maynard and Garrett, 2011).*

right way. He was my hero. I always said that I only came on the page when I developed my intuition, and that I got from Bob Leonard. He would say things instead of writing down equations. He just knew it" (Garrett, 1990). One of Izzy's characteristic pronouncements was,

"It's easier to do the calculation,
if you know the answer ahead of time."

In the last stages of his career, Izzy returned his attention to nonlinear acoustics and focused on shallow-water gravity waves. In an updated version of an experiment first performed by Faraday (1831), Robert Keolian and Junru Wu investigated the subharmonic response of a parametrically excited trough of water and discovered a new standing wave or "soliton," a nonlinear mode not predicted by the customary linear wave equation. We often heard Izzy say, "I know how to solve the wave equation in a trough, and this just isn't a solution to the wave equation." Nobody ever questioned his ability to solve the wave equation!

The Quantum Era

By the mid-1950s, it was clear that the interesting questions in physics were moving out of the classical domain and into the emerging arena of quantum mechanics. Once again, a seemingly innocuous event had a pivotal influence on what had already become a stellar career. The then physics department chair at UCLA had some leftover funds and decided to purchase a helium liquefier. "What happened was that Kinsey got money [that he spent to acquire] a helium liquefier, so we said, 'What should we do with it?'" (Garrett, 1990).

Izzy became interested in measuring the ultrasonic attenuation in metals at low temperatures shortly after reading an article by Hans Bömmel (1954), so that was the first use of the new helium liquefier. Bömmel had found the attenuation in a single-crystal lead sample increased when its temperature was decreased below 10 K. This effect was unexpected because most attenuation processes were expected to vanish at low temperatures. Ultimately, the attenuation did decrease, almost exponentially for temperatures below the superconducting transition temperature, which was another surprising result.

By the time Bardeen, Cooper, and Schrieffer (BCS) established their theory of superconductivity (Bardeen et al., 1957), it was understood that these effects were due to the interactions between sound waves ("phonons" in quantum mechanics) and the conduction electrons in metals. Izzy realized that two research areas were opened up by Bömmel's (1954) measurements. The first was the relationship between the numbers of free electrons in a metal to the absolute value of the sound attenuation due to electron-phonon interactions. The second was testing the validity of the BCS energy gap for various superconductors.

Izzy started a program to study the electron-phonon interaction by measuring the compressional wave speed and attenuation in aluminum and silver rods, using both pulse-echo techniques and resonance techniques. The results for the frequency and temperature dependence were in exact agreement with theoretical models. However, the experimentally determined absolute attenuation values were nearly twice the theoretical values.

Because both aluminum and silver have complicated electron environments, Izzy decided to measure sodium and potassium because these metals should have the simplest electron environments. Here again, Izzy and his students demonstrated their experimental ingenuity when they discovered that their samples had to be extruded at liquid nitrogen temperatures (77 K) to produce small crystalline grains that were not preferentially oriented and were also small enough that they did not produce significant Rayleigh scattering.

Similar investigations were made on Type II superconductors with Moises Levy, Dick Stern, Giuseppe Natale, and Reynold Kagiwada. Shear-wave experiments were added to test the BCS relationships for vanadium, niobium, and tantalum at frequencies up to 500 MHz, a regimen where the electron mean-free-path is shorter than the sound wavelength. These investigations led to the discovery that the attenuation of sound waves depended on the square root of the difference between the applied magnetic field and a "critical" field. In a pure Type II superconductor, the electrons sample the space average of the order parameter, which is proportional to that square root.

The Sextet of Sound Modes in Superfluid Helium

By the mid-1960s, Izzy's interest turned to the unusual properties of the liquid helium he and his students were using as the "refrigerant" for the study of the low-temperature properties of metals. This change in focus began a 20-year series of experiments that produced some of the most subtle and precise measurements of the dynamics of this fluid whose behavior was a direct consequence of quantum mechanics manifest on the macroscopic scale.

As a consequence of its quantum nature, superfluid helium supports six distinct sound modes (ordinal numbers zero through five); Izzy's research group discovered two of them, and he exploited all six to elucidate the behavior of quantum fluids.

Helium is the only element that remains liquid at temperatures down to absolute zero. This is because helium is so light that it has a large quantum mechanical zero-point motion and because the helium atom is spherically symmetrical so that it has a very small interatomic attractive potential. This also means that liquid helium is very pure because any contaminant would become a frozen solid and fall out of solution.

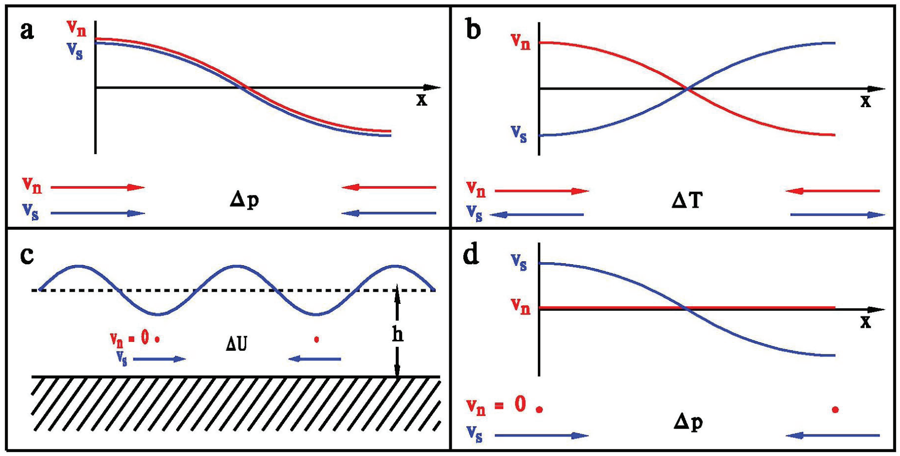


Figure 2. Schematic representation of four of the six sound modes that can be excited in superfluid helium. ***Red lines and arrows****, velocity of the normal-fluid component* (v_n)*;* ***blue lines and arrows****, velocity of the superfluid component* (v_s)*.* ***a:*** *First sound is restored by a pressure difference* (Δp)*.* ***b:*** *Second sound is restored by a temperature difference* (ΔT)*.* ***c:*** *Third sound is a surface wave in atomically thin helium layers of thickness* (**h**) *adsorbed on a solid substrate. The surface wave's restoring force is provided by the van der Waals attraction* (ΔU) *between the helium and the substrate. Only the superfluid can move (i.e.,* $v_n = 0$*) because the normal fluid is immobilized by its nonzero viscosity.* ***d:*** *Fourth sound propagates in porous media where the small pore size immobilizes the normal-fluid component, whereas the superfluid component can oscillate because it has no viscosity. Pressure differences* (Δp) *provide the restoring force for fourth sound. Fifth sound is not shown, but it also is present in porous media if the pressure is relieved by a free surface or in thick helium films. Temperature gradients provide the restoring force for fifth sound.*

At atmospheric pressure, liquid helium has a temperature of 4.2 K. If the pressure is lowered, the liquid helium is cooled by evaporation. At the "lambda temperature" (T_λ) of 2.172 K (−271°C), the fluid undergoes a second-order phase transition and a macroscopic fraction of the fluid condenses into a single macroscopic quantum state (i.e., a Bose-Einstein condensate); the quantum mechanical wave function of that ground state occupies the entire container. As the temperature is further decreased, a larger fraction of the fluid enters this superfluid ground state.

The Two-Fluid Model of Superfluidity

The phenomenological theory that describes the dynamics of superfluid helium was proposed by Lev Landau, who received the Nobel Prize in Physics in 1962 for his "two-fluid theory of superfluidity." This theory treats the superfluid as two independent interpenetrating fluids: a normal-fluid component and a superfluid component. Each component has its own temperature-dependent mass density (ρ_n and ρ_s, respectively), with the total mass density being simply their sum ($\rho = \rho_s + \rho_n$). Above the superfluid transition temperature (T_λ), the normal-fluid fraction is one ($\rho_n/\rho = 1$). As the temperature is decreased below T_λ, the superfluid fraction increases monotonically.

Both components carry mass and both move in response to pressure gradients according to ordinary fluid mechanics. The normal-fluid component and the superfluid component each move independently according to their own velocity fields ($\vec{v}_n$ and $\vec{v}_s$, respectively). The normal-fluid component acts like an ordinary fluid; it has viscosity and can transport entropy. The superfluid component has no viscosity and being described by a single macroscopic quantum state, it has no disorder and hence zero entropy.

Both components carry mass and both move in response to forces and, typically in acoustics, in differences in pressure (p) according to ordinary fluid mechanics. However, having the superfluid component in a macroscopic quantum ground state, with the normal-fluid atoms in thermally excited states, statistical mechanics can be involved in fluid motion; in particular, the superfluid component can move in response to differences in temperature (T) as well as in pressure. For ordinary fluids, temperature gradients lead to thermal energy diffusion, but for superfluids, temperature gradients can produce energy advection (i.e., mass flows). As demonstrated in the *Second Sound* section, this means that there can be "heat waves" (Holland et al., 1963) in superfluids as well as in sound waves.

Far more detail than can be included in this article is provided in the excellent review that Izzy wrote for an Enrico Fermi Summer School held in Varenna, Italy (Rudnick, 1976).

First Sound

With two fluid components, one may have a sound mode that is the same as ordinary sound in normal fluids. The motion of both the normal-fluid and superfluid components are equal and in phase, $\vec{v}_n = \vec{v}_s$, with the restoring force provided by pressure (p). This sound mode, called first sound, is shown schematically in **Figure 2a**. The speed of first sound, $c_1 = (\partial p / \partial \rho)^{1/2} \cong 220$ m/s, is nearly independent of temperature both below and above the λ-transition. Izzy's first experiments with superfluid helium began with quantitative measurements of the speed and attenuation of first sound near the superfluid transition temperature, with microkelvin temperature resolution at frequencies in the gigahertz range.

These first sound measurements, made with Marty Barmatz, Jim Imai, Richard Williams, and Dan Commins, pushed forward our understanding of the application of equilibrium thermodynamics to quantum fluids and demonstrated the utility of the Buckingham-Fairbank-Pippard relations at the λ-transition.

Second Sound

Because there are two independent flow fields, there can be two modes of oscillation. First sound is the symmetric mode where the flow fields move in phase so an ordinary vibrating "piston" can be used to excite first sound. It is possible to have antisymmetric mode where the two fluid components move out of phase, as shown in **Figure 2b**; this mode is called second sound. It is interesting to examine how such an antisymmetric mode might be excited.

When a boundary that is in contact with superfluid helium is heated, the superfluid component is attracted to the heat source. When the superfluid component reaches the heater, the absorption of thermal energy converts the superfluid component to the normal component that leaves the vicinity of the heater and carries away the heat. Because there are no mechanical forces communicated by this conversion, there can be no acceleration of the fluid's center of mass. As a result, the second sound wave's motion corresponds to a counterflow of the normal and superfluid components.

In regions of the wave where the superfluid becomes concentrated due to the counterflow of the two components, the average entropy of the fluid is diluted, corresponding to a local decrease in the fluid's temperature. In regions of the wave where the normal fluid becomes concentrated, the average entropy of the fluid is concentrated, corresponding to a local increase in the fluid's temperature. Second sound is a propagating wave of temperature and entropy; it is important to note that a detailed theory (Rudnick, 1976) would show that the speed of second sound (c_2) is a function of the superfluid's density, ρ_s; $c_2^2 = (\rho_s / \rho_n) s^2 (\partial s / \partial T)_P$.

The speed of second sound (c_2) is a strong function of temperature, vanishing above T_λ and reaching a maximum speed of 20.4 m/s at 1.65 K under saturated vapor pressure. The maximum second sound speed is an order of magnitude slower than the first sound speed.

Because electrical heating provides a positive-definite excitation (i.e., a heater is not cooled when the electrical current through it is reversed), it would be difficult to study the speed of second sound close to the λ-transition if a heater is used to excite second sound. Izzy realized that second sound could be excited mechanically by using a porous "piston" so that the normal-fluid component would be pushed out while the superfluid would be sucked in and vice versa. Using that mechanical excitation technique and the high signal-to-noise ratio it produced in a resonator, it was possible for Mary Beaver, Richard Williams, Jim Fraser, and Reynold Kagiwada to determine the scaling of the superfluid density as a function of temperature very close to the transition temperature [$\rho_s \propto (T_\lambda - T)^{2/3}$].

If nonlinear interactions are included, first and second sound can be coupled in a process where two second sound beams interact at an angle such that their intersection travels at the speed of first sound. This "mode conversion" is similar to three-phonon interaction, which is the nonlinear process of two slower shear waves in a solid that generate the faster longitudinal mode.

Izzy recognized that the way to achieve precise control over the second sound interaction angle and to ensure that the second sound waves were planar was to use the lowest frequency higher order mode of a waveguide. Because the largest helium Dewar in his lab had only a six-inch inner diameter, Izzy suggested the use of a spiral waveguide to provide a meter-long "end-fire array" interaction length, based on an anechoic termination that Bob Leonard developed to suppress reflections in a probe-tube microphone.

Measurements of the absolute amplitude of the mode conversion by Steve Garrett was enabled by a reciprocity calibration that was made in situ at temperatures below 2 K and demonstrated Seth Putterman's calculation predicting the largest component of the nonlinear coupling coefficient depended on the thermodynamic derivative of the fluids' density with respect to the square of the difference between superfluid and normal-fluid velocities $\left\{ \left[\partial \rho / \partial (\vec{v}_n - \vec{v}_s)^2 \right]_{T,P} \right\}$.

Because $\left(\vec{v}_n - \vec{v}_s\right)^2$ is a Galilean invariant, it is a legitimate thermodynamic variable, although its influence can only manifest in the regime of nonlinear acoustics.

Fourth Sound

It is also possible to immobilize the normal-fluid component when superfluid helium permeates a porous medium, like a tightly packed powder. That case is illustrated schematically in **Figure 2d**. Izzy's group was the first to observe this fourth sound mode, which is restored by the fluid's compressibility, and was the first to measure its velocity as a function of temperature, which necessarily vanishes above the λ-transition [$c_4^2 = \left(\rho_s / \rho\right) c_1^2$].

Because fourth sound propagates in tiny pores, it was possible for Étienne Guyon, Mike Kriss, Ray Scott, and Ken Shapiro to use fourth sound to determine the reduction in ρ_s/ρ and T_λ due to the healing length effects produced by the suppression of the quantum mechanical wave function in confined geometries. What is less obvious is that simultaneous measurement of the speeds c_1, c_2, and c_4 is sufficient to produce an accurate determination of all the thermodynamic properties of He II if the fluid's density is known at a single point! Joe Heiserman, Jean-Pierre Hulin, and Jay Maynard simultaneously measured c_1, c_2, and c_4 at more than 400 points over the pressure-temperature plane, making it possible for Maynard to determine the density, thermal expansion coefficient, normal-fluid fraction, specific entropy and specific heat at a constant pressure, the polytropic coefficient (i.e., ratio of specific heats), and isothermal compressibility. With the relative uncertainty of the sound speed measurements below ±0.2%, the resulting thermodynamic tables are still the best available.

Subsequent observation of the fourth sound mode by one of Izzy's former students, Haruo Kojima, was proof of superfluidity in the rare isotope ^{3}He and demonstrated that this new superfluid also behaves in accordance with the two-fluid theory.

Persistent Currents

One of the most astonishing features of superconductivity is the ability to produce an electrical current in a superconducting ring that will persist indefinitely. Such electrical currents are easy to observe due to the magnetic field such persistent currents produce. Because superfluids flow without viscosity, it should also be possible to create superfluid persistent currents. Because He II is an electrically neutral fluid, there would be no telltale magnetic signature for flow.

With Haruo Kojima, Wolfgang Veith, Seth Putterman, and Etienne Guyon, Izzy exploited fourth sound to determine the persistent current and make a quantitative determination of its decay rate, not a trivial task because the flow only decays by about 10% over the age of the universe! He was able to excite fourth sound in a cylindrical resonator and later in a toroidal resonator, into which a persistent current was introduced by rotating that resonator at a temperature above T_λ and then reducing the temperature below T_λ and letting the resonator come to rest.

The flowing superfluid split the degeneracy of the waves that propagate clockwise and counterclockwise, allowing those split modes to beat against each other. (Izzy always said, "Know your modes.") The beat frequency gave a precise measure of the superflow velocity, with the first measurement occurring less than a second after the rotation stopped. That prompt result was critical because the decay of the supercurrent is logarithmic in time (like flux unpinning in Type II superconductors); measuring two decades of decay in the first minute contains as much information as you would obtain in 100 hours if you had to wait an hour to make your first measurement.

Third and Fifth Sounds

One of Izzy's favorite modes was third sound, a surface wave that can be excited on atomically thin adsorbed films of superfluid helium (Putterman and Garrett, 1999). As shown in **Figure 2c**, the normal-fluid component is again immobilized by its viscosity. He liked third sound partly because it dramatically demonstrated one his favorite maxims,

"Superfluid helium obeys the laws of quantum mechanics on the macroscopic level and the laws of hydrodynamics on the microscopic level."

In films that were 1-2 atomic layers thick, he observed propagating modes by measuring the small change in temperature that they induced. This was accomplished with evaporated metal films operating near their superconducting transition.

In 1969, about three years before the Nobel Prize-winning Kosterlitz-Thouless theory of two-dimensional phase transitions was formulated, Izzy emphasized the universal aspects of the disappearance, as the film thickness decreased, of third sound at nonzero propagation velocities: "Superfluidity is disappearing at a finite speed of third sound so something deep must be going on." Apparently, the Nobel Prize Committee agreed. These third sound measurements, made with Ken Telschow, Taylor Wang, E. O. McLean, and John Scholtz, still comprise the most accurate test of the Kosterlitz-Thouless theory.

Figure 3. Professor Rudnick holding a large Rijke tube to demonstrate thermoacoustic sound production in the mid-1970s.

For very thin adsorbed helium films, the restoring force is the van der Waals attraction between the helium atoms and the substrate. As the films get thicker, their free surface relieves any pressure gradients, so thick-film wave motion in the superfluid component is restored by temperature gradients. This wave mode, known as fifth sound, was first observed in Izzy's lab for helium in a resonator that was partially packed with fine powder so that the open part above the packed powder provided the pressure-released boundary condition.

Zero Sound

Zero sound is a collisionless mode of normal ^{3}He quasiparticles characterized by an asymmetric oscillation of the Fermi sphere, as explained by Landau using a Boltzmann equation model. Any of Izzy's graduate students would instantly acknowledge that such an obscure theoretical description would never sit well with "The Mentor's" desire for a *true physical explanation*. His discomfort led to the recognition that both longitudinal and transverse zero sounds were, in fact, just the modes one would predict for an ideal viscoelastic liquid. In the conclusion of a typically insightful and carefully worded article, Izzy gently chastised the low-temperature physics community for failing to cast zero sound into this simple phenomenological model that had been so well-known by earlier physicists, going back to Maxwell in 1867, "from bygone days, when courses in hydrodynamics and elasticity were normally in the physics curriculum" (Rudnick, 1980).

The Teacher and the Showman

Izzy was a soft-spoken and thoughtful man. As his teaching assistant for an upper-division physics course on acoustics, one of us (Garrett) would listen to his lectures and scribble notes furiously in an attempt to capture the cascade of insights that he would unleash. Rarely, there would be a pause that would allow a glance around the classroom. Typically, half the undergraduate students looked bored and the other half were asleep. You had to listen carefully to appreciate his wisdom.

On the other hand, Izzy's lecture demonstrations were "loud and clear." Luckily for us, many of those demonstrations were filmed and are readily available as part of his *Collected Works* (Maynard and Garrett, 2011). Izzy loved using demonstrations in his teaching. He is shown in **Figure 3** holding his large Rijke tube. His public lectures at UCLA, given under the title of "An Evening of Demonstration Experiments in Physics," would attract standing room only crowds. Izzy would use the high-intensity sound field of a siren to levitate objects and make cotton burst into flames as it absorbed the abundant acoustic energy (while also removing all of the chalk dust from the blackboards). Such demonstrations would always end the show because the campus police invariably were called to the auditorium to investigate the source of such a piercingly loud sound.

In 1976, Izzy was selected to present the 51st UCLA Faculty Research Lecture, an annual honor given to a distinguished scholar who would then give a public lecture in Schoenberg Hall. Rather than just a talk, he prepared a series of live demonstrations using superfluid helium, not an easy trick in a music building. That lecture was recorded and later condensed into a 17-minute film, *The Unusual Properties of Superfluid Helium*. It won Best of Category at the 21st Annual San Francisco International Film Festival in 1977, beating out several entries from major industrial sponsors. The film closed with a superfluid fountain spraying liquid helium throughout a clear glass Dewar in response to a saxophone solo that was played through an electrical resistor to convert the sound to heat that drove the superfluid (Rudnick and Packard, 1978). Also preserved for posterity in his *Collected Works* is a set of acoustics demonstrations that were presented during a plenary session at the 100th meeting of the ASA that was held in Los Angeles.

Izzy's influence as a teacher extended far beyond UCLA. In the hearts and minds of many of the ASA members, it was his presence at meetings, usually accompanied by his best friend Martin "Moe" Greenspan, that were his most cherished contributions. Whether in technical sessions, committee meetings, or just "hanging around" in a hallway or hotel lobby, Moe and Izzy were famous for making insightful (and usually humorous) remarks that could provide a new interpretation to research results or place years of work into the proper historical context. When they were seated anywhere during an ASA meeting, a crowd of investigators and students would form to seek their advice.

Unfortunately, Izzy's last decade was spent in a struggle against a debilitating progressive dementia. Although he had planned to write a textbook on acoustics with his son, Joe, who was also a physics professor at UCLA, that project started too late. The task of producing an acoustics textbook based on his unique understanding of sound and vibration fell to one of his former students (Garrett, 2017).

The Centenary

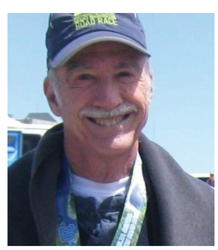
Izzy was born 100 years ago. This career retrospective was written by the last generation of academics that had the honor of working directly with Izzy, day after day, at the blackboard and in the laboratory, as a faculty colleague (Putterman), as a postdoctoral researcher (Maynard), and as a graduate student (Garrett). All three of us are in or very near our 70s. Our careers as researchers, teachers, and consultants are coming to their conclusions after influencing hundreds of our own students in classrooms and laboratories, along with dozens more through the advising of graduate students, postdocs, and faculty colleagues.

Through his inspiring example, Izzy was the single most influential person in our intellectual development. He taught us what to demand of an "answer" (i.e., an intuitively satisfying explanation of the physical processes that leads to a mathematically executable result, including a quantitative estimate of the result's uncertainty), what questions should be asked, and how such questions must be formulated. By his example, he taught us how to design an experiment, from its conception to its interpretation, so that the result would be clear and compelling. After that, he taught us that it was our responsibility to distill the essence of our research into a demonstration device that would capture the interest and imagination of a wider audience than just the readers of textbooks and archival journals. As he often said, "Today's research is tomorrow's homework."

If his influence had any deficiency, it would be in the area of signal processing; when Izzy designed an experiment, the desired effect would be so clear that the signals could be received in the fillings of your dental cavities. Maybe that last claim was a bit of an exaggeration, but thinking carefully about an experiment, optimizing the environment (he loved resonators!), paying careful attention to (and frequently inventing) the appropriate transduction mechanism, and documenting an end-to-end absolute calibration of the entire "signal chain" were all paramount to making significant contributions to the advancement of scientific understanding that was the legacy of our forefathers, from Galileo Galilei to Isadore Rudnick.

Biosketches

Steven Garrett received his PhD under the supervision of Izzy Rudnick and Seth Putterman in 1977. He continued research in quantum fluids at the University of Sussex, UK, as the Hunt Fellow of the Acoustical Society of America, followed by two years at the University of California, Berkeley as a Fellow of the Miller Institute. Dr. Garrett joined the faculty of the Naval Postgraduate School in 1982 and became the United Technologies Professor of Acoustics in the Graduate Program in Acoustics at Penn State in 1995. He retired from Penn State in 2016 and is now a freelance physicist.



Jay Maynard received degrees in physics at the University of Virginia and Princeton. He joined The Pennsylvania State University in 1977 and is currently Distinguished Professor Emeritus. His acoustics research has been featured in *The New York Times* Science Section and has appeared in *Nature*, *Physics Today*, *Reviews of Modern Physics*, and Nova TV. Professor Maynard is a Woodrow Wilson Fellow, Alfred P. Sloan Fellow, Fellow of the Acoustical Society of America (ASA) and the American Physical Society, and recipient of the ASA Silver Medal. Now he aspires to new heights by running the race up Mt. Washington, NH.

Seth Putterman is professor of physics at the University of California, Los Angeles (UCLA). He received a BS from Caltech and a PhD from The Rockefeller University under George Uhlenbeck. Putterman's thesis on the macroscopic theory of superfluids was followed by research in acoustics, nonlinear fluid mechanics, phenomena that spontaneously concentrate energy density, and intermittency in fluorescence. Findings include kink solitons in water, picosecond sonoluminescence, X-ray emission from triboelectrification, and crystal-generated nuclear fusion. Putterman was named the UCLA 2010-2011 Faculty Research Lecturer. *Nature* profiled his out-of-the-mainstream approach to science in the October 2005 issue (http://acoustics-research.physics.ucla.edu/).

References

All of the papers and demonstrations mentioned in the article are found in Maynard and Garrett (2011). Citations for the specific papers mentioned in the article can be found at http://acousticstoday.org/rudnick-references/.

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