Isadore Rudnick: Making Waves in Liquid Helium

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Dictum Number One of Izzy Rudnick was: “Know your modes!” In his liquid helium research this modus operandi led not only to artistic insights appropriate to resonator design but also to the canonization of scientific advances relating to the thermodynamics of superfluid helium 4, macroscopic quantum mechanics, and statistical mechanics of two dimensional phase transitions. According to Izzy, a scientist must not only seek out a discovery but also he must complete a measurement of the new parameters. In his superfluid research Izzy unleashed his preeminent acoustic abilities on five different propagating sound modes.

First sound is the mode in He⁴ that is most similar to the pressure wave that characterizes ordinary acoustics. Izzy realized that the key place in parameter space to learn about He⁴ is the transition temperature $T_s = 2.17$K. A region he and his students in the late 60’s measured the speed of propagation and attenuation of sound up to the GigaHertz domain. They were then able to obtain the first measurements of the coherence length and relaxation time of the superfluid order parameter.

In contrast to an ordinary fluid where heat diffuses, liquid helium below the lambda temperature even out thermal disturbances with propagating waves called second sound. A careful measurement of the various propagating modes yields a means of determining the equations of state and thermodynamic properties of liquid helium. This aspect of Izzy’s influenced research is the topic of another paper at this meeting. Here I would like to emphasize Izzy’s spectacular insight that second sound could be transduced mechanically. He noted that the temperature swings of second sound were accompanied by a relative motion of the thermal excitations [the so-called normal fluid component of He⁴ below the lambda temperature] and the macroscopically occupied ground state [the so-called superfluid component of the He⁴]. So he reasoned that if one could mechanically set up a relative motion of these components second sound would be excited. This could be achieved by oscillating a thin piece of foil with fine holes in it [millipore]. The normal fluid due to its viscosity would stick to the holes and oscillate with the foil while the superfluid which flows without friction would run right through the foil, thus setting up the counterflow. This method enabled him to excite and measure second sound with exquisite control right up to the transition temperature. Through these experiments the speed of second sound, size effects, and the scaling laws for the superfluid fraction of He⁴ were measured.

Third sound is a surface wave that propagates on a helium film. The restoring force which determines its speed of propagation is the fundamental van der Waals force that exists between neutral atoms. Here again Izzy realized that the normal fluid is locked in place by its viscous interactions with the boundary. Thus as with second sound, the third sound [which was generally viewed as a mechanical mode] must according to Izzy’s reasoning exhibit a temperature swing. So Izzy proceed to excite and detect third sound with heaters made from thin metal films [operating near their superconducting transition] evaporated onto the glass substrate below the helium film. His technique brought third sound to the masses. But as mentioned Izzy also carried out serious measurements. In this case he measured the speed and attenuation of third sound down to film thicknesses smaller than an atomic layer. In the course of these experiments he determined the healing length of the macroscopic wave function and the region of parameter space where superfluidity disappears due to size effects. These measurements were visionary in that they predated the publication of the now celebrated Kosterlitz-Thouless theory of two dimensional topological phase transitions. I can still remember Izzy marveling that “superfluidity is disappearing at a finite speed of third sound so something deep must be going on”, Izzy’s measurements on this system constitute the best and most quantitative experimental realization of the theories of vortex unbinding transitions.

Izzy’s lab was first to observe [and measure] fourth sound and the techniques which he developed also opened up this field of research. This mode propagates in liquid helium that fills the pores of a finely packed powder [say aluminum oxide particles with a 100A diameter]. In this case Izzy realized that the doppler shift of fourth sound could be used to measure the speed of a persistent current. To realize this he
built a resonator in the shape of a racetrack and packed it with fine powder, which was then filled with He^4. If the resonator was rotated and brought to rest the liquid helium [superfluid component] would continue to rotate in what is referred to as a persistent current. But fourth sound can propagate in this geometry and so the fourth sound should have a doppler shift due to the fluid’s drift. By measuring the resonant frequency as a function of time he could get the doppler shift and therefore the persistent current as a function of time. In this way Izzy was able to measure the decay of persistent current at times orders of magnitude earlier than had previously been achieved. He was also able to map out the transition from temperature-dependent decay rates to temperature-independent decay rates, and according to current theories may have been one of the first researchers to observe the transition to a domain of dynamics dominated by macroscopic quantum tunneling. Izzy’s measurements were so good that he was able to assign values to decay rates in terms of percent per age of the universe.

Fifth sound is the pressure-released part of fourth sound. This is a mode that propagates in a helium film that has become so thick that the van der Waals force has become small. This new mode predicted by Izzy has been found to be a powerful probe of helium films that coat the pores of a resonator packed with fine powder.

The sound modes which gave so much joy to Isadore Rudnick do not exist as orthogonal states of motion. When nonlinear effects are included their identities can become mixed. This possibility constitutes a richness and a challenge that Izzy also enjoyed, and this is a challenge that tied into his earlier work on nonlinear sound propagation. In the case of liquid helium Izzy designed a spiral resonator in which properly aligned second sound modes [launched by a heater] could transform into first sound as they propagated down the waveguide. The precision of these and the above-mentioned measurements will warm the hearts of all my colleagues who aspire to imitate Izzy Rudnick’s advances.