Extending the Franck-Hertz Experiment

University of Washington, June 29–July 1, 2017

(All you need is a lock-in to uncover a lot more physics in an old favorite)

Mentor

David Pengra, after a short career as an electric equipment repairman and radio engineer, received his Ph.D. in condensed matter experimental physics at the University of Washington in 1991, working under Greg Dash on the thermodynamics of low-temperature adsorbed films. He then completed two post-docs, the first with Jakob Bohr in Denmark on resonant magnetic x-ray diffraction from rare-earth crystals, and the second with Po-zen Wong at the University of Massachusetts, Amherst, on electrokinetics and fluid flow in porous media. He joined the faculty of Ohio Wesleyan University in 1996, where he continued his work in porous media and taught physics, specializing in advanced laboratory courses and electronics. David returned to the University of Washington in 2003, where he teaches laboratory courses at all levels and manages the department's advanced teaching laboratories, which include courses in analog and digital electronics, computer interfacing, optics, condensed matter physics, atomic and molecular physics, and nuclear and particle physics. During his time at Washington, he has also been deeply involved in revising the laboratory curriculum for the introductory physics sequence. David enjoys the wide range of physics he gets to think about and teach in the laboratory courses, and he especially likes to help students learn the skills, craft and techniques of experimental physics.

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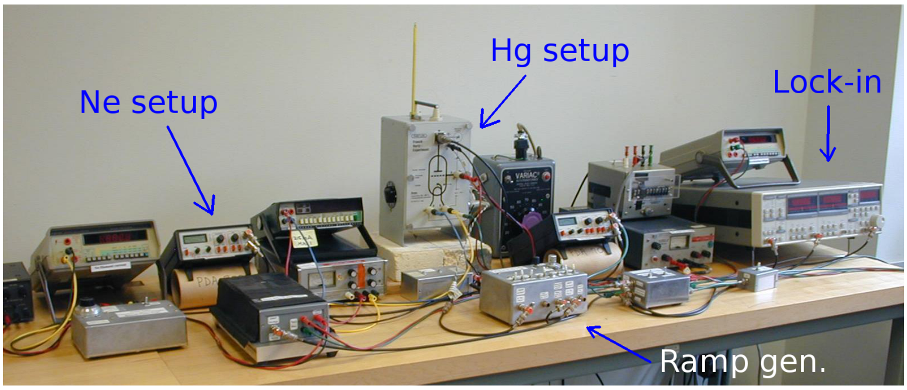
The Franck-Hertz experiment, one of the oldest to convincingly demonstrate quantized energy levels, has long been a staple of the undergraduate laboratory. In the experiment with mercury, the anode current as a function of accelerating voltage displays a familiar periodic peak and valley structure with the peak spacing roughly equal to the energy of the first exited state. However, much has been learned about the interactions of electrons and atoms since 1914, and it is known that this physics is much more complex (and interesting) than is usually discussed at the introductory level.

In this immersion, participants will revisit the Franck-Hertz experiment, in setups that use both mercury vapor and neon gas. We will review the basic ideas and then extend the studies along two lines. The first extension uses a recent AJP paper by Rapior, Sengstock and Baev (2006) who propose a simplified model of electron-atom interactions to explain the changing peak separation in the anode current as the accelerating voltage increases. The second extension adds a lock-in amplifier plus modulating voltage to the accelerating voltage which allows the experimenter to plot the derivative of the anode current signal as a function of accelerating voltage. This trick reveals hidden structure in the anode current curve, and makes possible measurements of higher energy excitations, which become more prominent in the Hg experiment as the temperature (and thus Hg vapor pressure) is reduced, allowing some electrons to gain more energy between inelastic collisions.

Our apparatus consists of two independent Franck-Hertz tubes, one with mercury (mounted inside an oven) and the other with neon gas, which are connected to a ramp generator and chart recorder via simple switchboxes that allow a quick change of apparatus. In addition a lock-in amplifier can be patched in to the setup to add a modulation voltage on top of the sweep voltage and the lock-in then measures the derivative of the anode current signal. The Franck-Hertz tubes, current amplifiers and lock-in are commercial products. The ramp generator and interconnecting boxes are home built. In the picture below, the chart recorder is not shown.



The apparatus. Click on photo for a higher resolution view.

Although the Franck-Hertz experiment is over 100 years old, the physics it explores—the interaction of energetic electrons and atoms—remains a topic of active research, for example, in the design and characterization of “drift tube” detectors used in high-energy physics. By digging deeper into the physics this old standby, the instructor can help students appreciate some of the subtleties of the concepts of mean-free path and elastic and inelastic cross sections, plus have them learn about a truly useful tool: the lock-in amplifier.

Acquired Skills: How to carry out basic current spectroscopy with different Franck-hertz tubes; how to deduce the energy of the excited states in a basic way; how to interpret details of the anode-current plots based on a model of inelastic scattering and electron energetics; how to operate a lock-in amplifier and optimize its settings; how to investigate higher energy Hg states using a lock-in and varying temperature.

Outline of the Immersion:

> **Lecture/discussion: The essential Franck-Hertz experiment: The Hg experiment; what was Franck & Hertz' big accomplishment; the energy states of Hg; the concepts of scattering cross section and how these depend on energy; neon and how it differs from mercury.**
> **First steps:**
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> > **The basic setups for Hg and Ne. Making a current spectrum trace.**
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> > **Comparing Ne to Hg results—why are they different?**
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> > **Calibration of the measurements; location and interpretation of first peak.**
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> **Intermediate Franck-Hertz theory. The Boltzmann transport equation and how to think about it. Relationship to electron drift in gases and the anode current curve. Simplified model of electron transport in Rapior, Sengstock & Baev (RSB) and its predictions.**
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> **Data analysis: Application of RSB model to Hg and Ne results**
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> **Lecture/discussion: what is a lock-in amplifier? Some common uses, and standard features of commercial lock-ins. How to make one yourself. Optimizing the settings.**
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> **Optional: an experiment to learn the principles of the lock-in from the ground up.**
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> **Connecting the lock-in to the Franck-Hertz experiment: some options for your home setup.**
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> **Measurements of the Hg curve with the lock-in. Looking for "buried" features.**
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> **Lowering the Hg temperature and seeing excited states. How to prove it's not just noise. Understanding the systematics of the lower-temperature anode current spectrum and relating the bumps to multiple collisions involving higher-energy states.**

All essential materials and equipment will be provided, but participants are encouraged to bring a camera (cellphone OK) and computer/notebook to record notes and results. If the participant has a favorite data analysis package, that will be useful during the lab.

Safety considerations: none.

Cost estimate: Each Frank-Hertz setup consists of a Frank-Hertz tube (either Hg or Ne), with a power supply that delivers filament current, bias voltages, and at least one must supply a ramp voltage, typically up to 70 volts (for Ne). Also necessary are an x-y recording device, such as a chart recorder, a (preferably digital) oscilloscope, or computer-interface capable of recording voltages up to 100V. Finally, a lock-in amplifier is required to study the higher-energy states of Hg. Although commercial units, such as the SRS830 are optimal, one can make a low-frequency lock-in with a much cheaper computer interface and software that is quite adequate. The following list provides a rough guide to the major costs.

Hg Franck-Hertz tube & oven (Klinger Educational Products)	$2500
Ne Franck-Hertz tube & mounting (Klinger Educational Products)	$800
Franck-Hertz power supply includes current amp (Klinger Educational Products)	$1600
Lock-in Amplifier, (digital) SRS830 (thinksrs.com)	$4950
OR Lock-in Amplifier, (analog) SRS530 (thinksrs.com)	$2995

Please note that the Jonathan F. Reichert Foundation has established a grant program (ALPhA webpage; Foundation website) to help purchase apparatus used in Laboratory Immersions. Limitations and exlusions apply, but generally speaking the foundation may support up to 40% of the cost of the required equipment.