THE FRANCK-HERTZ EXPERIMENT

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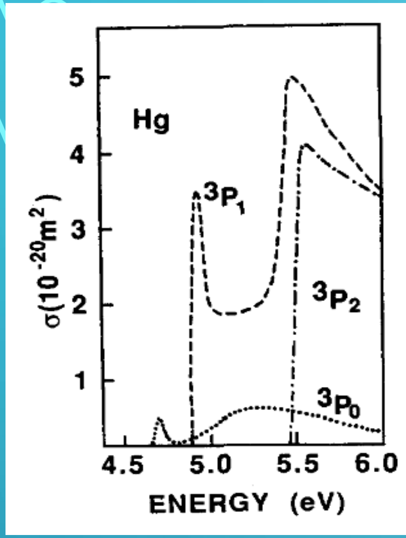
ELECTRON ENERGY AND SCATTERING CROSS-SECTION



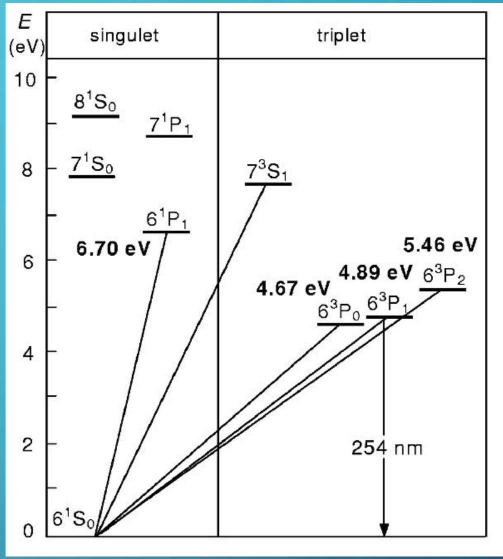
Cross-section of inelastic collisions vs. electron energy. Uncertainty of 30% due to measurement imprecisions. Haken & Wolf, p 698

The Franck-Hertz experiment, presented in 1914 by James Franck and Gustav Hertz, involves accelerating electrons through mercury (also done with neon) vapor via a potential grid, towards a beam current collecting anode. As the accelerated electrons gain sufficient energy for excitation, the cross-section of inelastic collisions increases. This can be seen in the diagram to the left, which shows roughly the cross section of inelastic electron-mercury collisions as a function of electron energy. The points of highest cross-section correspond approximately to the three lowest energy states at 4.67, 4.89, and 5.46 volts, respectively.

The cross-section can best be understood as an effective 'area' inside of which a scattering event can occur. It is not only related to accelerating electron energy, but also the mean free path of the electrons, as well as temperature.

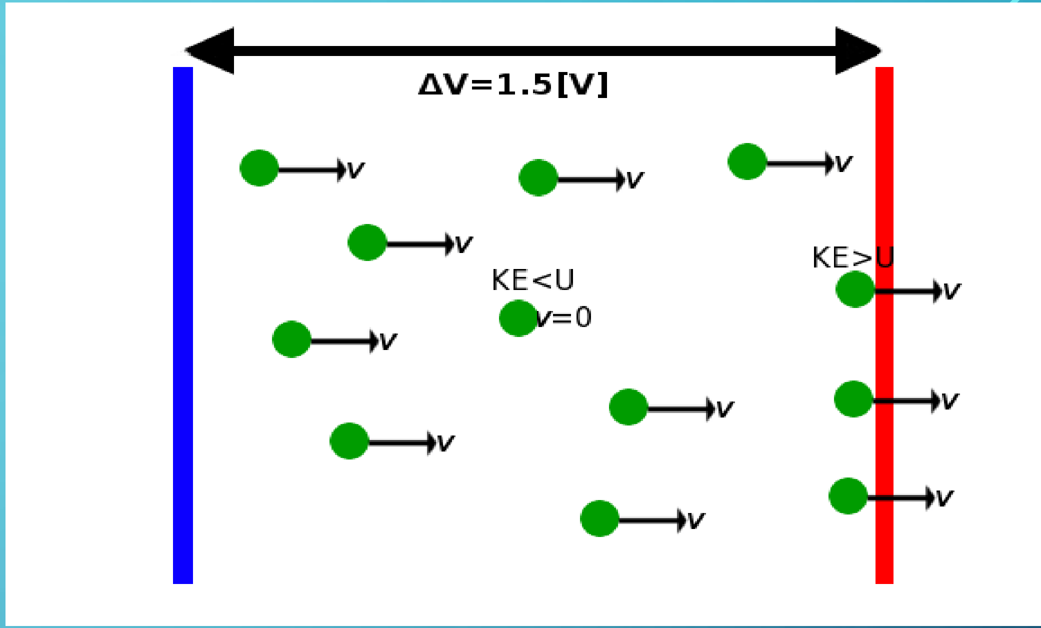
$$\sigma = \frac{k_B T}{P\lambda}$$

(Where P is the pressure, which is a function of the temperature T, and λ is the mean free path, which is dependent on electron energy.)



Lowest energy states of mercury.
Haken & Wolf, p 697

CURRENT MINIMA AT ENERGY INTERVALS



- To reach the collection plate, electrons must overcome a potential difference.
- Only electrons with sufficient energy can overcome this difference:

$$\frac{m_e}{2} v^2 = KE \geq U = q\Delta V$$

So electrons which have lost too much energy in collisions can't make it across the 1.5[V] potential.

- Current reflects this: $I = neAv$ increases as the number of electrons (that reach the collection plate, where the current is being read) increases.
- We see a smooth curve because velocity (and therefore energy) is a probabilistic distribution, not the same for each electron, and because not all electrons will collide.

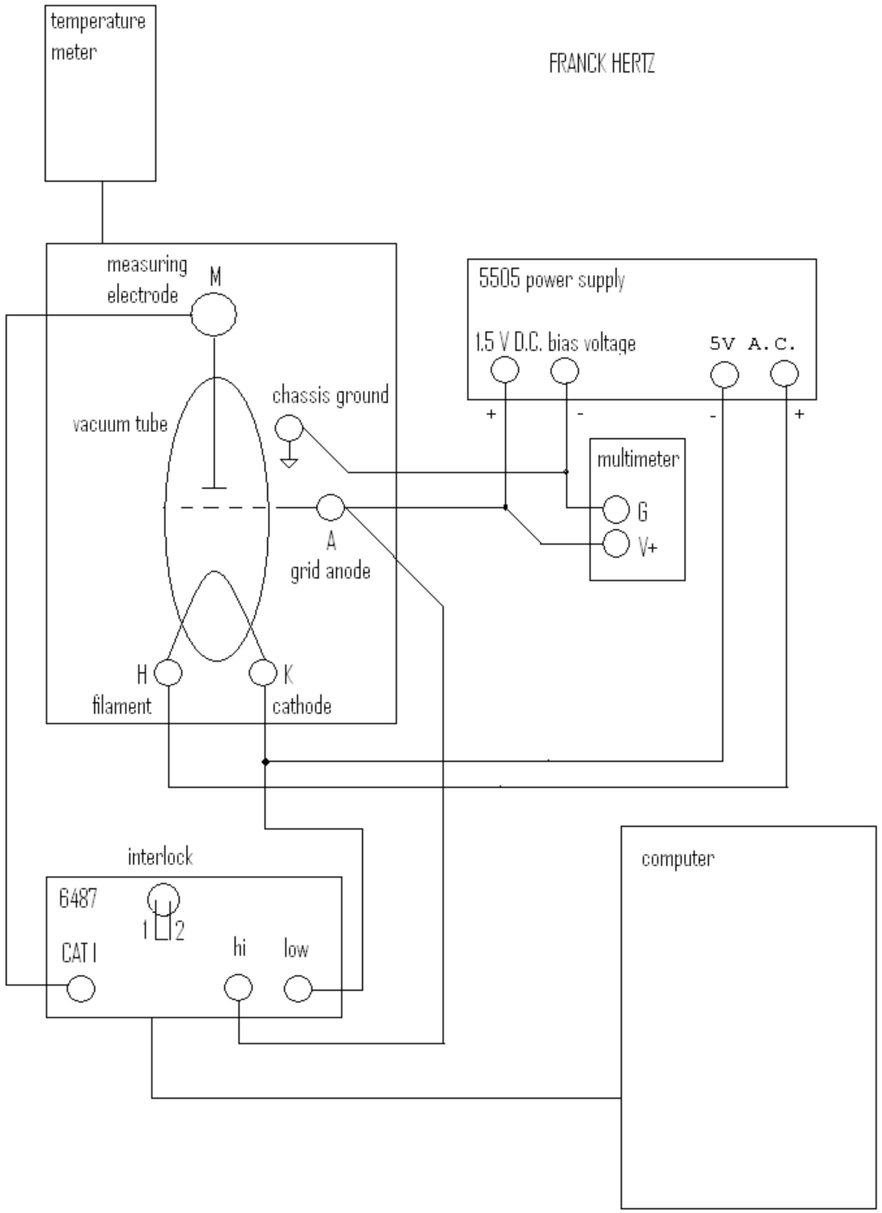
SETUP

We will be focusing on the Keithley 6487 and the portion inside the quartz tube.

Diagrams uploaded by Dr. Tagg to https://sites.google.com/site/experimentalphysicsdecathlon/home/04-fundamental-quantum-behavior/franck-hertz-experiment.

Diagram to the right is titled “FRANCK HERTZ.bmp”.

Diagram in the next slide is pulled from the safety instructions in “device.pdf”.



INSIDE THE QUARTZ TUBE

Quartz Tube

- Electromagnetically Non-Conductive
- Transparent
- Common: Makes it relatively cheap compared to alternatives
- Average thermal conductivity prevents it from having a major contribution to temperature.
- Vacuum prevents vapor from escaping, prevents other gases from entering, and keeps pressure low.

Mercury Vapor

- Boiling Point: 629.88[K] – much greater than the box.
    - However, pressure is very low (O~10^{-3}[atm]), so vapor is easy to maintain.
- Excited states are distinct.

Tungsten Fillament (Cathode)

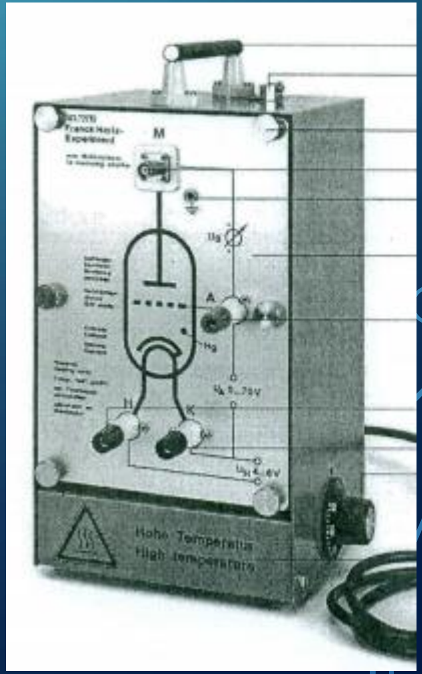
- Electrons are boiled off – high resistance > excess heat > high electron energy

Grid (Anode)

- This is where we sweep potential relative to the cathode.

Collection Plate

- Swept to stay at a 1.5[V] difference from the anode, reducing KE of incoming electrons.
- This is where current is measured.



KEITHLEY 6487

- Dual picoammeter and variable voltage source
- Ideal for low-, dark-, and beam-current measurements
- Fine resolution, low noise
- I/O trigger modes for automated production

- Ammeter Resolution: 10[fA]
- Sweeping Voltage:
  - 200 microvolts to 500 volts
  - 200 steps per second
  - 0.2 millivolt resolution
- Burden Voltage: <200 microvolts

Range	5½ Digit Default Resolution	Accuracy (1 Year) [1] ±(% rdg. + offset) 18°–28°C, 0–70% RH	Typical RMS Noise [2]	Typical Analog Rise Time (10% to 90%) [3] Damping [4] Off	On
2 nA	10 fA	0.3 % + 400 fA	20 fA	4 ms	80 ms
20 nA	100 fA	0.2 % + 1 pA	20 fA	4 ms	80 ms
200 nA	1 pA	0.15% + 10 pA	1 pA	300 µs	1 ms
2 µA	10 pA	0.15% + 100 pA	1 pA	300 µs	1 ms
20 µA	100 pA	0.1 % + 1 nA	100 pA	110 µs	110 µs
200 µA	1 nA	0.1 % + 10 nA	100 pA	110 µs	110 µs
2 mA	10 nA	0.1 % + 100 nA	10 nA	110 µs	110 µs
20 mA	100 nA	0.1 % + 1 µA	10 nA	110 µs	110 µs

TEMPERATURE-DEPENDENCE OF ΔE

Temperature [K]	433	447	462	476
Energy (E_a) [eV]	4.85	5.03	4.99	4.91

Uncertainties are ± 0.1[eV]

Since our carriers are electrons, voltage [V] and energy [eV] measurements are identical.

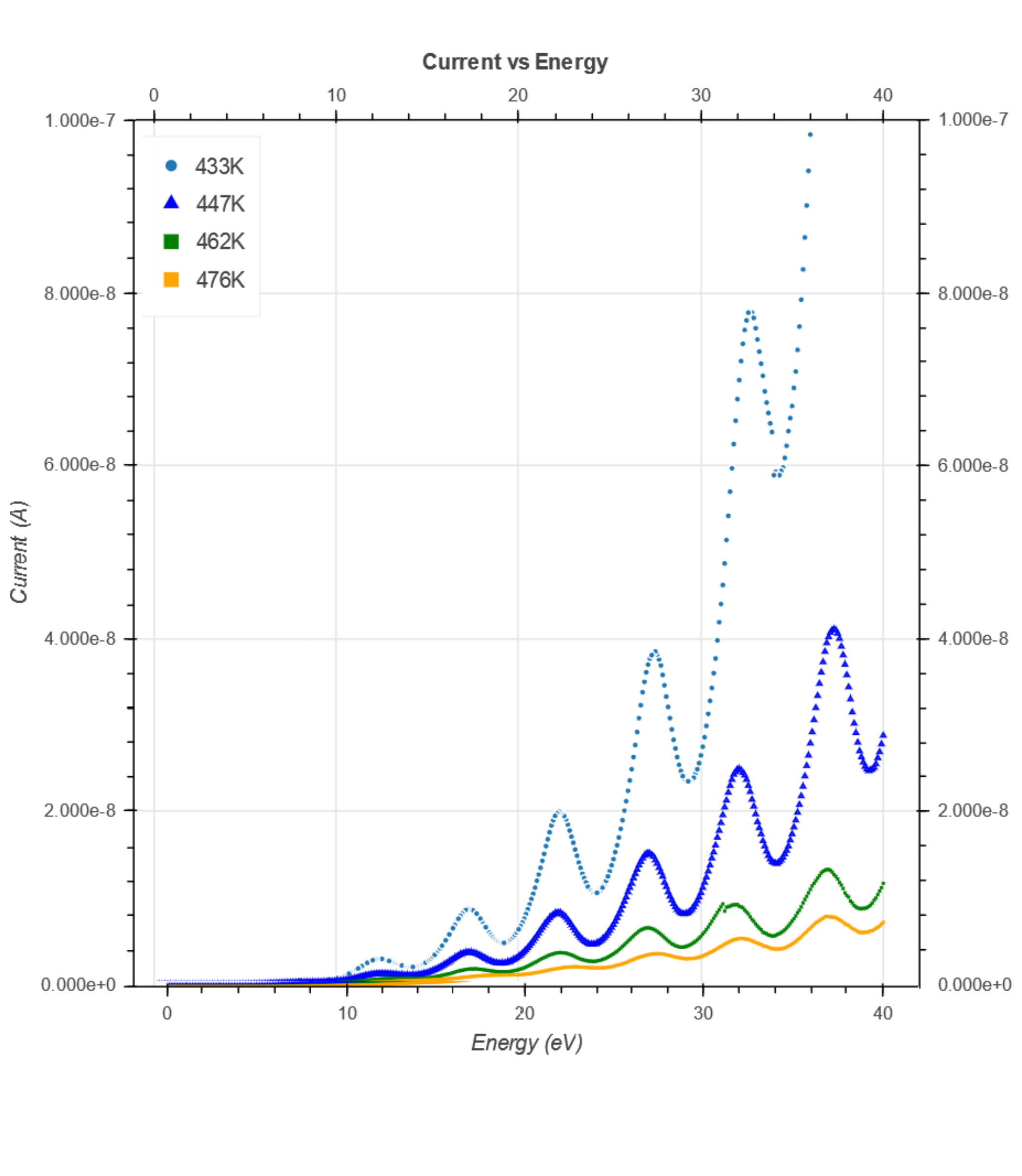
Minima were determined by taking curve fits to slices of data.

Then the distances between these minima were plotted.

$$\Delta E = \left[1 + \frac{\lambda}{L}(2n-1)\right] E_a$$

$$\sigma = \frac{k_B T}{p\lambda}$$

$$E_a = \Delta E_{(n=\frac{1}{2})}$$



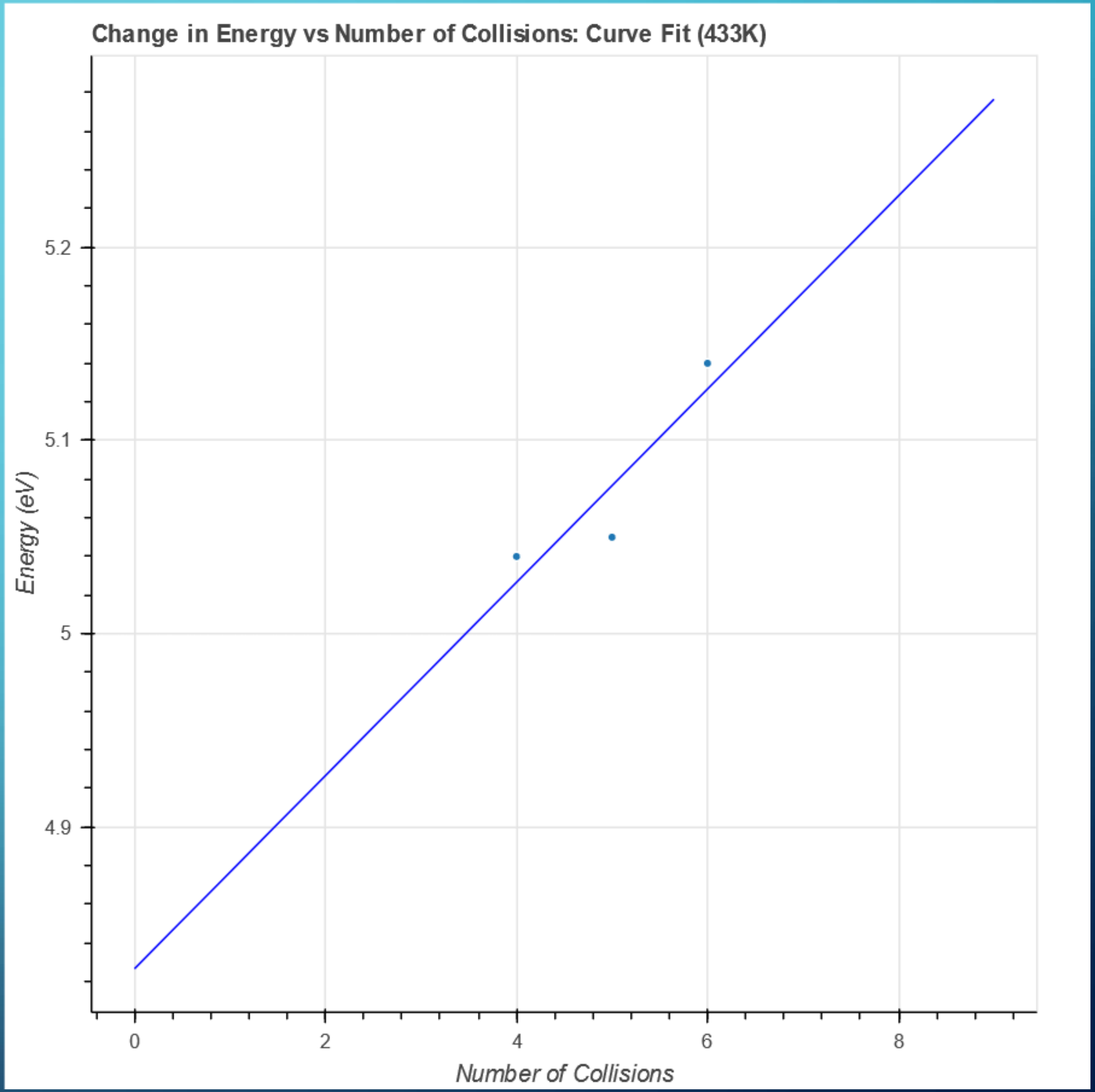
FINDING THE CROSS-SECTION FOR COLLISIONS

- Cross-section is sensitive to movement of particles, therefore varying with temperature:

$$\sigma = \frac{k_B T}{8.7 * 10^{9-\frac{3110[K]}{T}}[Pa]\lambda}$$

- The mean free path is taken from the slope of the function: $\frac{d\Delta E}{dn} = \frac{2\lambda}{L} E_a$

Temperature [K]:	433	447	462	476
λ [10^{-6}m]:	41.2	1.59	6.41	12.2
Uncertainty:	*9.24*	*8.90*	*8.96*	*9.12*
***σ* [10^{-18}m^2]:**	2.54	40.5	6.16	2.11
Uncertainty [m^2]:	*0.569*	*22.7*	*8.62*	*1.58*



WORKS CITED

- Abdulagatov, I. M., et al. "Thermal Conductivity of Fused Quartz and Quartz Ceramic at High Temperatures and High Pressures." *ScienceDirect*, Academic Press, May 2000, www.sciencedirect.com/science/article/pii/S0022369799002681.
- "Alpha: Making the World's Knowledge Computable." *Wolfram*, 2019, www.wolframalpha.com/.
- Friedman, Hershel. "Minerals.net." *Ice: The Mineral Ice Information and Pictures*, 2019, www.minerals.net/mineral/quartz.aspx.
- Hackman. "Information on Electronic Quartz Crystals." *Hackman's Realm*, lateblt.tripod.com/xtals.htm.
- Hann, G.F. "What Really Happens in the Franck-Hertz Experiment with Mercury?" American Journal of Physics 56, 696 (1988). http://home.uni-leipzig.de/~physik/sites/mona/wp-content/uploads/sites/3/2017/08/Franck-Hertz-Experiment.pdf.
- "What Is Important About Thermal Properties?" *Amethyst Galleries Mineral Gallery*, 2014, www.galleries.com/minerals/property/thermal.htm.
- "5: Thermionic Emission." http://www.physics.csbsju.edu/370/thermionic.pdf.