Vacuum Systems

Why much of physics sucks

Why Vacuum?

- Anything cryogenic (or just very cold) needs to get rid of the air
  - eliminate thermal convection; avoid liquefying air
- Atomic physics experiments must get rid of confounding air particles
  - eliminate collisions
- Sensitive torsion balance experiments must not be subject to air
  - buffeting, viscous drag, etc. are problems
- Surface/materials physics must operate in pure environment
  - e.g., control deposition of atomic species one layer at a time

Measures of pressure

- The "proper" unit of measure for pressure is Pascals (Pa), or $N \cdot m^{-2}$
- Most vacuum systems use Torr instead
  - based on mm of Hg
- Atmospheric pressure is:
  - 760 Torr
  - 101325 Pa
  - 1013 mbar
  - 14.7 psi
- So 1 Torr is 133 Pa, 1.33 mbar; *roughly* one milli-atmosphere

Properties of a vacuum

Vacuum	Pressure (torr)	Number Density (m^{-3})	M.F.P. (m)	Surface Collision Freq. ($m^{-2} \cdot s^{-1}$)	Monolayer Formation Time (s)
Atmosphere	760	2.7×10^{25}	7×10^{-8}	3×10^{27}	3.3×10^{-9}
Rough	10^{-3}	3.5×10^{19}	0.05	4×10^{21}	2.5×10^{-3}
High	10^{-6}	3.5×10^{16}	50	4×10^{18}	2.5
Very high	10^{-9}	3.5×10^{13}	50×10^{3}	4×10^{15}	2.5×10^{3}
Ultrahigh	10^{-12}	3.5×10^{10}	50×10^{6}	4×10^{12}	2.5×10^{6}

Kinetic Theory

- The particles of gas are moving randomly, each with a unique velocity, but following the Maxwell Boltzmann distribution:

$$f(v) = \left(\frac{m}{2\pi kT}\right)^{\frac{3}{2}} e^{-mv^2/2kT}$$

- The average speed is:

$$\bar{v} = \left(\frac{8kT}{\pi m}\right)^{\frac{1}{2}}$$

- With the molecular weight of air around 29 g/mole (~75% N_2 @ 28; ~25% O_2 @ 32), 293 °K:
  - m = 29×1.67×10^{-27} kg
  - <v> = 461 m/s
  - note same ballpark as speed of sound (345 m/s)

Mean Free Path

- The mean free path is the typical distance traveled before colliding with another air molecule
- Treat molecules as spheres with radius, *r*
- If (the center of) another molecule comes within 2*r* of the path of a select molecule:
- Each molecule sweeps out cylinder of volume:

  $V = 4\pi r^2 vt$
  - in time *t* at velocity *v*
- If the volume density of air molecules is *n* (e.g., m^{-3}):
  - the number of collisions in time *t* is

    notZ = $4\pi n r^2 vt$
- Correcting for relative molecular speeds, and expressing as collisions per unit time, we have:

$$Z = 4\sqrt{2}\pi n r^2 v$$

Mean Free Path, cont.

- Now that we have the collision frequency, *Z*, we can get the average distance between collisions as:

  $\lambda = v/Z$
- So that

$$\lambda = \frac{1}{4\sqrt{2}\pi n r^2}$$

- For air molecules, $r \approx 1.75\times10^{-10}$ m
- So $\lambda \approx 6.8\times10^{-8}$ m = 68 nm at atmospheric pressure
- Note that mean free path is inversely proportional to the number density, which is itself proportional to pressure
- So we can make a rule for λ = (5 cm)/(P in mtorr)

Relevance of Mean Free Path

- Mean free path is related to thermal conduction of air
  - if the mean free path is shorter than distance from hot to cold surface, there is a collisional (conductive) heat path between the two
- Once the mean free path is comparable to the size of the vessel, the paths are ballistic
  - collisions cease to be important
- Though not related in a 1:1 way, one also cares about transition from bulk behavior to molecular behavior
  - above 100 mTorr (about 0.00013 atm), air is still collisionally dominated (viscous)
    - λ is about 0.5 mm at this point
  - below 100 mTorr, gas is molecular, and flow is statistical rather than viscous (bulk air no longer pushes on bulk air)

Gas Flow Rates

- At some aperture (say pump port on vessel), the flow rate is

  S = dV/dt (liters per second)
- A pump is rated at a flow rate:

  S_p = dV/dt at pump inlet
- The mass rate through the aperture is just:

  Q = PS (Torr liter per second)
- And finally, the ability of a tube or network to conduct gas is

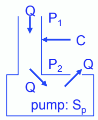
  C (in liters per second)
- such that

  $Q = (P_1 - P_2) \times C$

Evacuation Rate

- What you care about is evacuation rate of vessel
- $S = Q/P_1$
- but pump has $S_p = Q/P_2$
- Q is constant (conservation of mass)
- $Q = (P_1 - P_2)C$, from which you can get:

  $1/S = 1/S_p + 1/C$



- So the net flow looks like the "parallel" combination of the pump and the tube:
  - the more restrictive will dominate
- Usually, the tube *is* the restriction
  - example in book has 100 l/s pump connected to tube 2.5 cm in diameter, 10 cm long, resulting in flow of 16 l/s
  - pump capacity diminished by factor of 6!

Tube Conductance

- For air at 293 K:
- In bulk behavior (> 100 mTorr):

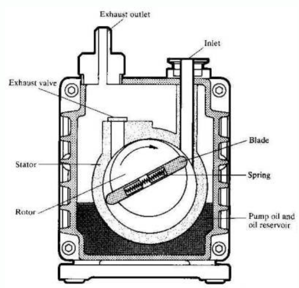
  $C = 180 \times P \times D^4/L$ (liters per second)
  - *D*, the diameter, and *L*, the length are in cm; *P* in Torr
  - note the *strong* dependence on diameter!
  - example: 1 m long tube 5 cm in diameter at 1 Torr:
    - allows 1125 liters per second
- In molecular behavior (< 100 mTorr):

  $C = 12 \times D^3/L$
  - now cube of *D*
  - same example, at 1 mTorr:
    - allows 0.1 liters per second (much reduced!)

Pump-down time

- Longer than you wish
  - Viscous air removed quickly, then long slow process to remove rest
  - to go from pressure P_0 to P, takes $t = (V/S) \times \ln(P_0/P)$
  - note logarithmic performance

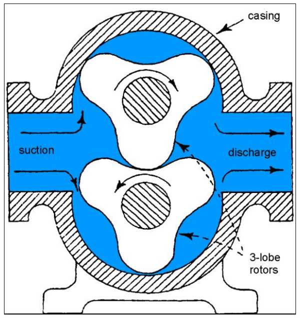
Mechanical Pumps



- Form of "positive displacement pump"
- For "roughing," or getting the the bulk of the air out, one uses mechanical pumps
  - usually rotary oil-sealed pumps
  - these give out at ~ 1–10 mTorr
- A blade sweeps along the walls of a cylinder, pushing air from the inlet to the exhaust
- Oil forms the seal between blade and wall

Lobe Injection Pumps

- Can move air very rapidly
- Often no oil seal
- Compression ratio not as good



Turbomolecular pumps

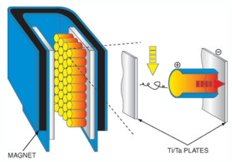
- After roughing, one often goes to a turbo-pump
  - a fast (24,000 RPM) blade achieves a speed comparable to the molecular speed
  - molecules are mechanically deflected downward
- Work only in molecular regime
  - use after roughing pump is spent (< 100 mTorr)
- Usually keep roughing pump on exhaust

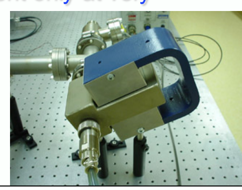
Cryopumping

- A cold surface condenses volatiles (water, oil, etc.) and even air particles if sufficient nooks and crannies exist
  - a dessicant, or getter, traps particles of gas in cold molecular-sized "caves"
- Put the getter in the coldest spot
  - helps guarantee this is where particles trap: don't want condensation on critical parts
  - when cryogen added, getter gets cold first
- Essentially "pumps" remaining gas, and even continued outgassing
- Called cryo-pumping

Ion Pump

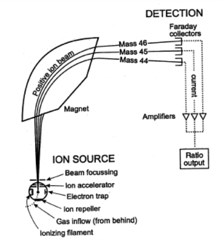
- Ionize gas molecules, deposit ions on chemically active surface, removed by chemisorption
- Best use is for Ultra-High Vacuum applications (10^{-11} Torr)
- Current is proportional to pressure (pump is also a pressure gauge)
- No moving parts, but efficient only at very low pressures



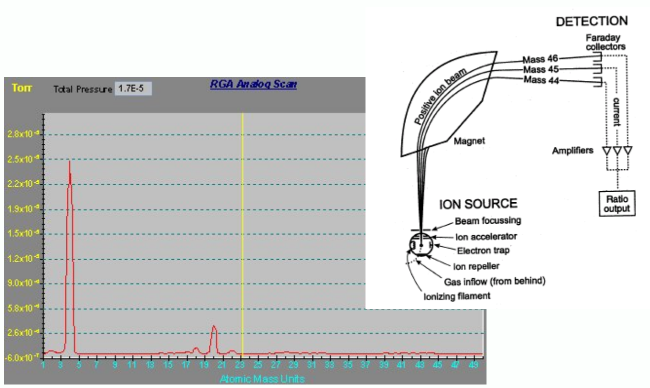


Residual Gas Analyzer (mass spectrometer)

- Electronic “nose”, sniffing inside the chamber
- Can detect partial pressure down to 10^{-14} Torr
- Useful as a He leak-detector
- Measures mass-to-charge ratio by ionizing a molecule and accelerating in EM field



Example of RGA spectra, He:Ne mixture 10:1



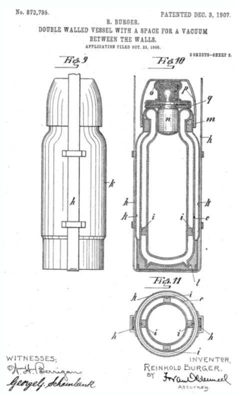
Typical problems in achieving UHV:

- Actual Leaks (valves, windows)
- Slow pump-down times
- “Virtual” leaks
- Outgassing – bulk and surfaces

Solutions:

- Leak-testing
- Re-design of vacuum chamber
- Bake-out
- Cryopumping

Dewars

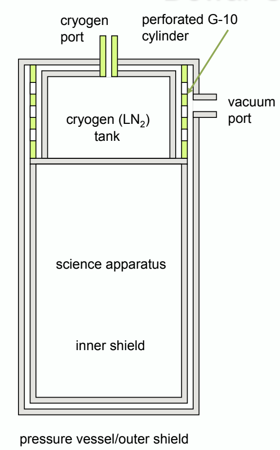


- Evacuating the region between the cold/hot wall and the ambient wall eliminates convection and direct air conduction
- Some conduction over the lip, through material
  - minimized by making thin and out of thermally non-conductive material
- Radiation is left, but suppressed by making all surfaces low emissivity (shiny)
- Heat paths cut → holds temperature of fluid

Liquid Nitrogen Dewar

- Many Dewars are passively cooled via liquid nitrogen, at 77 K
- A bath of LN_2 is in good thermal contact with the “inner shield” of the dewar
- The connection to the outer shield, or pressure vessel, is thermally weak (though mechanically strong)
  - G-10 fiberglass is good for this purpose
- Ordinary radiative coupling of $\sigma(T_h^4 - T_c^4)$ = 415 W/m^2 is cut to a few W/m^2
  - Gold plating or aluminized mylar are often good choices
  - bare aluminum has $\varepsilon \approx 0.04$
  - gold is maybe $\varepsilon \approx 0.01$
  - aluminized mylar wrapped in many layered sheets is common (MLI: multi-layer insulation)
  - MLI wants to be punctured so-as not to make gas traps: makes for slooooow pumping

Dewar Construction



- Cryogen is isolated from warm metal via G-10
  - but in good thermal contact with inner shield
- Metal joints welded
- Inner shield gold-coated or wrapped in MLI to cut radiation
- Windows have holes cut into shields, with vacuum-tight clear window attached to outside
- Can put another, nested, inner-inner shield hosting liquid helium stage

Cryogen Lifetime

- Note that LN_2 in a bucket in a room doesn’t go “poof” into gas
  - holds itself at 77 K: does not creep to 77.1K and all evaporate
  - due to finite “heat of vaporization”
    - LN_2 is 5.57 kJ/mole, 0.81 g/mL, 28 g/mol → 161 J/mL
    - L^4He is 0.0829 kJ/mol, 0.125 g/mL, 4 g/mol → 2.6 J/mL
    - H_2O is 40.65 kJ/mol, 1.0 g/mL, 18 g/mol → 2260 J/mL
- If you can cut the thermal load on the inner shield to 10 W, one liter of cryogen would last
  - 16,000 s ≈ 4.5 hours for LN_2
  - 260 s ≈ 4 minutes for LHe

Nested Shields

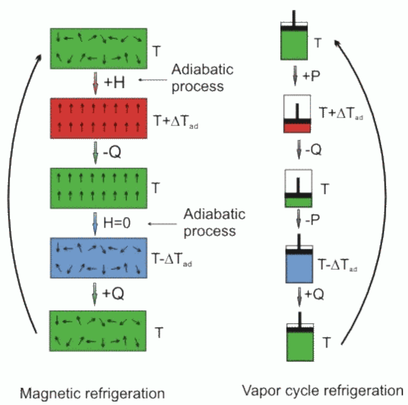
- LHe is expensive, thus the need for nested shielding
- Radiative load onto He stage much reduced if surrounded by 77 K instead of 293 K
  - $\sigma(293^4 - 4^4) = 418$ W/m^2
  - $\sigma(77^4 - 4^4) = 2.0$ W/m^2
  - so over 200 times less load for same emissivity
  - instead of a liter lasting 4 minutes, now it's 15 hours!
  - based on 10 W load for same configuration at LN_2

Coolest place on earth:

- Antarctica -89 °C, or 183K
- San Diego: Dilution fridges
  Mayer Hall (Maple, Goodkind), NSB (Butov) ~300 mK
- Cambridge, MA: Sub-500 picoKelvin achieved in Ketterle group at MIT

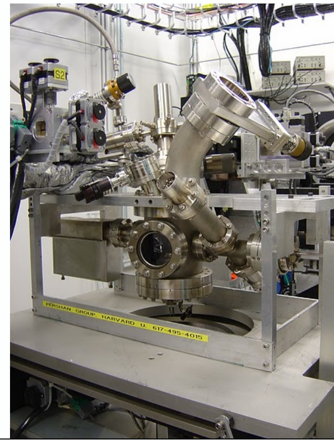
See "**Cooling Bose-Einstein Condensates Below 500 Picokelvin**"
Science 301, 5639 pp. 1513 - 1515 (2003)

Adiabatic Magnetization Cooling

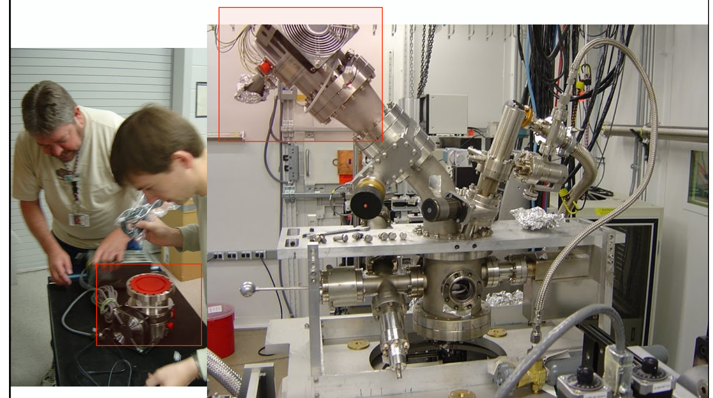


Photos: Displex Cryostat insert

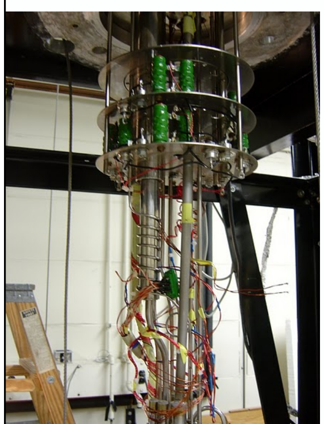
Photos: Ultra High Vacuum chamber



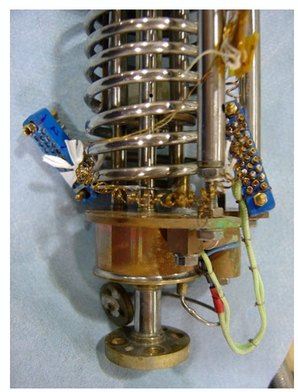
Photos: Turbomolecular “Turbo” Pump

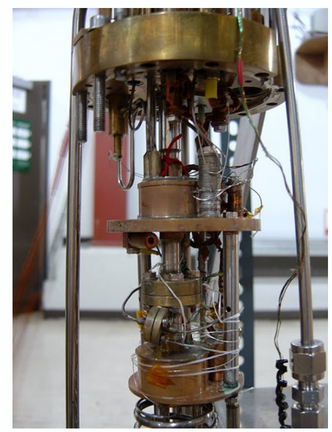


Photos: Dilution Refrigerator

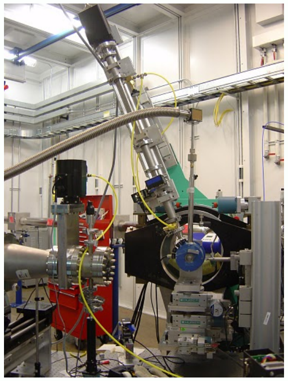


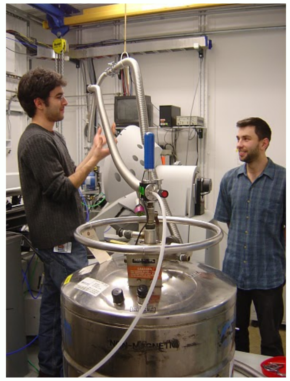
Photos: Dilution Refrigerator





Helium Flow Cryostat





Assignments

- Read 3.1, 3.2, 3.3.2, 3.3.4, 3.4: 3.4.1 (Oil-sealed and Turbomolecular, 3.4.3 (Getter and Cryo), 3.5.2 (O-ring joints), 3.6.3, 3.6.5
  - applies to both 3rd and 4th editions