Vacuum Technology

PHY451

October 22, 2014

MICHIGAN STATE UNIVERSITY

Some References

- http://uspas.fnal.gov/materials/13Duke/Duke_VacuumScience.shtml
- http://physics.ucsd.edu/~tmurphy/phys121/lectures/06_vacuum.ppt
- http://www.oerlikon.com/ecomaXL/files/oerlikon_FUNDAMENTALS.PDF&download=1

Vacuum – [1]

Vacuum when gas has the density of the particles less than atmospheric pressure

Vacuum systems necessary to remove and maintain removal of gases in some volume

- **Vacuum used e.g.**
  - Oxygen removed from light bulb to protect filament & in food processing to preserve
  - Create force for forming plastic sheets
  - Deposition to create insulators, conductors, etc
  - Electron beam microscope
  - Particle accelerators
  - Cryogenic system insulation

Vacuum - [2]

Pressure Ranges

- Atmosphere ~760 torr
- Rough Vacuum ~10^{-3} torr
- High Vacuum ~10^{-3} to 10^{-6} torr
- Very High Vacuum ~10^{-6} to 10^{-9} torr
- Ultra High Vacuum ~10^{-9} to 10^{-12} torr

Example Values

- Deep space ~<10^{-17} torr
- Mars surface ~5 torr
- Lunar surface ~10^{-11} torr
- Geosynchronous satellites ~10^{-11} torr
- Space station ~10^{-9} torr
- Above earth – [12 km (airline) ~140 torr], [32 km ~8torr], [80.5 km ~10^{-3} torr]

Vacuum – [3]

- **Gas composition and pressure can have wide variance.**
  - Depending on application – acceptable residual gas density can vary from 10^{10} to 10^{4} molecules per cm^{3}
  - Initial gas composition initially air but later largely driven by pumping technique and source of gas
    - » Initial "vacuum" – mainly air N_2 (78.08%), O_2 (20.95%), CO_2 (0.037%)

General Gas Equation

- P = pressure [Pa; N / m2]
- T = thermodynamic temperature [K]
- n = molecular number density [1 / m^3]
- k = Boltzmann's constant k = $1.380 \cdot 10^{-23}$ J/K

$$P = n \cdot k \cdot T$$

Pressure Units

- **Pressure = Force/Area**
  - **E.G., 6 inch diameter plate with vacuum / atmosphere interfaces ➔~416 pounds force**
- **Pressure units**
  - Pascal (N/m^2) = Pa, bar = 10^5 Pa, Torr = mmHg,
  - micron = μmHg, psi = $lbs/inch^2$
  - 1 atmosphere (atm) ➔
    - » 1.01325 bar = 1.01325 x 10^5 Pa
    - » 760 torr = 760 mmHg = 760 x 10^3 micron
    - » 14.7 psi (pounds per square inch)
  - 1 torr = 133.32 Pa = 1.3332 mbar
- **At standard temperature (273.15 K = 0^oC) & pressure (1atm)➔ 22.414 liters contains 6.02 x 10^{23} particles (molecular weight in grams) ➔ molecular density ($1/cm^3$) = 6.02 x 10^{23} particles / 22414 cm^3= 2.7 x 10^{19} molecules/cm^3**
- **At 10^{-3} torr ➔2.7 x 10^{19} / 760 x 10^3 = 3.6 x 10^{13} molecules/cm^3**

Maxwell Boltzman – [1]

Gas particles move randomly but with specific velocity given by Maxwell-Boltzmann Distribution = f

- **f is probability distribution that is function of particle velocity (v), mass, and temperature T – *velocity does <u>not</u> depend on pressure***

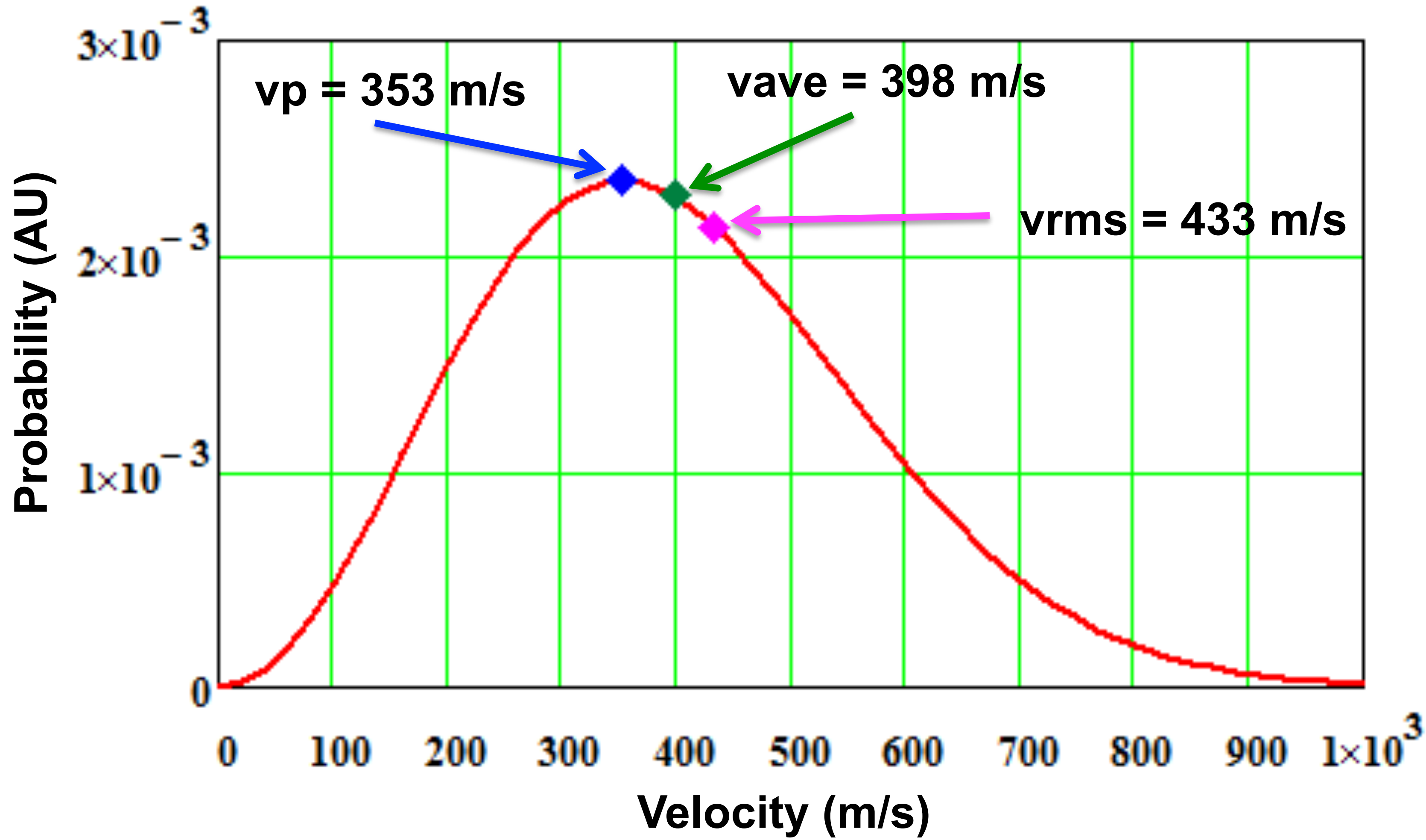
$$f(v, mass, T) := 4\pi \left(\frac{mass}{2\pi k T}\right)^{\frac{3}{2}} v^2 e^{-\frac{mass\, v^2}{2kT}}$$

  - k= Boltzman Constant = $1.380650424 \cdot 10^{-23}$ (joule/K)
  - T = temperature (K)
  - Mass = kg = molecular weight in AMU x $1.6605402 \cdot 10^{-27}$ *kg/AMU

- **Most probable velocity = vp** $\left(2k\frac{T}{mass}\right)^{0.5}$
- **Mean velocity = vave** $\left(8k\frac{T}{mass\,\pi}\right)^{0.5}$ **vave=1.1284 x vp**
- **RMS velocity = vrms** $\left(3k\frac{T}{mass}\right)^{0.5}$ **vrms=1.2247 x vp**

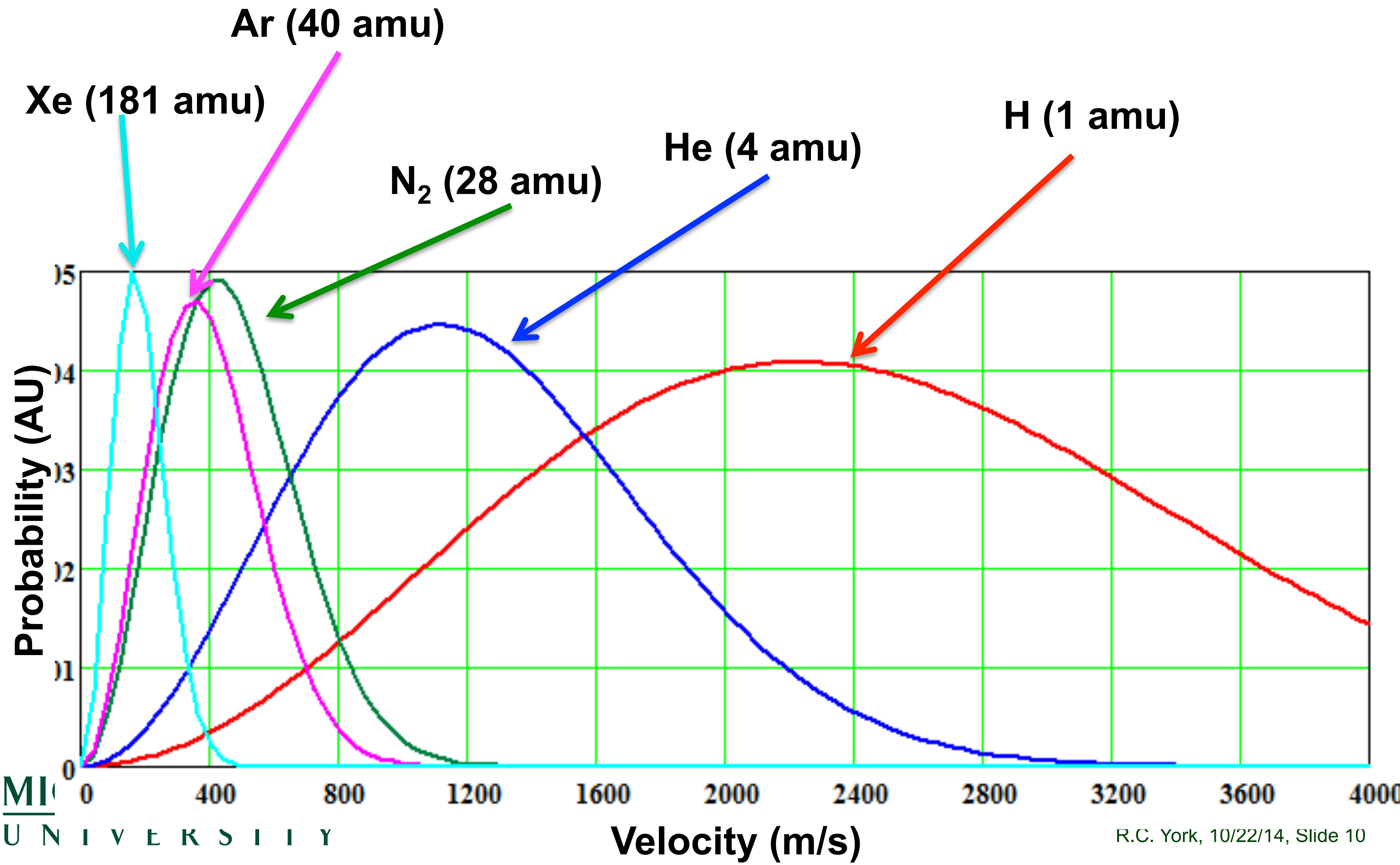
Maxwell-Boltzmann – [2]

Probability velocity distribution for ^{40}Ar at 300 K



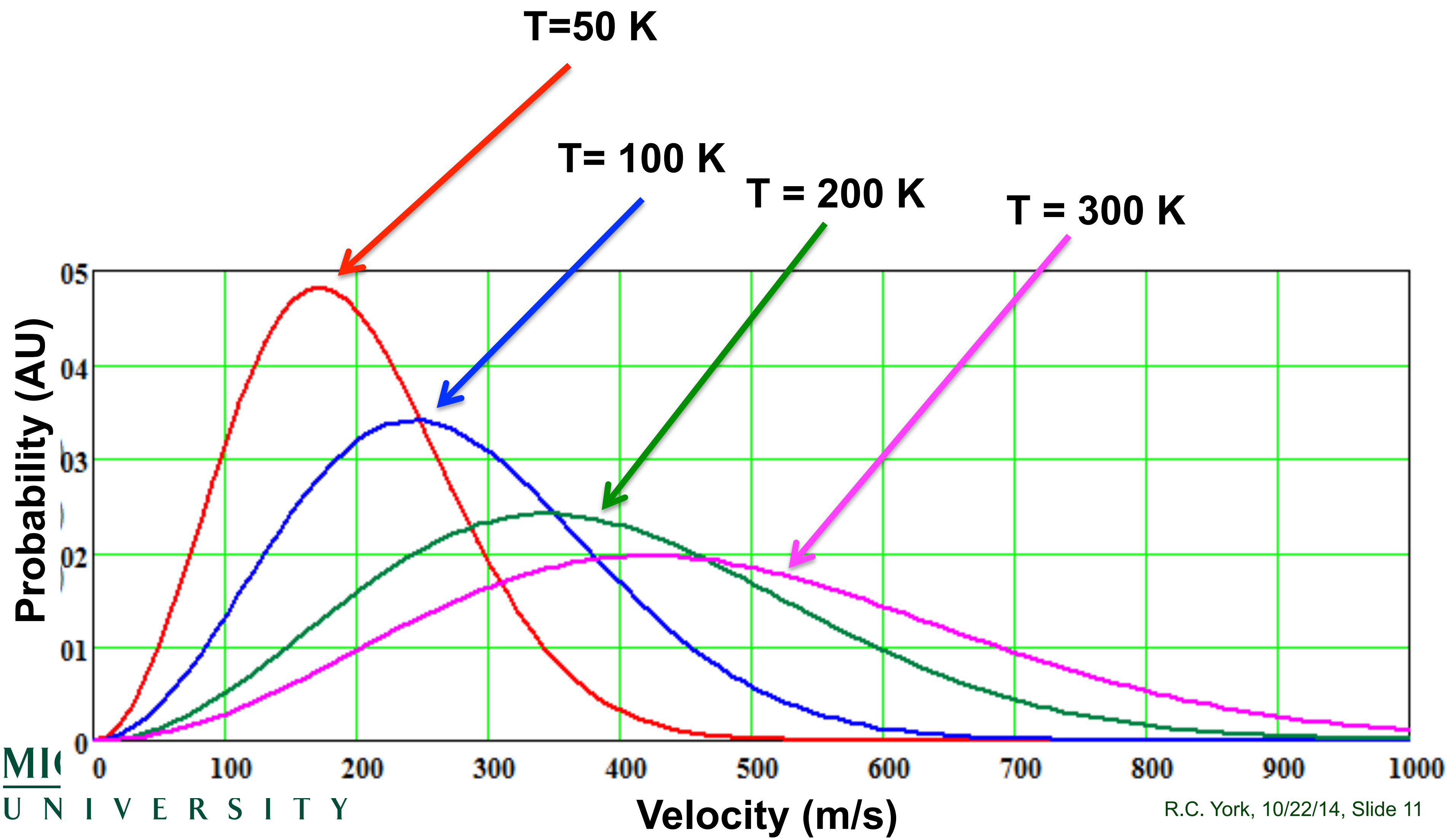
Maxwell-Boltzmann – [3]

Velocity mass dependent (T = 300 K)



Maxwell-Boltzmann – [4]

Velocity temperature (T) dependent (N_2 mass = 28 amu)



Maxwell Boltzman – [5]

Energy depends only on T

- Average energy = Eave = mass x $vrms^2/2$ = 3kT/2
- E(T=50K)=6.5 meV, E(T=100K)=12.9 meV, E(T=300K)=38.8 meV
- Most probable energy = Ep = mass x $vp^2/2$ = kT/2

Mean Free Path – [1]

Mean free path (λ) is average distance before colliding with another molecule

- $\lambda = 1/[(2)^{0.5} \pi d_o^2 n] = k T / [(2)^{0.5} \pi d_o^2 P]$
  - λ = mean free path (m)
  - d_o = diameter of molecule (m)
    - »For Air – average diameter ~3.74×10^{-10} m
  - n = molecular density (m^{-3})
    - » n (stand. temp. & pressure – STP)= nstp*Tstp*P/(T*Pstp)
      - – nstp (Tstp, Pstp)= 2.7×10^{19} molecules/cm^3
  - T = Temperature (K)
  - P = Pressure (Pa)
  - k = Boltzmann constant = $1.38 \times 10^{-23}\ m^2\ kg\ s^{-2}\ K^{-1}$

Mean Free Path – [2]

Mean free path (λ) is average distance before colliding with another molecule - values shown for air T=303.15 K (30 °C)

- λ (cm) = $1.646 \times 10^{-5} T$ (K)/P(torr)
- λ (cm) = $2.1945 \times 10^{-3} T$ (K)/P(Pa)
- Once λ similar to vacuum vessel dimension – only collisions with vacuum walls dominate – not molecules colliding with molecules
  - i.e. $<10^{-3}$ torr

P(torr)	760	1	10^{-3}	10^{-6}	10^{-9}
λ (cm)	6.6×10^{-6}	5.0×10^{-3}	5.0	5.0×10^{3}	5.0×10^{6}

Molecular Collisions

Rate of gas striking surface – Γ(molecules per $m^{-2}s^{-1}$):

- $\Gamma(m^{-2}s^{-1})$ = n vave/4 = $n\,(kT/(2\pi m))^{0.5}$ where n = gas density
- Since for Air – average diameter ~3.74×10^{-10} m
  - Area ~ 1.1×10^{-19} m^2
- Then for N_2 at 10^{-6} torr
  - get monolayer in $1.1 \times 10^{-19} \times 3.9 \times 10^{18} \sim 0.4$ s

P (torr)	n (m^{-3})	Particle Flux ($m^{-2}s^{-1}$)		
		H_2	H_20	N_2
760	2.5×10^{25}	1.1×10^{28}	3.7×10^{27}	2.9×10^{27}
10^{-6}	3.2×10^{16}	1.4×10^{19}	4.8×10^{18}	3.9×10^{18}

MICHIGAN STATE UNIVERSITY

Gas Flow – [1]

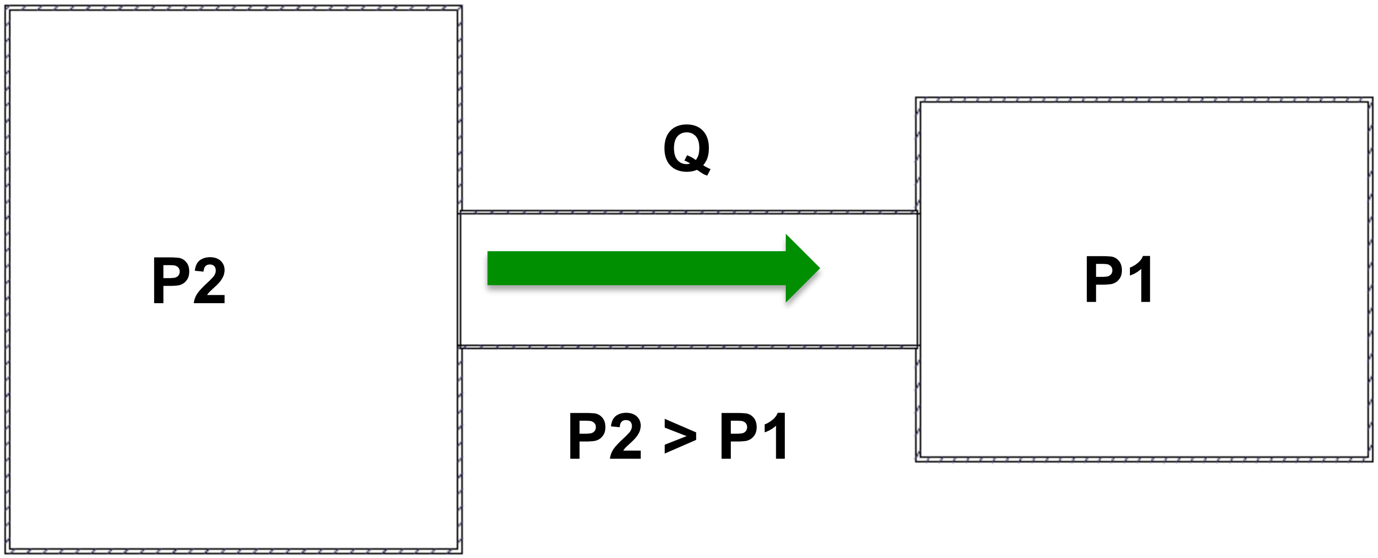
Knudsen number (Kn) is ratio of mean free path and flow channel diameter (a)

$Kn = \lambda / a$

- If Kn < 0.01 flow driven by molecule-molecule collisions
  - Molecules travel in uniform motion toward lower pressure
  - Can be laminar or turbulent
- If 0.01 < Kn < 1 flow is in transition
- If Kn > 1 flow driven by molecule-wall collisions

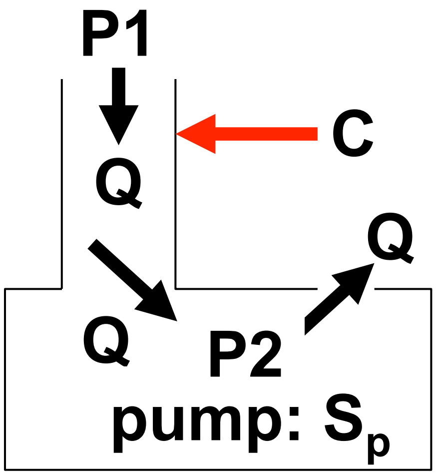
Gas Flow – [2]

- Throughput = Q = gas flow rate = d(PV)/dt
  - Q in Pa-m^3/s (= 7.5 torr-liter/s)
- Gas conductance = C = Q/(P2-P1)
  - P1 = pressure outlet, P2 = pressure inlet
  - C in m^3/s (= 1000 liter/s)
- Pumping speed = S = dV/dt (liters/second)
- Q = (P2-P1)xC



Evacuation Rate

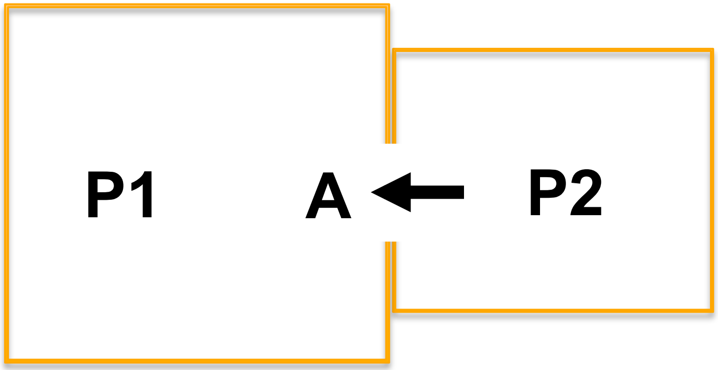
- Evacuation rate at chamber Seff = Q/P1
- Evacuation rate at pump is Sp = Q/P2
- Q = constant (mass conserved) = (P1-P2)C
- Combining get 1/Seff = 1/Sp + 1/C (like resistors in parallel)
  - Most restrictive will dominate



- E.G.
  - if pump has Sp = 100 liter/s
  - C for round tube is C = 12.1 D^3/L (liter/sec), D= ID of tube (cm), L = length of tube (cm) – NOTE diameter dependence to 3rd power
    - » For ID= 6, L=30 cm then C=86 liter/sec
    - » Seff = 46 liter/sec or pumping speed reduced to 46% by tube conductance!

Conductance

- Round Tube of diameter D, Length L ➔ C(m^3/s) α $(T/Mamu)^{0.5}$ D^3/L
  - –For Air (Mamu=29 at 22 °C) C = 12.1 D^3/L (liters/sec)
- For aperture A ➔ C(m^3/s) α $(T/Mamu)^{0.5}$ A(m^2)
  - –For Air (Mamu=29 at 22 °C) C(liters/sec) = 11.6 A (cm^2)



P2 > P1

Pump-down time

To go from pressure P1 to P2 takes time t

- **$t = V(\text{liters})/S(\text{liter/s}) \times \ln(P1/P2)$**
  - **E.G., If V = 10 liters, S = 10 liter/sec P1 = 760 torr, P2 = 10^{-6} torr**
  - **t ~ 18 s**
- **BUT other sources to vacuum load – e.g. water evaporating from vacuum surfaces – make time dramatically longer – e.g. hours**

Mechanical Pumps

Roughing pump

- To begin process from ~ atmosphere down to ~ 10^{-3} torr
- Uses oil to seal between rotating blade to push molecules from inlet to outlet

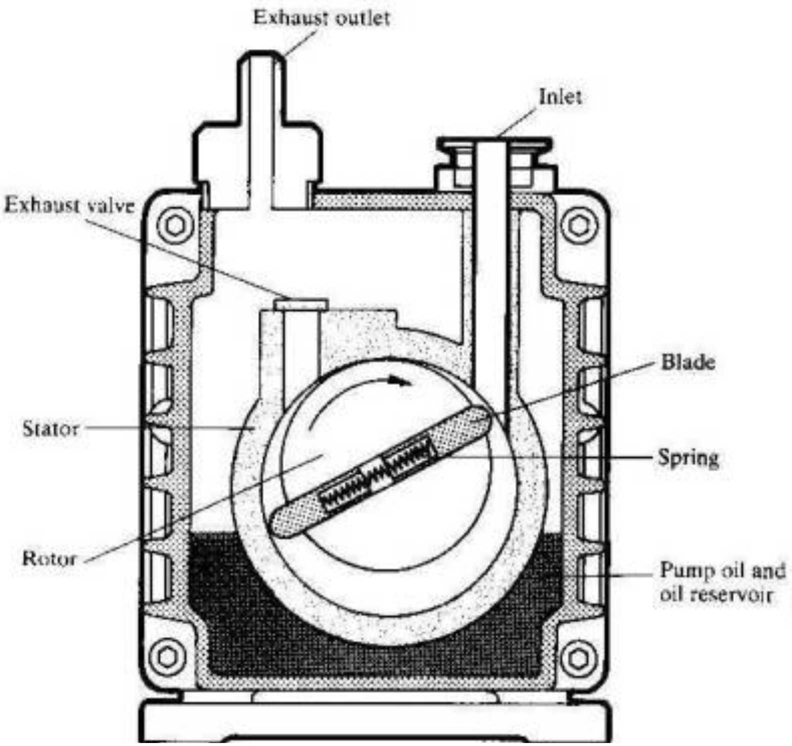
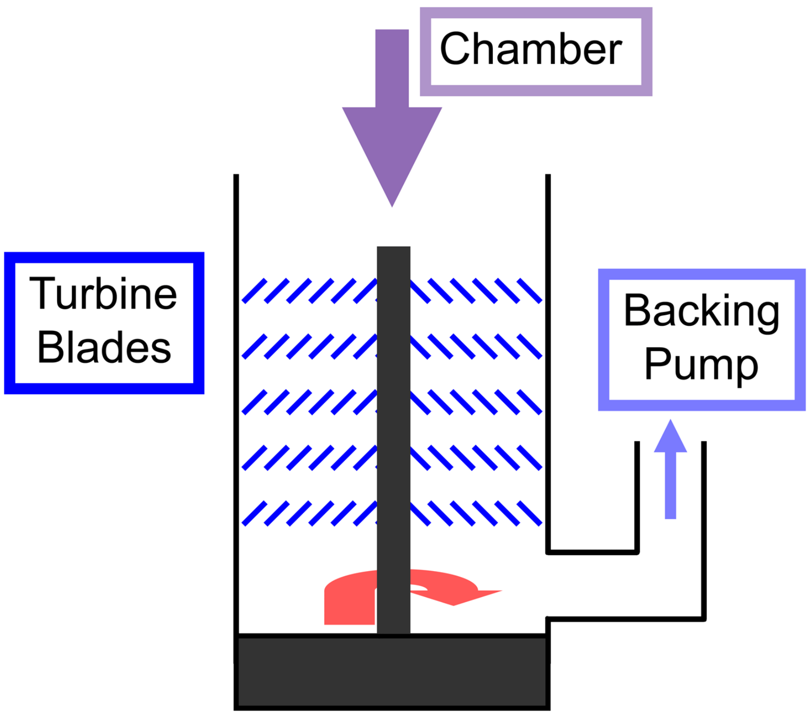


Figure from: http://physics.ucsd.edu/~tmurphy/phys121/lectures/06_vacuum.ppt

Turbomolecular Pumps

- Turbomolecular pumps often used at $<10^{-2}$ torr as next stage pumping after mechanical (roughing) pump
- Turbomolecular pump is connected to mechanical (backing) pump so that pressure differential is between chamber vacuum and $\sim10^{-3}$ torr of roughing (backing) pump
- Rotating blades (~ 24,000 rpm) push molecules from chamber to backing pump get vacuums $<\sim10^{-6}$ torr



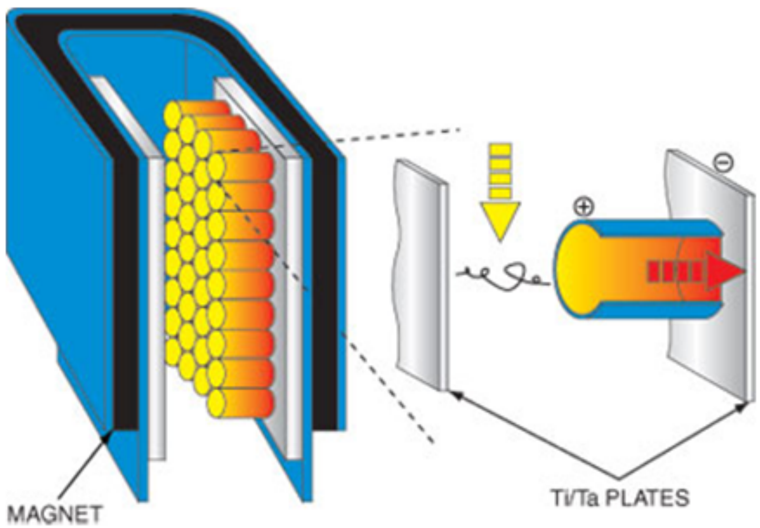
MICHIGAN STATE UNIVERSITY

Cryogenic Pumps

- Cryogenic pumps have surface cooled to LN_2 (77 K) or He (4 K)
- Pumping action is "freezing" molecules on cold surface
- Pumping speed determined by surface area
- Can be very fast and remove largest components of gas (e.g. H_2O and N_2)
- BUT – requires cryogenics to make/maintain temperature
- BUT – additional surface layers of "frozen molecules" makes pump increasingly less effective
  - Then needs to be "regenerated" – warmed up to release frozen molecules
  - If not isolated from vacuum system before regeneration – then full accumulated gas load dumped back into system
- Also used as "cold trap" to prevent e.g. carbon-based (oil from roughing pump) from contaminating vacuum chamber

Ion Pump

- **Removes molecules by ionizing molecules that are then driven by voltage to chemically active surface**
- **Typically for Ultra-High Vacuum applications (10^{-11} torr)**
  - **Used after Turbomolecular or when vacuum <~10^{-5} torr**
  - **Mechanically simple – but only for very low pressures**
- **Current from ionized molecules is proportional to pressure – so can use current as pressure gauge**



Principle of Operation

External View

Figure from: http://hivatec.ca/wp-content/uploads/2012/07/Ion-Pumps.png