TECHNISCHE UNIVERSITÄT DRESDEN

Vacuum Technology
WS 20/21
Virtually presented
Lecture 5, Nov. 24, 2020

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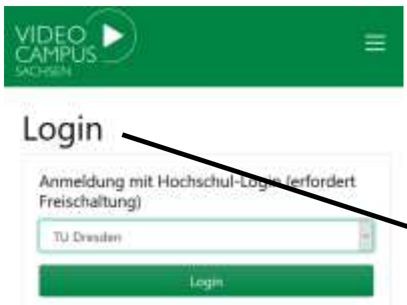

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Prof. Dr. Johann W. Bartha

Inst. f. Halbleiter und Mikrosystemtechnik
Technische Universität Dresden

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“VT L05 a 10:10

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0. Introduction

Air pressure as a force to the walls of an empty container

1. Gas kinetic

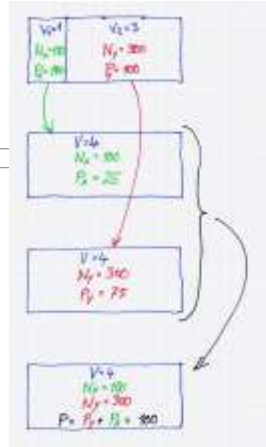
Pressure as momentum transfer, Mol & Molvolume, Pressure units, Partial pressure, Boltzmann Velocity distribution,

2. Pressure Ranges

3. Vacuum technical terms

4. Vacuum generation

5. Pressure measurement



Review L4

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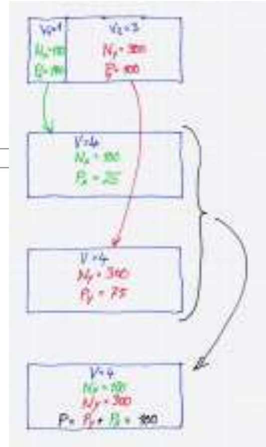

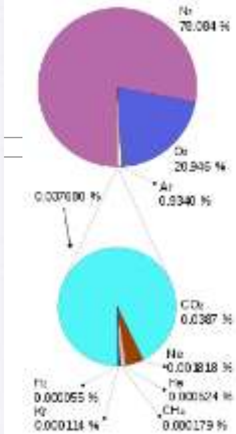

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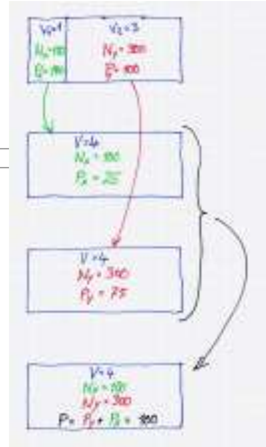

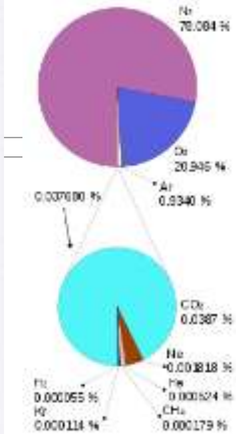

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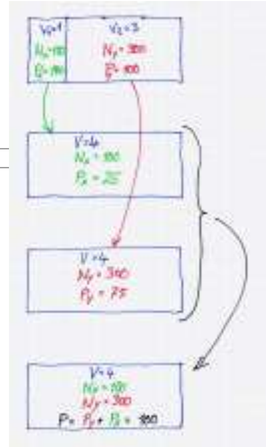

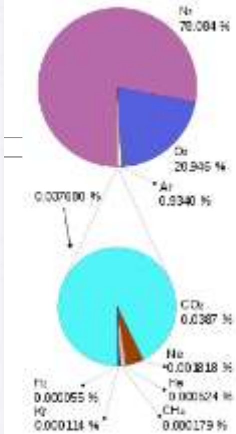

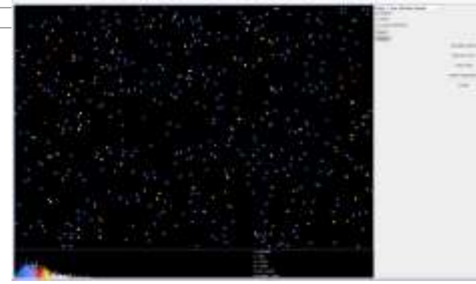

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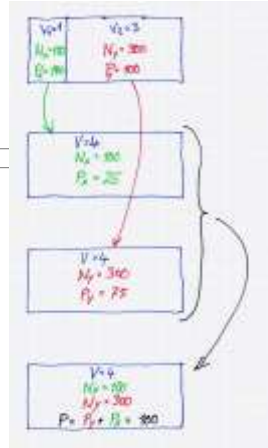

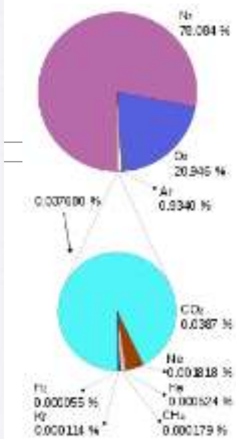

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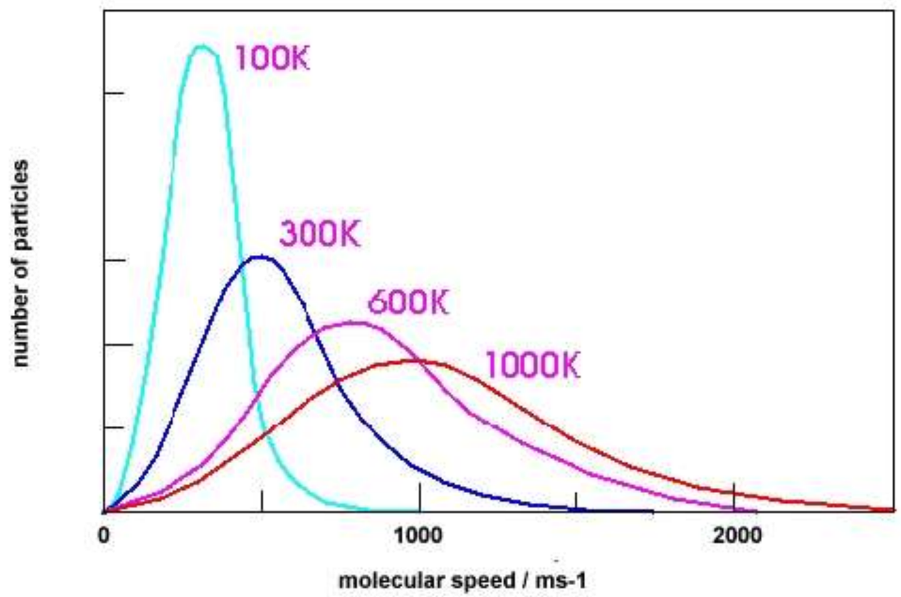

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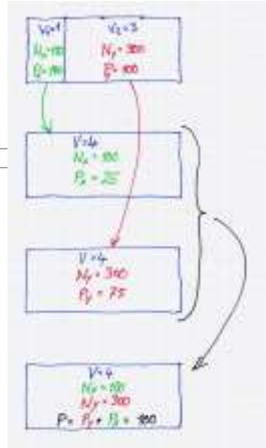

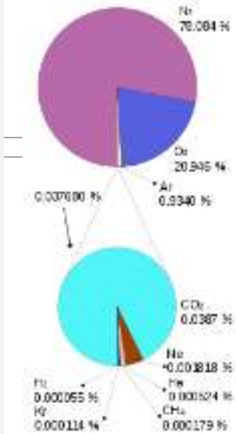

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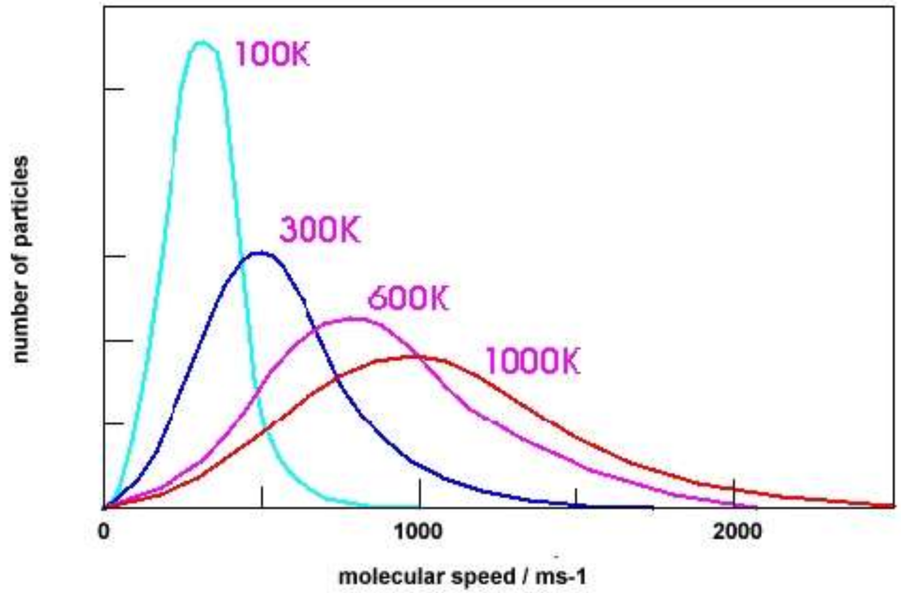

Characteristic of the velocity distribution

Characteristic of the velocity distribution

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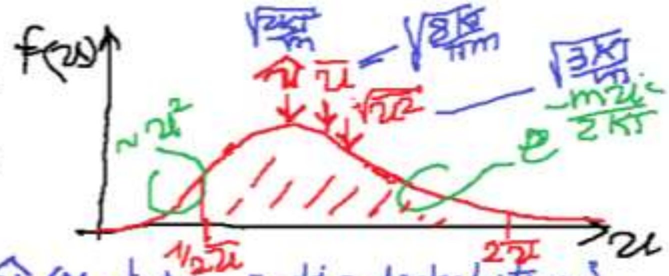
Velocity distribution:

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

$$f(v) = 4\pi\left(\frac{m}{2\pi kT}\right)^{3/2} v^2 e^{-\frac{mv^2}{2kT}}$$



— Most probable velocity $\hat{v}$ (Maximum in the distribution)

$f'(v) = 0$! $f'(v) = C_{rest} \cdot \left\{2v\,e^{-\frac{mv^2}{2kT}} - v^2 \frac{2mv}{2kT} e^{-\frac{mv^2}{2kT}}\right\} = 0$

$1 - v^2 \frac{m}{2kT} = 0 \Rightarrow v^2 = \frac{2kT}{m}$

$\Rightarrow \hat{v} = \sqrt{\frac{2kT}{m}}$

— Mean velocity $\bar{v}$

$\bar{v} = \int_0^\infty f(v)\,v\,dv = 4\pi\left(\frac{m}{2k\pi T}\right)^{3/2} \int_0^\infty v^3 e^{-\frac{mv^2}{2kT}} dv$

$\Rightarrow \bar{v} = \sqrt{\frac{8kT}{\pi m}}$

$\sqrt{2} = 1{,}4$

$\sqrt{\frac{8}{\pi}} = 1{,}6$

$\sqrt{3} = 1{,}7$

— Mean square velocity $\overline{v^2}$

$\overline{v^2} = \int_0^\infty v^2 f(v)\,dv = 4\pi\left(\frac{m}{kT2\pi}\right)^{3/2} \int_0^\infty v^4 e^{-\frac{mv^2}{2kT}} dv$

$\Rightarrow \overline{v^2} = \frac{3kT}{m}$ or $\sqrt{\overline{v^2}} = \sqrt{\frac{3kT}{m}}$

Remember

$E_{kin} = \frac{3}{2}kT = \frac{1}{2}m\overline{v^2}$

$\Rightarrow \overline{v^2} = \frac{3kT}{m}$

90% of all particles oscupy the interval between $\frac{1}{2}\bar{v}$ and $2\bar{v}$

Characteristic of the velocity distribution

Velocity distribution:

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

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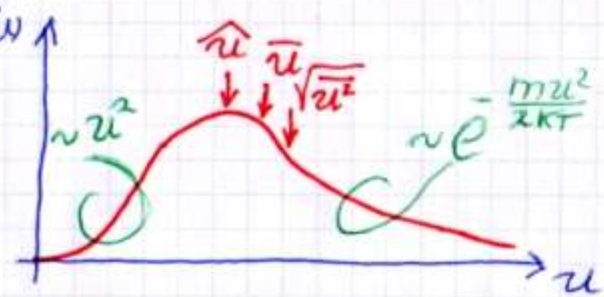

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$$\Rightarrow \overline{u^2} = \frac{3kT}{m} \quad \text{or} \quad \sqrt{\overline{u^2}} = \sqrt{\frac{3kT}{m}}$$

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Remember

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90% of all particles occupy the interval between ½ mean velocity and 2·mean velocity!

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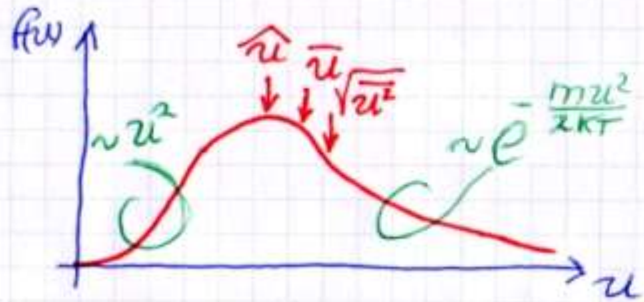

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Velocity Distribution versus mass

$$v_{\mathrm{mp}} = \left(\frac{2kT}{m}\right)^{1/2}$$

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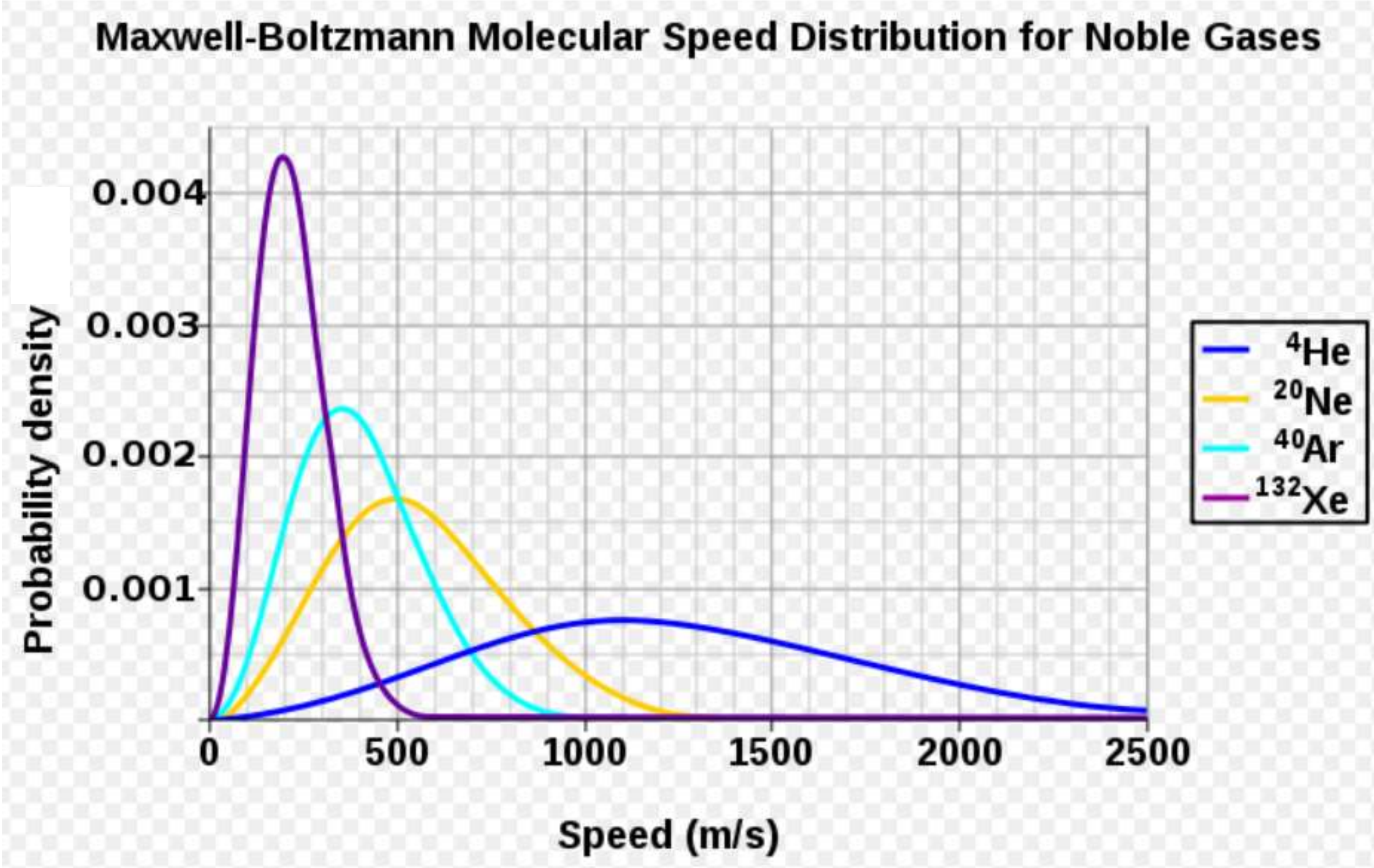
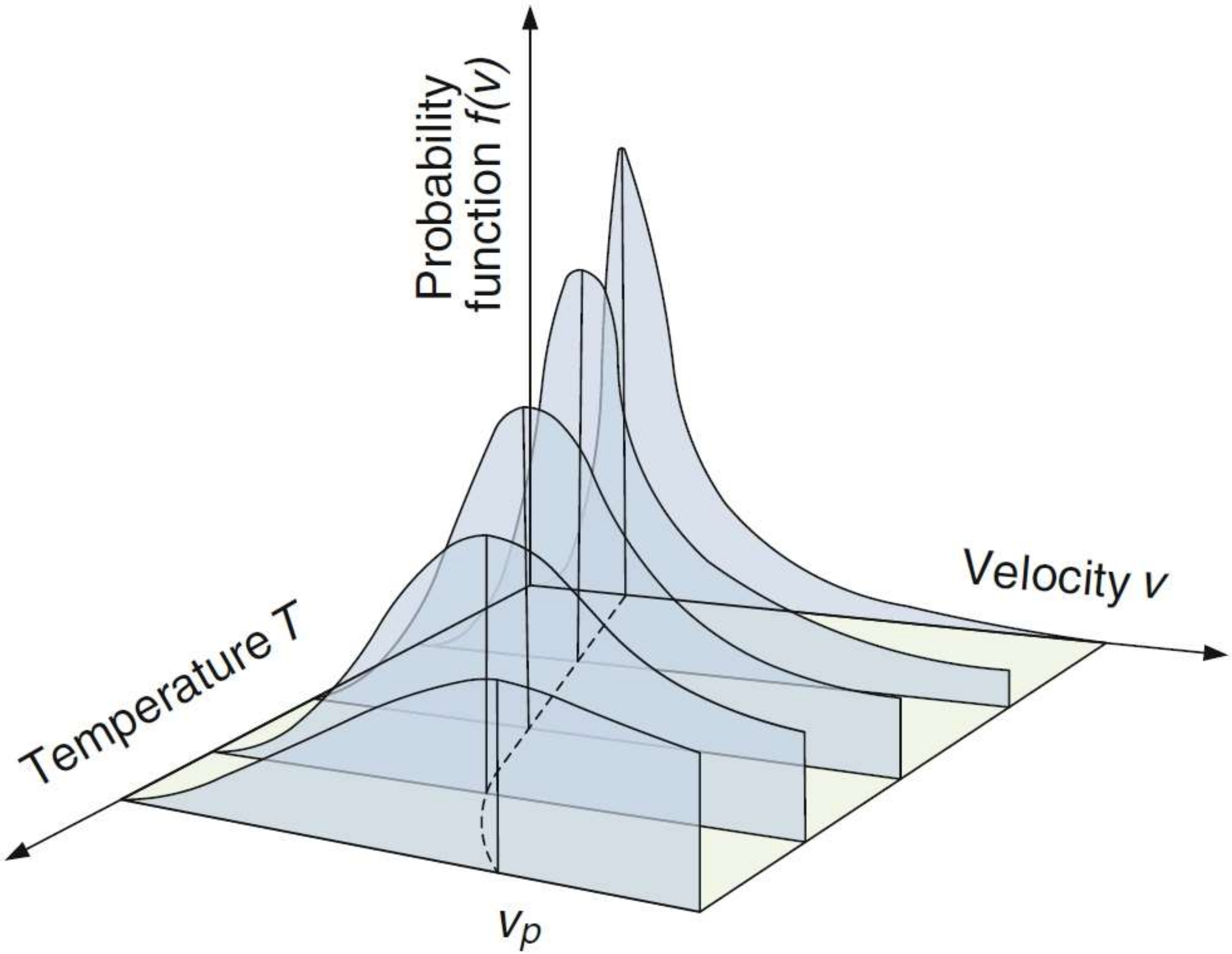


$$f(v) = \sqrt{\frac{2}{\pi}\left(\frac{m}{kT}\right)^3}\, v^2 \exp\left(\frac{-mv^2}{2kT}\right)$$

Velocity distribution depends on temperature and particle mass!



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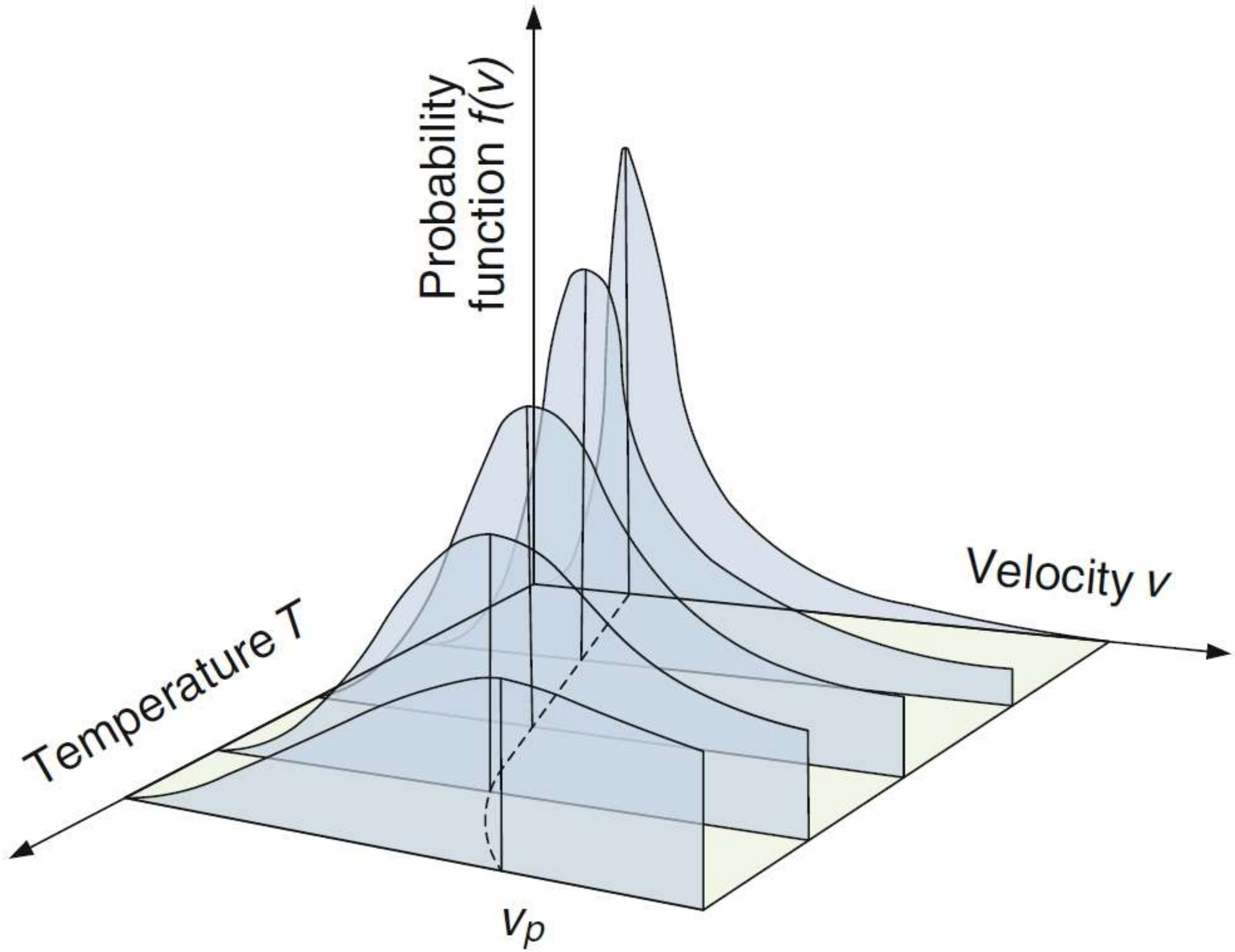

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Exercise:
Mean velocity of a particle (at RT)

For an Ar Atom:

For a SF_6 Molecule:

For a H_2 Molecule:

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Mean velocity of a particle (at RT)

For an Ar Atom:

For a SF_6 Molecule:

For a H_2 Molecule:

$\bar{u}(Ar)$; $\bar{u}(SF_6)$; $\bar{u}(H_2)$

$Ar \triangleq 40$ amu

$1 Ar \triangleq \frac{40\ g}{6{,}022 \cdot 10^{23}}$ in g!!

Unit of K is $\frac{Nm}{K}$ ← $\frac{kg\,m}{s^2}$

$K = 1{,}38 \cdot 10^{-23} \frac{Nm}{K}$ $\frac{J}{K} \cdot \frac{Ws}{K}$

$T = 293\ K$

$1 Ar \triangleq \frac{40 \cdot 10^{-3}\ kg}{6.02 \cdot 10^{23}}$

$m_{Ar} = 6.64\ 10^{-26} kg$ ← !

$\bar{u}_{Ar} = \sqrt{\frac{8KT}{\pi m}} = 394$ $\sqrt{\frac{kg\,m\,m\,K}{s^2\,K\,kg}} \Rightarrow \frac{m}{s}$

$m_{Ar} = 40$ amu $\qquad m_{SF_6} = 146$ amu

$\frac{\bar{u}_{SF_6}}{\bar{u}_{Ar}} = \sqrt{\frac{m_{Ar}}{m_{SF_6}}} = 0.523 \Rightarrow$ $\bar{u}_{SF_6} = 0.523 \cdot 394 = 206 \frac{m}{s}$

Particle velocities

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

For a SF_6 Molecule: 206 m/s resp. 742 Km/h

For an Ar Atom: 394 m/s resp. 1417 Km/h

For a H_2 Molecule: 1762 m/s resp. 6343 Km/h

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Velocity of sound in air: 331,3 m/s (740 mph)!

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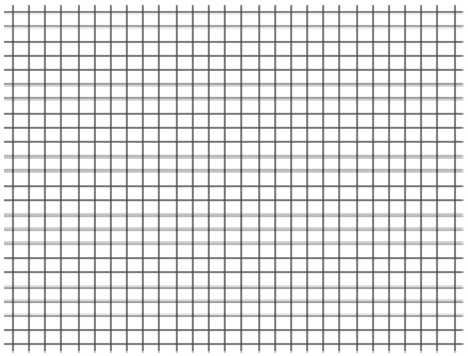

Pressure-pulse or compression-type wave (longitudinal wave) confined to a plane. This is the only type of sound wave that travels in fluids (gases and liquids).
For monatomic gases, the speed of sound is about 75% of the mean speed that the atoms move in that gas.

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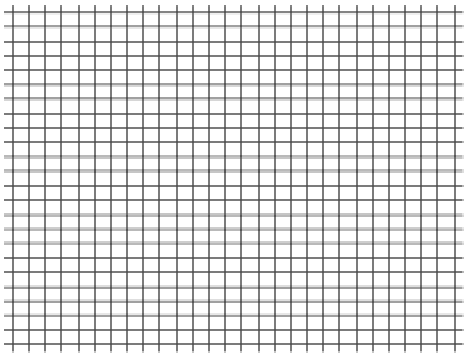

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Velocity of sound in air: 331,3 m/s (740 mph)!

Escape velocity from earth: 11000 m/s !

Particle velocity Ar and H_2?

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

For an Ar Atom:
394 m/s
or 1417 Km/h

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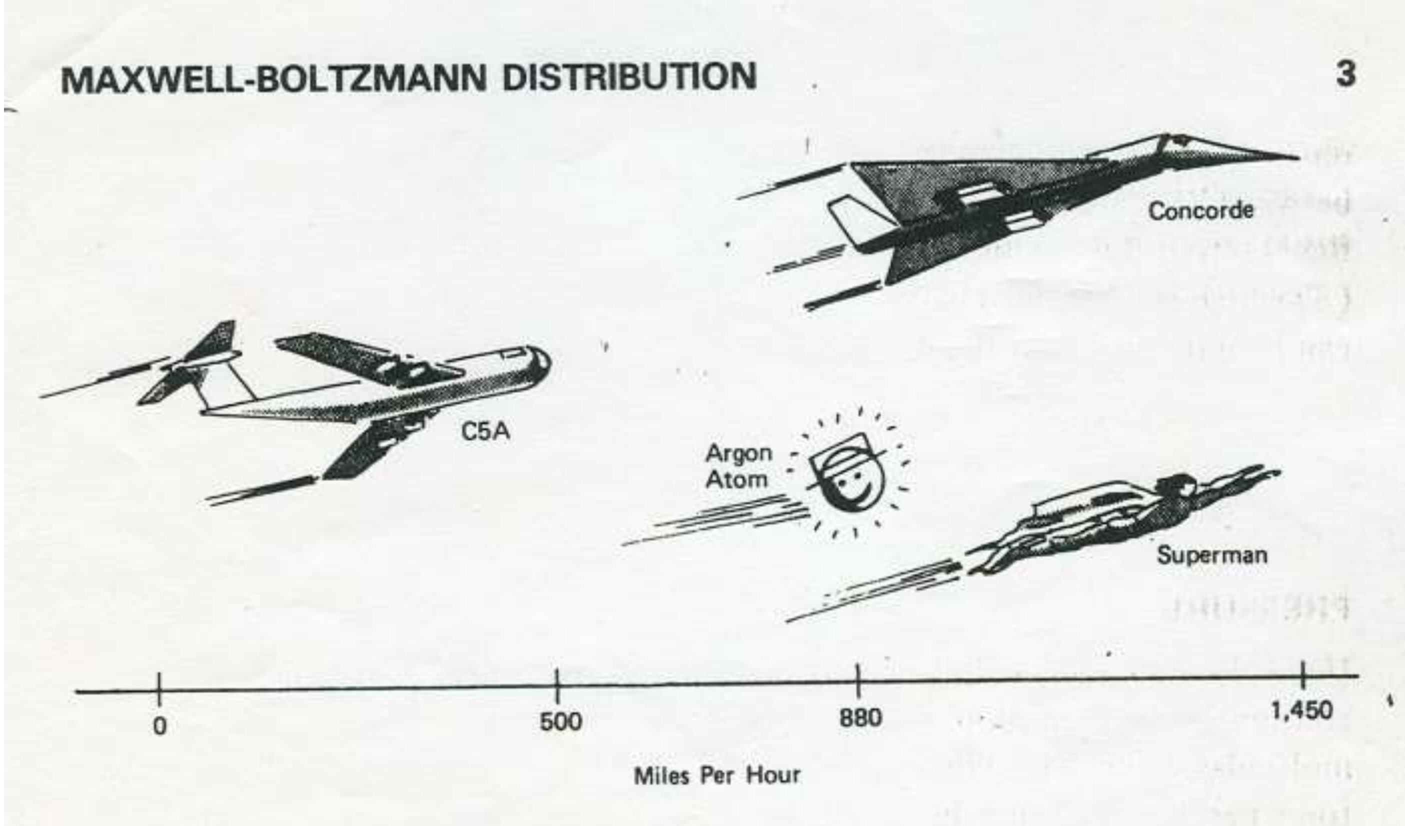

Figure 1-2. Relative speeds of argon atoms and other familiar bodies

This corresponds about to the sonic speed

Velocity distribution versus mass

$$v_{\mathrm{mp}} = \left(\frac{2kT}{m}\right)^{1/2}$$

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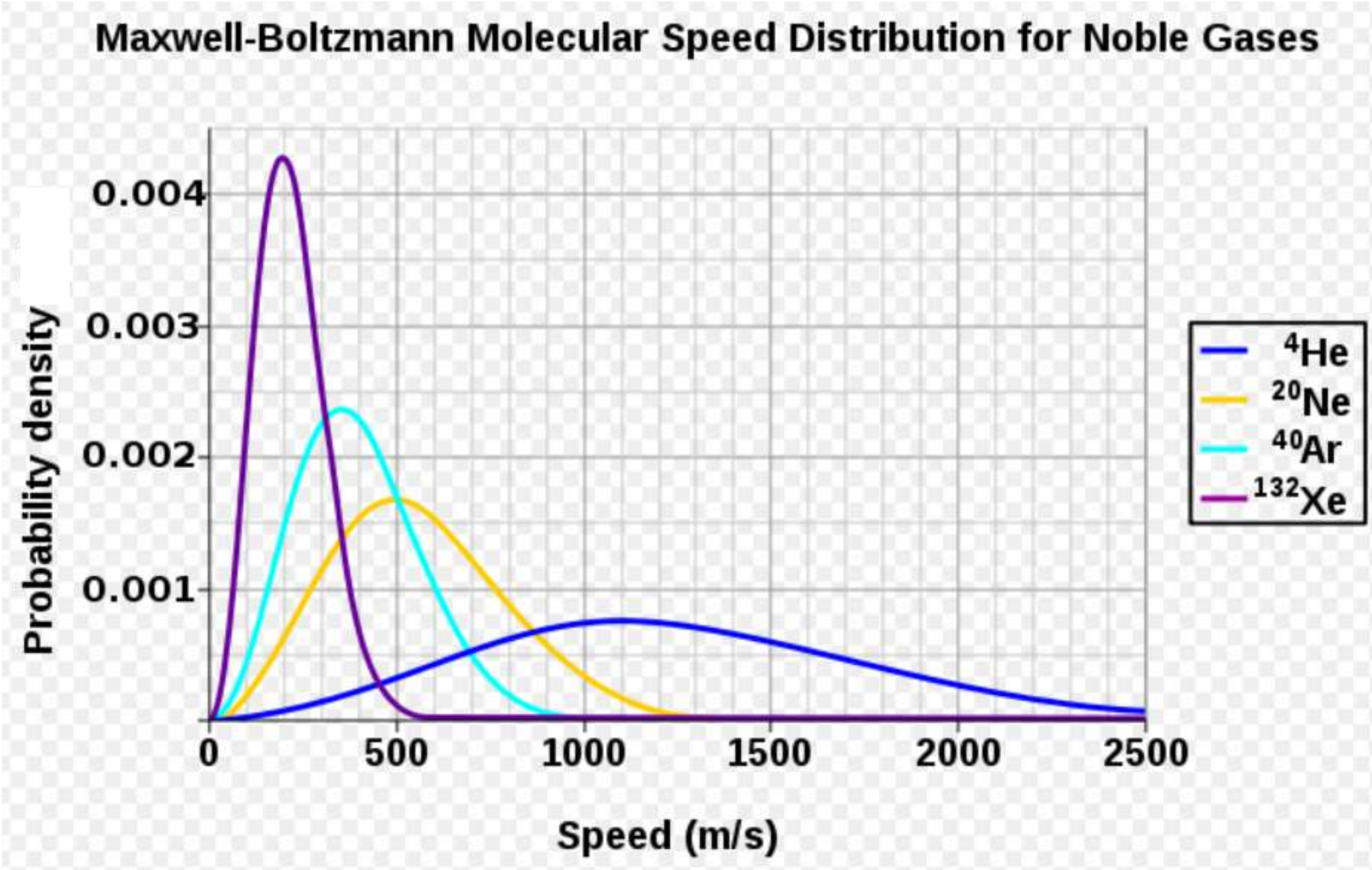
$$v_{\mathrm{rms}} = \left(\frac{3kT}{m}\right)^{1/2}$$



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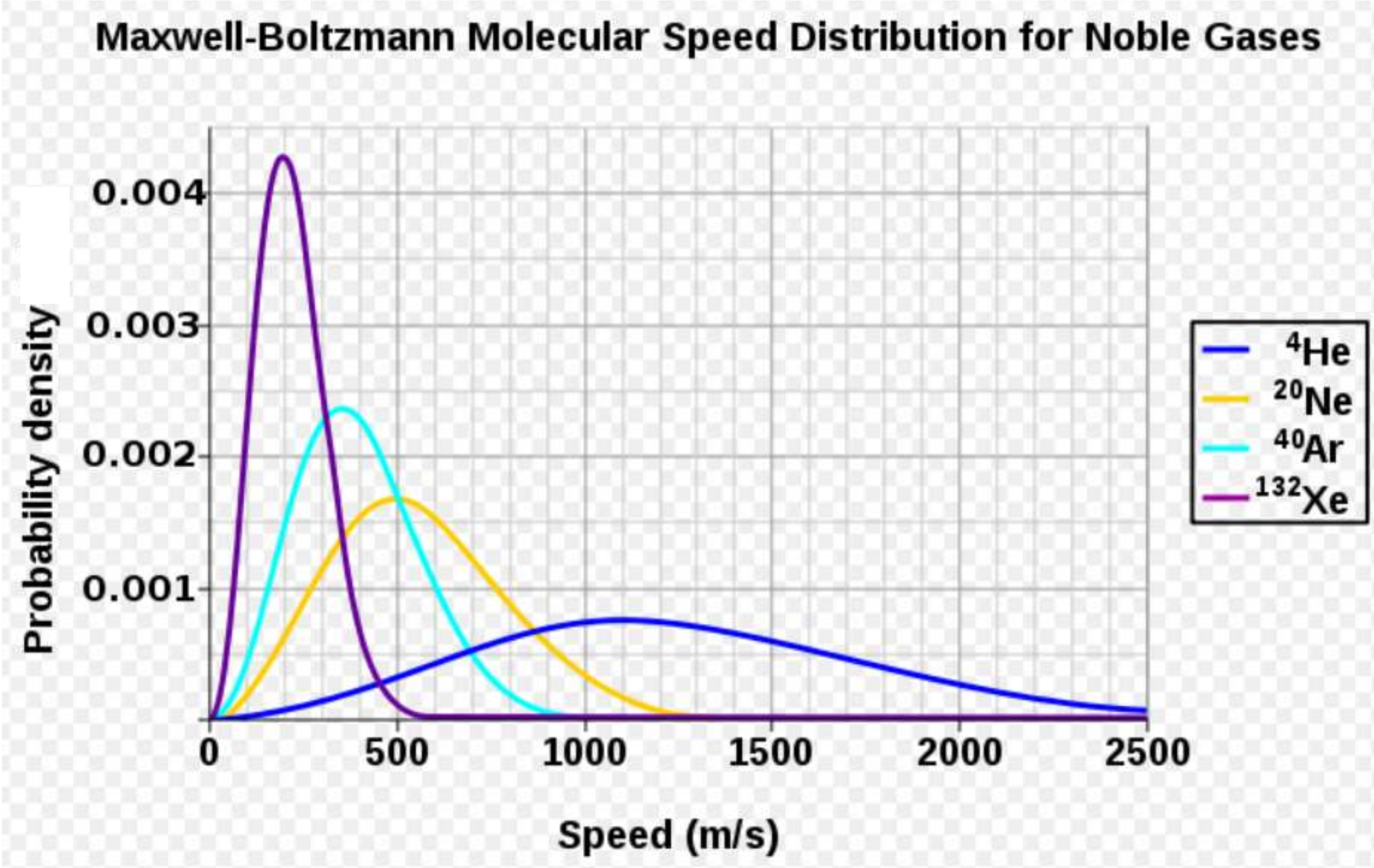

$$f(v) = \sqrt{\frac{2}{\pi}\left(\frac{m}{kT}\right)^3}\, v^2 \exp\left(\frac{-mv^2}{2kT}\right)$$

Exercise:
What is the unit of f(u)?

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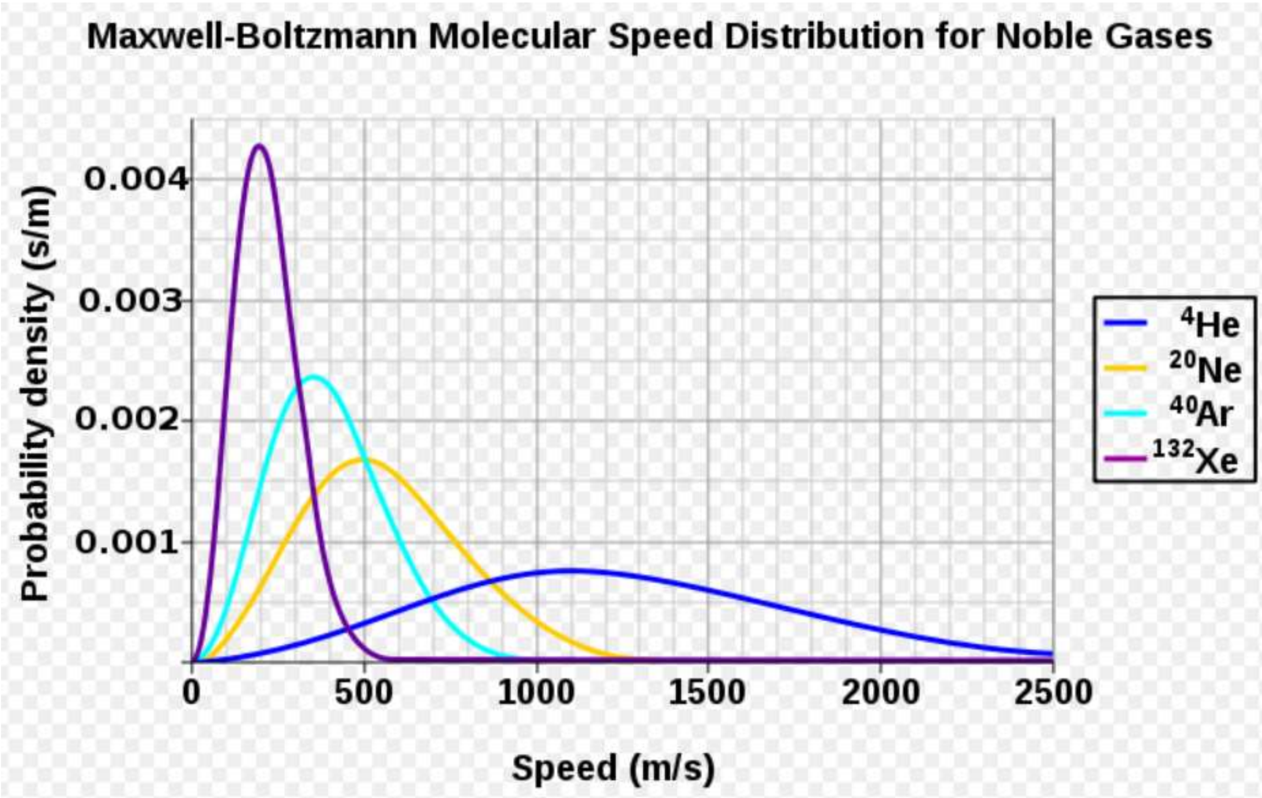

$$f(u) = \sqrt{\frac{2}{\pi}} \left(\frac{m}{kT}\right)^{3/2} u^2 e^{-\frac{mu^2}{2kT}}$$

$\frac{mu^2}{2kT}$ — dimensionless

$$\left(\frac{kg}{J}\right)^{3/2} \left(\frac{m}{s}\right)^2 = \left(\frac{kg}{kg}\frac{s^2}{m^2}\right)^{3/2}\left(\frac{m}{s}\right)^2 = \left(\frac{s}{m}\right)^3\left(\frac{m}{s}\right)^2 = \frac{s}{m}$$

Why is this unit evident?

$$\int_0^\infty f(u)\,du = 1 \leftarrow \text{dimensionless!}$$

$f(u) \rightarrow \frac{s}{m}$, $du \rightarrow \frac{m}{s}$

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What is the unit of f(u)?

$$f(u) = \sqrt{\tfrac{2}{\pi}}\left(\frac{m}{kT}\right)^{3/2} u^2 \, e^{-\frac{mu^2}{2kT}}$$

$-\frac{mu^2}{2kT}$ — dimensionslos

$$\left(\frac{kg}{J}\right)^{3/2} \left(\frac{m}{s}\right)^2 = \left(\frac{kg\ s^2}{kg\ m^2}\right)^{3/2} \left(\frac{m}{s}\right)^2 = \left(\frac{s}{m}\right)^3 \left(\frac{m}{s}\right)^2 = \frac{s}{m}$$

Why is this unit evident?

$$\int_0^\infty f(u)\, du = 1 \leftarrow \text{dimensionslos}$$

$f(u) \rightarrow \frac{s}{m}$, $du \rightarrow \frac{m}{s}$: $\frac{s}{m} \leftarrow \frac{m}{s}$

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What is the unit of f(u)?

$$f(u) = \sqrt{\tfrac{2}{\pi}} \left(\frac{m}{kT}\right)^{3/2} u^2 \, e^{-\frac{mu^2}{2kT}}$$

$\frac{mu^2}{2kT}$ — dimensionslos

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Going from the velocity- to the energy distribution function:

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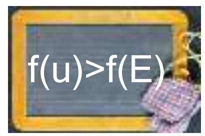


$$f(v) \longrightarrow f(E)$$

$$E = \frac{1}{2} m v^2 \curvearrowright \frac{dE}{dv} = m v \curvearrowright dv = \frac{1}{mv} dE$$

$$f(v)\, dv = \sqrt{\frac{2}{\pi}} (kT)^{-\frac{3}{2}} m^{\frac{3}{2}} v^2 e^{-\frac{mv^2}{2kT}} dv$$

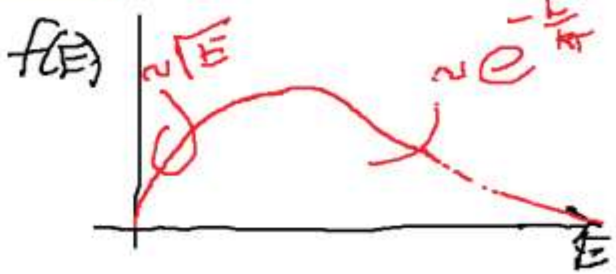
$\frac{mv^2}{2kT} \to E/kT$; $dv \leftarrow \frac{1}{mv} dE$

$$f(v)\, dv = \sqrt{\frac{2}{\pi}} (kT)^{-3/2} \frac{m^{3/2}}{m} \frac{v^2}{v} e^{-\frac{E}{kT}} dE$$

$\frac{m^{3/2}}{m} \to m^{1/2}$, $\frac{v^2}{v} \to v$

$$\sqrt{m}\, v = \sqrt{\frac{m v^2}{2}} \cdot \sqrt{2} = \sqrt{E}\sqrt{2}$$

$$\boxed{f(E)\, dE = \frac{2}{\sqrt{\pi}} (kT)^{-3/2} \sqrt{E}\, e^{-\frac{E}{kT}} dE}$$



Going from the velocity- to the energy distribution function:

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$$\frac{m v^2}{2kT} \rightarrow E/kT \qquad dv \leftarrow \frac{1}{m v}\, dE$$

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$$m^{1/2} \qquad v \qquad \sqrt{m}\, v = \sqrt{\frac{m v^2}{2}} \cdot \sqrt{2} = \sqrt{E} \cdot \sqrt{2}$$

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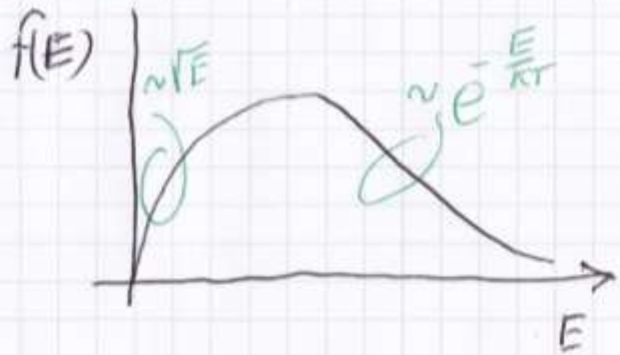
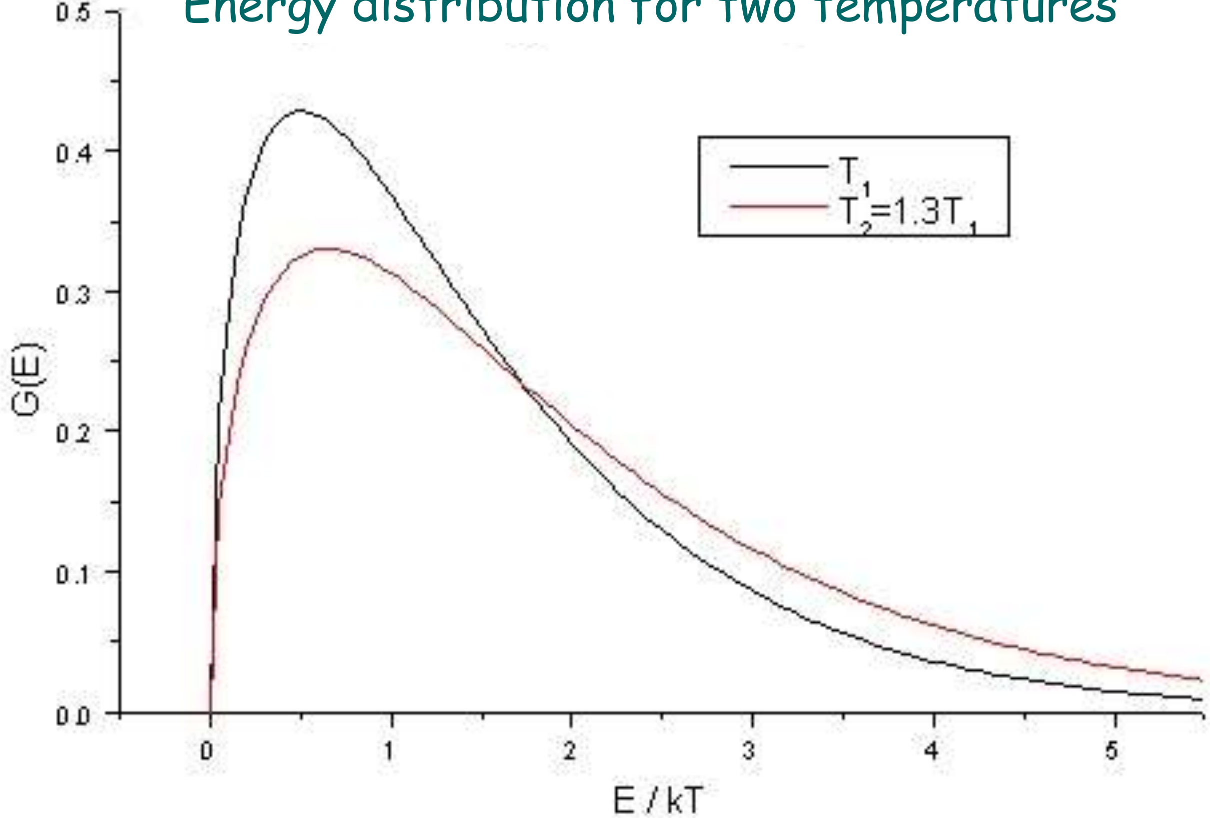
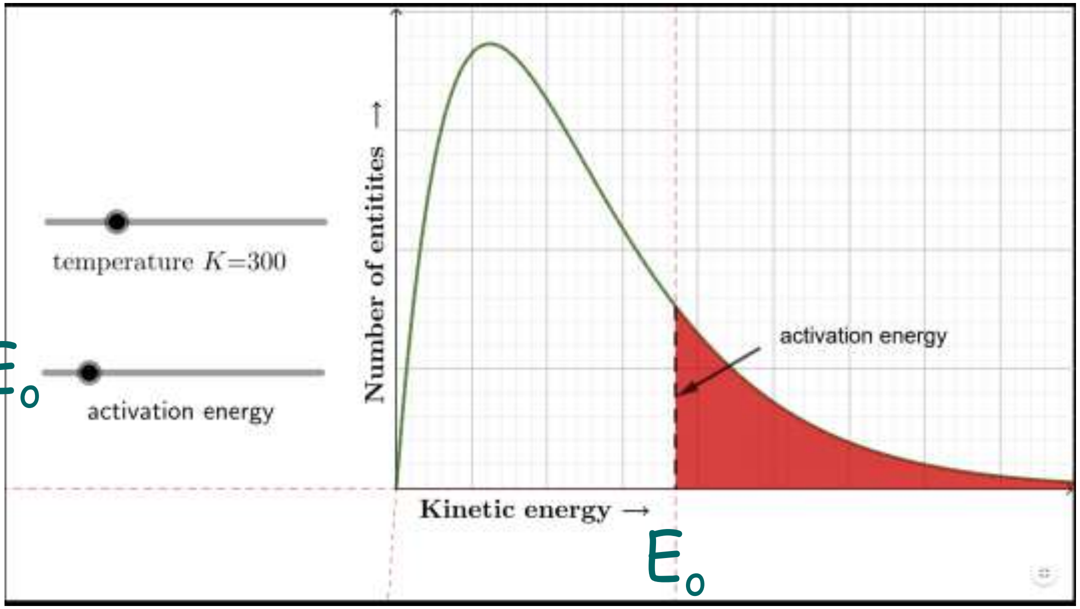


Energy distribution for two temperatures



http://www.pci.tu-bs.de/aggericke/PC5/Kap_I/Energievert_Boltzm.htm

The MB energy distribution function answers also the question: How many particles $n(E_o)$ have sufficient energy to initiate some specific process that require a certain threshold respectively activation energy E_o.



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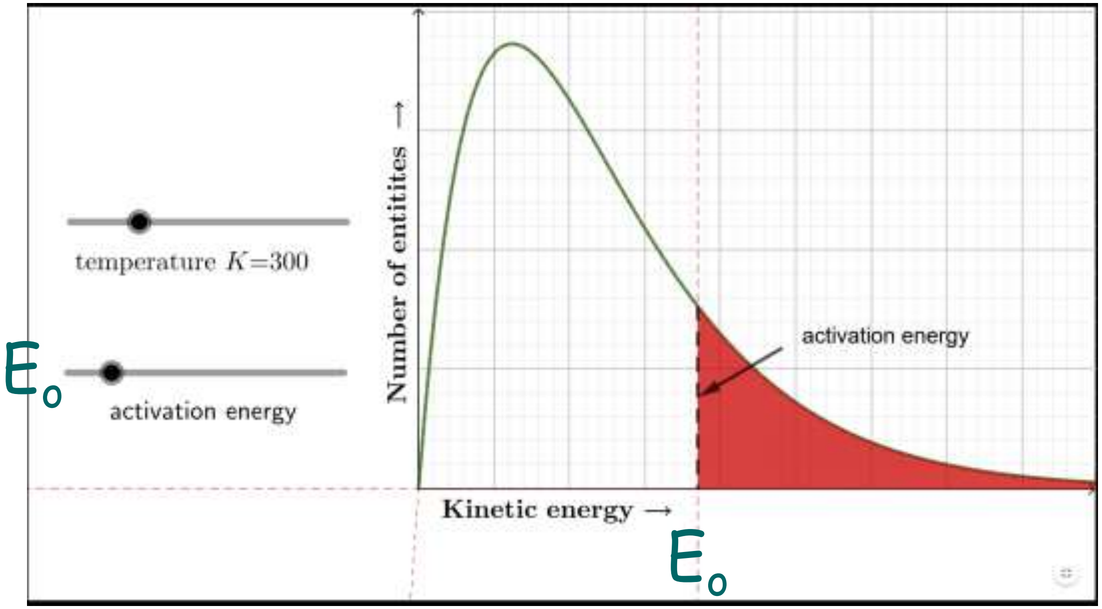

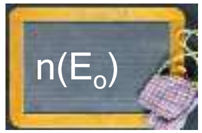

The MB energy distribution function answers also the question: How many particles $n(E_o)$ have sufficient energy to initate some specific process.

$$n(E_0) = \int_{E_0}^{\infty} f(E)\,dE$$

$$= \int_{E_0}^{\infty} \frac{2}{\sqrt{\pi}} (kT)^{-3/2} \sqrt{E}\, e^{-\frac{E}{kT}}\,dE$$

$$\vdots$$

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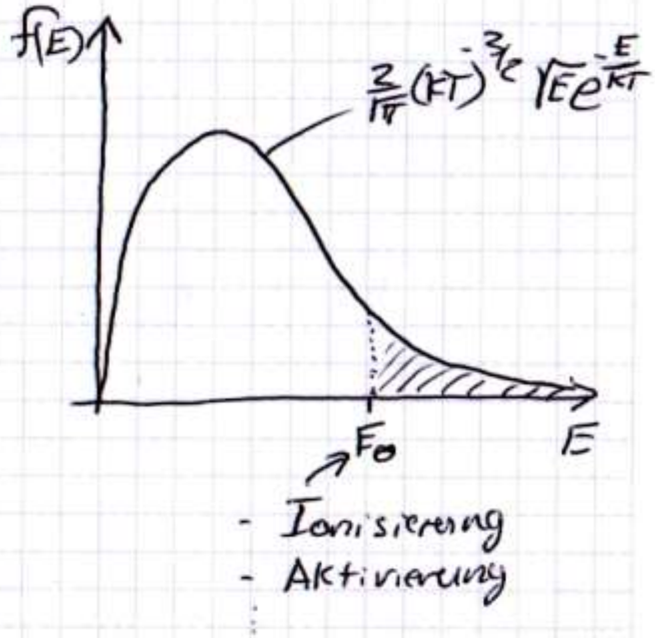

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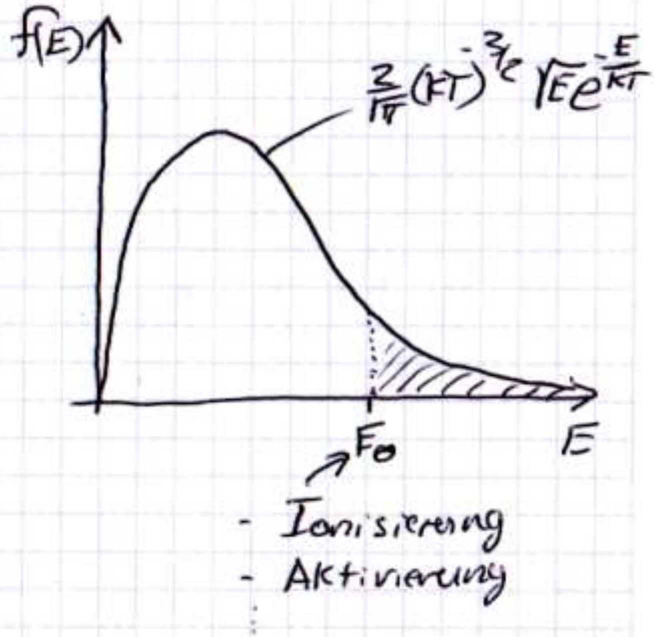
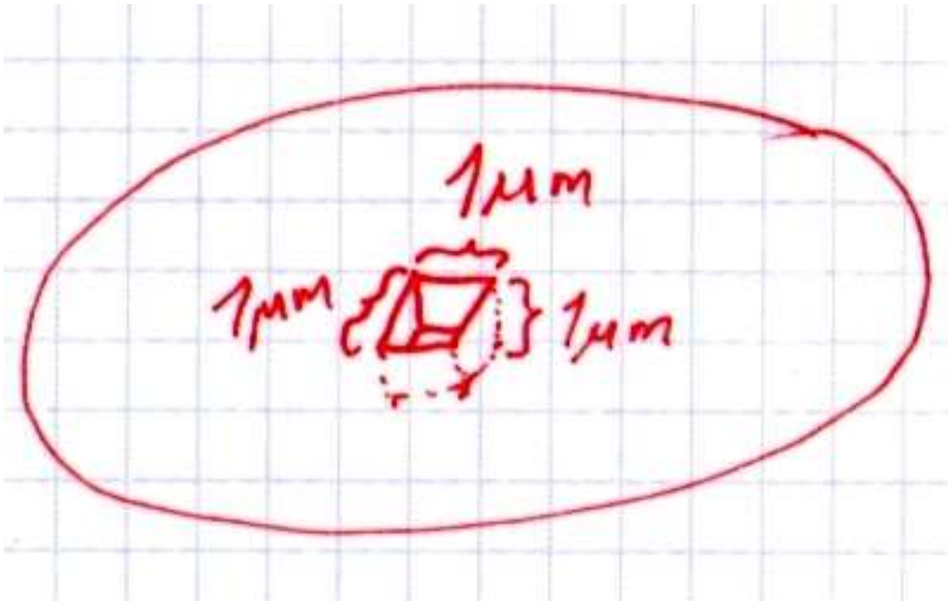


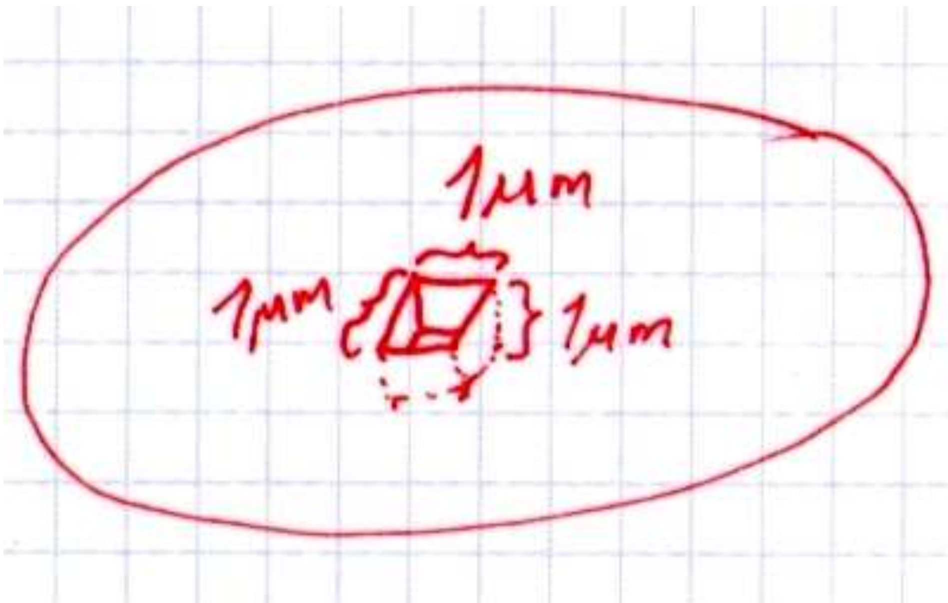
Homework:



Homework:

Exercise:
Scenario: Vacuum based dry etching of a Si trench!

How many gas particles reside at a pressure of 0,1 Pa (10^{-3} mBar) at a temperature of 23 °C inside of a 1x1x1 µm3 trench?



»Wissen schafft Brücken.«