WHY VACUUM?

There are several reasons why you need vacuum in a large class of experiments. This is a partial list that refers to the experiments you can do in this course.:

1) You want to prepare a system (a sample) with a particular composition, with a well defined and "clean" surface, and you do not want that foreign atoms or molecules spoil your sample. If you prepare a clean surface – e.g. a Cu surface made of Cu atoms only- in air at atmospheric pressure (10^5 Pa), it is covered by a first single layer of molecules or atoms coming from air (water, oxygen,....) in 10^{-9} s, and other layers form in the following nanosecond. The Cu surface atoms chemically react with them and an oxide layer forms in a nanosecond time scale. Therefore to keep clean your surface for hours (or the time needed for your experiment) you need a vacuum of the order of 10^{-8} Pa.

2) You want to grow your system atomic layer by atomic layer sending a controlled flux of molecules or atoms on a suitable substrate. You want to keep the density of unwanted atoms or molecules well below a limit (that often can be one part per billion or lower). To do this you often need to operate in a vacuum with a pressure of the order of 10^{-8} Pa.

3) You need to cool down your sample or part of your system for instance to 77 K (liquid nitrogen temperature) or 4 K (liquid He temperature). If you do it in air water, oxygen, nitrogen, CO_2,.... condense on the surface of your sample forming a thick layer in a very short time. Moreover the gas conducts heat and makes difficult to cool down the sample in an efficient way. Therefore the system that cools down the sample must operate in vacuum to obtain a good thermal insulation (consider for instance a thermos) and to keep the surface of the sample clean. In some cases a pressure of 10^{-5} Pa is enough, in others a pressure of 10^{-8} Pa is necessary.

4) If you use a beam of atoms, molecules, ions, electrons, elementary particles,...... the mean free path (the distance that they can travel before hitting a foreign atom or molecule must be larger than the size of your experimental system. Therefore a vacuum level corresponding to a pressure of 10^{-4}-10^{-9} Pa is needed.

For instance electrons with energy from about 1 eV to about 1 MeV cover much less a few mm in air at atmospheric pressure, photons with an energy between about 10 eV and about 1000 eV cover less than a few cm.

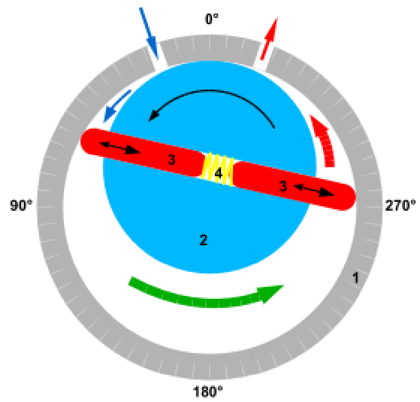
System	pressure (Pa)	mean free path	molecules cm^{-3}
Atmosphere at the sea level	100 kPa	50-60 nm	10^{19}
Rotary vane pump vacuum=			
Atmosphere at 100 km	0.1 Pa	10 cm	10^{13}
Thermos	0.01 Pa	1 m	10^{12}
Research system in ultra high			
Vacuum (UHV) = Moon surface	10^{-9} Pa	10^4 km	10^5
Interplanetary space			10
Intergalactic space			10^{-6}

1 Pa= $1 Nm^{-2}$, 1 atm=1.01325 10^5 Pa, 1 bar=10^5 Pa 1 torr= 1/760 atm

Some pumps used to produce vacuum:

Rotary vane pump: (partially from wikipedia)

A **rotary vane pump** is a pump that consists of vanes mounted to a rotor that rotates inside of a cavity. These vanes can be variable length or tensioned to maintain contact with the walls as the pump rotates. A simple vane pump is a circular rotor rotating inside of a larger circular cavity. The centers of these two circles are offset, causing eccentricity. Vanes are allowed to slide into and out of the rotor and seal on all edges, creating vane chambers that do the pumping work. On the intake side of the pump, the vane chambers are increasing in volume. These increasing volume vane chambers are filled with gas forced in by the inlet pressure. The inlet is connected to the system you want top ump. Often this inlet pressure is nothing more than pressure from the atmosphere. On the discharge side of the pump, the vane chambers are decreasing in volume, forcing fluid out of the pump. The action of the vane drives out the same volume of gas with each rotation. Multistage rotary vane vacuum pumps can attain pressures as low as 10^{-3} mbar (0.1 Pa). This limit is given by the vapour pressure of the lublicant (oil) used to seal the contacts between the vanes and the circular cavity.



Rotary vane pump 10^{-1} Pa

Scroll pumps

A scroll pump uses two interleaving scrolls pump, to pump gases. The vane geometry may be involute, archimedean spiral, or hybrid curves. Often, one of the scrolls is fixed, while the other orbits eccentrically without rotating, thereby trapping and pumping or compressing pockets of fluid between the scrolls. Another method for producing the compression motion is co-rotating the scrolls, in synchronous motion, but with offset centers of rotation. The relative motion is the same as if one were orbiting. It can reach a vacuum of the order of 10^{-2} mbar (1 Pa).

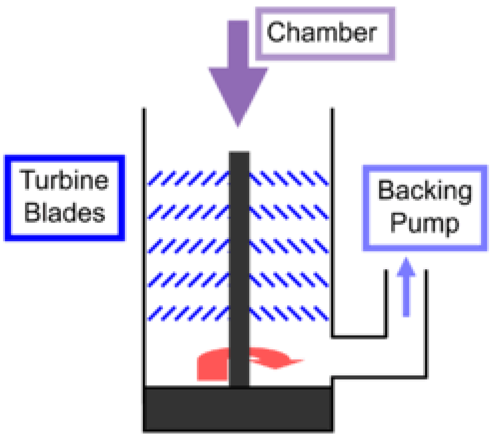
Scroll pump 1 Pa

Turbomolecular pumps (partially from wikipedia)

A **turbomolecular pump** is a type of vacuum pump used to obtain and maintain high or ultra-high vacuum. These pumps work on the principle that gas molecules can be given momentum in a desired direction by repeated collision with a moving solid surface. In a turbopump, a rapidly spinning turbine rotor 'hits' gas molecules from the inlet of the pump towards the exhaust in order to create or maintain a vacuum. This mechanism works well if the mean free path of the molecules is larger than the size of the turbine blades, i.e. if the pressure is below 1 Pa (molecular flow condition).

Turbomolecular pumps employ multiple stages consisting of rotor/stator pairs mounted in series. Gas captured by the upper stages is pushed into the lower stages and successively compressed to the level of the fore-vacuum (backing pump) pressure. As the gas molecules enter through the inlet, the rotor, which has a number of angled blades, hits the molecules. Thus the mechanical energy of the blades is transferred to the gas molecules. With this newly acquired momentum, the gas molecules enter into the gas transfer holes in the stator. This leads them to the next stage where they again collide with the rotor surface, and this process is continued, finally leading them outwards through the exhaust.

Because of the relative motion of rotor and stator, molecules preferably hit the lower side of the blades. Because the blade surface looks down, most of the scattered molecules will leave it downwards. The surface is rough, so no reflection will occur. A blade needs to be thick and stable for high pressure operation and as thin as possible and slightly bent for maximum compression. For high compression ratios the throat between adjacent rotor blades (as shown in the image) is pointing as much as possible in the forward direction. For high flow rates the blades are at 45° and reach close to the axis.



Schematic of a turbomolecular pump.

Because the compression of each stage is ~10, each stage closer to the outlet is considerably smaller than the preceding inlet stages. This has two consequences. The geometric progression tells us that infinite stages could ideally fit into a finite axial length. The finite length in this case is the full height of the housing as the bearings, the motor, and controller and some of the coolers can be installed inside on the axis.

Radially, to grasp as much of the thin gas at the entrance, the inlet-side rotors would ideally have a larger radius, and correspondingly higher centrifugal force; ideal blades would get exponentially thinner towards their tips and carbon fibers should reinforce the aluminium blades. However, because the average speed of a blade affects pumping so much this is done by increasing the root diameter rather than the tip diameter where practical.

Turbomolecular pumps must operate at very high speeds, and the friction heat buildup imposes design limitations. Some turbomolecular pumps use magnetic bearings to reduce friction and oil contamination. Because the magnetic bearings and the temperature cycles allow for only a limited clearance between rotor and stator, the blades at the high pressure stages are somewhat degenerated into a single helical foil each. Laminar flow cannot be used for pumping, because laminar turbines stall when not used at the designed flow. The pump can be cooled down to improve the compression, but should not be so cold as to condense ice on the blades. When a turbopump is stopped, the oil from the backing vacuum may backstream through the turbopump and contaminate the chamber (unless only magnetic bearings without lubricants are used). One way to prevent this is to introduce a laminar flow of nitrogen through the pump. The transition from vacuum to nitrogen and from a running to a still turbopump has to be synchronized precisely to avoid mechanical stress to the pump and overpressure at the exhaust. A thin membrane and a valve at the exhaust should be added to protect the turbopump from excessive back pressure (e.g. after a power failure or leaks in the backing vacuum).

The rotor is stabilized in all of its six degrees of freedom. One degree is governed by the electric motor. Minimally, this degree must be stabilized electronically (or by a diamagnetic material, which is too unstable to be used in a precision pump bearing). Another way (ignoring losses in magnetic cores at high frequencies) is to construct this bearing as an axis with a sphere at each end. These spheres are inside hollow static spheres. On the surface of each sphere is a checkerboard pattern of inwards and outwards going magnetic field lines. As the checkerboard pattern of the static spheres is rotated, the rotor rotates. In this construction no axis is made stable on the cost of making another axis unstable, but all axes are neutral and the electronic regulation is less stressed and will be more dynamically stable. Hall effect sensors can be used to sense the rotational position and the other degrees of freedom can be measured capacitively.

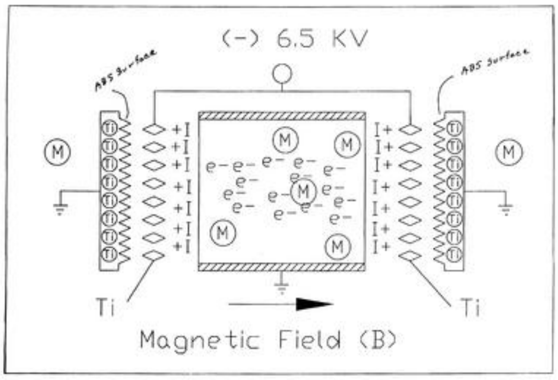
Laws of fluid dynamics do not apply in high vacuum environments. The maximum compression varies linearly with circumferential rotor speed. In order to obtain extremely low pressures down to 1 micropascal, rotation rates of 20,000 to 90,000 revolutions per minute are often necessary. Unfortunately, the compression ratio varies exponentially with the square root of the molecular weight of the gas. Thus, heavy molecules are pumped much more efficiently than light molecules. Most gases are heavy enough to be well pumped but it is difficult to pump hydrogen and helium efficiently.

An additional drawback stems from the high rotor speed of this type of pump: very high grade bearings are required, which increase the cost.

Because turbomolecular pumps only work in molecular flow conditions, a pure turbomolecular pump will require a very large backing pump to work effectively. Thus, many modern pumps have a molecular drag stage mechanism near the exhaust to reduce the size of backing pump required.

Ion pumps (partially from wikipedia)

An **ion pump** (or sputter ion pump) is a type of vacuum pump capable of reaching up to 10^{-11} mbar. An ion pump ionizes gases and employs a strong electrical potential, typically 3kV to 7kV, to accelerate them into a solid electrode. A swirling cloud of electrons produced in hollow Penning cells ionizes incoming gas atoms and molecules while they are trapped in a strong magnetic field. The swirling ions strike the chemically active cathode inducing sputter and are then pumped by chemisorption which effectively removes them from the vacuum chamber, resulting a net pumping action. Inert and lighter gases, such as He and H_2 do not effectively induce sputter and are absorbed by physisorption. Some fraction of the energetic gas ions (including gas that is not chemically active with the cathode material) that strike the metal cathode steal an electron from the surface and rebound as a neutral atom. These energetic neutrals are reflected back from the cathodes and buried as neutrals in exposed pump surfaces.[2]



The pumping rate and capacity of such capture methods is dependent on the specific gas species being collected and the cathode material absorbing it. Some species, such as carbon monoxide, will chemically bind to the surface of a cathode material. Others, such as hydrogen, will diffuse into the metallic structure. In the former example, pump rate can drop as the cathode material becomes coated. And, in the latter, the rate remains fixed by the rate at which the hydrogen diffuses.

There are three main types, the conventional or standard diode pump, the noble diode pump and the triode pump.

Ion pumps are commonly used in ultra high vacuum (UHV) systems, as they can attain ultimate pressures less than 10^{-11} mbar.[4] In contrast to other common vacuum pumps such as turbomolecular pumps and diffusion pumps, ion pumps have no moving parts and use no oil, and are therefore clean and low-maintenance, and produce no vibration, which is an important factor when working scanning probe microscopy.

Some definitions:

Volumetric flow rate S
It is the volume of gas flowing past a given point in a system per unit time. The volumetric rate measured at the pump entrance is called the pump speed S_p. (It is usually measured in liters per second)

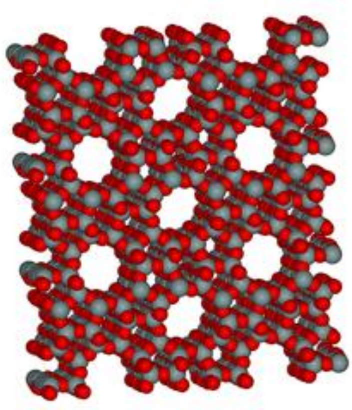
Throughput Q
It is proportional to the mass of the flowing gas.It is given by
Q=Sp
p is the pressure (it is generally measured in torr liter/s)

$-V\ d/dt + Q_l = S_p p$

V volume of the vessel, p the pressure , Q_l is the leak or degassing rate

Turbomolecular pump 10^{-12} Pa

Zeolites are aluminosilicate minerals with nanopores – pores with dimensions of the order of nanometers- they have a very large internal surface because of these nanopores. Some of the more common mineral zeolites are analcime, chabazite, clinoptilolite, heulandite, natrolite, phillipsite, and stilbite. An example mineral formula is: $Na_2Al_2Si_3O_{10}{\bullet}2H_2O$, the formula for natrolite.
The nanopores can adsorb or physisorb a vary large amount of gasses. When a zeolite is heated up to about 150 C it desorbs the gasses. .....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