References for the Vacuum Experiment:

1. O'Hanlon, A User's Guide to Vacuum Technology, John Wiley & Sons, 1989. Read the descriptions of the operation principles of each of the pumps and vacuum gauges used in the experiment. For a review of the mass spectrometer (residual gas analyzer RGA), read Ch. 8, especially pages 122-125 and 128-132. Read Ch. 9 on interpretation of RGA data; see appendix E for cracking fraction tables.

2. C. Rolfs and W. Rodney, Cauldrons in the Cosmos, University of Chicago Press, 1988. See fig. 9.8 on p. 460 and the related text for discussion of the origin of the nine stable isotopes of Xe, the abundance of which are measured in the experiment.

Exercises:

1. Calculate the density (i.e. number per cubic meter) of molecules at pressures of: a) 1 atmosphere; b) 1 torr; c) 1 millitorr; d) $10^{-6}$ torr; e) $10^{-10}$ torr (typical pressure inside a particle accelerator storage ring).

2. Calculate the mean free path between collisions for the above pressure (an important parameter for the design of a storage ring).

3. Calculate the number of molecules colliding on the wall per unit time for the above pressures.

4. If all the molecules that hit the wall stick to the wall, how long does it take to build up a monolayer of gas molecules? (A monolayer of molecules is made of about $10^{15}$ molecules per centimeter square.) This is the reason why modern surface studies require ultra high vacuum.

CAUTION: Read the instructions carefully and follow the operating procedures. Vacuum pumps are delicate instruments. Failure to follow the procedures can result in damage to the pumps or to the mass spectrometer system.

1.1 Introduction

The vacuum system in the EKA lab consists of four different vacuum pumps, a mass spectrometer and residual gas analyzer, two vacuum gauges and a gas inlet bleed valve (Figure 1). Pay close attention to the NOTES that follow, for they contain important safety information.

A mechanical pump, located at the bottom of the table that holds the vacuum system, is capable of pumping the system from atmospheric pressure down to a few millitorr (for a detailed description of the units for pressure and of the mechanical as well as of other pumps, see the
attached pages). The three other vacuum pumps (turbomolecular, ion and diffusion pumps) are high vacuum pumps, which can be operated only when the pressure is already lowered by the mechanical pump. In addition, when operating, the turbomolecular pump MUST be backed by the mechanical pump (the backing process will be described in Section 1.2). The high vacuum pumps can pump down the system to $10^{-6}$ Torr and are typical of those widely used in laboratories to achieve high vacuum (below $10^{-6}$ torr) and ultrahigh vacuum (below $10^{-9}$ torr). There are many references available which describe each type of pump; we will not describe them in detail here.

**NOTE: Even though it is there, we do not use the diffusion pump in this experiment.** We will only use the mechanical, turbomolecular and ion pumps. Do not open the valve on top of the diffusion pump during the experiment, or else air will leak into the vacuum system, ruining your data and potentially damaging the equipment. *(This may be done to return the vacuum system to atmospheric pressure between trials if all appropriate precautions are taken.)*

**NOTE: In order to use the turbomolecular pump, two conditions must be met.** (1) The system must first have been been “rough pumped” using the mechanical pump. (2) The backing valve of the turbomolecular pump must be connected to the mechanical pump. This creates two “levels” of vacuum: a high vacuum above the top of the turbo pump, and a “rough” vacuum connecting the bottom of the turbo pump to the mechanical pump (which itself pumps out to atmosphere). *Failure to properly rough the system and back the turbo pump can cause the turbo pump to burn out.*

Two vacuum gauges are used in this system to measure the pressure. One is a thermocouple gauge, located on the vacuum hose connecting to the mechanical pump, which can measure pressure down to millitorr range. The ionization gauge is used to measure lower pressure, ranging from $10^{-3}$ torr to $10^{-11}$ torr. The operation of both types of gauge, as with the pumps, can be found in any reference on vacuum technology.

**NOTE: The ionization gauge can only be operated under low-pressure conditions, i.e. when the turbomolecular pump is operating** (and, of course, both of the above conditions for operation of the turbo pump are met). *If you must turn off the turbo pump, shut off the ionization gauge first.* To measure pressures when only the mechanical pump is operating, use the thermocouple gauge.

The quadrupole mass spectrometer / residual gas analyzer can determine the mass/charge ratios of the molecules in the vacuum system. Electrons are generated by a hot filament via thermionic emission. These electrons are accelerated in an applied electric field, producing a beam that ionizes (and potentially cracks) gas molecules. A varying electric field is used to select the mass/charge ratio of the ionized molecules passed to the analyzer. A mass spectrum can be obtained, and each species identified by its mass and its cracking pattern by an electron beam.

**NOTE: The mass spectrometer can only be operated when the pressure is lower than $10^{-4}$ torr.** This can only be achieved when the turbomolecular pump is operational (and both conditions for its operation are met), and the ionization gauge indicates sufficiently low pressure. Operating under higher pressure can burn out the filament. If you must turn off either the ionization gauge or the turbo pump, then you must shut off the mass spectrometer first to prevent damage.
Figure 1: Schematic diagram of the vacuum system used for this experiment.

Valve 1: valve between the mechanical pump and the roughing valve
Valve A: leak valve for introduction of gases (last part of experiment)
Valve B: DO NOT OPEN this valve; only an instructor should open it
Valve C: gas inlet regulator valve
Gauge D: outlet pressure gauge of the regulator
Gauge E: inlet pressure gauge of the regulator (high pressure gauge)
1.2 Pump-down procedure for the mechanical and turbomolecular pump

IMPORTANT: for each step in the instruction, read the NOTES carefully before proceeding; read all the instructions before doing the experiment to get an idea of the procedure.

IMPORTANT: if at any time the turbopump stops operating or begins making strange noises, please shut it down (after shutting down the ionization gauge and mass spectrometer, if applicable) and ask one of the instructors how to proceed.

A. Roughing of the vacuum system.

NOTE: you must rough pump the vacuum system every time you come in to the laboratory.

NOTE: this procedure to roughly pump the vacuum system is not valid when bringing the ion pump in operation. For that case, follow the procedures described in part 1.4.

1. Close the valves on top of the high vacuum pumps, the leak valve, the roughing valve and the two valves stemming from the mechanical pump (the backing valve and Valve 1). CAUTION: Do not over-tighten valves.

2. Turn on the mechanical pump, then open valve 1. The line connecting the mechanical pump to the vacuum system will be pumped down. Make sure that the pressure reading from the thermocouple gauge is decreasing.

3. Open the valve between the mechanical pump and the vacuum system (roughing valve). If the vacuum chamber was at atmospheric pressure, you will observe at first an increase in the indication of the thermocouple gauge, and pressure will decrease monotonically afterwards.

4. You can take data of pressure as a function of time to demonstrate the exponential approach to the ultimate pressure attainable with the mechanical pump (see Section 2).

5. After the indication of the thermocouple gauge reads better than 10-20 millitorrs, close the roughing valve. The turbopump can pump down the system starting from this pressure.

NOTE: The roughing valve will maintain the pressure for the time necessary to take data during one session. But the system must be re-roughed if you leave the system for an extended period.

B. Backing of the turbo pump

1. To prepare the turbopump for operation, the pressure in the line connected to the exhaust of the turbopump must be decreased. This is accomplished by pumping this line using the mechanical pump. Open the valve (referred to as the backing valve) between the mechanical pump and the turbomolecular pump.
2. **After the thermocouple gauge reads better than 40 millitorrs turn on the turbomolecular pump from its power supply, and press the “Start” button.** **CAUTION:** Do not open the valve on top of the turbo pump yet. Any residual gas in the space between the turbopump and the valve on top of the turbopump will be removed. Monitor the reading of the thermocouple gauge (which now reads only the pressure in the “lower” part of the system since the closed turbopump valve and roughing valves isolate the top portion). The reading should increase at first, but then decrease steadily.

3. **Wait until the green normal operation light on the turbopump power supply lights up.** If the light does not light up for more than a minute, or the red “LEAK” light comes on steadily, it could mean there is a problem with the pump. Shut down the pump and find an instructor.

4. **Open the valve on top of the turbo pump** to connect the turbopump to the vacuum chamber.

5. Wait a few moments, then **turn on the ionization gauge** (“EMIS” button). The ionization gauge functions properly when the pressure is sufficiently decreased by the turbopump.

6. The system is in operation. The pressure of the system should eventually approach $10^{-6}$ torr.

**NOTE:** Never turn off the mechanical pump or let the system up to atmosphere while the turbo pump is working.

**NOTE:** The mass spectrometer can be turned on only when the pressure is $<10^{-4}$ torr.

### 1.3 Procedure for shutting down the turbo pump

1. **Turn off the mass spectrometer and the ionization gauge.** They could be broken if left to operate under higher pressures.

2. **Check that the roughing valve is closed and, especially, that the valve on top of the ion pump is closed** (the ion pump must be closed when turning off any other pump or when letting gas into the system).

3. **Close the valve on top of the diffusion pump** (if open) and the valve on top of the turbopump.

4. **Turn off the turbopump.**

5. **Close the backing valve.** The system must be left in its original configuration. This will ease following the procedures when working with it, and will also prevent accidents.

6. **Turn off the mechanical pump.**

### 1.4 Procedure for turning on the ion pump

**CAUTION:** The ion pump uses high voltage, up to 6000 volts. Do not disconnect or touch any of the cables while the pump is on.

**CAUTION:** Follow the procedure step-by-step, without leaving significant time intervals between successive steps.
CAUTION: The ion pump must not be turned on until the pressure is lower than $10^{-4}$ torr.
This pressure is achieved using the turbo pump. However, when the ion pump is initially connected
to the vacuum chamber, the vacuum may be spoiled due to air contained within the ion pump.
Keeping these facts in mind, you can understand the detailed procedure that follows:

1. Make sure the ion pump is off.
2. Turn off the ionization gauge and the mass spectrometer if they are on. They must be
   protected if a pressure higher than safe for the two instruments is created when opening the
   valve on top of the ion pump.
3. Close the valve on top of the turbopump. You can leave the turbopump on, but must operate
   quickly. When opening the valve on top of the ion pump and releasing any air contained within,
   the pressure may exceed even the limit bearable by the turbopump. Because of this, roughing of
   the vacuum system using the mechanical pump is necessary.
4. Open the valve on top of the ion pump.
5. Close the backing valve of the turbo pump.
6. Open the roughing valve.
7. Wait until the pressure in the thermocouple gauge is better than $10^{-2}$-$20$ millitorr. This will take
   a little time.
8. Close the roughing valve.
9. Open the backing valve of the turbopump. The thermocouple gauge will indicate now the
   pressure in the backing line. Make sure the power supply of the turbopump is on.
10. After the thermocouple gauge reads better than 40 millitorrs, open the valve on top of the
    turbo pump. This will bring the turbopump in operation.
11. Wait a few moments and turn on the ionization gauge.
12. Wait until the pressure is better than $10^{-4}$ torr.
13. Put the start/protect switch on the ion pump controller to the start position.
14. Turn on the ion pump.
15. Turn the knob on the ion pump controller to pressure, and the pressure inside the ion pump
    can be read.
16. Put the switch start/protect to protect position.
17. Turn on the mass spectrometer. Measurements of the residual gas can be taken.

NOTE: The ion pump can operate by itself without backing by mechanical pump. However,
MAKE SURE THE VALVE ON TOP OF THE ION PUMP IS CLOSED WHEN SHUTTING
DOWN OTHER PUMPS OR LETTING ANY GAS INTO THE SYSTEM.

1.5 Procedure to shut down the ion pump:

The ion pump can be left on all the time. Once operating, it does not need to be turned off.
However, in cases when the pump has to be shut down:

1. Close the valve on top of the ion pump.
2. Turn off the ion pump.

2. OVERVIEW OF DATA TAKING
A. For the mechanical pump and the turbo pump, measure the pressure as a function of time and plot it to demonstrate the exponential approach to the ultimate pressure attainable from each pump.

B. Determine the components of the residual gas for the turbo pump and the ion pump. How do they differ from each other and from the composition of air?

C. Is it possible to see any of the minor isotopes of carbon or oxygen (i.e. $^{13}\text{C}$ or $^{18}\text{O}$) or do other molecules of the same molecular weight obscure them?

D. Introduce a small amount of xenon gas into the vacuum system and measure the abundance of the nine stable Xe isotopes using the mass spectrometer. **CAUTION: Ask one of the instructors to work with you when you introduce the Xe gas into the vacuum system.** Introducing too much Xe will damage the mass spectrometer and the ionization gauge. Measure at the masses of the known stable isotopes and at several masses where no contribution from Xe is expected; this will give you another check on background. To keep the pressure within the range appropriate for the mass spectrometer, it is necessary to keep the turbo pump on while introducing the gas. The total pressure may change during the course of the measurement and this will of course introduce an error in the relative abundance measurements. Think about how to compensate for this. Take five measurements of the isotopic abundance, some of which should be at widely varying total pressure; one background measurement should be taken before introducing the Xe.

A. **Procedure for determining exponential approach to base pressure**

You will do this twice. First, you can use the thermocouple gauge to measure the roughing pump’s pressure over time. (If you need to repeat trials, you can open the valve on top of the diffusion pump to reset the vacuum chamber to atmosphere, provided all necessary precautions in the foregoing notes have been taken.)

Second, you can use the ionization gauge to measure the pressure of the turbopump versus time. (To repeat a trial, turn off the ionization gauge, close the valve on top of the turbopump, and open the roughing valve to bring the top part of the vacuum system back up to rough vacuum.)

The residual pressure as a function of time decreases exponentially from an initial pressure toward a long-time baseline, or residual pressure $P_r$:

$$P(t) = P_0 e^{-kt} + P_r$$

where $P(t=0) = P_0 + P_r$ is the initial pressure and $k$ is the rate at which gas is pumped out.

You need not worry about starting your count at “exactly $t=0$.” The exponential function is self-similar; no matter what moment you call $t=0$, you will always see the same exponential function with the same $k$ – different starting times are accommodated by a change in the coefficient $P_0$ (i.e. the initial pressure). (For this reason an ensemble of radioactive atoms with characteristic
lifetime $T$ will, on average, survive for a time $T$ from when you start observing them, no matter how long they were sitting there before you started counting. The only cost of delaying your measurement is that fewer atoms would be left.)

Note that this is an overly simplistic model, though. In reality, atmospheric gas has many components which are pumped out at their own characteristic rates ($H_2O$, for example, is notoriously slow to pump), so a better function to use may be of the form:

$$P(t) = P_0 e^{-kt} + P_1 e^{-k't} + P_r$$

which would allow for two components. The need for such a function is usually apparent because of a “fast front end” at early times which does not fit well to a single exponential. You should make sure to select initial guesses for $k$ and $k'$ which are well separated from one another in order to prevent the two $k$’s from converging and “playing off” of one other and giving a pathological fit. (For this reason, simultaneously fitting more than two exponentials is usually asking for trouble.)

Another alternative: It can be shown that a sum of multiple exponentials with different $k$’s can be represented as a stretched exponential:

$$P(t) = P_0 \exp(-(kt)^\beta) + P_r$$

where $0<\beta<1$ is the “exponent of the exponent.” The stretched exponential is a generalization of the familiar cases $\beta=1$ (simple exponential) and $\beta=2$ (Gaussian). But beware that this function becomes increasingly pathological as $\beta \to 0$. In addition, while the stretched exponential is an extremely good phenomenological fit function with wide applicability, it is often difficult to extract meaningful physical information, so you may fit your data beautifully but be unable to make any physically useful statements.

**B,C: Suggestions for performing mass spectrometry of atmospheric gas**

Once you have set up the equipment as described in Section 1.2 or 1.4, you are ready to turn on the mass spectrometer and collect data using the Dycor software on the computer.

The software is rather straightforward, although the instructors can help you in case of trouble. Most menus can be accessed from the top menu bar, or by right-clicking on the display.

On the x axis is plotted the mass/charge ratio of the observed molecules. On the y axis is the abundance of molecules at that specific mass/charge ratio. Different species are seen as Gaussian-shaped peaks in the mass spectrum.

If you mouse over an individual peak, the computer will give a list of suggested species at that mass/charge ratio. The software is intended for a wide range of research and industrial applications, so the list of suggestions is much broader than what we will encounter. Although the program may suggest species such as toluene, methane, freon, carbon monoxide, and other nasty substances, the only molecules we will see are those present in abundance in the earth’s atmosphere and those substances that we introduce into the system; the two chief examples of the latter are the xenon and
argon gases we will introduce into the system in the last part of the experiment, and various types of oil used in the vacuum system. The various pump oils generally have \( m/q \) in the 40’s through 70’s, and some of the more common types are indicated in the list of suggestions.

Also, since some species are pumped out more easily than others, there is no reason to expect that the composition of residual gas will be identical to that of atmospheric gas. Certain gases, such as \( \text{O}_2 \) and \( \text{N}_2 \), for example, are pumped out relatively efficiently, whereas \( \text{H}_2\text{O} \) is very difficult to pump and will be over-represented in your spectrum.

The species are ionized, and possibly dissociated, by the mass spectrometer’s electric field. Therefore, it is reasonable to see radicals such as \( \text{H}^+ \) and \( \text{OH}^- \) produced by the breakup of \( \text{H}_2\text{O} \), as well as doubly ionized species such as \( \text{N}_2^{++} \) at half the expected \( m/q \) ratio.

If the peaks are not centered on integer values of \( m/q \), the spectrometer needs to be calibrated in the software. Ask an instructor to help with this.

You should take spectra with the turbopump operating alone, and for the turbopump operating alongside the ion pump. Do you see any differences between the two? If so, why?

Additionally, you may be able to see less common isotopes of some common elements, such as \( ^{13}\text{C} \) or \( ^{17}\text{O} \). If so, it may be possible to estimate the isotopic ratio by comparing the height of the two peaks. Since they are very close, they will almost certainly overlap (the smaller peak will appear as a “shoulder” to the larger peak). Thus, in order to accurately extract the intensities, you’ll need to fit each peak to a Gaussian curve:

\[
y(x) = A \exp[\sigma(x-x_0)^2/2]
\]

where \( A \) is the intensity, \( \sigma \) is the width (which should be the same for nearby peaks), and \( x_0 \) is the center of the peak (which may or may not correspond to an integer depending on the accuracy of calibration). Overlapping peaks should be simultaneously fit to a sum of two or more Gaussians in order to get the best estimates of abundances.

**Saving data with the mass spectrometer program**

It is possible to save your spectra in an ASCII text format, so that you may analyze them later with a program of your choice. To do so, select *Save Data* under the *File* menu. There are several options for saving your data in various formats, so we suggest that you check your saved data files before clearing the screen to ensure that they have saved satisfactorily.

**D: Measurements of introduced xenon and argon gas**

In the final part of the experiment, you will introduce two gases which are not appreciably present in the atmosphere. In order to see the effects of these two gases, you will make a background measurement before introducing the gas, and a measurement after introducing the gas. The detailed procedure for introducing the gas is given in the final section of this manual.
We will use two gases, xenon and argon, each of which are interesting for various reasons. While the following section is not necessary to understand this experiment, this is interesting material to consider as you watch the data come in.

**Xenon: The isotope-rich gift from the stars**

Xenon is a noble gas. Like its more familiar brethren helium and neon, xenon does not actively engage in chemical reactions, although it can be coaxed into forming oxides and fluorides under the right conditions. It is also rather rare, existing in the earth’s atmosphere at parts-per-million (ppm) levels. Xenon is extracted from atmospheric gas via condensation. A large container of air is very gradually cooled to low temperatures; as the condensation temperature of each component gas is reached, it will condense on the sides and bottom of the container where it can be separated out.

Xenon (Z=54) is also notable for having one of the largest numbers of abundant stable isotopes of any element. There are nine stable isotopes, at least five of which are reasonably abundant in naturally occurring xenon, ranging in atomic mass from 124 to 136 (you may need to expand the m/q scale of the scan and the display; those menus can be accessed by right-clicking on the display). Each of these isotopes will be visible as a separate peak in your mass spectrum.

Finally, we may ask where xenon comes from. The Big Bang produced only the lightest elements: hydrogen (Z=1), helium (Z=2) and a bit of lithium (Z=3). All heavier elements have been produced inside stars. Elements up to Z=26 (iron) can be produced exothermically by colliding lighter nuclei together, powering stars such as the Sun. But above iron, fusion processes become endothermic and thus cannot be a source of energy production in stellar cores; the very heaviest elements, such as uranium and plutonium, in fact release energy when they break down into smaller components by alpha decay or by fission. Thus even the most massive stars, capable of producing enormous temperatures and pressures at their centers, cannot fuse heavy elements in the same way that they fuse light elements. In fact, because of this limitation, the most massive stars die in supernova explosions when their cores run out of usable energy sources. But in supernovae, gravitational energy released by the star’s core collapse can be harnessed to activate these endothermic heavy-element fusion reactions, creating all the heavy elements in the Universe. The supernova then ejects this material into space, where it coalesces into new stars and planets, enriched with silver, gold, lead, xenon and a wealth of other heavy elements.

**Argon: Link to the Earth’s past**

Argon (Z=18) is also a noble gas. It also does not participate readily in chemical reactions. All the other noble gases, even the cosmically abundant helium, are rather rare on earth, and one would expect the same of argon.

But argon is the exception. Unlike helium, neon, krypton and xenon, argon is abundant in the earth’s atmosphere. Although it only comprises 1% of atmospheric gas, that is orders of magnitude more than all the others put together. Further, while argon has three stable isotopes, well over 99% of the earth’s argon is of one isotope: \(^{40}\text{Ar}\). (The abundances of the other argon isotopes are actually reasonably in line with the abundances of the other noble gases; \(^{40}\text{Ar}\) is the singular exception.)
Why is there so much $^{40}$Ar, and so little of any of the noble gas isotopes? It turns out that $^{40}$Ar is continually produced in the earth’s crust by the reverse-beta decay of $^{40}$K. Potassium is one of the most abundant elements in the earth’s crust, and $^{40}$K is one of the most abundant radioactive isotopes on earth, with a lifetime of slightly over 1 billion years. ($^{40}$K decay, and that of other natural radioisotopes, are the dominant source of geothermal energy as well.)

This is extremely useful. Because argon-40, like all the other noble gas isotopes, should be extraordinarily rare on earth, the radioactive decay of $^{40}$K is by far the dominant source of atmospheric argon-40. And, since it is a gas, a molten rock will expel any pre-existing argon-40 before it cools. Thus, by measuring the ratio of $^{40}$K/$^{40}$Ar in a rock you can determine how many $^{40}$K lifetimes have elapsed since the rock solidified. Since $^{40}$K’s lifetime is over 1 billion years, the history that can be obtained by potassium-argon dating stretches all the way back to the earth’s formation.

**Procedure for Data Analysis of Xe and Ar gas**

Your main goal will be to determine the abundances of each of the principal isotopes of each gas. Since xenon will likely yield more useful data, we suggest that you try it first.

Since in many cases the $m/q$ peaks will overlap, you will need to fit Gaussian curves to each peak in order to reliably extract the relative abundances. Keep in mind that the $\sigma$ for each peak in that region should be approximately the same, so if you fit one clear peak, you can use the same value of $\sigma$ for the rest, even if they are not clearly separable. Also keep in mind that if one clear peak has a non-integer center (say, displaced by +0.27 from the closest integer), then the other peaks will be displaced by approximately the same amount as well; this means you only have to fit the amplitude – one free parameter – in such cases.

Once you determine the relative abundances of the visible Xe isotopes, you should compare your values to the accepted values for atmospheric xenon.

Once you’ve done xenon, next try argon, although because of the dominance of $^{40}$Ar, you may not have much luck.

**Procedure for taking the background measurement before introducing the xenon/argon gas:**

To pump down the residual gas on the line connecting the xenon/argon tube to the vacuum chamber, use the following procedure:

1. **Ensure that the mass spectrometer and ionization gauge are off** (to protect them against overpressure).
2. **Ensure that the valves on top of the high vacuum pumps are closed.** If they are not closed, close first the valve on top of the ion pump, then the valve on top of the turbopump. If the turbopump was on, do not turn off its power supply. The ion pump can be shut down.
3. Make sure that C (the gas regulator outlet valve) is closed. This will prevent gas from flowing from the compressed gas cylinder into the vacuum system.

4. Open valve A and then the leak valve completely. Any residual gas in the line connecting the compressed gas cylinder to the vacuum chamber will flow into the vacuum chamber.

5. Close the backing valve and open the roughing valve. The mechanical pump will decrease the pressure in the vacuum chamber to ~10 millitorrs.

6. Close the roughing valve.

7. At this point, close completely valve A.

8. Open the backing valve. If the turbopump was off, turn on the power to the turbopump. The pressure indication of the thermocouple gauge will jump to the pressure in the line connecting to the exhaust of the turbopump. After the thermocouple gauge reads <40 millitorrs, open the valve on top of the turbomolecular pump.

9. Turn on the ionization gauge.

10. Wait until the pressure becomes low enough for the mass spectrometer (10^{-4} millitorrs) and rather stable. Turn on the mass spectrometer and take a measurement of the residual gas.

**Procedure for introducing xenon/argon gas:**

**CAUTION:** There is an arrow on the regulator adjusting knob indicating the direction in which you need to rotate the knob in order to increase the gas flow from the compressed gas cylinder into the vacuum system. This is the opposite of the common direction.

11. Make sure no gas flows through the regulator by turning the regulator adjusting knob counterclockwise until it turns freely. **Note: do not overturn the knob, as when it reaches the end of the course it stops completely.** The regulator adjusting knob has an adjusting spring. When the spring is uncompressed and the knob turns freely, the gas flow is completely stopped.

12. Open - slightly - the valve right on top of the compressed gas cylinder. Ask an instructor to show you this.

13. **Turn the regulator adjusting knob** as to **finely increase** the gas flow. The pressure indicated by the outlet gauge of the regulator must be **a few psi** (the needle indicator should jump across approximately one division).

14. **Slowly open C, the regulator outlet valve.** Gas will flow up to the leak valve.

15. While monitoring the ionization gauge, **VERY SLIGHTLY open the leak valve. Do not allow the pressure in the vacuum chamber to increase above 10^{-4} millitorrs.**

**Procedure for shutting down the gas flow:**

1. **Close the valve on top of the leak valve.**

2. **Close the leak valve.**

3. **Close C, the regulator outlet valve.**

4. **Turn the regulator adjusting knob counterclockwise** to completely decrease the flow of gas.

5. **Close the valve on top of the compressed gas cylinder.**

6. Follow the procedure for turning off the turbopump to shut down the system.