NEUTRALIZING FAST BEAMS OF IONS

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1. Introduction

In the field of atomic, molecular and optical physics, it is of particluar interest to study collisions between different species of particles, or between particles and laser pulses. A large amount of research has been given to species of molecules which could be considered ionic: they possess some net charge. This is because it is possible to easily and reliably accelerate and control ion beams in a vacuum to speeds of many electron-Volts (eV), allowing for easy detection. However, everyday matter tends to be made up of neutral particles - those possessing an equal number of electrons and protons, particles which by their nature will not react in any convenient way with the electromagnetic fields used to accelerate a beam line. These neutral particles are by their nature difficult to detect at their low energies. Neutral particles will, however, be detected after interaction with a short-pulse laser, or close passes with another atomic particle, provided that prior to the interaction, the neutral particles had a few keV's of energy. In order to do that, we must first create a fast beam of neutral particles to study, which one can achieve by creating fast ions aimed at a target, and then neutralize them in their path.

Two modes of operation exist for this neutralization process: remove an electron(s) from a negatively charged ion, or add an electron(s) to a positively charged ion. Since the ECR and EBIS beamlines in the JRM lab tend to run positive ion beams, we will talk about the secondary approach – adding electrons. This process, commonly referred to as Charge Transfer or Electron Capture[1] occurs when a positively charged ion beam collides with some target atom or molecule and an electron is transfered from the target to the projectile.

In our specific case, we will be trying to neutralize a beam of 5keV Hydrogen molecular ions.

[1]Not the same as the nuclear process $p + e^- \rightarrow n + v_e$, also referred to as electron capture

2. Choosing a Target

When we look for possible targets to neutralize the beam, there are a few factors to consider.

First, will the interaction allow the projectile to continue in a straight line? Any single atom (*not* a molecule) which can exist as a gas should allow this. Second, how easily will the target give up an electron? This can be determined by the first ionization energy of the atom. Lastly, how easy is it to create a cloud of target molecules inside the beamline? This varies by species.

We look first to the alkali metals (Li, Na, K, Rb, Cs, Fr) because they have only one valence electron. The amount of enery needed to extract one electron is about 4-5 eV per atom. This is the lowest of any family on the periodic table, and makes elements like Cesium and Potassium common choices for charge transfer processes. At room temperature cesium is a solid, but just above room temperature it melts, and as temperature is increased to about 150°-200°C, cesium atoms will vaporize from the surface of the liquid, increasing the vapor pressure, well below the boiling point of 671°C. This creates a 'cloud' of cesium atoms, rich with electrons for the ion beam to pass through. However, cesium is moderately expensive, and very volatile in air. A cesium oven would require a special containment apparatus – or a 'cold finger' to prevent the gas from entering the rest of the system. Temperature control, both heating and cooling, are required for this system, and this might add unnecessary complications to the neutralization apparatus that we make. Threfore, we look to see if there are simpler alternatives.

Our next approach is to look at the Noble gases (He, Ne, Ar, Kr, Xe, Rn), which are inert, relatively abundant, and relatively easy to introduce into a beamline. In fact, recent projects in the JRM lab have used argon and xenon gases as jets and cells as both collision and calibration devices. In particular, Dr. Xavier Urbain recommends the use of argon, because of near-resonant transfers of electrons from Ar to H_2^+. We will take this advice and design a device based around the use of argon as a gas target.

3. Collision Cross Sections

Let's look at some of the basic theory of collisions between a beam of particles and a stationary target. Consider the case where a beam of ions passes through a gas cloud wider than the ion beam. Provided that one has sufficient detection machanisms, one ought to see evidence of collisions between the two species. A typical representation of the

particle yield has the form

$$\frac{Y}{N_P} = n_T \cdot l_T \cdot \sigma$$

Where Y is the number of desired particles yielded by the interaction, N_P is the number of incoming particles, n_T is the number of target particles per unit length, l_T is the length of the target region, and σ is the cross section. In this parlance, the cross section is not necessarily the profile of a particle, but rather a representation of the probability that two particles will interact, conceptualized as a representation of area. This allows for convenient interpretation of data, and the use of the above formula.

In our design, we were looking to get a yield-per-projectile ratio of about 10%, meaning that one in every ten projectile ions becomes converted to its neutral form. Plugging in an l_T of 3cm, and reported cross sections from literature about cross sections on the order of 10^{-15}cm^2, we can solve for the target density (on the order of $3 \times 10^{13} \frac{atoms}{cm^3}$. From this, using the $PV = nRT$ formula, we found that at standard temperature and pressure (a reasonable approximation), we would need a pressure of about 1 mTorr inside the gas target for our experiment.

4. The Apparatus

So how do we create a gas cloud with 1 mTorr of argon pressure in our beamline? The answer is a design that has to obey a few parameters.

Can we make a small gas cell with apertures in either side? Not really. The gas would begin to leak out into the surrounding area, worsening the vacuum and requiring more gas to be pumped in. There ought to be a better way.

Can we use an effusive jet of the gas? Maybe. This has a much lower interaction length, but would allow us to direct the gas toward a turbo pump to prevent it from entering the rest of the system.

Can we use a series of gas jets along the beam path? Probably. This allows for a longer interaction region and a reasonable amount of pressure needed for a 10% yield.

Can we use the tubes in a microchannel plate to direct the gas? Yes. Pumping argon through long, narrow tubes creates a system of directed flow towards a turbo pump, allowing us to create a controlled area with directed argon target atoms.

Now that we have some method to direct the atoms, how do we control the pressure of the interaction region? In theory, controlling the pressure on one side of the MCP allows us to control the flow thorugh the tubes, and thus the pressure on the other side. By letting a circular

MCP plate act, say, as one end of a cylinder, we can regulate the gas pressure inside the cylinder, thus modulating the flow coming through the tubes in the MCP. By covering and blocking holes with a mask so that the only open holes match the width of the ion beam and using the full length of the diameter of the MCP, we can create an interaction region for the ion beam in argon atoms above the MCP. In the interest of preventing leaks, we can put an o-ring near the perimeter of the MCP. Placing this entire apparatus on a push-pull manipulator with a gas feedthrough into the cylinder, we can place this entire apparatus into the beamline, creating a neutralization zone. Because of the amount of gas being introduced, this cell ought to be placed in a cross with small aperture tubes on the entrance and exit to allow for differential pumping in the region.

5. A Collision

Take for example the case of a positively charged hydrogen molecule (H_2^+, a simple ion) of a few keV colliding in some fashion with an argon atom (Ar^0, a noble gas with 18 electrons) moving relatively slowly. This interaction can have multiple outcomes, which come as a result of the collision's parameters (species involved, angle of incidence, energy of the molecules, etc.). For the $H_2^+ + Ar^0$ collision, some possible reactions are

$$H_2^+ + Ar \rightarrow H_2 + Ar^+ \quad (1)$$
$$\rightarrow H_2^* + Ar^+ \quad (2)$$
$$\rightarrow H + H^+ + Ar \quad (3)$$
$$\rightarrow H + H + Ar^+ \quad (4)$$

While a few other collision channels are possible, we will focus on these channels, as they are the main channels that produce the neutral particles that we might detect. In reaction number (1), we see that a product is a hydrogen molecule in its ground state. Reaction number (2) shows that an outcome of this interaction leaves the neutral H_2 with an electron in an excited state. Both of these are considered fast neutrals, and together these reactions correlate to the cross-section listed in section 3.

Reaction number (3) represents the dissiciation channel, producing both a neutral and ionic fragment. This will contribute to the neutral "current," but can be subtracted out by the magnitude of the H^+ current. Reaction number (4) represents either a charge transfer dissociation or a second collision that is dissociative. These fragments will have some transverse momentum, so if the detector is sufficiently

far away, one could create an aperture or iris to allow only the central beam to pass through, containing mainly H_2 neutrals.

6. Conclusion

If we want to detect particles, they need a few keV of energy. Neutral particles in the ground state don't have nearly enough energy to be detected efficiently. If we can get a beam of ions moving energetically and then neutralize it, we gain access to a fast beam of neutral particles to study. There are different methods of neutralization, our approach was to create a cloud of argon molecules for an ion beam to pass through and interact with. Future investigation will go into optimization of neutralized yield, and incorporation of this design into the ECR beamline for running experiments with femtosecond pulses on neutral H_2.