I. Introduction

In this experiment, an octopole ion-beam guide (**OPIG**) technique is used in conjunction with the **K**ansas **S**tate **U**niversity **(KSU) C**ryogenic **E**lectron **B**eam **I**on **S**ource **(CRYEBIS)**, to facilitate studies of low energy collisions. The **OPIG** generates an r-f oscillatory electric field, which confines and modulates the radial motion of the ions, but does not affect the motion along the beam axis. In this manner, the ions are confined in the transverse direction of the beam line. The translational kinetic energy of the ions can be reduced along the beam line axis by raising the potential of the **OPIG**. In this manner, low energy collisions can be examined with little intensity loss. Molecular hydrogen and helium were the most commonly used as the target in these studies (argon and neon targets were also used). Both of these targets have two bound electrons. Net cross sections have been measured for the case when one, and two of the target atom electrons are captured to the projectile ion, and are referred to as single and double electron capture. Targets with more than two electrons allowed the possibility to measure triple (or quadruple, etc.) capture cross sections, but was not examined in this work.

With a conventional collision cell, without the use of an **OPIG**, it is typically difficult to measure ions that are scattered through large angles. One of the features that make an **OPIG** so useful in the study of low energy collisions is its ability to collect product ions with a large angular spread. In a collision cell with an **OPIG**, the product ions with a positive axial velocity component in the laboratory frame are guided along the beam axis toward the downstream side of the **OPIG**. After passing through the **OPIG**, the ions are charged state analyzed using a magnet, and measured using a position sensitive ion detector.

The process that is being investigated in this experiment is explained as follows. Ions (in this study, positive ions, or atoms that are missing one or more electrons) that are directed towards neutral atoms, will have a certain probability of taking one or more of the electrons that were orbiting the neutral atom, and of capturing them into orbits around the ion. It is this probability of capturing electrons that is measured. When an ion captures one electron, it is called single electron capture, and if two electrons are captured in the same collision, it is called double electron capture. The probability of a capture event happening may depend on how quickly the ion passes by the atom. We measure electron capture cross sections where the ions are passing by the neutral atoms very slowly (the projectile ions speed is much slower than the speed of the target electrons).

Briefly, the experiment is conducted as follows: Ions are directed into a gas target. The gas target consists of a single species of atoms or molecules. The ions are positively charged; therefore, when they come into close range with atoms in the gas target, the electrons on the atoms will be attracted to the ions. In each close encounter between an ion and an atom, there is some probability that one, two, or more of the electrons from the atom, will transfer to the ion as it passes through the gas target region. After the ions have passed through the gas target region, they are deflected, by directing them through a region where a magnetic field is present. The greater the charge these ions have, the more they will be deflected in the magnetic field. When many ions are passed through the gas target, ions that have captured one electron, ions that captured two electrons, and ions that have not captured any electrons, will all be deflected through different angles, and become spatially separated from each other. By counting how many ions pass through without capturing any electrons, and counting those that capture one

and two electrons after having passed through the gas cell, we can determine the probability, or likelihood, that the corresponding electron capture process will occur. When enough ions have passed through the target region, statistical fluctuations become small, so that electron-transfer probabilities can be accurately determined.

A. Electron Capture, Photon Emission, and Auger Decay, and the Q-Value

In a collision between an ion and an atom, one (or more) of the electrons can be removed from the atom. This is referred to as ionization if the removed electron(s) are lost to the continuum. If the electron(s) from the atom are transferred to the ion, we refer to this process as electron capture. Previous to being captured, the electron is bound to the target atom with an energy E_i. Following capture the electron will be bound to the projectile ion with an energy E_f. Generally, the energies E_i and E_f, are not equal. The difference in energy between E_i and E_f is defined as the Q-value. If the Q-value is positive, energy is released in the collision, and the collision is referred to as exoergic. If the Q-value is negative, energy is absorbed by the ion-atom system, and the collision is referred to as endoergic.

In cases of electron capture, an electron may be captured into an excited state. When an electron is captured into an excited state, it generally decays to a lower state very quickly. In this decay process, the electron(s) will either decay to a lower, less excited state, emitting a photon, or, if there is more than one electron on the ion, the electrons may rearrange which states they populate on the ion. Often, in this rearrangement process, one or more electrons will be ejected from the ion. This process

of electron emission is called the Auger effect, or Auger decay. The process in which the electron decays to a lower state, and the energy that is lost by the electron is emitted as a photon, is referred to as photon emission. These different processes happen in nature, and by simulating interactions in a laboratory setting, and studying these interactions, understanding of our environment and universe can be deepened.

When an ion, A^{q+}, undergoes a collision with atom, B, the following single and double electron capture processes can take place.

$$A^{+q} + B \rightarrow A^{+(q-1)} + B^{+} + Q, \qquad s_{q,q-1} \qquad \textbf{(Eq. 1.1)}$$

and

$$A^{+q} + B \rightarrow A^{+(q-2)} + B^{+2} + Q, \qquad s_{q,q-2} \qquad \textbf{(Eq. 1.2)}$$

$$+> \; A^{+(q-1)} + e. \qquad s_{TI}$$

In both processes, Q is the energy defect or Q-value of the reaction. In the first process, a projectile ion captures one electron from atom B. In the second process, a projectile ion captures two electrons from the atom. The projectile ion can capture two electrons into a doubly excited state, which may decay through an Auger-type process. In an Auger-type process one of the two captured electrons will immediately be ejected from the ion, and the other electron will subsequently make a transition(s) to an orbital with lower energy, leaving the ion in a much less excited state. The net effect is known as transfer ionization, and is what the third process corresponds to.

For cross sections measured in this experiment, there is no way to distinguish between a projectile ion that has undergone a transfer ionization process from one that has only captured one electron, so the measured single electron capture cross section is s_1

$= s_{q,q-1} + s_{TI}$, and the measured double electron capture cross section is $s_2 = s_{q,q-2} - s_{TI}$. In other words, what is referred to as single or double capture, is the "net" single or double capture.

In an ion-atom collision where charge transfer occurs, an electron is generally captured into an excited state, and then quickly decays to a lower energy level, with the ion emitting a photon. A collision of a multiply charged ion A^{q+}, with a neutral atom B, in which an electron is captured into an excited state, and subsequently decays through photon emission, is given by

$$A^{q+} + B \rightarrow A^{(q-1)+}(nl) + B^{+} \qquad \textbf{(Eq. 1.3)}$$

and

$$A^{(q-1)+}(nl) \rightarrow A^{(q-1)+}(n'l') + h\nu\,, \qquad \textbf{(Eq. 1.4)}$$

where (*nl*) are quantum numbers representing the state that the electron is captured to, and (*n'l'*) represents the state the electron occupies after decaying. The quantity, *hv*, is the energy of the emitted photon, and is equal to the difference in the electron potential energy before and after decay. Since the energy levels of most atoms and ions are well known, and the energy, *hv*, of the emitted photon is equal to this difference, the photon emission spectrum can be used as a method to "fingerprint" the state selective capture process.

B. Motivation

Beyond the "pure science" motivation for studying charge transfer dynamics at low energy, there are applications where knowledge of the charge exchange process is needed. It is important to examine ion-atom collisions at low energies, and measure electron capture cross sections in order to deepen our understanding in areas such as

ionosphere research, the study of the creation of molecules in interstellar space, astrophysical plasmas **[1.1]**, and laboratory plasmas for fusion research **[1.2]**. Charge transfer between ions and atoms has been studied extensively for high energy collisions (> 1keV), but there have been relatively few studies for lower energy collisions. At low energies, technical difficulties arise with ion beam focusing. Space charge, stray fields, and ion beam transport in general, are all contributing factors that increase the difficulty of controlling an ion beam. Furthermore, collecting scattered ions that are produced in the collision cell becomes more difficult as the beam energy is reduced. Because of all these difficulties, there are relatively few experiments involving the measurement of charge exchange cross sections at low energies.

Measurements of charge transfer for highly charged ions, and very low energy ion-atom collisions are important to deepen our fundamental understanding of the mechanisms of collision processes. There is a relatively small amount of data on this subject that are available to assist in improving existing theories, and many of the existing theories are in disagreement with each other. By performing controlled experiments, where the exact collision energy is known, we can isolate and more clearly determine these cross sections for very low energies, and use this body of data as a tool to make improvements in theory. With more accurate theoretical cross section information, it may be possible to generalize this knowledge to model, and better understand what is happening in astrophysical and laboratory plasmas.

Typically, interactions in these plasmas have kinetic energies in the range of 0.1 to 100 eV/amu. One indication that charge transfer has occurred in an ion-atom interaction, is that light is emitted from the plasmas. Examples where the observation of light

emitted in ion-atom collisions have been studied, are the plasma torus of Jupiter at the orbit of its moon Io, and vacuum ultraviolet (VUV) emission from the tails of earth-passing comets such as Hale-Bopp and Hyakutake **[1.3,1.4,1.5]**. Attempts to determine basic Io torus properties have not yet succeeded due to deficiencies in the modeling. A major drawback is thought to be the inaccuracy of theoretical cross sections for state selective electron capture by multi-charged ions **[1.6]**. Accurate knowledge of total electron capture cross sections, and state selective cross sections, would help in explaining these observations, and may also enable the use of VUV emission as a diagnostic tool for charge state and flux distributions of the solar wind ions **[1.7]**.

One of the potential applications, where knowledge of accurate charge transfer cross sections is important is in fusion research. The main reason for studying fusion is the possibility of the extraction of electrical power. Of course, in this day and age, people use electrical power for nearly everything, so the potential benefits to be gained by society make it an attractive topic of study. One of the main methods that have been investigated to achieve fusion is magnetic confinement of a hot plasma in a Tokamak device **[1.8]**. A Tokamak magnetically confines a mixture of deuterium and tritium gas, which is ionized after being injected into the reactor vessel. Nuclear fusion requires a high temperature and density of the plasma. Ultimately, it has been a challenge for scientists to maintain fusion due to power losses, which lower the efficiency for extracting power. The effect of impurity ions is that they raise the ignition temperature for fusion to occur by increasing the radiative losses **[1.9]**. The main way that the plasma is heated, is by passing a current through it, but auxiliary heating is accomplished by injecting a fast neutral beam into the plasma. The fuel gas will capture or ionize

electrons from the neutral beam, and the resulting protons will become magnetically trapped. This additional heating occurs by collisions between the fast protons, and the fuel gas. However, impurity ions near the edge of the plasma also have an appreciable probability of capturing electrons into excited states from the hydrogen atoms **[1.10]**. The impurities near the walls of the confinement vessel can cause significant deposition of neutral beam energy at the plasma edge, which can lead to instabilities and a greater production of impurity ions. The formation of hydrogen atoms from the fuel gas can be due to electron capture from the impurity atoms and ions. As neutral atoms, the fuel gas is no longer magnetically confined, and will escape the trap, which ultimately reduces the temperature of the plasma. These power losses, due to charge transfer to the fuel gas, which cool the fusion plasma and thereby limit the reality of nuclear fusion as a power source, are critically dependent on the magnitude of the electron capture cross sections.

The goals of this project were to perform low energy collisions with a variety of different ion charge states and species, and measure total single and double electron capture cross sections. Some of the collision systems measured were specifically chosen so that cross section comparisons could be made with cross sections measured by other groups. Professor Okuno, from Tokyo Metropolitan University (TMU), created the **OPIG** design, and has been conducting low energy experiments for several years in Japan, using a mini-**EBIS**. An **OPIG** was constructed for use at Kansas State Universities J. R. Macdonald laboratory, and was set up on a beam-line from the **CRYEBIS**. The **CRYEBIS** at Kansas State University has the ability to produce more highly charged ions than the mini-**EBIS** at TMU, which was one of the motivating factors for doing this experiment. Besides comparing experimentally measured cross

sections with Okuno's data and others, a few theoretical cross section calculations have been compared with the cross sections from this research work.

This dissertation describes a few different theoretical models that can be used to calculate single electron capture in chapter II. Chapter III, contains a detailed description of the experimental setup, and explains two different methods used to measure cross sections. The first method employed a retarding mesh to separate charge states of the product ions after passing through the **OPIG**, and a modified beam viewer to record the ion beam current. The retarding mesh system didn't allow for recording more than one charge state simultaneously, and did not have a good energy resolution for heavier ion species. Therefore, an alternate method was adopted, using a charge-state analyzing magnet in combination with a position sensitive ion detector to record the cross section information. Chapter IV is devoted to presenting results from the measurements for the different collision systems studied, including comparisons to others theoretical and experimental work for some cases. Finally, conclusions drawn from this body of work are presented in chapter V.