Conclusion and outlook

The purpose of this thesis project was to investigate the possibility of using cryogenic noble gases and superfluid helium as stopping media for ion catchers.

Cryogenic noble gas ion stopping medium

Underlying physics and mechanisms

Based on the literature survey of physical processes in ionized cryogenic helium gas, the following conclusions are drawn:

- Most physical processes involved in the cryogenic ion catcher fall within the classical and elastic collision limit. The positive ion mobility is an important parameter determining the efficiency as it determines the extraction time of ions from the stopping volume.

- Given the helium densities used in noble gas ion catchers, $\text{He}_2^+$ is the dominant ion in ionised helium gas above a temperature of about 200 K. Below this temperature, $\text{He}_3^+$ is dominant. The electric field to density ratios considered here are not large enough to induce the breakup of $\text{He}_3^+$.

- The main ion-loss mechanism in a cryogenic helium gas ion catcher is recombination loss. Recombination of thermalized high-energy ions obviously has a negative impact on the total efficiency whereas helium ion recombination is a positive factor. Recombination of helium ions decreases the space charge problem associated with the ion beam and removes the free electrons from the ionization region.

- For the helium gas densities and temperatures relevant for the cryogenic helium gas ion catchers, 3-body recombination dominates the 2-body recombination by an order of magnitude.
• The recombination coefficient of helium ions shows a temperature dependence of $T^{-2.5}$ for the 3-body recombination coefficient $\alpha_3$. The same temperature dependence is observed for simple molecular ions in helium down to 77 K. Recombination also depends strongly on the electron temperature which in turn depends on the ionization method and can be much higher than the gas temperature.

• Most of the available data on the recombination mechanism is restricted to helium gas densities less than $10^{18} \text{ cm}^{-3}$ at room temperature. A detailed theoretical and experimental study dedicated to understand the recombination process in low-temperature high-density helium gas is necessary for a deeper understanding of the physical processes involved.

Key experimental observations

Off-line experiments on cryogenic helium gas as a stopping medium demonstrated large stopping and transport efficiencies of $^{219}\text{Rn}$ ions in noble gas stopping media of low purity in a container that is not ultra-high vacuum compatible by in-situ purification of the noble gas upon cooling to below 90 K. In an on-line experiment we have investigated the survival and transport efficiency of $^{219}\text{Rn}$ ions in high-density cryogenic helium gas, with ionisation of the gas induced by a proton beam. The combined efficiency of ion survival and transport by an applied electric field was measured as a function of ionisation rate density for electric fields and for three temperature and density combinations. The main results from the off-line and on-line measurements are:

• For high enough electric field, no neutralization takes place after slowing down. The measured efficiency is the result of charge exchange during slowing down and as such represents a fundamental upper limit to the efficiency of noble gas ion catcher devices. This upper limit depends on the chemical nature and the atomic structure of both ion and gas.

• In a separate experiment the mobility of $^{219}\text{Rn}$ ions in helium, neon and argon at 77 K is measured. The results are comparable to those of xenon in the respective gases.

• On-line results demonstrate the importance of a high electric field to quickly pull ions and electrons apart and as such reduce the neutralisation probability in the ionization region. Both on-line and off-line measurements demonstrate that the cryogenic helium at high density and high electric field is a promising medium for an ion catcher.

• The main conclusion of the studies on cryogenic noble gas ion stopping media is that helium is the most ideal among noble gases to be used as stopping medium for high-energy ion beams due to its high ionization potential.
• The measured efficiencies at low temperature are comparable to those achieved with ultra-high purity gas catchers at room temperature. However, constructing a cryogenic noble gas ion catcher operating at liquid nitrogen temperature is technically easier. To reach the required purity levels of less than 1 ppb, room temperature gas cells have to be pumped to high vacuum and baked for a long time before being operational, whereas in cryogenic gas cells this is achieved without long pre-preparations. It may therefore be a more reliable and practical choice.

• The idea of freezing out the impurities in a helium gas catcher has caught the attention of several groups in recent years. Unknown to us at the time of our experiments, M. Wada at RIKEN tested a cold trap at liquid nitrogen temperature placed inside the gas cell in order to purify the helium gas. Although this system did not maintain a low temperature in the helium gas, an increase in efficiency of a factor of 10 was reported [125, 124]. Wada et al. are planning a fully cryogenic gas cell to be installed at the universal slow RI-beam facility (SLOWRI) at the RIBF at RIKEN [126]. New gas catchers being developed at the National Superconducting Cyclotron Laboratory at Michigan State University are planned to be cryogenic [52]. Plans to replace the gas cell at the SHIPTRAP facility at GSI with a cryogenic version have been presented [37].

Superfluid helium ion stopping medium

Underlying physics and mechanisms

The possibility of superfluid helium as stopping medium for ion catchers is investigated. An overview of the properties of positive ions and electrons in superfluid helium shows strikingly different behavior due to the different nature of their interactions with the ambient medium. This project concentrated on properties of snowballs such as their survival and extraction efficiencies. On the basis of the literature survey on underlying physical processes the following observations could be made:

• The interaction of snowballs with the superfluid-vapor interface is not well understood. If we believe that the potential barrier present is purely image charge character, there should be no change in barrier height with respect to temperature.

• The barrier height and location of the potential minimum at the superfluid-vapor interface depend strongly on the density profile of the interface. An accurate theoretical description of the extraction of positive ions and the size of the potential barrier is not available yet. For a more realistic image charge potential barrier calculation one should include the actual density profile of the superfluid-vapor interface.
• The size of the snowball is comparable to the width of the interface. This may very well influence the extraction process. A detailed theoretical study is necessary to understand the mechanism of positive ion extraction across the superfluid-vapor interface.

• When pushed towards the superfluid-vapor interface, electron bubbles explode as a result of the combination of thermal motion and quantum tunneling and release the bare electron into the vapor phase. This indicates that the structure of the charged complex plays a key role in the extraction mechanism.

• An experimental study on extraction of alkaline earth metal ions from superfluid helium will give a more clear picture of the ion extraction process across the superfluid-vapor interface. The role of quantum tunneling in the extraction can be ruled out due to large mass of the ions as compared to the electron.

Key experimental observations

The main objective of the off-line experiments on superfluid helium was to study the dependence of the survival of snowballs on applied electric fields and the dependence of their extraction across the superfluid-vapor interface on temperature. A new idea to enhance the extraction by evaporating the superfluid helium layer containing the trapped ions and thus release them to the vapor phase is also experimentally investigated. Key results from our experimental studies on superfluid helium as ion stopping medium are:

• The survival of thermalized snowballs in superfluid helium depends strongly on how fast they are transported out of the electron-rich region where they are produced from slowed-down recoil ions. The snowball efficiency reaches a saturation value at sufficiently high electric fields. The electric field strength needed to reach saturation depends strongly on the ionization density.

• The exponential increase in the extraction efficiency of positive ions across the superfluid-vapor interface above about 1.3 K with increasing temperature indicates that the extraction is a thermally activated process. Our data yields a potential barrier of about 20 K.

• The extraction efficiency below about 1.3 K is constant and much larger than the extrapolation of the thermally activated extraction. This points to another mechanism being dominant below 1.3 K.

• No clear explanation for the observed phenomenon related to second sound assisted evaporation of the superfluid surface layer is yet available as the physical processes involved are unknown. One may speculate the trapping of ions in the vortex tangle created by the second sound induced turbulence. A detailed theoretical study is necessary to help understand the results.
• The constant snowball efficiency for superfluid surface evaporation assisted by second sound pulses indicates that the number of ions trapped below the surface layer remains constant regardless of the destruction of the extraction efficiency.

• Given extraction efficiencies of positive ions across the superfluid-vapor interface, superfluid helium can be used as a stopping medium for ions with high snowball efficiencies. Snowball efficiencies between 5 to 30% observed for different ionic species and an extraction efficiency of about 30% at 2 K gives a total efficiency between 1 to 10%. The high vapor density at higher temperatures is however not favorable for the fast transport of ions in the vapor phase.