A series of off-line experiments was carried out at the Department of Physics, University of Jyväskylä (JYFL), Finland in 2001-2002 to investigate the possibility to use liquid helium as ion catcher stopping medium. The measurements employed \(^{219}\)Rn ions recoiling from \(^{223}\)Ra (see Section 4.2.1) as an ion source. Among the reported results was the first observation of the extraction of heavy positive ions across the superfluid helium surface [56, 57, 108]. The efficiency for extraction across the liquid surface was 23(4)% at 1.60 K, the release time was 90(10) ms at 1.50 K and the barrier for positive ions moving through a free superfluid-helium surface was 19.4(45) K. Earlier experiments which tried to extract positive ions/snowballs from liquid helium were unsuccessful [15]. A difference is that in earlier works mostly helium ions were investigated. The electronic structure of heavy ions may have a relation to the different behavior observed in the JYFL experiments.

The experiments described in this section aim towards a better understanding of the ion extraction at the superfluid-vapor interface. Further, as a new idea the possibility to enhance the ion extraction efficiency by second sound assisted superfluid surface evaporation is also investigated.

### 6.1 Extraction of \(^{219}\)Rn ions across the superfluid-vapor interface

#### 6.1.1 Experimental setup

The experiments were carried out inside a helium bath-cryostat working in the temperature range of 1.0 K to 1.8 K (see Chapter 4).

The principle of this experiment consists of five consecutive steps:
1. Thermalization of $^{219}$Rn recoil ions in superfluid helium where they spontaneously form snowballs (see Section 3.1).

2. An electric field pushes the snowballs towards the superfluid-vapor interface.

3. Ions are extracted across the superfluid-vapor interface (see Section 3.5).

4. The extracted ions are transported by an electric field to an aluminum catcher foil, from where

5. $\alpha$-particles are detected with a surface barrier spectrometer.

An open $^{223}$Ra $\alpha$-decay-recoil source was mounted at the bottom of the experimental cell. Several ring electrodes are used to provide a favorable static electric field to transport the ions from the source to a thin aluminum catcher foil. The experimental cell is cooled down to superfluid temperature and then helium gas from a room temperature buffer volume is let in to be condensed. The buffer volume filled with 1 bar helium gas at room temperature gives 23 cm$^3$ superfluid helium on condensation. The volume profile of the experimental cell is known, therefore the height of the superfluid helium can be controlled with an accuracy of $\sim 0.5$ mm by admitting the appropriate amount of buffer volume fillings to the cold cell. In the experiments described here the $^{223}$Ra source was covered by 6 mm of liquid helium.

As long as the source is above the superfluid helium surface, $\alpha$-particles from the source can be recorded by the $\alpha$-particle detector. Once the $\alpha$-particles from the source can no longer be recorded by the detector, an amount of superfluid helium sufficient to cover the source with about 0.4 mm (the range of $\alpha$-particles in liquid helium) is condensed. An applied electric field has been designed with a small radially focusing component at the superfluid helium surface in order to achieve radial confinement of the ions. Displacement of ions more than a few millimeters away from the cell axis would lead to transport loss. If an electric field is applied to guide positive ions from the source to the foil two sets of $\alpha$-lines can be detected. One set corresponds to the ions which decay at the superfluid-vapor interface; the second set originates from the ions which are extracted across the superfluid-vapor interface and are transported to the aluminum foil and decay there. As explained in Section 4.2.3 both sets can be unambiguously identified because of the different energy loss. Different isotopes are identified based on their known $\alpha$ energies. The $^{223}$Ra $\alpha$-lines are not seen in either of these sets since $^{223}$Ra is the mother nucleus and as such does not recoil out of the source. With this setup two sets of experiments were carried out to measure the snowball efficiency and investigate the ion extraction across the superfluid-vapor interface.

Both experiments were performed with similar setups; they are referred to as experiment A (see Figure 6.1a) and experiment B (see Figure 6.1b). The differences between experiment A and B are the shape of the $^{219}$Rn recoil open ion source, the source strength, the number of intermediate guiding electrodes and the distance
6.1 Extraction of $^{219}\text{Rn}$ ions across the superfluid-vapor interface

Figure 6.1: Cross-sectional view of the experimental cells used in experiments A and B.

Figure 6.2: Schematic representation of the $^{219}\text{Rn}$ ion open source used in experiments A and B.
between the source and the aluminum catcher foil. The open source in experiment A is deposited on a flat copper tip (see Figure 6.2a) and in experiment B on a cone-shaped copper tip (see Figure 6.2b). The cone-shaped source was used in order to avoid deposition of $^{223}$Ra on the lateral side of the copper screw during the source preparation. The strength of the $^{223}$Ra source was 21000 Bq in experiment A and 5000 Bq in experiment B at the start of the experiment. Experiment A is equipped with four guiding electrodes whereas B is equipped with three. The source-foil distances in the experiments A and B are 70 mm and 62 mm respectively. The number of guiding electrodes and the distance between the recoil ion source and the catcher foil have no effect on any of the results because once the ions are extracted out of the superfluid helium they are transported with 100% efficiency to the catcher foil by a static electric field.

The main objective of experiment A was to find the effect of the applied electric field on the snowball efficiency which is the fraction of $^{219}$Rn recoil ions transported to the superfluid-vapor interface after thermalization. Experiment B was performed to investigate the temperature dependence of the extraction efficiency of ions across the superfluid-vapor interface.

### 6.1.2 Results

A fraction of the recoil ions is neutralized due to charge-exchange processes during slowing down and thermalization. The surviving thermalized ions are transported to the superfluid-vapor interface by the electric field.

A fraction of the ions reaching the superfluid-vapor interface can be extracted into the vapor phase; the remaining ions decay at the interface. Because there are few electrons present at the interface, we assume there is no neutralization at the interface. The extracted ions are transported to the aluminum catcher foil and decay there. The snowball efficiency $\epsilon_{sb}$ is determined as the ratio of the sum of $^{219}$Rn ion decays at the superfluid-vapor interface $N_{surf}$ to the total $^{219}$Rn recoil ions emitted from the source $N_{recoils}$:

$$
\epsilon_{sb} = \frac{N_{surf} + N_{foil}}{N_{recoils}} = \epsilon_{surf} + \epsilon_{foil}
$$

(6.1)

where $\epsilon_{surf}$ is the fraction of total $^{219}$Rn recoils that decay at the superfluid-vapor interface and $\epsilon_{foil}$ is the fraction of total $^{219}$Rn recoils that decay at the foil. The fraction $\epsilon_{foil}$ is the total efficiency of the system. These efficiencies are directly deduced from the observed $\alpha$-line intensities. The extraction efficiency $\epsilon_{extr}$ is the fraction of the snowballs arriving at the surface that are extracted across the superfluid-vapor interface, i.e. the ratio of total efficiency $\epsilon_{foil}$ to the snowball efficiency $\epsilon_{sb}$,

$$
\epsilon_{extr} = \frac{\epsilon_{foil}}{\epsilon_{sb}} = \frac{\epsilon_{foil}}{\epsilon_{surf} + \epsilon_{foil}}.
$$

(6.2)
6.1 Extraction of $^{219}$Rn ions across the superfluid-vapor interface

Figure 6.3 shows the $^{219}$Rn snowball efficiency as a function of the electric field in the vicinity of the recoil ion source obtained with the experimental configuration A. A gradual increase and saturation of the snowball efficiency with increasing electric field is observed. The saturation of the snowball efficiency occurs for electric field strengths above about 180 V cm$^{-1}$. A measurement series was performed within the temperature range 1.15 to 1.6 K. Figure 6.4a shows the snowball efficiency as a function of inverse temperature from experiment A. No significant temperature dependency is observed. An average snowball efficiency of 5.36(13)% is observed for temperatures between 1.15 and 1.6 K with an electric field of 180 V cm$^{-1}$ in all the measurements. A similar measurement in experimental condition B yields an average snowball efficiency of 1.04(6)% for temperatures between 1.2 and 1.6 K (see Figure 6.4b). Experiment B was performed within the temperature range 1.15 to 1.8 K. The snowball efficiency at 1.8 K could not be extracted because of low statistics and the large low-energy tail of the $\alpha$ spectral lines.

Figure 6.5b shows the total efficiency $\epsilon_{foil}$ as a function of inverse temperature obtained in experimental configuration B. Measurements were performed within the temperature range 1.2 K to 1.8 K with an applied electric field of 180 V cm$^{-1}$. Figure 6.5a shows results from similar measurements in experimental configuration A. An increase in total efficiency with increasing temperature is observed.

Figures 6.6a and 6.6b show the extraction efficiency $\epsilon_{extr}$ as function of inverse temperature obtained from experiments A and B. The point at 1.8 K in experiment B is calculated using the average snowball efficiency of 1.05%. It clearly shows an increase in extraction efficiency with increasing temperature.
Figure 6.4: Snowball efficiency $\epsilon_{\text{sb}}$ as a function of the inverse temperature $1/T$. The experiments were performed with an electric field of 180 V cm$^{-1}$ at the source.

Figure 6.5: Total efficiency $\epsilon_{\text{foil}}$ as a function of inverse temperature $1/T$. The experiments were performed with an electric field of 180 V cm$^{-1}$ at the source.
6.1 Extraction of $^{219}$Rn ions across the superfluid-vapor interface

6.1.3 Discussion

The growth and saturation of the snowball efficiency as a function of electric field observed in Figure 6.3 can be explained in terms of recombination losses. The ions undergo neutralization during the slowing down due to charge exchange processes. The region around the ion source is rich in excess electrons due to the ionization of helium atoms by recoil ions and the $\alpha$-particles emitted from the recoil ion source. The range of the recoil ions and the $\alpha$-particles in the liquid helium are about 0.55 $\mu$m and 0.4 mm respectively. If the $^{219}$Rn snowballs are not transported out of this region fast enough they will neutralize as a result of electron-ion recombination. Once the ions are out of the electron-rich region, the neutralization is unlikely along the rest of the transport due to the very low electron density. The drift velocity of snowballs is proportional to the applied electric field (see Section 3.3). The snowball efficiency $\epsilon_{sb}$ can be represented in terms of the recombination loss factor $f$ as

$$\epsilon_{sb} = \epsilon_{sb}^{sat} (1 - f),$$

(6.3)

where $\epsilon_{sb}^{sat}$ is the saturation value of the snowball efficiency as a function of electric field. The recombination loss factor for a parallel plate ionization chamber is used as $f$ (see Section 2.4, Equation 2.8). At a constant temperature and ionization rate, $f$ is proportional to $E^{-2}$, where $E$ is the applied electric field at the ionization region.
Figure 6.7: Snowball efficiency $\epsilon_{sb}$ as a function of electric field $E$ at the source. The function $\epsilon_{sb}^{sat}(1 - KE^{-2})$ is fitted to the data. The snowball efficiency reaches a saturation value of 7.0% at electric fields above about 180 V cm$^{-1}$ at the source.

Using this result the snowball efficiency can be expressed as

$$\epsilon_{sb} = \epsilon_{sb}^{sat}(1 - KE^{-2})\,, \quad (6.4)$$

where $K$ is given by

$$K = \frac{Q\alpha_{SF}d^2}{6\mu_+\mu_-} \,, \quad (6.5)$$

where $Q$ is the ionization rate density (helium ion-electron pairs cm$^{-3}$ s$^{-1}$), $\alpha_{SF}$ is the recombination coefficient of ions in superfluid helium (see Section 3.4), $\mu_+$ and $\mu_-$ are the positive ion and electron mobility (see Section 3.3) and $d$ is the size of the ionization region along the applied electric field. As the range of the ionizing particles (recoils and alphas) is much smaller than the diameter of the source, we consider a cylindrical ionization region above the source with a radius equal to that of the source (4 mm). This ionization region consists of two parts: (1) a region of height 0.55 $\mu$m where the recoil ions with an energy of about 100 keV are thermalized, (2) a region of height 0.4 mm being the volume where the $\alpha$-particles with an average energy of about 6.5 MeV are stopped. Recoiled $^{219}\text{Rn}$ ions are thermalized in the first region and transported through the second region. The $^{223}\text{Ra}$ source strength at the time of the experiment was about 5000 Bq. The $Q$ associated with recoil ions, i.e. in the region 1 is about $1.3 \times 10^{12}$ cm$^{-3}$ s$^{-1}$ and the $Q$
6.1 Extraction of $^{219}$Rn ions across the superfluid-vapor interface

Table 6.1: Saturation value of snowball efficiency $\epsilon_{sb}^{sat}$ for different ions in superfluid helium.

<table>
<thead>
<tr>
<th>Ion</th>
<th>$\epsilon_{sb}^{sat}$ [%]</th>
<th>T [K]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{219}$Rn</td>
<td>6.95(7)</td>
<td>1.15</td>
<td>This work</td>
</tr>
<tr>
<td>$^{12}$B</td>
<td>30(3)</td>
<td>1.7</td>
<td>[107]</td>
</tr>
<tr>
<td>$^{12}$N</td>
<td>10(3)</td>
<td>1.7</td>
<td>[107]</td>
</tr>
<tr>
<td>$^{8}$Li</td>
<td>30(3)</td>
<td>1.7</td>
<td>[107]</td>
</tr>
</tbody>
</table>

associated with the $\alpha$-particle range, i.e. in the region 2 is about $0.2 \times 10^{12} \text{ cm}^{-3} \text{ s}^{-1}$. In this calculation, we assumed on average 40 eV is needed for the creation of a helium ion-electron pair (the same as in gaseous helium) and estimated the total number of recoils entering the superfluid helium to be 0.65 times the $^{223}$Ra source strength and the total number of $\alpha$-particles causing ionization of the helium to be 1.1 times the $^{223}$Ra source strength. Although $Q$ in region 1 is an order of magnitude larger than in region 2 the $\alpha$-particle range is about 3 orders of magnitude larger than the recoil range. The factor $Qd^2$ in Equation 6.5 is thus about 5 orders of magnitude larger in region 2 than in region 1. The ionization by the recoils is thus irrelevant for the recombination loss and the parameters of region 2 are used in the calculation. The recombination coefficient $\alpha_{SF}$ of ions in superfluid helium at a temperature of 1.15 K is about $2.7 \times 10^{-6} \text{ cm}^3 \text{ s}^{-1}$ (see Section 3.4). The positive ion mobility $\mu_+$ and electron mobility $\mu_-$ in superfluid helium at 1.15 K are about 1.25 cm$^2$ V$^{-1}$ s$^{-1}$ and 2.2 cm$^2$ V$^{-1}$ s$^{-1}$ respectively (see Section 3.3). Using these values, $K$ is calculated to be 436 V cm$^{-2}$. Thus the value of $f$ for an electric field of 50 V is 0.17. As the value $K$ in region 2 and region 1 differ only by the values of $Q$ and $d$, $f$ in region 1 is five orders of magnitude less than in region 2. This shows that the condition for Equation 6.4, i.e. $f < 1$ is satisfied here.

Figure 6.7 shows the best fit of Equation 6.4 to the snowball efficiency vs. electric field data. $\epsilon_{sb}^{sat}$ and $K$ obtained from the fit are 6.95(7)% and 1465(22) respectively. The value of $\epsilon_{sb}^{sat}$ from the fit is in good agreement with the experimental values obtained at electric fields higher than about 180 V cm$^{-1}$ (5.4%, see Figure 6.4a). $K$ obtained from the fit is about 4 times larger than the calculated value. There should be no error on $\alpha_{SF}$ and $\mu_-$. There is a chance for a 25% error on $\mu_+$ as we used the $^4$He ion mobility instead of the $^{219}$Rn ion mobility. The largest error may arise from the calculation of the ionization rate $Q$ as we considered a uniform energy loss of the $\alpha$ particles throughout the ionization region. Given these uncertainties, the calculated and experimentally determined value of $K$ are in good agreement.

The saturation of the snowball efficiency indicates that all the thermalized snowballs are moved out of the electron-rich region before recombination-neutralization. The saturation value of 6.95(7)% shows the charge exchange cross section limit of $^{219}$Rn ion thermalization in superfluid helium. The charge exchange cross section
limit of $^{219}\text{Rn}$ ion survival in helium gas is about 30% (see Section 5.1.2).

Takahashi et al. [109, 107] measured snowball efficiencies of $^{12}\text{B}$, $^{12}\text{N}$ and $^8\text{Li}$ ions in superfluid helium (see Table 6.1). Positively charged impurities were created through the injection of fast nuclear beams into superfluid helium. The snowballs involving a radioactive core ion were transported under a static electric field and were traced through the measurement of the radioactive decay of the impurity ions. Electric fields of 100 V cm$^{-1}$ to 500 V cm$^{-1}$ were used to transport the snowballs out of the stopping region. This shows that the snowball efficiencies are different for different species of impurity ions.

The offset in snowball efficiency observed at electric fields lower than about 40 V cm$^{-1}$ may be due to the shielding of the applied electric field by an induced field created by the charge polarization at the ionization region. A similar effect was observed in weakly ionized helium gas (see section 2.4). The main difference between the superfluid and gas cases is the different nature of the electron and ion mobility. The electron mobility in helium gas is several orders of magnitude higher than that of positive ions, whereas in superfluid helium they are very similar (see Sections 2.1, 2.2 and 3.3). Therefore in helium gas even a very small applied electric field will drive the ionized gas into a positive ion cloud. But in superfluid helium the ions and the electrons are removed at roughly the same rate and comparatively higher electric fields are necessary to quench the counter-balancing polarization field.
Both experiment A and B show a temperature independent snowball efficiency at high electric fields (see Figures 6.4a and 6.4b). The average snowball efficiency observed in experiment B is 5 times smaller than that in experiment A. No explanation of this difference is apparent. It may be due to a problem with the recoil source strength determination.

The total efficiency obtained in both experiments A and B shows a similar behavior as a function of temperature. An increase in total efficiency with increasing temperature is observed in both experimental configurations. This indicates that an increase in temperature favors the extraction process as the snowball efficiency is temperature independent. The values of total efficiency $\epsilon_{foil}$ as a function of temperature obtained in experiment A are higher than in experiment B (see Figures 6.5a and 6.5b). This is due to the high snowball efficiency observed in experiment A compared to experiment B.

Figure 6.8 shows the extraction efficiency as a function of inverse temperature from this experiment and the JYFL experiment [57]. $\epsilon_{extr}$ data from both experiment A and B are combined as $\epsilon_{extr}$ is independent of the experimental setup. The trend observed in both experiments is similar. Above $\sim 1.3$ K, $\epsilon_{extr}$ is compatible with the thermally activated crossing of particles across a potential barrier with height $E_b$

$$\epsilon_{extr} \propto e^{-E_b/k_B T}.$$  \hspace{1cm}(6.6)

The fact that $\epsilon_{extr}$ below $\sim 1.3$ K is much larger than the extrapolation of the thermally activated extraction towards lower temperature, points to another mechanism being dominant below $\sim 1.3$ K. The nature of this mechanism is at the moment unknown. The role of quantum tunneling in the extraction can be ruled out due to large mass of the ions as compared to the electron. This mechanism may very well also be present above 1.3 K but it is dominated by the thermal crossing of the barrier. In the absence of evidence to the contrary, we assume this mechanism to be temperature independent with efficiency $\epsilon_0$ and Figure 6.8 shows the best fit of the function

$$\epsilon_{extr} = \epsilon_0 + A exp \left( \frac{-E_b}{k_B T} \right)$$ \hspace{1cm}(6.7)

to the data. $\epsilon_0$ is similar for both experiments, i.e. 0.70(4)% in JYFL work and 0.79(27)% in this work. The function gives a perfect fit for JYFL data because the number of data points is equal to the number of fit parameters. The errors on the fit parameters come from the fact that it is a weighted fit with the experimental errors as weights.

Although the trend observed above $\sim 1.3$ K in both experiments is compatible with the thermally activated crossing of particles across a potential barrier (see Section 3.6.2), there is quite some difference in $\epsilon_{extr}$ and $E_b$. The reason for this is not clear; over-estimation of transport losses in the analysis of the JYFL experiment may be part of the answer. Given the quality of the temperature sensors used, an inaccuracy in temperature measurement can not explain the difference.
No theoretical model has yet been developed which adequately describes positive ion extraction across the superfluid-vapor interface. The most realistic model for the potential energy barrier was proposed by Stern [103]. According to this model the image charge potential barrier experienced by a unit charge at the superfluid-vapor interface is about 300 K. This is about 15 times higher than our measured result (taking an average barrier height from the data sets shown in Figure 6.8 to be 20 K). This difference may arise from the fact that Stern’s model lacks some important physical features of the real situation. Most important is the density profile at the superfluid-vapor interface assumed in the calculation. The width of the interface used in Stern’s calculation is 0.68 nm and the experimentally measured value by Lurio et al. is 0.92(10) nm [71]. For the density variation across the interface, Stern considers a linearly graded transition and sinusoidally rounded corners. A later experimental study by Lurio et al. [70, 71] showed that the actual rate of density change at the superfluid side of the interface is much slower than sinusoidal (see Figure 3.15). Stern’s calculation for a Si - SiO$_2$ interface in the same paper [103] showed that the resulting barrier height strongly depends on the density variation rate. Thus for a more realistic image charge potential barrier calculation one should include the density profile obtained by Lurio et al. If we believe that the potential barrier present is purely of image charge character, there should be no change in barrier height with respect to temperature because the permittivity of the superfluid helium has a temperature dependence of only about $10^{-3} \text{K}^{-1}$. One more important aspect that is missing in Stern’s model is the actual size and structure of the charge carrier. Stern considered a point charge for his calculation, however in reality the size of the snowball is comparable to the width of the interface. We consider it likely that a snowball will deform the liquid helium surface as it comes close enough. Given the fact that image charge potential is very sensitive to the surface density profile, such deformation is expected to have an influence on the image charge potential barrier and thus influence the extraction process. A detailed theoretical study is necessary to understand the mechanism of positive ion extraction across the superfluid-vapor interface.

6.2 Second sound assisted superfluid surface evaporation

Second sound is a quantum mechanical phenomenon exclusively known from the superfluid phase. It is a heat transfer mechanism by an entropy (or temperature) wave (see Chapter 3). A single second sound pulse can maintain an extremely sharp wavefront in temperature rise. T. Furukawa et al. [47] reported transient evaporation of helium at the superfluid helium surface if a second sound thermal pulse impinges onto the superfluid-vapor interface. This result triggered interest to investigate the possibilities to use this phenomenon to release the ions trapped below the superfluid helium surface.
6.2 Second sound assisted superfluid surface evaporation

6.2.1 Experimental setup

In an ion catcher device ions are continuously accumulated below the superfluid surface in a potential well, which is formed by the image charge potential and an external electric field normal to the interface. Above a temperature of about 1.6 K, an extraction efficiency of 10-20% is achieved due to thermal excitation of trapped ions. The new idea is to enhance the extraction efficiency in the present setup by evaporating the superfluid helium layer containing the trapped ions and thus release them to the vapor phase. Having second sound pulses at a high enough repetition rate might also reduce the average delay time due to the thermal crossing of the barrier. The second sound thus acts as a pulsed heat source for evaporation. A heat pulse is generated by resistive heating of a planar thin-film heater surrounding the radioactive source. This heat pulse evolves into a shock wavefront and propagates upwards in the superfluid helium and impinges on the surface. The only modification in the experimental setup (see section 6.1) is the addition of a heater to produce second sound pulses (see Figure 6.9). A nickel-chromium thin-film acts as heater to generate second-sound waves. Nickel-chromium was chosen because of its constant electric resistance down to superfluid helium temperatures. The thin-film heater is prepared at the KVI target laboratory by evaporative deposition of nickel-chromium on an annular quartz plate of 27 mm outer diameter, 7 mm inner diameter and 1 mm thickness which has a narrow radial gap. The film is deposited with a uniform thickness across the quartz substrate. A narrow copper thin-film

Figure 6.9: (a) Schematic side view of the bottom electrode incorporated with the second sound heater and top view of the second sound heater. (b) Photograph of the bottom electrode incorporated with the second sound heater from the top.
Figure 6.10: Net evaporation mass flux as a function of the temperature variation $\Delta T_W$ at the second sound wave front for the bulk helium temperatures 1.74 K and 2.04 K (from [47]).

strip is deposited on the nickel chromium edge along the radial gap to provide a uniform electrical contact. The thickness of the deposition is adjusted to obtain a resistance of about 100 $\Omega$ across the copper electrical contacts. The thin-film heater is placed at the same height as the $^{223}$Ra source. The second sound heater is kept at the same electric potential as the source and the bottom electrode, which all are connected in series. In order to create a second sound pulse, the bias voltage of one of the thin-film heater contacts is pulsed with a rectangular voltage pulse from a floating power supply. The resulting current pulse creates a heat pulse with the same width and period as the driving voltage pulse. Its amplitude is proportional to the voltage amplitude. The generated second sound pulse travels along the ion transport trajectory. A pulse width of at least an order of magnitude less than the pulse period is used to avoid any significant effect on the ion transport. A pulse height of 150 V and a pulse width of 10 $\mu$s were chosen for all the measurements at 1.6 K and 1.15 K. The energy produced per pulse is 2.25 mJ. The heat input into the cell by the second sound pulse could be observed by a drop in the temperature controller heater power output. The power input by second sound pulses and the drop in temperature controller heater power are in agreement within about 10%, giving confidence in the proper operation of the second sound heater.

From the experimental results of Furukawa et al. [47] it is possible to calculate the thickness of the superfluid helium surface layer evaporated by a second sound
6.2 Second sound assisted superfluid surface evaporation

The heating of the nickel chromium heater creates a thermal pulse with a temperature amplitude $\Delta T_i$ given by linear acoustic theory as

$$\Delta T_i = \frac{q}{\rho_0 L C_{ss} c_p},$$  \hspace{1cm} (6.8)

where $q$ is the peak value of the heat flux supplied by the nickel chromium-heater, $\rho_0$, $L$, and $c_p$ are the density and the heat capacity of superfluid helium and $C_{ss}$ is the velocity of the second sound at the corresponding helium temperature $T$ (see Figure 3.4). The heat flux $q$ (W cm$^{-2}$) is given by

$$q = \frac{V_p^2}{A_h R_h},$$ \hspace{1cm} (6.9)

where $V_p$ is the amplitude of the voltage pulse and $R_h$ and $A_h$ are the resistance and area of the nickel-chromium heater. The thermal pulse emitted by the heater travels upwards and impinges onto the superfluid surface. The thermal pulse is partially reflected. The resulting temperature variation is given by

$$\Delta T_W = \Delta T_i + \Delta T_r,$$ \hspace{1cm} (6.10)

where $\Delta T_i$ and $\Delta T_r$ are the temperature rise at the impinging and reflected wave fronts. The reflection coefficient of a thermal pulse at normal incidence $R_{22} = \Delta T_r / \Delta T_i$ was measured by Murakami et al. [77] as 0.8. For superfluid helium $R_{22}$ is a temperature independent quantity [77]. Thus the $\Delta T_W$ can be expressed as $1.8 \Delta T_i$.

In this experiment the temperature rise at the superfluid surface at the incidence of the second sound pulse can be calculated and is about 125 mK and about 900 mK for 1.6 K and 1.15 K respectively. Figure 6.10 [47] shows the net evaporation mass flux as a function of the temperature variation $\Delta T_W$ at the second sound wave front for bulk helium temperatures of 1.74 K and of 2.04 K. The net evaporation mass flux is the mass of the superfluid helium evaporated from unit area of superfluid surface per second. The thickness of the superfluid surface layer evaporated by the heat pulse used in this experiment is larger than 100 nm, which should be sufficient to evaporate the surface layer containing the trapped ions.

6.2.2 Results

Contrary to expectation, the evaporation of the superfluid helium surface by second sound gave no enhancement but rather a negative effect on the extraction efficiency. Figure 6.11 shows the extraction efficiencies at 1.60 K and 1.15 K as a function of second sound pulse period. At long pulse periods the extraction efficiency remains the same as that obtained in measurements without second sound pulses. The extraction efficiency shows an exponential fall-off with decreasing pulse period. Figure 6.12 shows the snowball efficiency at 1.60 K and 1.15 K as a function of second sound pulse period. No significant change in the snowball efficiency as a function of second sound pulse period is observed.
Figure 6.11: Extraction efficiency $\epsilon_{\text{extr}}$ as a function of second sound pulse period $P_{ss}$ for the temperatures 1.15 K and 1.60 K. The lines represent a fit with an exponential plus a constant.

Figure 6.12: Snowball efficiency $\epsilon_{\text{sb}}$ as a function of second sound pulse period $P_{ss}$ for the temperatures 1.15 and 1.60 K. Rather similar and constant snowball efficiencies are obtained at 1.60 K and 1.15 K.
6.2.3 Discussion

Figure 6.11 shows the extraction efficiency as a function of the second sound pulse period. The extraction efficiency decreases with decreasing pulse period; for large pulse periods, the extraction efficiency saturates at the value measured without second sound pulses. Data points without second sound pulses are from experiment A (see section 6.1.2). Once the second sound pulse hits the superfluid helium surface the extraction process is apparently disturbed, and it recovers during the time gap between the pulses. Figure 6.11 shows the best fit of the function

$$
\epsilon_{\text{extr}}^{ss} = \epsilon_{\text{extr}}^0 - Ae^{-P_{ss}/\tau},
$$

(6.11)
to the data, where $\epsilon_{\text{extr}}^{ss}$ is the extraction efficiency with second sound pulsing, $\epsilon_{\text{extr}}^0$ is the extraction efficiency in the absence of second sound pulsing, $P_{ss}$ is the second sound pulse period and $\tau$ is the “recovery time” of the extraction after the creation of a second sound pulse. The recovery times $\tau$ for the measurements at 1.60 and 1.15 K are 3.2(6) s and 15(6) s respectively, and the extraction efficiencies $\epsilon_{\text{extr}}^0$ are 1.7(1) and 0.73(14)% respectively.

Figure 6.12 shows the snowball efficiency $\epsilon_{\text{sb}}^{ss}$ at 1.6 and 1.15 K as a function of the second sound pulse period. No considerable difference in the snowball efficiencies between the 1.6 and 1.15 K data is observed. The snowball efficiency rather remains constant with respect to the second sound pulse period. This indicates that the number of ions trapped below the surface layer remains constant regardless of the destruction of the extraction efficiency. This result also seems to indicate that the trapped ions move downwards follow the superfluid surface during the evaporation.

No explanation for the observed destruction of extraction phenomenon is yet available as the physical processes involved are unknown. A detailed theoretical study is necessary to help understand the results. One may speculate that snowballs attach themselves to vortices created by the second sound pulse. It is known that second sound pulses create quantum turbulence (see e.g. [55]), which in a simple picture is represented as a tangle of vortex lines (see [123] for a review on quantum turbulence). It is well-known that snowballs attach themselves to vortices [18] and under certain conditions, quantum turbulence has a long decay time (e.g. Milliken et al. measure a decay time of 1.7 s at 1.45 K [74]). The assumption that $^{219}$Rn snowballs attach themselves to vortices created by the second sound pulse and as while being attached cannot be extracted from superfluid helium together with a long turbulence decay time can explain our experimental observations.

6.3 Conclusion

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
the saturation depends strongly on the ionization density. The saturation value of
the snowball efficiency is independent of the superfluid helium temperature.

The exponential increase in the extraction efficiency of positive ions across the
superfluid-vapor interface with increasing temperature indicates that the extraction
is a thermally activated process. Our data between 1.4 and 1.8 K yield a potential
barrier of about 20 K. The extraction efficiency below about 1.3 K is much larger than
the extrapolation of thermally activated extraction and points to another mechanism
being dominant below 1.3 K. This mechanism may very well also be present above
1.3 K but it is dominated by the thermal crossing of the barrier. It is interesting
to note that the extraction efficiency below 1.3 K is quite similar in all experiments
(0.5-0.8%).

The evaporation of the superfluid surface by second sound heat pulses has a
lasting negative impact on the ion extraction efficiency. It takes $3.2(6)$ s at 1.60 K
and $15(6)$ s at 1.15 K for the extraction process to recover from a disturbed state of
yet unknown nature. One may speculate the trapping of ions in the vortex tangle
created by the second sound induced turbulence.