Positive ion extraction across the superfluid-vapor helium interface

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Abstract. The extraction efficiency of positive ²¹⁹Rn ions across the superfluid-vapor helium interface above ~1.3 K indicates that extraction results from thermal activation across a barrier of about 20 K. Below ~1.3 K, the extraction efficiency is constant at about 0.7%. The evaporation of the superfluid surface by second sound pulses has a negative impact on the ion extraction, but not on the ions themselves. 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.

1. Introduction

A variety of scientific disciplines makes use of radioactive isotopes in the form of a low-energy ion beam or an ion or atom cloud in a trap. So-called in-flight radioactive ion beam facilities produce and select isotopes at high energy, making fast and efficient ion catcher techniques to transform high-energy ions into low-energy ones essential. The extremely high ion energies (up to several 100 MeV per nucleon) at planned facilities cause problems for the standard ion catcher technique using noble gases as stopping medium. Due to its much higher density combined with high ion mobility, superfluid (SF) helium is an attractive alternative for an efficient stopping medium allowing fast ion extraction.

A series of experiments, involving some of the present authors, was carried out at the Physics Department of the University of Jyväskylä (JYFL), Finland in 2001-2002 [1]. Among the reported results was the first observation of the extraction of positive ions (²¹⁹Rn ions were used) across the SF helium surface. The extraction efficiency vs. temperature was compatible with the thermal crossing of a barrier of 20(5) K. Earlier experiments did not show any extraction of positive helium ions [2]. The experiments described here aim towards a better understanding of the ion extraction at the superfluid-vapor interface. T. Furukawa et al. report transient evaporation of helium at the SF helium surface if a second sound thermal pulse impinges onto the superfluid-vapor interface [3]. This result led us to additionally investigate the possibility to use this phenomenon to release ions trapped below the SF helium surface by evaporating the SF helium layer containing the trapped ions and thus release them to the vapor phase. More details on the work presented here can be found in [4].
2. Experimental setup

The experimental set-up used in this work is very similar to that used in [1]. An experimental cell is attached to the 1 K pot of a helium bath-cryostat. After cooling down the experimental cell to superfluid temperature, a known amount of helium gas is let in via a capillary and condenses, allowing to control the SF helium level with an accuracy of $\sim 0.5$ mm. In the experiments described here the $^{223}$Ra source was covered by 6 mm of liquid helium. A temperature range from 1.15 to 1.8 K was investigated. Figure 1 shows the inside structure of the experimental cell. An open $^{223}$Ra source is mounted at the bottom. The $\alpha$-decay of $^{223}$Ra gives $^{219}$Rn ions recoiling with an energy of $\sim 100$ keV into the SF helium. A fraction of the recoil ions is neutralized due to charge-exchange processes during slowing down and thermalization; those surviving as ions will form a snowball complex. An electric field is applied to (1) pull apart the ions and electrons, thus, for a high enough field, preventing neutralisation of the thermalized $^{219}$Rn ions; (2) transporting the ions to the superfluid-vapor interface. The electric field was designed with a small radially focusing component at the SF helium surface in order to achieve radial confinement of the ions. The snowball efficiency $\epsilon_{sb}$ is defined as the fraction of $^{219}$Rn recoil ions from the source that reach the superfluid-vapor interface. The extraction efficiency $\epsilon_{extr}$ is defined as the fraction of $^{219}$Rn ions reaching the interface that are extracted into the vapor phase. The extracted ions are transported with 100% efficiency onto a thin aluminum catcher foil.

\[ \text{Figure 1. Cut-away view of the inside structure of the experimental cell. Decreasing voltages on the bottom electrode/source, guiding electrodes and catcher foil create the electric field that transports ions from close to the source onto the catcher foil. (Inset) Top view of the annular second sound heater.} \]

$^{219}$Rn $\alpha$-decays to $^{215}$Po with a half-life of 3.96 s. Behind the catcher foil sits a silicon detector, operated as $\alpha$-energy spectrometer, detecting the alpha particles from the $^{219}$Rn decay. $\alpha$-particles originate from the decay of $^{219}$Rn at two locations: the superfluid-vapor interface and the aluminum foil. Due to the additional energy loss in the vapor between the interface and the foil, the $\alpha$’s from the interface are detected with a lower energy and can thus be distinguished from the $\alpha$’s from the foil. From the intensity of the $^{219}$Rn $\alpha$-lines from these two locations, we determine the fraction of $^{219}$Rn recoil ions from the source that decay on the aluminum foil ($\epsilon_{foil}$) and the fraction that decays at the surface ($\epsilon_{surf}$). The absence of electrons at the interface leads us to assume that $^{219}$Rn ions at the interface do not neutralise and drift away from the surface;
they are either extracted or decay at the interface. The snowball and extraction efficiencies are determined as $\epsilon_{sb} = \epsilon_{surf} + \epsilon_{foil}$ and $\epsilon_{extr} = \epsilon_{foil}/\epsilon_{sb}$

For the experiments involving pulsed second sound, the $^{223}$Ra source is surrounded by an annular nickel-chromium thin-film heater (Fig. 1), prepared by evaporative deposition of nickel-chromium on an annular quartz plate with a narrow radial gap. A narrow copper thin-film strip is deposited on top of the nickel-chromium at the edge of the radial gap to provide uniform electric contacts. The thickness of the deposition is adjusted to obtain a heater resistance of 50 to 100 $\Omega$. The second sound heater is kept at the same electric potential as the source and the bottom electrode, which are all connected in series. A second sound pulse is created by applying a rectangular voltage pulse to one of the thin-film heater contacts. The resulting current pulse creates a heat pulse with the same width and period as the driving voltage pulse and an amplitude proportional to the voltage amplitude. This heat pulse sends a second sound pulse propagating upwards towards the SF helium surface. A pulse width of at least an order of magnitude less than the pulse period is used to avoid any significant average effect on the ion transport.

3. Results and discussions
For high enough electric fields, the snowball efficiency $\epsilon_{sb}$ reaches a saturation value. A compilation of various measurements at the experimentally highest possible field of 180 V cm$^{-1}$ shows a temperature independent value of about 6% between 1.15 and 1.6 K. Fig. 2 shows the extraction efficiency as a function of inverse temperature from this experiment and the JYFL experiment [1]. 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 $E_b$: $\epsilon_{extr} \propto e^{-E_b/k_BT}$. 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; one possible explanation might be quantum tunneling of the ions. In the absence of evidence to the contrary, we assume this mechanism to be temperature independent (with efficiency $\epsilon_0$) and fit the data to the following function $\epsilon_{extr} = \epsilon_0 + Ae^{-E_b/k_BT}$ (the fits and parameters are given in Fig. 2). $\epsilon_0$ is similar for both experiments: 0.5 and 0.8%. Above $\sim 1.3$ K, there is quite some difference in $\epsilon_{extr}$ and $E_b$ between the two experiments. 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. The most realistic calculation for

![Figure 3. Extraction efficiency $\epsilon^{ss}_{extr}$ as a function of second sound pulse period $P_{ss}$](image)

the potential energy barrier experienced by a unit charge at the superfluid-vapor interface was presented by Stern [5] who calculated the image charge barrier using a density variation across the interface that is a reasonable approximation to the one measured by Lurio et al. [6]. The resulting barrier of about 300 K is 15 times higher than our measured result. Stern’s calculation for a $Si - SiO_2$ interface in the same paper [5] shows that the barrier height strongly depends on the details of the density profile. A more realistic image charge barrier calculation would thus result from including the density profile from [6]. Also, Stern considers a point charge; but as the snowball size is comparable to the width of the interface, the size and structure of the snowball may play an important role. Further theoretical study of a snowball being pushed against the superfluid-vapor interface is necessary to understand the mechanism of positive ion extraction.
The effect of pulsed second sound on the extraction of ions was investigated at 1.15 and 1.6 K. A voltage pulse with amplitude 150 V and width 10 µs was applied to the second sound heater. From the results of Furukawa et al. [3] we estimate that the thickness of the superfluid surface layer evaporated by the second sound pulse is larger than 100 nm, larger than the depth at which ions are trapped below the surface.

Contrary to expectation, the evaporation of the SF helium surface by second sound gave no enhancement but rather a negative effect on the extraction efficiency. Fig. 3 shows $\epsilon_{\text{extr}}$ as function of the second sound pulse period. At long pulse periods, $\epsilon_{\text{extr}}$ is the same as that obtained without second sound pulses; for decreasing period, $\epsilon_{\text{extr}}$ drops. At both 1.15 and 1.6 K, the snowball efficiency is constant at 5.0-5.5% as a function of second sound pulse period; indicating a constant number of ions trapped below the surface layer. Apparently, a second sound pulse hitting the SF helium surface disturbs the extraction process and it takes a certain time to recover. Fig. 3 shows the fit of the function $\epsilon_{\text{extr}}^s = \epsilon_{\text{extr}}^0 - Ae^{-P_{SS}/\tau}$ to the data, where $\epsilon_{\text{extr}}^s$ is the extraction efficiency with pulsed second sound, $\epsilon_{\text{extr}}^0$ is the extraction efficiency in the absence of pulsed second sound, $P_{SS}$ 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 $\tau$ at 1.60 and 1.15 K are 15(6) and 3.2(6) s respectively. The extraction efficiencies $\epsilon_{\text{extr}}^0$ of 1.7(1)% at 1.60 K and 0.73(14)% at 1.15 K are compatible with the results shown in Fig. 2. Our result seem to indicate that the trapped ions move downwards with the superfluid surface during the evaporation. A detailed study of the conditions for applying pulsed second sound is necessary to help understand the results and give information on the physical processes involved.

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