RIASH

Radioactive Ions and Atoms in Superfluid Helium

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Introduction

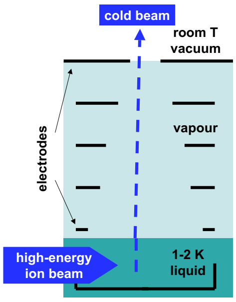
The RIASH project investigates several issues related to radioactive ions and atoms in superfluid helium.

The use of superfluid helium to stop high-energy radioactive ions and extract them as a **cold ion beam** will be developed. The use of superfluid helium as a storage medium for ions and atoms will be investigated. Here one can think of either studying the ions or atoms or the superfluid state. Adding muons to the mix in order to create **radioactive muonic atoms** will be looked at as well.

Cold radioactive ion beams from superfluid helium

Precision studies of exotic nuclei far from stability, such as high-resolution particle decay spectroscopy, and studies in traps, need low-energy beams, typically of a few tens of keV and of energy spread of the order of 1 eV. These beams are also required for the acceleration of radioactive ions in the next-generation Radioactive Ion Beam (RIB) facilities, which are considered of very high priority around the world. Unfortunately, exotic nuclei often emerge as a high-energy beam from nuclear reactions with unavoidably large emittance and energy spread. In order to go from a high-energy, poor quality to a low-energy, high-quality ion beam, the IGISOL (Ion Guide Isotope Separator On-Line) method [1,2] is being extended for use at high-energy fragmentation facilities [3–6]. However, the required long stopping length (0.5–2.0 m) and high pressure (0.5–2.0 bar) of the helium-gas–filled cell make the electric-field guidance of the ions an essential but non-trivial task.

The RIASH project plans to develop the use superfluid helium instead of helium gas for stopping high-energy radioactive ions and extracting them as a cold ion beam. The main benefit is the 800 times larger density, allowing a much smaller stopping volume and resulting in simpler ion transport.



Schematic view of the production of cold radioactive ion beams using superfluid helium. High-energy ions are stopped in superfluid helium. A sizeable fraction can survive as ions (snowballs) and be transported by means of electric fields across the liquid surface, through the vapour region to a room-temperature, high-vacuum environment.

Proof-of-principle experiments

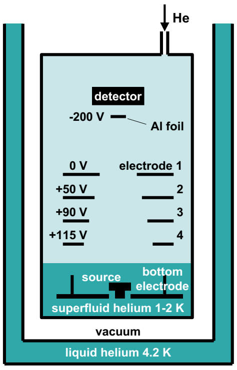
From 2001 to 2003, we performed proof-of-principle experiments at the University of Jyväskylä. As a substitute for a high-energy radioactive ion beam, we used alpha-decay daughter nuclei which get an energy of the order of 100 keV in the decay process.

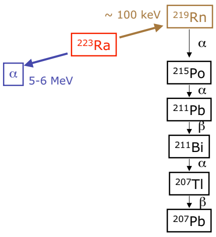
After thermalization in superfluid helium, positive ions will spontaneously form "snowballs": clusters of helium atoms that form around positive ions owing to electrostriction [7]. The formation and fast transport of snowballs in liquid helium have been demonstrated earlier by one of us (N.T.) at Osaka [8–11]. We have concentrated on the extraction of snowballs/ions from the liquid helium into the vapour phase. We observed for the first time ever the extraction of positive ions from the surface of superfluid helium.

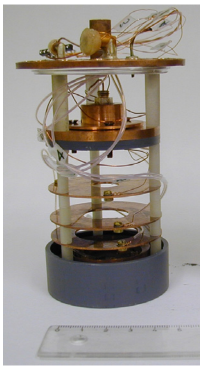
The main results are given here, more information can be found in refs. [12-14].

Experimental set-up

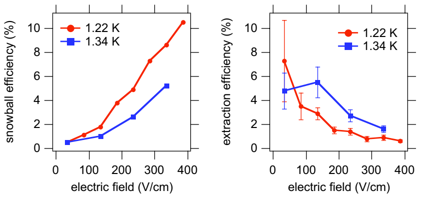
The experimental setup is shown schematically in the left figure, a picture is on the right. An open ^{223}Ra ($T_{1/2}$ = 11.4 days) alpha source with an activity of about 10 kBq is placed at the bottom of the experimental cell. The ^{223}Ra decay chain is shown in the middle. The ^{223}Ra alpha decay product ^{219}Rn, recoiling out of the source with an energy of about 100 keV and stopped within 1 μm of liquid helium, provides the source of thermalized positive ions. The electric field created by four ring electrodes guides the snowballs/ions from the source onto a thin aluminum foil in front of a silicon detector which detects the alpha decay of the transported nuclei. The experimental cell is placed inside a helium evaporation cryostat and cooled down to 1.2 K. Higher temperatures are easily obtained by heating the cell.



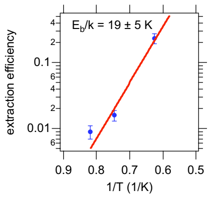




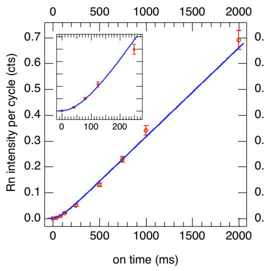
Experimental results



Investigation of the two main factors determining the ***overall efficiency*** *in our measurements. Left: The efficiency that snowballs are formed when ^{219}Rn is created in the alpha decay of ^{223}Ra in superfluid helium. Right: The efficiency to extract ^{219}Rn ions across the superfluid helium surface. These two efficiencies behave in opposite ways as a function of both temperature of and electric field in the superfluid helium. This is understood in terms of the separation of ions and electrons (snowball efficiency) and the barrier at the superfluid surface (extraction efficiency).*



The extraction of positive and negative ions across a free liquid helium surface is inhibited by a ***potential barrier****. For ions under Brownian motion, the extraction efficiency is proportional to exp[-E_b/kT]. We measured the barrier height E_b for positive ions for the first time (with an electric field at the surface of 200 V/cm).*



$$TTD(t) = 0 \quad \text{for } t < t_0$$
$$TTD(t) \propto e^{-(t-t_o)/\tau} \quad \text{for } t \geq t_0$$

The ***transport time distribution*** *TTD(t) for a snowball/ion to travel from the source to the aluminum foil was studied at T = 1.50 K and an electric field in the liquid of 85 V/cm. After a certain "on-time", the source was switched off (by putting it at a lower voltage than the bottom electrode) and the transport was blocked (by raising the voltage on one of the ring electrodes) long enough for all ions to be removed from the liquid and vapour regions. Plotted in the figure is the number of ^{219}Rn ions transported per cycle vs. "on-time". The data can be described by an exponential TTD which starts after an initial minimum transport time. A minimum transport time t_0 of less than a few milliseconds and a mean transport time τ of 90±10 ms are deduced. The observed mean transport time is due to at least two processes: snowball neutralization at the surface and transport across the surface; both of which are slower than 90 ms. This observation shows that ions/snowballs are, indeed, trapped at the surface prior to their extraction.*

Radioactive muonic atoms and nuclear muon capture

Why combine muons with radioactive isotopes ?

The study of muonic atoms has a long history of testing QED vacuum polarisation and of determining nuclear properties and sizes of stable isotopes (see e.g. [15]). Recently, the extension of these methods, in particular the exact measurement of muonic X-ray spectra, to radioactive isotopes has been proposed [16,17]. In general, muonic X-rays promise higher accuracy for most measurements compared to e.g. electron scattering, and are even required for the experimental calibration of electron scattering and laser spectroscopy data [18]. Following the atomic capture of muons, nuclear muon capture occurs with high probability [19]. This nuclear capture is the inverse process to β^- decay and therefore produces exotic nuclei one step further away from stability. It also populates rather high-lying excited states (typically up to 20 MeV) due to the high Q-value of the capture process and thus represents a unique way of producing very exotic nuclei at high excitation energy. Recent work indicates the usefulness in neutrino-less double beta decay [20] and nuclear structure studies [21].

Techniques

Since the capture of muons is of atomic nature, very high sensitivities are expected for combining muons and radioactive isotopes. If proven successful, it would be one of the most important developments in the physics of exotic nuclei. The main technical challenge is to bring the muons and atoms/ions close enough in high enough concentrations in order to form a sufficient amount of muonic atoms/ions. The following techniques have so far been considered: merging beams, ion traps (in vacuum) and solid hydrogen [22].

In the RIASH project, we plan to investigate a new technique: the use of superfluid helium for creating muonic radioactive ions. The underlying idea is to stop both radioactive ions and muons in the same volume of superfluid helium. Concentrating the ions, using electric fields, in the region where the muons are stopped is a way of increasing the formation rate of muonic ions. Very likely, muon capture will proceed via the formation of muonic helium.

References

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