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An RF-only ion-funnel for extraction from high-pressure gases

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ABSTRACT

An RF ion-funnel technique has been developed to extract ions from a high-pressure (10 bar) noble-gas environment into a vacuum (10^{-6} mbar). Detailed simulations have been performed and a prototype has been developed for the purpose of extracting ^{136}Ba ions from Xe gas with high efficiency. With this prototype, ions have been extracted for the first time from high-pressure xenon gas and argon gas. Systematic studies have been carried out and compared to simulations. This demonstration of extraction

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of ions, with mass comparable to that of the gas generating the high-pressure, has applications to Ba tagging from a Xe-gas time-projection chamber for double-beta decay, as well as to the general problem of recovering trace amounts of an ionized element in a heavy ($m > 40$ u) carrier gas.

1. Introduction

Ion extraction from gas environments at pressures $\gtrsim$1 mbar is challenging since collisions dominate ion motion [1]. Conventional mass-spectrometry techniques use a combination of skimmers and orifices to reduce the gas flow across differential pumping stages. Similar ion-extraction techniques are applied in ion source assemblies at radioactive ion beam facilities, e.g. IGISOL LIST [2]. Such techniques achieve low downstream pressures at some cost of efficient ion transport [1,3,4].

Radio-frequency (RF) ion funnels have been developed for ion extraction with increased ion-transmission efficiency; typically, RF funnels extract from air into vacuum and improve ion extraction efficiency by more than an order of magnitude (see [1,5] and references therein). RF funnels have also been developed for ion transport in gas stopper cells [6]. Technical improvements have included blocking the gas jet with a jet disrupter electrode [7] and a DC ion carpet at the exit [8]. Various funnel designs have been realized, including a recent design using electrodes etched on PCBs [9]. Typically, RF funnels are used with electrospray ion sources where gas is injected through a capillary. Capillary inlet pressures reach an atmosphere and pressures inside the funnel reach ~40 mbar. However, owing to the nature of this ion source, such funnels are not optimized for single ion extraction at close to 100% efficiency and require a longitudinal DC potential gradient to transport ions through the funnel, adding complexity and components that can contaminate the vacuum. To overcome these limitations and extend the use of RF-funnels to heavy-mass gases at a high-pressure, an RF-only ion funnel prototype has been developed. It aims to investigate the feasibility of extracting ions from 10 bar Xe gas into a 1 mbar vacuum in only one stage with high efficiency. This prototype realizes a novel concept of ion transport via carrier gas flow instead of via applied DC-drag potentials that was suggested [10] and described in detail [11,12].

The realization and trial of this RF-only funnel is an important step towards its application in the search for neutrinoless (0ν) double-beta ($\beta\beta$) decay in ^{136}Xe. Over the past decades, experiments searching for the lepton-number non-conserving $0\nu\beta\beta$-decay [13] have excluded half lives (at 90% CL) shorter than $T_{1/2}^{0\nu\beta\beta} \gtrsim 10^{25}$ yr (in ^{136}Xe [14–16] and in ^{76}Ge [17]). In order to extend experimental sensitivity, the development of larger detectors with reduced background is required. For the detection of the $0\nu\beta\beta$ decay signal such a detector would ideally have no backgrounds. The identification (Ba-tagging) of the atomic species produced in the decay, ^{136}Ba for $\beta\beta$-decay of ^{136}Xe, would drastically reduce the backgrounds that are dominated by radioactivity unrelated to the production of Ba in the detector. The association of decay energy and event topology to the Ba-tagging technique [18] would allow for the discrimination between the 2-neutrino decay, which produces a continuum spectrum, and the interesting neutrinoless decay, which produces a mono-energetic line at the sum energy of the two electrons.

Among the $\beta\beta$-decay candidates, the possibility of tagging the final atomic state appears to be possible only for the case of ^{136}Xe [18]. The nEXO collaboration is developing a multi-ton $\beta\beta$-decay experiment using liquid ^{136}Xe (LXe); Ba-tagging technology appropriate for LXe is being developed [19,20] for possible use in a second phase of detector operation with sensitivity into the region of the normal hierarchy of neutrino mass [21]. A multi-ton detector using gaseous xenon (GXe) may be appropriate at a later stage to investigate the physics of $0\nu\beta\beta$-decay, should it be discovered by the LXe detector; the relatively low-density gas would allow visualizing the tracks of low energy final state electrons. Such a detector calls for the development of Ba-tagging for gas phase operations [22].

Schematically, tagging of the Ba^{++} daughter from gas xenon will be implemented in the following consecutive steps: (i) The energy deposited and topology of each event is measured to determine whether it has a $\beta\beta$-like signature. (ii) If it does, the electric fields inside the time-projection chamber are modified such that ions from the previously determined decay volume are drifted to an appropriate extraction port where they are flushed out by the Xe gas. (iii) Ions are separated from the Xe gas and guided into vacuum. (iv) Ba^{++} is converted to Ba^{+} by electron exchange (e.g. in triethylethane gas [23]). (v) The ion is captured in a linear Paul trap and is unambiguously identified by means of laser spectroscopy [24]. The main challenge of this Ba-tagging method is the extraction of Ba-ions from a high-pressure Xe environment with near 100% efficiency.

This paper describes the RF-only funnel apparatus built to investigate the extraction of Ba ions from xenon gas for application in Ba tagging and its tests. The new technique is optimized for highly efficient extraction of single ions from an equal-mass carrier gas.

2. Apparatus

A schematic of the system is shown in Fig. 1. It has been optimized in gas dynamic calculations described in Section 3. Ions are created in a high-pressure noble-gas environment at the entrance of a converging-diverging supersonic nozzle. The ions are injected through this nozzle via the supersonic gas flow into the conical cavity of the RF-funnel. RF-voltage confines the ions while the majority of gas escapes and is pumped by a high capacity cryopump. Exiting the RF-funnel ~0.5 ms later, the ions cross into a second differential pumping stage where they are captured by a sextupole ion guide (SPIG). This guide transports the ions to a downstream chamber for detection, currently by a channel electron multiplier (CEM). Details of the individual subsystems follow.

2.1. Vacuum and gas handling system

The vacuum and gas handling systems are designed to ultra-high vacuum (UHV) standards. Only UHV compatible materials (with the exception of O-rings at apertures, in vacuum pumps and along forelines) were used in the funnel and the system, and trapped volumes were vented to avoid virtual leaks. Great effort is taken to avoid contamination of the system that could affect ion extraction or transport. Each part was ultrasonically cleaned for $\gtrsim$15 min each in acetone and then ethanol. A schematic of the gas handling and vacuum setup is shown in Fig. 2. The vacuum system has four chambers: (A) high-pressure chamber with ion source installed at the nozzle entrance, (B) cryopump chamber with RF-funnel