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A setup for Ba-ion extraction from high pressure Xe gas for double-beta decay studies with EXO

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ABSTRACT

An experimental setup is being developed to extract Ba ions from a high-pressure Xe gas environment. It aims to transport Ba ions from 10 bar Xe to vacuum conditions. The setup utilizes a converging–diverging nozzle in combination with a radio-frequency (RF) funnel to move Ba ions into vacuum through the pressure drop of several orders of magnitude. This technique is intended for use in a future multi-ton detector investigating double-beta decay in ^{136}Xe. Efficient extraction and detection of Ba ions, the decay product of ^{136}Xe, would allow for a background-free measurement of the ^{136}Xe double-beta decay.

1. Introduction

Several double-beta ($\beta\beta$) decay experiments are currently trying to determine the nature of neutrinos. An unambiguous observation of the lepton-number violating zero-neutrino $\beta\beta$ decay would require neutrinos to be Majorana particles. Furthermore, if the main contribution to this process is the exchange of light Majorana neutrinos, the effective Majorana neutrino mass can be extracted from the half life of the decay. However, half lives greater than 10^{25} years pose great experimental challenges. In order to reach the sensitivities needed to observe such decays requires a significant increase in detector mass and observation time relative to existing experiments, while minimizing naturally occurring radioactive backgrounds. Conventional detectors are limited by natural backgrounds, thus the reachable sensitivity to the effective Majorana neutrino mass scales as $(Nt)^{-1/4}$ where N is the number of mother nuclei and t is the observation time. In the case of a background-free experiment this situation is improved and the sensitivity scales as $(Nt)^{-1/2}$ [1]. Of all the isotopes under consideration for $\beta\beta$-decay studies, ^{136}Xe is the only one that allows one to tag, i.e., extract from the volume and identify, the daughter of the decay immediately after the decay occurred [2]:

$$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}^{++} + 2e^- + (2 \text{ or } 0)\ \bar{\nu}_e. \quad (1)$$

A positive identification of the decay product ^{136}Ba^{++} allows differentiation between $\beta\beta$ decays and natural background and hence a background-free measurement.

EXO-200, one of the experiments investigating the $\beta\beta$ decay of ^{136}Xe, was the first to determine the half life of $2\nu\beta\beta$ [3] and later published a limit for the half life of $0\nu\beta\beta$ in ^{136}Xe [4]. In parallel to the operation of EXO-200 the collaboration is developing techniques to tag Ba ions in both liquid and gaseous Xe (gXe). This work presents the concept and status of Ba-tagging endeavors in gXe, focusing on the extraction of Ba ions from a high-pressure Xe environment.

The general multi-ton gXe detector concept consists of a time-projection chamber (TPC) operated at 10 bar enriched ^{136}Xe. This records the energy and the position of events occurring in the active detector volume by conventional TPC techniques. When an event occurs within an energy window around $Q_{\beta\beta}(^{136}\mathrm{Xe})$, the electric field inside the TPC is modified to move ions from the decay volume to an exit port, where they are flushed out of the TPC in a continuous flow of Xe gas. This Xe gas, carrying the extracted ions, is injected into a RF funnel through a converging–diverging nozzle. In the RF funnel, Xe gas is removed through spaces in the

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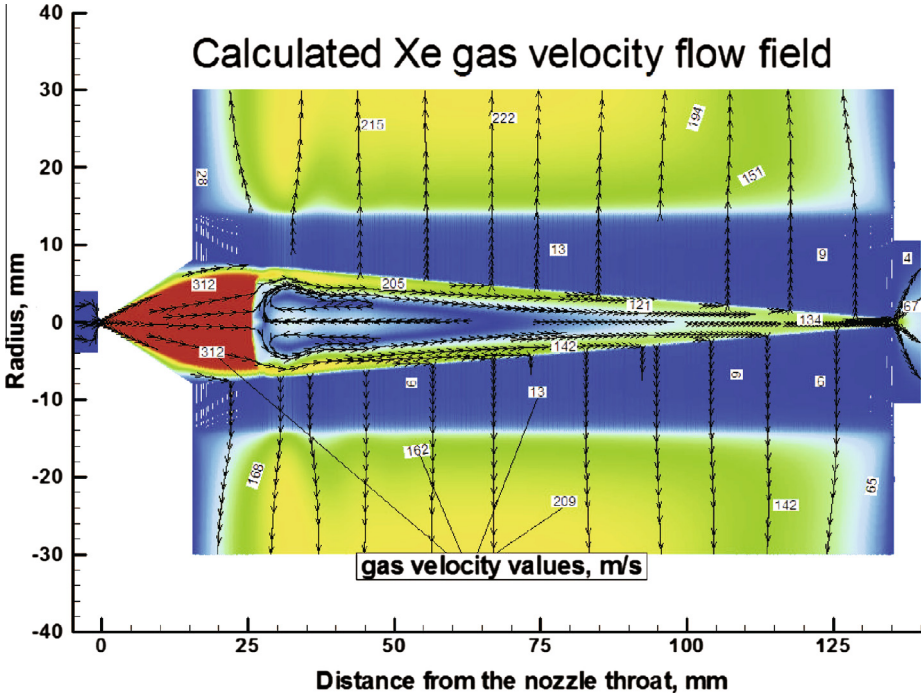

Fig. 1. Calculated Xe-gas velocity flow field of the converging–diverging nozzle in combination with the electrode stack.

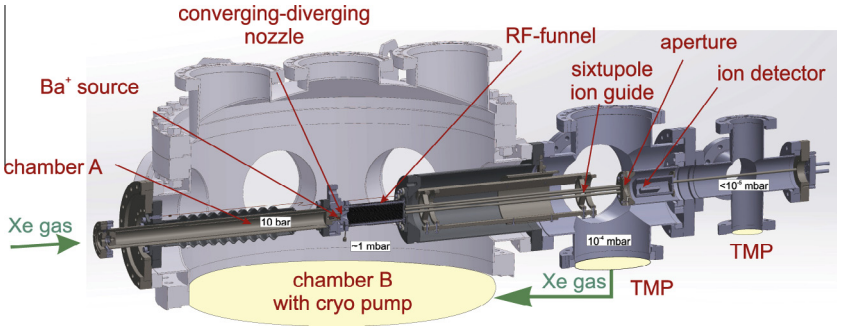

Fig. 2. Section view of Stanford's gXe setup. Xe gas is injected from the left through the supersonic nozzle. The RF funnel is placed in the center of the chamber. Downstream of the funnel the ions are guided through a differential pumping region before they are detected by an ion detector. Xe gas from this region is compressed back to chamber B by turbo-molecular pumps (TMPs).

Fig. 3. Photo of electrode #295 (Quarter for scale). The electrodes were photo-etched in a stainless-steel sheet and numbered individually. Prior to assembly, the electrode was held in place by 'legs' extending from the three equally spaced latches used to mount the electrode. During assembly these legs are cut off.

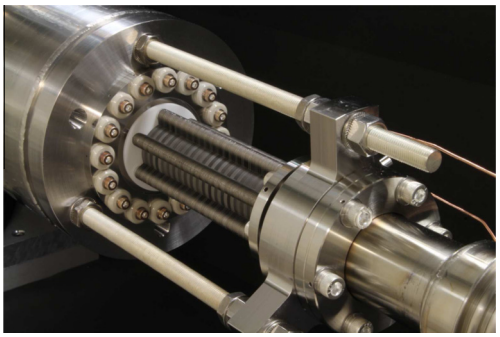

Fig. 4. Photo of the RF funnel installed in its final configuration. The high-pressure Xe will be injected from the right side, pass through the nozzle, then the RF funnel, and proceed into the vacuum chamber on the left, where the downstream ion guide will be installed.

funnel's electrode stack while Ba ions are confined by the applied RF field. Following the RF funnel, Ba ions are transported to a downstream chamber filled with triethylamine (TEA). There, Ba^{++} is converted to Ba^{+} [5]. After the charge exchange process, the Ba ions are captured in a linear Paul trap [6] where they are identified by means of laser spectroscopy [7].

2. Ba^+ extraction from Xe gas – a prototype

At Stanford a setup has been developed to operate a 10 bar natural Xe-gas jet with the ability to recycle Xe gas. The setup consists of a 10 bar Xe chamber (denoted chamber A) connected to a second vacuum chamber (denoted chamber B) through a nozzle. The latter vessel has a diameter of about 603 mm and a cryo pump mounted in it. During gas-jet operation, Xe freezes to the cryo pump. At gas flow rates of 0.5 g/s, a base pressure in the mbar range is present in the chamber B. At this flow rate 1.5 kg of Xe allows jet operation at 10 bar stagnation pressure in chamber A for more than 30 min. Afterwards, the Xe-gas storage bottles are submerged in LN_2 while the cryo pump is warmed up. The Xe gas condenses in the gas storage bottles for reuse. A SAES purifier installed in the Xe supply line cleans contaminants from the Xe gas each time the gas jet is operated.

2.1. Concept of an RF funnel

An ion beam extraction system for gas cells based on the RF funnel has been suggested in 2001 [8]. The operation of this system is described in detail elsewhere (see e.g. Refs. [9,10]). The RF-only ion funnel device, which consists of 301 stacked electrodes, is placed on the converging–diverging nozzle axis in the immediate vicinity of the nozzle exit plane. Ba ions are injected into the funnel via the supersonic Xe-gas jet. RF voltage is applied with alternating phases delivered to neighboring electrodes. This funnel works as a very good gas filter. The majority of the Xe gas is evacuated through the gaps between funnel electrodes by pumping while the Ba ions are confined by the repelling force, directed axially inwards near the inner surfaces of funnel electrodes, that the RF field generates. At the same time, the Xe-gas flow inside the funnel is strong enough to rapidly and very efficiently transport the Ba ions through the funnel into high vacuum conditions, eliminating the need for an additional electro-static drag potential. The funnel geometry has been optimized in Monte-Carlo simulations for operation in Stanford's Xe-gas recirculation setup, described above. A simulated gas flow map is presented in Fig. 1. At an RF frequency of $f = 2.6$ MHz and an amplitude of $V_{PP} = 50$ V the simulated transport efficiency is 72.0(7)%. Higher frequencies and amplitudes show simulated efficiencies of greater than 95%.

2.2. The RF funnel

Based on the RF-funnel simulations a mechanical setup that mounts inside chamber B has been designed and built. A section view of a model of the setup is presented in Fig. 2. The RF funnel is placed at the center of chamber B, above the cryo pump. Xe gas is injected through the nozzle that is mounted on the high pressure chamber A. Downstream of the funnel an ion guide transports the ions through a differential pumping section before they are detected with an ion detector: this is an intermediate step to test the performance of the funnel.

The converging–diverging nozzle was machined in a special CF2.75″ flange through electrode-spark discharge machining.[2] The subsonic and supersonic part half-angles are 45° and 26.6°, respectively. The subsonic and supersonic part lengths are 0.5 mm and 15.5 mm, respectively. The throat diameter is 0.3 mm and the exit diameter is 16.0 mm.

The 301 funnel electrodes were photo-etched[3] with manufacturing tolerances better than 0.025 mm [11] in a 0.1016 (±0.0025) mm thick stainless steel sheet.[4] The outer diameter of each ring electrode is 28 mm. Each electrode has an aperture etched at the center. The aperture diameter decreases from 16.0 mm to 1 mm in steps of 0.05 mm per electrode. Three mounting latches with holes are equally spaced on the electrode. Each electrode has its number etched in it to simplify the assembly process. A picture of electrode # 295 is shown in Fig. 3. The electrodes were held in place in the metal sheet by three small 'legs'. During the installation these legs were cut close to the electrode.

The electrodes were stacked alternating between two sets of three mounting rods. Both sets are electrically insulated. Within each stack the electrodes are spaced by 0.6096(+0.0051/−0.0102) mm thick stainless steel spacers[5] that were photo-etched. This results in a distance of 0.25 mm between the faces of two neighboring electrodes in the stack. The RF funnel stack was fixed to the nozzle, which was then mounted on the downstream vacuum chamber by three 3/8″ threaded rods. The funnel was mounted so that the exit aperture of the funnel is concentric with the entrance hole of the downstream vacuum chamber. The distance between electrode #301 and downstream vacuum chamber is 0.2334 mm. A picture of chamber A, nozzle and funnel mounted on the downstream chamber is presented in Fig. 4. The capacitance of this assembly installed in chamber B is 6.052 nF, resulting in a resonance frequency close to 2.6 MHz. At this frequency amplitudes up to 80 V_{PP} were successfully applied to the funnel. These measurements were taken in vacuum. In an initial test of RF funnel and vacuum system, chamber A was filled with 10 bar gXe resulting in a gas jet on the funnel. The Xe gas flow rate of 0.33 g/s resulted in a pressure of $3 \cdot 10^{-3}$ mbar in chamber B. At 2.6 MHz voltages of up to 80 V_{PP} were successfully applied. Afterwards Xe was successfully recovered.

3. Outlook

An RF-funnel setup to extract $Ba^{+(+)}$ from a 10 bar Xe gas jet is currently being designed and constructed. The RF-funnel is fully assembled and installed inside chamber B. A Gd driven Ba-ion source [12] is currently being fabricated. This source will be placed right at the nozzle as shown in Fig. 2. For the downstream ion guide a sextupole-ion guide is being constructed. The geometry of this guide has been optimized in SimIon simulations [13]. First ion extractions are planned for summer 2013.

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