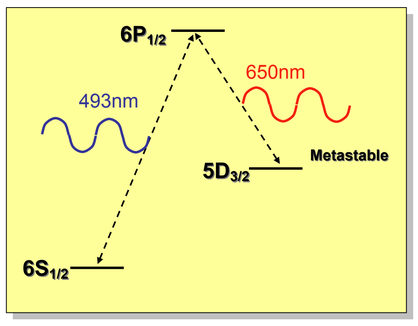
Development of a Barium Tagging System for Enriched Xenon Observatory (EXO)

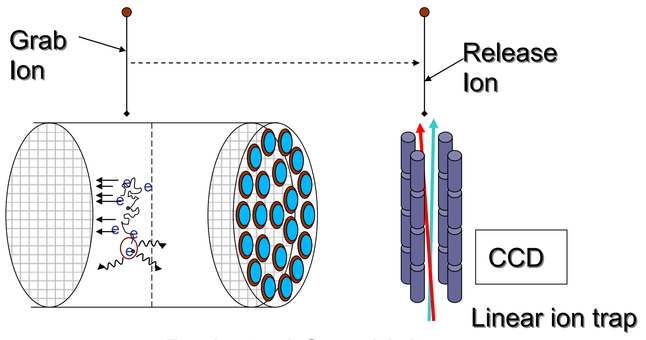
Kevin O'Sullivan, Liang Yang, Tim Daniels and Michelle Dolinski for EXO collaboration

Background rejection by final state identification

Abstract

The goal of the Enriched Xenon Observatory is to build a tonne scale Xenon time projection chamber to search for the neutrinoless double beta decay of ^{136}Xe. The daughter particle of this decay is a $^{136}Ba^{++}$ which could in theory be extracted from the detector. Single ion spectroscopy is a well known technique in atomic physics and is based around cycling the ion through its excited states using lasers of the appropriate frequencies and looking for the fluorescence. Various methods for ion transfer and detection are discussed. The implementation of such a system into a large detector could result in a drastic background reduction with the potential to probe for $<m_{\beta\beta}>$ down to the 10meV scale.





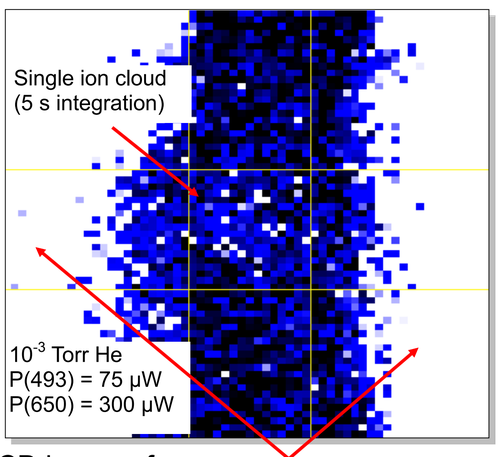
An energy level structure for barium is shown above. There is a 493nm transition to the $6P_{1/2}$ excited state which can decay to a $5D_{3/2}$ metastable state, which implies the need to pump both transition and this produces blue fluorescence. Because the laser frequencies are unique to barium, seeing the fluorescence positively identifies the ion as barium. Ions can be trapped in a radiofrequency Paul trap in a buffer gas and the fluorescence is detected using an electron multiplied CCD camera. Below is such an image and a fluorescence trace with time.

M. Green, et al. Phys. Rev. A 76 023404 (2007)

Projected Sensitivity

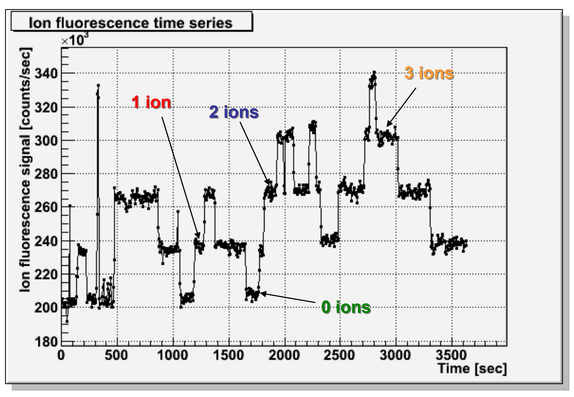
Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu}$ (yr, 90% CL)	Majorana mass (meV) QRPA[1]	Majorana mass (meV) NSM[2]
Conservative	1	70	5	1.6	0.5 (use 1)	$2*10^{27}$	19	24
Aggressive	10	70	10	1	0.7 (use 1)	$4.1*10^{28}$	4.3	5.3

1. Simkovic et al. Phys. Rev. C79, 055501(2009) [use RQRPA and g_A= 1.25]
2. Menendez et al., Nucl. Phys. A818, 139(2009), use UCOM results



CCD image of a trapped ion

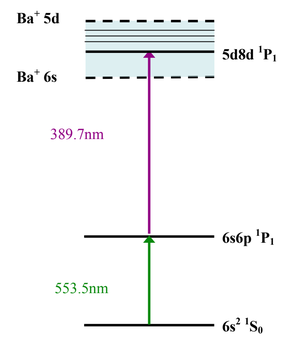
Electrodes glowing from scattered laser light



Integrating over a region of interest and 5s exposure produces a fluorescence signal. Notice the discrete steps for ions entering/ leaving the trap.

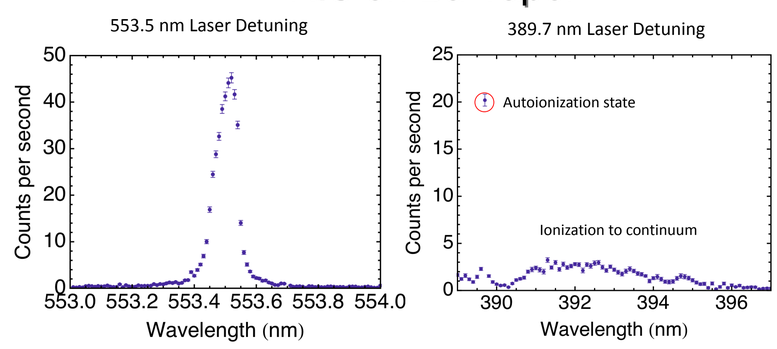
Resonance Ionization Spectroscopy (RIS)

Resonance ionization spectroscopy uses lasers to pump transition which lead to ionization of a particular species. Again, because particular atomic transitions are used, the technique is highly selective for barium. In this case a 553.5nm and 389.7nm laser are used to transition the barium atom into an autoionizing states, i.e. one with energy above the first ionization potential. The idea would be to implant the ion on a surface, thermally desorb the atom with a high power laser pulse, resonantly reionize it, and then detect the ion in the linear trap.

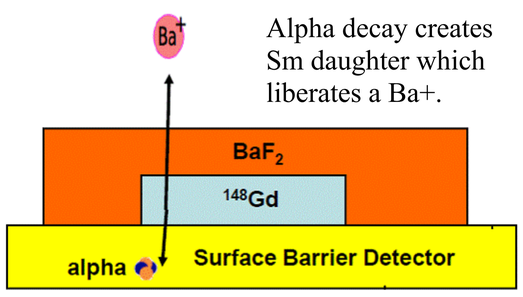


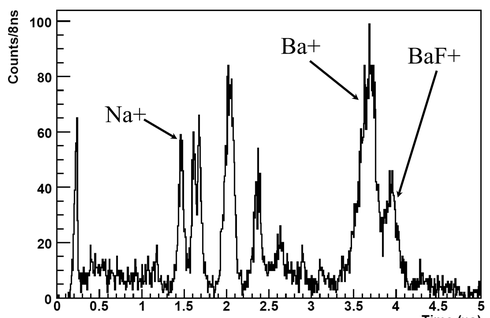
RIS on Ba Vapor

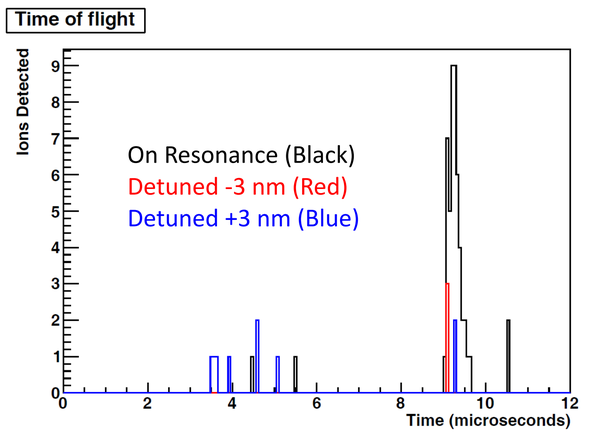
To the right are two plots of the rate of ion production from a barium vapor using the resonantly ionizing lasers. In each case, one laser wavelength is scanned to show the width of the transition.



Barium Ion Source



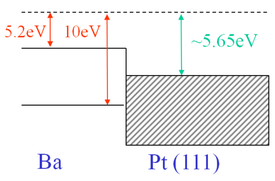




Using the source to implant barium on a target, a 1064nm Nd:YAG laser is used to desorb barium which is then resonantly ionized. Shown are flight times with the 553.5nm ionization laser detuning changed between runs and the 389.7nm laser set on resonance.

Time of flight spectrum for ions produced by the source. Time zero is defined to be the time of the alpha decay.

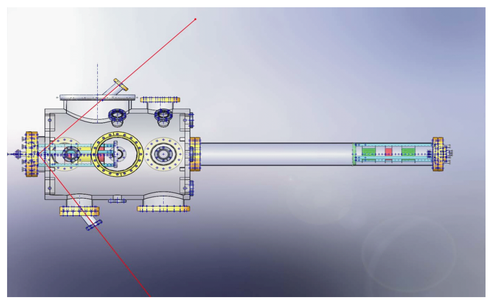
Surface Ionization (hot) Probe



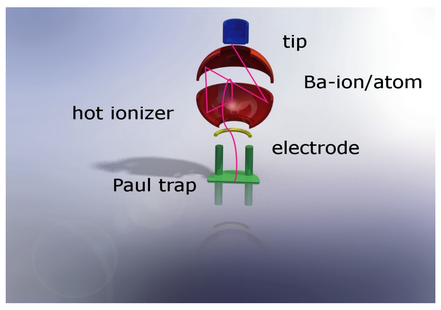
$$\frac{n^+}{n} = 2\exp\left[\frac{e(\phi - IP)}{kT}\right]$$

ϕ = Work function, IP = ionization potential (Saha equation)

The idea is to collect the barium ion on a metal tip, transport it to a vacuum region, release the neutral atom by heating, and reionize it using a hot, high work function surfaces. Then it can be detected in the ion trap.

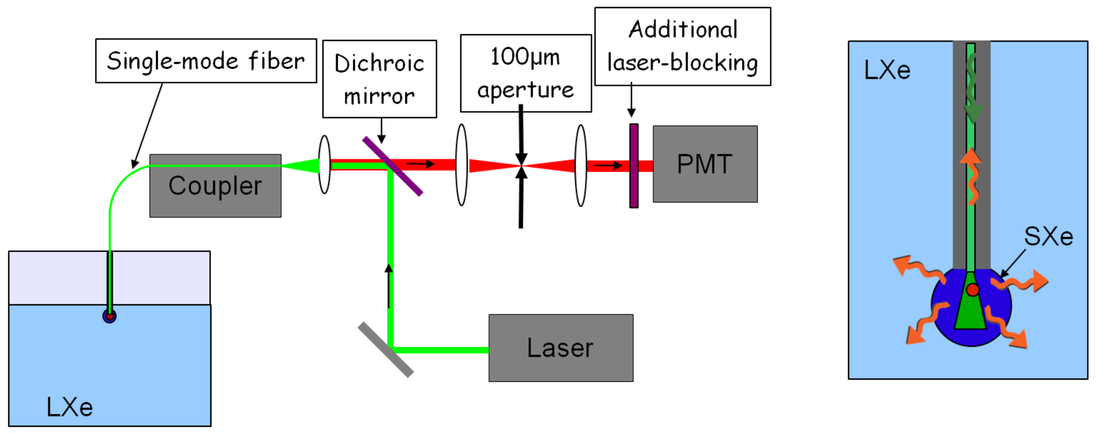


A time of flight spectrometer designed for the hot probe studies. It incorporates several heating techniques including resistive heating, laser pulse heating, and electron beam heating.

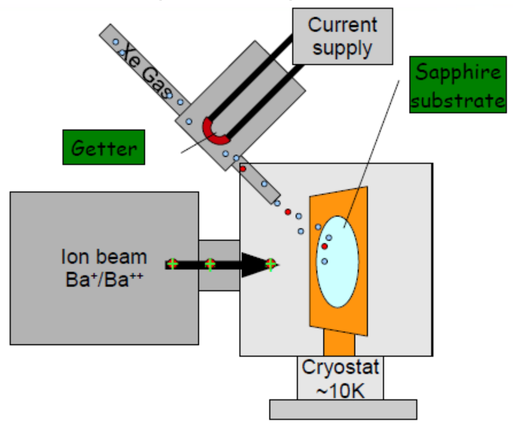


A hot cavity design to enhance the ionization probability of barium. As the barium is released from the surface, it will have multiple chances to bounce off the wall. Once ionized, the barium will be extracted out by an electric field.

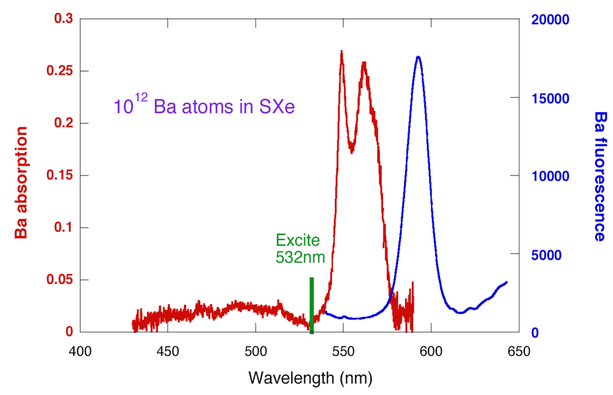
Direct Detection in Solid Xenon



Schematic of direct detection of barium in solid xenon. The barium atom or ion is frozen in solid xenon on the end of a fiber. The excitation laser is sent down the fiber. Fluorescence from barium atoms or ions is collected using the same fiber and detected through filters with a photomultiplier or avalanche photodiode.



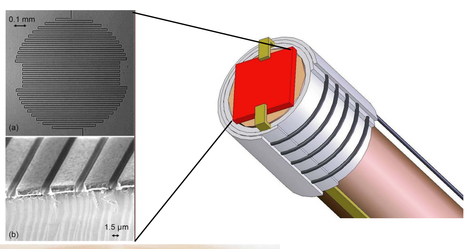
Apparatus for preparing argon and xenon ice samples with barium ion or atom implantation.



Absorption and fluorescence spectra of ~10^{12} barium atoms in solid xenon from a Ba+ ion deposit. The neutralization and appropriate spectral lines of Ba+ detection are being investigated.

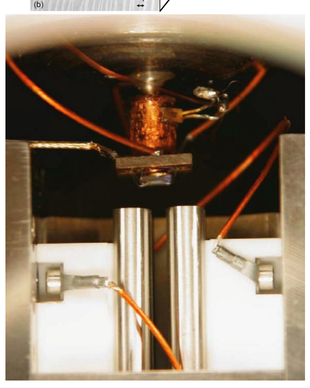
Cryogenic Xenon Ice (cold) Probe

The idea is to implant the barium ion in a thin ice layer without affecting its charge state, transport it to a vacuum region, sublime the ice to release the ion, then detect it in the ion trap.

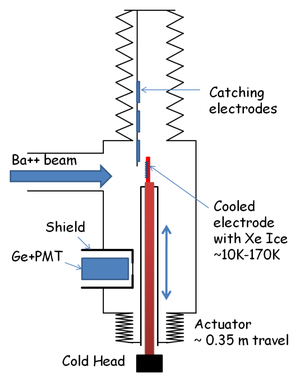


A cryogenic probe design for capturing ions on a solid xenon surface. Microfabricated capacitors can measure and stabilize solid xenon coating with an accuracy of several monolayers in liquid and vacuum.

P. Fierlinger et al., Rev. Sci. Inst. 79 (2008) 045101

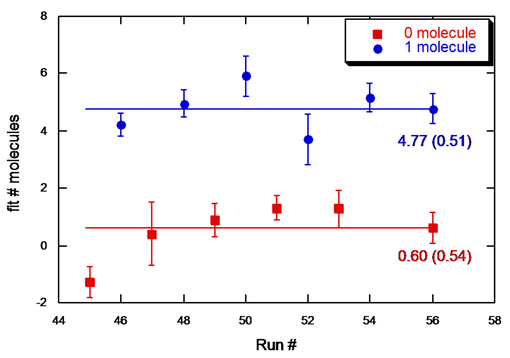


Cryogenic probe installed above the ion trap. Attempts to deliver ions from the probe into the ion trap has been unsuccessful, potentially due to barium neutralization or xenon ice ball formation.



Investigation of barium charge states in solid Xe with radioactive Ba ions at Argonne National Lab.

Principle: manipulation of ions with electrostatic field and moving electrodes, detection via conversion gammas.



Taking into account the large fluorescence signal and less than optimal excitation wavelength, the current sensitivity of the technique is 10^4-10^5 Ba atoms in SAr and SXe. Detection at the single atom level can be reached by increasing the collection efficiency by 10^4 and laser intensity by 10^2, e.g., by using the fiber. As a confirmation of these expectations, detection at the level of single dye molecules with the fiber setup has been demonstrated.