Ion Extraction from gas for Ba-tagging in nEXO

$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} + 2e^- + 0\nu$
Double beta decay

The most promising approach to determine the nature of the neutrino!
Lepton number is violated in this decay!

$2\nu\beta\beta$

This process can only occur for a Majorana neutrino!

M. Goeppert-Mayer, Phys. Rev. 48 (1935) 512

Ettore Majorana
An observation could provide some insight into the nature of $\nu$: 
• What is the absolute mass scale? How heavy is the neutrino?
• Why is the neutrino mass so small?
• **What is the nature of the $\nu$: Dirac or Majorana?**
Searching for $0\nu\beta\beta$ in $^{136}$Xe with nEXO

Liquid-Xe Time Projection Chamber
- Liquid Xe at 168K
- Cryogenic electronics in LXe
- Detection of scintillation light and secondary charges
- 2D read out of secondary charges at segmented anode
- Full 3D event reconstruction:
  1. Energy reconstruction
  2. Position reconstruction
  3. Event Multiplicity

Natural radiation decay rates
- A banana ~10 decays/s
- A bicycle tire ~0.3 decays/s
- 1 l outdoor air ~1 decay/min
- 100 kg of $^{136}$Xe (2$\nu$) ~1 decay/10 min

$T_{1/2}^{0\nu} > 10^{25}$ years !!

→ Need:
  - high target mass
  - high exposure
  - low background rate
  - good energy resolution

$0\nu\beta\beta$ decay >10000 x rarer than 2$\nu\beta\beta$

Age of universe $1.4 \times 10^{10}$ years
EXO—Enriched Xenon Observatory

The virtues of $^{136}$Xe in a large TPC

- **Easy to enrich**: 8.9% natural abundance but can be enriched relatively easily
- **Can be purified** continuously, and reused
- **High Q$_{\beta\beta}$ (2458 keV)**: higher than most naturally occurring backgrounds
- **Minimal cosmogenic activation**: no long-life radioactive isotopes
- **Energy resolution**: improves using scintillation and charge anti-correlation
- **LXe self shielding**
- **Background can be potentially reduced by Ba$^{++}$ tagging**

Phased approach:

1. EXO-200: 200kg liquid-Xe TPC
2. nEXO: 5-ton liquid Xe TPC with Ba tagging upgrade option (SNO lab cryopit)
nEXO Sensitivity & Discovery Potential

**Methodology:**
- 3860 kg fiducial Xe
- 90% enrichment
- 1% $\sigma E/E$ resolution
- Realistic background projections based on measurements
- nEXO200 - like analysis

Can we do better than this?

If we see a $0\nu\beta\beta$-like signal with nEXO (or any other $0\nu\beta\beta$ detector), how can we be sure it really is $0\nu\beta\beta$?

The answer might be Ba-tagging as a future upgrade to nEXO.
Ba-tagging concept

1. Is the event of interest?
   • Close to Q-value?
   • Beta-like event?

2. Localize event

3. Extract ion from detector volume and separate it from Xe

4. Identify ion: is it barium?

Ba tagging R&D ongoing for liquid- and gas-phase detector
Ba tagging for nEXO – a multi-faceted approach

Recent nEXO Ba-tagging publications

Imaging individual Ba atoms in solid xenon for barium tagging in nEXO

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

Spectroscopy of Ba and Ba$^+$ deposits in solid xenon for barium tagging in nEXO

An apparatus to manipulate and identify individual Ba ions from bulk liquid Xe

Laser spec.
Moving laser in x in 4 µm steps

To spectrometer/CCD

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Concept: nEXO RF-funnel based Ba-ion extraction and identification

- Extract $\text{Ba}^+$ from liquid Xe TPC into a Xe gas environment
- Extract $\text{Ba}^+$ with a Xe gas jet into a low pressure chamber
- After nozzle, pump Xe gas away and guide $\text{Ba}^+$ to identification
RF-funnel ion extraction prototype

RF-funnel concept by V. Varentsov:
- Converging-diverging nozzle
- 2 Stacks total 301 electrodes (0.1 mm thick)
- 0.25 mm electrode spacing
- RF-field applied to electrodes
- $P_0 = 10$ bar! to 1 mbar in only one stage
- Xe gas is recaptured by a cryo pump

$V_{RF} = 120$ V, $f = 10$ MHz
Simulated funnel Ba$^+$ transmission $\sim$95%

$V_{RF} = 25$ V, $f = 2.6$ MHz
Simulated funnel Ba$^+$ transmission $\sim$72%
RF-funnel assembly
Ion extraction in xenon gas

- Ions extracted up to 10 bar!
- Gd-148 and Cf-252 ion sources used
- Ions extracted from Ar, Kr, and Xe
- Ba-ions not identified!
- Fission products not identified!
- Ion extraction efficiency unknown!

![Spectra of ions extracted from 2.1 bar Xe]
Pressure dependant ion extraction

- Ion extraction from Xe gas using a $^{252}$Cf source (~3kBq)
- Inconclusive results. System limited by:
  - Ion production method
  - Ion identification method

![Graph showing rate vs. Xe pressure upstream of nozzle]
Improved RF-funnel concept

- Collaborative development of an improved ion-extraction system (Carleton, McGill, TRIUMF)
- Laser-ablation ion source in high pressure Xe gas
- Double (triple) RF funnel for improved operation → improved pumping
- Ba\(^+\)-ion identification through laser-fluorescence spectroscopy (element specific)
- Ion identification via time-of-flight mass spectrometry (Greifswald/ISOLDE design)
Setup for Laser Ablation Ion Source Test in High-Pressure Xe Gas

- Goals of Ba laser ablation source in high-pressure Xe gas
  - High-intensity: ion current reading (>pA = 10^6 ions/s) for absolute efficiency measurements of ion extraction through RF funnel
  - Cleaner ion beams: ideally fewer Xe ions and molecules

High-pressure viewport (Sapphire, <27 bar)

Ablation laser

Xe gas

Ion collector

Ba disk

V\textsubscript{Ba} = 100 V
V\textsubscript{chamber} = 0 V

V\textsubscript{col} = -5 V

Ba ions

SIMION trajectory

Xe: 10 bar

V. Thomas, brunner@mcgill.ca
Linear Paul trap development

- Quadrupole mass filter (QMF): selectively transport ions of $A/z=136$
- Cooler: Ion cooling with helium buffer gas
- Store ions for laser spectroscopy → open geometry
- Bunch ions for a Multi-Reflection Time-of-Flight mass spectrometer (MT-TOF)
Ba ion detection & identification

Using a relatively simple and well understood fluorescing system

Demonstrated ion cloud imaging and accurate position control

Demonstrated single ion sensitivity using intermodulation technique (background control)

Summary and Outlook

• Observation of $0\nu\beta\beta$ would imply new physics.
• Ba-tagging allows identification of $0\nu\beta\beta$ events as true $\beta\beta$-decays.
• Ba-tagging is a challenging endeavor and the collaboration is exploring different approaches, one of them using a RF ion funnel.
• Ion-extraction from GHe of up to 10 bar has been achieved.
• Planned upgrades to the RF-funnel setup based on lessons learned → Improve ion production and increase ion-detection sensitivity.

Recently renovated lab at McGill. We are looking for people to join our Ba-tagging developments.
Thanks to the TITAN group at TRIUMF...

Especially Jens Dilling, Ania Kwiatkowski, Dan Lascar, Kyle Leach and Mel Good.

... and Victor Varentsov at GSI and FAIR (Germany).