Cryogenic Distillation for Xenon Isotopic Enrichment

Abo-Bakr Emara
Supervisor: Dr.Caio Licciardi
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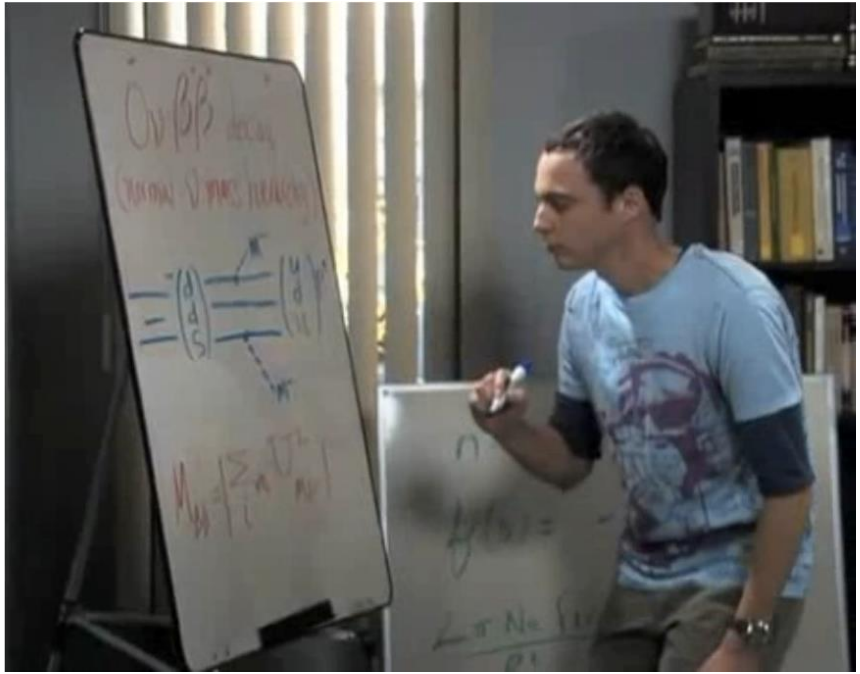
Carleton University

Motivation

- Double beta decay process has been observed in several isotopes.
- The search for neutrinoless double beta ($0\nu\beta\beta$) decay (which is hypothetical process) is one of the most pressing problems in particle physics today. If observed, it could help explain the dominance of matter over antimatter in the Universe.
- 136Xe is an attractive nuclide to search for $0\nu\beta\beta$
- 136Xe only around 9% of natural composition of Xenon.
- Future experiments will need a detector at the ~50 tonnes scale to probe the so called normal ordering of neutrino masses.



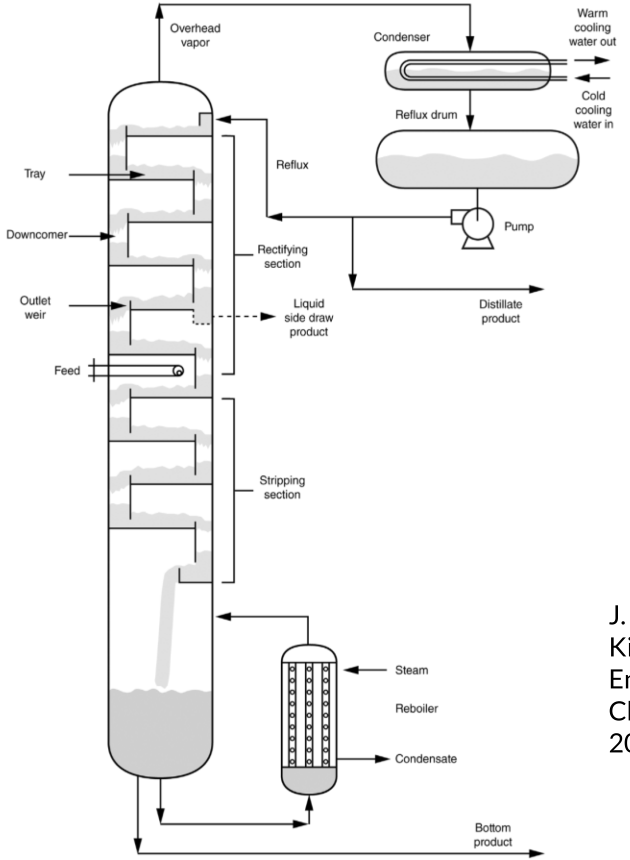
"Look, I found my missing neutrino." The Big Bang Theory quote S02E04 Sheldon Cooper

Introduction

- There are several known methods for isotopic enrichment (Centrifugal, Diffusion, Electromagnetic).
- The only method used for xenon enrichment is centrifugal.
- One of the promising process for isotopic separation is distillation.
- Distillation separation relies on the small difference in vapour pressure of different isotopes.
- These vapour pressures are known for the lighter noble gases (Kr, Ar) but no credible experimental data existed for xenon.
- Small still (2m high) was installed at Carleton university and data has been obtained and first credible measurement for xenon vapour pressure published.
- A theoretical calculation of 1000m height column is needed to reach the required enrichment, but data from Carleton's still has 15% precision so a higher column is required for more accurate measurements.
- A higher column 16m high is at SNOLAB and data is being obtained and analysis is ongoing (this work).

Distillation Process

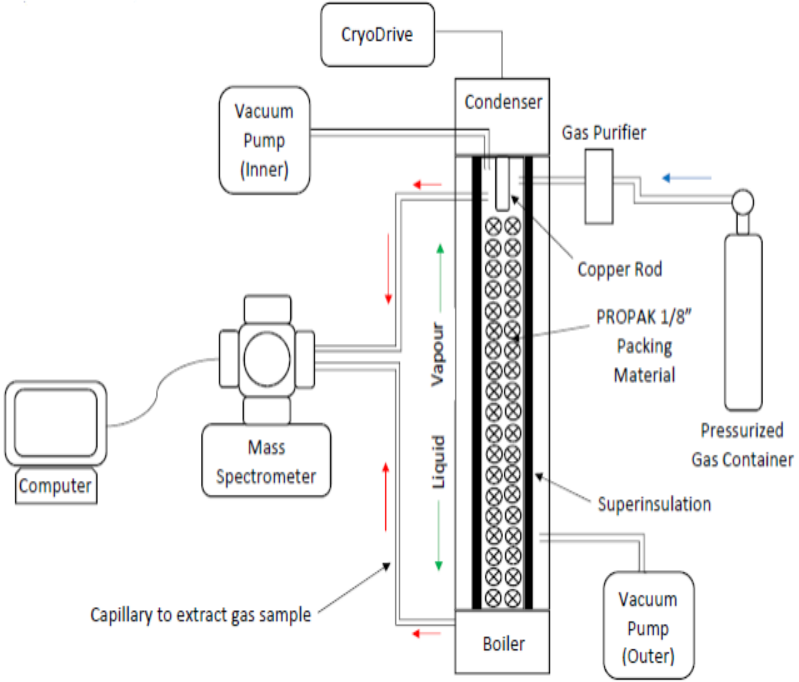
- Distillation separates products from a liquid mixture based on their boiling point differences.
- The overall separation achieved between the components primarily arises from the dissimilar effective vapor pressures, or volatilities.
- Cryogenic distillation is process of cooling a gas mixture to induce a phase change for effective separation.



J. R. Fair, Distillation, Kirk-Othmer Encyclopedia of Chemical Technology, 2018.

Experiment Setup

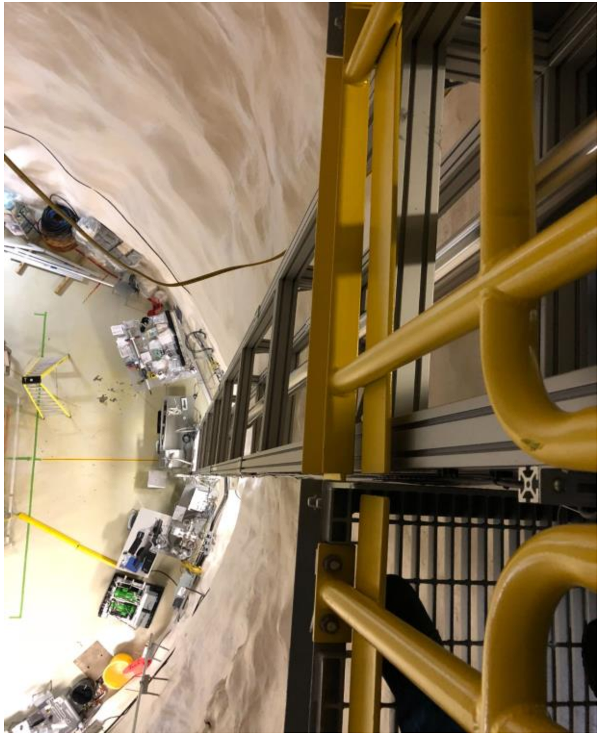
- Instead of plates we have packing.
- Every few centimeters (2-3 cm) consider as theoretical plate.
- Random packing filling the whole still.
- A mass spectrometer is connected to the still with capillary tubes to get the spectrum of different isotopes.



Height Comparison

Carleton's still

SNOLAB still

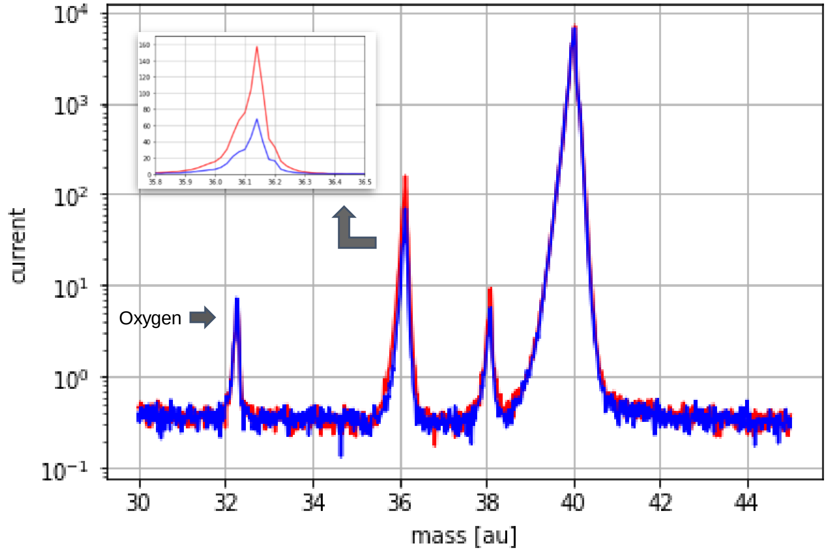


SNOLAB still

Data Analysis

- Spectrum from quadrupole mass spectrometer.
- Samples are taken from top and bottom through capillary tubes.
- Quantitatively compare the spectrum from the top and the bottom of the still and measure the change of enrichment for each isotope over time.

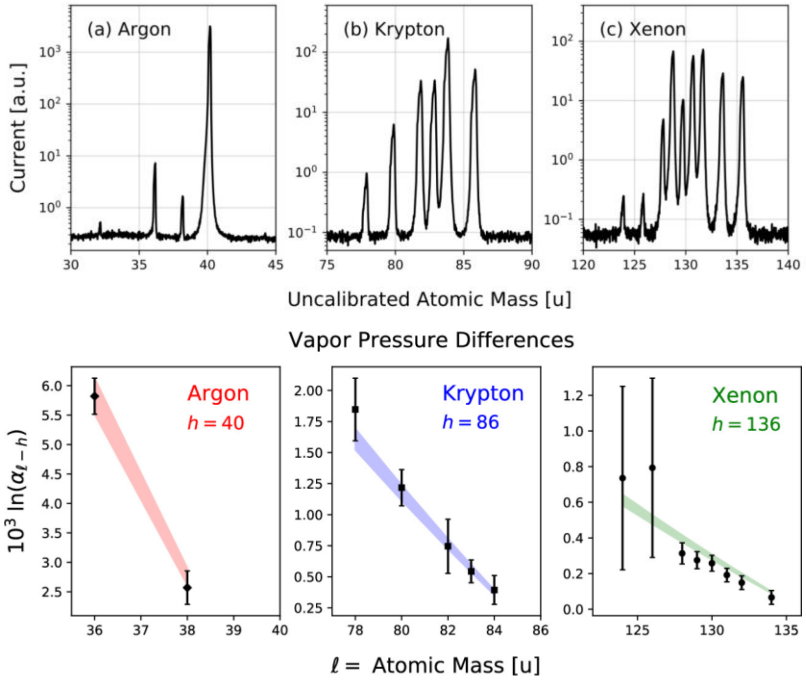
Spectrum at beginning of the run(Blue)
Spectrum at end of the run (Red)



Spectrum of Argon gas

Procedure to get the vapour pressure of Xenon

- We start with Argon gas to calibrate our still, vapour pressure for Ar-40 and Ar-36 well known from the literature.
- After Argon gas we run with Krypton gas to validate our calibration, the vapour pressure difference between Kr-80 and Kr-84 is compared to the published data.
- Same procedure is applied to Xenon gas to get the vapour pressure of xenon.
- The experimental results from the literature is only between two isotopes, our data (from Carleton's still) compare all the isotopes and it matched the theoretical expectation (color bands)



Isotopic Dependence of Vapor Pressure in Xenon
Amal Alamre, Ibtesam Badhrees, Brandon Death, Caio Licciardi, and David Sinclair, ACS Omega 2020 *5* (45), 28977-28983

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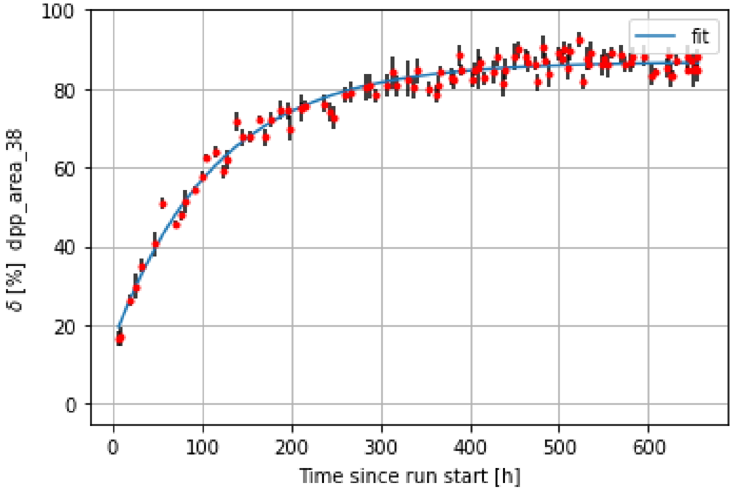
Stabilization Time Of The Still

- It take some time for the still to be stable and get to the maximum enrichment.
- Kown the stabilization time we allow us to have more data in the stable period and be able to extrapolate this to a higher still.
- Comparing enrichment of A-38 and stabilization time from Carleton's with SNOLAB, enrichment increase from 10.8% to 86.8% , and time increased from 4.6 h to 115 h
- In order to calculate the vapor pressure for different isotopes we need to get the maximum enrichment.

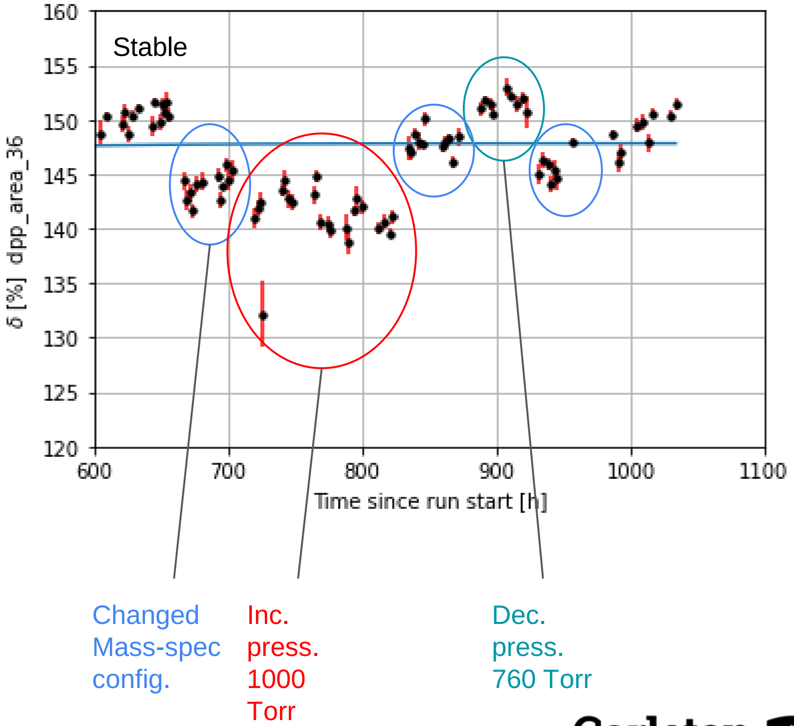
$$\delta_i = \frac{f_{i,\,\mathrm{top}} - f_{i,\,\mathrm{bot}}}{(f_{i,\,\mathrm{top}} + f_{i,\,\mathrm{bot}})/2} \times 100$$



Initial enrichment 15.6 %
final enrichment 86.8 %
Stabilization time 115 h

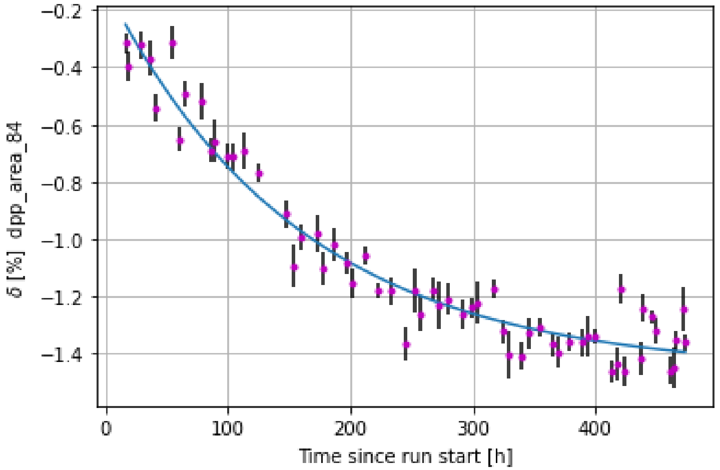
Different operation conditions at SNOLAB

- Separation happen best around the triple point of the gas.
- We tried different operation conditions with different pressures and different spectrometer tuning.
- The aim is to do more comprehensive study from the still at SNOLAB.



On-Going Data taking And Analysis

- Run with argon is done and data is being analyzed.
- Krypton run is also done, still evolved and reached stability, under going analysis.
- Xenon run expected to start in June, recovery system for xenon should be connected first.



Summary and Conclusion

- Studying the cryogenic distillation process as a reliable way to separate Xe isotopes by studying the Xe isotopes vapour pressure.
- To create material for next generation ($0\nu\beta\beta$) experiments.
- Results from Carleton's still show that in fact xenon isotopes have different vapour pressure and separation by cryogenic distillation is doable, but have around 15% error in measurement.
- Still at SNOLAB will produce more accurate results and help us understand more the physics process of separation. Give us insight about the effect of the height.
- May help in future solving one of the unknown questions in physics today.

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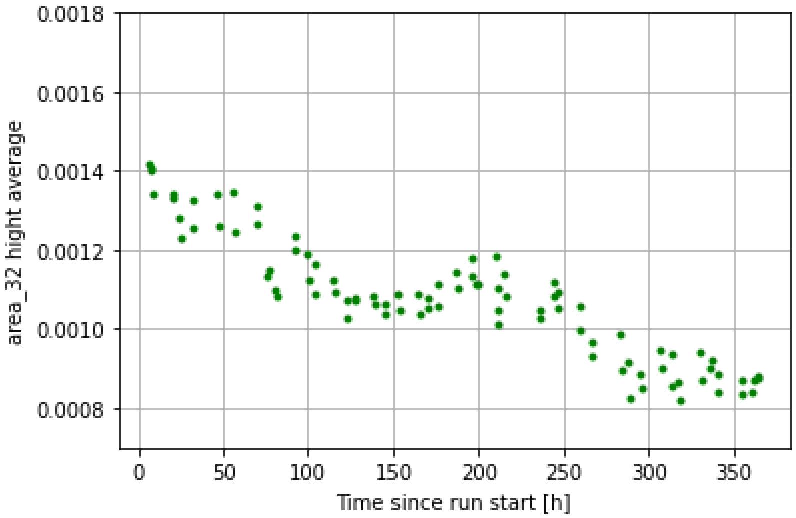
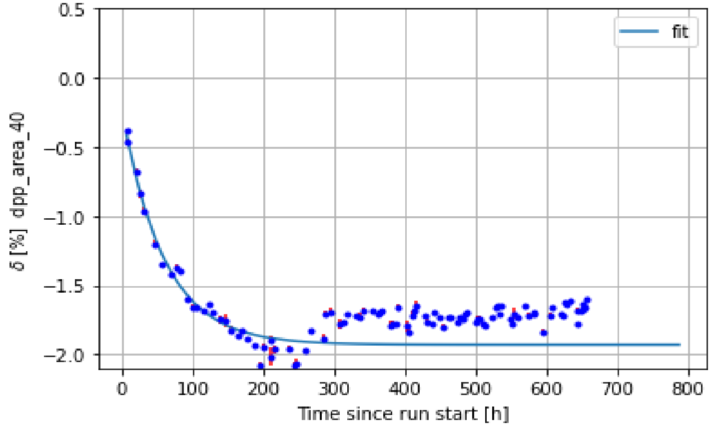
Extra Slide

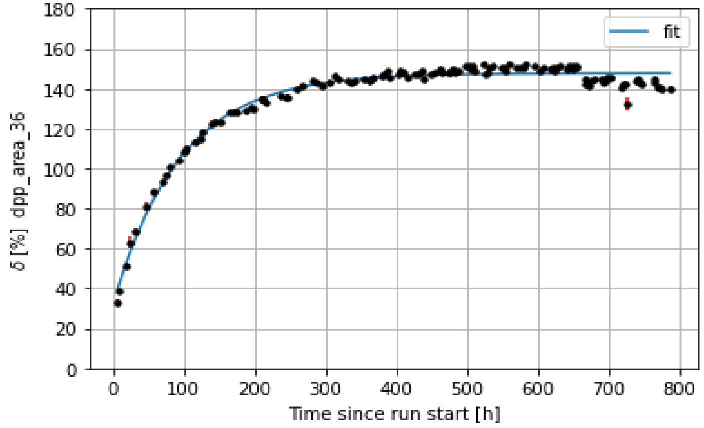
Source of contamination

- Outside the still
- Decreasing from both top and bottom
- Not evolving with time



Extra Slide





$$y = (p0 - p1) \cdot \exp\left(-\frac{t}{p2}\right) + p1$$