Xenon 100: Concentration of Krypton in a Xe sample.

By: Kristin Hannings
Advisor: Dr. Elena Aprile
A Brief History: Dark Matter

- Dark Matter-
  - Dark matter was postulated by Fritz Zwicky in 1933. He discovered that the mass of the Coma Cluster galaxies was much more than expected. This yielded a theory of a “missing mass” which was invisible.
  - In 1970 Vera Rubin also made a discovery which supported Zwicky’s theory. She discovered that the orbital velocities of stars on the outskirts of the galaxy were similar to the velocities of stars near the center of the galaxy. This is weird because the mass doesn’t have strong enough gravitational force to hold the stars in their orbit.
74% of the universe is dark energy, 22% is dark matter, and 4% is visible matter.
First let's rule out what dark matter isn't:

- **Antimatter**: No unique gamma rays are seen, that are created with annihilation of antimatter with matter.
- **Large Black Holes**: Do not see enough gravitational lensing events to account for the 22% dark matter.

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Now what are theories which are viable?

- **MACHOs**: Massive Compact Halo Objects, which is baryonic matter that doesn't emit light and doesn't associate with any other matter as it "drifts" through space.
- **Axions**: Elementary particle postulated by Peccei-Quinn theory to resolve the CP problem in quantum chromodynamics
- **WIMPs**: Weakly Interacting Massive Particle. Interact through the weak force and gravity.
Xenon is a dark matter search which is interested in detecting WIMPs.

WIMPs: Weakly Interacting Massive Particles
- Weakly Interacting: Account for why no interactions have been observed between visible and dark matter; no electromagnetic observation
- Massive particle: Account for missing mass, and is not relativistic so it will not destroy galaxy and galaxy clusters in their formation.
- Such a particle is hypothesized by theories such as supersymmetry.
Xenon 100 is a WIMP detector which uses a time projection chamber filled with liquid xenon. The xenon nuclei are the medium for which the WIMP will interact-producing photons and electrons which are detected by PMTs.

- Located in Gran Sasso Underground Lab, Italy

- Collaboration: Columbia University, Rice University, RWTH-Aachen University, University of Coimbra, Yale University, Brown University, Case Western Reserve University, Gran Sasso National Laboratory, and Lawrence Livermore National Laboratory
Why Xenon?

- Non-reactive: Noble gas
- High electron mobility
  - Important because the electrons are the product of ionization of xenon atoms by WIMP interaction. This ionization produces scintillation light which is detected by photomultipliers and travels via electric field to the gas phase of the detector, where the electron has enough energy to excite other molecules, producing a second scintillation, which is again detected.
- Self-shielding
- Effectively purified (ppb)
- Higher mass therefore higher probability for interaction
- Xenon doesn’t have radioactive isotopes, however Kr 85 is an isotope of krypton present in xenon
Krypton is present in xenon due to nuclear reactors. Krypton isn’t a threat, the isotope Kr 85 is. It decays to Rb 85 via two paths. Both via beta decay.

Beta and Gamma background
- 99.57% Decay via beta decay
- 0.43% Decay via beta and gamma decay (double coincidence)
When a WIMP particle interacts with a xenon atoms nucleus, it causes nucleus recoil, and emits a small amount of energy.

However when Kr 85 interacts with xenon it creates an electron recoil, and emits energy from 0-600keV. 1 out of every 200 electron recoil events is confused with a WIMP nucleus recoil.
Kr 85 is detected by counting the double coincidence events of the Kr 85 decay. There are two coincidences in a few microseconds, one small coincidence (beta) followed by a large coincidence (gamma).

Issue:
- Takes a long time and low concentration to observe delay coincidence
The new method studied is done using an RGA (residual gas analyzer), for the detection of krypton.

- The RGA contains a small mass spectrometer, and uses quadrupole technology. The mass spectrometer takes a vapor sample, ionizes, accelerates, deflects, and detects the ions.
  - Ionization: Done using a filament which releases electrons which interacts with the atoms within the vapor sample tested.
  - Accelerated: Via electric field
  - Deflection: By a magnetic field, where the trajectory of the ions is based on their masses. The more massive the ion the less it deflects and vice versa.
  - Detected: elements within the sample are separated using the quadrupole mass analyzer. The quadrupole mass analyzer is four rods, which separates the ions based on their mass-to-charge ratio in an oscillating electric field that is applied between the rods. Only ions with a specific mass-to-charge ratio will reach the detector, separating the ions into the different element.
Cold tank helps vacuum pumps to perform better.

Uses the concept of sublimation where a gas or vapor is crystallized on a cold metal surface, reducing the pressure within trap.

Liquid nitrogen trap: a cold trap is immersed in a liquid nitrogen bath. The low temperature of liquid nitrogen cools down the cold tank, and provides a cool metal surface where sublimation can occur.

Xenon flows through the cold tank, and the majority of it crystallizes on the metal surface, creating a lower pressure vacuum system with a pressure around 10^-5 torr. The remaining vapor than travels onto the RGA.
Why is this useful?

- Krypton is an intrinsic background in Xe.
- Knowing the krypton concentration will help determine the probability of mistaking an electron recoil event from krypton decay as a nuclear recoil from WIMP interaction.
  - When distinguishing electron from nuclear recoil, there is an area where the two recoils overlap. Statistically this is 1 out of every 200 electron recoil events.

**Ratio of Kr to Kr85 1 : 10^-11**

- Knowing this ratio will allow us to relate the concentration of krypton to the concentration of Kr85 to determine the amount of events expected to be seen due to Kr 85 beta emission. Also the krypton concentration will let us know if the xenon sample is purified enough. For the more Kr the more Kr 85 , resulting in more beta emission.
Xenon 100 uses a cryogenic distillation column for purification of the xenon. Primary purpose to rid of krypton and other noble gases.

Cryogenic Distillation Column-
- Cryogenic means that the separation of a mixture at low temperatures.
- The distillation column separates a mixture based on the different boiling points of the elements within the mixture. To separate the mixture, krypton is boiled at 115.95 K, which rids of the other noble gases present in the mixture, leaving all elements which are heavier than Xenon.
Why is this method beneficial?

- **Mobile** - easily created system which can be created in Italy
- **Quick** - takes up to an hour to conduct a measurement
- **Cheap**
First Part: Determination of optimal flow rate and repeatability
- Check to see if flow yields consistent partial pressure results.

Second Part: Calibration Graph
- Addition of known krypton concentration to xenon, flow through system, and measure partial pressure as a function of time. This will allow to calibrate the partial pressure measurements of the RGA in terms of the true krypton concentration.
Flow Rate

- The flow rate of the xenon is crucial, for this determines the pressure within the system. Therefore to produce consistent results, various flows of xenon were tested to see which produced the most consistent pressure results.

- A sample of xenon is entered into the system, after reducing the pressure with the cold trap, various flow rates are tested using the sample. The RGA output is then analyzed.
Flow Rate Analysis

- Once the RGA separates the sample into Ar,Kr,Xe,N,O,H2O, the Ar and Kr graphs are analyzed.

- Line of best fit is taken between the intervals where the flow rate is changed. This line of best fit is used to compare the partial pressures during various measurements to determine the flow rates that provided consistent partial pressure results.
An example of one of the measurements taken by the RGA for a xenon. The flows used were 0.01, 0.04, and 0.08 slpm.
<table>
<thead>
<tr>
<th>Measurement</th>
<th>Kr Pressure (torr)</th>
<th>Zero Flow (slpm)</th>
<th>Flow (slpm)</th>
<th>Real Flow (slpm)</th>
<th>Interval(s)</th>
<th>Period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4.586E-8</td>
<td>0.28</td>
<td>0.029</td>
<td>0.01</td>
<td>2173.3-2200.8</td>
<td>27.5</td>
</tr>
<tr>
<td>2</td>
<td>1.5E-7</td>
<td>0.28</td>
<td>0.32</td>
<td>0.04</td>
<td>2395.5-2424.2</td>
<td>27.5</td>
</tr>
<tr>
<td>2</td>
<td>1.866E-7</td>
<td>0.28</td>
<td>0.35</td>
<td>0.07</td>
<td>2459.4-2486.9</td>
<td>27.5</td>
</tr>
<tr>
<td>1</td>
<td>8.03E-8</td>
<td>0.27</td>
<td>0.28</td>
<td>0.01</td>
<td>1898.6-1927.2</td>
<td>27.5</td>
</tr>
<tr>
<td>1</td>
<td>1.46E-7</td>
<td>0.27</td>
<td>0.32</td>
<td>0.05</td>
<td>1898.6-1926.1</td>
<td>27.5</td>
</tr>
<tr>
<td>1</td>
<td>2.1E-7</td>
<td>0.27</td>
<td>0.35</td>
<td>0.08</td>
<td>2211-2238.5</td>
<td>27.5</td>
</tr>
</tbody>
</table>
- Next step is to create a krypton system which has the ability to mix a known krypton concentration and xenon sample. The mixture enter the system and goes through the cold tank and the rest of the vapor sample that doesn’t freeze goes to the RGA. A plot of is created of partial pressure as a function of time.

- For each concentration of krypton which is used, the pressure which is put in a 6.75 cubic cm pipe is determined.
Given the scenario: That xenon is being pumped into a one gallon bottle at 2 bars; the pressure of krypton that is put into a 6.75 cubic cm pipe is determined knowing the concentration of krypton which is desired.

Calculation: Density of xenon is 10.6 g/l, and xenon is being pumped into a 1 gallon bucket = 3.79 liters.

10.6 g/l = \( \frac{\text{XeMass}}{3.79 \text{ liter}} \)

From the mass of the xenon it is possible to determine what the krypton mass needs to be in order to have a specific concentration.

For Example: 100 ppb

\[ 100 \times 10^{-9} = \frac{x}{0.306 \text{ moles}} \]

\[ x = 3.06 \times 10^{-8} \text{ moles} \]

\[ x = 2.56 \times 10^{-6} \text{ grams} \]

Once the mass of the krypton is determined, using a NIST Standard Source Data site, the Thermalphysical properties of xenon can be found, including the isoberic properties such as pressure.
Once various concentrations were measured the graphs were analyzed and using the same method as before, the line of best fit was found for each flow interval for each the different concentrations of krypton. The purpose of adding this additional krypton to a xenon sample is to be able to create a graph which will relate the partial pressure of krypton to the concentration using the relationship:

\[ P = a\Delta C_k + b \]

- \( P = \) Partial Pressure
- \( \Delta C_k = \) Added krypton concentration
- \( B = \) Krypton concentration in xenon sample (unknown)
- \( a = \) unknown (determined from graph)
<table>
<thead>
<tr>
<th>Kr Pressure (torr)</th>
<th>Concentration (ppb)</th>
<th>Flow (slmp)</th>
<th>Period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.094E-9</td>
<td>100</td>
<td>0.04</td>
<td>27.5</td>
</tr>
<tr>
<td>3.51E-9</td>
<td>100</td>
<td>0.04</td>
<td>27.5</td>
</tr>
<tr>
<td>1.634E-9</td>
<td>50</td>
<td>0.04</td>
<td>27.5</td>
</tr>
<tr>
<td>5.077E-9</td>
<td>100</td>
<td>0.06</td>
<td>27.5</td>
</tr>
<tr>
<td>4.67E-9</td>
<td>100</td>
<td>0.06</td>
<td>27.5</td>
</tr>
<tr>
<td>1.96E-9</td>
<td>50</td>
<td>0.06</td>
<td>27.5</td>
</tr>
<tr>
<td>5.78E-10</td>
<td>0</td>
<td>0.04</td>
<td>27.5</td>
</tr>
<tr>
<td>6.12E-10</td>
<td>0</td>
<td>0.05</td>
<td>27.5</td>
</tr>
</tbody>
</table>
Calibration graphs for 0.04 slpm, and 0.06 slpm. Additional krypton concentrations of 0, 50, and 100 ppb.

Line of Best fit for both graphs is: 

\[ P = (4 \times 10^{-11}) \Delta C_k + (3 \times 10^{-10}) \]
## Conclusions

The error in the pressure compared to line of best fit; at 0.06 slpm flow.

The error in the pressure compared to the line best fit; at 0.04 slpm flow.

<table>
<thead>
<tr>
<th>Kr Pressure (torr)</th>
<th>Concentration (ppb)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.09E-9</td>
<td>100</td>
<td>18.4%</td>
</tr>
<tr>
<td>3.51E-9</td>
<td>100</td>
<td>18.2%</td>
</tr>
<tr>
<td>1.63E-9</td>
<td>50</td>
<td>29%</td>
</tr>
<tr>
<td>5.78E-10</td>
<td>0</td>
<td>92%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Kr Pressure (torr)</th>
<th>Concentration (ppb)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.67E-9</td>
<td>100</td>
<td>8.6%</td>
</tr>
<tr>
<td>5.077E-9</td>
<td>100</td>
<td>18%</td>
</tr>
<tr>
<td>1.96E-9</td>
<td>50</td>
<td>14.7%</td>
</tr>
<tr>
<td>6.12E-10</td>
<td>0</td>
<td>104%</td>
</tr>
</tbody>
</table>
Wimp Detection Data 2011:
In the future the apparatus which I worked on will be created in San Grasso, Italy and used on Xenon 100.

Constrained the cross section of WIMP models—yet no signal found.

Xenon 1 Ton:
- Lxe distributed in ten identical time projection chambers
- Higher sensitivity for wimp-nucleon scattering
- Use one-ton liquid xenon, with highly specialized light-detectors that are 100 times more sensitive than Xenon 100
- Use cryocooler with a heat exchanger (demonstrator) cutting down the cooling cost (energy).
- Improved thermal insulation.
Another method Xenon Dark Matter Project will use is atom trap trace analysis (ATTA). This is an atom counting method which is more sensitive and precise than mass spectrometry. This will allow different isotopes in xenon to be differentiated, importantly krypton. This method is used to analyze the amount of impurities that are left in xenon after it has been through the cryogenic distillation column.
Elena Aprile

Xenon Collaboration at Columbia

REU Program and John Parsons