Development of an IEC Device for the Study of $^3$He($^3$He,2p) $^4$He Reactions

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Presentation Overview

• $^3\text{He}$-$^3\text{He}$ reaction basics
• Benefits of IEC for $^3\text{He}$-$^3\text{He}$ studies
• Anticipated source regimes for $^3\text{He}$-$^3\text{He}$ reactions
• Experimental setup
  – IEC device
  – Ion source
  – Noise suppressing detection system
• Results
• Summary of research effort
\[ ^3\text{He}(^3\text{He},2p)^4\text{He} \] Reaction Overview

Most of the time, this reaction is a three body reaction, generating a continuum of particle energies

Roughly 10% of the time, a resonance occurs generating a pair of two-body decays, which gives the reaction products discrete energies

- \(^3\text{He}\)\(^3\text{He}\) \(\rightarrow\) \(\text{unstable}\) \(\rightarrow\) \(\text{metastable}\)
  - \(\text{metastable} \rightarrow \text{4He} \rightarrow \text{p} \rightarrow 0.8\ MeV\)
  - \(\text{metastable} \rightarrow \text{4He} \rightarrow \text{p} \rightarrow 3.2\ MeV\)
  - \(\text{unstable} \rightarrow \text{p} \rightarrow 8.9\ MeV\)

\[ 12.9\ \text{MeV} \]
$^3$He-$^3$He Cross-Section at IEC Energies

- Curve based on fit to data from “AEP Barnbook DATLIB” (1987)
- Cross section for projectiles on zero velocity targets
- Green range accessible to He$^{+1}$
- Yellow range accessible to He$^{+2}$
IEC Effective for Studying $^3$He-$^3$He Reactions Below 1 MeV

- Accelerators very effective at measuring cross section at energies above 1 MeV
  - Good statistics become difficult as energy is decreased due to limited beam current (< 100 μA)
- IEC can provide relatively high ion current at lower energies
  - Recirculation allows for ion currents as high as 100 mA or more
  - Cathode voltages from -200 to 0 kV currently available
Reactions in IEC Devices Known to Come From Several Regimes

- **Beam-background**
  - Primary ions fuse with background neutral gas

- **Beam-embedded**
  - Primary or secondary ions collide with fuel embedded in grid

- **Fast neutral-background**
  - Primary or secondary ions that have charge-exchanged and become fast neutrals fuse with background gas

- **Converged Core**
  - Fast ions collide with other fast ions in device center
### $^3$He-$^3$He Fusion Source Regimes

Anticipated to be Similar those for D-$^3$He

<table>
<thead>
<tr>
<th>Regime</th>
<th>D-D (Exp., 2 mtorr, 100 kV)</th>
<th>D-$^3$He (Exp., 2 mtorr, 100 kV)</th>
<th>$^3$He-$^3$He (Theory, 0.2 mtorr, 200 kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam-background (near cathode)</td>
<td>22%</td>
<td>5%</td>
<td>7%</td>
</tr>
<tr>
<td>Embedded</td>
<td>8%</td>
<td>95%</td>
<td>93%</td>
</tr>
<tr>
<td>Fast neutral-background + beam-background elsewhere</td>
<td>70%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Converged core</td>
<td>0%</td>
<td>0%</td>
<td>? But likely very small</td>
</tr>
</tbody>
</table>
IEC System Specifically Designed to Meet the Requirements to Observe $^3$He-$^3$He Reactions

- New stainless steel, double walled vacuum chamber
  - Water cooled to allow for long runs
  - Free from D contamination
  - Equipped with various gas diagnostics (ion gauge, RGA, others)
- High voltage system
  - Current supply capable of 200 kV, 75 mA
  - Buffer circuit design stabilizes operation with plasma
  - Advanced insulator allows long lifetimes
- Helicon ion source
  - Allows for large ion current with minimal gas flow
  - Allows for direct measurement of ion current
- Gas recycle system
  - Uses liquid nitrogen to freeze out impurity gasses
  - Capable of operating for > 1 hour with only a few minutes of $^3$He flow
$^3$He-$^3$He IEC System

- Turbo-pump
- IEC Device
- Recycle System
- Ion Source
- RF Matching
- HV FT
- RGA
- Ion Source
Helicon Ion Source Allows Operation in New Regimes

- Maximum ion current: 12 mA— independent of IEC conditions
- Minimum reaction chamber pressure at high current: 20 mPa
- Maximum run time: indefinite

**Other characteristics:**
- Max RF Power: 3kW
- Max B field: 2 kG
- Approx. Density: $10^{19} / \text{m}^3$
- Antenna type: Water cooled Nagoya III
- Antenna coupling: inductive
- Magnet type: water cooled solenoid
Helicon Source Allows High Currents at Low Pressures Compared to Previous Devices

$\text{Max. Current (mA)}$

$\sim 1 \text{ mA @ 1.3 mPa}$

$1 \text{ mtorr} = 0.13 \text{ Pa}$
IEC Performance has Reached Voltages Necessary for Detection of $^3$He-$^3$He Reactions

- Maximum voltage achieved: 170 kV
- Maximum sustained voltage (for 900 seconds): 150 kV
- Typical repeatable voltages: 120 kV – 140 kV
- About a dozen $^3$He runs have been done at these conditions, and half of these with direct comparison between $^3$He and $^4$He fuel
- Typical current ~ 25 mA cathode ( ~ 7 mA ion current) at 0.03 Pa (200 μtorr) in He gasses
Noise Suppressing Detection System Required to Observe Low Reaction Rate

- System works by detecting instability, and disabling the MCA for a time before and after said instability occurs.
- Result is a factor of 50-100 noise reduction.

No noise suppression

Noise suppression enabled

Energy (MeV)
Completion of IEC and Detection Enhancements
Allowed Observation of $^3\text{He}-^3\text{He}$ Reactions

- 900 second acquisition time; 25 mA cathode; 7 mA source current; runs back to back to ensure similar background data
Observed $^3$He-$^3$He Reaction Rate is within 50% of Theoretical Estimate

- To improve statistics, all runs added together and averaged

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Theoretical Beam-Background Rate(^1) (reactions / sec)</th>
<th>Theoretical Detectable Embedded Rate(^*1) (reactions / sec)</th>
<th>Measured Rate (reactions / sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>124 kV</td>
<td>16 ± 5</td>
<td>99 ± 15</td>
<td>144 ± 44</td>
</tr>
<tr>
<td>134 kV</td>
<td>31 ± 9</td>
<td>206 ± 30</td>
<td>400 ± 67</td>
</tr>
</tbody>
</table>

\(^*\) Detectable rate is one half of actual embedded rate

\(^1\) Cross section based on figure in slide 4, with error neglected
Summary of this Effort

- IEC device constructed that can run steady-state at high power levels
- High voltage components designed that allow operation in He at up to 170 kV, and sustained at 120-140 kV
- High voltage system reliability increased such that component failures have become rare
- Gas recycle system developed to allow for long term operation in $^3$He gas with minimal gas use
Summary of This Effort (cont.)

• Ion source developed that allows for IEC operation at much lower pressure than previous devices without sacrificing ion current
• Ion source developed for independent control over source current, which allows for more accurate knowledge of ion current
• Proton detection system noise decreased by 50-100 times
• $^3$He-$^3$He reactions detected in UW IEC device at an average rate of $400 \pm 67$ reactions / sec (maximum $600 / \text{sec}$) at 134 kV
Summary of This Effort (cont.)

- Actual fusion rate is higher than detected rate since only half of embedded reactions are counted
- Using the theoretical prediction for the ratio of embedded to beam-background fusion gives an estimate of the true reaction rate

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Theoretical % of Reactions from Beam-Embedded Fusion</th>
<th>Measured Rate (reactions / sec)</th>
<th>Inferred Total Fusion Rate (reactions / sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>124 kV (ave.)</td>
<td>86%</td>
<td>144 ± 44</td>
<td>268 ± 76</td>
</tr>
<tr>
<td>134 kV (ave.)</td>
<td>87%</td>
<td>400 ± 67</td>
<td>748 ± 117</td>
</tr>
<tr>
<td>134 kV (max.)</td>
<td>87%</td>
<td>600 ± 89</td>
<td>1122 ± 155</td>
</tr>
</tbody>
</table>
Questions?

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Fusion Cross Section Indicates High Energy Needed to Observe ${^3\text{He}(^3\text{He},2p)^4\text{He}}$ Reactions

- Operation at high cathode voltage and low background pressure required
• Dual stage LN₂ condenser traps filter turbo-pump exhaust, which runs back into main system
• High compression turbo-pumps allow for operation of recycle system with no additional pumping stage
• Operation tested up to 1 hour with 2-3 minutes of $^3$He flow
Motivation

- Overarching physics goal: study $^3$He-$^3$He reactions in IEC device
  - Nuclear physics
    - Very few measurements of fusion reaction cross section
    - Measurements at energies < 1 MeV are statistically poor
  - Stellar physics
    - Observed number of neutrinos emitted by the sun did not match theoretical predictions, which led some to theorize that there was a low energy resonance in $^3$He-$^3$He
    - Current models of stellar evolution indicate there should be a larger amount of $^3$He in the universe than observed, which requires a mechanism for stars to burn $^3$He more efficiently
Overarching physics goal: study $^3$He-$^3$He reactions in IEC device (cont.)

$^3$He-$^3$He nuclear energy (advantages)
- All energy emitted in the form of charged particles
  - Minimal reactor activation
  - Possibility of direct conversion (non-thermal conversion)
- No radioactivity associated with reactants or products
- Tremendous resource believed to be available in lunar soil (1000 yrs)

$^3$He-$^3$He nuclear energy (disadvantage)
- High temperatures required make $Q > 1$ reaction impossible in a thermal plasma
Helicon Source Allows High Currents at Low Pressures Compared to Previous Devices

\[
\text{With Ion Source} \quad \text{Pre Ion Source}
\]

\[
1 \text{ mtorr} = 0.13 \text{ Pa}
\]

\[
\sim 1 \text{ mA} @ 1.3 \text{ mPa}
\]
Ion Current Versus Cathode Voltage (weak dependence)

Ion Current vs Cathode Voltage

Cathode Voltage

Ion Current (mA)

- 2100 W 700 G
- 2100 W 900 G
- 2100 W 1200 G
- 2100 W 1400 G
- 2100 W 1600 G
Cathode Current Versus Voltage

Graph showing the relationship between cathode voltage (kV) and cathode current (mA). The graph includes four different lines, each representing different conditions:
- Blue line: 2400 W 900 G
- Orange line: 2400 W 1200 G
- Green triangle line: 2400 W 1400 G
- Red dot line: 2400 W 1600 G
Grid Effective Secondary Emission Coefficient

![Graph showing the relationship between cathode voltage (kV) and secondary emission coefficient. The graph includes data points for different power levels (2100 W 900 G, 2100 W 1200 G, 2100 W 1400 G, 2100 W 1600 G) and显示了不同功率水平（2100 W 900 G，2100 W 1200 G，2100 W 1400 G，2100 W 1600 G）的次级发射系数之间的关系。图表中还包括垂直入射（Perpendicular Incidence）的指示。]