Measurement of $^3\text{He}(^3\text{He,2p})^4\text{He}$ Reactions in an IEC Device

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Argonne National Lab
Presentation Overview

- $^3$He-$^3$He reaction basics
- Benefits of IEC for $^3$He-$^3$He studies
- Anticipated source regimes
- IEC experimental setup
  - IEC device
  - Ion source
- Results/Conclusions
$^3\text{He}(^3\text{He}, 2p)^4\text{He}$ Reaction Overview

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

- $^3\text{He}$
- $^3\text{He}$
- $^4\text{He}$
- $p$
- $p$
- $12.9$ MeV

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

- $^3\text{He}$
- $^3\text{He}$
- $^{unstable}$
- $p$
- $8.9$ MeV

- $^3\text{He}$
- $^3\text{He}$
- $^{metastable}$
- $p$
- $0.8$ MeV

- $^3\text{He}$
- $^3\text{He}$
- $^4\text{He}$
- $p$
- $3.2$ MeV
$^3\text{He}-^3\text{He}$ 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 $^\text{He}^+\text{He}^+\text{He}^+$
- Yellow range accessible to $^\text{He}^+\text{He}^+\text{He}^+$

![Graph showing cross-section values for different projectile energies and cross-sections.](image-url)
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 for Studying $^3$He-$^3$He Reactions

• New stainless steel, double walled vacuum chamber
  – Water cooled to allow for long runs
  – Gas recycle system to allow for extended runs
  – Free from D contamination

• 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
$^3$He-$^3$He IEC System

- Turbo-pump
- IEC Device
- Recycle System
- HV FT
- RGA
- Ion Source
- RF Matching
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
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 gases
- Noise suppression system eliminates EMP interference reducing background noise by a factor of 50
Completion of Performance Objectives Allowed
Observation of $^3$He-$^3$He Reactions

- 900 second acquisition time; 25 mA cathode; 7 mA source current; runs back to back to ensure similar background data
Observed $^3\text{He}-^3\text{He}$ 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$^1$</th>
<th>Theoretical Detectable Embedded Rate$^*1$</th>
<th>Measured Rate</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 10, with error neglected
Results of Thesis 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 140-150 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
• 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 / sec) at 134 kV
• Actual fusion rate probably 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 can give 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</th>
<th>Inferred Total Fusion Rate</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>
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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