Angular and Energy Distributions of H$_3^+$ in an Ion Trap

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Overview

1. Scientific Background
2. The Apparatus
3. My Work
4. Conclusions
5. Acknowledgments
Cosmic Cycle of Gas

Diffuse Cloud → Dense Molecular Cloud → Protostellar Core → Protoplanetary disks → Stars and Planets
What are Dense Molecular Clouds?
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- \( n = 10^4 \text{ cm}^{-3} \)
What are Dense Molecular Clouds?

- 10-20 K
What are Dense Molecular Clouds?

- Ion-neutral reaction driven chemistry
What are Dense Molecular Clouds?

- Cosmic rays initiate the chemistry in DMCs instead of UV photons.
$H_3^+$ formation

$$H_2 + \text{cosmic ray} \rightarrow H_2^+ + e^- + \text{cosmic ray}'$$

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$
$\text{H}_3^+$ Chemistry

- $\text{H}_3^+$ is major driver in the chemistry of DMCs
  - Reacts as a proton donor

- Participates in many ion-neutral reactions which tend to be barrierless and exoergic
  - Favored due to the low temperatures characteristic of DMCs
H$_3^+$ Observations

- H$_3^+$ has no dipole moment:
  - No pure rotational spectrum
  - Not excited at DMC temperatures

- Observation of H$_2$D$^+$ and D$_2$H$^+$:
  - Has dipole moment
  - Can be excited at these low temperatures
  - Enables the H$_3^+$ abundance to be inferred
  - Formed from two possible reactions
\[ \text{H}_3^+ \text{ Deuteration} \]

- \[ \text{H}_3^+ + \text{HD} \rightarrow \text{H}_2\text{D}^+ + \text{H}_2 \]
  - Rate coefficient calculations are beyond quantum mechanical capabilities
  - Reaction rates known experimentally up to 15\% uncertainty

- \[ \text{H}_3^+ + \text{D} \rightarrow \text{H}_2\text{D}^+ + \text{H} \]
  - Rate coefficient calculations are beyond quantum mechanical capabilities
  - Classical and semi-classical calculations differ by almost an entire order of magnitude
  - No experiments have been done
Merged Fast-Beams Apparatus
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Measuring the Cross Section

\[ \sigma = \left( \frac{S}{T_a T_g \eta} \right) \left( \frac{e^2 v_D v_{H_3^+}}{I_D I_{H_3^+}} \right) \left( \frac{1}{\Omega} \right) \]  \hspace{1cm} (1)

- \( \sigma \) = absolute cross section
- \( S \) = Count rate
- \( e \) = elementary charge
- \( v_D, v_{H_3^+} \) = D and H_3^+ velocity
- \( I_D, I_{H_3^+} \) = D and H_3^+ current
- \( \Omega \) = Overlap factor
Cross Section Measurement

- $\text{H}_3^+ + \text{D} \rightarrow \text{H}_2\text{D}^+ + \text{H}$
Internal Energy Problem

- Beam production leads to unknown internal excitation of $\text{H}_3^+$
Ion Source Issues

- Gives hot \( \text{H}_3^+ \)
- Continuous source
- Duty Cycle = 100%
- \( S = 10 \text{ s}^{-1} \)

- Gives cold \( \text{H}_3^+ \)
- Pulsed
- Duty Cycle \( 10^{-4}\% \)
- \( S = 10^{-3} \text{ s}^{-1} \)
Solution for Higher Beam Current

- Simulate $\text{H}_3^+$ ion trajectories
- Determine trapping voltage for $\text{H}_3^+$ ions
- Determine angular distribution
- Determine energy distribution
Ion Trap Trajectory Simulations

- Modeling performed using SIMION, an ion optics simulation program

- Trap Characteristics:
  - 2D cylindrically symmetric potential array

- Beam Characteristics:
  - 2500 particles
  - Energy = 18.02 keV
  - Conical Distribution of 1 mrad
  - Simulations used either 5 mm or 10 mm diameter beam
  - Required a trapping voltage of 28.71 kV
Angular Distribution Measurements

- Angular distributions from the center of the trap for a 5mm beam after 50 cycles:

![Angular Distributions](image)
Trapping Efficiency

- Measurements taken at the center of the trap after 5, 10, and 50 cycles:

![Graph showing percentage of particles with angular distributions that fall between -0.006 to 0.006 radians in 5mm beam as a function of time.](image)

- The graph plots the percentage of particles as a function of cycles.
Angular Distribution Measurements

- Angular distributions from the center of the trap for a 10mm beam after 50 cycles:
Trapping Efficiency

- Measurements taken at the center of the trap after 5, 10, and 50 cycles:

![Graph showing percentage of particles with angular distributions that fall between -0.006 to 0.006 radians in a 10mm beam as a function of time.](image)
Measuring the angular distributions allows us then measure the relative energy distributions of this reaction. For mono-energetic beams:

\[ E_r = \mu \left( \frac{E_n}{M_n} + \frac{E_i}{M_i} - 2\sqrt{\frac{E_n E_i}{M_n M_i}} \cos \theta \right) \]  

- \( \mu \) = reduced mass
- \( E_n \) = Energy of neutrals (12 keV - D)
- \( E_i \) = Energy of ions (18.02 keV - \( \text{H}_3^+ \))
- \( M_n \) = Neutral Mass (1.88 GeV/c^2 - D)
- \( M_i \) = Ion Mass (2.81 GeV/c^2 - \( \text{H}_3^+ \))
- \( \theta \) = Intersection angle
Energy Distribution Measurements
Conclusions

- The angular distributions over time were kept minimal
- We can keep the majority of the beam in a defined range.
- Enables us maximize the beam current from the pulsed gas jet while minimizing beam loss from the trap
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