Production and trapping of $C_2^-$ in a digital RF trap

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Talk Outline

• Motivation of the experiment
• $\text{C}_2^-$ production
• Mass selection
• Trapping results
• Outlook for spectroscopy of $\text{C}_2^-$
• Outlook for laser cooling of $\text{C}_2^-$
• Outlook for sympathetic cooling of antiprotons
MOTIVATION

• Main goal: Show laser cooling with anionic species ($\text{C}_2^-$)
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• Only a few atomic anions with the necessary electric dipole transitions known: La$^-$, Os$^-$, Ce$^-$
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WHY not another anionic species?
• Only a few atomic anions with the necessary electric dipole transitions known: La-, Os-, Ce-
• These ions have very complex level schemes in a magnetic field due to Zeeman splitting
Valve Chamber

Even-Lavie Valve

- 5% C₂H₂, 3% CO₂ in He
- Supersonic expansion
- followed by DBD discharge
- DBD discharge
  - Current in discharge limited by dielectric barrier
  - Very short current spikes
  - No electric arc
  - No avalanche breakdown
  - No particle heating
- Production of ionic molecules in vibrational ground state

This is important for spectroscopy and laser cooling of C₂⁺
3mm Skimmer

- Particle beam goes through skimmer
- Pulsed acceleration to 1.8 keV
  Necessary because of space charge effects
- Beam steering in electronic lenses
Wien velocity filter
Wien velocity filter

Measurement of mass spectrum with elongated tube and MCP detector
Beam Bender redirects particles “around the corner”
Beam Bender separates charged from neutral particles
Beam Bender redirects particles “around the corner”

Beam Bender separates charged from neutral particles

$\text{C}_2^-$ and other anions

Electronic lenses steer beam in front of deceleration stage
Deceleration stage
- Glass tube coated with high resistive ink
- Gold meshes at both ends of tube
- Provides homogenous static electric field

Particle deceleration to a few eV in static electric field (~1.8 kV)
MCP detectors

- The whole trap including electronics is floated to deceleration voltage (~1.8 kV)
- Linear ion trap is driven by an RF switch up to 3 MHz
- Static field at endcaps via push pull switch
Digital ion trap

- Trap driven by RF switch (up to 3 MHz)
Digital ion trap

- Digital trap driven by RF switch
- Radial kick out possible

MCP detectors
Digital ion trap

• Digital trap driven by RF switch
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• Digital trap has rectangular waveform
Digital ion trap

- Digital trap driven by RF switch
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- Digital trap has rectangular waveform
- Digital trap can change the duty cycle

![Graph showing the change in duty cycle (d = 50% and d = 60%)](image)

Duty cycle $d = 50\%$

Duty cycle $d = 60\%$
Digital ion trap

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"Virtual" DC field

Duty cycle $d = 50\%$

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- Duty cycle can be used for mass selection

“Virtual” DC field

Mathieu stability diagram (analog trap)

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Mathieu stability diagram (analog trap)

\[ a_x = -a_z = \frac{4eU}{mr^2\omega^2} \quad q_x = -q_z = \frac{2eV}{mr^2\omega^2} \]

“Virtual” DC field

Analog linear Paul trap

Digital ion trap

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Mathieu stability diagram (analog trap)

Analog linear Paul trap

$$\alpha_x = -a_z = \frac{4eU}{m r^2 \omega^2}$$

$$q_x = -q_z = \frac{2eV}{m r^2 \omega^2}$$

Analog vs digital trap a/q ratio

$$\frac{a}{q} = \frac{2U_{dc}}{V_{rf}} = \frac{2d - 1}{4d(1 - d)}$$

\[ a_x = -a_z = \frac{4eV}{mr^2 \omega^2} \]

\[ q_x = -q_z = \frac{2eV}{mr^2 \omega^2} \]

\[ \frac{a}{q} = \frac{2U_{dc}}{V_{rf}} = \frac{2d - 1}{4d(1 - d)} = \text{slope of working line} \]

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\[ \frac{a}{\eta} = \frac{2U_{dc}}{V_{rf}} = \frac{2d - 1}{4d(1 - d)} = \text{slope of working line} \]

Scanning this line by changing \( \Omega \)

$\text{C}_2^-$ spectroscopy

Two step mechanism:

- $X \rightarrow A$ transition with IR laser $\lambda = 2.5$ \text{um}
- Photodetachment with UV laser $\lambda = 399$ \text{nm}

$$\text{C}_2^- + h\nu \rightarrow \text{C}_2 + e^-$$

Photodetachment Cooling

• Step 1: \( X \rightarrow A \) transition with detuned IR laser \( \lambda = 2.5 \ \text{um} \)

Only the hottest ions are excited

• Step 2: Photodetachment with UV laser \( \lambda = 399 \ \text{nm} \)

\[
C_2^- + h\nu \rightarrow C_2 + e^-
\]
Photodetachment Cooling Simulation (Penning Trap)

• Step 1: X \rightarrow A transition with detuned IR laser $\lambda=2.5$ um

  Only the hottest ions are excited

• Step 2: Photodetachment with UV laser $\lambda=399$ nm

$C_2^- + h\nu \rightarrow C_2 + e^-$

Kinetic energy of $C_2^-$ is decreasing

• AC stark shift with dipole laser (blue detuned from resonance by 1 GHz)
• Pump laser resonant with shifted levels
• Lifetime excited state 50 us
• Cooling time ~ 10s
• Doppler cooling time >100s (narrow linewidth X → A)
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Simulated Sisyphus Cooling


- $T_{\text{init}} = 10$ K
- $B = 5$ T
- Yellow: standing wave pattern included
- Blue: not included
Simulated Sisyphus Cooling


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Simulated Sympathetic Cooling

- Adopted model to shorten simulation time
- 20% of $C_2^-$ replaced by mass $m'$ particles
Thank you!
Fig. 29 a: Excitation waveform high voltage burst (1kV at 0.5 microseconds spacing). Notice the short duration of the light (current) pulses. b: Cross section of the D6D electrode. The high voltage pulses are applied to the magnet disc outside the ceramic nozzle.