Interactions in Cold, Trapped Dilute Gas Mixtures

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Academic Chronology

- **Doctoral Thesis (TIFR, India)**
  - Resonant electron capture to molecules
    - Dissociative electron attachment
    - Some accelerator based work

- **Post-Doctoral Research (Institut d’Optique, France)**
  - Bose Einstein Condensation, Atom Lasers, Trap Design

- **Post-Doctoral Research (MPQ, Germany)**
  - Cold molecules; guides, electrostatic molecule traps, time varying electrostatic traps for atoms and molecules, Cold atoms.
Dissociative Electron Attachment
Bose-Einstein Condensation and Atom Lasers
Cold Molecule Beams and Traps

- Gas Inlet 10^3-10^1 mbar
- Channel
- Mass-Spectrometer
- Ion pump
- Differential pumping stages

- TMP 300 l/s
- TMP 500 l/s
- Ti Sublimator

- r = 2.2 cm
- l_guide = 50 cm
Experiments at RRI: Study of Interactions

At RRI, we

• Trap and cool: atoms, ions and molecules
• This is done simultaneously for any combination of the above
• These overlapped trapped ensembles interact in very specific way
• The goal is to measure the interactions between these systems
• Interactions are collisions at very cold temperatures

• **We study;**
  1. How collisions affect the energetics in the partners
  2. Quantum Interactions
  3. Methods for non-destructive detection of interactions
  4. …
Some two particle asymptotic interaction energies

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion – Ion</td>
<td>$V_{\text{ion-ion}}(r) \propto \pm \frac{q_1 q_2}{r}$</td>
</tr>
<tr>
<td>Ion – Dipole</td>
<td>$V_{\text{ion-d}}(r) \propto -\frac{\mu_1 q_2}{r^2}$</td>
</tr>
<tr>
<td>Dipoles – Dipoles</td>
<td>$V_{\text{d-d}}(r) \propto \pm \frac{\mu_1 \mu_2}{r^3}$</td>
</tr>
<tr>
<td>Dipoles – Dipoles</td>
<td>$V_{\text{d-d}}(r) \propto -\frac{\mu_1^2 \mu_2^2}{r^6}$</td>
</tr>
<tr>
<td>Ion – Atom</td>
<td>$V_{\text{ion-at}}(r) \propto -\frac{q_1 \alpha_2}{r^4}$</td>
</tr>
<tr>
<td>Atom – Atom</td>
<td>$V_{\text{at-at}}(r) \propto -\frac{\alpha_1 \alpha_2}{r^6}$</td>
</tr>
</tbody>
</table>

static dipoles
freely rotating dipoles
Our Hybrid Trap experiment: concept

- Ions
- Atoms
Atom-Ion-Molecule-Light Hybrid Trap: Detail

Linear Paul trap electrodes and extraction electrodes for the spherical Paul trap

Both ion trap endcap electrodes

Trapped atom density at the center of the experiment

Volume for stable ion trapping

Spherical Paul trap rf electrodes
Collisional cooling or buffer gas cooling:

The neutral buffer gas floods the entire volume of the ion trap

In this situation ions are collisionally cooled by the neutral atoms when...

<table>
<thead>
<tr>
<th>Mass of Ion (M_I) / Mass of Atom (M_A)</th>
<th>Cooled/Heated</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)        M_I / M_A &lt;&lt; 1</td>
<td>Rapid Heating</td>
</tr>
<tr>
<td>(b)        M_I / M_A ~ 1</td>
<td>No Heating/Cooling</td>
</tr>
<tr>
<td>(c)        M_I / M_A &gt;&gt; 1</td>
<td>Cooled</td>
</tr>
</tbody>
</table>
**Experimental schematic:** ATOM ION MOLECULE

- **Rb\(^+\) ions**
- **Rb MOT**

Rb\(^+\) ions are optically dark

Rb MOT has 2.3 \(10^6\) atoms at a temperature of 100\(\mu\)K
Ion cooling for mass ratios $>$, $=$, $<$ 1

(a) $m_A / m_i = 1.565$

(b) $m_A / m_i = 1.00$

(c) $m_A / m_i = 0.639$

$\text{Rb}^+ / \text{Cs MOT} + \text{BG}$

$\text{Cs}^+ / \text{Cs MOT}$

$\text{Cs}^+ / \text{Rb MOT}$
Cooling due to localization
The Motion Trapped Ions

Overall motion = macromotion
Macromotion is the ion motion in the effective secular potential of the trapping fields

Field synchnonous Motion = micromotion
Forced motion with RF field

Collisional cooling of trapped ions: 2 cases

Case 1: Ion trajectory smaller than volume of uniform gas density

Case 2: Ion trajectory larger than volume of gas density

Wuerker and Langmuir, 1959
Ion cooling by collisions with stationary atoms

\[ \vec{c} = \vec{u} + \vec{v} \]

\[ \vec{c}' = (m_A/M)c \hat{\theta}_c + (m_I/M)c. \]

After substitution and manipulation

\[ u'^2 - u^2 = -2m_I m_A (u^2 + 2\mathbf{u} \cdot \mathbf{v} + v^2)(1 - \cos \theta_c)/M^2 + 2m_A (v^2 + \mathbf{u} \cdot \mathbf{v} - c \hat{\theta}_c \cdot \mathbf{v})/M. \]

Case 1 \( \langle |\mathbf{u}| \rangle \to 0 \) and \( \langle |\mathbf{v}| \rangle \gg 0 \)

ion cooling for \( m_A < m_I \)

no net change of ion temperature for \( m_A = m_I \)

ion heating for \( m_A > m_I \)

Major & Dehmelt, 1968

Case 2 \( \langle |\mathbf{u}| \rangle \gg 0 \) and \( \langle |\mathbf{v}| \rangle \to 0 \)

The ion cools irrespective of the mass ratio

For fastest cooling, \( m_I = m_A \) is the best ratio
Resonant Charge Exchange Cooling

When Rb and Rb$^+$ collide, charge exchange process is resonant at all collision energies.
Cross sections for elastic and RCE collision, and their ratio

\[ \sigma_{\text{ion-at}}(E) \propto \frac{1}{E^{1/3}} \quad \text{Cs-Cs}^+ \]

\[ \sigma_{\text{ion-at}}^{\text{elastic}}(E) \propto \frac{1}{E^{1/2}} \quad \text{Elastic} \]

\[ \sigma_{\text{ion-at}}^{\text{chg-exch}}(E) \propto \frac{1}{E^{1/2}} \quad \text{Resonant Charge Exchange} \]
Ion cooling for mass ratios $>$, $=$, $<$ 1

(a) $m_A / m_I = 1.565$
(b) $m_A / m_I = 1.00$
(c) $m_A / m_I = 0.639$

Rb$^+$ / Cs MOT + BG  
Cs$^+$ / Cs MOT  
Cs$^+$ / Rb MOT
From Classical Mobility to Hopping Conductivity: Charge Hopping in an Ultracold Gas

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FIG. 3. Schematic of an experiment to detect charge hopping: ions are formed at the “tip” of the cold gas (a), and a weak electric field accelerates them toward a detector (b). If $T$ is varied, the time of flight should exhibit two time scales (c).

\[ \sigma_{\text{cond}} = n_h e \mu_h + n_{\text{ion}} e \mu_{\text{ion}} = n_{\text{ion}} e \mu_{\text{tot}}, \]

where $\mu_{\text{tot}} = \mu_h + \mu_{\text{ion}}$ is the total mobility, and $\mu_h$ and $\mu_{\text{ion}}$ are, respectively, the hole and the ion mobility. We

FIG. 2. In a gas with few ions, the absence of charge in a positive ion can be regarded as a hole with a positive charge. In (a), the electron from the nearest neighbor ($d_1 < d_2$) tunnels through to the empty level of Na$^+$ (or the hole jumps to the neutral atom). In (b), the shaded region represents the probability $P(x)$ of the neutral atom to be within the hopping radius $\rho_{\text{ch}}$ if the ion is located at $x$. 

\[ p_{\text{ion}}(x, x_i) \]

\[ \rho_{\text{ch}} \]

\[ P(x) \]

\[ p_{\text{at}}(x, x_A) \]
The DiLi$^+$thium (and Ca$^+$ experiment)
The experimental schematic

(a) MOT beams

Blue laser beam

Probe light

Mirror

-5 V

V_{rf}

-5 V

PMT

(b) $F' = 3$

(c) $F' = 3$

VRS

(d) $F' = 3$

$F = 2$
An example of possible activity in AEgIS - I

- One of the principal challenges for the g measurement with $\overline{H}$ is the formation of $\overline{H}$ in large quantities.
- A process to create this involves double charge exchange.
- A suitable precursor for this is the availability of trapped $H^-$.

$$H_2 + e \rightarrow [H_2^-]^* \rightarrow H^- + H$$

This process needs to be done in an ion trap, which has never been done (to my knowledge), so that the $H^-$ ions are collected in the ion trap in large numbers.

This is done at pressures of $1 \times 10^{-7}$ mbar.
An example of possible activity in AEgIS - II

The $H^-$ so created needs to be transported to the UHV ion trap.

This can be done by adapting the neutral trap differential pumping and transport designs, and ion transport in quadrupole structures is fairly routine.
An example of possible activity in AEgIS - III

\[ H^- + h\nu \rightarrow H, \]

Creation of a Rydberg protonium by capture of the proton with an anti-proton

Intersection with a positron cloud trapped downstream

Creation of \( \overline{H} \)
People

Graduated Doctoral Students:
K. Ravi
Arijit Sharma
Seunghyun Lee
S. Jyothi
Tridib Ray
Rahul Sawant

Current Doctoral Students:
Niranjan Myneni
Nishant Joshi
Subodh Vashist
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Anand Prakash
Arun Bahuleyan
Vardhan Thakar
Gokul V I

Post Doctoral Researchers (Past):
N Bhargava Ram
Sourav Dutta
Amrendra Pandey

Post Doctoral Researchers (Future):
Sachin Barthwal

Collaborations (Past and Present):
Dmitry Budker (U. C. Berkeley), Derek F Kimball (Cal State East Bay),
Guenter Werth (University of Mainz), Olivier Dulieu and Daniel Comparat
(Laboratoire Amie Cotton), Bruno Laburthe-Tolra (Uni. Paris XIII)