Cold and ultracold molecules

Cold

- Few (≈ 5 – 10) partial wave scattering
- $T \sim 0.1 – 1$ K

Ultracold

- Single partial wave scattering
- $T \sim 0.000001$ K

Notes:
Temperature scale (Kelvin)
Temperature scale (Kelvin)

cold
Temperature scale (Kelvin)

- ultra-cold
- cold
Temperature scale (Kelvin)

- **ultra-cold**
- **cold**
- **warm**
- **hot**
Temperature scale (Kelvin)

- ultra-cold
- cold
- warm
- hot

Coldest T in the Universe
How to create ultracold molecules?

Notes:
How to create ultracold molecules?

- Photoassociation of ultracold atoms
  (Stwalley, Demille, Bigelow, Heinzen, Masnou-Seeuws, ...)

- Feshbach resonance sweep
  (Jin, Ketterle, Wieman, Cornell, Heinzen, ...)

- Stark deceleration of molecular beams
  (Meijer, Barker, Peters, Friedrich, ...)

- Skimming
  (Abraham, Shafer-Ray, ...)

- Free expansion
  (Gupta, Friedrich, Hershbach, ...)

- Buffer gas loading
  (Doyle, Peters, ...)

- Optical dipole force slowing
  (DeMille, ...)

- Mechanical slowing
  (Gupta, Hershbach, ...)

- Sympathetic cooling by collisions with ultracold atoms
  (Meijer, ...)

- Billiard-ball-like collisions to stop molecules
  (Chandler, ...)

Notes:
Magnetic trap

Magnetic field

middle of the trap
Evaporative cooling

Trapping potential

Elastic collisions

Length

$T > T_c$

$T < T_c$

$T << T_c$

1.0 mm
Why study ultracold molecules?

New phases of matter
Molecular BEC
BEC of polar species
(Ketterle, Wieman, Cornell, Jin, Pfau, Doyle ...)

Quantum computation with
cold trapped molecules
(DeMille, Lukin, Doyle ...)

Test of fundamental symmetries
Search for time variation of
fundamental constants
(DeMille, Ye, Prentiss, Flambaum ...)

Chemistry in the quantum regime
Bose-enhanced chemistry
Controlled molecular dynamics
(Balakrishnan, Bohn, Hutson, Dalgarno, Kosloff, Doyle ...)

Notes:
Are chemical reactions possible at such low temperatures?
Reactions at ultralow temperatures

\[ \text{Typical Rate Coefficient} \]

\[ \text{Temperature (K)} \]

A + BC → AB + C

Balakrishnan et al., PRL 80, 3224 (1998)

Notes:
Reactions at ultralow temperatures

A + BC → AB + C

Balakrishnan et al., PRL 80, 3224 (1998)

Notes:
Reactions at ultralow temperatures

\[ \text{A} + \text{BC} \rightarrow \text{AB} + \text{C} \]

Balakrishnan et al., PRL 80, 3224 (1998)

Notes:
Reactions at ultralow temperatures

A + BC $\rightarrow$ AB + C

Balakrishnan et al., PRL 80, 3224 (1998)

Notes:
Reactions at ultralow temperatures

Notes:
Reactions at ultralow temperatures

Wigner’s laws:
elastic cross section ~ constant
reaction cross section ~ 1/velocity
Reactions at ultralow temperatures

Wigner’s laws:
elastic cross section ~ constant
reaction cross section ~ 1/velocity

rate ~ velocity \times \text{cross section}
elastic rate ~ 0
reaction rate ~ constant

Notes:
Reactions at ultralow temperatures

Quantum Dynamics of Ultracold Na + Na₂ Collisions
Pavel Soldán, Marko T. Cvitaš, and Jeremy M. Hutson
Department of Chemistry, University of Durham, South Road, Durham DH1 3LE, England
Pascal Honvault and Jean-Michel Launay
UMR 6627 du CNRS, Laboratoire de Physique des Atomes, Lasers, Moléculales et Surfaces, Université de Rennes, France
(Received 3 May 2002; published 18 September 2002)

Zero temperature reaction rate \( \approx 5 \times 10^{-10} \, \text{cm}^3 \, \text{s}^{-1} \)

Chemistry at ultracold temperatures
N. Balakrishnan *, A. Dalgarno
Institute for Theoretical Atomic and Molecular Physics, Harvard Smithsonian Center for Astrophysics, 60 Garden Street,
Cambridge, MA 02138, USA
Received 22 February 2001; in final form 26 April 2001

\[ F + H₂ \rightarrow HF + F \] reaction: Zero temperature reaction rate \( \approx 10^{-12} \, \text{cm}^3 \, \text{s}^{-1} \)

Notes:
Chemical reactions do occur at subKelvin temperatures!

They may be very efficient!

Notes:
External field control of molecular collisions
Principles of the Quantum Control of Molecular Processes

MOSHE SHAPIRO
PAUL BRUMER
“Experimental and theoretical studies of the Coherent Control of unimolecular processes have seen spectacular growth over the last two decades. By contrast, Coherent Control of collisional processes remains a significant challenge...”

Paul Brumer, DAMOP 2007, Bulletin of the APS
Thermal gas is difficult to control
Low temperature gas under external field
Low temperature gas in superimposed fields
Feshbach resonance
Effective potential for interaction between two atoms or molecules

s-wave

p-wave
Zero electric field
Zero electric field

100 kV/cm
Zhiying Li and RK:
Electric-field-induced Feshbach resonances in ultracold alkali-metal mixtures

Z. Li and R. V. Krems*
Department of Chemistry, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1
(Received 25 November 2006; published 13 March 2007)

Total Control over Ultracold Interactions via Electric and Magnetic Fields

Bout Marcelis, Boudewijn Verhaar, and Servaas Kokkelmans
Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
(Received 3 October 2007; published 18 April 2008)

The scattering length is commonly used to characterize the strength of ultracold atomic interactions, since it is the leading parameter in the low-energy expansion of the scattering phase shift. Its value can be modified via a magnetic field, by using a Feshbach resonance. However, the effective range term, which is the second parameter in the phase shift expansion, determines the width of the resonance and gives rise to important properties of ultracold gases. Independent control over this parameter is not possible by using a magnetic field only. We demonstrate that a combination of magnetic and electric fields can be used to get independent control over both parameters, which leads to full control over elastic ultracold interactions.
Chemical reactions in magnetic traps
Spin-changing reactions

$\text{Na}(^2S) + \text{CaH}(^2\Sigma) \rightarrow \text{NaH} + \text{Ca}$
Energy diagram of a $^2\Sigma$ diatomic molecule

How do electric fields affect spin relaxation?

• Induce couplings between the rotational levels ($N = 1$)
• Increase the energy gap between the rotational levels

Enhancement of spin relaxation

- **First-order Stark effect**

Enhancement of spin relaxation (a 3D view)
Reactions in confined geometries
Quantum Gases in Confined Geometries

Reactions at ultralow temperatures

Wigner’s laws:
elastic cross section ~ constant
reaction cross section ~ 1/velocity

rate ~ velocity \times cross section
elastic rate ~ 0
reaction rate ~ constant

Notes:
Threshold collision laws

<table>
<thead>
<tr>
<th>Collision</th>
<th>3D</th>
<th>quasi-2D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$-wave elastic</td>
<td>$\sigma = \text{const}$</td>
<td>$\sigma \sim \frac{1}{v \ln^2 v}$</td>
</tr>
<tr>
<td>$s$-wave reaction</td>
<td>$\sigma = \frac{1}{v}$</td>
<td>$\sigma \sim \frac{1}{v \ln^2 v}$</td>
</tr>
<tr>
<td>$s$-wave to non-$s$-wave</td>
<td>$\sigma \sim v^{2l'}$</td>
<td>$\sigma \sim v^{2</td>
</tr>
<tr>
<td>non-$s$-wave to non-$s$-wave</td>
<td>$\sigma \sim v^{2l+2l'}$</td>
<td>$\sigma \sim v^{2</td>
</tr>
</tbody>
</table>

Chemical dynamics in an ultracold quasi-2D gas,
Zhiying Li and RK, manuscript in preparation
\[ \psi_\alpha(r) = \frac{i \sqrt{\pi}}{\kappa_r} e^{-ik_ar - S_{\alpha \alpha} e^{ik_ar}} \phi_\alpha Y_{00}(\hat{r}) \]
\[ \psi_\alpha(r) = i \sqrt{\pi} \eta \varphi_0(0) \frac{1}{\kappa_r} e^{-ik_ar - S_{\alpha \alpha} e^{ik_ar}} \phi_\alpha Y_{00}(\hat{r}) \]
\[ \left[ -\frac{\hbar^2}{\mu} \Delta + V(r) + \frac{\mu \omega_z^2}{4} - \frac{\hbar}{2} \nu_0 \right] \psi(r) = E \psi(r) \]
\[ \psi(\vec{r}) = \left[ \varphi_0(z) J_0(qp) + A_0 \mathcal{G}_e(\vec{r}, 0) \right] \phi_\alpha Y_{00}(\hat{r}) \]
\[ \psi(\vec{r}) = \left[ \varphi_0(z) e^{i \vec{q} \cdot \vec{r}} - f_{00}(\epsilon) \varphi(z) \sqrt{\frac{i}{8 \pi q p}} e^{i \vec{q} \cdot \vec{r}} \right] \phi_\alpha Y_{00}(\hat{r}) \]
\[ f_{00} = -A_0 \varphi_0(0) \theta(\epsilon - \hbar \omega_0) \]
\[ \frac{\cos kr}{kr} - i \frac{\sin kr}{kr} - \frac{S_{\alpha \alpha}}{kr} - \frac{i S_{\alpha \alpha}}{kr} \]
\[ \psi_\alpha(\vec{r}) = i \sqrt{\pi} \eta \varphi_0(0) \phi_\alpha Y_{00}(\hat{r}) \]
\[ \psi(\vec{r}) = \left[ \frac{1}{kr} - i - S_{\alpha \alpha} \frac{1}{kr} - i S_{\alpha \alpha} \right] \]
\[ \left[ 1 + i \frac{\sqrt{\pi} \eta \varphi_0(0)}{\kappa_0} (1 - S_{\alpha \alpha}) + \sqrt{\pi} \eta \varphi_0(0)(1 + S_{\alpha \alpha}) \right] \]
\[ G_e(\vec{r}, 0) \approx \frac{1}{4 \pi r} + \frac{1}{4 \pi \sqrt{2 \pi l_0^2}} \frac{\omega}{2 \hbar \omega_0} \]
\[ \omega(\frac{\epsilon}{2 \hbar \omega_0}) = \ln(B \hbar \omega_0/\pi \epsilon) + i \pi \]
\[ \psi(\vec{r}) = [\varphi_0(z) J_0(qp) + A_0 \mathcal{G}_e(\vec{r}, 0)] \phi_\alpha Y_{00}(\hat{r}) \]
\[ = [\varphi_0(z) + A_0 \mathcal{G}_e(\vec{r}, 0)] \phi_\alpha Y_{00}(\hat{r}) \]
\[ = [\varphi_0(z) + A_0 \mathcal{G}_e(\vec{r}, 0)] \phi_\alpha Y_{00}(\hat{r}) \]
\[ A_0 = \frac{i \sqrt{\pi} \eta \varphi_0(0)}{\kappa_0} (1 - S_{\alpha \alpha}) \]
\[ \eta = \frac{1}{(1 - S_{\alpha \alpha}) \frac{\omega}{2 \hbar \omega_0}} + \sqrt{\pi}(1 + S_{\alpha \alpha}) \]
\[ \psi_\alpha = \nu_\alpha^{-\frac{1}{2}} r^{-1} \left[ A_\alpha e^{-ik_ar} - B_\alpha e^{ik_ar} \right] \phi_\alpha Y_{00}(\hat{r}) \]
\[ B_\alpha = \sum_{\alpha'} S_{\alpha \alpha} - A_{\alpha'} \quad \mathcal{B}_\alpha = S_{\alpha \alpha} - \mathcal{A}_\alpha \]
\[ = \nu_\alpha^{-\frac{1}{2}} r^{-1} \phi_\alpha Y_{00}(\hat{r}) \]
\[ \left[ A_\alpha e^{-ik_ar} - \sum_{\alpha'} S_{\alpha \alpha} - A_{\alpha'} e^{ik_ar} \right] \]
\[ \psi_\alpha = \nu_\alpha^{-\frac{1}{2}} r^{-1} \left[ \mathcal{A}_\alpha e^{-ik_ar} - \mathcal{B}_\alpha e^{ik_ar} \right] \phi_\alpha Y_{00}(\hat{r}) \]
\[ \psi_\text{inc} = \psi_{\text{incoming}} + \psi_{\text{outgoing}} - \left( \psi_{\text{incoming}} + \psi_{\text{outgoing}} \right) \]
\[ \psi_\text{outgoing} = -\sum_{\alpha' \neq \alpha} \sum_{l'} \nu_{\alpha'}^{-\frac{1}{2}} r^{-1} S_{\alpha' \alpha'} Y_{l'm_l'}(\hat{r}) \]
\[ \psi_\text{outgoing} = \sum_{\alpha' \neq \alpha} \sum_{l'} \nu_{\alpha'}^{-\frac{1}{2}} r^{-1} S_{\alpha' \alpha'} Y_{l'm_l'}(\hat{r}) \]
\[ \psi_{\text{inc}} = \psi_{\text{outgoing}} - \psi_{\text{outgoing}} \]
\[ \psi_{\text{sc}} = \psi_{\text{outgoing}} - \psi_{\text{outgoing}} \]
\[ \psi_{\text{sc}} = \sum_{\alpha' \neq \alpha} \sum_{l'} \nu_{\alpha'}^{-\frac{1}{2}} r^{-1} S_{\alpha' \alpha'} Y_{l'm_l'}(\hat{r}) \]
\[ \psi_{\text{sc}} = \sum_{\alpha' \neq \alpha} \sum_{l'} \nu_{\alpha'}^{-\frac{1}{2}} r^{-1} S_{\alpha' \alpha'} Y_{l'm_l'}(\hat{r}) \]
\[ \psi_{\text{sc}} = \sum_{\alpha' \neq \alpha} \sum_{l'} \nu_{\alpha'}^{-\frac{1}{2}} r^{-1} S_{\alpha' \alpha'} Y_{l'm_l'}(\hat{r}) \]
\[ \psi_{\text{sc}} = \sum_{\alpha' \neq \alpha} \sum_{l'} \nu_{\alpha'}^{-\frac{1}{2}} r^{-1} S_{\alpha' \alpha'} Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
\[ \sigma_{\alpha' \alpha} = \sum_{l'} \sum_{m_l'} \frac{\pi}{k_0} \chi_{\alpha'} Y_{l'm_l'}(\hat{r}) Y_{l'm_l'}(\hat{r}) \]
Elastic collisions
3D collision core

Elastic collisions
\[ \psi(\vec{r}) = \left[ \varphi_0(z) e^{i\vec{q} \cdot \vec{r}} - f_{00}(\epsilon) \varphi_0(z) \sqrt{\frac{i}{8\pi q \rho}} e^{i q \rho} \right] \phi_{\alpha} Y_{00}(\hat{r}) \]
\[ \psi(\vec{r}) = \left[ \varphi_0(z) e^{i\vec{q} \cdot \vec{r}} - f_{00}(\epsilon) \varphi_0(z) \sqrt{\frac{i}{8\pi q \rho}} e^{iq \rho} \right] \phi_{\alpha} Y_{00}(\hat{r}) \]

3D collision core

The wave function is proportional to the regular 3D wave function

Asymptotic region

Elastic collisions
\[ \psi(\vec{r}) = \left[ \varphi_0(z) e^{i\vec{r} \cdot \vec{p}} - f_{00}(\epsilon) \varphi_0(z) \sqrt{\frac{i}{8\pi q \rho}} e^{iq\rho} \right] \phi_\alpha Y_{00}(\hat{r}) \]

3D collision core

The wave function is proportional to the regular 3D wave function

\[ \psi_\alpha(r) = i \sqrt{\pi \eta} \varphi_0(0) \frac{1}{k_\alpha r} \left[ e^{-ik_\alpha r} - S_\alpha e^{ik_\alpha r} \right] \phi_\alpha Y_{00}(\hat{r}) \]

Elastic collisions
Inelastic collisions
Couplings occur in 3D collision core

Inelastic collisions
Couplings occur in 3D collision core

\[ r_e \]

The confined and unconfined channels can be treated separately

Inelastic collisions
From the Schrödinger equation

\[ \psi_{sc}^{\alpha' \neq \alpha} = - \sum_{\alpha' \neq \alpha} \sum_{l'} \sum_{m'_l} \nu_{\alpha'}^{\frac{1}{2}} \frac{i2\pi}{k_\alpha} Y_{00}^* \left( \hat{r}_i \right) e^{i(k_{\alpha'} r - l' \pi/2)} \phi_{\alpha'} Y_{l'm'_l} \left( \hat{r} \right) \]

Couplings occur in 3D collision core

The confined and unconfined channels can be treated separately

Inelastic collisions
From the Schrödinger equation

\[ \psi_{\text{sc}}^{\alpha' \neq \alpha} = - \sum_{\alpha' \neq \alpha} \sum_{l'} \sum_{m'_l} \nu_{\alpha'}^{-\frac{1}{2}} r^{-1} S_{\alpha' l' m'_l}^{\alpha 00} \chi \frac{i2\pi}{k_{\alpha'}} Y_{00}^* (\hat{r}_i) e^{i(k_{\alpha'} r - l' \pi / 2)} \phi_{\alpha'} Y_{l' m'_l} (\hat{r}) \]

Couplings occur in 3D collision core

The confined and unconfined channels can be treated separately

Asymptotic wave function for inelastic collisions:

\[ \psi_{\text{sc}}^{\alpha' \neq \alpha} = \sum_{\alpha' \neq \alpha} \nu_{\alpha'}^{-\frac{1}{2}} f_{\alpha'}^{\alpha} \frac{e^{ik_{\alpha'} r}}{r} \phi_{\alpha'} \]

Inelastic collisions
From the Schrödinger equation

\[ \psi_{sc}^{\alpha' \neq \alpha} = -\sum_{\alpha' \neq \alpha} \sum_{l'} \sum_{m'_l} \nu_{\alpha'}^{-\frac{1}{2}} r^{-1} S_{\alpha' l' m'_l \leftarrow 0 0 0} \chi \frac{i2\pi}{k_{\alpha}} Y_{00}^{*}(\hat{r}_i)e^{i(k_{\alpha'} r - l'\pi/2)} \phi_{\alpha'} Y_{l' m'_l}(\hat{r}) \]

Couplings occur in 3D collision core

The confined and unconfined channels can be treated separately

Asymptotic wave function for inelastic collisions:

\[ \psi_{sc}^{\alpha' \neq \alpha} = \sum_{\alpha' \neq \alpha} \nu_{\alpha'}^{-\frac{1}{2}} \left( \int_{\alpha'}^{\alpha} f_{\alpha'}^{\leftarrow \alpha} \frac{e^{ik_{\alpha'} r}}{r} \phi_{\alpha'} \right) \]

Inelastic collisions
\( ^7\text{Li} + ^6\text{Li}^6\text{Li} \rightarrow ^6\text{Li}^7\text{Li} + ^6\text{Li} \) chemical reaction

\( \sigma_{\text{quasi-2D}} / \sigma_{\text{3D}} \) vs. \( l_0 \) (in units of \( 10^3 \) Bohr)

Graph showing the ratio of cross-sections for quasi-2D to 3D as a function of \( l_0 \). The graph compares elastic collisions and chemical reactions.
Li + HF → LiF + H
Cold controlled chemistry  
Theory of reactive scattering in external fields  
Li + HF → LiF + H  
Molecular collisions in fields

Energy diagram of the reaction Li + HF(v=0, j=0)

Timur V. Tscherbul and Roman V. Krems: Department of Chemistry, University of British Columbia, Vancouver BC, Canada

Effects of electromagnetic fields on cold chemical reactions
Possible applications of cold controlled chemistry
• Inelastic collisions and chemical reactions at ultra-cold temperatures are extremely state selective

→ can be used to produce molecules with inverted populations
→ chemical lasers based on ultra-cold collisions
• Controlled photodissociation of ultra-cold molecules

M. G. Moore and A. Vardi, PRL 88, 160402 (2002):

→ entangled pairs of molecules
→ coherent control of bi-molecular collisions
• Chemical reactions in magnetic traps

→ reactions near tunable avoided crossings
→ geometric phase effects
→ chemical reactions induced by fine interactions
Chemistry in confined geometries

→ stereodynamics of ultra-cold collisions
→ effects of symmetry breaking
→ effects of long-range interactions
Ultracold chemistry

- new regime of molecular dynamics research
- new tool to address fundamental problems
- multidisciplinary research field
- very dynamic and rapidly expanding research area
References


Reviews


Book

Cold Chemistry Group at UBC

Sergey Alyabyshiev
Chris Hemming
Felipe Herrera
Zhiying Li
Timur Tscherbul → Harvard University
Erik Abrahamsson → UBC Physics

Funding:

UBC
Harvard University
Peter Wall Institute for Advanced Studies
CRUCS