ATOMIC AND MOLECULAR ACCELERATION VIA ONE DIMENSIONAL OPTICAL LATTICE

By

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High Speed Flows

Neutral Beam Etching

Surface
High Temperature Gases

High Temp. Boundary Layer
Proof of Concept

• Laser manipulation of atoms and molecules for the creation of high speed flows or high temperature gases
• Such optical techniques have significant precedent in atomic cooling and trapping
• No experimental precedent for energy and momentum deposition
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Standing Wave \( (\omega_1 = \omega_2) \)

\[
E_0 \sin(k_L x + \omega_L t) \quad E^2(x, t) = 4E_0^2 \cos^2(k_L x) \sin^2(\omega_L t) \quad E_0 \sin(k_L x + \omega_L t)
\]
Standing Wave \((\omega_1 = \omega_2)\)

\[ E_0 \sin(k_L x + \omega_L t) \]

\[ E^2(x,t) = 4E_0^2 \cos^2(k_L x) \sin^2(\omega_L t) \]

\[ E_0 \sin(k_L x + \omega_L t) \]
Moving - Standing Wave \((\omega_1 \neq \omega_2)\)

\[
E_{01} \sin(k_{L1} x + \omega_{L1} t)
\]

\[
E_{02} \sin(k_{L2} x + \omega_{L2} t)
\]

\[
E^2 (x, t) = E_{L1}^2 \cos^2 (k_{L1} x - \omega_{L1} t) + E_{L2}^2 \cos^2 (k_{L2} x - \omega_{L2} t)
\]

\[
+ E_{L1} E_{L2} \left[ \cos \left( (k_{L1} - k_{L2}) x - (\omega_{L1} - \omega_{L2}) t \right) + \cos \left( (k_{L1} + k_{L2}) x - (\omega_{L1} + \omega_{L2}) t \right) \right]
\]
Moving - Standing Wave \((\omega_1 \neq \omega_2)\)

\[
E_{01} \sin(k_{L1} x + \omega_{L1} t)
\]

\[
E_{02} \sin(k_{L2} x + \omega_{L2} t)
\]
Dielectric & Capacitor

- Capacitor
- Dielectric Slab
- DC Electric Field
- Force Draws the Dielectric into the Capacitor
- Less Potential Within the Capacitor
Non-Resonant Theory

\[ F = -\nabla U = -\frac{1}{2} \alpha \nabla E^2 \]

Like the dielectric slab in a capacitor, there is a force pulling a particle towards locations of least potential

\[ F = -\frac{1}{2} \alpha \nabla \left[ E_{l1} E_{l2} \left( 1 + \cos(k_{\Delta} x - \omega_{\Delta} t) \right) \right] \]

\[ k_{\Delta} = k_{l1} - k_{l2} \text{ and } \omega_{\Delta} = \omega_{l1} - \omega_{l2} \]

For the intersection of two beams with different frequencies, the force on a polarizable atom or molecules is periodic with a periodicity of half the laser wavelength
Resonant Theory - Unsolvable

\( \alpha \) can no longer be treated as a static polarizability, but must be addressed as a quantum mechanical dipole interaction

\[
i\hbar \frac{\partial}{\partial t} \psi(\vec{r}, t) = \hat{H} \psi(\vec{r}, t)
\]

The analytic formulation of the interaction between a resonant radiating field and an atom is unsolvable
Resonant Theory - Approximation

Assumptions:

• TDPT $\rightarrow$ the radiation field is treated as a perturbation to the atomic state
• Resonant approximation $\rightarrow$ two level system
• Rotating wave approximation $\rightarrow$ fast oscillating terms are ignored
• First order OBE approximation $\rightarrow$ the atom moves slow enough within the field that spatial gradients cause an adiabatic state change within the atom
Resonant Theory – The Force

\[ F = -\hbar q_r \frac{s\delta}{1+s} \left( 1 - \nu x q_r \frac{(1-s)\Gamma^2 - 2s^2(\delta^2 + \Gamma^2/4)}{(\delta^2 + \Gamma^2/4)(1+s)^2\Gamma} \right) \]
High Speed Experiment

852 nm Laser

Modulators

Cs Oven

Optical Lattice

Hot Wire Detection System

852 nm Path (red)

Cesium Path (black)

Vacuum Equip. (blue)
Cs Oven Effluence

Probability [Arb. Units] vs. Velocity [m/s]

- The graph shows the probability distribution of Cs effluence as a function of velocity.
- The probability is expressed in arbitrary units (Arb. Units).
- The velocity range is from 0 to 500 m/s.

Mathematical expression:

\[ P(v) = 3 \times 10^{-3} \left(1 - \frac{v}{100}\right) \]

for \( v \leq 100 \)

\[ P(v) = 3 \times 10^{-3} \left(1 - \frac{100}{v}\right) \]

for \( v > 100 \)

where \( P(v) \) is the probability at velocity \( v \).
Skimmer Transverse Selection

- Probability [Arb. Units]
- Velocity [m/s]

Graph showing probability distribution against velocity.
Hot Wire Detector

• If the work function of the wire exceeds the ionization energy of the atom (>0.5 V) the atom will be ionized by contact with the wire (Ramsey 1956)

• Trade-off between high temperature to drive off adsorption and low temperature to facilitate ionization

• Critical temperature exists such that all impacting atoms will be ionized and not adsorbed (Taylor and Langmuir 1937)
Expected Baseline Signal

Transverse Position [m]

Signal [pA]

$8 \times 10^5$

$6 \times 10^{-1}$

$4 \times 10^{-1}$

$2 \times 10^{-1}$

$0 \times 10^{-1}$

$-0.5$ $-1$ $0$ $0.5$ $1$ $1.5$

$\times 10^{-3}$
Deflected Atoms

- Monte-Carlo simulation using the force of a moving atom in a standing wave
- Start from 0 m/s and accelerate the lattice to 4 m/s in 4 μs = 10^6 m/s²
- Throw out atoms which violate the first order approximation inequality
- After acceleration, let free flight until travelling the distance require to reach the detector
Deflected Atoms

\[ \text{Deflection} [\text{m}] \times 10^{-3} \]

\[ \text{Start Location} \left[ \frac{x}{\lambda_L} \right] \]
High Temperature Simulation

• Non-resonant theory straightforward to implement in existing numerical simulation package
• SMILE DSMC code used as kinetic approach
• Previous work indicates several hundred Kelvin increase in gas temperature during one pulse
Simulation Method

- $Kn \approx 0.2$ for 1 atm gases at 300 K
  - Lattice period = 266 nm
- Axisymmetric DSMC (SMILE code)
- 393 mJ, 100 ps laser pulses
- 532 nm wavelength (Nd:YAG)
- 10.64 μm (x) by 133 μm (r)
Simulation Method

- Pulse simulation duration 200 ps
- Intervening time from 0-10 ns
Intervening Time vs. Gas

- Peaks for N\textsubscript{2} and Ar consistent with relaxation times
- Temperatures fall with increasing time due to diffusion
- Short time N\textsubscript{2} temperature higher than Ar, consistent with polarizability to mass ratio
Nitrogen at 1 atm

0 ns intervening time

10 ns intervening time

1 ns intervening time
How hot can you go?

- Nitrogen with 1 ns intervening time
- 2480 K temperature after 50 pulses
- Higher temperature induces higher thermal diffusion
- Increasing gas temperature prefers shorter intervening time for later pulses
High Temperature Experiments

Beam Positioning

Lattice Interaction

Beam Analysis

Seeded Nd:YAG Laser

Upper Aluminum w/ Sensor Access

Quartz Capillary Wafer

Lower Aluminum w/ Gas Access
Conclusion

• Prove the use of high intensity lasers for the acceleration of atoms and molecules
• Creation of neutral, mono-energetic, high speed flows
• Creation of high temperature, well characterized non-equilibrium flows
• Understand the phenomena for extrapolation to production processes