Strong-field Kapitza-Dirac Scattering of Neutral Atoms

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Outline

• Neutral excited atoms in strong laser fields
  Excitation in the tunneling regime via frustrated tunneling ionization

• Limits on strong-field excitation?
  Stabilization of atoms in strong laser field above $10^{16}$ Wcm$^{-2}$?

• Importance of the intensity gradient in a focused laser field

• Realization of the strong field Kapitza Dirac effect for neutral atoms
Atomic physics in strong laser fields (tunneling picture)

Typical assumptions

- **Traveling wave laser field**
  - laser intensity $< 10^{16} \text{ W/cm}^2$, pulse duration $< 40\text{fs}$, wavelength 800nm

- **Dipole approximation holds**, Keldysh parameter $<1$

  $$\vec{E}(\vec{r},t) \equiv \vec{E}(t)$$

  No electric field gradients, no magnetic fields

Models:

- **Tunneling model** (*Keldysh 1964*):

- **Simple man’s model** (*Gallagher 1988; Muller, VandenHeuvel 1988*)
  - classical motion of an electron in the laser field

- **Special case**: **Rescattering model** (linearly polarized light), *Corkum 1993*
  - Focus on return of the electron to the ionic core (HHG, HATI, NSDI)
  - Electron is considered to be ionized after tunneling
Frustrated tunneling ionization (FTI)

**Extension: Including the Coulomb potential in the trajectory calculation**

- Electron set free close to the maximum of a field cycle gains hardly any drift or recollison energy

- Electron cannot overcome the Coulomb potential, => electron has total energy negative after the laser pulse ⇒ electron is left in a bound Rydberg states

- Excitation of atoms in the tunneling regime

- Strong exit channel, up to 20% of tunneled electrons remain bound

*Nubbemeyer et al., PRL 101, 233001 (2008)*
Frustrated tunneling ionization (FTI)

\[ \vec{F} = m \dddot{x} = -e \vec{E}_0 \cos(\omega t) f(t) + \vec{F}_c \]

Linearly polarized light

\[ \vec{E}_0 = E_0 \hat{e}_x \]

Initial conditions

\[ x(t_{tun}) = x_{tun}, \quad \dot{x}(t_{tun}) = 0; \quad y, z(t_{tun}) = 0, \quad \dot{y}(t_{tun}) = p_{perp} / m \]

Tunneling probability according to strong field tunneling theory
Frustrated tunneling ionization (FTI)

Formation of bound states as a function of the parameter space $p_{\text{perp}}$ and field phase

Energy corresponds to $n = 8$, $\ell = 0-10$

Detection of excited He atoms

He* radiative decay scheme

Position sensitive detector

He atomic beam

Pulsed field strength
Up to 200KV/cm

Time of flight 130μs
Measurement on Helium atoms

Total He*, He* yield

Polarization dependent He⁺, He* yield

Nubbemeyer et al., PRL 101, 233001 (2008)
Confirmation of predicted $n$ distribution


Spin effect: Direct singlet to triplet transitions by excitation of the singlet component of a singlet/triplet wavepacket

For $l > 2$ LS coupling in He breaks down
He excitation at high intensities (according to FTI)
He excitation at high intensities (according to FTI)

Sample trajectory at $10^{17}$ Wcm$^{-2}$

At $10^{17}$Wcm$^{-2}$ electron tunnels at early times

Addressing the old problem: stabilization of atoms in strong laser fields

Intensity gradient in a focused laser field?

Ponderomotive force on neutral atoms through the FTI mechanism

- Quivering electron feels the ponderomotive force during the laser pulse
- As long as the average Coulomb force is higher than $F_p$
  electron drags the ionic core
- After the pulse the electron is bound

Ponderomotive force on electron causes centre of mass motion

$$M \dddot{\mathbf{R}} = -\frac{e^2}{4m_e \omega^2} \nabla |\mathbf{E}_0|^2$$

Neutral atoms feel the ponderomotive force!
Deflection of atoms in strong focused laser fields

Negligible ponderomotive force (heavy atoms)

Ponderomotive force (light atoms, He, Ps)
Deflection of atoms in strong focused laser fields

Highest acceleration of neutral matter: $10^{14} \text{g}$

He at $7 \times 10^{15} \text{ Wcm}^{-2}$

Strong-field Kapitza-Dirac Scattering of Neutral Atoms

- Standing wave laser field (two counterpropagating fs-laser pulses)
  laser intensity $\sim 10^{15}$ W/cm$^2$
- Breakdown of dipole approximation
  \[ \vec{E}(\vec{r},t); \vec{B}(\vec{r},t) \]
  strong field gradient on the wavelength scale: $k = 2\pi/\lambda$
- Tunneling picture + (semi)classical electron dynamics needs to be modified
  \[ E \approx \cos(kz) \quad B \approx \sin(kz) \]

S. Eilzer et al., PRL 112, 113001 (2014)
Kapitza and Dirac (1933)

Reflections of electrons from standing light waves

Kapitza-Dirac effect observable for particles in general

Measurements with electrons (pulse duration several hundred ps, I= 10^{13} W/cm^2)

- ATI electrons (Bucksbaum et al. PRL 1988)
- Free electron beam  Freimund et al., Nature 413, 142 (2001)
- Only recently: fs electron beam diffracted in fs standing wave (D Miller (2008))

Atoms (cold quantum gases) in cw standing light waves (optical lattices, very popular)
Kapitza-Dirac effect

### Classical approach:
- Acceleration of (charged) particles through the cycle averaged force ponderomotive force
  \[ \vec{F}_p \approx -\nabla \left| \vec{E}_0 \right|^2 \]

### Quantum mechanical approach (two-photon process)
- Absorption of one photon from one of the laser pulses
- Stimulated emission by one photon from the counterpropagating laser pulse
  - Net momentum transfer: 2 photon momenta

At low intensity: Bragg scattering (photon picture)
At higher intensities: classical picture (up to 1000 two-photon process)
Standing wave: Circularly polarized beams

\[ \vec{E}_1 = E_0 (\hat{e}_x \cos(\omega t - kz) + \hat{e}_y \sin(\omega t - kz)) \]

\[ \vec{E}_2^{(\pm)} = E_0 (\hat{e}_x \cos(\omega t + kz) \pm \hat{e}_y \sin(\omega t + kz)) \]

\[ I_{sw}^{(-)} = (\vec{E}_1 + \vec{E}_2^{(-)})^2 = 4E_0^2 \sin^2(wt) \]

\[ I_{sw}^{(+)} = (\vec{E}_1 + \vec{E}_2^{(+)})^2 = 4E_0^2[1 + \cos(2kz)] \]

Result: linear polarization, excitation possible
no standing wave

Result: circular polarization, no excitation
full standing wave
Standing wave: Elliptically polarized beams

\[ \vec{E}_1 = E_0 (\hat{e}_x \cos(\omega t - kz) + \hat{e}_y \varepsilon \sin(\omega t - kz)) \]

\[ \vec{E}_2^{(\pm)} = E_0 (\hat{e}_x \cos(\omega t + kz) \pm \hat{e}_y \varepsilon \sin(\omega t + kz)) \]

\[ I_{sw}^{(-)} = (E_1 + E_2^{(-)})^2 = 2E_0^2 \left[ 1 + \varepsilon^2 + (1 - \varepsilon^2) \cos(2kz) \right] \sin^2(\omega t) \]

Linear polarization intensity ("visibility") of the standing wave is tunable
Experimental setup

Excitation volume:
- length of standing wave: $ct = 17 \mu m$
- diameter of standing wave: $2w_0 = 70 \mu m$

Collimated effusive atomic beam ($\text{He, Ne, Ar}$)

No signal from each laser alone!

Position sensitive detector

S. Eilzer et al., PRL112, 113001 (2014)
Final velocity distribution for different gases

$I = 1.5 \times 10^{15} \text{ W/cm}^2$, $\varepsilon = 0.85$

Mass dependent final velocity
Final velocity distribution

Intensity dependence

\( \varepsilon = 0.85 \)

Intensity of standing wave

a) 3.7, b) 4.6, c) 5.5, d) 6.9 \((x10^{14} \text{ W/cm}^2)\)

Dependence on ellipticity
Acceleration in a standing light wave

I ~ cos(2kz)
Excitation probability
~ ADK rate
Intensity gradient ~ sin(2kz)

Final velocity for randomly distributed atoms, acceleration for a fixed time t

Velocity distribution

\[ v \approx \frac{1}{\sqrt{1 - (v/v_0)^2}} \]

\[ v/v_0 \]
Acceleration in standing light wave

First approach: stable atom, polarizability $\sim 1/\omega^2$

Instance of tunneling matters

$$v \approx \nabla I \int_{t_0}^{\infty} \exp \left( -\frac{t^2}{\tau^2} \right) dt$$

$\varepsilon = 0.85$
$\varepsilon = 0.9$
cutoff
Experimental data

Introduction of a maximum gradient intensity above which an atom is assumed to be ionized
Strength determined from experimental results
Results: simplest model

Using experimental parameters, the cutoff gradient determined by best fit is

\[ \epsilon = 0.85 \]

Intensity gradient cutoff: \( 1.5 \times 10^{-4} \) a.u.

Experimental data

Cutoff gradient corresponds to ionizing field for principal quantum number \( n > 4.5 \).
Results: Simplest model

Using experimental parameters, cutoff gradient determined from fit
Full calculations (Coupled Lorentz equation)

S. Eilzer PhD thesis 2015, unpublished
Conclusion

- Excitation of atoms in strong laser fields through frustrated tunneling ionization
- Excited atoms feel the intensity gradient of the focused laser field -> deflection
- Gradient limits excitation to intensities of $5 \times 10^{15}$ Wcm$^{-2}$
- Observation of Kapitza-Dirac scattering of neutral atoms in strong short pulse standing laser waves
  Observed final velocity suggests a scattering rate exceeding $10^{16}$ photons /second
Hamiltonian

\[ H = \frac{1}{2m_i} (\vec{p}_i - q\vec{A}_i)^2 + V(r) \quad i: \text{either ion or electron} \]

Dipole approximation:

\[ \vec{A}(\vec{r}, t) \equiv \vec{A}(t) \quad \vec{A}_x = E_x / \omega \]

CMS and relative coordinates

\[ H = \frac{P^2}{2M} + \frac{p^2}{2\mu} - \frac{e}{2\mu} \vec{A}(t) \cdot \vec{p} + \frac{e^2}{2\mu} \vec{A}^2(t) + V(r) \]

Standing wave:

\[ \vec{A}(\vec{r}_i, t) = -\vec{A}(t) \cos(kz_i) \]

First order:

\[
\begin{align*}
  H &= \frac{p^2}{2\mu} - \frac{e}{2\mu} \vec{A}(t) \cdot \vec{p} \left[ \cos(kZ) + kz \sin(kZ) \right] + V(r) \\
  &+ \frac{P^2}{2M} + \frac{e^2}{2\mu} \vec{A}^2(t) \left[ \cos^2(kZ) + kz \sin(2kZ) \right]
\end{align*}
\]
Kapitza-Dirac-Effect (quantum mechanically, simplest model)

Ponderomotive potential for electrons (neutrals) in a standing wave light field

\[ U_p = \frac{e^2 I}{4m_e \omega^2} \cos^2 kz \]

Quantum mechanics (1D)

\[ H = -\frac{\hbar}{2m} \frac{\partial^2}{\partial z^2} + U_p \]

Wavefunction expanded in plane waves with momentum \( n\hbar k \)

\[ \Psi = \sum_n c_n(t) e^{inkz} \]

solutions
(\( \varepsilon \): kin. energy)

\( \varepsilon \ll \frac{V_0}{\hbar} \)

diffraction regime

\( \varepsilon \gg \frac{V_0}{\hbar} \)

Bragg regime
Kapitza-Dirac-effect for neutrals

\[ |c_n|^2 = J_n^2 \left( \frac{V_0 t}{\hbar} \right) \]
\[ n = 0, \pm 2, \pm 4 \ldots \]

Results similar to classical description (transfer of more than 800 photon momenta)