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} W/cm^2, pulse duration < 40fs, 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:

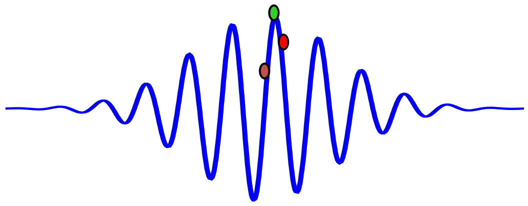
- **Tunneling model** *(Keldysh 1964):*
- **Simple man's model** *(Gallagher 1988; Muller, VandenHeuvell 1988)*
  classical motion of an electron in the laser field
- Special case: **Rescattering model** (linearly polarized light), *Corkum 1993*
  Focus on return of the electron to the ionic core (HHG, HATI,NSDI)
  Electron is considered to be ionized after tunneling

Frustrated tunneling ionization (FTI)

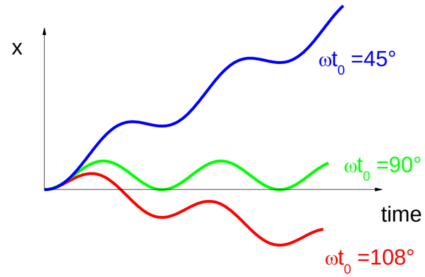
Nubbemeyer et al., PRL 101, 233001 (2008)

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
  $\Rightarrow$ 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

Frustrated tunneling ionization (FTI)

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

Linearly polarized light

$$\vec{E}_0 = E_0 \vec{e}_x$$

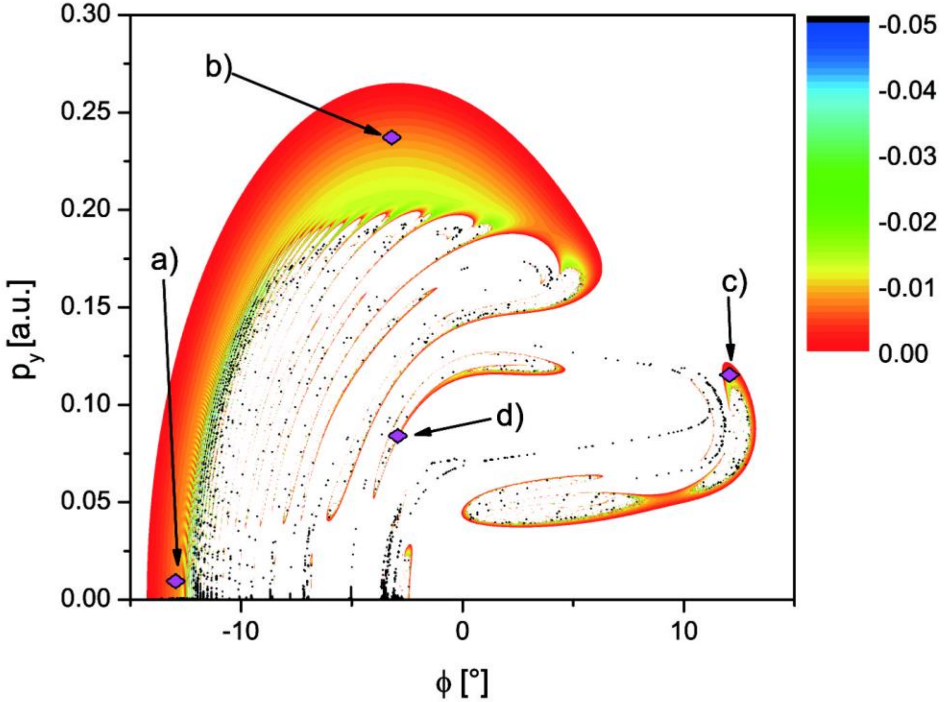
Initial conditions

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

Tunneling probability according to strong field tunneling theory

Frustrated tunneling ionization (FTI)

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



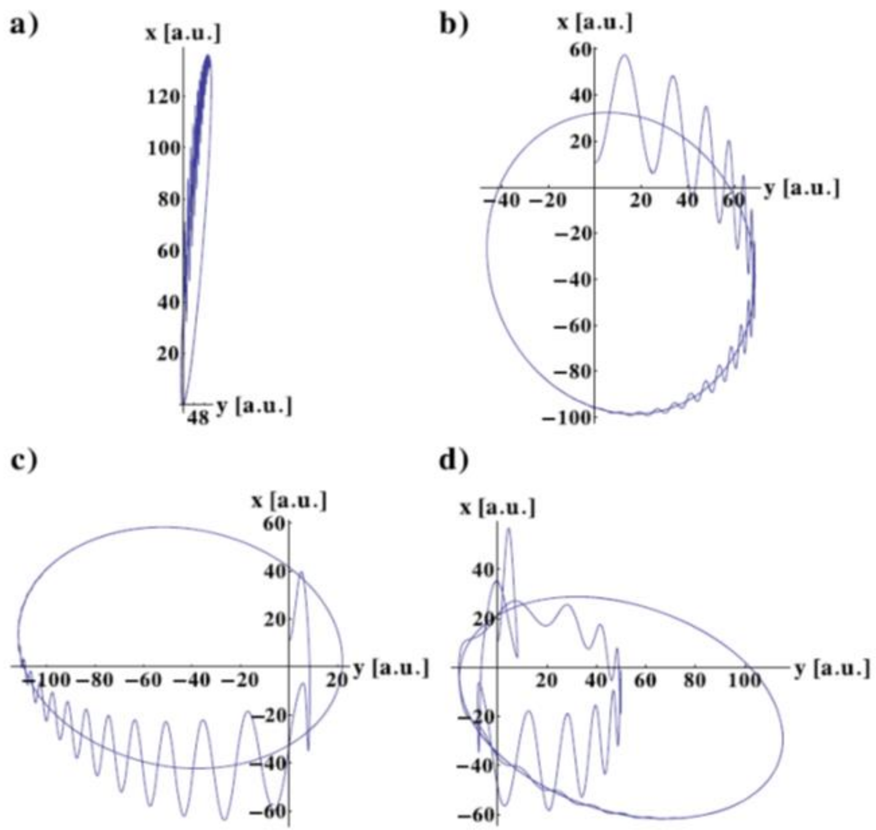
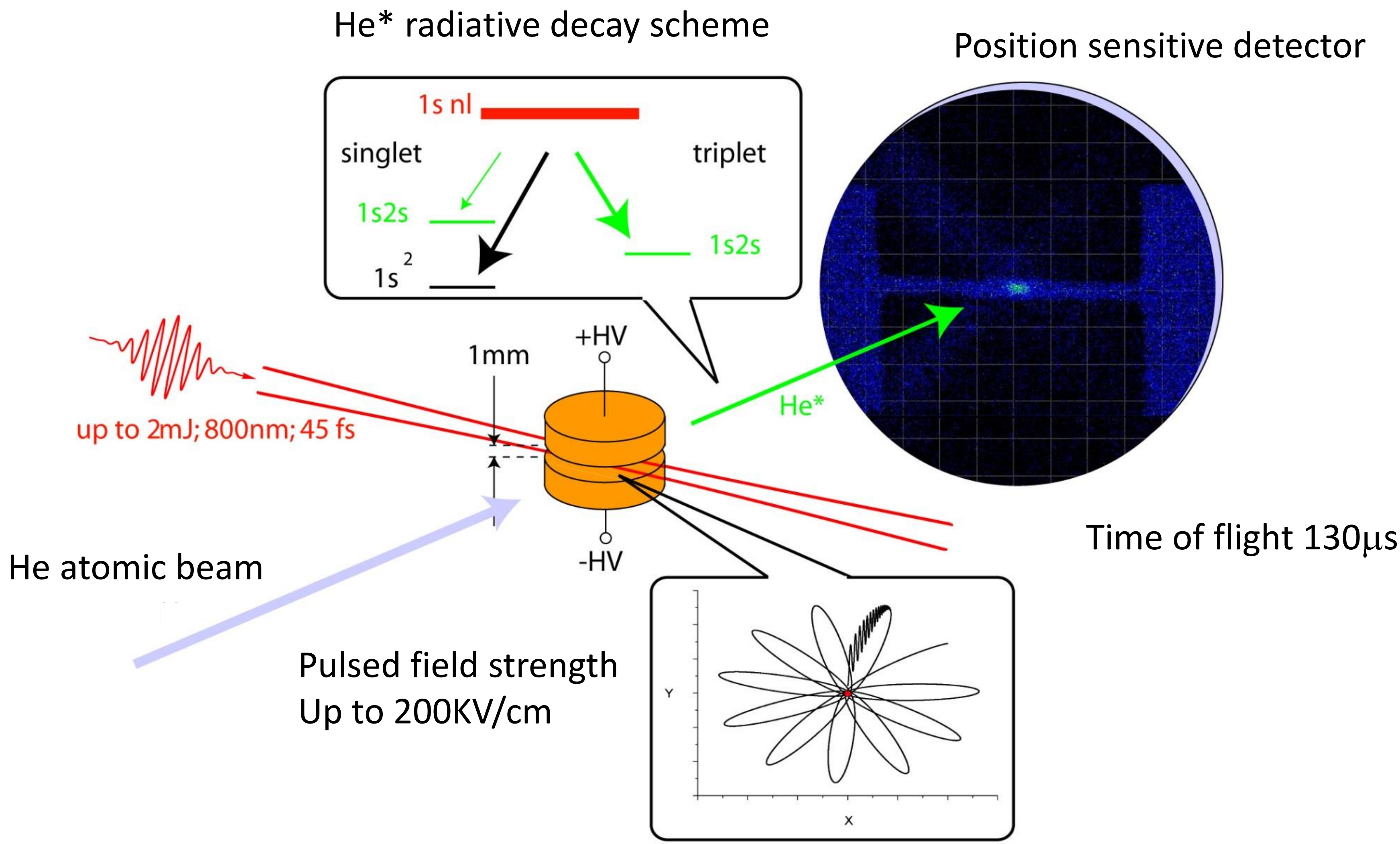


Figure 2. Sample trajectories calculated for initial conditions indicated in figure 1.

Energy corresponds to n = 8 , ℓ =0-10

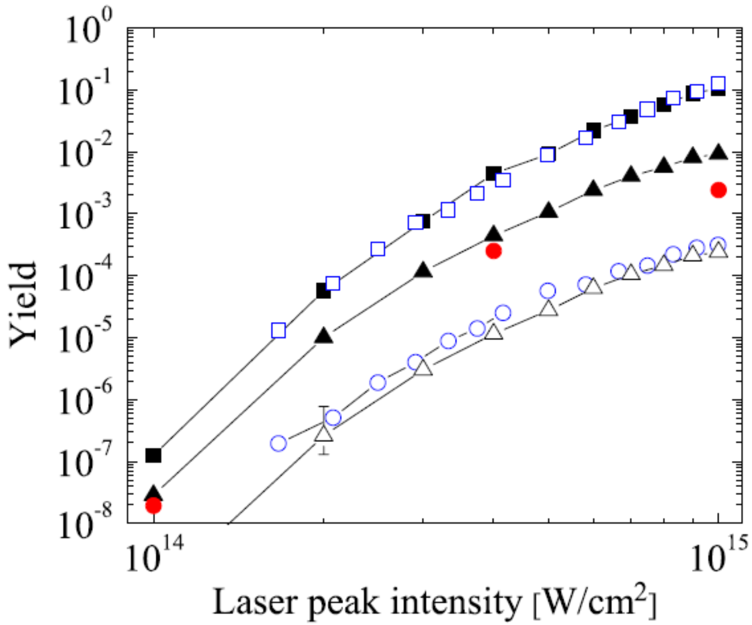
S. Eilzer and U. Eichmann, J Phys B 47, 204014 (2014)

Detection of excited He atoms



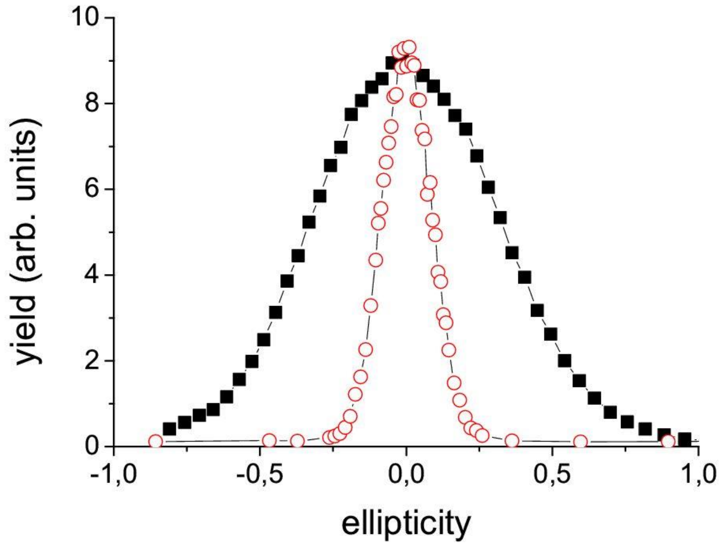
Measurement on Helium atoms

Total He*, He* yield



■	He^+	TDSE (A. Saenz)
▲	He*	
□	He^+	measurement
○	He*	
●	He*	FTI model

Polarization dependent He^+,He* yield



■ He^+

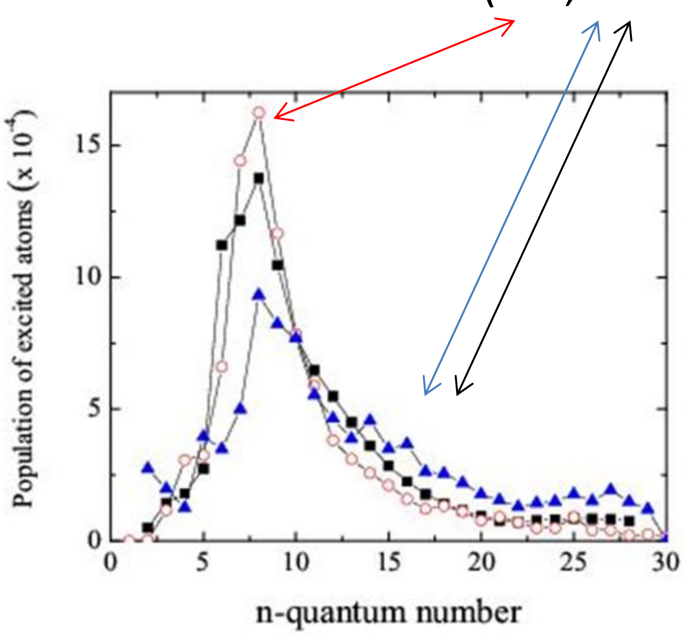
○ He*

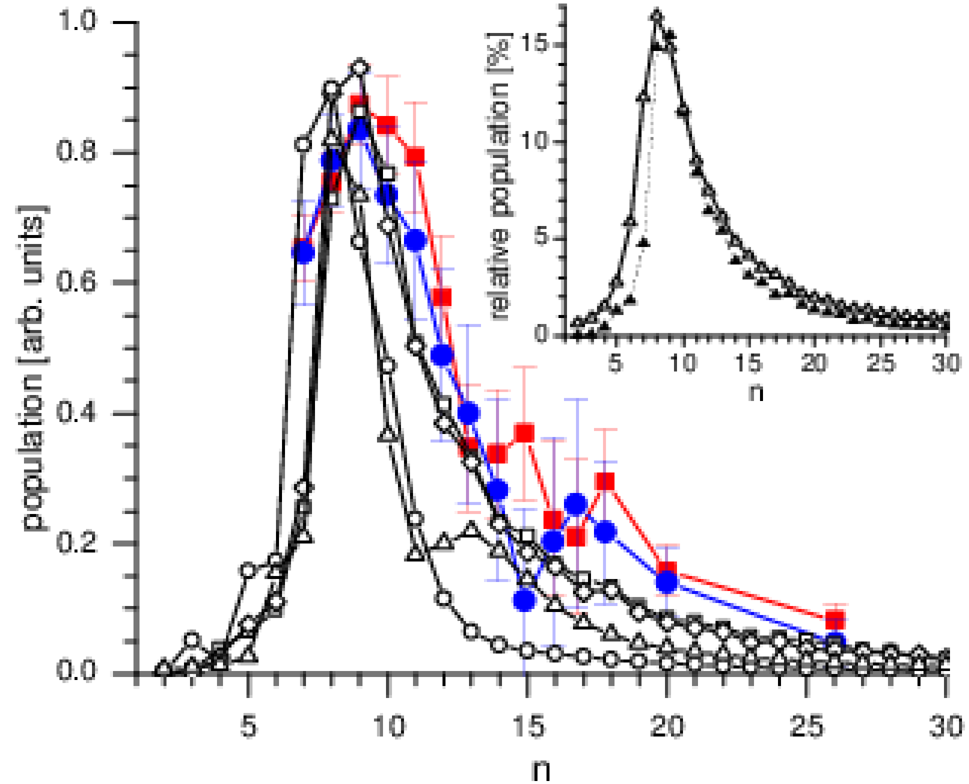
Nubbemeyer et al., PRL 101, 233001 (2008)

Confirmation of predicted n distribution

H. Zimmermann *et al.*,*Phys. Rev. Lett*. **114** 123003 (2015)

Prediction n distribution (FTI, TDSE)



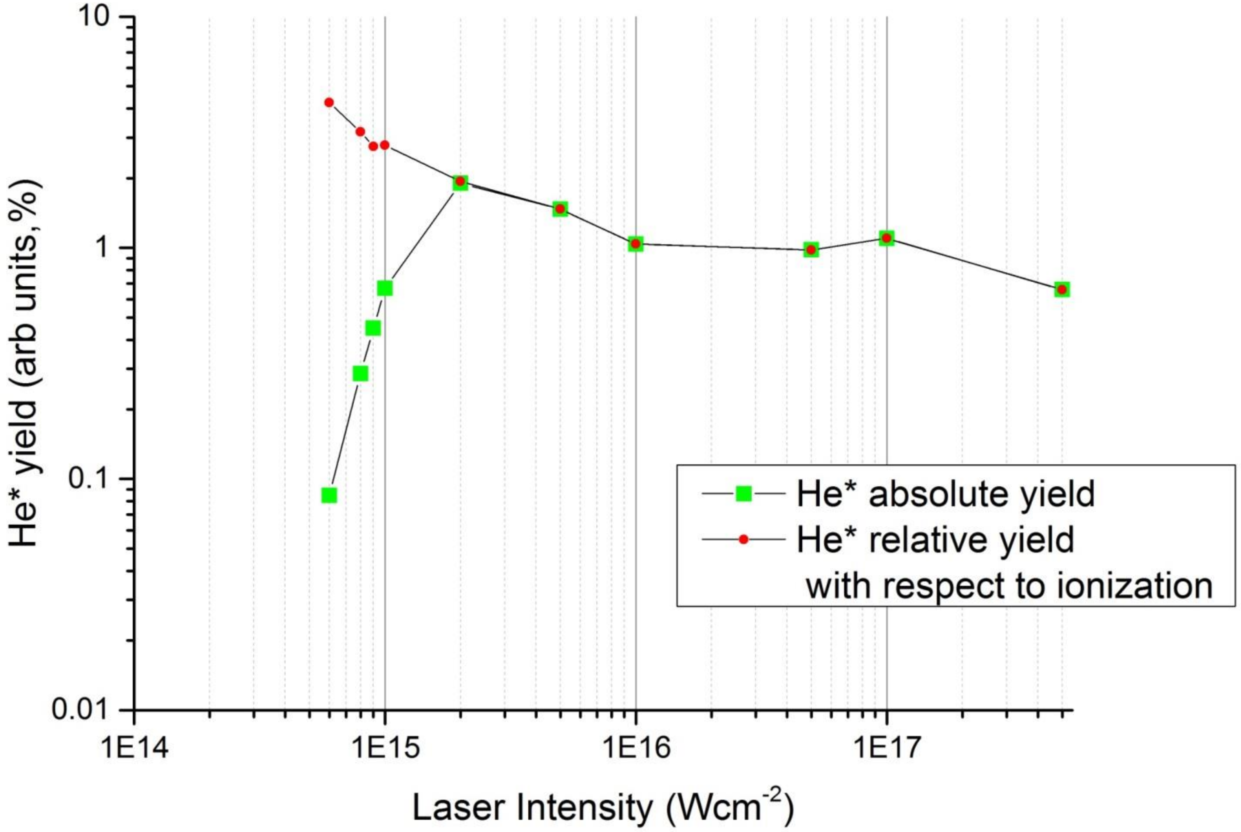


Spin effect: Direct singlet to triplet transitions

by excitation of the singlet component of a singlet/triplet wavepacket

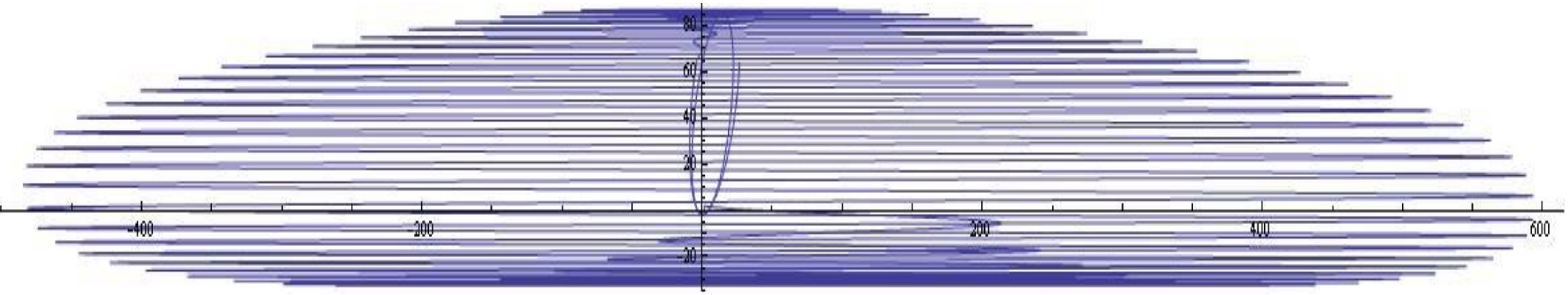
For l >2 LS coupling in He breaks down

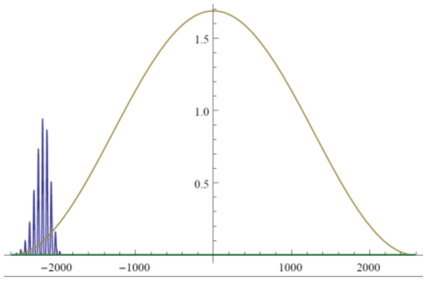
He excitation at high intensities (according to FTI)



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

Henneberger PRL 21 838 (1968), Gavrila et al PRL 1990, Popov et al J. Phys B36 R125 (2003), Morales et al. PNAS2011

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 Fp
  electron drags the ionic core
- After the pulse the electron is bound

:

Ponderomotive force on electron causes centre of mass motion

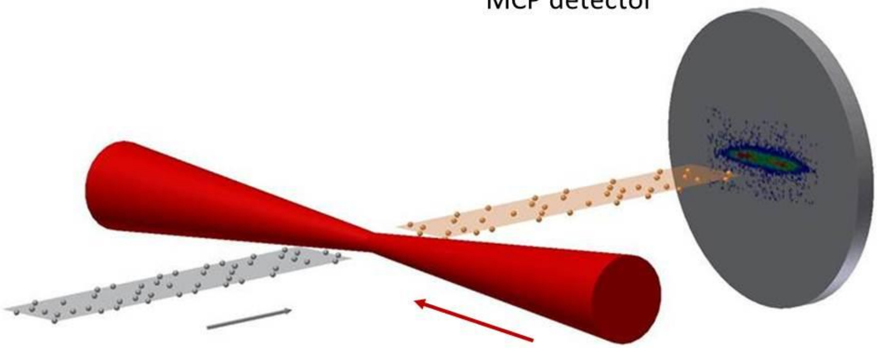
$$M\ddot{\vec{R}} = -\frac{e^2}{4m_e\omega^2}\nabla\left|\vec{E}_0\right|^2$$

equation of motion
for the center of mass

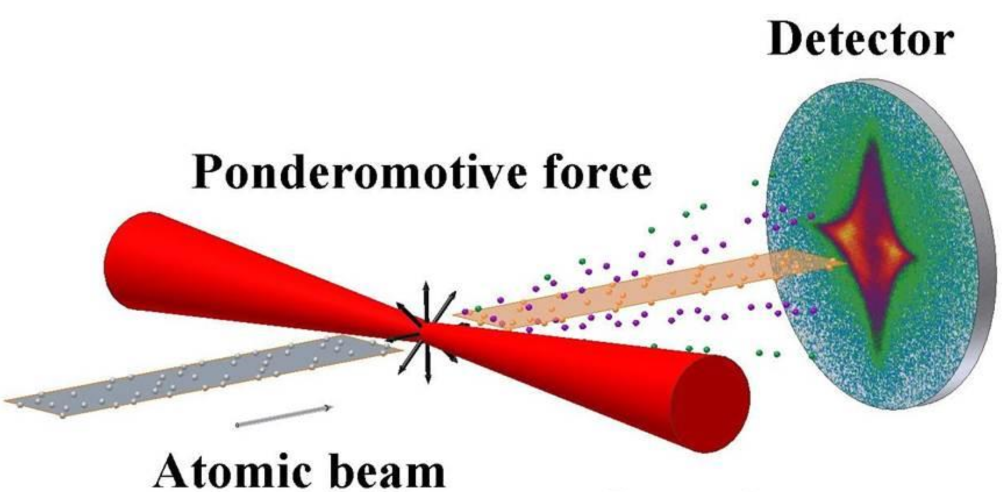
Neutral atoms feel the ponderomotive force!

Deflection of atoms in strong focused laser fields

Negligible ponderomotive force (heavy atoms)



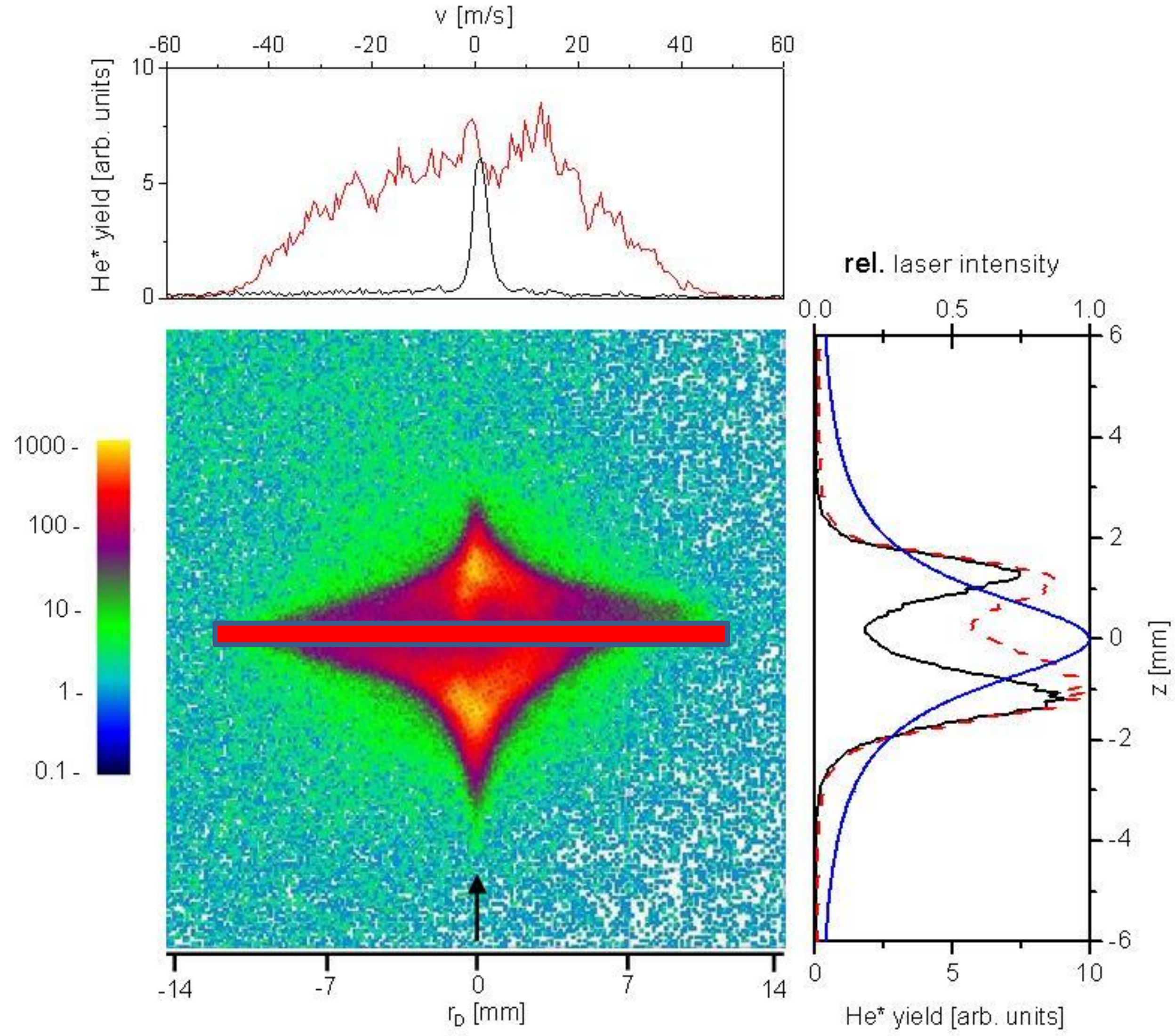
Ponderomotive force (light atoms ,He, Ps)



Deflection of atoms in strong focused laser fields

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

He at 7 10^{15} Wcm^{-2}



U Eichmann et al. Nature 461 1261 (2009)

Strong-field Kapitza-Dirac Scattering of Neutral Atoms

- Standing wave laser field (two counterpropagating fs -laser pulses)
  laser intensity ~ 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

$$E \approx \cos(kz) \qquad B \approx \sin(kz)$$

S. Eilzer et al., PRL112 ,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)

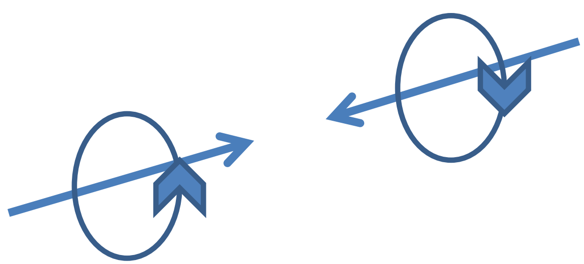
Standing wave : Circularly polarized beams

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

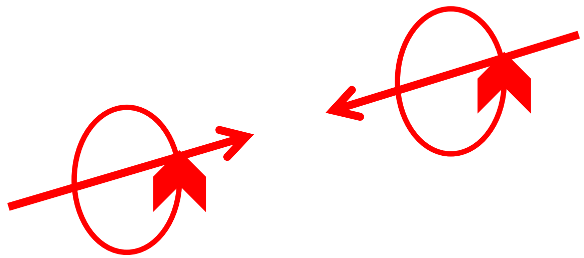
$$\vec{E}_2^{(\pm)} = E_0(\hat{e}_x \cos(\omega t + kz) \pm \hat{e}_y \sin(\omega t + kz))$$

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

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



Result: linear polarization, excitation possible
no standing wave

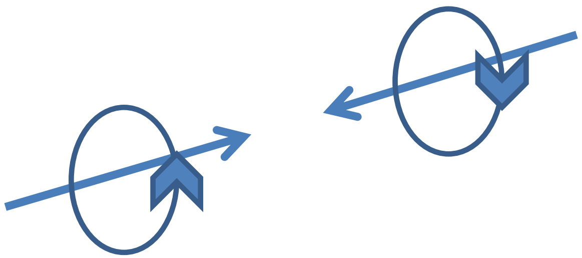


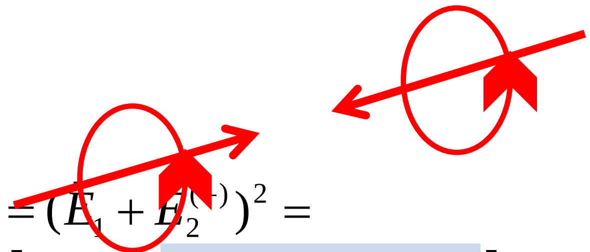
Result: circular polarization , no excitation
full standing wave

Standing wave: Elliptically polarized beams

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

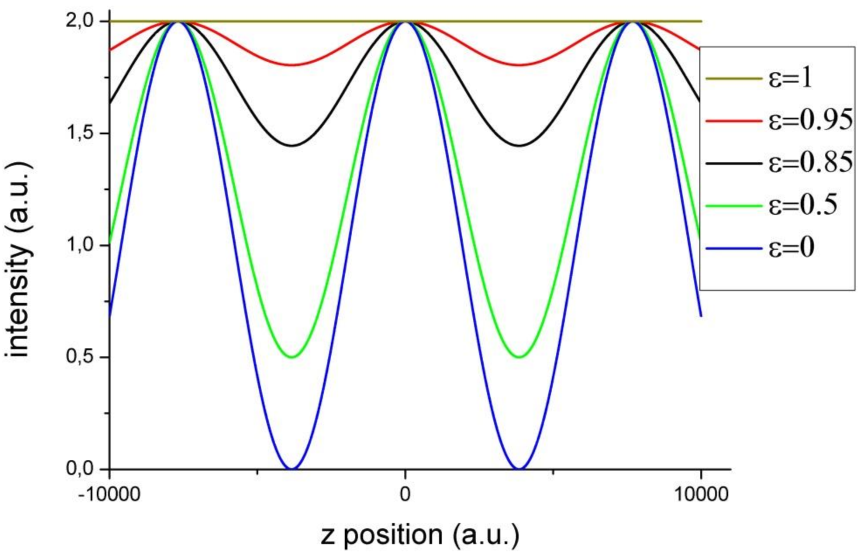
$$\vec{E}_2^{(\pm)} = E_0(\hat{e}_x \cos(\omega t + kz) \pm \hat{e}_y \varepsilon \sin(\omega t + kz)$$





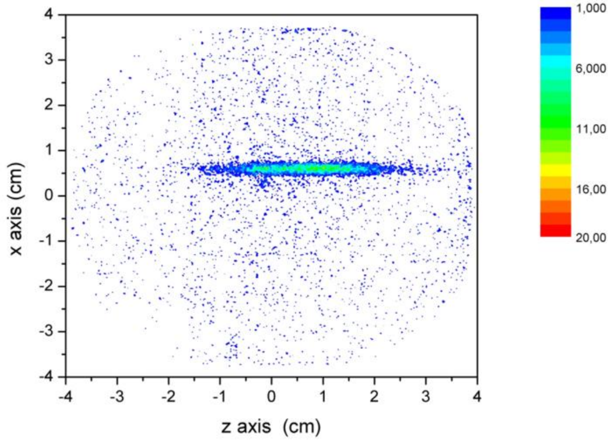
$$I_{sw}^{(-)} = (E_1 + E_2^{(-)})^2 =$$

$$2E_0^2\left[1 + \varepsilon^2 + (1-\varepsilon^2)\cos(2kz)\right]\sin^2(wt)$$

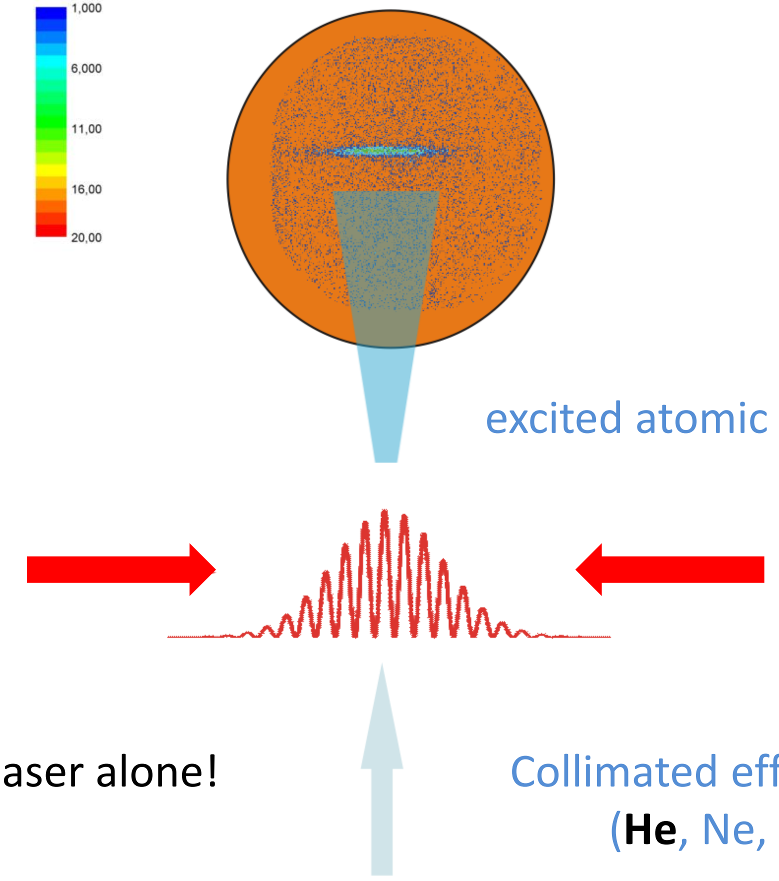


Linear polarization

intensity („visibility“)
of the standing wave is tunable



Position sensitive detector



excited atomic beam

No signal from each laser alone!

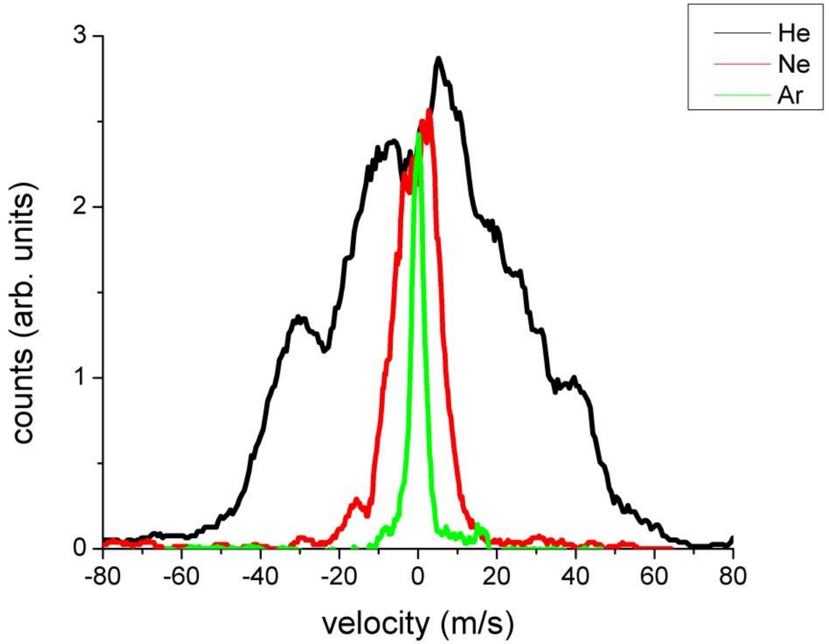
Collimated effusive atomic beam
(**He**, Ne, Ar)

Excitation volume : length of standing wave: $c\tau = 17\mu m$

diameter of standing wave: $2\ w_0 = 70\ \mu m$

S. Eilzer et al., PRL112 ,113001 (2014)

Final velocity distribution for different gases



I= 1.5 10^{15} W/cm^2 , ε =0.85

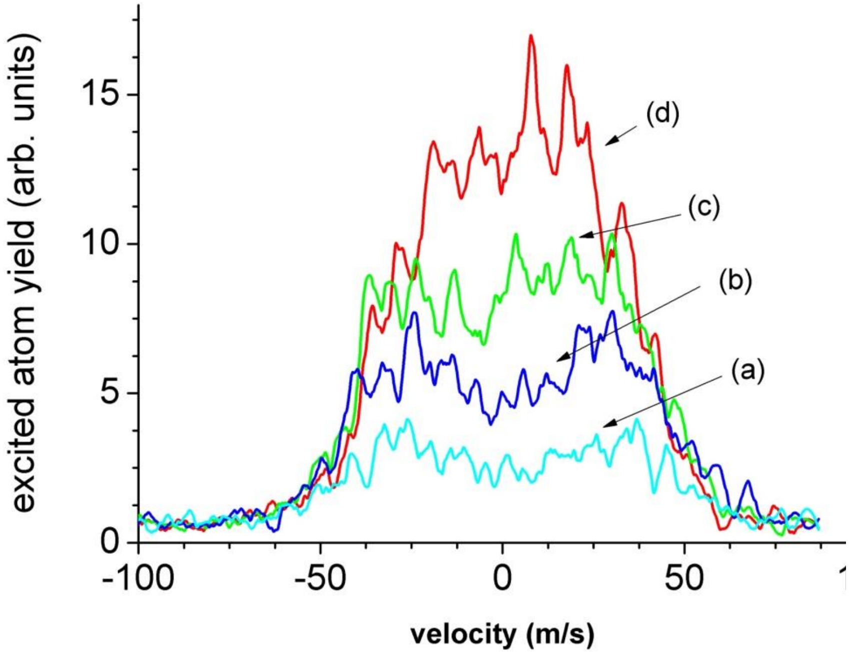
Mass dependent final velocity

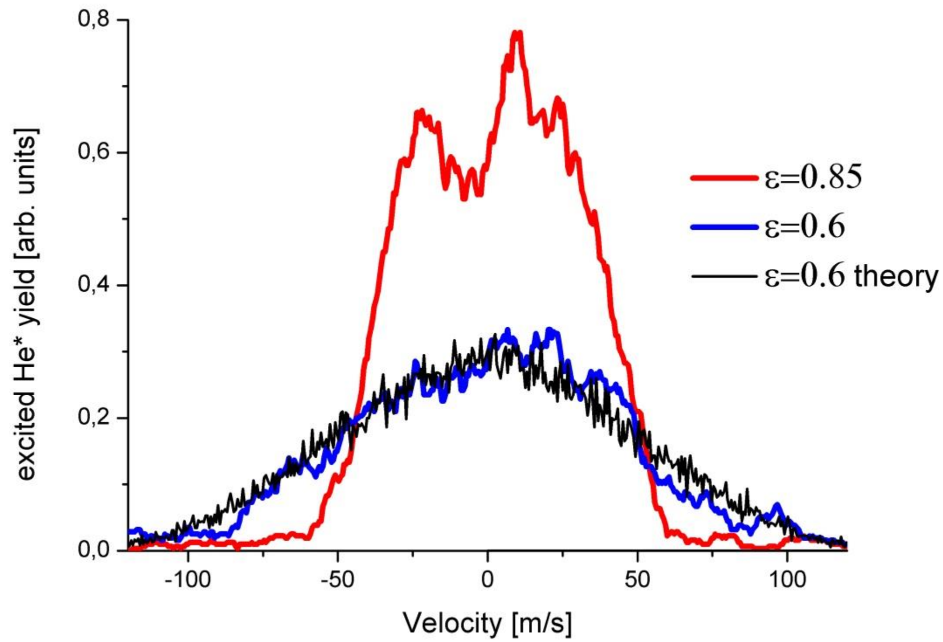
Final velocity distribution

Intensity dependence

ε=0.85

Dependence on ellipticity

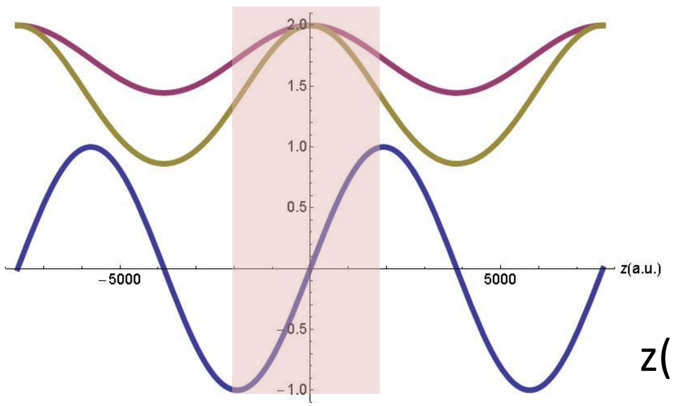




Intensity of standing wave

a) 3.7, b) 4.6 , c) 5.5, d) 6.9 ($\times 10^{14}$ W/cm^2)

Acceleration in a standing light wave



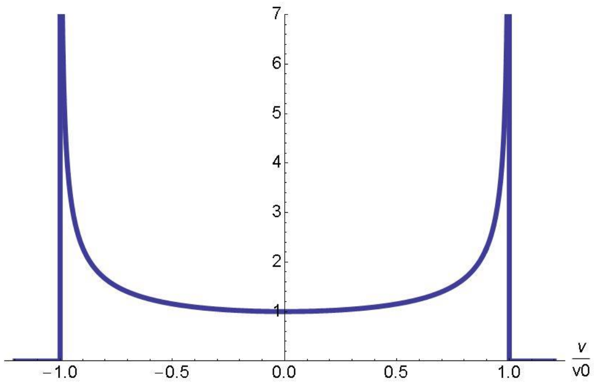
z(a.u.)

I ~ cos(2kz)

Excitation probability
~ADK rate

Intensity gradient ~ sin(2kz)

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



v/v_0

Velocity distribution

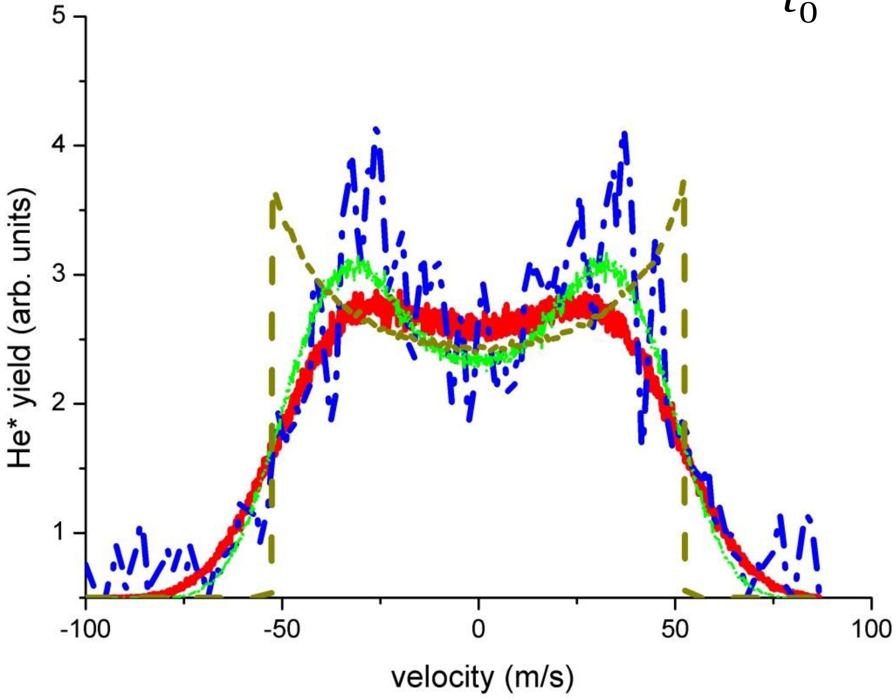
$$v \approx \frac{1}{\sqrt{1-(v/v_0)^2}}$$

Acceleration in standing light wave

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

Instance of tunneling matters

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



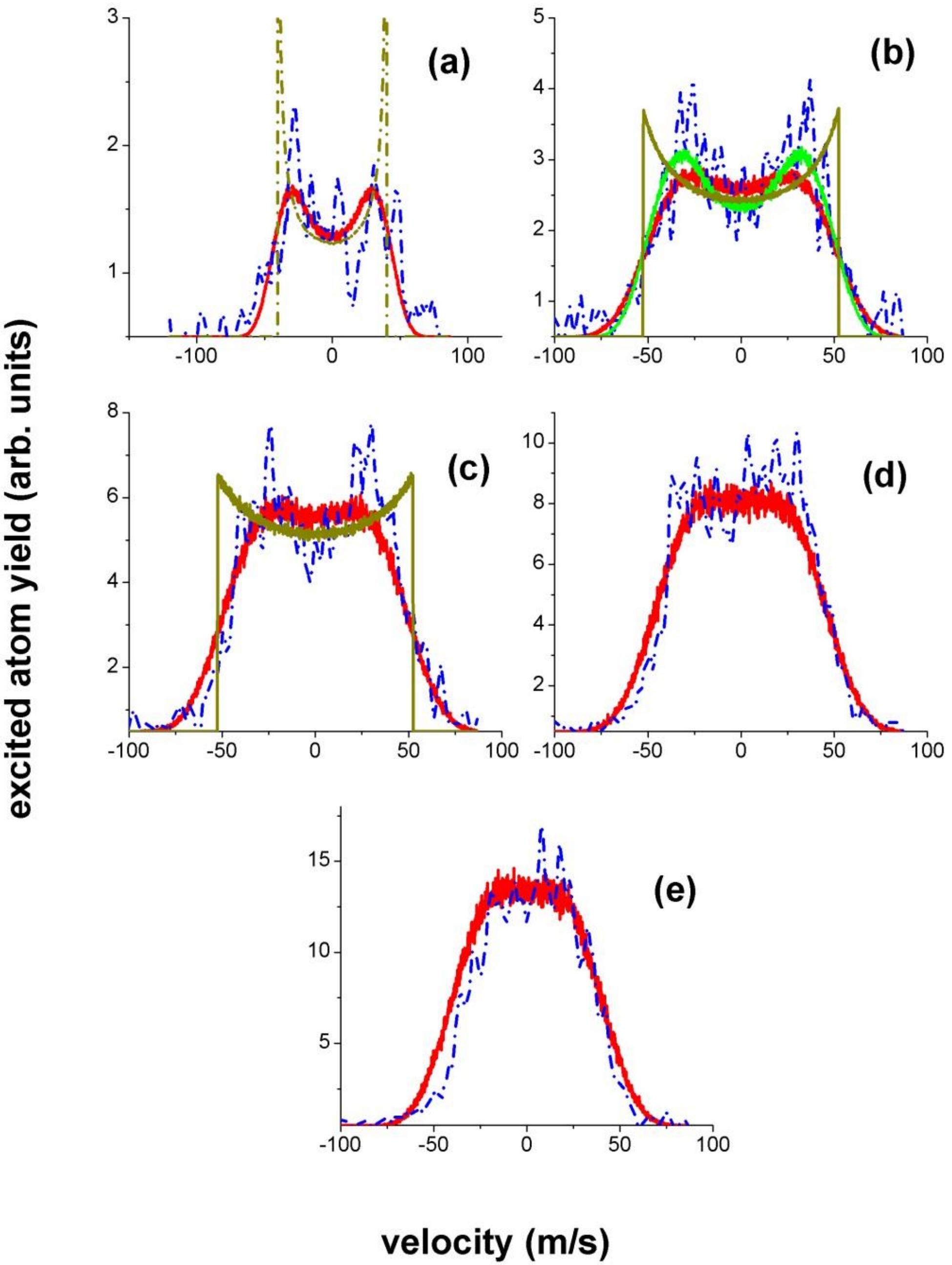
ε= 0.85
ε=0.9
cutoff
Experimental data

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 cutoff gradient determined by best fit



ε= 0.85

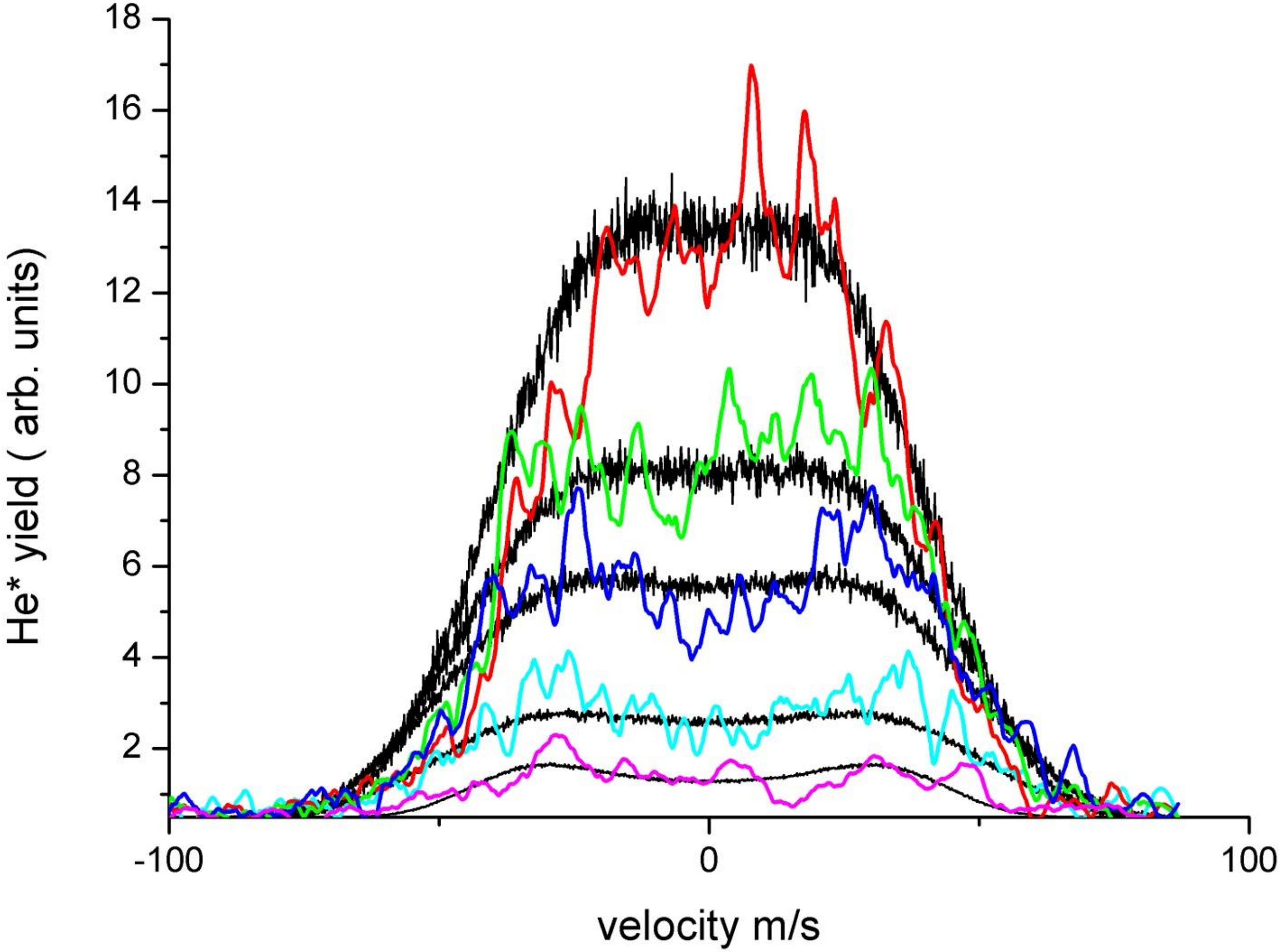
Intensity gradient cutoff **1.5 10^{-4} a.u**.

Experimental data

Cutoff gradient
corresponds to ionizing field for
principal quantum number n>4.5

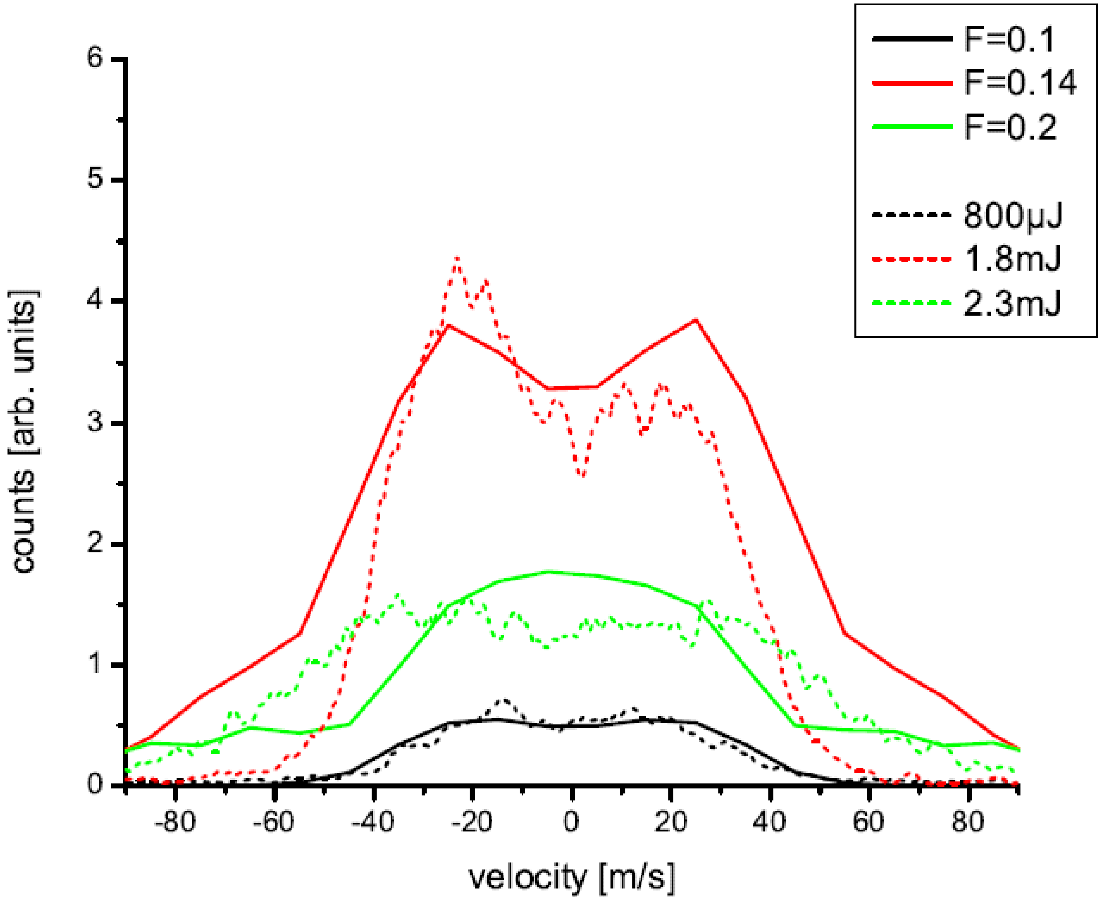
Results: Simplest model

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 10^{15} Wcm^{-2},
- Obervation 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

$$H = 1/2m_i(\vec{p}_i - q\vec{A}_i)^2 + V(r)$$ i: either ion or electron

Dipole aproximation: $\vec{A}(\vec{r},t) \equiv \vec{A}(t)$ $\vec{A}_x = \vec{E}_x / \omega$

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:

$$H = \frac{p^2}{2\mu} - \frac{e}{2\mu}\vec{A}(t)\cdot\vec{p}\left[\cos(kZ) + kz\sin(kZ)\right] + V(r)$$

$$+\frac{P^2}{2M} + \frac{e^2}{2\mu}\vec{A}^2(t)\left[Cos^2(kZ) + kz\sin(2KZ)\right]$$

Kapitza-Dirac-Effect (quantum mechanically, simplest model)

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

$$U_P = \frac{e^2 I}{4 m_e \omega^2} \cos^2 kz$$

Quantum mechanics (1D)

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

Wavefunction expanded in plane waves with momentum $n\hbar k$

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

$$i\frac{dc_n}{dt} = \left(\varepsilon n^2 + \frac{V_0}{2\hbar}\right)c_n + \frac{V_0}{4\hbar}(c_{n-2} + c_{n+2})$$

solutions

(ε: kin. energy)

$$\varepsilon << V_0 / \hbar$$

diffraction regime

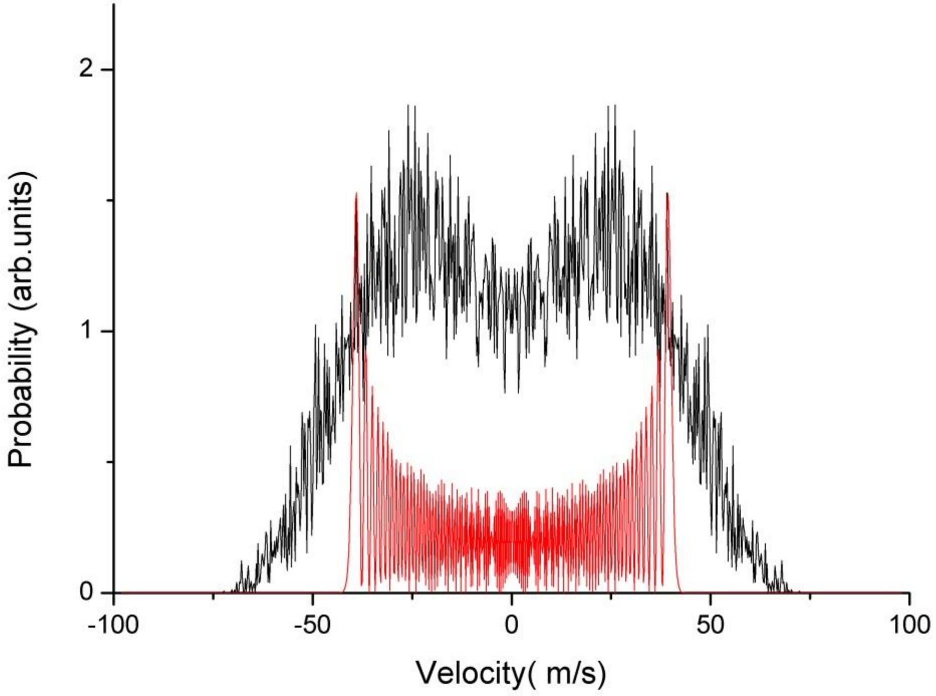
$$\varepsilon >> V_0 / \hbar$$

Bragg regime

Kapitza-Dirac-effect for neutrals

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

Realistic time of acceleration



Fixed time of acceleration

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