Quantum-quasiclassical method for few-body processes in atomic and nuclear physics

V.S. Melezhik

Bogoliubov Laboratory of Theoretical Physics, JINR, Dubna

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MMCP 2024, 20 — 25 October 2024, Yerevan, Armenia

quantum-quasiclassical approach -> FBS

VOLUME 84, NUMBER 9 PHYSICAL REVIEW LETTERS 28 FEBRUARY 2000

Quantum Energy Flow in Atomic Ions Moving in Magnetic Fields

V. S. Melezhik[1,*] and P. Schmelcher[2]

PHYSICAL REVIEW A **69**, 032709 (2004)

Stripping and excitation in collisions between *p* and $He^+(n \leqslant 3)$ calculated by a quantum time-dependent approach with semiclassical trajectories

Vladimir S. Melezhik,[1,*] James S. Cohen,[2] and Chi-Yu Hu[1]

Hyperfine Interactions **138:** 351–354, 2001.

Recent Progress in Treatment of Sticking and Stripping with Time-Dependent Approach

VLADIMIR S. MELEZHIK[1,2]

PHYSICAL REVIEW A **103**, 053109 (2021)

Improving efficiency of sympathetic cooling in atom-ion and atom-atom confined collisions

Vladimir S. Melezhik[*]

Eur. Phys. J. A (2022) 58:34
https://doi.org/10.1140/epja/s10050-022-00684-z
THE EUROPEAN PHYSICAL JOURNAL A

Investigation of low-lying resonances in breakup of halo nuclei within the time-dependent approach

Dinara Valiolda[1,2,3], Daniyar Janseitov[1,2,3,a], Vladimir Melezhik[3,4,b]

hydrogen atom + EM pulse

- Nondipole effects (NDE) in interaction of atoms with short-wave EM radiation
- NDE → nonseparability of CM and electron variables → acceleration
- Mechanisms for acceleration of neutral atoms by EM pulses
- Acceleration and «twisting» of atoms by circularly polarized EM pulse

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electron vortex beams to study: chirality, magnetization mapping, transpher of angular momentum to nanoparticls ...

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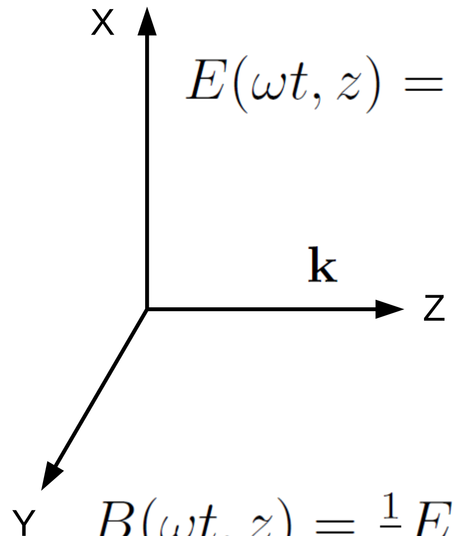
- Conclusion & perspectives

Non-dipole effects

electromagnetic wave + atom



$$E(\omega t, z) = E_0 \cos(\omega t - kz) = E_0 \cos(\omega t - \frac{\omega}{c} z)$$

$$B(\omega t, z) = \frac{1}{c} E(\omega t, z) \qquad \frac{1}{c} = \alpha = \frac{1}{137}$$

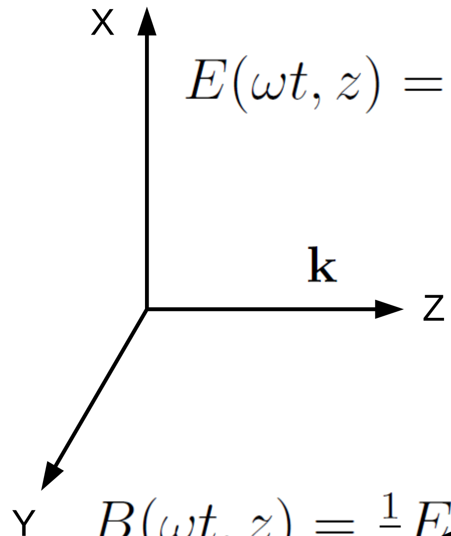
optical range

$$\lambda \sim 500\text{nm} \quad \omega \sim 10^{-1} a.u.$$

$$\frac{\omega}{c} \simeq \frac{10^{-1}}{137} \to 0$$

Non-dipole effects

electromagnetic wave + atom



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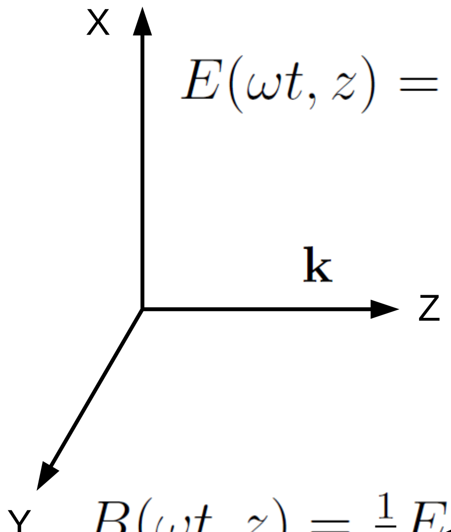
dipole approximation

Non-dipole effects

electromagnetic wave + atom



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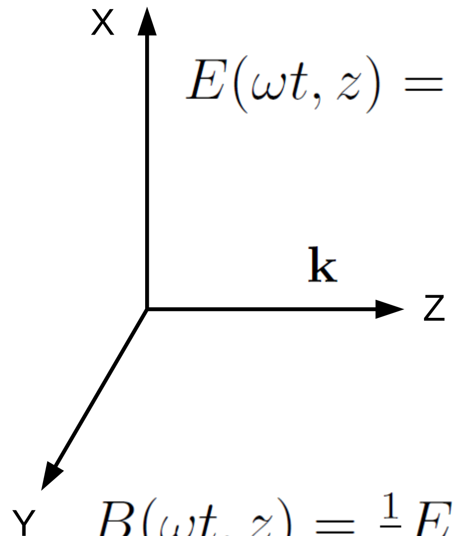
optical range $\lambda \sim 500\text{nm} \quad \omega \sim 10^{-1} a.u.$

$$\frac{\omega}{c} \simeq \frac{10^{-1}}{137} \to 0$$ dipole approximation

X-ray $\lambda \sim (10^2 - 10^{-3}) nm \quad \omega \sim (1 - 10^4) a.u. \quad \frac{\omega}{c} \sim \frac{1}{137} - 10^2$

Non-dipole effects

electromagnetic wave + atom



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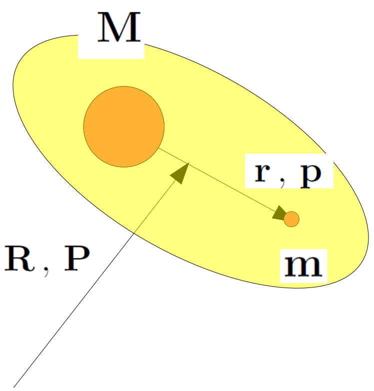
optical range $\quad \lambda \sim 500\mathrm{nm} \quad \omega \sim 10^{-1} a.u.$

$$\frac{\omega}{c} \simeq \frac{10^{-1}}{137} \rightarrow 0$$ ~~dipole approximation~~

X-ray $\quad \lambda \sim (10^2 - 10^{-3}) nm \quad \omega \sim (1 - 10^4) a.u. \quad \frac{\omega}{c} \sim \frac{1}{137} - 10^2$

Hydrogen atom in strong laser field (non-dipole effects)



$$M \gg m$$

$$P = MV \gg p = mv$$

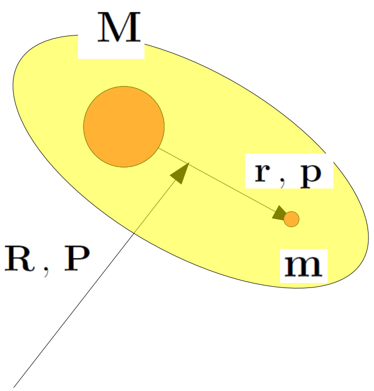
$$H(\boldsymbol{r},\boldsymbol{R},t) = \frac{\boldsymbol{P}^2}{2M} + h_0(\boldsymbol{r}) + V_1(\boldsymbol{r},t) + V_2(\boldsymbol{r},\boldsymbol{R},t)$$

$$h_0(\boldsymbol{r}) = \frac{\hat{\boldsymbol{p}}^2}{2\mu} - \frac{1}{r}$$

$$V_1(\boldsymbol{r}) = E_0 f(t)\{\cos(\omega t)x + \frac{1}{c}[\cos(\omega t)\hat{l}_y + \omega\sin(\omega t)xz]\},$$

$$V_2(\boldsymbol{r},\boldsymbol{R}) = \frac{1}{c}E_0 f(t)\{\cos(\omega t)[Z\hat{p}_x - X\hat{p}_z] + \omega\sin(\omega t)[xZ + zX]\}$$

Hydrogen atom in strong laser field (non-dipole effects)



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$$h_0(\boldsymbol{r}) = \frac{\hat{\boldsymbol{p}}^2}{2\mu} - \frac{1}{r}$$

$\mathrm{M} \gg \mathrm{m}$

$\mathrm{P} = \mathrm{MV} \gg \mathrm{p} = \mathrm{mv}$

2D

$$\boxed{V_1(\boldsymbol{r}) = E_0 f(t)\{\cos(\omega t)x} + \frac{1}{c}[\cos(\omega t)\hat{l}_y + \omega\sin(\omega t)xz]\},$$

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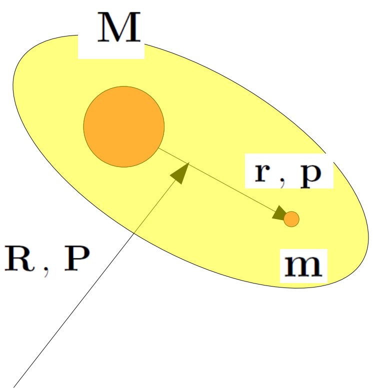
Hydrogen atom in strong laser field (non-dipole effects)



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3D

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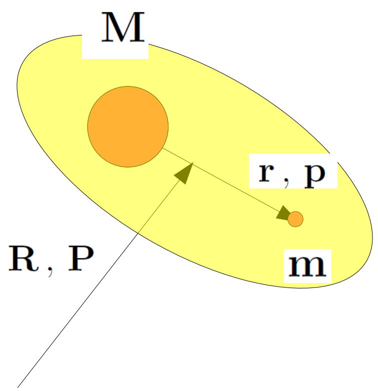
Hydrogen atom in strong laser field (non-dipole effects)



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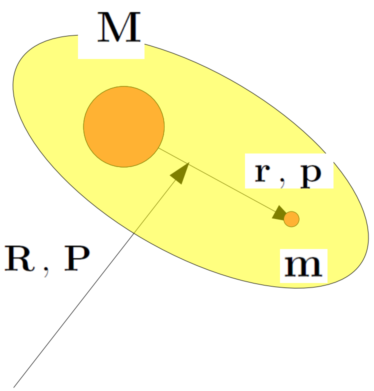
6D !! $$V_2(\boldsymbol{r},\boldsymbol{R}) = \frac{1}{c}E_0 f(t)\{\cos(\omega t)[Z\hat{p}_x - X\hat{p}_z] + \omega \sin(\omega t)[xZ + zX]\}$$

non-separable variables of CM and electron ~ $\frac{1}{c}$, $\frac{\omega}{c}$

Hydrogen atom in strong laser field (non-dipole effects)



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$$h_0(\boldsymbol{r}) = \frac{\hat{\boldsymbol{p}}^2}{2\mu} - \frac{1}{r}$$

PHYSICAL REVIEW LETTERS **124**, 233202 (2020)

Dissecting Strong-Field Excitation Dynamics with Atomic-Momentum Spectroscopy

A. W. Bray,[1,2,*] U. Eichmann,[2,†] and S. Patchkovskii[2,‡]
[1]*Australian National University, Canberra ACT 2601, Australia*
[2]*Max-Born-Institute, 12489 Berlin, Germany*

$$\mathrm{P} = \mathrm{MV} \gg \mathrm{p} = \mathrm{mv}$$

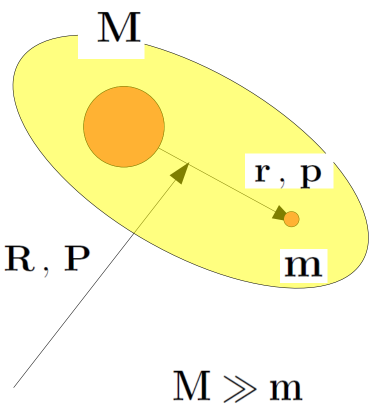
$$H(\mathbf{r},\mathbf{R},t) \rightarrow H_{eff}(\mathbf{r},t) = h_0(\mathbf{r}) + V_{eff}(\mathbf{r},t)$$

3D !!

We propose using the c.m. degrees of freedom of atoms and molecules as a "built-in" monitoring device for observing their internal dynamics in nonperturbative laser fields.

detection of the internal electron quantum dynamics with CM-velocity spectroscopy.

Hydrogen atom in strong laser field
(quantum-quasiclassical method)



$$\mathrm{M} \gg \mathrm{m}$$

$$\mathbf{P} = \mathbf{MV} \gg \mathbf{p} = \mathbf{mv}$$

classical ideal gas perfectly describes gas laws

$$\lambda_{dB} = \frac{h}{MV} \to 0$$

$$i\hbar \frac{\partial}{\partial t}|\psi(\mathbf{r},t)\rangle = [H_0(\mathbf{r}) + V(\mathbf{r},\mathbf{R}(t))]|\psi(\mathbf{r},t)\rangle$$

$$H_{cl}(\mathbf{P},\mathbf{R},t) = \frac{\mathbf{P}^2}{2M} + \langle\psi(\mathbf{r},t)|V(\mathbf{r},\mathbf{R}(t))|\psi(\mathbf{r},t)\rangle$$

$$\frac{d}{dt}\mathbf{P} = -\frac{\partial}{\partial \mathbf{R}} H_{cl}(\mathbf{P},\mathbf{R},t)$$

$$\frac{d}{dt}\mathbf{R} = \frac{\partial}{\partial \mathbf{P}} H_{cl}(\mathbf{P},\mathbf{R},t)$$

$$\psi(\boldsymbol{r}, t = -n_T T/2) = \phi_{nlm}(\boldsymbol{r}),$$

$$\boldsymbol{R}(t = -n_T T/2) = \boldsymbol{R}_0 \;,\; \boldsymbol{P}(t = -n_T T/2) = \boldsymbol{P}_0,$$

IOP Publishing Journal of Physics A: Mathematical and Theoretical

J. Phys. A: Math. Theor. **56** (2023) 154003 (15pp) https://doi.org/10.1088/1751-8121/acc0e9

Quantum-quasiclassical analysis of center-of-mass nonseparability in hydrogen atom stimulated by strong laser fields*

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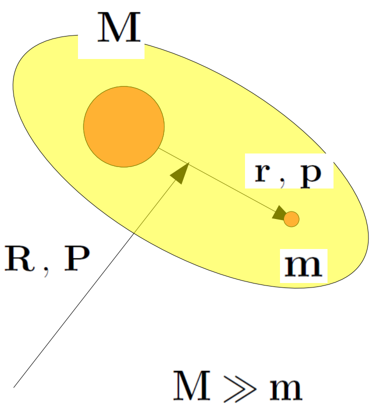
Published 22 March 2023

Abstract

We have developed a quantum-quasiclassical computational scheme for quantitative treating of the nonseparable quantum–classical dynamics of the 6D hydrogen atom in a strong laser pulse. In this approach, the electron is treated

Hydrogen atom in strong laser field (quantum-quasiclassical method)



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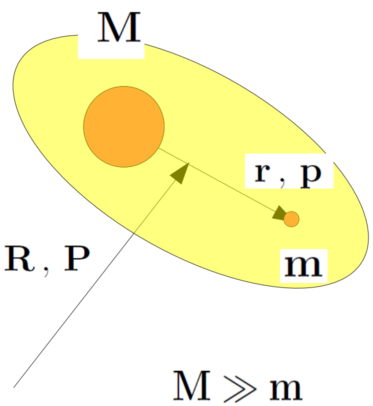
$$i\hbar\frac{\partial}{\partial t}|\psi(\mathbf{r},t)\rangle = [H_0(\mathbf{r}) + V(\mathbf{r},\mathbf{R}(t))]|\psi(\mathbf{r},t)\rangle$$

splitting method + DVR for angular variables

V. Melezhik, Phys Lett A230, 203 (1997)

V. Melezhik, EPJ Web Conf 108, 01008 (2016)
S. Shadmehri, V. Melezhik, Laser Phys. 33, 026001 (2023)

Hydrogen atom in strong laser field (quantum-quasiclassical method)



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$$H_{cl}(\mathbf{P}, \mathbf{R}, t) = \frac{\mathbf{P}^2}{2M} + \langle \psi(\mathbf{r}, t) | V(\mathbf{r}, \mathbf{R}(t)) | \psi(\mathbf{r}, t) \rangle$$

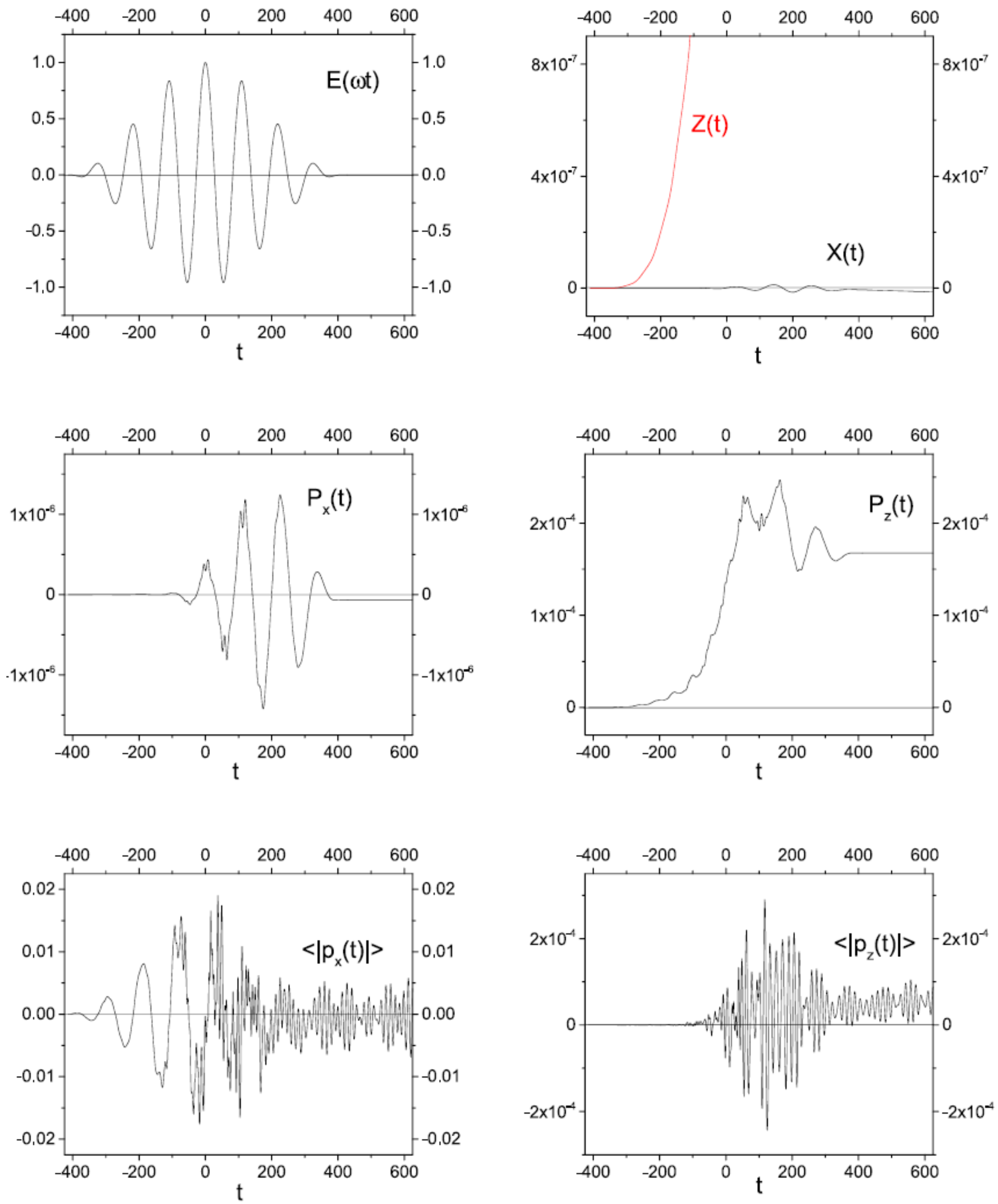
$$\frac{d}{dt}\mathbf{P} = -\frac{\partial}{\partial \mathbf{R}} H_{cl}(\mathbf{P}, \mathbf{R}, t)$$

$$\frac{d}{dt}\mathbf{R} = \frac{\partial}{\partial \mathbf{P}} H_{cl}(\mathbf{P}, \mathbf{R}, t)$$

modified Stormer-Verlet method

V. Melezhik, Phys Rev A103, 053109 (2021)

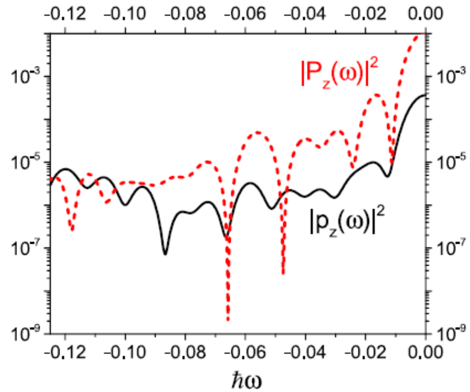
Hydrogen atom in strong laser field (results of calculations)

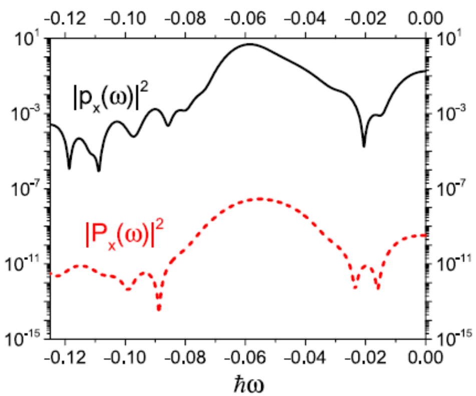


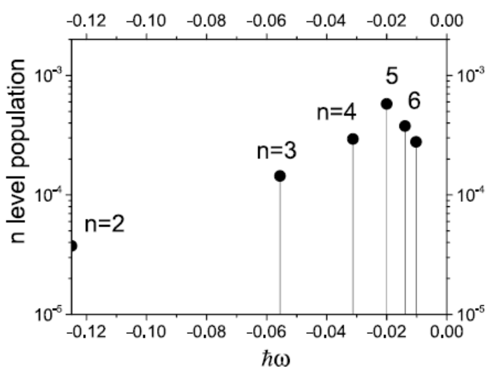
$$\lambda = 800\ \text{nm}\ (\omega = 0.057\ \text{a.u.})$$

$$10^{14}\ \frac{\text{W}}{\text{cm}^2}$$

Hydrogen atom in strong laser field
(results of calculations)







$$\lambda = 800\ \text{nm}\ \ (\omega = 0.057\ \text{a.u.})$$

$$\langle E_{kin} \rangle = \frac{1}{T_{out} - T_{in}} \int_{T_{in}}^{T_{out}} \frac{\boldsymbol{P}^2(t)}{2M} dt \sim \int_{-\infty}^{\infty} \left[\sum_{s=x,y,z} |P_s(\omega)|^2 \right] d\omega,$$

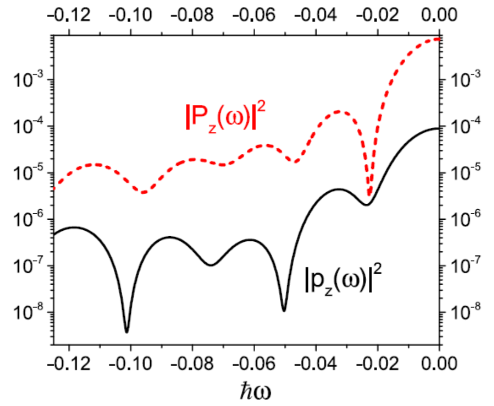
$$\langle E_{kin}^{(el)} \rangle = \frac{1}{T_{out} - T_{in}} \int_{T_{in}}^{T_{out}} \frac{\boldsymbol{p}^2(t)}{2\mu} dt \sim \int_{-\infty}^{\infty} \left[\sum_{s=x,y,z} |p_s(\omega)|^2 \right] d\omega.$$

$$P_s(\omega) = \int_{T_{in}}^{T_{out}} P_s(t) e^{i\omega t} dt.$$

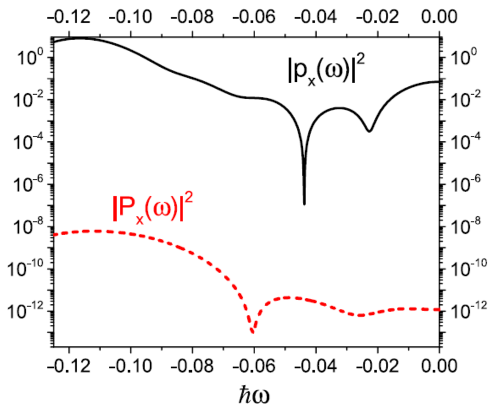
$$p_s(\omega) = \int_{T_{in}}^{T_{out}} \langle |p_s(t)| \rangle e^{i\omega t} dt$$

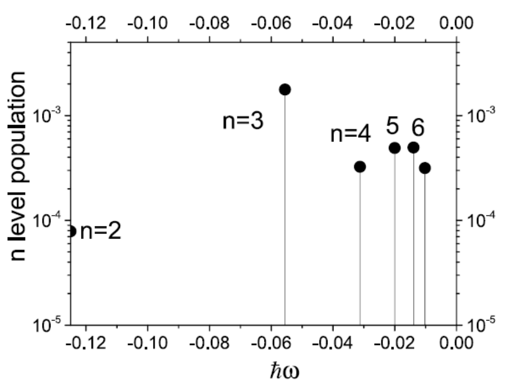
$$\langle |p_s(t)| \rangle = \int \psi^*(\boldsymbol{r}, t) \hat{p}_s \psi(\boldsymbol{r}, t) d\boldsymbol{r}.$$

Hydrogen atom in strong laser field (results of calculations)

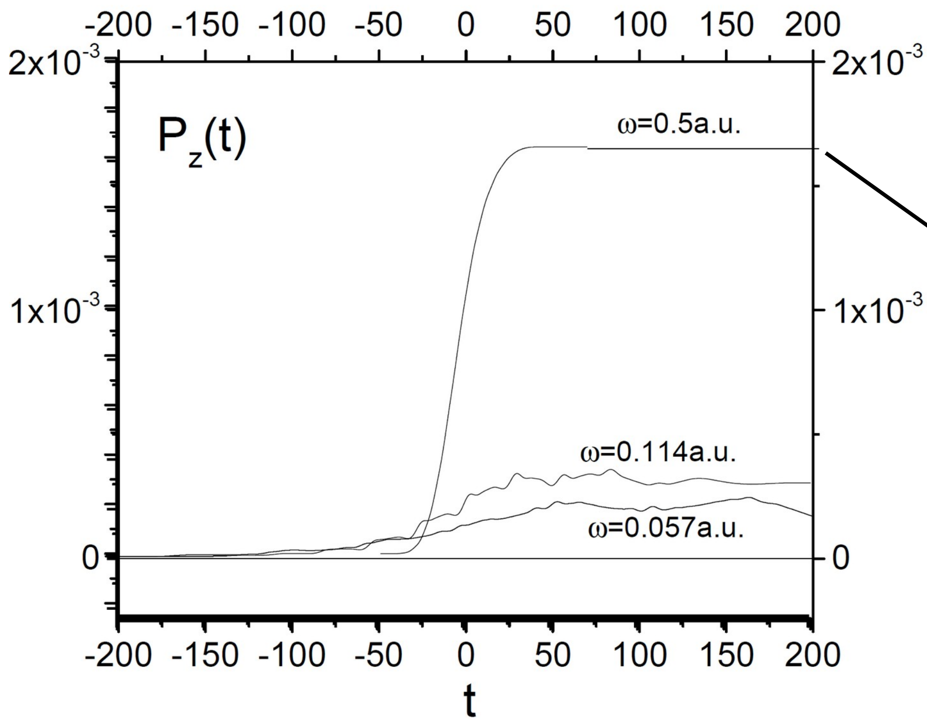


$\lambda = 400$ nm ($\omega = 0.114$ a.u.)





Promising tasks: acceleration of atoms by strong EM pulses



$10^{14}\,\frac{W}{cm^2}$ ~10fs

$E_{kin} \sim 10^{-8}\,eV \sim 10^{-4}K$

$a \sim 10^{15} g$

Vol 461 | 29 October 2009 | doi:10.1038/nature08481 nature

Acceleration of neutral atoms in strong short-pulse laser fields

U. Eichmann[1,2], T. Nubbemeyer[1], H. Rottke[1] & W. Sandner[1,2]

$$a_{exp} \sim 10^{14} g$$

$8 \times 10^{15} \frac{W}{cm^2}$, $(700-1100)nm$, $(40-100)fs$, He, Ne atoms

Mechanisms of acceleration of atoms by EM pulses

photonics MDPI

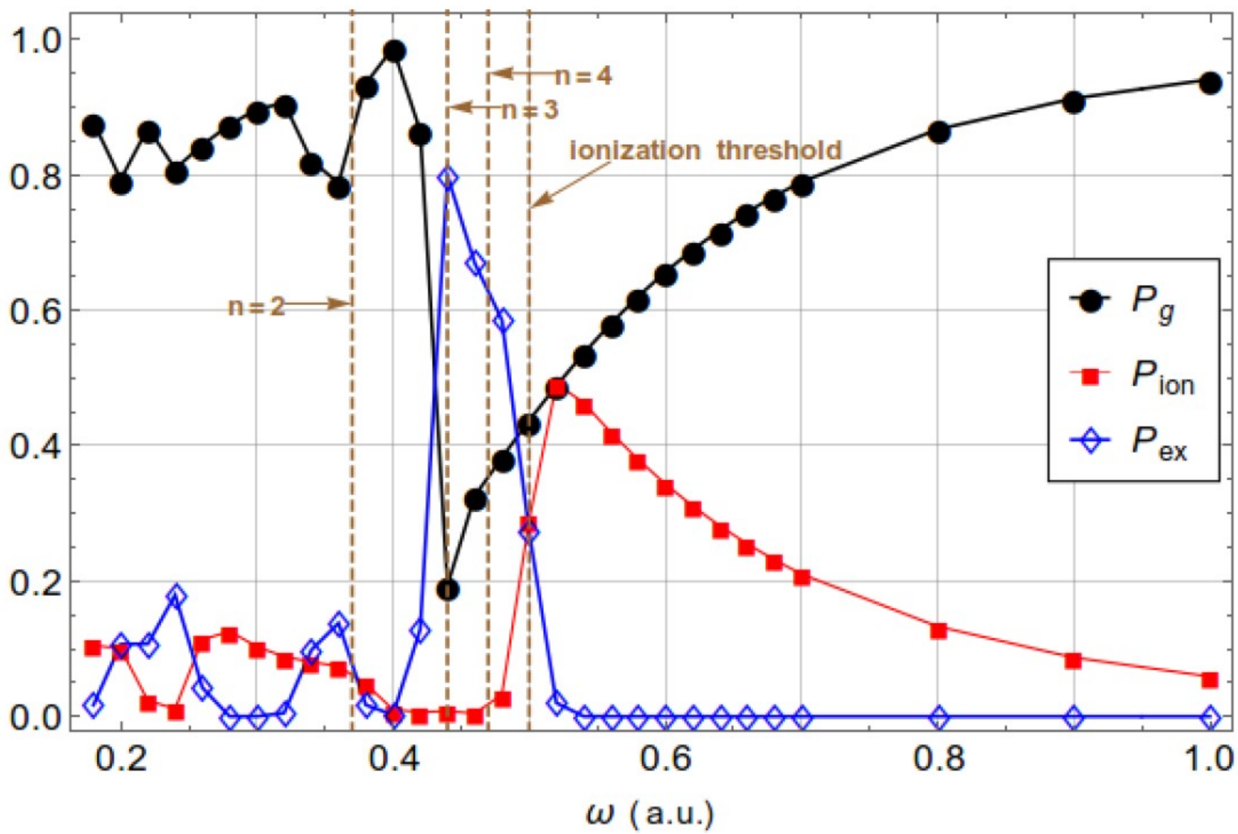
Article

Acceleration of Neutral Atoms by Strong Short-Wavelength Short-Range Electromagnetic Pulses

Vladimir S. Melezhik [1,2,*] and Sara Shadmehri [1,*]

[1] Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, Moscow Region 141980, Russian Federation
[2] Dubna State University, 19 Universitetskaya Street, Dubna, Moscow Region 141982, Russian Federation
* Correspondence: melezhik@theor.jinr.ru (V.S.M.); shadmehri@theor.jinr.ru (S.S.)

Citation: Melezhik, V.S.; Shadmehri, S. Acceleration of Neutral Atoms by Strong Short-Wavelength Short-Range Electromagnetic Pulses. *Photonics* **2023**, *10*, 1290. https://doi.org/10.3390/photonics10121290



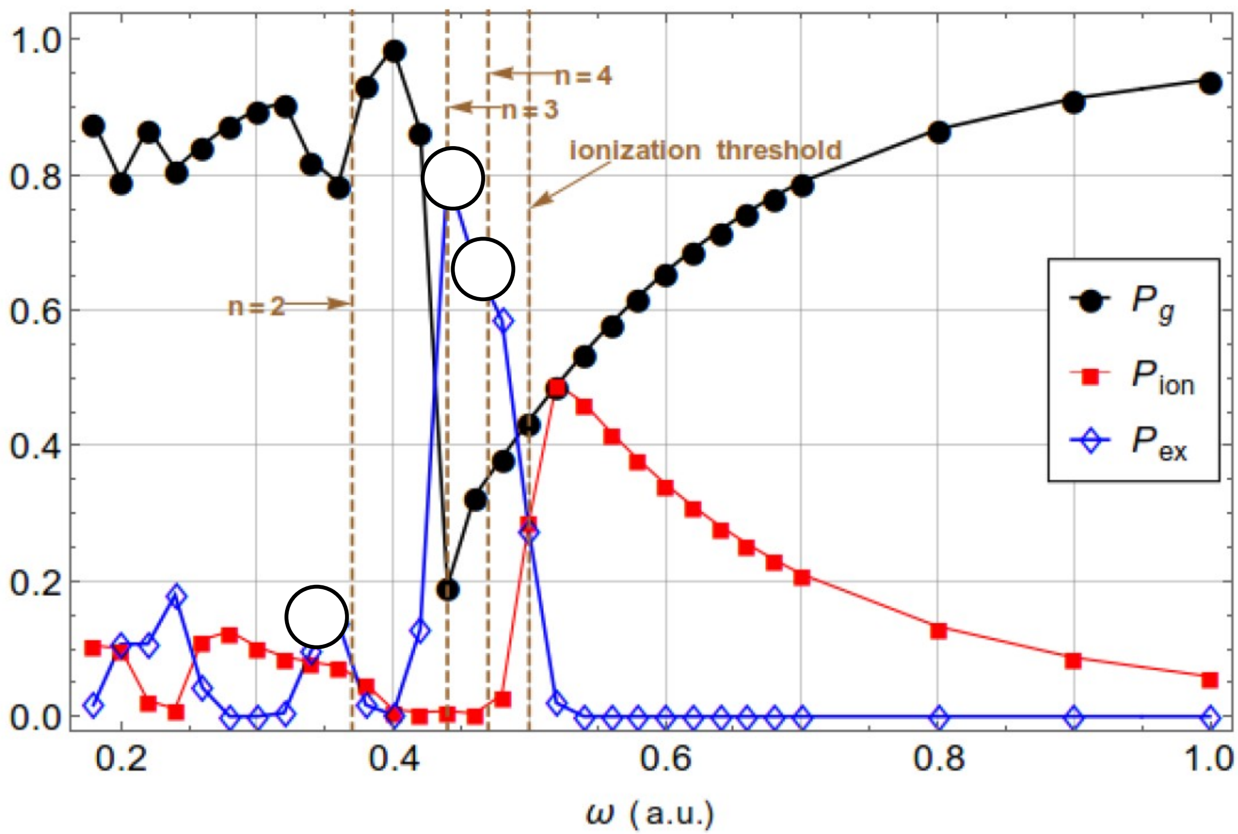
$$P_g(\omega) = |\langle\psi|\phi_{100}\rangle|^2 = \left|\int \psi(\mathbf{r},\omega,T_{out})\phi_{100}(\mathbf{r})d\mathbf{r}\right|^2$$

$$P_{ex} = \sum_{n=2}^{\infty} P_n = \sum_{n=2}^{N'} P_n + \sum_{n=N'+1}^{\infty} P_n$$

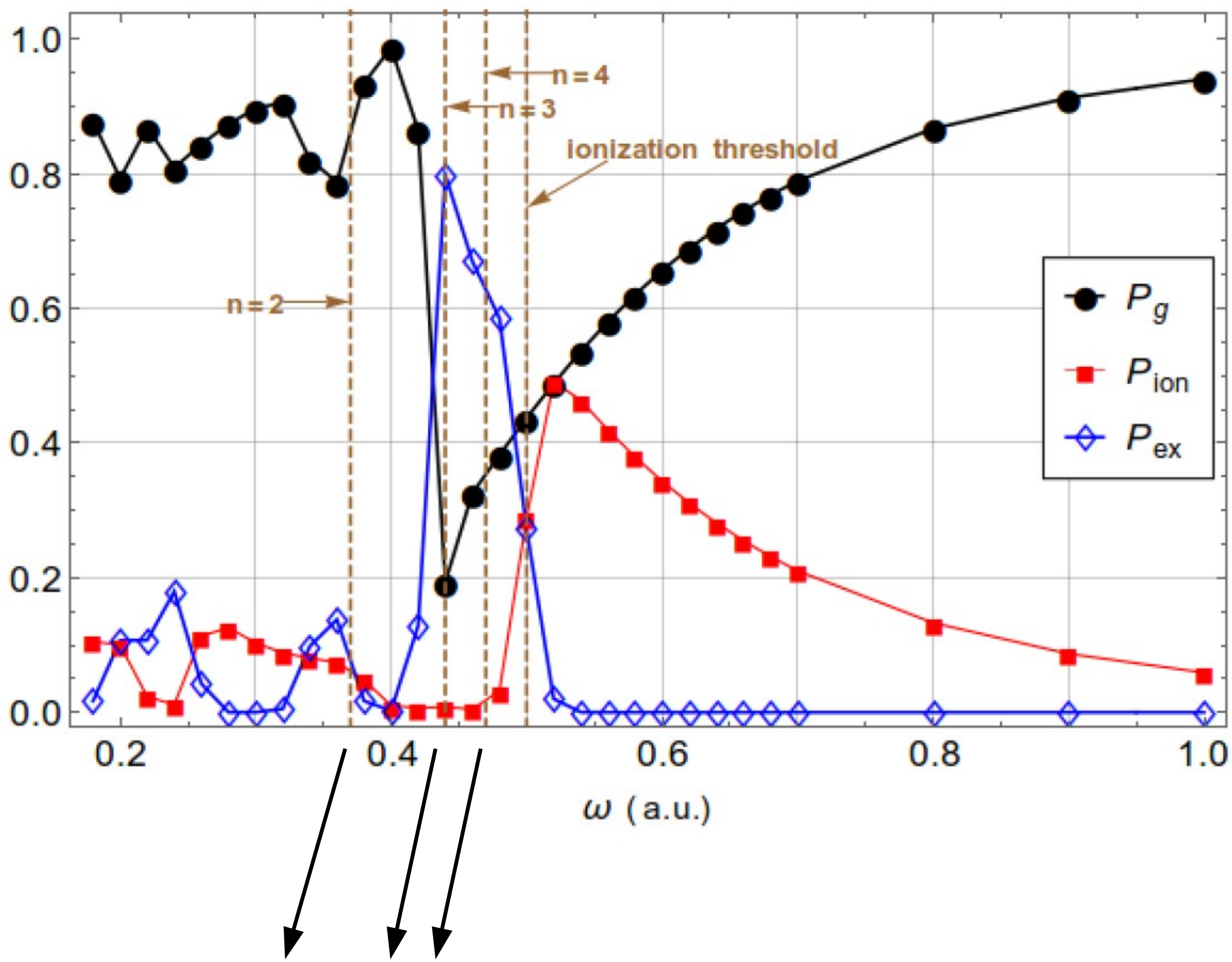
$$P_{ion} = \int_0^{+\infty} \frac{dP}{dE} dE$$

$$\sum_{n=1}^{\infty} P_n + \int_0^{+\infty} \frac{dP}{dE} dE = 1$$

Shadmehri, S.; Melezhik, V.S. *Laser Phys.* **2023**, *33*, 026001.



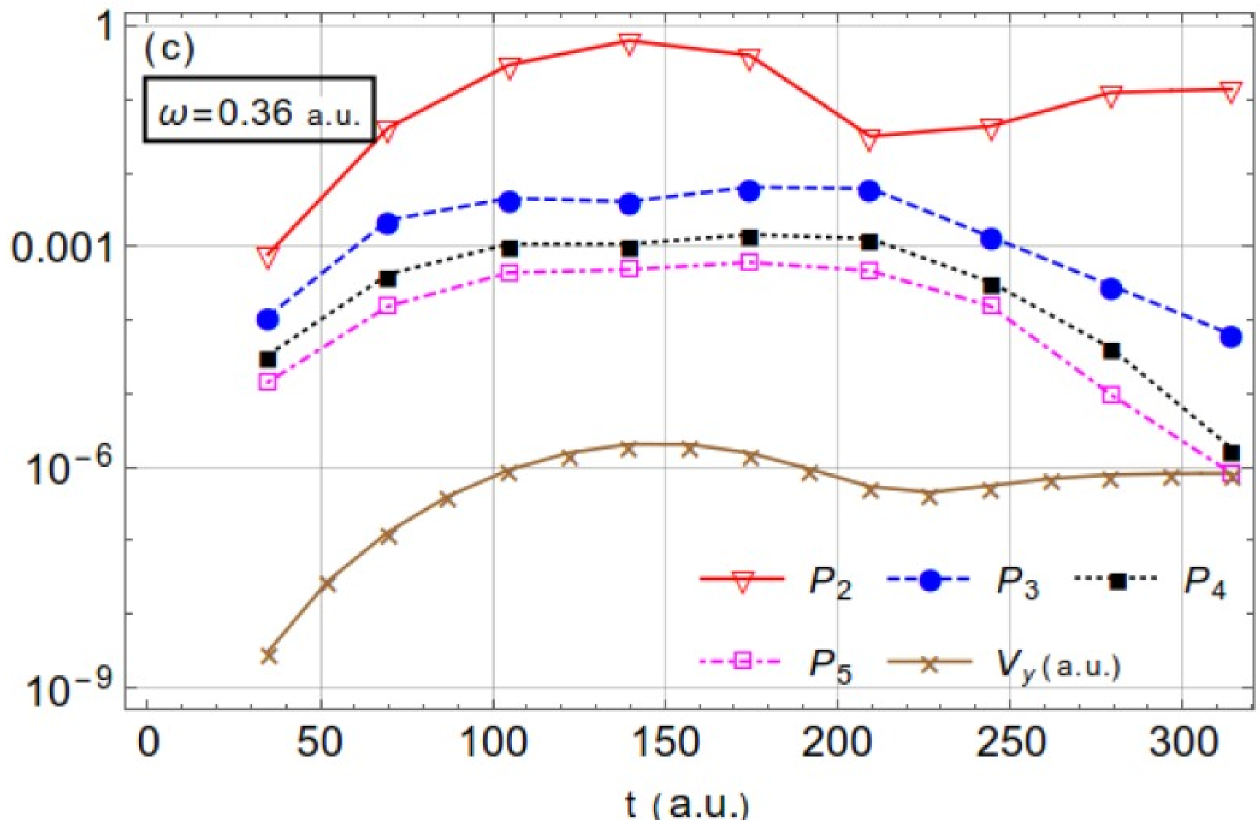
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
n = 2
n = 3
n = 4
ionization threshold
P_g
P_{ion}
P_{ex}
ω (a.u.)

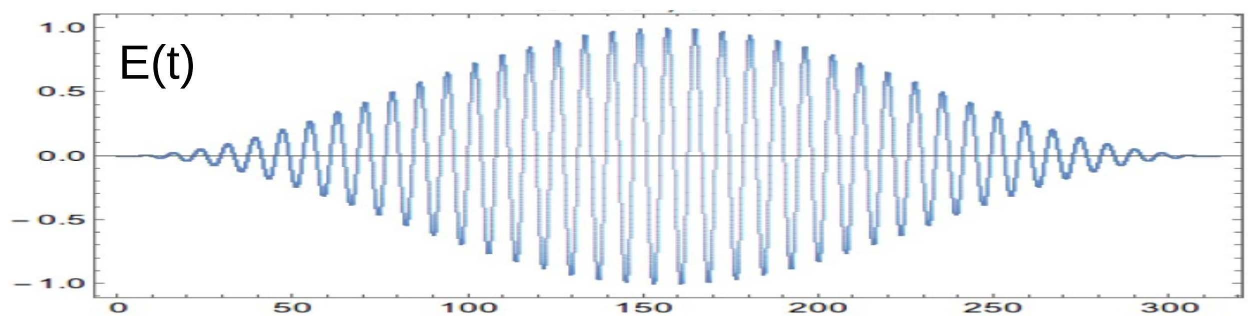


$$H_{n=1} + \hbar\omega \to H_{n'}\,, \quad n' = 2, 3, 4$$

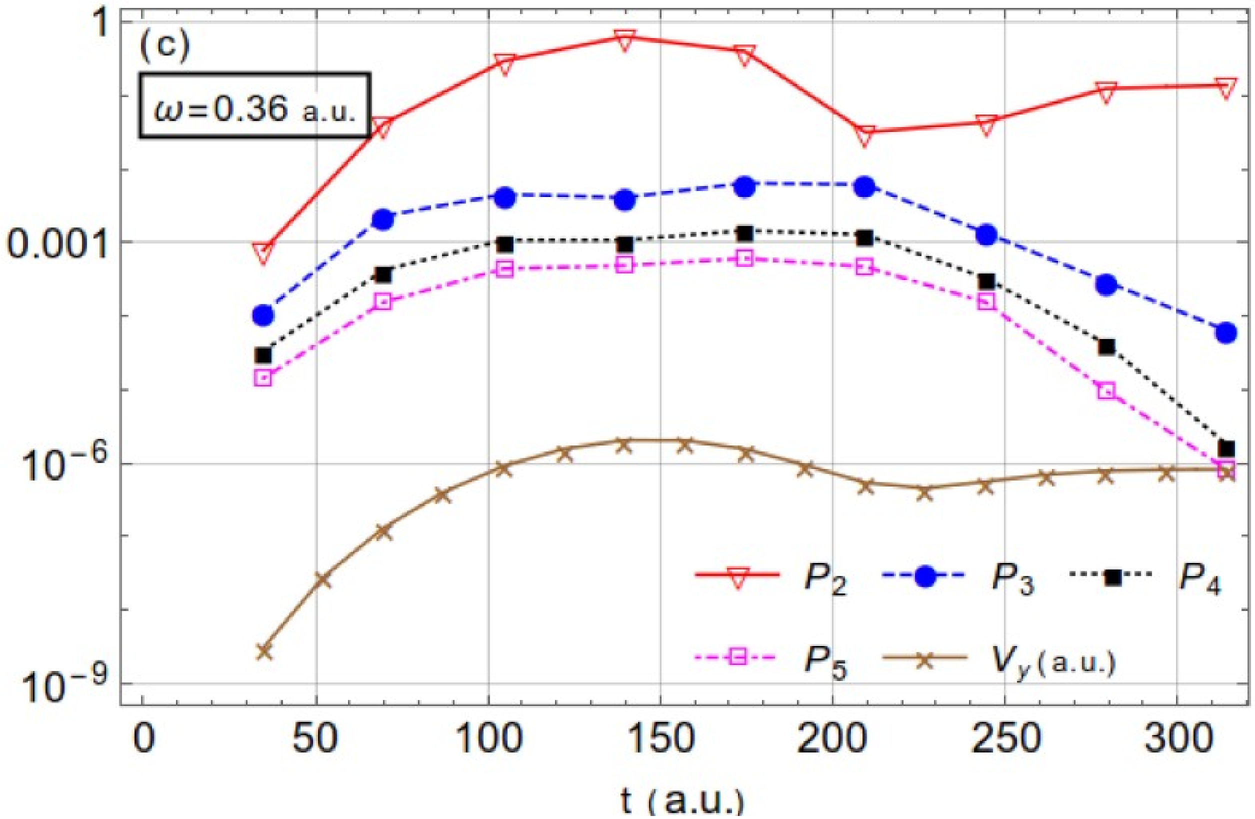
$$\hbar\omega = \frac{1}{2n^2} - \frac{1}{2n'^2} \qquad \omega = 0.38,\ 0.44,\ 0.47\ \text{(a.u.)}$$

$$P_n(\omega, t) \xrightarrow{t \to T_{out}} P_n(\omega)$$



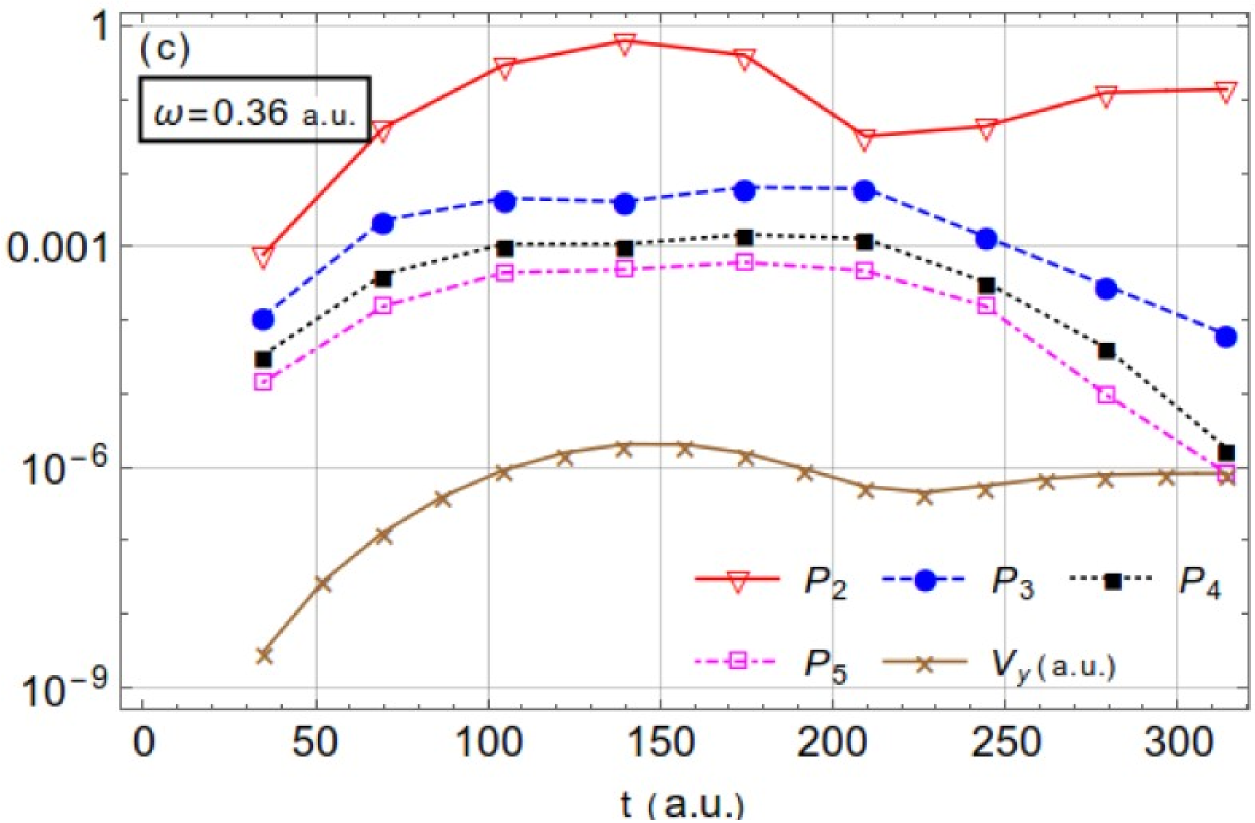


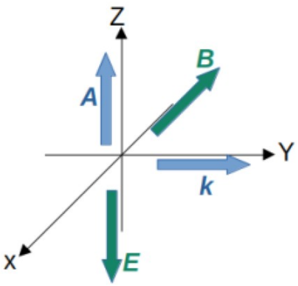
$$P_n(\omega, t) \xrightarrow{t \to T_{out}} P_n(\omega)$$



$$H_{n=1} + \hbar\omega \to H_{n'}, \quad n' = 2,$$

$$P_n(\omega, t) \xrightarrow{t \to T_{out}} P_n(\omega)$$

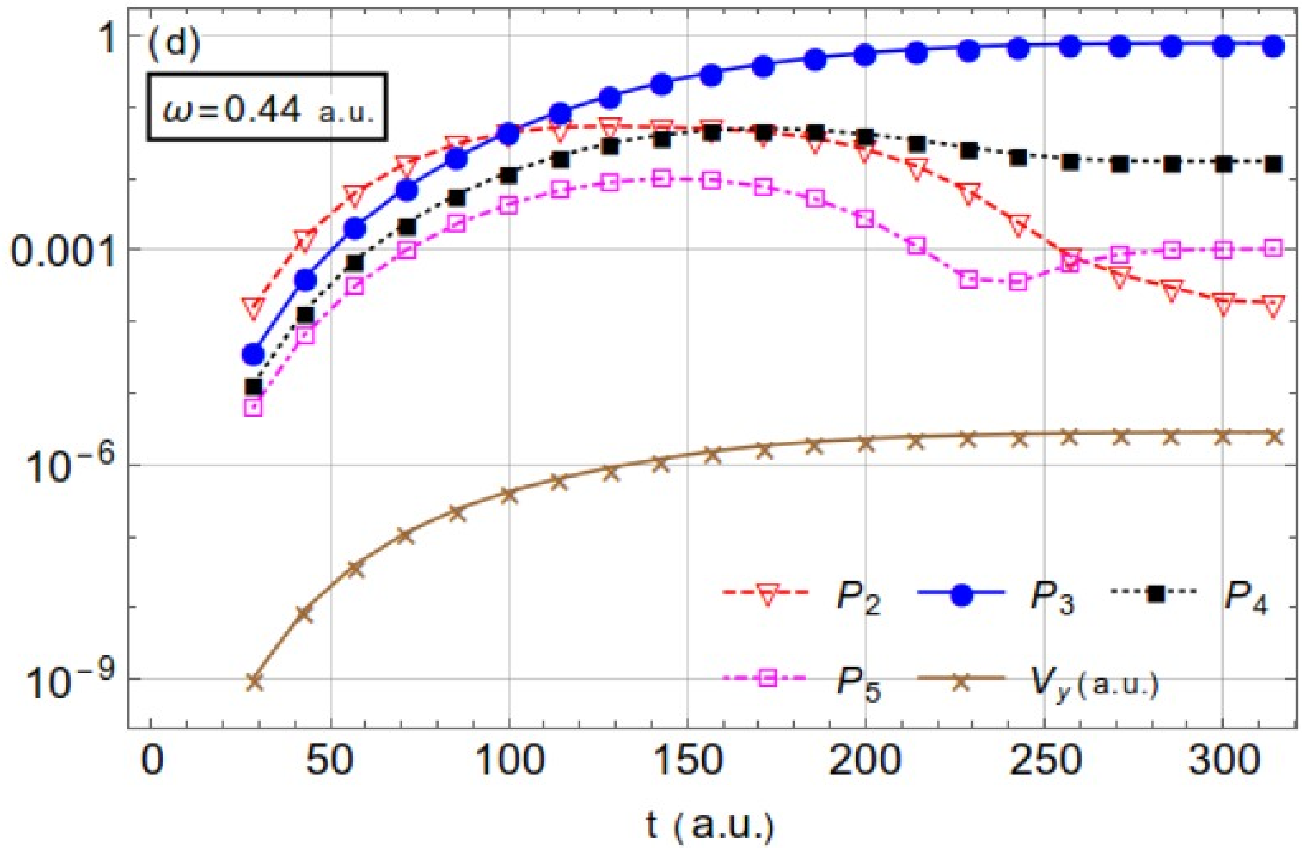




$$H_{n=1} + \hbar\omega \to H_{n'}, \quad n' = 2,$$

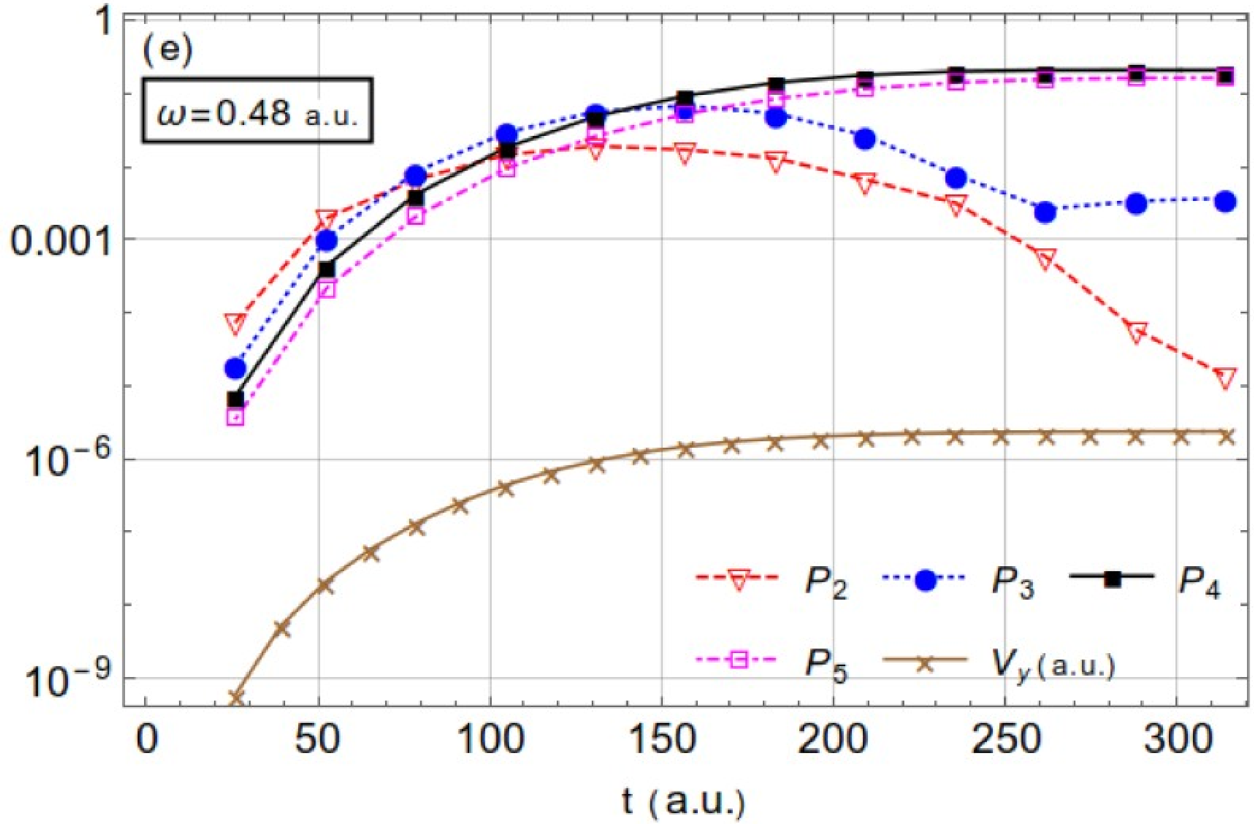
$$\mathbf{A}(\mathbf{r}, t) = \hat{\mathbf{z}} \frac{E_0}{\omega} \sin^2\left(\frac{\pi t}{NT}\right) \sin(\omega t - \mathbf{k} \cdot \mathbf{r})$$

$$P_n(\omega, t) \xrightarrow{t \to T_{out}} P_n(\omega)$$

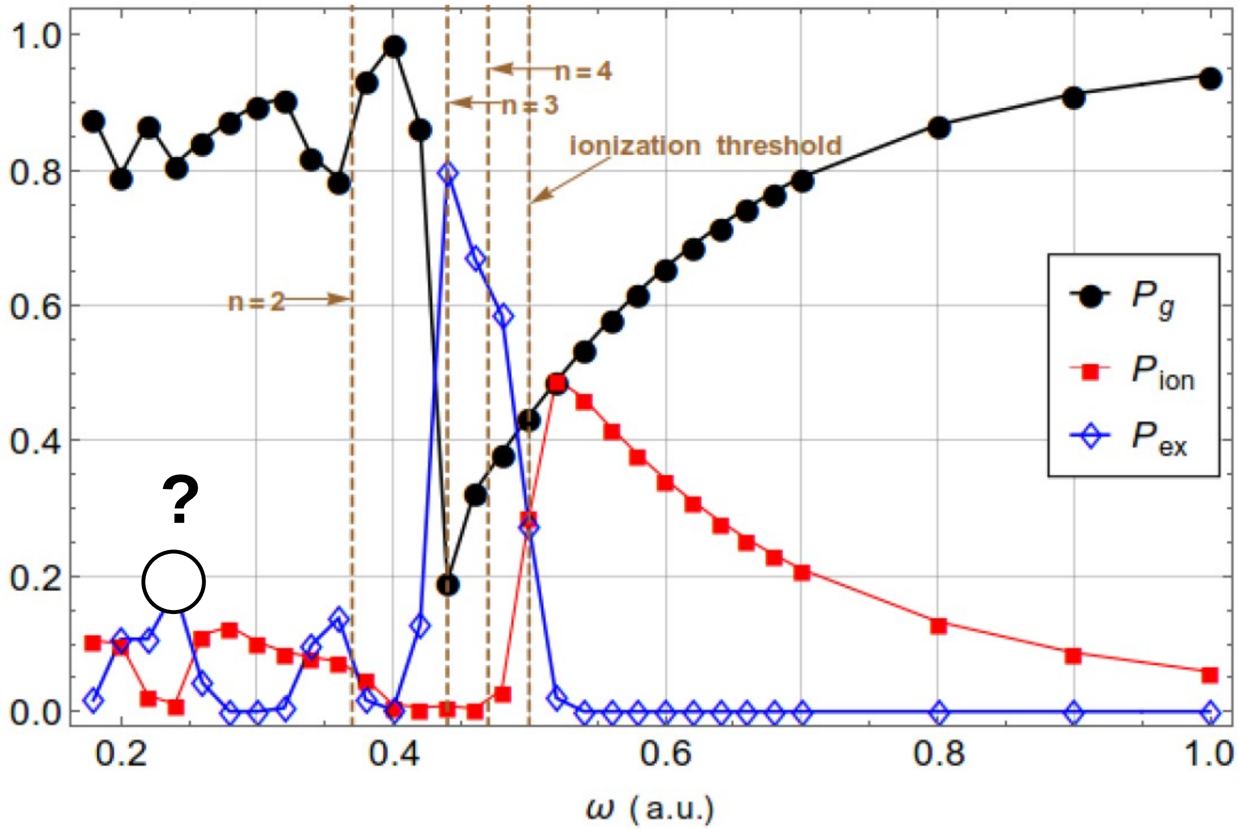


$$H_{n=1} + \hbar\omega \to H_{n'} \quad n' = 3.$$

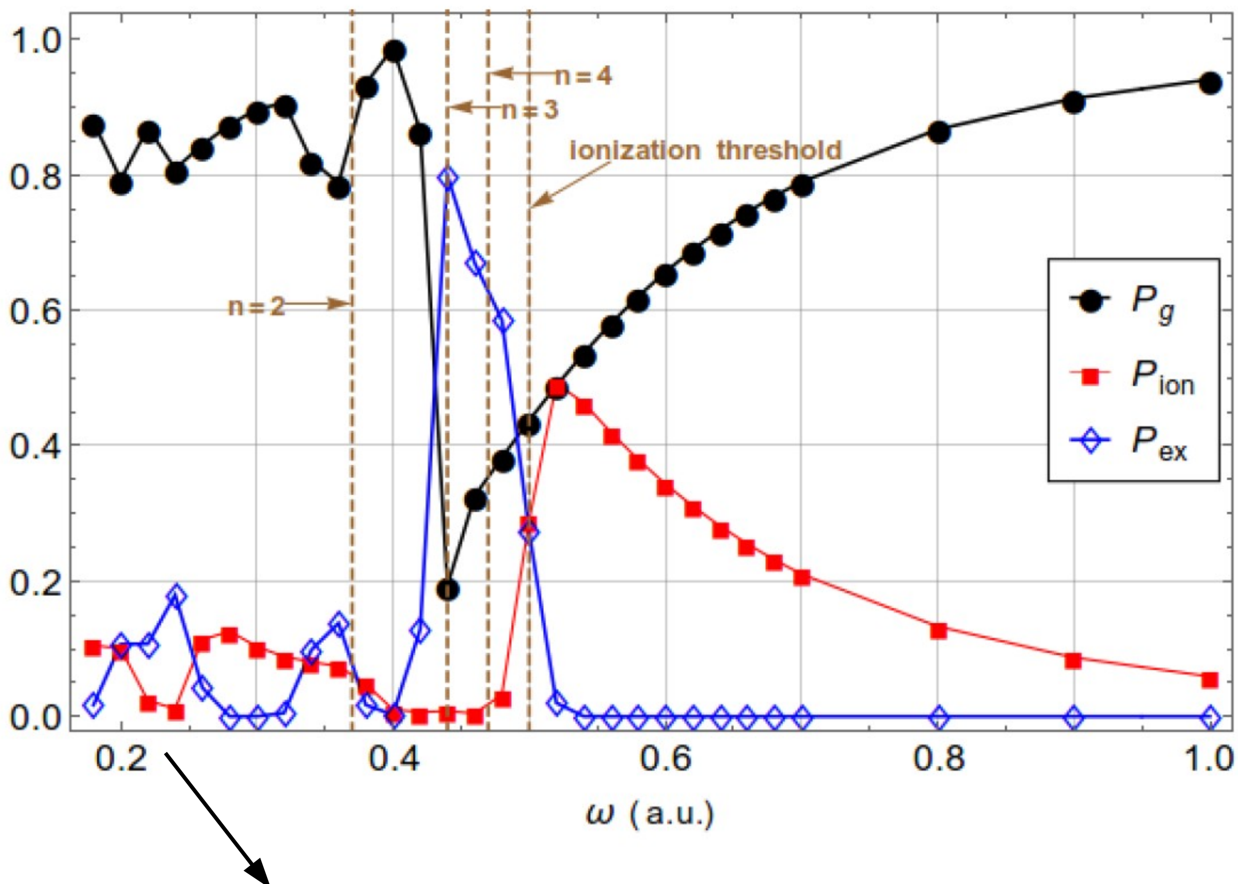
$$P_n(\omega, t) \xrightarrow{t \to T_{out}} P_n(\omega)$$



$$H_{n=1} + \hbar\omega \to H_{n'} \quad n' = 4$$



1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
ω (a.u.)
n = 4
n = 3
n = 2
ionization threshold
?
P_g
P_{ion}
P_{ex}

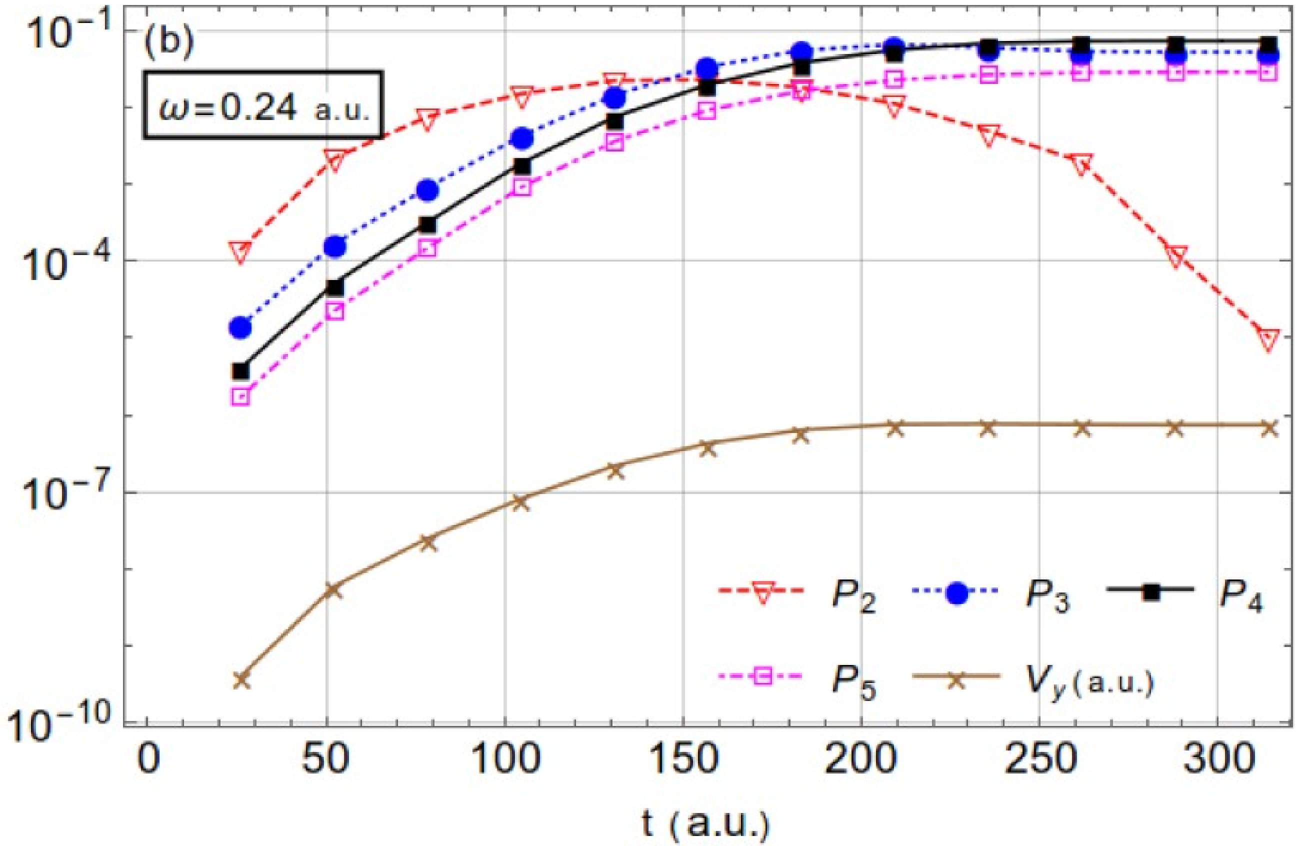


$$H_{n=1} + \hbar\omega \to H_{n'} \qquad 2\hbar\omega = \frac{1}{2n^2} - \frac{1}{2n'^2}$$

two-photon transition $2\hbar\omega \approx 0.47$ a.u. for $n = 1$ and $n' = 4$

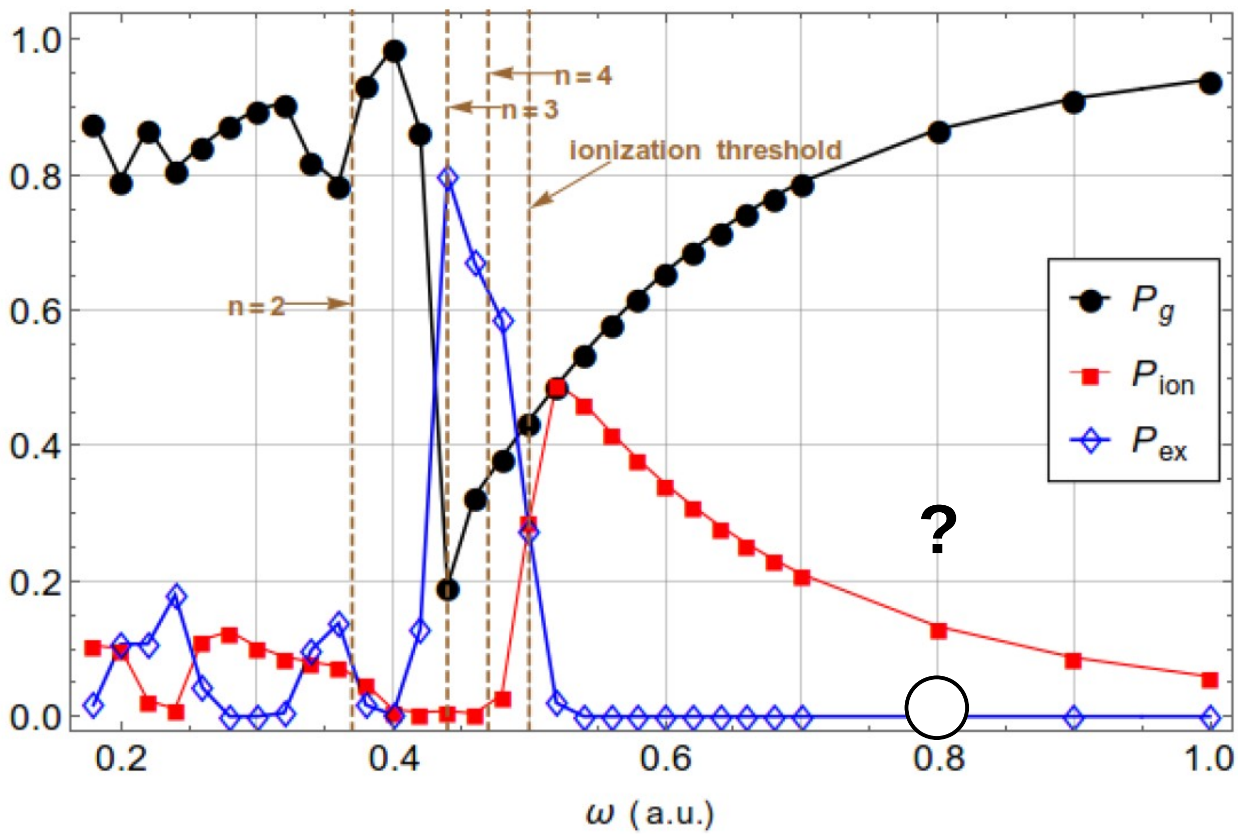
peak in $P_{ex}(\omega)$ at $\omega = 0.24$ a.u.

$$P_n(\omega, t) \xrightarrow{t \to T_{out}} P_n(\omega)$$



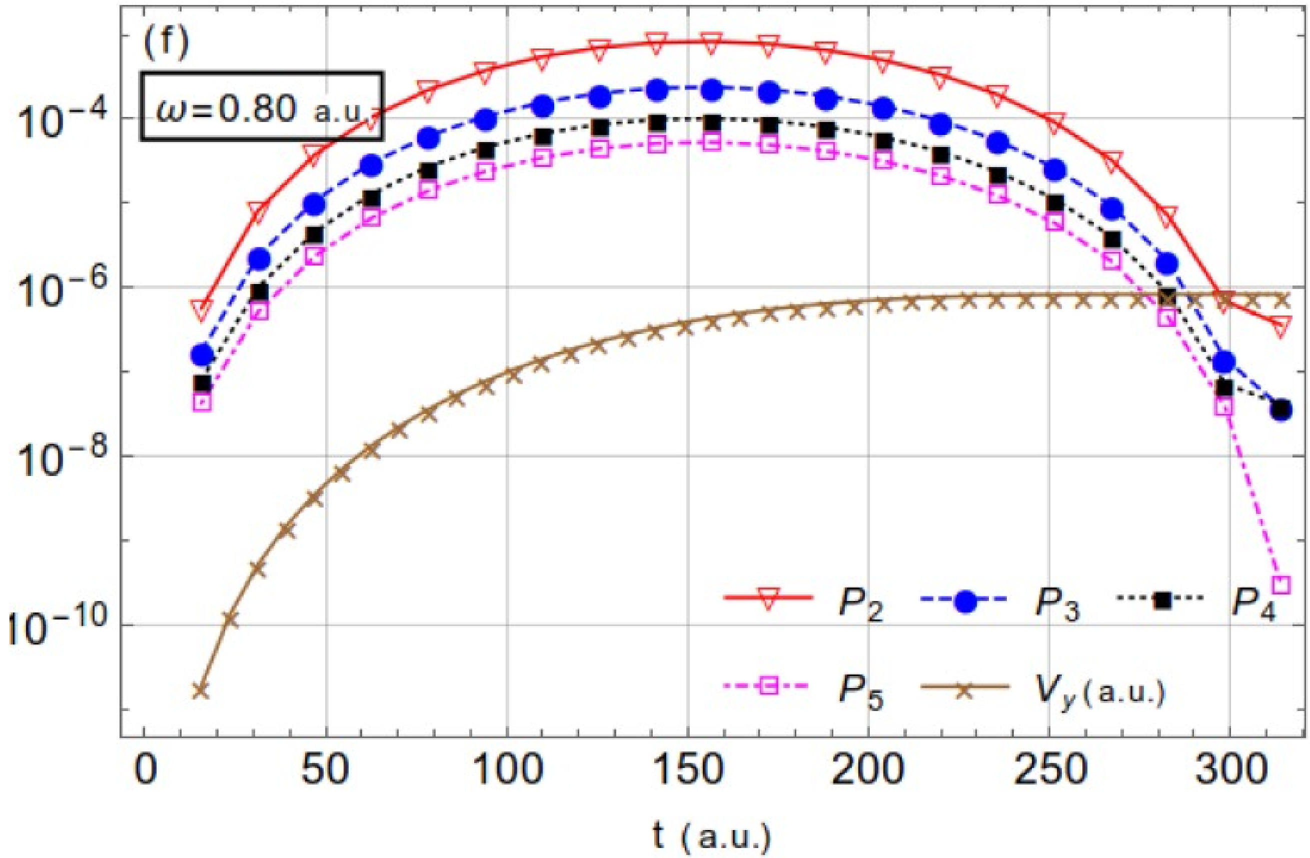
$$H_{n=1} + \hbar\omega \to H_{n'} \quad 2\hbar\omega = \frac{1}{2n^2} - \frac{1}{2n'^2}$$

two-photon transition $\quad 2\hbar\omega \approx 0.47$ a.u. for $n = 1$ and $n' = 4$

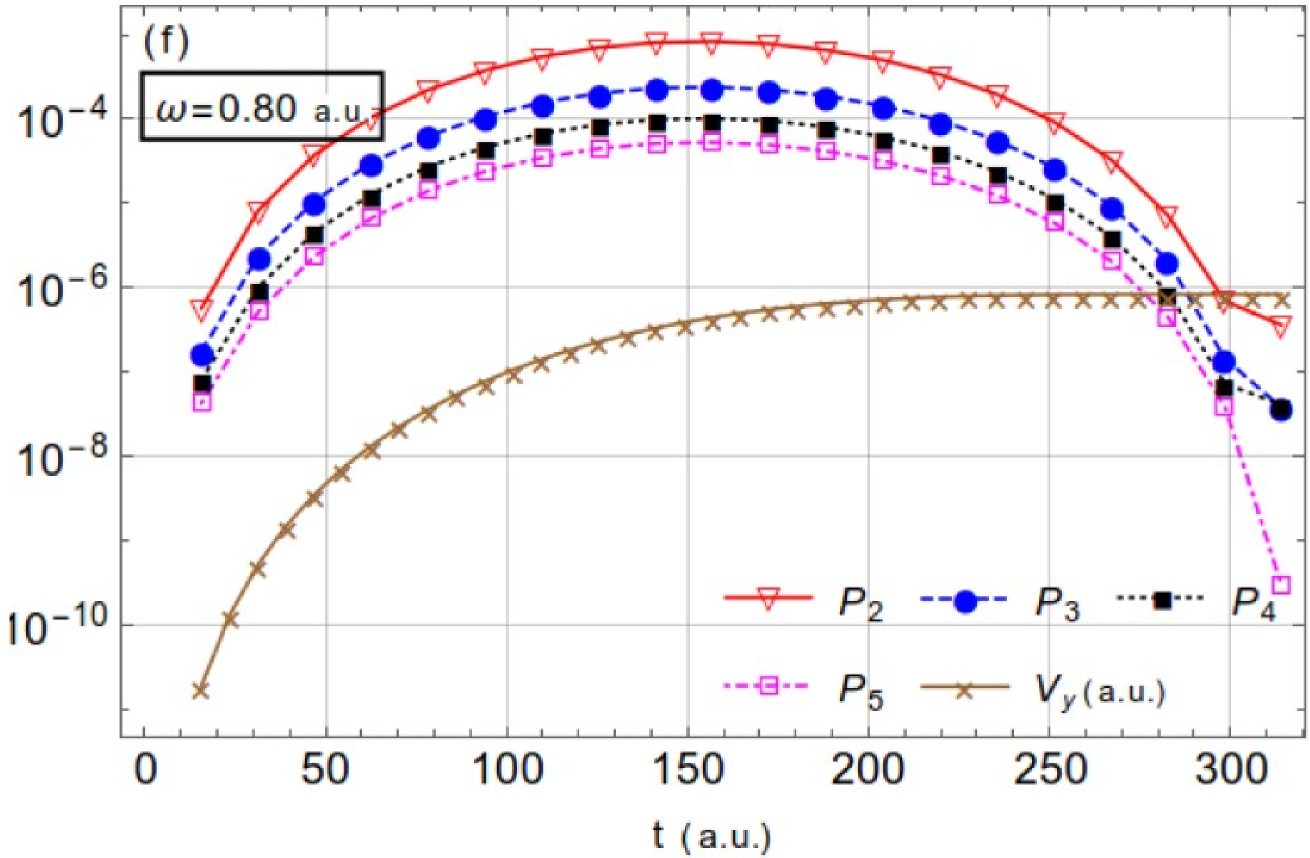


1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
ω (a.u.)
n = 2
n = 3
n = 4
ionization threshold
P_g
P_{ion}
P_{ex}
?

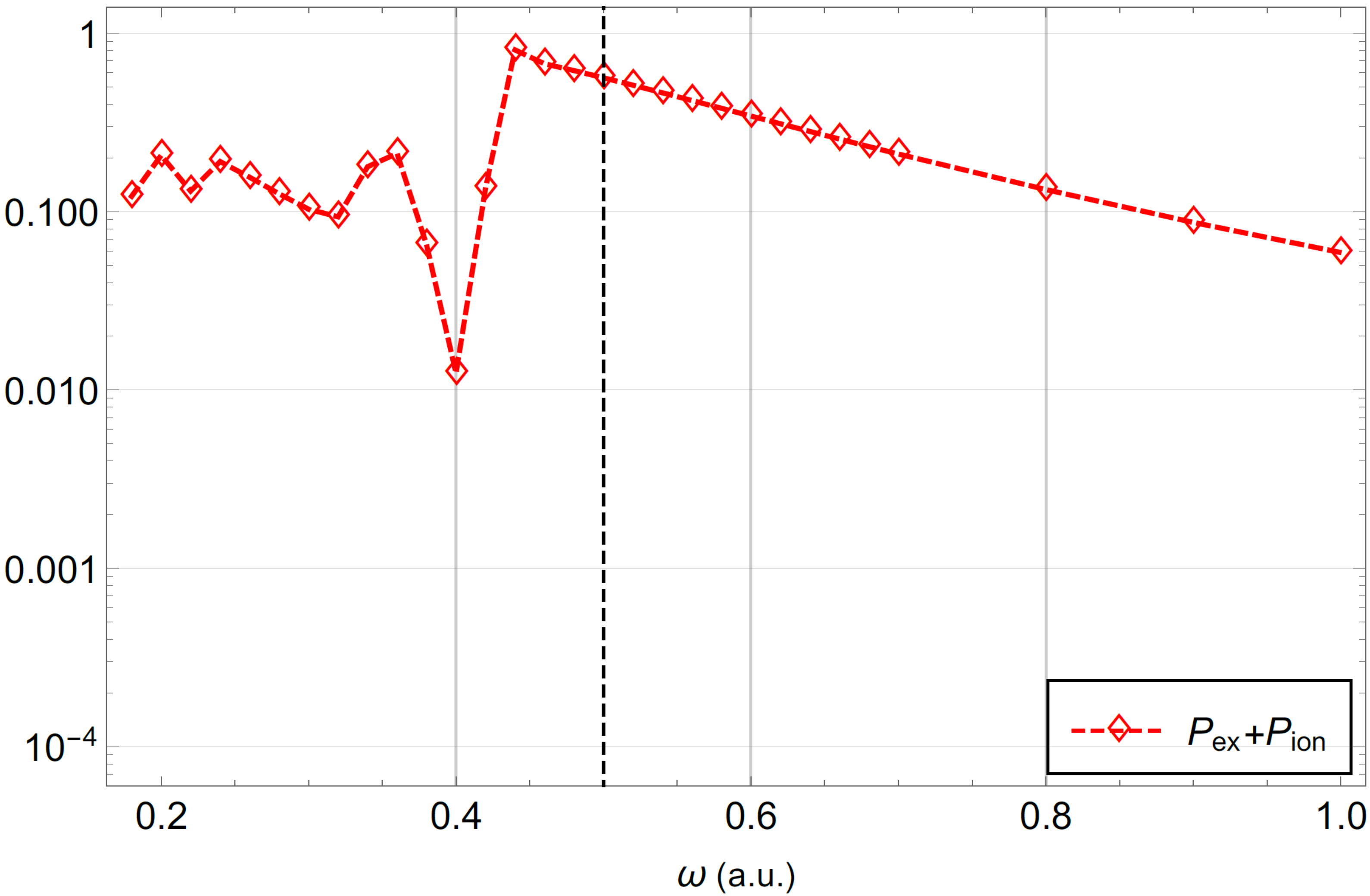
$$P_n(\omega, t) \xrightarrow{t \to T_{out}} P_n(\omega)$$



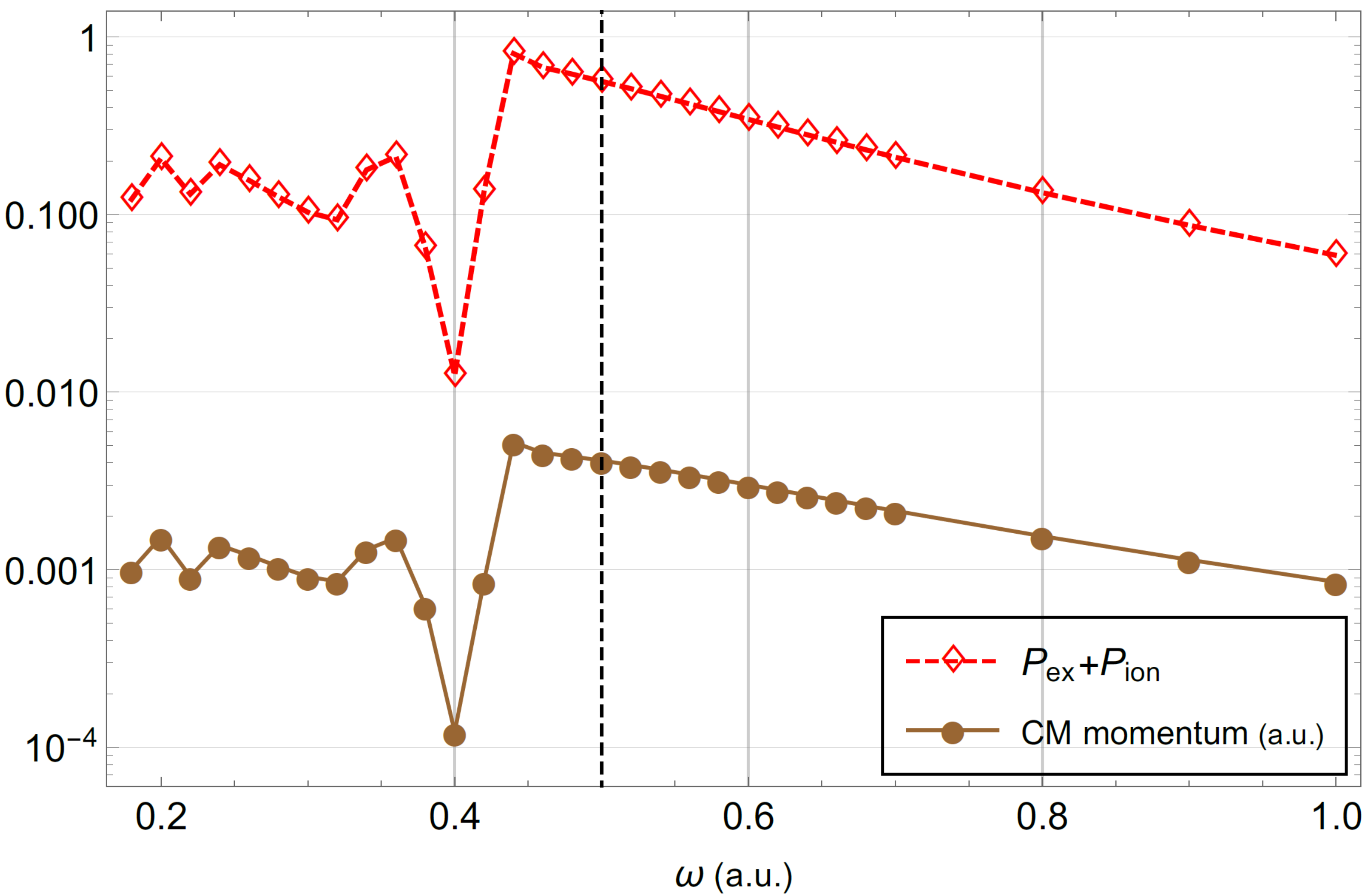
$$P_n(\omega, t) \xrightarrow{t \to T_{out}} P_n(\omega)$$

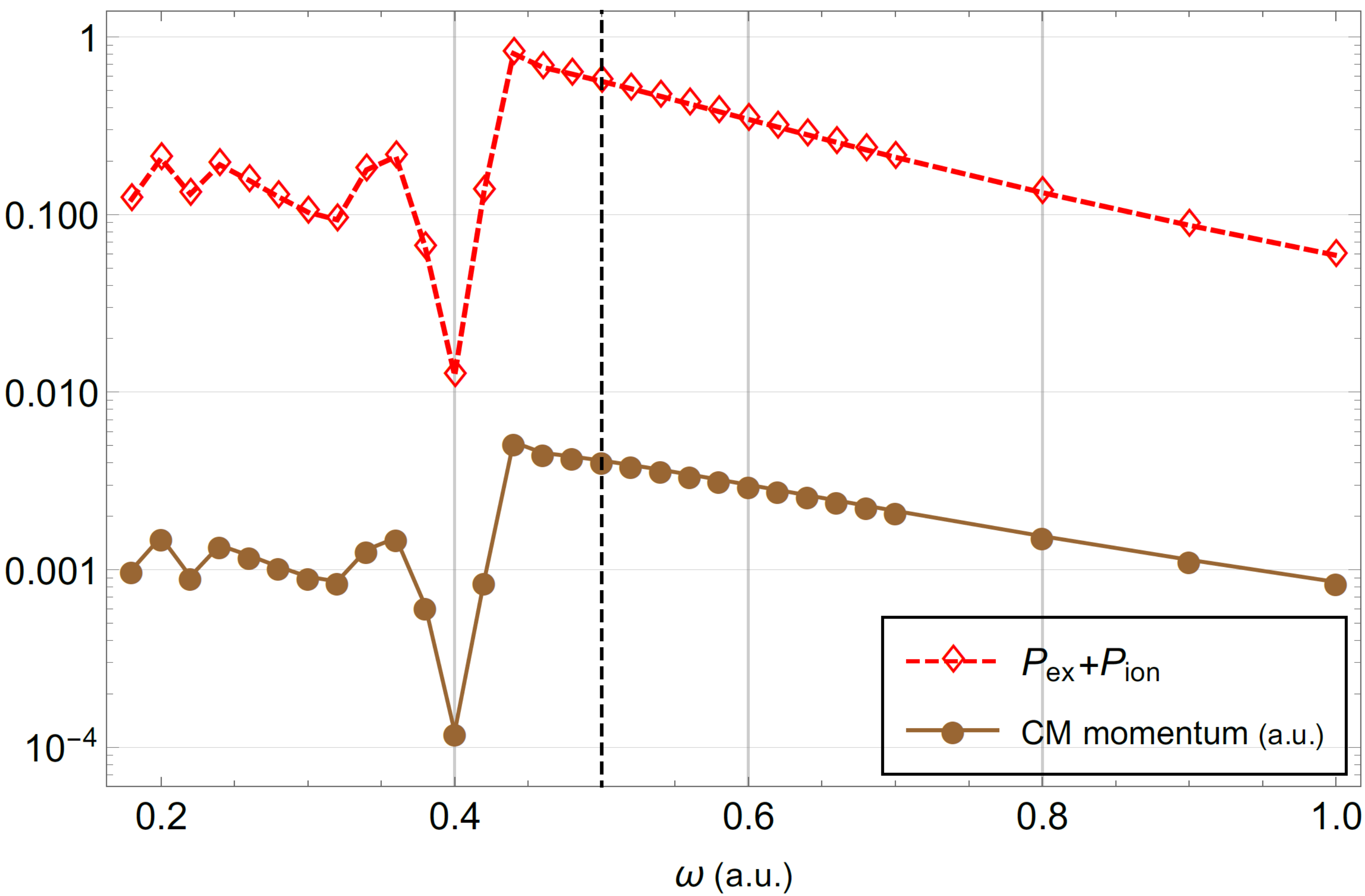


non-resonant mechanism

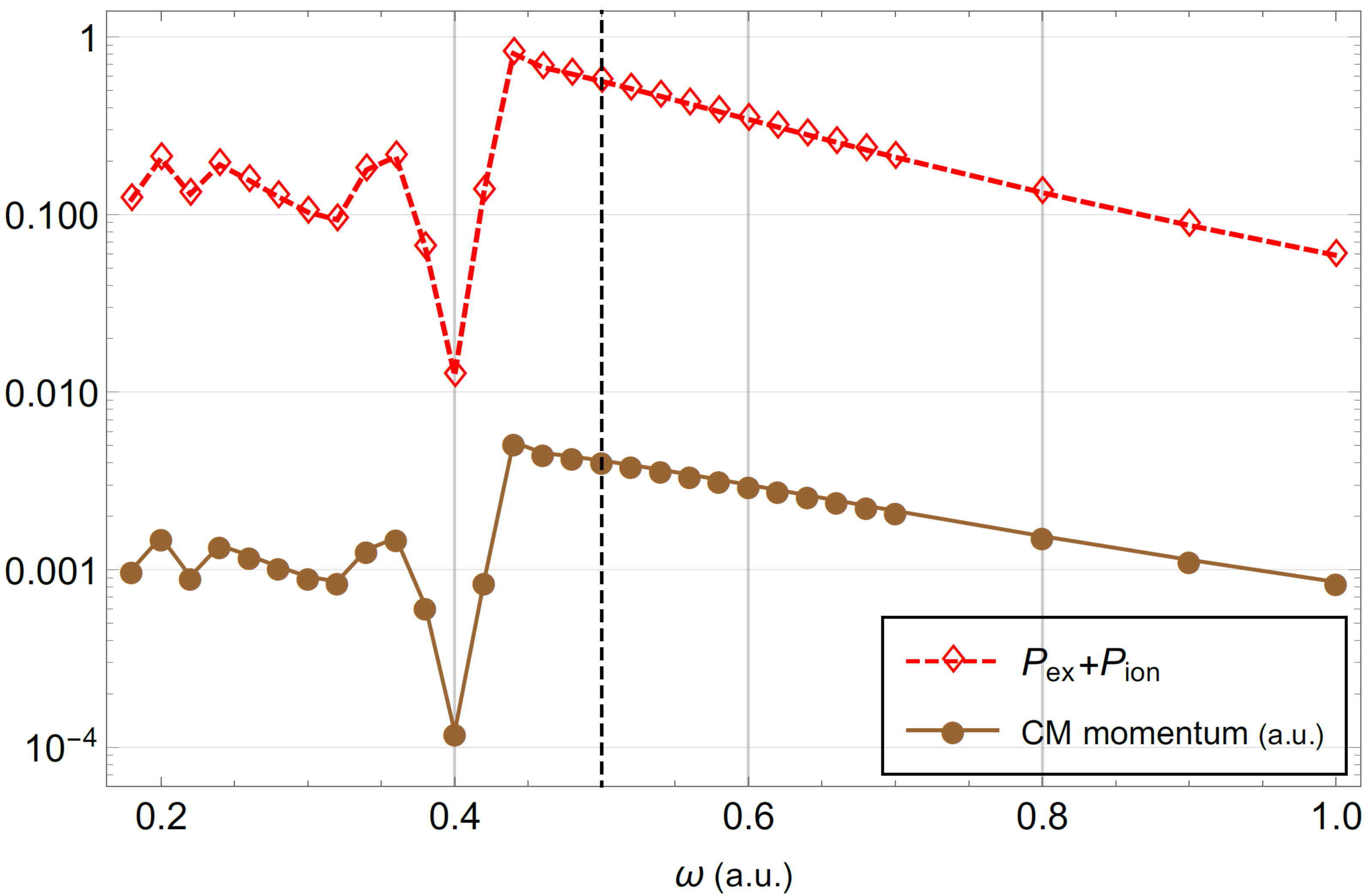


1
0.100
0.010
0.001
10^{-4}
0.2
0.4
0.6
0.8
1.0
ω (a.u.)
$P_{ex}+P_{ion}$


1
0.100
0.010
0.001
10^{-4}
0.2
0.4
0.6
0.8
1.0
ω (a.u.)
$P_{ex}+P_{ion}$
CM momentum (a.u.)



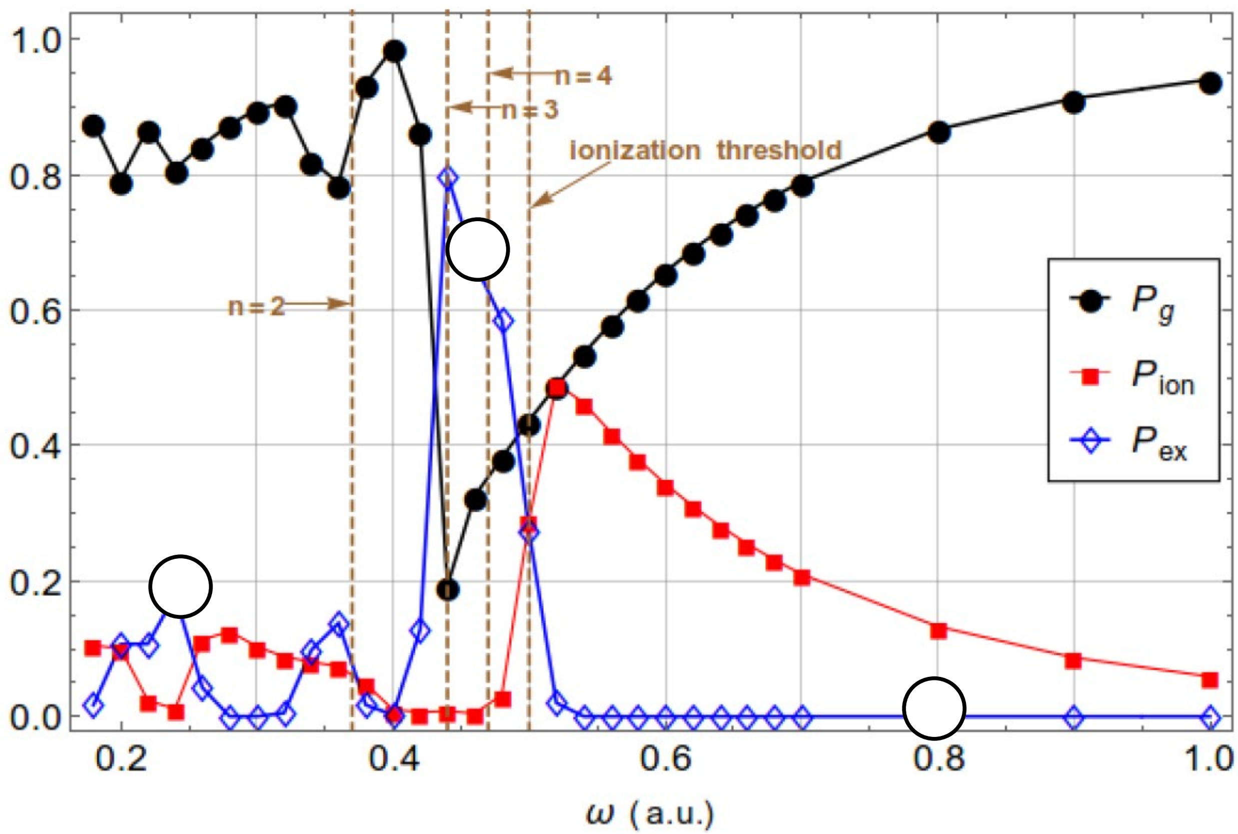
strong correlation between $P_{ex} + P_{ion}$ and V_y (CM momentum $= MV_y$)



strong correlation between $P_{ex} + P_{ion}$ and V_y (CM momentum $= MV_y$)

mechanism of CM acceleration:

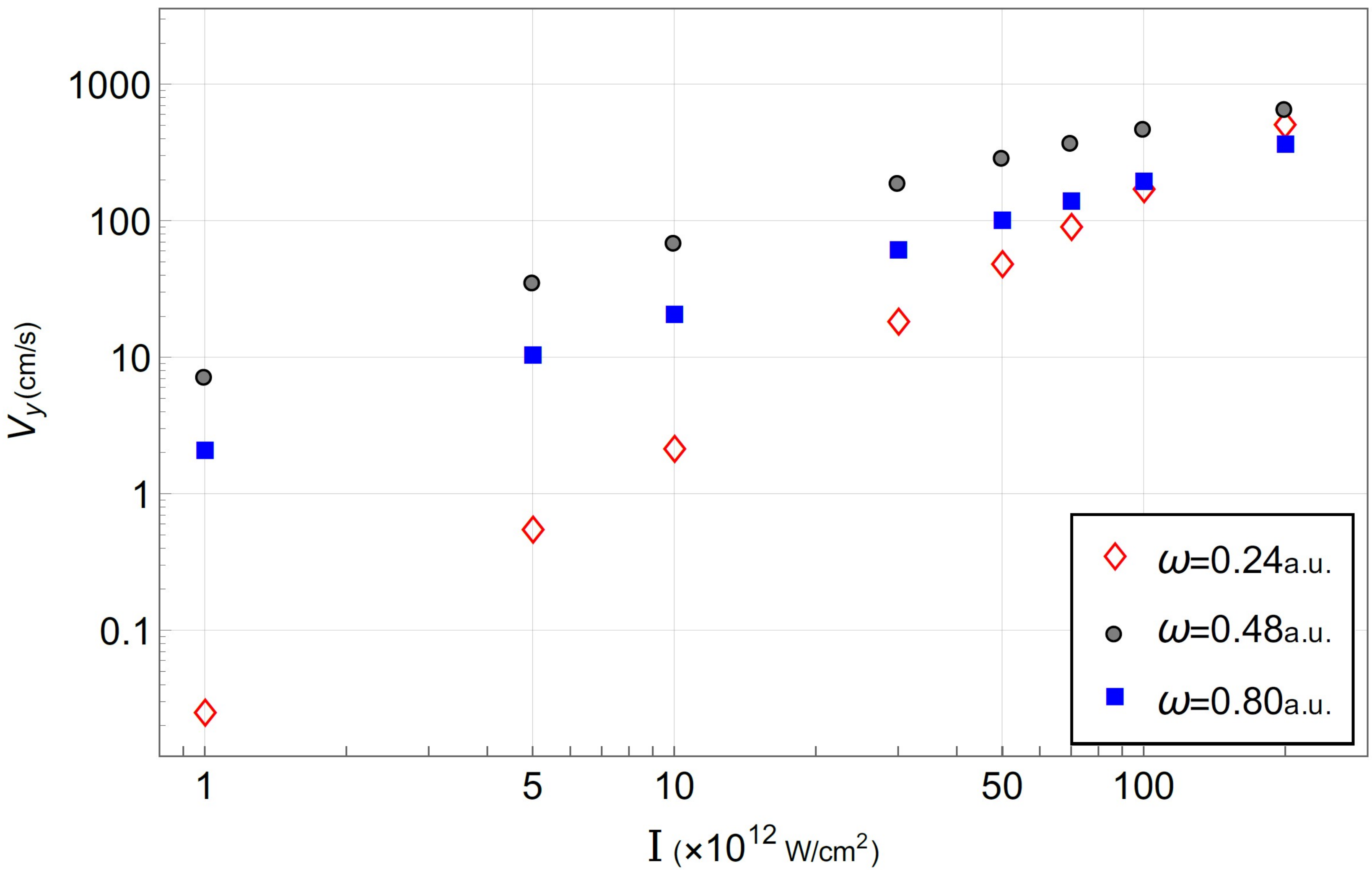
generation of nonzero dipole between proton and electron cloud
transferred either to excited states of atom or to its continuum



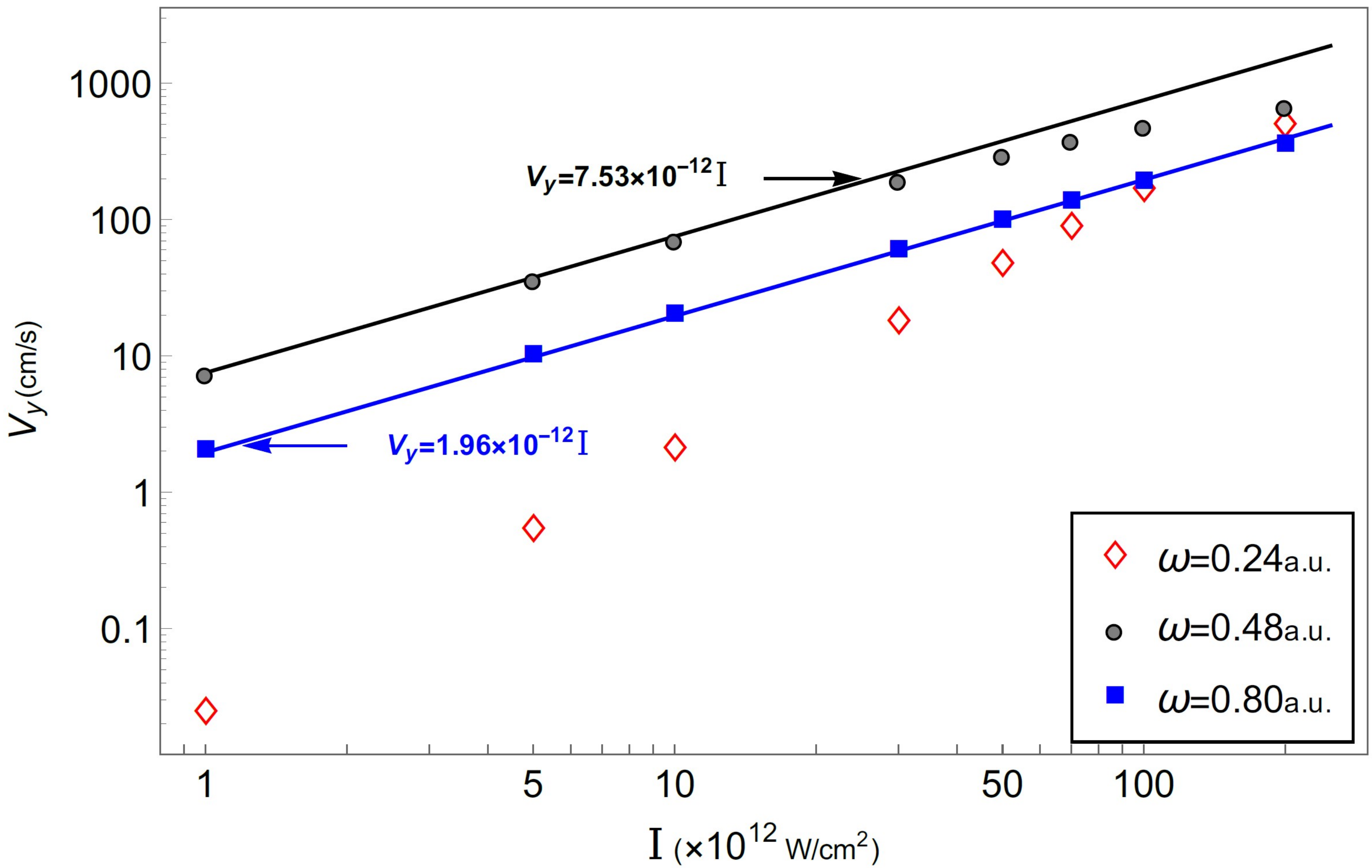
$\omega = 0.48$a.u. one-photon resonant transition $n = 1 \rightarrow n' = 4$

$\omega = 0.24$a.u. two-photon resonant transition $n = 1 \rightarrow n' = 4$

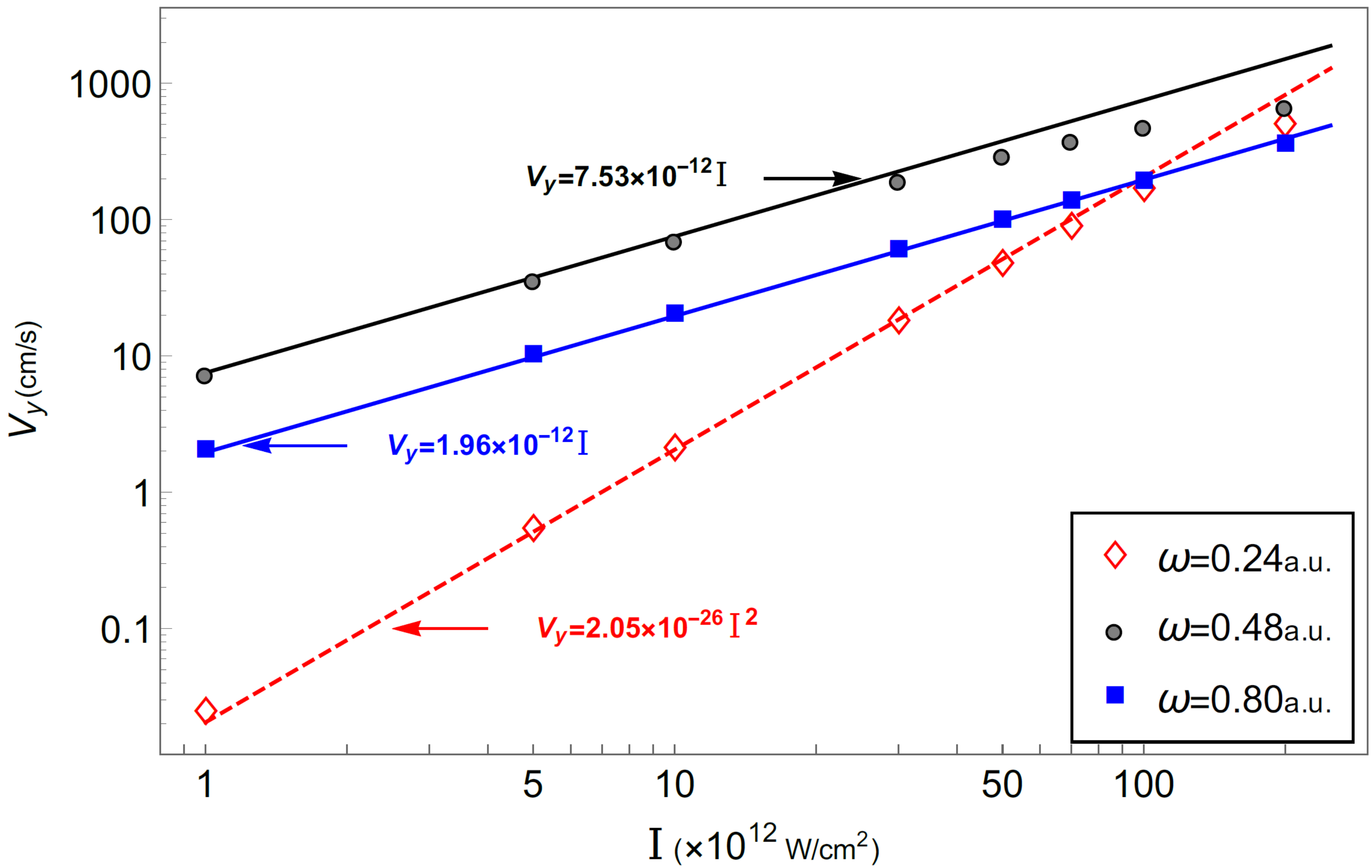
$\omega = 0.8$a.u. non-resonant mechanism



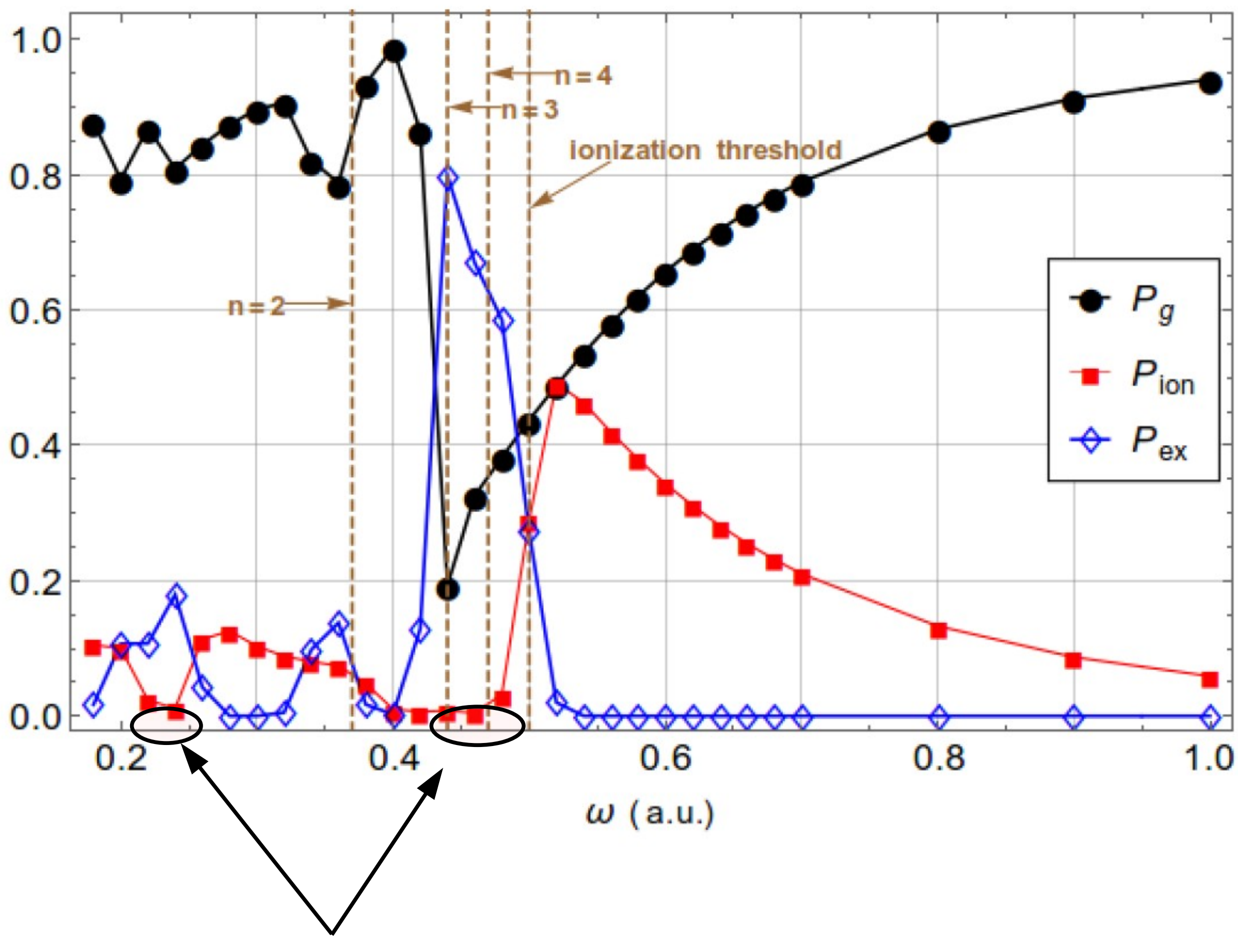
1000
100
10
1
0.1
V_y(cm/s)
1
5
10
50
100
I (×10^{12} W/cm^2)
ω=0.24a.u.
ω=0.48a.u.
ω=0.80a.u.



1000
100
10
1
0.1
V_y(cm/s)
V_y=7.53×10^{-12} I
V_y=1.96×10^{-12} I
ω=0.24a.u.
ω=0.48a.u.
ω=0.80a.u.
1
5
10
50
100
I (×10^{12} W/cm^2)



V_y=7.53×10^{-12} I
V_y=1.96×10^{-12} I
V_y=2.05×10^{-26} I^2
ω=0.24a.u.
ω=0.48a.u.
ω=0.80a.u.
V_y(cm/s)
1000
100
10
1
0.1
1
5
10
50
100
I (×10^{12} W/cm^2)



areas promising for accelerating atoms where ionization is suppressed

Twisting of atoms by EM pulses

QUANTUM PHYSICS

Vortex beams of atoms and molecules

Alon Luski[1]†, Yair Segev[1]†‡, Rea David[1], Ora Bitton[1], Hila Nadler[1], A. Ronny Barnea[2], Alexey Gorlach[3], Ori Cheshnovsky[2], Ido Kaminer[3], Edvardas Narevicius[1]*

SCIENCE · 1 Sep 2021 · Vol 373, Issue 6559 · pp. 1105-1109

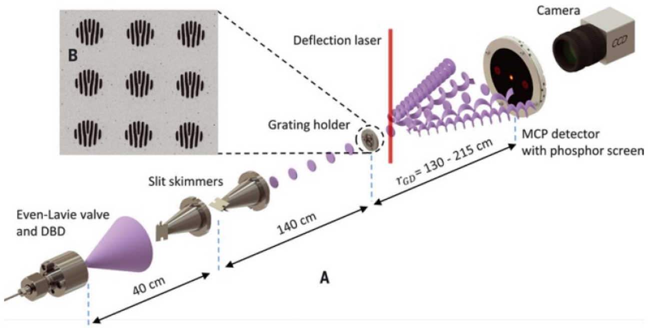


Fig. 2. Experimental setup for the production and detection of atomic and molecular vortex beams.

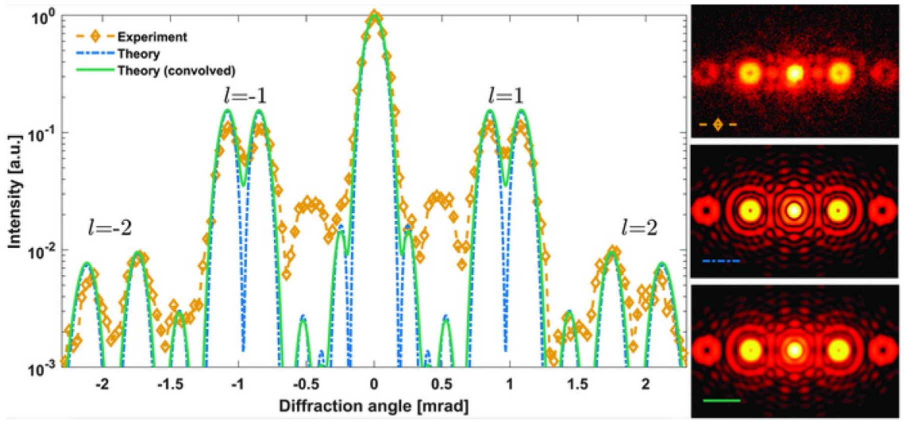
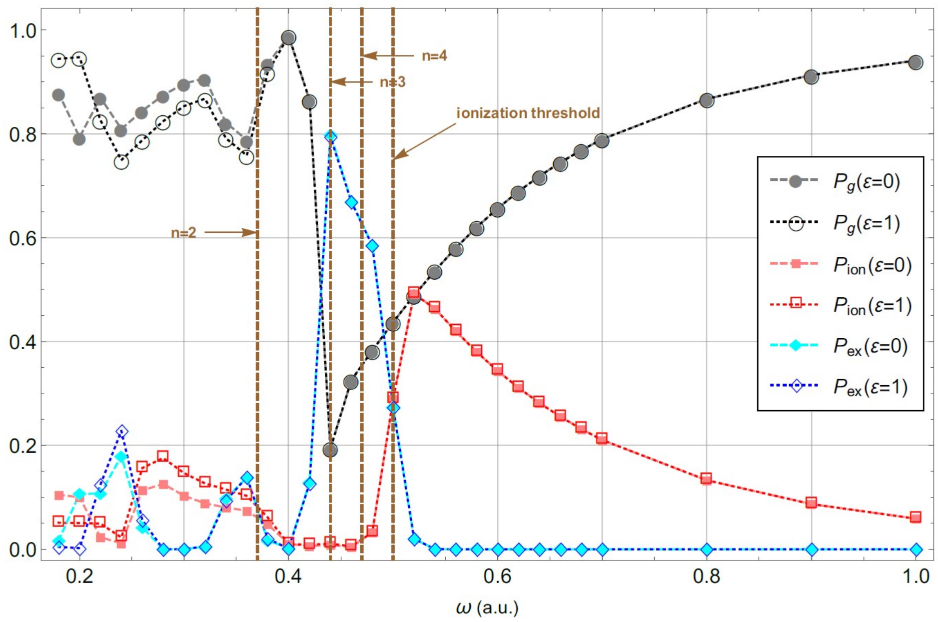


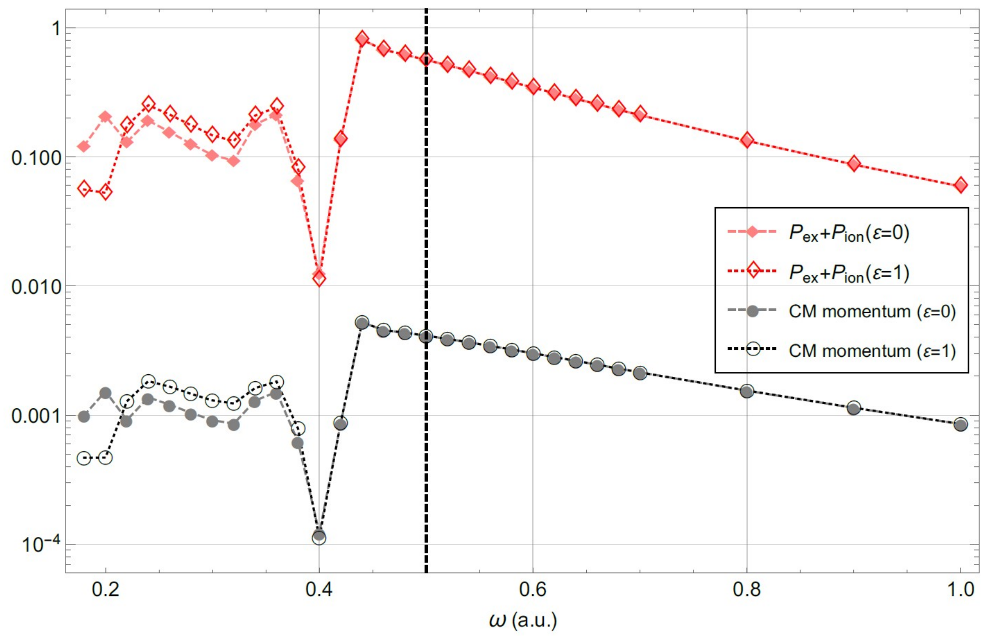
Fig. 4. Comparison of intensity measured in the experiment to theory, with simulated contribution of only the atoms.

Luski *et al.*, *Science* **373**, 1105–1109 (2021) 3 September 2021

Twisting of atoms by EM pulses



Twisting of atoms by EM pulses

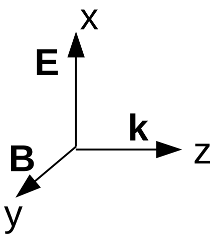


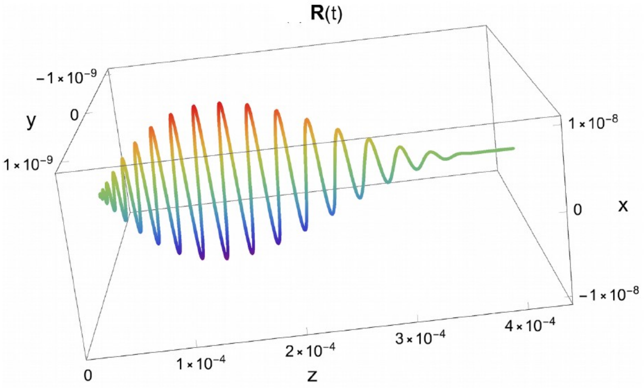
Twisting of atoms by EM pulses

10^{14} вт/см^2 , ~10фс, hν ~13эВ~ 0.48a.u.

Linear polarization (ϵ=0)

$$\mathbf{A} = \frac{E_0}{\omega\sqrt{2}} \sin^2(\frac{\pi t}{NT}) \left[-\hat{\mathbf{x}} \sin(\omega t - kz)\right]$$





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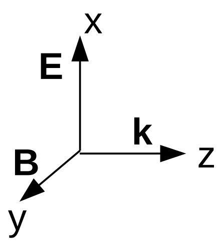
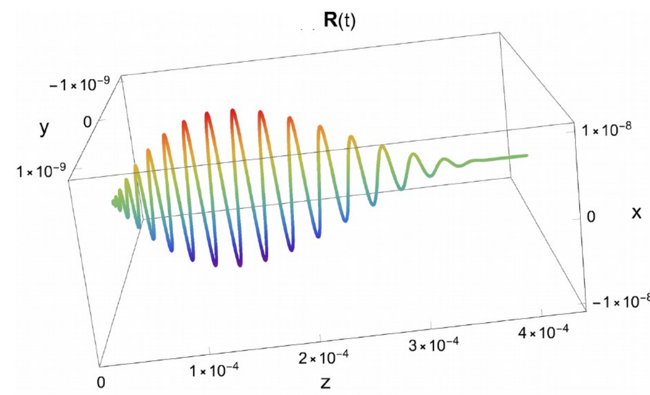
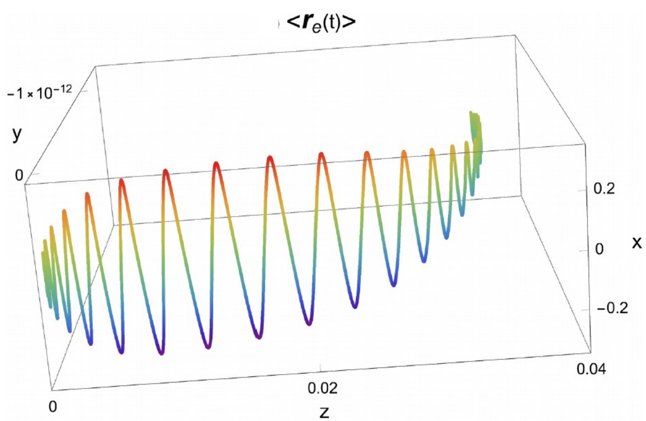
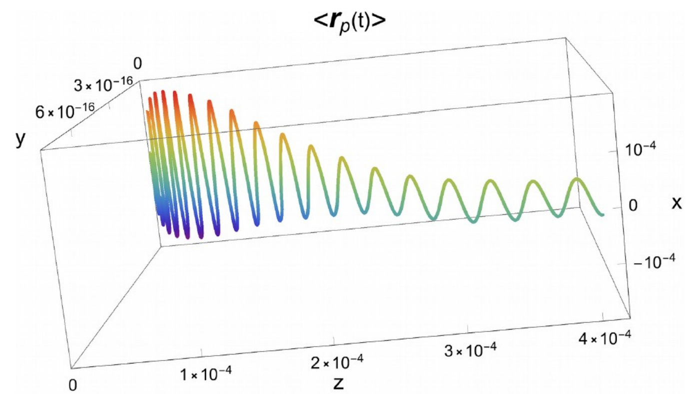




$$\langle x_e(t)\rangle = X_{cm}(t) + \frac{m_p}{M}\langle x(t)\rangle$$
$$\langle x_p(t)\rangle = X_{cm}(t) - \frac{m_e}{M}\langle x(t)\rangle$$





Twisting of atoms by EM pulses

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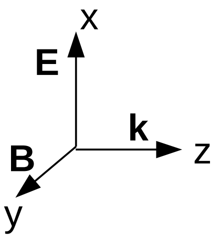
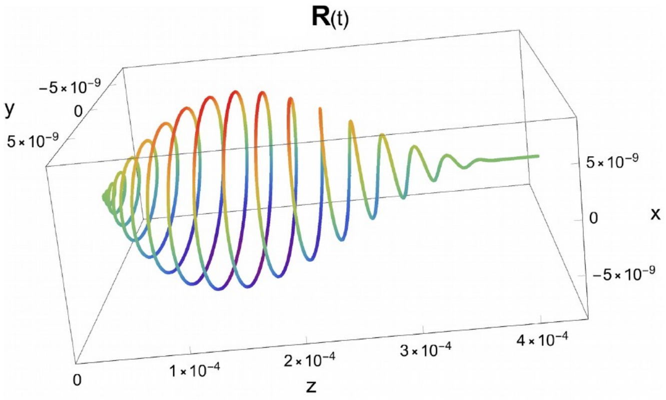
Circular polarization (ϵ=1)

$$\mathbf{A} = \frac{E_0}{\omega\sqrt{2}} \sin^2(\frac{\pi t}{NT}) \left[-\hat{\mathbf{x}} \sin(\omega t - kz) + \hat{\mathbf{y}} \cos(\omega t - kz)\right]$$





Twisting of atoms by EM pulses

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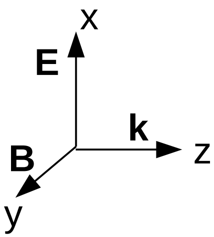
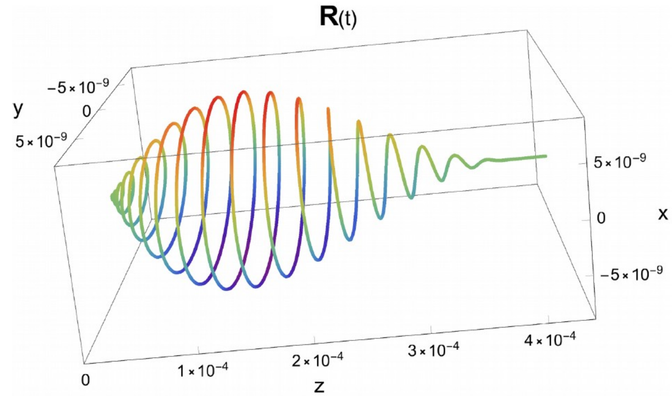
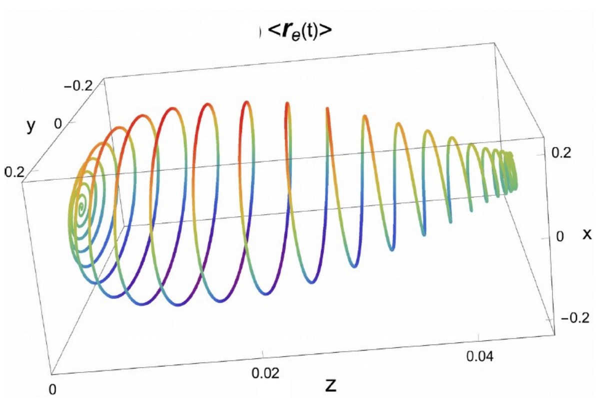
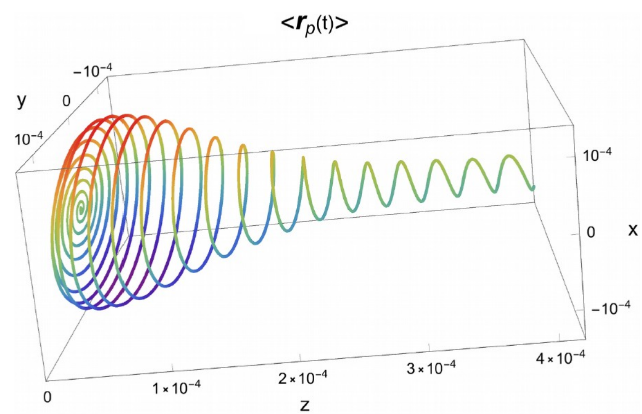






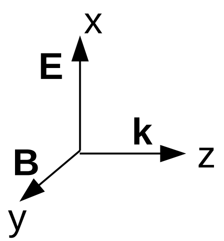


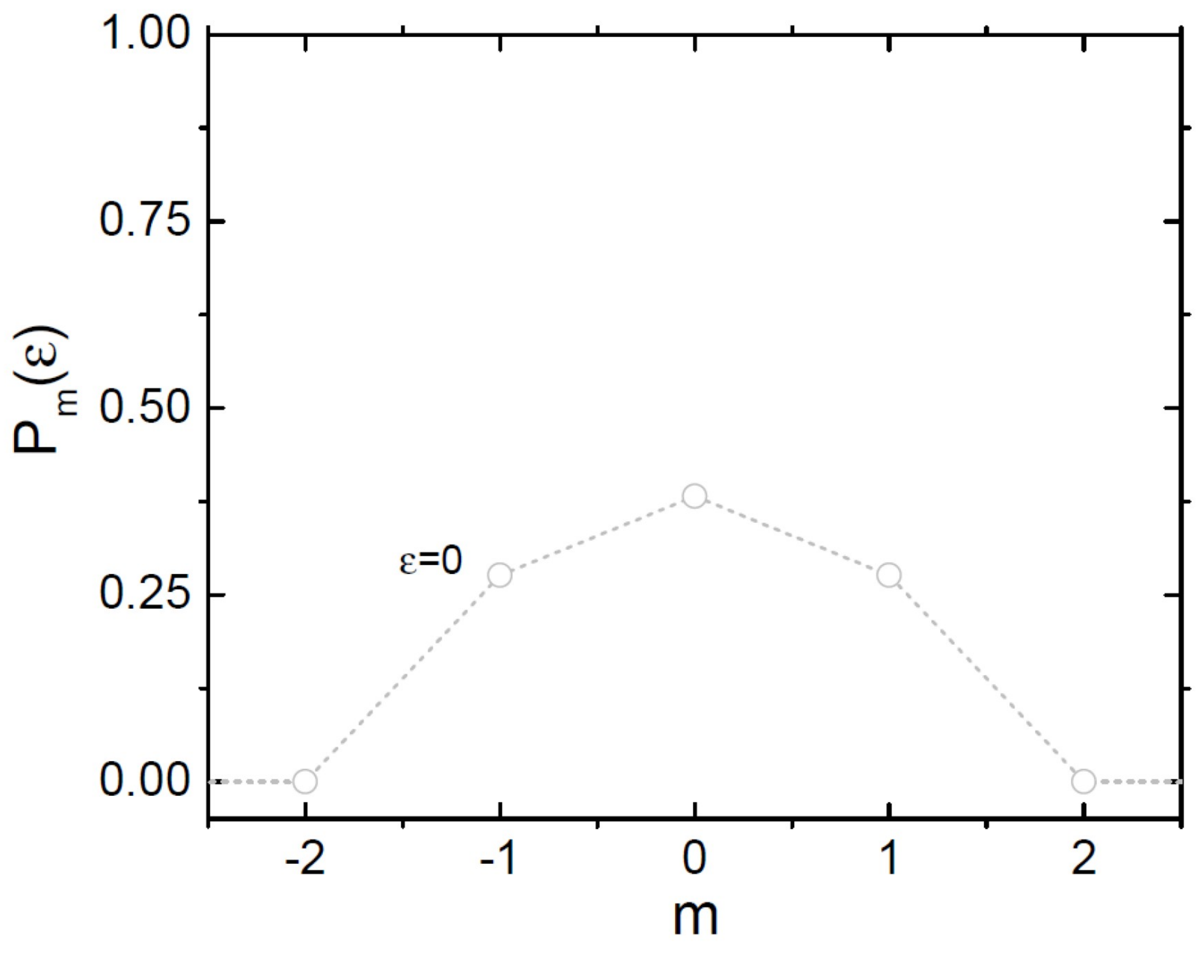
Twisting of atoms by EM pulses

10^{14} вт/см^2 , ~10фс, hν ~13эВ~ 0.48a.u.

Elliptical polarization (ε=0-1)

$$P_m = \sum_{n=l+1}^{n_{max}} \sum_{l=|m|}^{n_{max}-1} |\langle \psi | \phi_{nlm} \rangle|^2$$





Twisting of atoms by EM pulses

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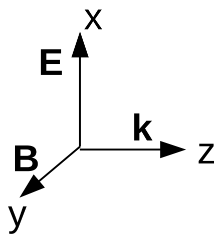
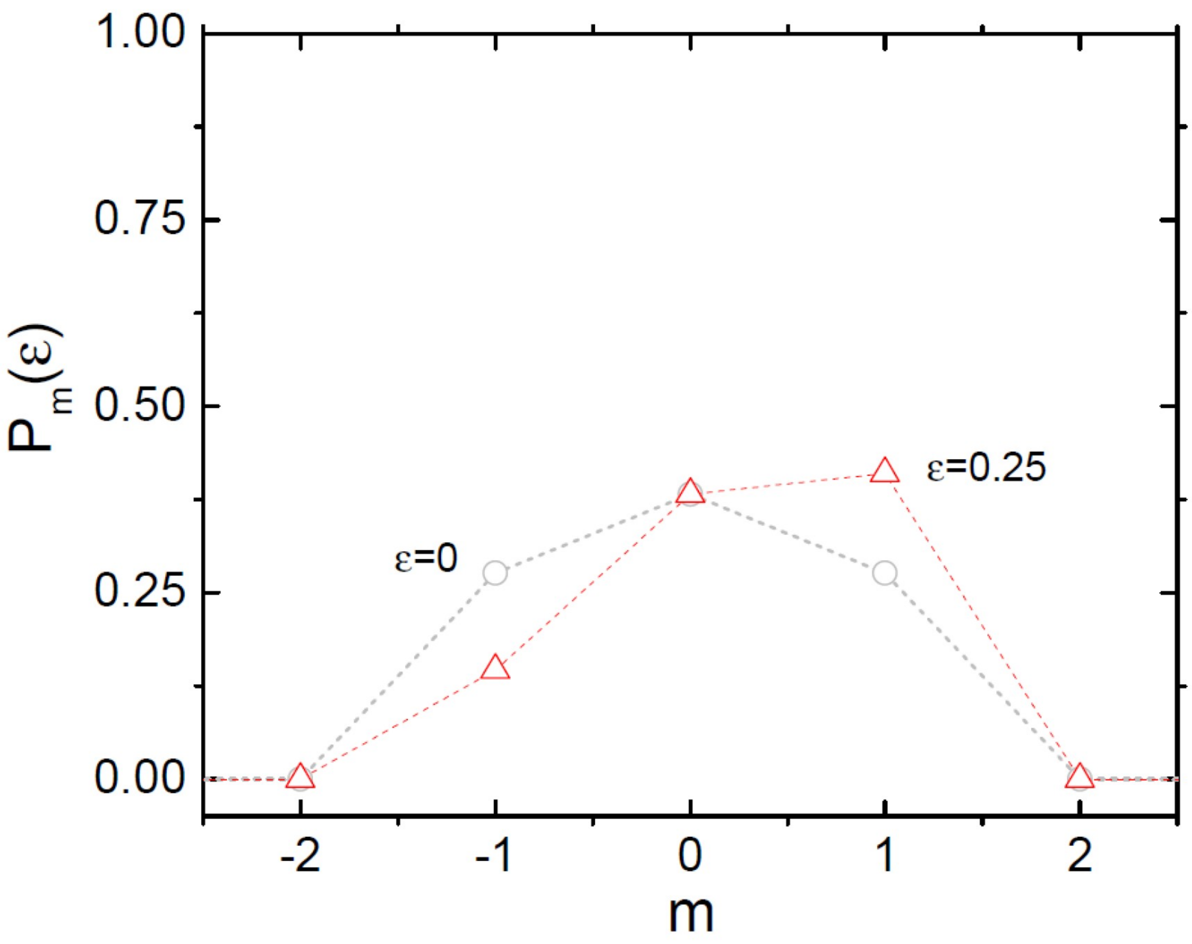
Elliptical polarization (ϵ=0-1)





Twisting of atoms by EM pulses

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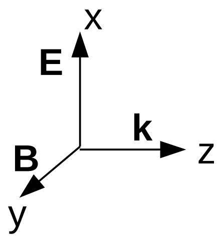
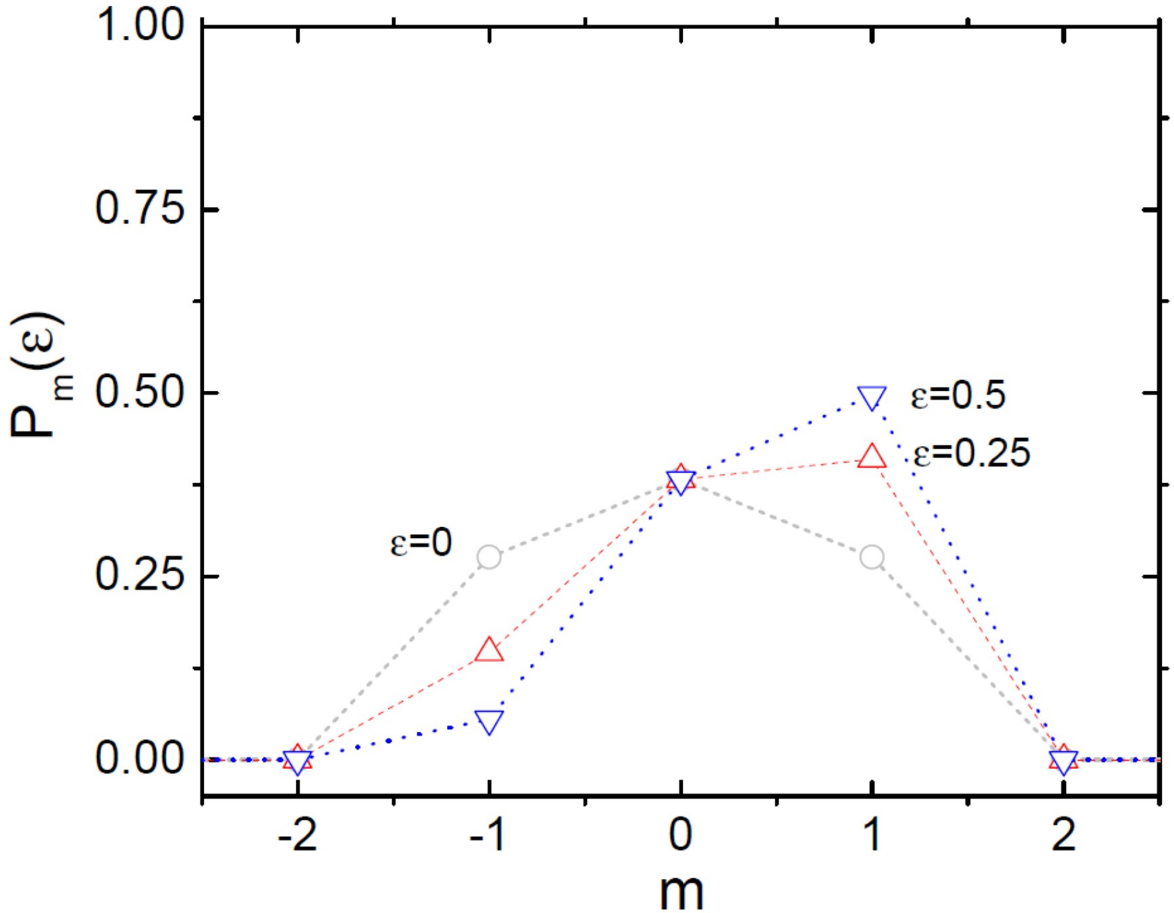
Elliptical polarization (ϵ=0-1)

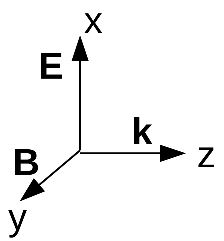


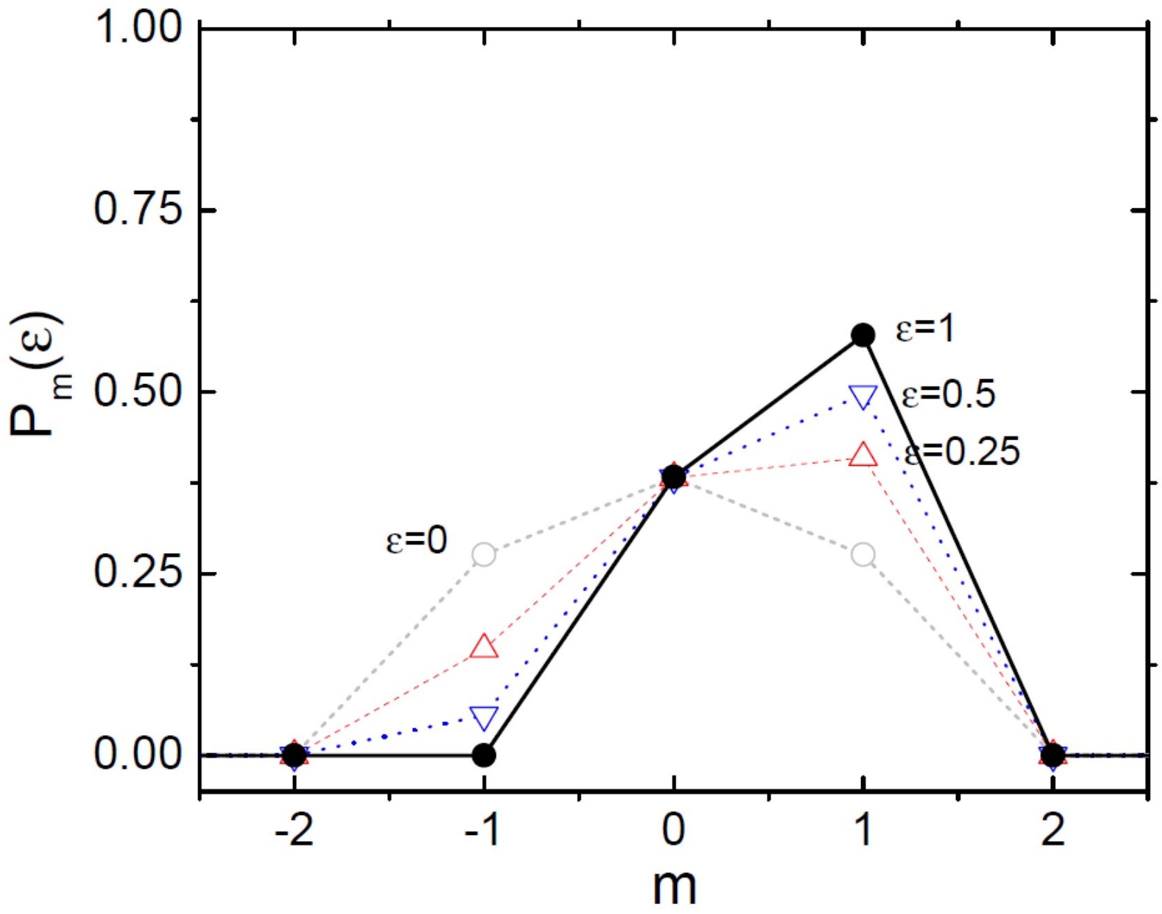


Twisting of atoms by EM pulses

10^{14} вт/см^2 , ~10фс, hν ~13эВ~ 0.48a.u.

Circular polarization (ε=1)



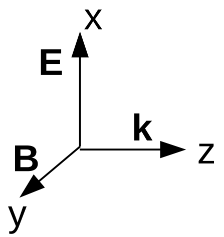


Twisting of atoms by EM pulses

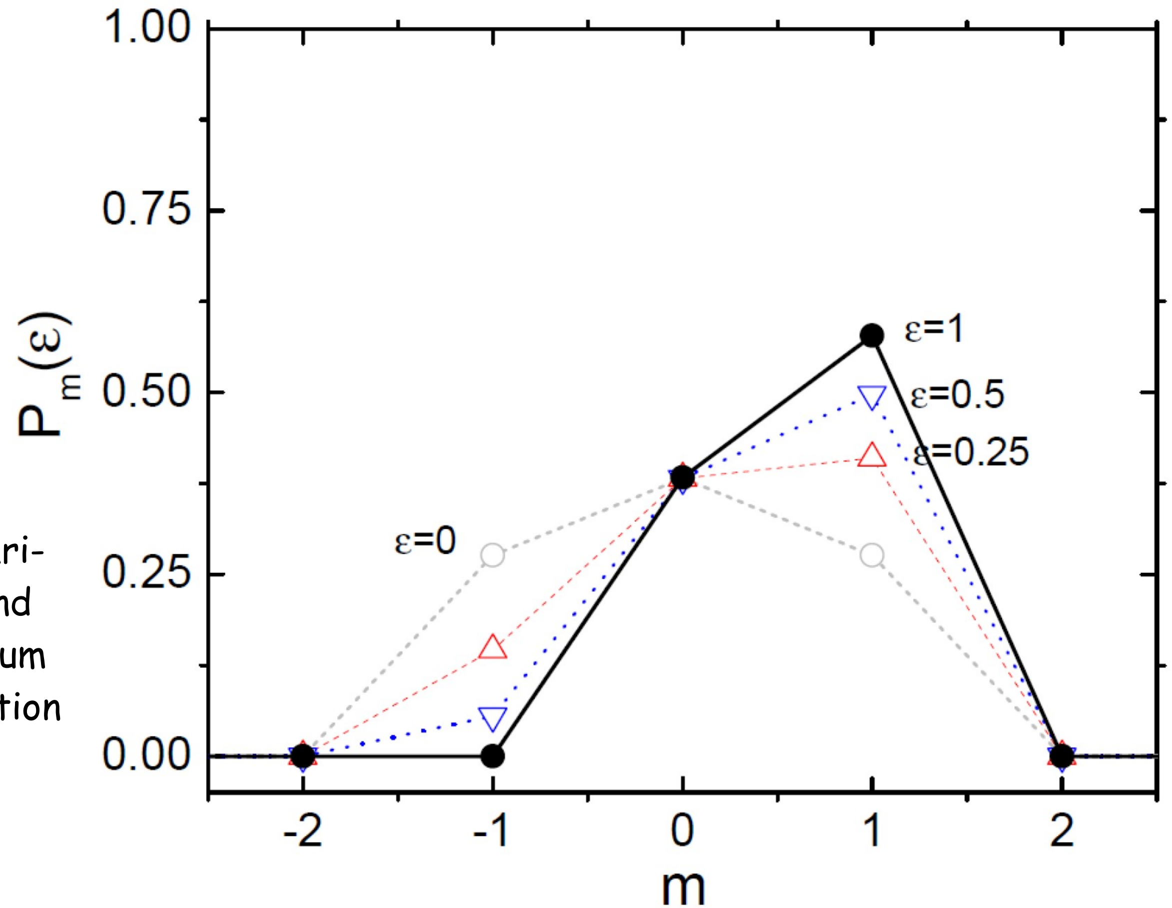
10^{14} вт/см^2, ~10фс, hν ~13эВ~ 0.48a.u.

Circular polarization (ε=1)

$$P_m = \sum_{n=l+1}^{n_{max}} \sum_{l=|m|}^{n_{max}-1} |\langle \psi | \phi_{nlm} \rangle|^2$$



$$\langle \hat{l}_z \rangle = \sum_m P_m(\varepsilon) m$$



when interacting with a circularly polarized EM pulse, the atom accelerates and «twists» - acquires an orbital momentum with a projection of m=+1 in the direction of its motion (pseudo-chirality=+1)

Conclusion & outlook

- acceleration of atom due to non-dipole corrections kr in EM wave and magnetic component B/c in it was invastigated
- strong correlation was found between V (MV) and $P_{ex} + P_{ion}$
- two resonant mechanisms of atom acceleration were found: through single-photon and two-photon excitation of atom

single-photon $V \sim I$

two-photone $V \sim I^2$

Conclusion & outlook

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single-photon $V \sim I$

two-photone $V \sim I^2$

three-photone $V \sim I^3$?

Conclusion & outlook

- acceleration of atom due to non-dipole corrections kr in EM wave and magnetic component B/c in it was invastigated
- strong correlation was found between V (MV) and $P_{ex} + P_{ion}$
- two resonant mechanisms of atom acceleration were found: through single-photon and two-photon excitation of atom
- <u>potential applications:</u>

accelerated atoms — lithography of micro-chips for micro-electronics, plasma diagnostics in TOKAMAK, ...
«twisted» atoms — modification of fundamental interactions, new «tool» for investigation of atomic collisions, ...

Conclusion & outlook

- acceleration of atom due to non-dipole corrections kr in EM wave and magnetic component B/c in it was invastigated
- strong correlation was found between V (MV) and $P_{ex} + P_{ion}$
- two resonant mechanisms of atom acceleration were found: through single-photon and two-photon excitation of atom
- non-dipole effects (accounting nuclei motion) in atomic int. with EM pulse $V_2(r, R, t) = \frac{\omega}{c} E_0(....)$: influence on high harmonic generation, stabilization of atoms, ...
  groundwork was created for study of non-dipole effects: different atoms, accounting of spatial inhomogeneity of EM pulse, different polarizations, twisted atoms, ...

Conclusion & outlook

hybrid quantum-quasiclassical approach + DVR

S Shadmehri, V S Melezhik, Laser Phys. 33, 026001 (2023)

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