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Electromagnetically induced transparency for x-rays by high intensity lasers

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February 21, 2007

Contents

X-ray probe of laser-manipulated atoms

- Pump-probe-experiments with lasers and x-rays since the advent of synchrotron radiation sources
- Mostly weak laser
- **Review:** Wuilleumier, Meyer, **J. Phys. B 39, R425 (2006)**

- **Pump:** valence **ionization** by linearly polarized laser
  - Electrons are ejected predominantly along the laser axis
  - Hole orbital is aligned in ion
- **Probe:** electron **excitation** from *K*-shell to hole orbital
  - Background free; only absorption for ionized atoms
  - Different photoabsorption for parallel and perpendicular x-rays
- **Krypton atom:** Young *et al.*, **Phys. Rev. Lett. 97, 083601 (2006)**

Quantum state-resolved EUV probe of xenon ions

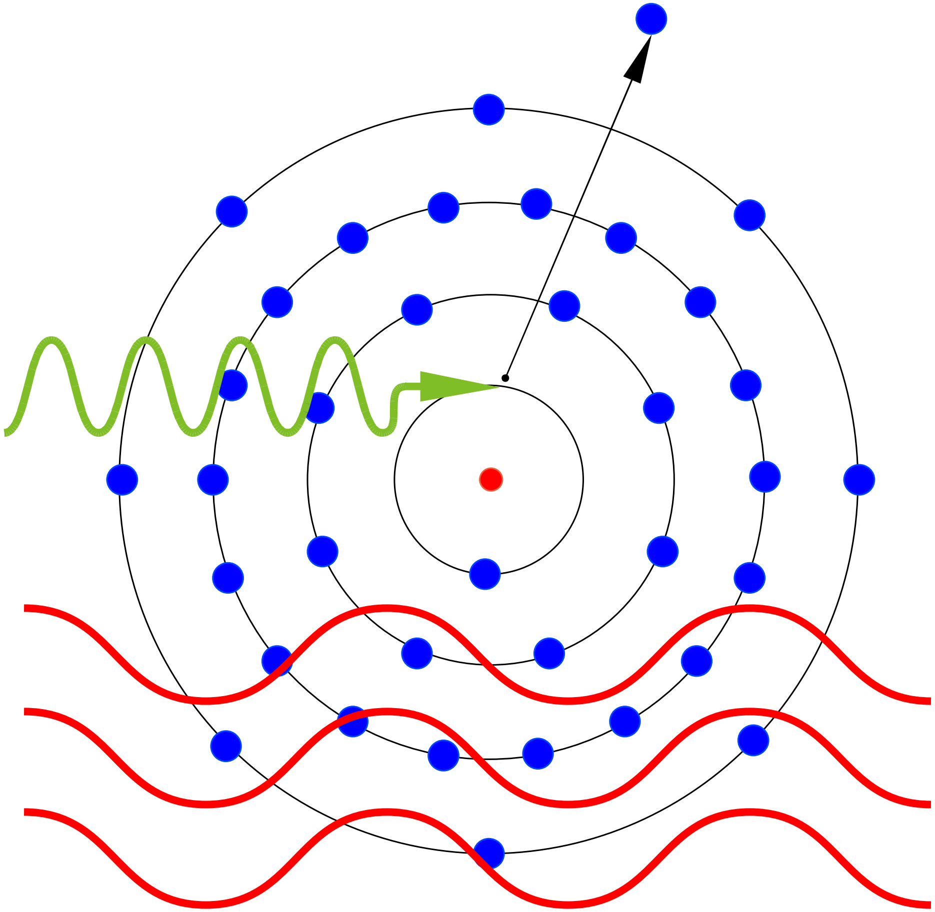
- **Pump:** Laser ionization of $5p$ valence electron of xenon atoms
- **Probe:** Excitation of $4d$ core electron to $5p$ valence hole for parallel and perpendicular polarizations
- **Experiment:** femtosecond high-order harmonic transient absorption spectroscopy of a xenon atom

- **Theory:** xenon is a heavy atom with appreciable spin-orbit coupling
- Strong-field tunnel ionization of $5p$ valence electron of xenon atoms
- Ionization produces a distribution of $|j, m>$ quantum states
- Probabilities to find the accessible quantum states are calculated

[Loh *et al.*, Phys. Rev. Lett. 98, 143601 (2007)]

X-ray probe of laser-dressed atoms

- Atoms are in the field of an **optical laser**
- Probed by x-rays
- Laser dressing barely influenced by x-rays



[Buth, Santra, Phys. Rev. A 75, 033412 (2007)]

Laser characteristics

- Assume an $800\ \mathrm{nm}$ (**Ti:Sapphire**) laser system
- Laser is of **moderately high intensity** $10^{13}\ \mathrm{W\,cm^{-2}}$
  - Atomic electrons are neither excited nor ionized
  - Only final states are modified

- **Keldysh parameter** for Rydberg orbitals (here Ne $3p$)

$$\gamma = \sqrt{\frac{I_{3\mathrm{p}}}{2\,U_{\mathrm{p}}}} = 1.5 \approx 1$$

- **Strong field regime**
  [$\gamma \ll 1$ adiabatic tunneling picture; $\gamma \gg 1$ perturbative multiphoton process]

- **Multiphoton** physics
- Need **sophisticated** theoretical treatment!

[Buth, Santra, Young, Phys. Rev. Lett. 98, 253001 (2007)]

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Quantum electrodynamic description of atoms

- **Hartree-Fock-Slater** one-electron model
  [radial part of the wave function is given in a flexible finite-element basis]

$$\hat{H}_{\mathrm{AT}} = -\frac{1}{2}\vec{\nabla}^2 + V_{\mathrm{HFS}}(r)$$

- Non-relativistic quantum electrodynamics in electric dipole approximation
- **Free electromagnetic field** for the two-modes (laser plus x-rays)

$$\hat{H}_{\mathrm{EM}} = \omega_{\mathrm{L}} \hat{a}_{\mathrm{L}}^{+} \hat{a}_{\mathrm{L}} + \omega_{\mathrm{X}} \hat{a}_{\mathrm{X}}^{+} \hat{a}_{\mathrm{X}}$$

- **Interaction** of electrons with laser- or x-ray-light $\lambda = \mathrm{L}, \mathrm{X}$

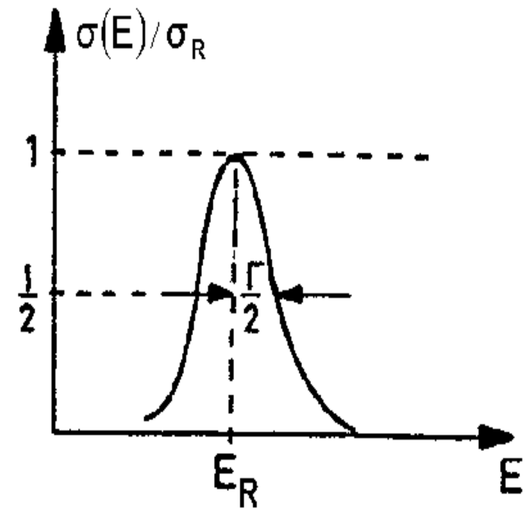
$$\hat{H}_{\lambda} = \vec{x} \cdot \mathrm{i} \sqrt{2\pi V^{-1} \omega_{\lambda}} \; [\vec{e}_{\lambda} \hat{a}_{\lambda} - \vec{e}_{\lambda}^{*} \hat{a}_{\lambda}^{+}]$$

[Buth, Santra, Phys. Rev. A 75, 033412 (2007)]

Resonance energies using complex absorbing potentials

- **Complex absorbing potential (CAP)** $\hat{W}$ added to the Hamiltonian
- CAP derived from smooth exterior complex scaling
- Spectrum of Hamiltonian is modified by CAP
- Decaying state becomes a bound state with a complex **Siegert energy**

$$E_{\mathrm{res}} = E_{\mathrm{R}} - \mathrm{i}\frac{\Gamma}{2}$$



- Wave function

$$\psi \propto \mathrm{e}^{-\mathrm{i}E_{\mathrm{res}}t} \propto \mathrm{e}^{-\mathrm{i}E_{\mathrm{R}}t}\,\mathrm{e}^{-\frac{\Gamma}{2}t}$$

- Resonance position E_{R} and width Γ ; lifetime $\frac{1}{\Gamma}$

[Buth, Santra, Phys. Rev. A 75, 033412 (2007)]

Laser-atom interaction

- Hamiltonian for the atom in the laser field **[no x-rays so far]**

$$\hat{H}_0 = \hat{H}_{\mathrm{AT}} + \hat{H}_{\mathrm{EM}} + \hat{H}_{\mathrm{L}} + \hat{W}$$

- Direct product basis set of atomic orbitals and laser Fock states

$$|\Phi_{n\,l\,m\,\mu}> = |\psi_{n,l,m}> \; |\mu>$$

- Diagonalization of matrix yields **laser-dressed atomic energy levels**

$$\left(\boldsymbol{H}_0^{(m)}\right)_{n\,l\,\mu,\,n'\,l'\,\mu'} = \langle \Phi_{n\,l\,m\,\mu} | \hat{H}_0 | \Phi_{n'\,l'\,m\,\mu'} \rangle$$

$$\boldsymbol{H}_0^{(m)} \vec{c}_F^{(m)} = E_F^{(m)} \vec{c}_F^{(m)}$$

[Buth, Santra, Phys. Rev. A 75, 033412 (2007)]

X-ray photon absorption

- Decaying core excited state with complex Siegert energy
- Relaxes [Kr $230\,\mathrm{as}$, Ne $2.3\,\mathrm{fs}$] by **Auger decay** and **x-ray fluorescence**
- Decay of 1*s* core hole is accounted for by $E_F^{(m)} = E'^{(m)}_F - \mathrm{i}\,\Gamma_{1\mathrm{s}}^{\exp}/2$
- X-ray probe $\hat{H}_1 \equiv \hat{H}_{\mathrm{X}}$ is a **weak, one-photon** process
  => Non-Hermitian Rayleigh-Schrödinger perturbation theory
- Initial ground state $|I>$ and laser-dressed core-excited final states $|F^{(m)}>$

$$E_{I,0} = \langle I | \hat{H}_0 | I \rangle, \quad E_{I,1} = \langle I | \hat{H}_1 | I \rangle = 0$$

$$E_{I,2} = \sum_{F,m} \frac{\langle I | \hat{H}_1 | F^{(m)} \rangle \langle F^{(m)} | \hat{H}_1 | I \rangle}{E_{I,0} - E_{F,0}^{(m)}} \quad \Rightarrow \quad \sigma_{1\mathrm{s}} = 2 \frac{\Gamma}{J_{\mathrm{X}}}$$

$$\Gamma = -2\ \mathrm{Im}[E_{I,0} + E_{I,1} + E_{I,2}],$$

[Buth, Santra, Phys. Rev. A 75, 033412 (2007) and Buth, Santra, Cederbaum, Phys. Rev. A 69, 032505 (2004)]

Total x-ray absorption cross section

$$\sigma_{1s}(\omega_X, \vartheta_{LX}) = \sigma_{1s}^{\parallel}(\omega_X)\cos^2(\vartheta_{LX}) + \sigma_{1s}^{\perp}(\omega_X)\sin^2(\vartheta_{LX})$$

$$\sigma_{1s}^{\parallel}(\omega_X) \equiv \sigma_{1s}^{|0|}(\omega_X), \qquad \sigma_{1s}^{\perp}(\omega_X) \equiv \sigma_{1s}^{|1|}(\omega_X)$$

$$\sigma_{1s}^{|m|}(\omega_X) = \frac{8\pi}{3}\alpha\omega_X \operatorname{Im}\left[\sum_F \frac{(d_F^{|m|})^2}{E_F^{|m|} - E_{1s} - \omega_X}\right]$$

- Atom is **cylindrically deformed** along the laser polarization axis
- Dependence on angle between polarizations ϑ_{LX}
- Atomic properties described by $\sigma_{1s}^{\parallel}(\omega_X)$, $\sigma_{1s}^{\perp}(\omega_X)$
- Electron correlations and **non-dipole effects** ignored
  => manifest in deviations from the angular behavior

[Buth, Santra, Phys. Rev. A 75, 033412 (2007)]

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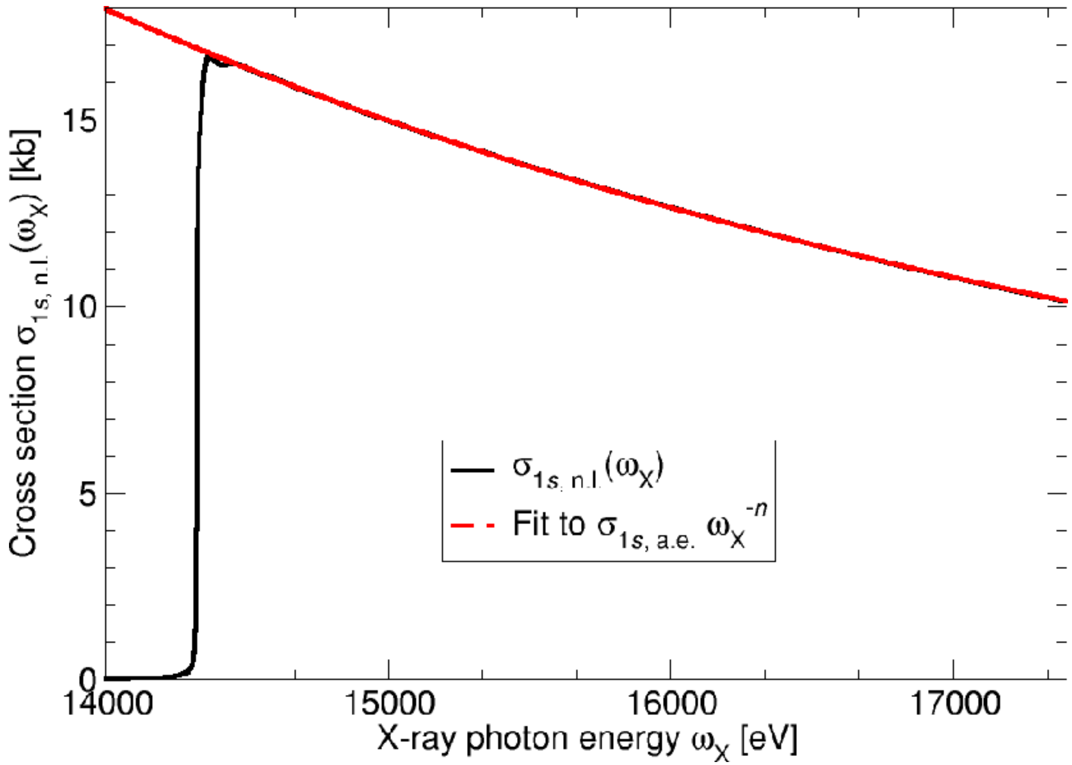
Krypton above the K-edge

- **Without** laser dressing; **only** x-ray absorption
- Above edge Bethe and Salpeter give

$$\sigma_{1s}(\omega_X) = \frac{\sigma_{1s,\mathrm{a.e.}}}{\omega_X^n}$$

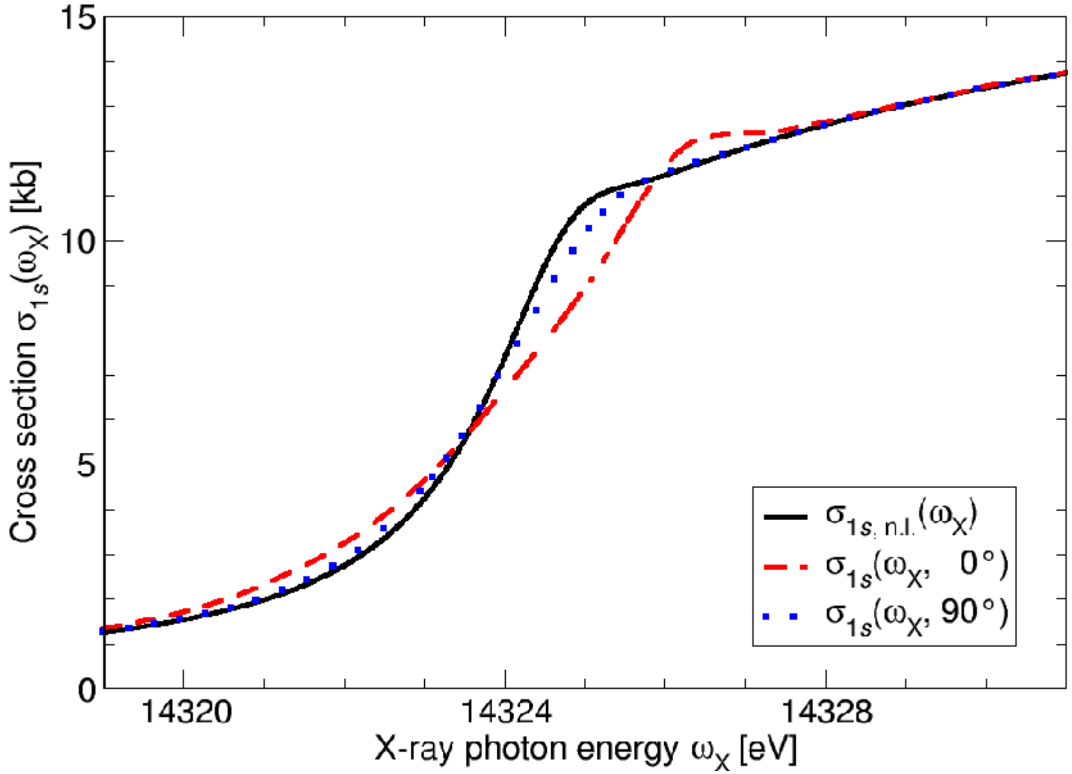
- Non-linear fit yields $n = 2.63$
- For hydrogen $n = \frac{8}{3} = 2.\overline{6}$
- Test of Hartree-Fock-Slater model, radial finite-element basis, and CAP method



[Buth, Santra, Phys. Rev. A 75, 033412 (2007)]

Krypton K-edge

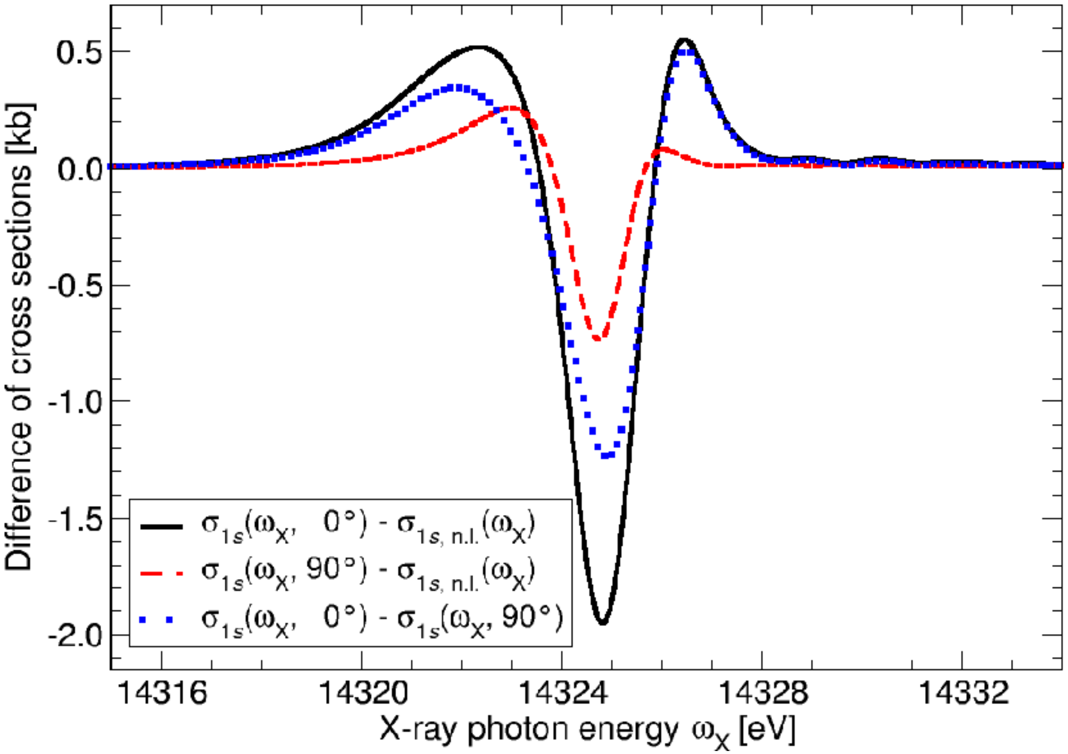
- Laser dressing with $800\ \mathrm{nm}$ at $10^{13}\ \mathrm{W\,cm^{-2}}$
- Laser influences cross section in the **vicinity** of the K-edge
- Dependence on the polarization between laser and x-rays
- **Appreciable** effect (20%)



[Buth, Santra, Phys. Rev. A 75, 033412 (2007)]

Differences of cross sections at the krypton K-edge

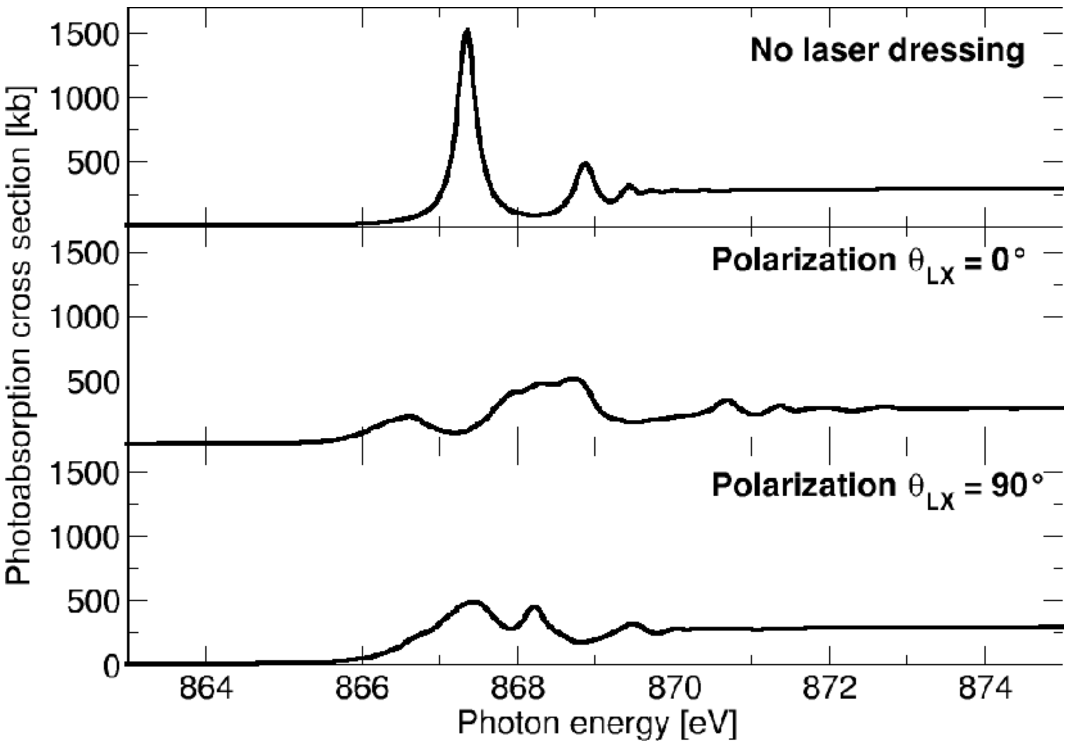
- Impact revealed by looking at differences
- **Largest effect** for parallel polarization in relation to the case without laser
- Shape understood: transition $1s \rightarrow 5p$ is **suppressed** by laser. Oscillator strength is redistributed to $5s$ and $4d$
- Reason for moderate effect: the **width** $\Gamma_{1s} = 2.7\ \text{eV}$



[Buth, Santra, Phys. Rev. A 75, 033412 (2007)]

Neon K-edge

- Rydberg series clearly resolved due to a **lower line width** $\Gamma_{1s} = 0.27\ \mathrm{eV}$
- Big effect of laser dressing
- For **parallel polarizations** transparency at the $1s \rightarrow 3p$ transition
- Suppression but no transparency for **perpendicular polarizations**



- Absorption and emission of up to **20 laser photons** to converge calculations

[Buth, Santra, Young, Phys. Rev. Lett. 98, 253001 (2007)]

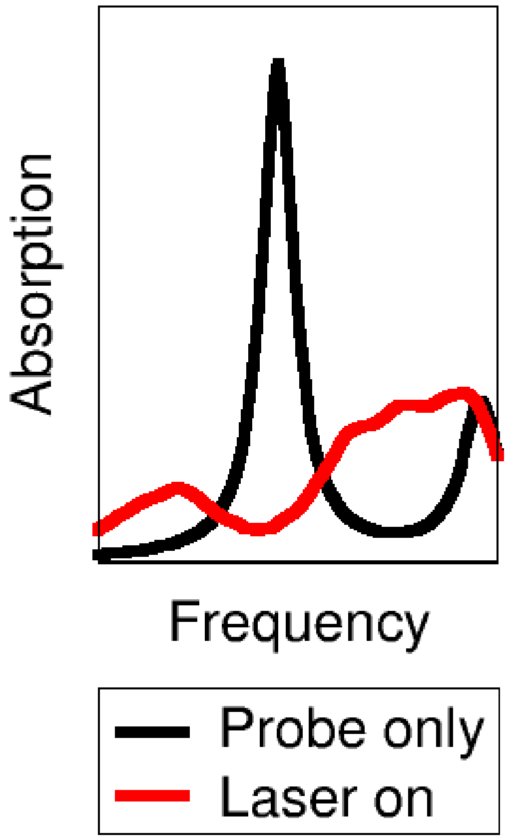
Electromagnetically induced transparency (EIT)

- Gas is **opaque** for light at an intraatomic transition
- Gas becomes **transparent** for this light by laser-dressing

- So far EIT for **optical** wavelengths has been studied
- We investigate EIT for **x-rays**

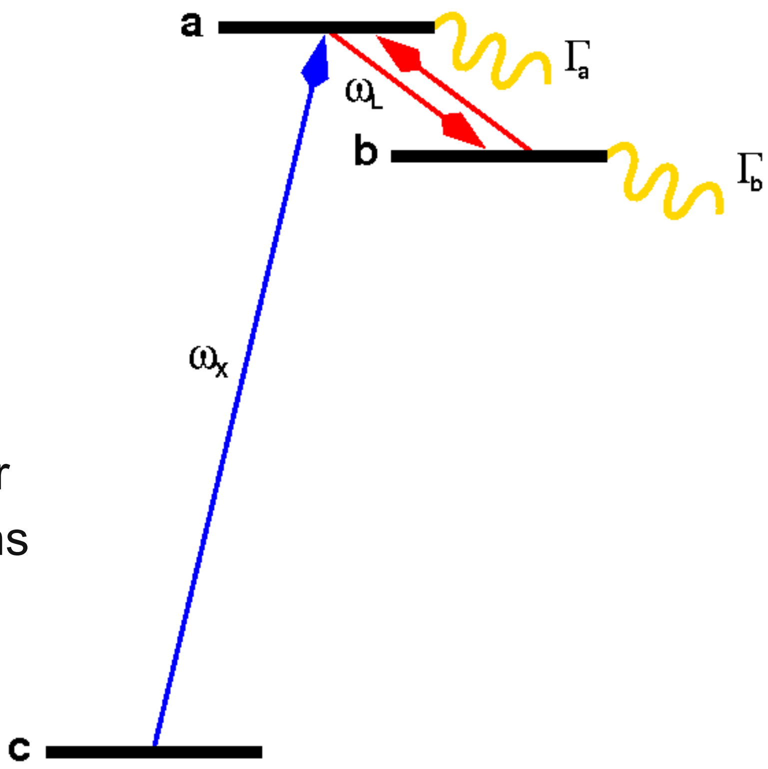
- **Review:** Fleischhauer, Imamoğlu, Marangos, **Rev. Mod. Phys. 77, 633 (2005)**

- Extremely versatile tool in quantum optics
  - Nonlinear optics
  - Atomic clocks
  - Quantum computer



Λ-type three-level model for EIT

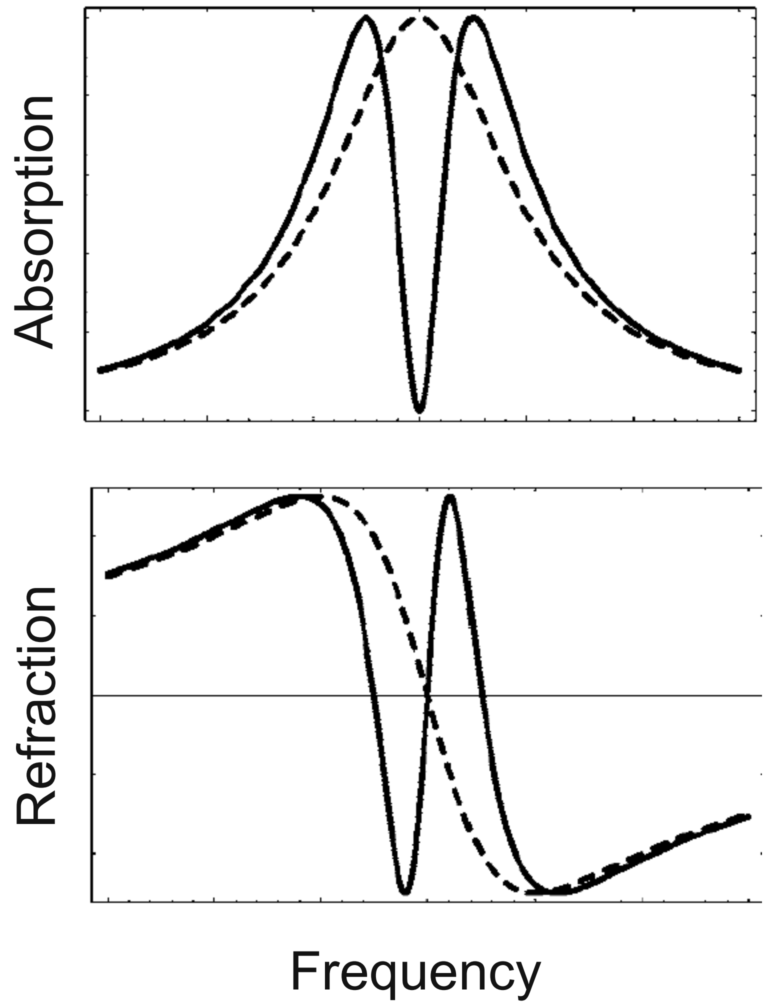
- EIT is understood in terms of a Λ -type three-level model
- Two-color light
  - Probe transition $c \rightarrow a$
  - Laser coupling $a \rightarrow b$
- In resonance transition **without** coupling laser
- Laser resonant with transition within line widths
- Coupling laser dresses levels a, b
  - Rabi flopping
  - Autler-Townes doublet
- Destructive interference



[Buth, Santra, Young, Phys. Rev. Lett. 98, 253001 (2007)]

Optical properties of EIT media

- The EIT dramatically changes the **refraction** of the medium
- Absorption vanishes on resonance => ideal for optics
- **Phase velocity** speed of light in vacuum
- **Group velocity** substantially reduced => **slow light** 17 m/s [Hau *et al.*, Nature **397**, 594 (1999)] in a Bose-Einstein Condensate of sodium atoms
- Few photons; light stored in excitations

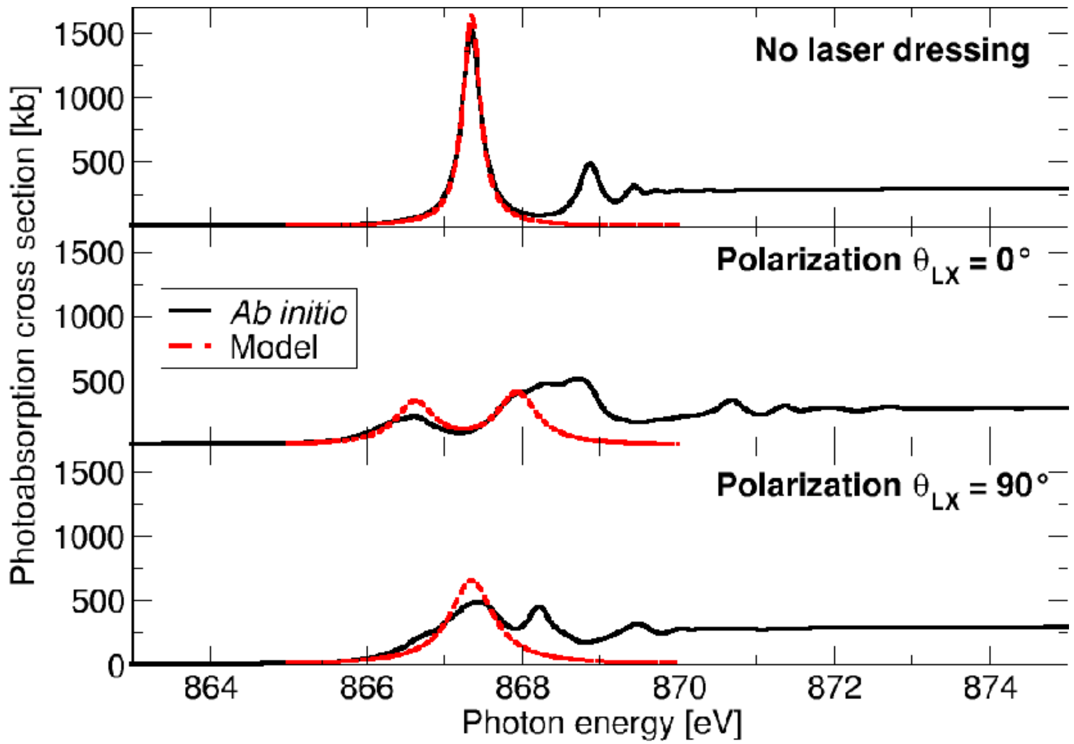


EIT in strontium

- **First observation** by Boller, Imamoğlu, Harris, **Phys. Rev. Lett. 66, 2593 (1991)** in strontium
- **Probe** laser with intensity $10^4 \ \mathrm{W\,cm^{-2}}$
- Laser **coupling** with intensity $1.5\times10^7 \ \mathrm{W\,cm^{-2}}$
- Upper level is autoionizing with lifetime $4.4 \ \mathrm{ps}$ larger by more than **three orders of magnitude** than lifetime of neon core hole
- Transmission change from $\exp(-1)$ to $\exp(-20)$ by coupling laser

Λ-type EIT model for neon

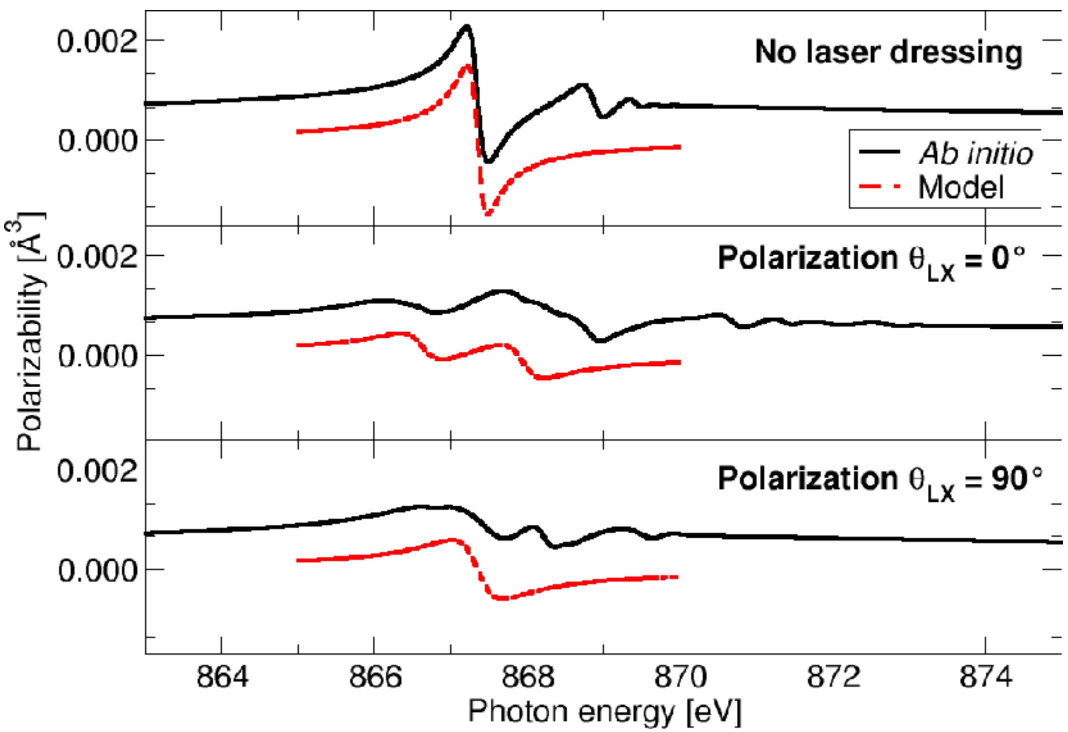
- Assume dominant physics results from three levels of neon: $1s$, $3s$, and $3p$.
- Parameters are level energies and widths; dipole moments between $3p$ and $1s$, $3s$.
- Other levels contribute
- Multiphoton processes



[Buth, Santra, Young, Phys. Rev. Lett. 98, 253001 (2007)]

Polarizability of laser-dressed neon atoms

- Atomic polarizability proportional to real part of the **index of refraction**
- EIT at optical frequencies leads to a large change in the atomic polarizability
- Instead for x-rays the atomic polarizability with laser dressing is lower than without



[Buth, Santra, Young, Phys. Rev. Lett. 98, 253001 (2007)]

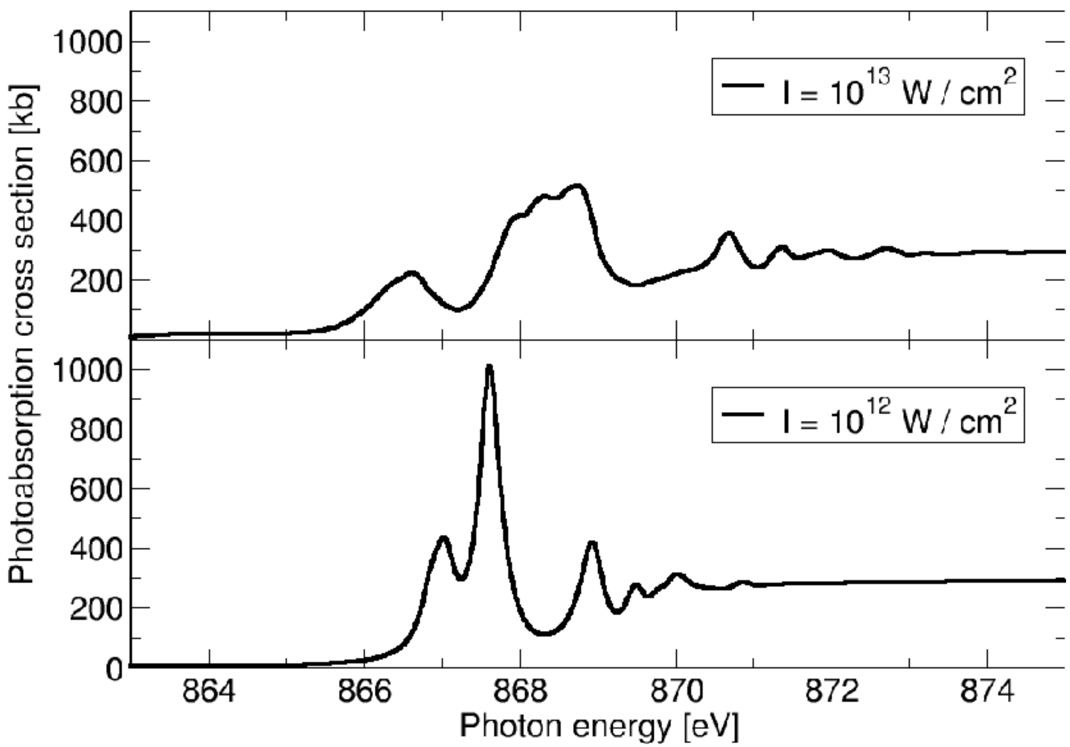
Laser-intensity dependence for parallel polarizations

- Crude estimate for the laser intensity $|\Omega_{ab}| > \Gamma_{1s}$ to see EIT yields:

$$I_{\mathrm{L}} > 4.3 \times 10^{11} \frac{\mathrm{W}}{\mathrm{cm}^2}$$

- The cross section depends crucially on the laser intensity

- Main features persist even if the intensity is lowered by a factor of 10



[Buth, Santra, Young, Phys. Rev. Lett. 98, 253001 (2007)]

Experimental feasibility

- Number density 10^{17} atoms cm^{-3} for characteristic absorption length of $1\,\mathrm{cm}$
- EIT for x-rays for **pulse shaping** of the intensity envelope

- Dispersion of 2π after $1\,\mathrm{cm}$ requires 10^{19} atoms cm^{-3}
- Hard to use as an experimental tool

- X-ray pulses must be **shorter** than laser pulse to probe laser-dressed atom
- Ti:Sapphire laser system produces pulses with energy, $1\,\mathrm{mJ}$ waist $300\,\mu\mathrm{m}$ and **duration** $140\,\mathrm{fs}$ at the intensity $10^{13}\ \mathrm{W\,cm}^{-2}$

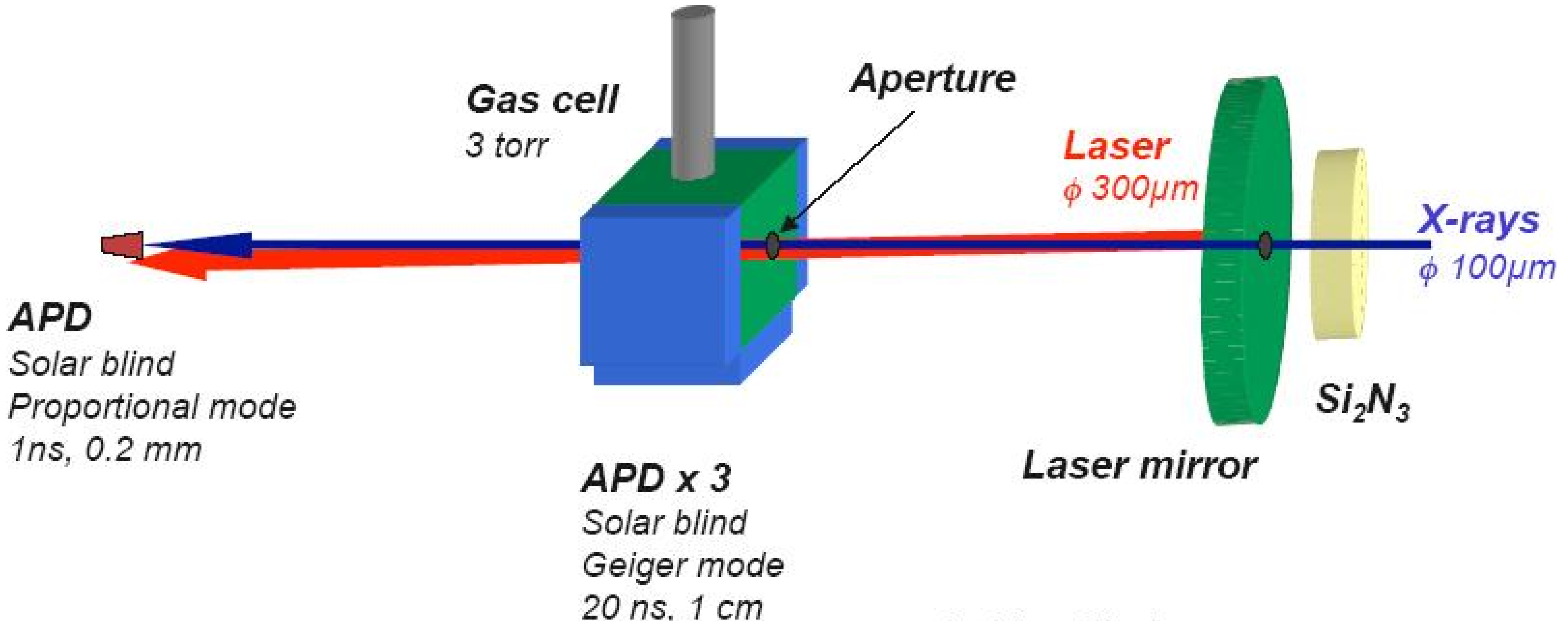
- Need **ultrafast slicing source** for neon experiment

- Weak dependence on dressing-laser wavelength
  [for a variation of 30% there is still EIT]

[Buth, Santra, Young, Phys. Rev. Lett. 98, 253001 (2007)]

Schematic experimental setup of two-color neon experiment

- Overlap x-ray and laser beams both in **space** and **time**



Inside a 8"cube
for pumping speed 1000l/s
Aperture1mm, cell @10 torr
base pressure ~10^{-3} torr

Conclusion

- X-ray probe of laser-dressed atom is described using **Hartree-Fock-Slater** approximation and nonrelativistic **quantum electrodynamics**
- Laser dressing causes **strong field multiphoton physics**
- X-ray probe is treated as a **one-photon** process
- Formalism suitable to investigate multiphoton x-ray processes for x-ray FELs

- Laser influences the photoabsorption cross section of krypton and neon
- Large width of core-excited states yields a moderate effect in krypton
- Find **electromagnetically induced transparency** effect in neon

- EIT effect can be measured in neon
- **High intensity laser**
- Need **ultrafast** x-rays due to ultrashort laser pulses

Acknowledgment