

Atoms in Intense Fields

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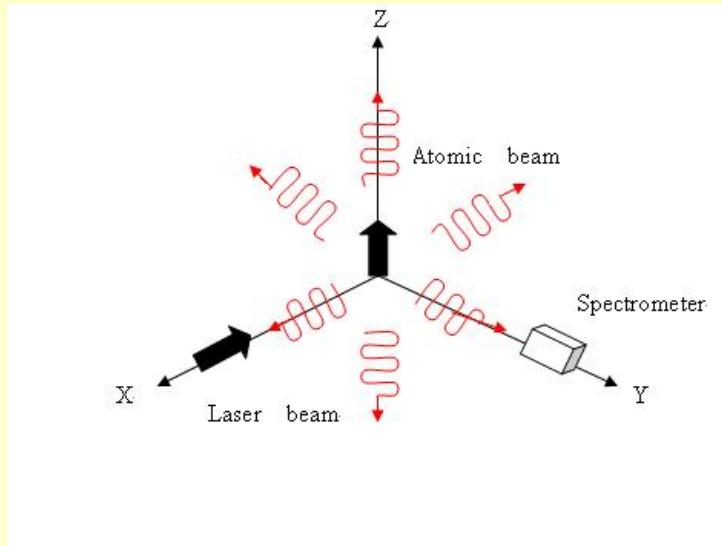
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- The dressed-atom approach
- Applications to two-level atoms
- Applications to degenerate two-level atoms
- Projects

I. Introduction

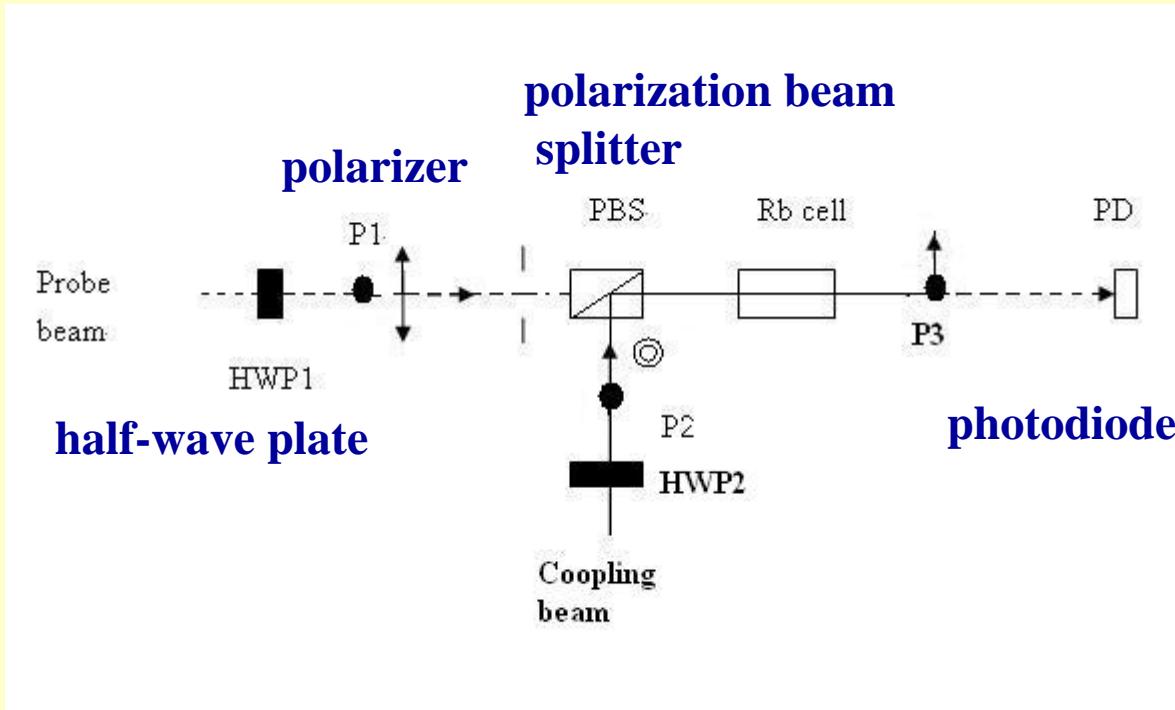
- **Subject:** The behaviors of atoms in intense laser fields.
- **Methods:** perturbative approach, dressed-atom approach
- **Example:** resonance fluorescence, absorption spectra

Resonance fluorescence



- Is the scattering elastic or inelastic?
- What are the changes observed on the spectral distribution of the fluorescence light when the laser intensity increases?

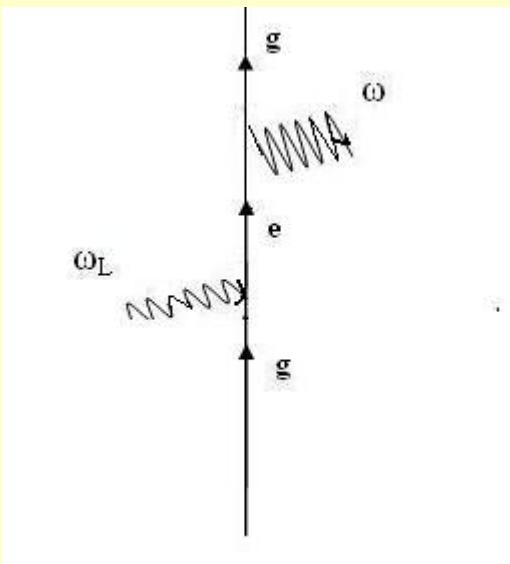
Absorption spectra of a probe beam



The modification of the absorption spectra of the probe beam due to the presence of the coupling beam.

Resonance fluorescence in the perturbative approach

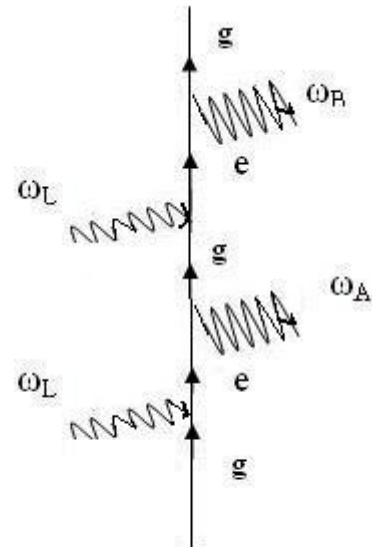
- Lowest order diagram (low intensity)



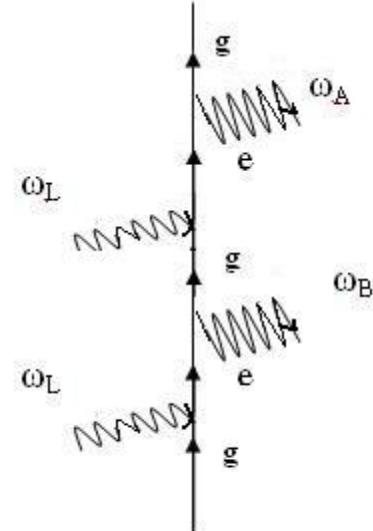
Conservation of energy: $\omega = \omega_L$ elastic scattering

- Second order diagram (high intensity)

(a)



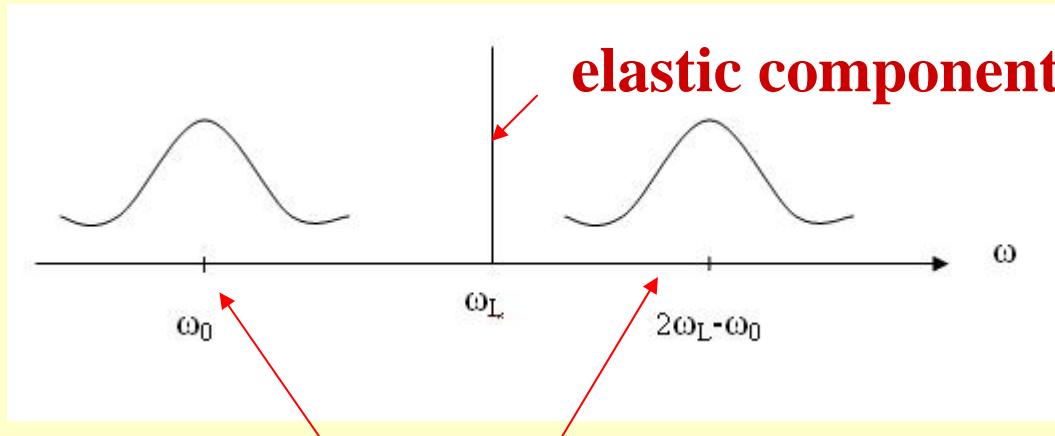
(b)



Conservation of energy:

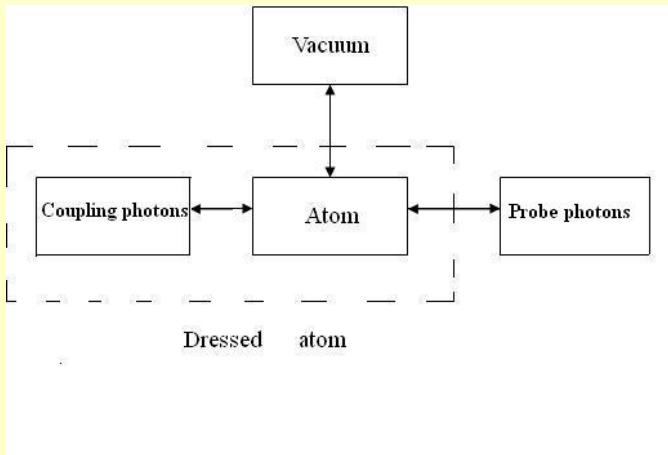
$$2\omega_L = \omega_A + \omega_B$$

Fluorescence triplet



$$\omega_0 = E_e - E_g \quad : \text{atomic frequency}$$

II. The dressed-atom approach



Step 1: Consider only the system “atom + coupling photons interacting together” .

Step 2: Consider the coupling with the vacuum or the probe photons.

Total Hamiltonian: $H = H_A + H_L + H_{AL}$

H_A : **Atomic Hamiltonian**

H_L : **Laser Hamiltonian**

H_{AL} : **Interacting Hamiltonian**

Two-level systems

- Two-level atoms in the presence of a single-mode radiation field

$$H_A |g\rangle = -\frac{1}{2}\omega |g\rangle$$

$$H_A |e\rangle = \frac{1}{2}\omega |e\rangle$$

$$H_L |n\rangle = \omega_L \left(n + \frac{1}{2}\right) |n\rangle$$

ω : Atomic frequency ω_L : Laser frequency

State of the laser field

- **Coherent state** $|\alpha\rangle = e^{-\frac{1}{2}|\alpha|^2} \sum_n \frac{\alpha^n}{n!} |n\rangle$

Mean number of photons: $\langle n \rangle = |\alpha|^2$

The variance of the photon number: $\Delta n = |\alpha|$

(i) $\langle n \rangle \gg \Delta n \gg 1$

(ii) Only $\frac{\langle n \rangle}{V}$ is significant, because it is related to the electromagnetic energy density. Here V is the quantization volume.

Uncoupled states (bare states)

Uncoupled Hamiltonian : $H_0 = H_A + H_L$

Uncoupled states : $\left\{ |I\rangle = |g, n\rangle , |F\rangle = |e, n-1\rangle \right\}$

$$H_0 |I\rangle = E_I |I\rangle \quad \text{with} \quad E_I = -\frac{1}{2}\omega + n\omega_L$$

$$H_0 |F\rangle = E_F |F\rangle \quad \text{with} \quad E_F = \frac{1}{2}\omega + (n-1)\omega_L$$

$$E_F - E_I = \omega - \omega_L = \Delta \text{ :detuning}$$

As $\Delta = 0$, $E_F = E_I = (n - \frac{1}{2})\omega$

Coupled states (dressed states)

Dressed states: $H|\Psi\rangle = E|\Psi\rangle$

$$E_{\pm}(n) = (n - \frac{1}{2})\omega \pm \frac{1}{2}\Omega$$

$$|+, n\rangle = e^{-i\phi} \sin \theta |I\rangle + \cos \theta |F\rangle$$

$$|-, n\rangle = \cos \theta |I\rangle - e^{i\phi} \sin \theta |F\rangle$$

Rabi frequency: $\Omega = \sqrt{\Delta^2 + 4|g|^2 n}$

Dipole matrix element: $g = -i \sqrt{\frac{\omega}{2\epsilon_0 \hbar V}} \langle e | \vec{d} \bullet \hat{\varepsilon} | g \rangle = |g| e^{i\phi}$

$$\tan 2\theta = \frac{2|g|\sqrt{n}}{\Delta}$$

- (i) The physical quantities depend on $\frac{\langle n \rangle}{V}$.
- (ii) We can neglect the variation with n of the physical quantities when n varies within Δn .

Coupled states (dressed states)

At resonance: $\Delta = 0$ $\theta = \pi/2$

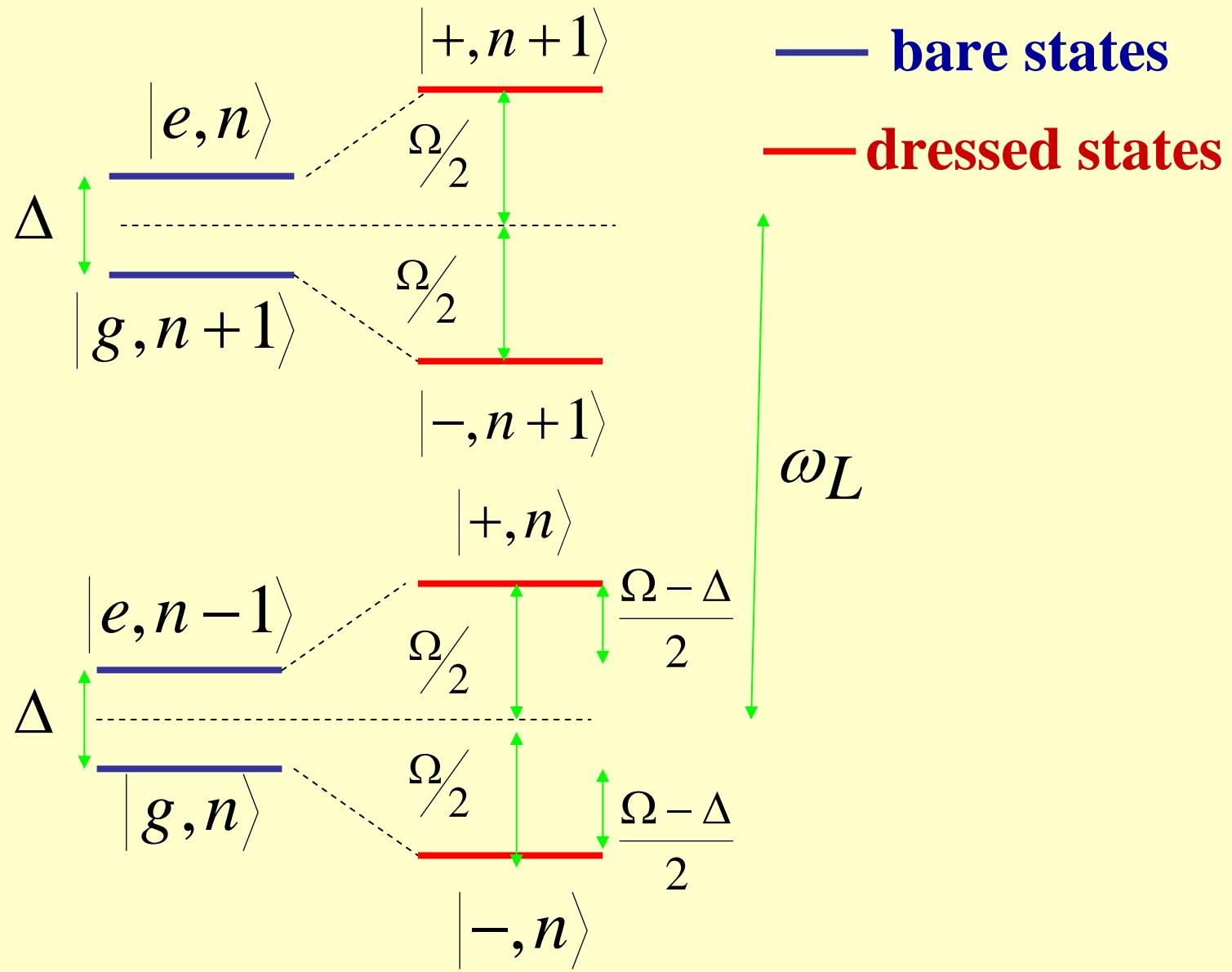
$$E_{\pm}(n) = (n - 1/2)\omega \pm 1/2\Omega$$

$$|+,n\rangle = \frac{1}{\sqrt{2}}(e^{-i\phi}|I\rangle + |F\rangle)$$

$$|-,n\rangle = \frac{1}{\sqrt{2}}(|I\rangle - e^{i\phi}|F\rangle)$$

Resonant Rabi frequency: $\Omega = 2|g|\sqrt{n}$

Ladder of energy levels (periodic)



Light shift (dynamic Stark effect)

- **Light shift:** $\Delta E_e = -\Delta E_g = \frac{\Omega - \Delta}{2}$
- **Perturbation expansions in powers of** $\frac{4n|g|^2}{\Delta^2}$

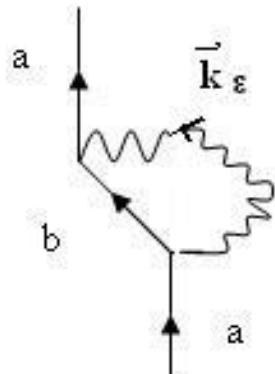
$$\Delta E_{g(e)} = \Delta E_{g(e)}^{(1)} + \Delta E_{g(e)}^{(2)} + \dots$$

with $\Delta E_e^{(1)} = -\Delta E_g^{(1)} = \frac{n|g|^2}{\Delta}$

$$\Delta E_e^{(2)} = -\Delta E_g^{(2)} = -\frac{n^2|g|^4}{\Delta^3}$$

Radiative Corrections

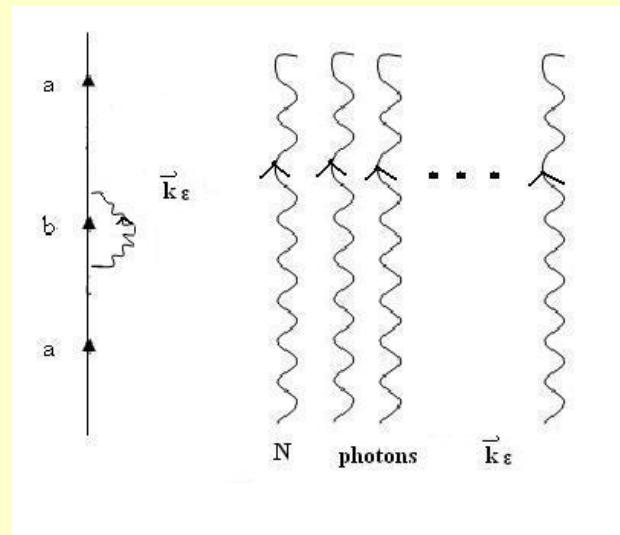
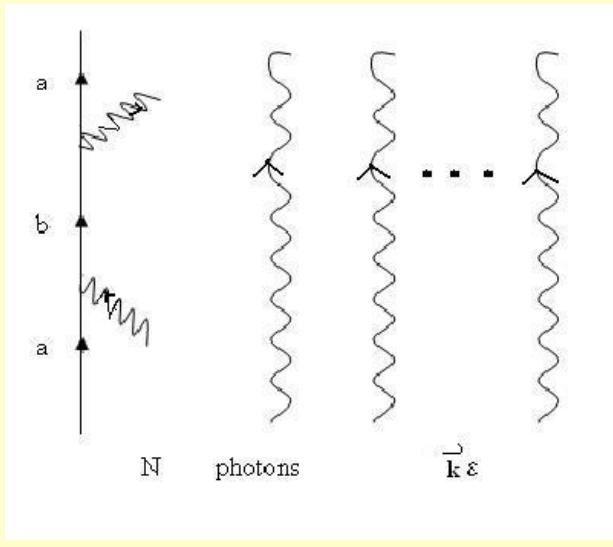
- Spontaneous radiative corrections



The spontaneous radiative corrections lead to the Lamb shift.

Radiative Corrections

- Stimulated radiative corrections

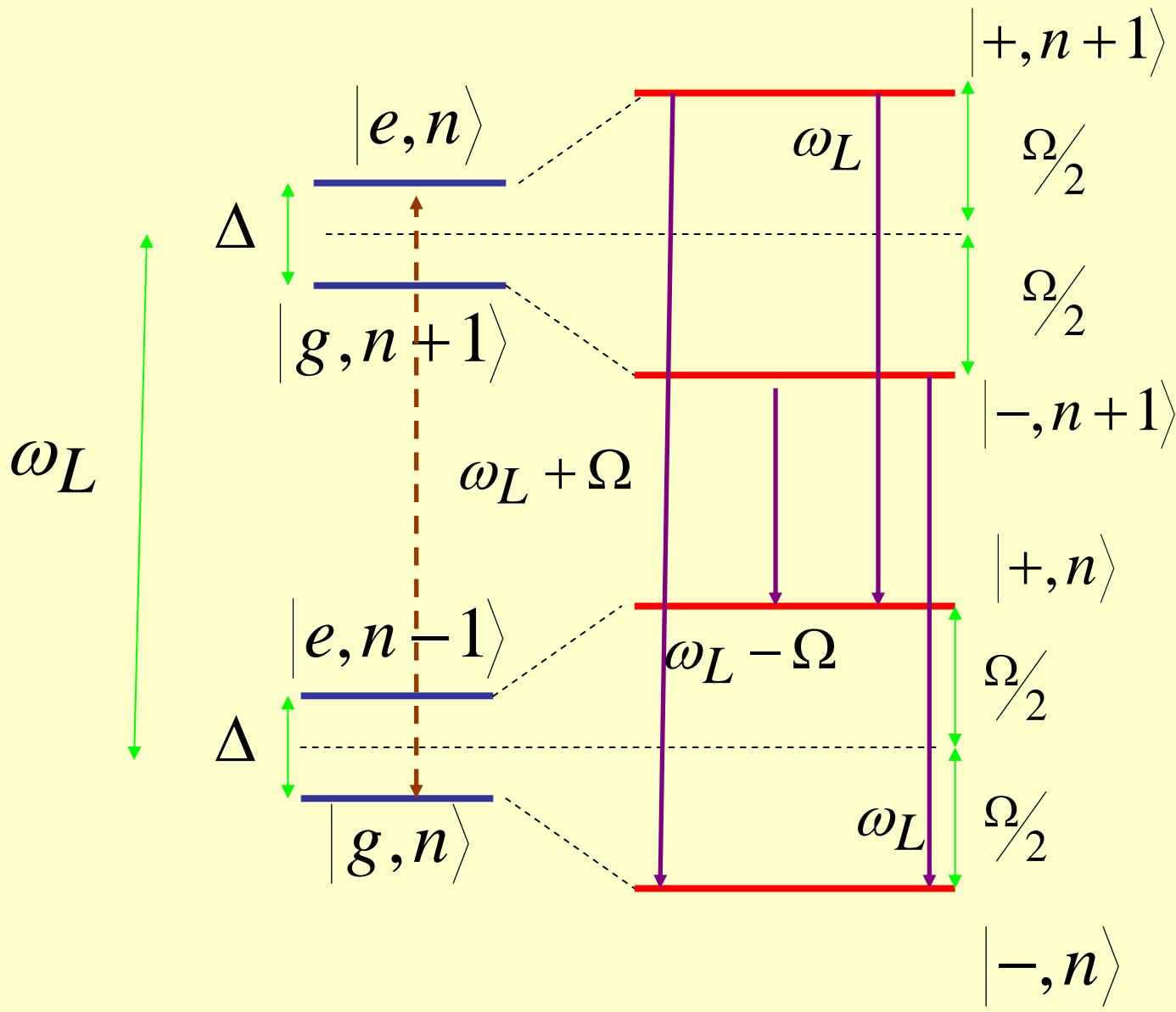


The stimulated radiative corrections lead to the Light shift.

III. Applications to two-level atoms

- Resonance fluorescence
- Absorption spectrum of a weak probe beam

Resonance fluorescence in the dressed-atom approach



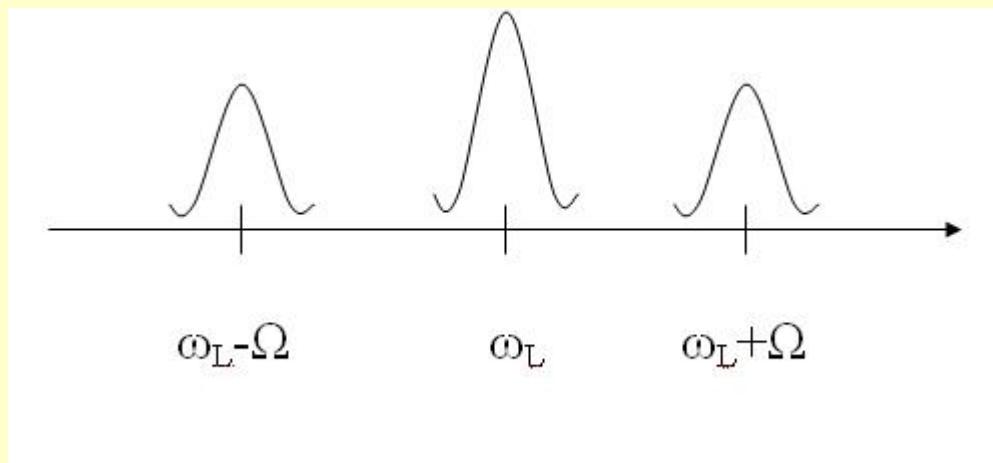
Fluorescence triplet

$$|+,n+1\rangle \rightarrow |-,n\rangle : \omega_L + \Omega \cong \omega_L + \Delta = \omega$$

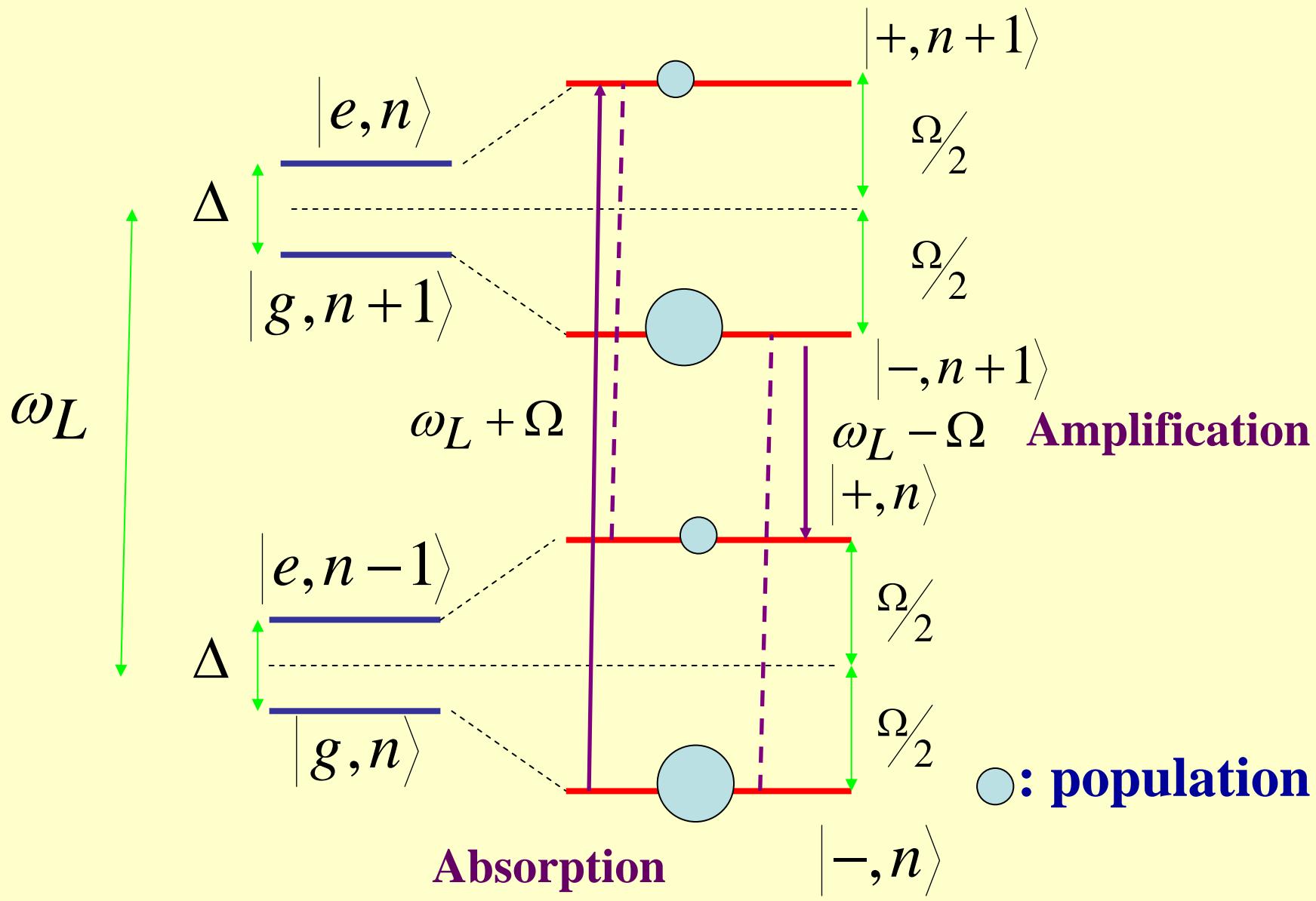
1st order in $\frac{4n|g|^2}{\Delta^2}$

$$|-,n+1\rangle \rightarrow |+,n\rangle : \omega_L - \Omega \cong \omega_L - \Delta = 2\omega_L - \omega$$

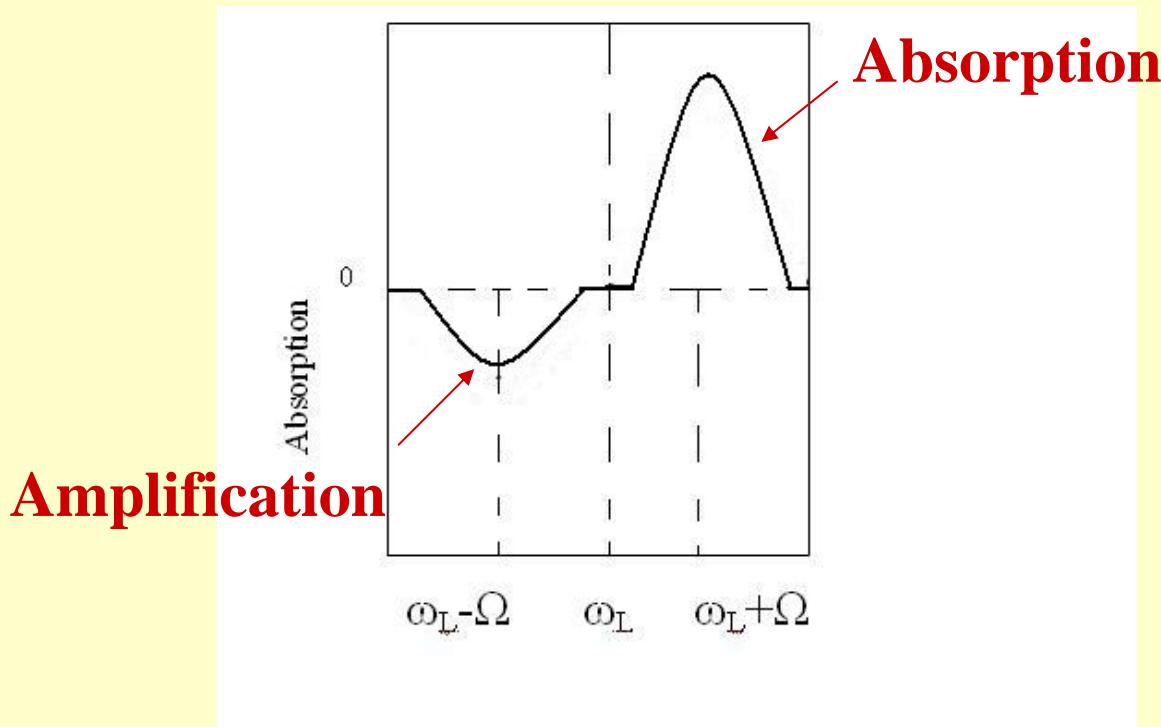
$$|+,n+1\rangle \rightarrow |+,n\rangle \text{ and } |-,n+1\rangle \rightarrow |-,n\rangle : \omega_L$$



Absorption spectrum of a weak probe beam



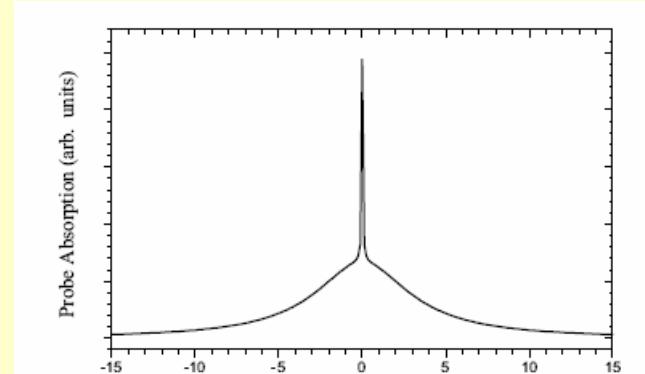
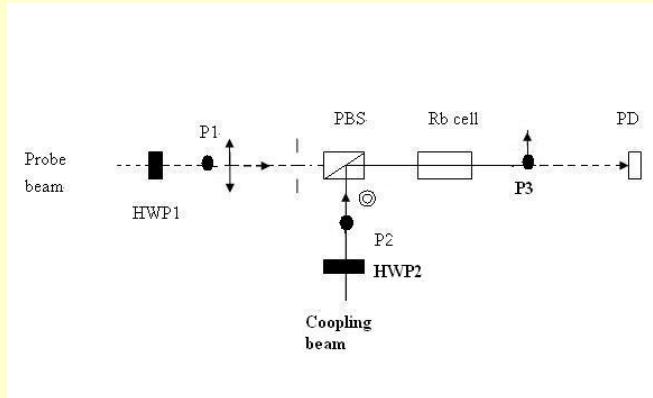
Absorption spectrum of a weak probe beam



The central component is missing.

IV. Applications to the degenerate two-level atoms

- Electromagnetically induced absorption (EIA)



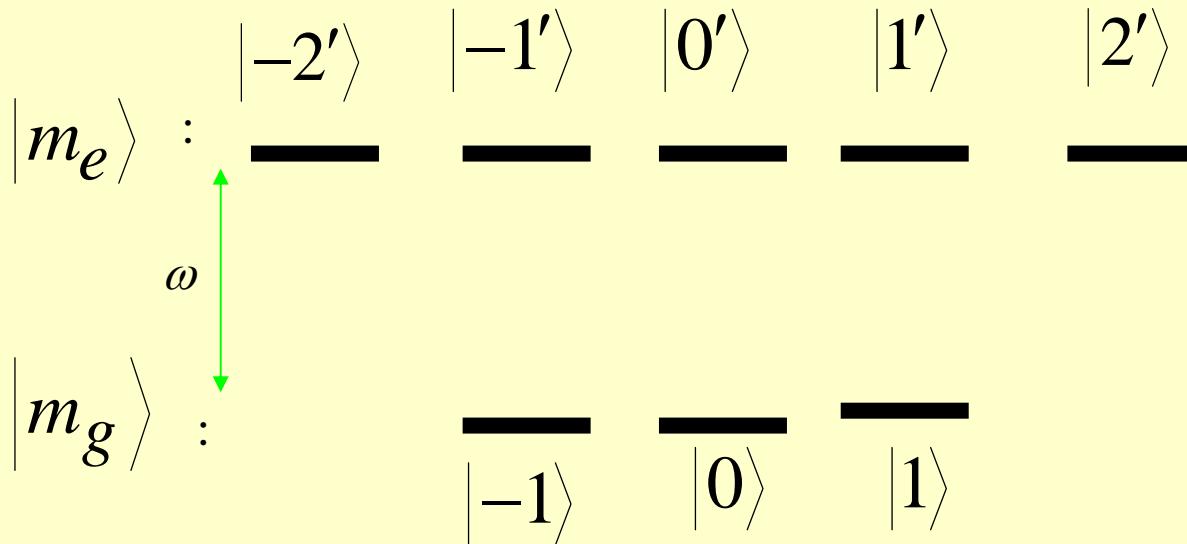
probe-coupling detuning (MHz)

The absorption of the probe beam is substantially enhanced when copropagating orthogonally polarized probe and coupling beams interact with a degenerate two-level system [Ref. : EIA-1].

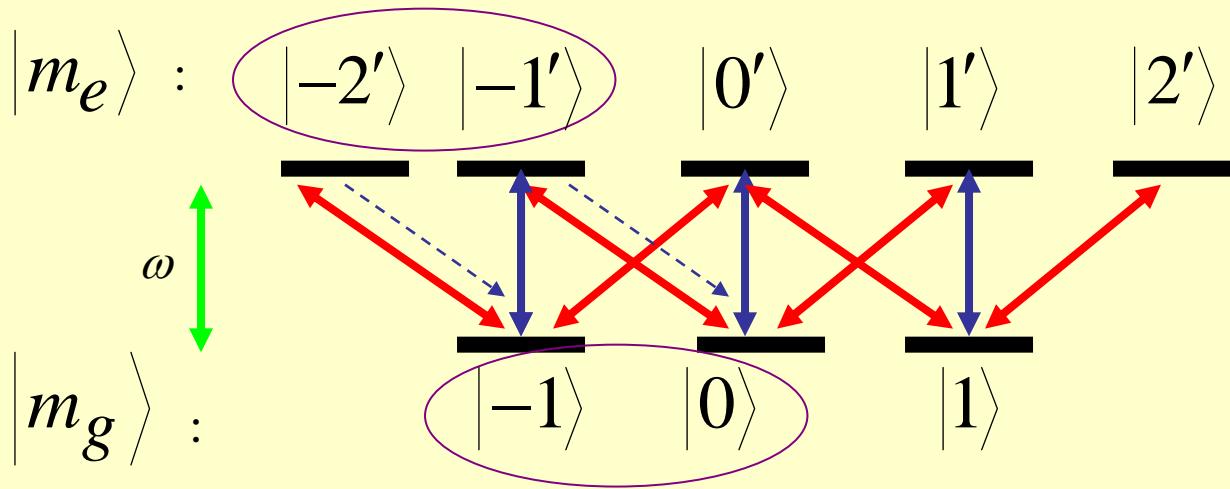
Lezama's condition for EIA

$$F_e = F_g + 1$$

Ref. : EIA-2



Spontaneous coherence transfer (SCT)

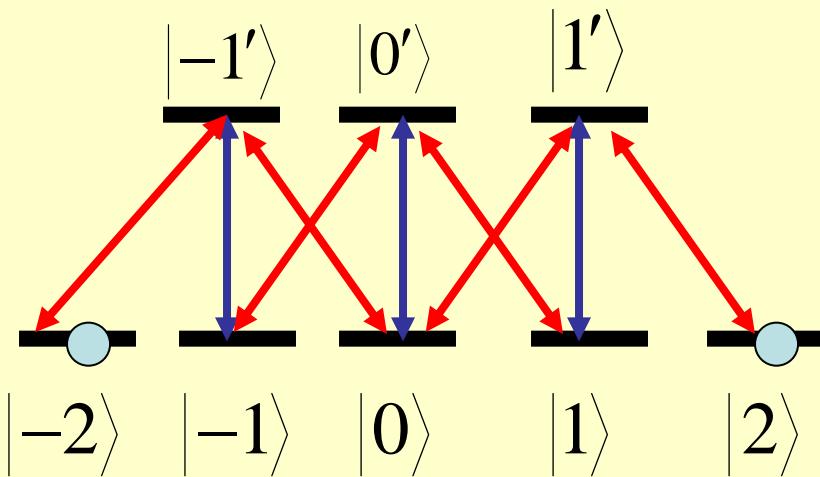


↔ :coupling beam ↔ :probe beam ⤵ :SCT

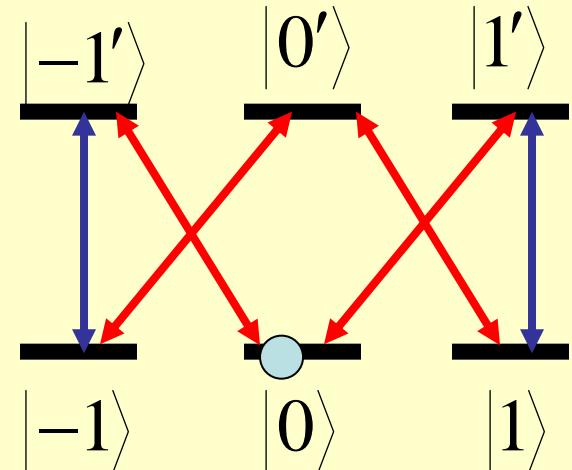
EIA is caused by the spontaneous transfer of the light-induced Zeeman coherence from the excited level to the ground level [Ref. : EIA-3].

Interpretations of Lezama's condition

$$(I): F_e = F_g - 1$$



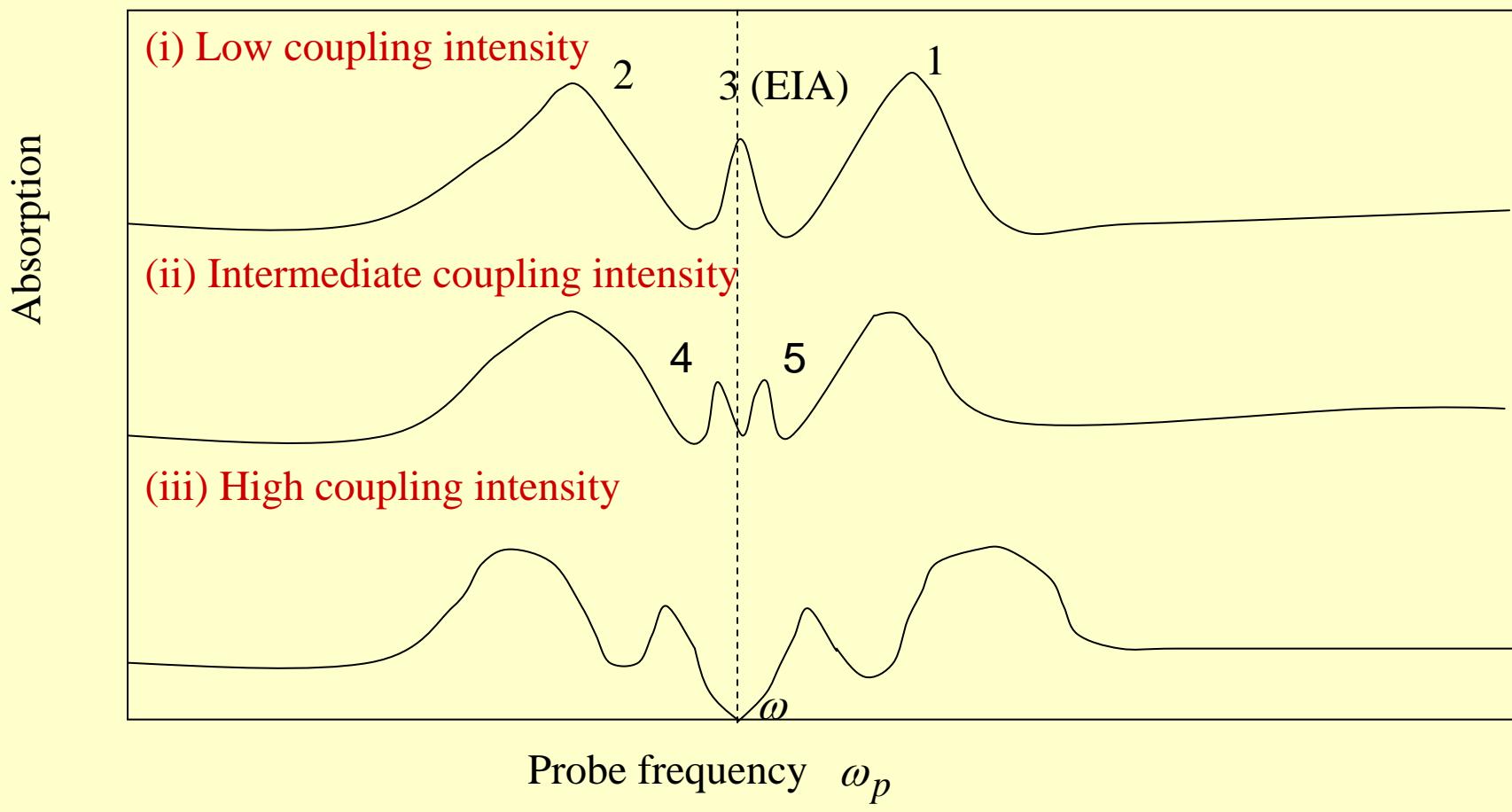
$$(II): F_e = F_g$$



The excited-state coherences are very small for systems with $F_e = F_g - 1$ and $F_e = F_g$, because the populations are trapped in the lower levels. **SCT and EIA can not take place for such systems** [Ref. : EIA-4].

Anomalous EIA $F_e = F_g - 1$

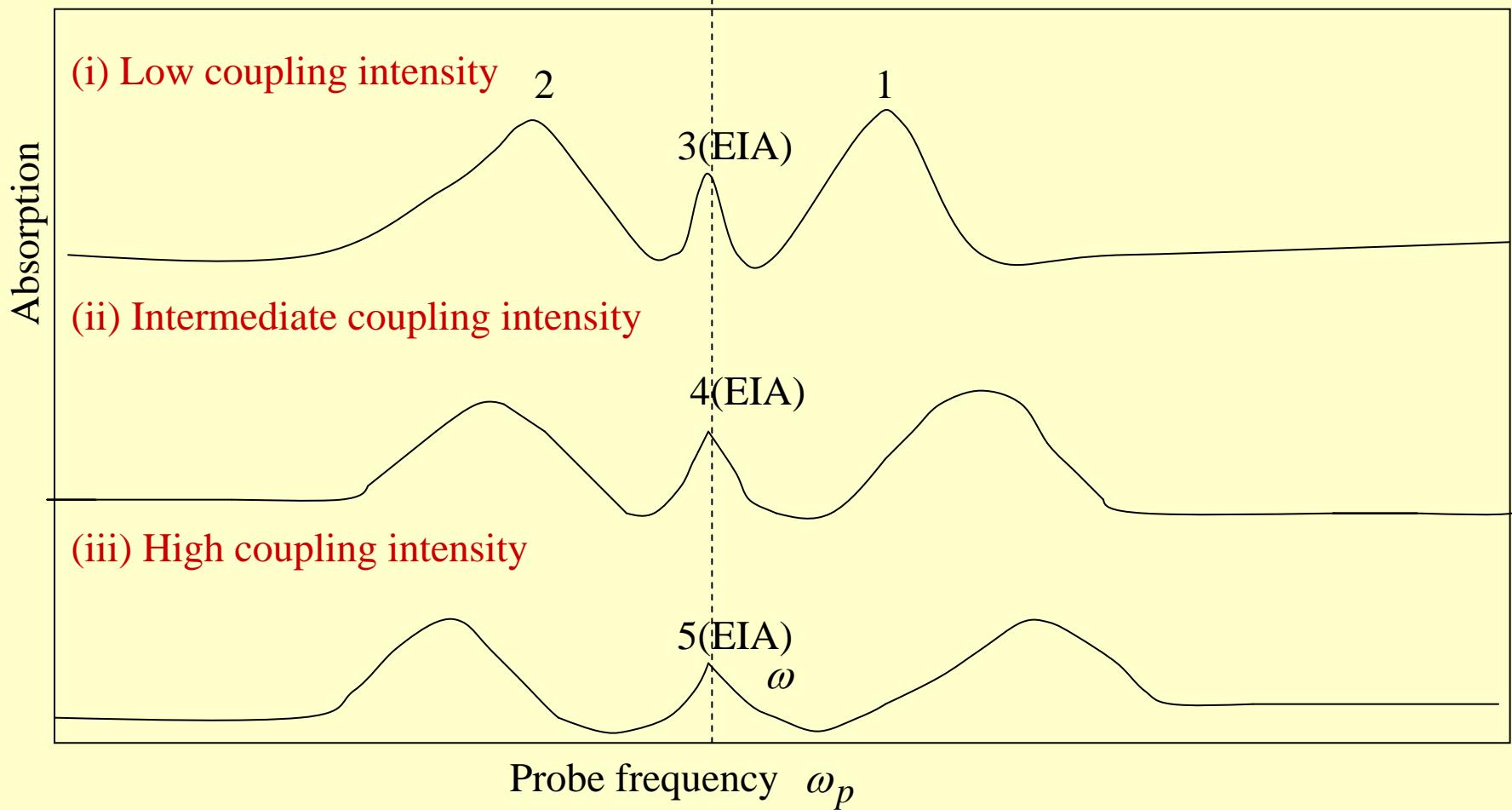
- Transition $F_g = 3 \rightarrow F_e = 2$ in the D_1 line of ^{85}Rb



Ref. : Anomalous EIA-1

Anomalous EIA $F_e = F_g$

- Transition $F_g = 1 \rightarrow F_e = 1$ in the D_1 line of ^{87}Rb

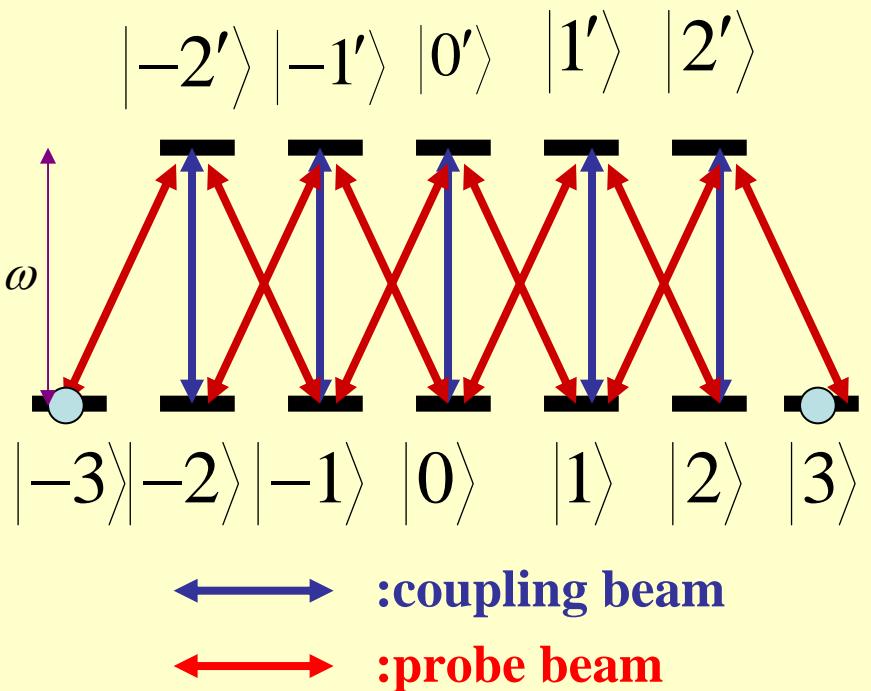


Anomalous EIA $F_e = F_g$

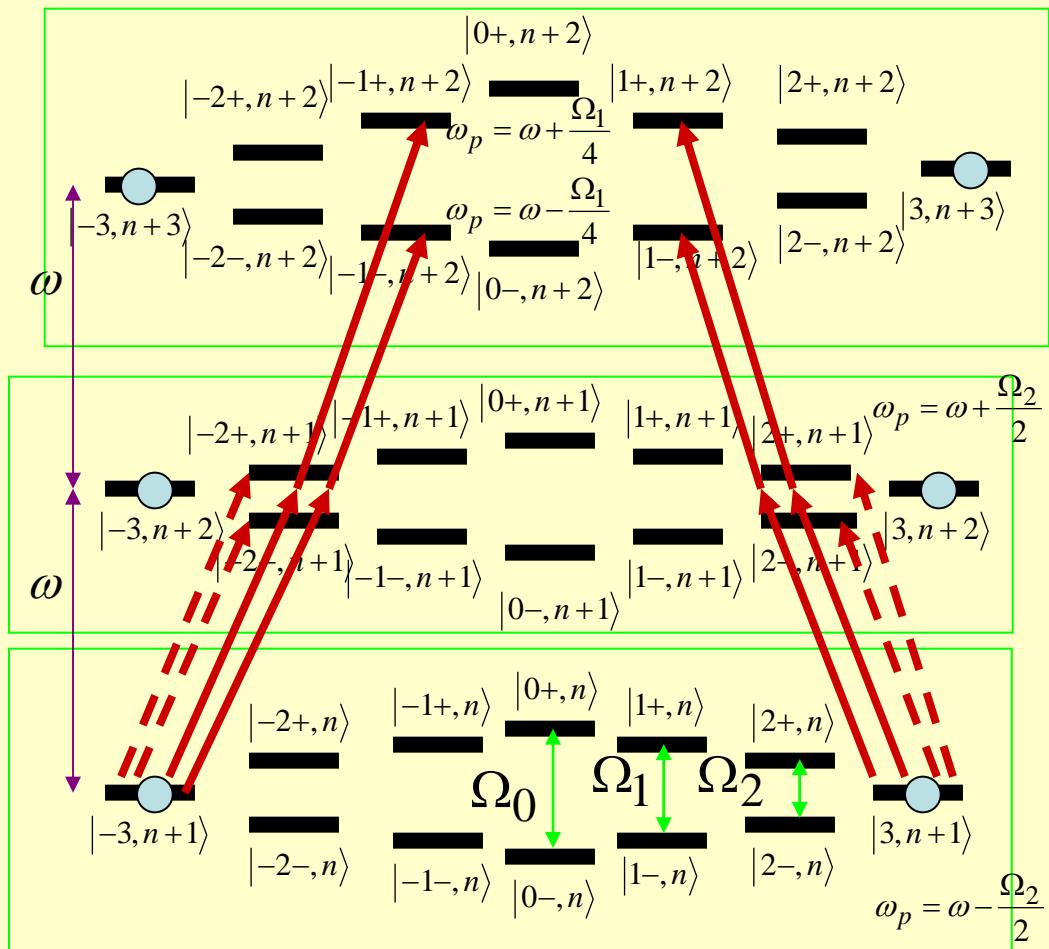
- **Transitions** $F_g = 2 \rightarrow F_e = 2$ **and** $F_g = 3 \rightarrow F_e = 3$ **in the D_1 line of ^{87}Rb**

The EIA peak breaks up again at intermediate coupling intensity.

EIA in $F_g = 3 \rightarrow F_e = 2$ transition



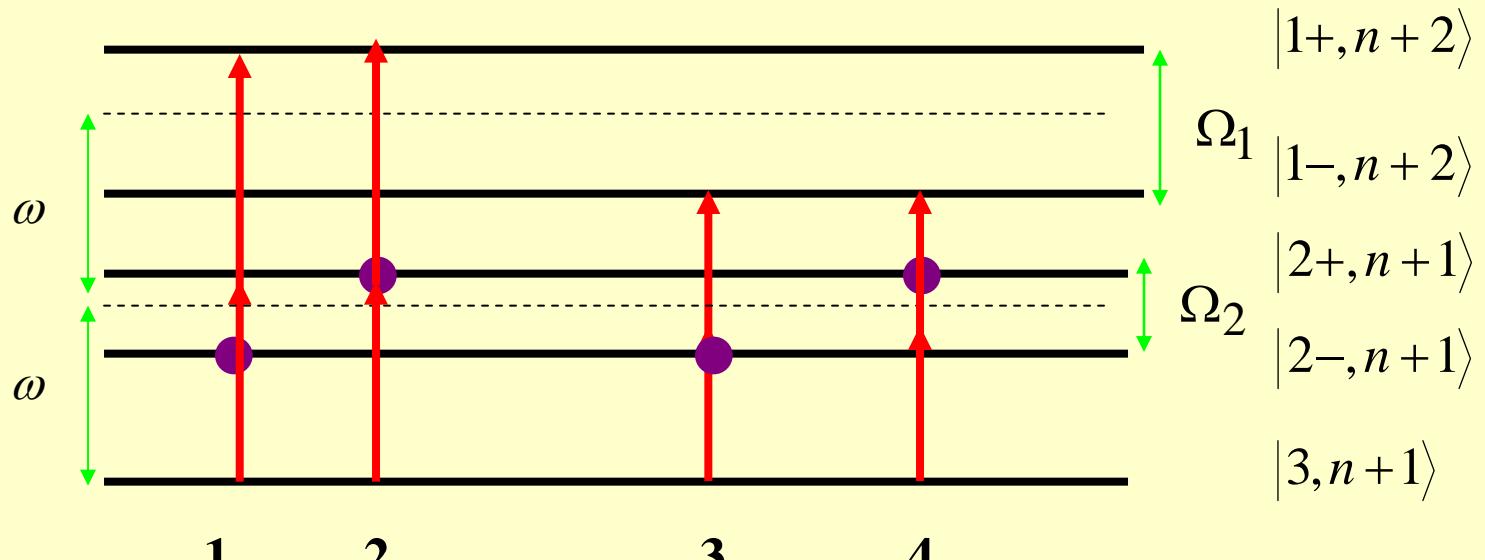
(I) Bare-atom picture



(II) Dressed-atom picture

Ref. : Anomalous EIA-2

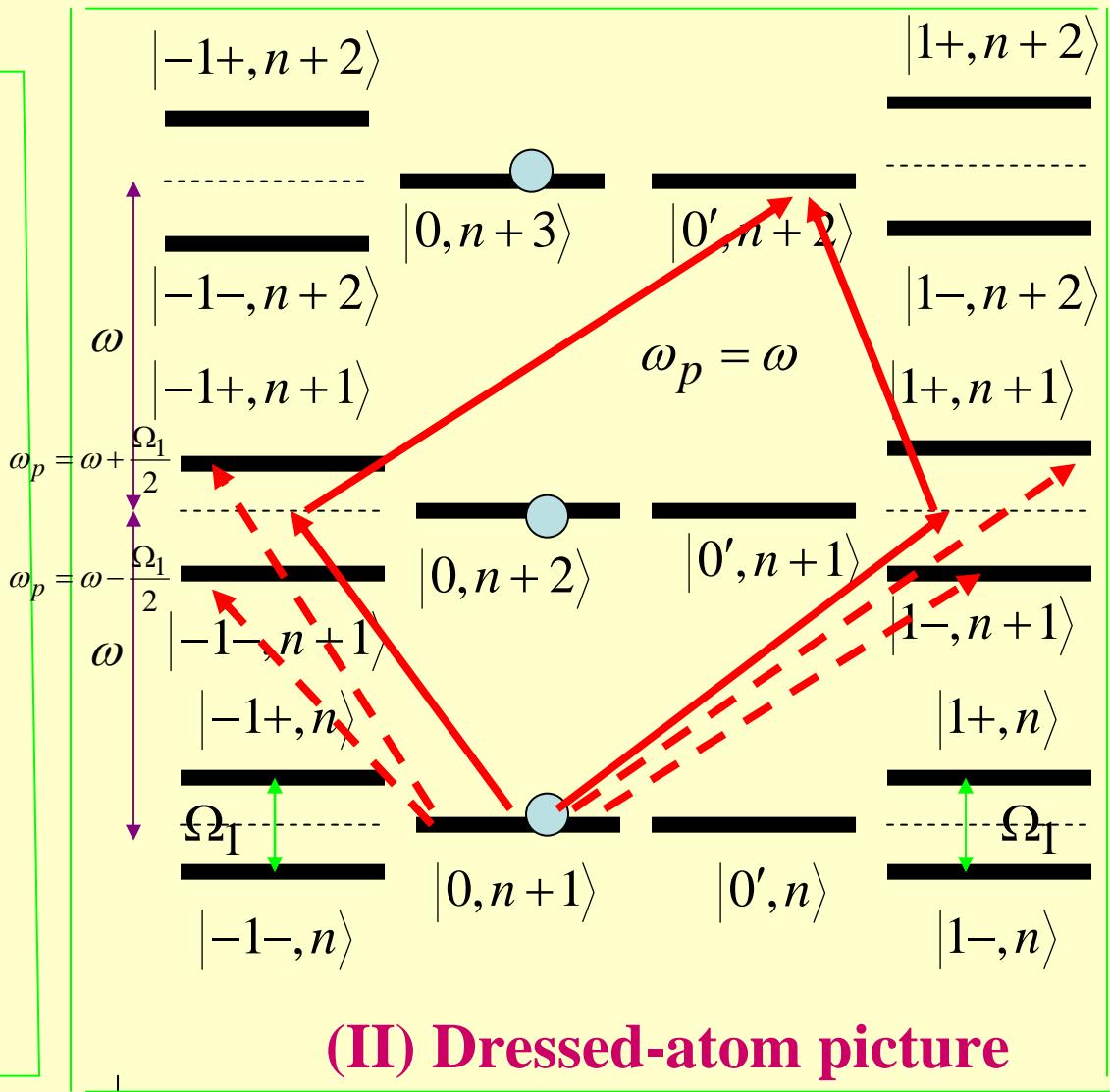
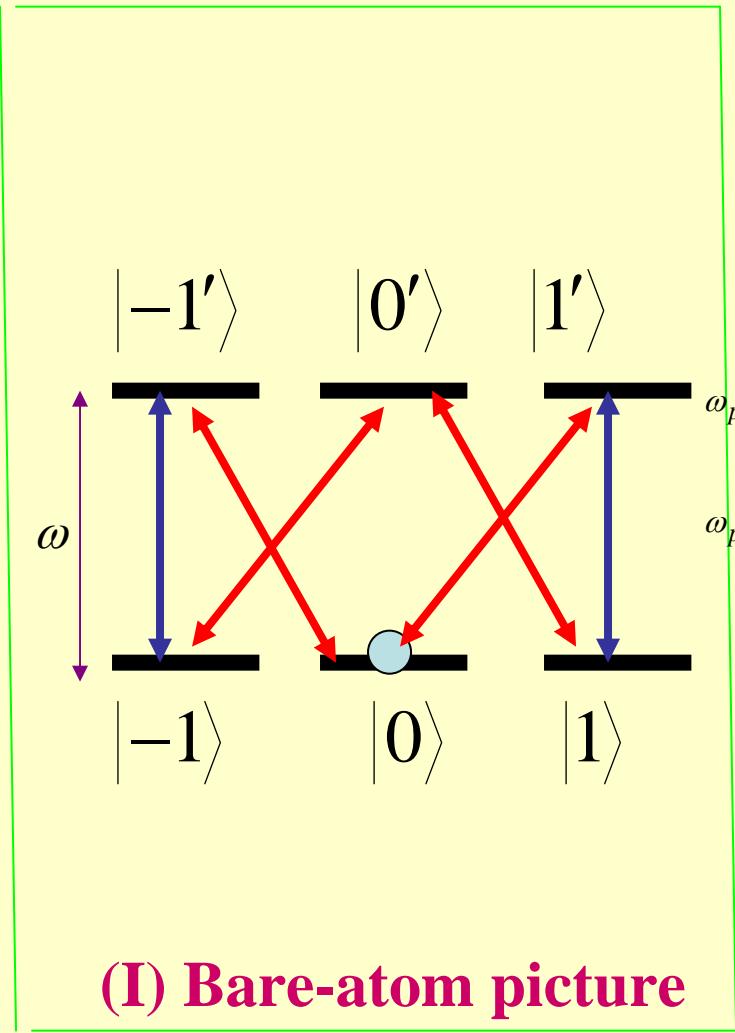
Two-photon processes



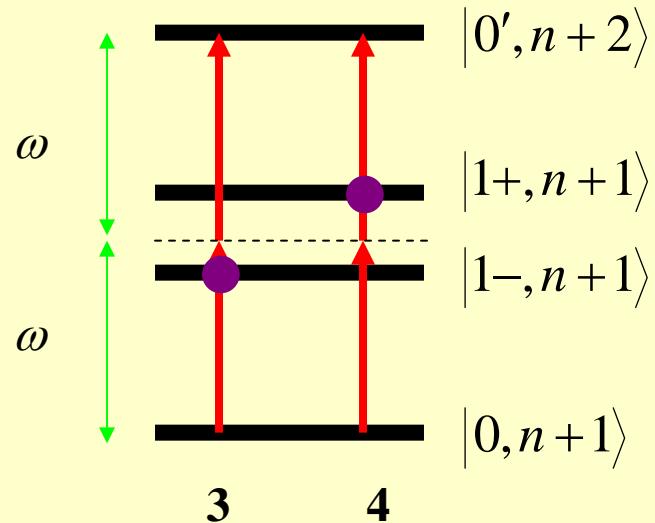
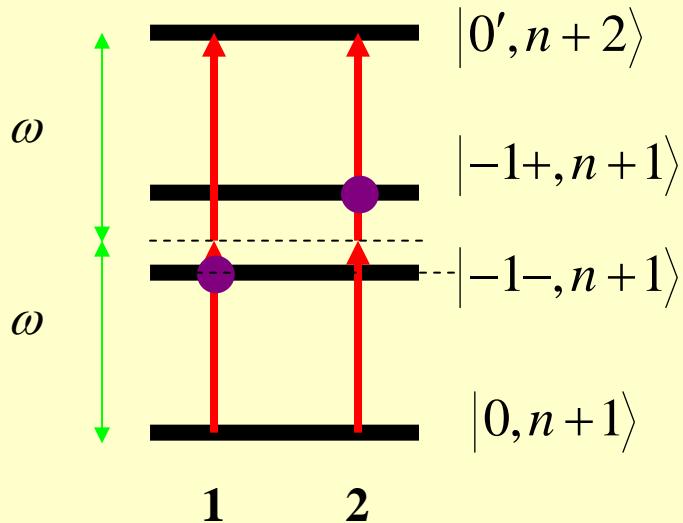
● : intermediate states

- Positions of 1,2 : $\omega_p = \omega + \frac{\Omega_1}{4}$, Positions of 3,4 : $\omega_p = \omega - \frac{\Omega_1}{4}$
- **Constructive interferences between 1,2(3,4) lead to two peaks.**
- At low coupling intensity, the two peaks overlap at $\omega_p = \omega$ and produce an EIA peak. At intermediate intensity, the peak splits.

EIA in $F_g = 1 \rightarrow F_e = 1$ transition

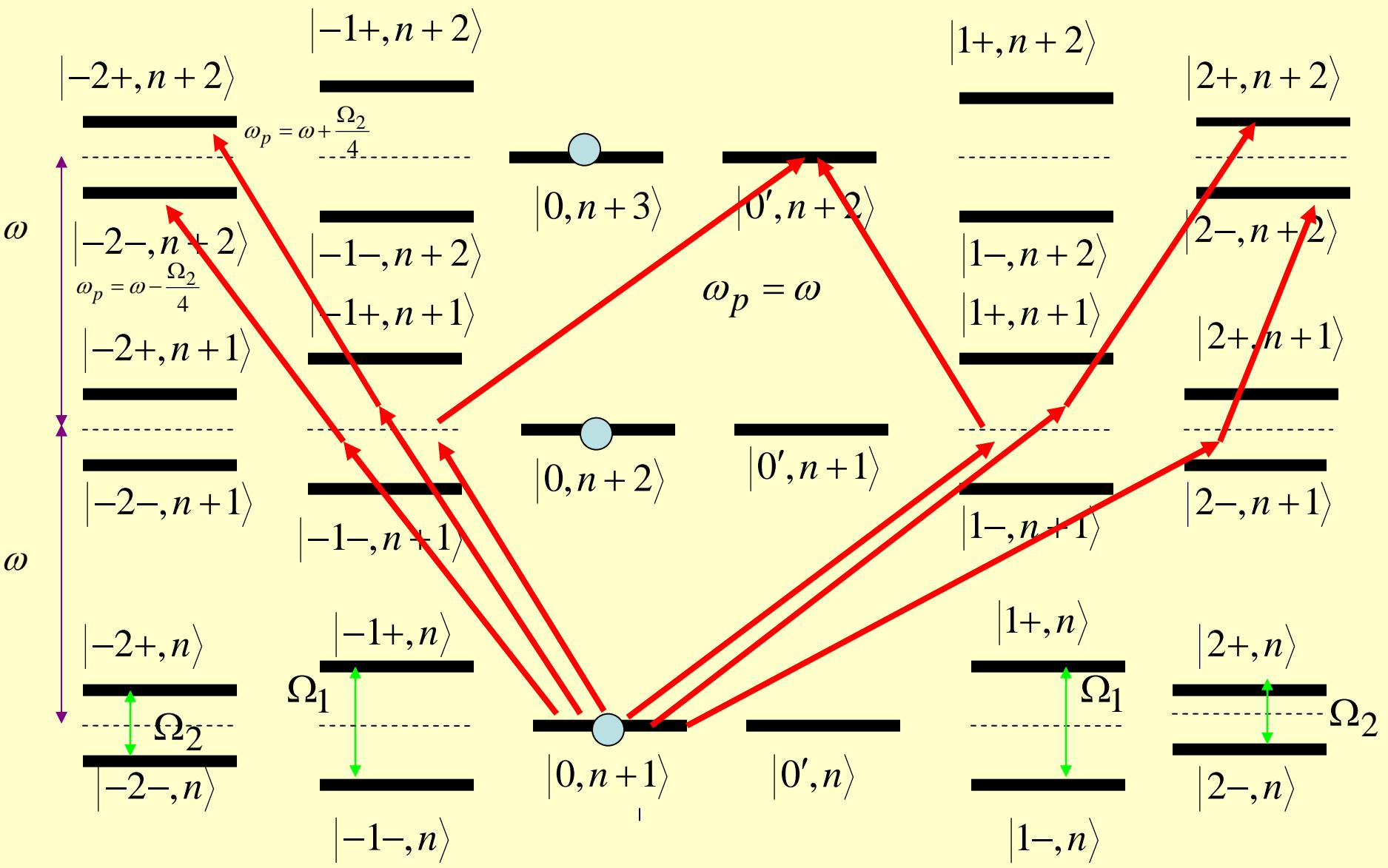


Two-photon processes



- **Positions of 1,2,3,4 :** $\omega_p = \omega$
- **Transition amplitudes :** $T^{(1)} = T^{(2)} = T^{(3)} = T^{(4)}$
- **Constructive interferences among 1,2,3,4 lead to an EIA peak at $\omega_p = \omega$.**

EIA in $F_g = 2 \rightarrow F_e = 2$ transition



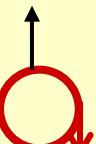
Coupling-probe polarization configurations

(1) **lin \perp lin** : coupling \uparrow probe \rightarrow

(2) **lin \parallel lin** : coupling \uparrow probe \uparrow

(3) **$\sigma \parallel$ lin** : coupling  probe \uparrow

(4) **$\sigma \perp$ lin** : coupling  probe \rightarrow

(5) **$\sigma \parallel \sigma$** : coupling  probe 

(6) **$\sigma \perp \sigma$** : coupling  probe 

Prediction for the Anomalous EIA

(I) $F_e = F_g - 1$

$$\text{lin} \perp \text{lin} \quad \sigma \parallel \text{lin} \quad \sigma \perp \text{lin}$$

(II) $F_e = F_g$

$$\text{lin} \perp \text{lin} \quad \sigma \parallel \text{lin} \quad \sigma \perp \text{lin} \quad \sigma \perp \sigma$$

V. Projects

- Investigate the anomalous EIA in the limit when the atom-laser coupling is much stronger than the hyperfine interactions.
- Investigate the possibility of switching the anomalous EIA to the EIT.

References for dressed-atoms

- Claude Cohen-Tannoudji, Jacques Dupont-Roc, Gilbert Grynberg, *Atom-Photon Interactions*, (John Wiley & Sons, INC.) 1992.
- Claude Cohen-Tannoudji, “Atoms in strong resonant fields”, in *Frontiers in Laser Spectroscopy* pp. 1-104 (North-Holland, 1977).
- Claude Cohen-Tannoudji and Serge Reynaud, J. Phys. B10, 345 (1977).

References for EIA

- **A. M. Akulshin, S. Barreiro, and A. Lezama, Phys. Rev. A57, 2996 (1998).**
- **A. Lezama, S. Barreiro, and Akulshin, Phys. Rev. A59, 4732 (1999).**
- **A. V. Taichenachev, A. M. Tumaikin, and V. I. Yudin, JETP Lett. 69, 819 (1999).**
- **C. Goren, A. D. Wilson-Gordon, M. Rosenbluh, and H. Friedmann, Phys. Rev. A67, 033807 (2003).**

References for anomalous EIA

- **S. K. Kim , H. S. Moon, K. Kim, J. B. Kim, Phys. Rev. A68, 063813 (2003).**
- **H. S. Chou and Jörg Evers, Phys. Rev. Lett. 213602 (2010).**