Atoms in Intense Fields

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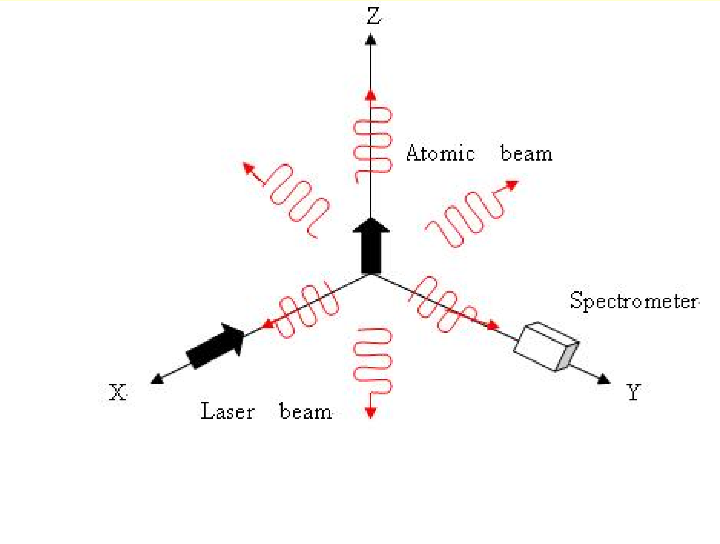
Contents

I. Introduction

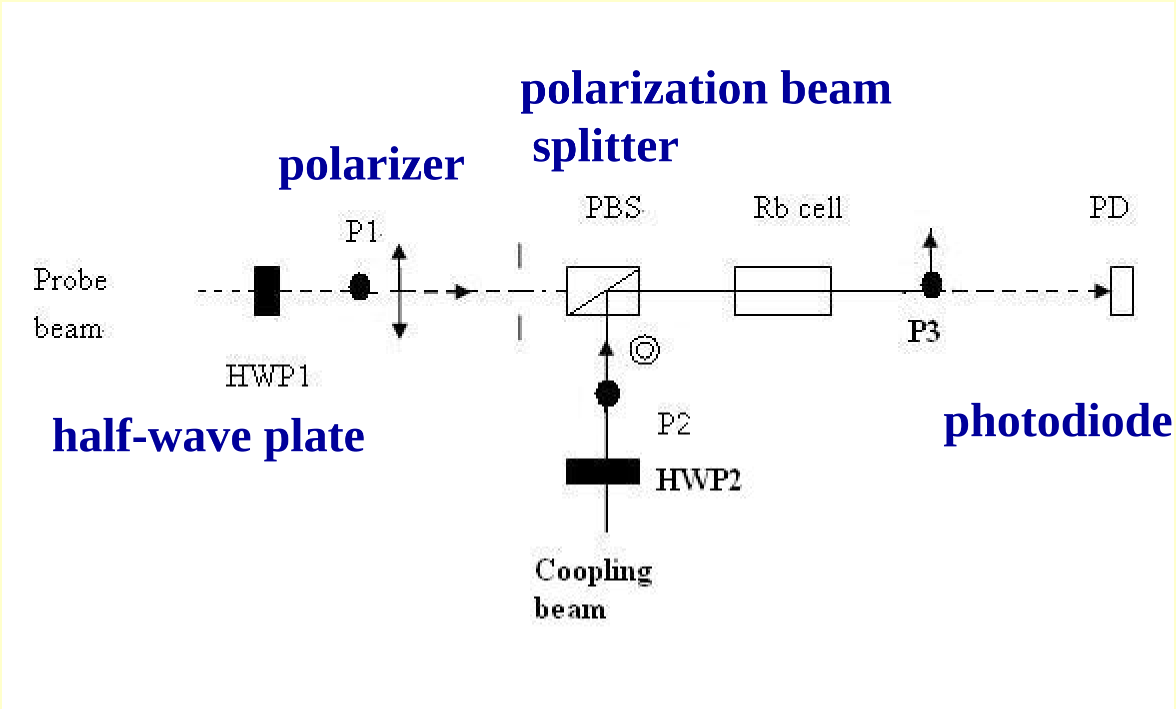
- **Subject:** **The behaviors of atoms in intense laser fields.**
- **Methods:** **bare-atom approach**
  dressed-atom approach
- **Example:** **resonance fluorescence,**
  pump-probe spectrum

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?

Pump-probe spectrum



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

II. Theoretical approaches

Schrödinger picture

$$i\frac{d}{dt}|\psi(t)\rangle = H|\psi(t)\rangle$$

State for the global system "atom +laser": $|\psi(t)\rangle$

Global Hamiltonian: $H = H_A + H_R + H_{AR}$

Atomic Hamiltonian: H_A

Radiation Hamiltonian: H_R

Interaction Hamiltonian: H_{AR}

Two-level atoms

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

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

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

$$H_R|n\rangle = \omega_R(n+\frac{1}{2})|n\rangle$$

$|n\rangle$: **photon number state**

ω : **Atomic frequency** ω_R : **Radiation frequency**

Phase and superposition

Expectation value of the electric field operator:

$$\langle n | \hat{E}(\vec{r}) | n \rangle = 0$$

Photon number states exhibit no phase information. Phase or coherence is exhibited only by a superposition of photon number states.

Quasi-classical (coherent) states

Classical free field

$$\vec{E}_{cl}(\alpha;\vec{r},t) = i\sqrt{\frac{\omega}{2\varepsilon_0 V}}\left(\alpha\hat{\varepsilon}e^{i(\vec{k}\cdot\vec{r}-\omega t)} - c.c\right)$$

Quasi-classical state

$$\left\langle \alpha(t)\middle|\hat{E}(\vec{r})\middle|\alpha(t)\right\rangle = \vec{E}_{cl}(\alpha;\vec{r},t)$$

$$\left|\alpha(t)\right\rangle = e^{-\frac{|\alpha|^2}{2}}\sum_n \frac{\left(\alpha e^{-i\omega t}\right)^n}{\sqrt{n!}}\left|n\right\rangle$$

Poisson distribution

Radiation from a classical source

Classical sources:

Quantum fluctuations of the current is negligible.

Coherent state:

The quantum radiation field emitted by a classical source is a coherent state.

Ref.：QED-1

Bare-atom approach

Uncoupled Hamiltonian： $H_0 = H_A + H_R$

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

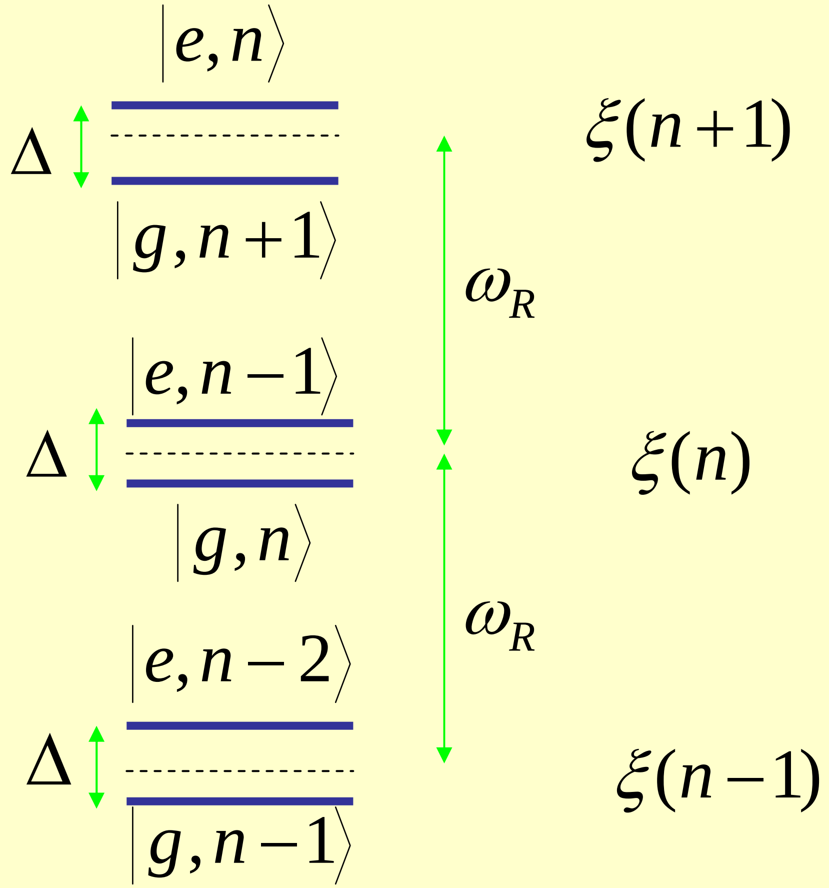
$$H_0|I\rangle = E_I|I\rangle \quad \text{with} \quad E_I = -\frac{1}{2}\omega + n\omega_R$$

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

$E_F - E_I = \omega - \omega_R = \Delta$ **:detuning**

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

Ladder of energy levels



Manifold：$\xi(n) = \{|g,n\rangle, |e,n-1\rangle\}$

Resonant couplings

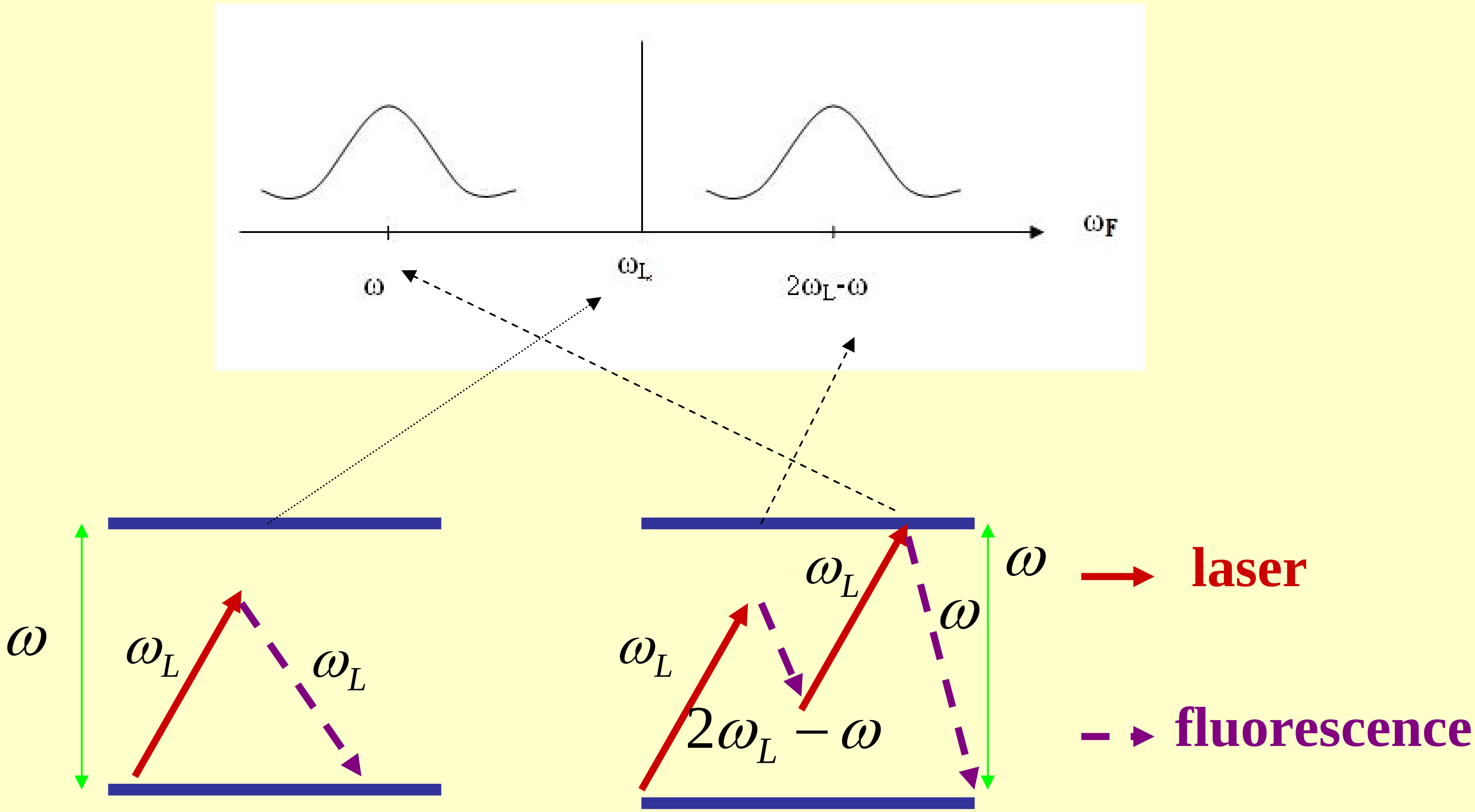
The interaction Hamilton H_{AR} couples the two states in each manifold.

$$\langle e, n-1 | H_{AR} | g, n \rangle = g\sqrt{n}$$

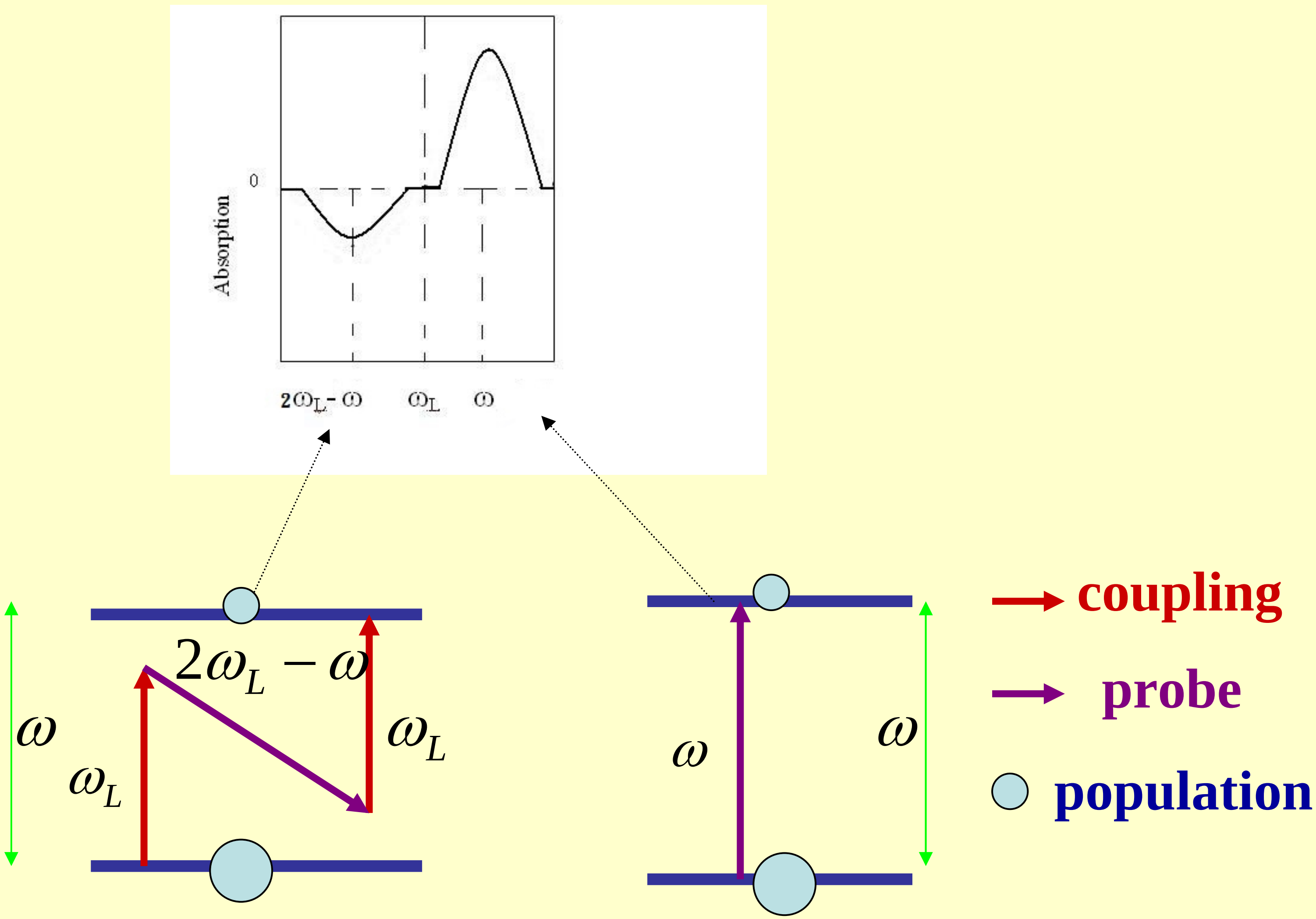
where

$$g = -i\sqrt{\frac{\omega_R}{2\varepsilon_0 V}}\langle e | \vec{d} \cdot \hat{\varepsilon} | g \rangle = |g| e^{i\phi}$$

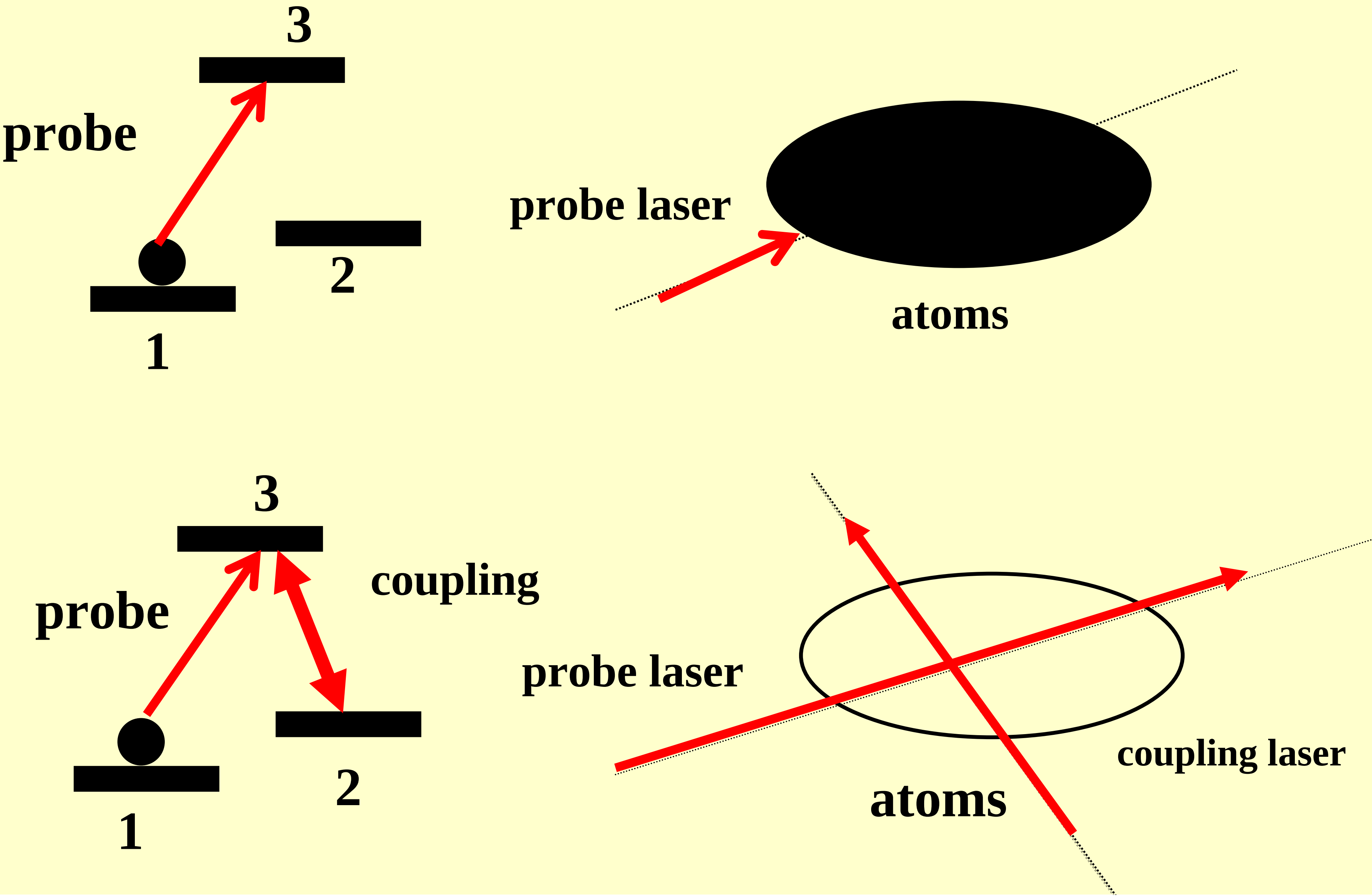
Resonance fluorescence



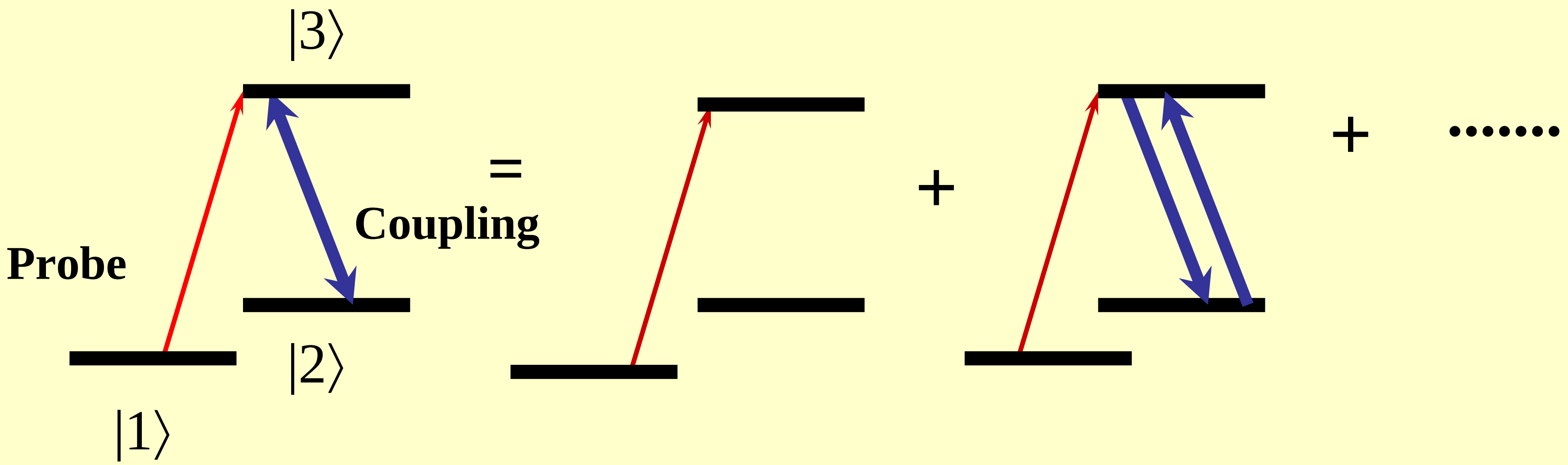
Mollow absorption spectrum



Electromagnetically induced transparency



EIT (Λ -type) in the bare-atom approach



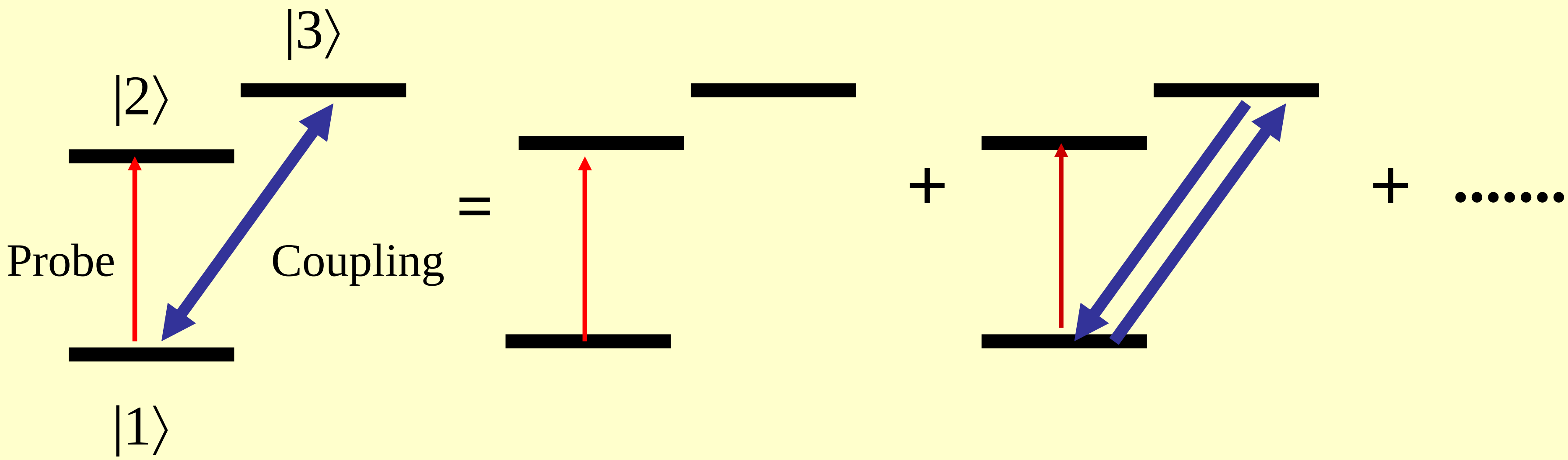
Transition amplitude: $T^{(1)}$ $T^{(3)}$

Transition probability of $|1\rangle \rightarrow |3\rangle$ **=** $\left|T^{(1)} + T^{(3)} + \cdots\right|^2$

Destructive interference between $T^{(n)}$ **and** $T^{(n+2)}$ **.**

$\Rightarrow$ **The probe absorption is suppressed.**

EIT (V-type) in the bare-atom approach



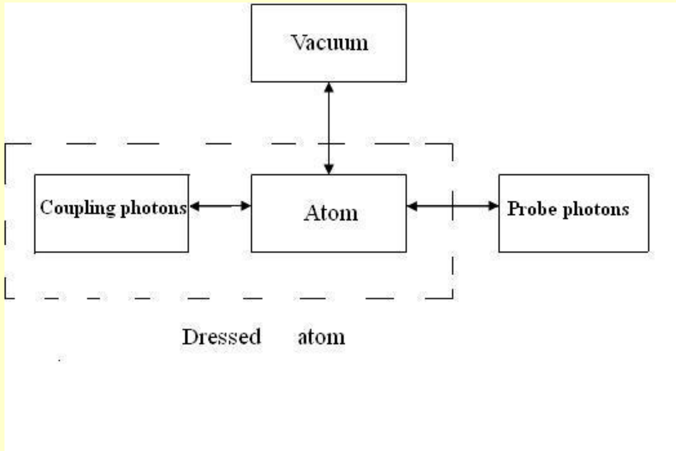
Transition amplitude: $T^{(1)}$ $T^{(3)}$

Transition probability of $|1\rangle \rightarrow |2\rangle$ **=** $\left|T^{(1)} + T^{(3)} + \cdots\right|^2$

Destructive interference between $T^{(n)}$ **and** $T^{(n+2)}$ **.**

$\Rightarrow$ **The probe absorption is suppressed.**

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.**

Dressed states (1/2)

$$H\left|\pm,n\right\rangle = E_{\pm}(n)\left|\pm,n\right\rangle$$

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

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

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

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

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

Dressed states (2/2)

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

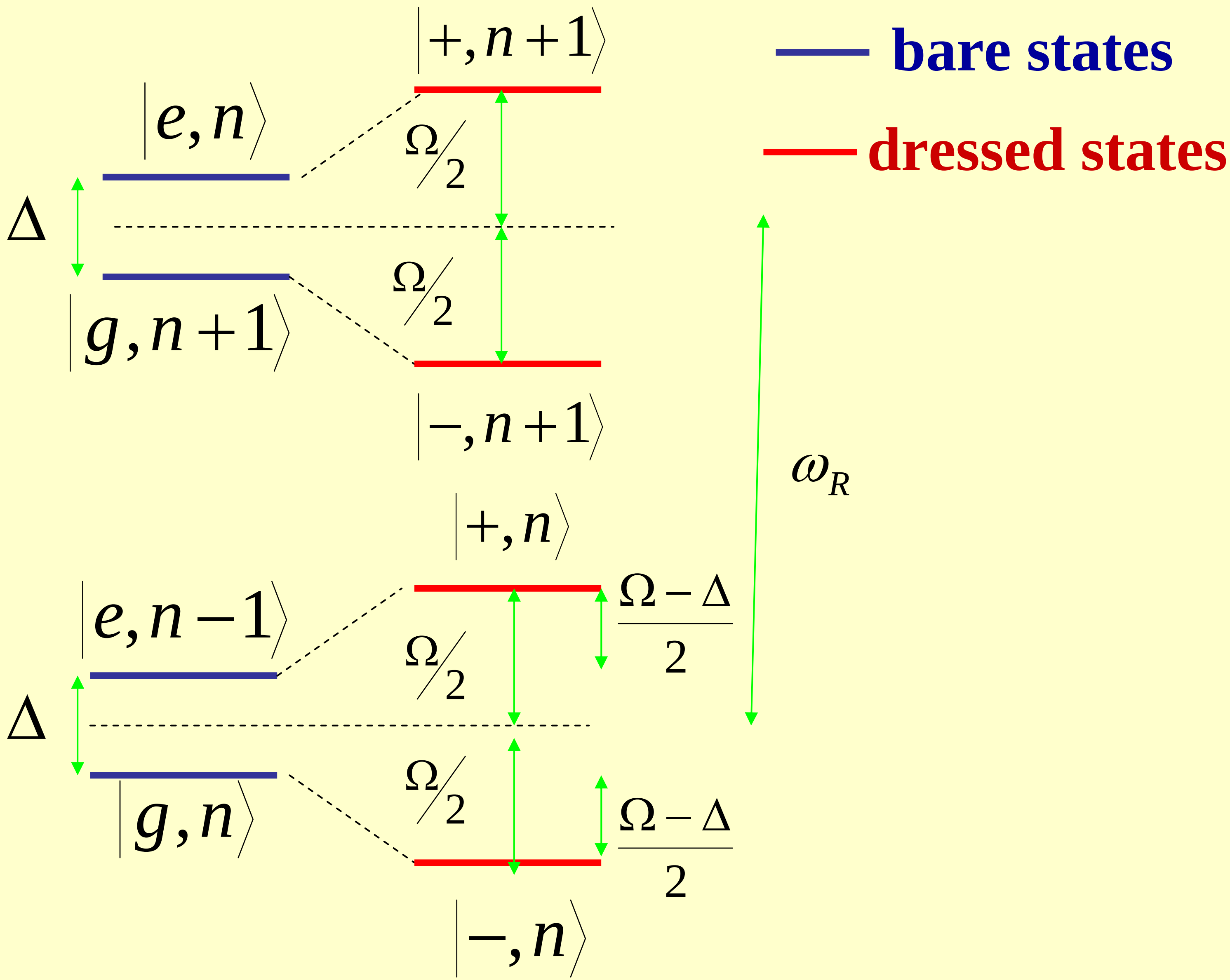
$$E_{\pm}(n) = (n - 1/2)\omega \pm 1/2\,\Omega$$

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

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

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

Ladder of energy levels



Light shift (dynamic Stark effect)

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

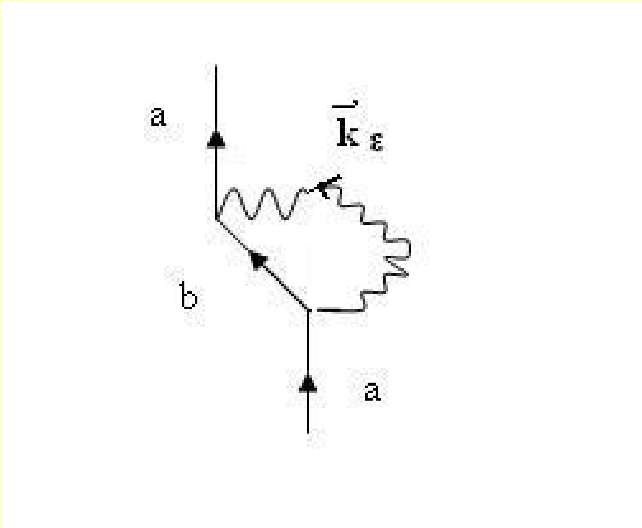
$$\Delta E_{g(e)} = \Delta E^{(1)}_{g(e)} + \Delta E^{(2)}_{g(e)} + \dots$$

with $$\Delta E^{(1)}_e = -\Delta E^{(1)}_g = \frac{n|g|^2}{\Delta}$$

$$\Delta E^{(2)}_e = -\Delta E^{(2)}_g = -\frac{n^2|g|^4}{\Delta^3}$$

Radiative Corrections

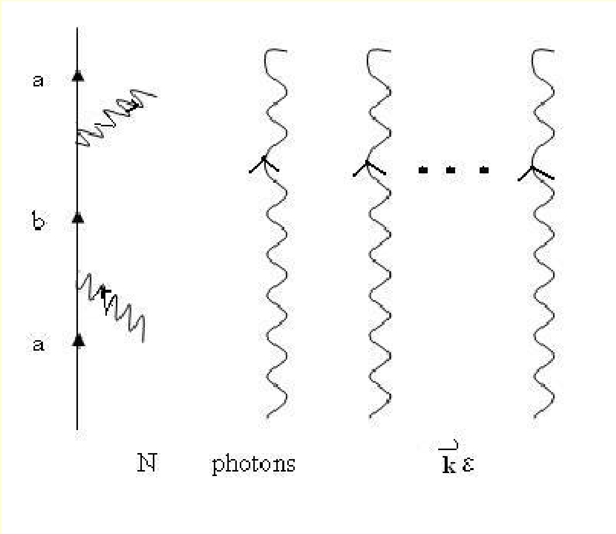
- **Spontaneous radiative corrections**

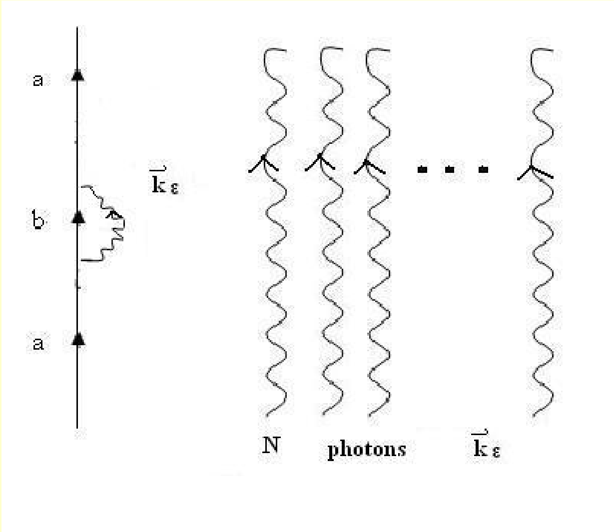


The spontaneous radiative corrections lead to the Lamb shift.

Radiative Corrections

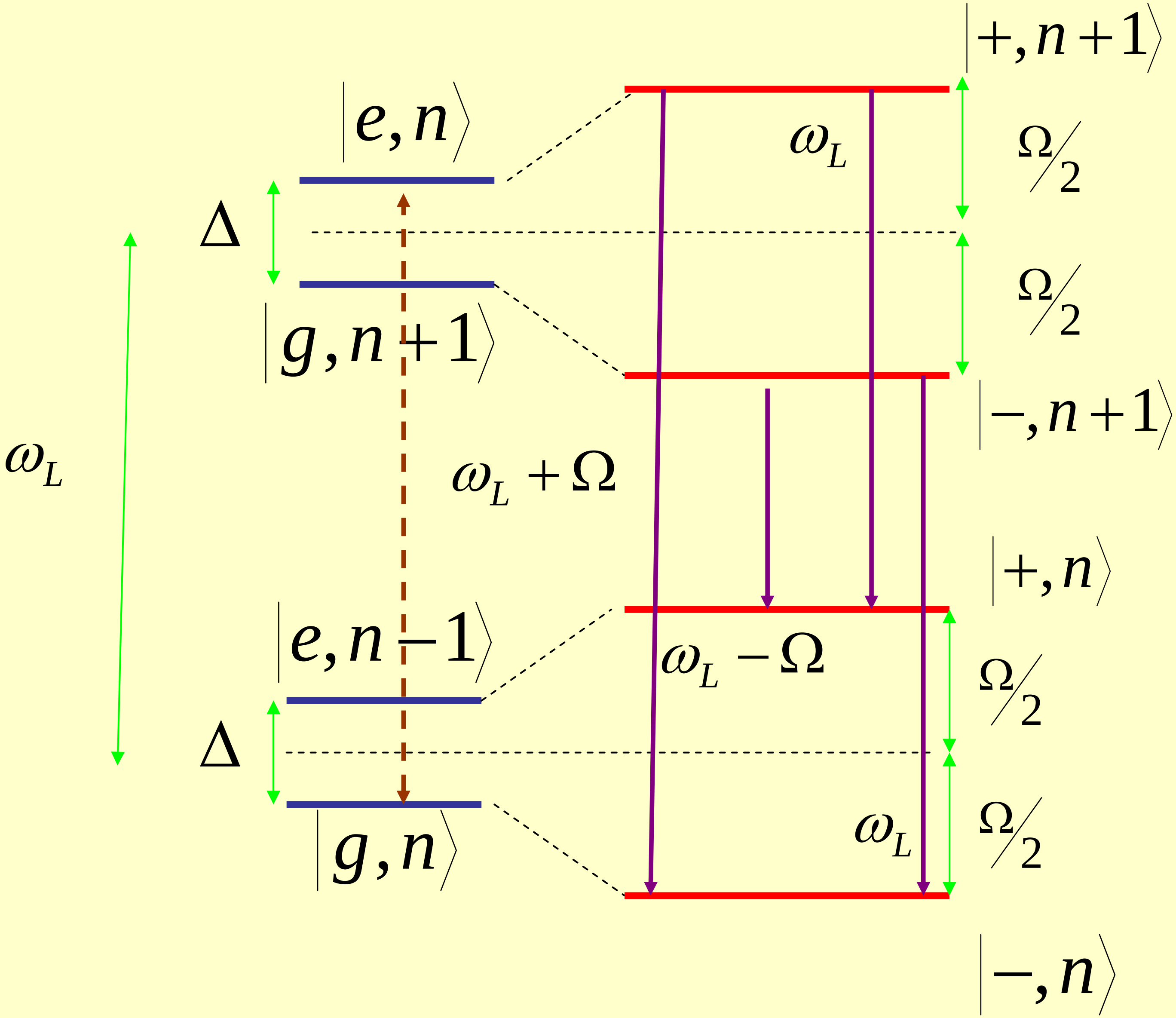
- **Stimulated radiative corrections**





The stimulated radiative corrections lead to the Light shift.

Resonance fluorescence



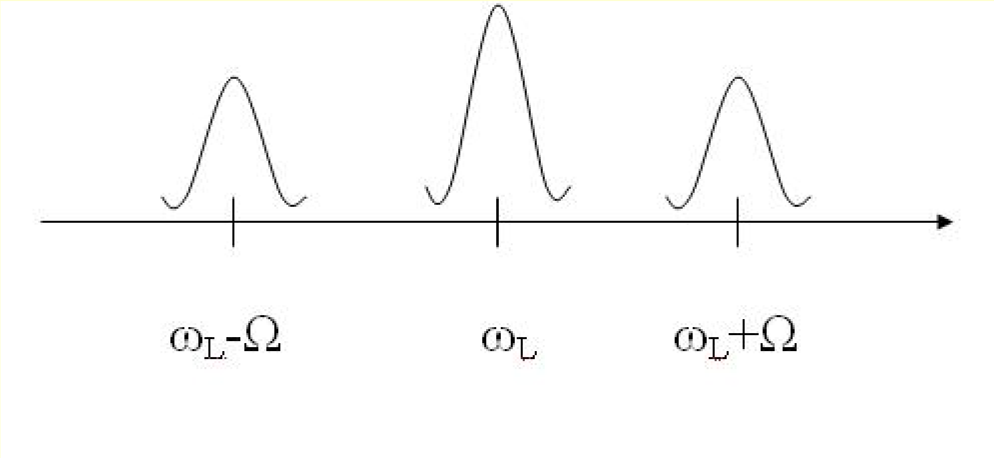
Fluorescence triplet

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

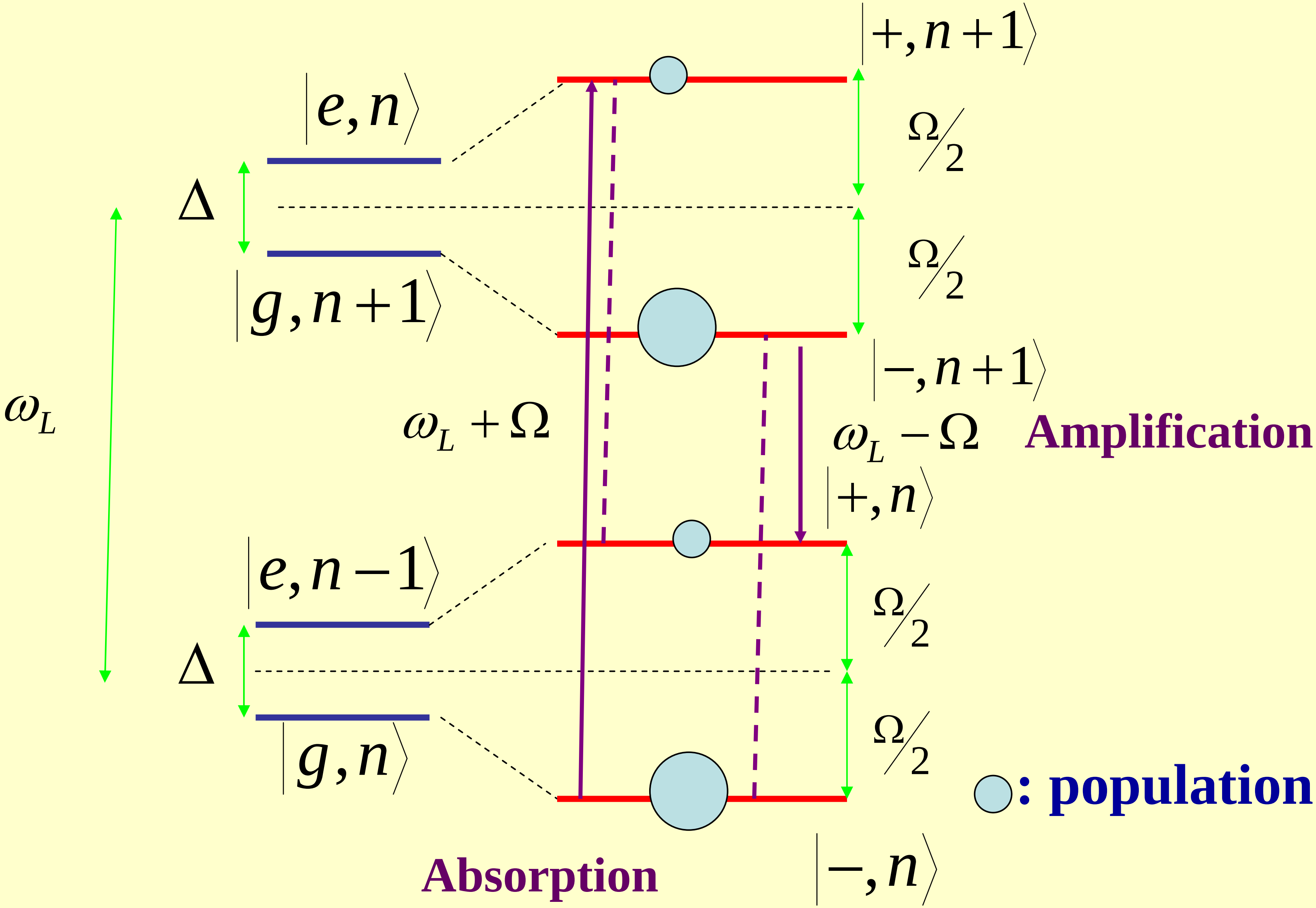
1st order in $\dfrac{4n|g|^2}{\Delta^2}$

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

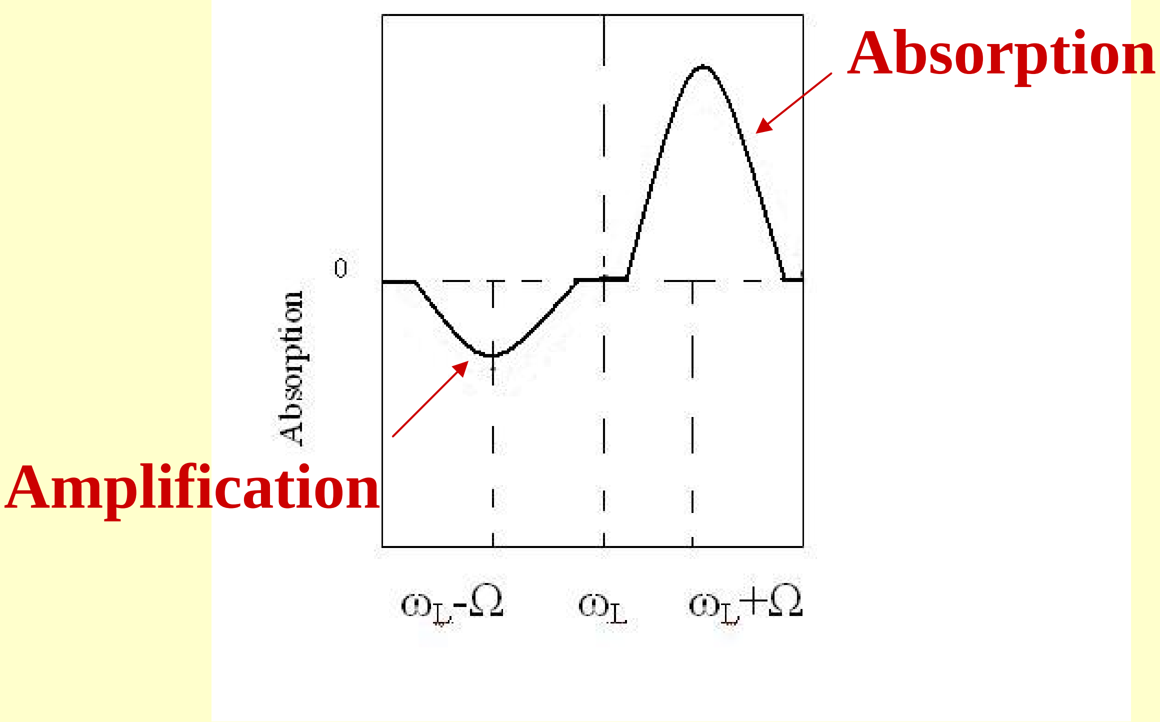
$|+,n+1\rangle \rightarrow |+,n\rangle$ **and** $|-,n+1\rangle \rightarrow |-,n\rangle \ : \ \omega_L$



Mollow absorption spectrum (1/2)



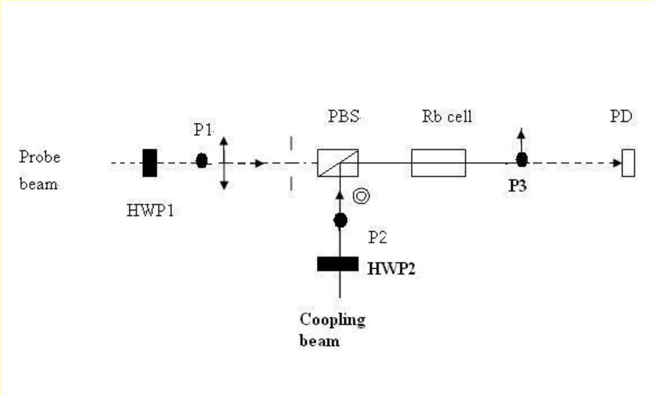
Mollow absorption spectrum (2/2)

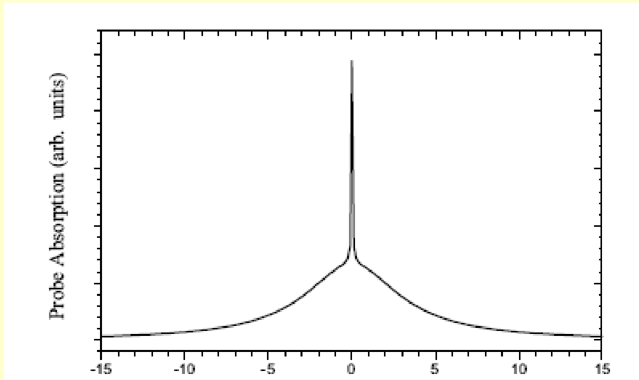


The central component is missing.

III. Anomalous electromagnetically induced absorption

- **Electromagnetically induced absorption (EIA)**





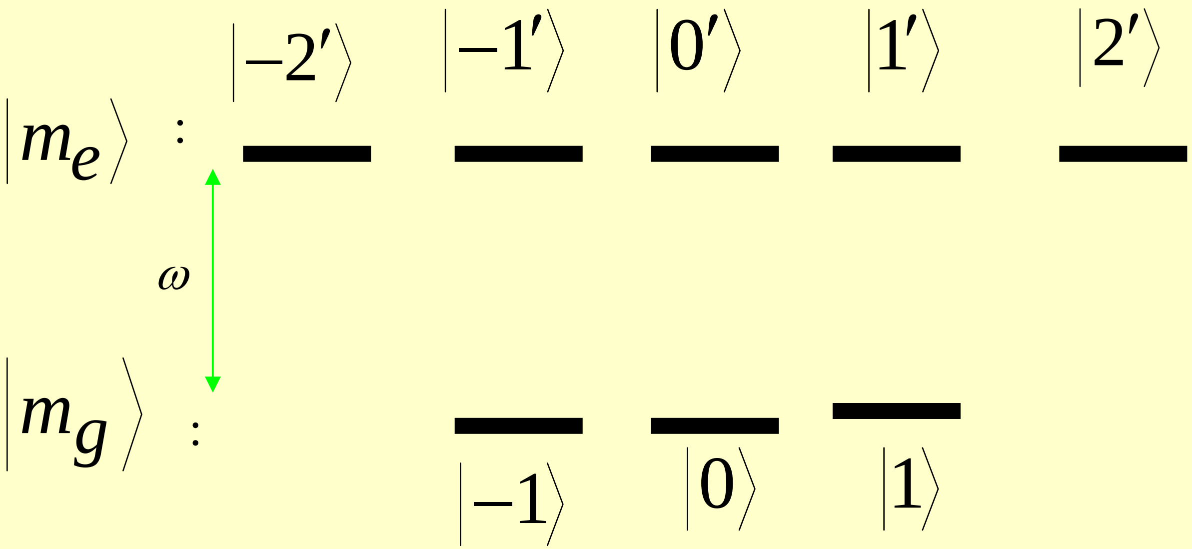
probe-coupling detuning (MHz)

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].

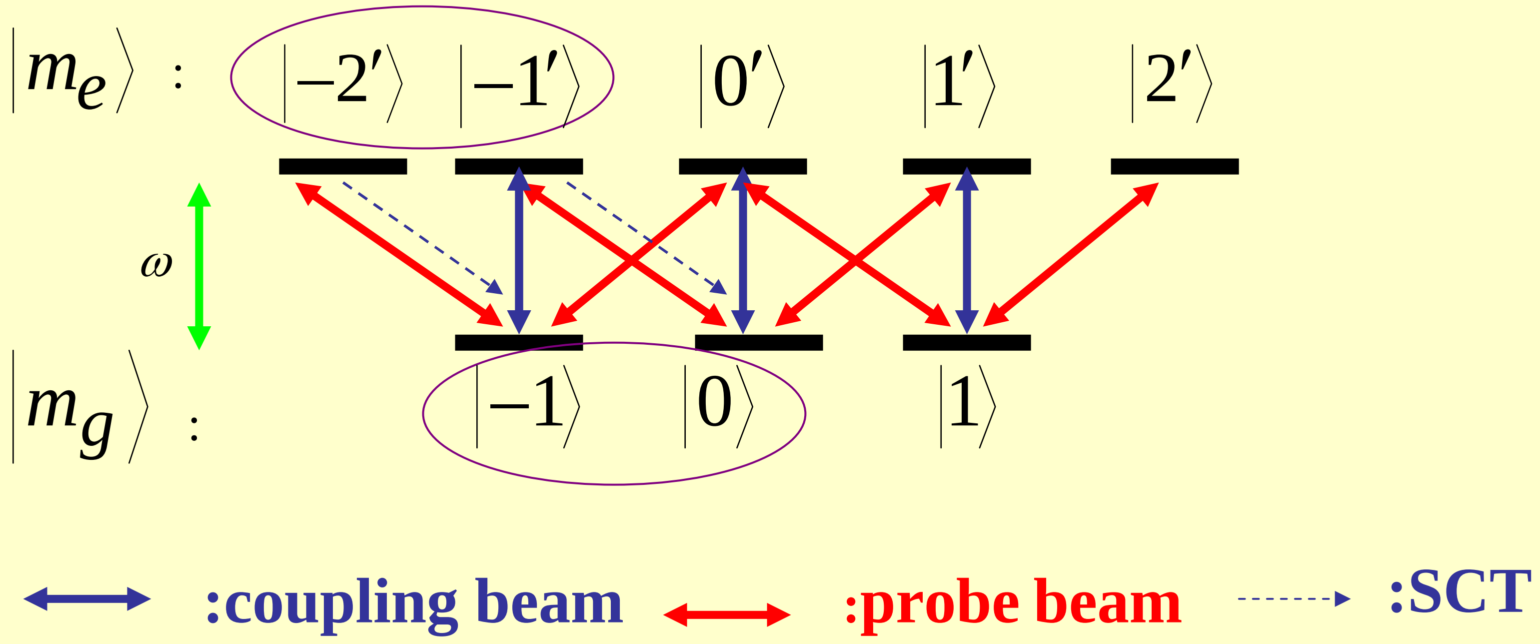
Lezama’s condition for EIA

$$F_e = F_g + 1$$

Ref.：EIA-2



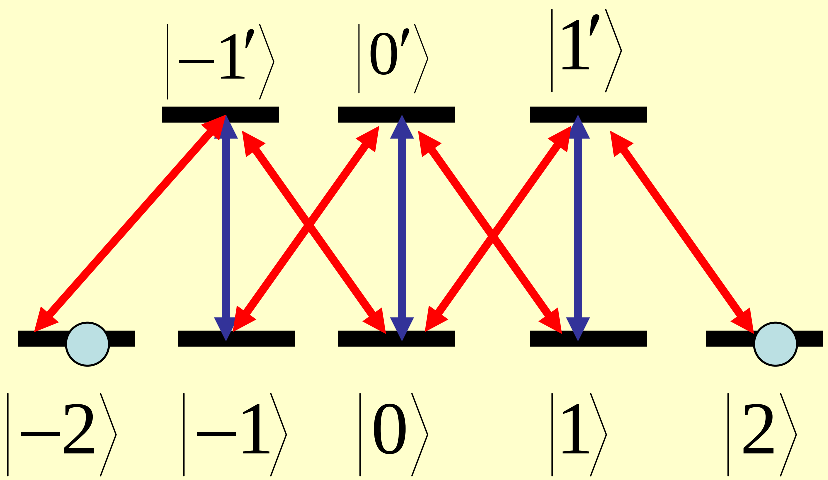
Spontaneous coherence transfer (SCT)



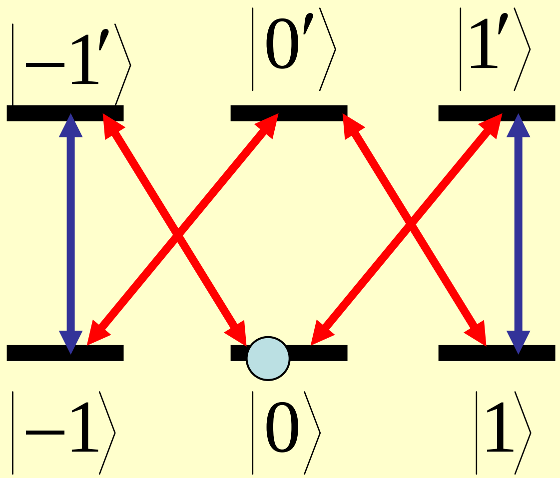
EIA is caused by the spontaneous transfer of the light-induced Zeeman coherence from the excited level to the ground level [Ref. : EIA-3].

Interpretations of Lezama's condition

(I): $F_e = F_g - 1$



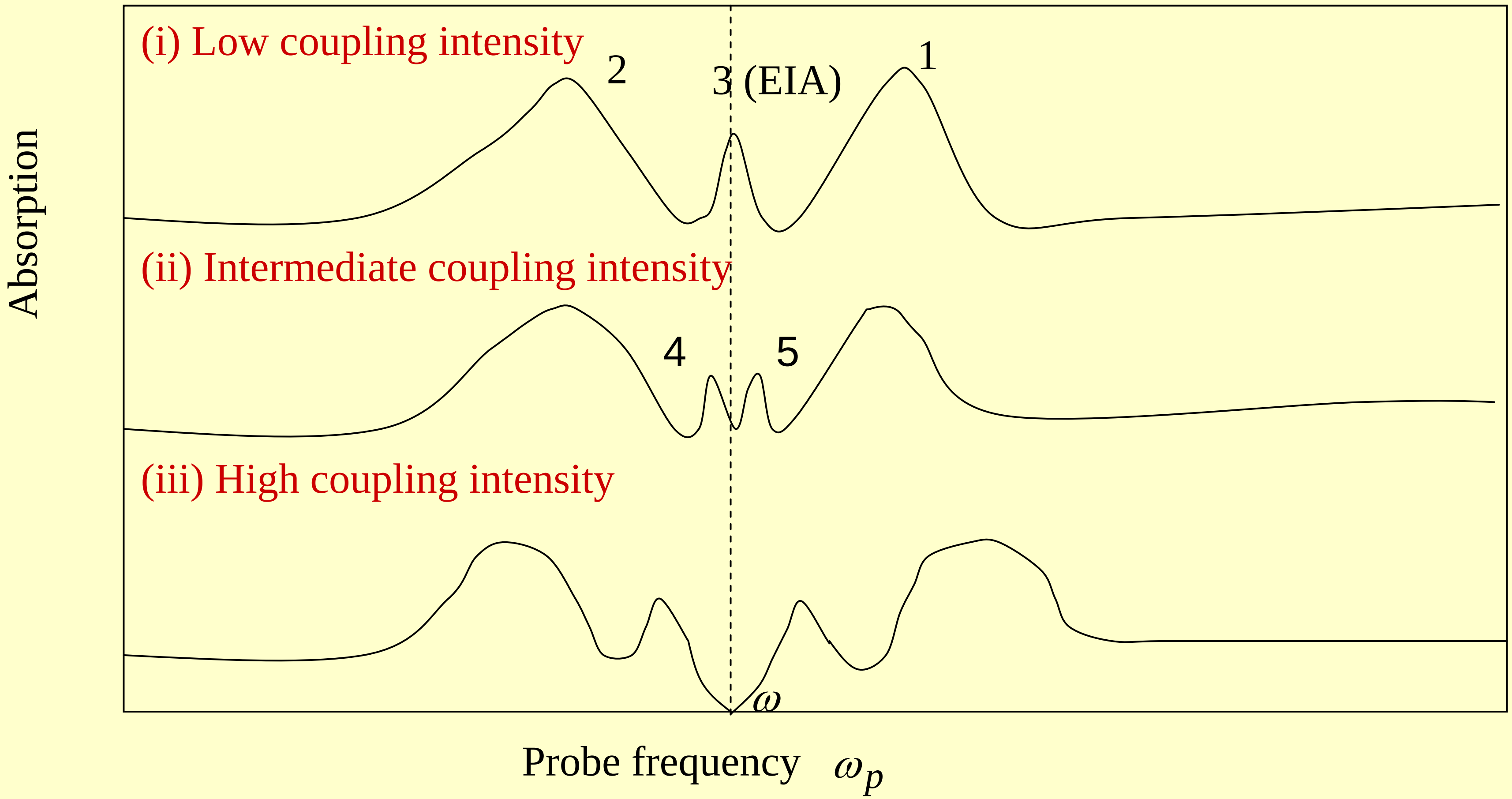
(II): $F_e = F_g$



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 $F_e = F_g - 1$

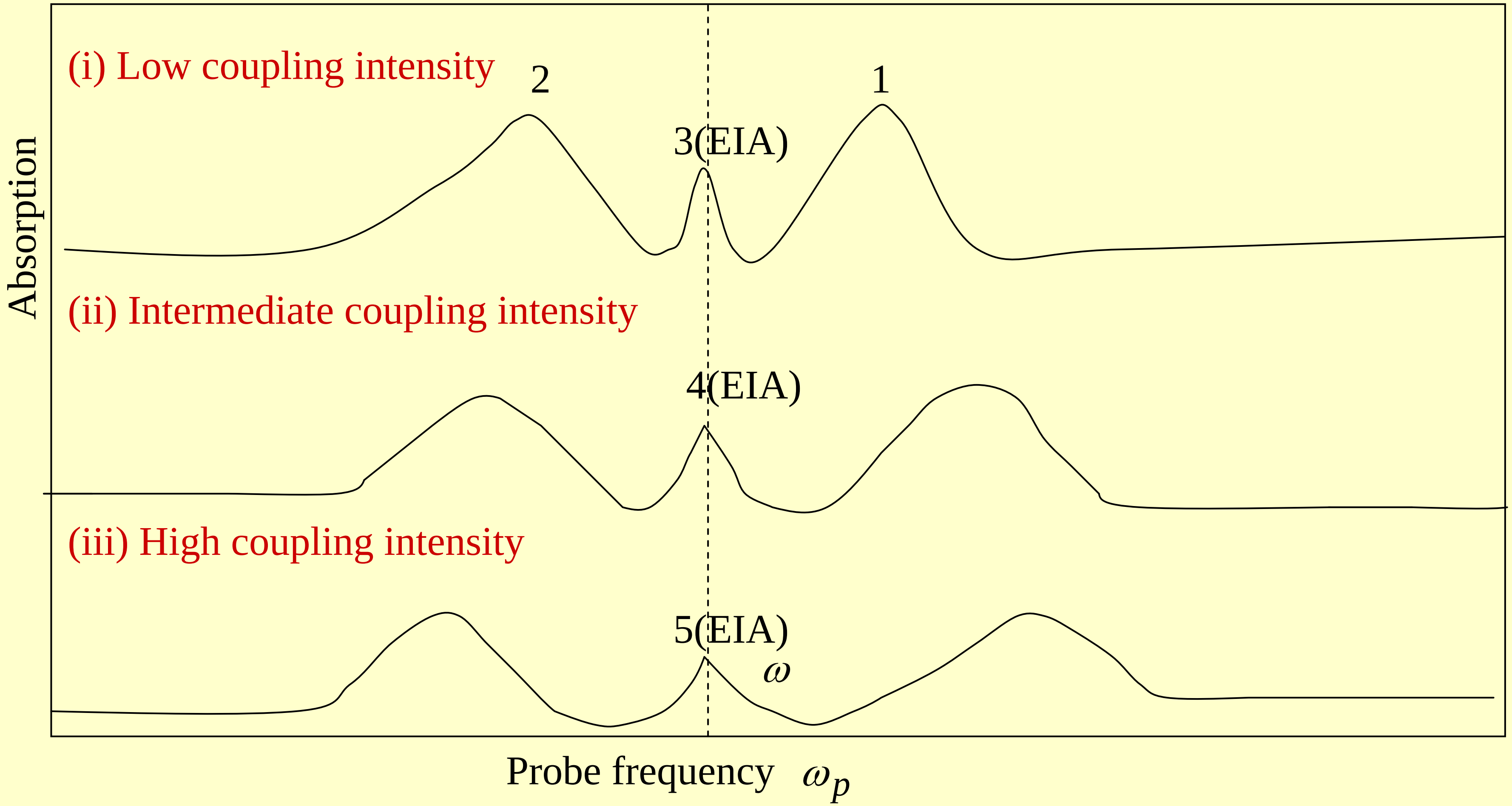
- **Transition** $F_g = 3 \rightarrow F_e = 2$ **in the** D_1 **line of** ^{85}Rb



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

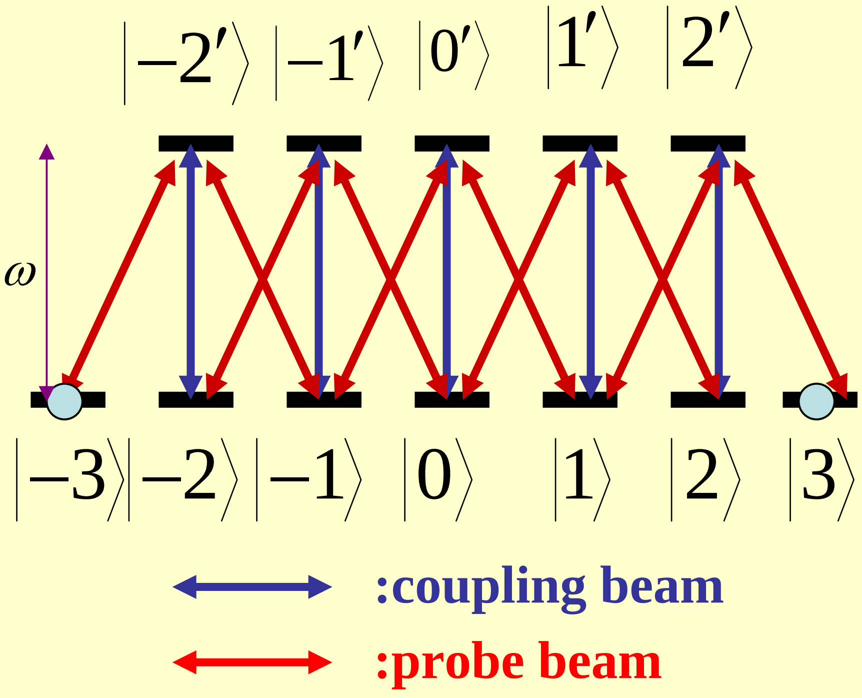


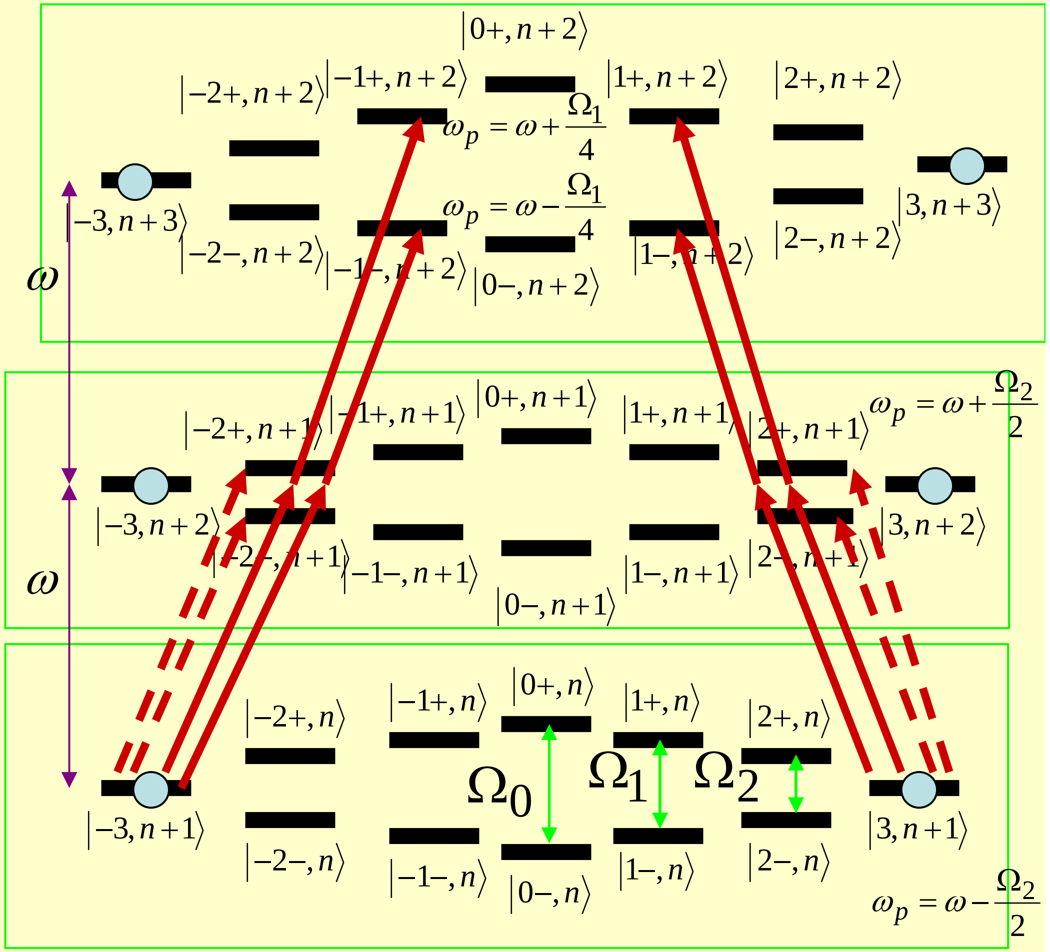
Anomalous EIA $F_e = F_g$

- **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.

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

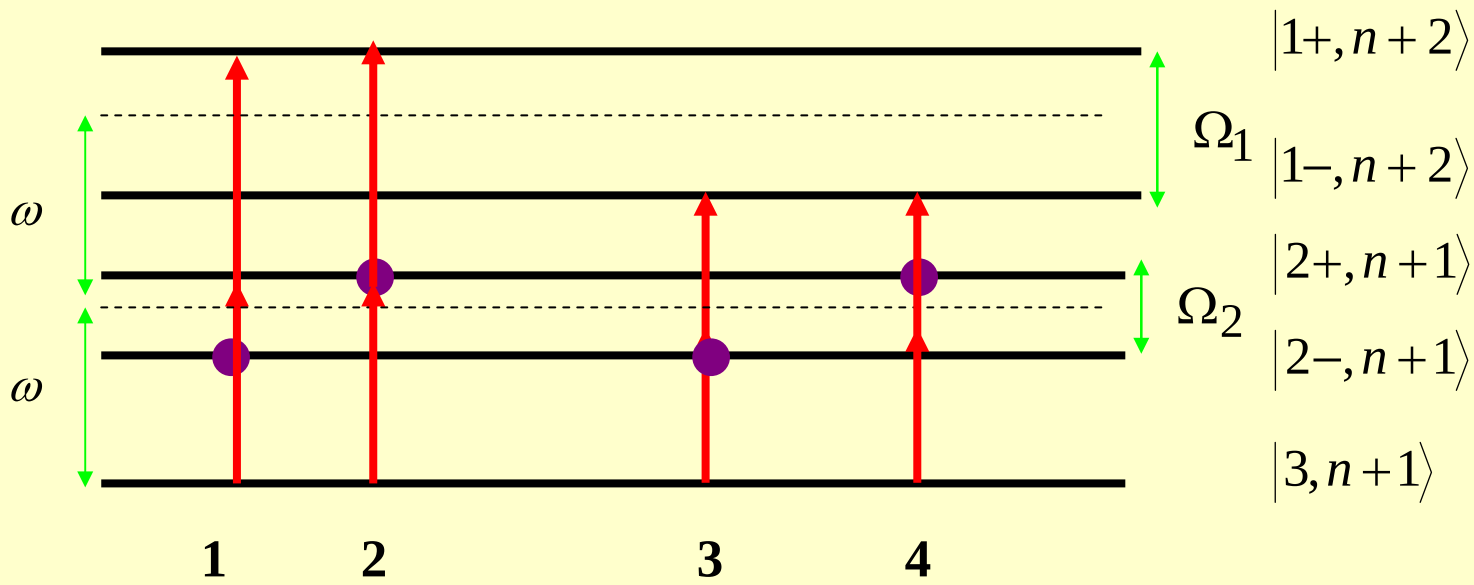




(I) Bare-atom picture **(II) Dressed-atom picture**

Ref.：Anomalous EIA-2

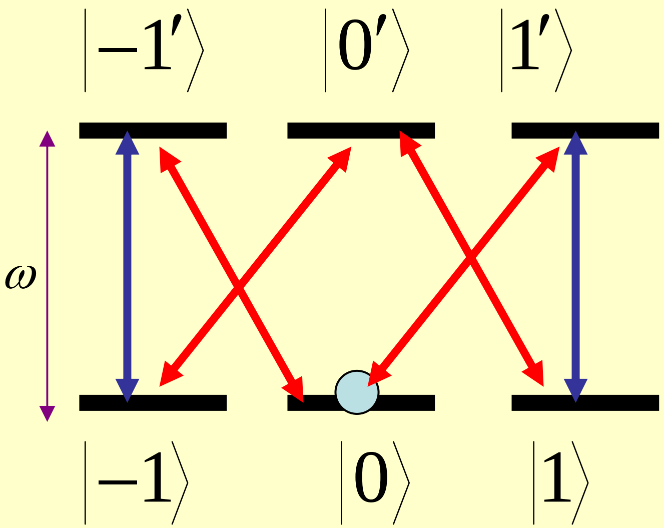
Two-photon processes



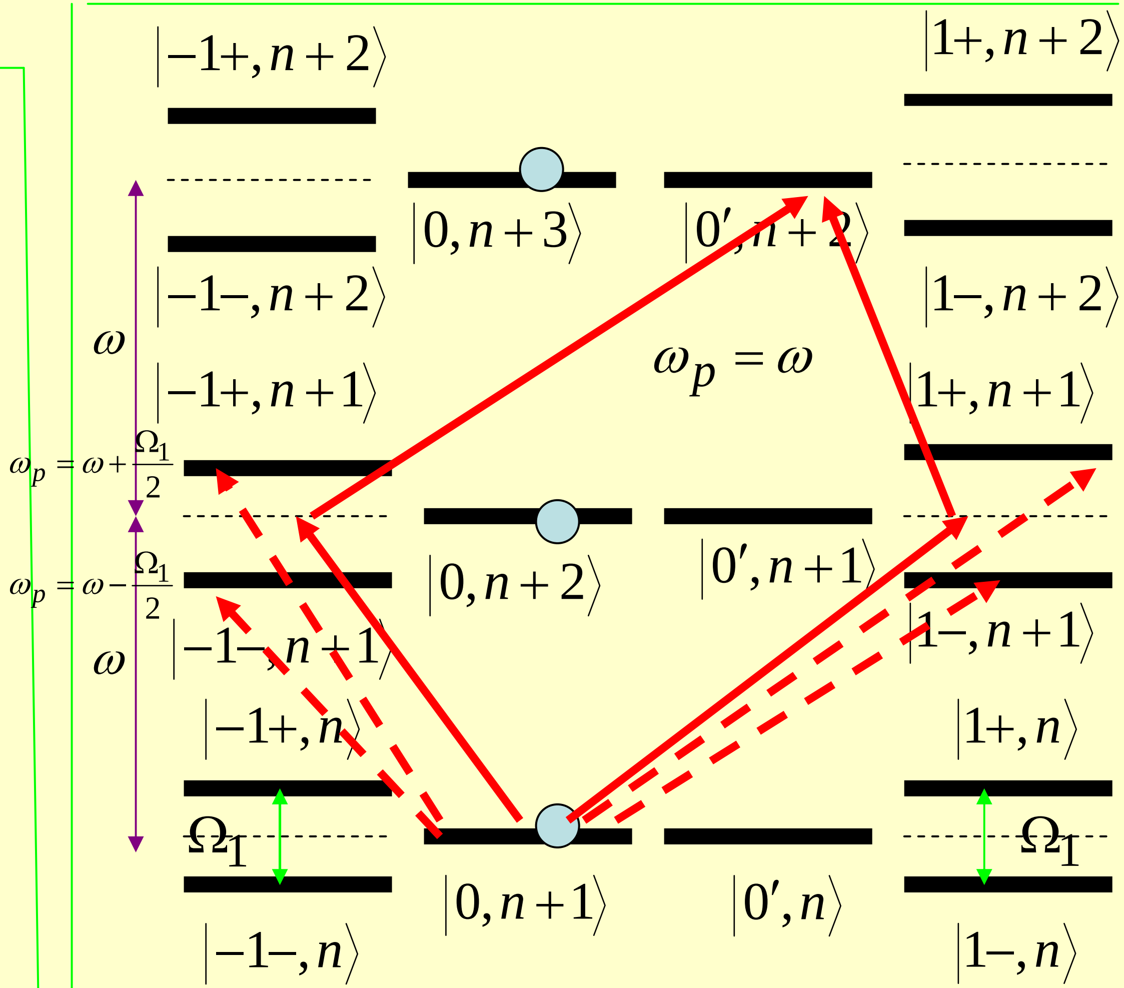
● **: intermediate states**

- **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.**

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

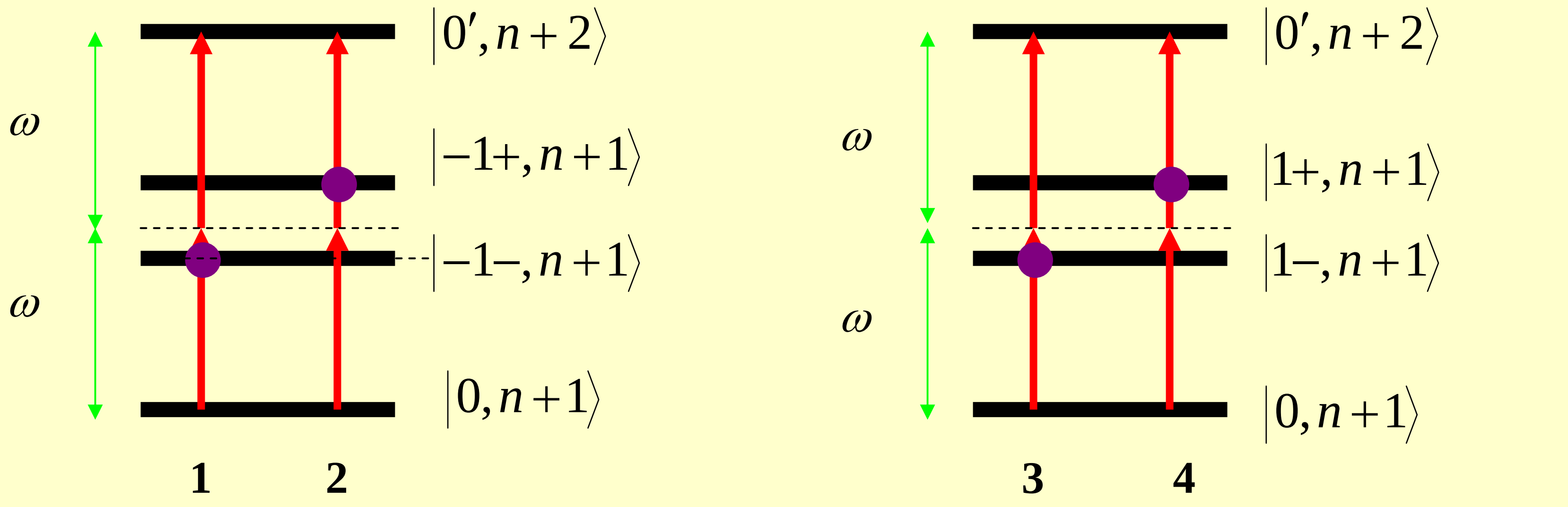


(I) Bare-atom picture



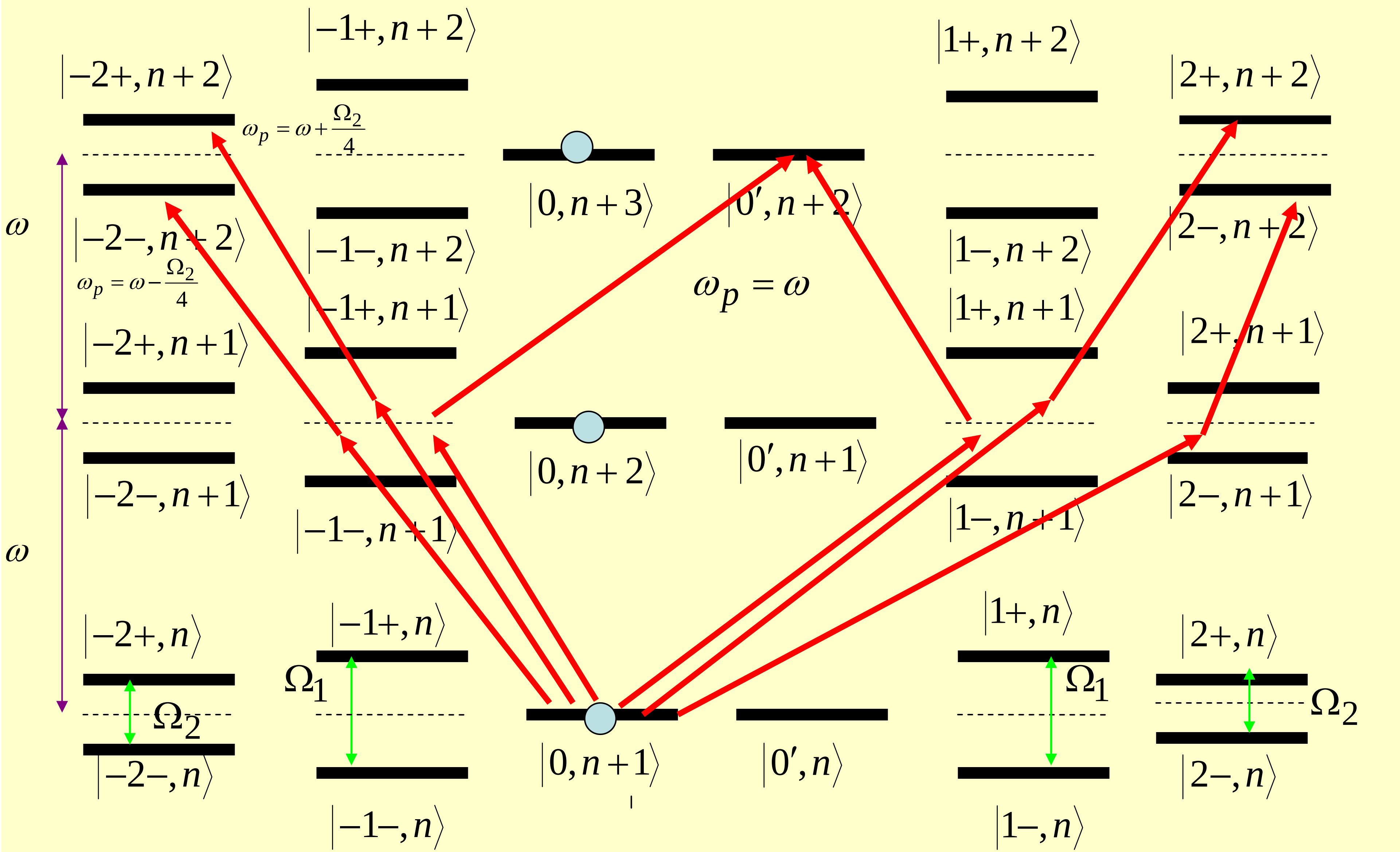
(II) Dressed-atom picture

Two-photon processes

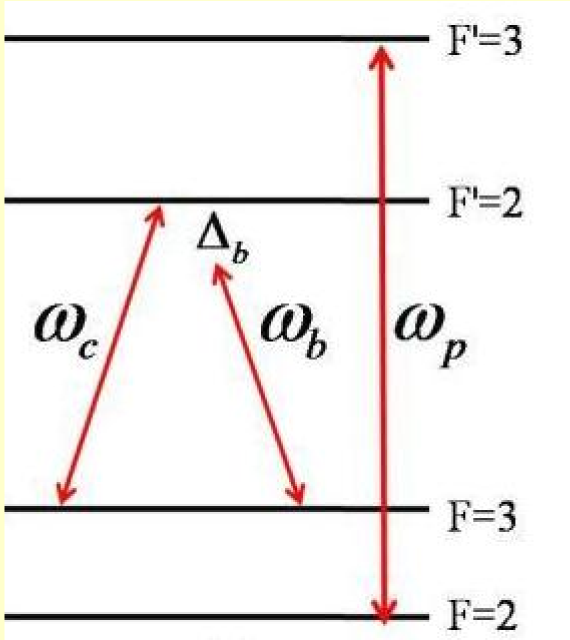


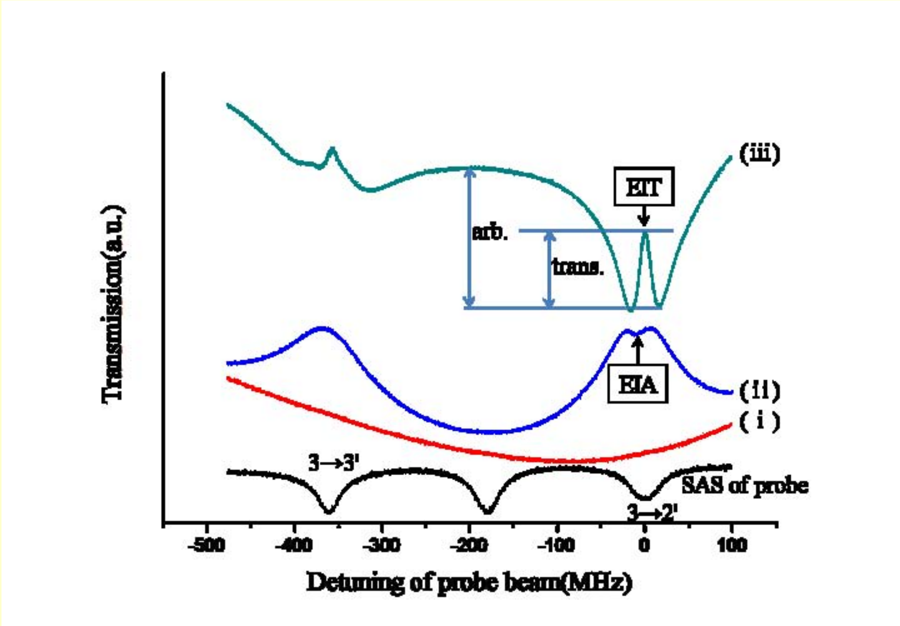
- **Positions of 1,2,3,4：** $\omega_p = \omega$
- **Transition amplitudes：** $T^{(1)} = T^{(2)} = T^{(3)} = T^{(4)}$
- **Constructive interferences among 1,2,3,4 lead to an EIA peak at** $\omega_p = \omega$ **.**

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



Switch from EIA to EIT





ω_C **coupling**

ω_b **probe**

ω_p **pumping**

(ii) coupling

(iii) coupling+pumping

Ref.：Anomalous EIA-3

IV. Summary

- **The dressed-atom approach provides simple interpretations for the behaviors of atoms in intense fields.**
- **The dressed-atom approach sheds new lights on the pump-probe spectrum involving several probe photons.**

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