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# Resonant ATOM MAJORANA MIXING

Mainly based on :

- Neutrinoless Double Electron Capture as a Tool to Measure the ve Mass, J. B., A. De Rujula, C. Jarlskog, Nucl.Phys. B223 (1983) 15
- Developments and papers in the last decade triggered by atomic Traps
- Stimulated transitions in resonant Atom Majorana Mixing, J. B., A. Segarra, arXiv:1706.08328 [hep-ph]

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# Outline

- Massive Neutrinos
- Neutrinoless Double Beta Decay
- Neutrinoless Double Electron Capture
- Atom Majorana Mixing
- Resonant Enhancement
- Time History
- Spontaneous Observables
- Stimulated Transitions
- Outlook

# MASSIVE NEUTRINOS

- Neutrino Flavour Oscillations observed in atmospheric, solar, reactor and accelerator sectors have demonstrated that
  **NEUTRINOS HAVE MASS AND FLAVOUR MIXING**

  Two mass differences and Three Mixings already measured

- Most important Open Questions:

**ARE NEUTRINOS DIRAC OR MAJORANA PARTICLES ?**

| | |
|---|---|
| $\bar{\nu}_R \ \ m_D \ \ \nu_L$ | $\bar{\nu}_L^c \ \ m_M \ \nu_L$ |
| *Needs sterile* $\nu_R$ | *Breaks Global Lepton Number* |
| *Origin by Standard Higgs Doublet* | *Beyond Standard Origin* |

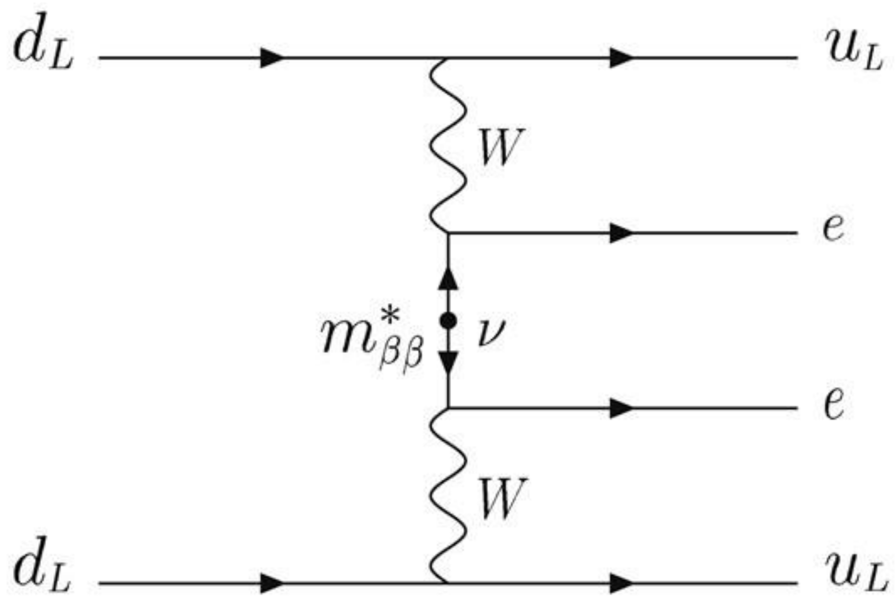
- CP-Violating Flavour Phase and (?) Two CPV Majorana Phases

$$U=\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}$$

- Absolute Neutrino Mass Scale
- Neutrino Mass Spectrum Hierarchy → normal, inverted
- (2,3) Mixing above or below 45 degrees?

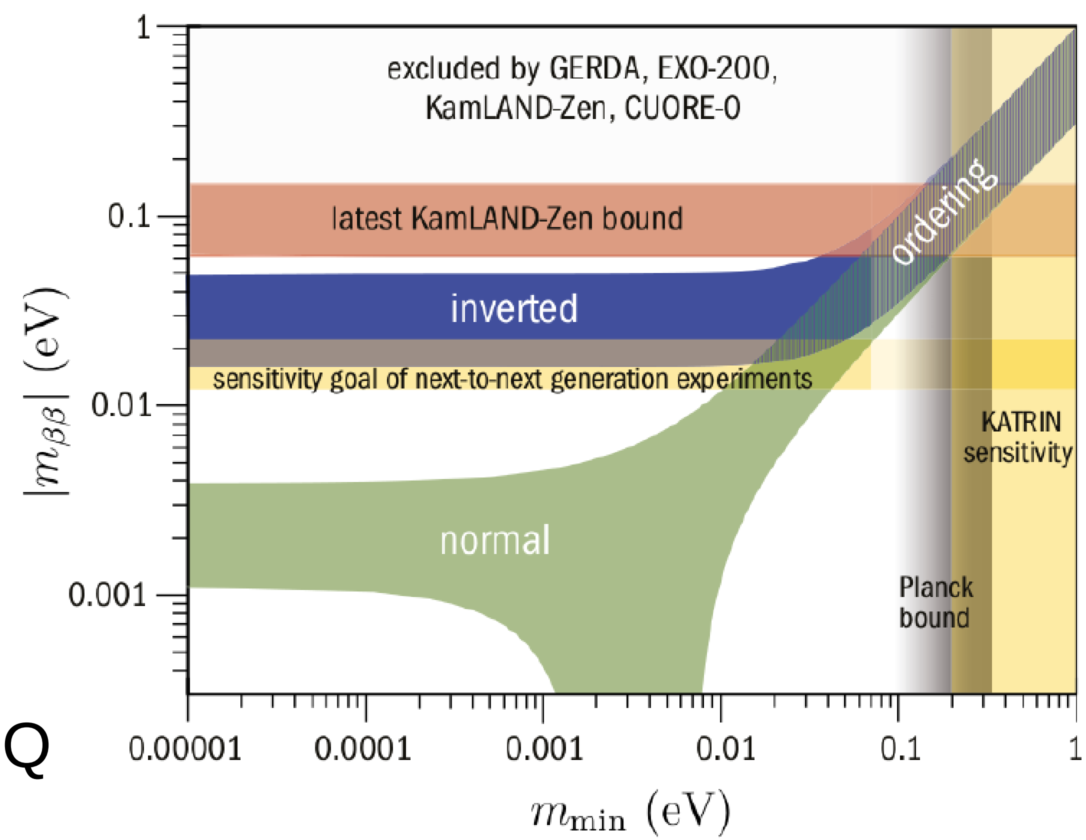
# Neutrinoless Double BetaDecay

$$^{A}Z \rightarrow {}^{A}(Z+2) + 2e^{-}$$




$$m_{\beta\beta} \equiv \sum_i U_{ei}^2\, m_{\nu_i}$$

[S. Pascoli, CERN Courier, July-August 2016]

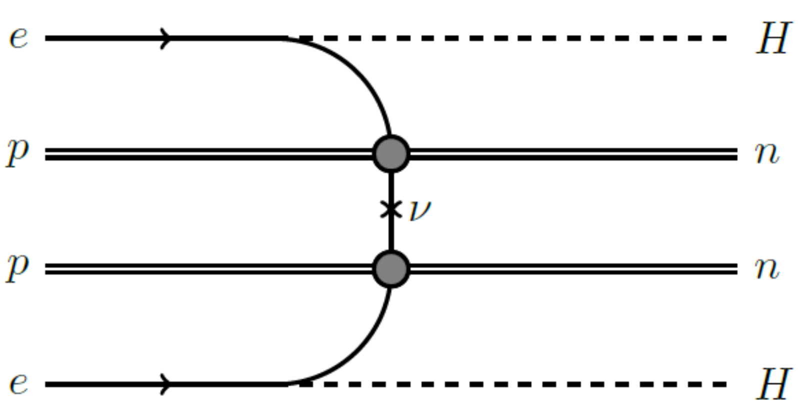



- ΔL=2 process, only if Majorana ν
- Signature: $T_{ee} = Q$
- Background by 2ν mode with $T_{ee} < Q$

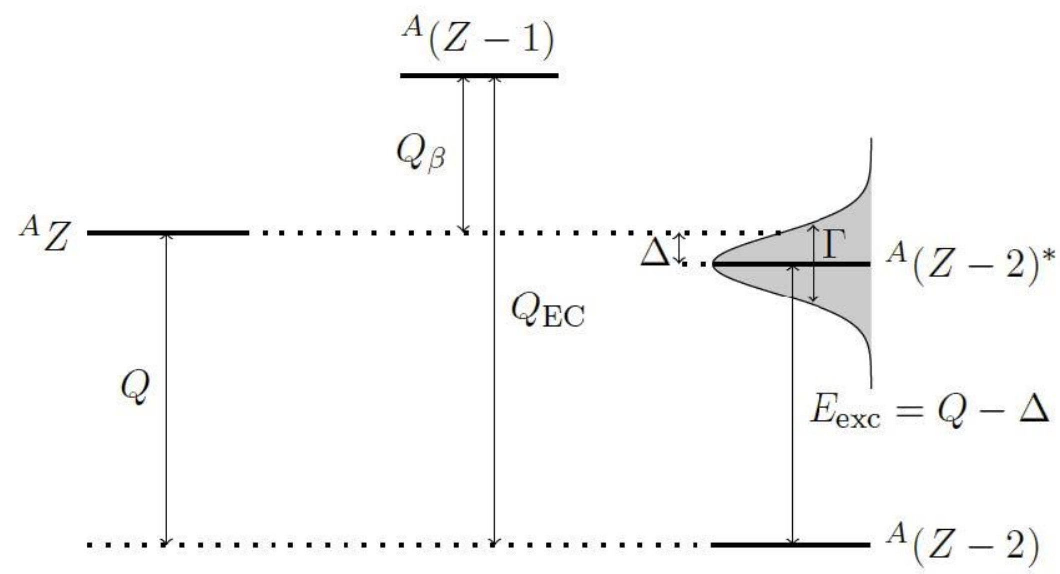
# Neutrinoless Double Electron Capture

$$^{A}Z + 2e^{-} \rightarrow {}^{A}(Z-2)^{*}$$

$$m_{\beta\beta} \equiv \sum_i U_{ei}^2 \, m_{\nu_i}$$




Majorana Mixing $M_{21} \sim m_{\beta\beta}^{*} \langle F_{21} \rangle M_{0\nu}$




- ΔL = 2 mixing, only if Majorana ν, X-ray emission
- Signature: $T_{YY} = Q$
- No intrinsic background on the resonance

$M_{0\nu}$ from nuclear QRPA (Faessler et al, PRC(2012)) and IBM (Iachello et al, PRC (2014))

# ATOM MAJORANA MIXING

Two–state Hamiltonian $\mathbb{H} = \mathbb{M} - \frac{i}{2}\mathbb{\Gamma} = \begin{bmatrix} M_1 & M_{21}^* \\ M_{21} & M_2 \end{bmatrix} - \frac{i}{2}\begin{bmatrix} 0 & 0 \\ 0 & \Gamma \end{bmatrix}$

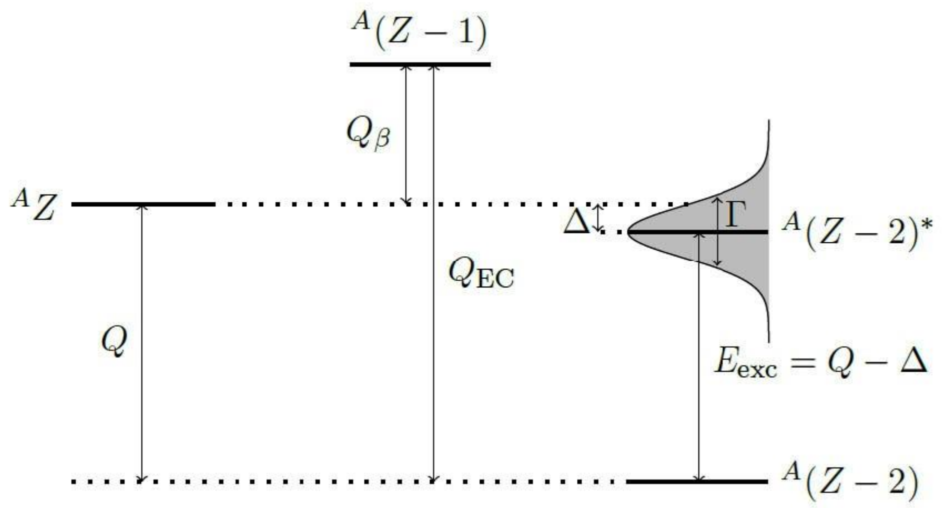
Non-orthogonal eigenstates: $[\mathbb{M}, \mathbb{\Gamma}] \neq 0$, $\langle \lambda_S | \lambda_L \rangle = \alpha - \beta$

$$|\lambda_L\rangle = |1\rangle + \alpha\,|2\rangle\,,$$
$$E_L \approx M_1\,,$$
$$\Gamma_L \approx |\alpha|^2\,\Gamma\,,$$

$$|\lambda_S\rangle = |2\rangle - \beta^*\,|1\rangle\,,$$
$$E_S \approx M_2\,,$$
$$\Gamma_S \approx \Gamma\,.$$

$$\alpha = \frac{M_{21}}{\Delta + \frac{i}{2}\Gamma}$$

$$\beta = \frac{M_{21}}{\Delta - \frac{i}{2}\Gamma}$$



# Resonant Enhancement

- $$\frac{^{152}\mathrm{Gd} \to {}^{152}\mathrm{Sm}}{\Delta \sim 30\,\Gamma}$$ Eliseev et al, PRL (2011)

$$\Delta \sim \Gamma$$

- $$|\alpha|^2 = 10^{-54}\left[\frac{|m_{\beta\beta}|}{0.1\ \mathrm{eV}}\right]^2$$

$$\alpha = \frac{M_{21}}{\Delta + \frac{i}{2}\Gamma}$$

$$\beta = \frac{M_{21}}{\Delta - \frac{i}{2}\Gamma}$$

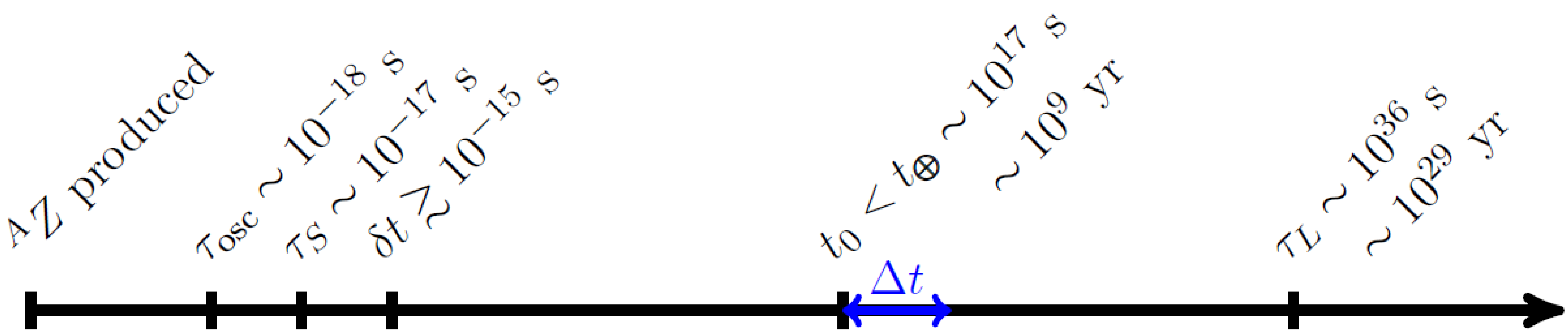
- Intense experimental searches looking for a better fulfilment of the Resonance Condition.
- Precise measurement of atomic masses achievable due to the development of atomic traps.

# Time History

$$\left|\langle {}^A(Z-2)^*|{}^A Z(t)\rangle\right|^2 = |\alpha|^2 \left\{1 + e^{-\Gamma t} - 2e^{-\frac{1}{2}\Gamma t}\cos(\Delta \cdot t)\right\}$$

- Different time-scales given by $|\Delta|$, $\Gamma$ and $\Gamma_L$
- For observable times, the system has evolved to three "stationary" states

$$\tau_S \ll t \ll \tau_L \quad \Longrightarrow \quad \begin{cases} P_L(t) \approx 1 - \Gamma_L\, t \\ P_S(t) \approx 0 \\ P_{\text{g.s.}}(t) \approx |\alpha|^2\, \Gamma\, t \end{cases}$$

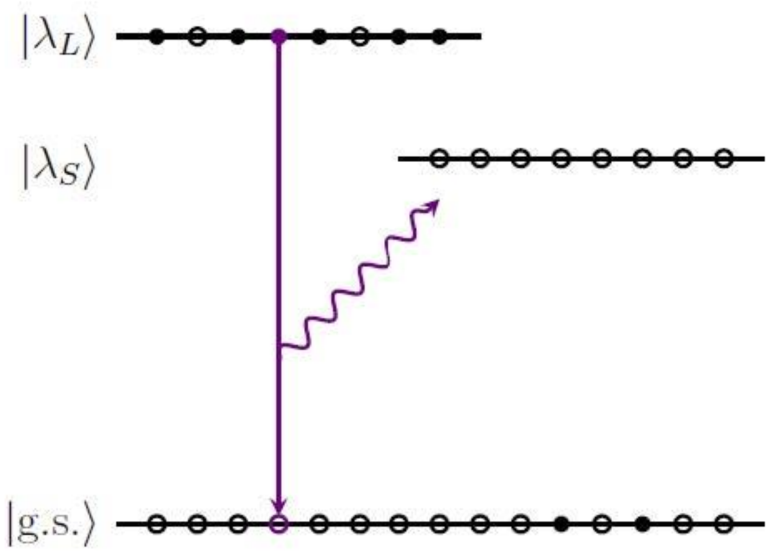


# Spontaneous Observables

- **Spontaneous emission**

$$P_L(\Delta t) \approx 1 - \Gamma_L \, \Delta t$$

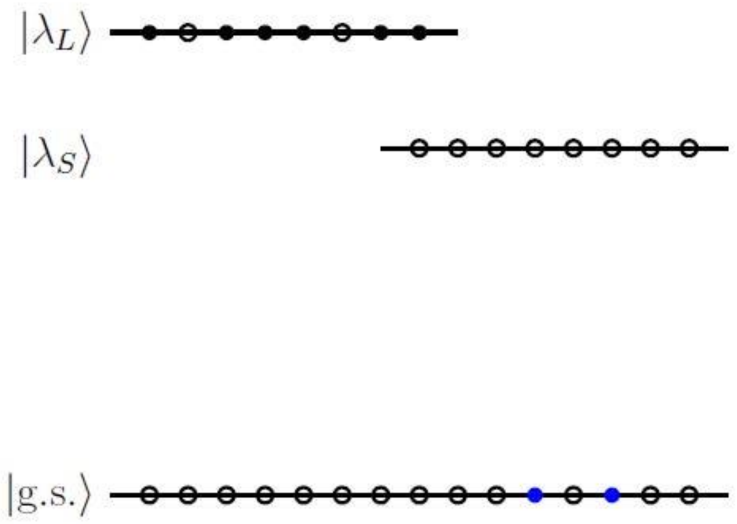
$$\tau_L \sim 10^{29} \text{ yr}$$




- **Daughter atom population**

$$P_{\text{g.s.}}(t) \approx |\alpha|^2 \, \Gamma \, t_0$$

1 mole Gd from $T_{\text{Earth}}$
includes 20 000 Sm atoms



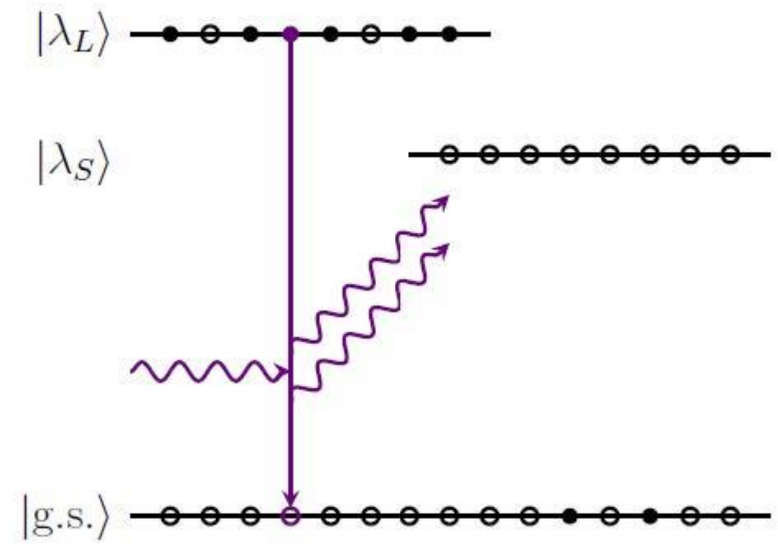
# Stimulated transitions

- **Stimulated emission**

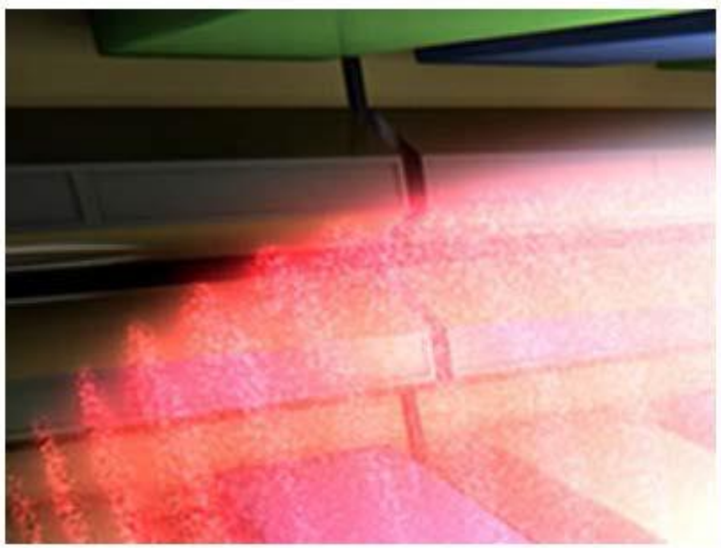
$$\frac{\mathrm{d}N_L^{\mathrm{st}}}{\mathrm{d}t} = G\,\frac{\mathrm{d}N_L^{\mathrm{sp}}}{\mathrm{d}t}$$

$$G = \hbar\,(\hbar c)^2\,\frac{\pi^2}{(\hbar\omega)^3}\,\frac{\mathrm{d}N}{\mathrm{d}t\,\mathrm{d}S}\left[\frac{\mathrm{d}\omega}{\omega}\right]^{-1}$$

**Natural population inversion!**




$$\hbar\omega \sim \text{tens of keV}$$



**Generation of X-ray flashes**

To generate the extremely short and intense X-ray laser flashes bunches of high-energy electrons are directed through special arrangements of magnets (the green-blue structure).

European XFEL / Marc Hermann, tricklabor

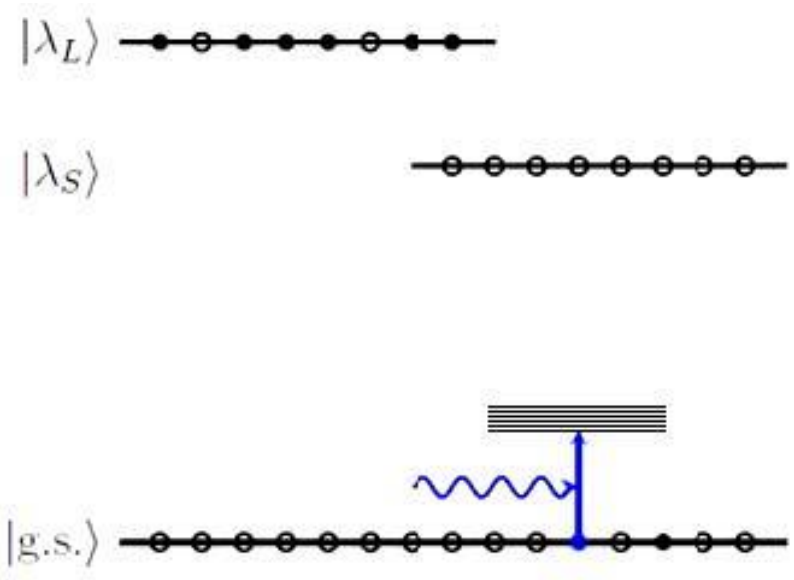
Click on the image to see it full size.

- 100 fs pulse
- 100 nm spot size
- 20W mean power

$$G \sim 100$$

# Stimulated transitions II

- **Daughter Atom Absorption Spectrum**




Laser:
- 100 fs pulse
- 40 µm spot size
- 5 W mean power

$$\frac{dN_{g.s.}}{dt}\bigg|_{abs} = -60\%\, N_{g.s.} \left[\frac{100\ \text{ns}}{\tau}\right] \text{fs}^{-1}$$

The daughter atom can be excited to any of its atomic levels!

- Typical atomic lifetimes of $^{152}Sm$ range from 10 to 1000 ns

# Outlook

- Neutrinoless double electron capture is a quantum Majorana Mixing between two atoms, generated by $\Delta L = 2$ Majorana mass neutrino, which provides **enhanced observables under the resonance condition**.
- Intense experimental searches looking for a better candidate. Today's best one, $^{152}Gd$, is still a factor 30 away of the resonance, implying a **1000 factor** loss in any observable.
- Time evolution of these mixed states presents the phenomenon of **Atom Oscillations**. At observable times, the description is the same as any 3-level atomic system with natural **population inversion**.
- Many interesting **observables** besides spontaneous emission: probes of **daughter atom population** (both geochemical and optical) **and XFEL-stimulated X-ray emission**.

**Thank you very much for your attention**

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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