Why the GSI anomaly cannot be explained by Quantum Beats

Alexander Merle (Alexander.Merle@mpi-hd.mpg.de)

Max–Planck–Institut für Kernphysik
Heidelberg

- AM: *Why a splitting in the final state cannot explain the GSI-Oscillations*, to appear soon
- H. Kienert, J. Kopp, M. Lindner, AM: *The GSI anomaly*, J. Phys. Conf. Ser. **136**, 022049, 2008, arXiv:0808.2389

SFB Tr 27 Meeting, Project C1, Heidelberg, 2009

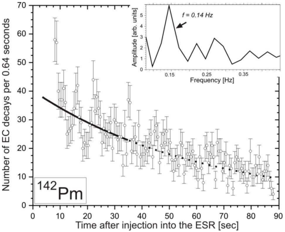
Outline

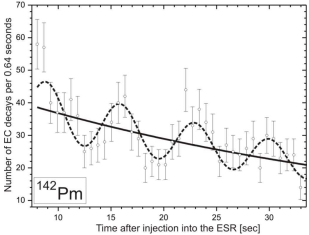
Outline

The measurement at GSI

- measurement: lifetime of several H-like ions with respect to EC (electron capture)
- observation: cos-modulation superimposed on the exponential decay law
- oscillation frequency ~ 7 sec $\Rightarrow \sim 10^{-15}$ eV!!!
- Ivanov, Kienle, Lipkin, et al.: ν-oscillations
- Giunti, we, et al.: reason unknown, but no ordinary ν-oscillations
- often mentioned in that context: *Quantum Beats*

The measurement at GSI

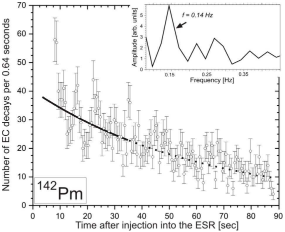


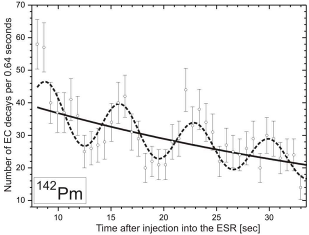


Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079

- measurement: lifetime of several H-like ions with respect to EC (electron capture)
- observation: cos-modulation superimposed on the exponential decay law
- oscillation frequency $\sim$ 7 sec $\Rightarrow \sim 10^{-15}$ eV!!!
- Ivanov, Kienle, Lipkin, et al.: ν-oscillations
- Giunti, we, et al.: reason unknown, but no ordinary ν-oscillations
- often mentioned in that context: *Quantum Beats*

The measurement at GSI

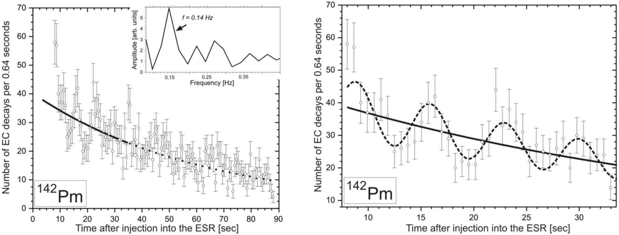




Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079

- measurement: lifetime of several H-like ions with respect to EC (electron capture)
- observation: cos-modulation superimposed on the exponential decay law
- oscillation frequency ~ 7 sec $\Rightarrow \sim 10^{-15}$ eV!!!
- Ivanov, Kienle, Lipkin, et al.: ν-oscillations
- Giunti, we, et al.: reason unknown, but no ordinary ν-oscillations
- often mentioned in that context: *Quantum Beats*

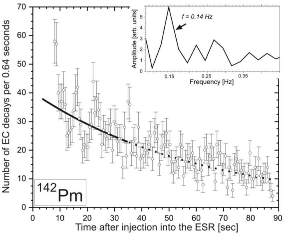
The measurement at GSI

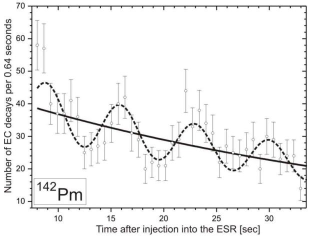


Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079

- measurement: lifetime of several H-like ions with respect to EC (electron capture)
- observation: cos-modulation superimposed on the exponential decay law
- oscillation frequency $\sim$ 7 sec $\Rightarrow \sim 10^{-15}$ eV!!!
- Ivanov, Kienle, Lipkin, et al.: ν-oscillations
- Giunti, we, et al.: reason unknown, but no ordinary ν-oscillations
- often mentioned in that context: *Quantum Beats*

The measurement at GSI

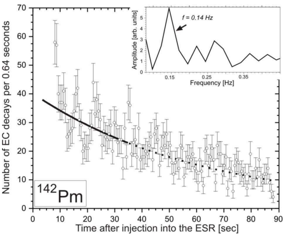


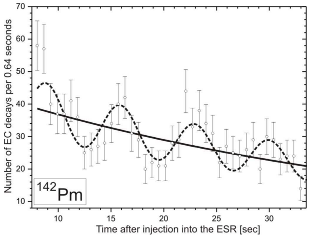


Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079

- measurement: lifetime of several H-like ions with respect to EC (electron capture)
- observation: cos-modulation superimposed on the exponential decay law
- oscillation frequency $\sim$ 7 sec $\Rightarrow \sim 10^{-15}$ eV!!!
- Ivanov, Kienle, Lipkin, et al.: ν-oscillations
- Giunti, we, et al.: reason unknown, but no ordinary ν-oscillations
- often mentioned in that context: *Quantum Beats*

The measurement at GSI

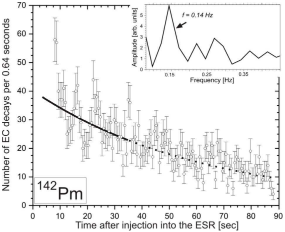


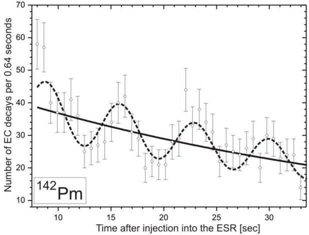


Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079

- measurement: lifetime of several H-like ions with respect to EC (electron capture)
- observation: cos-modulation superimposed on the exponential decay law
- oscillation frequency ~ 7 sec $\Rightarrow \sim 10^{-15}$ eV!!!
- Ivanov, Kienle, Lipkin, et al.: ν-oscillations
- Giunti, we, et al.: reason unknown, but no ordinary ν-oscillations
- often mentioned in that context: *Quantum Beats*

The measurement at GSI

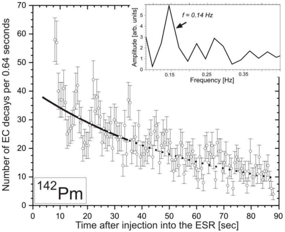


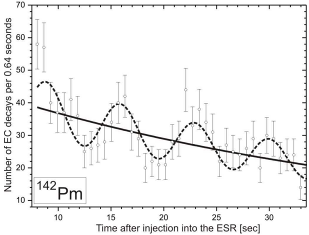


Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079

- measurement: lifetime of several H-like ions with respect to EC (electron capture)
- observation: cos-modulation superimposed on the exponential decay law
- oscillation frequency $\sim$ 7 sec $\Rightarrow \sim 10^{-15}$ eV!!!
- Ivanov, Kienle, Lipkin, et al.: ν-oscillations
- Giunti, we, et al.: reason unknown, but no ordinary ν-oscillations
- often mentioned in that context: *Quantum Beats*

The measurement at GSI





Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079

- measurement: lifetime of several H-like ions with respect to EC (electron capture)
- observation: cos-modulation superimposed on the exponential decay law
- oscillation frequency $\sim$ 7 sec $\Rightarrow \sim 10^{-15}$ eV!!!
- Ivanov, Kienle, Lipkin, et al.: ν-oscillations
- Giunti, we, et al.: reason unknown, but no ordinary ν-oscillations
- often mentioned in that context: *Quantum Beats*

Outline

Type in "Quantum Beats" into Google!!

↪ This is what you find... But we're interested in something else!

Type in “Quantum Beats” into Google!!

$\hookrightarrow$ This is what you find... But we’re interested in something else!

Type in “Quantum Beats” into Google!!

Type I

Type II

↪ This is what you find... But we’re interested in something else!

Type in “Quantum Beats” into Google!!

Type I

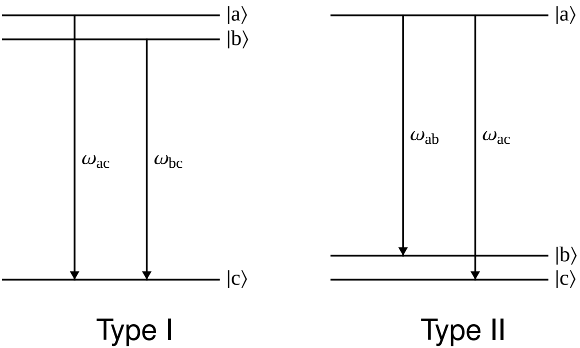
Type II

⟶ This is what you find... But we're interested in something else!

Quantum Beats (Chow et al., Phys. Rev. A, **11**, 1380)

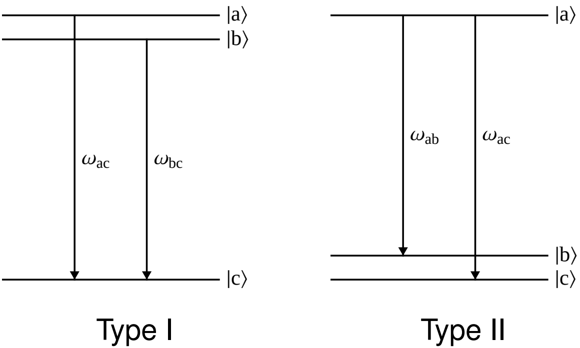
- usual setting: superposition of three atomic states
- important: the states $|a\rangle$, $|b\rangle$, and $|c\rangle$ correspond to different energy eigenvalues
  $\Rightarrow$ They are orthogonal!
- this orthogonality is not touched by the uncertainty relation
- BUT: an uncertainty allows for a coherent superposition

Quantum Beats (Chow et al., Phys. Rev. A, **11**, 1380)



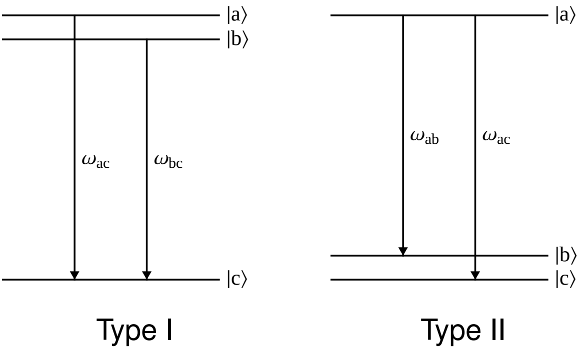
- usual setting: superposition of three atomic states
- important: the states $|a\rangle$, $|b\rangle$, and $|c\rangle$ correspond to different energy eigenvalues
  $\Rightarrow$ They are orthogonal!
- this orthogonality is not touched by the uncertainty relation
- BUT: an uncertainty allows for a coherent superposition

Quantum Beats (Chow et al., Phys. Rev. A, **11**, 1380)



- usual setting: superposition of three atomic states
- important: the states $|a\rangle$, $|b\rangle$, and $|c\rangle$ correspond to different energy eigenvalues
  $\Rightarrow$ They are orthogonal!
- this orthogonality is not touched by the uncertainty relation
- BUT: an uncertainty allows for a coherent superposition

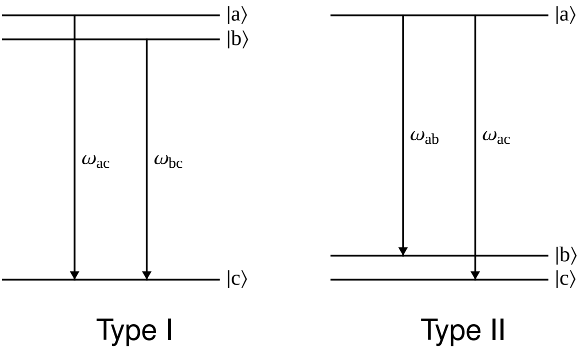
Quantum Beats (Chow et al., Phys. Rev. A, **11**, 1380)



- usual setting: superposition of three atomic states
- important: the states $|a\rangle$, $|b\rangle$, and $|c\rangle$ correspond to different energy eigenvalues

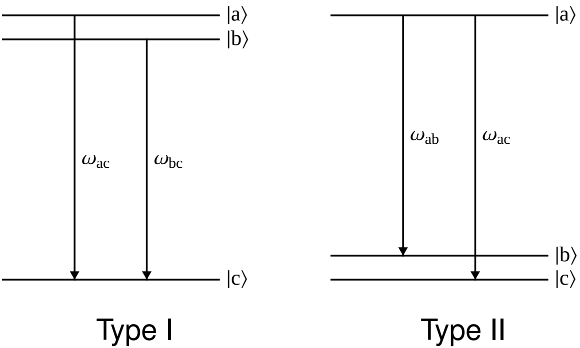
  ⇒ They are orthogonal!
- this orthogonality is not touched by the uncertainty relation
- BUT: an uncertainty allows for a coherent superposition

Quantum Beats (Chow et al., Phys. Rev. A, **11**, 1380)



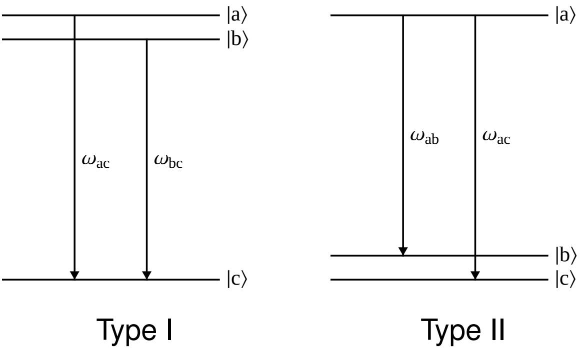
- usual setting: superposition of three atomic states
- important: the states $|a\rangle$, $|b\rangle$, and $|c\rangle$ correspond to different energy eigenvalues
  $\Rightarrow$ They are orthogonal!
- this orthogonality is not touched by the uncertainty relation
- BUT: an uncertainty allows for a coherent superposition

Quantum Beats (Chow et al., Phys. Rev. A, **11**, 1380)



- usual setting: superposition of three atomic states
- important: the states $|a\rangle$, $|b\rangle$, and $|c\rangle$ correspond to different energy eigenvalues
  $\Rightarrow$ They are orthogonal!
- this orthogonality is not touched by the uncertainty relation
- BUT: an uncertainty allows for a coherent superposition

Quantum Beats (Chow et al., Phys. Rev. A, **11**, 1380)



- usual setting: superposition of three atomic states
- important: the states $|a\rangle$, $|b\rangle$, and $|c\rangle$ correspond to different energy eigenvalues
  $\Rightarrow$ They are orthogonal!
- this orthogonality is not touched by the uncertainty relation
- BUT: an uncertainty allows for a coherent superposition

Outline

Single atom of type I

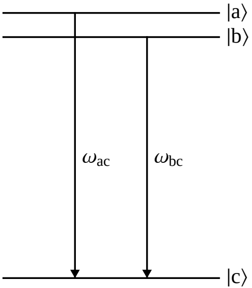
- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower state gets populated by photon emission

- corresponding state $|\Psi(t)\rangle$:

$$\mathcal{A}(t)|a\rangle|0\rangle_\gamma + \mathcal{B}(t)|b\rangle|0\rangle_\gamma + \mathcal{C}(t)|c\rangle|0\rangle_\gamma + \mathcal{C}_1(t)|c\rangle|1_{ac}\rangle_\gamma + \mathcal{C}_2(t)|c\rangle|1_{bc}\rangle_\gamma$$

- 1-photon state: $|1_x\rangle_\gamma = a_x^\dagger|0\rangle_\gamma$, with $[a_{\vec{k},\lambda}, a^\dagger_{\vec{k}',\lambda'}] = \delta_{\vec{k},\vec{k}'}\delta_{\lambda,\lambda'}$
  $\hookrightarrow$ $\vec{k}$: momentum, λ: polarization

Single atom of type I



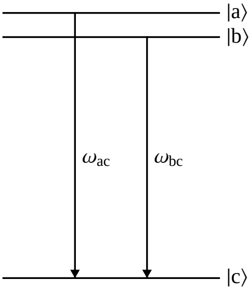
- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower state gets populated by photon emission

- corresponding state $|\Psi(t)\rangle$:

  $$\mathcal{A}(t)|a\rangle|0\rangle_\gamma + \mathcal{B}(t)|b\rangle|0\rangle_\gamma + \mathcal{C}(t)|c\rangle|0\rangle_\gamma + \mathcal{C}_1(t)|c\rangle|1_{ac}\rangle_\gamma + \mathcal{C}_2(t)|c\rangle|1_{bc}\rangle_\gamma$$

- 1-photon state: $|1_x\rangle_\gamma = a_x^\dagger|0\rangle_\gamma$, with $[a_{\vec{k},\lambda}, a^\dagger_{\vec{k}',\lambda'}] = \delta_{\vec{k},\vec{k}'}\delta_{\lambda,\lambda'}$
  $\hookrightarrow \vec{k}$: momentum, λ: polarization

Single atom of type I



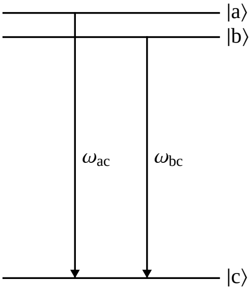
- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower state gets populated by photon emission

- corresponding state $|\Psi(t)\rangle$:

  $$\mathcal{A}(t)|a\rangle|0\rangle_\gamma + \mathcal{B}(t)|b\rangle|0\rangle_\gamma + \mathcal{C}(t)|c\rangle|0\rangle_\gamma + \mathcal{C}_1(t)|c\rangle|1_{ac}\rangle_\gamma + \mathcal{C}_2(t)|c\rangle|1_{bc}\rangle_\gamma$$

- 1-photon state: $|1_x\rangle_\gamma = a_x^\dagger|0\rangle_\gamma$, with $[a_{\vec{k},\lambda}, a^\dagger_{\vec{k}',\lambda'}] = \delta_{\vec{k},\vec{k}'}\delta_{\lambda,\lambda'}$
  $\hookrightarrow$ $\vec{k}$: momentum, λ: polarization

Single atom of type I



- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower state gets populated by photon emission

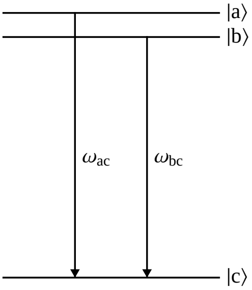
- corresponding state $|\Psi(t)\rangle$:

  $\mathcal{A}(t)|a\rangle|0\rangle_\gamma + \mathcal{B}(t)|b\rangle|0\rangle_\gamma + \mathcal{C}(t)|c\rangle|0\rangle_\gamma + \mathcal{C}_1(t)|c\rangle|1_{ac}\rangle_\gamma + \mathcal{C}_2(t)|c\rangle|1_{bc}\rangle_\gamma$

- 1-photon state: $|1_x\rangle_\gamma = a_x^\dagger|0\rangle_\gamma$, with $[a_{\vec{k},\lambda}, a^\dagger_{\vec{k}',\lambda'}] = \delta_{\vec{k},\vec{k}'}\delta_{\lambda,\lambda'}$

  $\hookrightarrow$ $\vec{k}$: momentum, λ: polarization

Single atom of type I



- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower state gets populated by photon emission

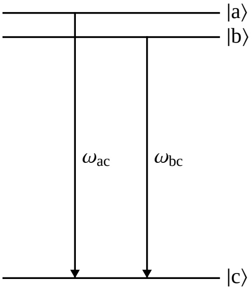
- corresponding state $|\Psi(t)\rangle$:

  $\mathcal{A}(t)|a\rangle|0\rangle_\gamma + \mathcal{B}(t)|b\rangle|0\rangle_\gamma + \mathcal{C}(t)|c\rangle|0\rangle_\gamma + \mathcal{C}_1(t)|c\rangle|1_{ac}\rangle_\gamma + \mathcal{C}_2(t)|c\rangle|1_{bc}\rangle_\gamma$

- 1-photon state: $|1_x\rangle_\gamma = a_x^\dagger|0\rangle_\gamma$, with $[a_{\vec{k},\lambda}, a^\dagger_{\vec{k}',\lambda'}] = \delta_{\vec{k},\vec{k}'}\delta_{\lambda,\lambda'}$

  $\hookrightarrow$ $\vec{k}$: momentum, λ: polarization

Single atom of type I



- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower state gets populated by photon emission

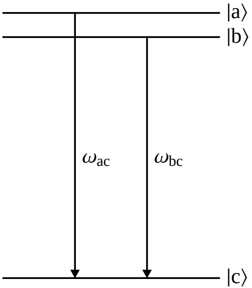
- corresponding state $|\Psi(t)\rangle$:

  $\mathcal{A}(t)|a\rangle|0\rangle_\gamma + \mathcal{B}(t)|b\rangle|0\rangle_\gamma + \mathcal{C}(t)|c\rangle|0\rangle_\gamma + \mathcal{C}_1(t)|c\rangle|1_{ac}\rangle_\gamma + \mathcal{C}_2(t)|c\rangle|1_{bc}\rangle_\gamma$

- 1-photon state: $|1_x\rangle_\gamma = a_x^\dagger|0\rangle_\gamma$, with $[a_{\vec{k},\lambda}, a^\dagger_{\vec{k}',\lambda'}] = \delta_{\vec{k},\vec{k}'}\delta_{\lambda,\lambda'}$

  $\hookrightarrow \vec{k}$: momentum, λ: polarization

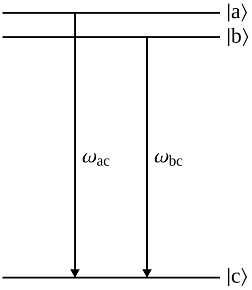
Single atom of type I



- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower state gets populated by photon emission

- corresponding state $|\Psi(t)\rangle$:
  $\mathcal{A}(t)|a\rangle|0\rangle_\gamma + \mathcal{B}(t)|b\rangle|0\rangle_\gamma + \mathcal{C}(t)|c\rangle|0\rangle_\gamma + \mathcal{C}_1(t)|c\rangle|1_{ac}\rangle_\gamma + \mathcal{C}_2(t)|c\rangle|1_{bc}\rangle_\gamma$
- 1-photon state: $|1_x\rangle_\gamma = a_x^\dagger|0\rangle_\gamma$, with $[a_{\vec{k},\lambda}, a^\dagger_{\vec{k}',\lambda'}] = \delta_{\vec{k},\vec{k}'}\delta_{\lambda,\lambda'}$
  $\hookrightarrow$ $\vec{k}$: momentum, λ: polarization

Single atom of type I



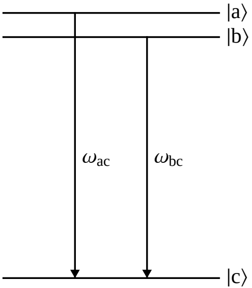
- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower state gets populated by photon emission

- corresponding state $|\Psi(t)\rangle$:

$$\mathcal{A}(t)|a\rangle|0\rangle_\gamma+\mathcal{B}(t)|b\rangle|0\rangle_\gamma+\mathcal{C}(t)|c\rangle|0\rangle_\gamma+\mathcal{C}_1(t)|c\rangle|1_{ac}\rangle_\gamma+\mathcal{C}_2(t)|c\rangle|1_{bc}\rangle_\gamma$$

- 1-photon state: $|1_x\rangle_\gamma = a_x^\dagger|0\rangle_\gamma$, with $[a_{\vec{k},\lambda}, a^\dagger_{\vec{k}',\lambda'}] = \delta_{\vec{k},\vec{k}'}\delta_{\lambda,\lambda'}$
  $\hookrightarrow$ $\vec{k}$: momentum, λ: polarization

Single atom of type I



- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower state gets populated by photon emission

- corresponding state $|\Psi(t)\rangle$:

  $$\mathcal{A}(t)|a\rangle|0\rangle_\gamma + \mathcal{B}(t)|b\rangle|0\rangle_\gamma + \mathcal{C}(t)|c\rangle|0\rangle_\gamma + \mathcal{C}_1(t)|c\rangle|1_{ac}\rangle_\gamma + \mathcal{C}_2(t)|c\rangle|1_{bc}\rangle_\gamma$$

- 1-photon state: $|1_x\rangle_\gamma = a_x^\dagger|0\rangle_\gamma$, with $[a_{\vec{k},\lambda}, a^\dagger_{\vec{k}',\lambda'}] = \delta_{\vec{k},\vec{k}'}\delta_{\lambda,\lambda'}$
  $\hookrightarrow$ $\vec{k}$: momentum, λ: polarization

Single atom of type I

- electric field operator: $\vec{E}(\vec{x},t) = \sum_{\vec{k},\lambda} \epsilon_{\vec{k},\lambda} \left(a_{\vec{k},\lambda} e^{-ikx} + a^\dagger_{\vec{k},\lambda} e^{+ikx} \right)$
- radiated photon intensity:

$$I \propto \langle \Psi(t) | \vec{E}^2(\vec{0},t) | \Psi(t) \rangle$$

- effectively:

$$\vec{E}^2(\vec{0},t) = \epsilon_{ac}^2 (1 + 2 a^\dagger_{ac} a_{ac}) + \epsilon_{bc}^2 (1 + 2 a^\dagger_{bc} a_{bc}) + \\ + 2 \epsilon_{ac} \epsilon_{bc} (a^\dagger_{ac} a_{bc} e^{i\Delta t} + a^\dagger_{bc} a_{ac} e^{-i\Delta t})$$

- already used: e.g. ${}_\gamma\langle 0| \underbrace{a^\dagger_{ac}}_{0\leftarrow} a^\dagger_{ac} |...\rangle_\gamma = 0$
- photon energy difference: $\Delta = \omega_{ac} - \omega_{bc}$

Single atom of type I

- electric field operator: $\vec{E}(\vec{x},t) = \sum_{\vec{k},\lambda} \epsilon_{\vec{k},\lambda} \left(a_{\vec{k},\lambda} e^{-ikx} + a^\dagger_{\vec{k},\lambda} e^{+ikx} \right)$
- radiated photon intensity:

$$I \propto \langle \Psi(t) | \vec{E}^2(\vec{0},t) | \Psi(t) \rangle$$

- effectively:

$$\vec{E}^2(\vec{0},t) = \epsilon_{ac}^2 (1 + 2a^\dagger_{ac} a_{ac}) + \epsilon_{bc}^2 (1 + 2a^\dagger_{bc} a_{bc}) +$$
$$+ 2\epsilon_{ac}\epsilon_{bc} (a^\dagger_{ac} a_{bc} e^{i\Delta t} + a^\dagger_{bc} a_{ac} e^{-i\Delta t})$$

- already used: e.g. ${}_\gamma\langle 0 | \underbrace{a^\dagger_{ac}}_{0 \leftarrow} a^\dagger_{ac} | ... \rangle_\gamma = 0$
- photon energy difference: $\Delta = \omega_{ac} - \omega_{bc}$

Single atom of type I

- electric field operator: $\vec{E}(\vec{x},t) = \sum_{\vec{k},\lambda} \epsilon_{\vec{k},\lambda} \left(a_{\vec{k},\lambda} e^{-ikx} + a^{\dagger}_{\vec{k},\lambda} e^{+ikx} \right)$
- radiated photon intensity:

$$I \propto \langle \Psi(t) | \vec{E}^2(\vec{0},t) | \Psi(t) \rangle$$

- effectively:

$$\vec{E}^2(\vec{0},t) = \epsilon_{ac}^2 (1 + 2a^{\dagger}_{ac} a_{ac}) + \epsilon_{bc}^2 (1 + 2a^{\dagger}_{bc} a_{bc}) + \\ +2\epsilon_{ac}\epsilon_{bc} (a^{\dagger}_{ac} a_{bc} e^{i\Delta t} + a^{\dagger}_{bc} a_{ac} e^{-i\Delta t})$$

- already used: e.g. ${}_{\gamma}\langle 0 | \underbrace{a^{\dagger}_{ac}}_{0 \leftarrow} a^{\dagger}_{ac} | ... \rangle_{\gamma} = 0$
- photon energy difference: $\Delta = \omega_{ac} - \omega_{bc}$

Single atom of type I

- electric field operator: $\vec{E}(\vec{x},t) = \sum_{\vec{k},\lambda} \epsilon_{\vec{k},\lambda} \left(a_{\vec{k},\lambda} e^{-ikx} + a^\dagger_{\vec{k},\lambda} e^{+ikx} \right)$
- radiated photon intensity:

$$I \propto \langle \Psi(t) | \vec{E}^2(\vec{0},t) | \Psi(t) \rangle$$

- effectively:

$$\vec{E}^2(\vec{0},t) = \epsilon_{ac}^2 (1 + 2 a^\dagger_{ac} a_{ac}) + \epsilon_{bc}^2 (1 + 2 a^\dagger_{bc} a_{bc}) + \\ + 2 \epsilon_{ac} \epsilon_{bc} (a^\dagger_{ac} a_{bc} e^{i\Delta t} + a^\dagger_{bc} a_{ac} e^{-i\Delta t})$$

- already used: e.g. ${}_\gamma\langle 0 | \underbrace{a^\dagger_{ac}}_{0 \leftarrow} a^\dagger_{ac} | \ldots \rangle_\gamma = 0$
- photon energy difference: $\Delta = \omega_{ac} - \omega_{bc}$

Single atom of type I

- electric field operator: $\vec{E}(\vec{x},t) = \sum_{\vec{k},\lambda} \epsilon_{\vec{k},\lambda} \left(a_{\vec{k},\lambda} e^{-ikx} + a^\dagger_{\vec{k},\lambda} e^{+ikx} \right)$
- radiated photon intensity:

$$I \propto \langle \Psi(t) | \vec{E}^2(\vec{0},t) | \Psi(t) \rangle$$

- effectively:

$$\vec{E}^2(\vec{0},t) = \epsilon_{ac}^2 (1 + 2a^\dagger_{ac} a_{ac}) + \epsilon_{bc}^2 (1 + 2a^\dagger_{bc} a_{bc}) + \\ +2\epsilon_{ac}\epsilon_{bc} (a^\dagger_{ac} a_{bc} e^{i\Delta t} + a^\dagger_{bc} a_{ac} e^{-i\Delta t})$$

- already used: e.g. ${}_\gamma\langle 0 | \underbrace{a^\dagger_{ac}}_{0\leftarrow} a^\dagger_{ac} | ... \rangle_\gamma = 0$
- photon energy difference: $\Delta = \omega_{ac} - \omega_{bc}$

Single atom of type I

- electric field operator: $\vec{E}(\vec{x},t) = \sum_{\vec{k},\lambda} \epsilon_{\vec{k},\lambda} \left(a_{\vec{k},\lambda} e^{-ikx} + a^\dagger_{\vec{k},\lambda} e^{+ikx} \right)$
- radiated photon intensity:

$$I \propto \langle \Psi(t) | \vec{E}^2(\vec{0},t) | \Psi(t) \rangle$$

- effectively:

$$\vec{E}^2(\vec{0},t) = \epsilon^2_{ac}(1 + 2a^\dagger_{ac} a_{ac}) + \epsilon^2_{bc}(1 + 2a^\dagger_{bc} a_{bc}) + \\ +2\epsilon_{ac}\epsilon_{bc}(a^\dagger_{ac} a_{bc} e^{i\Delta t} + a^\dagger_{bc} a_{ac} e^{-i\Delta t})$$

- already used: e.g. ${}_\gamma\langle 0| \underbrace{a^\dagger_{ac}}_{0\leftarrow} a^\dagger_{ac} |...\rangle_\gamma = 0$
- photon energy difference: $\Delta = \omega_{ac} - \omega_{bc}$

Single atom of type I

- there are oscillating terms in the intensity I, e.g. $\mathcal{C}_1^*(t)\mathcal{C}_2(t)e^{i\Delta t}$ oscillates and is proportional to:

$$_\gamma\langle 0|a_{ac}a_{ac}^\dagger a_{bc}a_{bc}^\dagger|0\rangle_\gamma = {}_\gamma\langle 0|(1+\underbrace{a_{ac}^\dagger}_{0\leftarrow} a_{ac})(1+a_{bc}^\dagger \underbrace{a_{bc}}_{\rightarrow 0})|0\rangle_\gamma = 1$$

$\Rightarrow$ Quantum Beats!

- intuitively:
both upper level decay into *the same* final state via photon emission, but the energy of the photon cannot be determined by measuring it directly $\rightarrow$ interference terms

Single atom of type I

- there are oscillating terms in the intensity I, e.g. $\mathcal{C}_1^*(t)\mathcal{C}_2(t)e^{i\Delta t}$ oscillates and is proportional to:

$$_\gamma\langle 0|a_{ac}a_{ac}^\dagger a_{bc}a_{bc}^\dagger|0\rangle_\gamma = {}_\gamma\langle 0|(1+\underbrace{a_{ac}^\dagger}_{0\leftarrow} a_{ac})(1+a_{bc}^\dagger \underbrace{a_{bc}}_{\rightarrow 0})|0\rangle_\gamma = 1$$

$\Rightarrow$ Quantum Beats!

- intuitively:
  both upper level decay into *the same* final state via photon emission, but the energy of the photon cannot be determined by measuring it directly $\rightarrow$ interference terms

Single atom of type I

- there are oscillating terms in the intensity I, e.g. $\mathcal{C}_1^*(t)\mathcal{C}_2(t)e^{i\Delta t}$ oscillates and is proportional to:

$$_\gamma\langle 0|a_{ac}a_{ac}^\dagger a_{bc}a_{bc}^\dagger|0\rangle_\gamma = {}_\gamma\langle 0|(1+\underbrace{a_{ac}^\dagger}_{0\leftarrow} a_{ac})(1+a_{bc}^\dagger \underbrace{a_{bc}}_{\rightarrow 0})|0\rangle_\gamma = 1$$

$\Rightarrow$ Quantum Beats!

- intuitively:
  both upper level decay into *the same* final state via photon emission, but the energy of the photon cannot be determined by measuring it directly $\rightarrow$ interference terms

Single atom of type I

- there are oscillating terms in the intensity I, e.g. $\mathcal{C}_1^*(t)\mathcal{C}_2(t)e^{i\Delta t}$ oscillates and is proportional to:

$$_\gamma\langle 0|a_{ac}a_{ac}^\dagger a_{bc}a_{bc}^\dagger|0\rangle_\gamma = {}_\gamma\langle 0|(1+\underbrace{a_{ac}^\dagger}_{0\leftarrow} a_{ac})(1+a_{bc}^\dagger \underbrace{a_{bc}}_{\rightarrow 0})|0\rangle_\gamma = 1$$

$\Rightarrow$ Quantum Beats!

- intuitively:
both upper level decay into *the same* final state via photon emission, but the energy of the photon cannot be determined by measuring it directly $\rightarrow$ interference terms

Single atom of type I $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ ion, photon $\rightarrow$ neutrino

- if there is a splitting in the initial state, this can cause oscillations in the decay rate
- HOWEVER: splitting $\sim 10^{-15}$ eV $\Rightarrow$ tiny, not at all explained...
- furthermore: preliminary data on β^+-decays show no oscillatory behavior (Ivanov et a., 0905.1904)
  $\Rightarrow$ if such a splitting were present, it could only be there in the electron energy level, but not in the nucleus

Single atom of type I $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ ion, photon $\rightarrow$ neutrino

- if there is a splitting in the initial state, this can cause oscillations in the decay rate
- HOWEVER: splitting $\sim 10^{-15}$ eV $\Rightarrow$ tiny, not at all explained...
- furthermore: preliminary data on β^+-decays show no oscillatory behavior (Ivanov et a., 0905.1904)
  $\Rightarrow$ if such a splitting were present, it could only be there in the electron energy level, but not in the nucleus

Single atom of type I $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ ion, photon $\rightarrow$ neutrino

- if there is a splitting in the initial state, this can cause oscillations in the decay rate
- HOWEVER: splitting $\sim 10^{-15}$ eV $\Rightarrow$ tiny, not at all explained...
- furthermore: preliminary data on β^+-decays show no oscillatory behavior (Ivanov et a., 0905.1904)
  $\Rightarrow$ if such a splitting were present, it could only be there in the electron energy level, but not in the nucleus

Single atom of type I $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ ion, photon $\rightarrow$ neutrino

- if there is a splitting in the initial state, this can cause oscillations in the decay rate
- HOWEVER: splitting $\sim 10^{-15}$ eV $\Rightarrow$ tiny, not at all explained...
- furthermore: preliminary data on β^+-decays show no oscillatory behavior (Ivanov et a., 0905.1904)
  $\Rightarrow$ if such a splitting were present, it could only be there in the electron energy level, but not in the nucleus

Single atom of type I $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ ion, photon $\rightarrow$ neutrino

- if there is a splitting in the initial state, this can cause oscillations in the decay rate
- HOWEVER: splitting $\sim 10^{-15}$ eV $\Rightarrow$ tiny, not at all explained...
- furthermore: preliminary data on β^+-decays show no oscillatory behavior (Ivanov et a., 0905.1904)

  $\Rightarrow$ if such a splitting were present, it could only be there in the electron energy level, but not in the nucleus

Single atom of type I $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ ion, photon $\rightarrow$ neutrino

- if there is a splitting in the initial state, this can cause oscillations in the decay rate
- HOWEVER: splitting $\sim 10^{-15}$ eV $\Rightarrow$ tiny, not at all explained...
- furthermore: preliminary data on β^+-decays show no oscillatory behavior (Ivanov et a., 0905.1904)
  $\Rightarrow$ if such a splitting were present, it could only be there in the electron energy level, but not in the nucleus

Outline

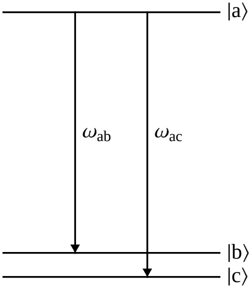
Single atom of type II

- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower states get populated by photon emission

- corresponding state $|\Psi(t)\rangle$:

$$\mathcal{A}(t)|a\rangle|0\rangle_\gamma + \mathcal{B}(t)|b\rangle|0\rangle_\gamma + \mathcal{C}(t)|c\rangle|0\rangle_\gamma + \mathcal{B}'(t)|b\rangle|1_{ab}\rangle_\gamma + \mathcal{C}'(t)|c\rangle|1_{ac}\rangle_\gamma$$

Single atom of type II

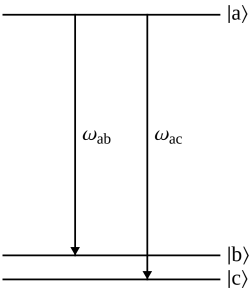


- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower states get populated by photon emission

- corresponding state $|\Psi(t)\rangle$:

$$\mathcal{A}(t)|a\rangle|0\rangle_\gamma+\mathcal{B}(t)|b\rangle|0\rangle_\gamma+\mathcal{C}(t)|c\rangle|0\rangle_\gamma+\mathcal{B}'(t)|b\rangle|1_{ab}\rangle_\gamma+\mathcal{C}'(t)|c\rangle|1_{ac}\rangle_\gamma$$

Single atom of type II

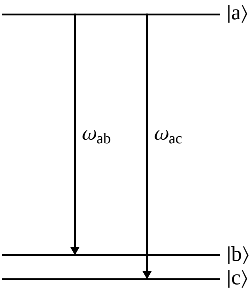


- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower states get populated by photon emission

- corresponding state $|\Psi(t)\rangle$:

$$\mathcal{A}(t)|a\rangle|0\rangle_\gamma + \mathcal{B}(t)|b\rangle|0\rangle_\gamma + \mathcal{C}(t)|c\rangle|0\rangle_\gamma + \mathcal{B}'(t)|b\rangle|1_{ab}\rangle_\gamma + \mathcal{C}'(t)|c\rangle|1_{ac}\rangle_\gamma$$

Single atom of type II

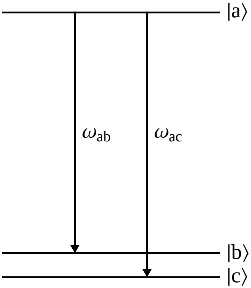


- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower states get populated by photon emission

- corresponding state $|\Psi(t)\rangle$:

$$\mathcal{A}(t)|a\rangle|0\rangle_\gamma + \mathcal{B}(t)|b\rangle|0\rangle_\gamma + \mathcal{C}(t)|c\rangle|0\rangle_\gamma + \mathcal{B}'(t)|b\rangle|1_{ab}\rangle_\gamma + \mathcal{C}'(t)|c\rangle|1_{ac}\rangle_\gamma$$

Single atom of type II

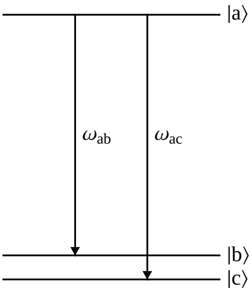


- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower states get populated by photon emission

- corresponding state $|\Psi(t)\rangle$:

$$\mathcal{A}(t)|a\rangle|0\rangle_\gamma + \mathcal{B}(t)|b\rangle|0\rangle_\gamma + \mathcal{C}(t)|c\rangle|0\rangle_\gamma + \mathcal{B}'(t)|b\rangle|1_{ab}\rangle_\gamma + \mathcal{C}'(t)|c\rangle|1_{ac}\rangle_\gamma$$

Single atom of type II

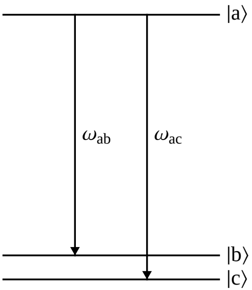


- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower states get populated by photon emission

- corresponding state $|\Psi(t)\rangle$:

$$\mathcal{A}(t)|a\rangle|0\rangle_\gamma + \mathcal{B}(t)|b\rangle|0\rangle_\gamma + \mathcal{C}(t)|c\rangle|0\rangle_\gamma + \mathcal{B}'(t)|b\rangle|1_{ab}\rangle_\gamma + \mathcal{C}'(t)|c\rangle|1_{ac}\rangle_\gamma$$

Single atom of type II



- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted yet $\rightarrow$ vacuum $|0\rangle_\gamma$
- time-evolution $\Rightarrow$ lower states get populated by photon emission

- corresponding state $|\Psi(t)\rangle$:

$$\mathcal{A}(t)|a\rangle|0\rangle_\gamma + \mathcal{B}(t)|b\rangle|0\rangle_\gamma + \mathcal{C}(t)|c\rangle|0\rangle_\gamma + \mathcal{B}'(t)|b\rangle|1_{ab}\rangle_\gamma + \mathcal{C}'(t)|c\rangle|1_{ac}\rangle_\gamma$$

Single atom of type II

now we have:

$$\vec{E}^2(\vec{0},t) = \epsilon_{ac}^2(1+2a_{ac}^\dagger a_{ac}) + \epsilon_{ab}^2(1+2a_{ab}^\dagger a_{ab}) +$$
$$+2\epsilon_{ac}\epsilon_{ab}(a_{ac}^\dagger a_{ab} e^{i\Delta t} + a_{ab}^\dagger a_{ac} e^{-i\Delta t})$$

possibilities:

- 0-photon state with 0-photon state: e.g. $|\mathcal{A}(t)|^2 e^{\pm i\Delta t}$
  $\propto {}_\gamma\langle 0|a_{ac}^\dagger \underbrace{a_{ab}}_{\to 0}|0\rangle_\gamma = 0$ or $\propto {}_\gamma\langle 0|a_{ab}^\dagger \underbrace{a_{ac}}_{\to 0}|0\rangle_\gamma = 0$
- 1-photon state with 1-photon state: e.g. $|\mathcal{B}'(t)|^2 e^{\pm i\Delta t}$
  $\propto {}_\gamma\langle 1_{ab}|a_{ac}^\dagger a_{ab}|1_{ab}\rangle_\gamma = {}_\gamma\langle 0|a_{ab} \underbrace{a_{ac}^\dagger}_{0\leftarrow} a_{ab} a_{ab}^\dagger|0\rangle_\gamma = 0$ or

  $\propto {}_\gamma\langle 1_{ab}|a_{ab}^\dagger a_{ac}|1_{ab}\rangle_\gamma = {}_\gamma\langle 0|a_{ab} a_{ab}^\dagger \underbrace{a_{ac}}_{\to 0} a_{ab}^\dagger|0\rangle_\gamma = 0$

Single atom of type II

now we have:

$$\vec{E}^2(\vec{0},t) = \epsilon_{ac}^2(1+2a_{ac}^\dagger a_{ac}) + \epsilon_{ab}^2(1+2a_{ab}^\dagger a_{ab}) + \\ +2\epsilon_{ac}\epsilon_{ab}(a_{ac}^\dagger a_{ab} e^{i\Delta t} + a_{ab}^\dagger a_{ac} e^{-i\Delta t})$$

possibilities:

- 0-photon state with 0-photon state: e.g. $|\mathcal{A}(t)|^2 e^{\pm i\Delta t}$ $\propto {}_\gamma\langle 0|a_{ac}^\dagger \underbrace{a_{ab}}_{\to 0}|0\rangle_\gamma = 0$ or $\propto {}_\gamma\langle 0|a_{ab}^\dagger \underbrace{a_{ac}}_{\to 0}|0\rangle_\gamma = 0$
- 1-photon state with 1-photon state: e.g. $|\mathcal{B}'(t)|^2 e^{\pm i\Delta t}$ $\propto {}_\gamma\langle 1_{ab}|a_{ac}^\dagger a_{ab}|1_{ab}\rangle_\gamma = {}_\gamma\langle 0|a_{ab} \underbrace{a_{ac}^\dagger}_{0\leftarrow} a_{ab} a_{ab}^\dagger|0\rangle_\gamma = 0$ or

  $\propto {}_\gamma\langle 1_{ab}|a_{ab}^\dagger a_{ac}|1_{ab}\rangle_\gamma = {}_\gamma\langle 0|a_{ab} a_{ab}^\dagger \underbrace{a_{ac}}_{\to 0} a_{ab}^\dagger|0\rangle_\gamma = 0$

Single atom of type II

now we have:

$$\vec{E}^2(\vec{0},t) = \epsilon_{ac}^2(1+2a_{ac}^\dagger a_{ac}) + \epsilon_{ab}^2(1+2a_{ab}^\dagger a_{ab}) +$$
$$+2\epsilon_{ac}\epsilon_{ab}(a_{ac}^\dagger a_{ab} e^{i\Delta t} + a_{ab}^\dagger a_{ac} e^{-i\Delta t})$$

possibilities:

- 0-photon state with 0-photon state: e.g. $|\mathcal{A}(t)|^2 e^{\pm i\Delta t}$ $\propto {}_\gamma\langle 0|a_{ac}^\dagger \underbrace{a_{ab}}_{\to 0}|0\rangle_\gamma = 0$ or $\propto {}_\gamma\langle 0|a_{ab}^\dagger \underbrace{a_{ac}}_{\to 0}|0\rangle_\gamma = 0$
- 1-photon state with 1-photon state: e.g. $|\mathcal{B}'(t)|^2 e^{\pm i\Delta t}$ $\propto {}_\gamma\langle 1_{ab}|a_{ac}^\dagger a_{ab}|1_{ab}\rangle_\gamma = {}_\gamma\langle 0|a_{ab} \underbrace{a_{ac}^\dagger}_{0\leftarrow} a_{ab} a_{ab}^\dagger|0\rangle_\gamma = 0$ or

  $\propto {}_\gamma\langle 1_{ab}|a_{ab}^\dagger a_{ac}|1_{ab}\rangle_\gamma = {}_\gamma\langle 0|a_{ab} a_{ab}^\dagger \underbrace{a_{ac}}_{\to 0} a_{ab}^\dagger|0\rangle_\gamma = 0$

Single atom of type II

now we have:

$$\vec{E}^2(\vec{0},t) = \epsilon_{ac}^2(1+2a_{ac}^\dagger a_{ac}) + \epsilon_{ab}^2(1+2a_{ab}^\dagger a_{ab}) + \\ +2\epsilon_{ac}\epsilon_{ab}(a_{ac}^\dagger a_{ab} e^{i\Delta t} + a_{ab}^\dagger a_{ac} e^{-i\Delta t})$$

possibilities:

- 0-photon state with 0-photon state: e.g. $|\mathcal{A}(t)|^2 e^{\pm i\Delta t}$ $\propto {}_\gamma\langle 0|a_{ac}^\dagger \underbrace{a_{ab}}_{\to 0}|0\rangle_\gamma = 0$ or $\propto {}_\gamma\langle 0|a_{ab}^\dagger \underbrace{a_{ac}}_{\to 0}|0\rangle_\gamma = 0$
- 1-photon state with 1-photon state: e.g. $|\mathcal{B}'(t)|^2 e^{\pm i\Delta t}$ $\propto {}_\gamma\langle 1_{ab}|a_{ac}^\dagger a_{ab}|1_{ab}\rangle_\gamma = {}_\gamma\langle 0|a_{ab} \underbrace{a_{ac}^\dagger}_{0\leftarrow} a_{ab} a_{ab}^\dagger|0\rangle_\gamma = 0$ or

  $\propto {}_\gamma\langle 1_{ab}|a_{ab}^\dagger a_{ac}|1_{ab}\rangle_\gamma = {}_\gamma\langle 0|a_{ab} a_{ab}^\dagger \underbrace{a_{ac}}_{\to 0} a_{ab}^\dagger|0\rangle_\gamma = 0$

Single atom of type II

now we have:

$$\vec{E}^2(\vec{0},t) = \epsilon_{ac}^2(1+2a_{ac}^\dagger a_{ac}) + \epsilon_{ab}^2(1+2a_{ab}^\dagger a_{ab}) +$$
$$+2\epsilon_{ac}\epsilon_{ab}(a_{ac}^\dagger a_{ab} e^{i\Delta t} + a_{ab}^\dagger a_{ac} e^{-i\Delta t})$$

possibilities:

- 0-photon state with 0-photon state: e.g. $|\mathcal{A}(t)|^2 e^{\pm i\Delta t}$ $\propto {}_\gamma\langle 0| a_{ac}^\dagger \underbrace{a_{ab}}_{\to 0} |0\rangle_\gamma = 0$ or $\propto {}_\gamma\langle 0| a_{ab}^\dagger \underbrace{a_{ac}}_{\to 0} |0\rangle_\gamma = 0$
- 1-photon state with 1-photon state: e.g. $|\mathcal{B}'(t)|^2 e^{\pm i\Delta t}$ $\propto {}_\gamma\langle 1_{ab}| a_{ac}^\dagger a_{ab} |1_{ab}\rangle_\gamma = {}_\gamma\langle 0| a_{ab} \underbrace{a_{ac}^\dagger}_{0\leftarrow} a_{ab} a_{ab}^\dagger |0\rangle_\gamma = 0$ or
  $\propto {}_\gamma\langle 1_{ab}| a_{ab}^\dagger a_{ac} |1_{ab}\rangle_\gamma = {}_\gamma\langle 0| a_{ab} a_{ab}^\dagger \underbrace{a_{ac}}_{\to 0} a_{ab}^\dagger |0\rangle_\gamma = 0$

Single atom of type II

- 0-photon state with 1-photon state: e.g. $\mathcal{B}(t)^*\mathcal{B}'(t)$

$$\propto {}_\gamma\langle 0|1_{ab}\rangle_\gamma = {}_\gamma\langle 0|\underbrace{a^\dagger_{ab}}_{0\leftarrow}|0\rangle_\gamma = 0 \text{ or}$$

$$\propto {}_\gamma\langle 0|\underbrace{a^\dagger_{ac}}_{0\leftarrow} a_{ac}|1_{ab}\rangle_\gamma = 0 \text{ or } \propto {}_\gamma\langle 0|\underbrace{a^\dagger_{ab}}_{0\leftarrow} a_{ab}|1_{ab}\rangle_\gamma = 0 \text{ or}$$

$$\propto {}_\gamma\langle 0|\underbrace{a^\dagger_{ac}}_{0\leftarrow} a_{ab}|1_{ab}\rangle_\gamma = 0 \text{ or } \propto {}_\gamma\langle 0|\underbrace{a^\dagger_{ab}}_{0\leftarrow} a_{ac}|1_{ab}\rangle_\gamma = 0.$$

$\Rightarrow$ No oscillatory terms left! $\Rightarrow$ No Quantum Beats!

Intuitively:
By waiting long enough, one could determine the photon's energy by measuring the atomic final state. $\Rightarrow$ No interferences expected!

Single atom of type II

- 0-photon state with 1-photon state: e.g. $\mathcal{B}(t)^* \mathcal{B}'(t)$

$$\propto {}_\gamma\langle 0|1_{ab}\rangle_\gamma = {}_\gamma\langle 0| \underbrace{a_{ab}^\dagger}_{0\leftarrow} |0\rangle_\gamma = 0 \text{ or}$$

$$\propto {}_\gamma\langle 0| \underbrace{a_{ac}^\dagger}_{0\leftarrow} a_{ac}|1_{ab}\rangle_\gamma = 0 \text{ or } \propto {}_\gamma\langle 0| \underbrace{a_{ab}^\dagger}_{0\leftarrow} a_{ab}|1_{ab}\rangle_\gamma = 0 \text{ or}$$

$$\propto {}_\gamma\langle 0| \underbrace{a_{ac}^\dagger}_{0\leftarrow} a_{ab}|1_{ab}\rangle_\gamma = 0 \text{ or } \propto {}_\gamma\langle 0| \underbrace{a_{ab}^\dagger}_{0\leftarrow} a_{ac}|1_{ab}\rangle_\gamma = 0.$$

$\Rightarrow$ No oscillatory terms left! $\Rightarrow$ No Quantum Beats!

Intuitively:
By waiting long enough, one could determine the photon's energy by measuring the atomic final state. $\Rightarrow$ No interferences expected!

Single atom of type II

- 0-photon state with 1-photon state: e.g. $\mathcal{B}(t)^* \mathcal{B}'(t)$

$$\propto {}_\gamma\langle 0|1_{ab}\rangle_\gamma = {}_\gamma\langle 0| \underbrace{a^\dagger_{ab}}_{0\leftarrow} |0\rangle_\gamma = 0 \text{ or}$$

$$\propto {}_\gamma\langle 0| \underbrace{a^\dagger_{ac}}_{0\leftarrow} a_{ac}|1_{ab}\rangle_\gamma = 0 \text{ or } \propto {}_\gamma\langle 0| \underbrace{a^\dagger_{ab}}_{0\leftarrow} a_{ab}|1_{ab}\rangle_\gamma = 0 \text{ or}$$

$$\propto {}_\gamma\langle 0| \underbrace{a^\dagger_{ac}}_{0\leftarrow} a_{ab}|1_{ab}\rangle_\gamma = 0 \text{ or } \propto {}_\gamma\langle 0| \underbrace{a^\dagger_{ab}}_{0\leftarrow} a_{ac}|1_{ab}\rangle_\gamma = 0.$$

$\Rightarrow$ No oscillatory terms left! $\Rightarrow$ No Quantum Beats!

Intuitively:
By waiting long enough, one could determine the photon's energy by measuring the atomic final state. $\Rightarrow$ No interferences expected!

Single atom of type II

- 0-photon state with 1-photon state: e.g. $\mathcal{B}(t)^*\mathcal{B}'(t)$

$$\propto {}_\gamma\langle 0|1_{ab}\rangle_\gamma = {}_\gamma\langle 0|\underbrace{a^\dagger_{ab}}_{0\leftarrow}|0\rangle_\gamma = 0 \text{ or}$$

$$\propto {}_\gamma\langle 0|\underbrace{a^\dagger_{ac}}_{0\leftarrow} a_{ac}|1_{ab}\rangle_\gamma = 0 \text{ or} \propto {}_\gamma\langle 0|\underbrace{a^\dagger_{ab}}_{0\leftarrow} a_{ab}|1_{ab}\rangle_\gamma = 0 \text{ or}$$

$$\propto {}_\gamma\langle 0|\underbrace{a^\dagger_{ac}}_{0\leftarrow} a_{ab}|1_{ab}\rangle_\gamma = 0 \text{ or} \propto {}_\gamma\langle 0|\underbrace{a^\dagger_{ab}}_{0\leftarrow} a_{ac}|1_{ab}\rangle_\gamma = 0.$$

$\Rightarrow$ No oscillatory terms left! $\Rightarrow$ No Quantum Beats!

Intuitively:
By waiting long enough, one could determine the photon's energy by measuring the atomic final state. $\Rightarrow$ No interferences expected!

Single atom of type II $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ neutrino, photon $\rightarrow$ ion (!!!)

- the neutrino is not expected to interact before losing its coherence (estimates: $L_{\rm coh} \lesssim 10^{19}$ m, mean free path $\sim 10^{40}$ m in the Galaxy)
- ones the neutrino interacts, there is no principle problem to determine its mass (e.g., by exploiting the spatial separation of the wave packet components belonging to different mass eigenstates)

$\Rightarrow$ accordingly, no Quantum Beats are expected

Single atom of type II $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ neutrino, photon $\rightarrow$ ion (!!!)

- the neutrino is not expected to interact before losing its coherence (estimates: $L_{\rm coh} \lesssim 10^{19}$ m, mean free path $\sim 10^{40}$ m in the Galaxy)
- ones the neutrino interacts, there is no principle problem to determine its mass (e.g., by exploiting the spatial separation of the wave packet components belonging to different mass eigenstates)

$\Rightarrow$ accordingly, no Quantum Beats are expected

Single atom of type II $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ neutrino, photon $\rightarrow$ ion (!!!)

- the neutrino is not expected to interact before losing its coherence (estimates: $L_{\mathrm{coh}} \lesssim 10^{19}$ m, mean free path $\sim 10^{40}$ m in the Galaxy)
- ones the neutrino interacts, there is no principle problem to determine its mass (e.g., by exploiting the spatial separation of the wave packet components belonging to different mass eigenstates)

$\Rightarrow$ accordingly, no Quantum Beats are expected

Single atom of type II $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ neutrino, photon $\rightarrow$ ion (!!!)

- the neutrino is not expected to interact before losing its coherence (estimates: $L_{\rm coh} \lesssim 10^{19}$ m, mean free path $\sim 10^{40}$ m in the Galaxy)
- ones the neutrino interacts, there is no principle problem to determine its mass (e.g., by exploiting the spatial separation of the wave packet components belonging to different mass eigenstates)

$\Rightarrow$ accordingly, no Quantum Beats are expected

Single atom of type II $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ neutrino, photon $\rightarrow$ ion (!!!)

- the neutrino is not expected to interact before losing its coherence (estimates: $L_{\text{coh}} \lesssim 10^{19}$ m, mean free path $\sim 10^{40}$ m in the Galaxy)
- ones the neutrino interacts, there is no principle problem to determine its mass (e.g., by exploiting the spatial separation of the wave packet components belonging to different mass eigenstates)

$\Rightarrow$ accordingly, no Quantum Beats are expected

Outline

Two atoms of type II

- if the spatial separation of the two atoms is smaller than the wavelength of the photon, one can write down a combined state:

$$|\Psi(0)\rangle = \mathcal{A}_0|a\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{B}_0|b\rangle_1|b\rangle_2|0\rangle_\gamma + \mathcal{C}_0|c\rangle_1|c\rangle_2|0\rangle_\gamma +$$
$$+\mathcal{D}_{1,0}|a\rangle_1|b\rangle_2|0\rangle_\gamma + \mathcal{D}_{2,0}|b\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{E}_{1,0}|a\rangle_1|c\rangle_2|0\rangle_\gamma +$$
$$+\mathcal{E}_{2,0}|c\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{F}_{1,0}|b\rangle_1|c\rangle_2|0\rangle_\gamma + \mathcal{F}_{2,0}|c\rangle_1|b\rangle_2|0\rangle_\gamma$$

- time evolution $|\Psi(t)\rangle$ (trivial, but lengthy):

$$\mathcal{A}(t)|a\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{B}(t)|b\rangle_1|b\rangle_2|0\rangle_\gamma + \mathcal{C}(t)|c\rangle_1|c\rangle_2|0\rangle_\gamma +$$
$$+\mathcal{D}_1(t)|a\rangle_1|b\rangle_2|0\rangle_\gamma + \mathcal{D}_2(t)|b\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{E}_1(t)|a\rangle_1|c\rangle_2|0\rangle_\gamma +$$
$$+\mathcal{E}_2(t)|c\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{F}_1(t)|b\rangle_1|c\rangle_2|0\rangle_\gamma + \mathcal{F}_2(t)|c\rangle_1|b\rangle_2|0\rangle_\gamma +$$
$$+\mathcal{G}_1(t)|b\rangle_1|a\rangle_2|1_{ab}\rangle_\gamma + \mathcal{G}_2(t)|a\rangle_1|b\rangle_2|1_{ab}\rangle_\gamma +$$
$$+\mathcal{H}_1(t)|c\rangle_1|a\rangle_2|1_{ac}\rangle_\gamma + \mathcal{H}_2(t)|a\rangle_1|c\rangle_2|1_{ac}\rangle_\gamma +$$
$$+\mathcal{I}_1(t)|b\rangle_1|b\rangle_2|1_{ab}\rangle_\gamma + \mathcal{I}_2(t)|c\rangle_1|c\rangle_2|1_{ac}\rangle_\gamma +$$
$$+\mathcal{J}_1(t)|b\rangle_1|c\rangle_2|1_{ab}\rangle_\gamma + \mathcal{J}_2(t)|c\rangle_1|b\rangle_2|1_{ab}\rangle_\gamma +$$
$$+\mathcal{K}_1(t)|b\rangle_1|c\rangle_2|1_{ac}\rangle_\gamma + \mathcal{K}_2(t)|c\rangle_1|b\rangle_2|1_{ac}\rangle_\gamma$$

Two atoms of type II

- if the spatial separation of the two atoms is smaller than the wavelength of the photon, one can write down a combined state:

$$|\Psi(0)\rangle = \mathcal{A}_0|a\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{B}_0|b\rangle_1|b\rangle_2|0\rangle_\gamma + \mathcal{C}_0|c\rangle_1|c\rangle_2|0\rangle_\gamma +$$
$$+\mathcal{D}_{1,0}|a\rangle_1|b\rangle_2|0\rangle_\gamma + \mathcal{D}_{2,0}|b\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{E}_{1,0}|a\rangle_1|c\rangle_2|0\rangle_\gamma +$$
$$+\mathcal{E}_{2,0}|c\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{F}_{1,0}|b\rangle_1|c\rangle_2|0\rangle_\gamma + \mathcal{F}_{2,0}|c\rangle_1|b\rangle_2|0\rangle_\gamma$$

- time evolution $|\Psi(t)\rangle$ (trivial, but lengthy):

$$\mathcal{A}(t)|a\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{B}(t)|b\rangle_1|b\rangle_2|0\rangle_\gamma + \mathcal{C}(t)|c\rangle_1|c\rangle_2|0\rangle_\gamma +$$
$$+\mathcal{D}_1(t)|a\rangle_1|b\rangle_2|0\rangle_\gamma + \mathcal{D}_2(t)|b\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{E}_1(t)|a\rangle_1|c\rangle_2|0\rangle_\gamma +$$
$$+\mathcal{E}_2(t)|c\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{F}_1(t)|b\rangle_1|c\rangle_2|0\rangle_\gamma + \mathcal{F}_2(t)|c\rangle_1|b\rangle_2|0\rangle_\gamma +$$
$$+\mathcal{G}_1(t)|b\rangle_1|a\rangle_2|1_{ab}\rangle_\gamma + \mathcal{G}_2(t)|a\rangle_1|b\rangle_2|1_{ab}\rangle_\gamma +$$
$$+\mathcal{H}_1(t)|c\rangle_1|a\rangle_2|1_{ac}\rangle_\gamma + \mathcal{H}_2(t)|a\rangle_1|c\rangle_2|1_{ac}\rangle_\gamma +$$
$$+\mathcal{I}_1(t)|b\rangle_1|b\rangle_2|1_{ab}\rangle_\gamma + \mathcal{I}_2(t)|c\rangle_1|c\rangle_2|1_{ac}\rangle_\gamma +$$
$$+\mathcal{J}_1(t)|b\rangle_1|c\rangle_2|1_{ab}\rangle_\gamma + \mathcal{J}_2(t)|c\rangle_1|b\rangle_2|1_{ab}\rangle_\gamma +$$
$$+\mathcal{K}_1(t)|b\rangle_1|c\rangle_2|1_{ac}\rangle_\gamma + \mathcal{K}_2(t)|c\rangle_1|b\rangle_2|1_{ac}\rangle_\gamma$$

Two atoms of type II

- if the spatial separation of the two atoms is smaller than the wavelength of the photon, one can write down a combined state:

$$|\Psi(0)\rangle = \mathcal{A}_0|a\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{B}_0|b\rangle_1|b\rangle_2|0\rangle_\gamma + \mathcal{C}_0|c\rangle_1|c\rangle_2|0\rangle_\gamma + \\ +\mathcal{D}_{1,0}|a\rangle_1|b\rangle_2|0\rangle_\gamma + \mathcal{D}_{2,0}|b\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{E}_{1,0}|a\rangle_1|c\rangle_2|0\rangle_\gamma + \\ +\mathcal{E}_{2,0}|c\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{F}_{1,0}|b\rangle_1|c\rangle_2|0\rangle_\gamma + \mathcal{F}_{2,0}|c\rangle_1|b\rangle_2|0\rangle_\gamma$$

- time evolution $|\Psi(t)\rangle$ (trivial, but lengthy):

$$\mathcal{A}(t)|a\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{B}(t)|b\rangle_1|b\rangle_2|0\rangle_\gamma + \mathcal{C}(t)|c\rangle_1|c\rangle_2|0\rangle_\gamma + \\ +\mathcal{D}_1(t)|a\rangle_1|b\rangle_2|0\rangle_\gamma + \mathcal{D}_2(t)|b\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{E}_1(t)|a\rangle_1|c\rangle_2|0\rangle_\gamma + \\ +\mathcal{E}_2(t)|c\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{F}_1(t)|b\rangle_1|c\rangle_2|0\rangle_\gamma + \mathcal{F}_2(t)|c\rangle_1|b\rangle_2|0\rangle_\gamma + \\ +\mathcal{G}_1(t)|b\rangle_1|a\rangle_2|1_{ab}\rangle_\gamma + \mathcal{G}_2(t)|a\rangle_1|b\rangle_2|1_{ab}\rangle_\gamma + \\ +\mathcal{H}_1(t)|c\rangle_1|a\rangle_2|1_{ac}\rangle_\gamma + \mathcal{H}_2(t)|a\rangle_1|c\rangle_2|1_{ac}\rangle_\gamma + \\ +\mathcal{I}_1(t)|b\rangle_1|b\rangle_2|1_{ab}\rangle_\gamma + \mathcal{I}_2(t)|c\rangle_1|c\rangle_2|1_{ac}\rangle_\gamma + \\ +\mathcal{J}_1(t)|b\rangle_1|c\rangle_2|1_{ab}\rangle_\gamma + \mathcal{J}_2(t)|c\rangle_1|b\rangle_2|1_{ab}\rangle_\gamma + \\ +\mathcal{K}_1(t)|b\rangle_1|c\rangle_2|1_{ac}\rangle_\gamma + \mathcal{K}_2(t)|c\rangle_1|b\rangle_2|1_{ac}\rangle_\gamma$$

Two atoms of type II

- there can indeed be oscillatory terms, e.g. $\mathcal{J}_1^* \mathcal{K}_1 e^{-i\Delta t}$, which is proportional to:

$$
{}_\gamma\langle 1_{ab} | a^\dagger_{ab} a_{ac} | 1_{ac} \rangle_\gamma = {}_\gamma\langle 0 | a_{ab} a^\dagger_{ab} a_{ac} a^\dagger_{ac} | 0 \rangle_\gamma =
$$
$$
= {}_\gamma\langle 0 | (1 + \underbrace{a^\dagger_{ab}}_{0\leftarrow} a_{ab})(1 + a^\dagger_{ac} \underbrace{a_{ac}}_{\rightarrow 0}) | 0 \rangle_\gamma = {}_\gamma\langle 0 | 0 \rangle_\gamma = 1
$$

- intuitively: If the distance of the atoms is less then the photon's wavelength, one cannot determine, which atom has emitted the radiation.
  $\Rightarrow$ No way to measure the photon's frequency!
  $\Rightarrow$ Quantum Beats!

Two atoms of type II

- there can indeed be oscillatory terms, e.g. $\mathcal{J}_1^* \mathcal{K}_1 e^{-i\Delta t}$, which is proportional to:

$$
{}_\gamma\langle 1_{ab} | a^\dagger_{ab} a_{ac} | 1_{ac} \rangle_\gamma = {}_\gamma\langle 0 | a_{ab} a^\dagger_{ab} a_{ac} a^\dagger_{ac} | 0 \rangle_\gamma =
$$

$$
= {}_\gamma\langle 0 | (1 + \underbrace{a^\dagger_{ab}}_{0\leftarrow} a_{ab})(1 + a^\dagger_{ac} \underbrace{a_{ac}}_{\rightarrow 0}) | 0 \rangle_\gamma = {}_\gamma\langle 0 | 0 \rangle_\gamma = 1
$$

- intuitively: If the distance of the atoms is less then the photon's wavelength, one cannot determine, which atom has emitted the radiation.
  $\Rightarrow$ No way to measure the photon's frequency!
  $\Rightarrow$ Quantum Beats!

Two atoms of type II

- there can indeed be oscillatory terms, e.g. $\mathcal{J}_1^* \mathcal{K}_1 e^{-i\Delta t}$, which is proportional to:

$$
\begin{aligned}
&{}_\gamma\langle 1_{ab} | a_{ab}^\dagger a_{ac} | 1_{ac} \rangle_\gamma = {}_\gamma\langle 0 | a_{ab} a_{ab}^\dagger a_{ac} a_{ac}^\dagger | 0 \rangle_\gamma = \\
&= {}_\gamma\langle 0 | (1 + \underbrace{a_{ab}^\dagger}_{0\leftarrow} a_{ab})(1 + a_{ac}^\dagger \underbrace{a_{ac}}_{\rightarrow 0}) | 0 \rangle_\gamma = {}_\gamma\langle 0 | 0 \rangle_\gamma = 1
\end{aligned}
$$

- intuitively: If the distance of the atoms is less then the photon's wavelength, one cannot determine, which atom has emitted the radiation.

  $\Rightarrow$ No way to measure the photon's frequency!

  $\Rightarrow$ Quantum Beats!

Two atoms of type II

- there can indeed be oscillatory terms, e.g. $\mathcal{J}_1^* \mathcal{K}_1 e^{-i\Delta t}$, which is proportional to:

$$
\begin{aligned}
&{}_\gamma\langle 1_{ab} | a^\dagger_{ab} a_{ac} | 1_{ac} \rangle_\gamma = {}_\gamma\langle 0 | a_{ab} a^\dagger_{ab} a_{ac} a^\dagger_{ac} | 0 \rangle_\gamma = \\
&= {}_\gamma\langle 0 | (1 + \underbrace{a^\dagger_{ab}}_{0\leftarrow} a_{ab})(1 + a^\dagger_{ac} \underbrace{a_{ac}}_{\to 0}) | 0 \rangle_\gamma = {}_\gamma\langle 0 | 0 \rangle_\gamma = 1
\end{aligned}
$$

- intuitively: If the distance of the atoms is less then the photon's wavelength, one cannot determine, which atom has emitted the radiation.
  $\Rightarrow$ No way to measure the photon's frequency!
  $\Rightarrow$ Quantum Beats!

Two atoms of type II

- there can indeed be oscillatory terms, e.g. $\mathcal{J}_1^* \mathcal{K}_1 e^{-i\Delta t}$, which is proportional to:

$$
{}_\gamma\langle 1_{ab}| a_{ab}^\dagger a_{ac} | 1_{ac}\rangle_\gamma = {}_\gamma\langle 0| a_{ab} a_{ab}^\dagger a_{ac} a_{ac}^\dagger |0\rangle_\gamma =
$$
$$
= {}_\gamma\langle 0|(1 + \underbrace{a_{ab}^\dagger}_{0\leftarrow} a_{ab})(1 + a_{ac}^\dagger \underbrace{a_{ac}}_{\rightarrow 0})|0\rangle_\gamma = {}_\gamma\langle 0|0\rangle_\gamma = 1
$$

- intuitively: If the distance of the atoms is less then the photon's wavelength, one cannot determine, which atom has emitted the radiation.
  $\Rightarrow$ No way to measure the photon's frequency!
  $\Rightarrow$ Quantum Beats!

Two atoms of type II ↔ GSI-oscillations

Relation to the GSI-experiment: atom → ion, photon → neutrino

- even in runs where there was only one EC-decay, there might have been more ions in the ring → this possibility has to be considered!
- the wavelength has to be replaced by the de Broglie wavelength of the neutrino
- Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079 $\Rightarrow$ Q-value $\sim$ 1 MeV
- then: $E_\nu \sim 1$ MeV $\Rightarrow \lambda_\nu \approx \frac{2\pi\hbar c}{E_\nu c} \sim 10^{-12}$ m
- M. Steck et al., Phys. Rev. Lett., **77**, 3803 $\Rightarrow$ typical separation of the ions in the ring $\sim$ size of the ring $\sim$ 100 m

$\Rightarrow$ This possibility is excluded for the GSI-experiment!

Two atoms of type II $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ ion, photon $\rightarrow$ neutrino

- even in runs where there was only one EC-decay, there might have been more ions in the ring $\rightarrow$ this possibility has to be considered!
- the wavelength has to be replaced by the de Broglie wavelength of the neutrino
- Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079 $\Rightarrow$ Q-value $\sim$ 1 MeV
- then: $E_\nu \sim 1$ MeV $\Rightarrow \lambda_\nu \approx \frac{2\pi\hbar c}{E_\nu c} \sim 10^{-12}$ m
- M. Steck et al., Phys. Rev. Lett., **77**, 3803 $\Rightarrow$ typical separation of the ions in the ring $\sim$ size of the ring $\sim$ 100 m

$\Rightarrow$ This possibility is excluded for the GSI-experiment!

Two atoms of type II $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ ion, photon $\rightarrow$ neutrino

- even in runs where there was only one EC-decay, there might have been more ions in the ring $\rightarrow$ this possibility has to be considered!
- the wavelength has to be replaced by the de Broglie wavelength of the neutrino
- Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079 $\Rightarrow$ Q-value $\sim$ 1 MeV
- then: $E_\nu \sim 1$ MeV $\Rightarrow \lambda_\nu \approx \frac{2\pi\hbar c}{E_\nu c} \sim 10^{-12}$ m
- M. Steck et al., Phys. Rev. Lett., **77**, 3803 $\Rightarrow$ typical separation of the ions in the ring $\sim$ size of the ring $\sim$ 100 m

$\Rightarrow$ This possibility is excluded for the GSI-experiment!

Two atoms of type II $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ ion, photon $\rightarrow$ neutrino

- even in runs where there was only one EC-decay, there might have been more ions in the ring $\rightarrow$ this possibility has to be considered!
- the wavelength has to be replaced by the de Broglie wavelength of the neutrino
- Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079 $\Rightarrow$ Q-value $\sim$ 1 MeV
- then: $E_\nu \sim 1$ MeV $\Rightarrow \lambda_\nu \approx \frac{2\pi\hbar c}{E_\nu c} \sim 10^{-12}$ m
- M. Steck et al., Phys. Rev. Lett., **77**, 3803 $\Rightarrow$ typical separation of the ions in the ring $\sim$ size of the ring $\sim$ 100 m

$\Rightarrow$ This possibility is excluded for the GSI-experiment!

Two atoms of type II $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ ion, photon $\rightarrow$ neutrino

- even in runs where there was only one EC-decay, there might have been more ions in the ring $\rightarrow$ this possibility has to be considered!
- the wavelength has to be replaced by the de Broglie wavelength of the neutrino
- Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079 $\Rightarrow$ Q-value $\sim$ 1 MeV
- then: $E_\nu \sim 1$ MeV $\Rightarrow \lambda_\nu \approx \frac{2\pi\hbar c}{E_\nu c} \sim 10^{-12}$ m
- M. Steck et al., Phys. Rev. Lett., **77**, 3803 $\Rightarrow$ typical separation of the ions in the ring $\sim$ size of the ring $\sim$ 100 m

$\Rightarrow$ This possibility is excluded for the GSI-experiment!

Two atoms of type II $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\to$ ion, photon $\to$ neutrino

- even in runs where there was only one EC-decay, there might have been more ions in the ring $\to$ this possibility has to be considered!
- the wavelength has to be replaced by the de Broglie wavelength of the neutrino
- Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079 $\Rightarrow$ Q-value $\sim$ 1 MeV
- then: $E_\nu \sim 1$ MeV $\Rightarrow \lambda_\nu \approx \frac{2\pi\hbar c}{E_\nu c} \sim 10^{-12}$ m
- M. Steck et al., Phys. Rev. Lett., **77**, 3803 $\Rightarrow$ typical separation of the ions in the ring $\sim$ size of the ring $\sim$ 100 m

$\Rightarrow$ This possibility is excluded for the GSI-experiment!

Two atoms of type II $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ ion, photon $\rightarrow$ neutrino

- even in runs where there was only one EC-decay, there might have been more ions in the ring $\rightarrow$ this possibility has to be considered!
- the wavelength has to be replaced by the de Broglie wavelength of the neutrino
- Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079 $\Rightarrow$ Q-value $\sim$ 1 MeV
- then: $E_\nu \sim 1$ MeV $\Rightarrow \lambda_\nu \approx \frac{2\pi\hbar c}{E_\nu c} \sim 10^{-12}$ m
- M. Steck et al., Phys. Rev. Lett., **77**, 3803 $\Rightarrow$ typical separation of the ions in the ring $\sim$ size of the ring $\sim$ 100 m

$\Rightarrow$ This possibility is excluded for the GSI-experiment!

Two atoms of type II $\leftrightarrow$ GSI-oscillations

Relation to the GSI-experiment: atom $\rightarrow$ ion, photon $\rightarrow$ neutrino

- even in runs where there was only one EC-decay, there might have been more ions in the ring $\rightarrow$ this possibility has to be considered!
- the wavelength has to be replaced by the de Broglie wavelength of the neutrino
- Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079 $\Rightarrow$ Q-value $\sim$ 1 MeV
- then: $E_\nu \sim 1$ MeV $\Rightarrow \lambda_\nu \approx \frac{2\pi\hbar c}{E_\nu c} \sim 10^{-12}$ m
- M. Steck et al., Phys. Rev. Lett., **77**, 3803 $\Rightarrow$ typical separation of the ions in the ring $\sim$ size of the ring $\sim$ 100 m

$\Rightarrow$ This possibility is excluded for the GSI-experiment!

Outline

Conclusions

- in principle, Quantum Beats seem to be a tempting possibility for an explanation for the GSI anomaly
- a single type I model would work, but has its problems
- a single type II model is claimed to be the solution by some authors, but actually it does not work
- a double type II model might be okay, but the numbers are wrong by orders
- a satisfying explanation is still missing...

Conclusions

- in principle, Quantum Beats seem to be a tempting possibility for an explanation for the GSI anomaly
- a single type I model would work, but has its problems
- a single type II model is claimed to be the solution by some authors, but actually it does not work
- a double type II model might be okay, but the numbers are wrong by orders
- a satisfying explanation is still missing...

Conclusions

- in principle, Quantum Beats seem to be a tempting possibility for an explanation for the GSI anomaly
- a single type I model would work, but has its problems
- a single type II model is claimed to be the solution by some authors, but actually it does not work
- a double type II model might be okay, but the numbers are wrong by orders
- a satisfying explanation is still missing...

Conclusions

- in principle, Quantum Beats seem to be a tempting possibility for an explanation for the GSI anomaly
- a single type I model would work, but has its problems
- a single type II model is claimed to be the solution by some authors, but actually it does not work
- a double type II model might be okay, but the numbers are wrong by orders
- a satisfying explanation is still missing...

Conclusions

- in principle, Quantum Beats seem to be a tempting possibility for an explanation for the GSI anomaly
- a single type I model would work, but has its problems
- a single type II model is claimed to be the solution by some authors, but actually it does not work
- a double type II model might be okay, but the numbers are wrong by orders
- a satisfying explanation is still missing...

Conclusions

- in principle, Quantum Beats seem to be a tempting possibility for an explanation for the GSI anomaly
- a single type I model would work, but has its problems
- a single type II model is claimed to be the solution by some authors, but actually it does not work
- a double type II model might be okay, but the numbers are wrong by orders
- a satisfying explanation is still missing...

Conclusions

- in principle, Quantum Beats seem to be a tempting possibility for an explanation for the GSI anomaly
- a single type I model would work, but has its problems
- a single type II model is claimed to be the solution by some authors, but actually it does not work
- a double type II model might be okay, but the numbers are wrong by orders
- a satisfying explanation is still missing...

$\rightarrow$ If you have any idea...

Conclusions

- in principle, Quantum Beats seem to be a tempting possibility for an explanation for the GSI anomaly
- a single type I model would work, but has its problems
- a single type II model is claimed to be the solution by some authors, but actually it does not work
- a double type II model might be okay, but the numbers are wrong by orders
- a satisfying explanation is still missing...

$\rightarrow$ If you have any idea...
Phone: +49/6221/516-817
E-Mail: Alexander.Merle@mpi-hd.mpg.de

THANK YOU!!!