Why the GSI anomaly cannot be explained by Quantum Beats

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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

1. Introduction
2. Quantum Beats
3. One atom of type I
4. One atom of type II
5. Two atoms of type II
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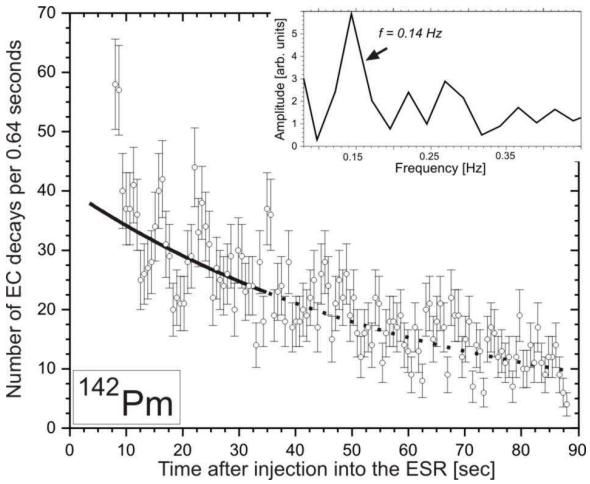

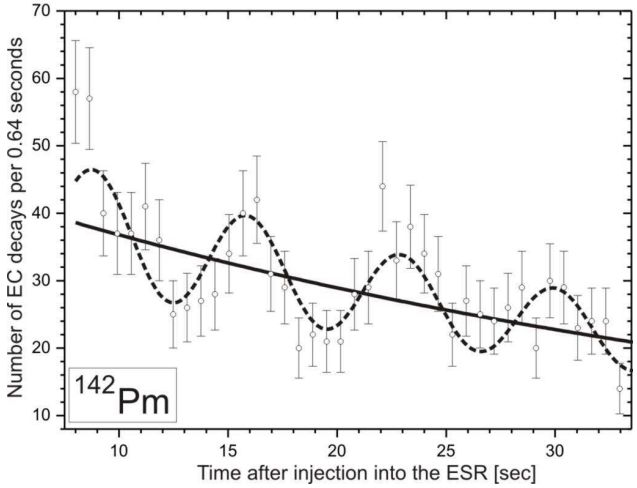

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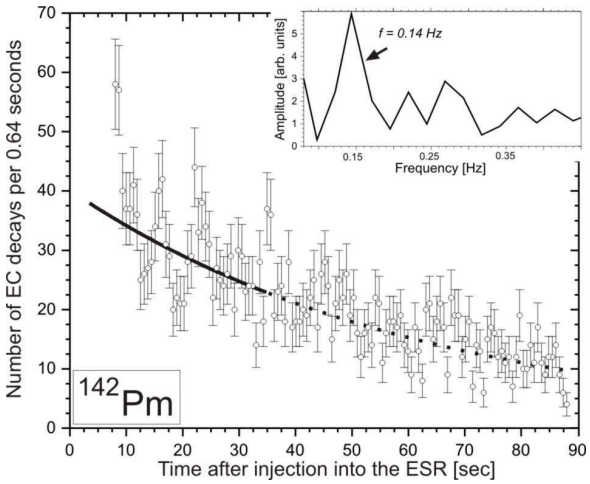

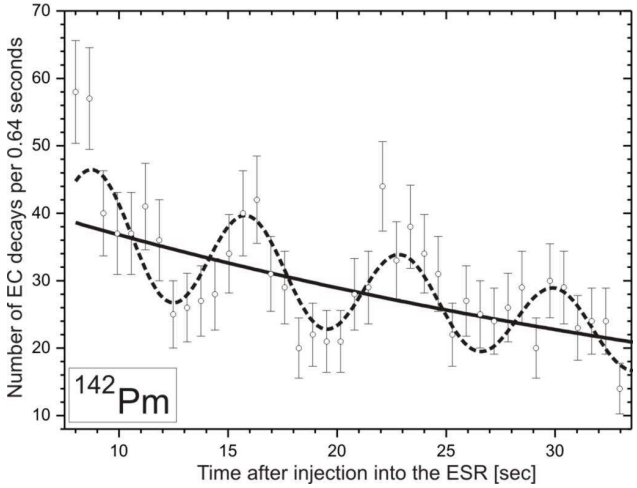

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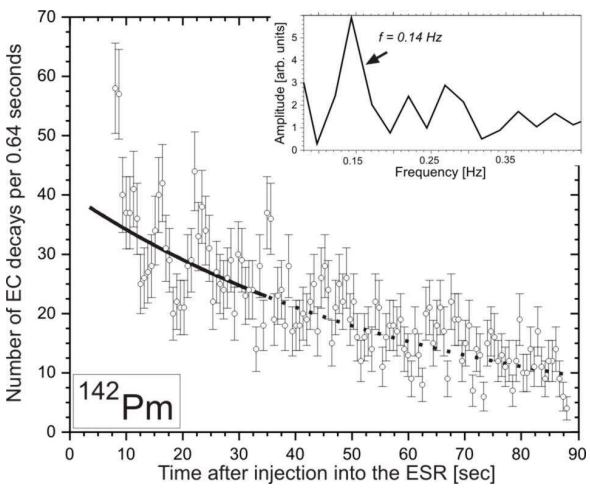

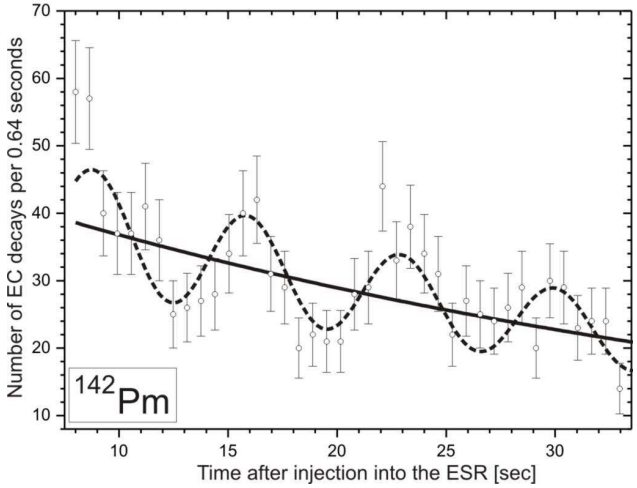

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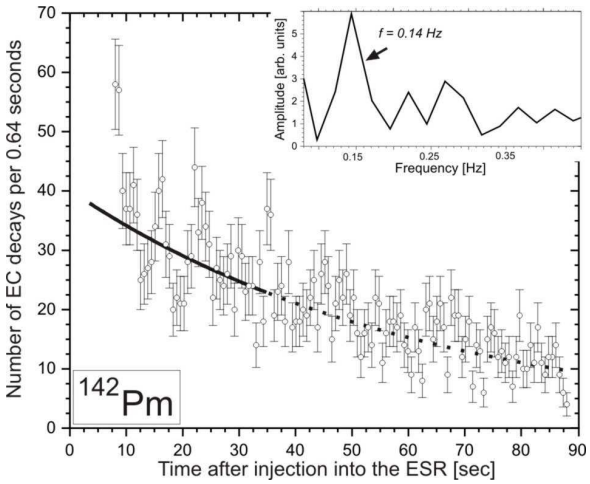

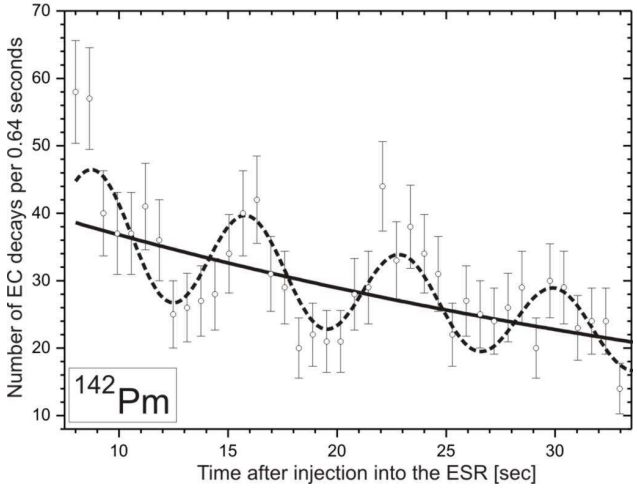

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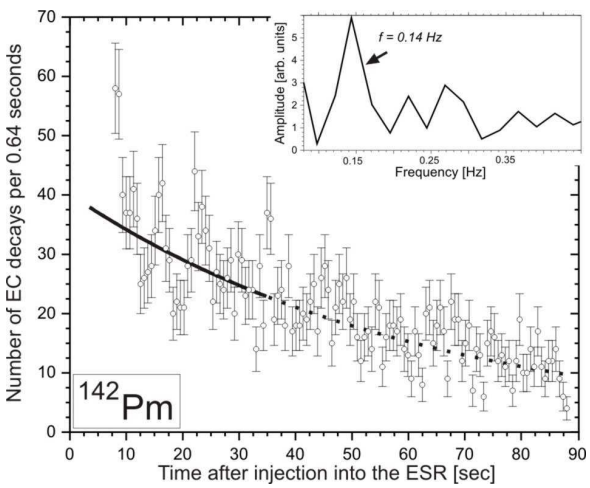

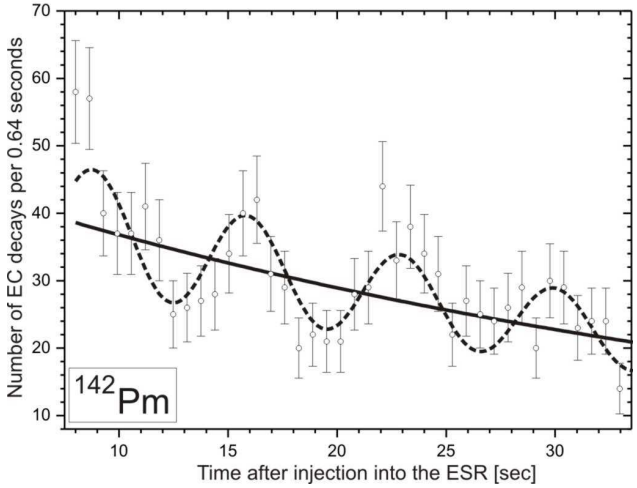

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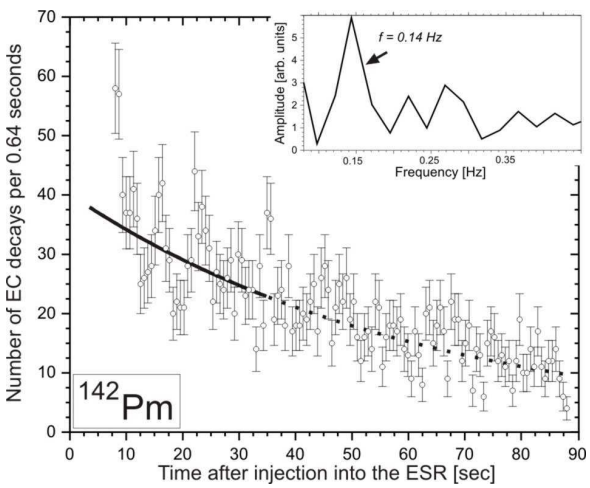

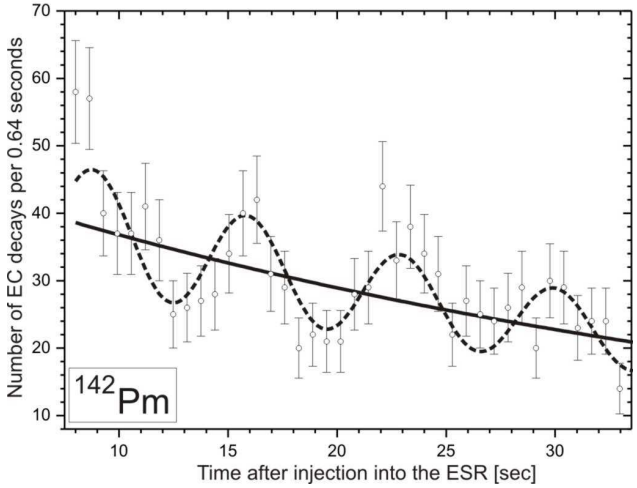

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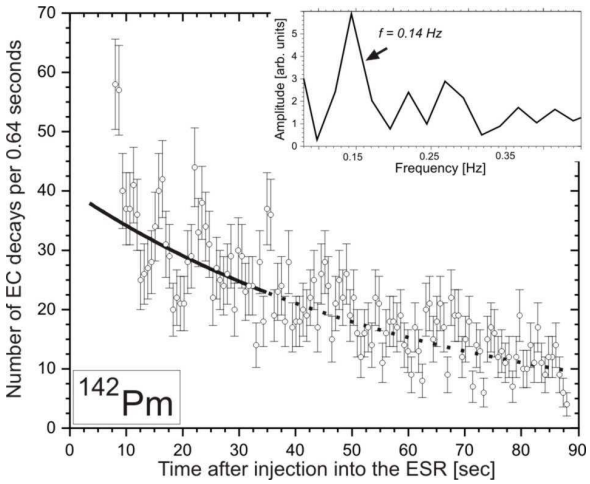

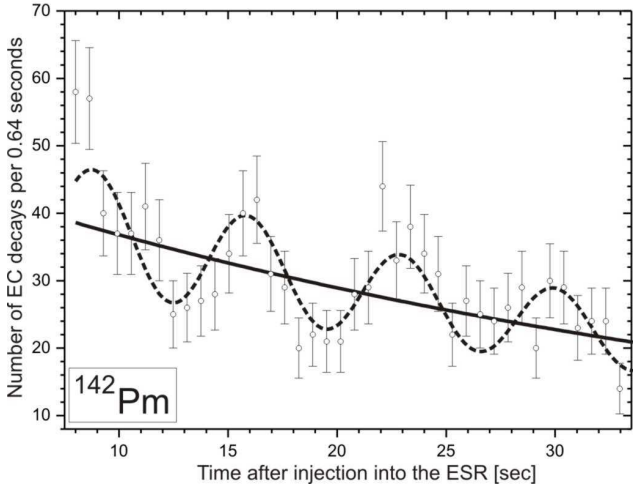

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Quantum Beats (Chow et al., Phys. Rev. A, **11**, 1380)

- 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

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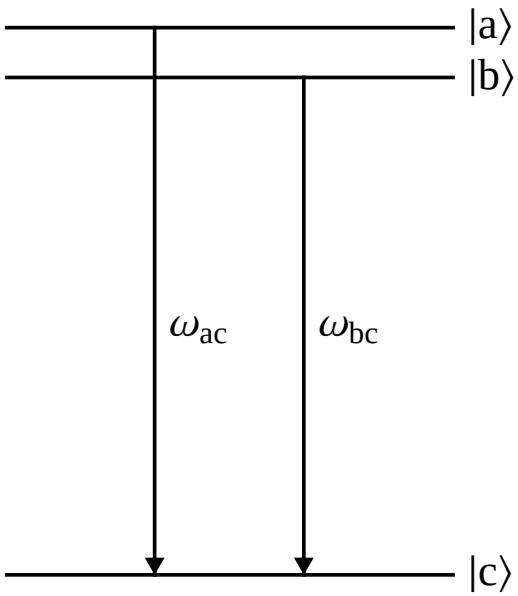

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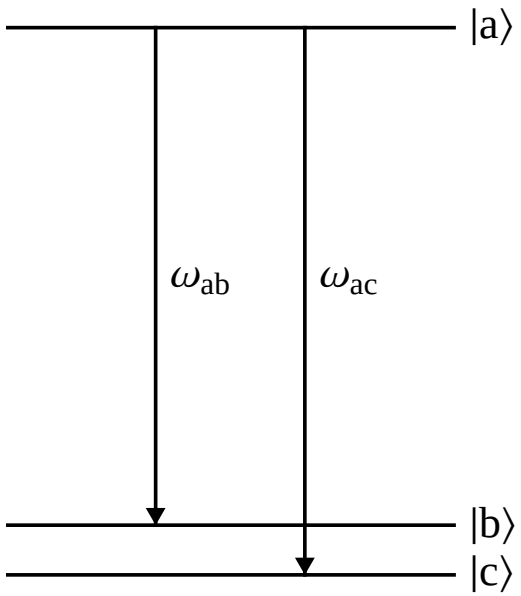

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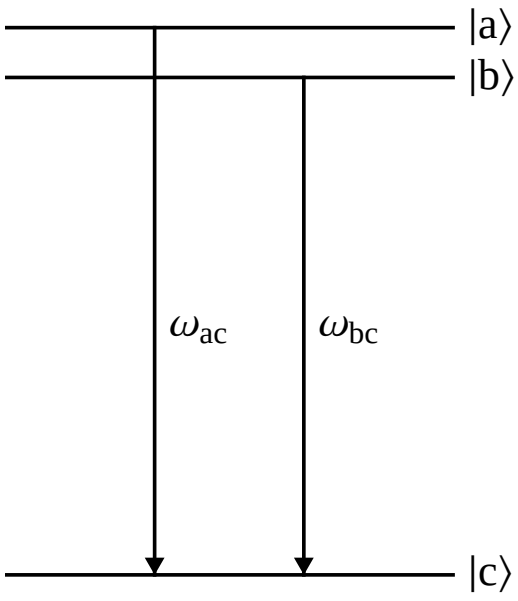

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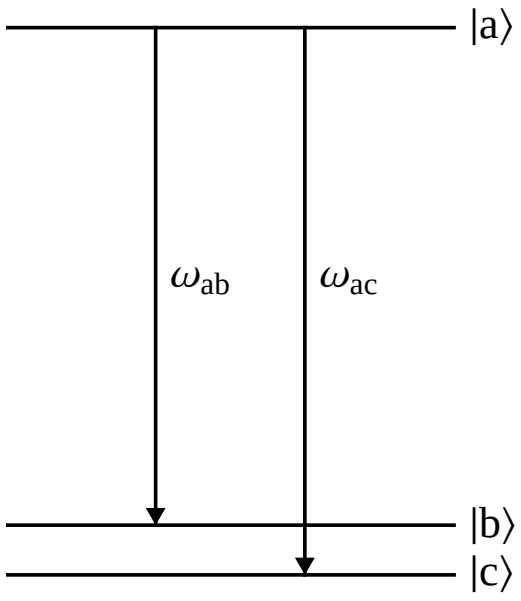

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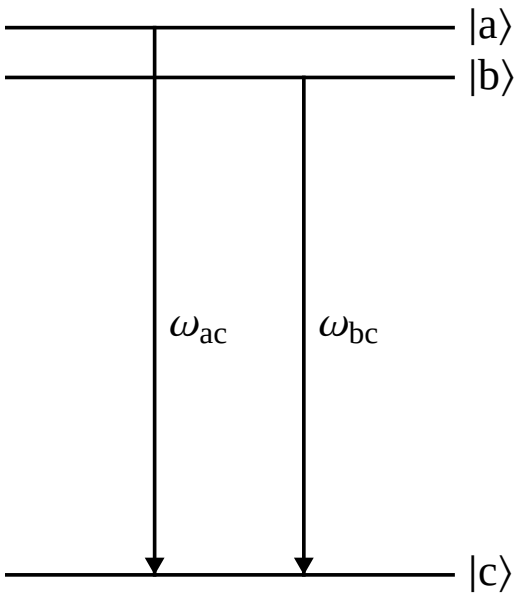

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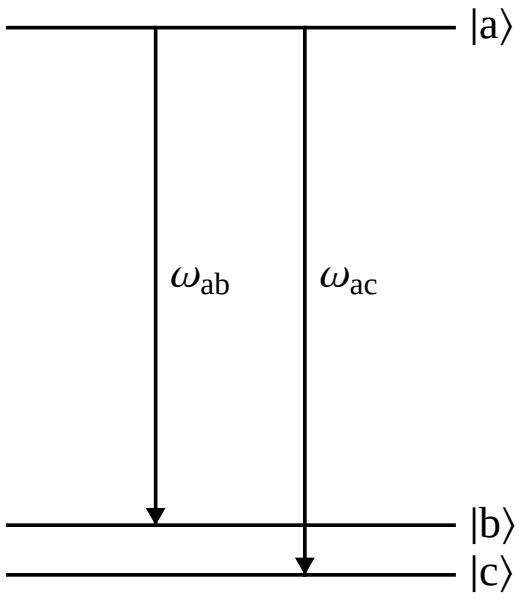

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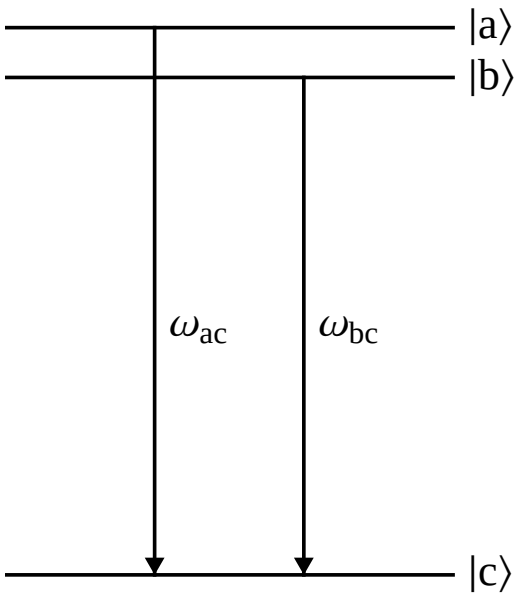

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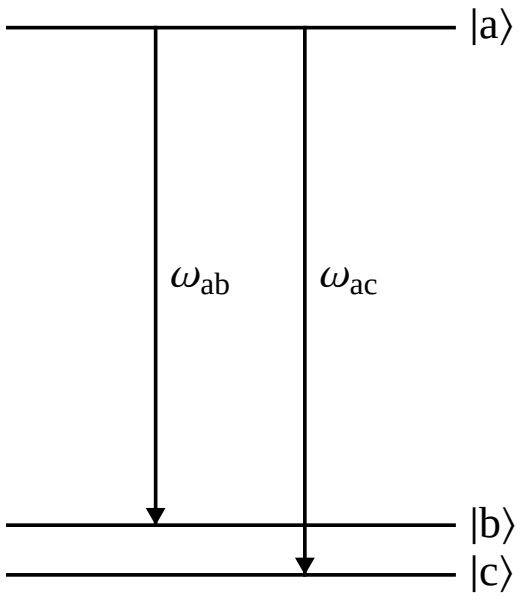

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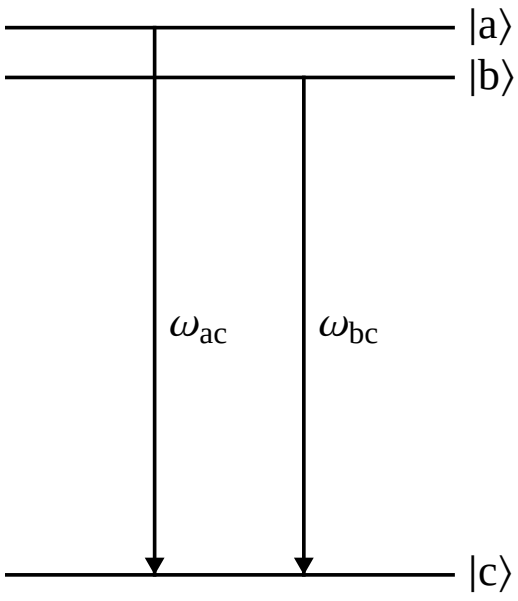

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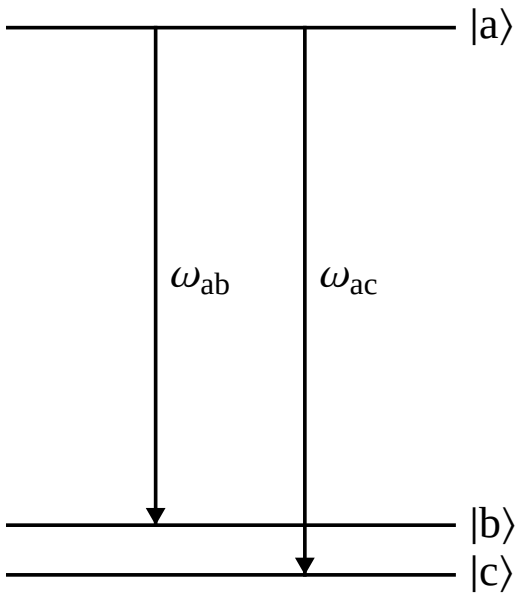

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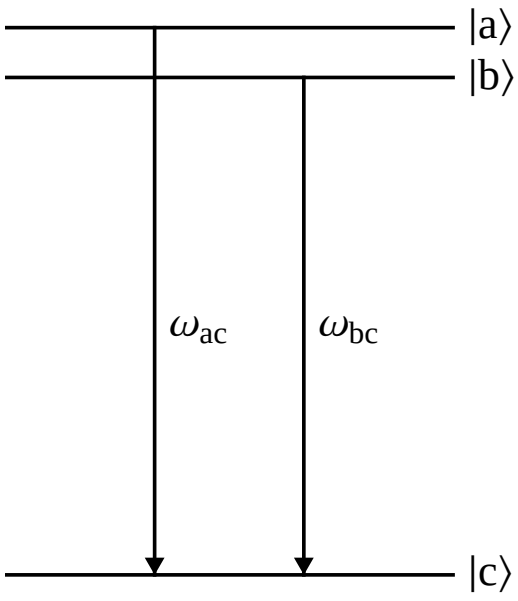

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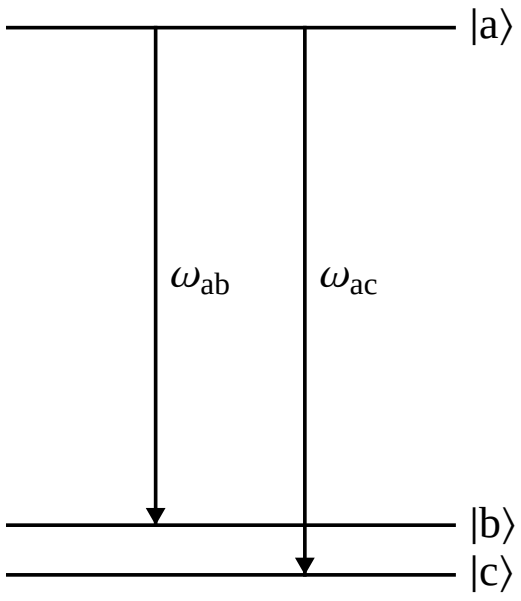

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  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$
- no photons emitted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

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

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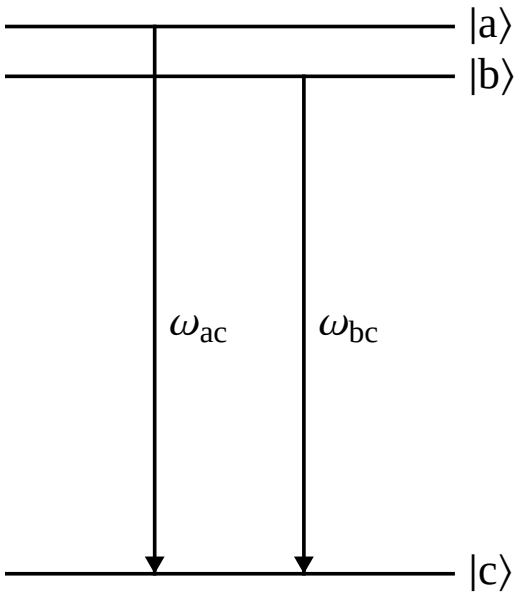

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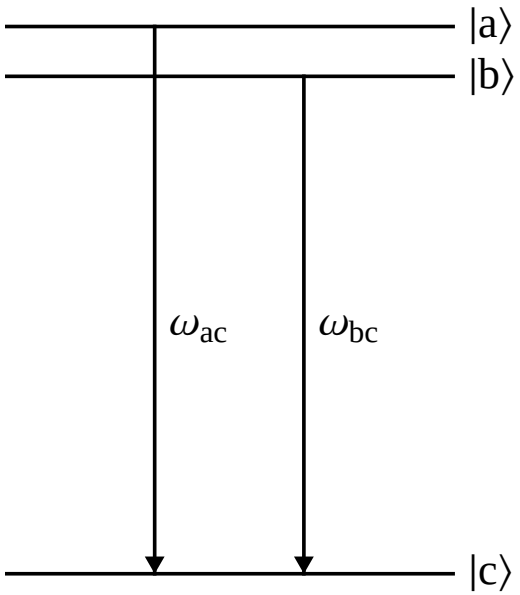

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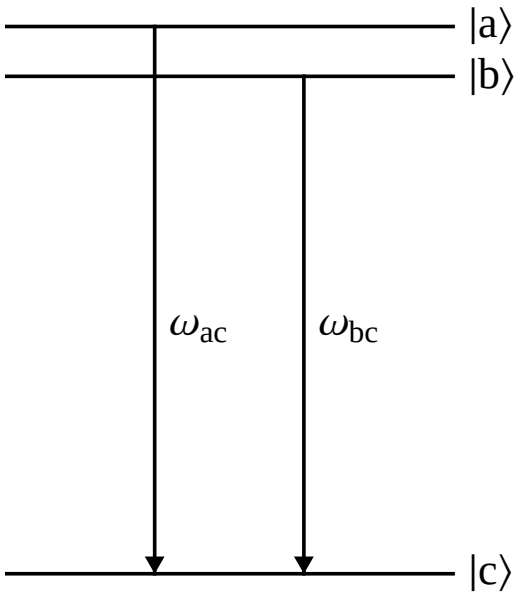

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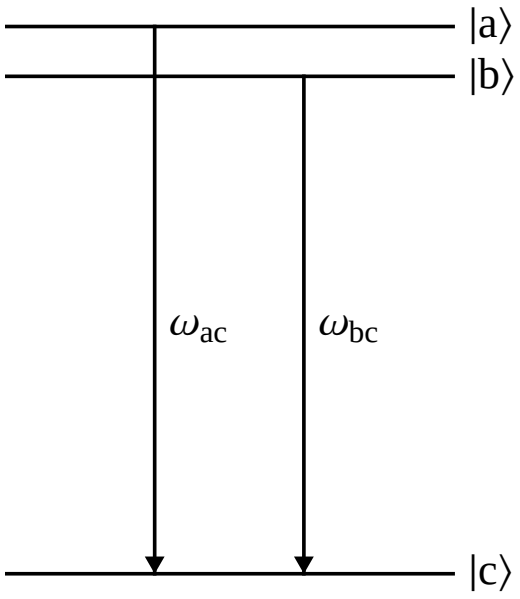

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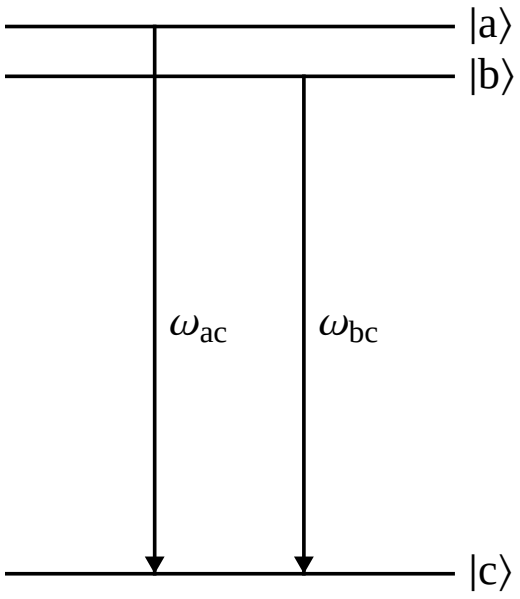

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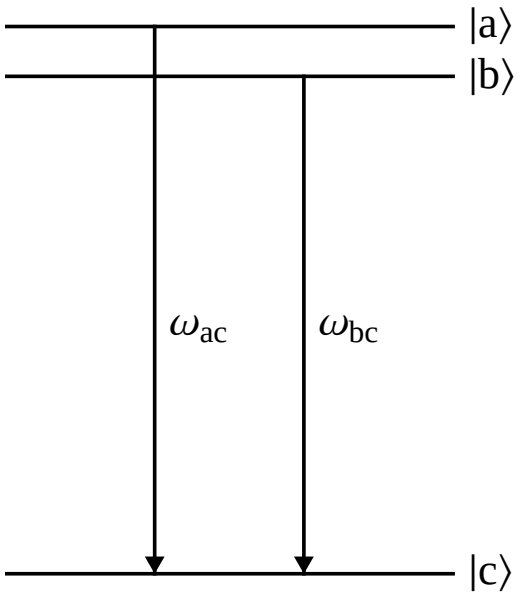

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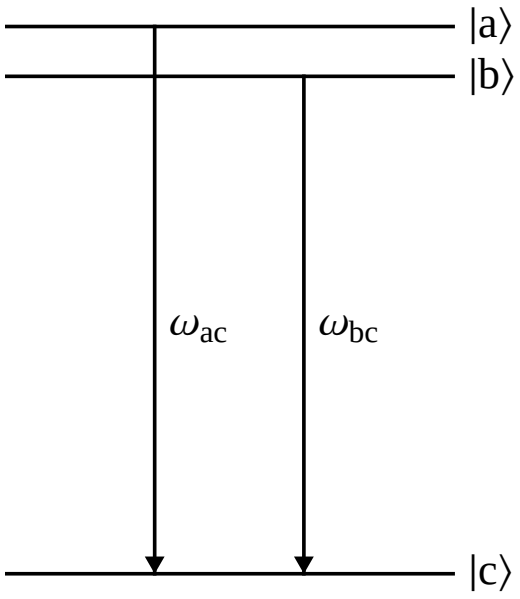

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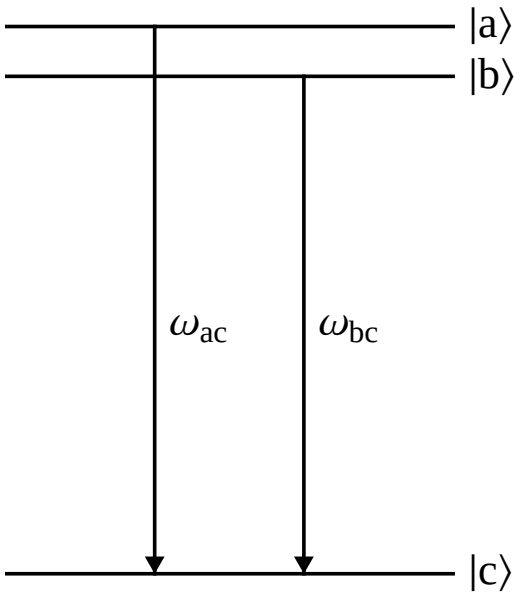

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Relation to the GSI-experiment: atom $\rightarrow$ ion, photon $\rightarrow$ neutrino

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Outline

1. Introduction
2. Quantum Beats
3. One atom of type I
4. One atom of type II
5. Two atoms of type II
6. Conclusions

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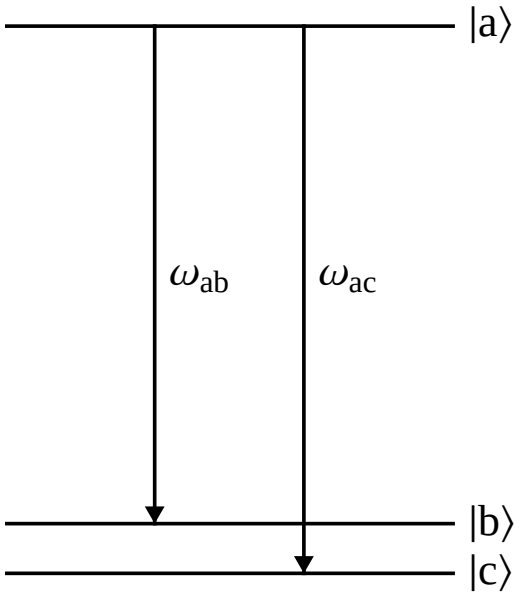

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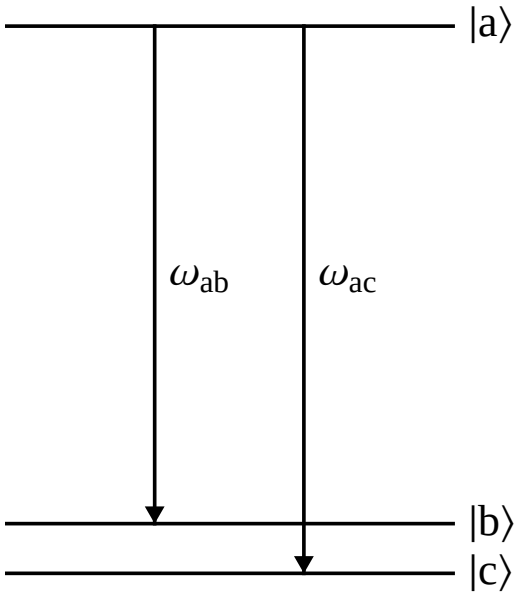

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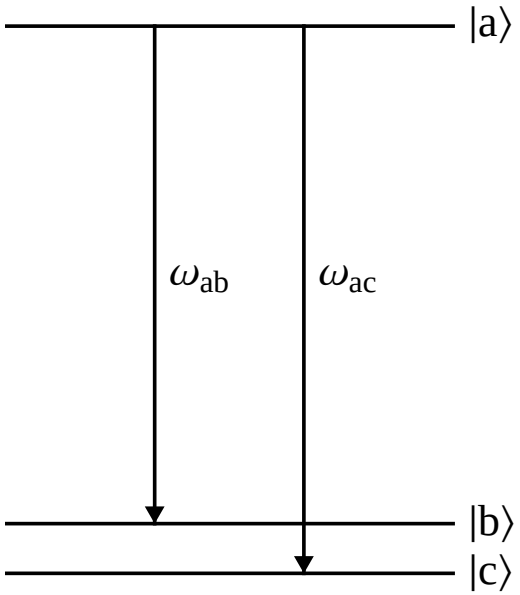

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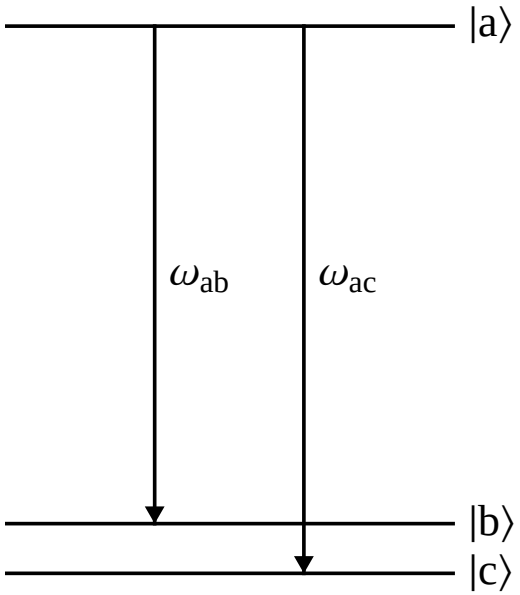

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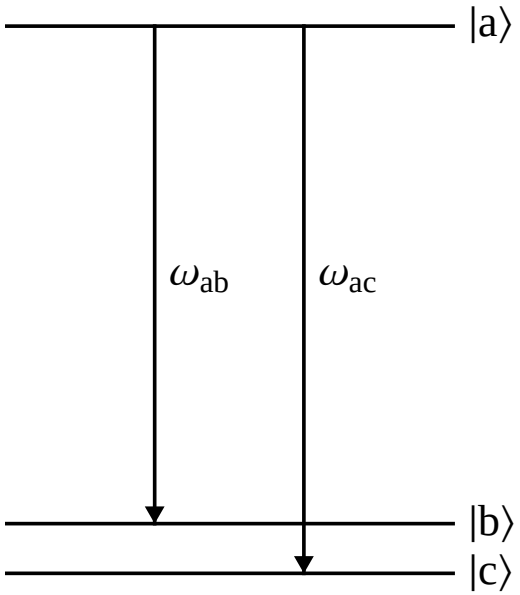

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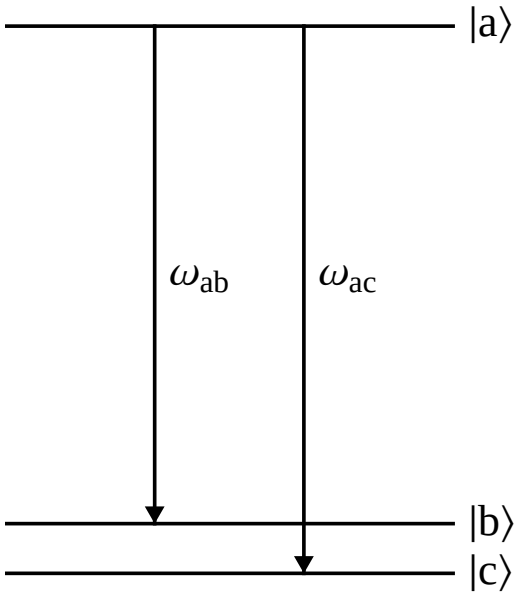

- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
  $|\Psi(0)\rangle = \mathcal{A}_0|a\rangle|0\rangle_\gamma + \mathcal{B}_0|b\rangle|0\rangle_\gamma + \mathcal{C}_0|c\rangle|0\rangle_\gamma$
  $\rightarrow$ with: $|\mathcal{A}_0|^2 + |\mathcal{B}_0|^2 + |\mathcal{C}_0|^2 = 1$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

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

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

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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 $\propto {}_\gamma\langle 0|a_{ab}^\dagger \underbrace{a_{ac}}_{\to 0}|0\rangle_\gamma = 0$
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By waiting long enough, one could determine the photon's energy by measuring the atomic final state. $\Rightarrow$ No interferences expected!

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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)

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Outline

1. Introduction
2. Quantum Beats
3. One atom of type I
4. One atom of type II
5. Two atoms of type II
6. Conclusions

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:

$$|\Psi(0)\rangle = \mathcal{A}_0|a\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{B}_0|b\rangle_1|b\rangle_2|0\rangle_\gamma + \mathcal{C}_0|c\rangle_1|c\rangle_2|0\rangle_\gamma +$$
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&= {}_\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 $\leftrightarrow$ 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

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Outline

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2. Quantum Beats
3. One atom of type I
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5. Two atoms of type II
6. Conclusions

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- a single type I model would work, but has its problems
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- a double type II model might be okay, but the numbers are wrong by orders
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The End

THANK YOU!!!