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

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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*

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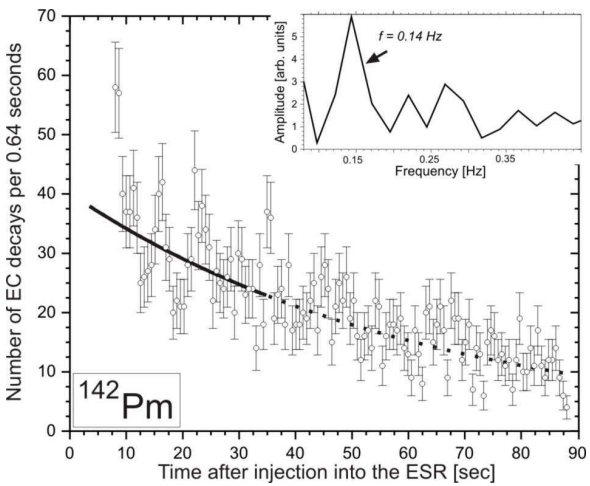

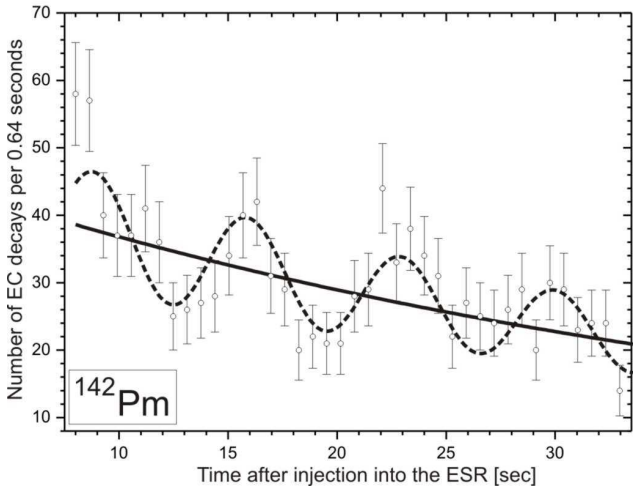

Y. A. Litvinov et al., Phys. Lett. **B664**, 162 (2008), arXiv:0801.2079

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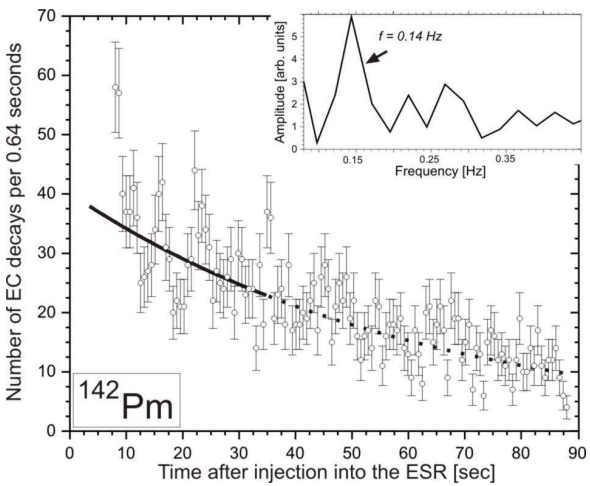

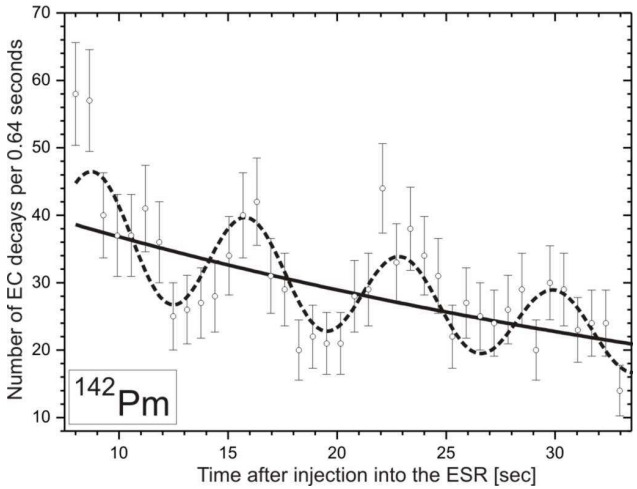

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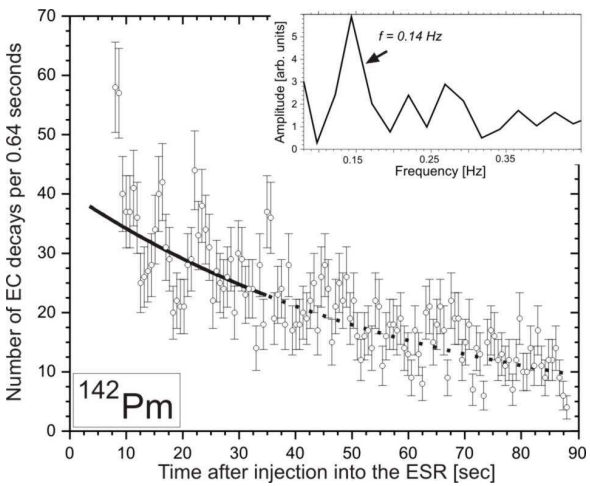

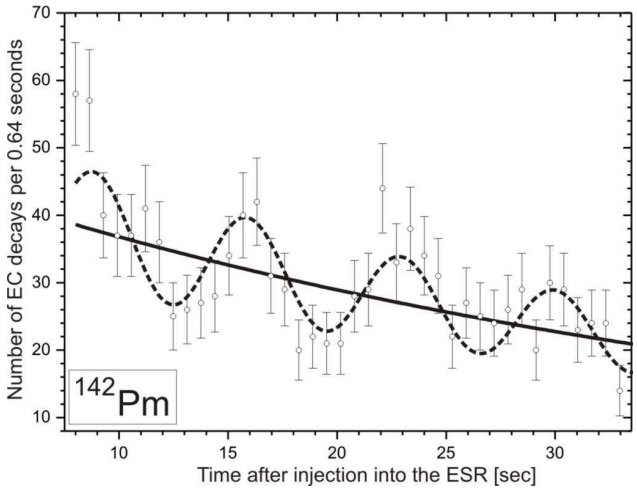

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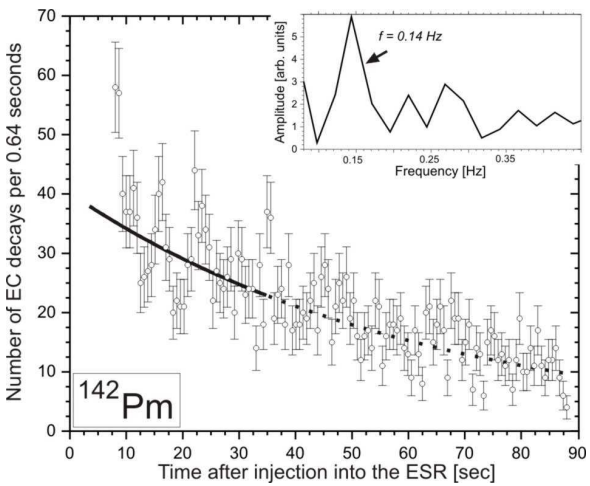

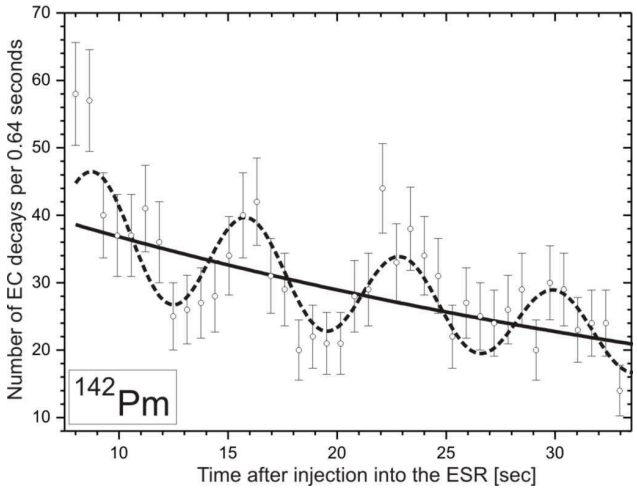

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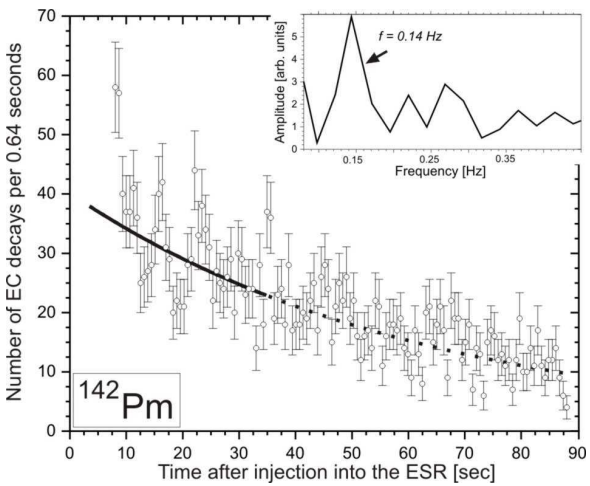

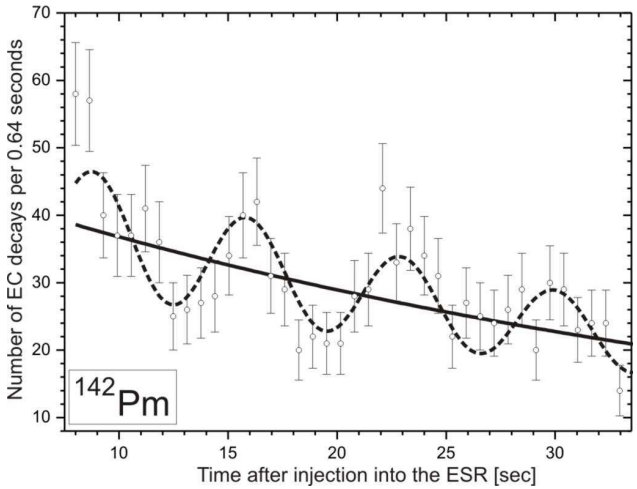

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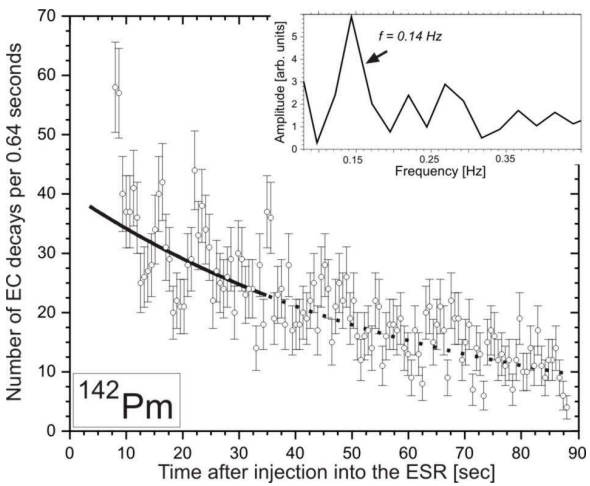

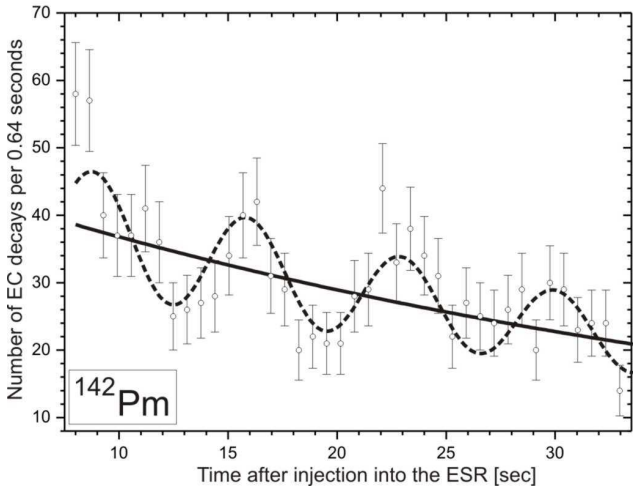

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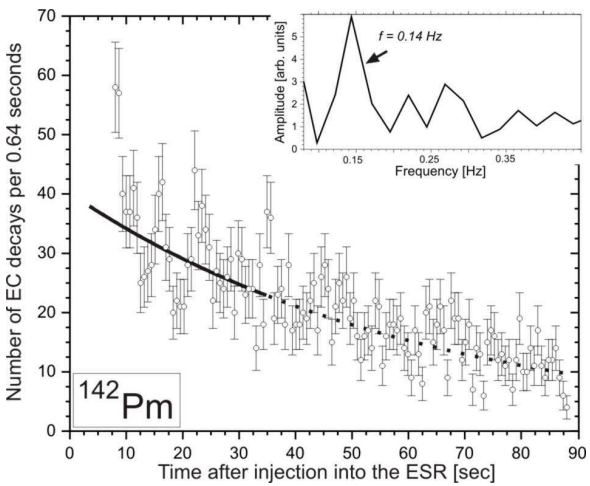

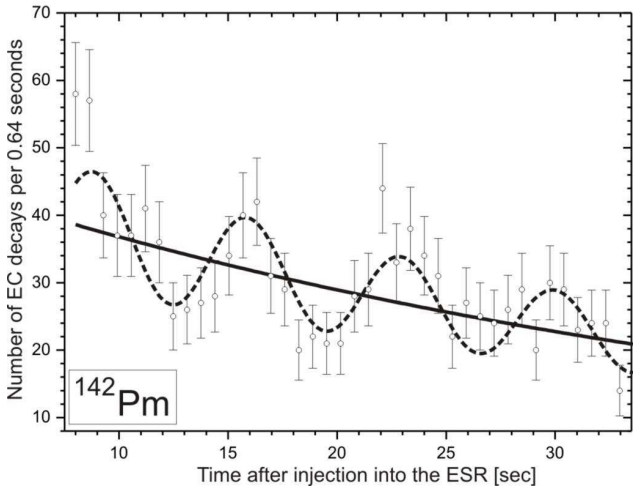

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Quantum Beats (Chow et al., Phys. Rev. A, **11**, 1380)

- 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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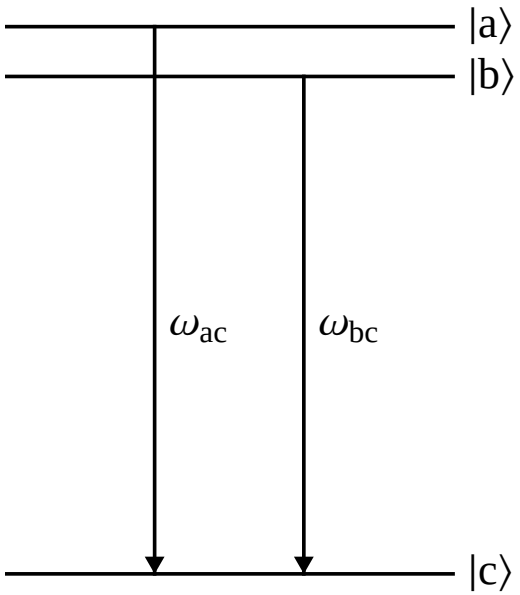

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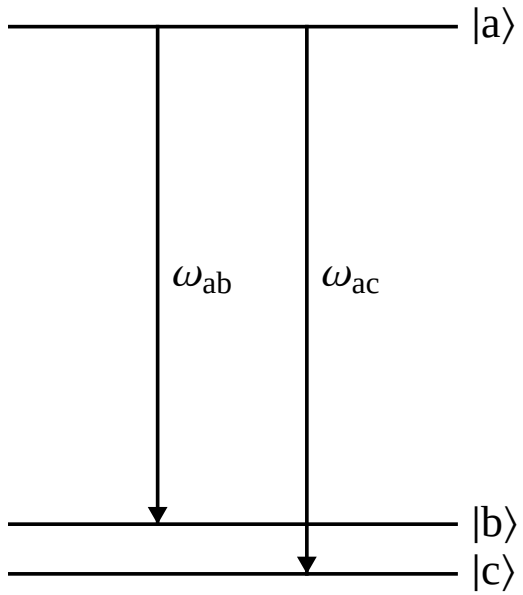

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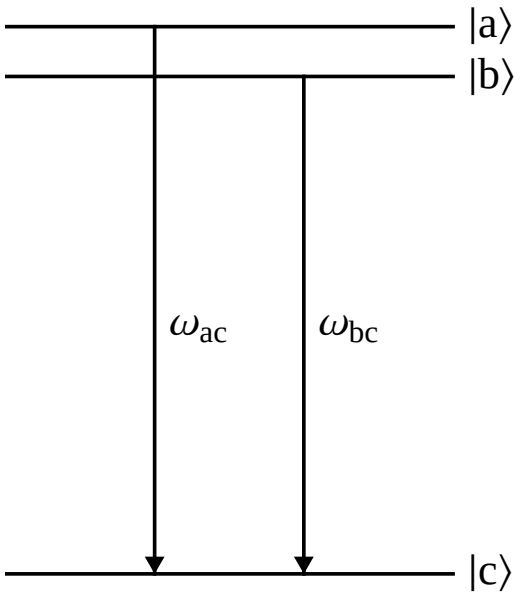

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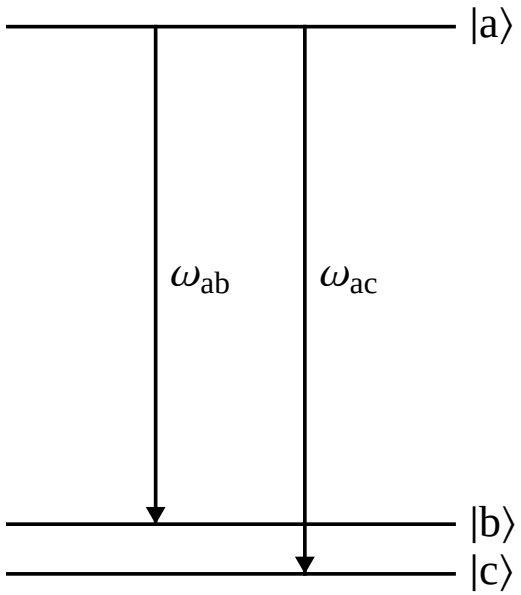

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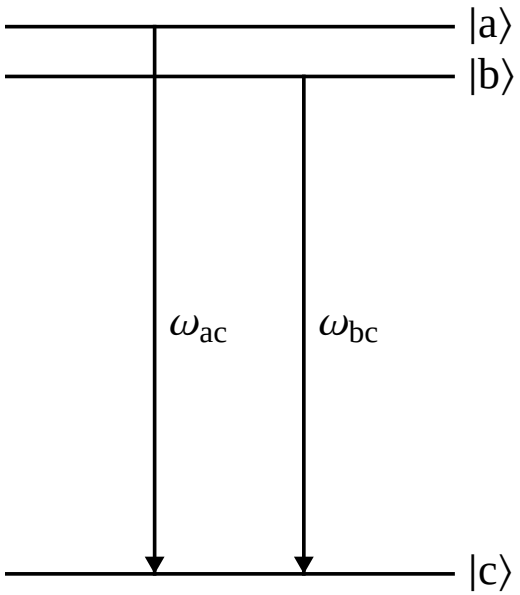

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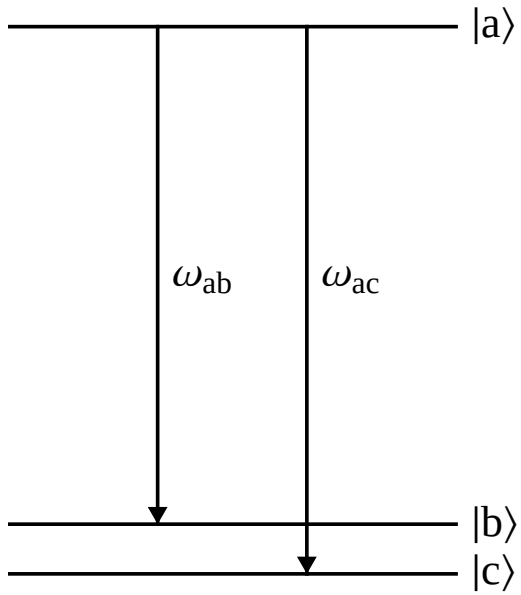

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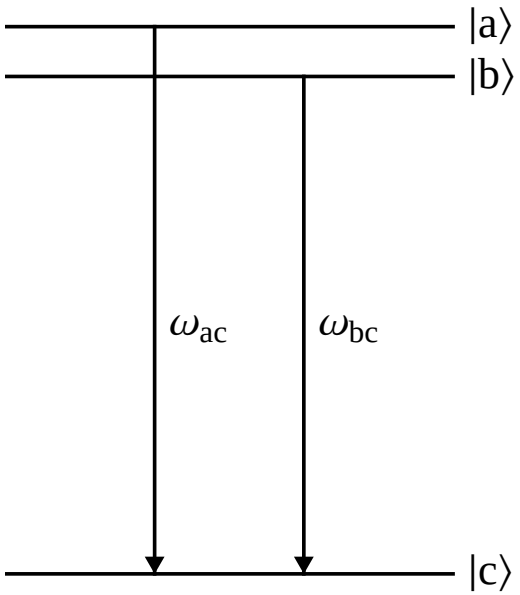

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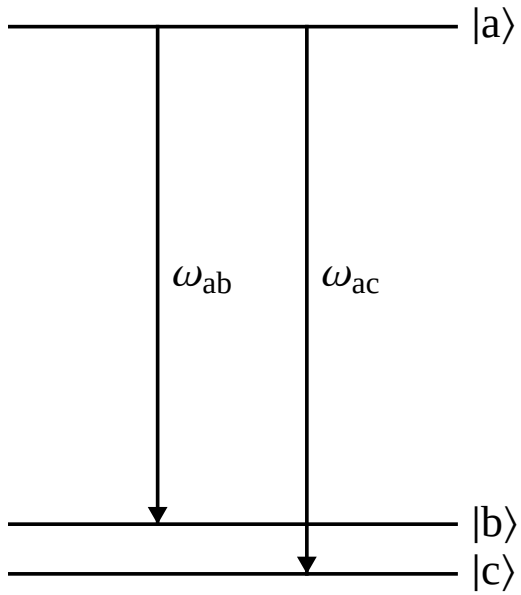

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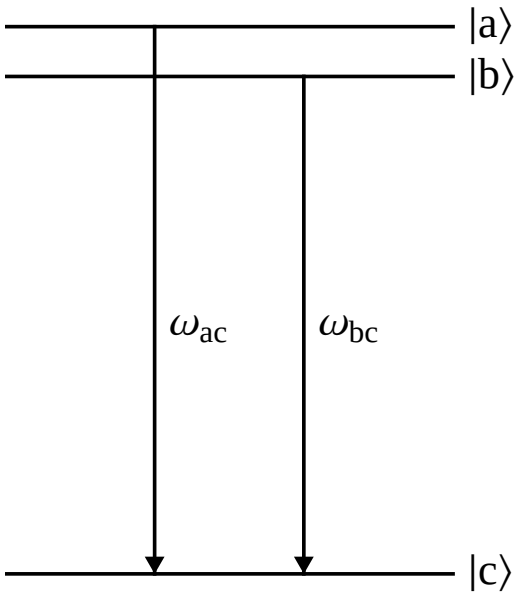

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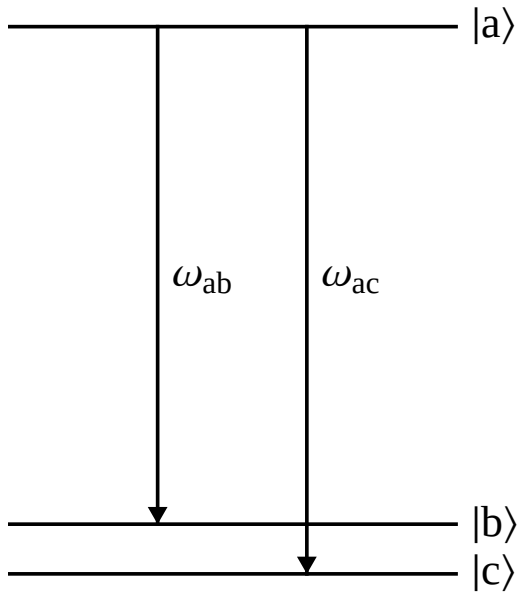

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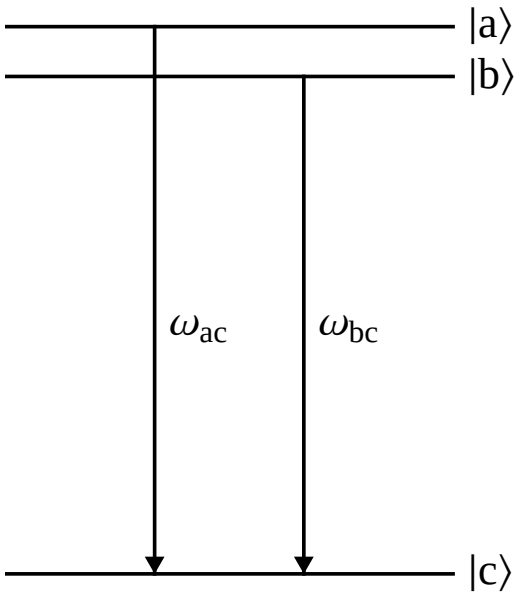

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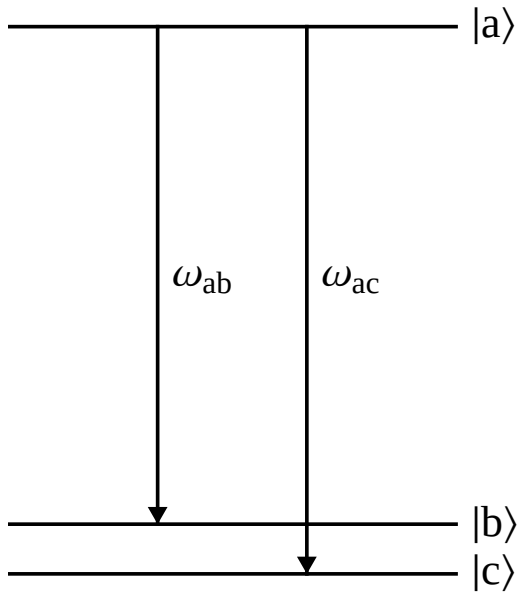

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Outline

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- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
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  $\rightarrow$ 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 $|\Psi(t)\rangle$:

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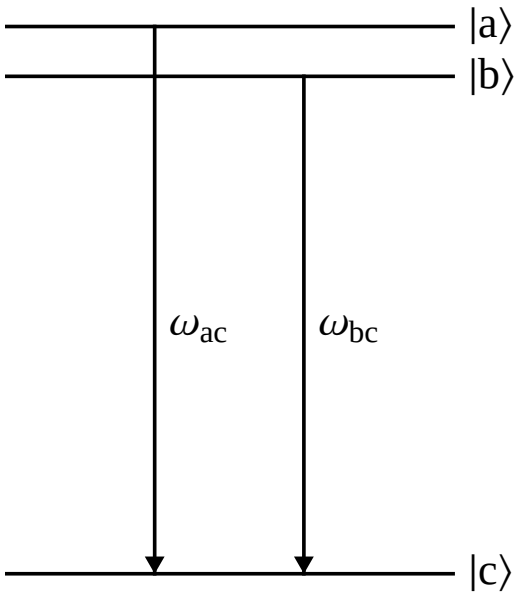

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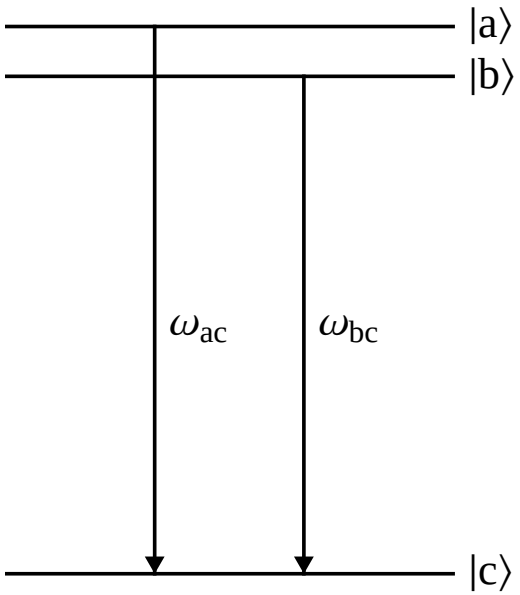

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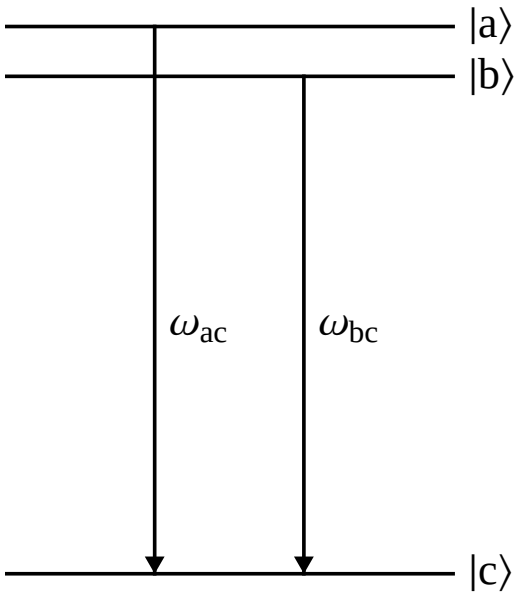

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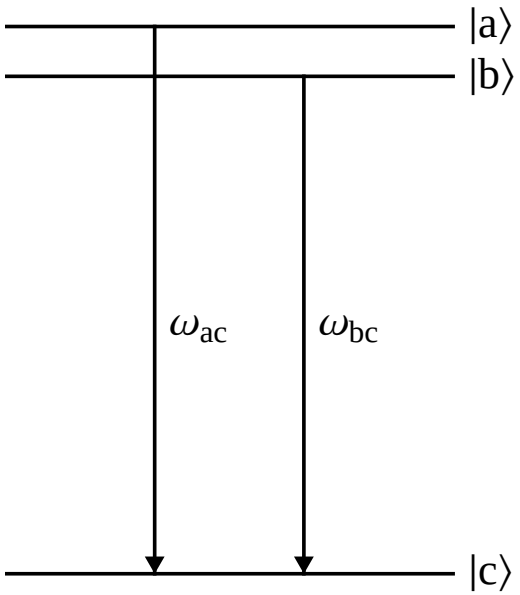

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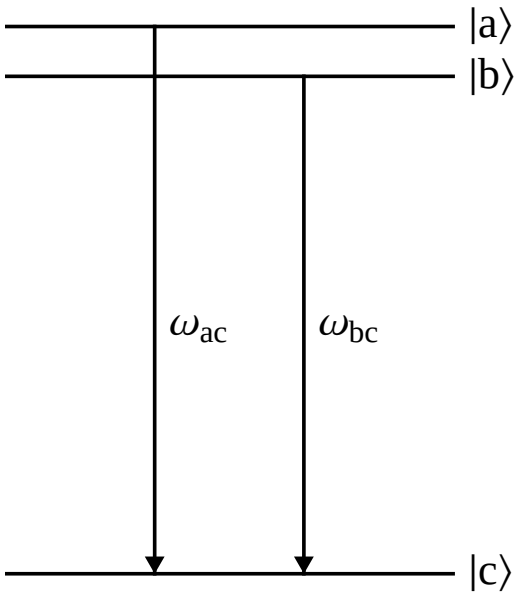

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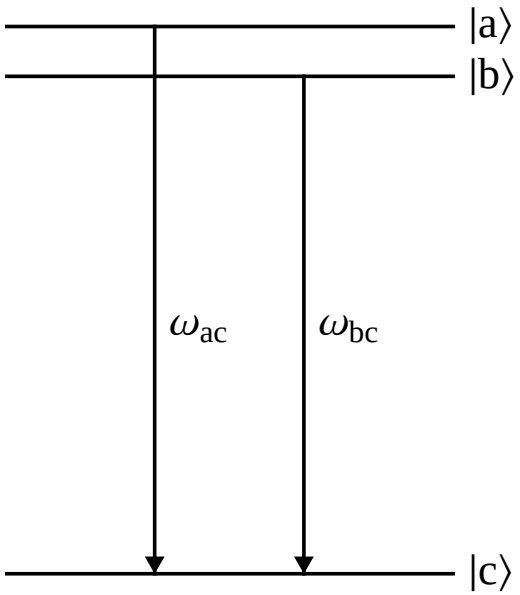

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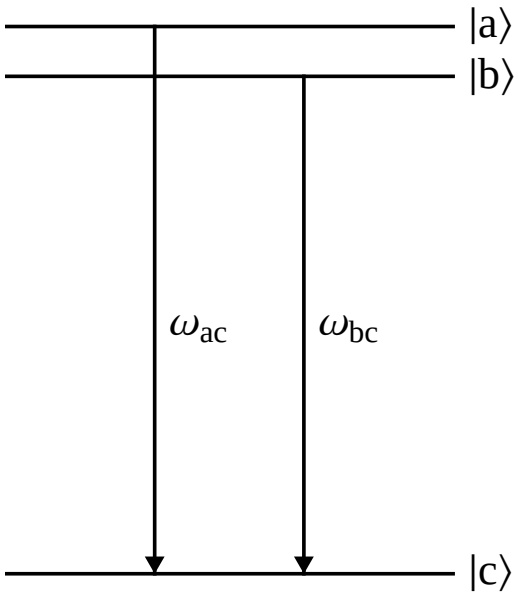

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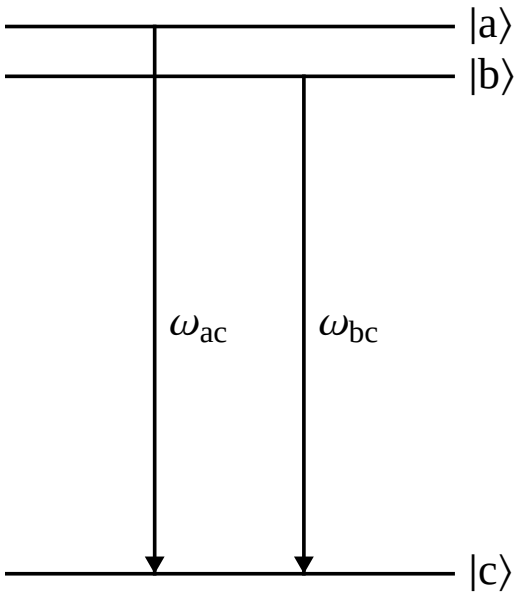

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$$\vec{E}^2(\vec{0},t) = \epsilon_{ac}^2 (1 + 2a_{ac}^{\dagger} a_{ac}) + \epsilon_{bc}^2 (1 + 2a_{bc}^{\dagger} a_{bc}) +$$
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Relation to the GSI-experiment: atom $\rightarrow$ ion, photon $\rightarrow$ 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)
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Outline

Single atom of type II

- superposition of $|a\rangle$, $|b\rangle$, and $|c\rangle$
- initially:
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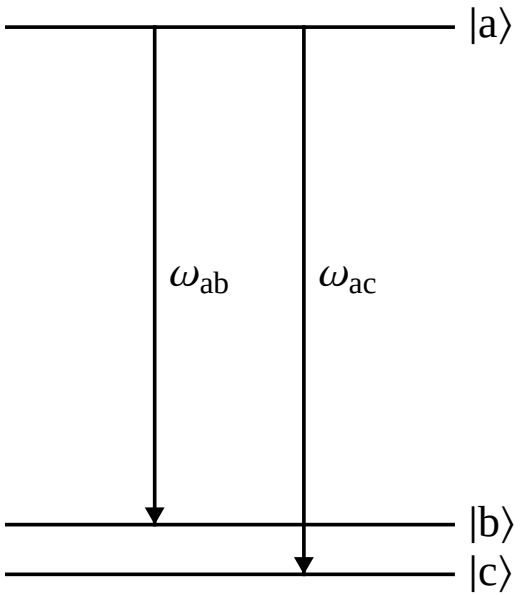

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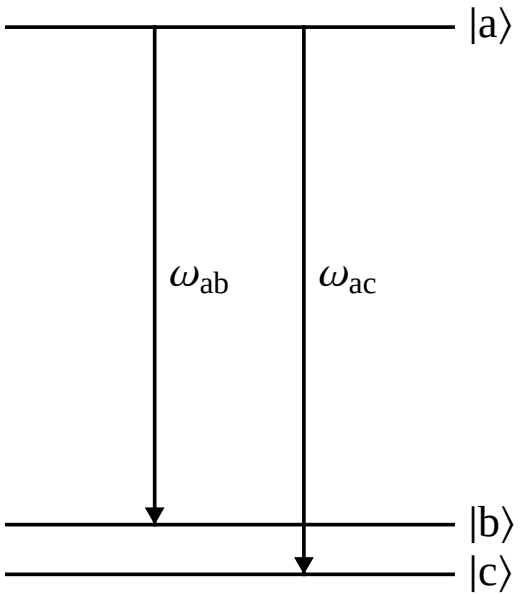

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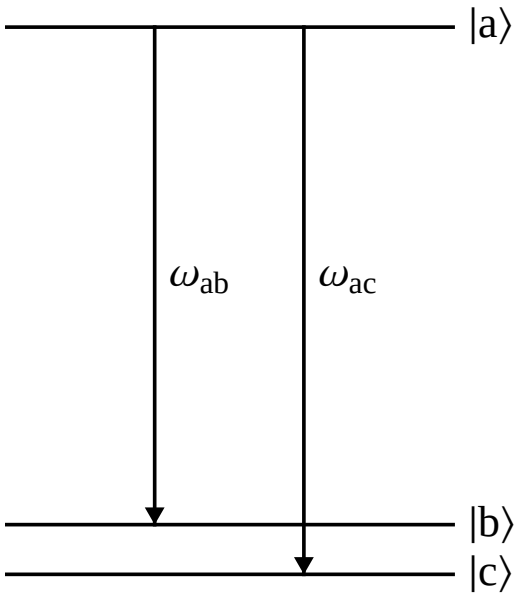

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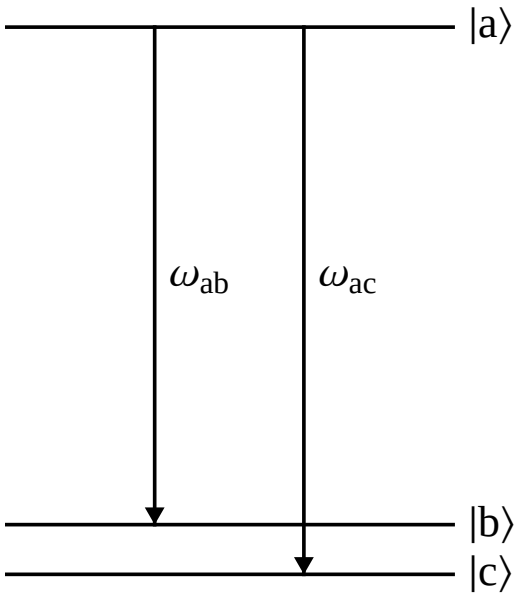

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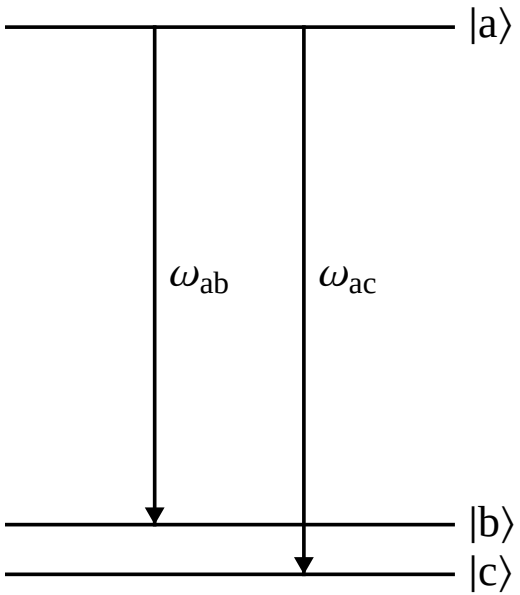

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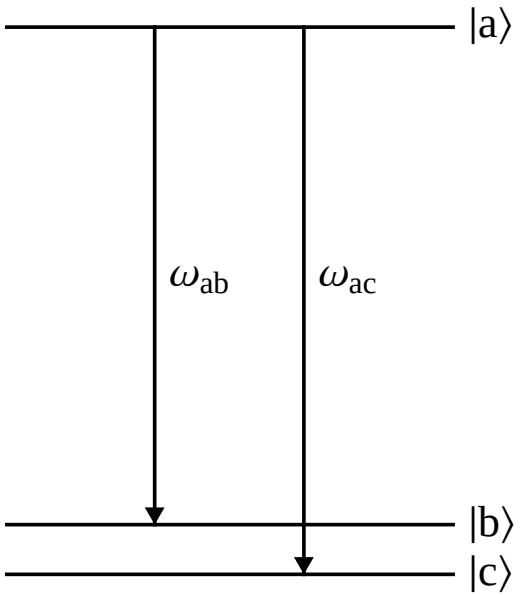

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now we have:

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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. $|\mathcal{B}'(t)|^2 e^{\pm i\Delta t}$
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now we have:

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- 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

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):

$$\mathcal{A}(t)|a\rangle_1|a\rangle_2|0\rangle_\gamma + \mathcal{B}(t)|b\rangle_1|b\rangle_2|0\rangle_\gamma + \mathcal{C}(t)|c\rangle_1|c\rangle_2|0\rangle_\gamma +$$
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- there can indeed be oscillatory terms, e.g. $\mathcal{J}_1^* \mathcal{K}_1 e^{-i\Delta t}$, which is proportional to:

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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
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Outline

Conclusions

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- 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...

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The End

THANK YOU!!!