Protected state enhanced quantum metrology

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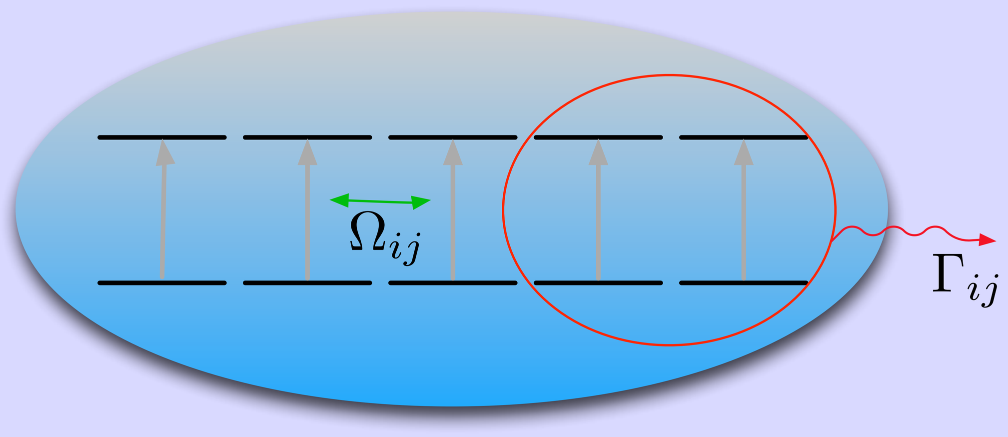
1 Introduction and Goals

- Redesign Ramsey procedure to excite slowly decaying states
- Improvement of sensitivity in Ramsey interferometry
- Large effects for dense ensembles or regular arrays
- Contribute to accuracy gains in optical lattice clocks
- Next: investigate the situation at $T \neq 0$ and re-pumping during evolution

2 Model

N identical two-level emitters with levels $|g\rangle$ and $|e\rangle$, separated by ω_0, coherently coupled by dipole-dipole interaction and subject to collective decay



Time evolution is governed by the master equation

$$\frac{\partial \rho}{\partial t} = i\left[\rho, H\right] + \mathscr{L}\left[\rho\right]$$

with

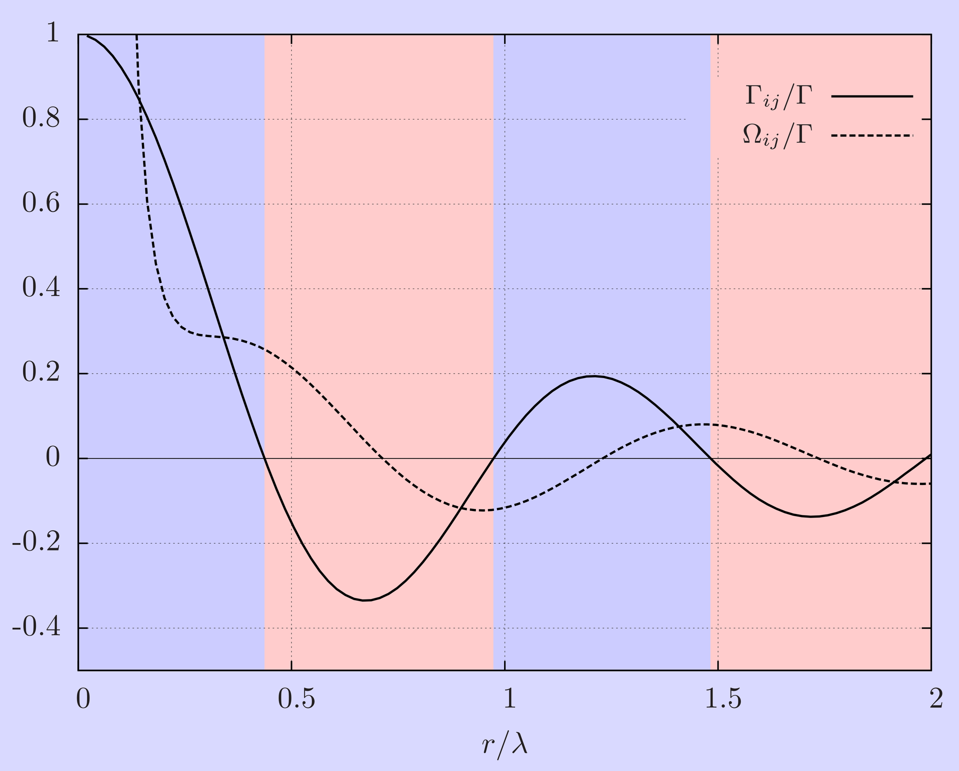
$$H = \frac{\omega}{2}\sum_i \sigma_i^z + \sum_{i \neq j} \Omega_{ij}\sigma_i^+\sigma_j^-$$

where $\omega = \omega_0 - \omega_l$ (ω_l is the reference frequency) and Ω_{ij} is the resonant coupling. The Liouvillian is given by

$$\mathscr{L}\left[\rho\right] = \frac{1}{2}\sum_{ij}\Gamma_{ij}\left(2\sigma_i^-\rho\sigma_j^+ - \sigma_i^+\sigma_j^-\rho - \rho\sigma_i^+\sigma_j^-\right)$$

featuring the collective damping Γ_{ij}.

The collective couplings Ω_{ij} and Γ_{ij} are a function of the system's geometry. Their dependence on the interatomic distances (for $\mu \perp \mathbf{r}$) is given below.



The colored regions indicate the distances, which feature a positive dissipative coupling, which leads to superradiance (red) in contrast to the distances with a negative collective coupling leading to subradiance (blue). The distance is crucial when trying to determine the optimal strategy (see section *Results*).

The figure of merit in spectroscopy is the sensitivity

$$\delta\omega = \frac{\Delta S^z}{\left|\partial_\omega \left\langle S^z\right\rangle\right|},$$

where $S^z = \frac{1}{2}\sum_i \sigma_z^{(i)}$ and is therefore a measure of population inversion. For independently decaying atoms this minimum sensitivity is

$$\left[\delta\omega\right]_{indep} = \frac{\exp\left(\Gamma\tau/2\right)}{\sqrt{N}\cdot\tau}.$$

Thus, it is very clear that the main impediment of Ramsey spectroscopy is the lifetime of the addressed states. The main goal of our concept is therefore to employ long-lived states as opposed to quickly decaying ones, which are implicitly used by the regular Ramsey procedure.

References and Acknowledgements

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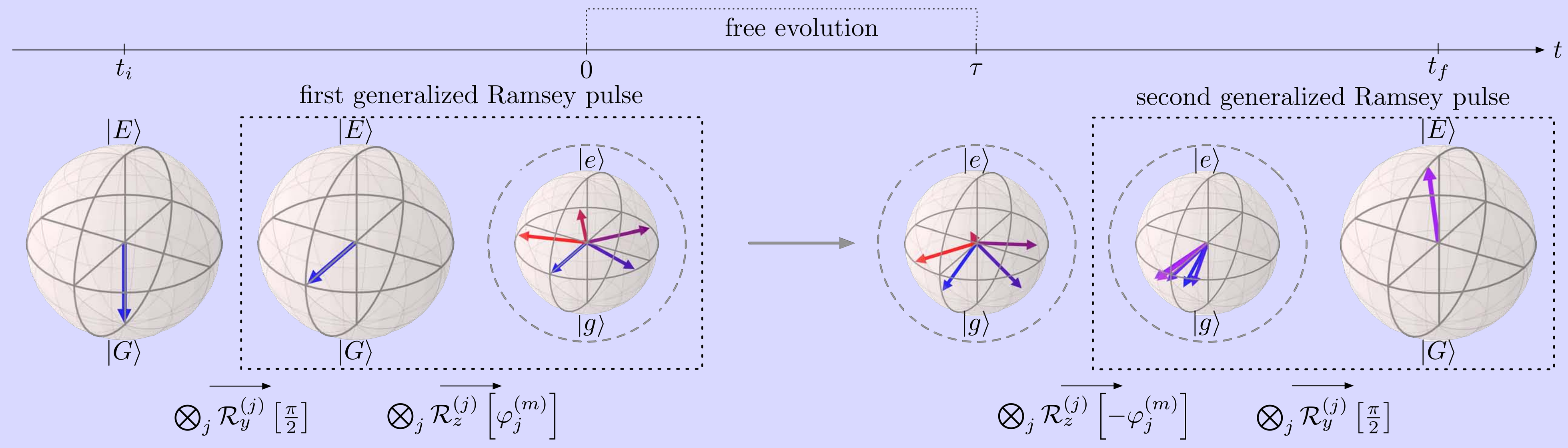
3 'asymmetric Ramsey procedure'

The Ramsey procedure of (i) $\pi/2$ pulse, (ii) free evolution and (iii) $\pi/2$ pulse is complemented by a phase distribution after the first half-excitation and its reversal before the second half-excitation.



The generalized procedure is performed like this:

(i) The ensemble is initialized with every atom in the ground state, $\rho_i = |G\rangle\langle G| = |g\ldots g\rangle\langle g\ldots g|$.

(ii) Individual quick $\pi/2$ pulses prepare a maximally coherent state in the xy-plane of the collective Bloch sphere.

(iii) The individual coherences are rotated about the z-axis of their Bloch spheres, each with a distinct phase, to obtain

$$\rho_0 = \mathscr{R}_1\rho_i\mathscr{R}_1^\dagger \text{ with } \mathscr{R}_1 = \bigotimes_j \mathscr{R}_z^{(j)}\left[\varphi_j^{(m)}\right]\mathscr{R}_y^{(j)}\left[\frac{\pi}{2}\right].$$

(iv) The system evolves freely (including dipole-dipole interaction and collective decay) for time $t = 0$ to τ resulting in ρ_τ.

(v) The phase imprinting is reversed, rotating back each individual atomic state about the z-axis.

(vi) The second quick $\pi/2$ pulse is applied to each atom, resulting in the final state

$$\rho_f = \mathscr{R}_2\rho_\tau\mathscr{R}_2^\dagger \text{ with } \mathscr{R}_2 = \bigotimes_j \mathscr{R}_y^{(j)}\left[\frac{\pi}{2}\right]\mathscr{R}_z^{(j)}\left[-\varphi_j^{(m)}\right].$$

Asymmetric preparation means slower decay

In contrast to the regular Ramsey procedure, which implicitly populates symmetric states only, the redesigned Ramsey procedure populates anything but these states. To illustrate, we consider the case of two atoms. While the regular Ramsey procedure will create the initial pure state ρ_0^{sym} s

$$\psi_0^{sym} = \frac{1}{2}\left(|G\rangle + \sqrt{2}|S\rangle + |E\rangle\right),$$

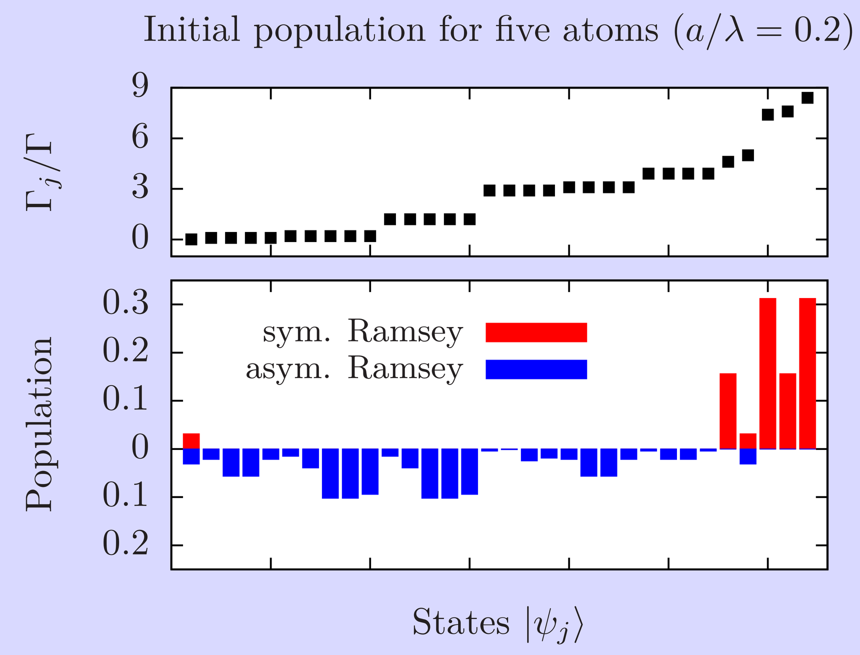
the altered procedure produces an initial pure sstate ρ_0^{asym} with

$$\psi_0^{asym} = \frac{1}{2}\left(|G\rangle + \sqrt{2}|A\rangle - |E\rangle\right),$$

shifting the majority of the population to the asymmetric state, which features a diminished collective spontaneous emission rate.

This behaviour becomes more pronounced, the larger the ensemble is.

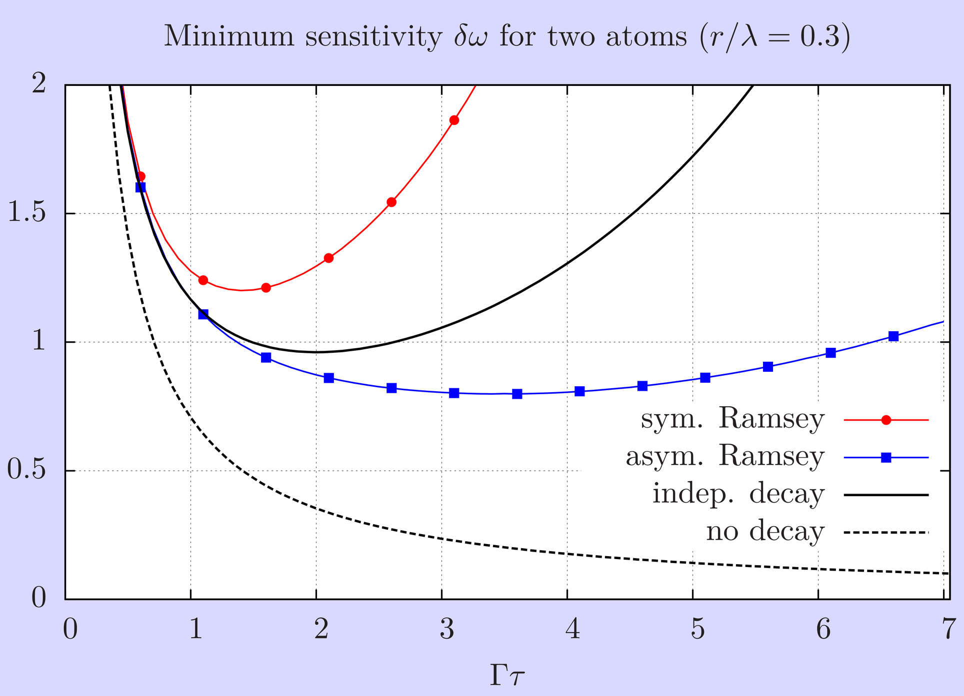
The figure below shows the initial state population for a system of five equally coupled atoms. Here it can be observed that the regular Ramsey procedure populates the symmetric states, which feature the largest emission rates exclusively, while the redesigned procedure does not populate them at all. The distance that was chosen for the plot is $a/\lambda = 0.2$.



4 Results

With the asymmetric Ramsey procedure one is able to obtain sensitivities which beat the regular Ramsey procedure and can even go beyond the case of independently decaying ensembles.

In the quite illustrative case of two atoms, the asymmetric procedure beats the symmetric one, whenever the collective dissipative coupling is positive. On the other hand, the regular procedure is the best choice in the regions featuring a negative collective coupling (this includes the $^{87}Sr\ ^1S_0 \rightarrow {}^3P_0$ magic wavelength).



The expressions for the minimum sensitivity can be calculated analytically and give

$$\left[\delta\omega\right]_S = \frac{\sqrt{2\left(1 + a_S e^{-2\Gamma\tau} + b_S e^{-\gamma_S\tau} - c_S e^{-\gamma_A\tau}\right)}}{\tau\cdot e^{-\gamma_S\tau/2}\left(e^{-\Gamma\tau}\mathscr{A}_S^- + \mathscr{A}_S^+\right)}$$

and

$$\left[\delta\omega\right]_A = \frac{\sqrt{2\left(1 + a_A e^{-2\Gamma\tau} + b_A e^{-\gamma_A\tau} - c_A e^{-\gamma_S\tau}\right)}}{\tau\cdot e^{-\gamma_A\tau/2}\left(e^{-\Gamma\tau}\mathscr{A}_A^+ + \mathscr{A}_A^-\right)}.$$

For large and even intermediate $\Gamma\tau$ these expressions resemble the one for independently decaying atoms with Γ replaced by γ_S and γ_A, respectively. The constants a, b, c and $\mathscr{A}^\pm$ are functions of the system's geometry.