A macroscopically extended coherent state

DFA, Padova

C. Braggio

January 21, 2020

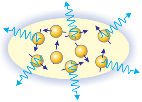
Outline

- introduce a test bed for new quantum technologies: a macro-coherent atomic state
- how we accomplished coherence among 10^{13} atoms
  - ⇒ rare-earth doped materials (Er:YSO, Er:YLF)
  - ⇒ spectroscopic properties and coherence time
- macro-coherence in superfluorescence
  - ⇒ pulsed emission dynamics
  - ⇒ average intensity of the coherent emission
- applicability to elusive particles detection: axions, neutrinos (quantum sensing in particle physics)

EMISSION BY AN ENSEMBLE OF N EXCITED ATOMS

independent atoms

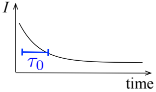
FLUORESCENCE



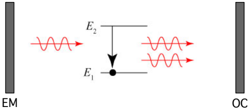
— spontaneous emission
(O) incoherent emission

$I_t \propto N$

$I = I_0 \exp(-t/\tau_0)$

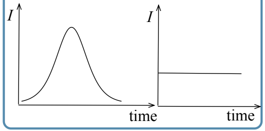


LASER/ASE (OSCILLATION AND AMPLIFICATION)



— stimulated emission
(O) coherent emission

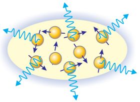
$I_t \propto N$



Emission by an ensemble of N excited atoms

independent atoms | correlated atoms

FLUORESCENCE



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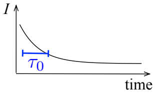

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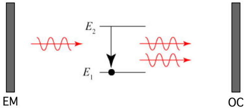

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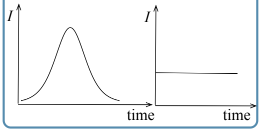
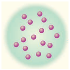


SUPERRADIANCE R. Dicke (1954)

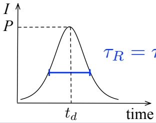
$V \ll \lambda^3$



— initial moment
(O) pulsed coherent emission

$I_t \propto N^2$

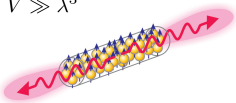
$$I(t) = 4P\,\mathrm{sech}^2\left(\frac{t-t_d}{2\tau_R}\right)$$



$\tau_R = \tau_0/N$

MACROCOHERENCE/ SUPERFLUORESCENCE

$V \gg \lambda^3$



— macro-dipole formation
(O) pulsed coherent emission

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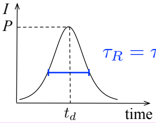
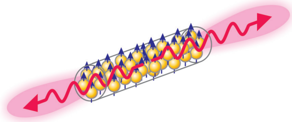


$\tau_R = \tau_0/N$

as the coherent region is limited by the emission wavelength (~1 μm) → N < 10^8 (for 10^{20} cm^{-3})

N can reach the Avogadro number

MACROCOHERENCE/
SUPERFLUORESCENCE



— macro-dipole formation
(out) bunched coherent emission

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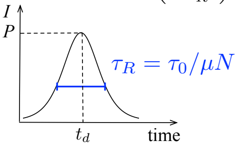
$$I(t) = 4P \,\mathrm{sech}^2 \left(\frac{t - t_d}{2\tau_R} \right)$$



$$\mu = \frac{3\Omega_0}{8\pi}, \text{ with } \Omega_0 = \frac{\lambda^2}{\pi\omega_0^2}$$

λ emission wavelength
ω_0 beam width

REQUIREMENTS

Superfluorescence, which is the signature of macrocoherence, is observed when other interactions (collisions, thermal noise, ...) do not influence the phase of **identical** atoms during emission

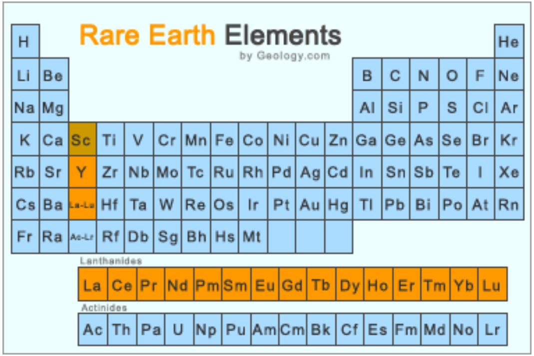
$$\tau_R < T_2^\star, \quad T_2^\star = \frac{1}{\pi\Gamma_{\mathrm{inh}}} \quad (\Gamma_{\mathrm{inh}} \text{ inhomogeneous linewidth})$$

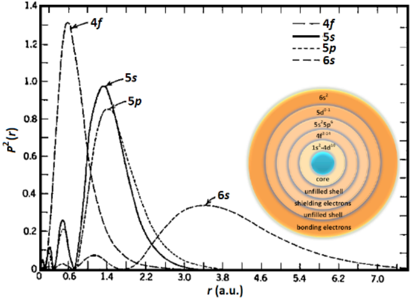
$$\tau_E < \tau_c < \tau_R < T_2, T_2^\star \quad \text{with } \tau_E = L/c \ (L \text{ sample length})$$

$\Rightarrow$ **Long coherence time** T_2:
The coherence time T_2 is defined as the time during which a single atom keeps its state unperturbed both in terms of energy level and transition dipole phase. $T_2 = \frac{1}{\pi\Gamma_h}$, with Γ_h the homogeneous linewidth.

$\Rightarrow$ **Identical emitters**:
To phase-lock, the oscillators must have similar frequencies $\Delta\phi = \Delta\omega t$.
$T_2^\star = \frac{1}{\pi\Gamma_{\mathrm{inh}}}$, with Γ_{inh} the inhomogeneous linewidth.

Rare Earth (RE)-doped materials (laser crystals, scintillators, quantum computing etc...)
Re^{3+}=[Xe]$4f^n$ (trivalent) with [Xe]=$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 5s^2 5p^6$





4f electrons:
— their wavefunctions are compressed by the $5s^2 5p^6$ outer orbitals of the Xe configuration
→ they are shielded from the environment

⇒ when doped into solid matrices, the crystal field is treated as a perturbation
⇒ when $T \lesssim 4\,K$ longest coherence times are observed

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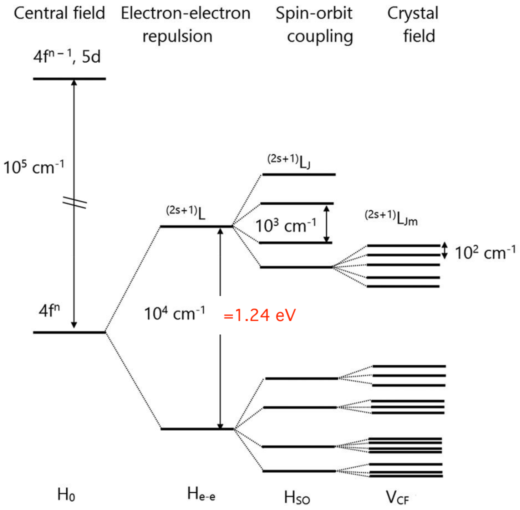

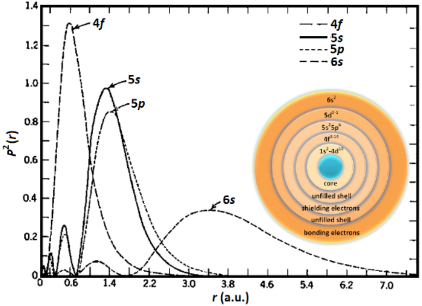

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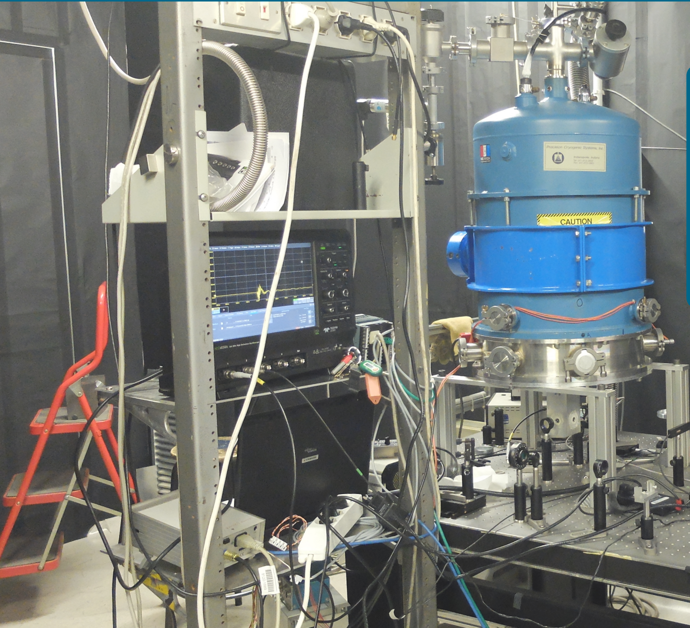
Macro-coherence in our lab

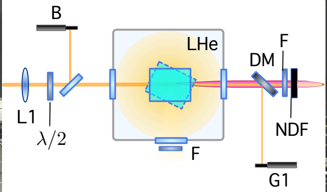
A macroscopic dipole involving $N = 4 \times 10^{12}$ atoms,
whose decay rate is enhanced by more than 1-million times
compared to τ_0 (spontaneous emission, independently emitting atoms)

C. Braggio et al., *Spontaneous formation of a macroscopically extended coherent state* arXiv:1909.00999 (2019)



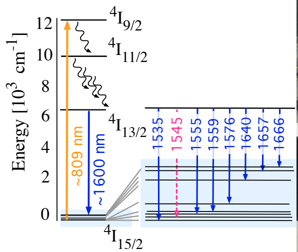
the cryogenically cooled crystal

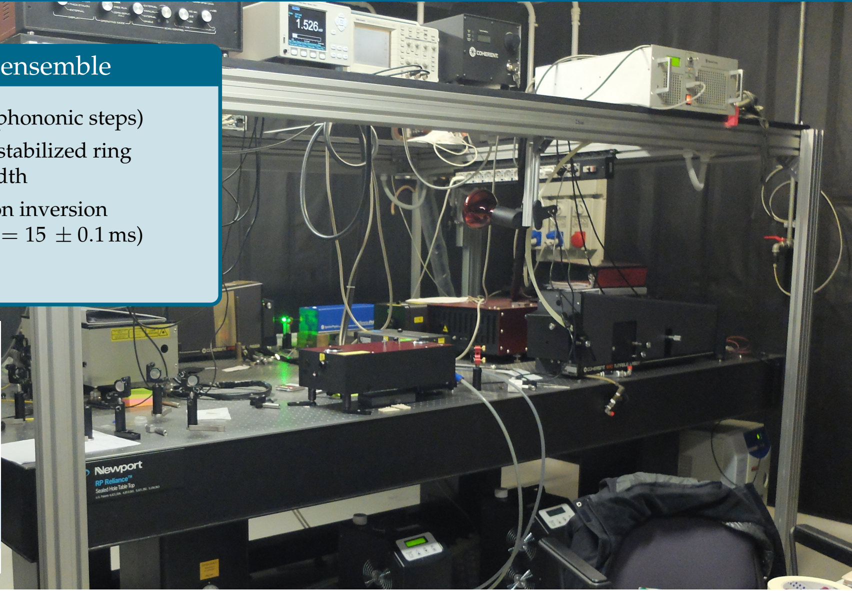
- $T \sim 1.6\,\mathrm{K}$
- $4 \times 5 \times 6.2\,\mathrm{mm}^3$-volume Er:YSO
- $0.1\% \rightarrow \mathrm{Er}^{3+}$ ions at $\sim 5\,\mathrm{nm}$ relative distance ($\sim 10^{19}\,\mathrm{ions/cm}^3$)
- pencil-shaped sample ($L < \omega_0 \ll \lambda$)



the EXCITED ATOMS ensemble

- incoherently excited (phononic steps)
- CW pump laser Ti:Sa stabilized ring cavity, 10 MHz linewidth
- steady-state population inversion between $|e\rangle$ ($^4I_{13/2}$, $\tau_0 = 15 \pm 0.1$ ms) and $|g\rangle$ $^4I_{15/2}$





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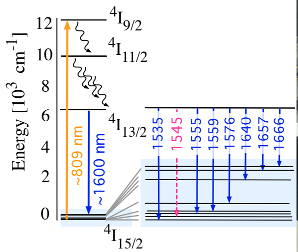
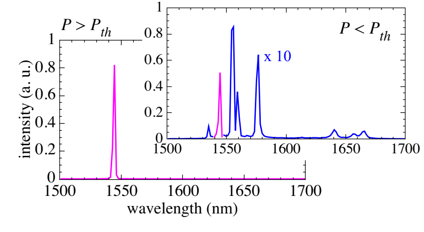
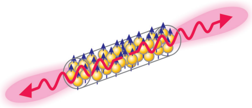




Pulsed emission dynamics

MACROCOHERENCE/ SUPERFLUORESCENCE



— macro-dipole formation
(out) bunched coherent emission

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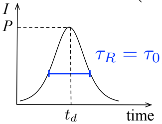
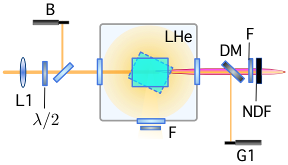


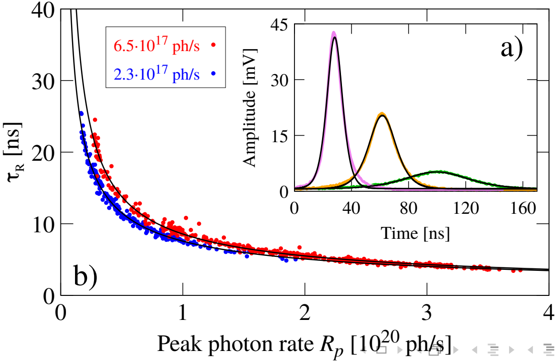
$\tau_R = \tau_0/\mu N$

$$\mu = \frac{3\Omega_0}{8\pi},\ \text{with}\ \Omega_0 = \frac{\lambda^2}{\pi\omega_0^2}$$

λ emission wavelength
ω_0 beam width

- stochastic process: Fig. a) obtained for identical excitation conditions
- signatures are those expected for pure superfluorescence regime (Fig. b)
  (sech^2-shape and $1/\sqrt{P}$ scaling of τ_R)





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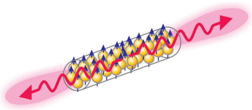

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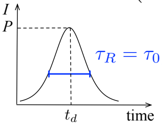
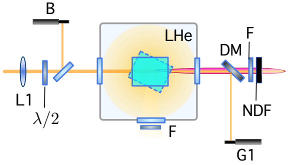


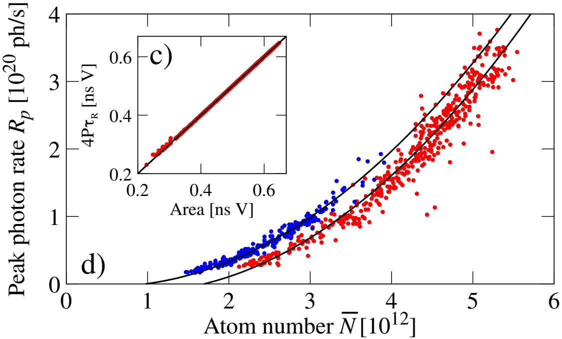
$\tau_R = \tau_0/\mu N$

$$\mu = \frac{3\Omega_0}{8\pi}, \text{ with } \Omega_0 = \frac{\lambda^2}{\pi\omega_0^2}$$

λ emission wavelength
ω_0 beam width

- for higher laser fluence (red dots) $\rightarrow$ greater N (correlated atoms)
- signatures are those expected for pure superfluorescence regime (N^2-dependence of intensity)

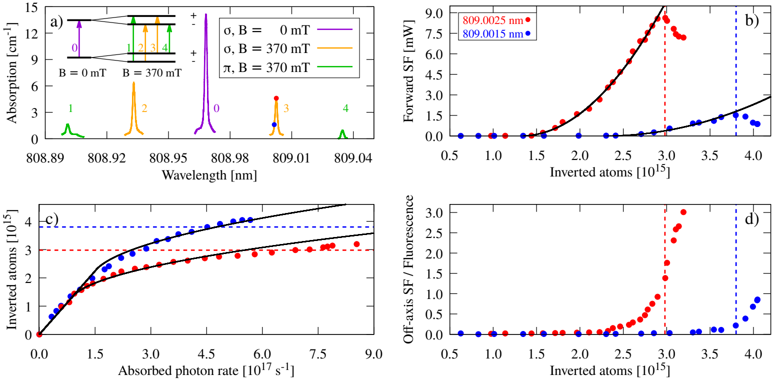




Average forward emission intensity

spontaneous selection of a subensemble of $\sim 10^{12}$ "identical" atoms

from a steady state population inversion of 10^{15} atoms



→ the demonstrated control of the process is crucial to elaborate a strategy to further increase N

OBJECTIVE

to introduce a new paradigm in elusive particle detection, in which the smallest of interaction rates is intrinsically amplified by a mechanism of macrocoherence

FIELD OF APPLICATION

- axion searches: conventional haloscopes, but also blooming of new concept, table-top experiments (complementary effort)
- neutrino physics (accelerators, big detectors)

Prior: macro-coherent amplification mechanism [M. Yoshimura, N. Sasao, M. Tanaka, Phys. Rev. A 86, 013812 (2012)] in the Radiative Emission of Neutrino Pair (RENP) [M. Yoshimura, Phys. Rev. D 75, 113007 (2007)]

limited by QED backgrounds

Emission rate enhancement via MACROCOHERENCE

Coherent emission of particles (in a generic process involving axions/neutrinos and photons) from a collective ensemble of target (and excited) atoms is characterised by a quantum mechanical rate:

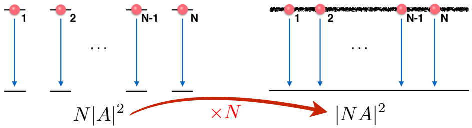
$$|\sum_{n=1}^{N} e^{i\sum_{m=1}^{M}\vec{k}_m\cdot(\vec{r}-\vec{r_n})}\mathcal{A}_n(\vec{r},t)|^2$$

$\vec{k}_m$ momenta of the emitted particles
r_n atom position
$\mathcal{A}_n(\vec{r},t)$ atomic amplitude part, slowly varying with $\vec{r_n}$ in the wavelength scale of $\vec{k_i}$

one emitted photon $(m = 1)$ as in SF/SR:

$|e\rangle \to |g\rangle + \gamma$

$\mathcal{R}_\gamma \propto |\sum_{n=1}^{N} e^{i\vec{k}\cdot(\vec{r}-\vec{r_n})}\mathcal{A}_n(\vec{r},t)|^2 \propto N^2$



Thanks to:

C. Braggio, F. Chiossi, N. Crescini
University of Padova and INFN

G. Carugno,
INFN Padova

A. Ortolan, G. Ruoso,
INFN-LNL

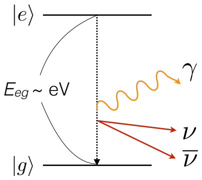
Group funding ID

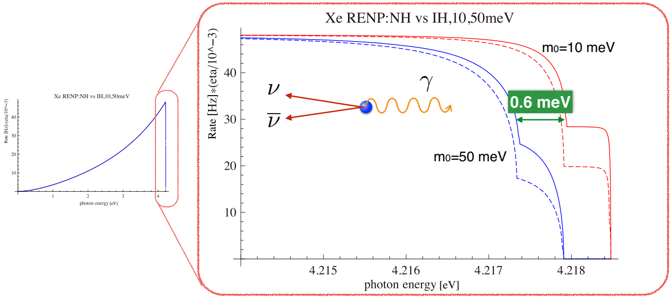
INFN gr2 (QUAX), gr5 (AXIOMA call),
STEMS-ATTRACT (EU Commission)

Radiative emission of neutrino pairs

A. Fukumi *et al* Prog. Theor. Exp. Phys. (2012), 04D002

- radiative emission of neutrino pairs from excited atoms decaying to the ground level
- photon spectrum reveals: absolute mass, NH/IH, Majorana-Dirac, CP phases (α, $\beta - \delta$) ($\omega_{eg} \sim m_\nu$, in laser spectroscopy sub-meV energy resolution)
- rate of the RENP process $\sim 1/(10^{26}$years) for single atom (current sensitivity of $0\nu\beta\beta$)





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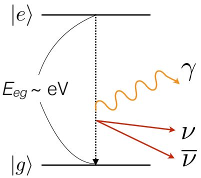
→ coherence between $|e\rangle$ and $|g\rangle$ via Raman adiabatic process

- + trigger laser



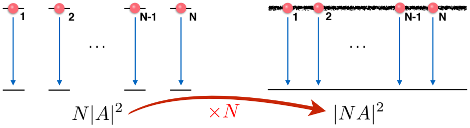
three emitted particles ($m = 3$): $|e\rangle \to |g\rangle + \gamma + \nu_i + \nu_j$

$$\mathcal{R}_\gamma \propto |\sum_{n=1}^{N} e^{i(\vec{k_1}+\vec{k_2}+\vec{k_3})\cdot(\vec{r}-\vec{r_n})} \mathcal{A}_n(\vec{r},t)|^2 \propto N^2$$

$$\text{if } \vec{k_1}+\vec{k_2}+\vec{k_3}=0$$

LIMITATIONS

strong QED backgrounds (McQn, n involved photons)



AXION DETECTION