A cavity-mediated collective quantum effect in sonoluminescing bubbles



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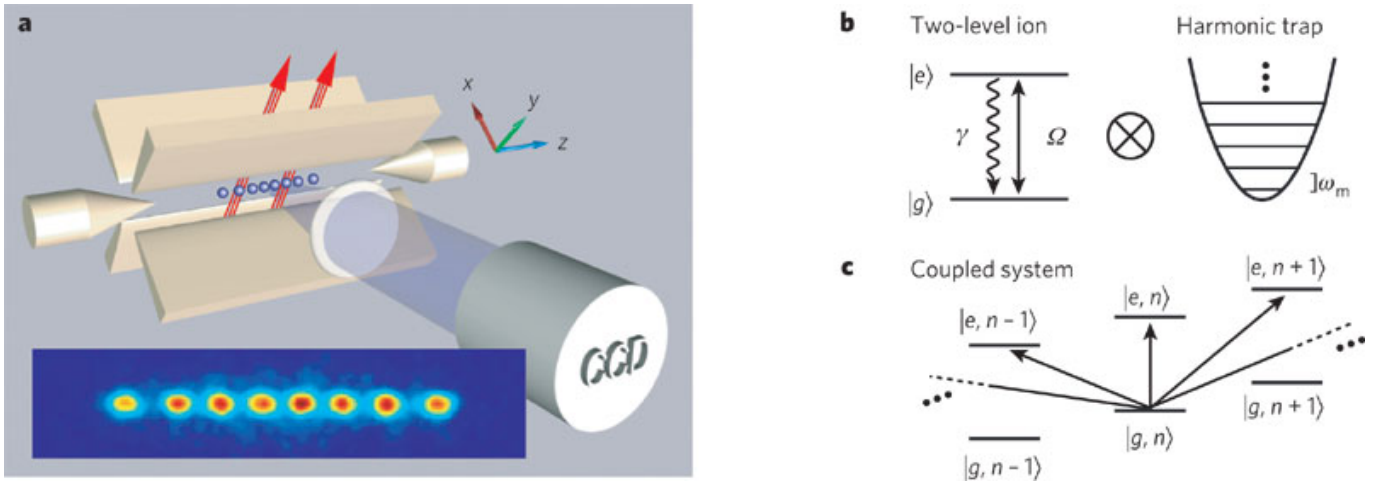
I

Laser cooling of individually trapped ions [1,2]

[1] Stenholm, Rev. Mod. Phys. **58**, 699 (1986).

[2] Blake, Kurcz, Saleem, and Beige, Phys. Rev. A **84**, 053416 (2011).

A typical ion trap experiment

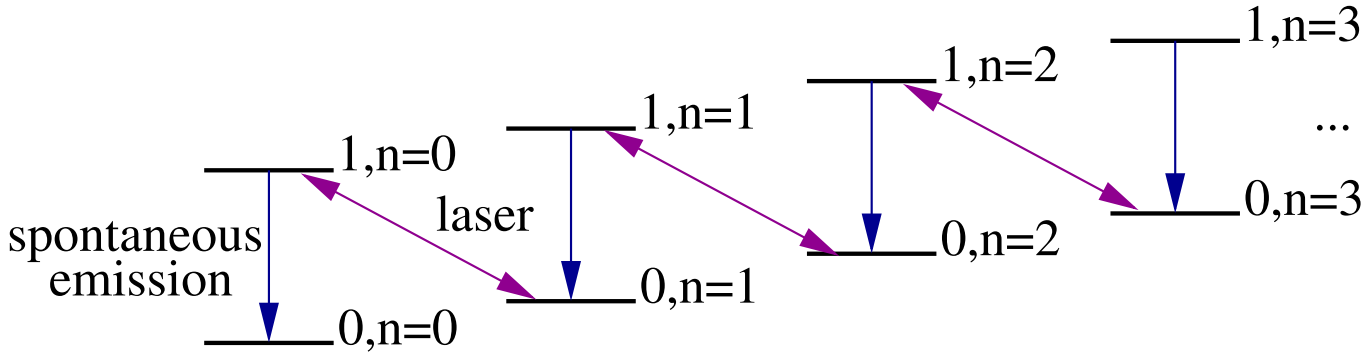


- A laser excites the ions with a frequency $\omega_{\mathrm{L}} = \omega_0 - \nu$.
- The emission of a photon removes one phonon permanently from the motion of the ion.

$\Rightarrow$ **cooling to nanoKelvin temperatures**

Relevant level scheme

We consider the motion of the ion as quantised.
The phonons are the particles of the corresponding harmonic oscillator Hamiltonian.



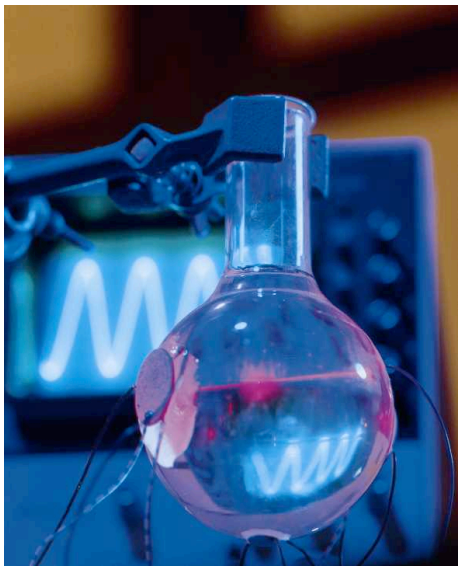
Eventually, the ion decays spontaneously into its ground state with zero phonons, where it no longer sees the laser driving.

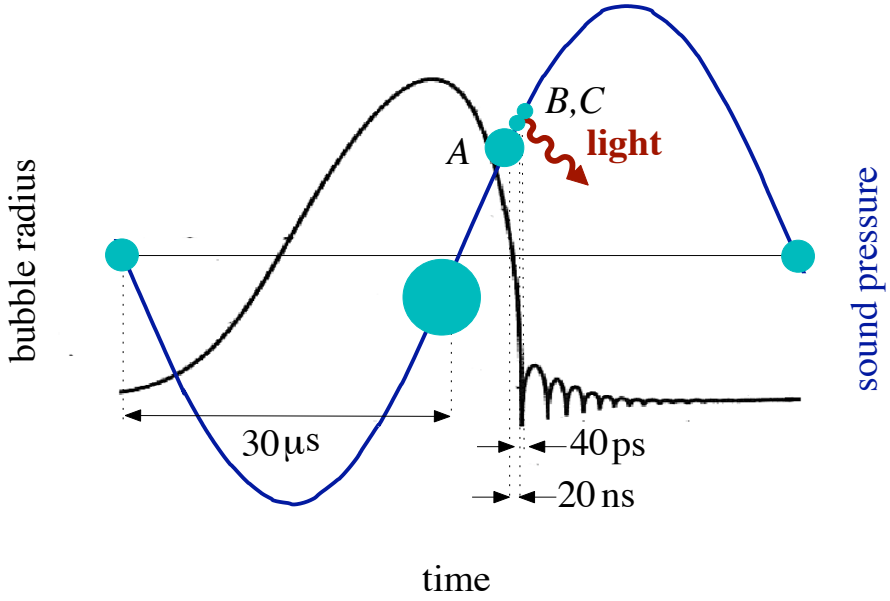
II

Comparison with sonoluminescence experiments [1]

[1] Kurcz, Capolupo, and Beige, New J. Phys. **11**, 053001 (2009).

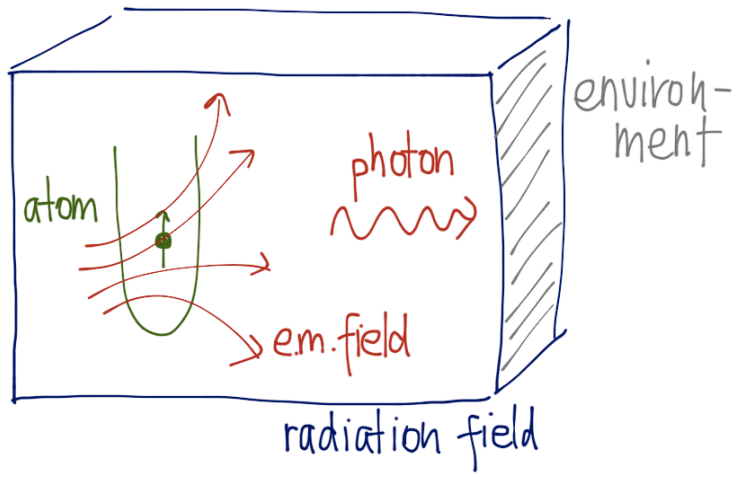
Single bubble sonoluminescence





There are many similarities between the collapse phase of sonoluminescence experiments and ion trap experiments.

A naive quantum optics approach to sonoluminescence [1]



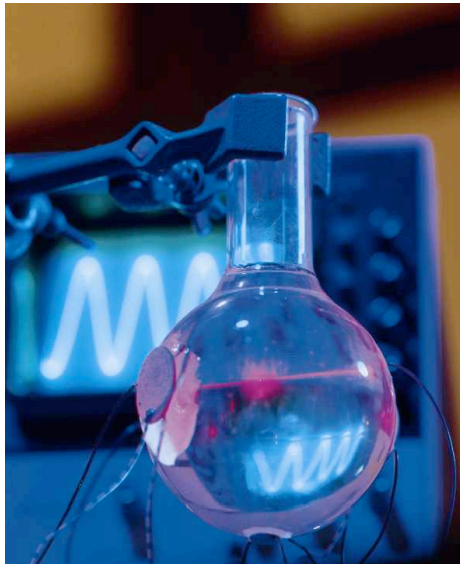
- We replaced the ion by an atom.
- We replaced the cooling laser by an electric field gradient.
- Heating due to the creation of a phonon being more likely than its annihilation:

$$b^\dagger |m\rangle = \sqrt{m+1}\,|m+1\rangle$$
but $\quad b\,|m\rangle = \sqrt{m}\,|m-1\rangle$

Problem: No collective enhancement for many atoms in the bubble.
The described effect relatively small.

[1] Kurcz, Capolupo, and Beige, New J. Phys. **11**, 053001 (2009).

Motivating questions [1,2]



- What exactly happens during the bubble collapse phase? Is there any additional heating?
- What is the role of the atoms? Why are some species more efficient than others?
- What is the origin of the sudden photon emission?
- Why do we need the formation of a plasma?

How to best control sonoluminescence experiments with lasers?

[1] Suslick and Flannigan, Annu. Rev. Phys. Chem. **59**, 659 (2008).
[2] Khalid, Kappus, Weninger and Putterman, Phys. Rev. Lett. **108**, 104302 (2012).

III

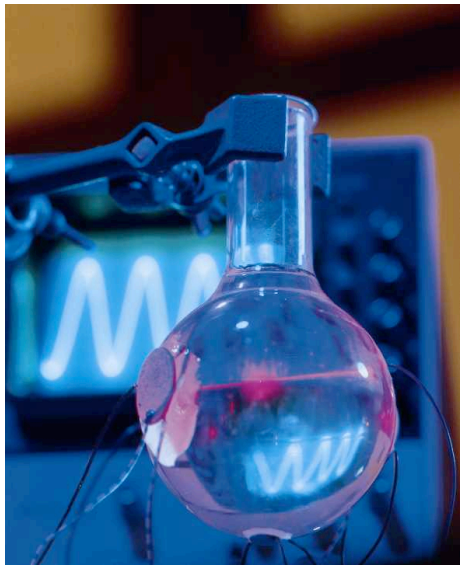
A more realistic quantum model for sonoluminescence [1,2,3]

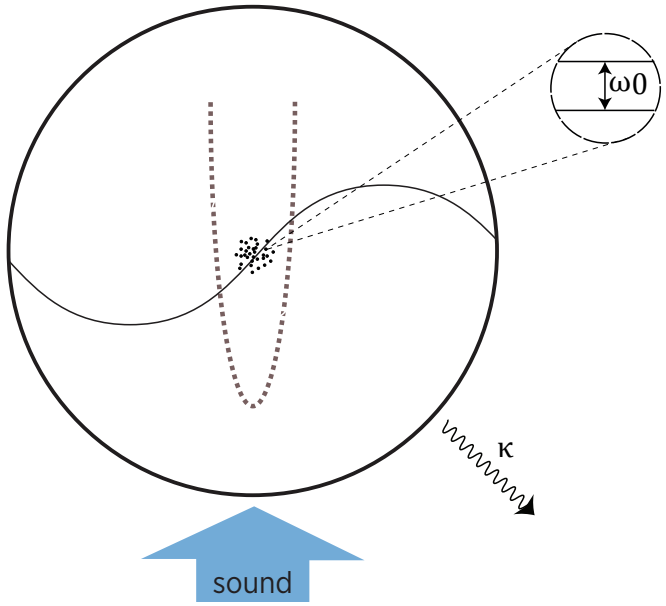
[1] Kim and Beige, Conf. Proc. for *Cavitation 2015*, arXiv:1508.07160 (2015).

[2] Kim, *Collectively enhanced quantum light-matter interactions*, Doctoral Thesis, University of Leeds (2015).

[3] Kim and Beige, *Cavity-mediated collective heating in opaque sonoluminescing bubbles*, in preparation (2016).

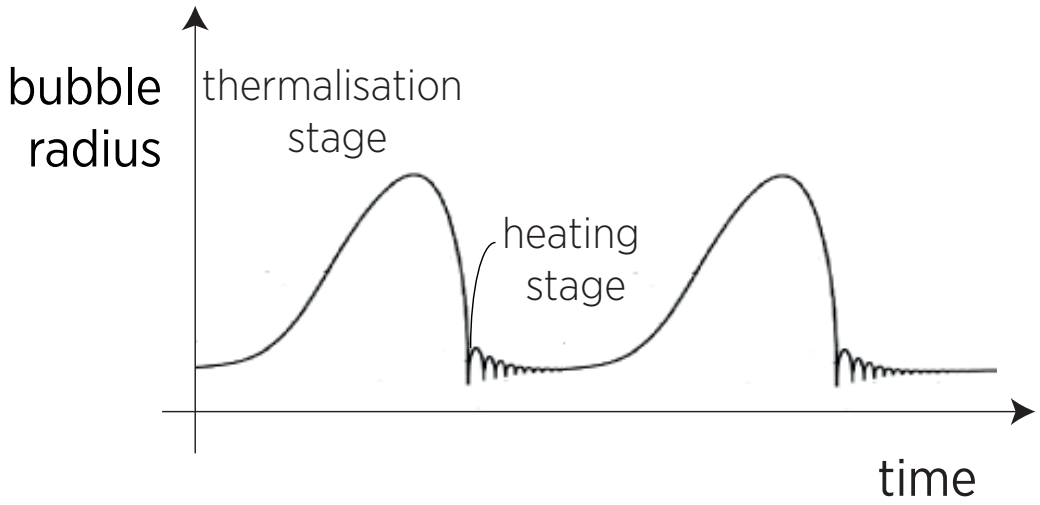
Schematic view of the experiment





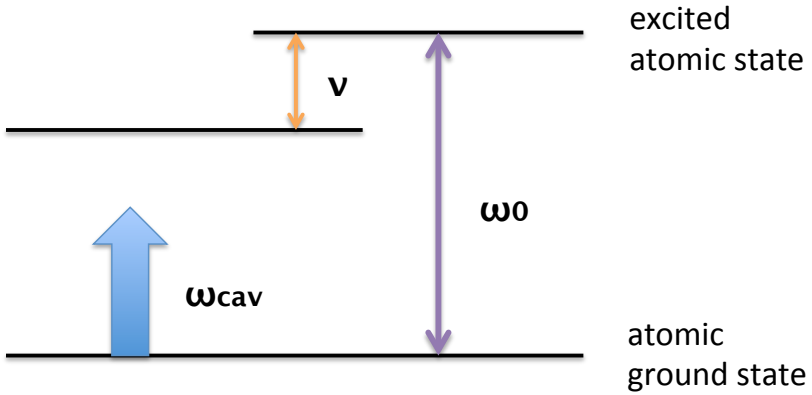
We now consider the atoms, their motion and the electromagnetic field inside the bubble as quantised. Opaque bubble walls acts as the mirrors of a so-called optical cavity.

Thermalisation stage



- The atoms evolve adiabatically and remain in a thermal state.
- As their temperature increases, the atoms become more excited.
- Collisions between the atoms result in long-range correlations due to the exchange of electronic excitation and phonons.
- The atoms do not see the cavity field.

Collapse (or heating) stage



- Cavity frequency increases very rapidly, as bubble shrinks.
- The atoms suddenly see the electromagnetic field inside the bubble.
- Transfer of energy from atoms into cavity results in photon emissions.
- Light pulse is accompanied by phonon creation!

$\Rightarrow$ **heating during every bubble collapse**

Quantum dynamics of the system [1,2,3]

Hamiltonian:

$$
\begin{aligned}
H &= H_{\mathrm{free}} + H_{\mathrm{int}} \\
H_{\mathrm{free}} &= H_{\mathrm{atom}} + H_{\mathrm{vib}} + H_{\mathrm{cav}} \\
H_{\mathrm{int}} &= H_{\mathrm{coll}\,1} + H_{\mathrm{coll}\,2} + H_{\mathrm{atom-cav}}
\end{aligned}
$$

Spontaneous emission:

$$
\dot{\rho}_{\mathrm{I}} = -\frac{\mathrm{i}}{\hbar}\left[H_{\mathrm{I}}, \rho_{\mathrm{I}}\right] + \tfrac{1}{2}\kappa\left(2\,c\rho_{\mathrm{I}}c^{\dagger} - c^{\dagger}c\rho_{\mathrm{I}} - \rho_{\mathrm{I}}c^{\dagger}c\right)
$$

[1] Kim and Beige, Conf. Proc. for *Cavitation 2015*, arXiv:1508.07160 (2015).

[2] Kim, *Collectively enhanced quantum light-matter interactions*, Doctoral Thesis, University of Leeds (2015).

[3] Kim and Beige, *Cavity-mediated collective heating in opaque sonoluminescing bubbles*, in preparation (2016).

Effective dynamics during collapse stage

- Suppose the excitation of atomic states remains low.
- Suppose collisions remain negligible during collapse stage. [1]

$$\dot{m} = \dot{\zeta} = a_1 \, \mu\zeta \, , \quad \dot{\mu} = -a_2 \, \mu\zeta$$

$$\zeta \equiv \frac{1}{N(N-1)} \sum_{i=1}^{N} \sum_{j \neq i} \left\langle b_i^\dagger b_j \right\rangle \, , \quad \mu \equiv \frac{4}{N(N-1)} \sum_{i=1}^{N} \sum_{j \neq i} \left\langle \sigma_i^+ \sigma_j^- \right\rangle$$

$$a_1 \equiv \frac{16N(\eta g)^2 \nu\kappa\Delta}{\kappa^4 + 16(\Delta^2 - \nu^2)^2 + 8\kappa^2(\Delta^2 + \nu^2)}$$

$$a_2 \equiv \frac{8N(\eta g)^2 \kappa(\kappa^2 + 4\nu^2 + 4\Delta^2)}{\kappa^4 + 16(\Delta^2 - \nu^2)^2 + 8\kappa^2(\Delta^2 + \nu^2)}$$

[1] Kim, *Collectively enhanced quantum light-matter interactions*, Doctoral Thesis, University of Leeds (2015).

Change of the mean phonon number m

- The heating rate during each collapse stage now scales as N.
- The heating rate has a resonance (a maximum) at $\omega_0 - \omega_{\mathrm{cav}} = \nu$.
- There is a maximum amount by which m can change during each bubble collapse stage: [1]

$$\Delta m \propto \frac{\nu}{\kappa^2} \quad \text{with} \quad \nu \propto \frac{1}{M(\Delta x)^2}, \quad (\Delta x)^3 \propto \frac{1}{N}$$

ν: phonon frequency
M: atomic mass
Δx: position uncertainty of trap
N: particle number

[1] Kim, *Collectively enhanced quantum light-matter interactions*, Doctoral Thesis, University of Leeds (2015).

Qualitative predictions

Noble gas atoms: [1]

- If there was an ideal gas in the bubble, all atoms would yield the same amount of sonoluminescence.
- Here, noble gas atoms with large atomic masses produce light with higher intensity and are heated more. For example, Xenon gets hotter than Argon and Helium.

Ionic liquids: [2]

- Ionic liquids are expected to yield much stronger heating effects and to emit significantly more light than noble gas atoms.

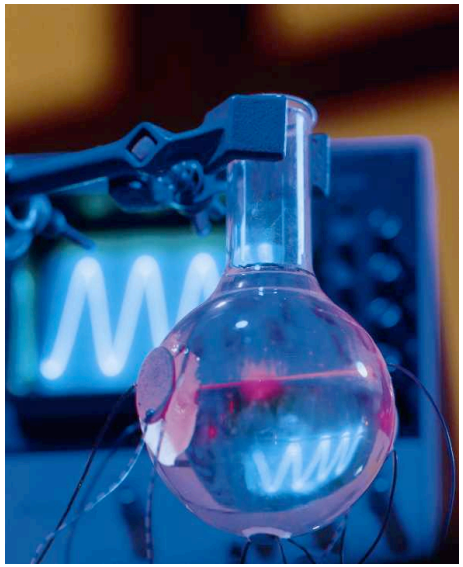
[1] Kim, *Collectively enhanced quantum light-matter interactions*, Doctoral Thesis, University of Leeds (2015).

[2] Flannigan, Hopkins and Suslick, Journal of Organometallic Chemistry **690**, 3513 (2005).

IV

Final comments

Conclusions



- We discussed a collective quantum effect, which heats atomic species during the collapse stage of sonoluminescence experiments.
- Most of the photon emission comes directly from the bubble cavity.
- Plasma formation needed before quantum heating can occur.
- Ionic liquids show much stronger effects than noble gas atoms.

More work needs to be done to see, how best to control sonoluminescence with lasers.