Zsonglőrködés kvantumrészecskékkel

Kutatásaink a 2012. évi Nobel díj fényében

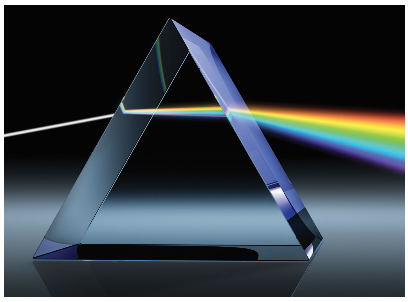
Domokos Péter

Wigner Fizikai Kutatóközpont, Magyar Tudományos Akadémia

MAFIHE Téli Iskola, ELTE TTK, 2014. február 3., Budapest

Fázismanipuláció a fény-anyag kölcsönhatásban

Tartalomjegyzék



Serge Haroche, 1998 Ecole Normale Supérieure

Kísérleti kvantummechanika, Nobel díj 2012.

Egyedi kvantumrendszerek manipulációja

„Serge Haroche and David J. Wineland have independently invented and developed methods for measuring and manipulating individual particles while preserving their quantum-mechanical nature, in ways that were previously thought unattainable."

Kölcsönhatás

- kétrészecskés rendszer
- kvantumosan koherens csatolás
- kontrollált és megfigyelhető

Ioncsapda

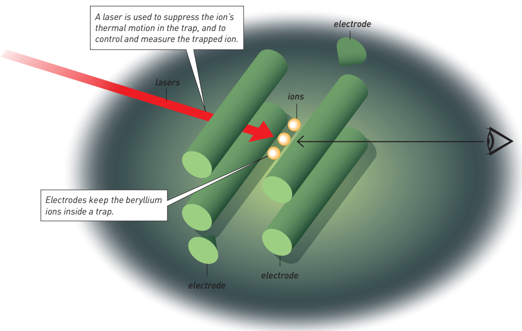


Figure 2. In David Wineland's laboratory in Boulder, Colorado, electrically charged atoms or ions are kept inside a trap by surrounding electric fields. One of the secrets behind Wineland's breakthrough is mastery of the art of using laser beams and creating laser pulses. A laser is used to put the ion in its lowest energy state and thus enabling the study of quantum phenomena with the trapped ion.

Rezonátor

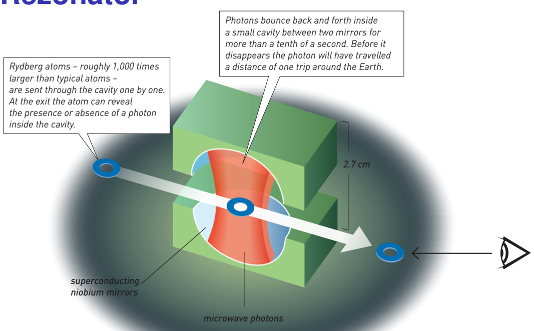
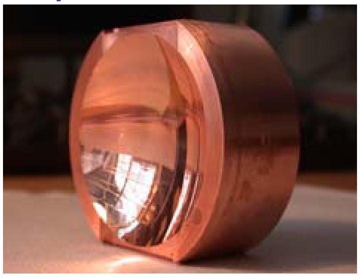


Figure 3. In the Serge Haroche laboratory in Paris, in vacuum and at a temperature of almost absolute zero, the microwave photons bounce back and forth inside a small cavity between two mirrors. The mirrors are so reflective that a single photon stays for more than a tenth of a second before it is lost. During its long life time, many quantum manipulations can be performed with the trapped photon without destroying it.

from www.nobelprize.org

Rezonátoros kvantumelektrodinamika

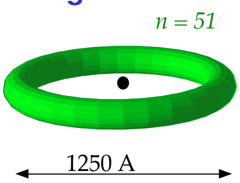
Szupravezető Nb tükör

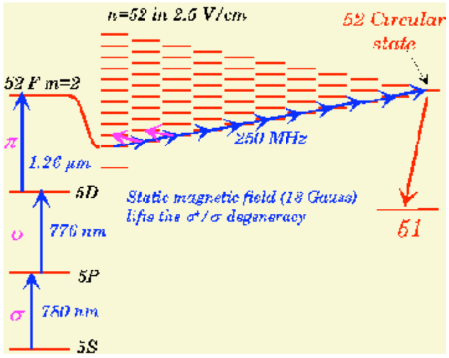


Rezonátor

- $T_{\text{cav}} = 130ms$ (hideg kell $T = 0.8$K)
- $Q = 4.2 \times 10^{10}$, $\mathcal{F}/\pi = 10^9$ round-trip

Circuláris Rydberg atom

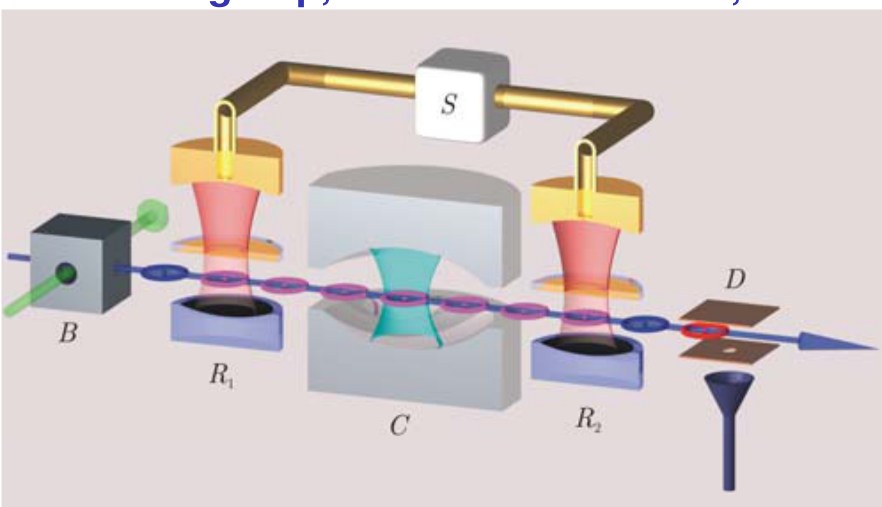




- $\omega_A = 51.099$ GHz, $T_{\text{at}} = 30ms$
- hangolhatóság (Stark effektus)
- sebességszelekció, nincs hűtés
- detektálás állapotszelektív ionizációval

Kísérleti elrendezés

Haroche-Raimond group, Lab. Kastler Brossel, ENS Paris)



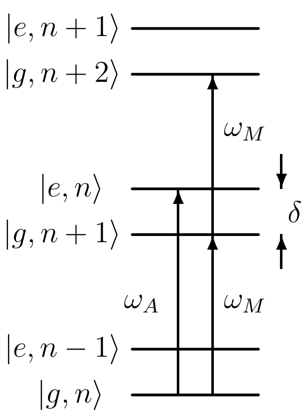
Jaynes-Cummings model

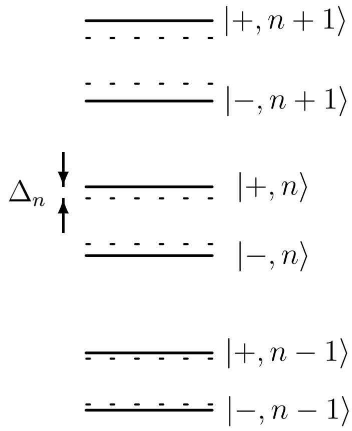
$$H_{JC} = \hbar\omega_C a^\dagger a + \hbar\omega_A \sigma_z + \hbar\Omega(a^\dagger \sigma_- + \sigma_+ a)$$

Jaynes-Cummings spectrum

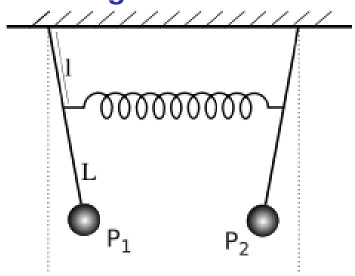
$$H_{JC} = \hbar\omega_M a^\dagger a + \hbar\omega_A \sigma_z + \hbar\Omega(a^\dagger\sigma_- + \sigma_+ a)$$

Felöltöztetett állapotok

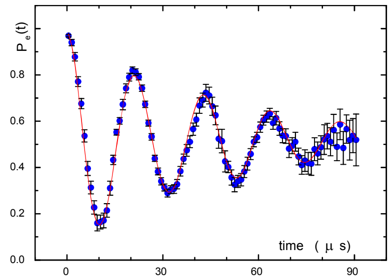




Kettős inga



Rabi-oszcilláció



Erős csatolás

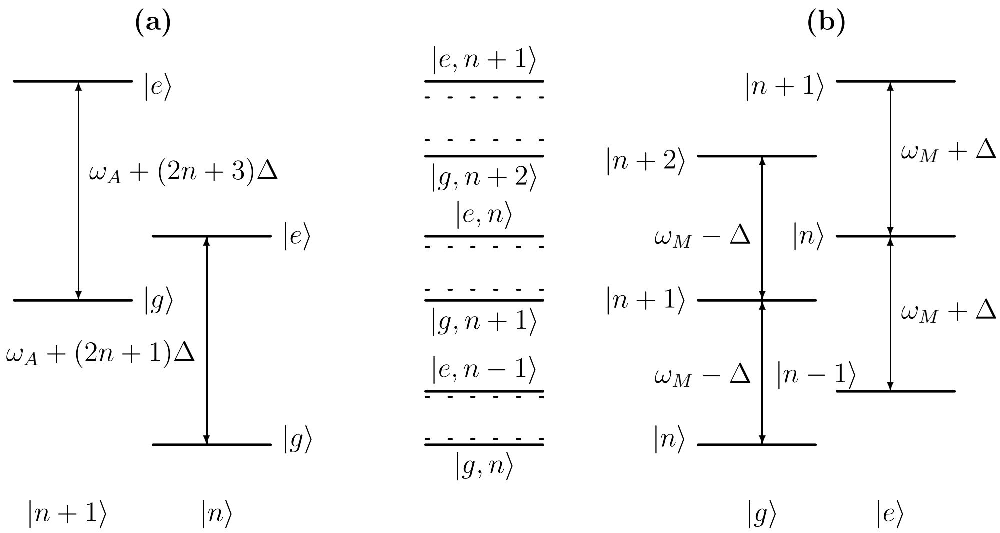
$$\delta = \omega_A - \omega_M$$

$$\Delta_n = \sqrt{(n+1)\Omega^2 + \frac{\delta^2}{4}}$$

$$\Omega^{-1} = 3\,\mu\text{s}$$
$$\gamma^{-1} = 32\text{ms}$$
$$\kappa^{-1} = 133\text{ms}$$

Mi történik, ha a két inga hossza nagyon különböző?

Nemrezonáns fény-anyag kölcsönhatás



$$|\omega_A - \omega_C| \gg \Omega, \kappa, \gamma$$

$$\Delta = \frac{\Omega^2}{\delta}$$

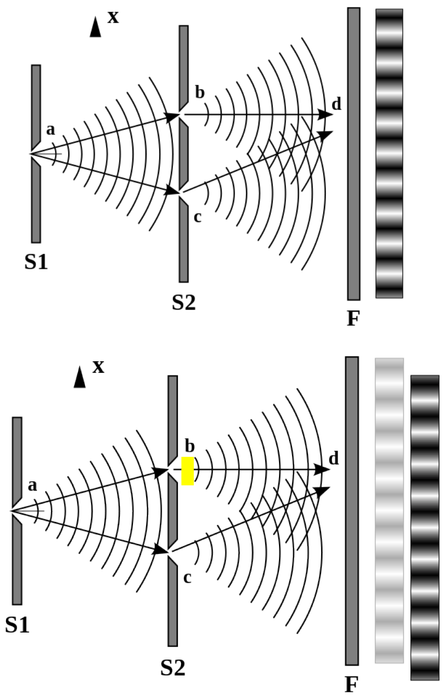
- nincs energiacsere, de az energiaszintek eltolódnak

$$H/\hbar = \omega_M a^\dagger a + \omega_A \sigma_z + \frac{\Omega^2}{\delta}\left[|e\rangle\langle e| \otimes (a^\dagger a + 1) - |g\rangle\langle g| \otimes a^\dagger a\right]$$

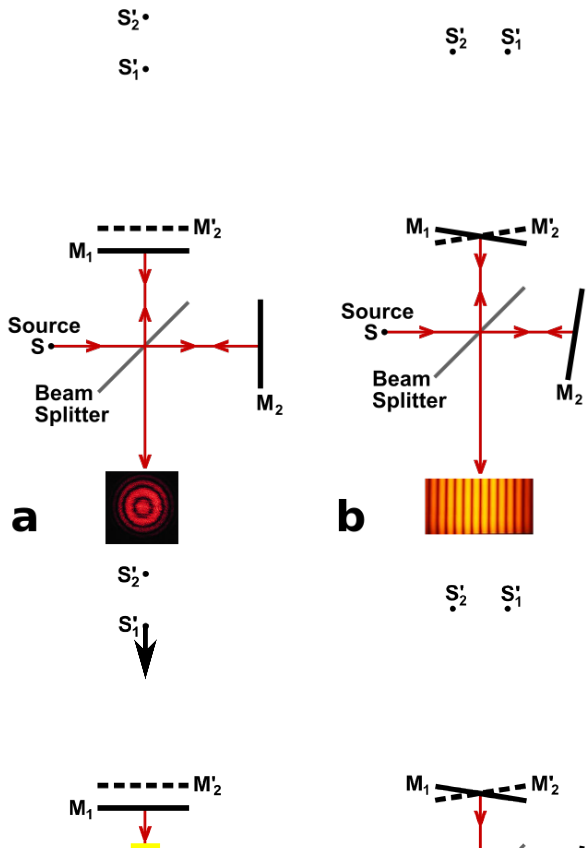
- hullámfüggvények fázisa eltolódik a kölcsönhatás következtében
- atom $\rightarrow$ EM mező: törésmutató
- EM mező $\rightarrow$ atom: potenciál

Interferométerek: fázis $\longrightarrow$ intenzitás

Hullámfrontosztás
Young interferométer

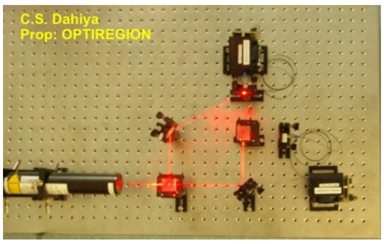


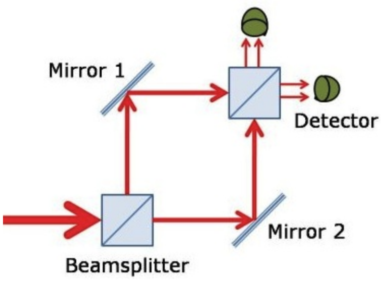
Nyalábosztás
Michelson interferométer



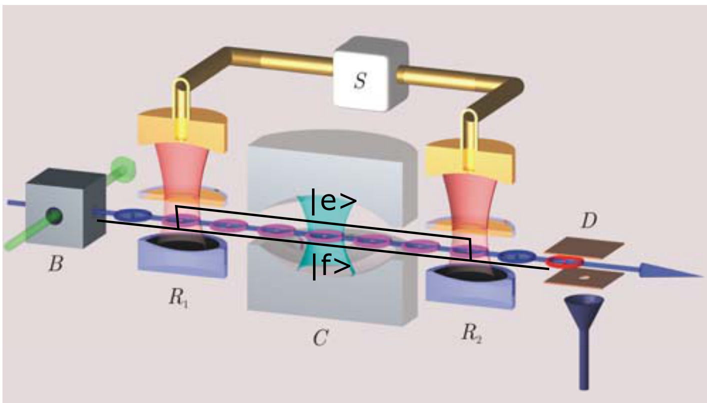
Interferométer az elektron hullámfüggvényre

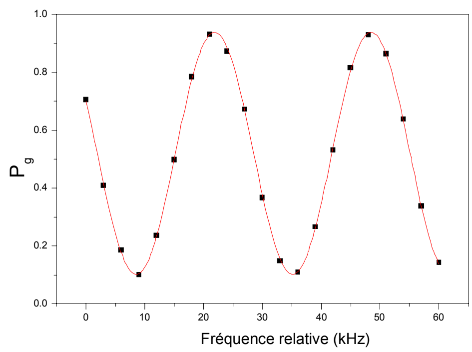
Mach-Zehnder



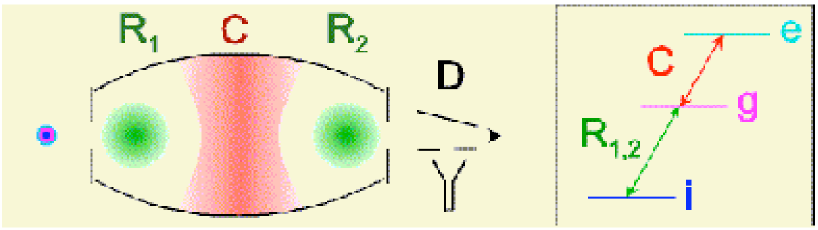


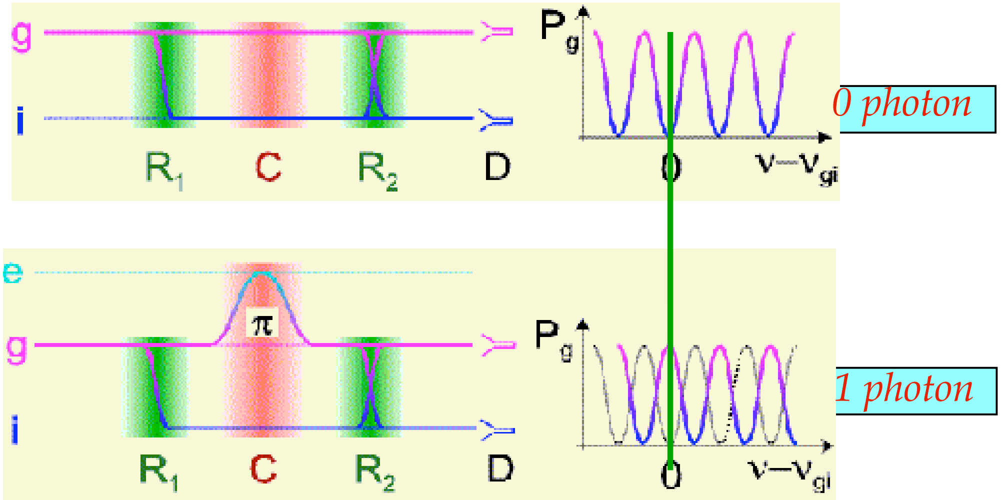
Ramsey (1989 Nobel díj)





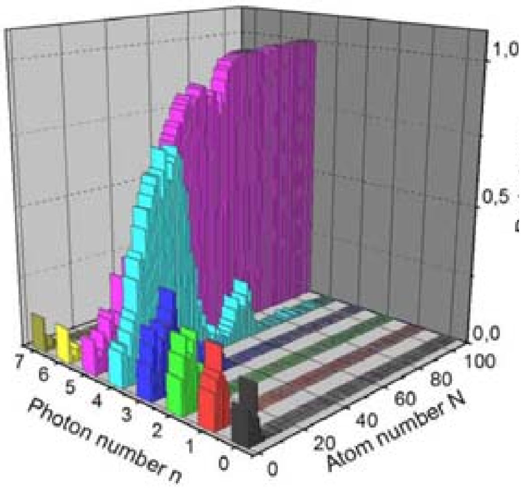
Fotonmérés elnyelés nélkül

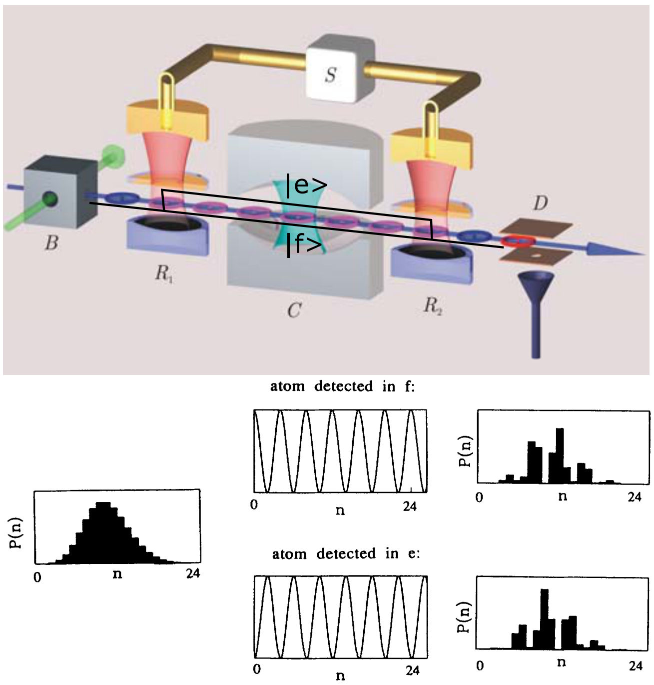




Fotonszámmérés és preparálás

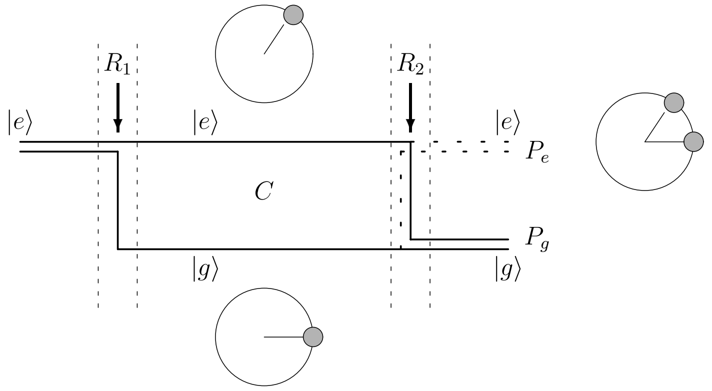
n=0 . . . 7



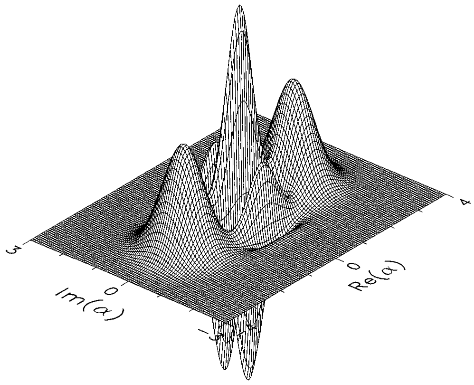


Kvantumállapot tervezés

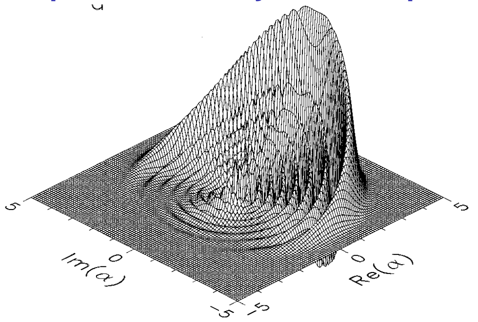
Visszahatás a mezőre (fázisára)



Koherens állapotok szuperpozíciója



Amplitúdó összenyomott állapot

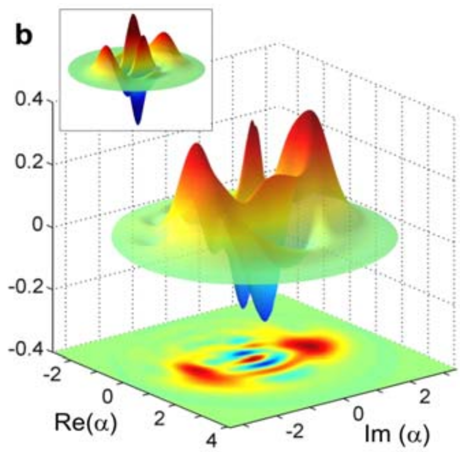


Hilbert tér feltérképezése

- [Janszky, Domokos, Ádám, Physical Review A (1993)]: Coherent states on a circle and quantum interference
- [Szabó, Ádám, Janszky, Domokos, Physical Review A (1996)]: Construction of quantum states of the radiation field by discrete coherent-state superpositions

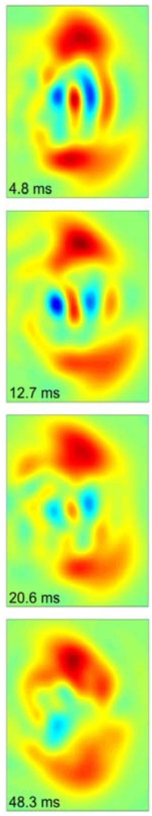
Dekoherencia időfelbontott mérése

Páratlan Schrödinger-macska állapot



[Deléglise et al., Nature (2007)]

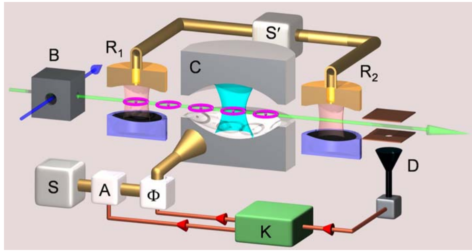
Dekoherencia



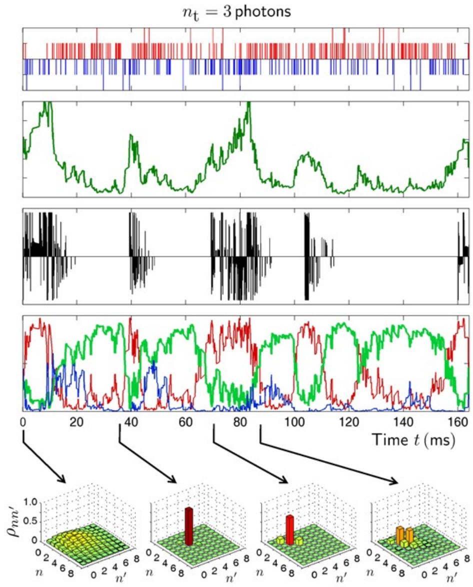
Statisztikus kvantumfizikai elméletek

- dekoherencia időfelbontott mérése: tesztelhetőség
- kvantumtrajektória módszer (MCWF)
- szemléletes kép + numerikus hatékonyság
- [Vukics, Janszky, Domokos, J. Phys. B (2005)] ⇒ C++QED

Kvantumállapot stabilizálása visszacsatolással

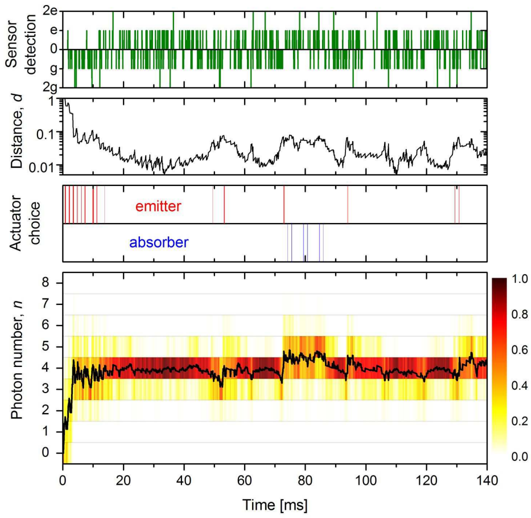


Klasszikus forrás



Sayrin et al.Nature2011

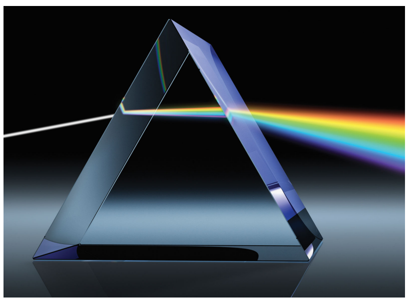
Kvantumos küldönc



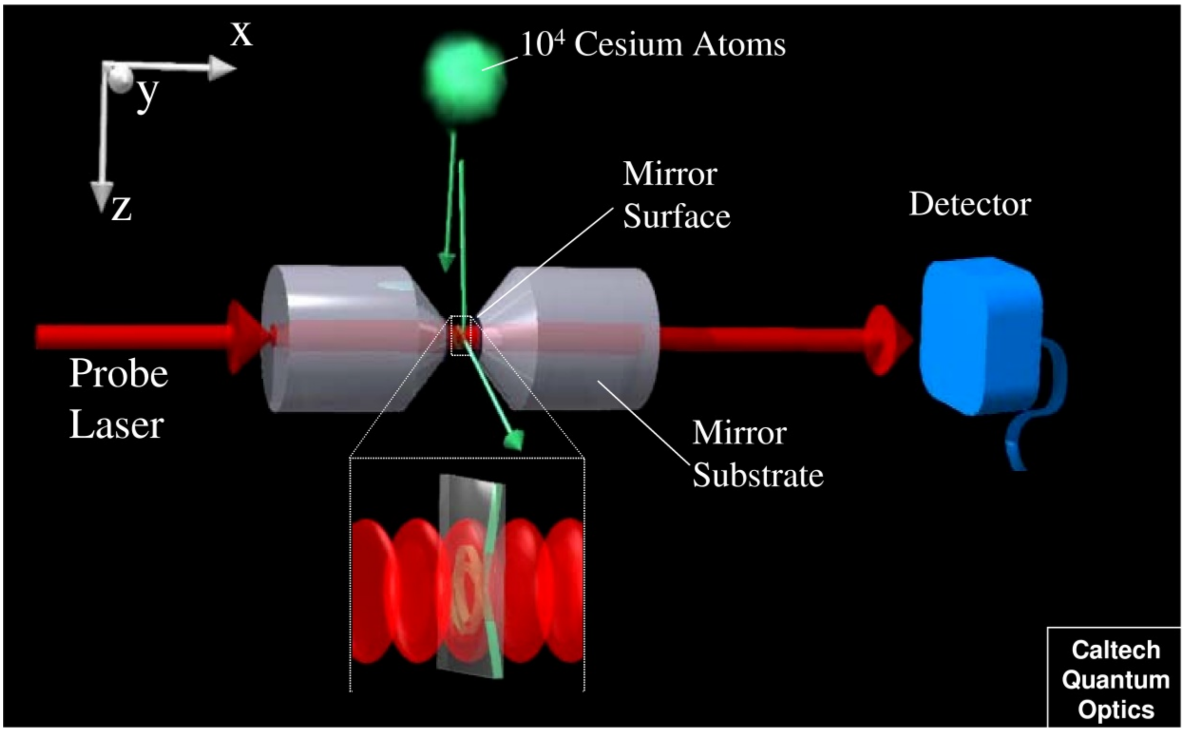
Zhou et al.Phys. Rev. Lett.,2012

Fázismanipuláció a fény-anyag kölcsönhatásban

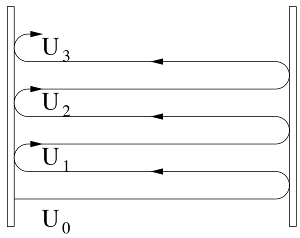
Tartalomjegyzék



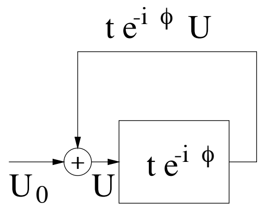
Optikai rezonátoros QED

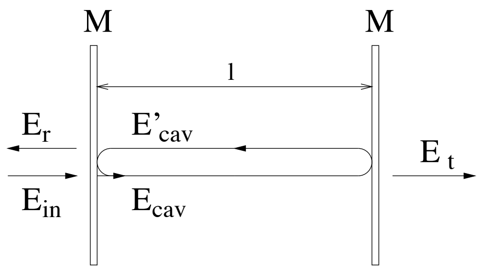


Fabry-Pérot interferométer



U= $U_0 + U_1 + U_2 + \ldots$





Önkonzisztens stacionárius megoldás

$$\left.\begin{array}{lcl} E_r & = & \sqrt{R}e^{i\theta}E_{\rm in} + i\sqrt{T}E'_{\rm cav} \\ E_{\rm cav} & = & i\sqrt{T}E_{\rm in} + \sqrt{R}e^{-i\theta}E'_{\rm cav} \\ E'_{\rm cav} & = & e^{i\phi}\sqrt{R}e^{i\theta}E_{\rm cav} \end{array}\right\} \quad \frac{|E_{\rm cav}|^2}{|E_{\rm in}|^2} = \left|\frac{i\sqrt{T}}{1-(1-T)e^{i\phi}}\right|^2 = \frac{T^{-1}}{1+\left(\frac{\mathcal{F}}{\pi}\right)^2\sin^2\frac{\phi}{2}}$$

$$\text{Finesse: } \mathcal{F} = \frac{\pi\sqrt{1-T}}{T}$$

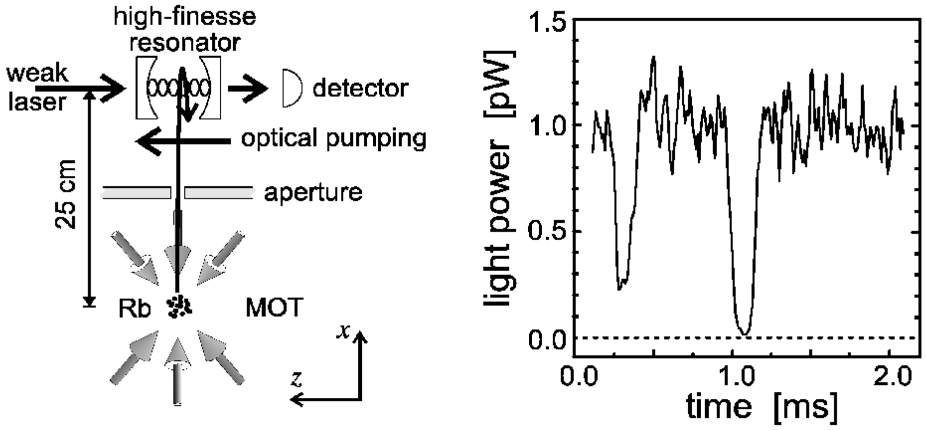
Rezonancia ↔ módus (Lorentz)

$$n_{\rm cav} = \frac{2\kappa j_{\rm in}}{(\omega-\omega_\nu)^2+\kappa^2}$$

$\kappa = Tc/2l\,, \phi = \omega 2l/c\,, j_{\rm in} = \epsilon_0|E_{\rm in}|^2 cA/\hbar\omega$

Egyetlen atom detektálása

Max-Planck Intézet, Garching, 1999

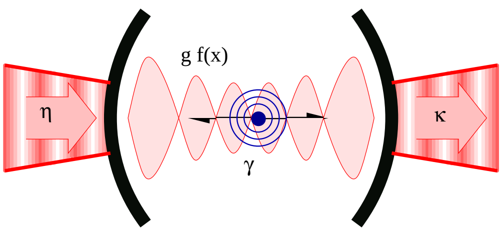


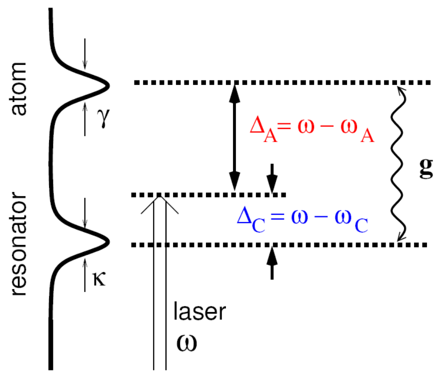
rezonátor
$\mathcal{F} \approx 10^6$

Kérdések

- Hogyan mozog az atom amikor a rezonátorban van?
- Meg lehet-e növelni a kölcsönhatás idejét (csapdázás)?
- Lehet-e az atom zajos mozgását hűteni?

Erős csatolás atom és módus között





Semiclassical model

$$\dot{x} = \frac{p}{M}$$
$$\dot{p} = -\hbar U_0 |\alpha|^2 \nabla f^2(x) + \xi_p$$

$$\dot{\alpha} = \eta - i\left(U_0 f^2(x) - \Delta_C\right)\alpha - \left(\kappa + \Gamma_0 f^2(x)\right)\alpha + \xi_\alpha$$

$\rightarrow$ force depends not only on the position but also on the velocity $\Longrightarrow$ cavity cooling $\Rightarrow$ + fluctuations needed

Polarizability

$$U_0 = -\frac{\omega_C}{V}\chi' \approx \frac{g^2}{\Delta_A}$$

$$\Gamma_0 = -\frac{\omega_C}{V}\chi'' \approx \gamma\frac{g^2}{\Delta_A^2}$$

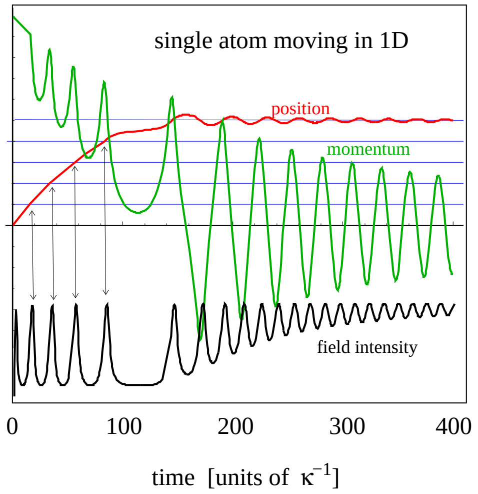
Atom és mező korrelált mozgása

Zajmentes mozgás példa

$$\left.\begin{aligned}\Delta_C &= -4\kappa \\ U_0 &= -3\kappa\end{aligned}\right\} \quad |\Delta_C - U_0| = \kappa$$

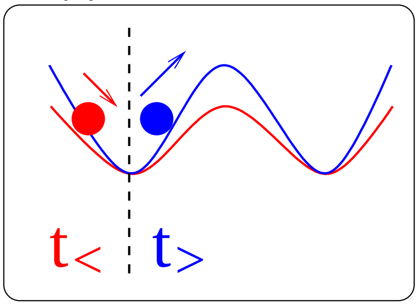
$$\eta = 1.5\kappa$$

$$\gamma = 0.1\kappa \qquad \text{(negligible)}$$



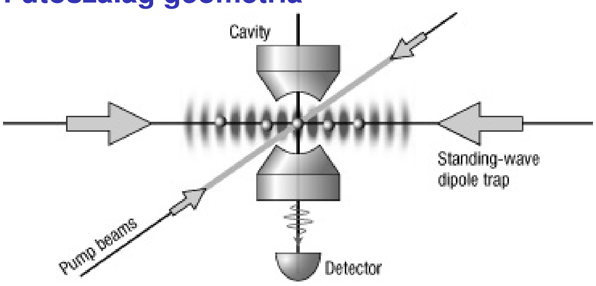
Sisyphus interpretation

Cooling can be attributed to the time lag with which the field adapts itself to the momentary position of the atom.



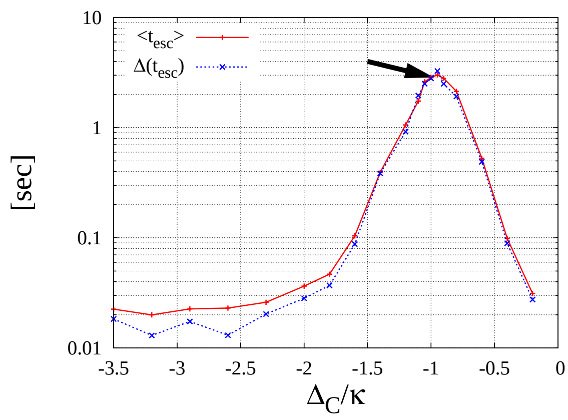
Atomok optikai hűtése rezonátorban

Futószalag geometria

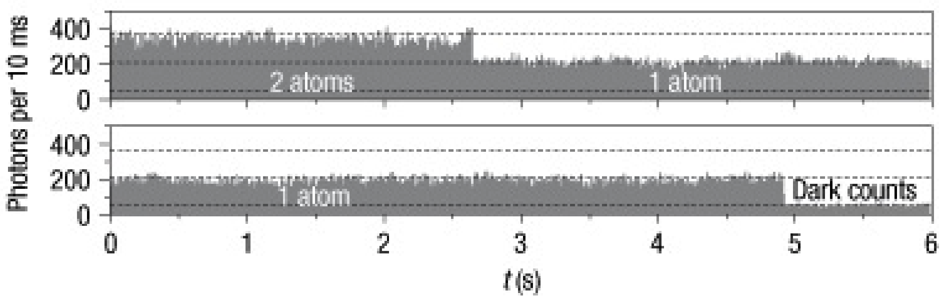


Elmélet

Domokos, Vukics, Ritsch, Phys. Rev. Lett. 2004



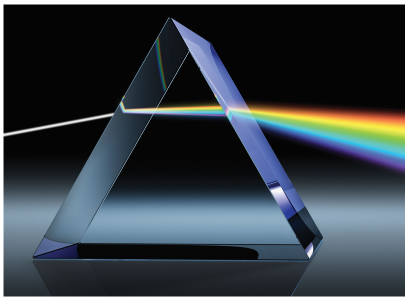
Nussmann et al, Nature Phys, 2006



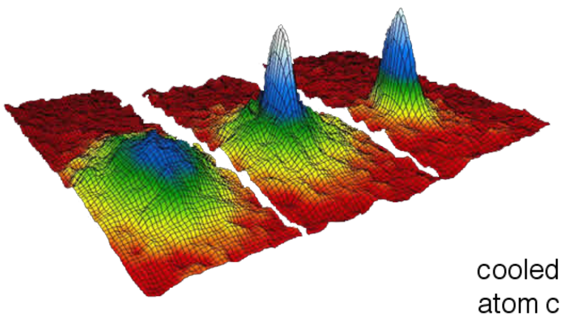
Fázismanipuláció a fény-anyag kölcsönhatásban

Tartalomjegyzék

1. Kölcsönható kvantum részecskék
    - mikrohullámú CQED, Ramsey interferométer
    - Schrödinger-macska állapotok
    - kvantumállapot mérés és preparálás
2. Atomok mozgása fény hatására
    - Fabry-Pérot interferométer
    - optikai rezonátorok
    - hűtés koherens fotonszórással
3. Atom-atom kölcsönhatás a sugárzási mezőn keresztül
    - atomok önszerveződése fénykristályba
    - kvantumfázisátalakulás



Mágneses-optikai csapda, Bose-Einstein kondenzáció

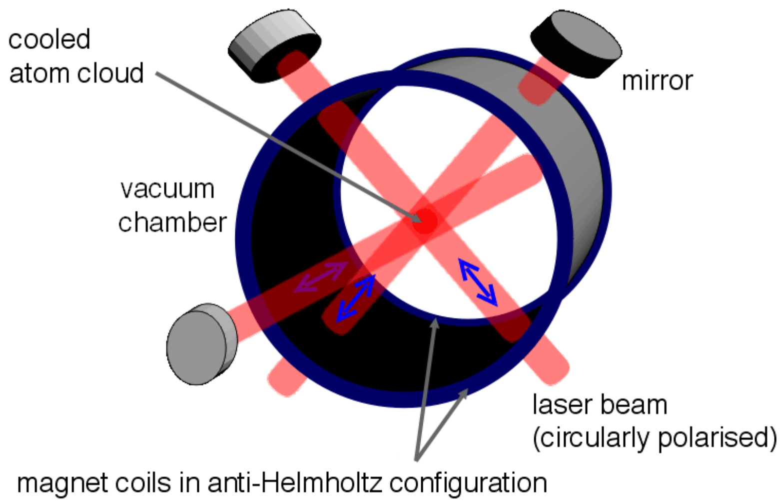


Bose-Einstein kondenzátum (1995)
Nobel-díj 2001

Ideális kvantum objektum

- mozgási & elektronikus alapállapot
- kollektív erősítés a csatolásban

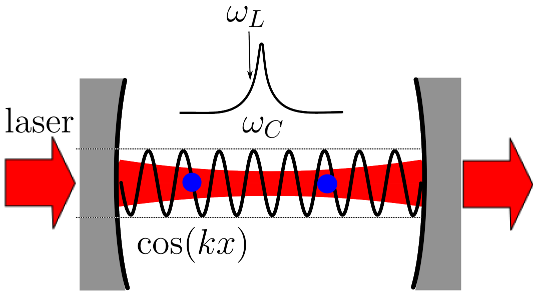
mágneses optikai csapda

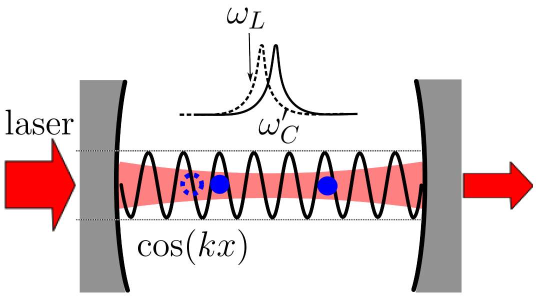


párologtatásos hűtés

Atom-atom coupling I. Cavity pump

Spatially dependent detuning





Significant?

- single-atom strong coupling regime

$$g > \kappa, \gamma$$

- far detuning $\Delta_A \gg \gamma$

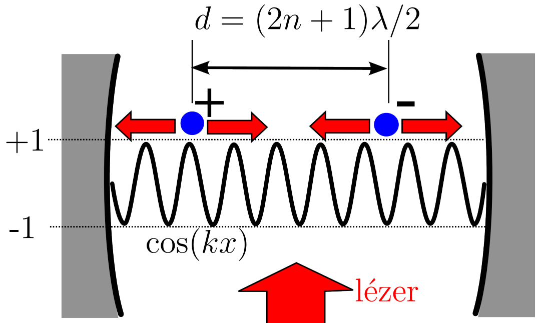
$$\frac{g^2}{\Delta_A} \approx U_0 > \kappa$$

- Many-body enhancement

$$U_0 \longrightarrow N\, U_0$$

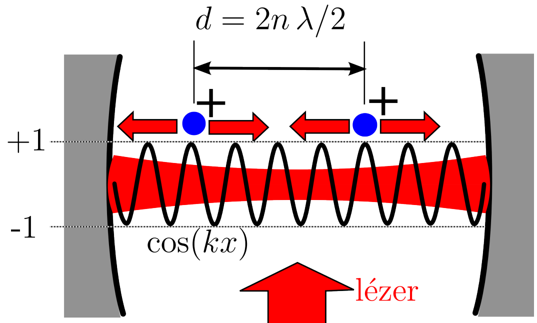
Atom-atom coupling II. Atom driving

Destructive interference



$F_x = 0$

Constructive interference



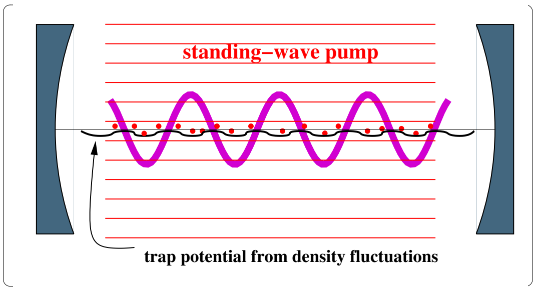
$F_x \neq 0$, superradiance

Features of the cavity mediated interaction

- radiative $\Longrightarrow$ long-range (infinite range)
- not binary $\Longrightarrow$ global coupling ($\propto N$)
- cavity radiation field is lossy $\Longrightarrow$ driven open system, out of equilibrium

Kollektív instabilitás

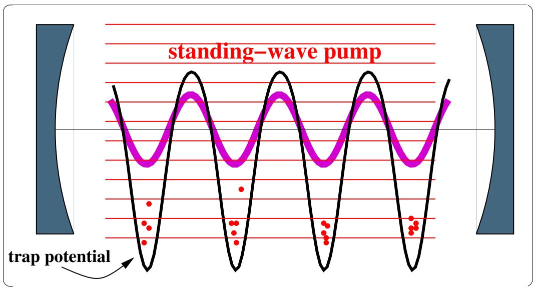
homogén eloszlás



pumpa erősség / hőmérséklet > kritikus érték

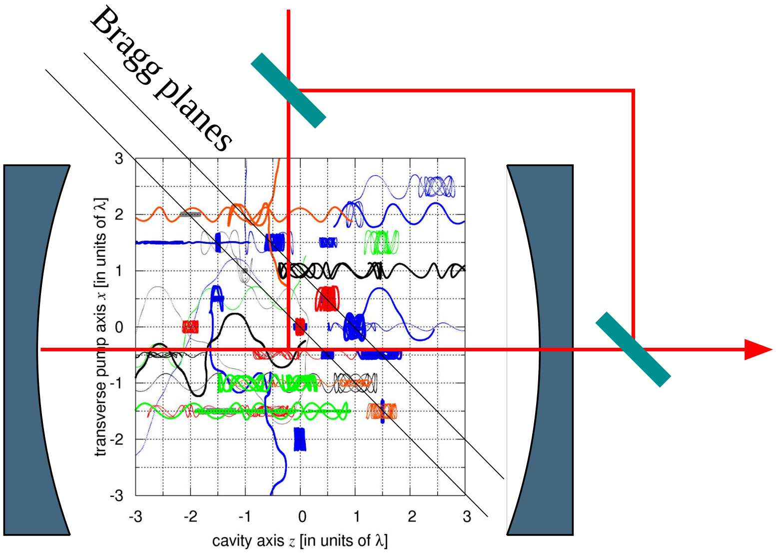
↓

λ-periódikus rend



Atomok önszerveződése optikai rezonátorban

Atomok trajektóriái



[Domokos, Ritsch, Phys Rev Lett (2002)]

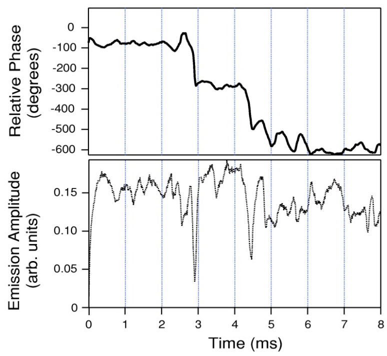
[Asboth,Domokos,Ritsch,Vukics, PRA (2005)]

⟶ nemegyensúlyi fázisátalakulás, globális csatolás

Továbblépés: $T = 0$ kvantum tartomány, BEC

MIT kísérlet

[Black, Chan, Vuletic, PRL (2003)]

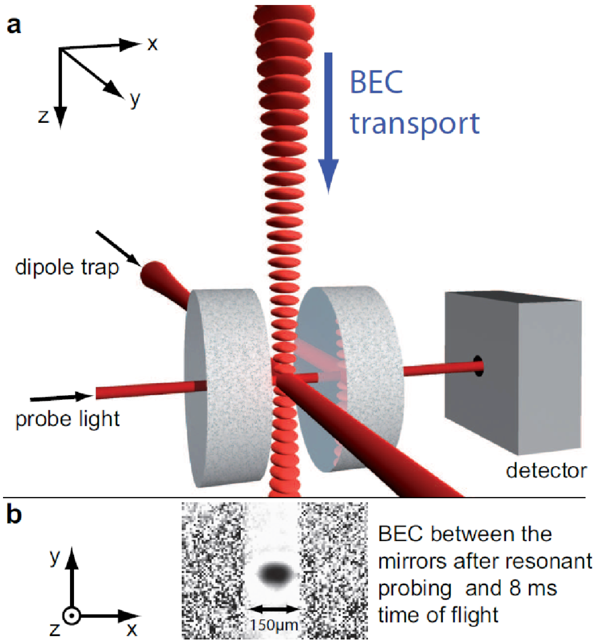


Hamburg, Imperial College,...

[Arnold, Baden, Barrett, PRL (2012 október)] Self-Organization Threshold Scaling for Thermal Atoms Coupled to a Cavity

Bose-Einstein kondenzátum optikai rezonátorban

$$H = \omega_C\, \hat{a}^\dagger \hat{a} + i\eta(\hat{a}^\dagger e^{-i\omega t} - \hat{a} e^{i\omega t}) + \int \hat{\Psi}^\dagger(x)\Big[-\frac{\hbar}{2\,m}\frac{d^2}{dx^2} + Ng_c \hat{\Psi}^\dagger(x)\hat{\Psi}(x)$$
$$+ U_0\, \hat{a}^\dagger \hat{a} \cos^2(kx) + i\eta_t \cos kx (\hat{a}^\dagger e^{-i\omega t} - \hat{a} e^{i\omega t})\Big]\hat{\Psi}(x)dx,$$



dissipation and noise ($k_B T = 0$)

$$\frac{d}{dt}\hat{\rho} = -\frac{i}{\hbar}[H, \hat{\rho}] + \kappa\left(2\,a\,\hat{\rho}\,a^\dagger - a^\dagger\, a\,\hat{\rho} - \hat{\rho}\,a^\dagger\, a\right)$$

Time scales

$\omega_R = \hbar k^2/2m$	recoil frequency
κ	cavity resonance
$NU_0, N\eta_t$	tunable interaction

Ultracold limit of self-organization

Fourier-expansion of the matter wave

$$g_c = 0 \Longrightarrow$$

$$\hat{\Psi}(x) = \frac{1}{\sqrt{L}}\hat{c}_0 + \sqrt{\frac{2}{L}}\hat{c}_1 \cos kx + \sqrt{\frac{2}{L}}\hat{c}_2 \cos 2kx + \ldots$$

$$\left[c_i, c_i^\dagger\right] = 1 \quad i = 0, 1, 2, \ldots$$

two-mode approx

$$N = c_0^\dagger c_0 + c_i^\dagger c_1 = \text{const}$$

$$\hat{S}_x = \frac{1}{2}(c_i^\dagger c_0 + c_0^\dagger c_i)$$
$$\hat{S}_y = \frac{1}{2i}(c_i^\dagger c_0 - c_0^\dagger c_i)$$
$$\hat{S}_z = \frac{1}{2}(c_i^\dagger c_i - c_0^\dagger c_0)$$

Realization of the Dicke-model

$$H/\hbar = -\delta_C\, a^\dagger a + \omega_R \hat{S}_z + iy(a^\dagger - a)\hat{S}_x/\sqrt{N} \quad \left(+ua^\dagger a\left(\tfrac{1}{2} + \hat{S}_z/N\right)\right)$$

$$\omega_R = \hbar k^2/m$$

$$\left.\begin{aligned} \delta_C &= \Delta_C - 2u < 0 \\ u &= N\,U_0/4 \\ y &= \sqrt{2N}\eta_t \end{aligned}\right\} \text{tunable parameters}$$

$$y_{\text{crit}} = \sqrt{-\delta_C \omega_R}$$

kHz frequency range

[Nagy, Kónya, Szirmai, Domokos, PRL (2010)]

Phase transition – thermodynamic limit

Mean field approach

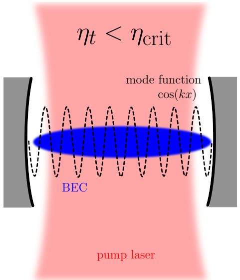
$$a = \sqrt{N}\alpha_0 + \delta a$$

$$c_k = e^{-i\mu t}\left(\sqrt{N}\gamma_k + \delta c_k\right)$$

two-mode:

$$\gamma_1 = \beta \quad \gamma_0 = \sqrt{1-\beta^2}$$

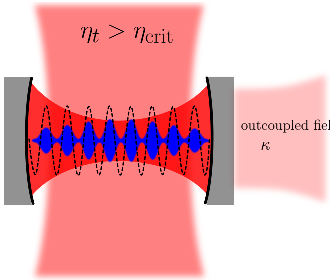
Critical point



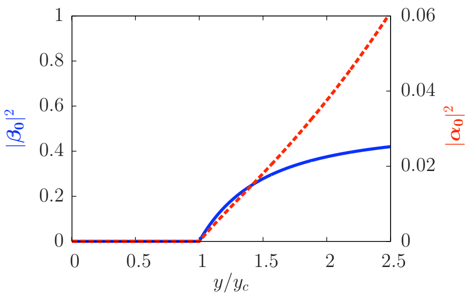
$$\alpha = 0$$
$$\beta = 0$$

threshold

$$y_C^2 = -\omega_R \frac{\delta_C^2 + \kappa^2}{\delta_C}$$



populations

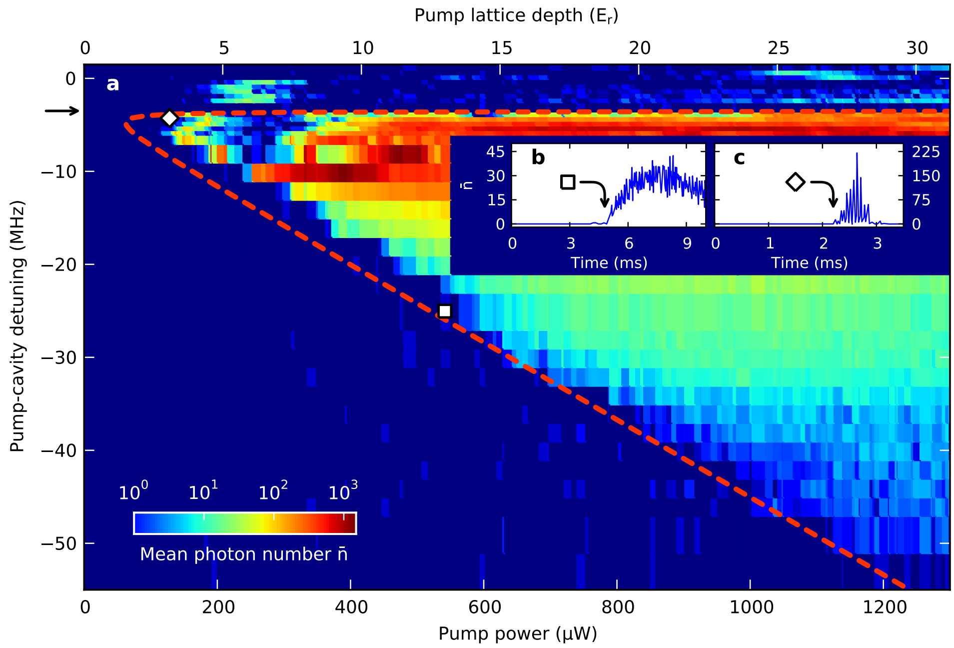


$$\beta^2 = \frac{\delta_C}{u}\left(1 - \sqrt{1 - \frac{u}{\delta_C}\frac{y^2 - y_C^2}{y^2 + u\omega_R}}\right)$$

$$\approx \frac{1}{2} - \frac{y_C^2}{2y^2} \quad \text{(for } u \approx 0\text{)}$$

both for gs and ss

Experimental mapping of the phase diagram



From: [Baumann, Guerlin, Brennecke, Esslinger, Nature (2010)]

First calculated: [Nagy, Szirmai, Domokos, EPJD (2008)]

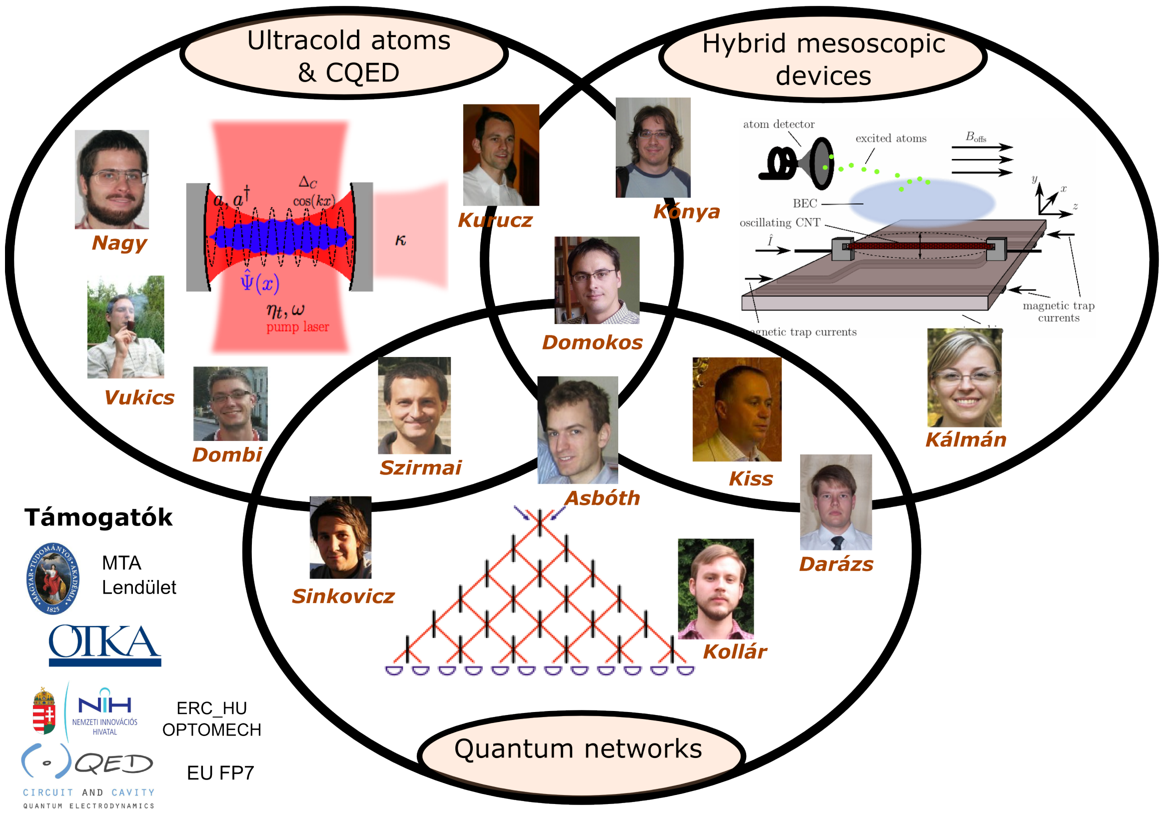
Konklúzió

- hullámfüggvény (elektrodinamika, kvantummechanika, ...)
- fázis
- fázismanipuláció eszköze: interferométerek

SPECIK:

- Rezonátoros kvantumelektrodinamika
- Semleges atomok lézeres hűtése és csapdázása

Kvantummérés Lendület csoport



Támogatók

MTA Lendület

OTKA

ERC_HU OPTOMECH

EU FP7