Quantum-Atom Optics: Present and Future

P. D. Drummond,

Australian Centre for Quantum Atom Optics

February 8, 2006

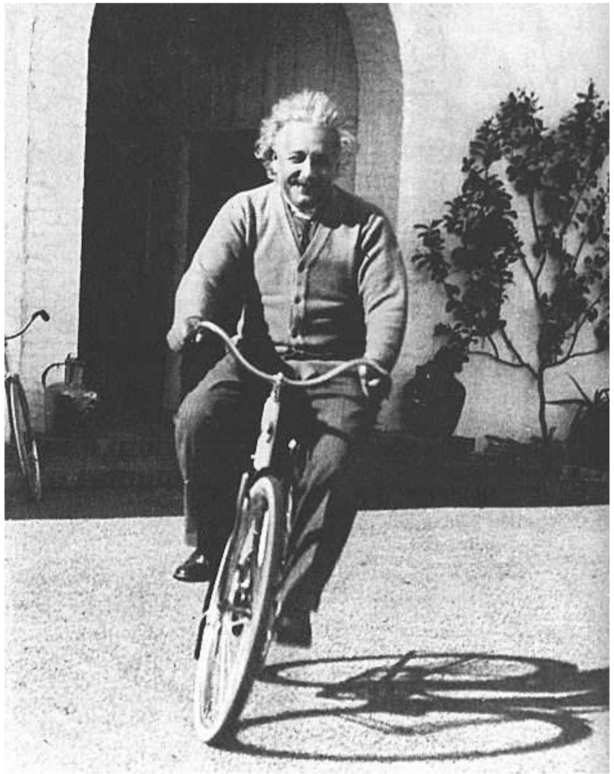
Quantum Optics: the 2005 Nobel Prize in Physics

The Royal Swedish Academy of Sciences awarded one half of the Nobel Prize in Physics for 2005 to

Roy J. Glauber

- ***for his contribution to the quantum theory of optical coherence***

Roy at ETH



Postdoctoral Work:

Glauber followed

EINSTEIN'S

footsteps, working at:

Institute for Advanced Study (Princeton, USA)

Swiss Federal Polytechnic Institute (ETH, Zurich)

Caltech (USA)

Roy and Wolfgang Pauli

Wolfgang PAULI

inventor of the ‘exclusion principle’ -
liked to tease his postdocs.
He is laughing at Roy who is
trying to photograph him -
while Pauli kicks a soccer ball
at the camera.

Roy at Harvard

LYMAN/JEFFERSON LABS

where Glauber has worked for 53 years, since joining Harvard in 1952, with full tenure from 1955

Glauber's correlation function

Define the n-th order correlation function:

$$G^{(n)}_{\mu_1 \dots \mu_{2n}}(x_1, .x_{2n}) = \langle E^{(-)}_{\mu_1}(x_1)..E^{(-)}_{\mu_n}(x_n) E^{(+)}_{\mu_{n+1}}(x_{n+1})..E^{(+)}_{\mu_{2n}}(x_{2n})\rangle$$

For symmetric arguments, $G^{(n)}(x_1 \dots x_n, x_n \dots x_1)$ is:

- the rate of counting n photons at locations $x_1 \dots x_n$, where $x = (\mathbf{r}, t)$.

Coherence

Define the n-th order **normalized** correlation function:

$$g^{(n)}_{\mu_1 \ldots \mu_{2n}}(x_1 \ldots x_{2n}) = \frac{G^{(n)}_{\mu_1 \ldots \mu_{2n}}(x_1 \ldots x_{2n})}{\prod_{j=1}^{2n} \sqrt{G^{(1)}_{\mu_1,\mu_j}(x_j, x_j)}}$$

First order coherence: $\left| g^{(1)}_{\mu_1 \mu_2}(x_1, x_2) \right| = 1$

Second order coherence: $\left| g^{(2)}_{\mu_1 \ldots \mu_4}(x_1 \ldots x_4) \right| = 1$

Lasers and Lightbulbs?

Roy's coherence theory answered the question:

is there a **FUNDAMENTAL** difference between lasers and lightbulbs??

- Is it because the laser has a narrow spectrum?
- NO - you can filter light to have a narrow spectrum!
- **What is the difference?**

PHOTON ARRIVAL TIMES

- Photons from a lightbulb BUNCH together.
- They are CORRELATED
- Photons from a laser arrive independently.
- They are UNCORRELATED

Lasers and Coherence

Lightbulbs:

✔ Might have first order coherence -

✘ but NEVER second order

Lasers: can have coherence to ALL orders (if perfect)

Where did this lead?

Photon antibunching: Photons that never arrive together: suppressed intensity noise (Mandel, Walls)

Bell inequalities: Optical demonstrations of the Bell inequality (Bell, Aspect et al)

Quantum Squeezing: Reduced fluctuations in one quadrature, increased in another (Slusher, Gardiner)

EPR correlations: Optical demonstrations of the Einstein-Podolsky-Rosen paradox (Reid, Kimble)

What are coherent states?

These are idealized states which are coherent to all orders! If $\hat{a}$ is a field operator, then:

$$\hat{a}\,|\alpha\rangle = \alpha\,|\alpha\rangle$$

- Coherent states are a **complete mathematical basis**
- **Also can have SU(N) coherent states for spins**

Glauber-Sudarshan P-representation

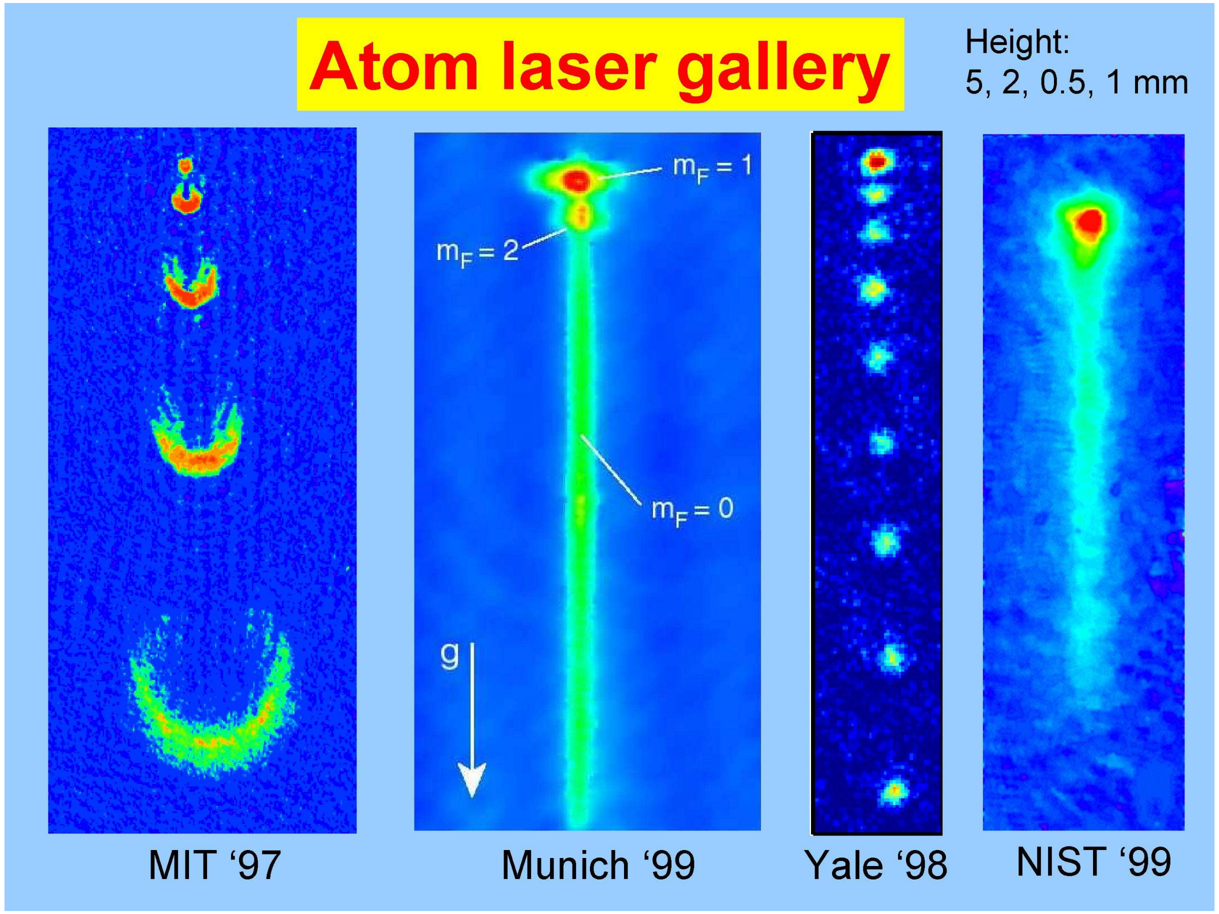
- Coherent states can be used to construct **quantum operator representations**
- $\hat{\rho} = \int P(\alpha) \left|\alpha\right\rangle \left\langle\alpha\right| d^2\alpha$
- Glauber's P-representation used to treat quantum noise in lasers
- Restricted to classical states ($g^{(2)}(0) \geq 1$)

QUANTUM-ATOM OPTICS: PRESENT

Out of the last TEN Nobel prizes awarded to physicists

- ✔ THREE: low-temperature physics, many-body theory
- ✔ TWO: Ultra-cold atoms, BEC
- ✔ ONE: Computational physics/chemistry
- ✔ ONE: Quantum Optics/ Laser Spectroscopy
- ✔ SCIENCE (Top Ten breakthroughs in 2004): ultracold fermions

Atom laser experiments



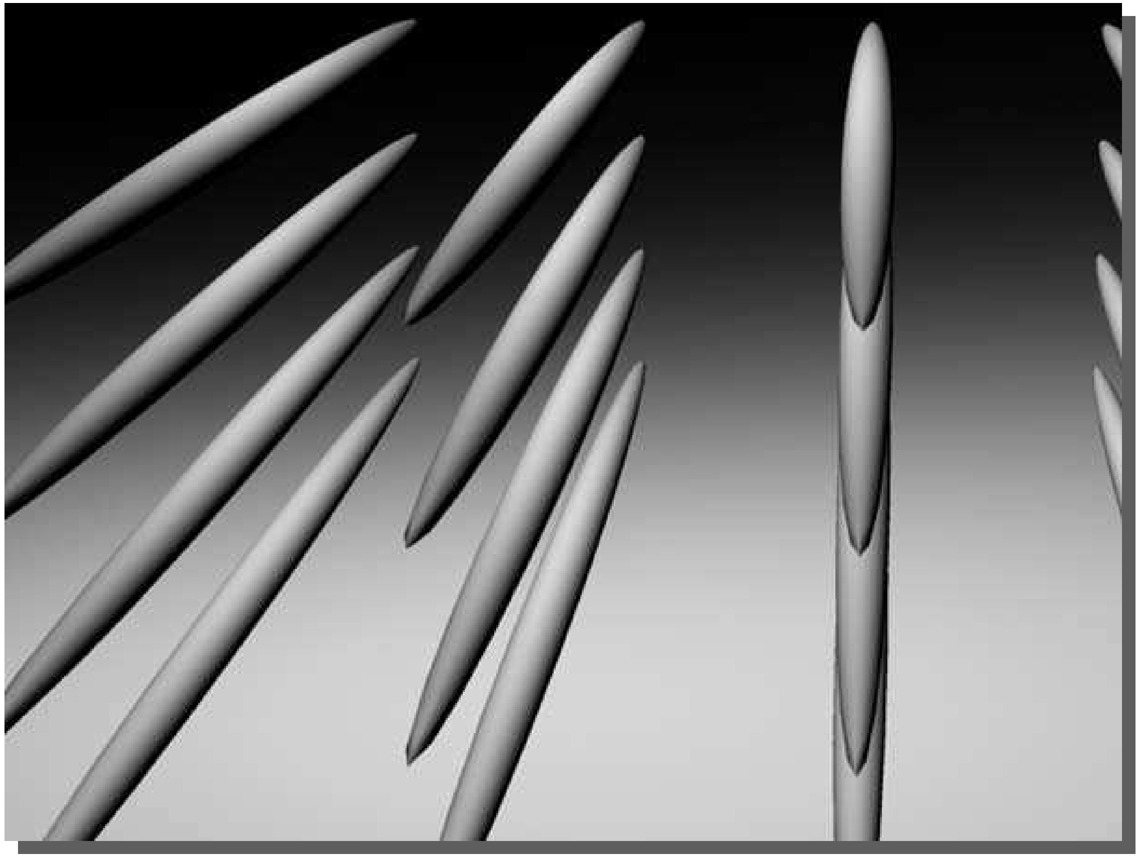
Current experiments: Quantum Optics

- Quantum noise limited lasers to $1kHz$
- Sqeezed/entangled beams with up $10dB$ squeezing
- Laser frequency stability to 1 part in 10^{15} Hz
- Demonstration of EPR (non-causal)
- Bell inequality tests (efficiency loopholes)
- Spin/light entanglement demonstration

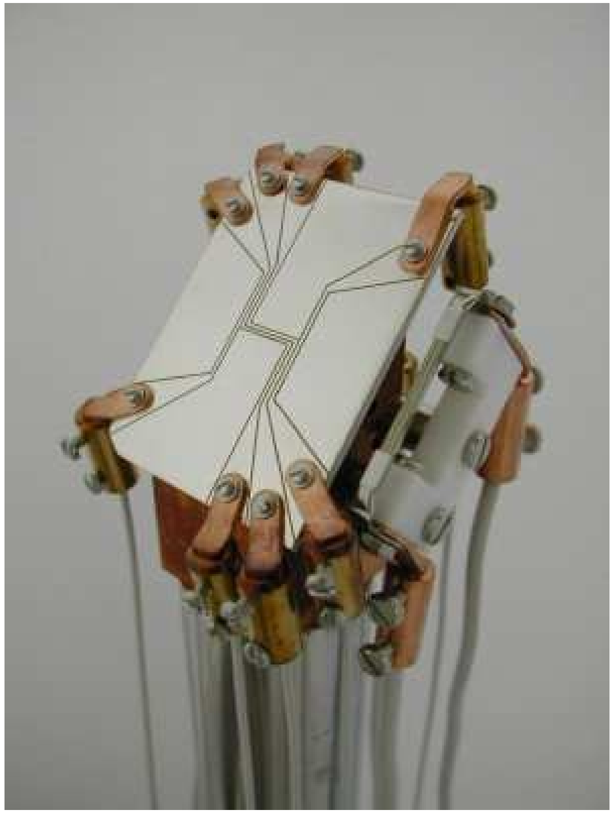
Current experiments: Atom Optics

- Cold BEC and Fermi gases to $1nK$
- Dimensional control in optical lattics
- Nonlinear coupling, via four-wave mixing
- BEC-BCS crossover, via molecule formation
- Correlated atom *emission* measured by light scattering
- Correlated atom *detection* using MCP technology

Atoms on lattices



Atoms on chips



Current Theory: Quantum Optics

Many good techniques, weak interactions

- Direct calculations for small photon number
- Can linearize in some cases
- Truncated Wigner (semiclassical) OK for large photon number
- First-principles phase-space methods (positive-P) very successful

Positive P-representation

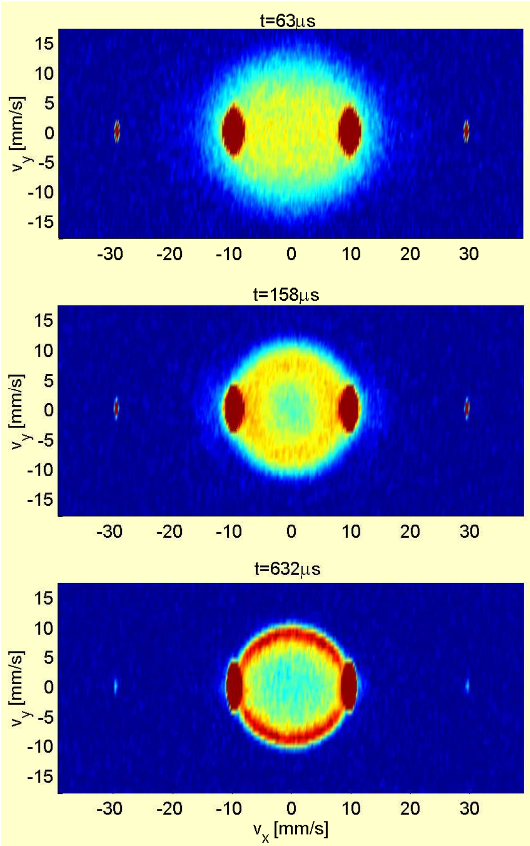
- Extends Glauber's P-representation to ***non-classical*** states
- $$\hat{\rho} = \int P(\alpha,\beta)\frac{|\alpha\rangle\langle\beta|}{\langle\beta|\alpha\rangle}d^2\alpha d^2\beta$$
- Used for first principles quantum dynamical simulations
- Led to predictions of quantum squeezing in solitons

Current Theory: Atom Optics

More challenging, stronger interactions

- Mean-field and classical field approximations common
- Perturbation theory for ground states: but excited states difficult
- Aproximate semiclassical has sampling error and other problems
- Monte-Carlo good in some cases at thermal equilibrium
- Positive-P useful, but only for short times

Largest Hilbert Space Ever Simulated



- BEC Four-wave mixing
- 10^5 Rubidium atoms
- Total of 2×10^6 modes
- Experiment: Ketterle, MIT
- Theory: Drummond, Deuar, UQ (+P)

QUANTUM-ATOM OPTICS: FUTURE

- Lower temperatures: what is the current limit?
- More atomic/molecular species: can we cool every isotope?
- Light-atom entanglement: how strongly entangled?
- Spinor atoms on optical lattices
- Fermions in engineered environments
- Progress towards true ‘SCHROEDINGER CATS’

Theoretical Challenges

- Does the 2D Fermi-Hubbard model have superconductivity?
- Ground state of strongly interacting Fermi gas?
- How does a BEC interact with an optical cavity?
- Quantum ground state of spinor gas in a lattice?
- Excited states of Bose gases: are they bosonic/fermionic?
- First-principles time-domain quantum simulations?

Complexity Issues

- many-body problems become exponentially complex.
- consider n atoms distributed among m modes
- Each mode can have one or all atoms; take $n \simeq m \simeq 500,000$:
- Number N_s of quantum states is ENORMOUS:

$$N_s = 2^{2n} = 10^{100,000}$$

Classical phase-space

Wigner and Glauber used a classical-like phase-space or quasi-probability description. Here, for $M = LD$ modes, and a maximum of N particles/mode

Usual QM: $\longrightarrow N^M$ (complex) coordinates

Wigner, Glauber: QM$\longrightarrow M$ coordinates

Problem: the Wigner function has negative values and obeys a complicated differential equation. The Glauber-Sudarshan is negative or singular for non-classical states.

Quantum phase-space representations

Expand the density matrix $\widehat{\rho}$, using operators $\widehat{\Lambda}(\overrightarrow{\lambda})$:

$$\widehat{\rho} = \int P(\overrightarrow{\lambda})\widehat{\Lambda}(\overrightarrow{\lambda})d\overrightarrow{\lambda}$$

Quantum dynamics $\longrightarrow$Trajectories in $\overrightarrow{\lambda}$.

Different basis choice $\widehat{\Lambda}(\overrightarrow{\lambda})$ $\longrightarrow$different representation

More than one $P(\overrightarrow{\lambda})$ is possible $\longrightarrow$different stochastic gauges

THE BIG QUESTIONS IN QUANTUM-ATOM OPTICS

- ✔ Is there a coldest temperature we can reach?
- ✔ Can we prove the existence of ‘Schroedinger Cat’ states?
- ✔ Are there fermionic excitations in 2D or 3D Bose gases?
- ✔ Does gravity play a role in quantum decoherence?
- ✔ Is there an ‘Infodynamics’ of quantum entanglement?
- ✔ Can we solve quantum complexity with digital computers?