LETTER

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Measurement of the internal state of a single atom without energy exchange

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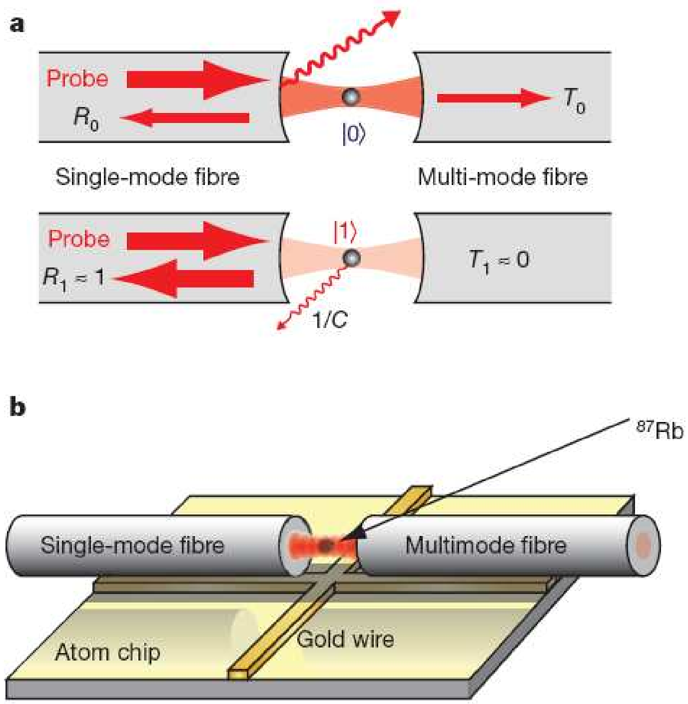


A measurement necessarily changes the quantum state being measured, a phenomenon known as back-action. Real measurements, however, almost always cause a much stronger back-action than is required by the laws of quantum mechanics. Quantum non-demolition measurements have been devised[1–6] that keep the additional back-action entirely within observables other than the one being measured. However, this back-action on other observables often imposes its own constraints. In particular, free-space optical detection methods for single atoms and ions (such as the shelving technique[7], a sensitive and well-developed method) inevitably require spontaneous scattering, even in the dispersive regime[8]. This causes irreversible energy exchange (heating), which is a limitation in atom-based quantum information processing, where it obviates straightforward reuse of the qubit. No such energy exchange is required by quantum mechanics[9]. Here we experimentally demonstrate optical detection of an atomic qubit with significantly less than one spontaneous scattering event. We measure the transmission and reflection of an optical cavity[10–13] containing the atom. In addition to the qubit detection itself, we quantitatively measure how much spontaneous

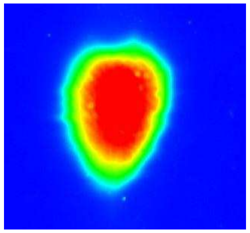
Rockson Chang - July 20th group meeting

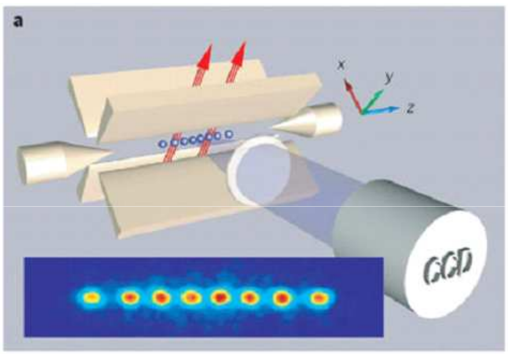
Outline

- Motivation
  - *Imaging of ultracold atoms, QIP with atoms and ions*
- Example measurements
  - Ideal fluoresence measurement
  - Interaction free measurement
- Cavity assisted detection of an atomic qubit
  - Characterization of ‘knowledge’ available, accessed
  - Unavoidable effect of measurement (backaction)
  - Avoidable effect of measurement (photon scattering)

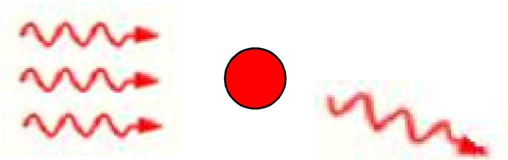
Trapped atom imaging techniques

Fluoresence imaging



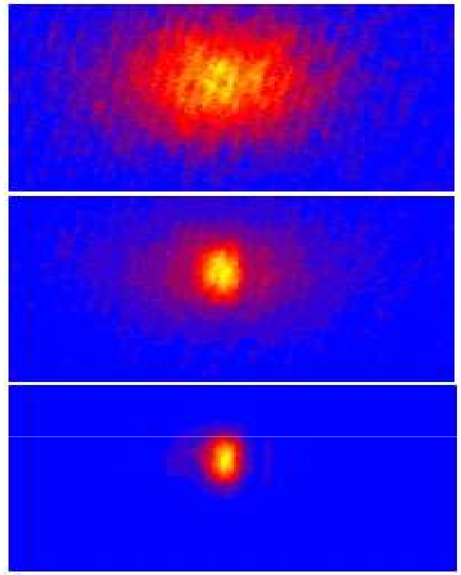


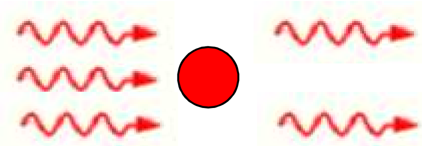
Nature **453**, 1008-1015 (19 June 2008)



b/g free but, low collection efficiency

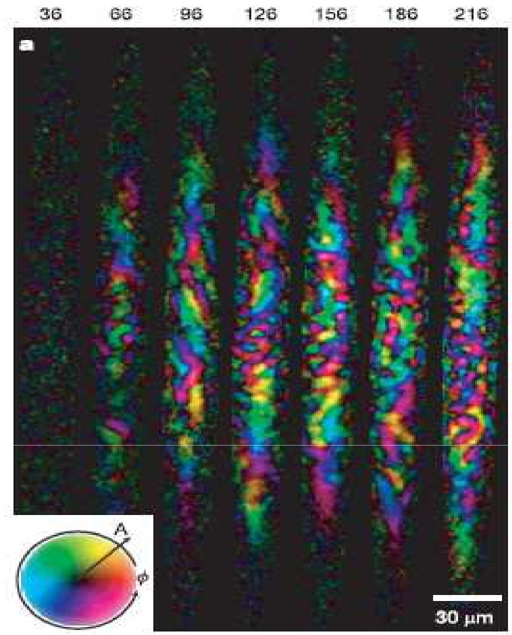
Absorption imaging



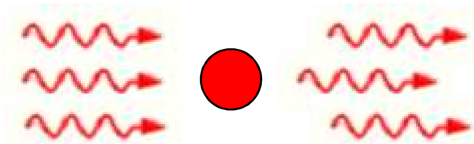


Single shot, destructive, goal is to maximize s/n given your one shot

Phase contrast imaging



L. Sadler et al, Nature London **443**, 312 2006.

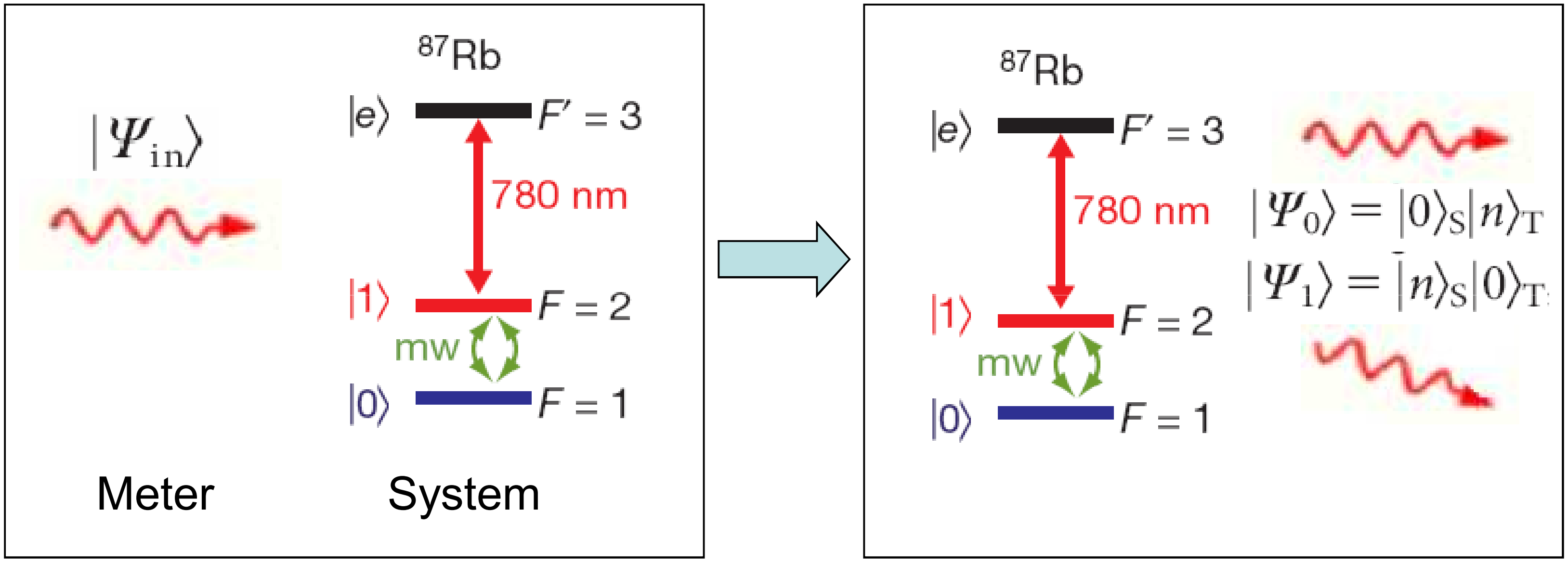


Multi-shot, balance information gained with destructiveness of imaging

Both absorptive and dispersive techniques have the same SNR for a given level of destruction for low OD samples (*see Making, Probing, and Understanding BECs*)

How destructive does measurement of an atomic state have to be?

- Consider an ideal fluoresence measurement



$$(\alpha|0\rangle + \beta|1\rangle) \otimes |\Psi_{in}\rangle$$

$$\alpha|0\rangle \otimes |\Psi_0\rangle + \beta|1\rangle \otimes |\Psi_1\rangle.$$

$$\rho_{0,1} \rightarrow \langle\Psi_0|\Psi_1\rangle\rho_{0,1}$$

AND

atom picks up a recoil due to spontaneous emission

Elitzur and Vaidman's Interaction free measurement

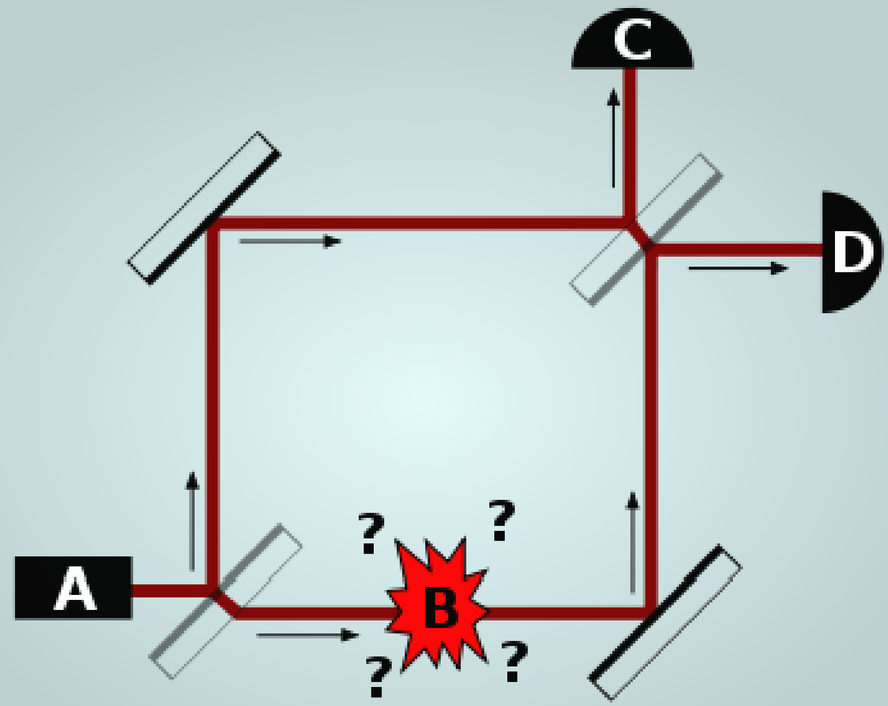
Possible outcomes

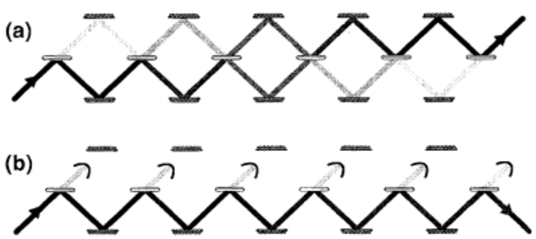
- No detector clicks (P=1/2)

2) Detector C clicks (P=1/4)

3) Detector D clicks (P=1/4)

Elitzur A. C. and Vaidman L. (1993). *Found. Phys.* **23**, 987-97





Kwiat et al (1995). *Phys. Rev. Lett.* **74** (24)

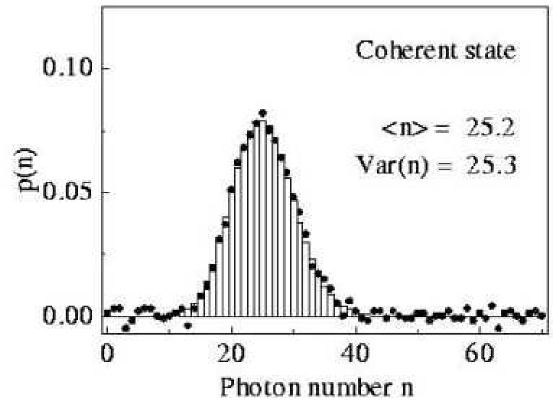
Detection error and ‘knowledge’

$$\varepsilon_{\mathrm{H}} = \frac{1}{2}\left(1 - \sqrt{1 - |\langle \Psi_0 | \Psi_1 \rangle|^2}\right)$$

- For coherent states

$$|\Psi_0\rangle = |0\rangle_{\mathrm{S}}|n\rangle_{\mathrm{T}} \quad |\Psi_1\rangle = |n\rangle_{\mathrm{S}}|0\rangle_{\mathrm{T}}$$

$$|\langle \Psi_0 | \Psi_1 \rangle|^2 = \exp(-2n)$$



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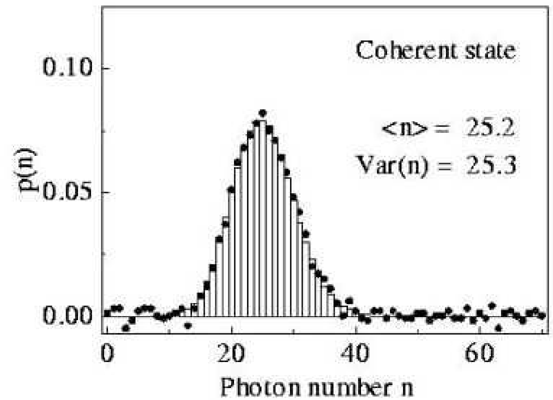

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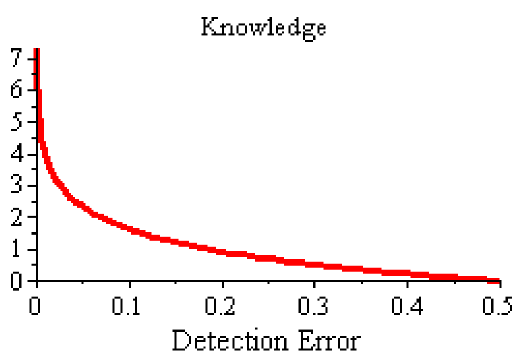
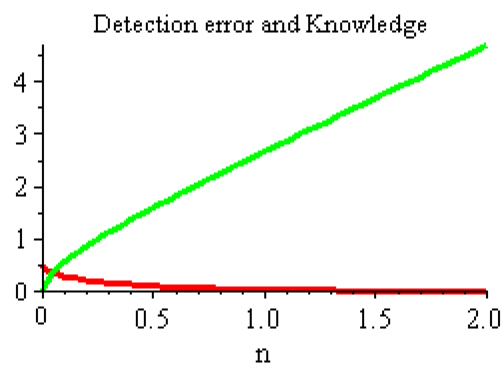
This exponential decrease of the minimum detection error with n naturally leads to a heuristic definition of the 'knowledge' of the atomic state

$$K_{\mathrm{H}} = -\ln 2\varepsilon_{\mathrm{H}} \qquad f(2n) \approx 2n$$





- For an ideal fluoresence measurement $K_{\mathrm{H}} = f(2m) \approx 2m$

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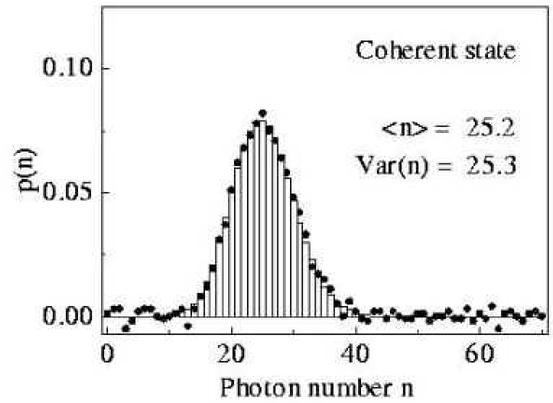

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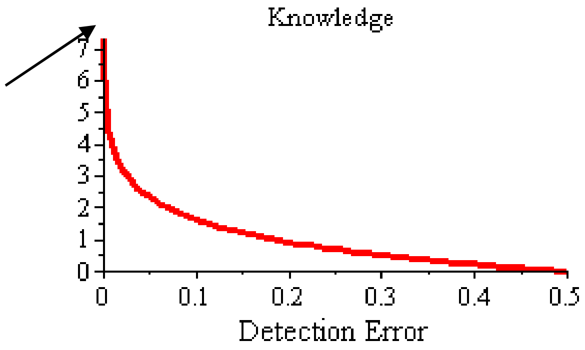

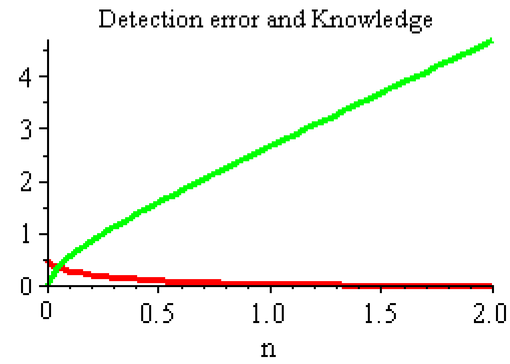

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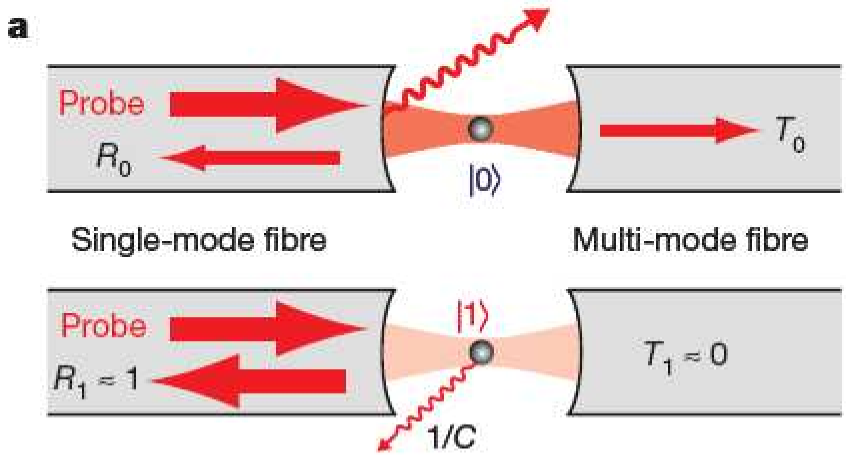
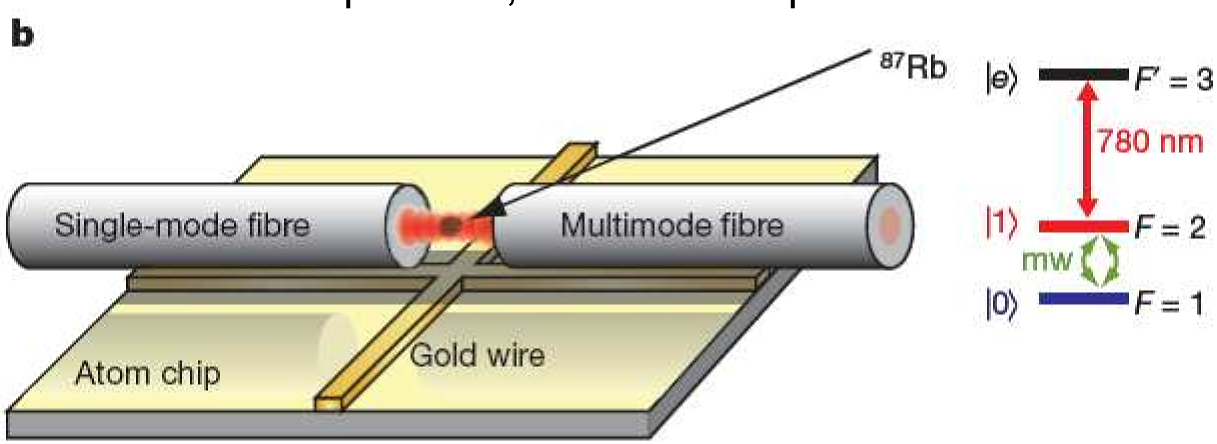
Cavity assisted detection of an atomic qubit



$$C = g^2/2\kappa\gamma \gg 1$$
$$g = 2\pi \times 185(\pm 8)\ \text{MHz},$$
$$\kappa = 2\pi \times 53(\pm 0.5)\ \text{MHz},$$
$$\gamma = 2\pi \times 3\ \text{MHz},$$
$$C = 108 \pm 8$$

n incident photons, ***m*** scattered photons

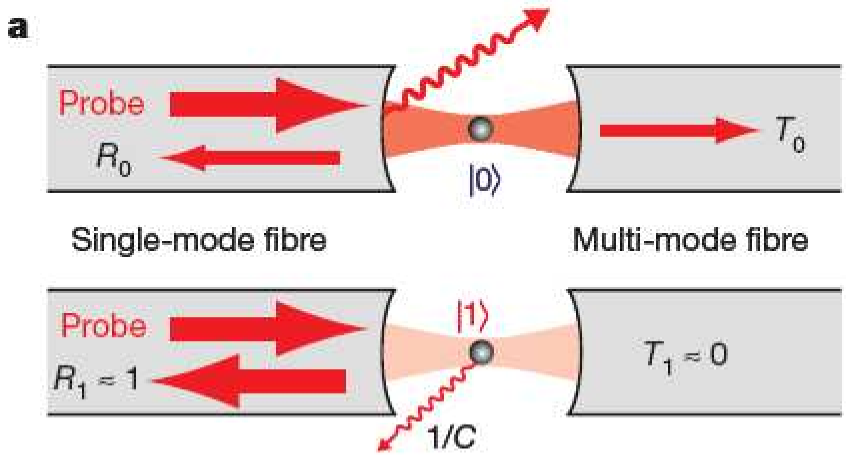


ideal

$$|\Psi_0\rangle = |0\rangle_R |n\rangle_T$$
$$|\Psi_1\rangle \approx |n\rangle_R |0\rangle_T$$

$$f(2n) \approx 2n$$

Cavity assisted detection of an atomic qubit



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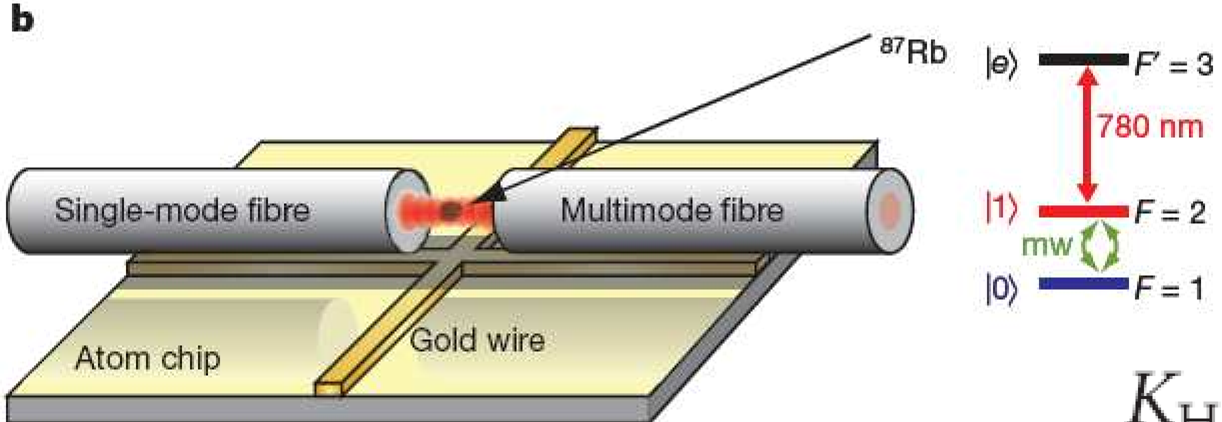
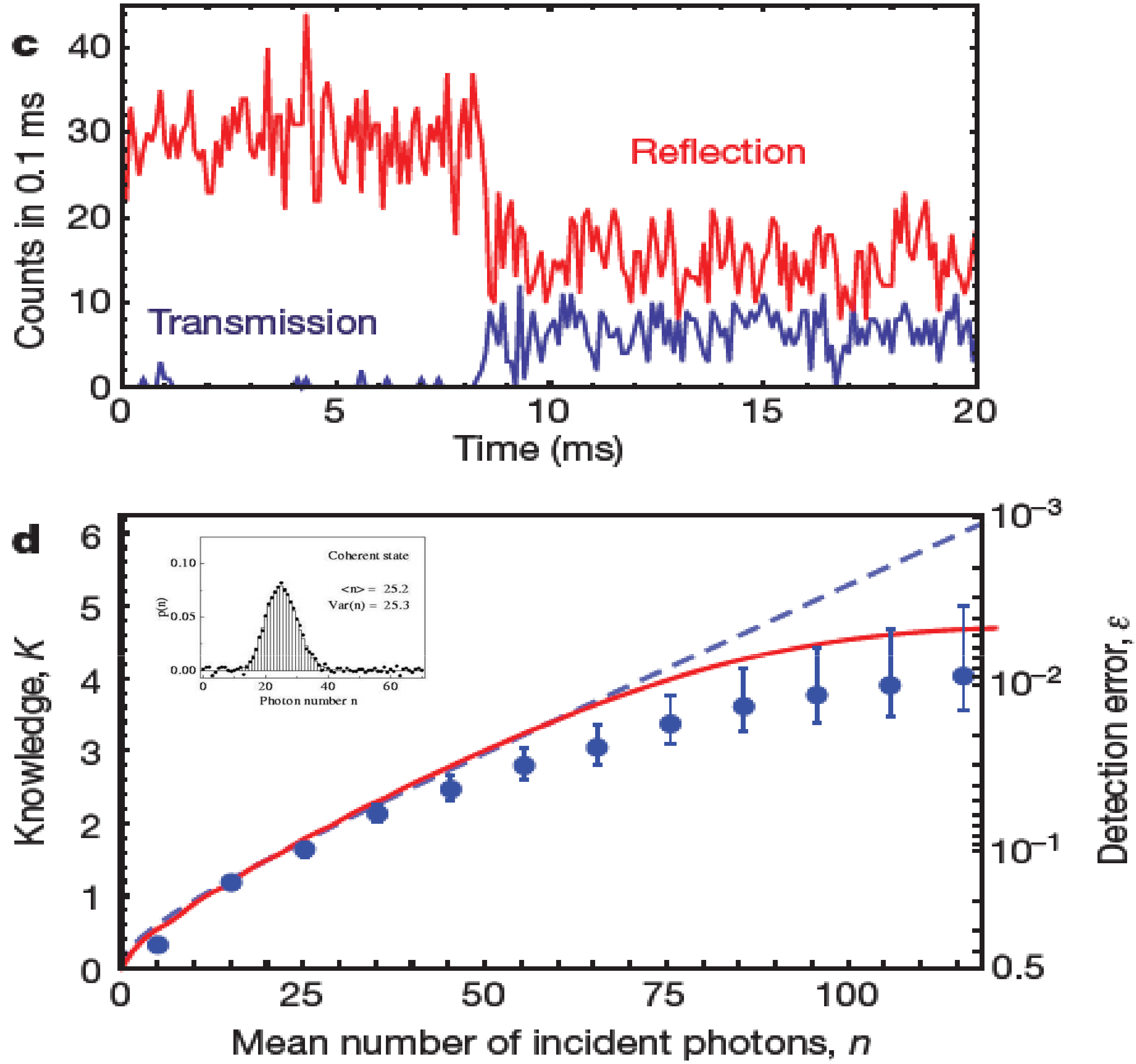


ideal

$$|\Psi_0\rangle = |0\rangle_R |n\rangle_T$$
$$|\Psi_1\rangle \approx |n\rangle_R |0\rangle_T$$

$$f(2n) \approx 2n$$
$$K_H = f(2Cm) \approx 2Cm$$

Every one of the ***n*** photons probes atomic qubit, but only ***n/C=m*** are scattered.



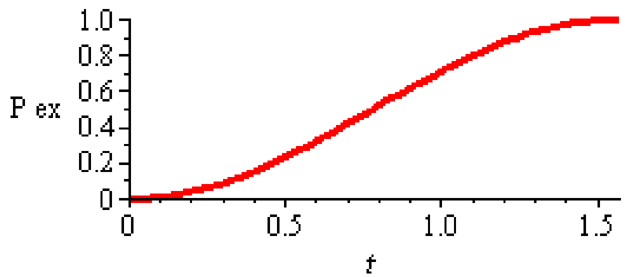
$$K_{acc} = f(4.6 \times 10^{-2} n)$$

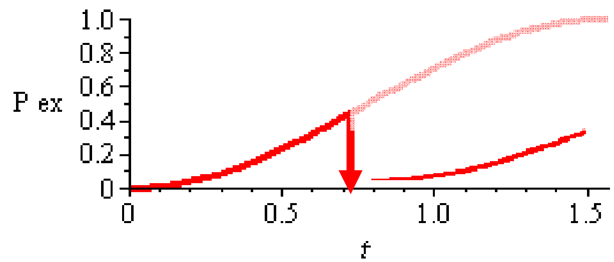
Knowledge accessed
(measured)

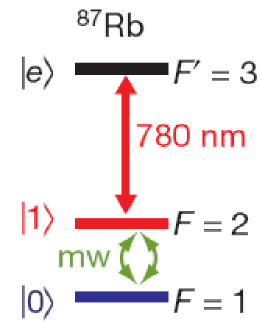
$$K_{H} = f(0.62n)$$

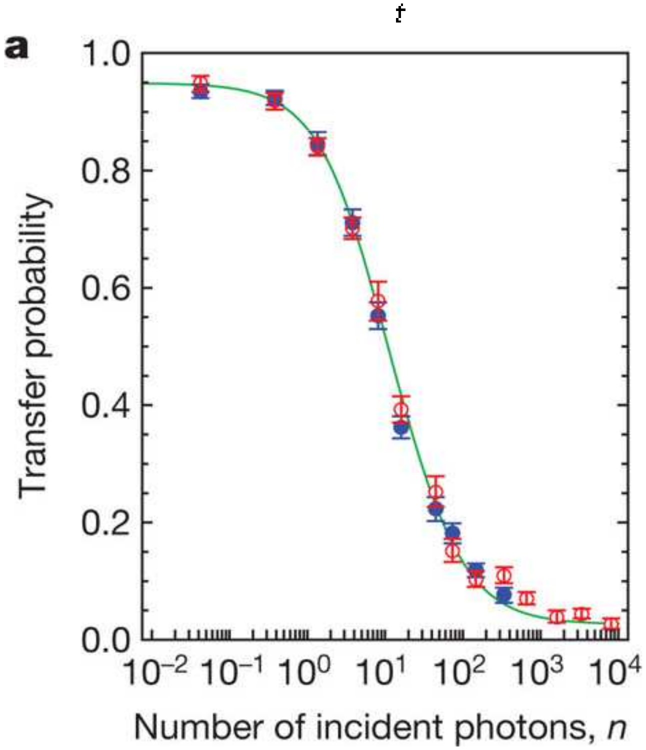
Max knowledge available
(estimated)

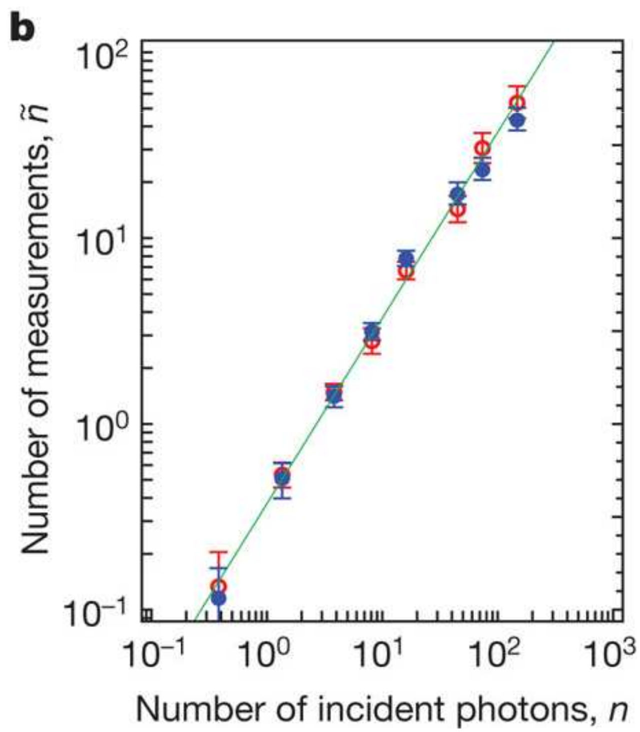
Back-action measurement using the quantum Zeno effect.











$$\tilde{n} = (0.37 \pm 0.02)n$$

$$\langle \Psi_1 | \Psi_0 \rangle = \exp(-\tilde{n})$$

$$K_{\mathrm{H}} = f(2\tilde{n})$$

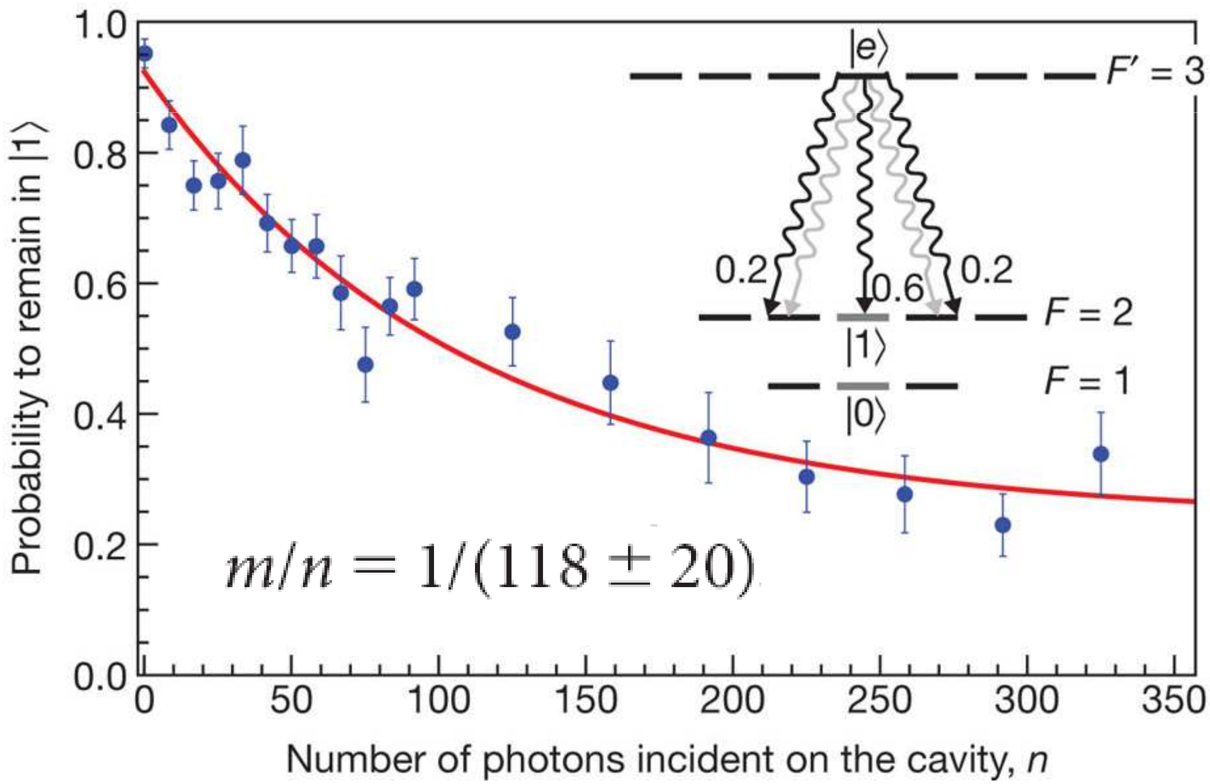
$$K_{\mathrm{H}} = f(0.62n)$$

$$K_{\mathrm{H}} = f((0.74 \pm 0.04)n)$$

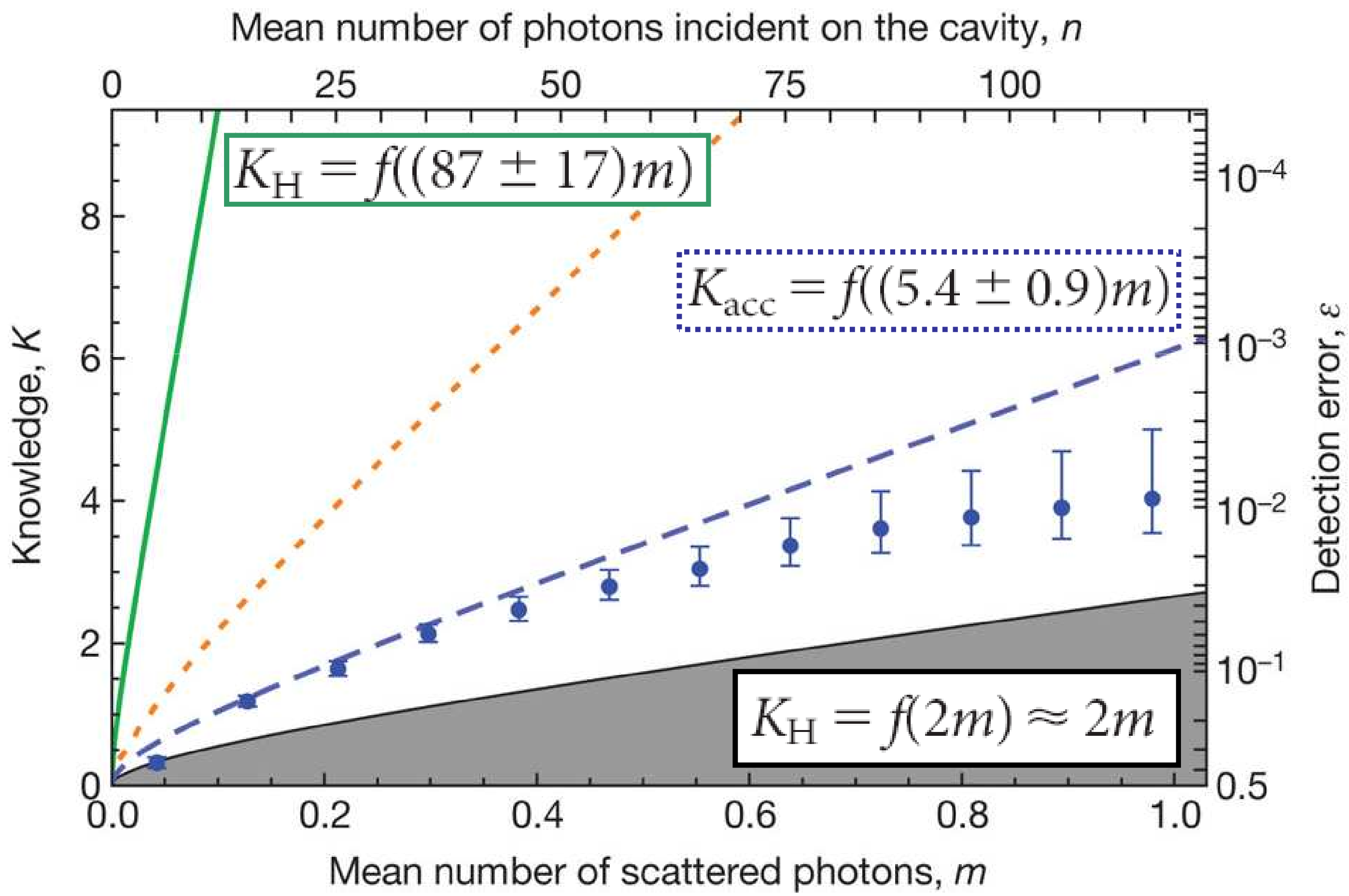
$$K_{\mathrm{acc}} = f(4.6 \times 10^{-2} n)$$

Spontaneous emission during detection.

- Initialize in bright state |1>
- Apply detection light
- Apply microwave Pi pulse
- Check if atom is in |0>
- Based on survival probability of |1>, estimate scattering assuming known branching ratios



Detection error and knowledge versus number of scattered photons.



Detection error below 10% while scattering less than 0.2 photons on average

Conclusions

- A full experimental characterization of a quantum measurment in the 'energy exchange-free'
  - 'knowledge' gained (~measurement error)
  - State collapse (backaction)
  - Spontaneous scattering
- Demonstrated higher knowledge/ lower detector error per scattered photon than possible with free-space fluoresence measurements
- Applications: non-destructive imaging of ultra-cold atoms, QIP with neutral atoms and ions.