Superposition, entanglement and raising Schrödinger’s cat

D. J. Wineland, NIST, Boulder, Colorado

Dilbert confronts Schrödinger’s cat, 4/17/12
Time magazine
(February 17, 2014)
Article about D-Wave “quantum computer”
Take note neutral atom trappers!

“The coldest place in the universe [20 milliKelvins] is actually in a small city directly east of Vancouver…”

Time magazine  
(February 17, 2014)  
Article about D-Wave “quantum computer”
A quantum computer can:

“HELP CARS DRIVE THEMSELVES  Google is using a quantum computer to design software that can distinguish cars from landmarks”

“BOOST GDP  Hyperpersonalized advertising, based on quantum computation, will simulate consumer spending”

Wow!
Summary:
- Schrödinger’s cat
- one person’s path
- spectroscopy, clocks
- quantum information
  - elements of quantum computing
  - quantum simulation
- many people & many groups worldwide
Erwin Schrödinger’s Cat (1935)
(extrapolating quantum mechanics from microscopic to macroscopic world)

At “half-life” of particle, quantum mechanics says cat is simultaneously dead and alive!

“superposition” \[ \Psi = |\bullet\rangle|\text{cat}\rangle + |\circ\rangle|\text{poisoned cat}\rangle \]
Schrödinger (1952):  
“We never experiment with just one electron or atom or (small) molecule. In thought experiments, we sometimes assume that we do; this invariably entails ridiculous consequences…”

But this is now our world! 
* at least for at least for small systems; e.g., atoms  
* precise control + isolation from environment  
* macroscopic systems: why not?
Norman Ramsey’s group, Harvard, 1966
Thesis: atomic deuterium maser
deuterium hyperfine frequency:
\[ f_0 = 327\ 384\ 352.5222(17) \text{ Hz} \]

- precise control of environment
- long-lived (~ 1 s) superpositions of hyperfine states (ensemble)
On to Hans Dehmelt’s lab (Univ. Washington) - trapped electrons/ions

**Goal:** electron magnetic moment measurement: smallest uncertainty with single electrons, $N = 1$
Single electrons

precursor to measurement of $\mu_{\text{electron}}$


$\text{ELECTRON CURRENT } \propto N$

$\tau \approx 3 \text{ sec}$

$u_s \approx 0.4 \mu V$

$\text{100 sec}$

signal out $\propto N$
Single electrons

**precursor to measurement of** $\mu_{\text{electron}}$


and, some ideas about laser cooling


laser cooling suppresses time-dilation shifts in spectroscopy & atomic clocks
On to NIST, 1975 (National Institute of Standards and Technology) (then NBS, National Bureau of Standards)

Cs beam frequency standard
“NBS-6”

Built by David Glaze

Group leader: Helmut Hellwig (persuaded NBS to support research on laser cooling)
Optical-Sideband Cooling of Visible Atom Cloud Confined in Parabolic Well

W. Neuhauser, M. Hohenstatt, and P. Toschek
Institut für Angewandte Physik I der Universität Heidelberg, D-69 Heidelberg, West Germany

H. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195

(Received 25 April 1978)

An assemblage of <50 Ba⁺ ions, contained in a parabolic well, has been visually observed and cooled by means of near-resonant laser irradiation.

Radiation-Pressure Cooling of Bound Resonant Absorbers

D. J. Wineland, R. E. Drullinger, and F. L.
Time and Frequency Division, National Bureau of Standards, Boulder, Colorado

(Received 26 April 1978)

We report the first observation of radiation-pressure cooling of Ba⁺ absorbers which are elastically bound to a laboratory fixed apparatus. The ions confined in a Penning electromagnetic trap are cooled to <40 K by irradiating them with a 8-μW output of a frequency doubled, single-mode dye laser tuned to the side of the Doppler profile on the ⁰S₁/₂ → ⁰P₃/₂ (M_J = +½ ⟷ M_J = +½) transitions. Cooling to approximately 10⁻³ K should be possible.
Mercury ion (Hg\(^+\)) experiments at NIST, 1981 →
40 GHz hyperfine transition
+ 282 nm narrow optical transition

\[ |0\rangle = |^2S_{1/2}\rangle \]
\[ |1\rangle = |^2D_{5/2}\rangle \]

\[ \tau = 0.1 \text{ s} \]

\[ |0\rangle \rightarrow \alpha |0\rangle + \beta |1\rangle \]

199\(^{199}\)Hg\(^+\)
“Electron shelving amplifier” detection (Hans Dehmelt)
- Bulletin APS 20, 60 (1975)

\[ |e\rangle = |^2P_{1/2}\rangle \]

\[ \tau \approx 2 \text{ ns} \]

Observation of fluorescence indicates \( |0\rangle \) state

Doppler cooling and detection!
“Electron shelving amplifier” detection (Hans Dehmelt)

- Bulletin APS 20, 60 (1975)

Absence of fluorescence indicates $|1\rangle$ state

$2P_{1/2}$

Hg$^+$

$|0\rangle$

$|1\rangle$

194 nm

absence of fluorescence indicates $|1\rangle$ state
Shelving spectroscopy

\[ \Delta n = -1 \quad \Delta n = +1 \]

Hg\(^{+}\)

\[ ^2P_{1/2} \quad ^2D_{5/2} \]

optical Mössbauer effect (recoilless absorption)

Single $^{199}$Hg$^+$ ions for (optical) clocks:
J. C. Bergquist et al., (NIST) 1981

- trapping $\Rightarrow$ first-order Doppler shift $\Rightarrow$ 0
- laser cooling $\Rightarrow$ time dilation small
- trapping in high vacuum at 4 K
  $\Rightarrow$ small environmental perturbations (collisions, black body shifts, etc.)
$\Rightarrow$ first clock with systematic uncertainly $(7 \times 10^{-17})$ below Cesium
Single $^{199}$Hg$^+$ ions for (optical) clocks:
J. C. Bergquist et al., (NIST)1981 →

Plus several other ion species: $^{88}$Sr$^+$, $^{171}$Yb$^+$, $^{27}$Al$^+$, $^{40}$Ca$^+$, $^{115}$In$^+$, $^{229}$Th$^{3+}$

see, e.g., P. Gill, Phil. Trans. R. Soc. A 369, 4109 (2011)
Atomic ion quantum computation:

1. START MOTION IN GROUND STATE
2. SPIN $\rightarrow$ MOTION MAP
3. SPIN $\leftrightarrow$ MOTION GATE

MOTION “DATA BUS”
(e.g., center-of-mass mode)

INTERNAL STATE “SPIN” QUBIT

$|m = 3\rangle$
$|m = 2\rangle$
$|m = 1\rangle$
$|m = 0\rangle$

“$m$” for motion

Motion qubit states

$|1\rangle$
$|0\rangle$
Atomic ion quantum computation:

1. START MOTION IN GROUND STATE
2. SPIN → MOTION MAP
3. SPIN ↔ MOTION GATE

Spin-motion coupling through
Jaynes-Cummings type Interaction
⇒ close connections to Cavity-QED

“m” for motion

Motion qubit states
SPIN → MOTION MAP

initial state

transfer information onto motion

quantized motion levels

\[(\alpha |0\rangle + \beta |1\rangle) |m=0\rangle \rightarrow |0\rangle (\alpha |m=0\rangle + \beta |m=1\rangle)\]

“\(\pi\) - pulse”
Conditional dynamics for quantum logic

<table>
<thead>
<tr>
<th>control bit (motion state)</th>
<th>target bit (atomic internal state)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m = 1 )</td>
<td>(</td>
</tr>
<tr>
<td>( m = 0 )</td>
<td>(</td>
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</tbody>
</table>

“Controlled-NOT” gate between motion and atom’s internal state

**Atomic ion experimental groups pursuing Quantum Information Processing:**

<table>
<thead>
<tr>
<th>Aarhus</th>
<th>MIT</th>
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<tbody>
<tr>
<td>Amherst</td>
<td>NIST</td>
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<td>The Citadel</td>
<td>Northwestern</td>
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<td>Tsinghua (Beijing)</td>
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<td>Osaka</td>
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<td>Duke</td>
<td>Paris (Université Paris)</td>
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<td>ETH (Zürich)</td>
<td>Pretoria, S. Africa</td>
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<td>Freiburg</td>
<td>PTB</td>
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<td>Garching (MPQ)</td>
<td>Saarland</td>
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<td>Georgia Tech</td>
<td>Sandia National Lab</td>
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<td>Griffiths</td>
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<td>Hannover</td>
<td>Simon Fraser</td>
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<td>Innsbruck</td>
<td>Singapore</td>
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<td>JQI (U. Maryland)</td>
<td>Sussex</td>
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<td>Lincoln Labs</td>
<td>Sydney</td>
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<td>Imperial (London)</td>
<td>U. Washington</td>
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<tr>
<td>Mainz</td>
<td>Weizmann Institute</td>
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</tbody>
</table>
Simulation:

Center-of-mass)mode
tilt mode

Exps: Shätz group, Freiburg
Monroe group, U. Maryland
Blatt group, Innsbruck
Bollinger et al., NIST

9 ions

transverse mode spectrum

“moving standing
wave” state-
dependent
forces

add magnetic field:

\[ H = \sum_{i<j} J_{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} + B \sum_i \hat{\sigma}_y^{(i)} \]

Transverse Ising model

Porras and Cirac, PRL 92, 207901 (2004)
Porras and Cirac, PRL 96, 250501 (2006)
Deng, Porras, Cirac, PRA 7782, 063407 (2005)
Taylor and Calarco, PRA, 062331 (2008)

for \( \omega_{\text{force}} \approx \omega_{\text{COM}} \)

\[ H = J \sum_{i<j} \hat{\sigma}_z^i \hat{\sigma}_z^j \Rightarrow \text{GHZ states} \]

for larger detunings ( \( \omega_{\text{force}} > \omega_{\text{COM}} \) )

\[ H = \sum_{i<j} J_{i,j} \hat{\sigma}_z^i \hat{\sigma}_z^j \]

\( J_{i,j} \sim \frac{J_0}{|i-j|^\alpha} \)

vary \( \alpha \) by varying detuning
- N > 100 spins
- "self assembled" triangular lattice

transverse mode spectrum (modes out of plane)

\[ J_{i,j} \sim \frac{+J_0}{|i - j|^\alpha} \]
- Observe Ising coupling
- \( \alpha = 0.01 - 2.72 \) (vary \( \delta \))
  \[ J_0 \sim 1 \text{ kHz} \ (\alpha = 1) \]

J. Britton et. al., Nature 484, 489 (2012)
Building block: gates between ions in separated wells ($d = 30 \, \mu m$)


Chiaverini and Lybarger, PRA 77, 022324 (2008)
Schmied, Wesenberg, Leibfried, PRL 102, 233002 (2009)

\[ \alpha | \downarrow_{Al} \rangle + \beta | \uparrow_{Al} \rangle \rightarrow \text{motion superposition} \rightarrow \alpha | \downarrow_{Mg} \rangle + \beta | \uparrow_{Mg} \rangle \]

- Laser-cooled Mg$^+$ keeps Al$^+$ cold
- Mg$^+$ helps to calibrate \( \langle B^2 \rangle \) from all sources
- Collisions observed by ions switching places
- \( \Delta f/f_0 \) (systematic) = \( 8.0 \times 10^{-18} \)

\( \lambda = 167 \text{ nm} \)

\[ \begin{array}{c}
\text{\( ^1P_1 \)} \\
\text{\( ^3P_0 \)} \\
\text{\( ^1S_0 \)}
\end{array} \rightarrow \begin{array}{c}
\text{\( ^2P_{3/2} \)} \\
\text{\( ^2S_{1/2} \)}
\end{array} \]

\( \tau \approx 4 \text{ ns} \)
Moving target!

Jun Ye’s group (JILA), Sr neutral atoms in optical lattice:

\[ \frac{\Delta f}{f_0} \text{(systematic)} = 6.4 \times 10^{-18} \]

(B. J. Bloom et al., Nature 506, 71 (2014))

\[ \Delta T \approx 30 \text{ mK} \]

PTB, Braunschweig, Germany

\[ \frac{\Delta f}{f_0} \text{(systematic)} = 3.9 \times 10^{-18} \]

(unpublished)

weak (octupole) transition, laser Stark shifts, …

H. Katori group (Riken) Sr neutral atoms in optical lattice

\[ \frac{\Delta f}{f_0} \text{(systematic)} = 7.2 \times 10^{-18} \text{ (arXiv:1405.4071)} \]

record low instabilities: Sr (JILA,Riken), Yb (NIST) \( \sim 2 \times 10^{-18} \) \( (\tau = 10^4 \text{ s}) \)
Schrödinger’s cat?

\[ \Psi(t) = |0\rangle_0 |0\rangle_1 |0\rangle_2 \ldots |0\rangle_{N-1} + |1\rangle_0 |1\rangle_1 |1\rangle_2 \ldots |1\rangle_{N-1} \]

For large \( N \) \thinspace \[ \Psi = |0\rangle_0 \vec{M}_{\downarrow} + |1\rangle_0 \vec{M}_{\uparrow} \]

\[ \vec{M} \]

macroscopic magnetization
Schrödinger’s cat?

\[ \Psi(t) = |0\rangle_0 |0\rangle_1 = |\bigcirc\rangle |\text{cat}\rangle + |\bigcirc\rangle |\text{mouse}\rangle \quad ? \quad \ldots |1\rangle_{N-1} \]

For large \( N \) \( \Psi = |0\rangle_0 \vec{M}_\downarrow + |1\rangle_0 \vec{M}_\uparrow \)

macroscopic magnetization
● plus students, postdocs, visitors (> 100)
● institutional support: Helmut Hellwig, Sam Stein, Don Sullivan, Tom O’Brian, Carl Williams, Katharine Gebbie…
And good friends along the way!