Experimental certification of millions of genuinely entangled atoms in a solid

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Entanglement: more than correlation

\[ |\psi\rangle \propto |01\rangle - |10\rangle \]

- Correlation: learn about A by measuring B

- Entanglement: “One particle does not carry (full) information (about itself)”
Conceptual challenges

- Complexity of multipartite entanglement, e.g.

\[ |000\rangle + |111\rangle \iff |100\rangle + |010\rangle + |001\rangle \]
Technical challenges

- Some sorts of multipartite entanglement very fragile; others
  \[ |\text{GHZ}\rangle = |000\ldots0\rangle + |111\ldots1\rangle \]
  
- Simple entanglement witnesses needed

- Limited measurements: basis and precision

\[ |\text{W}\rangle = |10\ldots0\rangle + |01\ldots0\rangle + \cdots + |00\ldots1\rangle \]
How the absorption of a single photon entangles millions of atoms

- Entanglement Depth: concept to order structure of entanglement
- Theory: Intuition for our experiment
- Experimental results
$k \ldots$ Entanglement Depth =
Largest group of entangled atoms
(each atom = two levels)

Separable states
$k = 1$

Mølmer, Sørensen PRL (2001)
• Lücke et al. PRL 2014: over-squeezing
  Entanglement depth $k \sim 45$ (1σ)
• Haas et al. Science 2014: W state
  Entanglement depth $k \sim 13$ (1σ)
• McConnell et al. Nat. Phys. 2015: W state
  Entanglement depth $k \sim 2600$ (1σ)

Our AFC quantum memory

• $\sim 4 \times 10^{10}$ ions
• Absorption of single photon $\rightarrow$ W state
Scenario

- Prepare atomic ensemble (ground state preparation + absorption of single photon)

\[ |1\rangle \rightarrow |egg \ldots \rangle + |geg \ldots \rangle + |gge \ldots \rangle + \ldots \]

- Spontaneous re-emission

- Measure emitted light
Spontaneous emission
Directed emission ↔ Collective effect

See also Scully et al., PRL 2006
Increase of $k$

$k = 1$

$k = N$
Bounds on entanglement depth for 40 billion atoms
Experiment

Setup

Results
Setup: Atomic frequency comb

- Herald single photon $\rightarrow$ store in memory
- **Signal** in forward mode $\rightarrow p_1$ and $p_2$
- **Noise** (=fluorescence) in backward mode $\rightarrow$ Signal/Noise: number of involved atoms

QM ... quantum memory:
Nd$^{3+}$:Y$_2$SiO$_5$ @ 7% efficiency
Result

![Graph showing separable states and incorporating detector inefficiencies]

<table>
<thead>
<tr>
<th>Entanglement depth $k$</th>
<th>$k - 3\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw data 0.5 million</td>
<td>0.08 million</td>
</tr>
<tr>
<td>W/o detector inefficiency 16 million</td>
<td>4 million</td>
</tr>
</tbody>
</table>
Conclusion

• 16 million genuinely entangled atoms
  (improvement by four orders of magnitudes)

  Certain entanglement can be revealed even with limited control.

Entanglement depth for W state:
- 16 (Haas et al., 2014)
- 2900 (McConnel et al., 2014)
- 16 million

“GHZ-like” entanglement:
See arXiv:1706.06178

![Graph showing Neff values for different types of entanglement states.]
• Entanglement depth
  → classification of large q. systems

• Directionality
  + single-photon character
  → large entanglement depth

• Measured data with AFC quantum memory
  \[ k \sim 16 \text{ million} \]
2 steps from intuition to experiment

- Model-independent entanglement directly from atomic ensemble
  \[ \langle W | \rho | W \rangle \]
  \[ \langle D_2 | \rho | D_2 \rangle \]
  \[ N \]

- Model-dependent arguments to identify
  \[ p_1 = \langle W | \rho | W \rangle \]
  \[ p_2 = \langle D_2 | \rho | D_2 \rangle \]
  - Source
  - Light-matter interaction
  - Memory preparation
Experimental setup
Entanglement in large spin ensembles

- Many spins $\frac{1}{2}$

- No access to single particles; only collective observables:

  \[ J_x = \frac{1}{2} \sum_{i=1}^{N} \sigma_x^{(i)} \]
  \[ J_z = \frac{1}{2} \sum_{i=1}^{N} \sigma_z^{(i)} \]

What can we say about entanglement?

- Large polarization
  \[ \langle J_z \rangle = \frac{N}{2} \]
  \[ \text{Var}(J_x) = \frac{N}{4} \]

- No polarization
  \[ \langle J_z \rangle = 0 \]
  \[ \text{Var}(J_x) = 0 \]
Lower repetition rate
\[ g^{(2)} = 0.020 \pm 0.003 \]
Signal-to-noise ratio

• Ideal Fluorescence: $\langle \hat{n} \rangle / N \approx 10^{-10} \langle \hat{n} \rangle$

• Small intensity $\rightarrow$ technical noise dominant

• Subtract electronic detector noise
Coherence between atoms

- Spin-coherent state: classical coherence
  \[ |\alpha\rangle = |\phi_\alpha\rangle \otimes |\phi_\alpha\rangle \otimes \cdots \otimes |\phi_\alpha\rangle \]

- W state: quantum coherence = \textit{entanglement}
  \[ |W\rangle = |egg\ldots\rangle + |gge\ldots\rangle + |gge\ldots\rangle + \ldots \]

\[ p_1 = \langle 1 | \rho | 1 \rangle \]

Both states have large

! Nonclassicality of emitted light → Ratio \( p_1, p_2 \) is important

- Spin-coherent state
  \[ p_2 = p_1^2 / 2 \]

- W state
  \[ p_2 = 0 \]
New states – new bounds

- Squeezing and Dicke states

\[ |W\rangle = |egg \ldots \rangle + |egg \ldots \rangle + \ldots \]

Mølmer, Sørensen PRL (2001)

Lücke et al., PRL (2014)

Haas et al., Science (2014)