Multi-particle entanglement dynamics induced by decoherence

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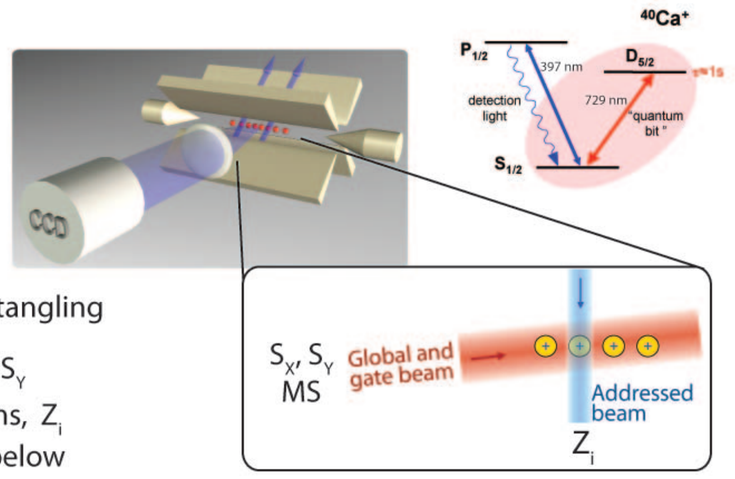
Goal: To experimentally characterize the dynamics of entanglement of a multiparticle state under the influence of decoherence.

How? By embedding an entangled state of four qubits in a decohering environment (via spontaneous decay)

What? We observe a rich dynamics crossing distinctive domains: Bell-inequality violation, entanglement superactivation, bound entanglement, and full separability.

Where?

Linear string of 4 trapped ions



Tools?

(i) Mølmer-Sørensen entangling operation, MS
(ii) Global rotations, S_X, S_Y
(iii) Single-qubit rotations, Z_i
(iv) Dissipation, see [2] below

In 3 steps...

Preparation [1]

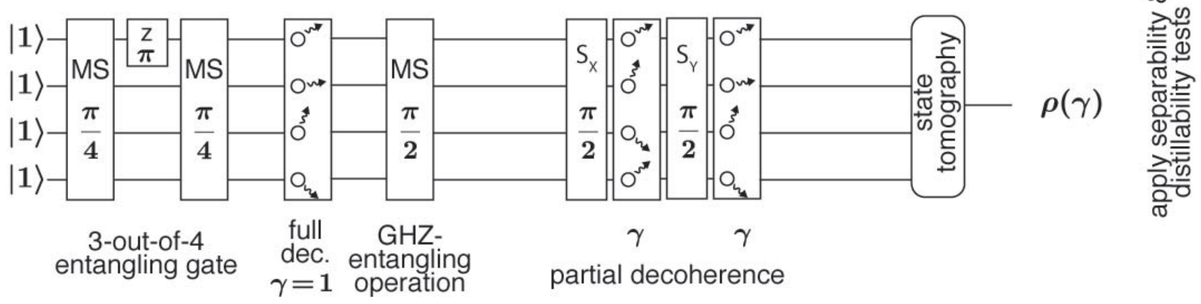
To prepare an entangled and distillable state near Bound Entanglement (BE): an imperfect Smolin state

Decoherence [2]

Controllably drive the state into & past bound entanglement

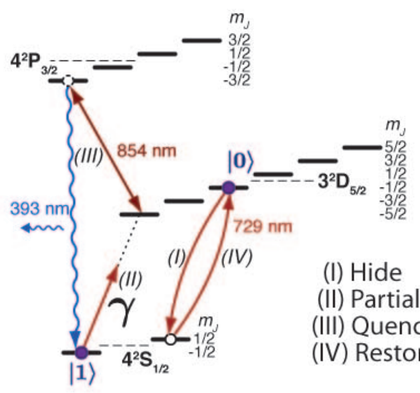
Characterization [3]

Reconstruct state & determine entanglement & distillability properties



[2]

For each ion, partially transfer the population in $|1\rangle$ to a state that spontaneously decays.



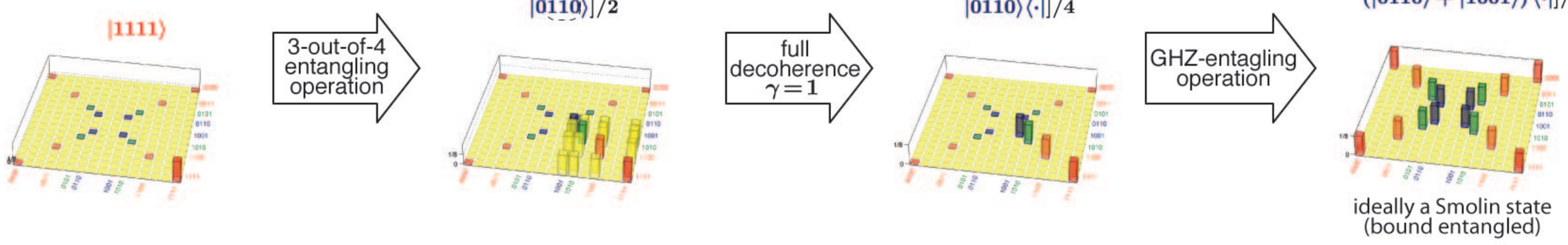
(I) Hide
(II) Partial transfer γ
(III) Quench & decay
(IV) Restore

Effectively each qubit decoheres as:

$$a|0\rangle + b|1\rangle \rightarrow \begin{pmatrix} |a|^2 & \sqrt{1-\gamma}ab^* \\ \sqrt{1-\gamma}a^*b & |b|^2 \end{pmatrix}$$

[1]

All ions in motional ground-state & sideband cooled, & optically pumped to $4^2S_{1/2}$,m=-1/2



[3] Entanglement & Distillability

If ρ can be written as

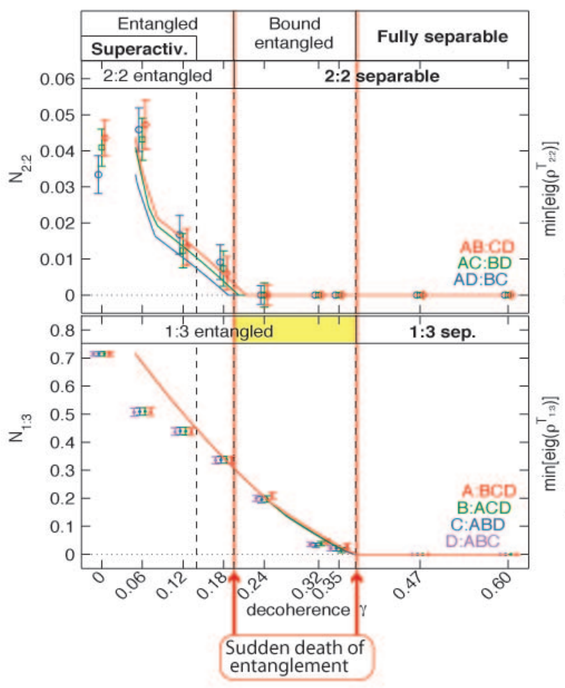
$$\rho = \sum_k p_k |\psi_k\rangle\langle\psi_k|$$

then it's called :

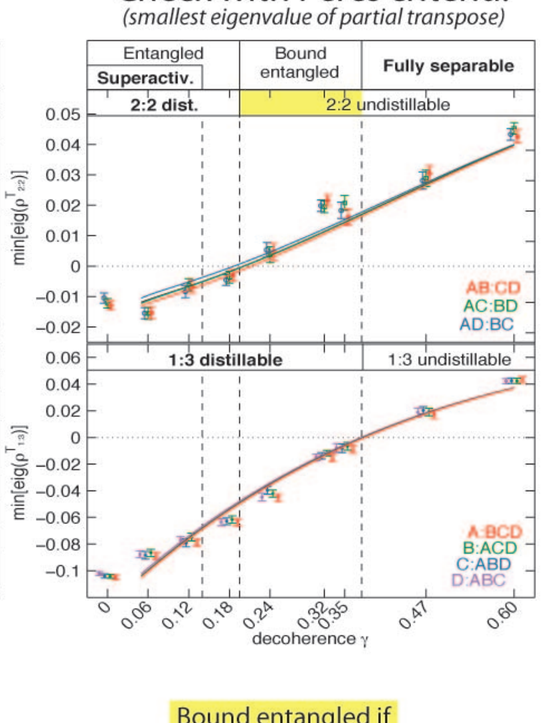
2:2 separable if $|\psi_{2:2}\rangle = |\alpha,\beta\rangle \otimes |\gamma,\delta\rangle$
2:2 entangled if not

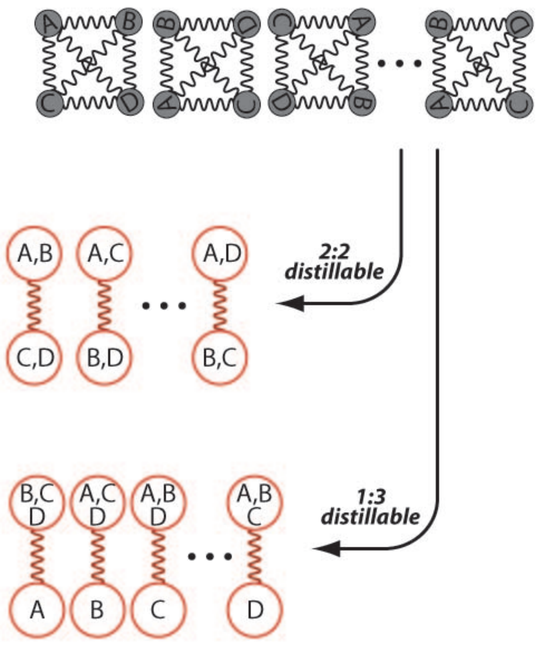
1:3 separable if $|\psi_{1:3}\rangle = |\alpha\rangle \otimes |\beta,\gamma,\delta\rangle$
1:3 entangled if not

Check with negativity, N



Check with Peres criteria:
(smallest eigenvalue of partial transpose)





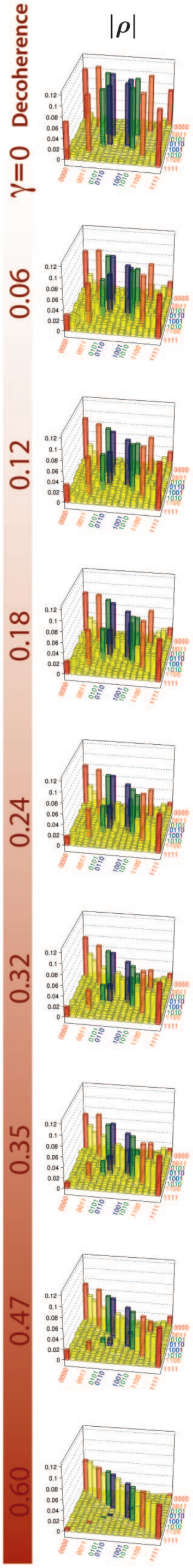
Entanglement superactivation:
Enables five parties (A,B,C,D, and E) sharing two copies of the state (ρ_{ABCD} and ρ_{ABCE}) to distill entanglement between the two parties holding a single particle (D and E).

fully separable if $\rho = \rho_A \otimes \rho_B \otimes \rho_C \otimes \rho_D$
entangled if not

Bound entangled if 1:3 entangled & 2:2 undistillable

entangled but undistillable !

Note: Separability, distillability, and superactivation properties determined from tests independent of the plotted data.



Outlook

* Our decoherence mechanism drives a GHZ into bound entanglement too! Experimentally feasible?
* See bound entanglement from XY spin models, or other many-body states, and, in particular, see it occur *naturally and incontrovertibly* in other physical systems.
* Look for techniques to avoid the decay into bound entanglement.
* Use tools for an open system quantum simulator.

We answered Horodecki$^{\otimes 3}$'s question: YES, there is bound entanglement in nature*!

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