Quantum entanglement between an atom and a molecule

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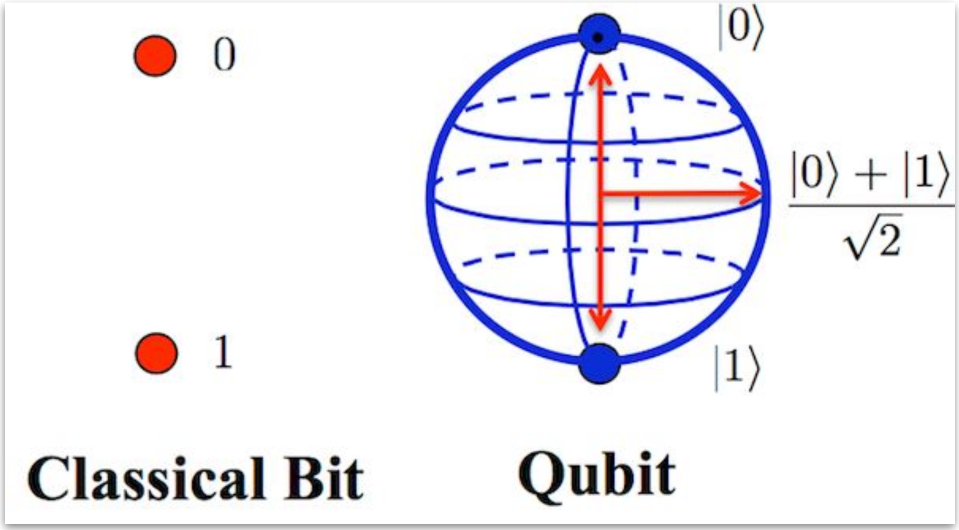
Lin, Y., Leibrandt, D.R., Leibfried, D. et al. Nature 581, 273–277 (2020).
https://doi.org/10.1038/s41586-020-2257-1

PHYS-596 Journal Club Presentation - Group 3
arXiv:1912.05866

Qubits: units of quantum computation

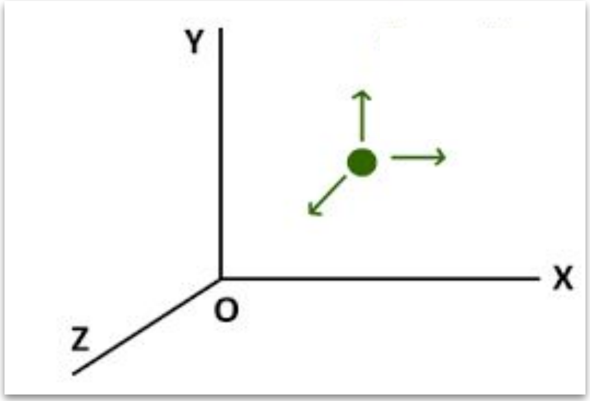
- Qubits: a superposition of two quantum states
  - Possible with any quantum system that supports multiple states (one or more atomic/molecular ions)
- Qubit frequency: determined by the energy difference between states
  - Allows for different kinds of quantum computers

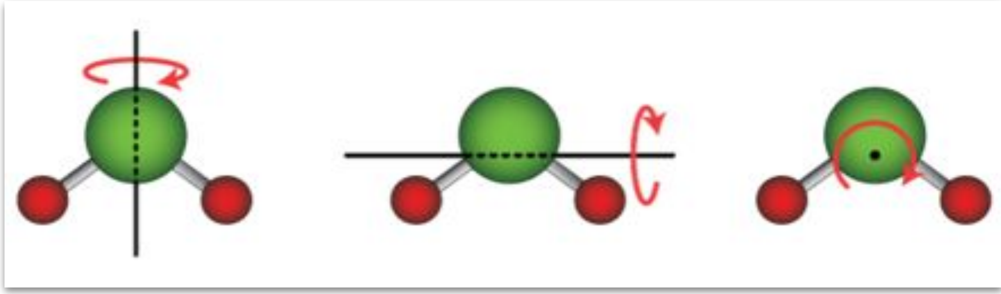


source: University of Strathclyde

Different ion qubit systems

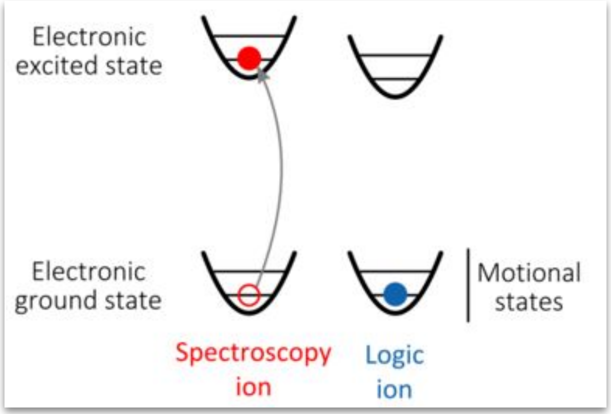
- Qubits with atoms
  - Has been achieved with 10s of qubits
  - Difficult to scale to more qubits or support different frequencies
- Qubits with molecules
  - More degrees of freedom
  - More difficult to manipulate
- Entanglement and qubits
  - Allows coherence between qubits
  - Has been achieved with atomic qubits (reviewed here)





Source: Wikimedia Commons

How to entangle ions: quantum logic spectroscopy (QLS)



Source: Institute for Experimental Quantum Metrology

- Use a well-known atom (*logic* ion) to understand a novel molecule (*spectroscopy* ion)
- Couple the ions in the same potential to allow for entanglement

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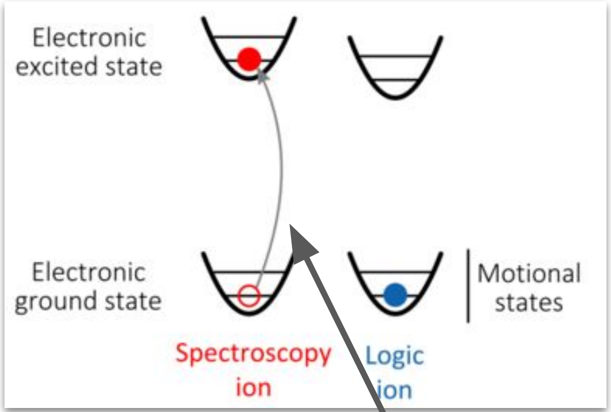
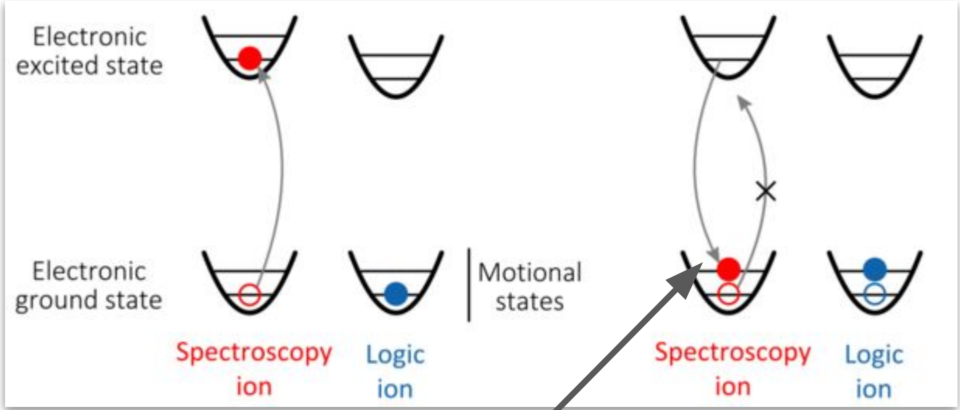


Laser to try exciting the *molecular* ion

How to entangle ions: quantum logic spectroscopy (QLS)



Molecular ion decays to energized motional state

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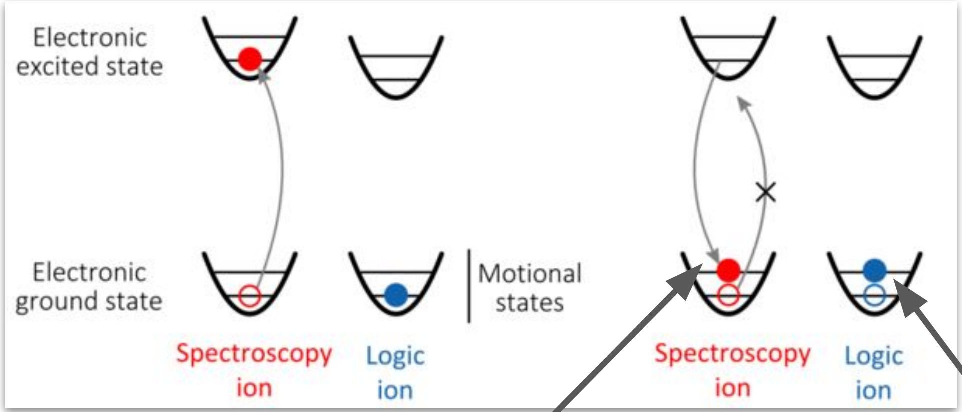
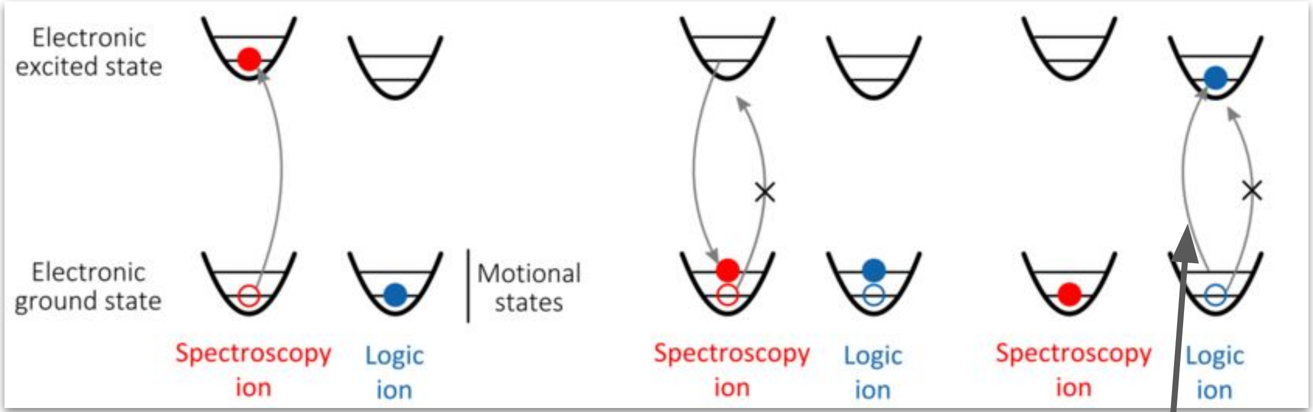


Molecular ion decays to energized motional state

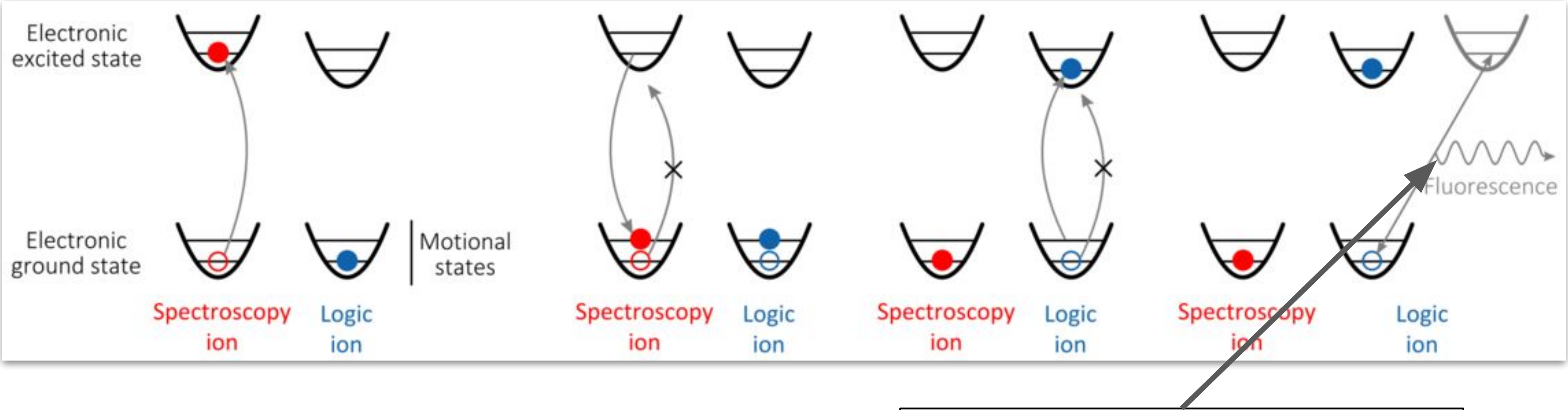
Atomic ion is also in an energized motional state

How to entangle ions: quantum logic spectroscopy (QLS)



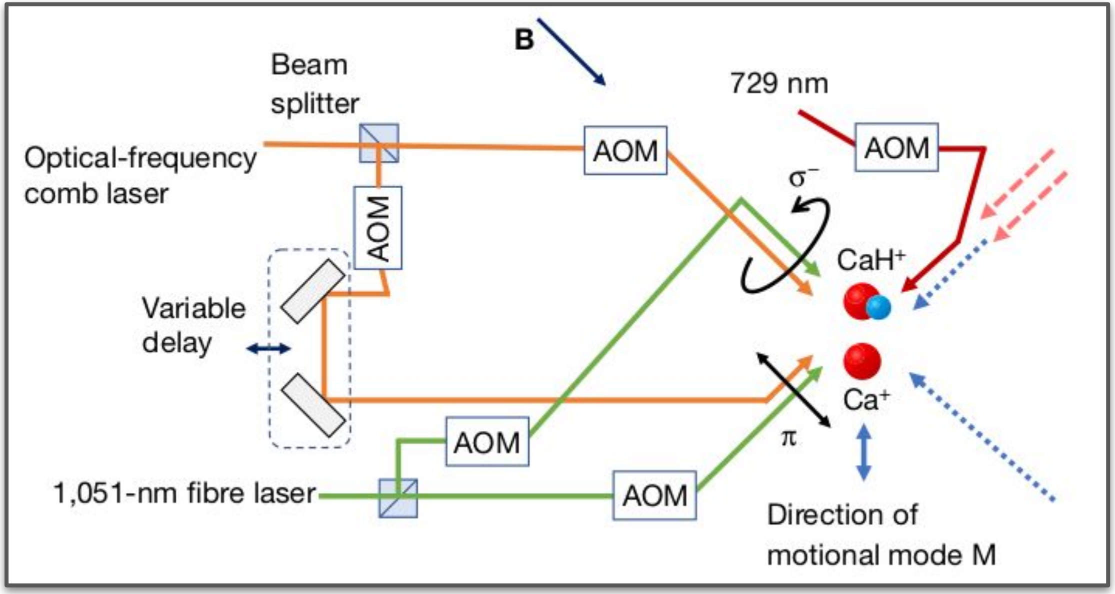
Laser to excite the *atomic* ion

How to entangle ions: quantum logic spectroscopy (QLS)



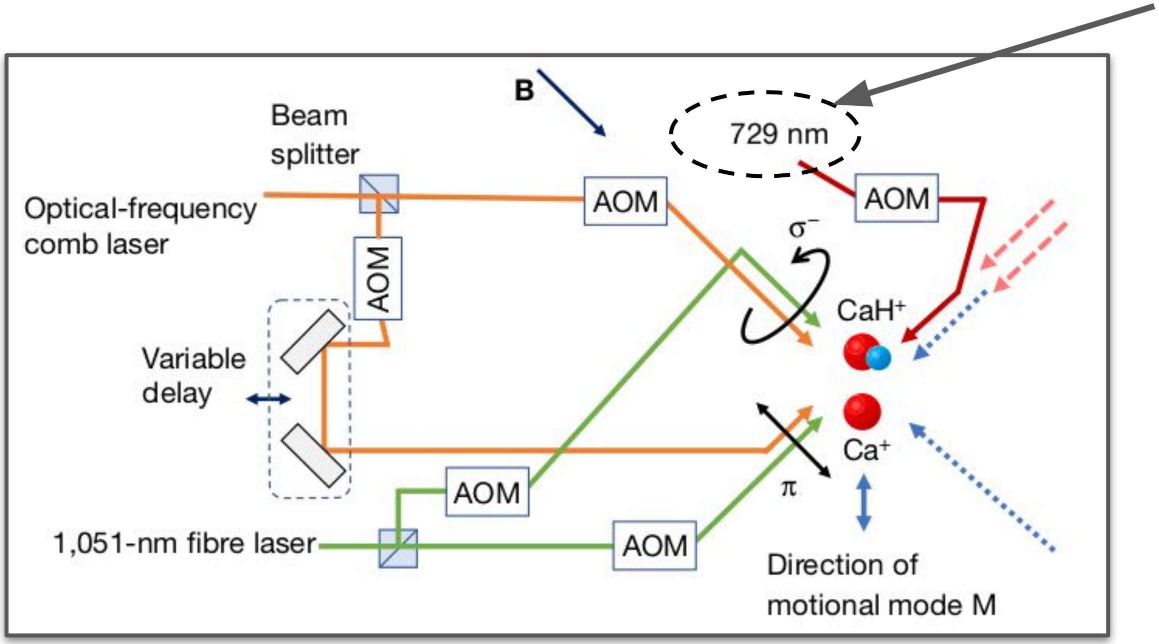
Detect the state of the *atomic* ion: signal is visible only if the experiment was unsuccessful

Experiment to manipulate molecular qubits



Experiment to manipulate molecular qubits

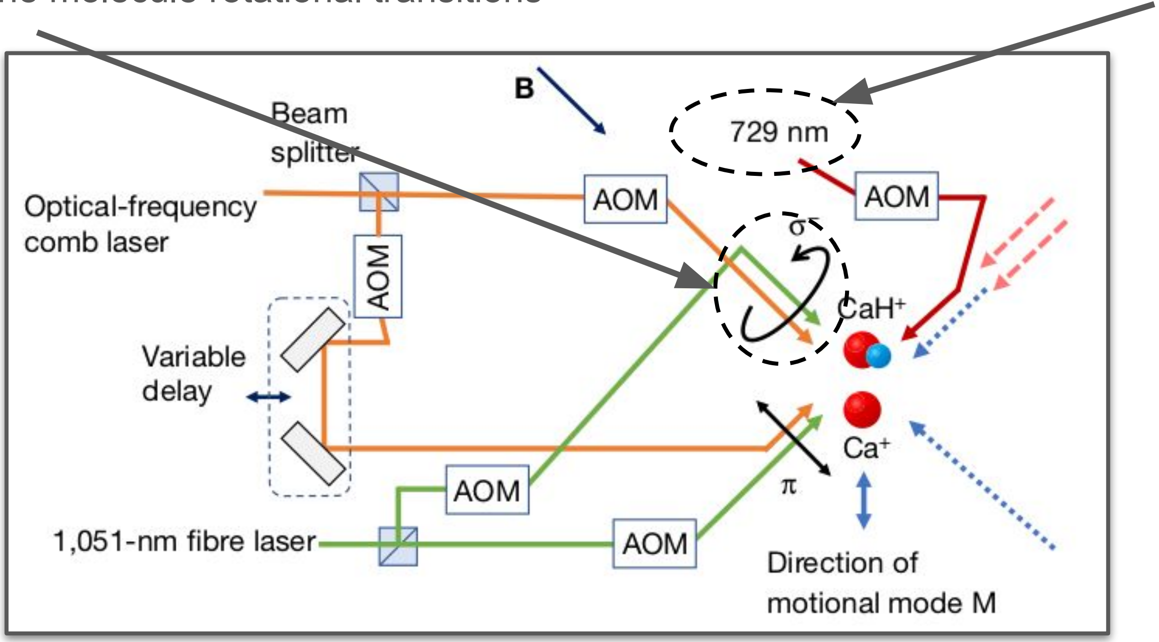
Laser to prepare the atomic qubit



Experiment to manipulate molecular qubits

Lasers to manipulate the molecule rotational transitions

Laser to prepare the atomic qubit



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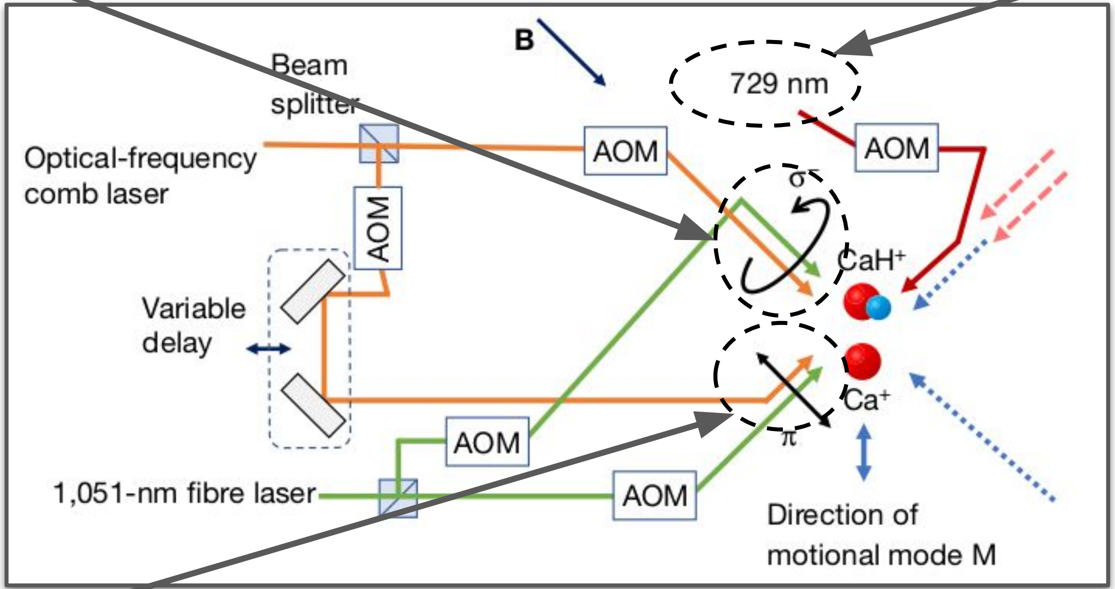

Lasers to drive molecule sideband transitions

Experiment to manipulate molecular qubits

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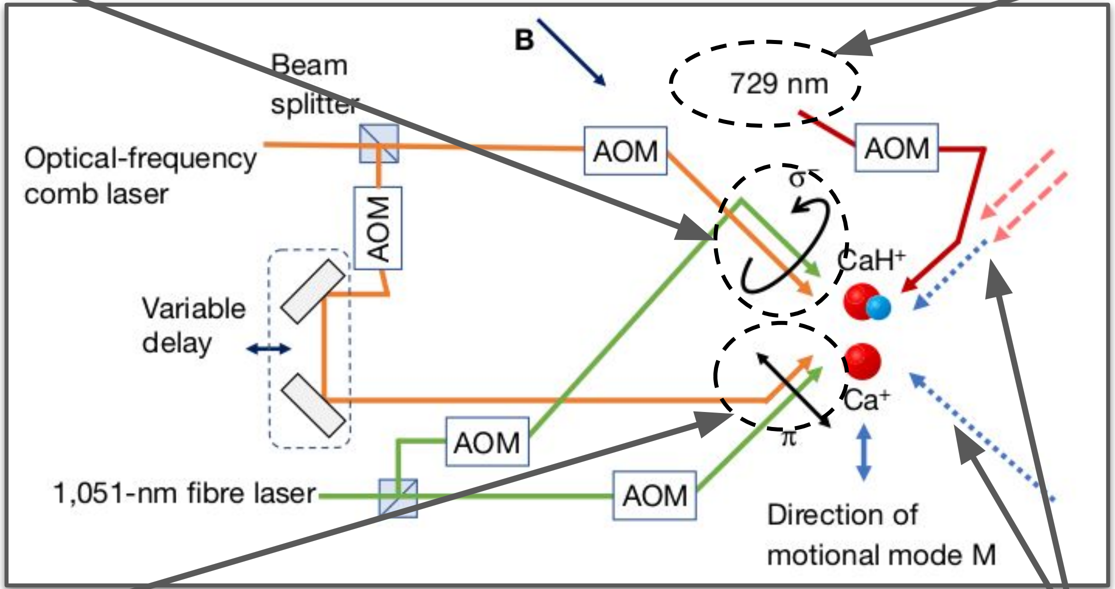
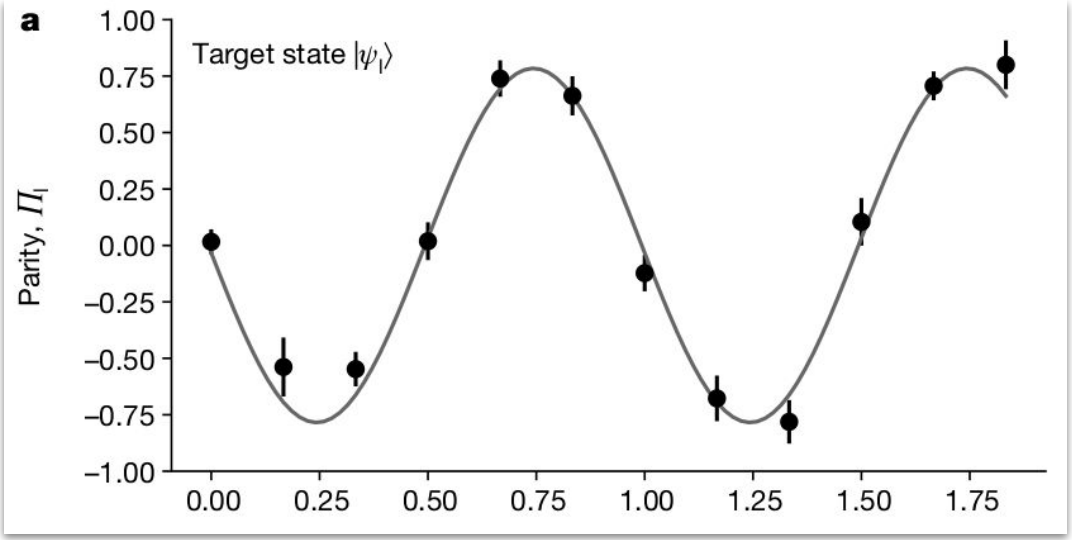


Lasers to drive molecule sideband transitions

Lasers to measure the state of the atomic ion

Demonstration of entangled atomic and molecular qubits

- Quality of entanglement, “fidelity”: scales with amplitude of oscillation
- x-axis: phase of the laser used to measure parity
- Each point is ~99 measurements of entanglement



C=0.78(4)

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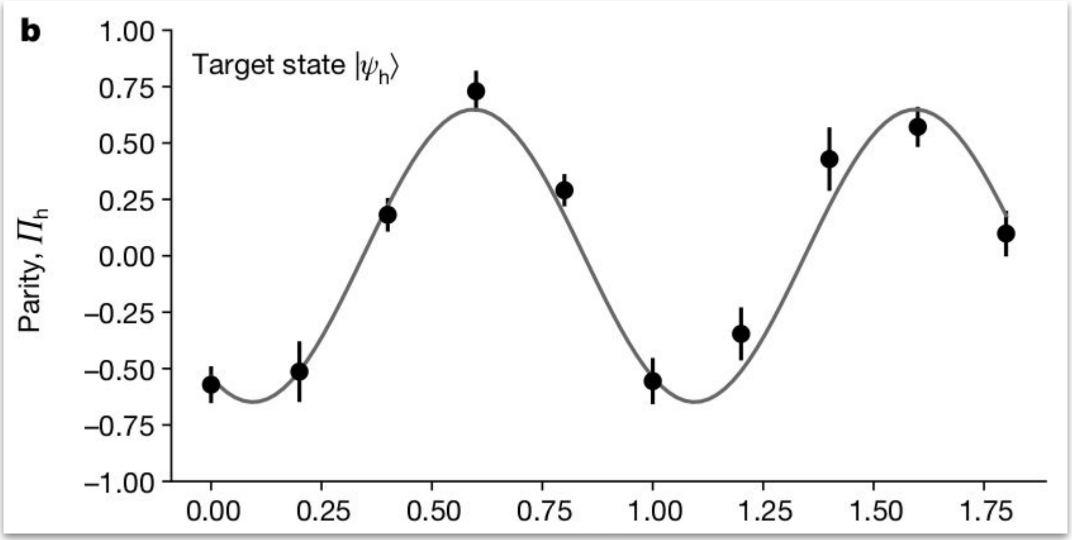

C=0.65(8)

Main Conclusions

- Experimental evidence that a molecular ion and atomic ion can be entangled

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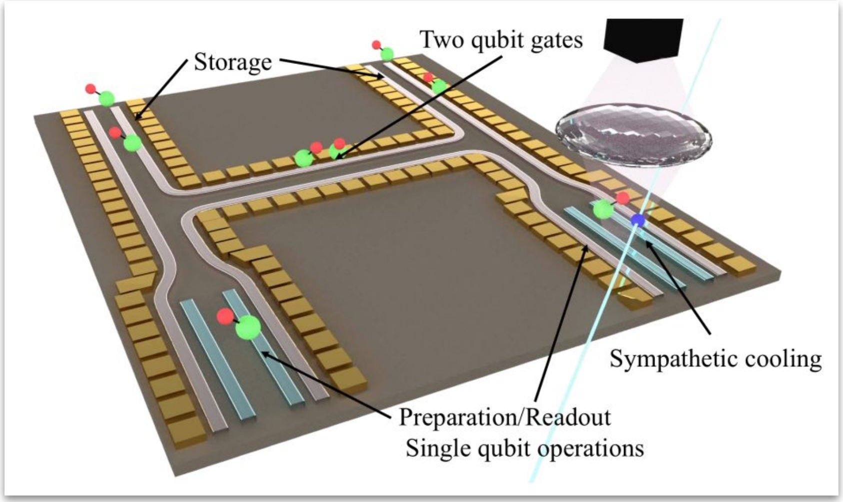
- Entanglement with molecular qubit at different frequencies

Realization of previous theories

- Two 2018 theory papers suggesting the use of rotational molecule states for qubits and qubit gates



Realization of previous theories

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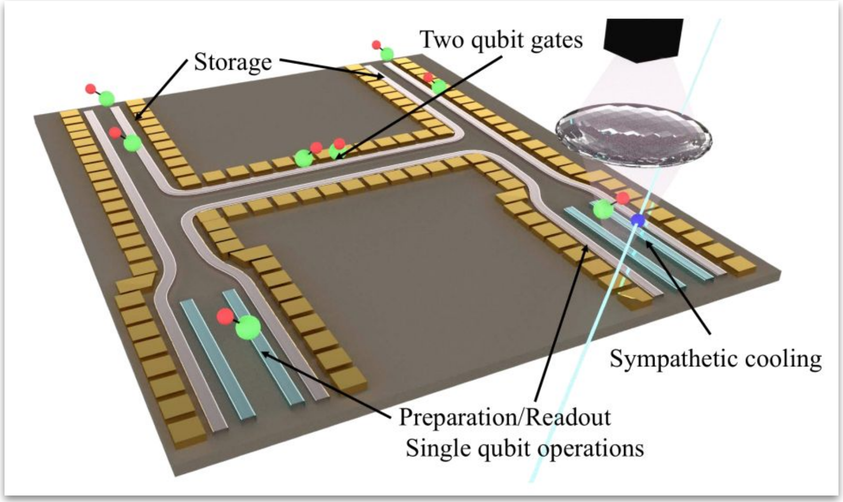
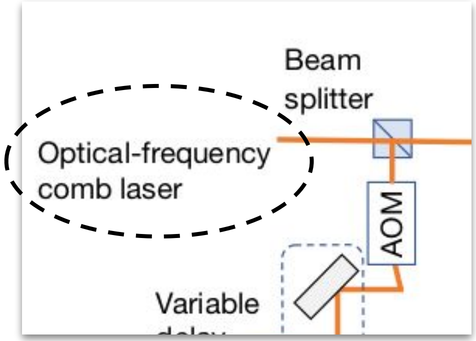
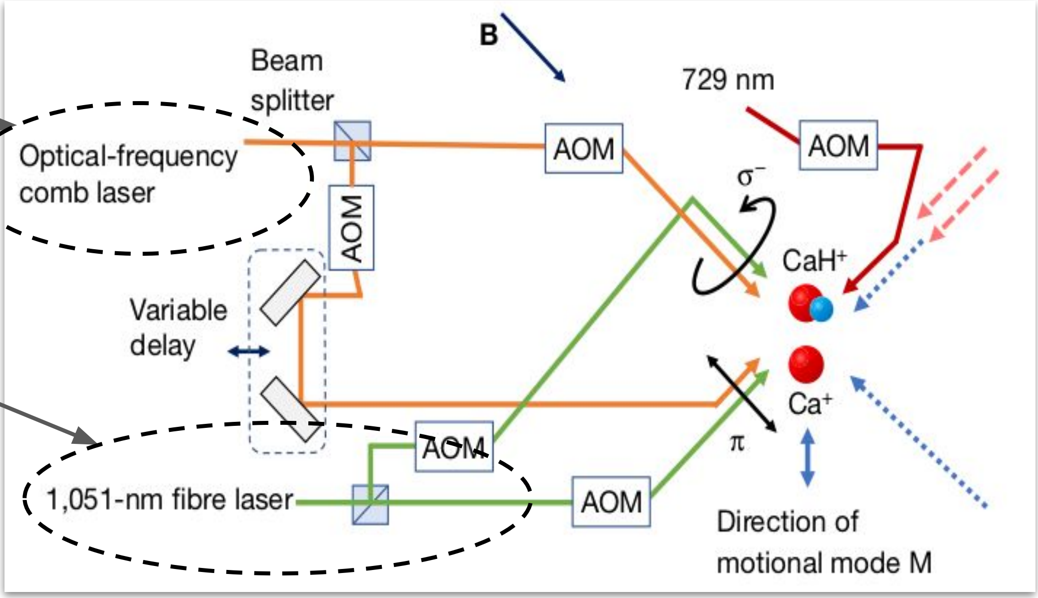
- Two theory papers on how to manipulate molecular qubits using laser comb





First paper to combine previous methodologies

- Applies methods from two previous papers to create the low-frequency and high-frequency molecular qubits



Later papers influenced by this research

Robust Encoding of a Qubit in a Molecule
https://journals.aps.org/prx/pdf/10.1103/PhysRevX.10.031050

This work “constructs quantum error-correcting codes that embed a finite-dimensional code space in the infinite- dimensional Hilbert space of rotational states of a rigid body”. Motivated by EAM (Quantum entanglement between an atom and a molecule), this work aims to process quantum information coherently using rotational states of a polyatomic molecule.

Later papers influenced by this research

High-Fidelity Bell-State Preparation with 40Ca+ Optical Qubits
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Motivated by EAM, this work demonstrate an entangling light shift gate “using a pair of 40Ca+ ions in a cryogenic surface-electrode ion trap and a commercial, high-power, 532 nm Nd:YAG laser “. They generate a Bell state in 35*10^(-6) s and measure an infidelity of 6(3) × 10^(-4)

Citation impact

Access & Citations

11k
Article Accesses

26
Web of Science

30
CrossRef

Online attention

- 69 tweeters
- 3 blogs
- 10 news outlets
- 3 Redditors
- 100 Mendeley

This article is in the 97th percentile (ranked 8,627th) of the 308,379 tracked articles of a similar age in all journals and the 52nd percentile (ranked 404th) of the 853 tracked articles of a similar age in *Nature*

Scopus metrics

28 86th percentile
Citations in Scopus

1.89
Field-Weighted citation impact

Views count
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Views count 2021

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Views count 2013-2022

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News Mentions

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Little explanation of entanglement fidelity F

$$F = |\langle \psi_{\text{generated}} | \psi_{\text{ideal}} \rangle|^2$$

F = 1 for perfect entanglement

F > 0.5 for bipartite entanglement

Other experiments have found F = 0.92 (9 photons) [1], F = 0.57 (4 ions) [2], for example

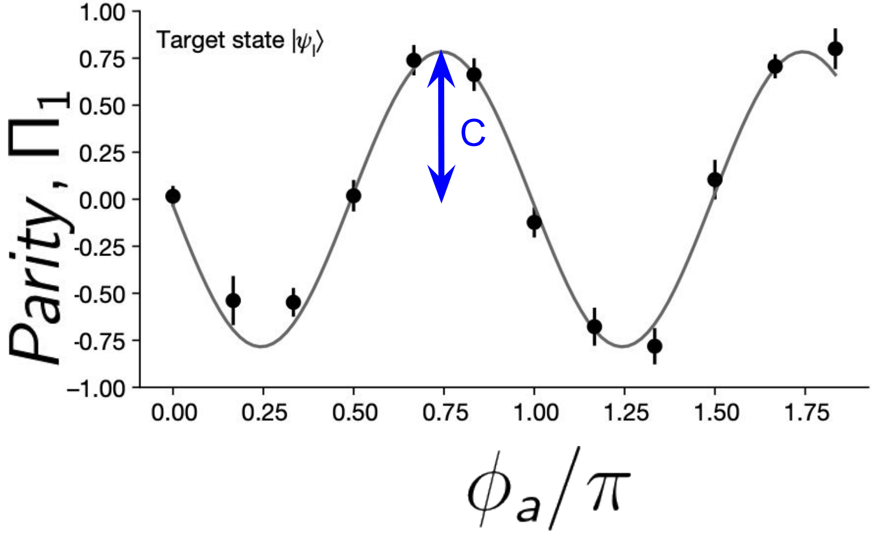
[1] https://www.science.org/doi/10.1126/sciadv.aar3931
[2] https://www.nature.com/articles/35005011

Not much data and not many figures

It's an experimental paper!

$$F = \frac{1}{2}(P_{S,-3/2} + P_{D,-5/2} + C)$$

Probability of finding the atom and molecule in the state $|S\rangle|-3/2\rangle$



Parity measurements of the entangled states.

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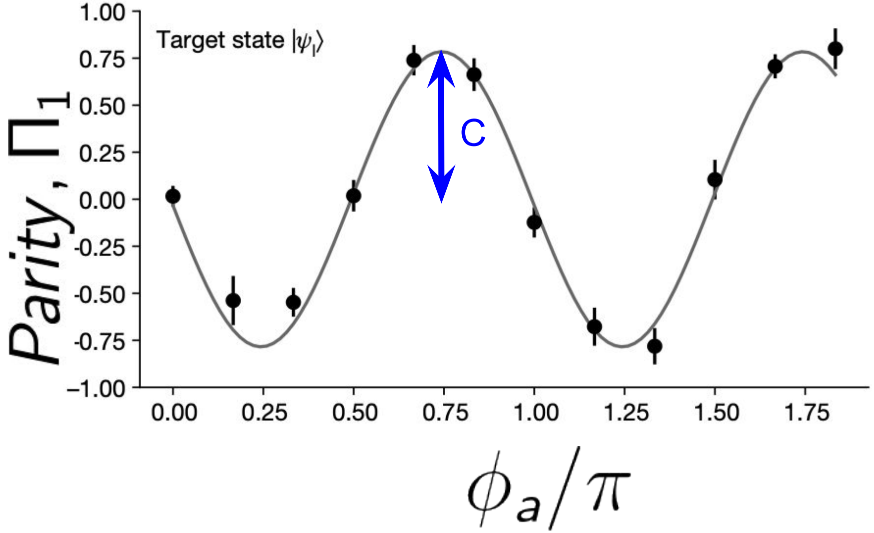
Without data, it's difficult to judge the credibility of their results.



Parity measurements of the entangled states.

An okay explanation of the work’s novelty

The authors could have emphasized:

Why molecule-atom entanglement has not been done in the past

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The authors could have emphasized:

- Why molecule-atom entanglement has not been done in the past
- What new technique allowed them to entangle a molecule and atom now

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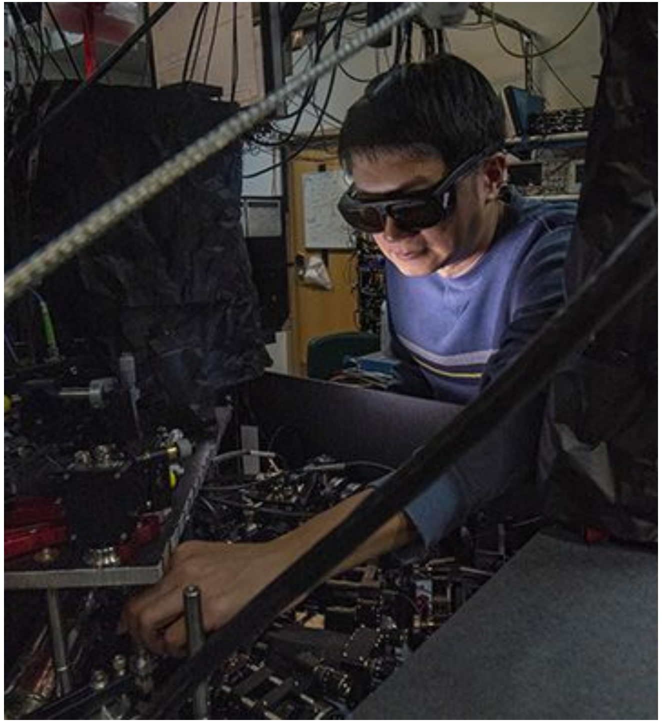
Overall, this paper seems significant and understandable for experts in the field, but not for novices like us :/

Summary

Entanglement between a molecule and atom has been demonstrated experimentally!

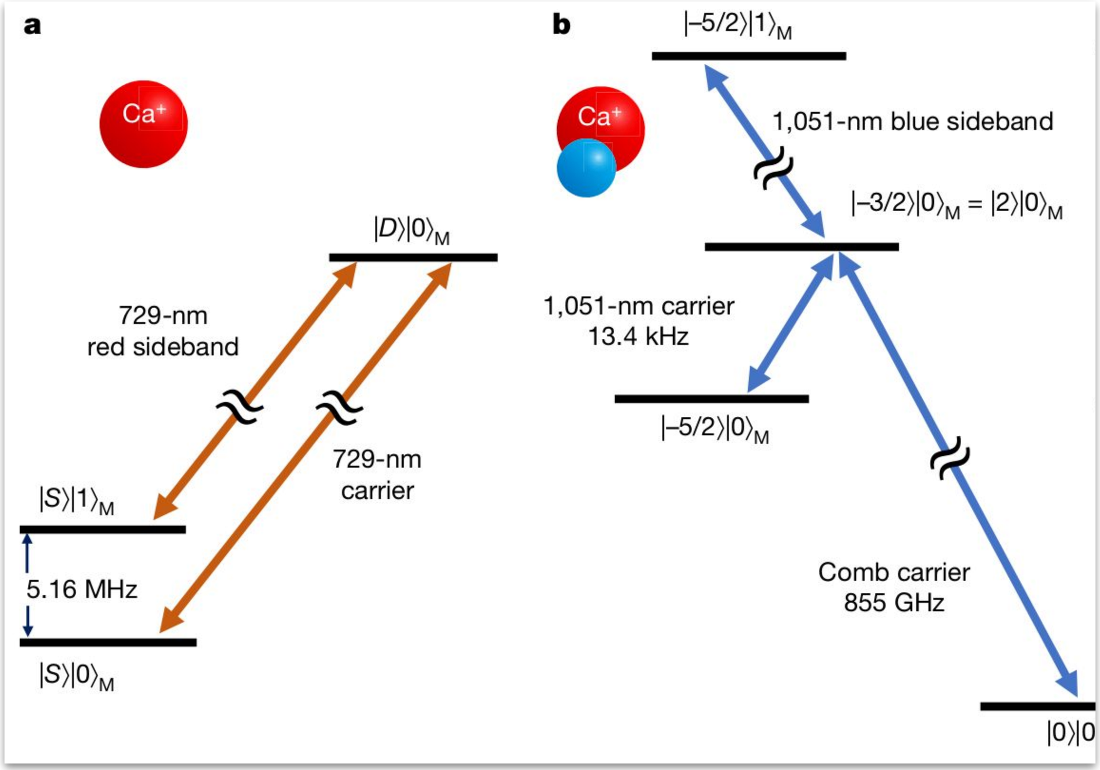
Potential applications in quantum information, quantum control, and more

Significant and comprehensible for experts



https://www.optica-opn.org/home/newsroom/2020/may/atom–molecule_entanglement/

QLS with an atomic qubit and two molecule qubits



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