Measurement of the time spent by a tunneling atom within the barrier region

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Nature 583, 529–532 (2020)

What are the ingredients?

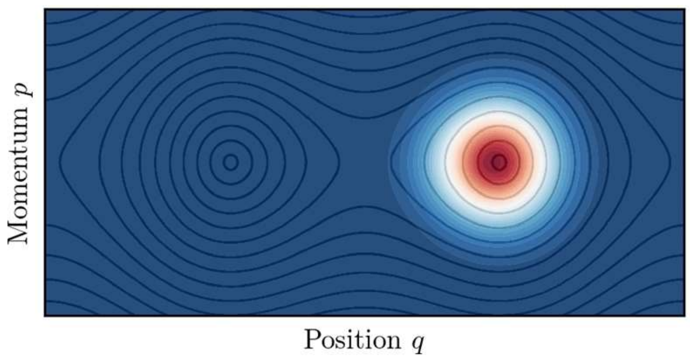
The paper describes an experiment to measure the tunneling time of the BEC through a barrier.

So, let's first look at:

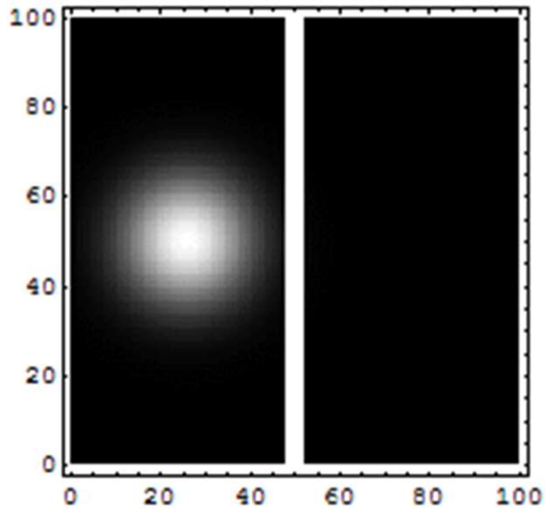
- What's tunnelling?
- What's a BEC?

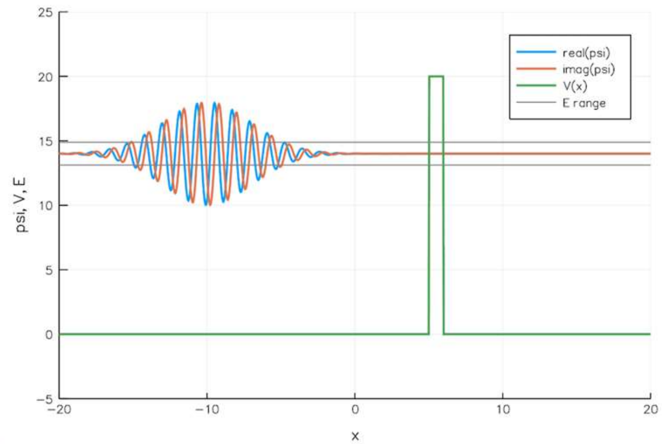
Quantum Tunneling

Time evolution of a superposition of states

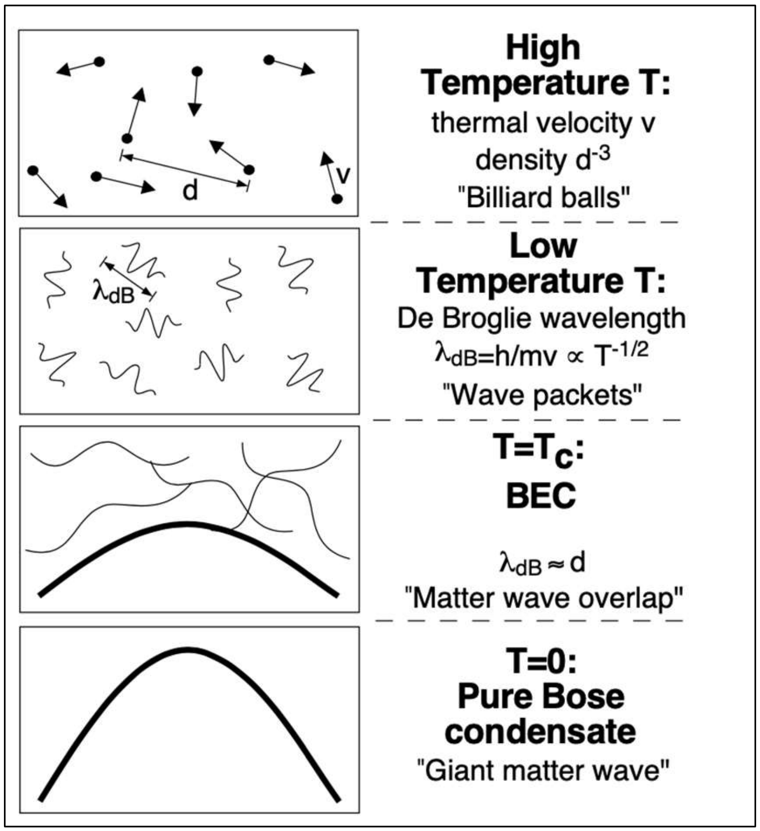


Wavepacket-barrier scattering





Bose-Einstein Condensates (BECs)



W. Ketterle, D.S. Durfee, and D.M. Stamper-Kurn, *Making, Probing, and Understanding Bose-Einstein condensates* (1999)

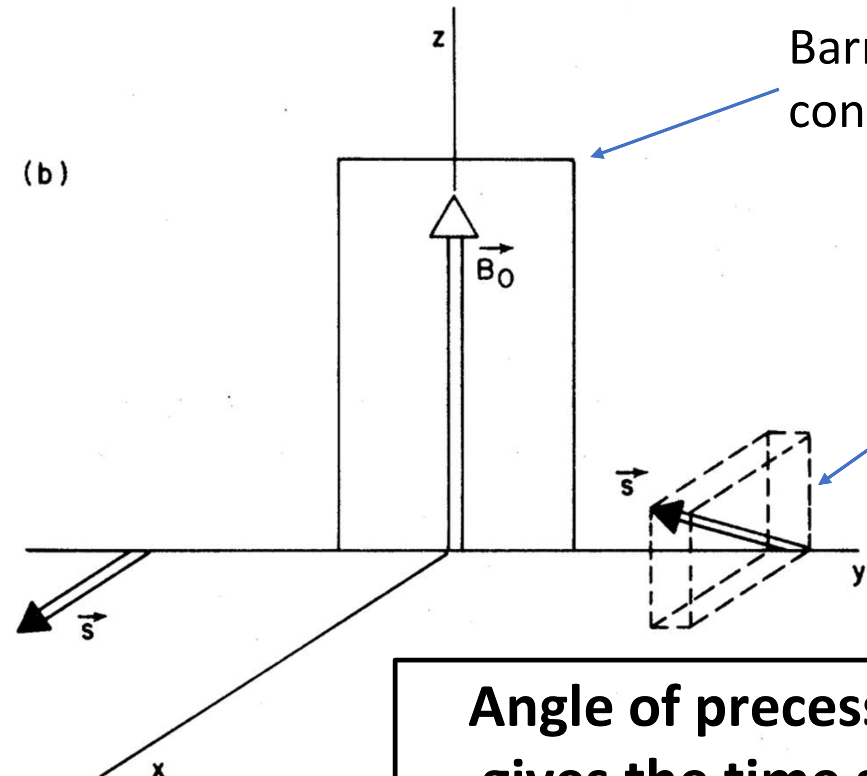
- For negligible atom-atom interactions, the single-atom is a product state

$$\psi_1(\mathbf{r}_1)\psi_2(\mathbf{r}_2)\cdots\psi_N(\mathbf{r}_N) \to \Psi(\mathbf{r})$$

- In a pure BEC, all atoms are in the same quantum state $\Psi(\mathbf{r})$.

Thought Experiment: spin-½ in a B-field

Initial State
- Spin-polarized



Barrier with confined B-field

Final state
- rotated to align with the B-field
- Precession in the *xy*-plane

Angle of precession in the *xy*-plane gives the time spent in the barrier

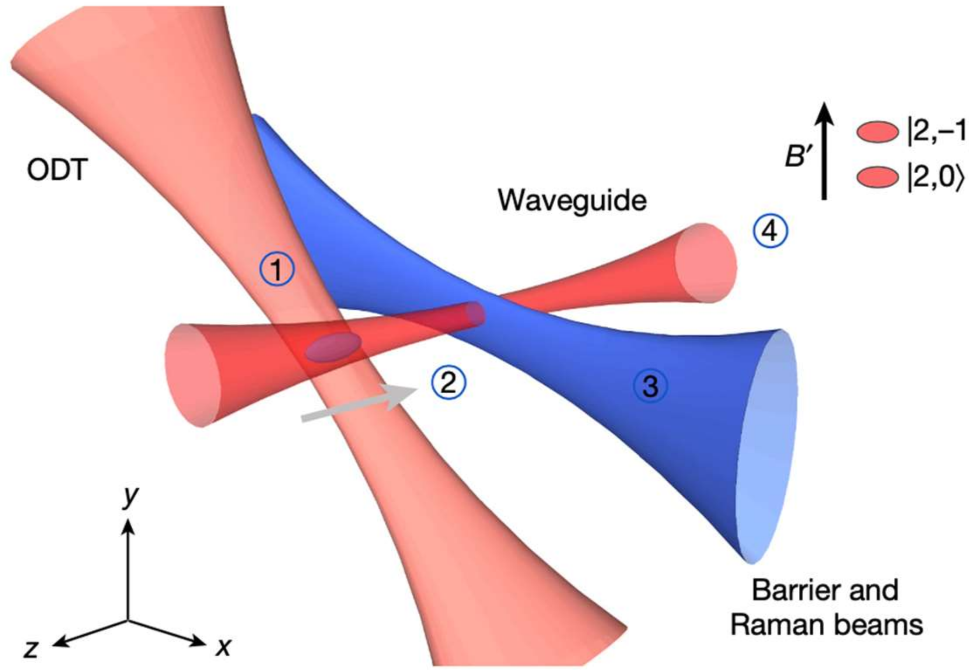
Büttiker, M. Larmor precession and the traversal time for tunneling. *Phys. Rev. B* **27**, 6178–6188 (1983).

Experimentally realized spin-½ in a "B-field"

1). BEC of ~8000 ^{87}Rb initialized in a crossed optical dipole trap (ODT)

2). The BEC is spin-polarized in the $|+x\rangle = \frac{1}{\sqrt{2}}\Big(|\uparrow\rangle + |\downarrow\rangle\Big)$ state

3). Cloud is pushed along the waveguide towards a potential barrier (blue beam)

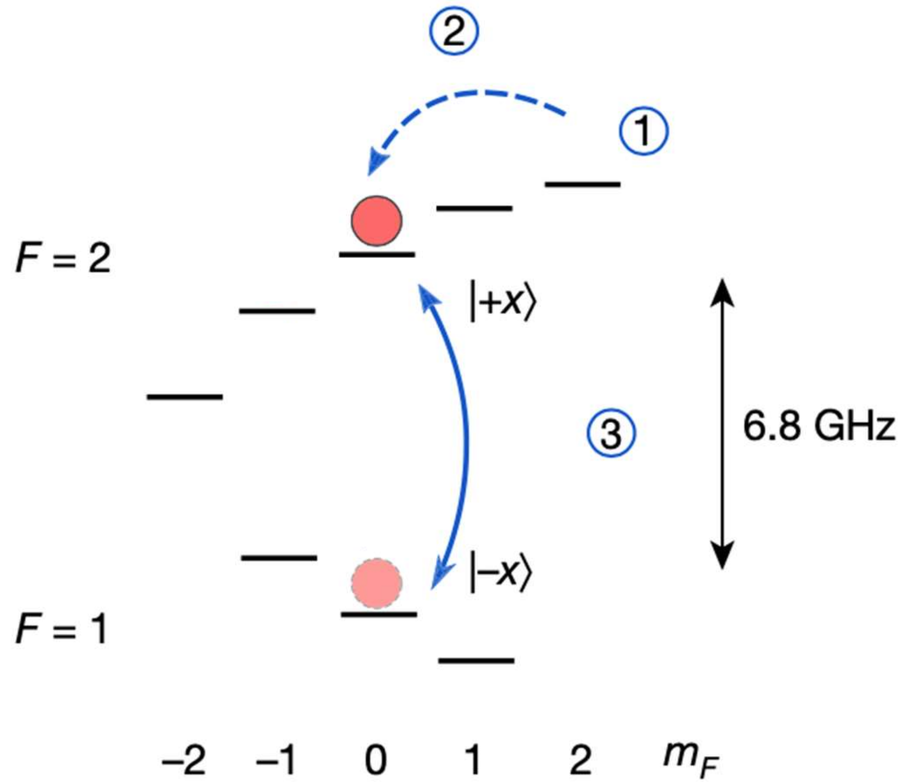


Effective Spin: ground state manifold of ^{87}Rb

Total angular momentum: $F = I + J$

Nuclear spin: $I = 3/2$

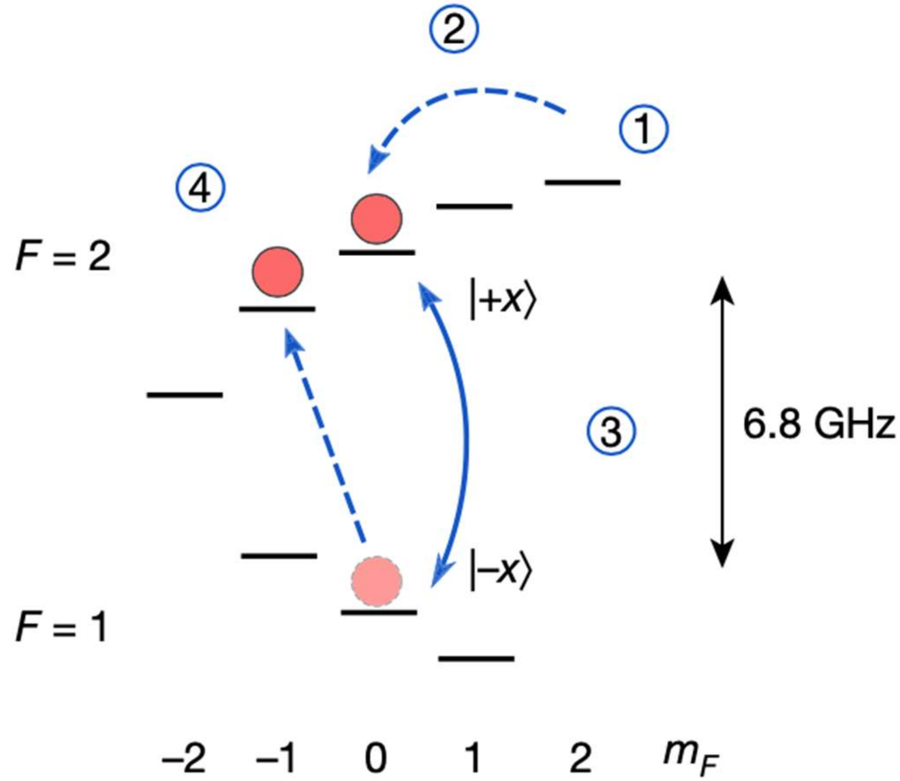
Electron angular momentum: $J = 1/2$



Ramos, R., Spierings, D., Racicot, I. *et al.* Measurement of the time spent by a tunnelling atom within the barrier region. *Nature* **583**, 529–532 (2020).

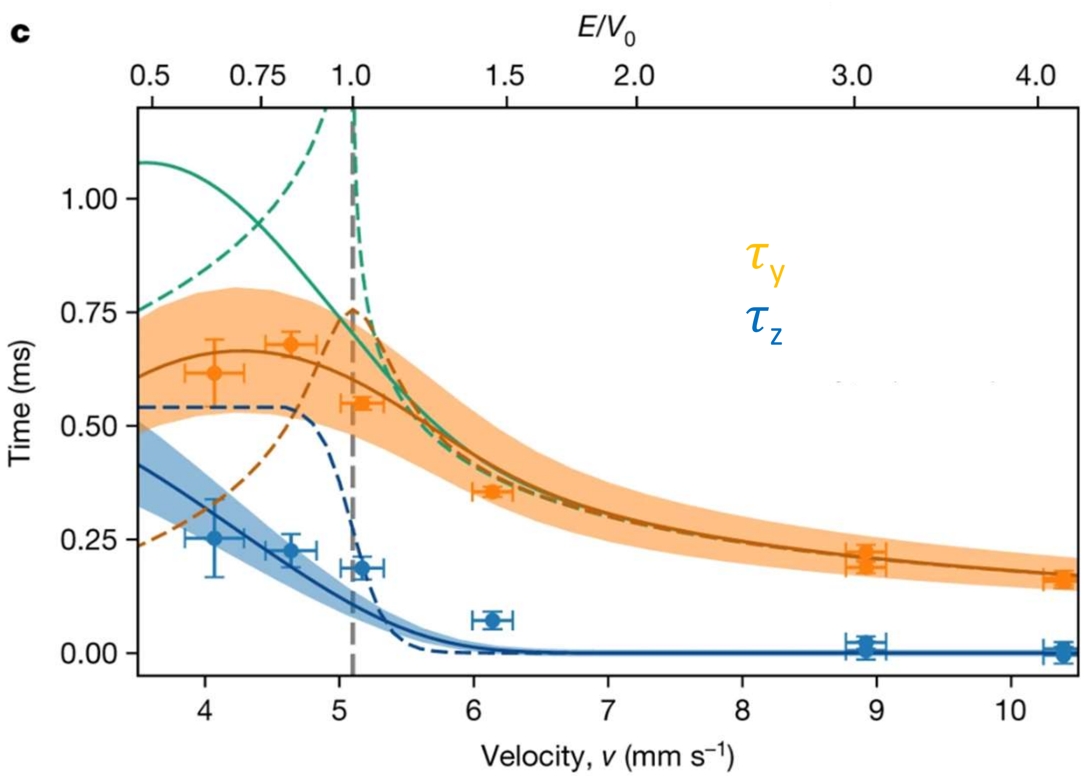
Effective Spin: ground state manifold of ^{87}Rb

Atoms in the $|-x\rangle$ state are transferred to the $|F=2, m_F=-1\rangle$ state so that a Stern-Gerlach measurement can be performed on the BEC



Ramos, R., Spierings, D., Racicot, I. *et al.* Measurement of the time spent by a tunnelling atom within the barrier region. *Nature* **583**, 529–532 (2020).

Conclusions of the study



τ_y = 0.61(7) ms at peak velocity distribution (4.8 mm/s)

"Semiclassical time" in green disagrees with previous predictions of τ_x

τ_y and τ_z are clearly separated, both can be observed separately during interaction

Implications

- τ_z becomes more important as the quantum regime is explored
- Tunneling takes a finite time that we can observe
- Using Larmor clock, we can infer more about the history of tunneling particles
  - i.e., position within the barrier
- More classical system can probe the quantum-classical boundary

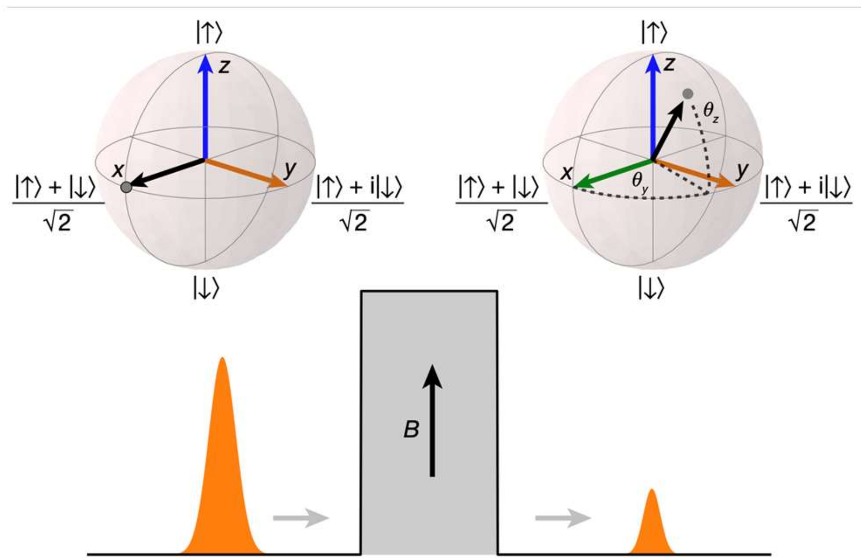
Conclusion Critiques

- Back-action not as important for this paper as results are not discussed after one figure
- Counter-intuitive prediction of lower energies corresponding to shorter time
  - Issue with transmission probability data?
- Experimental Larmor clock usage will have impacts on other fields
  - Back-action study could be enhanced

Is this really a traversal "time"?

Traversal time: $\theta_y = \omega_L \tau_y$

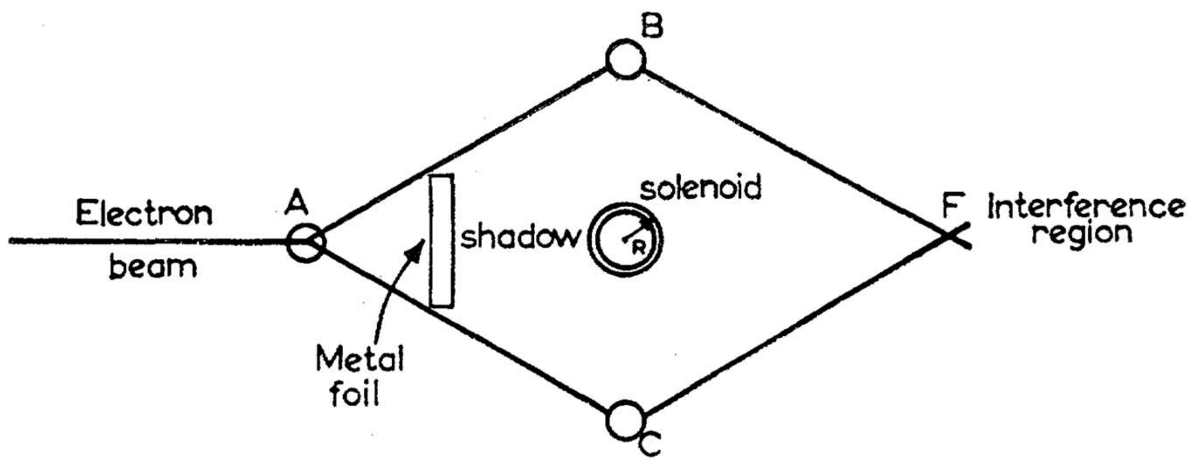
- This assumes the atoms spend the entire interaction in the barrier region



Is this really a traversal "time"?

Traversal time: $\theta_y = \omega_L \tau_y$

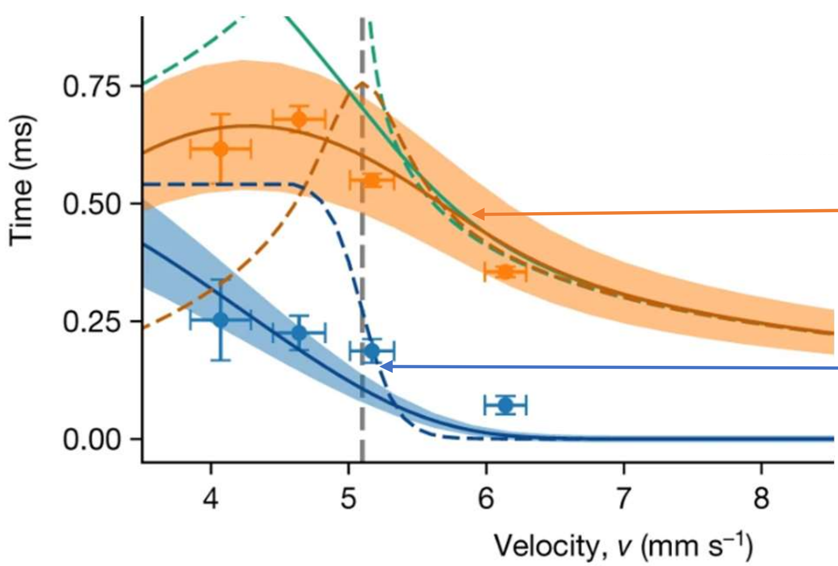
- However, there exist non-local interactions of spins and charged particles with magnetic fields – like the **Aharonov-Bohm effect**

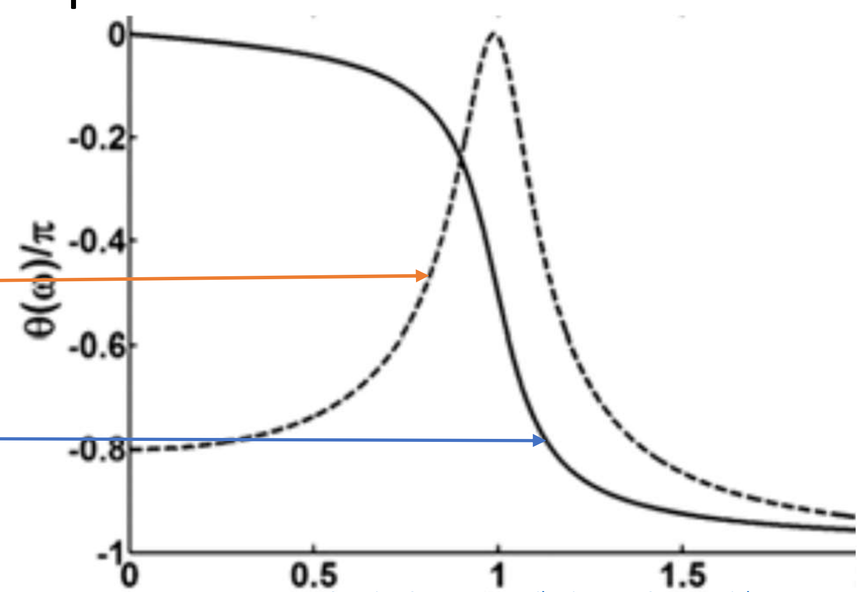


Aharonov Y., Bohm D. Phys. Rev., 115 (1959), pp. 485-491

Is this really a traversal "time"?

- Also, the matter-wave optical barrier interaction may be better viewed as a reflection/refraction interaction
- Here the phase picked up is also proportional to the index of refraction





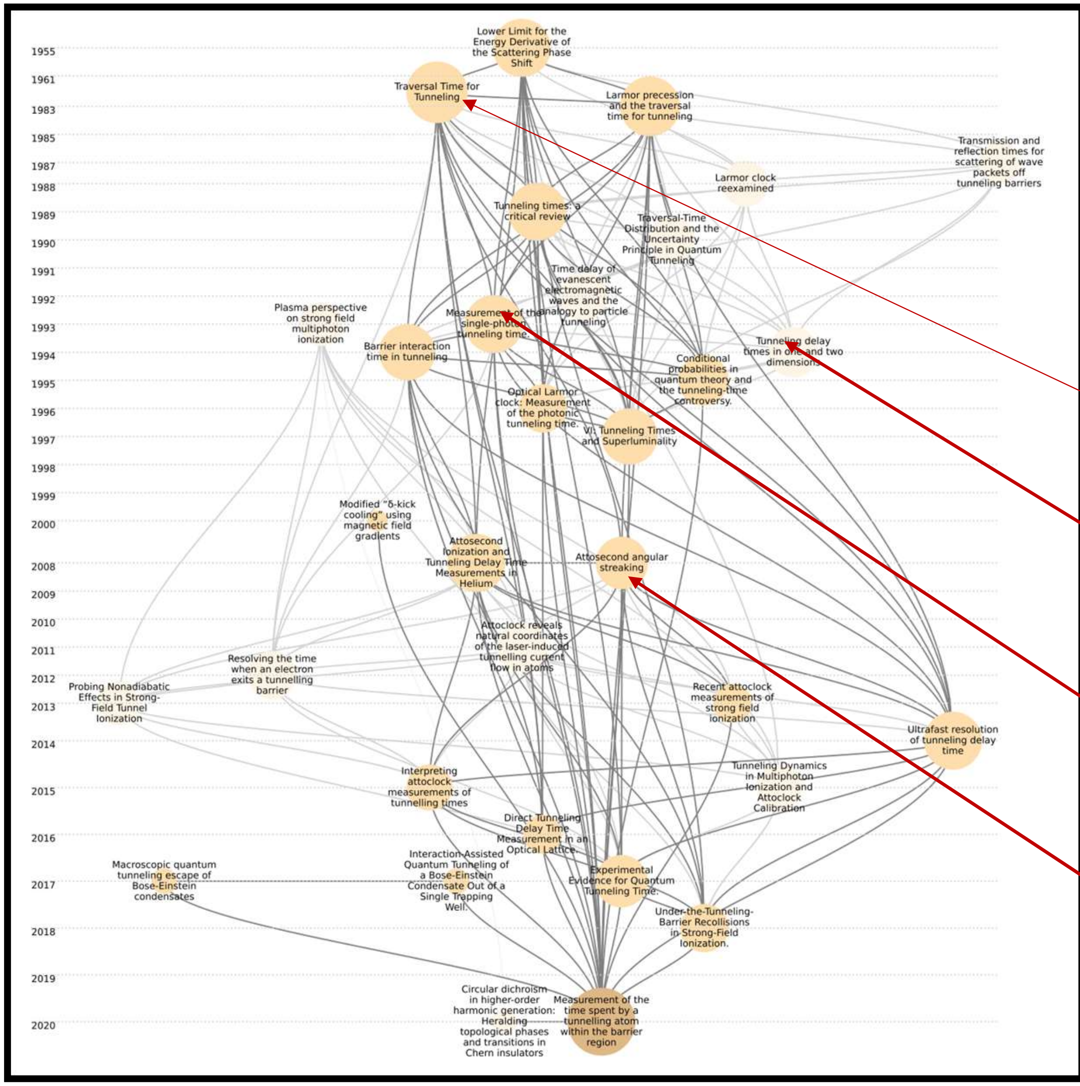
Controversies in tunneling

- This article provides a finite tunneling time
- Other theory projections show that not one finite time can be measured, but rather a distribution of times
- Some claim that tunneling takes "zero time" and is instantaneous

Hoffman, C., Bray, A., *et al.* "Quantum battles in attoscience: tunneling" Springer Link (2021)

Critical Analysis and Outlook

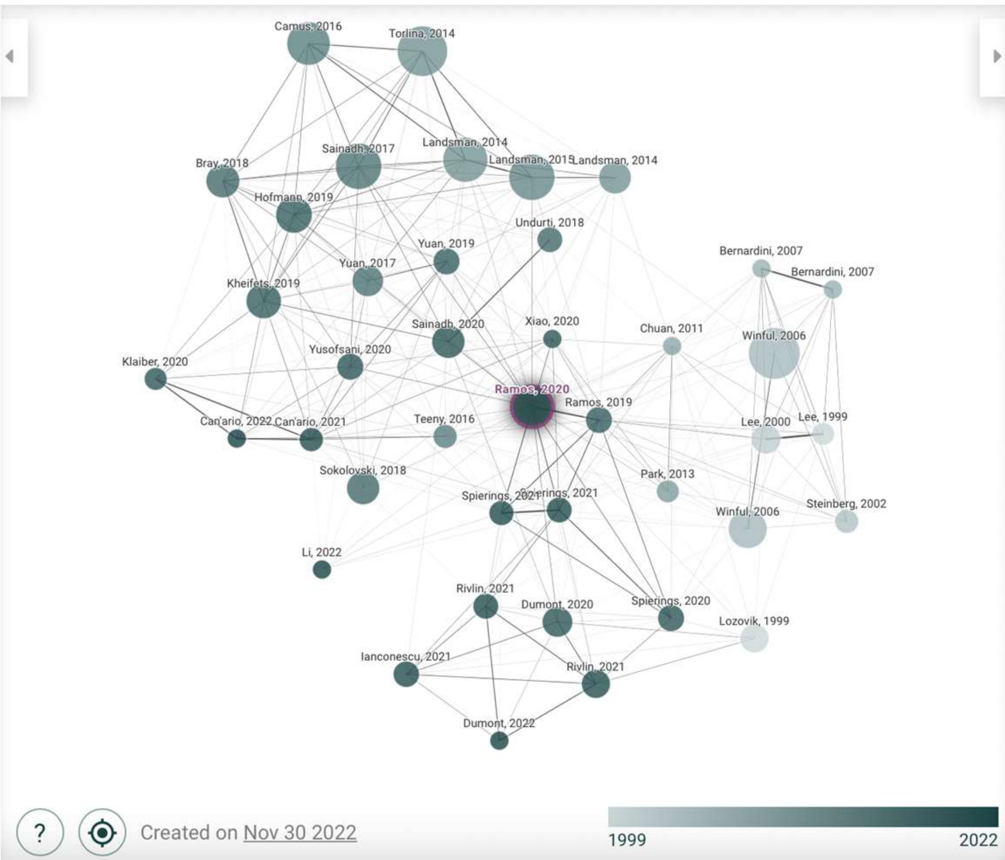
- Didn't address the main controversies of tunneling
- The results obtained are open to interpretation
- Authors didn't provide justification to their evaluation of the definite time measured
- No clear, agreed upon definition of onset and conclusion of tunneling
- Many approaches in the research arrive at opposing conclusions - much remains to be done!



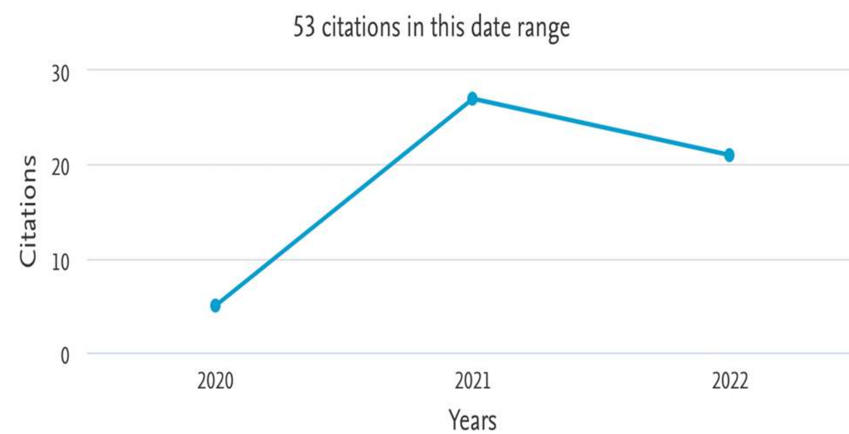
Evolution in the field

- ❑A note on transmission and reflection inside a barrier(1932)
- ❑Traversal Time for Tunneling (1982) - a similar one in 1983
- ❑Delay time measurements as a test of tunneling (1991)
- ❑Measurement of the single-photon tunneling time (1993).
- ❑Attosecond angular streaking and tunnelling time in atomic hydrogen

Citation Analysis



Connected trees



Many technologies and theoretical advancements led to the paper in 2020. Further studies and controversial discussions were published in the years followed.

Nature Citation Analysis

Access & Citations

15k	48	57
Article Accesses	[Web of Science]	[CrossRef]

Online attention

- 420 tweeters
- 23 news outlets
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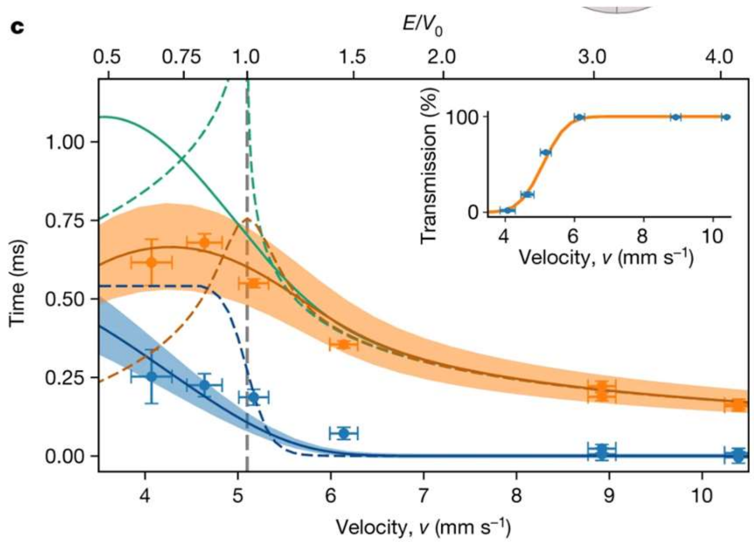
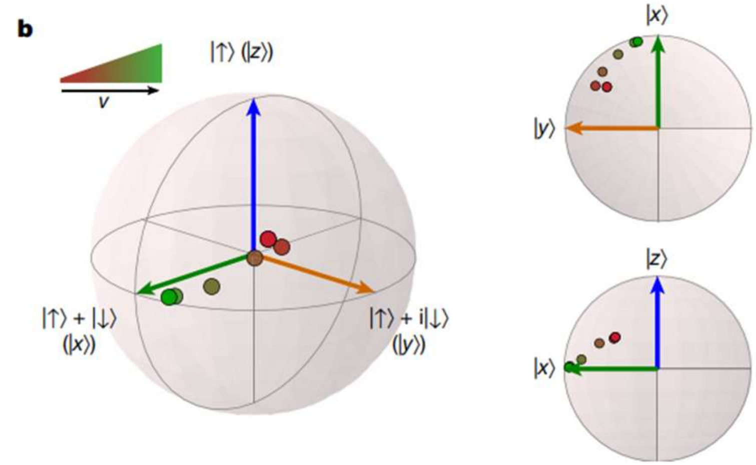
This article is in the 99^{th} percentile (ranked $1{,}638^{th}$) of the 315,222 tracked articles of a similar age in all journals and the 81^{st} percentile (ranked 164^{th}) of the 886 tracked articles of a similar age in *Nature*

Summary

- Sending 8000 ^{87}Rb atoms, restricted by a waveguide, through a 1.3 micrometer-thick optical barrier
- Larmor clock realized experiment with a pseudo-magnetic field to use spin precession as the clock
- Traversal time dependence on incident energy is studied
- Lowest energy for tunneling yields an observable 0.61 ms traversal time
- Groundwork for exploring quantum history could be set

Excess figures...





Excess figures...