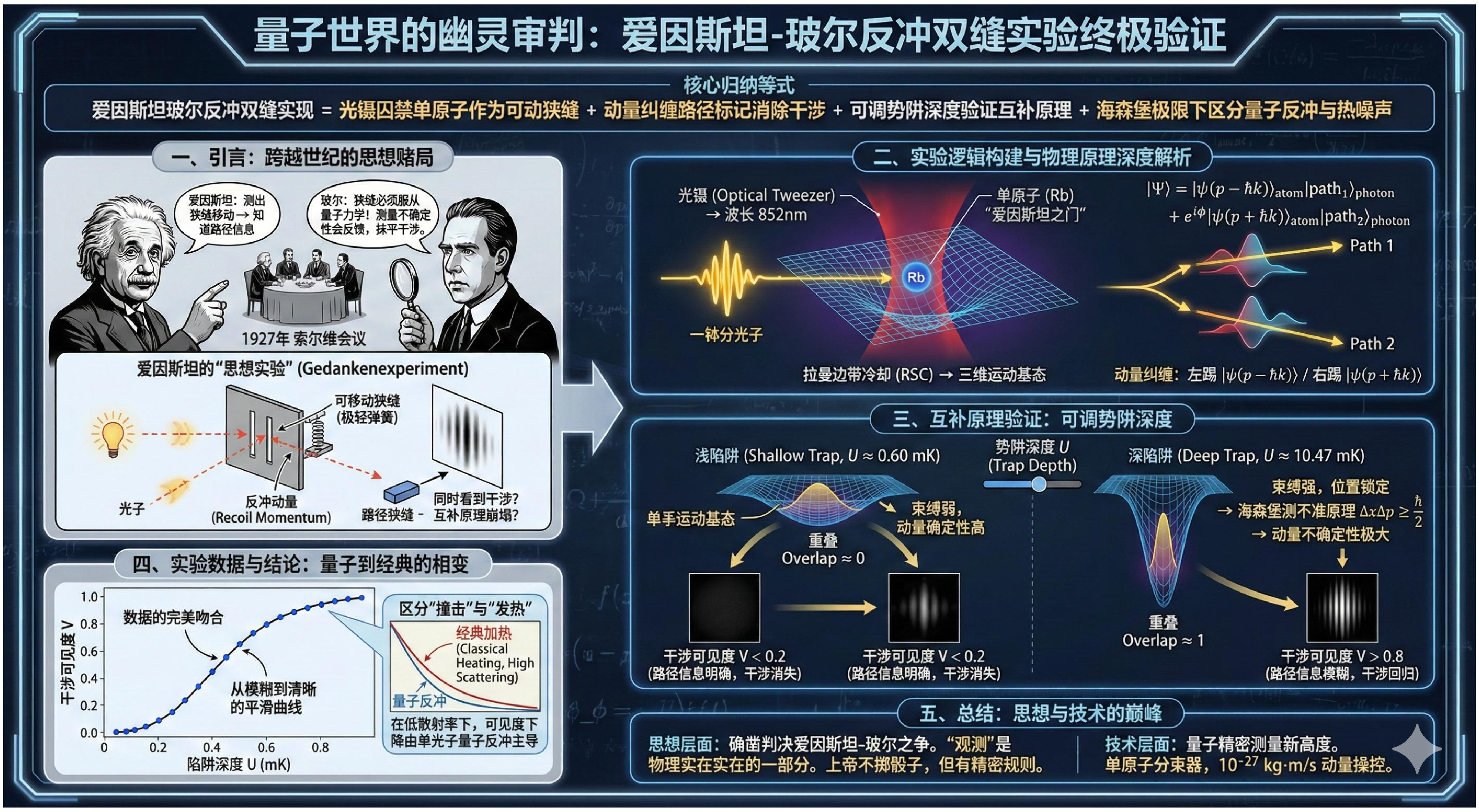
量子世界的幽灵审判：爱因斯坦-玻尔反冲双缝实验终极验证
核心归纳等式
爱因斯坦玻尔反冲双缝实现 = 光镊囚禁单原子作为可动狭缝 + 动量纠缠路径标记消除干涉 + 可调势阱深度验证互补原理 + 海森堡极限下区分量子反冲与热噪声
一、引言：跨越世纪的思想赌局
爱因斯坦：测出狭缝移动 → 知道路径信息
玻尔：狭缝必须服从量子力学！测量不确定性会反馈，抹平干涉。
1927年 索尔维会议
爱因斯坦的“思想实验” (Gedankenexperiment)
可移动狭缝 (极轻弹簧)
光子
反冲动量 (Recoil Momentum)
路径狭缝 -
同时看到干涉？互补原理崩塌？
二、实验逻辑构建与物理原理深度解析
光镊 (Optical Tweezer) → 波长 852nm
单原子 (Rb) “爱因斯坦之门”
Rb
$|\Psi\rangle = |\psi(p-\hbar k)\rangle_{\text{atom}}|\text{path}_1\rangle_{\text{photon}} + e^{i\phi}|\psi(p+\hbar k)\rangle_{\text{atom}}|\text{path}_2\rangle_{\text{photon}}$
一钵分光子
Path 1
Path 2
拉曼边带冷却 (RSC) → 三维运动基态
动量纠缠：左踢 $|\psi(p-\hbar k)\rangle$ / 右踢 $|\psi(p+\hbar k)\rangle$
三、互补原理验证：可调势阱深度
浅陷阱 (Shallow Trap, $U \approx 0.60$ mK)
势阱深度 U (Trap Depth)
深陷阱 (Deep Trap, $U \approx 10.47$ mK)
单手运动基态
束缚弱，动量确定性高
重叠 Overlap ≈ 0
干涉可见度 V < 0.2 (路径信息明确，干涉消失)
干涉可见度 V < 0.2 (路径信息明确，干涉消失)
束缚强，位置锁定
→ 海森堡测不准原理 $\Delta x \Delta p \geq \frac{\hbar}{2}$
→ 动量不确定性极大
重叠 Overlap ≈ 1
干涉可见度 V > 0.8 (路径信息模糊，干涉回归)
四、实验数据与结论：量子到经典的相变
干涉可见度 V
1.0
0.8
0.6
0.4
0.2
0.0
0
0.2
0.4
0.6
0.8
陷阱深度 U (mK)
数据的完美吻合
从模糊到清晰的平滑曲线
区分“撞击”与“发热”
经典加热 (Classical Heating, High Scattering)
量子反冲
在低散射率下，可见度下降由单光子量子反冲主导
五、总结：思想与技术的巅峰
思想层面：确凿判决爱因斯坦-玻尔之争。“观测”是物理实在实在的一部分。上帝不掷骰子，但有精密规则。
技术层面：量子精密测量新高度。单原子分束器，10^{-27} kg·m/s 动量操控。

Tunable Einstein-Bohr recoiling-slit gedankenexperiment at the quantum limit

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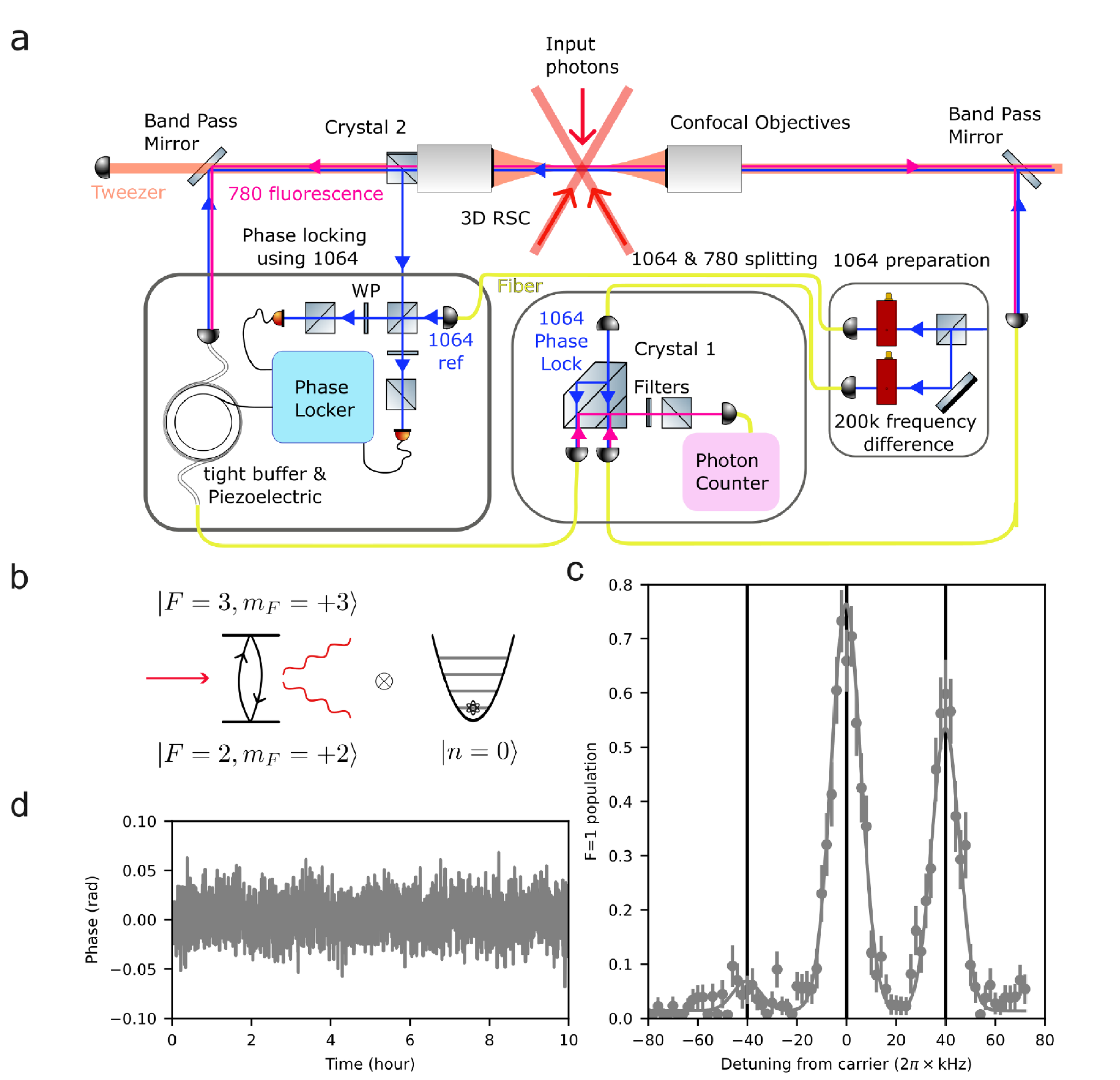
Abstract

In 1927, during the fifth Solvay Conference, Einstein and Bohr described a double-slit interferometer with a "movable slit" that can detect the momentum recoil of one photon. Their debate centered around this gedankenexperiment has provided profound insights into the central concepts of quantum mechanics. Despite many experimental efforts to realize this conceptual experiment, none has reproduced the original linear optical interferometer faithfully with pure one-photon momentum recoil and a full tunability. Here, we report a faithful realization of the Einstein-Bohr interferometer using a single atom in an optical tweezer, which is cooled to the motional ground state in three dimensions such that its momentum uncertainty is comparable to that of a single photon. We design an interferometric configuration where the single atom serves as an ultralight, quantum-limit beam-splitter that becomes momentum-entangled with the input photon. By varying the depth of the tweezer trap, we dynamically tune the atom's intrinsic momentum uncertainty, thus enabling the observation of a gradual shift in the visibility of single-photon interference. The interferometer also allows to distinguish the classical noise caused by atom heating from the quantum-limited noise due to the momentum transfer, illustrating a quantum-to-classical transition..

Experiment setup

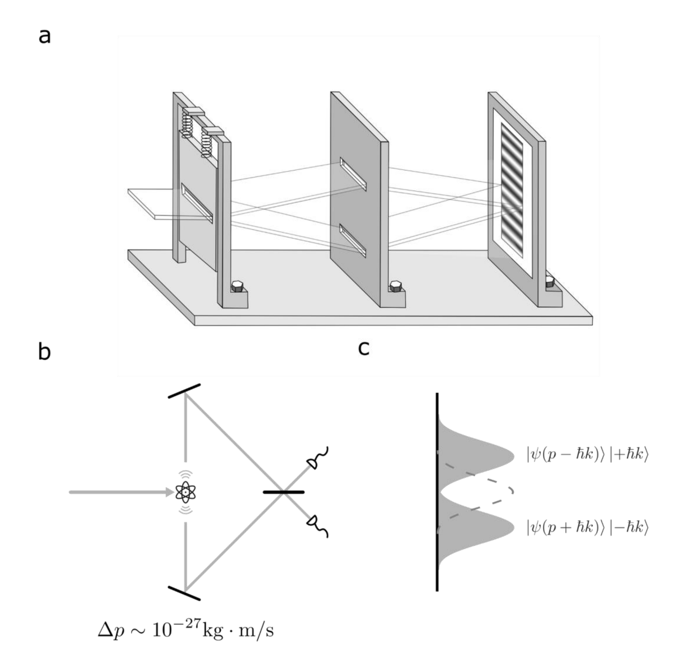


a, schematic setup of the experiment. An 852nm laser and a 0.55-NA microscope objective to form the tweezer. Two objectives on the opposite direction collect the fluorescence and couple the photons into fibers for detection and interference. A 1064nm laser is used for extracting the phase between two paths for active phase-locking. Two Raman beams separated by the same angle with the tweezer axis are used for axial Raman sideband cooling. **b**, energy level for interferometer excitation. The input photon is pure σ^+ polarization and drive the cycling transition between$|F=2, mF=2\rangle$ and $|F=3, mF=3\rangle$ which enables the decoupling between the internal and external degree of freedom. The atom is in the motional ground state to fulfill the Heisenberg smallest uncertainty principle just as what Bohr proposed. **c**, results for axial Raman sideband cooling. **d**, results for active phase-locking.

Reference

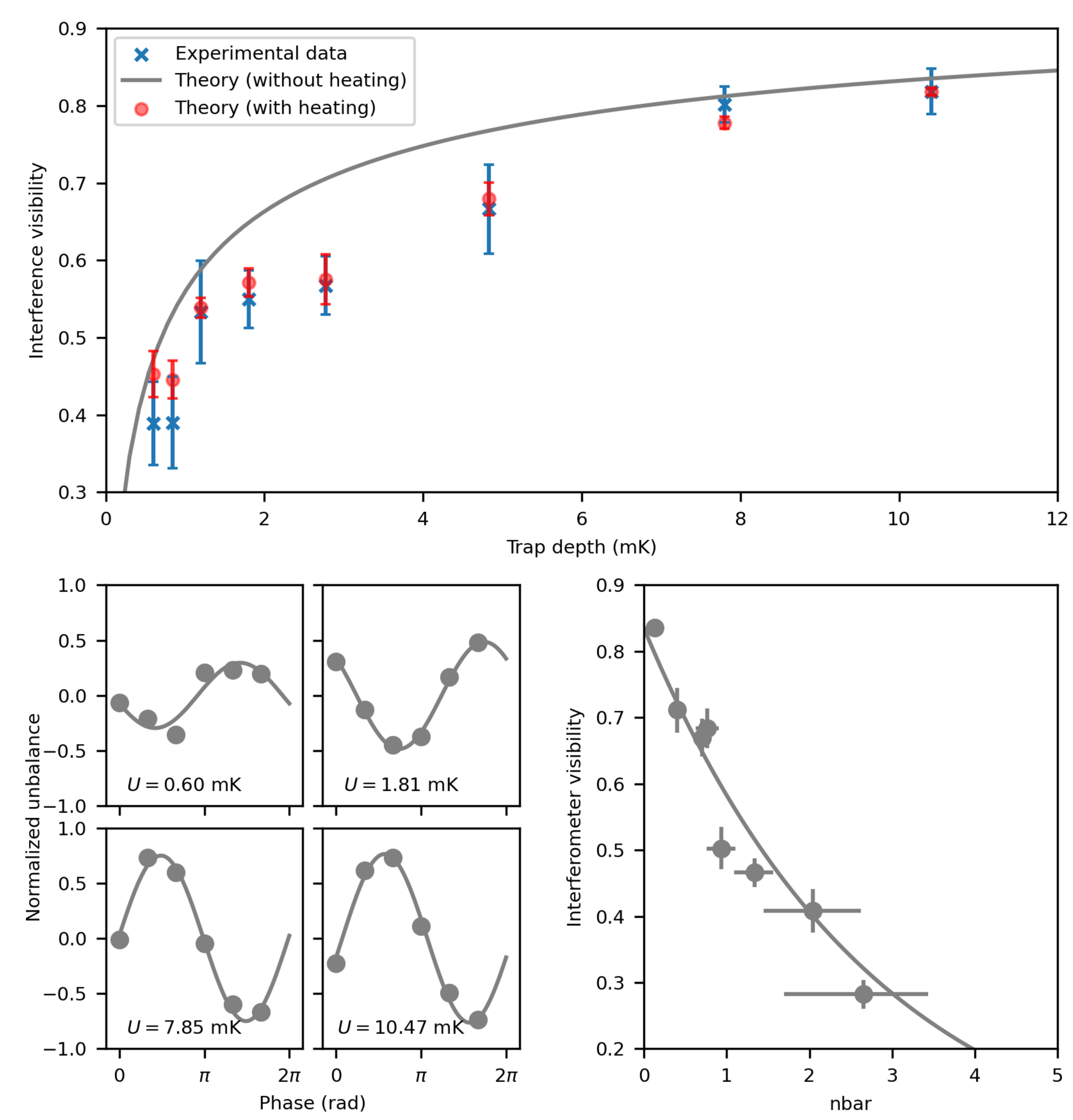
1. Eschner, Jürgen, et al. "Light interference from single atoms and their mirror images." Nature 413.6855 (2001): 495-498.
2. Wootters, William K., and Wojciech H. Zurek. "Complementarity in the double-slit experiment: Quantum nonseparability and a quantitative statement of Bohr's principle." Physical Review D 19.2 (1979): 473.
3. Wheeler, John Archibald, and Wojciech Hubert Zurek, eds. Quantum theory and measurement. Vol. 81. Princeton University Press, 2014.

Schematic of the Experiment

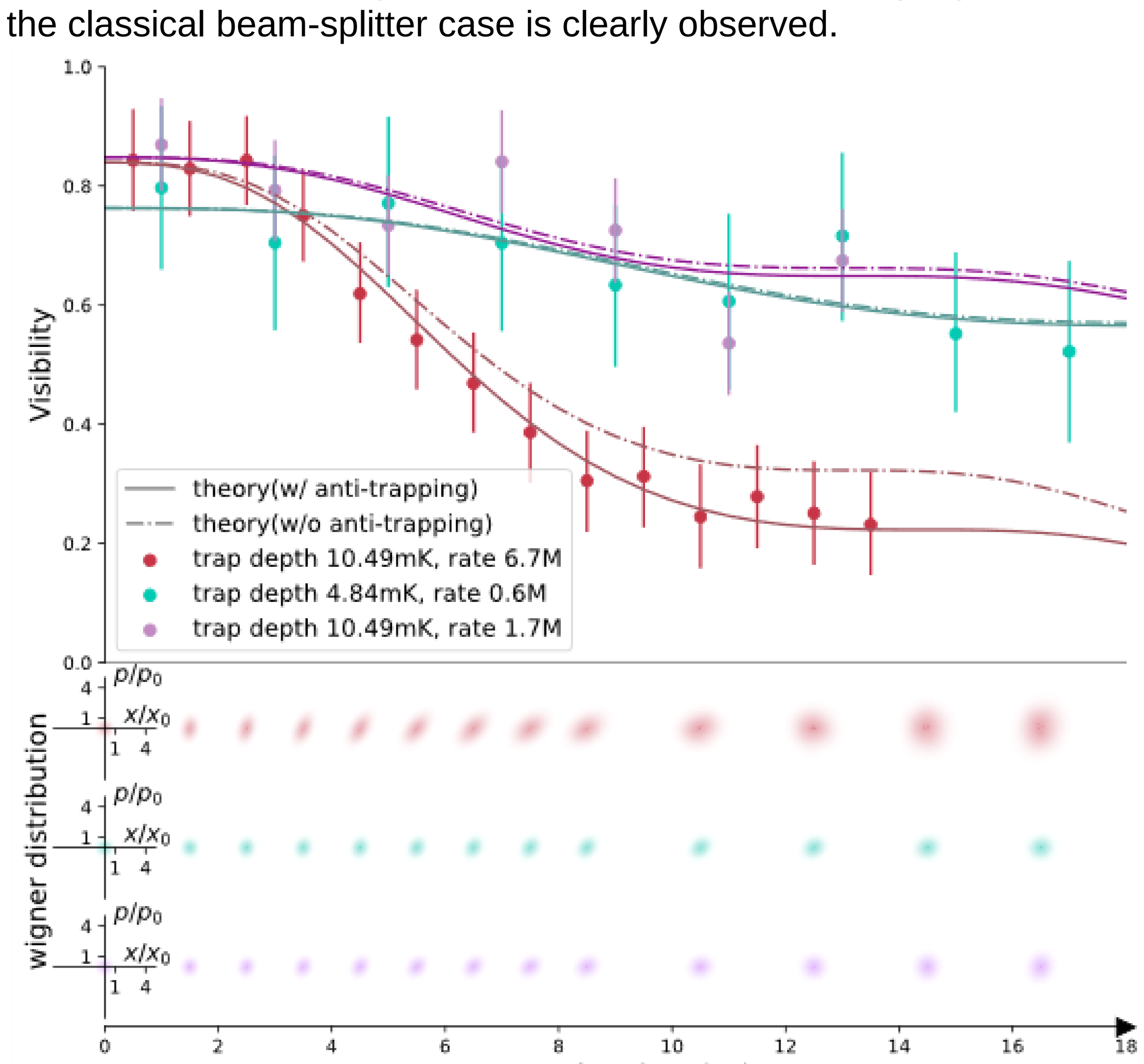


Schematic of the Einstein–Bohr recoiling double-slit experiment. a, Photons pass the first movable single slit and do the normal double-slit interferometry faithfully following the original proposal of Bohr. **b**, We use a single atom as the movable slit. The photons scattered by the atom will be collected and interfere. The momentum kick from a photon is around 10^{-27} kg·m/s which is on the same level with momentum uncertainty of a motional-ground-state atom so the change of the atom's wavefunction will influence the outcome of the interference. **c**, The atom and the photon form a maximally entangled state $|\psi(p-\hbar k)\rangle_{slit}|+\hbar k\rangle_{photon} + e^{i\phi}|\psi(p+\hbar k)\rangle_{slit}|-\hbar k\rangle_{photon}$after scattering so the contrast is $V = |\langle\psi(p-\hbar k)|\psi(p+\hbar k)\rangle|$

Results



Interference visibility in quantum and classical interferometer. a, visibility as a function of the trap depth. Measured data is depicted as blue points. The expectation from theory is shown by the black line. Considering the finite temperature of the atom, the experiment result fits perfectly with the theory. **b**, the interference fringes of four different trap depths. They follow a perfect sinusoidal curve. c, visibility as a function of the average vibrational quantum number $\bar{n}$. The trap depth is fixed to 10.49 mK which has the highest interference contrast. The progressive evolution from the quantum to the classical beam-splitter case is clearly observed.



Decline of visibility with continuous scattering. The atom scatters photons continuously and each point is the interference visibility of 1-2μs window. For 6.7MHz scattering rate, the picture shows the photons collected in every 1μs window. For 0.6MHz and 1.7MHz scattering rate, the picture shows the photons collected in every 2μs window. For large scattering rate, the atom is heated faster so the visibility drops faster. The equilibrium population in the excited state is also larger which causes the anti-trapping of the excited state to have more significant effect. For low scattering rate, the visibility drops slowly and since the excited population is smaller the predicted visibility with or without anti-trapping is almost the same.