

AI and Quantum Research Center (AIQRC), Asia University, Taiwan

Contents

[1] Activities

[2] Quantum Microscope: Seeing Beyond the Classical Limits of Light

[1] Asia University and AIQRC, supported by the Ministry of Education's Taiwan Global Pathfinders Grant Program, provide Taiwan students with world-class experiential learning opportunities through programs in IBM quantum technologies, UCLA academic exchange, quantum finance, humanoid robotics, and astronaut mission training.



(A) IBM dream program



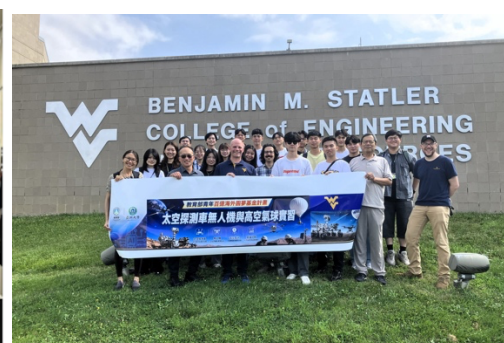
(B) UCLA elite program



(C) Quantum finance program



(D) Humanoid robot program



(E) Astronaut mission training program

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Quantum Microscope: Seeing Beyond the Classical Limits of Light

From quantum correlations to super-resolution bioimaging

I. Featured Report and In-Depth Technical Analysis

1. What Is a Quantum Microscope?

A quantum microscope is not simply a conventional microscope connected to a quantum computer. The term broadly describes microscopy techniques that exploit uniquely quantum properties of light or matter—including entanglement, squeezing, photon correlations, quantum interference, and quantum-state coherence—to improve measurement performance or enable imaging capabilities that are difficult or impossible with conventional methods.

The central question is: Can quantum mechanics allow us to extract more information from fewer photons? This is particularly important for biological imaging, where intense illumination can cause photobleaching or photodamage.

2. Why Do We Need Quantum Microscopy?

In conventional optical measurements, photon shot noise limits sensitivity. If N photons are detected, the associated statistical noise scales approximately as $\sqrt{N}$. Increasing illumination can improve the signal-to-noise ratio, but excessive light exposure can damage living cells.

Quantum microscopy approaches the problem differently by controlling the statistical and quantum correlations of the measurement field. Squeezed light can suppress fluctuations in a selected measurement variable, while entangled photons can provide correlations that carry additional information about a sample.

3. The Quantum Principles Behind the Microscope

A. Squeezed Light

Squeezed light is a nonclassical optical state in which fluctuations in one optical quadrature can be reduced below the corresponding classical shot-noise level. In quantum-enhanced Raman microscopy, this can reduce measurement noise without simply increasing the illumination.

Casacio et al. demonstrated quantum-enhanced nonlinear microscopy in 2021. Their coherent Raman microscope achieved a 35% improvement in signal-to-noise ratio and a 14% improvement in concentration sensitivity compared with conventional illumination while imaging molecular bonds in cells.

B. Entangled Photons

Entangled photons exhibit correlations that cannot be explained by treating the photons as independent classical particles. Quantum microscopy by coincidence uses pairs of entangled photons and coincidence detection to improve imaging performance.

A 2023 demonstration reported two-fold resolution improvement at the Heisenberg limit and strong resistance to background light, including imaging of cancer cells with approximately $1.4\text{ }\mu\text{m}$ resolution over a $100 \times 50\text{ }\mu\text{m}$ field of view.

C. Imaging with Undetected Photons

In imaging with undetected photons, one photon from a correlated pair interacts with the object while its partner is detected. Quantum interference transfers information about the object into the detected channel even though the photon interacting with the object is not directly measured.

This approach can decouple the wavelength used to illuminate the sample from the wavelength used for detection, potentially enabling imaging in spectral regions where efficient detectors are difficult to obtain.

II. Quantum Microscopy in Biology and Medicine

1. Low-Photodamage Live-Cell Imaging

Biological specimens are attractive targets because reducing photon exposure can extend imaging time while minimizing phototoxicity and photobleaching. Quantum-enhanced Raman microscopy is particularly promising because Raman methods can provide chemical information from molecular vibrations without conventional fluorescent labels.

Recent work has demonstrated quantum-enhanced stimulated Raman scattering microscopy in biological samples, including multispectral imaging of living cells. Bright squeezed light can allow operation below the conventional shot-noise limit while maintaining the optical intensity required for Raman excitation.

2. Label-Free Molecular Imaging

Fluorescence microscopy often requires fluorescent proteins or dyes. Coherent Raman techniques provide molecular information through vibrational fingerprints, offering a route to label-free chemical imaging. Quantum-enhanced versions seek to increase the information obtained from each photon while reducing the illumination burden.

- Cellular metabolism
- Protein and lipid imaging
- Drug–cell interactions
- Cancer-cell characterization
- Long-term live-cell studies
- Molecular dynamics

3. Cancer and Biomedical Imaging

Quantum microscopy remains primarily a research technology rather than a routine clinical instrument. Nevertheless, experimental demonstrations have moved beyond simple optical objects toward biological specimens. Quantum microscopy by coincidence has been demonstrated for cancer-cell imaging, showing improved resolution, contrast-to-noise ratio, imaging performance and resistance to stray light.

The emerging biomedical direction is therefore not to replace every existing microscope, but to develop specialized measurements that can obtain useful information with lower photon exposure or exploit quantum correlations for improved sensitivity and contrast.

III. Beyond Quantum Light: Matter as a Quantum Probe

Quantum microscopy is not restricted to photons. A 2026 study demonstrated an 'atom camera' in which a single ultracold 87Rb atom trapped in an optical tweezer acts as a scanning probe. Rather than recording the optical field with a conventional camera, the experiment measures shifts in the atom's internal energy levels caused by the field.

The atom's position was confined to quantum fluctuations of approximately 25 nm, while the experimentally demonstrated upper bound on spatial resolution was 96(4) nm. The system could also map optical intensity and polarization.

This represents a different form of quantum microscopy: it is primarily a nanoscale optical-field probe for quantum optics, cold atoms and nanophotonics, rather than a system designed to directly image biological cells.

IV. Major Quantum Microscopy Approaches

Approach	Quantum resource	Main advantage	Potential application
Quantum-enhanced Raman microscopy	Squeezed / correlated light	Lower measurement noise	Live-cell molecular imaging

Quantum microscopy by coincidence	Entangled biphotons	Improved resolution and contrast	Biological/cancer-cell imaging
Undetected-photon imaging	Quantum interference	Different illumination/detection wavelengths	Spectral and biomedical imaging
Quantum optical imaging	Entanglement correlations /	Noise resilience and sensitivity	Low-light imaging
Single-atom microscopy	Atomic coherence	Nanoscale optical-field mapping	Quantum optics / AMO physics
Quantum sensing microscopy	Quantum states of matter	High sensitivity to physical fields	Biomedical and materials research

V. Recent Advances and Research Trends

1. From Proof-of-Concept to Biological Imaging

Early quantum imaging experiments established that entanglement and quantum interference could generate unusual imaging capabilities. More recent work has increasingly focused on spatial resolution, imaging speed, contrast, photon efficiency and compatibility with biological samples.

2. Quantum-Enhanced Raman Microscopy

The combination of quantum optics and stimulated Raman scattering is emerging as an important direction. Experiments demonstrate that squeezed light can be generated with sufficient brightness for microscopy and applied to living biological samples.

3. Quantum Microscopy at the Heisenberg Limit

Quantum microscopy by coincidence has demonstrated a route toward Heisenberg-limited imaging, with experimental improvements in resolution and resistance to background illumination.

4. Single-Atom Quantum Probes

The 2026 atom-camera experiment demonstrates a different paradigm in which an individual quantum system becomes the imaging sensor itself. Such approaches could provide sensitive characterization of structured optical fields relevant to quantum computing, optical tweezers and nanophotonics.

VI. Challenges and Limitations

- Low photon flux and source efficiency: useful nonclassical light can be technically demanding to generate at high brightness.
- Experimental complexity: quantum optical systems can require nonlinear crystals, interferometric stability, high-performance detectors and precise synchronization.
- Detector limitations: efficiency, dark counts, timing resolution and camera noise can reduce the theoretical quantum advantage.
- Biological complexity: demonstrations in controlled samples must translate to heterogeneous, dynamic and optically complex biological systems.
- Speed and scalability: coincidence measurements or sequential scanning can limit acquisition speed in some systems.
- Cost and accessibility: many quantum microscopy systems remain specialized laboratory instruments.

The central challenge is not merely demonstrating a quantum advantage, but preserving that advantage under realistic experimental and biological conditions. Source brightness, optical loss, detection efficiency, background noise and system complexity remain major barriers.

VII. Quantum Microscope vs. Conventional Microscopy

Feature	Conventional microscopy	Quantum microscopy
Noise	Often limited by shot noise and technical noise	Can exploit nonclassical correlations to suppress selected noise
Illumination	Higher intensity can improve SNR	Can seek higher information efficiency per photon
Resolution	Determined by optics, wavelength and method	Quantum correlations can enable specialized resolution gains
Biological imaging	Well established	Promising but largely research-stage
System complexity	Ranges from simple to advanced	Often high due to quantum sources/detectors/interferometry
Clinical maturity	Many mature modalities	Not yet a general clinical replacement

VIII. Industry Observations and Future Outlook

Quantum microscopy represents a transition from 'more photons' to 'more information per photon.' In conventional microscopy, improving sensitivity often means increasing illumination or collecting more photons. Quantum microscopy instead engineers the quantum state of the light or matter used for measurement.

Future systems are likely to combine quantum light sources, high-efficiency single-photon detectors, advanced cameras and interferometers, AI-assisted image reconstruction, computational microscopy and quantum sensing. The integration of quantum optics with computational imaging and artificial intelligence could be particularly important. Machine-learning methods may help reconstruct images from sparse photon measurements, correct experimental imperfections and extract biological information from quantum-enhanced signals.

However, a distinction must be maintained between demonstrated quantum microscopy and future possibilities. Current experiments establish genuine quantum-enhanced measurements, but a general-purpose 'quantum microscope' capable of routinely replacing fluorescence, confocal, super-resolution or electron microscopy does not yet exist.

The long-term vision is more focused: using quantum physics to measure biological systems with fewer photons, higher information efficiency and fundamentally new measurement capabilities.

IX. Key Takeaways

- Quantum microscopy is an emerging family of imaging technologies that uses quantum properties of light or matter to improve measurement performance.
- Quantum correlations can suppress selected measurement noise below the conventional shot-noise limit.
- Squeezed light has enabled experimentally demonstrated improvements in Raman microscopy of biological samples.
- Entangled photons can provide improved resolution and strong resistance to background light.
- Quantum imaging can extract information from photons that are never directly detected.
- Quantum microscopy has been demonstrated on biological specimens, including cells.
- A 2026 single-atom 'atom camera' shows that an individual quantum system can act as a sensitive microscopy probe.

- Major challenges remain in source brightness, detection efficiency, speed, complexity, cost and biological compatibility.
- The future may combine quantum sensing, advanced optics, computational imaging and AI rather than rely on a single technology.

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