Putting the squeeze on axions

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Putting the squeeze ON AXIONS

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Microwave cavity experiments make a quantum leap in the search for the dark matter of the universe.

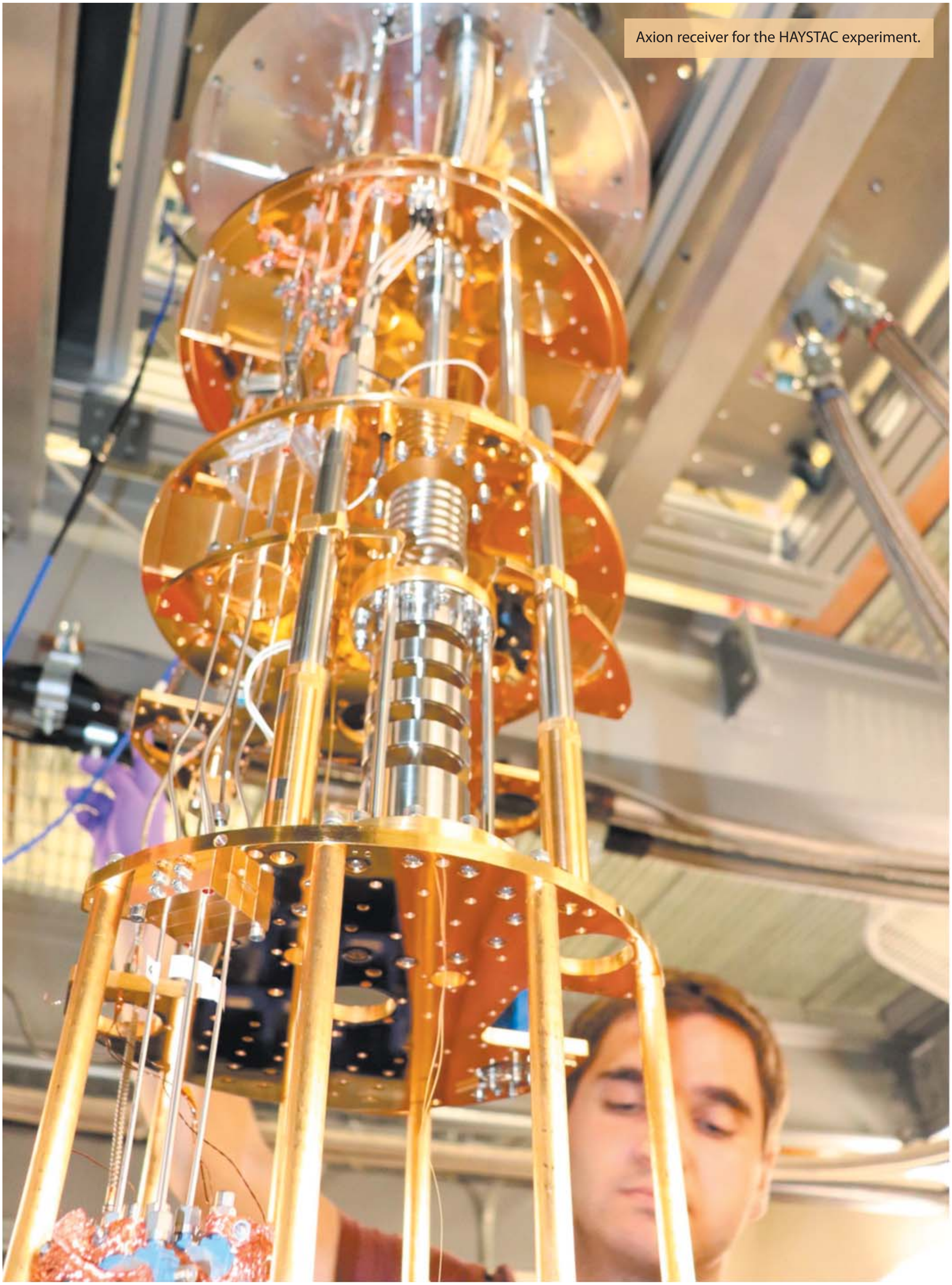
Sixty years ago Norman Ramsey and collaborators asserted that the neutron's electric dipole moment (EDM)—a measure of the separation of its positive and negative electric charge—was consistent with zero. More precisely, their experiment[1] bounded the neutron's EDM at less than 5×10^{-20} e·cm. Today, that limit is 3×10^{-26} e·cm, and experiments under development may push it lower by a factor of 100.

In the parlance of fundamental symmetries, the strong interaction is seemingly protected from *CP*-violating effects, where *CP* is the product operator of charge conjugation *C* and parity *P*. In the 1950s theorists had no compelling reason to expect *CP* violation—indeed, Tsung-Dao Lee and Chen Ning Yang did not believe that a nonzero neutron EDM would ever be found, though it was a worthy experimental question. However, with the advent of quantum chromodynamics (QCD) in the 1970s, a major problem loomed: The theory unavoidably includes a *CP*-violating angle θ associated with topological configurations of the QCD gluon field. For any generic value of θ, the neutron EDM should be a whopping 10^{-16} e·cm. The value implied by experiment is highly improbable: It's as if you spun a roulette wheel, and it came to rest at the winning number to within 1 part in 10 billion—just by dumb luck.

Or not? In 1977 Stanford University physicists Roberto Peccei and Helen Quinn conceived a minimal and appealing theory by which θ would be promoted to a dynamical variable. Just below some large energy scale, θ would assume a random value at each point in space. But in the low-energy limit of the theory, the nontrivial "washboard" potential of the QCD vacuum would drive θ to the *CP*-conserving minimum. That would be nice and tidy.

However, within a few months, Steven Weinberg and Frank Wilczek independently realized that the remnant sloshing of the θ field around that minimum implied the existence of an elementary particle called the axion—the smoking gun of Peccei and Quinn's theory—whose mass is possibly a trillion times lighter than an electron. Even such a light particle could, if sufficiently abundant, constitute the 27% of the mass–energy of the universe that is dark matter.

The story of the axion and its connection to dark matter is delightfully told with deep physical intuition in the form of a fable in which graduate students play snooker on Mars (see the article by Pierre Sikivie, PHYSICS TODAY, December 1996, page 22). In the current article, we focus on the ongoing experimental



Axion receiver for the HAYSTAC experiment.

hunt for the axion more than two decades later.

To date, the most sensitive searches rely on the fact that the axion couples to two photons. However, one may represent an external magnetic field as a sea of virtual photons, and as Pierre Sikivie realized in 1983, a massive axion can be converted into a single real photon in an external magnetic field with the same total energy. What's more, the axion–photon conversion can be resonantly enhanced in a high-Q cavity.[2] (See the article by van Bibber and Leslie Rosenberg, PHYSICS TODAY, August 2006, page 30.)

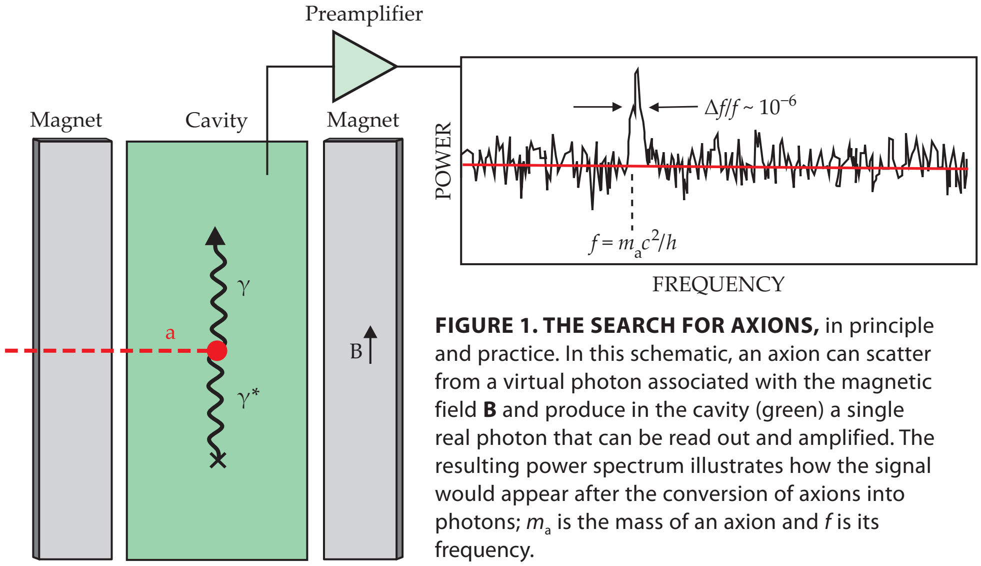


FIGURE 1. THE SEARCH FOR AXIONS, in principle and practice. In this schematic, an axion can scatter from a virtual photon associated with the magnetic field **B** and produce in the cavity (green) a single real photon that can be read out and amplified. The resulting power spectrum illustrates how the signal would appear after the conversion of axions into photons; m_a is the mass of an axion and f is its frequency.

Listening to the radio

Sikivie's proposed scheme was simplicity itself, and the experiments of today closely resemble larger and more technologically sophisticated incarnations of his first experiments 30 years ago. The new experiments boast a state-of-the-art low-noise amplifier that is coupled to a tunable microwave cavity inserted in the bore of a powerful superconducting solenoid magnet,[3] as shown in figure 1.

The cavity is tuned in small steps. At each frequency, the researchers pause for several minutes and listen for the signal—an excess of power over the noise floor—if the resonance condition is fulfilled, $h\nu = m_a c^2$. Here, m_a is the axion mass, ν the cavity frequency, and h Planck's constant, with 1 GHz corresponding to an axion mass of roughly 4 μeV. Think of the experiment as a revved-up version of your car's radio receiver.

The search strategy is dictated by the Dicke radiometer equation,

$$\frac{S}{N} = \frac{P_s}{k_B T_N} \cdot \sqrt{\frac{t}{\Delta\nu}},$$

where S/N is the signal-to-noise ratio, P_S is the signal power, k_B is Boltzmann's constant, and T_N is the system noise temperature. The factors under the square root are the integration time t at each step and the bandwidth of the axion signal $\Delta\nu$.

Although deceptively simple in concept, the experiment is one of the most daunting endeavors in physics today. Three factors complicate it. First, one must scan a range of axion masses over at least three decades. Because the search is narrowband, each decade must be covered by dint of many millions of tiny steps. Second, even for the most favorable axion–photon couplings predicted, and in the largest such experiment, the anticipated signal power is measured in units of yoctowatts, a trillionth of a trillionth of a watt. Third—and herein lies the real rub—unless one gets clever, a fundamental, irreducible noise floor set by quantum mechanics prevails for standard linear amplifiers.

Known as the standard quantum limit (SQL), the noise floor is expressed in terms of a temperature as $k_B T_{SQL} = h\nu$. More precisely, the system noise consists of a sum of two components, the familiar blackbody contribution (in parentheses below, where T is the physical temperature) and the noise accruing from the amplifier, T_A:

$$k_B T_N = h\nu\left(\frac{1}{e^{h\nu/k_B T} - 1} + \frac{1}{2}\right) + k_B T_A.$$

Half of the irreducible single quantum of noise $h\nu$ comes from the vacuum fluctuations of the cavity, even at zero temperature, and half comes from the linear amplifier itself. A convenient benchmark to keep in mind is that $k_B T_{SQL} \approx 50$ mK at 1 GHz. At high temperatures, $k_B T >> h\nu$ and $T_N \approx T + T_A$.

The first microwave cavity experiments in the late 1980s at Brookhaven National Laboratory and the University of Florida used transistor-based amplifiers (heterojunction field-effect transistors that operated with system noise temperatures typically 5–20 K), some 200 times the standard quantum limit, T_{SQL}, over the 1–3 GHz frequency range. In the mid 1990s, the first large-scale experiment, the Axion Dark Matter Experiment (ADMX), began taking data. It used the best broadband amplifiers of its time; based on high-electron-mobility transistors, those amplifiers steadily improved the noise temperature to about 100 T_{SQL} at subgigahertz frequencies.

By virtue of its large volume cavity, ADMX had scanned a significant range in mass at one of two representative axion–photon couplings—corresponding to one variant of the KSVZ (named for Jihn Eui Kim, Mikhail Shifman, Arkady Vainshtein, and Valentin Zakharov) family of models regarded by the axion community as a useful experimental goalpost. But delving much deeper into the model space seemed out of reach. Furthermore, the scanning rate was unacceptably slow. Unless much better amplifiers were devised, the search for dark-matter axions seemed headed for an abrupt dead end.

Closing in on the quantum

The axion experiment unexpectedly gained a new lease on life with a chance conversation during a 1994 workshop at the University of California, Berkeley. Speaking to Leslie Rosenberg and one of us (van Bibber), then ADMX spokespersons, John Clarke ventured that he could make gigahertz amplifiers based on superconducting quantum interference devices (SQUIDs). At the time, amplifiers were limited to DC applications such as

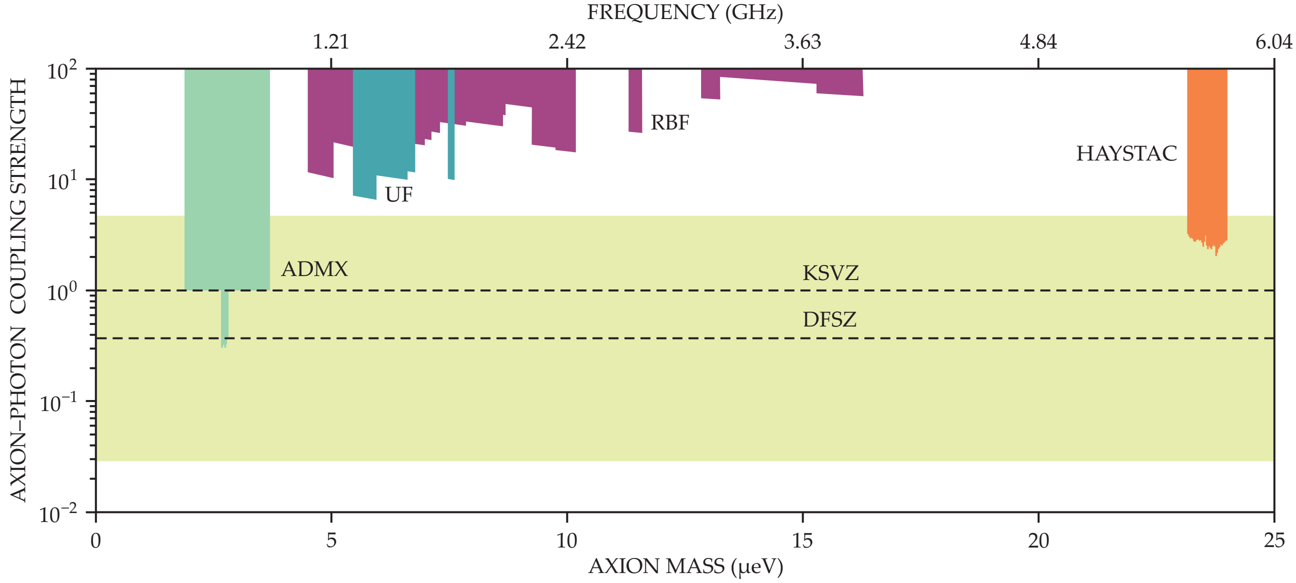


FIGURE 2. THE PARAMETER SPACE of axion mass and the axion–photon coupling strength excluded by microwave cavity axion experiments. The greenish yellow band delimits regions of the frequency spectrum already explored by theoretical models. The dashed lines are two specific realizations—from the KSVZ and DFSZ families of models—long used by the axion community as experimental benchmarks. UF and RBF denote first-generation experiments from the University of Florida and the Rochester-Brookhaven-Fermilab collaboration.[3] ADMX is the first large-scale US microwave cavity experiment, and HAYSTAC is the Yale-Berkeley-Colorado experiment. (Adapted from ref. 6.)

magnetometry. NSF took interest, and by 1998 Clarke and collaborators had invented the microstrip-coupled SQUID amplifier, or MSA. The achievement demonstrated quantum-limited performance on the bench.[4]

With a phased upgrade to MSAs and a dilution refrigerator approved by the Department of Energy, the experiment was finally able this past year to reach a more stringent goalpost in axion–photon coupling—one corresponding to a particular variant of the DFSZ (named for Michael Dine, Willy Fischler, Mark Srednicki, and Ariel Zhitnitsky) family of models. The system noise temperature[5] is now estimated to be only about 15 $T_{\rm SQL}$. Just two years ago, a Yale-Berkeley-Colorado experiment called HAYSTAC published results in the 6 GHz (roughly 24 μeV) range. Using so-called Josephson parametric amplifiers (JPAs), the researchers demonstrated a system noise temperature a mere factor of 2 above the quantum limit and probed the model band (figure 2) with a cavity volume only 1% that of ADMX.[6]

One might think that further technology development would be unnecessary, and that only the size scale of the experiment and scan time need be extended for a definitive observational campaign. Chastened by fruitless decades hunting for the dark matter, however, the community of axion hunters should be prepared for a long march yet and have every technological advantage in their quiver.

Today's experiments are already pressing up against a fundamental limitation of quantum mechanics. But might there be a loophole that will enable us to continue improving the signal-to-noise ratio and scan speed of the search? In fact, quantum measurement is a rich and subtle topic, providing much room to maneuver. Both NSF and DOE have recently launched bold initiatives in quantum sensing and information in high-energy physics. They are supporting, in particular, two quantum-enhanced strategies in the search for axionic dark matter.

Putting the squeeze on

The first attempt to circumvent the standard quantum limit in the axion search is already under way at Yale University. In the summer of 2018, the HAYSTAC experiment began an upgrade, led by one of us (Lehnert), to a squeezed-vacuum state receiver, shown in figure 3. If successful, the project may be the first fundamental science experiment to use the squeezed states of the vacuum as data. (Incidentally, the Laser Interferometer Gravitational-Wave Observatory has prototyped an analogous system to improve how sensitively it detects gravity waves.)

Squeezing overcomes an apparent compromise in selecting the quality factor of the resonant cavity in the axion "radio." A higher-quality cavity boosts the amplitude of an axion-induced microwave tone because the tone accumulates for a longer time inside the cavity. But a higher-quality cavity also narrows the range of frequencies, or bandwidth κ, over which the radio achieves its best sensitivity. The narrowing would consequently require that the cavity be tuned in smaller steps.

It is never desirable to increase the rate $\kappa_{\rm l}$ at which the cavity absorbs energy. But in addition to that intrinsic loss rate, energy stored in the cavity also leaves at a rate $\kappa_{\rm m}$ through its measurement port. The optimum value of $\kappa_{\rm m} = 2\kappa_{\rm l}$ in a search for a signal of unknown frequency already sacrifices some sensitivity to a resonant signal for a larger overall bandwidth $\kappa = \kappa_{\rm l} + \kappa_{\rm m}$. Although the conflict between sensitivity and bandwidth may seem to be a mundane detail of microwave engineering, overcoming it requires techniques that are at the forefront of quantum measurement science.

Quantum squeezing maintains high sensitivity over a larger bandwidth by reducing one component of the cavity's quantum noise and noiselessly measuring that component, as sketched in figure 4a. The cavity mode that couples to the axion field is modeled as a single quantum harmonic oscillator, in which the cavity electric field is the oscillating quantity. After factoring out the rapidly oscillating contribution at the cavity's resonance frequency, the cavity field can be described by its slowly varying cosine X and sine Y components; the dimensionless variables X and Y are normalized by the scale of the cavity vacuum fluctuations.

Those "quadrature" variables, which follow the commutation

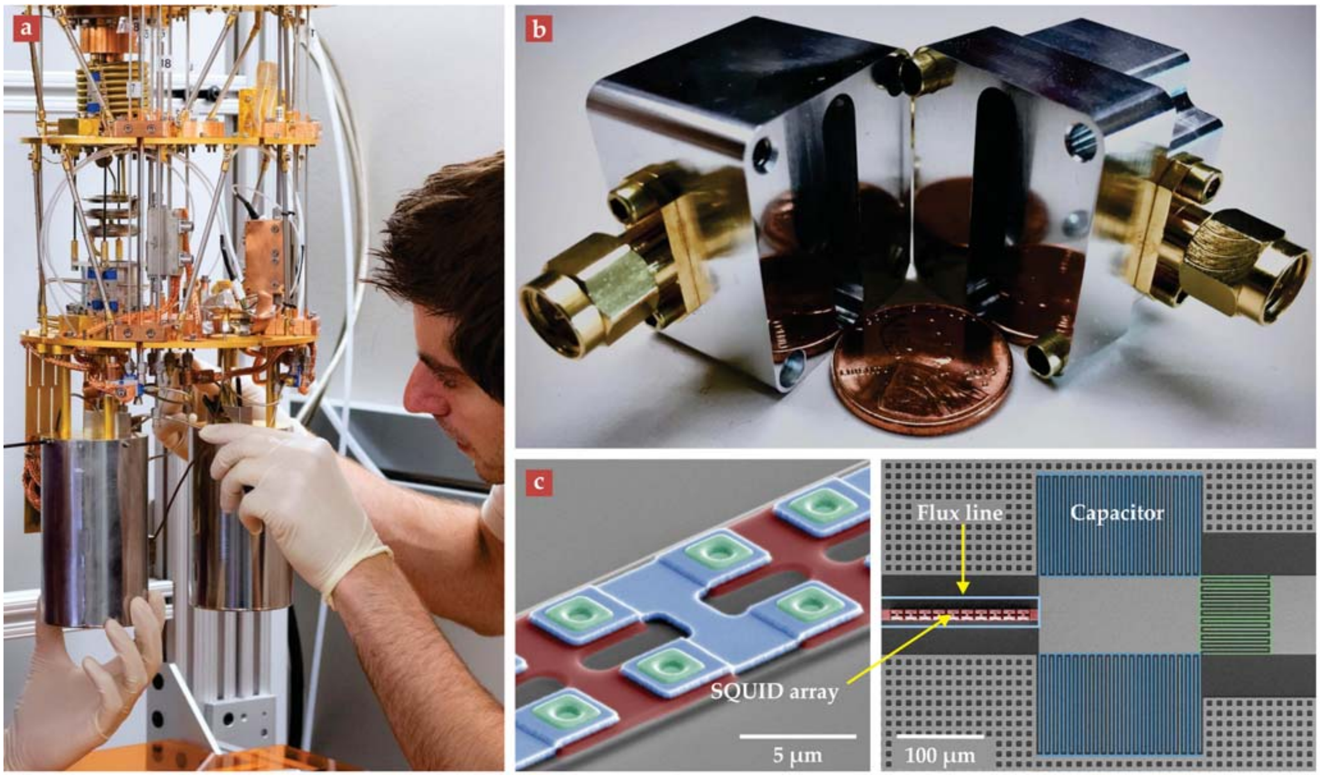


FIGURE 3. EXPERIMENTAL PROTOYPES. (a) Researchers assemble the two Josephson parametric amplifiers in this squeezed-state receiver for the HAYSTAC experiment. **(b)** The 7.1 GHz aluminum cavity for the squeezed-state receiver is split open. **(c)** This microphotograph shows a Josephson parametric amplifier composed of an array of superconducting quantum interference devices (SQUIDs). (Photographs courtesy of Dan Palken.)

relation $[X,Y] = i$, are constant under the evolution of the cavity Hamiltonian. The presence of an axion field can then be sensed through the fact that it would alter the state of the cavity in X,Y phase space. But unlike a classical description of a harmonic oscillator, a quantum oscillator cannot be localized in phase space with unbounded precision.

The axion cavity is continuously prepared in its ground state by virtue of the dilution refrigerator's cold environment. But zero-point (or vacuum) fluctuations $\Delta X^2 = \Delta Y^2 = \frac{1}{2}$ ensure that the state is only localized to the minimum area consistent with the uncertainty principle $\Delta X{\cdot}\Delta Y = \frac{1}{2}$. Simultaneous measurement of both X and Y must also add noise to preclude localizing the state beyond the Heisenberg uncertainty bound. Indeed, conventional amplifiers continuously measure both cavity quadratures when they boost the signal exiting the cavity. Repeatedly preparing the oscillator in its ground state and measuring its location in phase space results in values of X and Y that fluctuate[7] such that the apparent average energy of the oscillator is at least the standard quantum limit value of $h\nu$.

For the case of HAYSTAC, overcoming that SQL with squeezing is particularly natural because the JPAs already used in the experiment can noiselessly amplify one quadrature while squeezing the other. As outlined in figure 4, a first JPA prepares the cavity in a state with quantum fluctuations squeezed in X and equivalently amplified in Y. In a characteristic cavity storage time $t_s = 1/\kappa$, the cavity's state will be displaced by any axion field oscillating by an amount proportional to t_s near the cavity's resonance frequency. A second JPA then noiselessly amplifies and measures just the value of X. To the extent that the initial cavity state is arbitrarily squeezed in X and the subsequent measurement of X is noiseless, arbitrarily small axion displacements of the X component can be resolved.

A full analysis of the benefits of a squeezed-state receiver accounts for imperfections in the preparation of the squeezed state and in the single quadrature measurement and for the intrinsic loss of the axion cavity itself.[8] This last factor translates the notion of a measurement completely free of quantum noise into a practical increase in bandwidth and scan rate. In current experiments, the axion signal's coherence time is expected to be 10–100 times as long as a typical axion cavity storage time $1/\kappa$. If one knew the axion frequency, the signal-to-noise ratio would be maximized by bringing the cavity into resonance with the spectrally narrow axion signal and by choosing the cavity measuring rate to match its internal dissipation rate $\kappa_m = \kappa_l$.

At that "critical-coupling" condition, squeezing does not improve the signal-to-noise ratio of a signal exactly on resonance. The squeezed state decays back into an unsqueezed state during its storage in the lossy cavity. But by increasing κ_m above the critically coupled value, more of the squeezed state survives its now briefer time in the cavity and both the measurement noise and signal are reduced together, preserving their ratio. With arbitrarily large squeezing, the maximum signal-to-noise ratio can be maintained over a bandwidth much larger than the critically coupled value of $2\kappa_l$. In that way, squeezing benefits an axion search because it allows the cavity to be tuned in larger frequency steps; a particular frequency range can thus be scanned in a shorter time.

The first implementation of a squeezed-vacuum state receiver on HAYSTAC will use that strategy. In a test at JILA, the Lehnert group has demonstrated squeezing the noise variance by a factor of −4.5 dB (data shown in figure 4b). And in a mock axion search experiment, the group sped up the scan rate by a factor of 2.1, exactly in accord with predictions for the system.[9] The twin of that system is currently being commissioned in HAYSTAC with a target of 2–3 increase in scan rate. A new squeezed-state receiver design is being explored at JILA that may speed up the scan rate by a factor of 10.

Zero to one

Instead of measuring the cavity wave in the X,Y quadrature basis, one can instead measure its amplitude and phase in polar coordinates, which are themselves conjugate observables satisfying the Heisenberg uncertainty principle. The axion signal would appear as a nonvanishing cavity electric field amplitude, as evidenced by the occasional appearance of a single photon in the otherwise unoccupied cavity. That signal would be a zero-to-one transition, much like a spurious qubit error in a modern quantum computer.

A longer-term and more ambitious goal to beat the standard quantum limit will be the implementation of a photon-counting detector that measures the amplitude but not the phase of the cavity wave. Just as in the case of quadrature squeezing described above, only one of these conjugate observables is measured, and so there is no fundamental limit on the measurement noise due to quantum back action. As Yale's Steve Lamoreaux and colleagues have pointed out, the measurement errors that arise from a photon-counting detector's dark-count background rate—that is, its spurious noise hits—could therefore be made arbitrarily low. The result would be pristine resolution of tiny field amplitudes for ultrasensitive axion searches.[10]

A joint Fermilab and University of Chicago team led by one of us (Chou), Daniel Bowring, and David Schuster is conducting precisely such R&D to lay the groundwork for an ambitious axion search at masses above 40 μeV (above 10 GHz), utilizing novel microwave photon-counting detectors based on artificial atoms—superconducting qubits developed for quantum computing.

The new microwave photon-counting detectors employ quantum nondemolition (QND) measurements, which repeatedly probe the electric field of the photon stored in the cavity without actually absorbing and thus destroying the photon in the process. These measurements rely on the atom's electric polarizability, a quantity that describes the potential energy associated with the off-resonance dipole scattering of a photon by the atom—the same scattering process that makes the sky blue. The interaction energy associated with the repeated scattering by even a single photon confined in a cavity creates an observable shift in the atomic energy levels.

The atom may be considered a ball-and-spring oscillator with the atomic electron represented by the ball and the nonlinear spring represented by the anharmonic $1/R$ Coulomb potential. The rms electric field of the background photon stretches the spring and exercises its nonlinearity, thus causing the resonant frequency of the atomic oscillator to change. For sufficiently strong coupling, the electric field of even a single photon can be resolved by that nondestructive amplitude-to-frequency transducer.

The nonlinear response is responsible for the Lamb shift, which is due to interactions of the atom with zero-point photon fluctuations of the quantum vacuum. In the case of interactions with photon modes of the finite, nonzero occupation number, the corresponding effect is known as the AC Stark shift. Just as in the case of the Lamb shift, the atom absorbs no net photons; the atom thus acts as a nondestructive photon sensor.

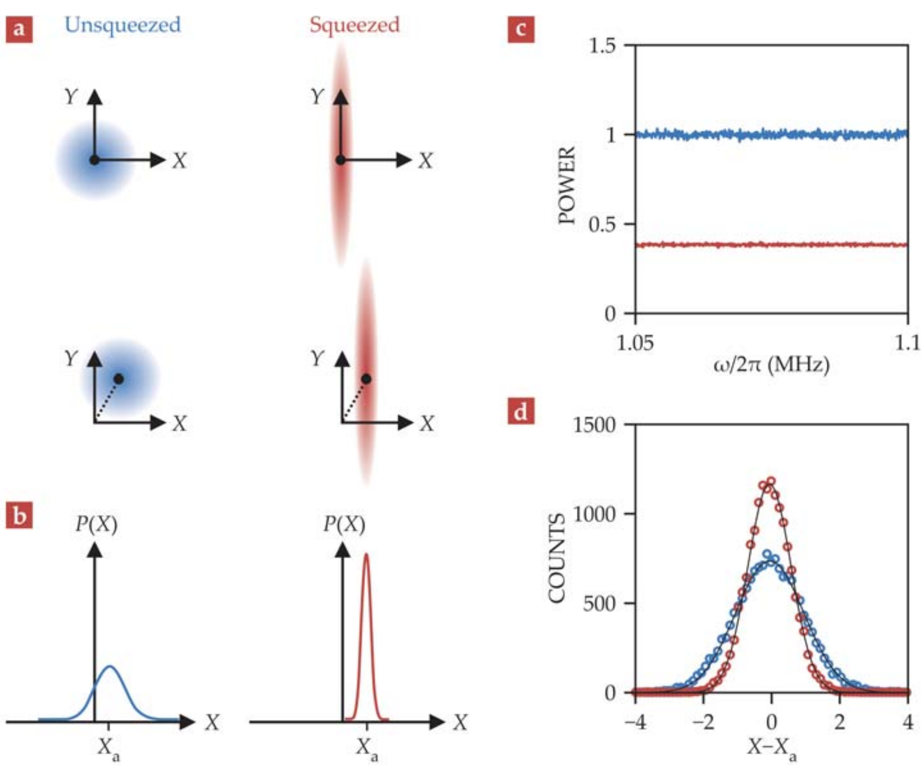


FIGURE 4. AN AXION SEARCH MEASUREMENT. In this illustration **(a)** of phase-space variables X and Y, the variables' noncommutation imply that the phase space cannot be localized to an area smaller than a Heisenberg uncertainty region. The cavity state is initially prepared in either its ground state (blue) or a squeezed state (red). But once an axion has entered the cavity, the state is displaced (the dotted line) by the axion field. **(b)** A noiseless measurement of the X component yields a probability density $P(X)$. Because noise has been squeezed from the X to the Y variable, the displacement in X by the actual axion signal is more easily detected. **(c)** Noise power from a squeezed-state receiver prototype is plotted versus frequency ω. **(d)** A histogram of measured values of X with (red) and without (blue) squeezing match the theoretical plot of panel b, in units of the vacuum noise.

By performing repeated spectroscopic measurements of the atomic transition frequencies, one can determine the exact photon occupation number of the cavity state and thus ascertain the presence or absence of the putative signal electric field. More specifically, in an axion search experiment, the cavity is cooled to its vacuum state and one measures how often the QND process observes a frequency shift corresponding to an $N = 1$ cavity state relative to the rate of observing the $N = 0$ vacuum state. The axion signal would then be a significant excess of photon counts above statistical fluctuations in the background counts (see figure 5). The methodology is equivalent to searching for excess narrowband power in signals read out with a linear amplifier. But the background dark count probability can now be reduced to a small fraction of the single photon per readout required by the standard quantum limit.

Although the measurement process conserves the cavity photon number, the atomic spectroscopy requires the atom to absorb probe photons at the shifted transition frequency. The increased atom–cavity interaction energy due to the extra absorbed probe photon causes a reciprocal shift of the cavity mode frequency. It thus also creates phase noise in the cavity photon state as measurement back action. In the limit of perfect QND measurement, the cavity state is projected into a state of definite photon number and maximally randomized and indefinite phase.

Any anharmonic oscillator with a nonlinear restoring force can act as the amplitude-to-frequency transducer necessary to implement a QND measurement. Physics Nobel laureate Serge Haroche and collaborators originally demonstrated the QND technique using beams of Rydberg atoms[11]—huge atoms of very large principal quantum number—but newer implementations exploit artificial atoms made of superconducting qubits.[12] In those qubits, the nonlinear kinetic inductance of a Josephson junction combines with the junction capacitance to form an anharmonic *LC* oscillator.

In practice, additional capacitance is added to reduce the susceptibility to charge noise, and that capacitance can be used to tune the resonant frequency of the circuit to any desired value. Also, unlike in real atoms, the strength of the qubit's electric dipole coupling to the background photon's electric field can be increased simply by attaching appropriately sized antennae to opposite sides of the capacitive junction. Again, the cavity photon's field can be thought of as an oscillating force that nonlinearly stretches the electromagnetic spring and changes its resonant frequency. The qubit-based QND sensor can be easily mounted inside the cavity on a dielectric substrate, as shown in figure 6.

Because the low temperatures achieved by dilution refrigerators suppress the cavity's blackbody photon population, the dark count rate in state-of-the-art superconducting qubit sensors is primarily determined by spurious readout errors. It's still a mystery why the qubits are found in their excited state far more often than are expected at the operating temperature. That situation produces false positives in the absorption spectroscopy used to probe the qubit frequency shifts. Typically, the probability of a spontaneously excited state is around 1%, which corresponds to an average of 0.01 dark counts per readout.

Although the resulting dark rate is less than the effective 1 dark count per readout for the standard quantum limit, the rate could still be improved. Efforts are under way to implement simultaneous or sequential QND readout of the cavity occupation number using gangs of independent qubit sensors and requiring all or a large fraction of them to report the same answer. Confirmation of a detection by many qubits should significantly reduce the resulting dark count rate below that from individual qubit readout errors.

More than a decade ago, Seishi Matsuki and collaborators on the CARRACK axion experiment in Kyoto, Japan, developed a single-photon detector using Rydberg atoms to resonantly absorb single microwave photons. It convincingly demonstrated a thermal-photon dark rate a factor of two below the standard quantum limit at 2.5 GHz;[13] an axion search was conducted over 10% bandwidth in mass with roughly DFSZ sensitivity, but it was never published. The QND techniques now being developed can achieve much greater fidelity in signal readout than that absorptive technique by making multiple redundant measurements, and the background photon rates can be dramatically reduced with subkelvin operation. A background-free axion experiment is potentially within reach.

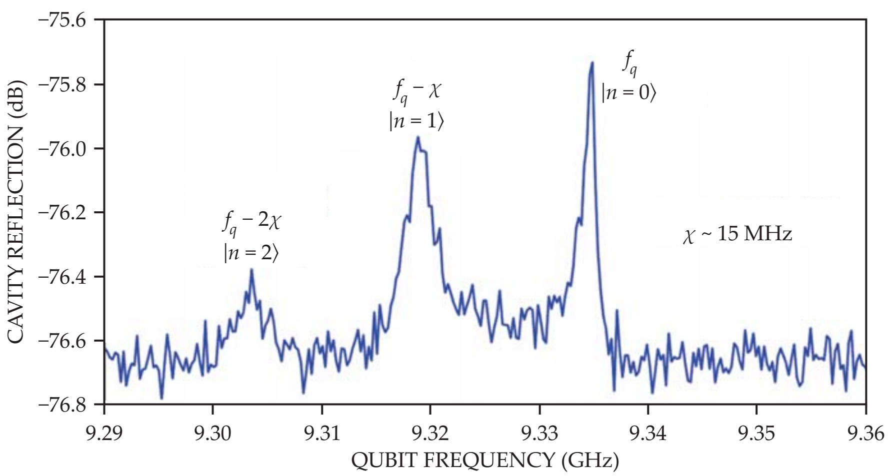


FIGURE 5. THE QUBIT RESPONSE SPECTRUM, measured when the cavity is driven with mean photon occupation number $\langle N\rangle \approx 1$. Due to the potential energy of interaction with a photon's electric field, the qubit's frequency f_q shifts by a quantized amount $\chi = 15$ MHz for each photon present in the cavity. The resulting spectrum exhibits a Poisson distribution that describes statistical fluctuations in the cavity occupation number. For the much smaller signals expected from axions, one would obtain a Poisson distribution with $\langle N\rangle \ll 1$, and the signature would be a single photon accompanied by a single unit of frequency shift. That signature would appear as the occasional population of the $N = 1$ peak of the spectrum. (Data courtesy of Akash Dixit.)

Controlling the quantum

More than half a century ago, Chester Gould's comic strip detective Dick Tracy famously predicted, "The nation that controls magnetism will control the universe." That prediction was off

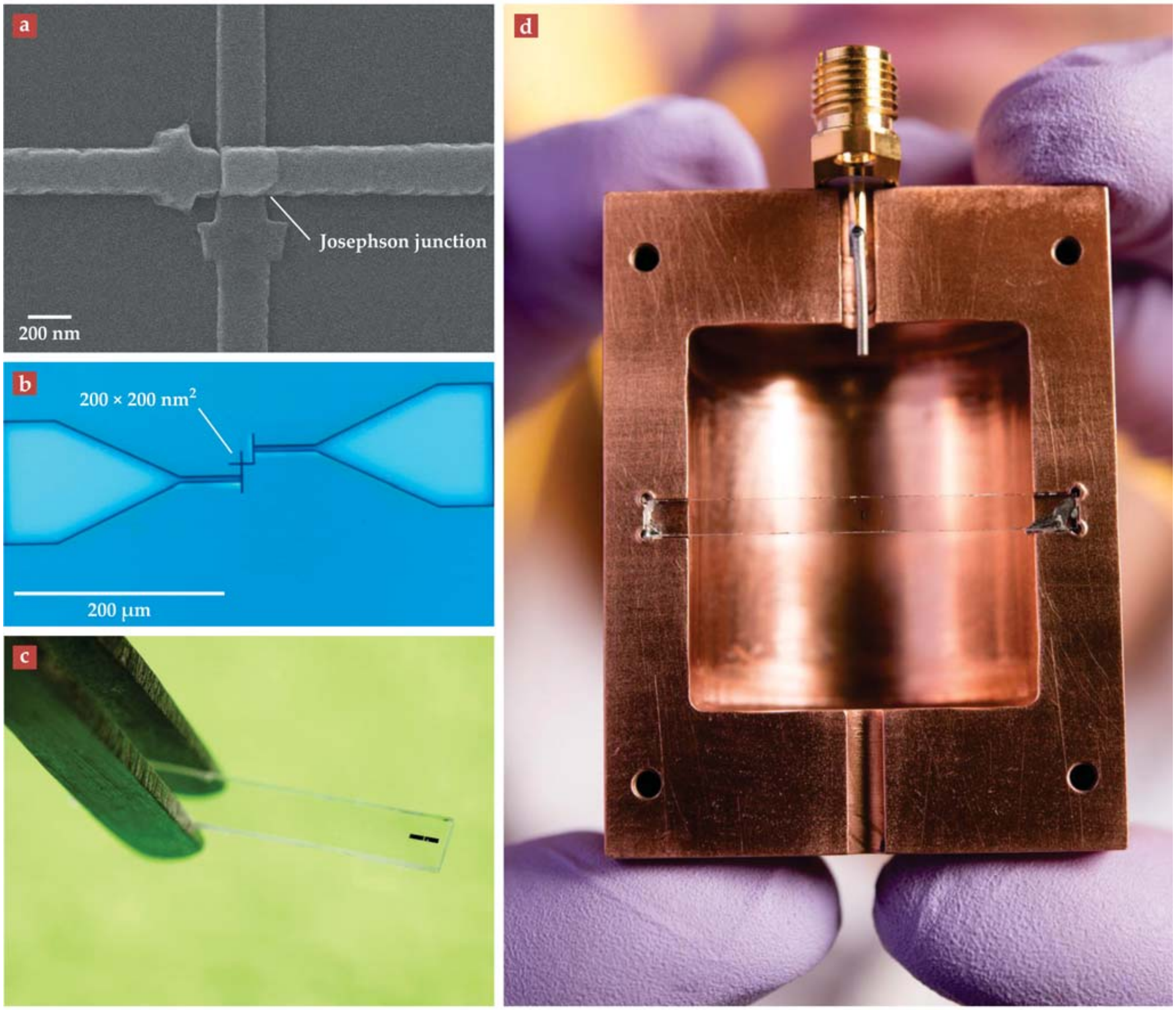


FIGURE 6. A SUPERCONDUCTING "ARTIFICIAL ATOM" QUBIT is an anharmonic *LC* oscillator **(a)** that uses the nonlinear inductance of a Josephson junction. **(b)** Larger superconducting structures may be attached to the junction to build up millimeter-size antennae **(c)**, which enable stronger coupling to the electric field of centimeter-wave cavity photons. **(d)** The qubit is mounted inside a cavity with a dielectric substrate. The vertically oriented electric field of a single-cavity photon "stretches" the qubit oscillator and exercises its nonlinearity. The quantum nondemolition photon detection protocol can be phrased as a yes–no question: Has the qubit's resonant frequency shifted in response to the appearance of a cavity photon or not? (Photographs courtesy of Akash Dixit and Reidar Hahn/Fermilab.)

the mark, perhaps, although Gould was spot on with his two-way video wristwatch. Controlling the quantum could be a different story, and we predict that the quantum will ultimately bring the dark matter of the universe into view.

Dramatically improved receivers based on quantum sensing are no panacea for the axion experiment. A parallel challenge not discussed in this article is the development of innovative microwave cavities satisfying multiple constraints of the axion experiment. Technologies that are being pursued include photonic bandgap resonators and the use of metamaterials and thin-film superconductors. But that's a story for another time.

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