ancestral animals that gave rise to Mammalia, or whether it evolved independently (by convergent evolution) in different groups as their middle ears became detached from their jaws.

Although their research is a major contribution to the understanding of Haramiyida, Wang and colleagues' study will not settle the debate about the placement and composition of this group. The striking increase in fossil discoveries, in particular new specimens from China, has fuelled routine revision of the mammalian tree of life during the past few years[10–12]. In the end, the lasting impact of Wang and colleagues' research will probably lie in their detailed evaluation of fossil and developmental morphologies of the middle ear, and the establishment of new terminology that is consistent with current evidence. Their work is a foundational reference for future studies that provides a framework on which to evaluate the evolution of the middle ear and new fossil discoveries.

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Astroparticle physics

Shedding squeezed light on dark matter

Igor G. Irastorza

Hypothetical particles called axions could constitute dark matter — the unseen component of the Universe. An experiment shows how quantum-manipulation technology can improve the sensitivity of axion detectors. **See p.238**

The Universe is filled with an invisible, unconventional form of matter, whose presence is betrayed by its gravitational attraction to ordinary matter. Scientists now have overwhelming evidence for the existence of such dark matter at galactic and cosmological scales. However, none of the known fundamental particles has the right properties to compose it. As a result, the nature of dark matter is one of the biggest puzzles in modern physics. For decades, researchers have struggled and failed to find signs of particles beyond the established catalogue. On page 238, Backes *et al.*[1] report an innovative way to accelerate future searches using quantum-manipulation techniques.

Among the particles suggested by theorists, the axion is a favourite for particle hunters[2]. Axions were originally proposed[3] to explain a somewhat obscure aspect of the current theory of particle physics, related to the fact that the dynamics of some particles seem to be unchanged when the arrow of time is reversed, contrary to expectation. More excitingly, axions are predicted to have the right properties to constitute dark matter. They would have been produced in large quantities after the Big Bang, and would permeate the Universe and behave exactly like dark matter.

If dark matter is made of axions, we would be embedded in a vast sea of these particles. An axion haloscope[4] is an instrument that looks for axions in our Galaxy's dark-matter halo (a roughly spherical region that extends beyond the stellar disk). In this device, a resonant cavity — a hollow metal structure that confines light of a particular frequency called a resonant frequency — is placed in a strong, uniform magnetic field. Inside the cavity, a potential axion can scatter from a quantum fluctuation of the magnetic field, known as a virtual photon, and produce a single real photon that has a frequency proportional to the axion mass (Fig. 1). If this frequency matches the resonant frequency of the cavity, the otherwise negligibly small axion signal will be amplified.

Even with this amplification, the signal expected for axions in the most realistic models of these particles is tiny and often buried under the 'noise' of the experiment. This noise has historically come from thermal radiation emitted from the cavity walls, or been introduced by the sensor technology used. Lowering the experimental noise is an effective way to improve the sensitivity to axions. As a result, the leading axion haloscopes[5–7] are cooled to cryogenic temperatures to reduce thermal emission, and use ultralow-noise sensor technologies. Unfortunately, until now, physics seemed to pose a fundamental barrier to this improvement.

Heisenberg's uncertainty principle of quantum physics[8] states that certain pairs of properties of a quantum system cannot be determined simultaneously with unlimited precision. Such properties are called complementary variables and include, for example, position and momentum. The uncertainty is sometimes referred to as quantum noise and is present even in the absence of any photons — a vacuum state. Consequently, quantum noise represents a limit to the achievable noise level in axion haloscopes. It is already a technological feat that the leading haloscopes reach noise levels extremely close to this quantum limit. But Backes and colleagues have now gone one step beyond the limit using a quantum state known as a squeezed state.

Squeezed states are specially prepared so that one of the properties in a pair has reduced uncertainty. To respect Heisenberg's principle, the complementary variable must then have larger-than-normal uncertainty. Squeezed states of light were first produced in the laboratory in the 1980s[9,10]. However, their potential to overcome the quantum limit in axion searches has been studied only in the past few years[11].

In the case of Backes *et al.*, the property being squeezed is the component of the quantum noise that resembles a mathematical curve called a sine wave, and the complementary variable receiving extra uncertainty is the component akin to a cosine wave. Fortunately, what is won by squeezing the former component is much greater than what is lost by 'unsqueezing' the latter. Therefore, preparing the vacuum state in the cavity of an axion haloscope in such a squeezed state enables the noise level to be reduced below the quantum limit.

Backes *et al.* have now implemented this concept in a real axion search. In doing so, they have proved that delicate quantum-manipulation technology is compatible with the environment of such a search. The authors report that a given region of axion parameter space (a plot of the axion–photon coupling versus the axion mass) can be explored in half the time when squeezing is included compared with when it is not.

This improvement might seem relatively modest, but it paves the way for further leaps forward in sensitivity. In principle,

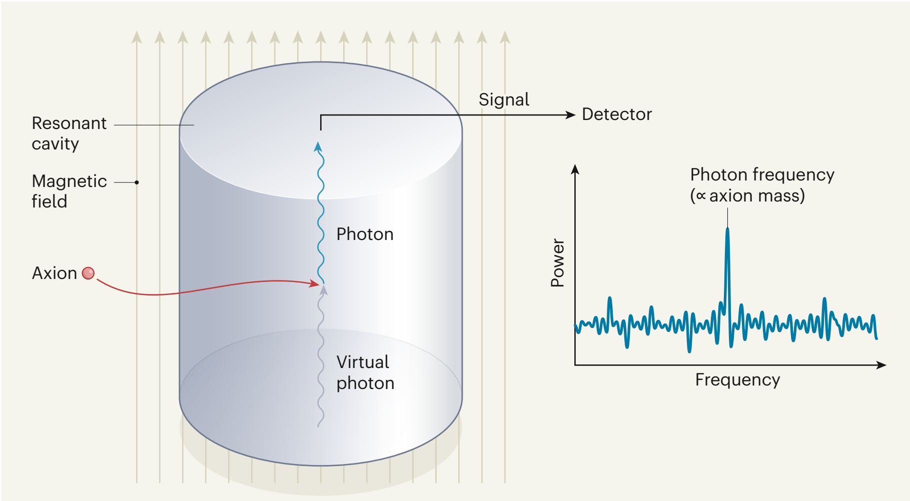

Figure 1 | Operation of an axion haloscope. Axions are hypothetical particles that could make up dark matter, the 'missing' mass in the Universe. Such particles might be detected using a device called an axion haloscope, which consists of a hollow metal structure known as a resonant cavity, embedded in a strong, uniform magnetic field. A potential axion can enter the cavity and interact with a virtual photon (a quantum fluctuation of the magnetic field) to generate a real photon. The resulting signal could then be detected as an excess of power in the cavity at the photon frequency, which is proportional to the axion mass. Backes *et al.*[1] demonstrate how the detection of such a signal can be improved using quantum technology (not shown).

arbitrarily large enhancements are possible, depending on the quality of the squeezing. Advances in this area are continuous, pushed by developments in quantum-information technologies. Therefore, improved squeezing is just around the corner.

Backes and colleagues' work is the first step towards quantum-enhanced particle searches. In the past few years, axions have attracted increased attention, in part because experiments worldwide are reaching sufficient technological maturity to start probing realistic axion candidates, although admittedly only marginally so far. The authors' result will certainly influence future searches, providing a boost in sensitivity that will be crucial for testing the hypothesis that dark matter is made of axions. Therefore, the work will help to shed light (in this case, squeezed light) on one of the biggest mysteries in modern science.

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