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NEWS & VIEWS

PARTICLE PHYSICS

# The first axion?

Steve Lamoreaux

**For almost 30 years, the hunt has been on for a ghostly particle proposed to plug a gap in the standard model of particle physics. The detection of a tiny optical effect might be the first positive sighting.**

Writing in *Physical Review Letters*[1], Emilio Zavattini and colleagues of the Italian PVLAS collaboration report that a magnetic field can be used to rotate the polarization of a light wave in a vacuum. Although this is the first experimental evidence for such an effect, there is a well-rehearsed, but controversial, explanation for it: the existence of a never-before-seen, chargeless, spinless and near-massless particle — the axion. Has the elusive axion finally allowed itself to be glimpsed?

The idea that static electric and magnetic fields alter the optical properties of matter, whether solid, liquid or gas, is not new. In 1845, Michael Faraday showed that the direction of polarization of light changes in a medium permeated by a magnetic field. Similar demonstrations followed: of the Cotton–Mouton and Kerr effects, for instance, in which the propagation speed of a light wave can be made to vary according to the orientation of its polarization with respect to an applied magnetic or electric field, respectively.

That static electromagnetic fields can be used to alter the properties of empty space might seem surprising. The culprit is quantum electrodynamics (QED), the quantum field theory that expresses the electromagnetic interaction in terms of the exchange of quanta of energy — photons — between particles. It was recognized in the early 1930s that the rules of QED allowed the creation and annihilation in an electromagnetic field of short-lived 'virtual' charged-particle pairs consisting of an electron and its antiparticle, the positron. The resulting 'self-interaction' of the field introduces a nonlinearity in the governing equations of electromagnetism (Maxwell's equations) analogous to that induced by the presence of matter. The vacuum self-interaction is further complicated by the fact that, given the presence of sufficiently energetic photons, real (as opposed to virtual) electron–positron pairs can be created. Nevertheless, by 1936, vacuum analogues of various optical effects in matter had already been calculated[2,3].

So what other particles might the vacuum be hiding? In the late 1970s, a suitable candidate was postulated to solve the so-called strong CP problem. This problem pops up as a term in the field equations of quantum chromodynamics (QCD) — the equivalent of QED for the strong nuclear force, which binds together the innards of neutrons and protons. This term is not symmetric when, in a process involving the strong force, particles are replaced by antiparticles (charge conjugation; C) and the process is viewed in a mirror (parity inversion; P). The degree of this 'symmetry breaking' can be parametrized by an angle that, according to a limit obtained from measurements of the electric dipole moment of the neutron, is less than a billionth of a radian. Strong-force interactions covered by QCD thus hardly seem to break CP symmetry at all.

This is an odd fact, because interactions involving the weak nuclear force (which can be incorporated with the electromagnetic force in QED) observably break CP symmetry. As there is no a priori reason for the discrepancy between these forces, Roberto Peccei and Helen Quinn proposed[4] a mechanism implying the existence of another electrically neutral particle that would force the QCD symmetry-breaking angle — which could otherwise be as large as that in QED — to become zero. This particle cleaned up the strong CP problem, so Frank Wilczek dubbed it the 'axion', after a

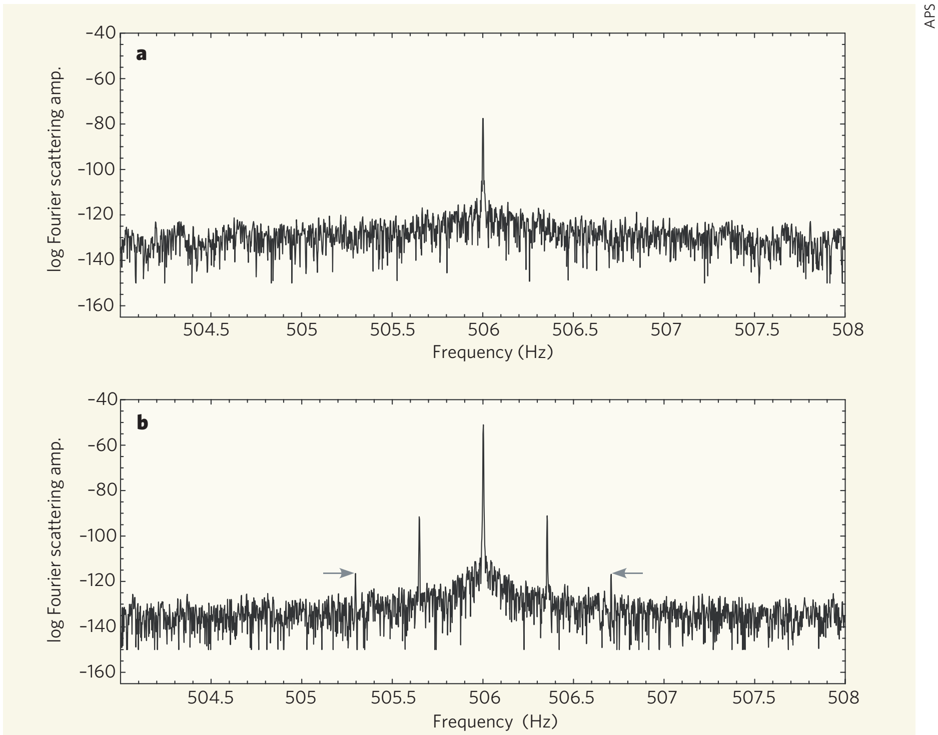


**Figure 1 | Now you see it?** Before (**a**) and after (**b**) Fourier amplitude spectra (logarithmic scale) of Zavattini and colleagues' vacuum polarization-rotation experiment[1]. A sine wave generated at 506 hertz is modulated by the frequency of rotation, $\nu \sim 0.3$ Hz, of the experimental apparatus, which consists of a 1-metre-long interaction region traversing the bore of a 5.5-tesla magnet cooled cryostatically to 4.2 kelvin. **a**, With the magnetic field off, a central peak is observed, corresponding to the generated sine frequency. **b**, With the magnet on, side peaks are observed at frequencies displaced from the central peak by $\pm\nu$, corresponding to the magnet's rotation. Crucially, a signal displaced by $\pm 2\nu$ is also observed (arrows). This unexpected additional rotation of the light polarization vector could be the signal of axion production.

laundry detergent that enjoyed limited commercial success in the United States[5].

Although no axion has been detected in the 30-odd years since it was proposed, much can be said about its properties. Its mass (expressed in energy units based on the electronvolt, eV) must be greater than 1 $\mu$eV; otherwise, it would have been too easily created in the Big Bang, so that there would be an amount of invisible 'dark matter' in the Universe that is incompatible with observations. On the other hand, its mass must be less than 0.01 eV; if it is not, an additional energy-loss mechanism would have been evident in the time course of the only supernova explosion, SN1987a, so far observed through modern telescopes[6]. Other astrophysical observations put a limit on the strength of the photon–axion interaction, dependent on the axion mass, of $0.6 \times 10^{-10}$ GeV$^{-1}$.

The axion is much lighter than an electron (at 511 keV, the electron weighs in at between 50 million and 500 billion times the axion mass), and can thus be produced more easily from a vacuum. Like the electron, it interacts with electromagnetic fields, so enhanced optical effects in a vacuum would also be expected. Such effects generally depend on the inverse fourth power of a particle's mass, so, even taking the upper limit of the axion mass, a factor of $10^{30}$ enhancement would be expected compared with the effect of an electron. This enhancement is, however, reduced by the much weaker coupling of the axion to the field.

It is just such an optical effect that the PVLAS collaboration claims to have seen[1] (Fig. 1). In their vacuum experiment, laser light of wavelength 1,064 nanometres — corresponding to a photon energy 1.2 eV greater than the maximum possible axion mass — propagated perpendicularly to an extremely strong (5 tesla) magnetic field 1 metre long. The light's polarization vector lay in the plane perpendicular to the direction of light propagation, and the authors varied its angle with respect to the magnetic field by turning the magnet at a constant rate around the laser beam.

Whenever the angle between the light field and the magnetic field was $\pm 45°$ or $\pm 135°$, the authors observed that the light polarization angle rotated with alternating sign and with a magnitude of $4 \times 10^{-12}$ radian per metre of rotation path. This optical rotation angle, which becomes modulated at twice the magnet rotation frequency, corresponds exactly to what one would expect if the production of axions was attenuating the component of the light-field vector along the direction of the magnetic field. The inferred axion mass is about 1 meV — within the expected range — but the strength of the axion–photon interaction is, at about $5 \times 10^{-5}$ GeV$^{-1}$, far greater than expected. The net implication is that, if there is something there, it cannot be the QCD axion as circumscribed by astrophysics.

The PVLAS collaboration has done a credible investigation of possible spurious signals that might explain its results. To reduce measurement errors and increase the experimental sensitivity, the authors magnified the rotation angle to about 0.1 microradian by repeatedly — around 44,000 times — passing the laser beam through the field region using a device known as an optical resonator. Also, the group calibrated the system and verified its efficient operation by introducing a low-pressure gas into the laser-beam vacuum region and confirming the Cotton–Mouton effect.

One worrisome point that has not been fully addressed, however, is the presence of a signal at the rotation frequency that is about 100 times larger than the putative axion signal. Although no correlation to the signal was found at twice the rotation frequency — the frequency at which the axion signal was identified — there could be a small component that is correlated, but that is masked by other random processes. That might be enough to generate a false signal. The presence of such a component might be due to inadvertent tilting of the apparatus, or the attraction of nearby ferromagnetic objects when the magnet is energized. Also still to be investigated is how the observed effect depends on the magnetic field strength, current reversal and laser wavelength.

The effect seen by the PVLAS collaboration is large enough for it also to be observed in other ways. In particular, a strong signal should be seen if laser light is polarized parallel to an applied static magnetic field and then blocked by an opaque barrier. Axions generated from the photons in the light would penetrate this barrier easily because of their feeble interaction with matter, and a back-conversion of axions to photons could be accomplished by a second, identical magnetic field region behind it[7].

Detecting such reconverted photons would be a much more robust signature of axions than determining the polarization state of light stored in an optical resonator. It had been thought that such an experiment would not be sufficiently sensitive because it requires a feeble conversion process to be applied twice. But as the large axion–photon coupling constant found by the PVLAS collaboration indicates a higher production rate of axions, one could imagine an axion 'factory' constructed of surplus powerful dipole magnets obtained from particle accelerators.

As befits the potentially revolutionary nature of the PVLAS result, the jury is still out. Such a direct verification would, however, propel it to a place among the most significant in the history of physics. ■

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1. Zavattini, E. *et al. Phys. Rev. Lett.* **96,** 110406 (2006).
2. Heisenberg, W. & Euler, H. *Z. Phys.* **98,** 714–732 (1936).
3. Bialynicka-Birula, Z. & Bialynicki-Birula, I. *Phys. Rev. D* **10,** 2341–2345 (1970).
4. Peccei, R. & Quinn, H. *Phys. Rev. D* **16,** 1791–1797 (1977).
5. Wilczek, F. http://nobelprize.org/physics/laureates/2004/wilczek-lecture.pdf (2004).
6. Raffaelt, G. *Phys. Lett. B* **592** (*Review of Particle Physics*), 391–393 (2004).
7. Ansel'm, A. A. *Yad. Fiz.* **42,** 1480–1483 (1985).

CELL BIOLOGY

# Divining cancer cell weaknesses

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**Tumour cells tend to carry many gene mutations, but at a potential cost to their overall fitness. Studying the interactions between genes on a large scale could be a way of identifying the chinks in the tumour cell armour.**

Cancer arises when the right combination of genes is mutated in a susceptible cell, much like lock tumblers falling into place. These mutations bestow various properties of malignancy upon the cell, such as independence from growth control and the ability to colonize other tissues. The fact that such cells contain multiple gene mutations tends to be viewed as problematic by developers of anticancer treatments — the typical thinking goes that each mutation is beneficial to the cancer cell and makes it hardier. But the mutations probably come at a cost to the cell with respect to its ability to respond to certain situations. Unfortunately, we cannot yet predict how cancer-associated mutations might make a cell vulnerable, and there have been no unbiased methods for systematically discovering these weaknesses. On page 106 of this issue, however, Louis Staudt and colleagues[1] describe an approach for identifying genes that become essential for the survival of cancer cells.

The idea that the deleterious consequences of a particular mutation might be revealed only under specific conditions is an old one. Not surprisingly, it has been most extensively explored in organisms such as yeast and fruitflies, in which the genome can be manipulated easily and the consequent changes seen rapidly. Such investigations uncovered a gene–gene interaction, called 'synthetic lethality', that has potential significance for cancer drug discovery. Two genes (*A* and *B*, say) are said to be synthetically lethal if the cell containing them dies when both genes are mutated, but it can survive if either gene alone is mutated. In