X-rays from highly magnetic neutron stars reveal strange "photon metamorphosis" phenomenon associated with quantum electrodynamics

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– Background:

Neutron stars (NSs) are the extreme remnants of massive stars. They typically have the mass comparable to that of the Sun, but radius of about 10 km. Magnetars are special types of NSs endowed with superstrong magnetic fields, with field strength of 10^{14} Gauss or more (that is 100 trillion times more than Earth's surface magnetic field). The energy output of a magnetar is dominated by the dissipation of such a super-strong magnetic field. The surface of a magnetar is hot (a few million degree Kelvin) and emits X-rays. Because of the strong magnetic field, these X-rays are expected to be highly polarized, i.e., the electric field of the X-ray radiation has a preferred direction rather than being random.

Recently the NASA/ASI Imaging X-ray Polarimetry Explorer (IXPE) reported the detection of linearly polarized x-ray emission from a magnetar called AXP 4U 0142+61. This is the first time that polarized x-rays have been detected from any astrophysical point sources.
Interestingly, the observation shows that there is a substantial variation of the polarization signal with the photon energy. In particular, the polarization (electric field) direction changes (or swings) by 90 degrees from low energy (2-4 keV) to high energy (5.5-8 keV). This is very puzzling.

– What is the paper about?

We show that this 90-degree swing can be explained by photon polarization conversion ("photon metamorphosis") at the so-called vacuum resonance in the magnetar's thin atmosphere, which consists of hot, magnetized gas (also called "plasma"). The resonance arises from the combined effects of plasma-induced birefringence and QED-induced vacuum birefringence in strong magnetic fields. ("Birefringence" is a general term that refers to the optical property of a material where the light travel speed depends on the polarization and propagation direction; many mineral crystals are birefringent.)

– In a bit more technical detail:

Quantum electrodynamics (QED) governs the microscopic interactions between electrons and photons, and is one of the most successful physics theory ever developed. Although a photon (which has no charge) does not directly interact with the magnetic field of the magnetar, it can temporarily convert into a pairs of "virtual" electron and positron, and therefore becomes

affected by the magnetic field, even in vacuum. This is the "vacuum birefringence". When a photon propagates in the atmosphere plasma, it also experiences "plasma birefringence" since the photon affects the electrons in the plasma and the electron's motion is influenced by the magnetar's magnetic field. It turns out that the "vacuum birefringence" and "plasma birefringence" operate in an orthogonal way, such that at the vacuum resonance, the two effects cancel each other. As a result, when a linearly polarized photon travels across the resonance, its direction of linear polarization can change by 90 degree. This photon polarization conversion/metamorphosis lies at the heart of the X-ray polarization swing observed from AXP 4U 0142+61.

Very recently, IXPE observed polarized X-rays from from another magnetar, AXP 1RXS J170849.0-400910. This magnetar does not show the 90° polarization swing. In this case, because the magnetar's magnetic field is stronger (larger than 5×10^{14} G), the polarization conversion at vacuum resonance takes place very deep in the neutron star atmosphere, and therefore the emitted X-rays do not exhibit the 90-degree swing.

– Why is it important?

The photon polarization conversion at the vacuum resonance provides a natural explanation of the 90-degree polarization swing observed in AXP 4U 0142+61. It demonstrates a beautiful QED effect ("vacuum birefringence") which has never been directly observed. It also puts useful constraints on the magnetar properties. The calculation reported in the PNAS paper suggests that the atmosphere of AXP 4U 0142 be composed of partially ionized heavy elements, and the surface magnetic field be comparable or less than 10^{14} G, consistent with other indirect constraint. It also implies that the rotation axis of AXP 4U 0142+61 is aligned with its velocity direction – This has very interesting implications for the formation of the neutron star.

More generally, the photon polarization conversion phenomenon has many analogies in other areas of sciences. For example, it is is analogous to the Mikheyev-Smirnov-Wolfenstein neutrino oscillation that takes place in the Sun, the Landau-Zener transition in atomic physics, and electromagnetic wave propagation in inhomogeneous media and metamaterials.

– Future perspectives

Overall, our work demonstrates the important role played by the vacuum resonance in producing the observed X-ray polarization signature from magnetars, as well as NSs with weaker magnetic fields. The observations of AXP 4U 0142 and 1RXS J170849.0-400910 by IXPE have now opened up a new window in studying the surface environment of NSs. Future X-ray polarization mission, such as eXTP, will provide more detailed observational data. Comprehensive theoretical modelings of magnetic NS surface radiation and magnetosphere emission will be needed to confront these observations – these will lead to new insight into these enigmatic objects.