



PRESS RELEASE



International Center for
Quantum-field Measurement Systems for
Studies of the Universe and Particles
WPI research center at KEK



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To the Media

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International Center for Quantum-field Measurement Systems for Studies of the Universe and Particle
(WPI-QUP/KEK)
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Beyond Qubits: Diamond Quantum Sensors Could Sharpen the Search for Dark Matter

Executive Summary

● Question

The nature of invisible dark matter, constituting most of the matter in the Universe, remains one of the deepest mysteries in science. Quantum sensors, such as those based on nitrogen-vacancy (NV) centers in diamond, are emerging as powerful tools for detecting weak signals from ultralight dark matter like axions. However, existing strategies have not fully exploited the potential of diamond NV centers for fundamental physics.

● Findings

The study demonstrates that the unique quantum properties of diamond NV centers can significantly improve sensing precision over conventional strategies in a realistic, noise-affected setting. In addition, a method that enhances response to dark matter induced signals with suppression of common environmental disturbances. Applied to axion dark matter searches, the approach can improve projected sensitivity to the axion-electron interaction by up to an order of magnitude relative to leading proposals.

● Meaning

This work translates general principles of multilevel quantum metrology into a concrete powerful strategy for dark matter and fundamental physics searches. The method established in this work has broad potential applications beyond dark matter searches. It opens a promising direction for detecting exceptionally weak fundamental signals with higher dimensional quantum sensors.

Overview

Quantum sensors are emerging as powerful tools for detecting dark matter, whose nature remains unknown. In particular, diamond quantum sensors based on nitrogen-vacancy (NV) centers in diamond are considered a promising tool for detecting weak signals generated by light dark matter candidates such as axions. However, previous detection methods have not fully exploited the quantum-mechanical properties of NV centers.

In this study, it was shown that three-level qutrit systems realized in diamond NV centers can achieve higher measurement precision than conventional approaches. When applied to axion dark matter searches, this method can improve measurement precision and may enhance the sensitivity to axion–electron interactions by up to a factor of ten.

This work opens a new door for exploring extremely weak signals in fundamental physics using high-dimensional quantum sensors.

This study was published as a Letter in Physical Review A in June 2026.

Background

Despite its fundamental importance, holding together galaxies including our own Milky Way, and decades of intensive experimental efforts, the underlying nature of dark matter remains one of the greatest open mysteries in science. Among compelling dark matter candidates are ultralight particles such as axions, whose masses can be many orders of magnitude lighter than the mass of an electron. These particles are predicted to behave as a wave-like state. Because of this, precision measurement devices may be able to detect the extremely weak oscillating signals induced by axions on spins.

Recent advances in quantum technologies have enabled quantum sensors to emerge as a powerful approach to detecting such extraordinarily weak signals in laboratories. Among them, diamond quantum sensors based on electron spins in diamond can detect tiny magnetic fields and spin variations with high sensitivity. These sensors exploit the quantum-mechanical properties of a special defect in the diamond crystal known as a

nitrogen-vacancy (NV) center. Their three quantum states can form “qutrits”. Despite their richer internal structure, NV centers in fundamental physics searches have so far primarily exploited only the two-level qubits, leaving untapped quantum dimensions. Although the general metrological advantage potential of multilevel quantum systems is known, realizing it in practical sensors requires protocols that preserve the gain in the presence of noise and decoherence.

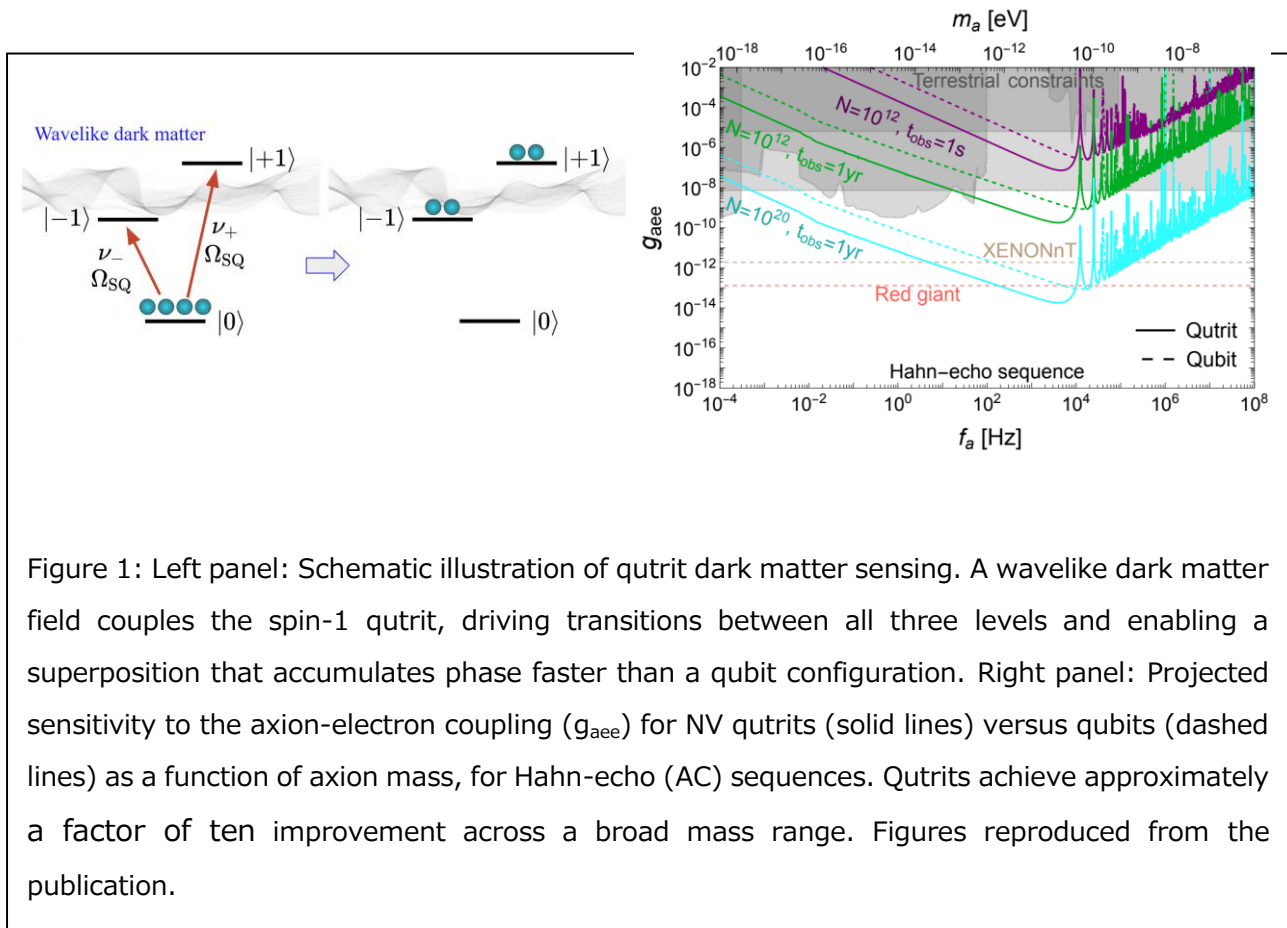
Findings

In the new interdisciplinary work, theoretical and experimental physicists from WPI-QUP/KEK and Kyoto University combined expertise in high energy physics and quantum sensing to show how the full three-level structure of NV diamond centers can improve searches for ultralight dark matter.

The team demonstrated that a NV-center qutrit can achieve this by using a superposition of the two quantum states separated by the largest energy difference. This approach doubles the accumulation rate of changes in the quantum state induced by weak external signals compared with a qubit configuration, corresponding in the ideal limit to a fourfold increase in quantum Fisher information, a measure of how sensitively a quantum state responds to small external changes and a factor-of-two improvement in amplitude sensitivity. In addition, the double-quantum sensing configuration, which compares a pair of quantum states within the qutrit suppresses common-mode noise, such as temperature and electric field fluctuations, enabling further performance gains.

The researchers derived explicit optimal quantum protocols and showed that they can reach the quantum precision bound. Applied to axion dark matter search, the qutrit setup enables improving the projected sensitivity to the axion electron interactions by up to a factor of ten relative to earlier qubit-based NV proposals (see Figure 1).

“Our work highlights the largely untapped



potential of multilevel quantum systems for basic science. Quantum properties can offer new ways to detect extraordinarily weak signals, and I expect these ideas to open broader directions beyond dark matter. We have only begun to explore what quantum sensors can reveal about nature’s underlying laws,” said Volodymyr Takhistov, a principal investigator and associate professor at WPI-QUP/KEK.

Future Prospects

The findings establish a broadly applicable framework for using multilevel quantum sensing in searches for fundamental physics. Since the underlying principle is not specific to diamond, similar strategies could be applied to other multilevel quantum platforms. This positions higher-dimensional quantum systems as a new frontier for

precision tests of fundamental physics across a wide range of experimental implementations.

Research group

This project was conceived and led by Volodymyr Takhistov, a principal investigator and associate professor at the International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles (WPI-QUP) at the High Energy Accelerator Research Organization (KEK) and affiliated member of the Theory Center, Institute of Particle and Nuclear Studies (IPNS), KEK, and a visiting scientist at the Kavli Institute for the Physics and Mathematics of the Universe, The University of Tokyo. Xiaolin Ma, a postdoctoral researcher at QUP, carried out the primary quantitative sensitivity analysis. Ernst David Herbschleb, a principal investigator and associate professor at QUP, contributed to the calculations. Herbschleb and Norikazu Mizuochi, a professor at the Institute for Chemical Research and the Center for Spintronics Research Network at Kyoto University, provided key expertise in the experimental implementation of diamond NV-center sensing.

About the Research Project

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