Bound States in the Continuum for Tunable High-Q PZT Resonators in Axion Dark Matter Detection

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ABSTRACT

Axion dark matter detection through the piezoaxionic effect exploits the coupling between axion fields and piezoelectric crystals with aligned nuclear spins, where axion-induced stress excites bulk acoustic modes (BAMs). The detection sensitivity of such experiments is strongly dependent on the quality factor (Q) of the resonator, while efficient scanning requires tunability across a wide frequency range corresponding to the axion mass window (10^{-11}–10^{-7} eV). Conventional strategies, which involve arrays of high-Q resonators, are limited in scalability and practicality. In this work, we propose a new approach based on bound states in the continuum (BICs) in coupled centimeter-scale lead zirconate titanate (PZT) resonators. We show how BIC-induced suppression of radiative losses can enhance the Q-factor by an order of magnitude and, at the same time, enable frequency tuning via passive capacitive and inductive components. This dual advantage makes BIC-enabled PZT resonators a promising platform for high-sensitivity, broadband axion dark matter searches.

Keywords: PZT, Axion, Dark matter.

1. INTRODUCTION

The existence of dark matter (DM) remains one of the most compelling open questions in modern physics. Axions, originally proposed to resolve the strong CP problem in quantum chromodynamics, are now among the leading candidates for DM. Direct detection strategies often rely on resonant enhancement of axion-induced effects. The axion is a hypothetical particle proposed in the late 1970s that could explain both dark matter, which makes up about 26% of the universe, and the symmetry puzzle of the strong force. Recent work suggests that anomalies in gravitational lenses fit better if dark matter is made of axions rather than WIMPs [1]. Experiments like DarkSide in Italy, buried 1,400 meters underground with liquid argon and ultrapure water shielding, aim to directly detect dark matter [2]. At CERN, the CAST experiment—originally built to track solar axions—has been adapted with a resonator to search for axions in the Milky Way's dark matter halo [3]. In strong magnetic fields, axions could convert into photons with frequencies between 4.774 and 5.434 GHz, corresponding to masses of 19.74–22.47 μeV. The team scanned this 660 MHz band in 200 kHz steps, while other studies now explore even lower frequencies, down to 100–600 MHz [4]. The piezoaxionic effect [5] provides a promising route to axion detection. In piezoelectric crystals with aligned nuclear spins, axion fields induce an oscillatory stress when the axion frequency matches a crystal's bulk acoustic mode (BAM). This stress excites mechanical vibrations that can be transduced into electrical signals through piezoelectric coupling [6]. We base our experience on previous work relative to piezoelectric materials, when we studied their behaviour and performances [7-9].

The sensitivity of such experiments depends critically on two factors:

- High quality factor (Q): to maximize the signal-to-noise ratio.
- Broad frequency tunability: to scan the axion mass range, typically corresponding to frequencies from kilo Hertz up to hundreds of Mega Hertz.

Traditional resonator arrays meet these requirements only partially, as switching among multiple high-Q devices is technically complex and time-consuming. We propose an alternative strategy: implementing bound states in the continuum (BICs) in coupled PZT resonators, which simultaneously yield ultra-high-Q and tunability.

2. THEORETICAL FRAMEWORK

2.1. Axion-induced stress in piezoelectric crystals

The axion field *a(t)* couples to nuclear spins and manifests as an effective oscillatory force density in piezoelectric media. Following [1], the induced stress can be written as:

$$\sigma_{ij}(t) \propto g_{qNN} < S_N > a_0 \cos{(\omega_a t)} \qquad \text{(Equation 1)}$$

where:

- g_{aNN} is the axion-nucleon coupling constant,
- $< S_N >$ is the average nuclear spin polarization,
- a_0 is the local axion field amplitude,
- $\omega_a = m_a c^2/\hbar$ is the axion angular frequency.

When ω_a matches the resonance frequency of a bulk acoustic mode ω_r, the stress resonantly excites vibrations with amplitude enhanced by the quality factor Q:

$$A \propto \frac{1}{\sqrt{(\omega_a - \omega_r)^2 + \left(\frac{\omega_r}{Q}\right)^2}} \qquad \text{(Equation 2)}$$

Thus, maximizing Q directly boosts sensitivity to axion signals.

2.2. Bound states in the continuum (BICs)

Bound states in the continuum (BICs) arise when destructive interference prevents radiative losses in a resonant system, despite the resonance frequency lying within the radiation continuum. In mechanical and acoustic systems, BICs allow for the trapping of vibrational energy with minimal leakage, thereby boosting the effective Q-factor. Recent studies have demonstrated ultra-high-Q resonators based on BICs in the ultra-sound regime [6]. Translating this concept to the piezoaxionic context, we consider the coupling of two centi-metre-scale PZT resonators. By carefully tuning the geometric and boundary conditions, the coupled system supports quasi-BIC modes, where energy dissipation is strongly suppressed. The resulting Q-factors can exceed those of single resonators by an order of magnitude, a crucial advantage for weak signal detection.

In open systems, resonant modes typically couple to radiation channels, leading to energy leakage and finite Q. However, under specific symmetry or interference conditions, radiative losses cancel, yielding bound states in the continuum [3].

For two coupled piezoelectric resonators, the effective Hamiltonian can be written as:

$$H = \begin{pmatrix} \omega_1 - i\gamma & \kappa \\ \kappa & \omega_1 - i\gamma \end{pmatrix} \qquad \text{(Equation 3)}$$

where $\omega_{1,2}$ are the uncoupled resonance frequencies, γ represents intrinsic losses, and κ is the coupling coefficient.

At the BIC condition, destructive interference eliminates radiation leakage, yielding a mode with decay rate limited only by intrinsic losses:

$$Q_{BIC} \approx \frac{\omega}{2\gamma} \qquad \text{(Equation 4)}$$

This results in an order-of-magnitude increase in Q compared to single-resonator configurations. Concept of axion-induced stress is illustrated in Fig. 1.

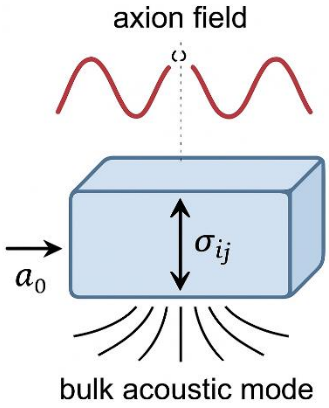

Fig. 1: Concept of axion-induced stress in a piezoelectric crystal.

3. PZT RESONATORS IN THE BIC REGIME

Lead zirconate titanate (PZT) is an excellent material for axion searches due to its:
- Strong piezoelectric coupling,
- Robust mechanical properties,
- Established fabrication scalability.

By coupling two centimeter-scale PZT resonators with controlled separation, we engineer quasi-BIC modes. Figure 1 (conceptual) illustrates the setup, where symmetric and antisymmetric hybridization of BAMs leads to destructive interference in the radiation continuum.

Additionally, BIC-enabled PZT resonators are compatible with electrical frequency tuning. Adding passive inductive (L) and capacitive (C) loads modifies the effective resonance:

$$\omega_{eff} = \frac{1}{\sqrt{L(C_0+C)}} \qquad \text{(Equation 5)}$$

where C_0 is the intrinsic capacitance of the resonator. This allows scanning across wide frequency bands without switching between separate devices. The concept of two coupled PZT resonators is given in Fig. 2. The Quality factor enhancement due to BICs is schematized on fig. 3. Frequency tunability via passive LC is illustrated on Fig. 4.

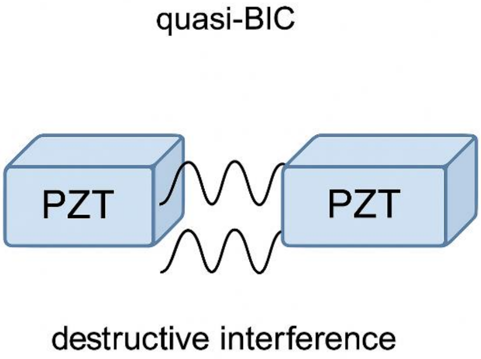

Fig. 2: Two coupled PZT resonators forming a quasi-BIC.

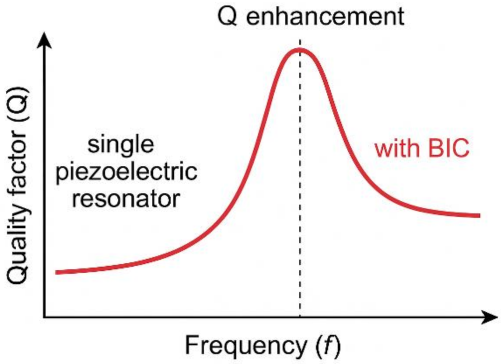

Fig. 3: Quality factor enhancement due to BICs (plot).

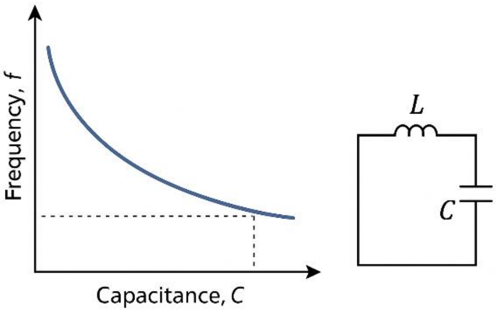

Fig. 4: Frequency tunability via passive LC components (plot/schematic).

4. EXPERIMENTAL CONSIDERATIONS

Resonator dimensions: centimeter-scale thickness to match MHz–hundreds of MHz frequency ranges.

- Coupling control: mechanical spacing or acoustic boundary conditions tuned for optimal destructive interference.
- Readout: high-sensitivity low-noise amplifiers coupled to the piezoelectric electrodes.
- Environmental stability: temperature and vibration isolation essential to preserve Q.

This experimental platform integrates seamlessly with existing piezoaxionic setups [2] while substantially improving performance.

5. IMPLICATIONS FOR AXION DARK MATTER DETECTION

The combination of high-Q operation and tunability makes BIC-enabled PZT resonators uniquely suited to axion DM detection experiments. The improved sensitivity increases the likelihood of observing axion-induced stresses, while the broad tunability expands the accessible mass window. Furthermore, PZT offers robust material properties, strong piezoelectric coupling, and established fabrication techniques, reinforcing its role as an optimal platform for piezoaxionic research. By leveraging concepts from acoustic metamaterials and quantum sensing, this approach represents a promising step toward scalable, high-performance detectors that can probe deeper into unexplored axion parameter space.

The proposed BIC-enabled PZT resonators address two central challenges:

1) Enhanced Q-factor: boosts signal-to-noise by suppressing radiative losses.
2) Broadband tunability: enables efficient scanning across the axion mass window.

Together, these advances enhance the reach of piezoaxionic searches, potentially probing unexplored regions of the axion parameter space.

Future developments will focus on experimental realization, Q-factor benchmarking, and integration with spin-polarized PZT crystals. We also could estimate uncertainties based on our knowledge and using modern methods [10-15].

5. CONCLUSION

We have presented a comprehensive strategy for improving axion dark matter detection sensitivity by exploiting the physics of bound states in the continuum (BICs) in piezoelectric resonators. Lead zirconate titanate (PZT), already known for its strong piezoelectric coupling, provides an optimal platform for this approach. By coupling centimetre-scale resonators under BIC conditions, one can achieve order-of-magnitude enhancements in quality factor, crucial for detecting the faint signals expected from axion interactions. At the same time, the use of passive electrical tuning elements ensures broad frequency coverage without requiring complex arrays of resonators. This dual capability—high-Q operation combined with tunability—represents a decisive step forward compared to conventional strategies. Beyond axion dark matter searches, the principles developed here may also find applications in other areas of precision measurement, quantum sensing, and fundamental physics experiments where ultra-high-Q and tunability are simultaneously required. In summary, BIC-enabled PZT resonators open a promising pathway toward next-generation piezoaxionic detectors, capable of probing wider mass ranges with higher sensitivity, and thus advancing the quest for unveiling the nature of dark matter.

REFERENCES

[1] Alfred Amruth et al., "Einstein rings modulated by wavelike dark matter from anomalies in gravitationally lensed images," Nature Astronomy, 7, 736–747 (2023). https://doi.org/10.1038/s41550-023-01943-9.

[2] P. Agnes et al. (DarkSide Collaboration), "Low-Mass Dark Matter Search with the DarkSide-50 Experiment," Phys. Rev. Lett. 121, 081307 (2023). https://doi.org/10.1103/PhysRevLett.121.081307.

[3] Adair, C.M., Altenmüller, K., Anastassopoulos, V. et al. Search for Dark Matter Axions with CAST-CAPP. Nat Commun 13, 6180 (2022). https://doi.org/10.1038/s41467-022-33913-6.

[4] Chakrabarty S. et al, "Low frequency, 100–600 MHz, searches with axion cavity haloscopes," Phys. Rev. D 109, 042004 (2024). http://dx.doi.org/10.1103/PhysRevD.109.042004.

[5] A. Arvanitaki, A. Madden, K. Van Tilburg, The Piezoaxionic Effect, Phys. Rev. D 109, 072009 (2024). http://dx.doi.org/10.1103/PhysRevD.109.072009.

[6] P. Salzenstein, M. Addouche, F. Lefebvre, "Preliminary study of the influence of the parameters of the piezoelectric element on the possible piezoaxionic effect," Proc. SPIE 13241, Optical Metrology and Inspection for Industrial Applications XI, 132411X (2024). http://dx.doi.org/10.1117/12.3036695.

[7] Brendel R., Addouche M., Salzenstein P., Rubiola E., Shmaliy Y., "Drive Level Dependence in Quartz Crystal Resonators at Low Drive Levels: A Review," IEE Conf. Pub. 2004, 11, 11-18 (2004) http://dx.doi.org/10.1049/cp:20040809.

[8] Salzenstein P., Kuna A., Sojdr L. and Chauvin J., "Significant step in ultra high stability quartz crystal oscillators," Electronics Letters 46(21), 1433–1434, (2010). http://dx.doi.org/10.1049/el.2010.1828.

[9] Salzenstein P., Cholley N., Kuna A., Abbé P., Lardet-Vieudrin F., Sojdr L. and Chauvin J., "Distributed amplified ultra-stable signal quartz oscillator based," Measurement 45(7), 1937–1939 (2012). https://doi.org/10.1016/j.measurement.2012.03.035.

[10] M. Farhat, Y. Achaoui, J. A. I. Martínez, M. Addouche, Y. Wu, A. Khelif, "Observation of Ultra-High-Q Resonators in the Ultrasound via Bound States in the Continuum," Adv. Sci. 2024, 11, 2402917. http://dx.doi.org/10.1002/advs.202402917.

[11] Salzenstein P., Pavlyuchenko E., Hmima A., Cholley N., Zarubin M., Galliou S., Chembo Y.K., Larger L., " Estimation of the uncertainty for a phase noise optoelectronic metrology system," Physica Scripta T 149, 014025. http://dx.doi.org/10.1088/0031-8949/2012/T149/014025.

[12] Pavlyuchenko E., Salzenstein P., "Application of modern method of calculating uncertainty to microwaves and opto-electronics," Laser Optics 2014 International Conference, Saint Petersburg, Russia, 30 June–4 July 2014. https://doi.org/10.1109/LO.2014.6886449.

[13] Salzenstein P., Wu T.Y., "Uncertainty analysis for a phase-detector based phase noise measurement system," Measurement 85, 118–123 (2016). https://doi.org/10.1016/j.measurement.2016.02.026.

[14] Salzenstein P., Pavlyuchenko E., "Uncertainty Evaluation on a 10.52 GHz (5 dBm) Optoelectronic Oscillator Phase Noise Performance," Micromachines 12(5), 474 (2021). http://dx.doi.org/10.3390/mi12050474.

[15] Salzenstein P., Wu T. Y., "Uncertainty estimation for the Brillouin frequency shift measurement using a scanning tandem Fabry-Pérot interferometer," Micromachines 14(7), 1429 (2023). https://doi.org/10.3390/mi14071429.