Frequency-resolved Gravitational Wave Spectrometer: A Thought Experiment

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Abstract

In this note, the authors (guided by LLMs) propose a novel spectrometer that uses cavity QED to detect the spectrum of gravitational radiation emitted by black hole binaries.

This note outlines a theoretical framework for detecting and analyzing gravitational waves emitted by binary black holes (BHBs) [1] using a multi-mode photon cavity setup. The proposed system utilizes the interaction between gravitational waves and quantum systems to create a frequency-resolved spectrometer for gravitational waves.

Theoretical Background

Binary black holes emit gravitational waves across a spectrum of frequencies during inspiral, merger, and ringdown phases. These waves induce oscillations in spacetime, which can interact with quantum systems. A cavity with photons in standing wave modes can couple to specific frequencies of gravitational waves, creating a stationary state for the photons [2]. The spatial oscillation frequency of a photon mode in a cavity is determined by:

$$f_{photon} = n/(2L), \tag{1}$$

where n is the mode number and L is the cavity length. When

$$f_{GW} = f_{photon}, \tag{2}$$

the wave counteracts the photon's oscillatory behavior, creating a stationary photon ring at the cavity location radius.

Multi-Mode Photon Cavities as a Spectrometer

By placing cavities at a fixed radius (e.g., cavity location radius approximately100 km) around the BHB, each containing photons in multiple modes, a spectrum of stationary photon rings can form. Each mode resonates with a specific gravitational wave frequency:

$$f_{GW} = n/(2L). \tag{3}$$

Monitoring which photon modes become stationary provides a direct measurement of the gravitational wave frequencies emitted by the BHB. The spectrum of cavity modes acts as a filter to analyze the gravitational wave spectrum.

Challenges and Implications

Designing cavities to operate in extreme environments near the BHB, where tidal forces and radiation dominate is a monumental challenge.

Implications:

1. This framework demonstrates a novel coupling of quantum mechanics and general relativity.

2. The proposed system provides a frequency-resolved spectrometer for gravitational waves, complementing existing broadband detectors.

Conclusion

This thought experiment offers a conceptual pathway for leveraging quantum systems to probe the dynamics of spacetime and gravitational waves, bridging two foundational pillars of modern physics.

Acknowledgments

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References

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