

# Can Gravitational Waves Modulate Light Emitted From Atoms? Atomic Spectroscopy In Dynamical Curved Spacetime

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**Abstract:** *The interaction between gravitational waves (GWs) and electromagnetic radiation constitutes one of the most subtle and profound predictions of relativistic physics. Since the historic detection of gravitational waves by the LIGO Scientific Collaboration in 2015 through the merger of binary black holes [1], the question naturally arises whether spacetime oscillations can influence microscopic quantum systems such as atoms and their emitted light. This paper investigates the theoretical possibility that gravitational waves modulate atomic emission spectra through perturbations of spacetime geometry, phase shifts in electromagnetic propagation, and induced variations in quantum transition frequencies. We examine how weak metric perturbations alter the propagation of photons emitted from atoms, leading to minute but potentially observable modulations in spectral lines, polarization states, and coherence properties. By combining general relativity, quantum electrodynamics, and atomic spectroscopy, we derive modulation equations governing photon frequency shifts in the presence of a passing GW background. Potential observational avenues involving interferometry, ultra-stable optical clocks, pulsar timing arrays, and cavity quantum electrodynamics are discussed. The study suggests that gravitational-wave-induced optical modulation may ultimately provide a bridge between quantum systems and dynamical spacetime geometry.*

**Keywords:** *Gravitational waves; atomic emission; spacetime perturbations; quantum optics; spectral modulation; photon phase shift; interferometry; curved spacetime electrodynamics; optical clocks; quantum gravity,*

## I. INTRODUCTION

The twentieth century witnessed two towering revolutions in physics: quantum mechanics and general relativity.[1,2,9] The former governs the microscopic behaviour of atoms and radiation, whereas the latter describes spacetime and gravitation. Their conceptual coexistence has often appeared uneasy, particularly in regimes involving strong gravitational curvature and quantum coherence [4,9].like two sovereign empires sharing a turbulent frontier. Yet nature itself may quietly reveal their hidden correspondence.

Gravitational waves, predicted by Albert Einstein in 1916 [2], are propagating perturbations of spacetime curvature generated by accelerating masses. Their detection from compact binary mergers opened a fresh observational window onto the universe [1]. These waves stretch and compress spacetime transversely as they pass through matter, an effect experimentally verified by kilometre-scale interferometers

[1,3]. Since atoms themselves inhabit spacetime, their internal dynamics cannot remain entirely immune to such distortions.

Atomic light emission arises from transitions between quantized electronic states governed by quantum electrodynamics and relativistic atomic theory [4].The emitted photon frequency is determined by

$$\nu = \frac{E_i - E_f}{h},$$

where  $E_i$  and  $E_f$  are the initial and final atomic energy levels. A perturbation of spacetime geometry can, in principle, alter these levels or modify photon propagation after emission.

The central question is therefore compelling:

*Can gravitational waves modulate light emitted from atoms?*

The answer appears to be yes — although extraordinarily weakly under ordinary astrophysical conditions.

## II. GRAVITATIONAL WAVES AS METRIC PERTURBATIONS

In linearized general relativity, weak-field spacetime distortions are represented through perturbative metric expansions [2,9], the spacetime metric may be written as

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu},$$

where  $\eta_{\mu\nu}$  is the Minkowski metric and  $h_{\mu\nu} \ll 1$  represents the GW perturbation.

For a plane gravitational wave traveling along the  $z$ -axis:

$$h_{\mu\nu}(t, z) = A_{\mu\nu} \cos(kz - \omega t).$$

The amplitude  $h$  detected on Earth from astrophysical events is typically

$$h \sim 10^{-21}.$$

This implies spacetime distortions smaller than a proton diameter across kilometre baselines. Yet interferometers such as Virgo Collaboration and LIGO can detect them with astonishing precision through laser interferometric phase measurements [1, 3].

A passing GW modifies proper distances:

$$ds^2 = -c^2 dt^2 + (1 + h_+) dx^2 + (1 - h_+) dy^2 + dz^2.$$

Hence the electromagnetic phase accumulated by photons traversing spacetime becomes perturbed.

## III. ATOMIC EMISSION IN CURVED SPACETIME

Atomic Hamiltonians depend implicitly on spacetime geometry through covariant couplings between quantum fields and gravitational curvature [4]. In curved spacetime, the Dirac equation becomes

$$(i\gamma^\mu D_\mu - m)\psi = 0,$$

where  $D_\mu$  denotes the covariant derivative incorporating gravitational effects [4].

The energy shift induced by a weak GW perturbation may be approximated as

$$\delta E_n \sim \langle n | H_{GW} | n \rangle.$$

Consequently, transition frequencies become time dependent:

$$\nu(t) = \nu_0 + \delta\nu \cos(\omega_{GW} t).$$

This is frequency modulation induced directly by spacetime oscillation.

The modulation depth is extremely tiny under ordinary astrophysical conditions, though ultra-coherent optical systems may eventually probe such effects [5]

$$\frac{\delta\nu}{\nu_0} \sim h.$$

For optical frequencies near  $10^{15}$  Hz, the expected modulation is of order

$$\delta\nu \sim 10^{-6} \text{ Hz},$$

far below ordinary laboratory linewidths but potentially detectable with future ultra-coherent systems.

## IV. PHASE MODULATION OF EMITTED LIGHT

Even if atomic energy levels remain nearly unchanged, emitted photons propagate through oscillating spacetime.

The electromagnetic phase is

$$\Phi = \int k_\mu dx^\mu.$$

A GW perturbs this phase:

$$\delta\Phi \propto h \sin(\omega_{GW} t).$$

This produces sideband frequencies:

$$\nu_{\pm} = \nu_0 \pm \omega_{GW}.$$

The phenomenon resembles classical frequency modulation in radio transmission., although here the modulation originates from spacetime geometry itself rather than electromagnetic circuitry [3,9].

The optical field may thus be written as

$$E(t) = E_0 e^{i[\omega_0 t + \beta \sin(\omega_{GW} t)]},$$

where  $\beta$  is the GW modulation index.

This predicts tiny spectral sidebands surrounding atomic emission lines.

## V. RESONANT ENHANCEMENT EFFECTS

Under special conditions, resonance may amplify the interaction.

If

$$\omega_{GW} \approx \omega_{\text{transition}},$$

the atomic response can become enhanced through parametric coupling.

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Such resonances might occur in highly coherent quantum systems including Rydberg atoms, superconducting qubits, Bose–Einstein condensates, and cavity-QED platforms [4,5]

- Rydberg atoms,
- superconducting qubits,
- Bose–Einstein condensates,
- cavity QED systems.

The modulation Hamiltonian may take the form

$$H_{\text{int}} = \lambda h(t) \hat{O},$$

where  $\hat{O}$  is an atomic observable coupled to spacetime strain.

Quantum coherence effects may accumulate over long durations, enhancing detectability.

## VI. OPTICAL CAVITIES AND LASER INTERFEROMETERS

Laser interferometers effectively exploit GW-induced phase modulation.

In a Fabry–Pérot cavity, the optical phase shift is

$$\delta\phi = \frac{2\pi L}{\lambda} h.$$

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For kilometre-scale interferometers:

- ✓  $L \sim 4 \text{ km}$ ,
- ✓  $\lambda \sim 10^{-6} \text{ m}$ .

the phase shift becomes measurable despite tiny  $h$ .

This principle underlies modern GW detection itself and forms the operational basis of LIGO and Virgo interferometry [1,3]

Thus one may say:

Gravitational waves already modulate light routinely inside interferometric detectors.

The unresolved frontier concerns direct modulation of light *emitted by atoms themselves*.

## VII. ATOMIC CLOCKS AS GW SENSORS

Modern optical lattice clocks achieve fractional precision approaching  $10^{-18}$ , representing one of the greatest triumphs

of precision metrology [5].

$10^{-18}$ .

National Institute of Standards and Technology and other institutions are approaching sensitivities where spacetime oscillations may become observable [5].

A GW passing between separated clocks induces relative timing shifts:

$$\frac{\delta t}{t} \sim h.$$

Networks of synchronized atomic clocks may therefore function as distributed galactic-scale gravitational-wave detectors [5]

The concept merges:

- ✓ spectroscopy,
- ✓ relativity,
- ✓ quantum metrology,
- ✓ cosmology.

It represents one of the most elegant syntheses in modern physics.

## VIII. QUANTUM VACUUM AND PHOTON CREATION

A more exotic possibility involves GW-driven vacuum modulation.

In curved spacetime, vacuum fluctuations are dynamical rather than static leading to particle-production phenomena in strong gravitational backgrounds [6,10]. A sufficiently intense GW background could perturb virtual photon populations:

$$\square A^\mu + R^\mu_\nu A^\nu = 0.$$

Strong spacetime curvature might therefore generate photon amplification or squeezing effects.

This connects naturally Hawking radiation, cosmological particle creation, the Unruh effect, and the dynamical Casimir phenomenon [6,10].

to:

- ✓ the dynamical Casimir effect,
- ✓ Hawking radiation,
- ✓ Unruh radiation,
- ✓ cosmological particle creation.

Although astrophysical GWs are too weak for dramatic vacuum excitation, primordial or early-universe gravitational waves may have played a role in shaping cosmic electromagnetic backgrounds.

## IX. OBSERVATIONAL PROSPECTS

Potential experimental avenues include:

### A. SPECTRAL SIDEBAND SEARCHES

High-resolution spectroscopy may reveal periodic line splitting induced by GW modulation.

### B. PULSAR TIMING ARRAYS

Pulsars behave as extraordinarily stable cosmic clocks whose timing residuals can reveal long-wavelength gravitational-wave backgrounds [7]. GWs modulate arrival phases of radio photons across interstellar distances [7].

### C. SPACE-BASED INTERFEROMETERS

The future European Space Agency mission LISA is expected to probe low-frequency gravitational-wave effects inaccessible to terrestrial interferometers [8]. Laser Interferometer Space Antenna may probe low-frequency GW effects on coherent laser beams [8].

### D. QUANTUM SENSORS

Entangled photon systems and squeezed-light interferometers may amplify GW-induced optical signatures.

## X. IMPLICATIONS FOR QUANTUM GRAVITY

The modulation of atomic light by gravitational waves carries immense conceptual significance.

It implies:

- ✓ Quantum transitions are sensitive to spacetime dynamics.
- ✓ Photons preserve geometric memory of curved spacetime.
- ✓ Atomic systems may become microscopic probes of gravity.

The phenomenon may eventually contribute toward reconciling quantum mechanics and gravitation by probing how quantum systems interact with dynamical spacetime curvature [4,9].

Indeed, the interaction suggests that spacetime is not merely a passive arena but an active participant in quantum processes.

## XI. CONCLUSION

Gravitational waves can, in principle, modulate light emitted from atoms through several intertwined mechanisms:

- ✓ perturbation of atomic energy levels,
- ✓ phase modulation during photon propagation,
- ✓ coherence alterations,
- ✓ resonant quantum coupling,
- ✓ spacetime-induced timing fluctuations.

Although the predicted effects are minute under presently accessible astrophysical conditions, advances in interferometry, optical metrology, and quantum sensing continue steadily to improve observational prospects [1,3,5].

The broader implication is philosophically striking and resonates with modern attempts to unify quantum theory, gravitation, and information physics [4,6,9]. Atoms — the quintessential quantum systems — may subtly vibrate to the rhythm of spacetime itself. The emitted photon becomes not merely a quantum messenger but a geometric witness to spacetime undulations generated by gravitational dynamics [2,9].

In this vision, light emitted from atoms does not travel through spacetime alone; it carries the trembling signature of spacetime within it.

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