

Fröhlich Condensates Meet 6G: Can Wireless Carriers Couple to Protein Collective Modes?

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Abstract

Between 2015 and 2022, several experiments reported nonequilibrium collective vibrational behavior in proteins consistent with Fröhlich’s long-discussed phonon condensation hypothesis. These studies identified prominent spectral features at 0.071, 0.096, and 0.314 THz. In parallel, wireless research toward 6G increasingly explores carrier frequencies above 100 GHz, with candidate bands approaching 0.1–0.3 THz. This frequency proximity has motivated speculation about possible biological relevance. However, frequency overlap alone is insufficient—meaningful interaction requires adequate coupling strength under realistic exposure conditions. This paper (i) summarizes the relevant experimental findings, (ii) clarifies the current state of 6G frequency proposals, (iii) provides an order-of-magnitude estimate suggesting that direct far-field coupling at guideline-level exposures is likely negligible, and (iv) proposes a concrete experimental program to definitively test whether realistic sub-THz fields can modulate reported protein collective modes. Whether the outcome is null or positive, such measurements would reduce uncertainty as sub-THz technologies mature.

Keywords: Fröhlich condensation; protein collective modes; terahertz; sub-THz; 6G; dosimetry; biological effects

1. Introduction

In 1968, Herbert Fröhlich proposed that biological systems driven sufficiently far from thermal equilibrium could concentrate vibrational energy into collective modes, producing coherent behavior despite room-temperature thermal noise [1,2]. The hypothesis remained controversial for decades. Reimers et al. (2009) provided an influential critique, analyzing conditions under which such condensation would be weak or absent [3]. The concept was widely regarded as theoretically interesting but experimentally unsubstantiated.

Since 2015, several experimental studies have reported observations in protein systems interpreted as consistent with Fröhlich-like collective behavior, including threshold-dependent signatures and narrow spectral features in the 0.07–0.10 THz and \sim 0.3 THz ranges [4–6]. More recently, Preto et al. (2025) demonstrated

theoretically that Fröhlich condensation can emerge at room temperature from classical Hamiltonians, directly addressing the earlier criticisms of Reimers et al. [7]. These findings remain an active research topic; their interpretation and generality—particularly in vivo—are not settled. Nonetheless, they motivate a precise question: **can externally applied sub-THz electromagnetic fields, at intensities relevant to real-world technology, measurably modulate these reported collective modes?**

Separately, wireless research toward 6G and beyond increasingly explores operation above 100 GHz, driven by bandwidth demands and advances in device technology [8,9]. While regulatory allocations and deployment parameters remain unsettled, carriers in the $\sim 100\text{--}300+$ GHz range feature prominently in roadmaps and prototypes.

This paper documents the frequency proximity between these two domains, emphasizes the necessity of quantitative coupling estimates rather than mere frequency coincidence, and proposes experiments that could resolve the question definitively.

2. Experimental Reports of Nonequilibrium Collective Modes in Proteins

This section summarizes what the cited papers report, distinguishing between observed signatures and broader mechanistic interpretations.

2.1 Lundholm et al. (2015): Lysozyme Crystals

Lundholm et al. exposed lysozyme crystals to terahertz radiation and reported structural changes they interpreted as not fully attributable to bulk thermal heating [4]. Lysozyme is ubiquitous in human biology, present in tears, saliva, and mucus. However, protein crystals are highly ordered systems with boundary conditions differing from proteins in aqueous solution or tissue. The study demonstrates that THz fields can influence protein crystal structure under controlled conditions; it does not establish in vivo Fröhlich condensation.

2.2 Nardecchia et al. (2018): BSA and a ~ 0.314 THz Feature

Nardecchia et al. investigated bovine serum albumin (BSA) driven out of equilibrium and reported a pronounced spectral feature near **0.314 THz (314 GHz)** with threshold-like dependence on applied drive [5]. They interpreted this as consistent with phonon condensation in a Fröhlich-like scenario.

The key observation for the present discussion: a narrow sub-THz feature emerged in a driven nonequilibrium protein system above a threshold. Whether weak external far-field radiation at 314 GHz can meaningfully drive or modulate that feature is an open, testable question.

2.3 Lechelon et al. (2022): R-Phycoerythrin

Lechelon et al. studied R-phycoerythrin, a natural light-harvesting protein, and reported observations interpreted as evidence for long-range electrodynamic in-

termolecular forces [6]. Prominent frequencies appeared near **0.071 THz (71 GHz)** and **0.096 THz (96 GHz)** under driven conditions. Above threshold, proteins clustered; below threshold, clusters disaggregated. The frequency shift scaled as $1/r^3$, consistent with dipole-dipole theory.

Claims of long-range forces in solution are extraordinary and warrant careful consideration of controls and alternative mechanisms. The conservative interpretation: some protein systems exhibit narrow-band features in the 70–100 GHz region under nonequilibrium conditions.

2.4 Preto et al. (2025): Theoretical Validation

Preto et al. addressed the theoretical objections raised by Reimers et al. [7]. Using classical Hamiltonian dynamics, they demonstrated that Fröhlich condensation can emerge at room temperature given appropriate coupling between oscillators and an energy bath. This work rehabilitated Fröhlich’s mechanism theoretically, complementing the experimental demonstrations.

2.5 Summary

Two frequency regions emerge from this literature:

Study	System	Frequency	Key Observation
Lechelon et al. 2022	R-phycoerythrin	0.071 THz (71 GHz)	Resonant clustering; $1/r^3$ dipole forces
Lechelon et al. 2022	R-phycoerythrin	0.096 THz (96 GHz)	Resonant clustering; $1/r^3$ dipole forces
Nardecchia et al. 2018	BSA	0.314 THz (314 GHz)	Threshold-dependent absorption
Preto et al. 2025	Theoretical	—	Room-temperature condensation validated

Whether these frequencies have any relevance to telecommunications exposure depends entirely on coupling strength—a question the experiments were not designed to address.

3. Candidate Sub-THz Wireless Frequencies

3.1 Current Status of 6G Spectrum

It is common in the 6G literature to discuss sub-THz carriers (broadly >100 GHz) as promising candidates for future high-capacity links [8,9]. However, it would be inaccurate to state that 6G is “planned” to use a fixed 0.1–0.3 THz allocation globally. The precise situation:

- **6G research and prototyping** frequently explores carriers in the ~100–300+ GHz regime

- Near-term mass deployment is more likely to focus on **FR3 (~7-24 GHz)**; sub-THz remains a longer-term candidate for specific high-bandwidth applications
- Spectrum allocations and consumer deployment parameters remain **region- and standard-dependent** and are still evolving
- Some national regulators have opened experimental licensing in these ranges, but mass-market specifications are not finalized

3.2 Exposure Limits and Dosimetry

ICNIRP’s 2020 guidelines extend to 300 GHz, with exposure metrics aimed primarily at preventing excessive tissue heating [10]. Above 300 GHz, optical and laser safety guidelines begin to apply, though the dominant concern remains thermal. At these frequencies, absorption is superficial and spatial gradients steep [10,11]. The guidelines increasingly emphasize absorbed power density (APD) rather than incident power density for frequencies above 6 GHz, recognizing that spatial averaging and near-field conditions complicate simple plane-wave assumptions.

Note that the 314 GHz feature reported by Nardecchia et al. sits slightly above ICNIRP’s 300 GHz upper limit. However, similar dosimetric considerations likely apply—absorption remains superficial at these frequencies.

For the question at hand—possible modulation of narrow collective protein modes—the relevant comparison is between realistic incident power densities from devices and the field strengths required to measurably perturb the reported nonequilibrium features. That comparison is rarely made explicitly.

4. Frequency Proximity: Real but Insufficient

4.1 The Overlap

Table 1 presents the relevant frequencies:

Table 1. Reported protein features and candidate sub-THz bands

Protein Feature	Frequency	Relationship to Sub-THz Research
Lechelon et al.	71 GHz	Upper mmWave / lower sub-THz
Lechelon et al.	96 GHz	Near ~100 GHz boundary
Nardecchia et al.	314 GHz	Near or above 300 GHz

The 71 and 96 GHz features sit at or near the lower edge of commonly discussed sub-THz bands. The 314 GHz feature sits slightly above the often-cited 300 GHz boundary—whether it falls “inside” a future telecom band depends on standardization choices not yet made.

4.2 Why Frequency Coincidence Is Not Enough

A common failure mode in frequency-overlap arguments is ignoring coupling strength. Resonance requires not just frequency matching but adequate energy transfer. The

critical question: at realistic exposure levels, can external fields deliver meaningful energy to these protein modes compared to thermal noise?

Additionally, the experimental systems studied (lysozyme crystals, BSA in specific buffer conditions, R-phycoerythrin preparations) are not representative of proteins in living tissue. The conditions required to observe Fröhlich-like features may be narrow and difficult or impossible to achieve in vivo at any field strength.

4.3 The Role of Interfacial Water

A factor complicating simple predictions is the hydration shell—interfacial water molecules surrounding proteins that facilitate collective vibrations. These water-protein complexes possess their own resonances in the 0.1–1.0 THz range [14]. Because terahertz radiation couples strongly to water, external fields might interact not only with protein modes directly but also with hydration dynamics. Such interaction could, in principle, de-tune or destabilize collective oscillations by altering the dielectric environment.

However, strong water absorption also implies rapid attenuation and energy dissipation—factors that work against sustained coherent driving by weak far-field radiation.

4.4 Anatomical Considerations

Sub-THz waves are strongly absorbed by water-rich tissue. Penetration depth at these frequencies is typically 0.1–1 mm [10–12]. Any interaction would therefore be concentrated in superficial structures:

- **Epidermis:** Skin proteins and nerve endings
- **Cornea:** Organized protein structures in the eye, routinely exposed during device use
- **Olfactory epithelium:** Nasal tissue proximate to handheld devices

This attenuation profile confines any plausible interaction to superficial tissues, while also increasing damping and reducing field amplitude with depth. The question becomes whether Fröhlich-active proteins in superficial sensory tissues could be affected at realistic exposure levels.

5. Order-of-Magnitude Coupling Estimate

This section provides a simple calculation that any reader can verify.

5.1 The Standard Biophysical Critique

Before proceeding, it is worth noting the established skeptical position. Adair (2002) provided an influential analysis arguing that microwave fields generally cannot interact with biological systems below the thermal limit due to viscous damping in aqueous media [16]. This analysis has been widely cited as evidence against non-thermal bio-effects at RF/microwave frequencies.

However, Adair’s analysis—like most standard biophysical critiques—assumes equilibrium or near-equilibrium conditions. The Fröhlich hypothesis specifically postulates a nonequilibrium state where standard damping relationships may be modified by coherent energy supply. The experiments cited in Section 2 explicitly created nonequilibrium conditions (via optical pumping or chemical drive) before observing collective features. Whether standard thermal-limit arguments fully apply to such driven systems is precisely what requires experimental test.

5.2 Field Amplitude at Guideline-Level Exposure

For a plane wave, incident power density S relates to RMS electric field by:

$$S = \frac{E_{rms}^2}{\eta_0}$$

where $\eta_0 \approx 377 \, \Omega$ is free-space impedance. Taking $S \sim 10 \, \text{W/m}^2$ (representative of public exposure limits above several GHz [10]):

$$E_{rms} \approx \sqrt{10 \times 377} \approx 61 \, \text{V/m}$$

Even at $S \sim 100 \, \text{W/m}^2$ (deliberately high):

$$E_{rms} \approx 194 \, \text{V/m}$$

Important caveat: This plane-wave relation is an approximation. Real exposures near device antennas are not plane waves; local E-fields very close to radiators can exceed far-field estimates substantially. The estimate above represents a far-field baseline, not a bound on all possible exposure geometries.

5.3 Dipole-Field Interaction vs. Thermal Energy

A molecular dipole moment is typically ~ 1 Debye ($3.3 \times 10^{-30} \, \text{C}\cdot\text{m}$). The interaction energy:

$$U \sim pE$$

Using $p \sim 1 \, \text{D}$ and $E \sim 100 \, \text{V/m}$:

$$U \sim (3.3 \times 10^{-30})(100) \approx 3.3 \times 10^{-28} \, \text{J} \approx 2 \times 10^{-9} \, \text{eV}$$

At room temperature, $k_B T \approx 25 \, \text{meV}$, so:

$$\frac{U}{k_B T} \sim 10^{-7} \text{ to } 10^{-8}$$

Implication: Direct coherent driving of individual molecular dipoles by far-field radiation at guideline levels is extremely small compared to thermal energy.

5.4 Limitations of This Estimate

The pE/k_BT comparison is a useful sanity check but not a complete criterion for detectability. A more rigorous analysis would compare:

- **Driving rate** (power absorbed into the collective mode) vs **damping rate** (thermalization)
- **Absorbed power per protein** at realistic incident intensity vs mode linewidth

Near threshold systems may exhibit measurable spectral changes even when $pE \ll k_BT$, if the relevant observable is a sharp resonance feature rather than bulk thermal equilibrium. The estimate above should be understood as a **strong null baseline**—if effects were observed at guideline-level far-field exposures, they would require explanation beyond simple dipole-field coupling.

5.5 Could Collective Enhancement Rescue the Coupling?

Fröhlich modes involve collective oscillations, potentially with effective dipole moments larger than single molecular dipoles. However, reaching $U \sim k_BT$ at $E \sim 100$ V/m would require:

$$p_{eff} \sim \frac{k_BT}{E} \sim \frac{4 \times 10^{-21}}{100} \sim 4 \times 10^{-23} \text{ C}\cdot\text{m} \sim 10^7 \text{ D}$$

This is extraordinarily large—requiring an implausible number of molecular dipoles oscillating coherently with minimal damping in aqueous conditions.

5.6 Impedance Matching Considerations

Even if a protein mode resonates at the applied frequency, efficient energy transfer from a macroscopic electromagnetic wave into a microscopic mechanical vibration involves a fundamental impedance mismatch. The radiation resistance of a molecular-scale oscillator is many orders of magnitude smaller than the impedance of free space, further reducing coupling efficiency beyond the simple pE estimate.

5.7 Conditions Under Which Coupling Might Still Matter

This estimate does not prove “no interaction.” It shows that frequency overlap alone does not guarantee meaningful coupling. Non-negligible effects could still arise if:

1. **Local-field enhancement:** Near-field hotspots near radiating structures could produce larger local fields than far-field estimates suggest
2. **Nonlinear transduction:** Weak high-frequency fields might produce low-frequency biological effects through nonlinear pathways

3. **High-Q resonances in situ:** If biological resonances were sufficiently narrow and weakly damped, small drives could accumulate energy. However, the Q-factors required for significant resonant enhancement are typically unachievable in aqueous environments at room temperature—water is highly lossy at THz frequencies, imposing strong damping that works against sharp resonances
4. **Indirect hydration-shell modulation:** THz-water coupling is strong; whether this could selectively affect protein modes beyond ordinary heating is an empirical question

Conclusion: The simplest physics suggests direct far-field coupling at guideline levels is likely negligible. But plausible alternatives exist that only experiment can address.

6. What Remains Unknown

A precise research gap can be stated without assuming harm:

1. **External-field modulation:** In systems where nonequilibrium features have been reported (e.g., ~ 314 GHz in BSA), does applying an external narrowband field at that frequency measurably change the threshold, linewidth, amplitude, or dynamics?
2. **Field-strength thresholds:** What incident field amplitudes are required for any observable modulation? How do these compare to realistic device exposures?
3. **Environmental dependence:** How do ionic strength, temperature, viscosity, and hydration affect resonance frequency, damping, and threshold behavior?
4. **Superficial tissue relevance:** Given strong attenuation in water-rich tissue, can any meaningful interaction occur in skin, cornea, or other exposed structures?

6.1 Enabling Technology: SPRATS

A recent development makes several of these investigations newly feasible. In December 2025, Huang et al. introduced SPRATS (Spatial-Resolved Asynchronous-Sampling Terahertz Spectroscopy), achieving simultaneous $20\text{ }\mu\text{m}$ spatial resolution and 100 MHz spectral resolution with 1.7 THz bandwidth [15]. This bypasses a longstanding tradeoff that previously forced researchers to choose between spatial detail and spectral precision.

SPRATS could enable direct investigation of whether Fröhlich-like collective modes exist in biological structures at cellular scales (tens of micrometers). Previous THz spectroscopy lacked the combined resolution to detect coherent oscillations in small structures like cell membranes or protein complexes while maintaining the spectral precision needed to identify narrow resonances. With SPRATS, one key instrumentation limitation is reduced, though sensitivity, sample preparation, and in vivo implementation remain challenging.

7. A Proposed Experimental Program

The most valuable contribution at this stage is not speculation but a decisive coupling experiment.

7.1 Minimal Decisive Experiment (In Vitro)

Using a preparation similar to Nardecchia et al. [5]:

1. Reproduce the reported nonequilibrium spectral feature and its threshold behavior using the original drive method
2. Add a **tunable narrowband external source** near the reported frequency (e.g., ~314 GHz) with calibrated incident field strength
3. Measure whether the external field changes:
 - The threshold (drive level at which the feature appears)
 - Feature amplitude and linewidth
 - Any associated structural or aggregation signatures
4. Repeat with modest detuning (± 5 –10 GHz) as a control

This directly tests whether an external sub-THz field can entrain or modulate the reported mode at realistic field strengths.

Recommended parameters: - Incident power density range: 0.1–100 W/m² in decade steps, spanning from well below to above guideline limits - Effect size threshold: Statistically significant change ($p < 0.01$) in threshold temperature, feature amplitude, or linewidth exceeding 10% of baseline value - Heating controls: Monitor bulk sample temperature with $\pm 0.1^\circ\text{C}$ precision; reject runs where temperature rise exceeds 0.5°C to distinguish resonant effects from thermal perturbation - Negative control: Apply equivalent power at detuned frequencies (± 10 –20 GHz from resonance)

7.2 Dosimetry and Near-Field Characterization

If modulation occurs at unexpectedly low fields, the next step is determining whether realistic devices produce comparable local fields in tissue:

- Validated computational dosimetry in layered tissue models at relevant frequencies
- Measurement of near-field distributions from candidate device antennas

7.3 In Vivo Relevance

Only if in vitro modulation occurs at low fields would subsequent work on tissue or tissue-like phantoms be warranted.

8. Distinguishing This Analysis from Unfounded Claims

Public discourse on wireless bioeffects is often contaminated by misinformation. Scope must be stated precisely.

This paper does not claim: - Sub-THz radiation is ionizing (it is not) - Established thermal safety metrics are invalid - Reported protein experiments imply in vivo harm - 6G deployment should be halted

This paper does claim: - Some protein systems have reported narrow sub-THz features under nonequilibrium drive - Sub-THz wireless is a plausible future technology direction - The physically correct way to connect these facts is through quantitative coupling tests, which appear under-explored - A well-designed experiment may yield a strong null result—which would be scientifically valuable and informative

The difference between this analysis and conspiracy narratives is quantitative: previous wireless generations (2G–5G) operate at frequencies with no known biological resonance mechanisms beyond thermal effects. The sub-THz case is qualitatively different in that experimentally reported protein resonances now exist in this frequency range. Whether this matters depends on coupling strength, which is testable.

8.1 The Internal vs. External Driving Question

It should be emphasized that the Fröhlich experiments achieved nonequilibrium conditions via *internal* driving mechanisms—optical pumping in Nardecchia et al. [5], chemical/metabolic energy input in other preparations—not via external far-field RF exposure. The experiments demonstrated that proteins *already driven out of equilibrium by internal sources* can exhibit collective modes at sub-THz frequencies.

This is a fundamentally different question from whether weak external RF radiation can: (a) create the nonequilibrium conditions necessary for Fröhlich condensation in the first place, or (b) meaningfully perturb a system that is already in a Fröhlich-condensed state due to metabolic drive

The former seems implausible given the coupling estimates in Section 5. The latter is more plausible but still requires the biological system to already be in the relevant nonequilibrium regime—a condition that may or may not obtain in living tissue. This distinction is often elided in discussions of “THz bioeffects” and deserves explicit attention in experimental design.

9. Conclusion

Experiments over the past decade have reported nonequilibrium collective behavior in certain protein systems with narrow spectral features near 71–96 GHz and ~314 GHz. Wireless research increasingly explores carriers above 100 GHz, approaching the same frequency scales.

A simple order-of-magnitude estimate suggests that **direct far-field coupling to molecular dipoles at guideline-level exposures is likely negligible** compared to thermal energy. Frequency coincidence alone does not establish biological relevance.

However, plausible alternatives—local-field enhancement, nonlinear transduction, unexpectedly high-Q modes, or indirect hydration-mediated pathways—cannot be ruled out a priori. These can be tested directly.

The most constructive path forward is a targeted experimental program measuring whether external narrowband sub-THz fields can modulate reported Fröhlich-like features in controlled protein systems, and at what field strengths. A null result would be valuable, providing empirical confirmation that the frequency overlap is inconsequential. A positive result would warrant further investigation.

Either outcome advances understanding. The question is tractable with current methods and worth resolving regardless of outcome.

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