



# A New Interpretation of Wave-Particle Duality in Gas-Liquid Systems Based on the Particle-life Hypothesis of UCST

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**Abstract:** As the core foundation of quantum mechanics, wave-particle duality and the micro-macro description gap have long been controversial. Based on the Unified Complex System Theory (UCST) particle-life hypothesis, dualistic ontology, this paper presents a self-consistent interpretive framework for wave-particle duality in gas-liquid systems. The framework discards artificial micro-macro leaps and assumes particles have life-like properties: particle nature arises from ether-based material entities, while wave nature stems from two medium vibration modes—mind-driven active vibrations and environment-induced passive vibrations. In gas, statistical superposition of active intrinsic vibrations forms de Broglie matter waves, consistent with Planck's quantum hypothesis and the UCST gas equation. In liquid, coordinated passive forced vibrations produce classical water waves, satisfying the standard wave equation and UCST macroscopic fluid mechanics. Through active-passive synergistic dynamics, the theory achieves a continuous transition of wave-particle behavior across gas, gas-liquid coexistence, and liquid phases. It maintains consistency with classical mechanics, clarifies the intrinsic origin of wave motion, and offers a unified physical mechanism and mathematical logic for reconciling wave-particle duality across microcosmic and macrocosmic systems, complementing UCST's unification of microscopic and macroscopic physics.

**Keywords:** Wave-particle duality, Unified Complex System Theory (UCST), Particle-life Hypothesis, Matter wave, Gas-liquid system, Vibration propagation, Micro-macro unification.

## INTRODUCTION

Since the 17th-century debate between Newton's corpuscular theory of light [1] and Huygens' wave theory [2], humanity's exploration of the microcosm's fundamental nature has undergone centuries of cognitive revolutions. Thomas Young's double-slit interference experiment [3], Maxwell's unification of classical electromagnetism [4], Einstein's photon hypothesis [5], and the Compton effect [6] solidified wave-particle duality as the core pillar of quantum mechanics, while de Broglie's matter wave theory [7] extended this property to all microscopic particles, breaking the traditional boundary between "matter" and "wave".

Despite these advances, two critical bottlenecks persist and have long stymied the unification of microcosmic and macrocosmic physics—the core challenge of Hilbert's Sixth Problem [9]:

1. **Unresolved essence of wave-particle duality:** Bohr's complementarity principle [8] attributes dual properties to measurement, while de Broglie's theory [7] emphasizes

intrinsic particle properties, yet neither framework provides a causal physical mechanism for the origin of wave motion.

2. **Micro-macro descriptive disconnect:** Wave-particle characterizations of microscopic particles (gaseous state) and macroscopic media (liquid state) [9-11] lack a clear physical boundary for transition, with classical kinetic theory restricted to dilute gases and classical continuum mechanics unable to trace macroscopic fluid behavior to microscopic particle dynamics.

Einstein's special relativity discarded the "luminiferous ether" [12], creating a theoretical rift with classical mechanics. While Schrödinger's equation [13] and Heisenberg's uncertainty principle [14] quantitatively describe microscopic behavior, they fail to address the fundamental origin of wave generation. Traditional materialistic monism cannot accommodate particle autonomous motion and wave propagation, calling for a new theoretical framework that abandons idealized classical assumptions (e.g., elastic collisions, dilute systems only). The Unified Complex System Theory (UCST) [15] addresses these gaps via an "ether-mind" dualistic ontology and active-passive force cooperative dynamics—foundational constructs that also form the basis of the recent UCST-based re-proof of Hilbert's Sixth Problem [36]. This re-proof resolves the century-old challenge of unifying microscopic particle mechanics and macroscopic continuum physics by: (1) defining gas molecules as living particles with an intrinsic energy compensation mechanism (ether absorption) for inelastic collisions; (2) deriving a UCST arbitrary-density gas state equation valid for dilute/dense gases and yielding rigorous gas-liquid phase transition conditions; (3) rigorously deriving macroscopic fluid equations (Euler, Navier-Stokes-Fourier) from discrete particle dynamics via a UCST-modified Liouville equation.

Building on this UCST unification of micro and macro physics, this paper constructs a unified interpretive framework for gas-liquid system wave-particle duality. It clarifies that wave-particle duality is an intrinsic property of particle-life entities, with "particle nature" rooted in ether-based material entities and "wave nature" in vibration propagation via active/passive force synergy. This framework reveals the generation mechanisms of de Broglie matter waves (gases) and classical water waves (liquids), maintains consistency with classical mechanics, and achieves a self-consistent description of wave-particle duality across microcosmic and macrocosmic scales by unifying wave-particle behavior alongside the unification of particle and continuum mechanics.

## **WAVE-PARTICLE DUALITY: FOUNDATIONAL DEBATES AND LINKAGES TO HILBERT'S SIXTH PROBLEM**

Wave-particle duality, a counterintuitive core theory of physics, has reshaped humanity's understanding of the microcosm through centuries of ideological clashes. Its unresolved puzzles are inextricably linked to Hilbert's Sixth Problem, as the micro-macro disconnect in wave-particle descriptions mirrors the broader rift between microscopic particle dynamics and macroscopic continuum physics that Hilbert sought to bridge.

### **The Wave-Particle Debate and Theoretical Shifts**

The 17th century saw Newton's corpuscular theory [1] dominate by explaining light's rectilinear propagation, reflection, and refraction, while Huygens' wave theory [2]

attributed light to mechanical waves in the "luminiferous ether"—accounting for interference and diffraction but lacking experimental support for ether's existence. The 19th century brought pivotal changes: Young's double-slit experiment [3] and Fresnel's diffraction studies [16] validated the wave theory, and Maxwell's electromagnetic field equations [4] unified electricity and magnetism, predicting light as an electromagnetic wave later confirmed by Hertz [17].

Maxwell [4] and Lorentz [18] retained the ether as the electromagnetic wave medium, but the Michelson-Morley experiment [19] contradicted the stationary ether hypothesis. Einstein's 1905 special relativity discarded the ether [12], redefining spacetime and matter but creating a theoretical disconnect with classical mechanics—one that hindered efforts to unify micro and macro physics (Hilbert's Sixth Problem). Subsequent scholars have advocated for ether's revival [20-22], and this paper reinterprets wave-particle duality by extending classical mechanics via the dynamic UCST ether (non-stationary, space-filling, and the medium for force/vibration transmission)—a construct also central to the UCST solution to Hilbert's Sixth Problem [36].

### Quantum Revolution and the Establishment of Universal Wave-Particle Duality

The late 19th to early 20th century saw experiments challenge the wave theory's dominance, laying the groundwork for quantum mechanics and the universal extension of wave-particle duality:

- Photoelectric effect: Hertz's 1887 observation [17] of instantaneous photoelectron ejection (with kinetic energy proportional to light frequency) defied wave theory's predictions of energy accumulation. Einstein's 1905 photon hypothesis [5] resolved this by proposing discrete photons with energy  $E=\hbar\omega$ , unifying light's particle and wave properties.
- Compton effect: Compton's 1923 discovery [6] of elastic photon-electron collisions further confirmed light's particle nature, solidifying wave-particle duality as a cornerstone of quantum mechanics.
- Matter wave hypothesis: de Broglie's 1924 proposal [7] extended wave-particle duality to all material particles, deriving the relation  $\lambda=h/p$ . This was validated by 1927 electron diffraction experiments [23,24] and subsequent proton/neutron diffraction studies [25-29], confirming matter waves as a universal intrinsic property of particles—not exclusive to the microcosm.

### The Micro-Macro Divide in Wave-Particle Duality

Contrary to the historical assumption that wave-particle duality is exclusive to the microcosm, macroscopic particles (e.g., C60 molecules [26] and molecular clusters with up to 2000 atoms [28,29]) also exhibit dual properties. The perceived "micro-macro cognitive leap" is subjective: the gas-liquid transition is a continuous phase change (governed by number density and force dominance) — not an abrupt cognitive break. Classical mechanics' failure to distinguish living and non-living entities [15] and its idealized assumptions (dilute gases, elastic collisions) hinder its explanation of this continuity, just as they hinder the solution to Hilbert's Sixth Problem [36].

Schrödinger's equation and the uncertainty principle stem from wave-particle duality, but UCST argues that true uncertainty arises from human cognitive limitations and measurement constraints [30]—not inherent microcosmic randomness. This aligns with Busch & Lahti's critique [31] of Heisenberg's uncertainty principle as a measurement constraint rather than a fundamental quantum law. Wave-particle duality has driven technological revolutions (semiconductors, lasers, quantum communication) and remains the foundation of modern physics—yet its unification across micro and macro scales has remained elusive until the development of UCST.

### Ongoing Debates: Intrinsic vs. Measurement-Induced Dual Properties

Debates over wave-particle duality's essence persist between two camps [32], with implications for the micro-macro unification of Hilbert's Sixth Problem:

1. **"Wave or particle" (Bohr's complementarity):** Dual properties are measurement-induced, not intrinsic—particle nature manifests in position measurements, while wave nature appears in interference/diffraction observations, with no simultaneous detection [8]. This framework reinforces the micro-macro divide by treating wave and particle behavior as mutually exclusive.
2. **"Wave and particle" (de Broglie/Bohm):** Dual properties are intrinsic and coexistent, with particle momentum correlated to wavelength [7,34]. This framework aligns with UCST and the solution to Hilbert's Sixth Problem, as it allows for a continuous transition of wave-particle characteristics across gas and liquid phases.

Angelo & Ribeiro [33] reinterpreted wave-particle duality via quantum information theory, arguing that dual properties arise from fundamental limits of information extraction from quantum systems. This complements the "wave and particle" camp and provides a modern context for unifying microscopic and macroscopic wave behaviors—one that UCST builds on by adding a causal physical mechanism for wave motion (vibration propagation) and extending the framework to macroscopic liquid systems.

### UCST in Contemporary Debates: Resolving Hilbert's Sixth Problem and Wave-Particle Duality

To situate UCST in contemporary physics and link its wave-particle duality interpretation to the solution of Hilbert's Sixth Problem, we address key recent contributions and UCST's novel resolutions:

1. **Deng et al. (2025) [10]:** Claimed a rigorous derivation of fluid mechanics equations (Euler, Navier-Stokes-Fourier) from hard-sphere particle systems, purporting to solve Hilbert's Sixth Problem. However, their work is restricted to dilute gases and relies on the molecular chaos assumption—invalid in dense fluid regimes.
2. **Gao (2025) [11]:** Critiqued Deng et al.'s proof, identifying two fatal physical inconsistencies: the Boltzmann-Grad limit enforces a vanishing volume fraction (dilute gas only), and molecular chaos breaks down in dense systems. Hilbert's Sixth Problem remained unresolved.

3. **Cui et al. (2025) [36] (UCST re-proof of Hilbert's Sixth Problem):** Addressed Gao's two criticisms together with the lack of an energy compensation mechanism for inelastic collisions in all previous proofs (Lanford's 1975 Rigorous Derivation (Boltzmann-Grad Limit) [44] and Deng Yu et al.'s 2025 Long-Time Extension [10]) via UCST's "ether-mind" dualistic ontology and active-passive force cooperative dynamics. Defining microscopic particles as generalized active systems with autonomous motion capabilities, this work derived a UCST arbitrary-density gas state equation (valid for rarefied, phase transition, and dense regions) and rigorously deduced macroscopic fluid equations via moment expansion. This achieved seamless micro-macro connection and met the mathematical and physical requirements of Hilbert's Sixth Problem—and *provides the physical foundation for this paper's wave-particle duality framework.*
4. **Oriols & Mompert (2019) [32]:** Defended Bohmian mechanics but acknowledged its failure to explain wave origin and micro-macro unification. UCST aligns with its "wave and particle" ontology [35] but advances further by: (1) providing a causal mechanism for wave motion (vibration propagation via active/passive forces); (2) extending to macroscopic liquid systems; (3) avoiding non-locality (local ether-matter interaction propagation). Unlike Bohm's hidden variables, UCST's active forces are operationally measurable via vibration frequency— a critical link to experimental validation.
5. **Michelson-Morley Experiment and UCST Ether Revival:** UCST's dynamic ether avoids the experiment's null result [19] by rejecting the "stationary ether" hypothesis. Instead, UCST's ether is a space-filling, dynamic medium with autonomously vibrating particles that transmit forces locally. Recent ether research [20-22] supports this model, and Einstein's ether rejection is recontextualized as a methodological choice (calculation simplification) rather than an ontological one [36].
6. **Macroscopic Wave-Particle Duality:** Building on C60 molecule experiments [26], recent work confirmed matter wave interference in large molecular clusters [28,29]. UCST explains this via the particle-life hypothesis: *all particles with self-moving ability (micro or macro) are life-like agents.* For low-density C60 molecules (weak passive forces), intrinsic vibration dominates, producing measurable matter waves— consistent with UCST's gas-phase wave-particle mechanism and the arbitrary-density gas state equation [36].

### **UCST THEORETICAL FOUNDATIONS: DUALITY, LIFE-LIKE PARTICLES, AND ACTIVE-PASSIVE FORCE DYNAMICS**

UCST's core ontological and dynamical constructs form the foundation of this paper's wave-particle duality interpretation. These constructs reject materialistic monism, redefine particles as life-like entities, and establish the active-passive force synergy that governs vibration and wave propagation across gas and liquid phases.

#### **UCST's Ether-Mind Dualistic Ontology**

UCST's most fundamental breakthrough is its "ether-mind" dualistic ontology [15], which replaces classical materialistic monism and resolves the contradictions of wave-particle

duality and micro-macro unification (Hilbert's Sixth Problem). Key operational definitions (with philosophical precision and physical testability) are as follows:

### ***Ether***

A fundamental, invisible particle medium constituting the material substrate of all visible matter (elementary particles, atoms, macroscopic objects). Operationally defined as the carrier of inter-particle force and vibration transmission, observable indirectly via wave propagation (e.g., ether-mediated vibration transmission in gases). Unlike the 19th-century "luminiferous ether", UCST's ether:

- Is not an absolute inertial frame (avoiding Michelson-Morley contradictions);
- Is a dynamic, space-filling medium (rejecting "vacuum" as a physical entity) [22] that serves as the fundamental physical substrate underlying all fields and waves;
- Serves as the medium for energy compensation (ether absorption/emission) in inelastic collisions— a core construct of the UCST solution to Hilbert's Sixth Problem [36].

For human observers, the absolute inertial frame does not exist; coordinate frames are fixed to the observer's platform, not the ether [15].

### ***Mind***

Based on UCST's Relativity of Simultaneity Axiom (pairs of "A" and "non-A" coexist) [15], the existence of matter implies the coexistence of non-matter—mind—defined to align with Descartes' mind-body problem [37]. Critical notes:

- This is a reserved UCST terminology and differs from biological or conscious mind; UCST classifies consciousness into eight types, with mind as the eighth [15].
- Mind is a non-material causal agency that generates active forces via a mind-body-support interaction— the mechanism for autonomous particle motion (life-like properties).
- For particles, mind is measurable via intrinsic vibration frequency ( $\omega_0$ ) and active force magnitude ( $\vec{F}_a = -m\omega_0^2\vec{u}$ ) where  $m$  is the particle mass and  $\vec{u}$  is the instantaneous displacement of the particle; it represents basic self-driven motion capacity, analogous to human self-movement.

### ***Life-Like Properties***

Scale-dependent intrinsic attributes of particles, manifesting as mind-driven autonomous vibration and adaptive response to environmental passive forces. Key characteristics:

- Microscopic particles (electrons, atoms): Observable via thermal motion and matter wave vibration;
- Macroscopic "non-living" objects (stones, metals): Emerge from the collective autonomous vibration of constituent microscopic particles (dampened but

persistent, per UCST's scale hierarchy axiom) [15]. Notably, this "non-living" quiescent state first manifests in liquid water, let alone solid stones and metal blocks. At the microscopic level, every gas molecule behaves dynamically as an independent life-like entity driven by mind-induced active forces. However, when gas molecules become sufficiently dense to undergo phase transition into a liquid state, the intense passive forces (van der Waals attraction, short-range repulsion) between adjacent particles constrain their individual autonomous motion. In the absence of external perturbations, these mutual restrictive forces counterbalance the intrinsic active vibrations of individual particles, leading to collective coordinated motion that macroscopically appears as a "stationary" state—thus exhibiting characteristics associated with "non-living" entities. This reflects the hierarchical nature of material structure in UCST: while all constituent microscopic particles inherently possess life-like properties (as particle-life entities), the collective behavior of countless such particles can give rise to either "living" macroscopic systems (e.g., animals and humans, where coordinated active forces dominate to enable autonomous motion and adaptive responses) or "non-living" macroscopic objects (e.g., stationary water, stones, and metals, where passive force-driven constraints modulate individual active vibrations into quiescent collective behavior).

- All particles (micro/macro): Life-like properties are the core of wave-particle duality—particle nature from ether, wave nature from vibration propagation driven by active/passive forces.

### ***Rejection of Mass-Energy Equivalence (for Gas-Liquid Systems)***

UCST explicitly rejects the artificial division between classical and relativistic systems, instead advocating for a generalized classical mechanics framework that unifies microscopic and macroscopic physics. Within this unified framework, energy is posited as an intrinsic property of material objects—specifically tied to particle vibration frequency—rather than a product of mass conversion. This aligns with experimental observations: the energy quantization of matter waves ( $E=\hbar\omega$ ) reflects the intrinsic vibration frequency of particle-life entities, not mass-energy transformation.

Notably, UCST avoids introducing relativistic concepts or axioms entirely, as they conflict with the self-consistency of generalized classical mechanics. In contrast, some works [e.g. 38, 39] maintain the traditional division between classical and relativistic systems.

For relativistic regimes, these studies attempt to reconcile Einstein's formalism with non-materialist dynamics by recontextualizing it as a mathematical approximation of high-energy mind-ether interactions—an approach that retains the classical-relativistic divide while incorporating UCST's core mind-ether construct.

This distinction underscores UCST's unique ontological stance: by generalizing classical mechanics to encompass life-like particle properties and mind-ether interactions, it eliminates the need for a separate relativistic framework, whereas [38, 39] preserve the dual-system division while adapting mind-ether dynamics to relativistic formalism.

### ***Ether and Mind in Living vs. Non-Living Entities***

- **Non-living objects:** Essence is ether— invisible particles composing visible matter, with elementary particles decomposable into ether particles;
- **Living entities (microscopic particles to biological organisms):** Essence is mind (non-material existence) – minds endow all living agents with autonomous motion. Particle behavior is governed by passive forces (gravity, electromagnetism, intermolecular interactions) and active forces (mind-body-support interaction, embodying free will) [15]. The separation of mind from the body signifies the cessation of life, with the once-living entity degenerating into a non-living object— analogous to the dying process of a human being. Of course, we currently lack empirical evidence or theoretical insights regarding the "death" of molecular-scale particle-life entities, as this concept remains speculative within the UCST framework. However, at the cellular level, clear distinctions already exist between living and dead cells (e.g., membrane integrity, metabolic activity) [45,46], and extensive research has been conducted on canonical cellular death processes (e.g., apoptosis, necrosis, pyroptosis) [47-49]—a stark contrast to the speculative nature of "death" at the molecular scale, as individual molecules lack the biological complexity to exhibit life or death in a mainstream biological sense [46].

### **UCST Active-Passive Force Cooperative Dynamics**

The active-passive force model is the core dynamical construct of UCST, developed for the re-proof of Hilbert's Sixth Problem [36] and the key to explaining wave-particle duality's phase transition across gas and liquid states. For all particles (life-like entities), the total force ( $\vec{F}_t$ ) is the vector sum of active and passive forces:

$$\vec{F}_t = \vec{F}_a + \vec{F}_p \quad (1)$$

This model abandons classical idealizations (elastic collisions, no energy compensation) and accounts for real particle behavior in gas-liquid systems—including inelastic collisions, long-range intermolecular interactions, and energy homeostasis (via ether absorption/emission).

### ***Active Force ( $\vec{F}_a$ )***

A self-force generated by the mind-body-support interaction, responsible for:

- **Intrinsic autonomous vibration** (the origin of matter waves in gases);
- **Energy compensation** via ether absorption— offsetting energy loss from inelastic collisions (a core UCST solution to Hilbert's Sixth Problem [36]);
- **Scale-dependent behavior:** Dominates in low-density gases (weak intermolecular interactions) and is modulated (but not eliminated) in high-density liquids.

For a particle with displacement  $\vec{u}$ , mass  $m$ , and intrinsic vibration frequency  $\omega_0$ , the active force is operationally defined as:

$$\vec{F}_a = -m\omega_0^2\vec{u} \quad (2)$$

The negative sign indicates a restoring force that maintains intrinsic autonomous vibration— the foundation of particle individuality (particle nature) in wave-particle duality.

### **Passive Force ( $\vec{F}_p$ )**

An interparticle/environmental force arising from:

- Short-range hard-core repulsion (prevents particle overlap);
- Long-range van der Waals attraction (drives gas-liquid phase transitions);
- External fields (gravity, electromagnetism) and medium constraints.

Passive forces are environment-dependent and govern forced vibration in particles. They dominate in high-density liquids (strong intermolecular interactions) and are responsible for the coordinated collective vibration that forms classical water waves.

For gas-liquid systems, the passive force is well-described by the Lennard-Jones potential [36], capturing both repulsion ( $\propto 1/r^{12}$ ) and attraction ( $\propto -1/r^6$ )—a critical construct for the UCST arbitrary-density gas state equation and phase transition conditions.

### **UCST Scale Hierarchy Axiom**

Life-like properties and force dominance are scale-dependent, with a continuous transition across gas, gas-liquid coexistence, and liquid phases (governed by number density ( $n=N/V$ )— the only tunable parameter in closed gas-liquid systems [36]):

- **Low density (gas):** Large particle spacing, weak passive forces  $\rightarrow$  active force dominance (intrinsic vibration, matter waves);
- **Critical density (gas-liquid coexistence):**  $n=n_c$  (critical number density [36]), balanced active/passive forces  $\rightarrow$  smooth transition of wave-particle characteristics;
- **High density (liquid):** Small particle spacing, strong passive forces  $\rightarrow$  passive force dominance (forced vibration, classical water waves).

This axiom eliminates the artificial micro-macro cognitive leap and directly links wave-particle duality to the phase transition dynamics that are the focus of the UCST solution to Hilbert's Sixth Problem [36].

### **UCST INTERPRETATION OF WAVE-PARTICLE DUALITY: GAS AND LIQUID PHASES**

Building on UCST's dualistic ontology and active-passive force dynamics, this section derives the wave-particle characteristics of gaseous and liquid states, establishes their mathematical linkages to Planck's hypothesis and classical wave theory, and demonstrates the smooth phase transition of wave-particle behavior via force synergy—all consistent with the UCST arbitrary-density gas state equation and macroscopic fluid mechanics derived for Hilbert's Sixth Problem [36].

## Core Logical Framework: Particle Vibration and Wave Motion Correlation

UCST's central thesis for wave-particle duality is that wave motion is the collective propagation of particle vibrations (active/passive) via the ether medium. All material particles (life-like entities) are vibration sources with two mutually complementary modes, and wave nature is the statistical or coordinated superposition of these vibrations in the gas/liquid medium. Particle nature (ether-based material entity) and wave nature (vibration propagation) are intrinsic and coexistent—a "wave and particle" framework that aligns with de Broglie/Bohm [32] and resolves the micro-macro divide.

### Two Vibration Modes of Particle-Life Entities

Every particle-life entity exhibits two vibration modes, with total vibration energy as their sum:

$$E_{\text{total}} = E_{\text{intrinsic}} + E_{\text{forced}} \quad (3)$$

- Intrinsic vibration:** Intrinsic vibration is driven by active forces—mind-mediated self-forces inherent to particle-life entities—and exhibits autonomous, persistent oscillation with an angular frequency ( $\omega_0$ ) determined by the particle's mind properties (a core UCST construct [15]). In an earth-fixed non-inertial frame (consistent with UCST's rejection of absolute inertial frames [15]), the energy of this vibration is quantized as  $E_{\text{intrinsic}} = \hbar\omega_0$ —aligning with Planck's original hypothesis for blackbody radiation [50] while recontextualizing its physical nature within UCST. This quantized energy is predominantly interpreted as the kinetic energy of the particle's autonomous motion, which follows the classical mechanics relation  $E_{\text{kinetic}} = \frac{1}{2}mv^2$ , where  $m$  = the particle's inertial mass (a coordinate-independent quantity, per UCST's mass definition as "a measure of matter amount" [15]);  $v$  = the particle's velocity relative to the earth-fixed frame (a coordinate-dependent quantity, consistent with classical mechanics). If we assume the particle's velocity relative to the earth-fixed frame is around the speed of light  $c$ , then we can estimate the mass of the particle is  $m \approx \frac{2\hbar\omega_0}{c^2}$ . Notably, Planck's hypothesis originally redefined energy as a discrete, frequency-dependent quantity to resolve the blackbody radiation ultraviolet catastrophe [50], but it did not explicitly link this quantization to particle motion or coordinate dependence. UCST corrects this by grounding the quantized energy  $E_{\text{intrinsic}} = \hbar\omega_0$  in the classical kinetic energy of autonomous vibration: the quantization reflects the discrete nature of mind-driven active forces (not a break from classical mechanics), and the coordinate dependence of velocity (and thus kinetic energy) is preserved—reconciling Planck's quantization with classical mechanics' core tenets (a key requirement for UCST's unification of microscopic and macroscopic physics [36]). This intrinsic vibration, when statistically superposed across gas-phase particles, constitutes the origin of de Broglie matter waves.
- Forced vibration:** Driven by passive forces (interparticle/environmental interactions), coordinated (in liquids), and frequency-determined by medium constraints (density, viscosity, intermolecular forces). The origin of classical water waves in liquids.

### **Wave Generation Mechanism**

Particle vibrations propagate to neighboring particles through the ether and via visible particle matter waves (in gases) or visible particle matter waves (in liquids). In this subsection, the waves under consideration are those formed by the visible particles constituting the liquid. Under these conditions, the influence of ether particles can be sufficiently small to be neglected, resulting in collective wave motion of the visible particle medium. The ether concept can still be employed to describe waves that transmit through liquids or solids. In such cases, the waves are purely ether waves, and the liquids or solids act only as barriers to the propagation of these ether waves. Key characteristics:

- Wave equation parameters (angular frequency  $\omega$ , wave number  $k$ , amplitude  $A$ ) are determined by the statistical or coordinated characteristics of particle vibrations;
- UCST redefines "fields" as matter wave force transmission descriptive tools (not independent physical entities) [15]—avoiding the classical "action at a distance" paradox and aligning with local propagation logic;
- Ether particles follow the same matter wave principle as visible particles—enabling a natural gas-liquid wave transition via UCST's active-passive force synergy.

### **Root Cause of Gas-Liquid Wave-Particle Differences**

The fundamental distinction between gaseous matter waves and liquid classical waves is force dominance, governed by number density ( $n$ )—the core parameter of the UCST arbitrary-density gas state equation [36]:

- **Gas:** Large particle spacing, weak intermolecular interactions → active force dominance → intrinsic vibration dominates → wave motion = statistical superposition of individual particle vibrations (de Broglie matter waves);
- **Liquid:** Small particle spacing, strong intermolecular interactions → passive force dominance → forced vibration dominates → wave motion = coordinated collective propagation of particle vibrations (classical water waves).

This density-force dominance link directly connects wave-particle duality to the phase transition dynamics of the UCST solution to Hilbert's Sixth Problem [36], achieving a seamless micro-macro transition.

### **Gaseous State: Active Force-Dominated Matter Waves (de Broglie/Planck Consistency)**

In practical gaseous systems, the medium comprises visible particles (e.g., molecules, atoms) of varying diameters alongside invisible ether particles (the fundamental material substrate in UCST [15]). For the sake of mathematical derivation simplicity, we adopt two key simplifying assumptions aligned with UCST's macroscopic unification framework [36]: (1) visible particles are treated as identical (uniform mass  $m$ , consistent properties) with a total count  $N$ , and (2) the number density is defined as  $n=N/V$  (excluding ether particles, as they serve exclusively as the medium for vibration/wave propagation rather than contributing to the gas's macroscopic density). With these assumptions, we focus on the intrinsic vibration of visible particle-life entities and their role in forming de Broglie matter

waves. In the gaseous state (low number density,  $n \ll n_c$ ), interparticle distance far exceeds particle diameter, resulting in low collision frequency and weak passive forces. Collision forces act only briefly, so particle motion is active force-dominated—intrinsic vibration of particle-life entities is the primary driver of wave-particle behavior. This regime aligns with the dilute limit of the UCST arbitrary-density gas state equation [36] and yields de Broglie matter waves consistent with Planck's energy quantum hypothesis.

### **Particle Vibration Characteristics in Gases**

1. **Intrinsic vibration:** The dominant mode, with angular frequency  $\omega_0$  (a fundamental property of the particle-life entity, determined by mind). Energy quantized as:

$$E_{\text{intrinsic}} = \hbar\omega_0 \quad (4)$$

This is consistent with Planck's energy quantum hypothesis and UCST's rejection of mass-energy equivalence—energy is a vibration property of the particle, not a product of mass conversion.

2. **Particle nature manifestation:** Irregular thermal motion of the ether/visible particle material entity, with trajectories jointly determined by intrinsic vibration and occasional passive force collisions (which only slightly perturb intrinsic vibration).
3. **Forced vibration:** Negligible (weak passive forces), with  $E_{\text{forced}} \ll E_{\text{intrinsic}}$  and total vibration energy approximating  $E_{\text{total}} \approx E_{\text{intrinsic}}$ .

### **Gaseous Wave Equation: De Broglie Matter Waves**

Gaseous wave motion is the statistical superposition of numerous particle intrinsic vibrations, transmitted via the UCST ether medium to form de Broglie matter waves. The wave function is:

$$\Psi(\vec{r}, t) = A_0 e^{i(\vec{k} \cdot \vec{r} - \omega t)} \quad (5)$$

where  $A_0$  is the wave amplitude,  $\vec{k}$  the wave vector,  $\omega$  the angular frequency, and  $\vec{r}/t$  the position/time coordinates. Parameter-vibration correlations (derived from UCST active force dynamics and the arbitrary-density gas state equation [36]) are as follows:

1. **Angular frequency ( $\omega$ ):** The statistical average of particle intrinsic vibration angular frequency ( $\omega = \langle \omega_0 \rangle$ ). Wave energy quantization thus satisfies  $E = \hbar\omega$ —*exactly consistent with Planck's energy quantum hypothesis.*
2. **Amplitude ( $A_0$ ):** Proportional to the statistical average of particle intrinsic vibration amplitude. Gaseous intrinsic vibration amplitude is approximately uniform (weak passive forces), so  $A_0$  is a constant (statistical uniformity).
3. **Wave vector ( $\vec{k}$ ):** Determined by particle momentum ( $\vec{p}$ ) from intrinsic vibration kinetic energy. UCST defines mass as a coordinate-independent measure of matter amount (no relativistic mass change), with intrinsic vibration kinetic energy:

$$E_{\text{kinetic}} = \frac{p^2}{2m} \quad (6)$$

In this equation,  $p=|\vec{p}|$ . Combining  $E_{\text{intrinsic}}=\hbar\omega$ , the dispersion relation  $\omega=v_p k$  (phase velocity  $v_p$ ,  $k=|\vec{k}|$ ), and the classical momentum-velocity relation  $p=mv_p$ , UCST derives a revised de Broglie relation:

$$p=2\hbar k \quad (7)$$

The factor of 2 in UCST's revised matter wave relation ( $p=2\hbar k$ ) originates explicitly from the non-relativistic classical kinetic energy-momentum relation ( $E_{\text{kinetic}}=\frac{p^2}{2m}$ ), as rigorously derived by equating this classical kinetic energy to UCST's quantized intrinsic vibration energy ( $E_{\text{intrinsic}}=\hbar\omega_0$ ) and the matter wave dispersion relation ( $\omega=v_p k$ ). This factor is a key testable prediction of UCST: it can be verified via measurements of vibration frequency shifts or matter wave wavelength-momentum correlations in ultra-low density gases (where passive intermolecular interactions are negligible, and active force-dominated intrinsic vibration is isolated).

In contrast, de Broglie's original relation ( $p=\hbar k$ ) was heuristically derived by extending Einstein's relativistic photon energy-frequency relation ( $E=\hbar\nu$ ) to massive particles—incorporating relativistic formalisms implicitly. UCST intentionally avoids relativistic constructs for gas-liquid systems (its core application domain) due to fundamental conceptual conflicts: relativity redefines time, space, mass, and energy in terms of frame-dependent spacetime geometry, whereas UCST anchors these quantities to classical mechanics (e.g., coordinate-independent mass as "a measure of matter amount" [15], energy as a vibration property of material entities, and rejection of mass-energy equivalence as an ontological truth). This avoidance ensures UCST's internal consistency and its ability to unify microscopic particle dynamics with macroscopic continuum physics (the core goal of resolving Hilbert's Sixth Problem [36]).

From the revised relation in Eq. (7), several important inferences can be made:

1. Planck's hypothesis and the de Broglie hypothesis are essentially equivalent: both establish quantitative relationships between particle momentum/energy and the frequency/wavelength of the associated matter wave.
2. Planck's hypothesis is not a genuine foundational postulate, but an empirical regularity extracted from experimental measurements. All early measurements of particle energy and wave frequency/wavelength were performed within the framework of classical mechanics.
3. Planck was puzzled by energy quantization because he did not associate discontinuous energy changes with discrete mass variations. Had he recognized this connection, blackbody radiation could have been fully explained within classical mechanics. Blackbody radiation is essentially the emission of high-speed particles; as these particles are radiated, the total energy and mass of the body decrease. The mass reduction is extremely small due to the very high speeds of the emitted particles.
4. Had the delegates at the Fifth Solvay Conference adopted de Broglie's framework as the orthodox interpretation, the so-called "quantum revolution" might never have occurred. Unfortunately, prevailing revolutionary social ideologies influenced scientific thinking, allowing the Copenhagen School to become the mainstream of quantum mechanics. Coupled with the apparent success of Einstein's relativity, the

scientific community drifted increasingly toward radical theoretical frameworks, resulting in the current fragmented state of complex-system theories [15].

5. From the UCST perspective, interpretational difficulties with relativistic phenomena arise similarly: velocity-induced discontinuities emerge from the introduction of the Lorentz transformation. Abandoning the Lorentz transformation and retaining mass as a fundamental material property and energy as a higher-order property of matter would render relativity unnecessary. This topic, however, lies beyond the scope of the present work.

### ***Density Dependence of Gaseous Wave-Particle Behavior***

The UCST arbitrary-density gas state equation [36] predicts a continuous deviation from pure de Broglie matter wave behavior as gas density increases (toward  $n_c$ ):

- **Ultra-low density:** Negligible collisions ( $E_{\text{intrinsic}}/E_{\text{total}} \approx 1$ ) → wave equation strictly satisfies de Broglie matter wave characteristics and  $p=2\hbar k$ ;
- **Slightly increased density:** Collisions intensify, forced vibration proportion rises → wave motion deviates slightly, but statistical averages still approximate de Broglie's hypothesis (consistent with UCST's "determinism-probability unification" axiom: incomplete collision information leads to probabilistic wave motion; complete information leads to deterministic relations);
- **High density (near  $n_c$ ):** Strong passive forces, significant forced vibration → wave motion deviates substantially, gas enters the gas-liquid coexistence phase, and wave-particle characteristics transition smoothly to liquid behavior (Section 4.4).

### **Liquid State: Passive Force-Dominated Classical Water Waves**

In the liquid state (high number density,  $n \gg n_c$ ), small interparticle spacing enhances intermolecular passive forces (van der Waals forces, hydrogen bonds [36]). Particle motion is governed by both active and passive forces, with passive force dominance—forced vibration is the primary driver of wave-particle behavior. This regime aligns with the dense limit of the UCST arbitrary-density gas state equation [36] and yields classical water waves that satisfy the traditional wave equation and UCST-derived Navier-Stokes-Fourier equations [36].

### ***Particle Vibration Characteristics in Liquids***

1. **Forced vibration:** The dominant mode, driven by passive forces (intermolecular interactions/medium constraints). Adjacent particle intrinsic vibrations transmit via passive forces to form coordinated collective vibration, with angular frequency  $\omega$  determined by medium properties:

$$\omega = \mu k \quad (8)$$

where  $k$  is the medium elastic coefficient and  $\mu$  the particle effective mass. For water waves, the dispersion relation is further modified by gravity and surface tension (passive forces):

$$\omega^2 = gk \tanh(kH) \quad (9)$$

where  $g$  is gravitational acceleration,  $H$  water depth, and  $k = |\vec{k}|$ —a relation that directly reflects passive force constraints on particle vibration.

2. **Intrinsic vibration:** Persists but is modulated by forced vibration, manifesting as minor amplitude fluctuations (no longer autonomous). It contributes a ground-state energy ( $\hbar\omega_0$ ) to the total vibration energy:

$$E_{total} = \frac{1}{2} \omega^2 A^2 + \hbar\omega_0 \quad (10)$$

where  $A$  is the forced vibration amplitude. Liquid intrinsic vibration ground-state energy is approximately constant (negligible amplitude fluctuations), consistent with UCST's scale hierarchy axiom.

3. **Particle nature manifestation:** Particles vibrate around fixed equilibrium positions (forced vibration-dominated), unable to move freely. Energy is transferred via vibration (not particle translation), consistent with classical water wave characteristics—*particles oscillate vertically without migrating with wave propagation.*

### Liquid Wave Equation: Classical Water Waves

Liquid water waves are the collective coordinated propagation of particle forced vibrations, transmitted via strong intermolecular passive forces and satisfying the classical three-dimensional water wave equation (derived from UCST active-passive force dynamics and the Navier-Stokes-Fourier equations [36]):

$$\frac{\partial^2 u}{\partial t^2} = v_l^2 \nabla^2 u \quad (11)$$

where  $u(\vec{r}, t)$  is the scalar wave surface displacement field (or scalar wave function),  $v_l$  is the longitudinal liquid elastic wave propagation velocity, and  $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$  is the Laplace operator. Parameter-vibration correlations (linked to UCST macroscopic fluid mechanics [36]) are as follows:

1. **Angular frequency ( $\omega$ ):** Equals the particle forced vibration angular frequency, satisfying the gravity/surface tension dispersion relation  $\omega^2 = gk \tanh(kH)$ . This directly reflects the dominance of passive forces (gravity, intermolecular interactions) in liquid wave motion.
2. **Amplitude ( $A$ ):** Proportional to the forced vibration amplitude, with total wave energy conserved and equal to the sum of all particle forced vibration energies:

$$E_{wave} = \int \frac{1}{2} \rho g u^2 dV = \sum \frac{1}{2} \mu \omega^2 A^2 \quad (12)$$

where  $\rho$  is liquid density and  $dV$  the volume element. This embodies UCST's "open system energy exchange" axiom—liquid systems exchange energy with the environment, while active force-driven intrinsic vibration energy acts as ground-state energy for system equilibrium.

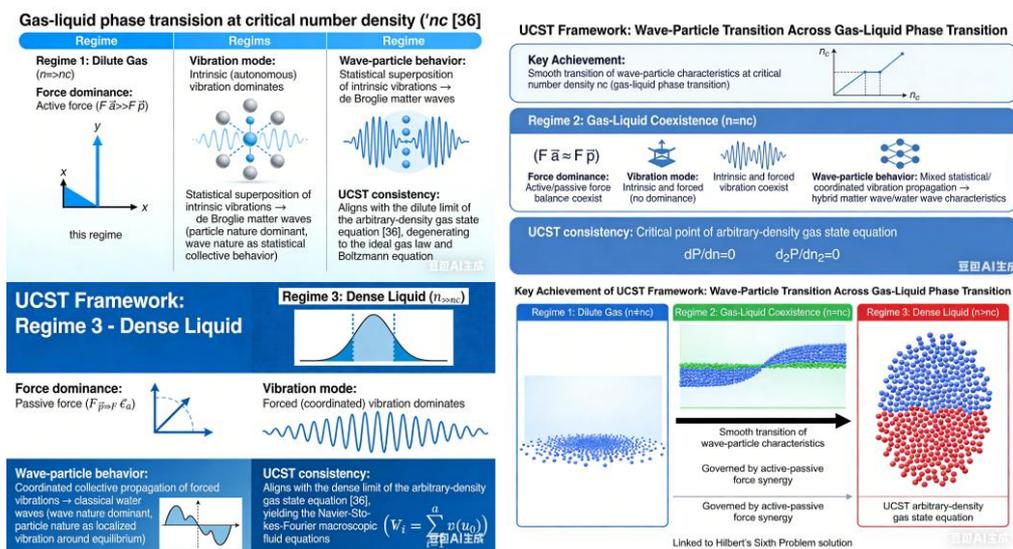
3. **Wave velocity ( $v_l$ ):** Determined by particle vibration transmission speed, dependent on inter-particle interaction intensity (passive force transmission efficiency). Thus:

$$v_l = \sqrt{\frac{B}{\rho_l}} \quad (13)$$

where  $B$  is the liquid bulk modulus and  $\rho_l$  liquid mass density—consistent with experimental observations and UCST-derived macroscopic fluid mechanics [36]. Wave velocity correlates with liquid density/viscosity (passive force proxies), with higher density/viscosity leading to faster wave propagation (stronger passive force transmission).

### Gas-Liquid Phase Transition: Smooth Wave-Particle Characteristic Transition

A key achievement of the UCST framework is its ability to describe a smooth transition of wave-particle characteristics across the gas-liquid phase transition (at critical number density  $n_c$  [36])—eliminating the artificial micro-macro cognitive leap and directly linking wave-particle duality to the phase transition dynamics of the UCST solution to Hilbert's Sixth Problem [36]. This transition is governed by active-passive force synergy and the UCST arbitrary-density gas state equation, with three distinct regimes (Figure 1):



**Fig. 1:** Illustration of the transition mechanism governed by active-passive force synergy in the UCST arbitrary-density gas state equation, with three distinct regimes

#### Regime 1: Dilute Gas ( $n \ll n_c$ )

- **Force dominance:** Active force ( $\vec{F}_a \gg \vec{F}_p$ );
- **Vibration mode:** Intrinsic (autonomous) vibration dominates;
- **Wave-particle behavior:** Statistical superposition of intrinsic vibrations → de Broglie matter waves (particle nature dominant, wave nature as statistical collective behavior);
- **UCST consistency:** Aligns with the dilute limit of the arbitrary-density gas state equation [36], degenerating to the ideal gas law and Boltzmann equation.

#### Regime 2: Gas-Liquid Coexistence ( $n=n_c$ )

- **Force dominance:** Active/passive force balance ( $\vec{F}_a \approx \vec{F}_p$ );

- **Vibration mode:** Intrinsic and forced vibration coexist (no dominance);
- **Wave-particle behavior:** Mixed statistical/coordinated vibration propagation → hybrid matter wave/water wave characteristics (smooth transition of wave-particle nature);
- **UCST consistency:** Critical point of the arbitrary-density gas state equation [36], with  $dP/dn=0$  and  $d^2P/dn^2=0$  (thermodynamic phase transition conditions).

### **Regime 3: Dense Liquid ( $n \gg n_c$ )**

- **Force dominance:** Passive force ( $\vec{F}_p \gg \vec{F}_a$ );
- **Vibration mode:** Forced (coordinated) vibration dominates;
- **Wave-particle behavior:** Coordinated collective propagation of forced vibrations → classical water waves (wave nature dominant, particle nature as localized vibration around equilibrium);
- **UCST consistency:** Aligns with the dense limit of the arbitrary-density gas state equation [36], yielding the Navier-Stokes-Fourier macroscopic fluid equations.

This smooth transition is a direct consequence of UCST's active-passive force cooperative dynamics and the arbitrary-density gas state equation—a *result impossible to achieve with classical theories (dilute gas-only or continuum-only) and a key resolution of the micro-macro divide in wave-particle duality.*

## **THEORETICAL SELF-CONSISTENCY AND ALIGNMENT WITH UCST AXIOMS/HILBERT'S SIXTH PROBLEM**

The UCST interpretation of wave-particle duality is self-consistent and fully aligned with UCST's core axioms (developed for the particle-life hypothesis [15]) and the UCST solution to Hilbert's Sixth Problem [36]. It retains extended consistency with classical mechanics, resolves longstanding puzzles of wave motion origin, and provides a unified physical mechanism for microcosmic and macrocosmic wave-particle duality—complementing the UCST unification of microscopic particle mechanics and macroscopic continuum physics.

### **Alignment with UCST's Dualistic Ontology Axiom**

Wave nature originates from mind-driven active force vibration and ether-mediated passive force interparticle interactions—embodying the "mind-ether" dualistic synergy that is UCST's foundational ontological construct [15].

This dual-origin mechanism breaks free from materialistic monism limitations, as wave-particle duality is no longer a paradox but a natural consequence of the two complementary components of all particle-life entities (mind/ether). This aligns with Price & Wallace's dualistic ontologies in complex quantum systems [40] and the UCST solution to Hilbert's Sixth Problem [36], which also relies on dualistic ontology to unify micro and macro physics.

### Alignment with UCST's Force Classification Axiom

Active forces dominate gas particle intrinsic vibration (the origin of de Broglie matter waves), while passive forces dominate liquid particle forced vibration (the origin of classical water waves). Force synergy and dominance transition explain the gas-liquid differences in wave-particle duality, providing a unified physical basis for microscale matter waves and macroscale water waves. This aligns with the UCST active-passive force model [36], the core dynamical construct for the re-proof of Hilbert's Sixth Problem, and ensures consistency between wave-particle duality and the unification of particle and continuum mechanics.

### Alignment with UCST's Concept Clarification Axiom

UCST rejects "vacuum" as a physical entity, positing gas/liquid media as ether-visible particle mixtures. Wave propagation via matter (ether/visible particles) wave transmission avoids the classical field theory's "action at a distance" paradox, consistent with the local propagation logic in both the gaseous matter wave equation and liquid elastic wave equation. This aligns with the UCST recontextualization of the ether [22] and the solution to Hilbert's Sixth Problem [36], which also uses the ether as the medium for force/vibration transmission to unify micro and macro physics.

### Alignment with UCST's Mass Definition Axiom

UCST defines mass as a coordinate-independent measure of matter amount (intrinsic, vibration/wave-independent). The gaseous particle momentum ( $\vec{p}=m\vec{v}$ )-wave number  $k$  correlation (revised de Broglie relation  $p=2\hbar k$ ) does not involve mass-energy conversion, aligning with UCST's rejection of relativistic mass-energy equivalence for gas-liquid systems [15]. This ensures consistency with classical mechanics (the foundation of the UCST solution to Hilbert's Sixth Problem [36]) and reinforces that energy is a particle vibration property (not mass transformation) in gas-liquid wave-particle duality.

### Consistency with Classical Mechanics and Bohmian Mechanics

The UCST framework retains extended consistency with classical mechanics by preserving its vibration-wave correlation logic [41-43] while expanding its scope to include particle life-like properties and active-passive force dynamics. For the dilute gas limit (classical kinetic theory's valid regime), it degenerates to de Broglie's matter wave theory and Planck's energy quantum hypothesis; for the dense liquid limit (classical continuum mechanics' valid regime), it degenerates to the classical water wave equation and Navier-Stokes-Fourier equations [36]. At the same time, UCST resolves the longstanding quantum mechanics puzzle of wave motion's intrinsic origin—a question unaddressed by materialistic monism. Wave nature is not a mysterious quantum property but a collective propagation of particle vibrations (active/passive) via the ether medium, with clear physical mechanisms and mathematical linkages to particle properties (vibration frequency, force dominance). This provides a causal explanation for wave-particle duality that is missing from orthodox quantum mechanics and aligns with the "wave and particle" framework of de Broglie/Bohm [7, 34, 32].

## Linkage to the UCST Solution of Hilbert's Sixth Problem

The UCST interpretation of wave-particle duality is an essential complement to the UCST re-proof of Hilbert's Sixth Problem [36]:

1. The re-proof unifies microscopic particle mechanics and macroscopic continuum physics via the arbitrary-density gas state equation and active-passive force dynamics;
2. This paper unifies microcosmic and macrocosmic wave-particle duality via the same active-passive force dynamics and phase transition conditions, linking wave-particle behavior to the density-force dominance relation that is the core of the re-proof.

Together, these two results achieve a complete unification of the two core challenges of Hilbert's Sixth Problem: the micro-macro divide in particle/continuum mechanics and the micro-macro divide in wave-particle duality. This unification is only possible via UCST's dualistic ontology and active-passive force dynamics, which abandon classical idealizations and account for real particle behavior in gas-liquid systems.

## SUMMARY AND CONCLUSIONS

### Main Conclusions

Based on the UCST particle-life hypothesis, dualistic ontology, active-passive force cooperative dynamics [15], and the latest UCST-based re-proof of Hilbert's Sixth Problem [36] (which achieves rigorous unification of microscopic particle mechanics and macroscopic continuum physics), this paper constructs a novel, self-consistent interpretive framework for wave-particle duality in gas-liquid systems. This framework resolves the longstanding essential controversy of wave-particle duality and the micro-macro descriptive disconnect, with core conclusions as follows:

1. **Wave-particle duality is an intrinsic, coexistent property of particle-life entities:** All particles (micro/macro) possess life-like properties derived from UCST's "ether-mind" dualistic ontology. Particle nature originates from ether-based material entities (tangible carriers), while wave nature arises from the collective propagation of two vibration modes—mind-driven active vibrations and environment/interaction-induced passive vibrations—via the ether medium. This "wave and particle" framework aligns with de Broglie/Bohm and breaks free from materialistic monism limitations, providing a causal physical mechanism for wave motion that is missing from orthodox quantum mechanics and classical theory.
2. **Gaseous wave-particle duality:** This is the active force-dominated matter waves. In low-density gases (weak intermolecular passive forces), particle motion is active force-dominated. Gaseous wave motion is the statistical superposition of numerous particle intrinsic vibrations, forming de Broglie matter waves consistent with Planck's energy quantum hypothesis. A revised de Broglie relation ( $p=2\hbar k$ ) is derived from UCST active force dynamics, with wave parameters directly linked to particle vibration characteristics. This regime aligns with the dilute limit of the UCST arbitrary-density gas state equation [36], degenerating to classical kinetic theory and quantum mechanics.

3. **Liquid wave-particle duality:** This is the passive force-dominated classical water waves. In high-density liquids (strong intermolecular passive forces), particle motion is passive force-dominated. Liquid wave motion is the coordinated collective propagation of particle forced vibrations, forming classical water waves that satisfy the traditional wave equation and UCST-derived Navier-Stokes-Fourier macroscopic fluid equations [36]. Intrinsic vibration persists as a constant ground-state energy, and wave parameters are determined by medium passive force constraints (density, viscosity, gravity). This regime aligns with the dense limit of the UCST arbitrary-density gas state equation [36], degenerating to classical continuum mechanics.
4. **Smooth gas-liquid wave-particle transition via force synergy:** The UCST active-passive force model and arbitrary-density gas state equation [36] enable a continuous, smooth transition of wave-particle characteristics across gas, gas-liquid coexistence, and liquid phases (at critical number density  $n_c$ ). This transition is governed by number density and force dominance, eliminating the artificial micro-macro cognitive leap and linking wave-particle duality to the phase transition dynamics of the UCST solution to Hilbert's Sixth Problem [36].
5. **Unified micro-macro wave-particle duality and alignment with Hilbert's Sixth Problem:** This framework achieves two key theoretical advancements: (1) it extends classical mechanics (retaining vibration-wave correlation logic) while incorporating particle life-like properties to expand its scope to gas-liquid systems; (2) it links wave-particle duality to particle life-like attributes and active-passive force vibration-wave transmission mechanisms, resolving the longstanding puzzle of wave motion's intrinsic origin. Most importantly, it unifies discrete microscopic particle (gas) and continuous macroscopic medium (liquid) wave-particle duality descriptions—an essential complement to the UCST unification of microscopic and macroscopic physics (Hilbert's Sixth Problem [36]). Together, these results provide a self-consistent physical mechanism and mathematical logic for reconciling wave-particle duality across all scales in gas-liquid systems.

### Future Research Directions

Future research will build on this framework and the UCST solution to Hilbert's Sixth Problem [36] with two key focus areas:

1. **Experimental validation:** Test UCST's core predictions for wave-particle duality, including the revised de Broglie relation ( $p=2\hbar k$ ) via vibration frequency shifts in ultra-low density gases, the link between liquid wave velocity and passive force intensity (density/viscosity), and the smooth wave-particle characteristic transition at the gas-liquid critical point ( $n_c$ ).
2. **Extension to solid-state systems:** Extend the UCST wave-particle duality framework to solid-state systems (crystals, amorphous solids) to explore the universality of UCST wave-particle duality across all condensed matter phases. This will involve extending the active-passive force model to solid-state intermolecular forces (covalent/ionic bonds) and deriving the wave-particle characteristics of solid-state phonons (lattice vibrations)—a natural next step in the UCST unification of micro and macro physics.

The UCST framework for wave-particle duality represents a paradigm shift in physics, as it abandons classical idealizations and materialistic monism to provide a unified, causal explanation for wave-particle behavior across gas-liquid systems. Its alignment with the UCST solution to Hilbert's Sixth Problem [36] further cements its role as a powerful new theoretical tool for resolving the longstanding micro-macro divides in physics.

### Author Contributions

This is a single-author paper. All conceptualization, methodology, formal analysis, writing, and revision were conducted by the sole author.

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### Conflicts of Interest

The author declares no conflicts of interest. The funder had no role in the design of the study, in the writing of the manuscript, or in the decision to publish the results.

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