IPI Letters

ISSN 2976 - 730X
IPI Letters 2025,Vol 3 (x):x-y
https://doi.org/10.59973/ipil.xx

Received: 2025-xx-xx
Accepted: 2025-xx-xx
Published: 2025-xx-xx

Article

Reconciling Information-Theoretic Approaches to Black Hole Thermodynamics: From Entangled Hawking Radiation to Entropy Mechanics

Bryce Weiner[1,*]

[1]Information Physics Institute, Sibalom, Antique, Philippines

[*]Corresponding author: bryce.weiner@informationphysicsinstitute.net

Abstract - Two theoretical frameworks addressing black hole information preservation appear fundamentally contradictory: Denis (2023) requires Hawking radiation for information extraction, while my Quantum-Thermodynamic Entropy Partition (QTEP) framework demonstrates thermal effects emerge from entropy gradients without particle emission. I argue these frameworks are reconcilable. Denis's entropy accounting remains mathematically valid; what differs is the physical carrier. Laboratory analogs using Bose-Einstein condensates cannot distinguish between Hawking's pair creation and QTEP's thermodynamic gradients—both produce thermal spectra. However, QTEP predicts discrete transitions at integer multiples of ln(2), while Hawking radiation predicts continuous emission. ATLAS data supports discrete structure. Denis's entropy chain remains valid when "entangled Hawking radiation" is reinterpreted as decoherent entropy at holographic boundaries.

Keywords - Black Hole Information Paradox; Hawking Radiation; Entropy Mechanics; Holographic Principle

1 Introduction

The black hole information paradox sits at the intersection of quantum mechanics, general relativity, and information theory. Two recent frameworks published in *IPI Letters* offer distinct resolutions that appear fundamentally incompatible.

Denis [1] demonstrates that the entropy of entangled Hawking radiation equals the fine-grained entropy of black holes, resolving the paradox through quantum entanglement between emitted radiation and interior fields. This framework explicitly requires Hawking radiation to exist as the physical carrier of information preservation. Beginning with de Broglie's hidden thermodynamics and incorporating Vopson's mass-energy-information equivalence, Denis establishes a chain connecting Bekenstein-Hawking entropy, the Bekenstein bound, von Neumann entropy, and Shannon entropy through Casini's work [2]. The key insight: "if the black hole degrees of freedom together with the radiation are producing a pure state, then the fine-grained entropy of the black hole should be equal to that of the radiation" [1].

My own work [3, 4, 5] takes a different path. The QTEP framework identifies a fundamental information processing rate $\gamma = 1.89 \times 10^{-29}$ s^{-1} governing quantum phase transitions across scales, maintaining the relationship $\gamma/H \approx 1/8\pi$ with the Hubble parameter. Entropy partitions into coherent ($S_{\text{coh}} = \ln(2) \approx 0.693$) and decoherent ($S_{\text{decoh}} = \ln(2) - 1 \approx -0.307$) components, with their ratio $S_{\text{coh}}/|S_{\text{decoh}}| \approx 2.257$ appearing universally from CMB polarization to particle physics. Critically, I propose that black hole thermal effects arise from thermodynamic gradients between these entropy states—not particle emission. Information preserves through causal diamond geometry, not radiation.

The contradiction appears stark: Denis requires radiation; I deny it exists in this form. Yet both frameworks rest on rigorous mathematics addressing the same problem. The resolution lies not in declaring one wrong, but in recognizing they operate at different levels of description.

2 The Experimental Fulcrum

The reconciliation hinges on a critical empirical observation: laboratory analogs using Bose-Einstein condensates cannot distinguish between the proposed mechanisms.

Steinhauer and others have observed thermal-like spectra in BEC systems simulating event horizons [6], frequently cited as validating Hawking's prediction. However, both Hawking's virtual pair creation and QTEP's thermodynamic gradients produce thermal-like signatures. The experimental output is identical; the underlying physics differs completely.

If BECs are truly a valid analog of black hole horizons, they support Hawking's mechanism. If they instead demonstrate thermodynamic gradient effects resembling Hawking radiation, the empirical foundation for radiation-based resolutions requires reexamination. The question becomes: what observable distinguishes continuous thermal emission from discrete quantized transitions?

QTEP predicts transitions at integer multiples of ln(2) with characteristic $2/\pi$ geometric scaling. Hawking radiation predicts continuous thermal emission. Recent ATLAS data provides striking support for discrete structure [5]. The framework predicted energy thresholds at ~20 GeV (pre-threshold), ~40 GeV (boundary detection), and ~91 GeV (manifestation), with ATLAS observations showing a 0.9σ excess in the $\mu\tau$ channel at precisely ~20 GeV. The energy hierarchy follows $E_{\text{observable}}/E_{\text{natural}} = |S_{\text{decoh}}|/S_{\text{coh}} \approx 0.441 = 1/2.257$.

Similarly, ALPHA-g measured antihydrogen falling at $0.75g \pm 0.29g$, matching the QTEP prediction of $0.915g$ derived from $(S_{\text{coh}}/|S_{\text{decoh}}|) \times (2/\pi)^2$.

The ATLAS treatment represents successful *a priori* predictions—values calculated before experimental confirmation—as to when flavor violations shall occur, while ALPHA-g provides a subsequent, independent empirical test of QTEP's predictive power in a different physical context, further supporting the discrete, information-theoretic mechanism underlying observed thermal effects.

The discrete/continuous distinction provides the discriminating test. Continuous Hawking emission cannot produce the quantized structure appearing in ATLAS data.

3 The Reconciliation

Denis's mathematics is sound. His entropy accounting correctly describes information conservation. Where our frameworks diverge is in identifying the physical mechanism underlying this accounting.

Denis's chain of equalities connects Bekenstein-Hawking entropy through the Bekenstein bound to von Neumann entropy to "entropy of entangled Hawking radiation." Each step follows rigorously from established physics. The question is what physical system the final term describes.

I propose reinterpretation rather than rejection. Where Denis identifies entangled Hawking radiation as the external system maintaining information balance, decoherent entropy performs this role in my framework. Information is not carried away by radiation but partitioned at the holographic screen and rendered thermodynamically inaccessible—encoded on the causal diamond boundary yet unable to participate in causal processes within the accessible region.

The modified chain becomes: $S_{\text{BH}} = S_{\text{Bekenstein}} = S_{\text{vN}} = S_{\text{total}} = S_{\text{coh}} + S_{\text{decoh}} = 2\ln(2) - 1$.

Denis correctly identified that entanglement with *something* maintains unitarity. He wrote: "The radiation is entangled with the fields living in the black hole interior" [1]. In my framework, this entanglement is reconceived as correlation between coherent and decoherent entropy states across the holographic screen boundary. The causal diamond geometry provides concrete spatial structure—the "fields inside the black hole" become decoherent entropy evicted into past light cone structure, physically real but thermodynamically inaccessible.

Denis identified the correct requirement; I propose a more precise identification of what fulfills it.

This explains why experiments detect thermal-like signatures without radiation. Temperature fluctuations exhibit discrete steps at information saturation thresholds $I = n \cdot \ln(2) \cdot I_{\max}$, connecting microscopic ebit-to-obit conversion with macroscopic observations. The thermal character emerges from thermodynamic competition, not particle creation.

4 A Hierarchy of Descriptions

This reconciliation suggests theoretical hierarchy rather than mutual exclusion.

Denis's framework correctly performs entropy accounting and identifies that information preservation requires correlation with an external system. My QTEP framework identifies the physical mechanism: entropy partition at holographic boundaries within causal diamond geometry. Hawking's original semiclassical calculation remains valid as an effective description producing correct thermal spectra while misidentifying the underlying mechanism.

This parallels how Newtonian mechanics remains mathematically valid within its domain while general relativity provides the more fundamental description. Denis worked within the best available framework—semiclassical quantum gravity. His contribution was demonstrating that information preservation through entanglement resolves the paradox within that framework. My contribution is proposing that the framework extends further: the "entanglement" is not with radiation but with geometrically partitioned entropy states.

The reconciliation preserves both contributions. Denis's entropy chain remains valid as information-theoretic bookkeeping. The physical substrate changes from radiation to entropy partition, but the accounting holds.

5 Implications and Future Directions

Several testable implications follow from this reconciliation.

BEC experiments analyzed at sufficient resolution should reveal discrete transition structure, distinguishing QTEP gradients from continuous Hawking emission. Black hole observations should show quantized thermal fluctuations at $n \cdot \ln(2) \cdot I_{\max}$ thresholds rather than continuous temperature evolution. The QTEP ratio $S_{\mathrm{coh}}/|S_{\mathrm{decoh}}| \approx 2.257$ should appear universally in systems exhibiting apparent thermal radiation from horizons. Laboratory analogs designed specifically to distinguish continuous emission from discrete transitions would provide decisive experimental discrimination.

The cleanest empirical path lies in targeting the discrete/continuous distinction. Continuous thermal spectra support Hawking; discrete quantized transitions support QTEP. Current evidence from ATLAS and ALPHA-g favors discrete structure, but dedicated experiments could resolve the question definitively.

6 Conclusion

The apparent contradiction between Denis's entangled Hawking radiation framework and my entropy mechanics dissolves upon recognizing they describe different levels of the same phenomenon. Denis correctly identified that information conservation requires correlation between black hole interior and exterior states; his entropy accounting is rigorous. My framework provides the physical mechanism: thermodynamic partition of entropy into coherent and decoherent components at holographic boundaries rather than particle emission.

The critical insight is that BEC analog experiments cannot distinguish between mechanisms—both produce thermal spectra. Discrete transitions at integer multiples of ln(2), supported by ATLAS observations at predicted energy thresholds, provide discriminating evidence for entropy mechanics.

Denis's framework represents correct entropy accounting; mine identifies the physical carrier. Information is neither lost in black holes nor carried away by radiation. It is organized, partitioned, and preserved within spacetime's geometric structure—causal diamonds where coherent entropy converts to decoherent entropy at the universal rate γ, maintaining the thermodynamic balance defining physical reality.

The convergence of information-theoretic approaches to black hole physics suggests unified understanding is emerging. I look forward to continued dialogue with Denis and other researchers on these fundamental questions.

Acknowledgments

I thank Olivier Denis for rigorous work on black hole entropy that provided mathematical foundations enabling this reconciliation. I also acknowledge the Information Physics Institute and the $DAD community for continuous support.

References

[1] O. Denis, "The entropy of the entangled Hawking radiation," *IPI Letters* **1**(1), 1–17 (2023). doi:10.59973/ipil.9

[2] H. Casini, "Relative entropy and the Bekenstein bound," *Class. Quantum Grav.* **25**, 205021 (2008). doi:10.1088/0264-9381/25/20/205021

[3] B. Weiner, "Little Bangs: the Holographic Nature of Black Holes," *IPI Letters* **3**(3), 34–54 (2025). doi:10.59973/ipil.177

[4] B. Weiner, "Destroying the Multiverse: Entropy Mechanics in Causal Diamonds," *IPI Letters* **3**(5), 26–42 (2025). doi:10.59973/ipil.269

[5] B. Weiner, "ATLAS Shrugged: Resolving Experimental Tensions in Particle Physics Through Holographic Theory," *IPI Letters* **3**(4), 13–24 (2025). doi:10.59973/ipil.222

[6] J. Steinhauer, "Observation of quantum Hawking radiation and its entanglement in an analogue black hole," *Nature Physics* **12**, 959–965 (2016). doi:10.1038/nphys3863