Emergence of Quantum Mechanics: Fermions, Bosons and Pauli Exclusion

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Abstract

Paper VI [7] presented the hypothesis that the quantum mechanical wavefunction is the compression signature of nature: the universe is a finite, static bitstring of n bits, and the path an internal observer experiences is the one that compresses best under a complex-valued spectral codec. The present paper supports this hypothesis with six experiments implemented in Python and included as supplementary material. We show that a photon-like boson emerges as the compression residual of a purely fermionic system, without any interaction term introduced by hand. All essential features of quantum mechanics are recovered: Born rule, Pauli exclusion, particle–antiparticle pairing, and the virtual propagator. The central result is an analytically exact theorem: for a single fermion in superposition between two sites, the off-diagonal (boson) amplitude is $\|B(\theta)\| = \sin(2\theta)/\sqrt{2}$, independent of system size, site separation, and encoding. This equals $\sqrt{2\,P(1-P)}$, the interference term of the Born rule, made visible as a matrix norm. These results suggest that quantum mechanics is not a foundational layer of reality but an emergent description — the story an observer tells about fermions sampled from a compression codec.

Contents

1 Introduction

Why does the universe exhibit wave-like behaviour at small scales? Standard quantum mechanics takes the wavefunction as a primitive object and the Born rule as a postulate. The present paper pursues a different direction, building on the informational framework of Papers I–VI [8, 5, 6, 9, 7, 10]: the universe is a finite, static collection of n bits, and an internal observer experiences a path through its 2^n configurations. The path selected is the one that compresses best. The wavefunction is the codec.

The analogy that makes this precise is video compression. In MPEG, a video is encoded not as a sequence of raw frames but as a sequence of compressed descriptions. The compression basis is the Discrete Cosine Transform (DCT) — a real-valued basis of smooth periodic functions. The complex-valued wavefunction of quantum mechanics is the natural generalisation: it is the simplest continuous, smooth, periodic codec for a universe whose configurations vary in both amplitude and phase.

Under this interpretation, particles fall into two classes that correspond directly to the two components of a compressed video:

- **Fermions** are pixels: discrete, localised, non-overlapping by construction. Two pixels cannot occupy the same site — not by postulate, but because a pixel is a site. Pauli exclusion is a pixel axiom.
- **Bosons** are compression residuals: the off-diagonal entries of the density matrix $\rho = |\psi\rangle\langle\psi|$ that remain after the per-site (fermionic) diagonal is removed. They are what the codec records when a fermion moves.

The actual causal chain is:

$$\text{wavefunction (codec)} \xrightarrow{\text{Born rule sampling}} \text{fermion configurations (pixel frames)}$$

An observer who sees only the pixel outputs, not the codec, invents a story:

$$\text{fermion} \xrightarrow{\text{“virtual boson exchange”}} \text{fermion.}$$

The boson is a compression residual made into a noun. It is not wrong as an effective description, but it is not fundamental. In MPEG, macroblocks do not exchange anything; the DCT coefficients just are what they are. If one watched only the decoded pixels and tried to explain their correlations without knowing about DCT, one would invent something that looks exactly like boson exchange.

The six experiments in this paper test whether this picture is self-consistent and quantitatively correct.

2 Experiment 1: Minimal Video

Python: minimal_video.py

We encode 2-frame videos of a 2×2 pixel grid as complex wavefunctions:

$$\psi(x) = f_0(x) + i\, f_1(x),$$

where frame 0 is the real part and frame 1 is the imaginary part. Each video is scored by the spectral complexity C_s of ψ — the information-theoretic cost of its Fourier representation. The off-diagonal density matrix $B = \rho - \mathrm{diag}(\rho)$ is computed for all $2^8 = 256$ possible two-frame videos, and its Frobenius norm $\|B\|$ is taken as the boson signal.

Results

The minimum-complexity states ($C_s = 0$) — uniform frames, all pixels identical — already carry the maximum boson signal $\|B\| = \sqrt{3}/2$. The maximally anti-correlated configuration (checkerboard transition, flipping to its complement) also achieves $\|B\| = \sqrt{3}/2$ at $C_s = 3$:

$$f_0 = \begin{pmatrix} 1 & 1 \\ 0 & 0 \end{pmatrix} \longrightarrow f_1 = \begin{pmatrix} 0 & 0 \\ 1 & 1 \end{pmatrix}.$$

The vacuum (zero information content) and the maximally structured transition produce identical boson signal.

Conclusion: The boson signal tracks something topological about the pixel transition, not its complexity. This motivates a structural analysis of the off-diagonal matrix.

3 Experiment 2: Boson Structure

Python: boson_structure.py

Rather than measuring $\|B\|$ alone, we analyse the structure of B:

- *Symmetry:* is B symmetric (spin-0 candidate) or antisymmetric (spin-1 candidate)?
- *Propagation:* does the dominant eigenvector of B resemble a plane wave?
- *Quantisation:* is $\|B\|$ a simple rational multiple of 2^{-C_s}?

Results

For the video $(1, 2)$ — a single fermion hopping from site 0 to site 1 — the boson matrix is purely antisymmetric, not approximately but exactly. Its eigenvalues are $\pm 1/2$, symmetric about zero. The forward hop $(1, 2)$ and reverse hop $(2, 1)$ produce identical boson structure with opposite momenta $k = \pm 0.157$, exactly as expected from a particle–antiparticle pair.

For the block hop $(3, 12)$ — two fermions moving together,

$$f_0 = \begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix} \longrightarrow f_1 = \begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix},$$

the boson has a longer wavelength and lower effective momentum, consistent with a heavier or composite mediator.

Conclusion: The compression residual of a single fermion hop is purely antisymmetric, has definite momentum, and pairs with its time-reverse into a particle–antiparticle pair. No interaction term was introduced; these properties follow from the codec structure alone.

4 Experiment 3: Scaling

Python: scaling_1.py, scaling_2.py

We scale to longer chains ($L = 4, 6, 8, 12, 16$) and more frames, testing whether momentum quantisation $k = 2\pi m/L$ holds and whether the boson properties depend on system size.

The key result — analytically exact

For any single fermion hop from site 0 to site d, regardless of L or d:

$$\psi = \frac{1}{\sqrt{2}}(e_0 + i\, e_d).$$

The boson matrix has exactly two non-zero entries:

$$B_{0,d} = +\tfrac{i}{2}, \qquad B_{d,0} = -\tfrac{i}{2}.$$

For the nearest-neighbour hop ($d = 1$, $L = 4$) this reads explicitly:

$$B \ = \begin{pmatrix} 0 & +\frac{i}{2} & 0 & 0 \\ -\frac{i}{2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}.$$

The same 2×2 antisymmetric block $\left(\begin{smallmatrix} 0 & +i/2 \\ -i/2 & 0 \end{smallmatrix}\right)$ is embedded at positions $(0, d)$ and $(d, 0)$ for any hop distance d and any chain length L; all other entries are zero. The matrix is always purely antisymmetric, always has eigenvalues $\pm 1/2$, and the phase of $B_{0,d}$ is always $-\pi/2$, giving:

$$k \cdot d = -\frac{\pi}{2} \quad \Longrightarrow \quad k = -\frac{\pi}{2d}.$$

This is not a plane-wave momentum but a phase relationship between the two fermion sites: the boson encodes exactly one number, the $\pi/2$ phase shift between where the fermion was and where it went. A quarter-turn in phase space is the defining property of a propagator. This is what a virtual photon does in QED.

Conclusion: The compression residual of a single fermion hop is an antisymmetric, purely imaginary, $\pm 1/2$-eigenvalued object carrying a universal $\pi/2$ phase, independent of chain length and hop distance.

5 Experiment 4: Two-Fermion Hops

Python: two_fermion_hop.py

We test whether the universal $\pi/2$ phase breaks for two fermions, and whether the breaking has physical meaning.

Result 1: Partial survival of universality

Every two-fermion boson matrix contains entries with phase $-\pi/2$, inherited from the individual single-fermion hops. It also acquires new phases 0 and $+\pi/2$, corresponding to inter-fermion correlations with no single-particle analogue. The two-fermion boson is a superposition of single-hop bosons plus an interaction residual.

Result 2: Path independence

Fermions crossing (passing through each other) produce an identical boson matrix to fermions moving in the same direction. The codec records only initial and final pixel configurations, not trajectories. Path independence emerges for free.

Result 3: Pauli exclusion as zero compressibility

Two fermions assigned to the same site produce a wavefunction $\psi \propto e_j$ (localised on a single site), for which $B = 0$ exactly. The density matrix of a single-site state is $\rho_{ik} = |\alpha|^2 \delta_{ij}\delta_{kj}$, which vanishes off-diagonal for $i \neq k$ since both $i = j$ and $k = j$ cannot hold simultaneously. Double occupancy produces no boson: it has zero compression residual and is informationally invisible. Pauli exclusion is not a law imposed on the system; it is the statement that double occupancy has nothing for the codec to encode.

6 Experiment 5: Pauli Exclusion and the Scope of the Encoding

Python: pauli_as_zero_residual.py

We verify that $B = 0$ for stationary fermions is exact and encoding-independent, and clarify the scope of the single-fermion codec.

The encoding question

When a single wavefunction is used to encode two stationary fermions at sites i and j:

$$\psi = (e_i + e_j) + i(e_i + e_j) = (1 + i)(e_i + e_j),$$

the result is not localised on a single site. This superposition has non-zero off-diagonal entries even with no motion, giving $\|B\| \neq 0$.

Conclusion: The single-wavefunction codec is a *one-fermion* codec: each wavefunction encodes the state of one fermion across two time slices. A system of N fermions requires N wavefunctions, one per particle. Encoding two particles into one wavefunction conflates a two-particle configuration with a single delocalised fermion.

Resolution

Under the correct one-fermion-per-wavefunction encoding:

- $B = 0$ for any stationary single fermion, for any phase or amplitude, across all chain lengths. This is analytically exact.
- $\|B\| = 1/\sqrt{2}$ for any single fermion hop, independent of hop distance and system size.
- $\|B\| = \sin(2\theta)/\sqrt{2}$ for a fermion in superposition $\psi(\theta) = \cos\theta\, e_i + i \sin\theta\, e_j$, where θ interpolates between stationary ($\theta = 0$) and mid-hop ($\theta = \pi/4$) and back to stationary ($\theta = \pi/2$).

The multi-fermion case requires a tensor product of single-fermion wavefunctions. This is consistent with standard quantum mechanics and is not a limitation of the framework.

Results

Configuration	$\|B\|$	**Reason**
Single fermion, stationary	0 (exact)	$\psi \propto e_j$, off-diagonal forced to zero
Single fermion, any hop	$1/\sqrt{2}$ (exact)	Universal, $-\pi/2$ phase
$\psi(\theta) = \cos\theta\, e_i + i \sin\theta\, e_j$	$\sin(2\theta)/\sqrt{2}$	Sharp onset, no threshold

7 Experiment 6: The θ-Scaling Theorem

Python: theta_scaling.py

We verify the $\sin(2\theta)/\sqrt{2}$ formula analytically and confirm it holds across all chain lengths and site separations.

Proof

For $\psi(\theta) = \cos\theta\, e_i + i\sin\theta\, e_j$ (normalised, $i \neq j$), the density matrix $\rho = |\psi\rangle\langle\psi|$ has the block structure (showing only the i, j subspace, all other entries zero):

$$\rho\big|_{ij} = \begin{pmatrix} \cos^2\theta & -\frac{i}{2}\sin 2\theta \\ +\frac{i}{2}\sin 2\theta & \sin^2\theta \end{pmatrix}.$$

Removing the diagonal gives the boson matrix restricted to the same subspace:

$$B\big|_{ij} = \begin{pmatrix} 0 & -\frac{i}{2}\sin 2\theta \\ +\frac{i}{2}\sin 2\theta & 0 \end{pmatrix}.$$

In full, the components are:

$$\begin{aligned} &\rho_{ii} = \cos^2\theta, \quad \rho_{jj} = \sin^2\theta, \\ &\rho_{ij} = \psi_i\psi_j^* = \cos\theta \cdot (-i\sin\theta) = -\tfrac{i}{2}\sin 2\theta, \\ &\rho_{ji} = +\tfrac{i}{2}\sin 2\theta. \end{aligned}$$

All other entries of ρ are zero since $\psi_k = 0$ for $k \neq i, j$. Therefore:

$$\|B\|^2 = |B_{ij}|^2 + |B_{ji}|^2 = 2\left(\frac{\sin 2\theta}{2}\right)^2 = \frac{\sin^2 2\theta}{2},$$

giving

$$\boxed{\|B(\theta)\| = \frac{\sin 2\theta}{\sqrt{2}}.}$$

This proof uses only the definition $B = \rho - \operatorname{diag}(\rho)$ and the normalisation of ψ. It is independent of L, the separation $|i - j|$, and any overall phase factor on e_j. Numerical verification confirms agreement to within floating-point precision ($< 4 \times 10^{-16}$) for $L \in \{4, 8, 16, 32, 64, 128\}$ and all hop distances.

Connection to Born rule

Let $P = \sin^2\theta$ be the Born-rule probability that the fermion occupies site j. Then:

$$\|B(\theta)\| = \frac{\sin 2\theta}{\sqrt{2}} = \frac{2\sin\theta\cos\theta}{\sqrt{2}} = \sqrt{2}\,\sqrt{P(1-P)}.$$

$\|B\|$ is $\sqrt{2}$ times the geometric mean of the hop and no-hop probabilities. This is the interference term of the Born rule, made visible as a matrix norm. The boson amplitude is not an approximation or an emergent average: it is the exact quantum interference encoded in the density matrix.

Lifecycle of a virtual boson

The formula $\|B(\theta)\| = \sin(2\theta)/\sqrt{2}$ traces the complete lifecycle:

- $\theta = 0$: fermion stationary, $\|B\| = 0$. No boson.
- $\theta = \pi/4$: fermion in equal superposition, $\|B\| = 1/\sqrt{2}$. Boson at maximum amplitude.
- $\theta = \pi/2$: fermion arrived, $\|B\| = 0$. Boson has vanished.

The boson is born when the fermion begins to move, peaks at mid-hop, and vanishes when the fermion arrives. This is the lifecycle of a virtual particle — a propagator in the language of quantum field theory, derived here without postulating field theory.

8 Core Results

The six experiments establish four results, each analytically exact:

1. **Pauli exclusion.** $B = 0$ for any stationary fermion, for any encoding of the form $\psi \propto e_j$. Double occupancy is informationally invisible: zero compression residual, zero boson.
   Proof: $\rho_{ik} = |\alpha|^2 \delta_{ij}\delta_{kj} = 0$ for $i \neq k$. □
2. **Universal boson.** Every single fermion hop produces $\|B\| = 1/\sqrt{2}$, independent of chain length, hop distance, and encoding. The boson carries a universal $-\pi/2$ phase.
3. **Born rule identity.** $\|B(\theta)\| = \sqrt{2\,P(1-P)}$, where $P = \sin^2\theta$ is the Born-rule hop probability. The boson amplitude is the interference term of Born rule.
4. **Virtual propagator.** The boson amplitude follows $\sin(2\theta)/\sqrt{2}$ over the fermion's journey: born at $\theta = 0$, maximum at $\theta = \pi/4$, vanished at $\theta = \pi/2$. This is the propagator of a virtual particle, derived without field theory.

All four results follow from the single definition $B = \rho - \mathrm{diag}(\rho)$ applied to the compressed wavefunction. No interaction terms, coupling constants, or postulated particle species were introduced.

9 Discussion

9.1 Quantum mechanics as an emergent description

The four results above suggest a coherent picture: quantum mechanics is not a foundational layer of reality but the effective description an observer constructs when observing fermions that are sampled from a compression codec.

The wavefunction is not a physical field propagating through space. It is the codec — the algorithm that selects which fermion configuration an observer experiences, given the constraint that the observed path through the 2^n configurations must be the one of minimum description length. Measurement is decompression. The Born rule is Solomonoff induction applied to a complex-valued codec: the probability of outcome j is proportional to the squared amplitude $|\psi_j|^2$ because $|\psi_j|^2$ is the spectral weight assigned to that configuration by the minimum-description-length codec.

Bosons, in this picture, are not fundamental. They are the codec's record of fermion motion, reified into particles by observers who do not know they are watching compressed data. This does not make quantum field theory wrong. It makes it an extraordinarily accurate effective description of compression residuals.

9.2 The 4π structure and spin

The universal $-\pi/2$ phase of the single-hop boson corresponds to a quarter-turn in the complex plane. Four such hops return the phase to its starting point: $4 \times (-\pi/2) = -2\pi$. This is the spinor structure of a spin-1/2 particle: a 2π rotation returns a fermion to its original state only up to a sign, while a 4π rotation is the identity. The $\pi/2$ phase quantisation is not imposed; it follows from the imaginary encoding $\psi = f_0 + if_1$ and the definition of the boson matrix.

9.3 The encoding uniqueness question

The framework relies on the complex exponential $e^{i\omega x}$ as the codec basis. Paper VI [10] argues that this is the minimum-description-length periodic smooth basis: the algorithm ($e^{i\omega x}$) is a fixed one-time cost shared across all wavefunctions, while the per-instance cost is carried entirely by the spectral modes (frequencies), which are unbounded. This is what makes spectral complexity C_s both computable and physically meaningful.

9.4 Relation to existing approaches

Several existing programs seek to derive quantum mechanics from information theory: reconstructions based on information-theoretic axioms [4, 2], the Bayesian/QBist programme [3], and entropic dynamics [1]. The present approach differs in two respects. First, it is constructive: it identifies a specific codec (complex spectral decomposition), a specific complexity measure (C_s), and derives specific quantitative predictions (the $\sin(2\theta)/\sqrt{2}$ theorem) rather than axiomatising quantum mechanics from abstract information principles. Second, it is embedded in the larger cosmological framework of Papers I–V, which derives spacetime geometry, the cosmological constant, and black hole entropy from the same finite bit budget n. Quantum mechanics is not postulated at the bottom of this hierarchy; it emerges at the same level as geometry, from the same codec.

9.5 Limitations

The present experiments use a one-dimensional chain of discrete sites. The extension to three spatial dimensions, continuous space, and the full Fock space of many-fermion systems requires tensor products of single-fermion wavefunctions and a treatment of indistinguishability that goes beyond the scope of this paper. Additionally, the experiments demonstrate the emergence of a photon-like boson from a scalar codec. Whether the model predicts other bosons, e.g. the massive bosons (W, Z, Higgs) and of the gauge structure of the Standard Model are not yet addressed.

10 Future Work

10.1 Many-fermion systems and the Fock space

The single-fermion codec must be extended to N-fermion systems via tensor products. The key question is whether the antisymmetry of the fermionic Fock space — the requirement that $\psi(x_1, x_2) = -\psi(x_2, x_1)$ — emerges from the boson matrix structure or must be imposed separately. The antisymmetry of B found in Experiment 2 suggests it may emerge naturally.

10.2 Connection to the Friedmann equation

Paper VI identified the analytic derivation of the Friedmann equation from the relational scale factor $R(t)$. Worldlines in GR are themselves compressible. An elliptic orbit is a single Fourier mode — the minimum-complexity trajectory consistent with the conserved quantities of the system. PoC to show these most probable path through the 2^n yield objects orbiting each reproducing Keplerian dynamics without a force law.

11 Conclusion

We have shown that a photon-like boson emerges from a purely fermionic system compressed by a complex-valued spectral codec, without postulating interactions, coupling constants, or particle species. The central result is:

$$\|B(\theta)\| = \frac{\sin 2\theta}{\sqrt{2}} = \sqrt{2\,P(1-P)},$$

where $P = \sin^2\theta$ is the Born-rule hop probability. The boson amplitude is the interference term of the Born rule. Pauli exclusion follows from the analytical result $B = 0$ for single-site states. The virtual propagator lifecycle — born, peaked, vanished — follows from the θ-dependence of $\|B\|$.

These results are analytically exact, encoding-independent, and hold for all system sizes and hop distances. They suggest that quantum mechanics is an emergent description: the story an observer constructs to explain fermions that are sampled from a minimum-description-length codec operating on a finite universe of n bits.

Supplementary Material

Python experiments:

- `wavefunction.py` — Wavefunction class with spectral complexity C_s and Solomonoff weight 2^{-C_s}.
- `minimal_video.py` — Minimal 2×2, 2-frame video: enumerate all 256 configurations, compute C_s and boson signal.
- `boson_structure.py`, `boson_structure_2.py` — Symmetry, propagation, and quantisation analysis of the off-diagonal density matrix.
- `scaling_1.py`, `scaling_2.py` — Longer chains ($L = 4$–16), more frames; momentum quantisation test.
- `two_fermion_hop.py` — Two-fermion hops; phase universality, path independence, Pauli exclusion.
- `pauli_as_zero_residual.py` — Encoding scope and analytical proof of $B = 0$ for stationary fermions.
- `theta_scaling.py` — Numerical and analytical verification of $\|B(\theta)\| = \sin(2\theta)/\sqrt{2}$ across all L.

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