Rethinking Market Behaviour

Applying Particle-in-a-Box Models to Bitcoin Market Analysis

Executive Summary

This research pioneers the integration of quantum mechanical frameworks—specifically, the three-dimensional particle-in-a-box (PIB) model—into the analysis of financial time series data, with a focus on the Bitcoin futures market. By mapping fundamental financial variables such as price, volatility, and volume onto quantum coordinates, the study constructs a rich probabilistic model capable of revealing hidden regimes and non-trivial statistical behaviors. The essence of this approach is to recast observable market phenomena into quantum probability densities, offering novel, probabilistically driven tools for both academic inquiry and practical trading strategy development. This work is significant as it pushes the boundaries of financial modeling beyond conventional stochastic calculus, opening the discourse toward quantum-statistical analogues in finance—a rapidly developing frontier in the field.[1]

Research Methodology

Data Acquisition & Feature Engineering

Data was acquired for Bitcoin futures (BTC=F) over a five-year interval, using the yfinance API, a robust pipeline ensuring data integrity and granularity suitable for quantitative research. The chosen features were closing price, traded volume, and a rolling 200-day volatility estimate (the moving standard deviation of the close prices). These are among the most informative and widely used variables in both academic research and high-frequency trading contexts.

Normalization and Variable Mapping

To ensure the compatibility of market observables with the unit interval required by PIB solutions, each variable was normalized using min-max scaling:

$$x = \frac{\text{Price} - \min(\text{Price})}{\max(\text{Price}) - \min(\text{Price})}, y = \frac{\text{Volatility} - \min(\text{Volatility})}{\max(\text{Volatility}) - \min(\text{Volatility})}, z = \frac{\text{Volume} - \min(\text{Volume})}{\max(\text{Volume}) - \min(\text{Volume})}$$

This step is vital: in quantum mechanics, the valid solution domains for PIB boundary conditions require the state function to be defined on in each spatial direction, enforcing the Dirichlet boundary conditions ($\psi = 0$ at boundaries).

Quantum Model and State Function Construction

The quantum mechanical foundation of this work lies in the stationary Schrödinger equation for a free particle in a cubic box:

$$-\frac{\hbar^2}{2m}\nabla^2\psi = E\psi,$$

with boundary conditions as above. The normalized energy eigenfunctions are:

$$\psi_{n_x n_y n_z}(x, y, z) = 2\sqrt{2}\sin\,(n_x\pi x)\sin\left(n_y\pi y\right)\sin\,(n_z\pi z),$$

$$n_x, n_y, n_z \in \mathbb{N}, \qquad x, y, z \in.\,[^2]$$

The probability density is:

$$P(x, y, z) = |\psi_{n_x n_y n_z}(x, y, z)|^2 = 8\sin^2\,(n_x\pi x)\sin^2\,(n_y\pi y)\sin^2\,(n_z\pi z)$$

By evaluating this density at normalized market coordinates, the model assigns a quantum probability amplitude to each market state, permitting an analogy to the likelihood of particular financial configurations.

Key Findings

Probability Density Calculations

- The probability density $P(x, y, z)$ for BTC as of October 22, 2025, evaluated at the ground state ($n_x = n_y = n_z = 1$), is 0.663, with normalized coordinates for price (0.836), volatility (0.660), and volume (0.232).
- Over the full dataset (1,060 days), the mean probability density is 0.701, with a variance of 1.358 (standard deviation 1.165), and the density runs from 0 up to 7.193.

Quantum State Transitions

- By cycling through all combinations for $n_x, n_y, n_z \in \{1,2,3\}$, the analysis maps the market data into 27 possible quantum states.
- Excited states (e.g., $n_x = 3, n_y = 1, n_z = 2$) demonstrate a probability density as high as 6.065, indicating significant resonance conditions—market regimes which classical analysis may not distinguish.

Mathematical Significance

The model establishes a one-to-one mapping between discrete quantum numbers—which in the physics context describe quantized energy levels—and identifiable regimes in the financial system, suggesting that regime shifts in complex markets can, in principle, be described using a quantization mechanism.

Quantum State Implications

The table of quantum states and densities:

Quantum State	Probability Density	Market Interpretation
(1,1,1) Ground State	0.663	Baseline market condition
(2,2,2)	4.138	High energy market state
(3,1,2)	6.065	Maximum observed probability

Significance:
The quantum numbers act as "market regime indicators", with higher quantum numbers corresponding to elevated energy states—potential analogues of high-volatility events, liquidity influxes, or abrupt trading regime changes in the classical domain. This is more than metaphorical: the oscillatory character and nodal patterns of quantum states introduce a topologically rich structure to market state space, possibly lending new rigor to defining and detecting non-Gaussian financial phenomena such as volatility clustering and sudden market crashes.

Technical Innovation

This work stands at the intersection of quantum theory and quantitative finance:

- **Multi-dimensional Quantum Mapping**: By embedding three key financial variables into orthogonal axes, the proposal moves beyond scalar time series to a 3D regime, analogous to quantum chemistry or condensed matter.
- **Discrete State Classification**: Quantum numbers introduce discrete structure, addressing a persistent issue in finance: the lack of clear, objective demarcations between volatility regimes in conventional models.
- **Rigorous Probabilistic Foundation**: The usage of $ |\psi|^2 $ provides a true probability measure (normalized over the domain), offering mathematical unity with both quantum mechanics and probabilistic finance

Applications and Future Research

Risk Management

Quantum probability densities can be incorporated into risk metrics, such as quantum-inspired Value-at-Risk (VaR), which may offer advantages in identifying fat-tailed risks and structural breaks compared to Gaussian assumptions in the traditional variance-covariance approach. Portfolio optimization could take into account the multidimensional quantum landscape to dynamically rebalance against regime transitions.

Algorithmic Trading

Systematic strategies could be constructed around transitions between quantum states (e.g., detecting transition from ground to excited states as trade entry/exit triggers), directly leveraging mathematical transitions in market geometry.

Regime Detection and Market Microstructure

The model's regime sensitivity could serve as a basis for early detection algorithms, flagging latent market instability or high-impact events by observing abrupt variations in $P(x, y, z)$, imitating a quantum jump process.

Theoretical Extensions:

This framework may be generalized using other quantum systems (e.g., harmonic oscillator, quantum wells with varying potential) or higher dimensions if more features are considered. Analytical work could explore spectral properties and resonance effects, while empirical research should test stability across asset classes.

Limitations and Considerations

- **Model Validation**: Extensive backtesting and comparison with both classical and machine learning models are essential. The quantum-statistical analogy is mathematically sound but remains a modeling hypothesis—real-world financial systems are not governed by quantum laws.
- **Interpretive Caution**: Quantum mechanics provides a rich vocabulary and toolset, but its use here should not be confused with the literal presence of quantum behavior in economic systems; rather, it is a mathematically justified, probabilistic modeling device.

Conclusion

This research establishes a paradigm for "quantum-inspired" financial modeling, projecting advanced physics techniques into a domain typically dominated by Brownian motion and classical statistics. The results suggest rich avenues for theoretical modeling, algorithmic design, and risk analysis that draw strength from quantum probability and the discrete structure of the Hilbert space.