A Theory of Complex Adaptive Systems and a Nonlocal Quantum Many-Body Wave Equation

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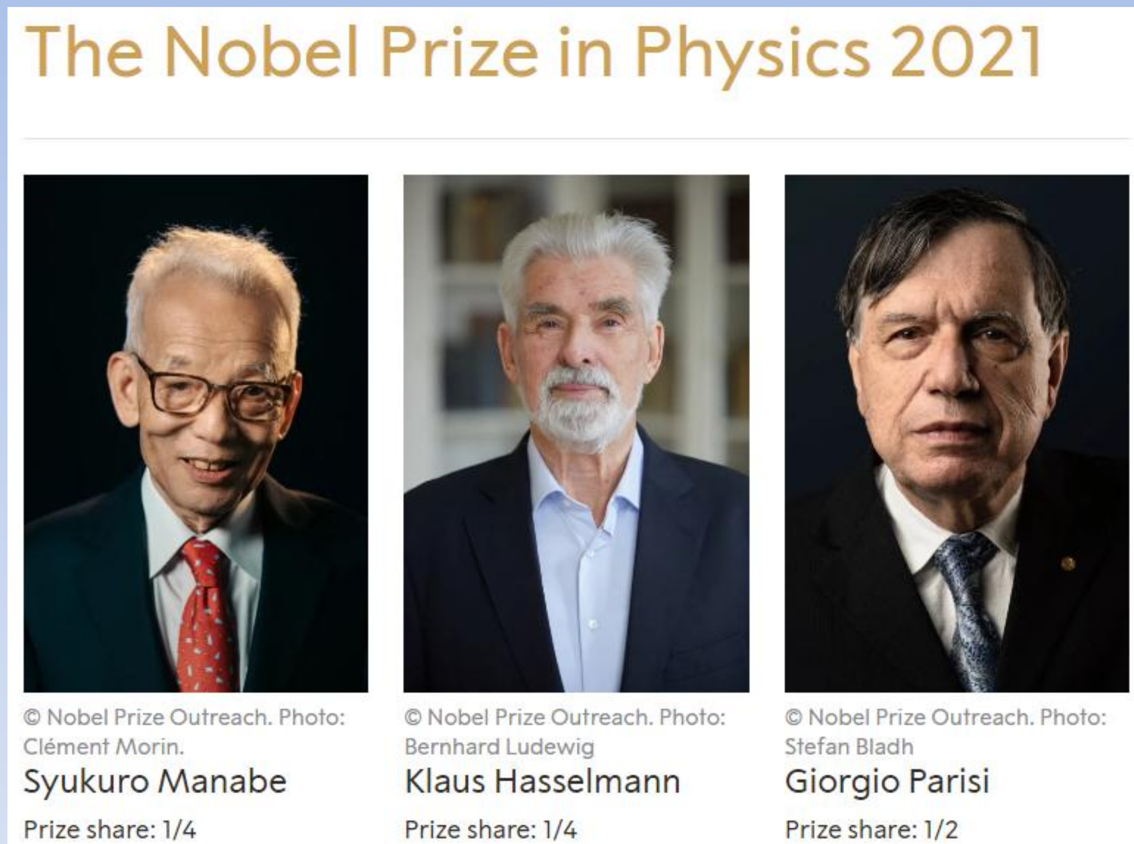
2021 Nobel Prize in Complex Systems



Stephen Hawking: "I think the next century (the 21st century) will be the century of complexity."

All complex systems consist of many interacting particles, parts or agents, emerge hidden patterns, and show uncertainty in an interactive evolution process, cutting across all traditional natural and social sciences disciplines.

Introduction—What

- Complex adaptive systems (CAS) represent a common kernel extracted from complex systems and highlight adaptation and uncertainty in an interactive evolution process (Holland, 1992*;* Carmichael and Hadzikadic, 2019);
- CAS are adaptive, learn in feedback loops, and generate hidden patterns as many individuals or particles interact;
- They can be simulated on massively parallel computers (Holland, 1992);
- **However,** studying CAS, discovering a universal law, and proposing a theory to understand the mechanism of the pattern formation remains highly challenging (Holland, 2006 JSSC) since complex systems are quite different the one from the other one and each complex system is complex in its own way (Parisi, 2022 JP Complex), for example, non-Gaussian distributions in stock market (Shi, 2006) and complex quantum entanglement (He, 2024).

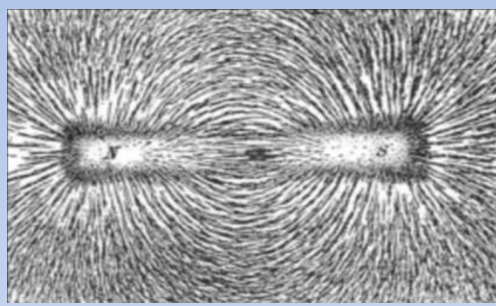
Introduction--Why

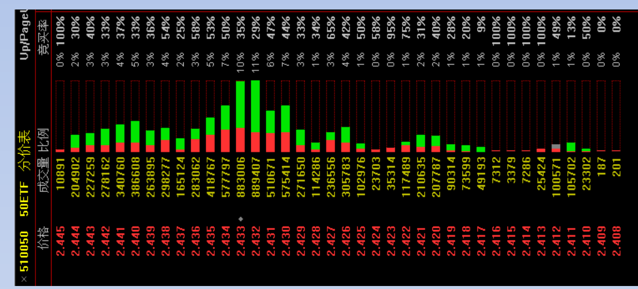
- Some scientists believe that complex systems spanning different disciplines have commonalities and are driven by the exact underlying mechanism (Carmichael and Hadzikadic, 2019; Tao, 2012; Di, 2023);
- Exploring a universal law and proposing a theory for CAS has become a desirable goal (Hernández-López et al., 2024 PRL);
- Stephen Hawking predicted, “I think the next century (the 21st century) will be the century of complexity”;
- Current achievements studying CAS: 1) trading volume-price probability wave equation in financial markets (Shi, 2006 Physica A; Shi et al., 2023 CFRI); 2) nonlocal quantum many-body wave equation in quantum mechanics (Shi et al., 2024 Working Paper).

Introduction—How (1)

- Quantifying the uncertainty of CAS by cumulative observable distribution—a many-body probability wave;
- Defining cumulative observables over a sensitive variable range in a time interval as density momentum and momentum force;
- We find a unified paradigm of CAS for a nonlocal quantum many-body wave equation in quantum mechanics (Shi et al., 2024) and a trading volume-price probability wave equation in the financial markets (Shi, 2006; Shi et al., 2023 CFRI).

Introduction—How (2)





(a) (b)

Fig.1: Density momentum force

- The higher the density of magnetic field lines, the stronger the magnetic field or force at a location (Fig. 1 (a));
- The higher the cumulative trading volume, the more trading preference at a price. The density trading momentum or momentum force is larger (Fig. 1(b)).

Introduction—Findings

- We have energy eigenvalue wave function and interactive eigenvalue (interactively coherent) wave function;
- We find conservation of interaction between density momentum force (repulsive force) and linear potential restoring force (attractive force) in CAS;
- We discover a unified paradigm between a nonlocal quantum many-body wave equation and Schrödinger's wave equation in quantum mechanics.

Introduction—Innovation

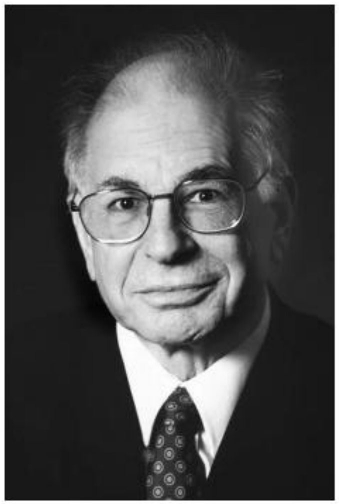
- Innovation:
  - Finding a nonlocal quantum many-body wave equation;
  - providing an innovative and testable interpretation of interactively coherent quantum entanglement when we apply a law of conservation of interaction in complex quantum systems;
  - mathematics and physics are usually applied to study economics and finance. Few explore a reverse application.
- Limitation:
  - it needs further experimental falsification.

Part Two

A Brief Review

A Trading Volume-Price Probability Wave Equation in Finance

Nobel Prizes in Economics



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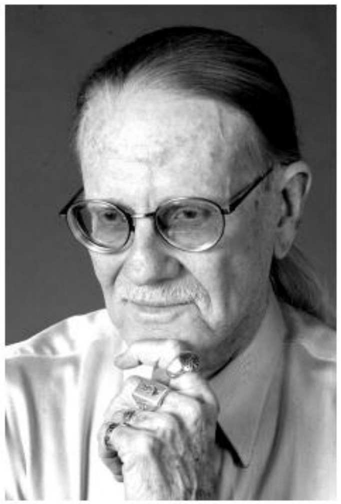
Daniel Kahneman
Prize share: 1/2



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Richard H. Thaler
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Behavioral Economics and Finance

Data Supports for Bounded-Rationality

FIGURE 1

Note: Real Standard and Poor's Composite Stock Price Index (solid line *p*) and *ex post* rational price (dotted line *p**), 1871–1979, both detrended by dividing a long-run exponential growth factor. The variable *p** is the present value of actual subsequent real detrended dividends, subject to an assumption about the present value in 1979 of dividends thereafter. Data are from Data Set 1, Appendix.

FIGURE 2

Note: Real modified Dow Jones Industrial Average (solid line *p*) and *ex post* rational price (dotted line *p**), 1928-1979, both detrended by dividing by a long-run exponential growth factor. The variable *p** is the present value of actual subsequent real detrended dividends, subject to an assumption about the present value in 1979 of dividends thereafter. Data are from Data Set 2, Appendix.

Fig. 1 Stock Prices Move Too Much to be Justified by Subsequent Changes in Dividends.

Trading Volume-Price Equation (1)

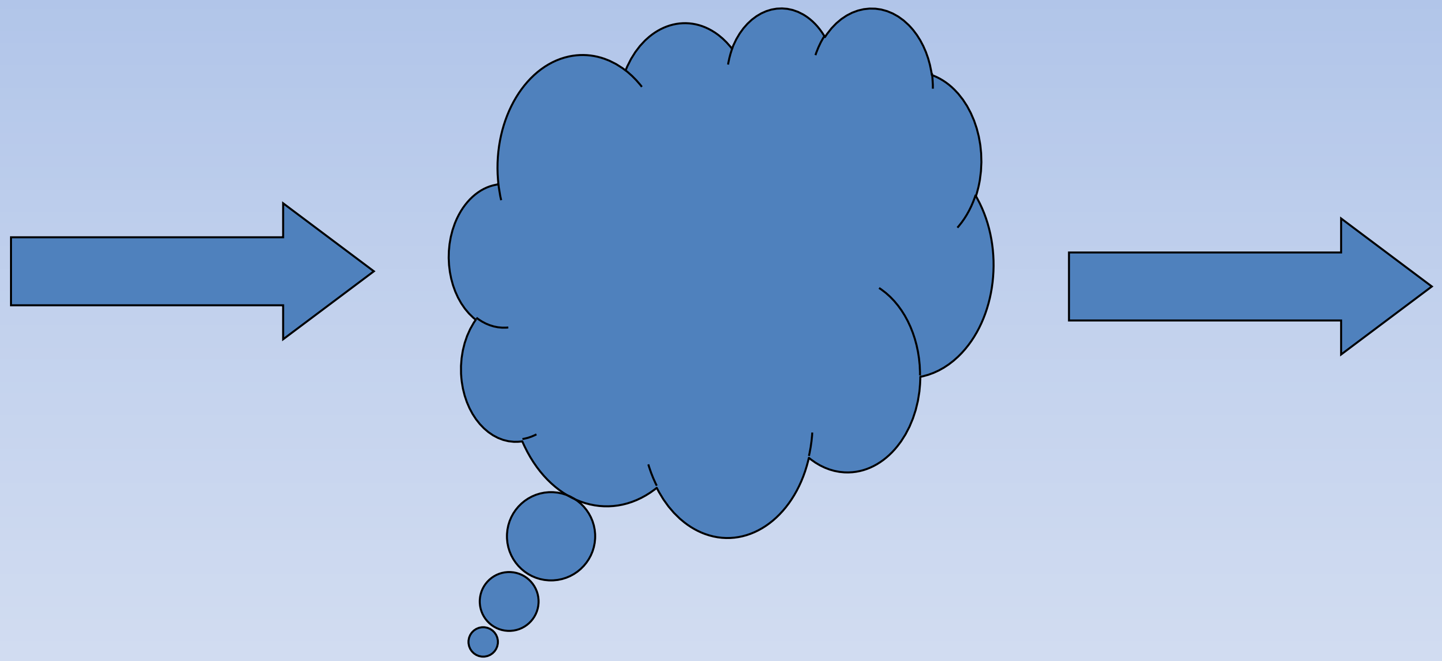


Fig. 2 Studying complex systems by “Black Box” (Shi, 2006).

Trading Volume-Price Equation (2)

- A financial market is typically a complex adaptive system;
- A trading volume-price probability wave equation governs the market behaviors (Shi, 2006 Physica A);
- It is a non-localized wave equation.

$$\frac{B^2}{V}\left(p\frac{d^2\psi}{dp^2}+\frac{d\psi}{dp}\right)+[E-U(p)]\psi=0. \quad (1)$$

and

$$E=pv_{tt}=p\frac{v_t}{t}=p\frac{v}{t^2}, \quad (2)$$

$$U(p)=A(p-p_0), \quad (3)$$

Trading Volume-Price Equation (3)

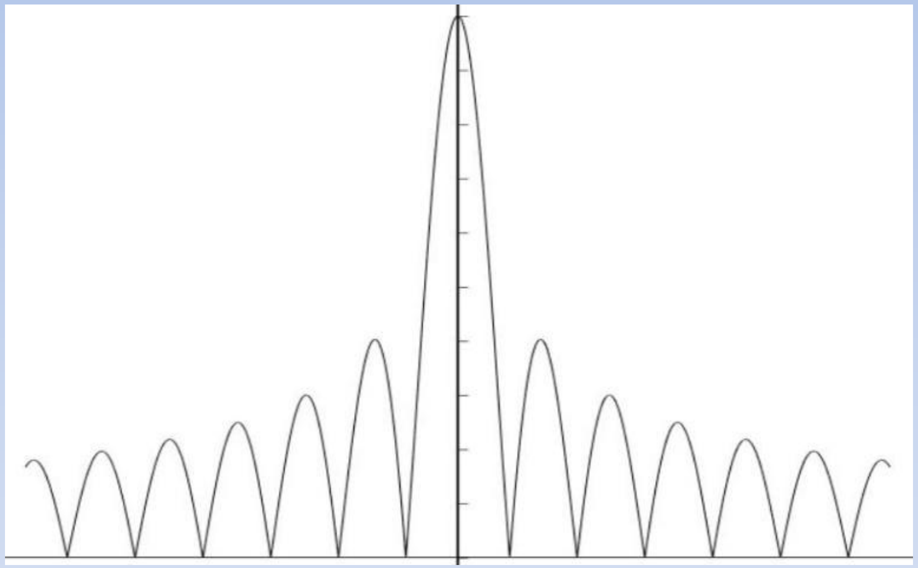


Fig. 3 Intraday cumulative trading volume distribution over a price range abides by a set of the square of zero-order Bessel eigenfuctions with interacting eigenvalues (Shi, 2006).

Trading Volume-Price Equation (4)

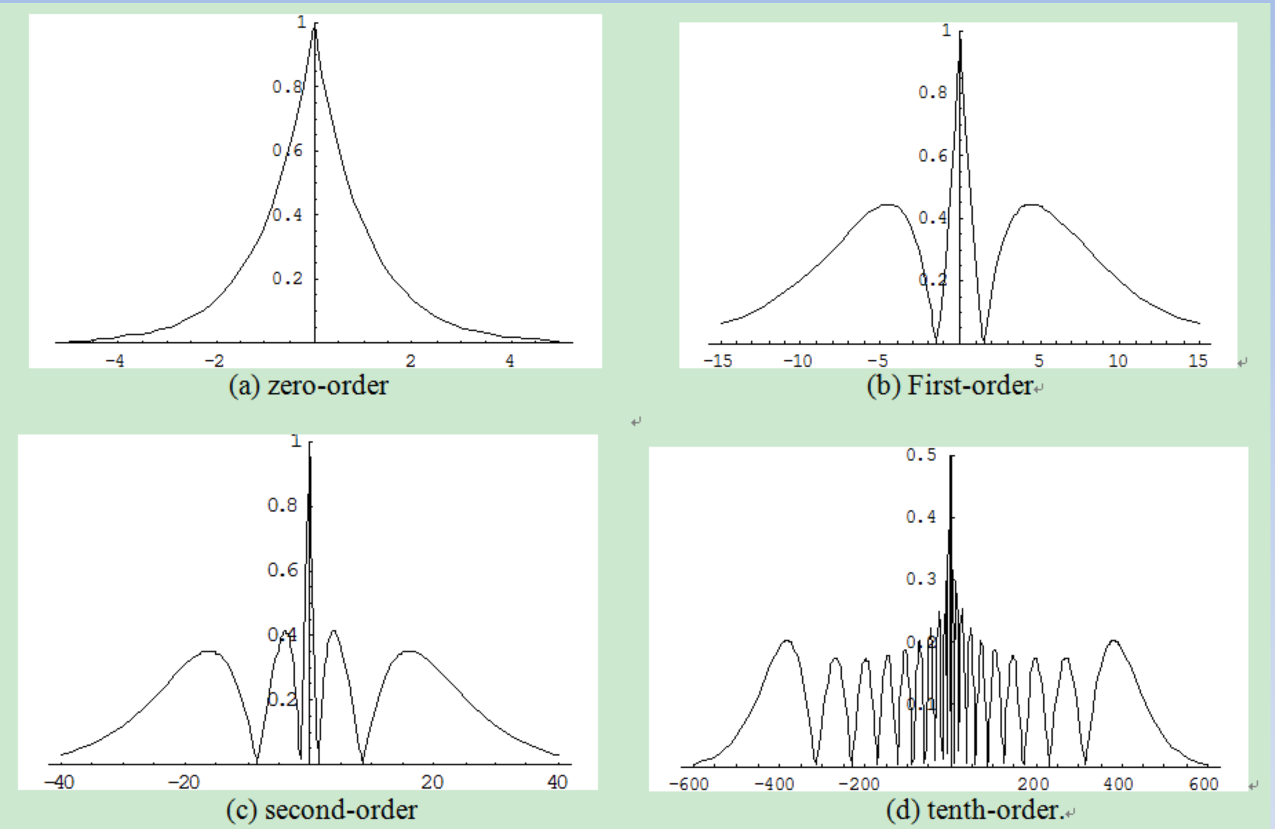
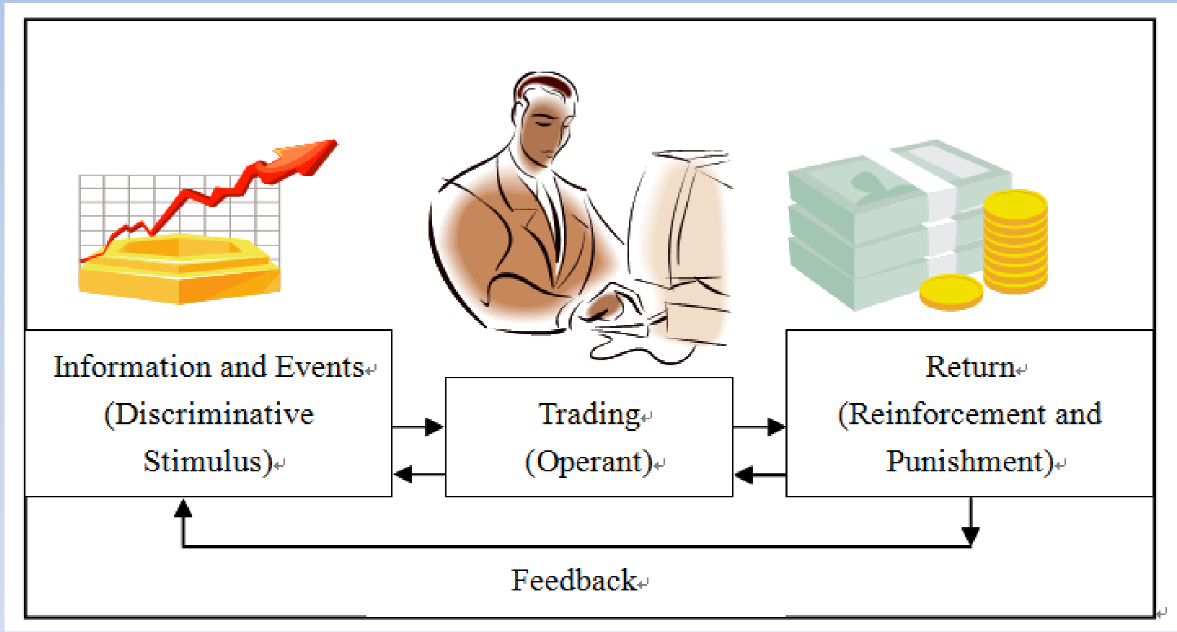


Fig. 4 Intraday cumulative trading volume distribution over a price range abides by a set of the square of multi-order eigenfuctions if traders are independent (Shi, 2006).

Trading Volume-Price Equation (5)



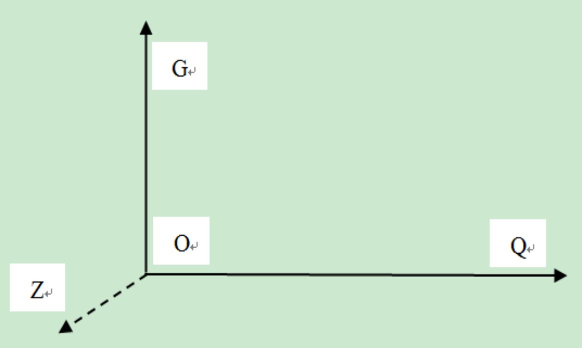


Fig. 5a (left above) Trading conditioning in feedback loops;
Fig. 5b (right above) Intelligently adaptive learning coordinates

Trading Volume-Price Equation (6)

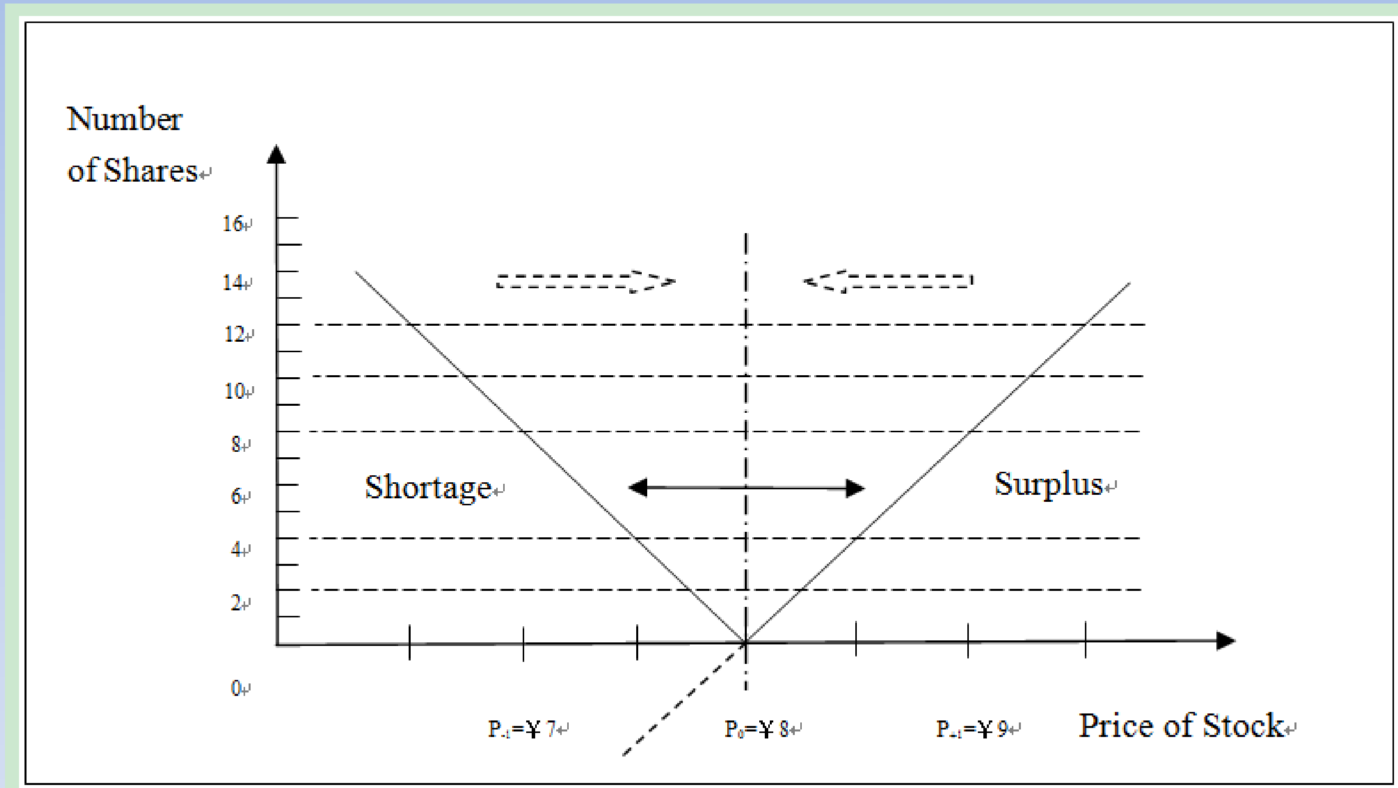
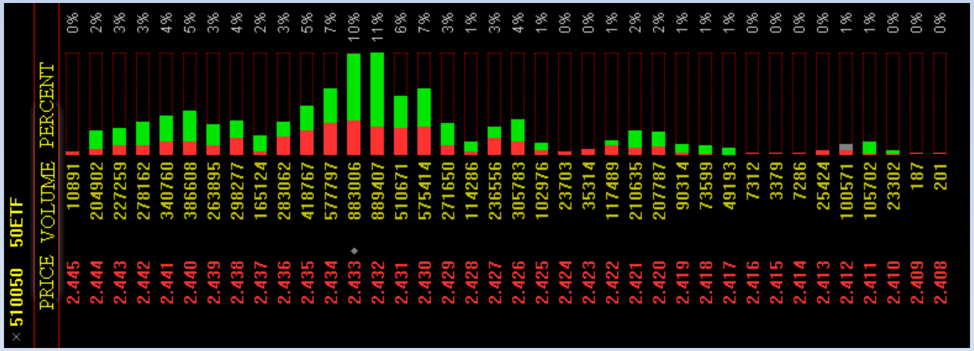


Fig. 6 A simple V-shaped curve illustrates that shortage or surplus generates reversal trading that returns the market price to an equilibrium price P_0 in intraday dynamic market equilibrium after momentum trading drives it to diverge (Shi et al., 2023).

Trading Volume-Price Equation (7)

- Data supports
  - the top 30 stocks on the Shanghai 180 Index in June 2003;
  - Huaxia SSE (Shanghai Stock Exchange) 50ETF (510050) from April 2007 to April 2009;
  - Huaxia Shanghai Stock Exchange 50ETF (510050) in January and February 2019.



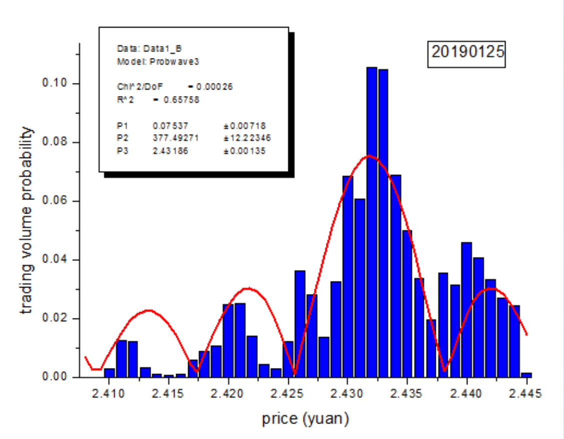


Fig. 8: Intraday cumulative trading volume distribution over prices

Trading Volume-Price Equation (8)

International Review of Financial Analysis 74 (2021) 101603

Contents lists available at ScienceDirect

International Review of Financial Analysis

journal homepage: www.elsevier.com/locate/irfa

A price dynamic equilibrium model with trading volume weights based on a price-volume probability wave differential equation

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ARTICLE INFO

JEL classifications:
G40
C61
D53
B41

Keywords:
Behavioral finance theory
Mathematical method
Market dynamic equilibrium
Volume distribution over price
Momentum and reversal

ABSTRACT

Guided by a price-volume probability wa
intraday market dynamic equilibrium in sto
over a price range as individual mental repr
volume utility price. We propose the hypoth
momentum and restore to it in reversal, a
Then, we examine it by a set of explicit pric
differential equation against a large numbe
data in Chinese stock market in 2019. It ho
because it embraces core mathematical cor
theory.

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Physica A 366 (2006) 419–436

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Does security transaction volume–price behavior resemble a probability wave?

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Received 13 July 2004; received in revised form 22 September 2005
Available online 18 November 2005

Abstract

Motivated by how transaction amount constrain trading volume and price volatility in stock market, we, in this paper, study the relation between volume and price if amount of transaction is given. We find that accumulative trading volume gradually emerges a kurtosis near the price mean value over a trading price range when it takes a longer trading time, regardless of actual price fluctuation path, time series, or total transaction volume in the time interval. To explain the volume–price behavior, we, in terms of physics, propose a transaction energy hypothesis, derive a time-independent transaction volume–price probability wave equation, and get two sets of analytical volume distribution eigenfunctions over a trading price range. By empiric test, we show the existence of coherence in stock market and demonstrate the model validation at this early stage. The volume–price behaves like a probability wave.

Keywords: Price volatility; Volume kurtosis; Volume–price behavior; Coherence; Probability wave

CFRI
13,4

568

Received 6 August 2022
Revised 27 October 2022
Accepted 28 November 2022

The underlying coherent behavior in intraday dynamic market equilibrium

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Abstract

Purpose – This paper applies a volume-price probability wave differential equation to propose a conceptual theory and has innovative behavioral interpretations of intraday dynamic market equilibrium price, in which traders' momentum, reversal and interactive behaviors play roles.

Design/methodology/approach – The authors select intraday cumulative trading volume distribution over price as revealed preferences. An equilibrium price is a price at which the corresponding cumulative trading volume achieves the maximum value. Based on the existence of the equilibrium in social finance, the authors propose a testable interacting traders' preference hypothesis without imposing the invariance criterion of rational choices. Interactively coherent preferences signify the choices subject to interactive invariance over price.

Findings – The authors find that interactive trading choices generate a constant frequency over price and intraday dynamic market equilibrium in a tug-of-war between momentum and reversal traders. The authors explain the market equilibrium through interactive, momentum and reversal traders. The intelligent interactive

JEL Classification — C60, D01, D90, G10, G40

The authors appreciate the opportunity provided by Wenfeng Wu, Managing Editor-in-Chief for China Finance Review International (CFRI) and anonymous reviews' reports from CFRI, International Review of Economics and Finance, Review of Asset Pricing Studies, and Review of Finance. The authors gratefully acknowledge comments by and discussions with Hui-Xia Lu (CFRI), Yancheng Qiu, Justin Mohr, Xinran Zhang, Xiao Li, Huaiyu Wang, Qiubin Huang, Ijaz Younis, Shen Lin, Zhenxi Chen, Zhifang Su, Tao Bing, Shouyu Yao and participants from 2022 China National Conference on Game Theory and Experimental Economics (Shanghai), 2022 The Chinese Economists Society Annual Conference (Guiyang), Economics of Financial Technology Conference (Edinburgh Business School, UK 2022), 2022 China Fin-Tech Research Conference (Tianjin, China), Future Finance Conference Nanchang 2021 (Nanchang, China), IFABS 2021 Oxford Conference (Oxford, UK), 2021 AEA Annual Meetings (Chicago, USA), the 19th China Economics Annual Conference (Tianjin, 2019), 3rd International Workshop on Financial Market and Nonlinear Dynamics (2017, Paris, France), 2017 China Finance Review International Conference (Shanghai, China). Shi thanks technical assistance from Huaiyu Wang, and Wang thanks the support from the National Natural Science Foundation of China (Grant No: 71874172). This work is supported by the National Natural Science Foundation of China (Grant No: 71874172).

Trading Volume-Price Equation (9)

- Media coverage and citation
  - Shi (2013 *Automated Trader*);
  - A research team from Sloan School of Management at Massachusetts Institute of Technology in the United States (Elkind, Kaminski, Lo, Siah, Wong, 2022 *JFDS*)

DEQUANTIFICATION

The Volume and Behaviour of Crowds

Volume is a comparatively neglected variable in academic finance – price and return usually attract far more research interest. An interesting recent exception to this rule, which examines the interaction of volume with behavioural finance, is "Market crowd trading conditioning, agreement price, and volume implications" by a group of Chinese researchers. Automated Trader discusses the paper with its lead author, Leilei Shi of the University of Science and Technology of China.

Automated Trader: *What prompted you to explore the significance and influence of volume and its interaction with trader behaviour?*

Leilei Shi: Well, it is relevant to our research background and the price-volume probability wave[1] equation I developed in an earlier paper, "Does security transaction volume–price behavior resemble a probability wave?". That earlier paper was in turn inspired by George Soros' book The Alchemy of Finance, which made me wonder whether it was possible to derive a wave equation for the stock market.

In the course of attempting to derive the equation, I discovered that liquidity levels directly drove the joint behaviour of volume and price, as well as how volume was distributed across a price range. Where price was volatile upward and downward on a daily basis, accumulated trading volume would show kurtosis[2] around a price mean value (for a practical illustration of this based on a stock price history, see Figure 1.)

From this analysis it was eventually possible to derive a price-volume probability wave equation and obtain a closed form solution[3] for the volume distribution.

Automated Trader: *Can you explain the assumptions behind the price-volume probability wave equation?*

The fundamental assumption is the existence of a trading liquidity utility expressed in terms of

Andrew W. Lo

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When Do Investors Freak Out? Machine Learning Predictions of Panic Selling

by Daniel Elkind, Kathryn Kaminski, Andrew W. Lo, Kien Wei Siah, and Chi Heem Wong

Authors' final manuscript as accepted for publication

Citation	Elkind, Daniel, Kathryn Kaminski, Andrew W. Lo, Kien Wei Siah, and Chi Heem Wong (2022), "When Do Investors Freak Out? Machine Learning Predictions of Panic Selling," *Journal of Financial Data Science* 4(1), 11–39.
As Published	https://doi.org/10.3905/jfds.2021.1.085
Publisher	Pageant Media Ltd.

2.1. Panic Selling

Although widely discussed in the financial industry (see, e.g., Rotblot (2004)), little of the available literature discusses the concept of panic selling during a period of lowered market performance. This is most likely due to the limited availability of datasets that cover a wide range of selling events and market environments. Using price and volume information as well as data from Chinese stock markets, Shi et al. (2011) provided a theoretical model based on conditioning to explain investor behavior. Their model shows that investors can be either overconfident or panicked based on price momentum. The strongest positive correlation in behavior occurs during price reversals, when many investors are more likely to sell their risky assets in a panic.

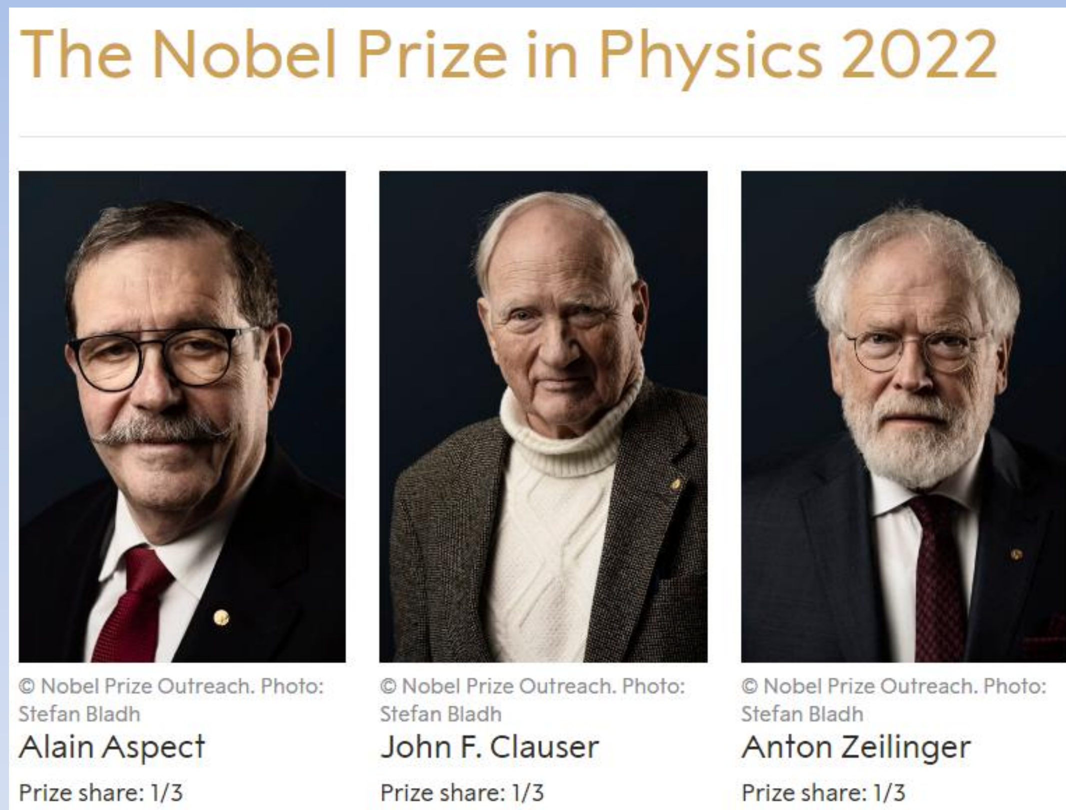
Part Three

A Nonlocal Quantum Many-Body

Wave Equation

2022 Nobel Prize in Physics

John S. Bell
1928-1990



Experiments have revealed the quantum violation of Bell's inequality and the quantum nonlocality.

A Nonlocal Many-Body Wave Equation (1)

- A nonlocal quantum many-body wave equation (Shi et al., 2024)
  - Assumptions
    - The momentum *Q* is a cumulative observable *m* at a point *q* over a sensitive variable in a time interval *t*. It is defined by equation (4);
    - The momentum force *F* is the momentum *Q* in a time interval *t.* It is defined by equation (5);
    - The energy is the product of momentum force and a sensitive variable *q*. It is defined by equation (6).

$$Q \equiv \frac{\partial S(q,t)}{\partial q} = \frac{m}{t} = m_t, \qquad (4)$$

$$F \equiv \frac{Q(q,t)}{t} = \frac{m_t}{t} = \frac{m}{t^2} = m_{tt}, \qquad (5)$$

$$E(q,t) = F * q = q m_{tt} = q\frac{m}{t^2} = q\frac{m_t}{t}, \qquad (6)$$

A Nonlocal Many-Body Wave Equation (2)

- An identical equation holds in complex adaptive quantum systems;
- It is an interdependent rule (互为因果关系), and Soros calls it “reflexivity” (Soros, 1994);

$$E(q) \equiv PE(q) + (1-P)E(q) = PE(q) + U(q-q_0), \qquad (7)$$

and

$$P = \frac{m}{M}, \qquad (8)$$

$$-E + q\frac{m_t^2}{M} + U(q-q_0) = 0. \qquad (9)$$

;

A Nonlocal Many-Body Wave Equation (3)

- Assume an unknown function *ψ(q,t)* and particles abide by the Hamilton-Jacobi equation in non-localized coordinates as follows;

$$\psi(q,t) = Re^{iS/B}, \qquad (10)$$

$$\frac{\partial s}{\partial t} + H\left(q, \frac{\partial s}{\partial q}\right) = 0, \qquad (11)$$

-

$$H\left(q, \frac{\partial s}{\partial q}\right) = q\frac{m_t^2}{M} + U(q - q_0). \qquad (12)$$

;

A Nonlocal Many-Body Wave Equation (4)

- We have

$$-E + \frac{q}{M}\left(\frac{\partial S}{\partial q}\right)^2 + U(q - q_0) = 0. \quad (13)$$

$$\delta \int L\,(q, \psi) dq = 0. \quad (14)$$

$$\frac{B^2}{M}\left(q\frac{d^2\psi}{dq^2} + \frac{d\psi}{dq}\right) + [E - U(q - q_0)]\psi = 0. \quad (15)$$

A Nonlocal Many-Body Wave Equation (5)

- **Schrödinger's wave and the nonlocal wave equations in a unified framework**

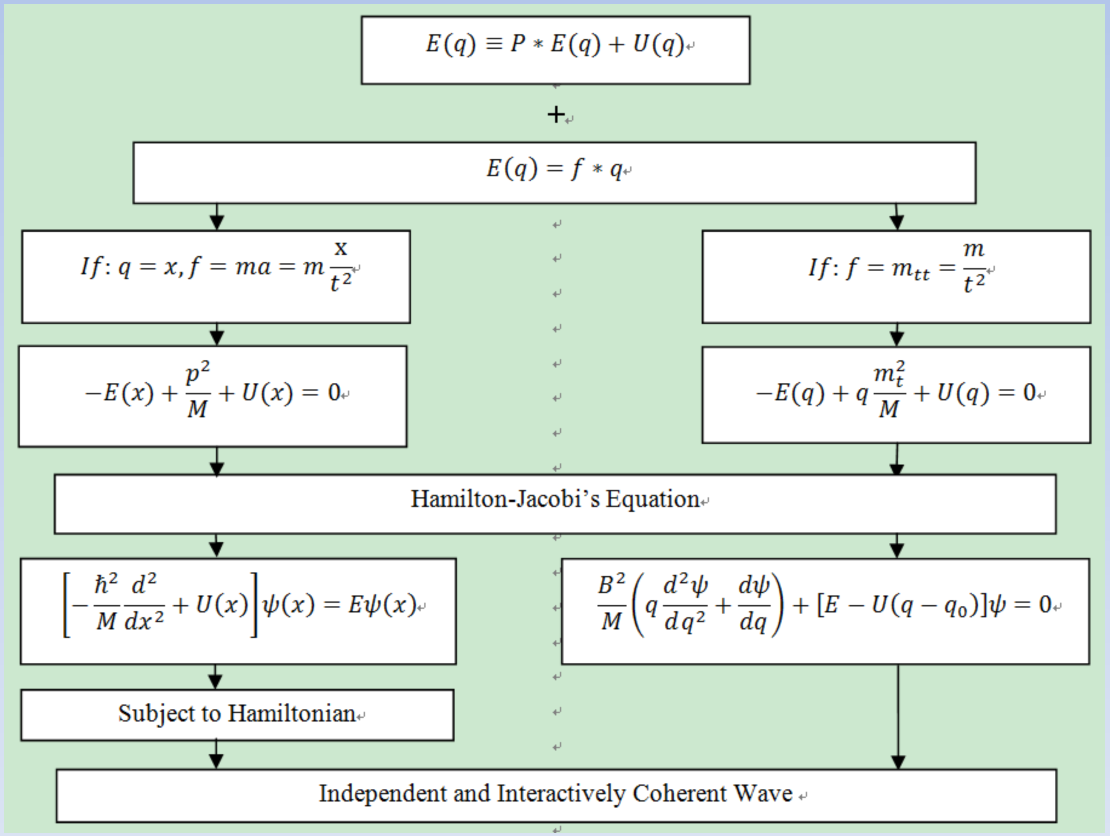


Fig. 9 A unified framework

Criterion (判据)

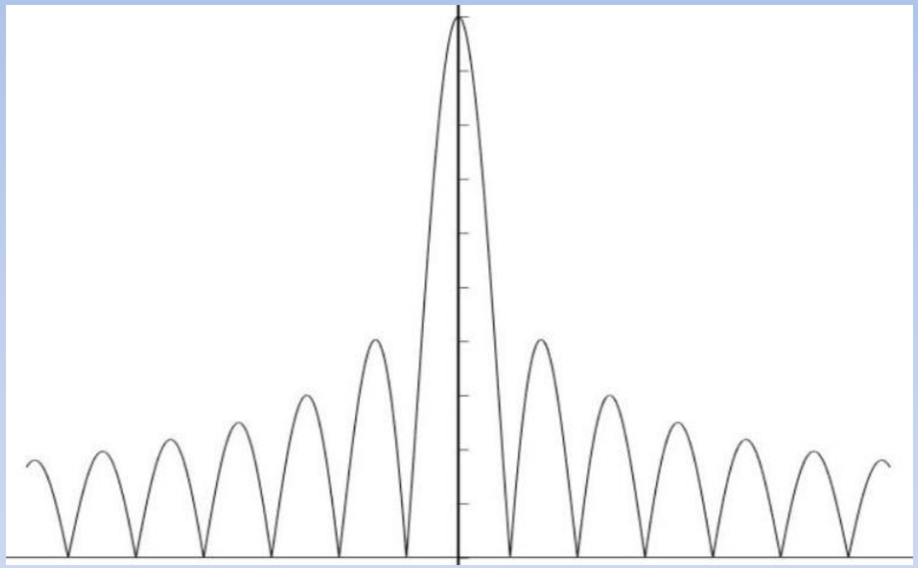


Fig. 10 Criterion for interactively coherent entanglement by the square of zero-order Bessel eigenfuctions with interacting eigenvalues.

Part Four

Results and Discussions

A Universal Law in CAS

- **A universal law in quantum mechanics and finance**
  - Conservation of interaction (interactive eigenvalue or coherence) holds between a density momentum force (repulsive force) m_{tt} and a linear potential restoring force (attractive force) *A* in nonlocal complex adaptive systems (相互作用相干守恒).

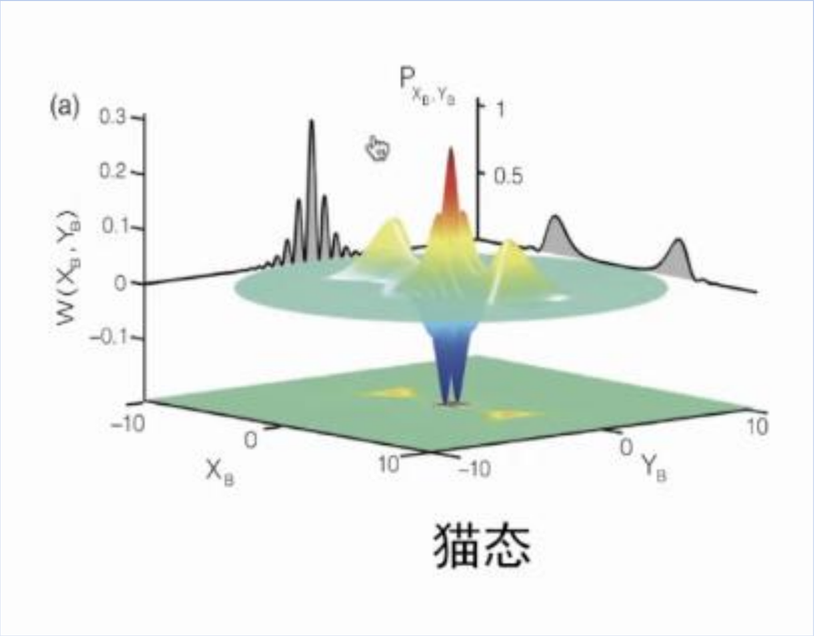
$$\omega_n^2 = \frac{m_{t,n,i}^2}{M} = \frac{m_{n,i}}{M} m_{tt,n,i} = m_{tt,n,i} - A_{tt,n,i} = const.$$

$$(n = 0,1,\cdots),(i = 1,2\ldots)$$

(16)

Complex Quantum Entanglement

- **Non-Gauss distribution in quantum entanglement (He, 2024 KouXiang)**



Peking U

Fig. 11 A cat’s state

Interpretation

- In an entanglement bipartite system between A and B, after spatially splitting the system, one party A or B can instantaneously "knows" the change of the other party B or A, makes adaptive "intelligence-like" compensation, and maintains a strong correlation and entanglement between A and B since the conservation of interaction between momentum force (repulsive force) and potential restoring force (attractive force).

Prediction

- It is predicted that interactively coherent entanglement has higher fidelity and stronger decoherent resistance than superposition entanglement and the ability to self-repair, making it a high-quality entangled resource.

$$\psi(q) = \begin{pmatrix} \psi_0 \\ \vdots \\ \psi_{n-1} \end{pmatrix} = \begin{pmatrix} c_{0,0} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & c_{n-1,k-1} \end{pmatrix} \begin{pmatrix} \psi_{0,0} \\ \vdots \\ \psi_{n-1,k-1} \end{pmatrix}, \quad (17)$$

Applications

- By the nonlocal quantum many-body wave equation, we can
  - measure the magnitude of the interactive coherence through interactively coherent eigenvalues;
  - quantify the distribution of complex quantum many-body systems by stationary wave functions, revealing the underlying mechanism of the formation of interactive coherence;
  - A criterion for interactively coherent entanglement.
- It will provide a theoretical criterion and technical guidance for the industrial production of high-quality entangled resources.

Conclusions

- Complex adaptive systems follow a nonlocal many-body wave equation
- There is a unified paradigm for the nonlocal quantum many-body wave equation and the Schrödinger wave equation;
- Quantum many-body interactively coherent wave function follows a set of the square of zero-order Bessel functions with interactive eigenvalues;
- If the complex quantum systems are entangled in the nonlocal interactive coherence, then they keep conservation of interaction between density momentum force and linear potential restoring force; in another word, after spatially splitting the bipartite systems A and B, one party A or B can instantaneously "knows" the changes in the other party B or A, makes adaptive "intelligence-like" compensation, and maintains a strong correlation and entanglement between them;
- It is predicted that interactively coherent entanglement has higher fidelity and stronger decoherent resistance than superposition entanglement and the ability to self-repair, making it a high-quality entangled resource.

Thank You!

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Full paper available at https://arxiv.org/abs/2306.15554