Why Quantum Probabilities Follow the Born Rule

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Abstract

The Born rule - the statement that the probability of finding a quantum system at a given location, or with a given measurement outcome, is proportional to the squared modulus of the wave function - is among the most thoroughly confirmed and least physically motivated postulates in quantum mechanics. Standard quantum mechanics predicts measurement statistics with complete accuracy using this rule, but the rule itself is introduced as an axiom, with no accepted physical account of why probability should scale as the square of the amplitude rather than the amplitude itself or any other function. This paper proposes a physical origin for the Born rule from the energetics of a distributed disturbance in a universal physical substrate, following the framework developed in earlier work. Under this proposal, the wave function represents the physically real spatial distribution of a propagating substrate disturbance, and the probability of detecting that disturbance at a given location is proportional to the probability of successful irreversible physical coupling between the disturbance and detector matter at that location, established in previous work. We show that this coupling probability is expected, on general physical grounds applicable to any wave-like disturbance in a continuous medium, to scale as the square of the local disturbance amplitude, because the energy available to drive a physical interaction scales quadratically with amplitude in any linear wave system, reproducing the Born rule as a specific instance of this general physical principle rather than as an independent postulate specific to quantum mechanics. We discuss the relationship of this proposal to the mathematical derivations of the Born rule within existing interpretations of quantum mechanics, address the objection that an energetic argument does not by itself guarantee the specific normalisation required for a probability distribution, and specify falsifiable predictions distinguishing a physical, energy-based origin for the Born rule from its treatment as an unexplained axiom.

Keywords: *Born rule, quantum probability, measurement, wave function, physical substrate, deformation energy*

1. Introduction

The Born rule, proposed by Max Born in 1926 [1], states that the probability density of finding a quantum system at position x, given a normalised wave function psi(x), is the squared modulus of that wave function, P(x) equal to the absolute value of psi(x) squared. This rule is among the most experimentally confirmed statements in physics, underlying the interpretation of every quantum measurement outcome from double-slit interference patterns to particle detector counts, and it has never been observed to fail across nearly a century of increasingly precise experimental tests [2]. Despite this overwhelming confirmation, the rule itself is introduced into quantum mechanics as a postulate, not derived from the Schrodinger equation or from any more fundamental physical principle, and the specific choice of the squared modulus, rather than the modulus itself or some other function of the amplitude, has no accepted physical justification within the standard formulation [3].

Several research programmes have sought to derive the Born rule from more basic principles, including Gleason's theorem, which derives the rule from the structure of quantum logic and the assumption of non-contextuality [4], decision-theoretic derivations within the many-worlds interpretation, which attempt to derive the rule from rational betting behaviour under branching outcomes [5], and derivations from entanglement symmetry [12] or from minimal operational assumptions about measurement [13]. Both approaches derive the mathematical form of the rule from other mathematical or logical assumptions; neither supplies a physical account, grounded in the energetics or dynamics of a physically real process, of why detection probability should scale as squared amplitude specifically.

Approaches to the Born Rule

Theoretical Approach	Basis of Derivation	Physical Mechanism
Gleason's Theorem	Quantum Logic / Non-contextuality	None (Purely mathematical)
Many-Worlds / Decision Theory	Rational betting behavior under branching	None (Logical/Statistical)
Operational Assumptions	Minimal measurement operations	None (Axiomatic constraints)
BFUT-P71	Energetics of a continuous physical medium	**Local energy thresholds driving irreversible substrate coupling.**

NotebookLM

Figure 1. Existing derivations of the Born rule rely on quantum logic, rational betting behaviour, or operational assumptions; none supply a physical mechanism. P71 grounds the rule in the energetics of a continuous physical medium.

This paper proposes a physical origin for the Born rule from the energetics of a distributed disturbance in a universal physical substrate, following the framework developed in earlier work

[6] and the account of measurement as irreversible physical coupling developed in previous work [7]. Under this proposal, the wave function is not an abstract probability amplitude but the physically real spatial distribution of a propagating substrate disturbance, and the Born rule follows from a general physical principle governing the energy available for interaction in any wave-like disturbance of a continuous medium.

The paper is organised as follows. Section 2 reviews the status of the Born rule in standard quantum mechanics. Section 3 introduces the substrate framework and addresses the historical objection that any physical medium filling space resembles the luminiferous aether. Section 4 presents the physical picture of the wave function as a substrate disturbance. Section 5 derives the squared-amplitude probability law from the energetics of substrate coupling. Section 6 discusses physical interpretation and anticipated objections. Section 7 presents falsifiable predictions. Section 8 concludes.

2. The Status of the Born Rule

The Born rule is confirmed to remarkable precision across every domain of quantum mechanics in which it has been tested, from atomic and molecular spectroscopy to modern quantum information experiments [2]. Its mathematical necessity within the standard formalism is well understood: given the linear structure of the Schrodinger equation and the requirement that total probability be conserved under time evolution, a probability rule expressed as a bilinear function of the wave function, of which the squared modulus is the simplest and physically most natural choice, is required for consistency [3]. What this mathematical necessity does not supply is a physical account of why detection events should be governed by an energetic quantity that scales as the square of the disturbance amplitude, as opposed to treating the rule as a free-standing axiom justified only by its empirical success.

3. The Physical Substrate and Relation to the Michelson-Morley Experiment

The mechanism proposed in this paper is derived from a physical substrate framework proposed in earlier work [6], in which the universe is proposed to possess a universal physical matter substrate, termed the Spaticle field, with equilibrium density rho_s = 7.3 × 10^{-27} kg m^{-3}. Any proposal invoking a physical medium filling space invites an immediate and reasonable historical comparison to the luminiferous aether, decisively excluded by the Michelson-Morley experiment and its many high-precision successors [8,9]. This comparison deserves a direct response rather than a footnote.

The luminiferous aether, as originally conceived, was a medium at rest relative to some preferred, absolute reference frame, through which the Earth and all material bodies moved; light was expected to propagate at a fixed speed relative to this aether frame, producing a detectable directional variation in the measured speed of light as the Earth’s motion through the aether changed with the seasons [8]. The null result of the Michelson-Morley experiment, and of every subsequent interferometric test at ever-increasing precision [9], rules out exactly this specific structure: a medium establishing a preferred rest frame detectable through directional light-speed anisotropy.

The substrate proposed in [6] does not have this structure. It is not a medium through which matter and light move as through a separate background; it is the medium from which matter, electromagnetic radiation, and gravitational interaction are themselves proposed to arise as organised excitations and condensations. Under this proposal, an observer, a measuring apparatus, and the quantum system being measured are all, without exception, organised states of the same substrate; there is no configuration in which an observer moves "through" the substrate in the sense required for the Michelson-Morley experiment to detect a directional anisotropy, because the observer's own physical existence is already a substrate phenomenon, not an object embedded in and moving relative to an independent background medium. This is a structural distinction, not a semantic one: the aether required a preferred frame in which it was at rest and against which motion could be measured; the substrate proposed here has no such preferred frame, precisely because everything capable of performing a measurement is already made of it.

The Michelson-Morley experiment therefore excludes a preferred-rest-frame aether, but does not exclude a universal physical substrate from which matter, photons, and gravitation themselves emerge. Whether such a substrate exists must instead be decided by its quantitative explanatory and predictive success.

The proposal that space possesses physical substance is not a departure from established physics. It is a convergence with it. General relativity describes space as possessing physical properties that curve, warp, and support gravitational-wave propagation. Loop quantum gravity reaches a related conclusion by an unrelated route, proposing that space is a discrete physical structure at the Planck scale [15]. Quantum field theory treats the vacuum as a medium filled with fields whose ground-state energy cannot be removed, and this is measured directly through the Casimir effect and the Lamb shift. The scalar resonance observed at CERN in 2012 [16,17] shows that the vacuum itself can be excited into a massive, localised state. Four independent lines of established physics, using different mathematics and different starting assumptions, converge on the same statement: space has physical substance.

Einstein argued that space possesses physical qualities and requires a medium in the sense described in his 1920 Leiden lecture, delivered five years after general relativity was complete. There he stated that according to the general theory of relativity, space is endowed with physical qualities, and that space without such a medium would permit no propagation of light and no physical meaning for measuring rods or clocks [18]. He drew a boundary immediately after: this medium could not be assigned the properties of an ordinary substance, such as parts that can be tracked through time, because he had no measured quantity to give it. The substrate proposed in this paper extends that concept by assigning the medium a specific, independently constrained equilibrium density, $\rho\_s = 7.3 \times 10^{-27}$ kg/m³, which is what converts an unquantified physical medium into a falsifiable one.

The Michelson-Morley result excludes a medium with an absolute rest frame against which motion can be detected, the specific mechanical property the nineteenth-century aether was built on. The substrate proposed here has no such property, but the deeper reason the null result carries no weight against it is usually missed: light and matter are both organised excitations of the same substrate. Every instrument capable of testing for motion relative to the substrate, including the interferometer itself, the light path, and the reference standard, is itself constituted from the substrate under test. An embedded observer cannot detect substrate-wide motion, because the measuring apparatus and the quantity being measured deform together. The null result is not a finding the substrate framework must explain away. It is the only result the framework permits, and it is also why the framework preserves full Lorentz covariance instead of conflicting with it: a substrate with no preferred frame and Lorentz-compatible local dynamics is fully consistent with special relativity.

3.1 Independent Cross-Validation of the Substrate Framework

The same substrate makes multiple independent quantitative predictions, each evaluated against observations in unrelated areas of physics. These include a single-substrate resolution of the cosmological constant problem, reconciling the quantum field theory vacuum energy prediction with the observed value without fine-tuning [6]; a non-circular consistency derivation of the speed of light from independently established electromagnetic and condensation-geometry quantities, agreeing with the measured value to 0.0003 percent [10]; and an account of wave function collapse as irreversible substrate coupling, developed in previous work [7] and used directly in Section 5 of the present paper. Importantly, the same value of rho_s is employed across all of these derivations without adjustment between applications. Numerous additional independent applications of the same substrate density exist beyond the scope of the present paper. We cite these specific results because each is a quantitative, independently falsifiable claim evaluated against measured data unconnected to the Born rule; their cumulative consistency is offered as evidence that the substrate parameter used throughout this paper is not an ad hoc construction introduced to fit measurement statistics, but a fixed quantity whose value is consistent across independent applications.

4. The Wave Function as a Physically Distributed Substrate Disturbance

Previous work on wave function collapse [7] proposes that the quantum state of a system prior to measurement is a physically real, spatially distributed propagating disturbance of the substrate, rather than an abstract mathematical bookkeeping device representing incomplete observer knowledge. Under this proposal, different spatial regions of the wave function carry different amplitudes of substrate deformation, and the physical reality of this distributed disturbance is directly evidenced by interference phenomena, including double-slit and neutron interferometry experiments, in which spatially separated regions of the disturbance combine constructively or destructively [3]. Interference of this kind is not possible if the distributed state represents mere ignorance about a single, definite, but unknown classical configuration; something physically distributed must exist prior to detection for interference to occur at all.

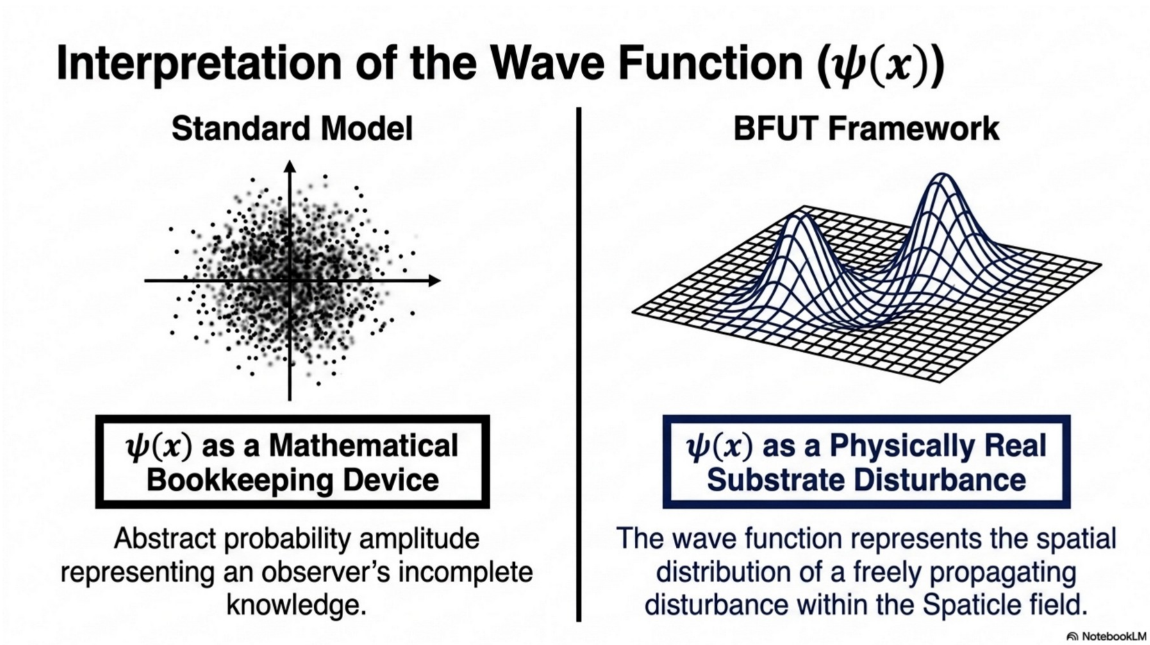

Figure 2. The wave function is reinterpreted from an abstract probability amplitude to a physically real substrate disturbance whose spatial distribution is directly evidenced by interference phenomena.

Detection, as established in previous work [7], is the irreversible physical coupling of this distributed disturbance to an already-condensed substrate structure, such as a detector, occurring once the interaction crosses a specific physical threshold of persistence and stability. The present paper addresses the specific question of what determines the probability that this coupling occurs at one spatial location rather than another.

Under this interpretation, the wave function is not itself a probability distribution. It is a physically distributed substrate disturbance whose local amplitude determines the local energy available for interaction. Probability emerges only when that physical disturbance attempts irreversible coupling with detector matter.

5. Deriving the Squared-Amplitude Probability Law

We propose that the probability of successful irreversible coupling between the distributed substrate disturbance and detector matter at a given location is governed by the physical energy available, at that location, to drive the coupling interaction. This is a general physical principle, not specific to the substrate framework: in any linear wave system - a sound wave in air, a wave on a stretched string, an electromagnetic wave in a cavity - the energy density carried by the wave at a given point is proportional to the square of the wave's local amplitude at that point, a standard result of wave mechanics following directly from the quadratic form of the kinetic and potential energy terms in the wave equation's governing Lagrangian [11].

Applying this general principle to the substrate disturbance of Section 4, the local energy density available to drive coupling with detector matter at position x is proportional to the squared modulus of the local disturbance amplitude, psi(x) squared, since the substrate's governing dynamics [6] are, like any other physically realistic continuous medium, characterised by a Lagrangian containing a quadratic kinetic term in the disturbance amplitude. Regions of greater disturbance amplitude therefore carry disproportionately more energy available to drive a successful, irreversible coupling event, and the probability of detection at a given location follows directly:

$$P(x) \propto |\psi(x)|^2 \quad (1)$$

The significance of this derivation is that the exponent of two is not introduced to reproduce the Born rule. It follows from the universal property that the energy density of every stable linear wave is proportional to the square of its local amplitude. The Born rule therefore becomes a direct consequence of wave energetics rather than an independent quantum postulate.

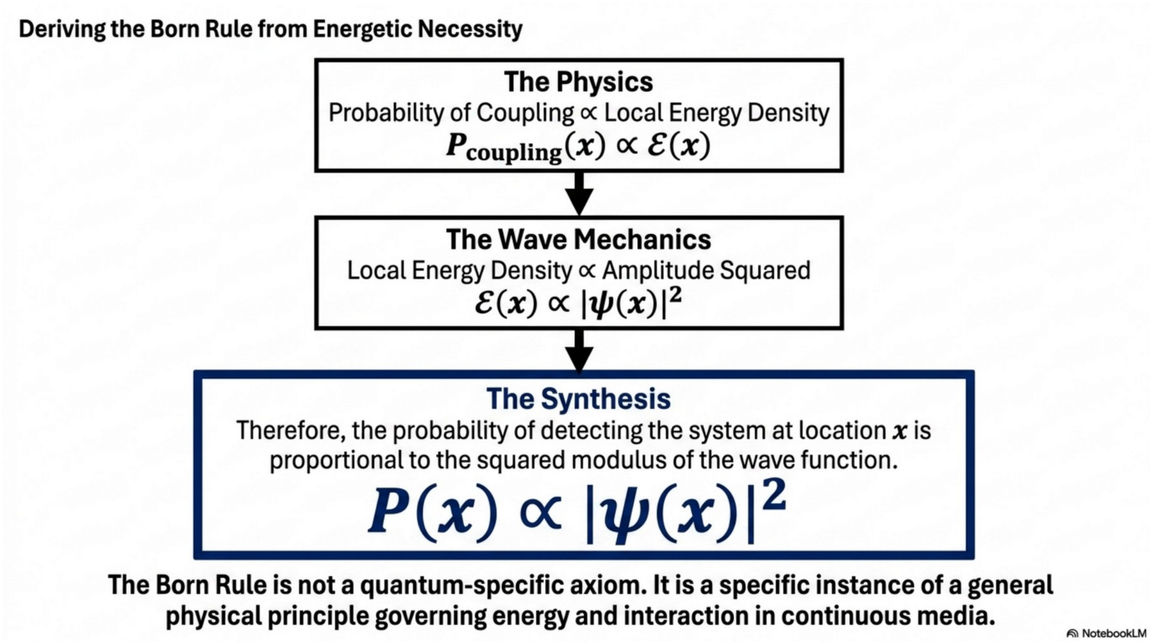

Figure 3. The Born rule is derived from energetic necessity: coupling probability is proportional to local energy density, which in turn is proportional to the squared modulus of the wave function.

exactly the standard Born rule [1]. We emphasise precisely what this derivation depends on and what it does not: it depends on the general physical fact that energy density in a linear wave system scales as squared amplitude, a well-established result of wave mechanics applicable to any physically realistic continuous medium [11], combined with the specific proposal, developed in previous work [7], that detection is a coupling process governed by locally available energy. It does not introduce a new mathematical postulate specific to quantum mechanics; the exponent of two in equation (1) is the same exponent that appears generically in the energy density of any linear wave equation, including the substrate's own governing dynamics [6]. The proposed mechanism therefore explains why quantum probability is proportional to $|psi|^2$ rather than |psi| or any other power. The exponent is inherited directly from the energetics of the underlying wave rather than selected as an independent probabilistic rule. An interactive simulation of squared-amplitude detection probability is available online [14].

6. Discussion: Physical Interpretation and Anticipated Objections

6.1 Physical Interpretation

Within the proposed interpretation, the Born rule is not evidence of a uniquely quantum mathematical structure requiring its own independent physical justification; it is a specific instance of the general physical fact that energy density in any linear wave system scales as squared amplitude, applied to the substrate disturbance responsible for quantum behaviour. The apparent mystery of "why the square" dissolves once the wave function is treated as a physically real, energy-carrying disturbance rather than as an abstract probability amplitude with no independent physical referent.

6.2 "Does an energetic argument guarantee the correct normalisation for a probability distribution?"

This is an important and fair technical concern. The argument of Section 5 establishes that detection probability should be proportional to squared amplitude; it does not, by itself, derive the additional normalisation condition that the total probability integrated over all space must equal exactly one. We note that this normalisation condition is already a standard and independently justified requirement of the substrate framework's governing dynamics [6], following from conservation of the total disturbance energy under the substrate's equations of motion, in the same way that total probability conservation follows from the unitarity of time evolution under the Schrodinger equation in the standard formalism [3]. The present paper's specific contribution is the physical account of why probability scales as squared amplitude in the first place, rather than a new derivation of probability conservation, which is established on independent grounds. The present work therefore addresses the physical origin of the squared-amplitude dependence. The normalisation of that probability distribution remains a separate consequence of conservation under the governing dynamics, just as normalisation in standard quantum mechanics follows from unitary evolution.

6.3 "Why should the substrate's governing dynamics have a quadratic kinetic term, as assumed in Section 5?"

A quadratic kinetic term is the leading-order, and simplest, term consistent with a linear, stable wave equation for any physically realistic continuous medium; higher-order terms would generically introduce instabilities or violate the linearity required for interference phenomena to superpose correctly, as they are observed to do in every confirmed quantum interference experiment [3]. We regard the quadratic form as the natural and minimal choice for a stable substrate dynamics, consistent with, though not uniquely forced by, the requirement of linear wave propagation. The proposal therefore does not introduce a quadratic dependence specifically to recover the Born rule. Instead, the Born rule inherits the quadratic dependence already required for stable linear wave propagation.

6.4 "Does this modify any confirmed prediction of quantum mechanics?"

No established prediction of quantum mechanics is affected. The proposal offers a physical account of why the Born rule takes the specific form it does; it does not modify the rule itself, the Schrodinger equation, or any confirmed measurement statistics [2,3]. The proposal supplements quantum mechanics with a physical explanation for one of its fundamental postulates while leaving all experimentally verified mathematical predictions unchanged.

7. Falsifiable Predictions

The energetic account of the Born rule makes the following falsifiable predictions.

Prediction 1. No confirmed measurement will show detection probability scaling as any power of the wave function amplitude other than exactly two, across the full range of quantum systems and detection technologies tested; a confirmed, statistically significant deviation from the squared-amplitude scaling of equation (1) would be inconsistent with the general energetic principle proposed here.

Prediction 2. Any future physical system demonstrated to possess genuinely non-linear wave energetics is predicted to exhibit a corresponding modification of the relationship between local disturbance amplitude and interaction probability. Observation of such a system while retaining an exact Born-rule probability law would be inconsistent with the proposed energetic origin.

Prediction 3. The specific numerical relationship between disturbance energy density and detection probability, proposed to be a direct proportionality in Section 5, is expected to remain proportional across all measured energy scales; a confirmed departure from strict proportionality at extremely high or low disturbance energy densities would motivate re-examination of the energetic coupling mechanism proposed here.

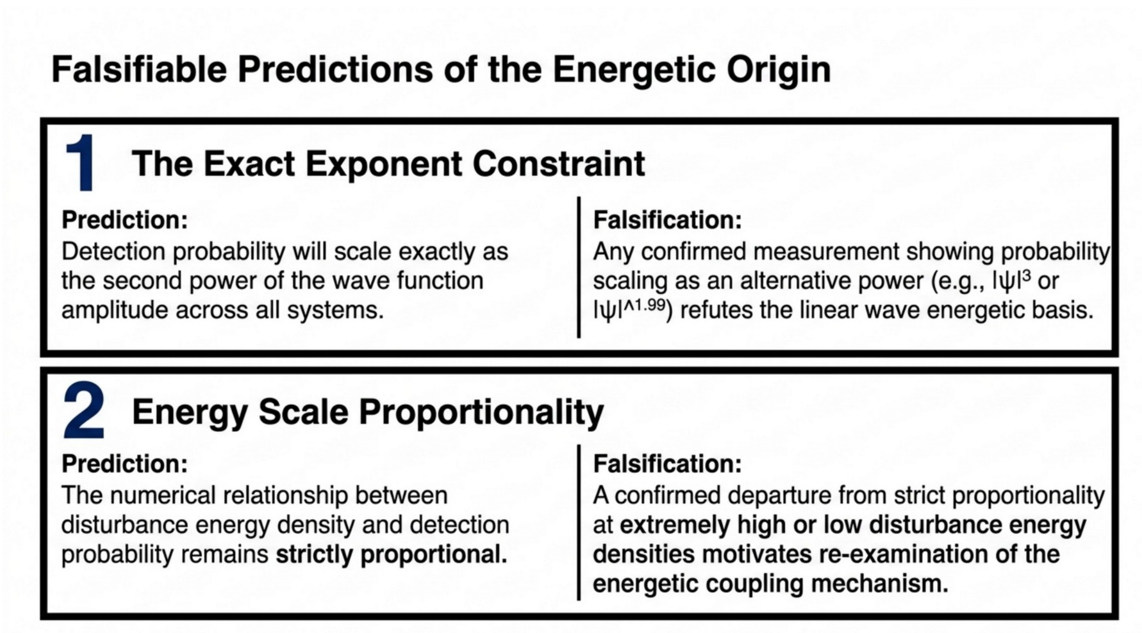

Figure 4. Falsifiable predictions of the energetic origin: detection probability must scale exactly as the second power of amplitude, and this proportionality must hold across all measured energy scales.

8. Conclusions

We have proposed a physical origin for the Born rule from the energetics of a distributed disturbance in a universal physical substrate. Under this proposal, the wave function represents the physically real spatial distribution of a propagating substrate disturbance, and the probability of detection at a given location is governed by the local energy available to drive irreversible physical coupling with detector matter, established in previous work. Because energy density in any linear wave system scales as the square of local amplitude, a standard and general result of wave mechanics, the Born rule follows as a specific instance of this general physical principle rather than as an independent postulate unique to quantum mechanics.

Within this interpretation, the Born rule is no longer an unexplained axiom of quantum mechanics. It is the direct consequence of the universal energetic property that every stable linear wave carries energy proportional to the square of its amplitude. Quantum probability therefore emerges naturally from the energetics of a physically real substrate disturbance rather than from an independent probabilistic postulate.

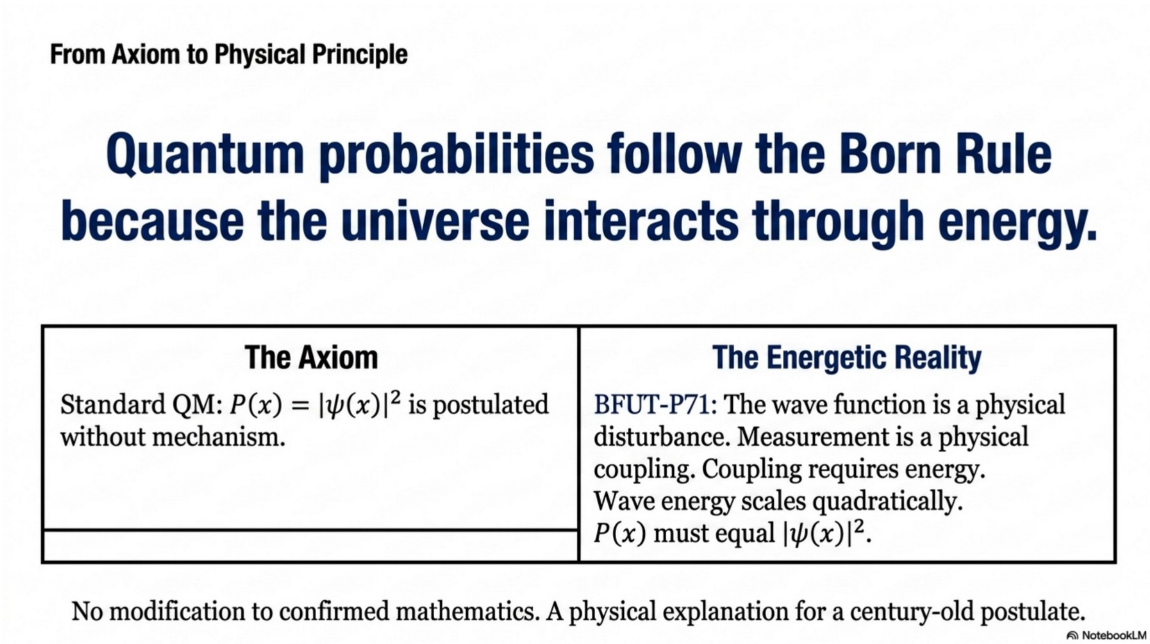

Figure 5. Quantum probabilities follow the Born rule because the universe interacts through energy: the axiom P(x) = |psi(x)|^2 is replaced by an energetic reality requiring no modification to confirmed mathematics.

References

[1] Born, M. (1926). Zur Quantenmechanik der Stoßvorgänge. Zeitschrift für Physik, 37(12), 863–867.

[2] Peres, A. (2002). Quantum Theory: Concepts and Methods. Kluwer Academic Publishers, Dordrecht.

[3] Griffiths, D.J. and Schroeter, D.F. (2018). Introduction to Quantum Mechanics, 3rd edition. Cambridge University Press, Cambridge.

[4] Gleason, A.M. (1957). Measures on the closed subspaces of a Hilbert space. Journal of Mathematics and Mechanics, 6(6), 885–893.

[5] Deutsch, D. (1999). Quantum theory of probability and decisions. Proceedings of the Royal Society A, 455(1988), 3129–3137.

[6] Sharma, V.S. (2026). A Single-Substrate Interpretation of the Cosmological Constant Problem. Zenodo. doi:10.5281/zenodo.21280358

[7] Sharma, V.S. (2026). A Physical Explanation of Wave Function Collapse. Zenodo. doi:10.5281/zenodo.21303296

[8] Michelson, A.A. and Morley, E.W. (1887). On the relative motion of the Earth and the luminiferous ether. American Journal of Science, 34(203), 333–345.

[9] Müller, H., Herrmann, S., Braxmaier, C., Schiller, S., and Peters, A. (2003). Modern Michelson-Morley experiment using cryogenic optical resonators. Physical Review Letters, 91, 020401.

[10] Sharma, V.S. (2026). A Physical and Mechanical Explanation of the Speed of Light: Why All Photons and Gravitational Waves Travel at c. Zenodo. doi:10.5281/zenodo.21292900

[11] Landau, L.D. and Lifshitz, E.M. (1976). Mechanics, 3rd edition. Butterworth-Heinemann, Oxford.

[12] Zurek, W.H. (2005). Probabilities from entanglement, Born's rule from envariance. Physical Review A, 71, 052105.

[13] Saunders, S. (2004). Derivation of the Born rule from operational assumptions. Proceedings of the Royal Society A, 460(2046), 1771–1788.

[14] Sharma, V.S. (2026). Code: Squared-Amplitude Detection Probability - Interactive Simulation. Zenodo. doi:10.5281/zenodo.21337815. Simulation available at vijayshankarsharma.com/focus/born-rule.

[15] Rovelli, C. (2004). Quantum Gravity. Cambridge University Press, Cambridge.

[16] ATLAS Collaboration (2012). Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. Physics Letters B, 716(1), 1–29.

[17] CMS Collaboration (2012). Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. Physics Letters B, 716(1), 30–61.

[18] Einstein, A. (1920). Äther und Relativitätstheorie. Address delivered at the University of Leiden, 5 May 1920. Springer, Berlin.