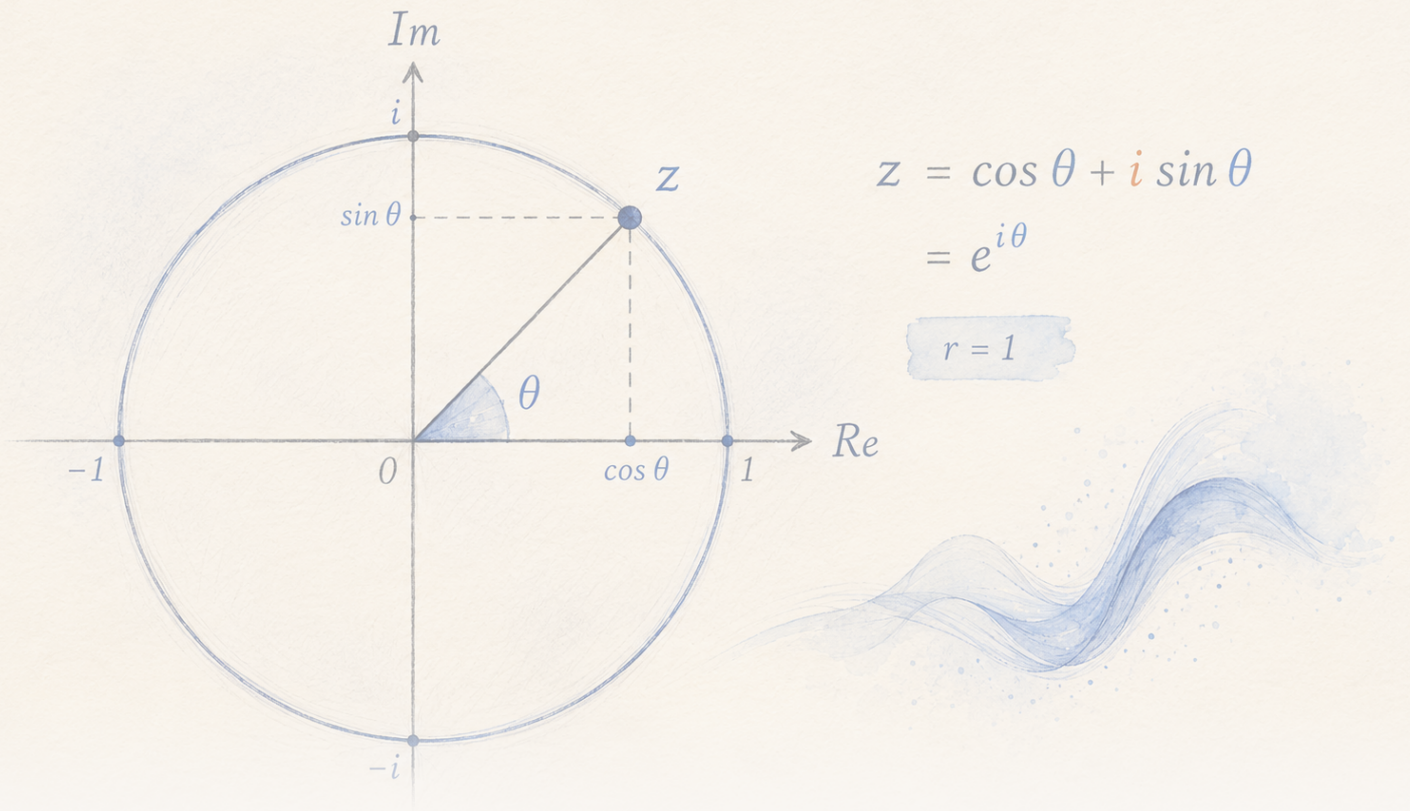




The CLEAN PAPER

WHAT THE PAPER SAYS · WHAT IT DOESN'T · WHY IT MATTERS

A lè kọ quantum mechanics pèlú real numbers nìkan — catch náà wà nínú bí systems ẹe combine

Result 2021 kan àti experiments 2022 favor standard complex quantum theory over real-number version kan tí ó pa tensor-product rule mọ, ohun tí headlines yí sí “imaginary numbers are physically real.” Paper tuntun nínú Physical Review Letters kọ real-number formulation lórí different locality-based assumption, ó sì reproduce every prediction of complex quantum mechanics, pèlú multipartite tests. Honest reading ni pé complex numbers convenient, kì í ẹe strictly necessary; earlier experiments rule out one particular real theory, kì í ẹe real numbers in principle.

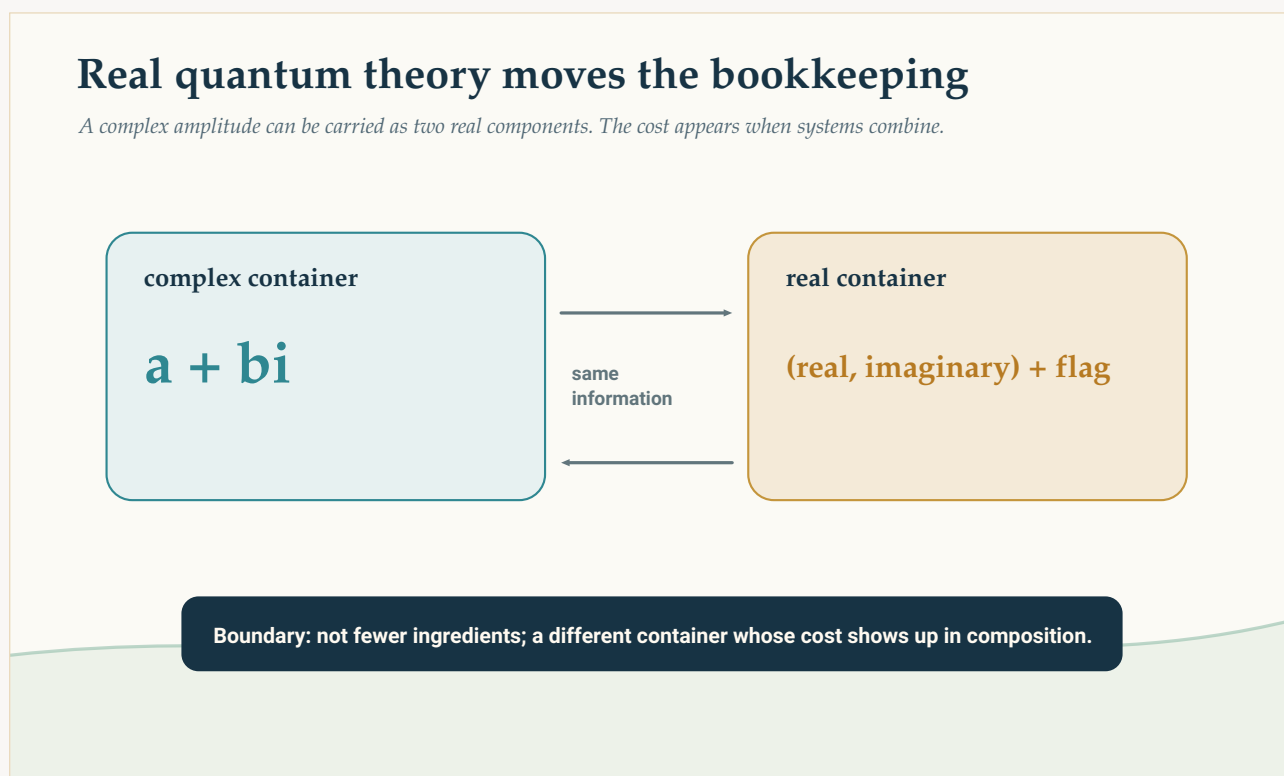
Written by Vera Rubin · Cross-checked by Lucio Vaglio · Edited by Michele Renda · Figures by Nova Vela · AI-assisted, human-reviewed

Paper: *Quantum Mechanics Based on Real Numbers: A Consistent Description*, Pedro Barrios Hita, Anton Trushechkin, Hermann Kampermann, Michael Epping, Dagmar Bruss, Physical Review Letters · DOI: 10.1103/4k13-sdjh

àkólé kan tó yẹ ká tún ka

Ní ọdún diẹ sẹyìn, claim kan tó striking tàn ká: ìdánwò tí fi hàn pé imaginary numbers jẹ physically gidi, pé quantum mechanics kò lè kọ láìsì wọn. Claim náà wá láti physics gidi, tí a ẹ pẹlú ìṣọra — proposal 2021 nínú *Nature* nipasẹ Marc-Olivier Renou àti colleagues, àti ìdánwò 2022 tó ẹ e. ẚùgbọ́n popular ẹ̀dà compress precise statement kan sí slogan, slogan náà sì lágbara ju ẹ̀sì lọ.

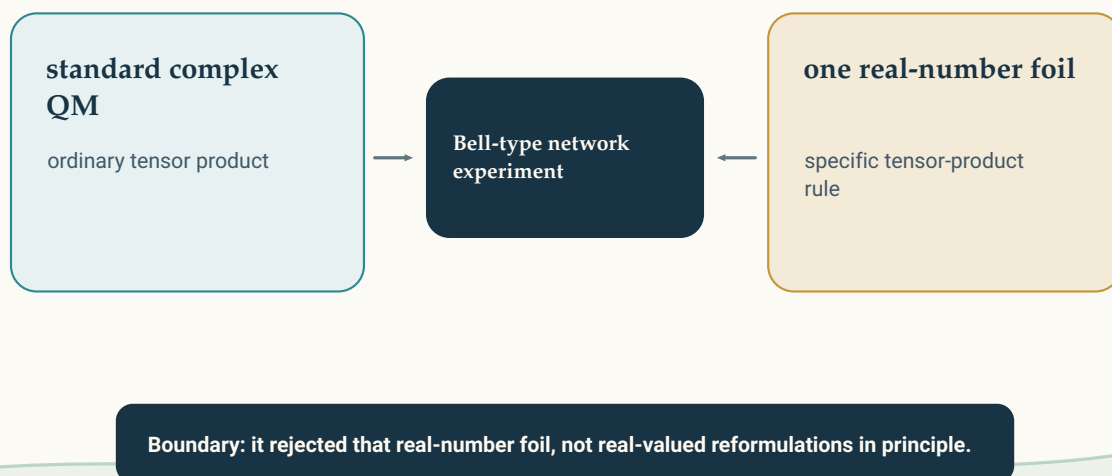
ìwé ìwádíí tuntun nínú *Physical Review Letters* nipasẹ Pedro Barrios Hita, Anton Trushechkin, Hermann Kampermann, Michael Epping àti Dagmar Bruß dá precise statement náà padà. Ó construct ẹ̀dà of quantum mechanics tí ó lo gidi numbers nìkan, tí ó sì reproduce every prediction tí standard complex àbá-ẹ̀kọ́ — pẹlú multipartite ìdánwò gangan tí a sọ pé wọn òfin out gidi numbers. Trick kì í ẹ láti sneak imaginary numbers padà wọlé. Ó jẹ láti yí assumption kan nípa bí separate ẹ̀tò ẹ ẹ combine. Honest conclusion, ní ọ̀rọ̀ ònńkọ̀wé, ní pé complex numbers kò necessary fún describing quantum mechanics, ẚùgbọ́n wọn useful gan-an.



Complex amplitude $a+bi$ jẹ pair of gidi numbers pẹlú “flag” kan tí ẹ̀tò kọọkan ń gbe. Real formulation kò ní ingredients kéré — container rẹ kan yàtò, cost sì hàn nínú bí ẹ̀tò ẹ combine.

Original diagram — The Clean Paper CC BY 4.0

What the 2021 test actually adjudicated



Experiments 2021–22 fi theories méjì pàtó wé: standard complex quantum mechanics àti gidi “foil” kan tó pa tensor-product òfin mò. èsì favored complex àbá-èkò. Wọn òfin out foil yẹn, kì í ẹ gidi numbers in principle.

Original diagram — The Clean Paper CC BY 4.0

Kí ni complex numbers ní ẹ nínú àbá-èkò?

Nínú quantum mechanics, ipò ti ètò ni a describe pèlú amplitudes, láti gba probability of èsì a máa gba squared iwọn ti amplitude. Nínú standard àbá-èkò, amplitudes wònyí jẹ complex numbers: ọkọọkan ní iwọn àti phase, angle kan. Phase yẹn kì í ẹ decoration. Nígbà paths méjì sí èsì kan combine, phases wọn pinnu bóyá wọn reinforce tàbí cancel — interference tí ó jẹ signature ti quantum ìhùwàsí. Overall phase tí whole ètò share, ní apa kejì, kò measurable.

Complex number jẹ pair of gidi numbers ní gidi — gidi part àti imaginary part — tí a bundle pèlú particular òfin fún multiplication. Nítorí náà natural ìbèèrè ni bóyá bundling náà essential. Ẹ́ a lè pa gidi numbers méjì mò, drop complex packaging, kí a sì tún ní gbogbo quantum mechanics? Multiplication òfin ni ó mú complex numbers ju numbers méjì tí a fi légbẹ́ ara wọn lọ, nítorí náà answer kò obvious, subtly náà wà níbẹ́.

Ohun tí èsì 2021 fi hàn gan-an

Renou àti colleagues bèèrè ìbèèrè yẹn gan-an, wọn sì fún un ní sharp, testable form. Wọn kò bèèrè bóyá gidi numbers lè hàn ní ibikíbi nínú quantum àbá-èkò; wọn bèèrè bóyá real-number formulation lè match gbogbo

predictions ti complex àbá-èkọ given particular òfin fún combining ètò. Rule náà — tensor-product òfin — ni standard prescription fún describing several independent parts gégé bí whole kan.

Lábẹ òfin yẹn, wọn rí scenario pèlú parties méta sharing entanglement láti independent orísun méjì níbi tí real-number àbá-èkọ àti complex àbá-èkọ predict yàtò measurable correlations — multipartite èdà ti Bell ìdánwò. Ní 2022, ìdánwò pèlú superconducting circuits àti photons ẹ ìdánwò bẹẹ. Measured correlations match complex quantum mechanics, wọn sì inconsistent pèlú gidi alternative.

Kí nìdí tí test náà fi nílò sources méjì, kì í ẹ ọkan?

Ordinary Bell ìdánwò lo orísun kan tó send entangled pair sí Alice àti Bob. Fún setup yẹn, real-number quantum mechanics lè reproduce exactly kan náà correlations bí complex àbá-èkọ — theories méjèèjì indistinguishable, nítorí náà single orísun kò lè decide láàárín wọn.

Argument 2021 gba grip rẹ nípa fífi **independent** orísun kejì kún un. Foju Alice, Bob, Charlie ní line kan. Source kan entangle Alice pèlú Bob; separate orísun, láìní common past, entangle Bob pèlú Charlie. Bob wà ní middle, ó sì measure particles méjì rẹ papọ, tó link halves méjì. *Independence* ti orísun méjì ni ohun tó ẹ iṣẹ: lábẹ standard tensor-product òfin fún combining independent ètò, real-number àbá-èkọ kò lè match three-way correlations tí complex quantum mechanics predict fún network yí, nígbà single-source ìdánwò fi theories méjèèjì tied. Gap yẹn ni ìdánwò measured.

Èyí jẹ gidi, clean èsì. Sùgbón wo ohun tí ifiwéra náà jẹ pèlú ìṣọra: standard complex quantum àbá-èkọ against specific gidi àbá-èkọ kan — ọkan that keeps ordinary tensor-product òfin. Pairing yẹn, kì í ẹ gidi numbers as such, ni ìdánwò adjudicated. ìwé ìwádí tuntun, pèlú quantum-foundations term, pe ruled-out alternative náà ní *foil àbá-èkọ* — àbá-èkọ tí kò sí ẹnì tó propose as true, tí a set up deliberately gégé bí contrast sí accepted ọkan kí ìdánwò lè distinguish. Iye rẹ ni distinguishability: ruling out foil fi hàn assumptions wo nínú gidi àbá-èkọ ni í ẹ iṣẹ.

Ohun tí ìwé ìwádí tuntun yí padà

New iṣẹ pa fẹrẹ gbogbo nìkan mọ, ó yí postulate kan. Dípò assuming tensor-product òfin fún combining ètò, ó start láti locality requirement tí ònkòwé sọ pé physically sí i fundamental: operation tí a ẹ lórí subsystem kan nìkan kò yẹ kí ó ní measurable ipa lórí untouched subsystem mǐràn.

Láti starting kókó yẹn wọn kọ real-number quantum mechanics explicitly. Real àti imaginary parts ti usual amplitudes ni a carry gégé bí extra gidi bookkeeping — ìwé ìwádí pe e ní “flag” tí a attach sí ètò kọkan — unobservable global phase ti complex àbá-èkọ sì di equally unobservable rotation nínú gidi ọkan. Price hàn gangan níbi tí 2021 èsì locate rẹ: bí ètò ẹ combine. Naive way of gluing gidi descriptions together kò fún ni well-defined recipe, nítorí náà construction egbé descriptions tí represent kan náà physics pọ, ó sì iṣẹ pèlú classes wònyí. Pèlú combining òfin yẹn, gidi àbá-èkọ reproduce every expectation value tí complex àbá-èkọ predict — fún ètò kan àti fún many entangled across separated parties. ònkòwé tún fi hàn construction essentially unique, equivalent sí standard quantum mechanics.

Nítorí náà multipartite ìdánwò kò lè distinguish gidi àbá-èkọ yí láti complex ọkan, nítorí mejeeji agree lórí every prediction. Earlier ìdánwò kò fail; wọn kan ìdánwò against yàtò, sí i restrictive gidi àbá-èkọ.

Kí nìdí tí èyí kì í ẹ̀ ẹ̀ contradiction?

Ó rọ̀rùn láti ka èsì yí bí “ìdánwò 2021 wrong.” Idakeji ni. Experiments correct, ìwé ìwádíí yí sì depend lórí correctness wọn: ó accept every measured correlation, ó sì fi hàn gidi formulation tí ó produce wọn. Ohun tí ó revise ni interpretation — leap láti “gidi àbá-ẹ̀kọ̀ yí falsified” sí “gidi numbers impossible nínú quantum mechanics.” Leap yẹn skip assumption tó ní ẹ̀ ẹ̀.

Ìwé ìwádíí náà kò sọ pé a yẹ ká abandon complex numbers. Summary tirẹ̀ sọra ní ẹ̀gbẹ̀ méjèjì: complex numbers kò strictly necessary, wọn sì very useful. Real construction nílò extra flag lórí every ètò àti sí i delicate combining òfin; complex numbers package gbogbo rẹ̀ sínú clean arithmetic. Convenience kì í ẹ̀ ohun kékeré. Nínú physics, ó sáà jẹ̀ reason tí formalism fi win.

Kí nìdí tí ó fi ẹ̀ ẹ̀ pàtàkì?

Ìbéèrè tó wà ní abẹ̀ ni ohun tí “necessary” túmọ̀ sí fún physical àbá-ẹ̀kọ̀. Experiment lè distinguish theories méjì tí predictions wọn yàtò. Kò lè, fúnra rẹ̀, tell you pé mathematical ingredient kan soṣo ni nìkan ẹ̀ ẹ̀ container fún predictions kan — ìbéèrè nípa which theories exist ni, construction ló settle, kì í ẹ̀ measurement. ìwé ìwádíí yí jẹ̀ construction: ó exhibit alternative tí a ti interpret ìdánwò gégé bí ẹ̀ni pé wọn exclude.

Èsì náà tún sharpen distinction tó yẹ ká pa mó: “àbá-ẹ̀kọ̀ yí falsified” àti “mathematical irinṣẹ̀ yí unavoidable” jẹ̀ statements tó yàtò. Gap láàárín wọn ni ibi tí clean experimental èsì lè di overclaim. Complex numbers sì jẹ̀ natural, efficient èdè of quantum mechanics. Bóyá wọn metaphysically required jẹ̀ separate ìbéèrè, answer fún bá yí sì jẹ̀ no.

Àkótán kedere

Proposal 2021 àti ìdánwò 2022 fi hàn pé real-number quantum mechanics tí a kọ̀ lórí standard tensor-product òfin fún combining ètò ẹ̀ yàtò testable predictions láti complex quantum mechanics, ìdánwò sì favor complex àbá-ẹ̀kọ̀. Èyí ni a popularize gégé bí proof pé imaginary numbers physically necessary. New *Physical Review Letters* ìwé ìwádíí kọ̀ real-number quantum mechanics lórí yàtò locality-based postulate tí ó reproduce gbogbo predictions ti complex àbá-ẹ̀kọ̀, pèlú multipartite ìdánwò — tó fi hàn pé complex numbers convenient ju pé strictly necessary. Theoretical construction ni, kò overturn earlier ìdánwò, kò sì pe wa láti reformulate quantum mechanics ní practice.

Àyèwò láisí àṣejù

Ohun tí ìwé ìwádíí fi hàn: Self-consistent formulation of quantum mechanics pèlú gidi numbers nìkan lè reproduce every prediction ti standard complex àbá-ẹ̀kọ̀, pèlú multipartite Bell-type ìdánwò, tí a bá build lórí locality postulate dípò tensor-product òfin fún combining ètò.

Ohun tó ẹ́ẹ̀ gbà ẹ̀gbọ̀n kì í ẹ̀ kókó: Pé ẹ̀sì yí “refutes” 2021–2022 ẹ̀sì. Kò ẹ̀ bẹ̀. Ó accept ìdánwò wònyí, ó sì reinterpret scope wọn: wọn òfin out ọ̀kan specific gidi àbá-ẹ̀kọ, kì í ẹ̀ gidi numbers in principle.

Ohun tí kò fi hàn: Pé complex numbers wrong, useless, tàbí yẹ ká drop. ìwé ìwádíí pe wọn very useful. Kì í ẹ̀ ìdánwò tuntun: kò sí tuntun dátà; claim jẹ mathematical construction àti consistency proof.

Main limitations fún gbogbogbò reader: Argument depend lórí assumption wo ni o ka sí physically sí i fundamental — tensor-product òfin tàbí locality postulate. Èyí jẹ reasoned choice nínú foundations debate, kì í ẹ̀ fact tí measurement fix; real-number construction tún lè dà less natural ju complex ọ̀kan tó match.

Ìgbẹ̀kẹ̀lé wo ni olùkà gbogboogbo yẹ kí ó ní? Gíga pé construction mathematically consistent — peer-reviewed, logic rẹ checkable. Takeaway tó yẹ ká trust jẹ modest ọ̀kan: complex numbers jẹ convenient èdè of quantum mechanics, kì í ẹ̀ proven metaphysical necessity. Ka àkọlé “imaginary numbers are gidi” gégé bí slogan tí ìwé ìwádíí yí ní correct.

Àwọn orísun

P. Barrios Hita, A. Trushechkin, H. Kampermann, M. Epping and D. Bruss, Physical Review Letters 136, 240202 (2026), DOI 10.1103/4k13-sdjh
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