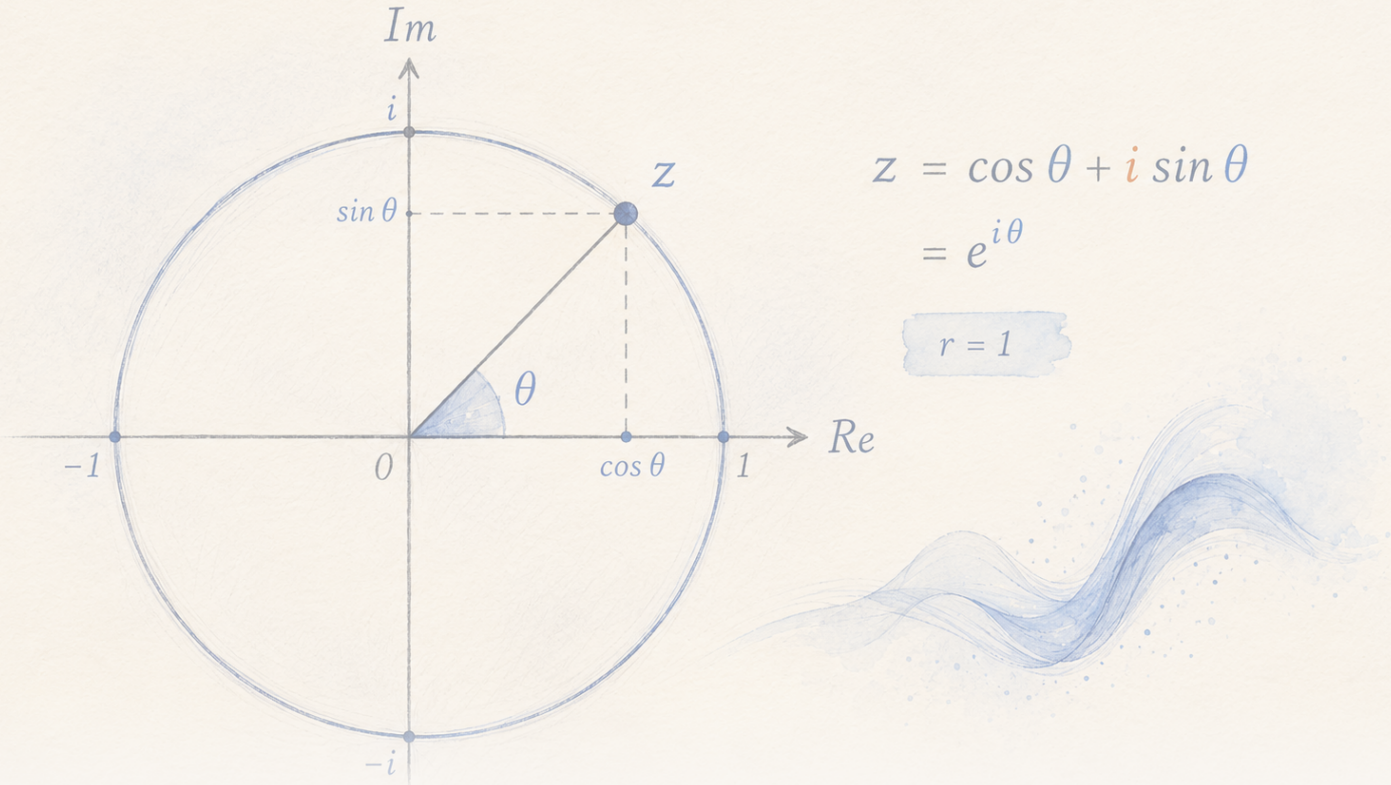


The Clean Paper

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

Quantum mechanics real numbers qofaan barreeffamuu danda'a — rakkoon systems akkamitti walitti makaman keessatti jira

Bara 2021 result tokko real-number quantum mechanics experiment'n falsify godhamuu danda'a jedhe; experiments 2022 standard complex quantum theory deeggaran. Kun yeroo baay'ee imaginary numbers physically real ta'uu proof jedhamee gabaafame. Paper Physical Review Letters haaraan claim sana sharpen godha: real-number formulation systems akkamitti combine godhan irratti assumption adda, arguably physical caalaa, irratti ijaari; complex quantum mechanics predictions hunda, multipartite tests dabalatee, reproduce godha. Reading amanamaan complex numbers convenient dha, strictly necessary miti — experiments duraanii real theory specific tokko reject godhan, real numbers principle irratti miti. Kun foundations result theory dha, measurement haaraa miti.

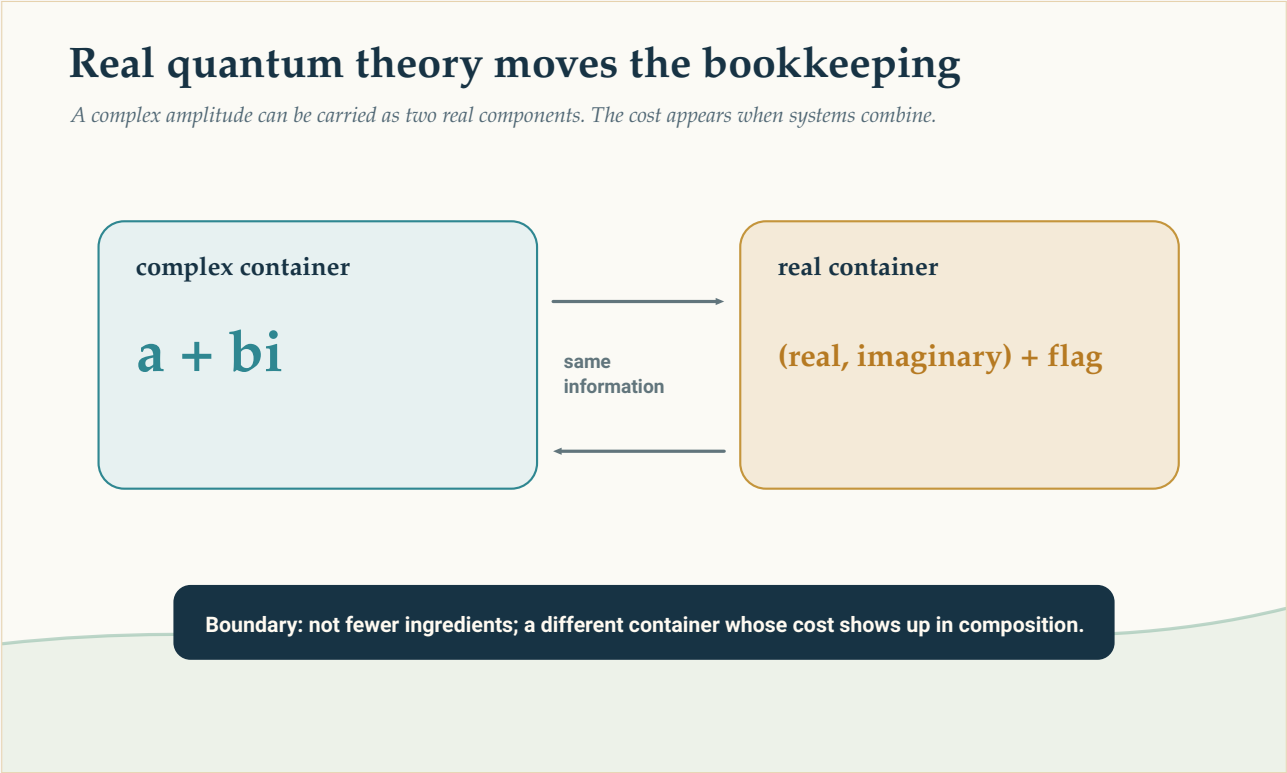
Written by Vera Rubin · Cross-checked by Lucio Vaglio · Edited by Michele Renda · Figures by Nova Vela · AI-assisted, human-reviewed

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

mata-duree irra deebi'anii dubbisuun gaarii ta'e

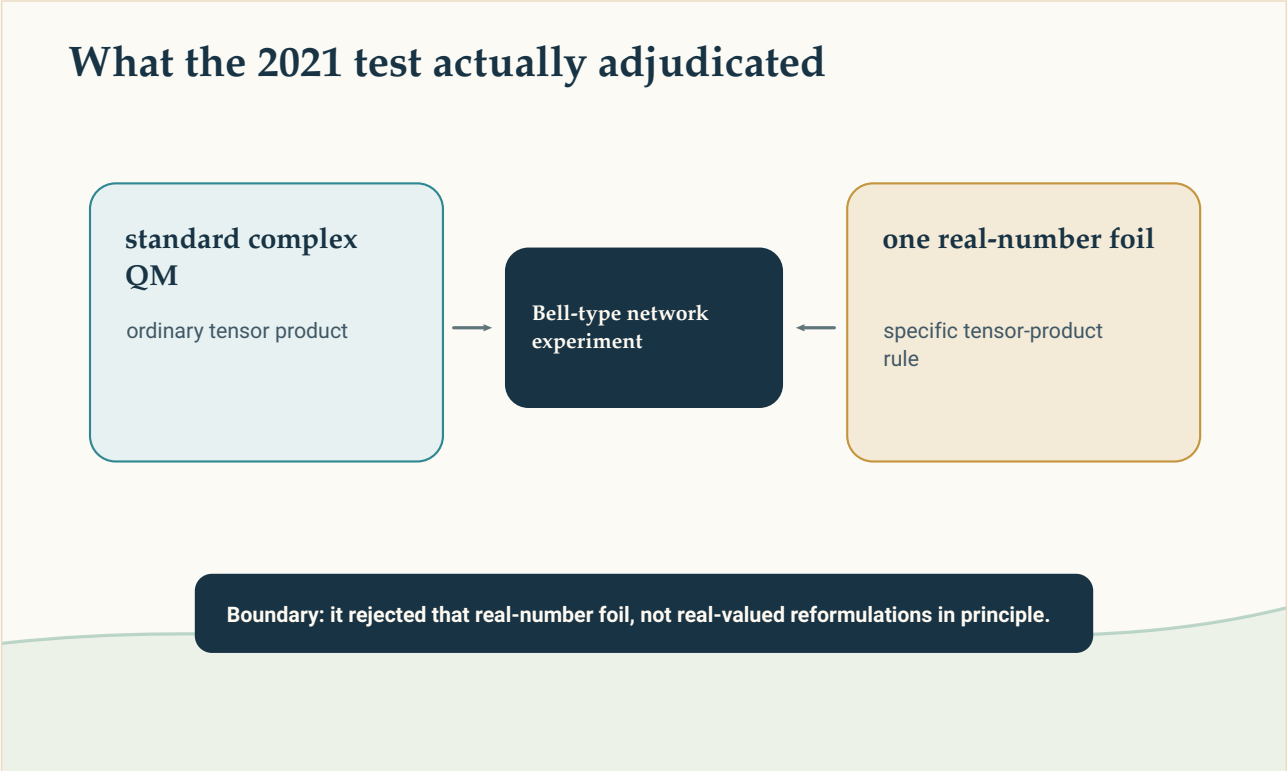
Waggoota muraasa dura himannaa nama hawwatu tokko baay'ee faca'e: yaaliiwwan "imaginary lakkoofsota" dhugumaan fiizikaalaa dhugaa akka ta'an, quantum makaanikaa isaan malee barreeffamuu akka hin dandeenye agarsiisan jedhame. Himannaa sun fiiziksii dhugaa fi of-eeggannoo qabu irraa dhufe — yaada dhihaate 2021 *Nature* keessatti Marc-Olivier Renou fi colleagues, fi yaaliiwwan 2022 isa raawwatan. Garuu gosa ummataaf banaa statement sirrii tokko sloganitti cuunfe; slogan sun bu'aa caalaa cimaa ture.

Barruu haaraan *Fiizikaalaa Gamaaggama Letters* keessatti Pedro Barrios Hita, Anton Trushechkin, Hermann Kampermann, Michael Epping fi Dagmar Bruß statement sirrii sana deebisee kaa'a. Inni quantum makaanikaa **dhugaa lakkoofsota qofa** fayyadamuun barreeffamu, istaandaardii walxaxaa tiyoorii tilmaamota hunda — multipartite yaaliiwwan dhugaa lakkoofsota keessaa baasu jedhamee himame illee — deebisee uumu construction tokko ijaara. Trick imaginary lakkoofsota dhoksaadhaan deebisuu miti. Yaada bu'uuraa tokko, sirnoota adda adda akkamitti walitti makaman irratti, jijjiiruu dha. Xumura of-eeggannoo qabu, akka barreessitoonni jedhanitti: walxaxaa lakkoofsota quantum makaanikaa ibsuuf dirqama miti, garuu baay'ee faayidaa qabu dha.



Walxaxaa amplitude a+bi jechuun dhugaa lakkoofsota lama, dhugaa fi imaginary kutaalee, flag tokko waliin bakka buufamuu danda'u. Dhugaa formulation wantoota bu'uuraa xiqqeessu miti; container bookkeeping jijjiira, cost isaa sirnoota yeroo compose godhan mul'ata.

Original diagram — The Clean Paper CC BY 4.0



Yaaliiwwan 2021–22 tiyooriiwwan addaa lama wal-bira qaban — istaandaardii walxaxaa quantum makaanikaa idilee tensor product waliin, fi dhugaa “foil” tokko tensor-product rule sanuma eegu. Yaalii foil sana reject godhe; real-valued reformulations hunda miti.

Original diagram — The Clean Paper CC BY 4.0

Walxaxaa lakkoofsota tiyoorii keessatti maal hojjatu

Quantum makaanikaa keessatti haala sirna tokko amplitudes’n ibsama; carraa bu’aa argachuuf amplitude magnitude squared fudhatama. Istaandaardii tiyoorii keessatti amplitudes **walxaxaa lakkoofsota** dha: tokko tokko hammamtaa fi sadarkaa, jechuun angle, qaba. Sadarkaa sun decoration miti. Paths lama bu’aa tokko bira ga’u yeroo walitti makaman, phases isaanii reinforce moo cancel akka godhan murteessu — interference quantum amala mallattoo ta’e. Waliigalaa sadarkaa sirna guutuu waliin qoodamu ammoo safartuu’n hin argamu.

Walxaxaa lakkoofsa jechuun dhugumaan dhugaa lakkoofsota lama — dhugaa kutaa fi imaginary kutaa — rules addaa multiplication waliin package godhame. Kanaaf gaaffiin uumama: packaging kun essential dha? Dhugaa lakkoofsota lamaan eegi, walxaxaa packaging dhiisi, quantum makaanikaa guutuu argachuu dandeessaa? Rules multiplication walxaxaa lakkoofsota “lakkoofsota lama wal-cina” qofa irraa adda godhu; kanaaf deebiin salphaa miti, subtlety achi jira.

Bu'aa 2021 dhugumaan maal mirkaneesse

Renou fi colleagues gaaffii kana boca testable tokkootti jijjiiran. Dhugaa lakkoofsota quantum tiyoorii keessatti bakka kamiyyuu mul'achuu danda'aa hin gaafanne; **sirnoota walitti makuuf rule addaa tokko** yoo fudhatame, real-number formulation walxaxaa tiyoorii tilmaamota hunda deebisee uumu danda'aa gaafatan. Rule sun — tensor-product rule — kutaalee walaba hedduu guutuu tokko keessatti ibsuuf ajaja qorichaa istaandaardii dha.

Rule sana jala, parties sadii maddoota walaba lama irraa entanglement qooddatan scenario tokko argatan, real-number tiyoorii fi walxaxaa tiyoorii walitti dhufeenyota safaramuu danda'an adda adda tilmaaman — multipartite Bell qormaata fakkaatu. Bara 2022 yaaliiwwan superconducting circuits fi photons fayyadamuun qormaatawwan kana raawwatan. Walitti dhufeenyota safarame walxaxaa quantum makaanikaa waliin wal-siman; dhugaa alternative sana waliin hin simne.

> **Maaliif qormaata kun madda lama barbaada, tokko miti**
>
> Bell qormaata idilee madda tokko entangled pair tokko Alice fi Bobtti erga. Setup kana keessatti real-number quantum makaanikaa walxaxaa tiyoorii walitti dhufeenyota sanuma deebisee uumu danda'a — tiyooriiwwan lamaan distinguish gochuun hin danda'amu; madda tokko qofa murteessuu hin danda'u.
> Argument 2021 madda **walaba** lammaffaa dabaluu irraa humna argata. Parties sadii sarara irratti yaadi: Alice, Bob, Charlie. Madda tokko Alice fi Bob entangle godha; madda adda, shared darbe hin qabne, Bob fi Charlie entangle godha. Bob jidduu zarraawwan isaa lama waliin safara, halves lamaan walitti hidha. **Walabummaa** maddoota lamaan — addaan prepared ta'uu isaanii — hojii ijoo hojjeta: istaandaardii tensor-product rule walaba sirnoota walitti maku jala, real-number tiyoorii network kana keessatti three-way walitti dhufeenyota walxaxaa quantum makaanikaa tilmaamu deebisee uumu hin danda'u; single-source qormaata keessatti tiyooriiwwan lamaan walqixa. Gap sana yaalii safare.

Kun bu'aa dhugaa fi qulqulluu dha. Garuu maal wal-bira qabame sirriitti ilaali: istaandaardii walxaxaa quantum tiyoorii fi **dhugaa tiyoorii addaa tokko** — idilee tensor-product rule eegu. Yaaliiwwan pairing sana irratti murtii kennan, dhugaa lakkoofsota mataa isaanii irratti miti. Barruu haaraan foundations terminology fayyadamuun alternative reject ta'e kana **foil tiyoorii** jedha — tiyoorii namni dhugaa jedhee dhiyeessu miti; accepted tiyoorii waliin intentional contrast ta'ee yaalii lamaan adda baasuuf ijaarame. Foil reject gochuun yaadota bu'uuraa dhugaa tiyoorii keessaa kam hojii ijoo hojjetaa ture agarsiisa.

Barruu haaraan maal jijjiira

Hojii haaraan waan hunda jechuun danda'amu eega; postulate tokko qofa jijjiira. Sirnoota walitti makuuf tensor-product rule assume gochuu dhiisee, **locality requirement** barreessitoonni caalaatti physically fundamental jedhu irraa jalqaba: subsystem tokko irratti operation godhamu, subsystem

biraa untouched irratti measurable dhiibbaa qabaachuu hin qabu.

Starting qabxii sana irraa real-number quantum makaanikaa explicit ijaaru. Dhugaa fi imaginary kutaalee amplitudes idilee bookkeeping dhugaa dabalataa ta'anii waliin deemu — barruun "**flag**" sirna tokko tokko waliin attached jedha — fi waliigalaa sadarkaa walxaxaa tiyoorii keessatti unobservable ta'e, dhugaa tiyoorii keessatti rotation unobservable ta'a. Price exactly bakka bu'aa 2021 itti argate irratti mul'ata: **sirnoota akkamitti walitti makaman**. Dhugaa descriptions kana naive ta'een glue gochuun recipe well-defined illee hin kennu; construction sun descriptions fiiziksii tokko bakka bu'an classes tokko keessatti garee godhee classes sana irratti hojjeta. Combining rule kanaan dhugaa tiyoorii expectation gatiiwwan walxaxaa tiyoorii tilmaamu hunda deebisee uumu — sirna tokkoofis, sirnoota hedduu parties adda addatti entangled ta'aniifis. Barreessitoonni construction sun essentially unique fi istaandaardii quantum makaanikaa waliin equivalent akka ta'es agarsiisu.

Kanaaf multipartite yaaliiwwan dhugaa tiyoorii kana walxaxaa tiyoorii irraa distinguish gochuu hin danda'an, sababni isaas tilmaamota hunda irratti walqixa. Yaaliiwwan duraanii hin dogoggorre; dhugaa tiyoorii adda, caalaatti restrictive ta'e qoru turan.

Kun maaliif wal-faallaa miti

"Yaaliiwwan 2021 dogoggora turan" jechuun dubbisuun salphaa dha. Faallaa isaa. Yaaliiwwan sirrii turan, barruu haaraan sirrii ta'uu isaanii irratti hirkata: safarame walitti dhufeenyota hunda fudhatee dhugaa formulation isaanis uumu agarsiisa. Wanti revise ta'e hiika dha — "dhugaa tiyoorii kun falsified dha" irraa "dhugaa lakkoofsota quantum makaanikaa keessatti impossible dha"tti jump godhame. Jump sun yaada bu'uuraa hojii ijoo hojjete darbite.

barruun walxaxaa lakkoofsota dhiisuu qabna illee hin jedhu. Cuunfaan isaa lamaan irratti ofeeggannoo qaba: walxaxaa lakkoofsota strictly necessary miti, garuu baay'ee faayidaa qabu dha. Dhugaa construction sirna hunda irratti flag dabalataa fi combining rule caalaatti delicataa barbaada; walxaxaa lakkoofsota waan hunda arithmetic qulqulluu tokko keessatti package godhu. Convenience waan xiqqaa miti. Fiiziksii keessatti sirna herregaa tokko maaliif injifatu sababni guutuu ta'uu danda'a.

Maaliif barbaachisaa dha

Gaaffiin gadi jiru "necessary" fiizikaalaa tiyoorii keessatti maal jechuu dha jedhu. Yaalii tiyooriiwwan lama tilmaamota adda ta'an yoo kennan adda baafachuu danda'a. Garuu yaalii qofti herregaa ingredient tokko tilmaamota set tokkoof container danda'amaa **tokko qofa** ta'uu hin mirkaneessu — gaaffiin kun tiyooriiwwan kam akka jiraachuu danda'an irratti dha, construction'n murtaa'a, safartuu qofa'n miti. barruun construction dha: alternative yaaliiwwan keessaa baasu jedhamee fudhatame ifatti agarsiisa.

Bu'aa kun distinction waliigalaa tokko illee sharpen godha. "Tiyoorii kun falsified dha" fi "herregaa

meeshaa kun unavoidable dha" statements adda adda. Gap gidduu jiru exactly bakka ifaa yaalii bu'aa overclaim ta'uu danda'u. Walxaxaa lakkoofsota quantum makaanikaa'f afaan natural fi efficient ta'ee hafa. Metaphysically required ta'uu isaanii gaaffii adda; gaaffii sana irratti, ammaaf, deebiin **lakki** dha.

Cuunfaa gabaabaa

Yaada dhihaate 2021 fi yaaliiwwan 2022, real-number quantum makaanikaa **istaandaardii tensor-product rule** sirnoota walitti maku irratti ijaarame, walxaxaa quantum makaanikaa irraa tilmaamota adda, testable akka kennu agarsiisan; yaaliiwwan walxaxaa tiyoorii deeggaran. Kun "imaginary lakkoofsota physically necessary" jechuun baay'ee gabaafame. Barruu *Fiizikaalaa Gamaaggama Letters* haaraan locality-based postulate adda irratti real-number quantum makaanikaa ijaaree walxaxaa tiyoorii tilmaamota hunda, multipartite qormaatawwan dabalatee, deebisee uumu — walxaxaa lakkoofsota convenient dha, strictly necessary miti. Kun tiyoorii construction dha; yaaliiwwan duraanii hin diigu; hojiirra oolu quantum makaanikaa dhugaa lakkoofsota qofaan irra deebi'anii barreessuu waamicha miti.

Sakatta'a ifaa

barruun maal agarsiisa: Sirnoota walitti makuuf tensor-product rule caalaa locality postulate irratti yoo ijaarame, dhugaa lakkoofsota qofa fayyadamuun self-wal-simu quantum makaanikaa istaandaardii walxaxaa tiyoorii tilmaamota hunda, multipartite Bell-type yaaliiwwan dabalatee, deebisee uumu danda'a.

Wanti amansiisaa garuu ijoo miti: Kun bu'aawwan 2021–2022 "refute" godha jechuun. Hin godhu. Yaaliiwwan sana sirrii jedhanii fudhata; scope isaanii reinterpret godha: dhugaa tiyoorii addaa tensor-product rule eegu tokko reject godhan, dhugaa lakkoofsota principle irratti miti.

Wanti hin agarsiifne: Walxaxaa lakkoofsota dogoggora, faayidaa hin qabne yookaan hojiirra oolu keessaa dhiisuu qabna jechuu miti — barruun baay'ee faayidaa qabu jedhu. Yaalii haaraa illee miti: daataa haaraa hin safaramne; himannaa herregaa construction fi consistency ragaa dha.

Daangaa dubbisaa waliigalaatiif: Argument yaada bu'uuraa kami caalaatti physically fundamental akka ta'e irratti hirkata — tensor-product rule moo locality postulate. Kun foundations debate keessatti reasoned choice dha, safartuu'n sirreessu fact miti; real-number construction walxaxaa tokko waliin walqixa tilmaama kennus arguably xiqqaa natural dha.

Dubbisaan waliigalaa hammam amanuu qaba? Construction mathematically wal-simu ta'uu irratti amantaa guddaa — gamaaggama ogeessotaa keessa darbe dha fi logic checkable. ergaa ijoo modest irratti amani: walxaxaa lakkoofsota quantum makaanikaa'f afaan convenient dha, metaphysical necessity mirkanaa'e miti. "Lakkoofsi imaginerii dhugaa dha" gosa mata-duree tokko slogan akka ta'etti ilaali; barruun sirreessuuf barreessame.

Maddoota

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