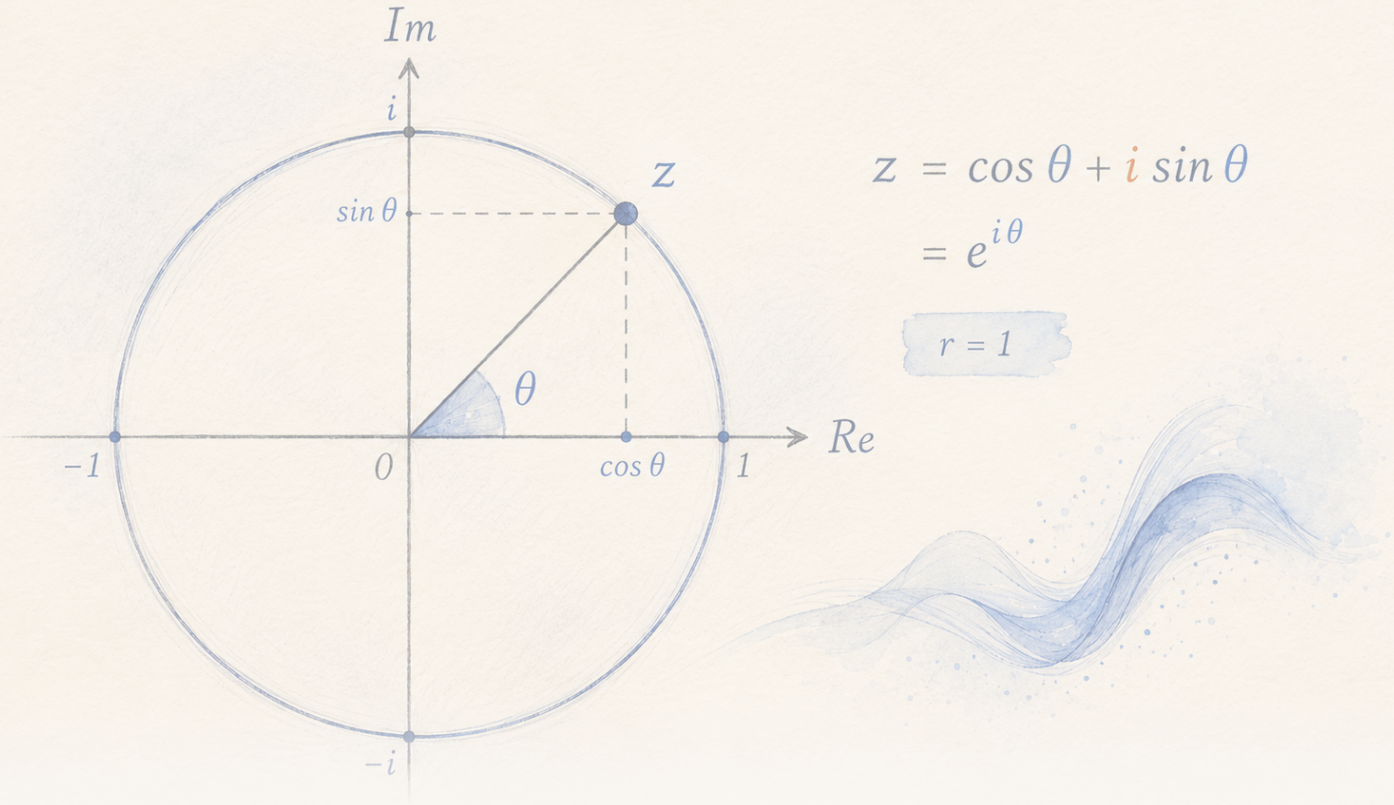

The Clean Paper

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

Quantum mechanics za a iya rubuta ta da real numbers kawai — amma caveat yana cikin yadda ake combine systems

A 2021 wani widely reported result ya nuna real-number quantum mechanics da standard tensor-product rule za a iya falsify experimentally, kuma 2022 experiments sun agree da complex quantum theory. Wannan ya zama headline cewa imaginary numbers physically real ne. Sabuwar Physical Review Letters paper ta sharpen claim: idan real formulation aka gina a different locality-based assumption game da combining systems, tana reproduce every prediction na complex theory, ciki har da multipartite tests. Honest reading: complex numbers convenient ne, ba strictly necessary ba; earlier experiments sun rule out particular real theory, ba real numbers in principle ba.

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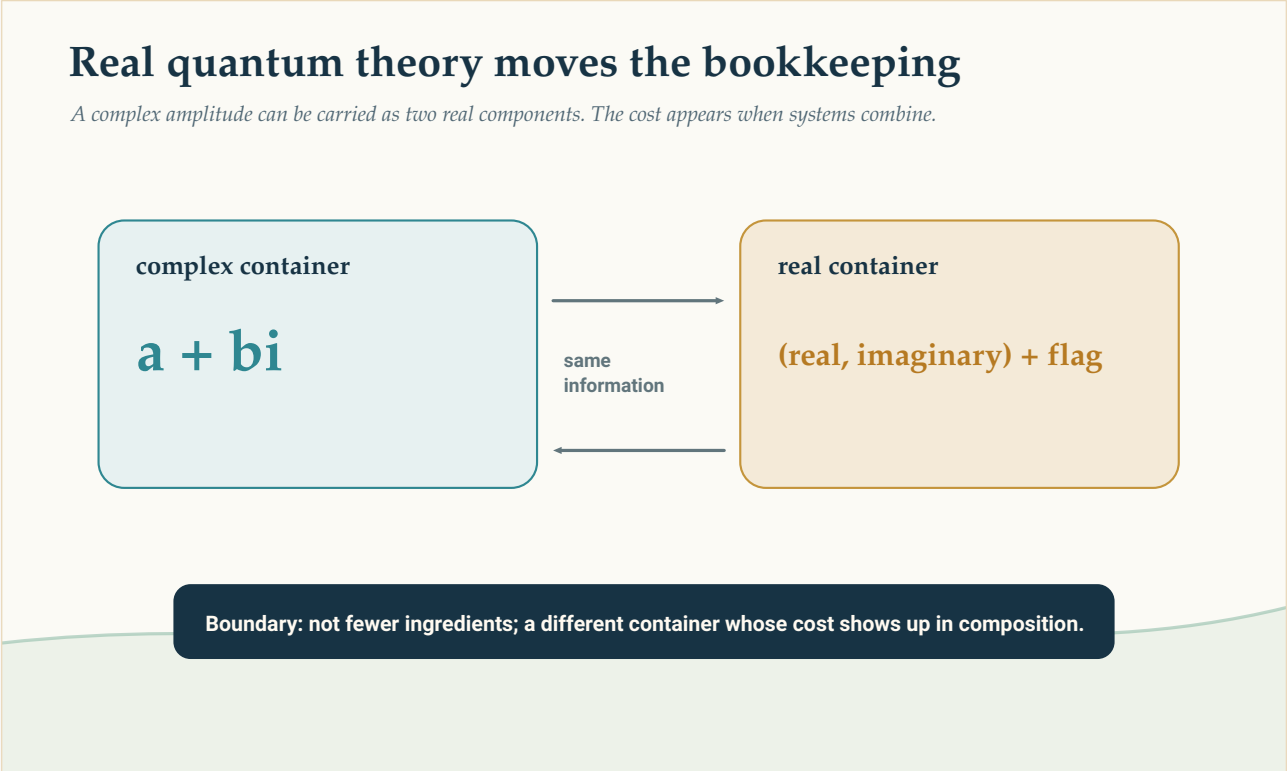
Paper: *Quantum Mechanics Based on Real Numbers: A Consistent Description*, Pedro Barrios Hita, Anton Trushechkin, Hermann Kampermann, Michael Epping, Dagmar Bruss, Physical Review Letters · DOI: 10.1103/4k13-sdjh

Kanun labari da ya cancanci a sake karantawa

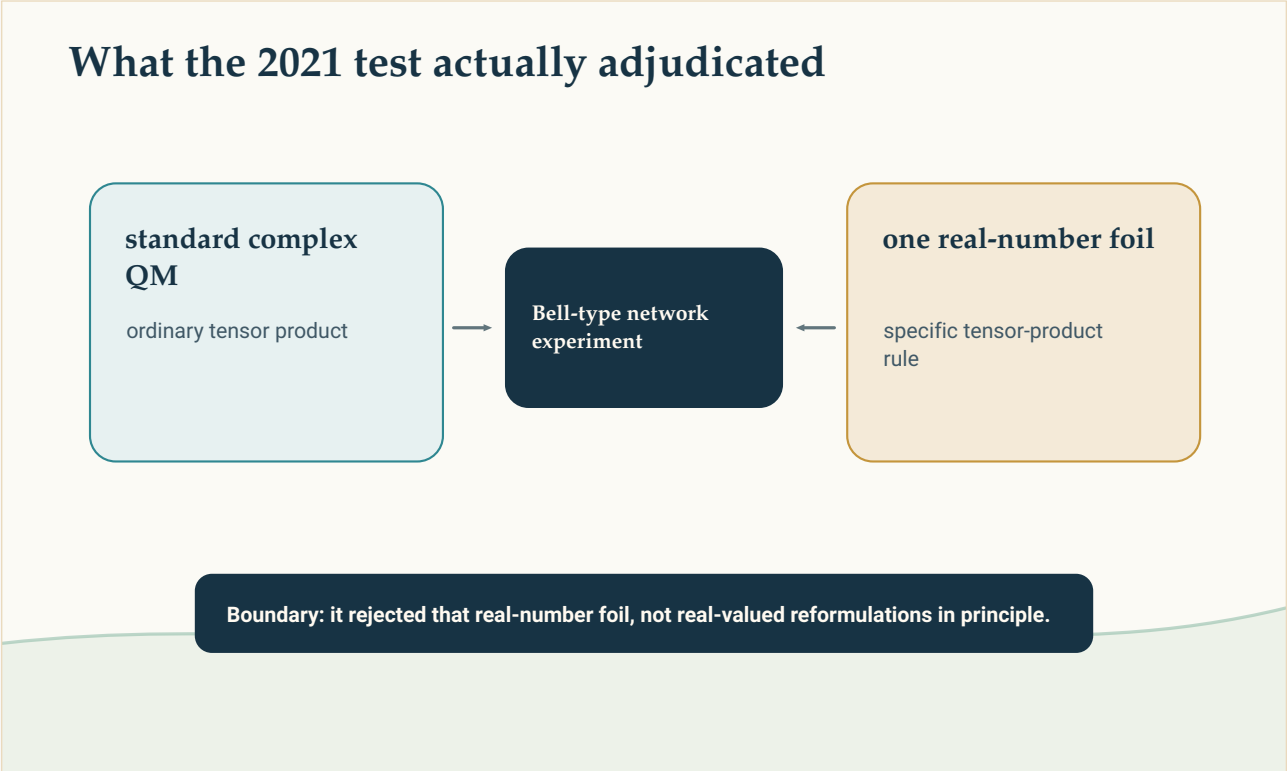
Shekaru kaɗan da suka wuce wani ikirari mai ɗaukar hankali ya yadu: wai gwaje-gwaje sun nuna cewa imaginary numbers suna da “gaskiyar zahiri,” kuma ba za a iya rubuta quantum mechanics ba tare da su ba. Ikirarin ya fito daga physics na gaske kuma mai kulawa — wani proposal na 2021 a *Nature* daga Marc-Olivier Renou da abokan aiki, sannan gwaje-gwaje a 2022 da suka aiwatar da shi. Amma labarin jama’a ya matsa wani takamaiman bayani zuwa slogan, kuma slogan ɗin ya fi sakamakon ƙarfi.

Sabuwar takarda a *Physical Review Letters* daga Pedro Barrios Hita, Anton Trushechkin, Hermann Kampermann, Michael Epping da Dagmar Bruß ta dawo da wannan takamaiman ma’ana. Ta gina sigar quantum mechanics da ke amfani da **real numbers kawai** kuma tana sake samar da duk predictions na standard complex theory — har da multipartite experiments da aka ce sun kore real-number theory. Dabarar ba ita ce a ɓoye imaginary numbers a wani wuri ba. Ita ce a canza assumption guda game da yadda systems daban suke haɗuwa. Kammalawa mafi gaskiya, kamar yadda marubutan suka faɗa, shi ne: **complex numbers ba dole ba ne wajen bayyana quantum mechanics, amma suna da amfani sosai.**



Complex amplitude a+bi za a iya ɗauka a matsayin real numbers biyu tare da wani “flag” da ake ɗauka da kowane system. Real formulation ba ta da ingredients kaɗan; wani container dabam ne, kuma farashin ya bayyana a yadda systems suke haɗuwa.

Original diagram — The Clean Paper CC BY 4.0



Gwaje-gwajen 2021–22 sun kwatanta theories biyu takamaimai — standard complex quantum mechanics da wata real "foil theory" da ta riƙe tensor-product rule — kuma sakamakon ya goyi bayan complex theory. Sun kore wannan foil ɗin, ba real numbers a principle ba.

Original diagram — The Clean Paper CC BY 4.0

Me complex numbers suke yi a ka'idar

A quantum mechanics, state na system ana bayyana shi da amplitudes, kuma probability na outcome ana samu daga squared size na amplitude. A standard theory, amplitudes ɗin complex numbers ne: kowanne yana da magnitude da phase, wato angle. Wannan phase ba ado ba ne. Idan paths biyu zuwa outcome guda suka haɗu, phases ɗinsu suna ƙayyade ko za su ƙarfafa juna ko su soke juna — wato interference, ɗaya daga alamomin quantum behaviour. Amma overall phase da system gaba ɗaya yake raba ba za a iya aunawa ba.

Complex number a lissafi real numbers biyu ne — real part da imaginary part — da aka haɗa tare da ƙa'idoji takamaimai na multiplication. Saboda haka tambaya ta dabi'a ita ce ko wannan packaging ɗin ya zama dole. Za a iya riƙe real numbers biyu, a cire complex packaging, amma har yanzu a samu duk quantum mechanics? Rules na multiplication ne suke sa complex number ya zama fiye da lambobi biyu da aka ajiye gefe da gefe, don haka amsar ba bayyananniya ba ce. A nan ne subtlety take.

Abin da sakamakon 2021 ya tabbatar a zahiri

Renou da abokan aiki sun tambayi wannan tambayar cikin hanyar da za a iya gwadawa. Ba su tambayi ko real numbers za su iya bayyana ko'ina a quantum theory ba. Sun tambayi ko real-number formulation za ta iya dacewa da duk predictions na complex theory idan aka riƙe wata takamaiman ƙa'ida ta haɗa systems. Wannan ƙa'ida — **tensor-product rule** — ita ce standard prescription na bayyana independent parts da yawa a matsayin whole system guda.

A ƙarƙashin wannan rule, sun gano scenario da parties uku suke raba entanglement daga independent sources biyu, inda real-number theory da complex theory suke yin predictions masu bambanci da za a iya auna — multipartite version na Bell test. A 2022, gwaje-gwaje da suka yi amfani da superconducting circuits da photons sun yi irin waɗannan tests. Correlations da aka auna sun dace da complex quantum mechanics kuma ba su dace da wannan real alternative ba.

> **Me ya sa gwajin yake buƙatar sources biyu, ba guda ba**
>
> Ordinary Bell test yana amfani da source guda da ke aika entangled pair ga Alice da Bob. A wannan setup, real-number quantum mechanics na iya reproduce correlations iri ɗaya da complex theory; ba za a iya bambance theories ɗin biyu ba, don haka source guda ba zai warware tambayar ba.
> Argument na 2021 ya samu ƙarfi ne da source na biyu mai **'yancin kansa**. Ka yi tunanin parties uku a layi: Alice, Bob, Charlie. Source ɗaya yana entangle Alice da Bob; wani source dabam, wanda bai raba common past da na farko ba, yana entangle Bob da Charlie. Bob yana tsakiya kuma yana auna particles biyu tare, yana haɗa bangarorin biyu. **Independence na sources biyu** ne yake yin aikin: ƙarƙashin standard tensor-product rule, real-number theory ba za ta iya dacewa da three-way correlations da complex quantum mechanics take hango a wannan network ba, yayin da single-source test ba ya raba su. Wannan tazara ce gwaje-gwajen suka auna.

Wannan sakamako ne na gaske kuma mai tsabta. Amma a lura da abin da aka kwatanta: standard complex quantum theory da **real theory guda takamaimai**, wadda ta riƙe ordinary tensor-product rule. Wannan pair ɗin ne gwaje-gwajen suka warware tsakaninsu, ba real numbers gaba ɗaya ba. Sabuwar takardar ta kira wannan alternative da kalmar quantum foundations da ta dace: **foil theory** — ka'idar da ba a gabatar da ita a matsayin gaskiya ba, sai a gina ta da gangan domin ta bambanta da accepted theory ta yadda experiment zai iya raba su. Darajarta ita ce kasancewa distinguishable: idan aka kore foil, ana ganin wane assumptions ne ke yin aikin.

Abin da sabuwar takardar ta canza

Sabon aikin ya riƙe kusan komai amma ya canza postulate guda. Maimakon ɗaukar tensor-product rule a matsayin tushen haɗa systems, ya fara daga locality requirement da marubutan suke ganin ta fi fundamental a physics: **operation da aka yi a subsystem guda kaɗai bai kamata ya sami measurable effect a wani subsystem da ba a taɓa ba.**

Daga wannan starting point suka gina real-number quantum mechanics a sarari. Real da imaginary parts na usual amplitudes ana ɗaukar su a matsayin ƙarin real bookkeeping — takardar tana kiransa **"flag"** da ke tare da kowane

system — kuma unobservable global phase na complex theory yana zama unobservable rotation a real version. Farashin ya bayyana daidai inda sakamakon 2021 ya nuna: **a yadda systems suke haɗuwa**.

Naive hanyar haɗa waɗannan real descriptions ba ta ma ba da well-defined recipe. Saboda haka construction ɗin yana haɗa descriptions da suke wakiltar physics iri ɗaya cikin classes, sannan yana aiki da waɗannan classes. Da wannan combining rule, real theory tana reproduce **kowane expectation value** da complex theory take hango — ga system guda da ga systems da yawa masu entanglement tsakanin parties masu nisa. Marubutan sun kuma nuna cewa construction ɗin essentially unique ne kuma equivalent da standard quantum mechanics.

Saboda haka multipartite experiments ba za su iya bambance wannan real theory da complex one ba, domin suna yin predictions iri ɗaya gaba ɗaya. Gwaje-gwajen baya ba su yi kuskure ba; suna gwada ne wani real theory dabam, mai takurawa fiye da wannan.

Me ya sa wannan ba contradiction ba ne

Yana da sauƙi a karanta wannan a matsayin "gwaje-gwajen 2021–22 sun yi kuskure." Akasin haka ne. Gwaje-gwajen sun yi daidai, kuma wannan takarda tana dogara da su kasance daidai: tana karɓar duk measured correlations sannan ta nuna real formulation da ke samar da su ma. Abin da take gyarawa shi ne **fassarar girman sakamakon** — tsalle daga "wannan real theory an falsify ta" zuwa "real numbers ba za su iya yin quantum mechanics ba." Wannan tsalle ya wuce assumption da yake yin aikin.

Haka kuma takardar ba ta ce ya kamata a bar complex numbers ba. Takaitawarta tana taka-tsantsan a bangarorin biyu: complex numbers ba strictly necessary ba ne, kuma suna **da amfani sosai**. Real construction tana buƙatar flag a kowane system da rule mai ɗan rikitarwa na haɗa systems; complex numbers suna nannade waɗannan abubuwan cikin arithmetic mai tsabta. Convenience ba ƙaramin abu ba ne. A physics, sau da yawa shi ne dalilin da formalism ɗaya yake cin nasara.

Me ya sa wannan yake da muhimmanci

Tambayar da ke ƙasa ita ce ma'anar kalmar **"dole"** a physical theory. Experiment zai iya bambance theories biyu idan predictions ɗinsu sun bambanta. Amma experiment kaɗai ba zai iya gaya maka cewa wani mathematical ingredient shi ne **kaɗai possible container** na predictions ba. Wannan tambaya ce game da irin theories da za a iya ginawa, kuma construction ne yake amsa ta, ba measurement kaɗai ba. Wannan takarda construction ce: ta nuna alternative da aka yi tunanin experiments sun riga sun kore shi a principle.

Sakamakon kuma yana kaifafa wani bambanci da ya dace a riƙe: **"an falsify wannan theory"** da **"wannan mathematical tool ba za a iya kauce masa ba"** statements biyu ne daban. Tazarar da ke tsakaninsu ita ce inda clean experimental result zai iya zama overclaim. Complex numbers suna ci gaba da kasancewa natural da efficient language na quantum mechanics. Ko suna da metaphysical necessity tambaya ce daban, kuma a wannan takardar amsar ita ce: a'a, ba dole ba ne.

Takaitaccen bayani

Proposal na 2021 da gwaje-gwajen 2022 sun nuna cewa real-number quantum mechanics da aka gina da standard tensor-product rule na haɗa systems tana yin measurable predictions dabam da complex quantum mechanics, kuma gwaje-gwajen sun goyi bayan complex theory. Wannan ya yadu a matsayin hujjar cewa imaginary numbers suna da physical necessity. Sabuwar takarda a *Physical Review Letters* ta gina real-number quantum mechanics a kan locality postulate dabam wadda take reproduce **duk predictions** na complex theory, ciki har da multipartite tests. Wannan yana nuna cewa complex numbers suna da matuƙar amfani amma **ba strictly necessary ba**. Theoretical construction ne; ba ta rushe gwaje-gwajen baya, kuma ba ta bayar da dalilin sake rubuta quantum mechanics a aikace ba.

Bincike ba tare da ƙarin gishiri ba

Abin da takardar ta nuna: Za a iya gina self-consistent quantum mechanics da real numbers kawai wadda take reproduce kowane prediction na standard complex theory, ciki har da multipartite Bell-type experiments, idan aka gina ta daga locality postulate maimakon tensor-product rule na haɗa systems.

Abin da yake yiwuwa amma ba shi ne babban batu ba: Cewa wannan "ya soke" sakamakon 2021–2022. Bai yi ba. Yana karɓar gwaje-gwajen a matsayin daidai kuma yana gyara scope ɗinsu: sun kore real theory guda takamaimai da ta riƙe tensor-product rule, ba real numbers a principle ba.

Abin da bai nuna ba: Cewa complex numbers kuskure ne, ba su da amfani, ko ya kamata a bar su a practice — takardar kanta ta ce suna da amfani sosai. Haka kuma ba sabon experiment ba ne: babu data sabo da aka auna; ikirarin mathematical construction da consistency proof ne.

Babban iyaka ga mai karatu na gama gari: Argument ɗin yana juyawa ne a kan wane assumption ake ɗauka ya fi fundamental — tensor-product rule ko locality postulate. Wannan zaɓi ne mai hujja a ongoing foundations debate, ba gaskiyar da measurement kaɗai ta kulle ba. Real-number construction ɗin kuma yana iya zama less natural fiye da complex formalism da yake reproduce.

Yawan amincewar da ya dace ga mai karatu na gama gari: Babba cewa construction ɗin mathematically consistent ne kuma peer-reviewed. Takeaway mafi kyau shi ne mai natsuwa: **complex numbers su ne convenient language na quantum mechanics, ba proven metaphysical necessity ba.** Kanun labari irin "imaginary numbers are real" ya fi sakamakon da experiments suka tabbatar ƙarfi.

Majiyoyi

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