Title: Single-photon test of Hyper-Complex Quantum Theories

Date: Sep 23, 2016 11:00 AM

URL: http://pirsa.org/16090053

Abstract: One of the most successful theories in physics until now is quantum mechanics. However, the physical origins of its mathematical structure are still under debate, and a "generalized" quantum theory to unify quantum mechanics and gravity is still missing. Recently, in an effort to better understand the mathematical structure of quantum mechanics, theories containing the essence of quantum mechanics, while also having a broader description of physical phenomena, have been proposed. These so-called "post-quantum theories" have only been recently tested at the lab. In this talk, I will present the results of our experimental test using single photons to probe one of these post-quantum theories; namely, hyper-complex quantum theories. Interestingly, in hyper-complex theories simple phases do not necessarily commute. To study this effect, we apply two physically different optical phases, one with a positive and one with a negative refractive index, to single photons inside of a Sagnac interferometer. Through our measurements we are able put bounds on this particular prediction of hyper-complex quantum theories.

Outline

- Motivation(QQM)
- Experimental Status
- Our proposal
- Results
- Criticism and replay
- Conclusions

Motivation

Pioneer in the foundation
of quantum mechanics
John von Neumann (1903-1957)

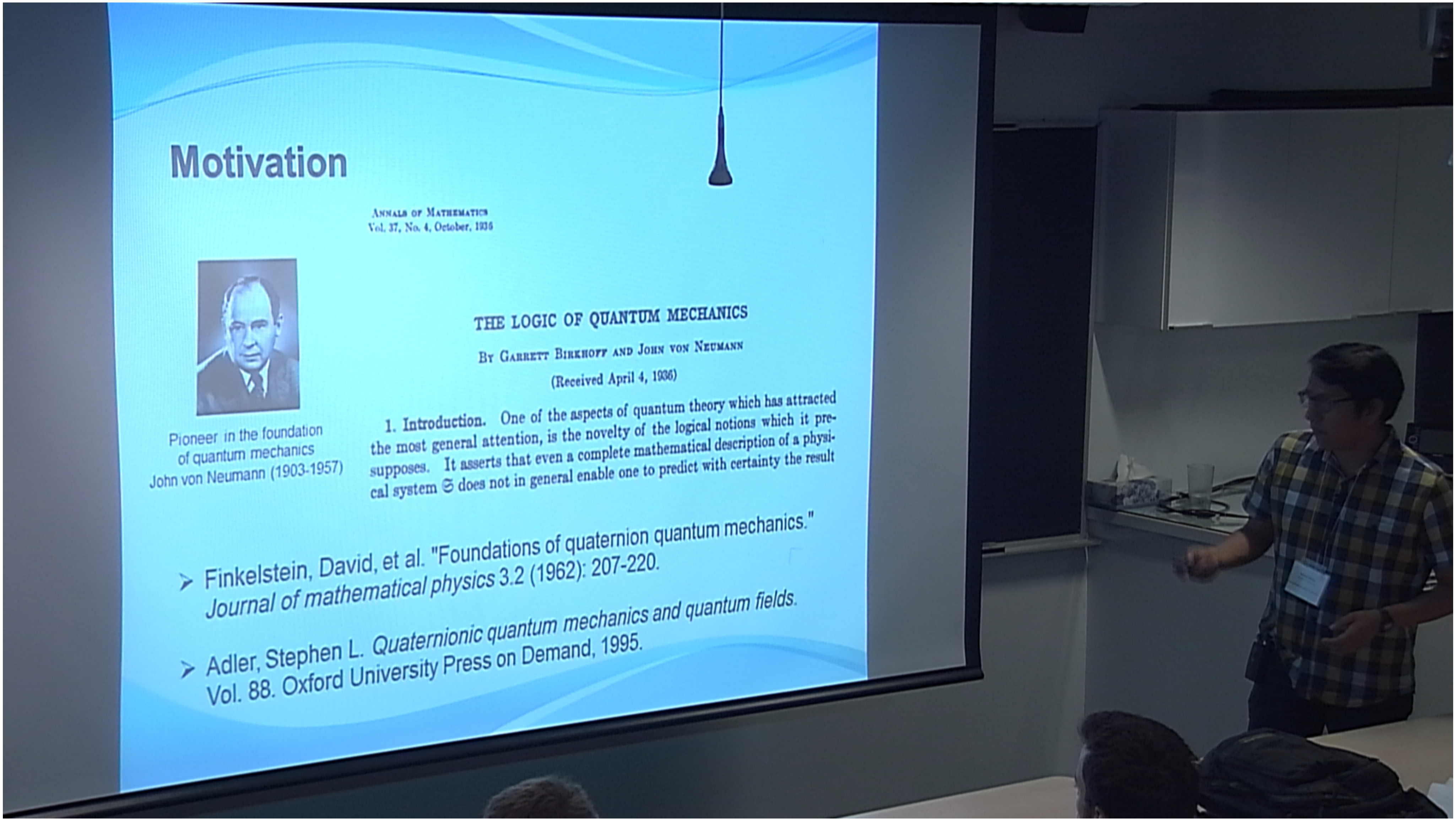
ANNALS OF MATHEMATICS
Vol. 37, No. 4, October, 1936

THE LOGIC OF QUANTUM MECHANICS

BY GARRETT BIRKHOFF AND JOHN VON NEUMANN

(Received April 4, 1936)

1. Introduction. One of the aspects of quantum theory which has attracted the most general attention, is the novelty of the logical notions which it presupposes. It asserts that even a complete mathematical description of a physical system $\mathfrak{S}$ does not in general enable one to predict with certainty the result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Finkelstein, David, et al. "Foundations of quaternion quantum mechanics."
Journal of mathematical physics 3.2 (1962): 207-220.
Adler, Stephen L. Quaternionic quantum mechanics and quantum fields.
Vol. 88. Oxford University Press on Demand, 1995.

What are Quaternions?

The father of quaternions

William Rowan Hamilton
(1805–1865)

They are an extension of complex numbers:

$$q = q_0 + q_1 i + q_2 j + q_3 k$$

where,

$$i^2 = j^2 = k^2 = -1,$$
$$ij = -ji = k.$$

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$$q = q_0 + q_1 i + q_2 j + q_3 k$$

where,

$$\Psi = \Psi_0 + i\Psi_1 + j\Psi_2 + k\Psi_3$$

Quaternions do not commute !!!

$$qp \neq pq$$

Peres proposal

Pioneer of quantum information theory
Asher Peres (1934–2005)

PHYSICAL REVIEW LETTERS

VOLUME 42 | 12 MARCH 1979 | NUMBER 11

Proposed Test for Complex versus Quaternion Quantum Theory

Asher Peres
Department of Physics, Technion–Israel Institute of Technology, Haifa, Israel

(Received 7 December 1978)

If scattering amplitudes are ordinary complex numbers (not quaternions) then there is a universal algebraic relationship between the six coherent cross sections of any three scatterers (taken singly and pairwise). A violation of this relationship would indicate either that scattering amplitudes are quaternions, or that the superposition principle fails. Some experimental tests are proposed, involving neutron diffraction by crystals made of three different isotopes, neutron interferometry, and K_0-meson regeneration.

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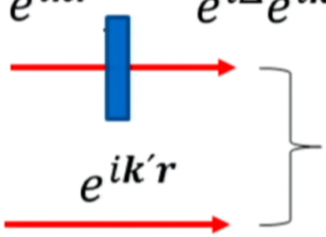
e^{ikr} $\quad e^{i\Delta}e^{ikr}$

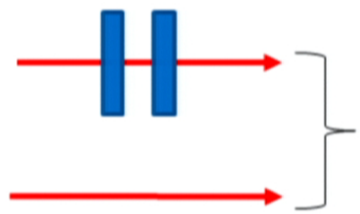


$e^{ik'r}$

$k \approx k'$

By means of interference, you can measure Δ

$\Delta_1 \quad \Delta_2$



$\Delta_{12} = \Delta_2 + \Delta_2$ CQM

$\Delta_{12} \neq \Delta_2 + \Delta_2$ QQM

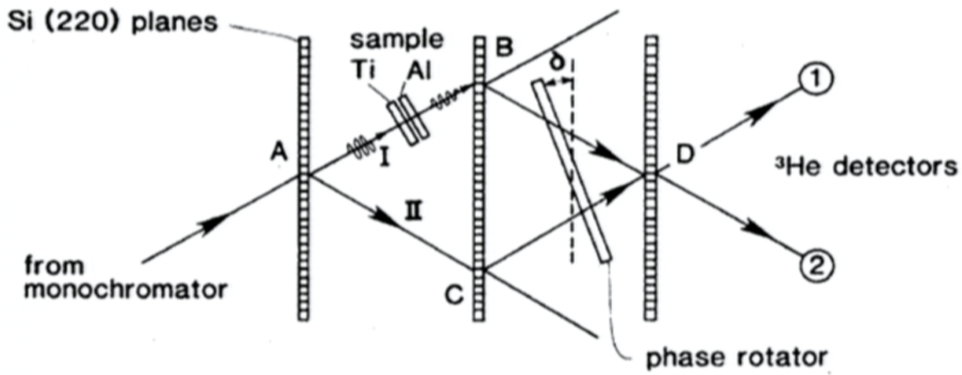
Our motivation

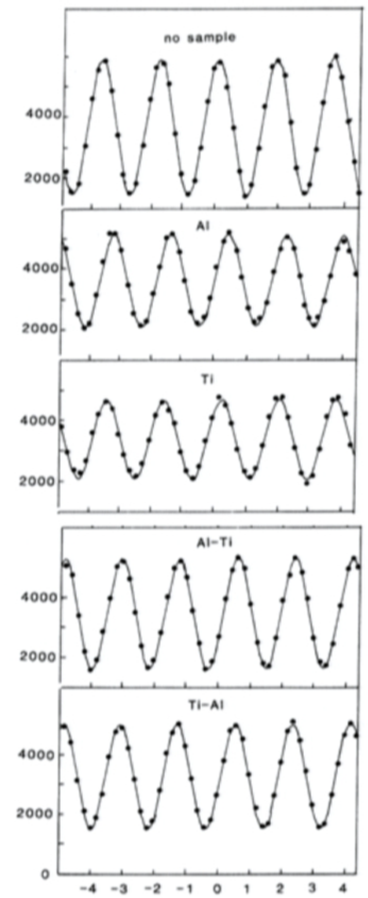
To test complex quantum mechanics(CQM) against exotic alternative theories which use hyper-complex numbers into the phase transformations.

The non-commutativity of phases

Neutron Interferometry[1]

[1]H. Kaiser *et al*, *Phys. Rev.* A **29**, 4, 1984





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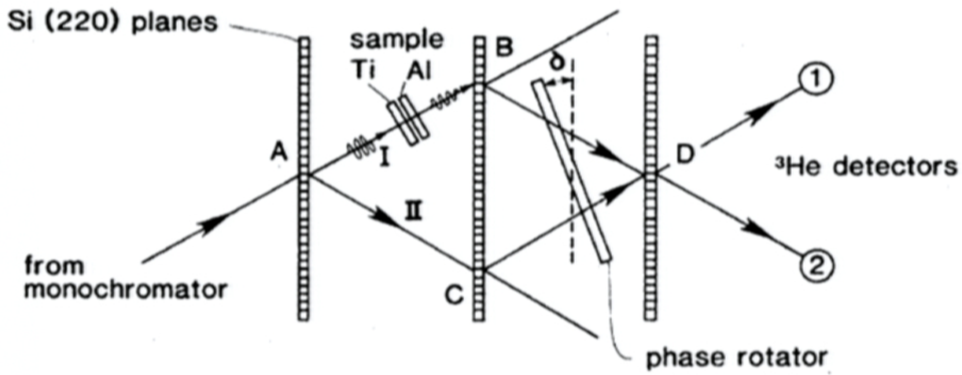
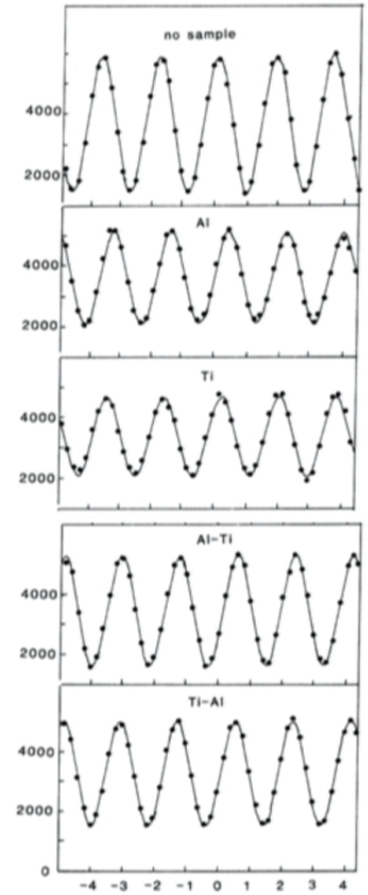




Phase shift $\phi = -\lambda N b D$

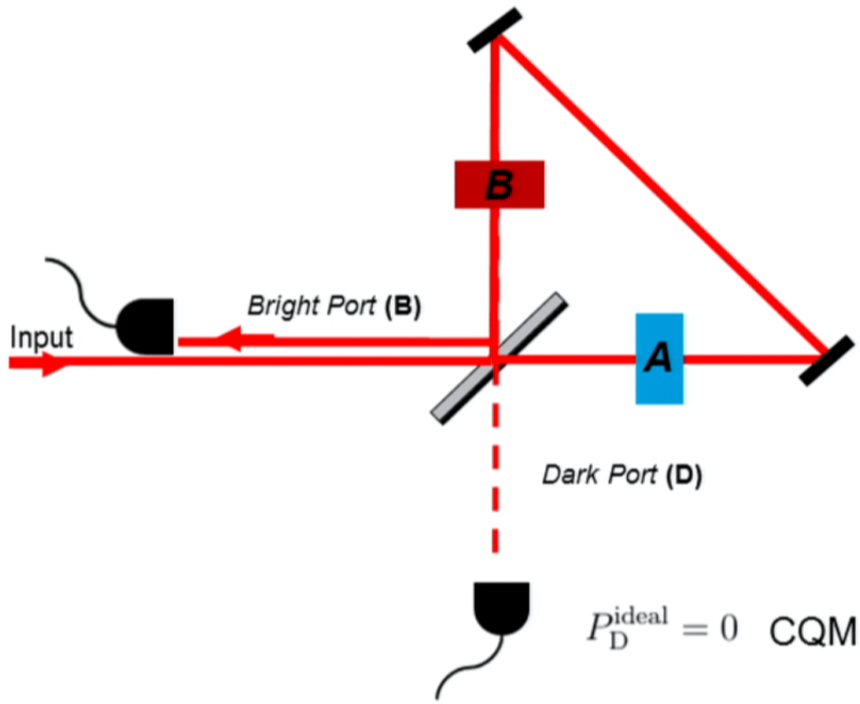
Null result found: $|\,\phi_{\text{Al-Ti}} - \phi_{\text{Ti-Al}}\,| \ll 0.3^\circ$

Theoretical background

Operators

$A = \alpha\mathcal{I}$ $B = \beta\mathcal{I}$

Sagnac interferometer



$P_{\mathrm{D}}^{\mathrm{ideal}} = 0$ CQM

Theoretical background

Operators

$A = \alpha \mathcal{I} \qquad B = \beta \mathcal{I}$

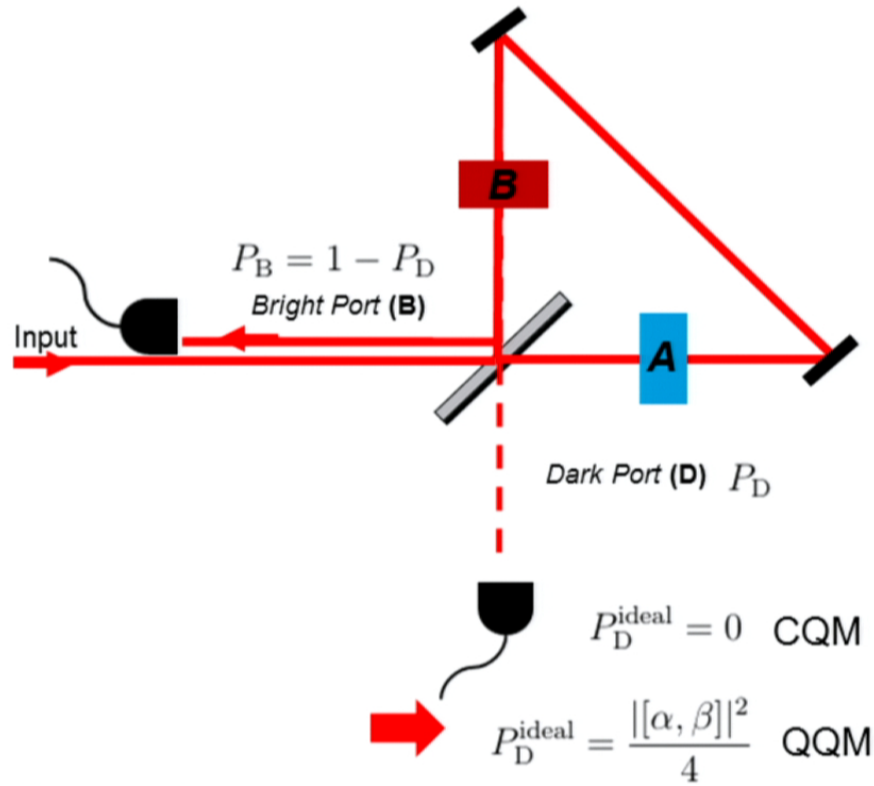
Quaternionic Phases

$\alpha = e^{i\phi_A^1 + j\phi_A^2 + k\phi_A^3}$

$\beta = e^{i\phi_B^1 + j\phi_B^2 + k\phi_B^3}$

$i^2 = j^2 = k^2 = ijk - 1$

Sagnac interferometer



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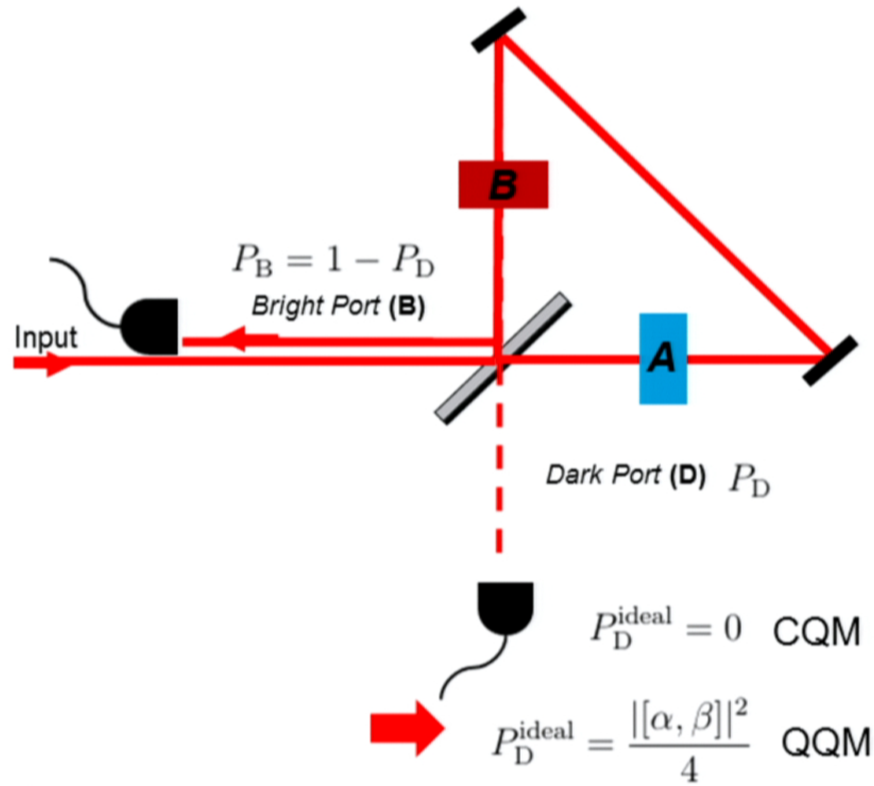
Imperfect Sagnac

- Spatial-mode mismatch
- Polarization mismatch
- No 50:50 BS condition

} v

Sagnac interferometer



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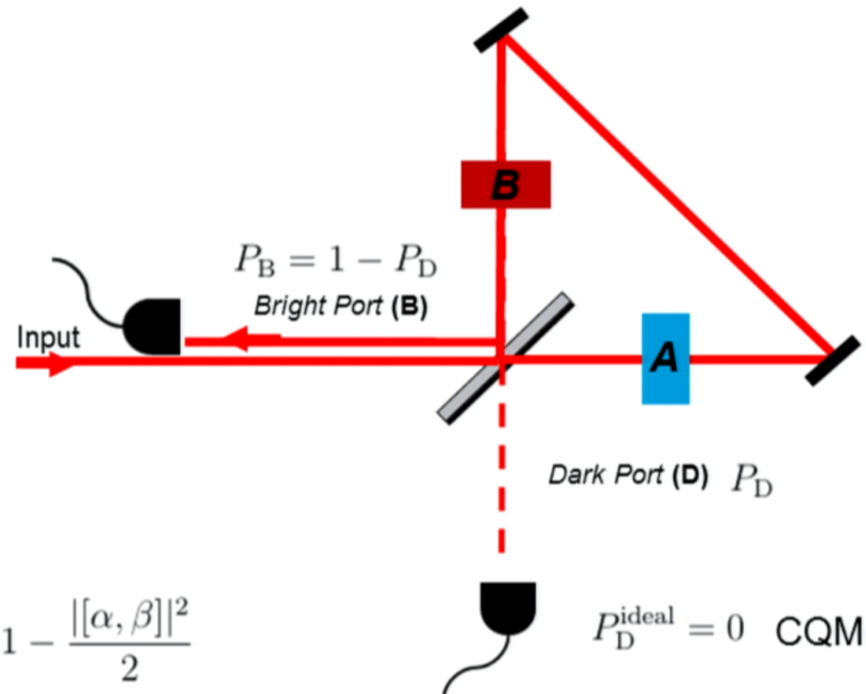


Imperfect Sagnac

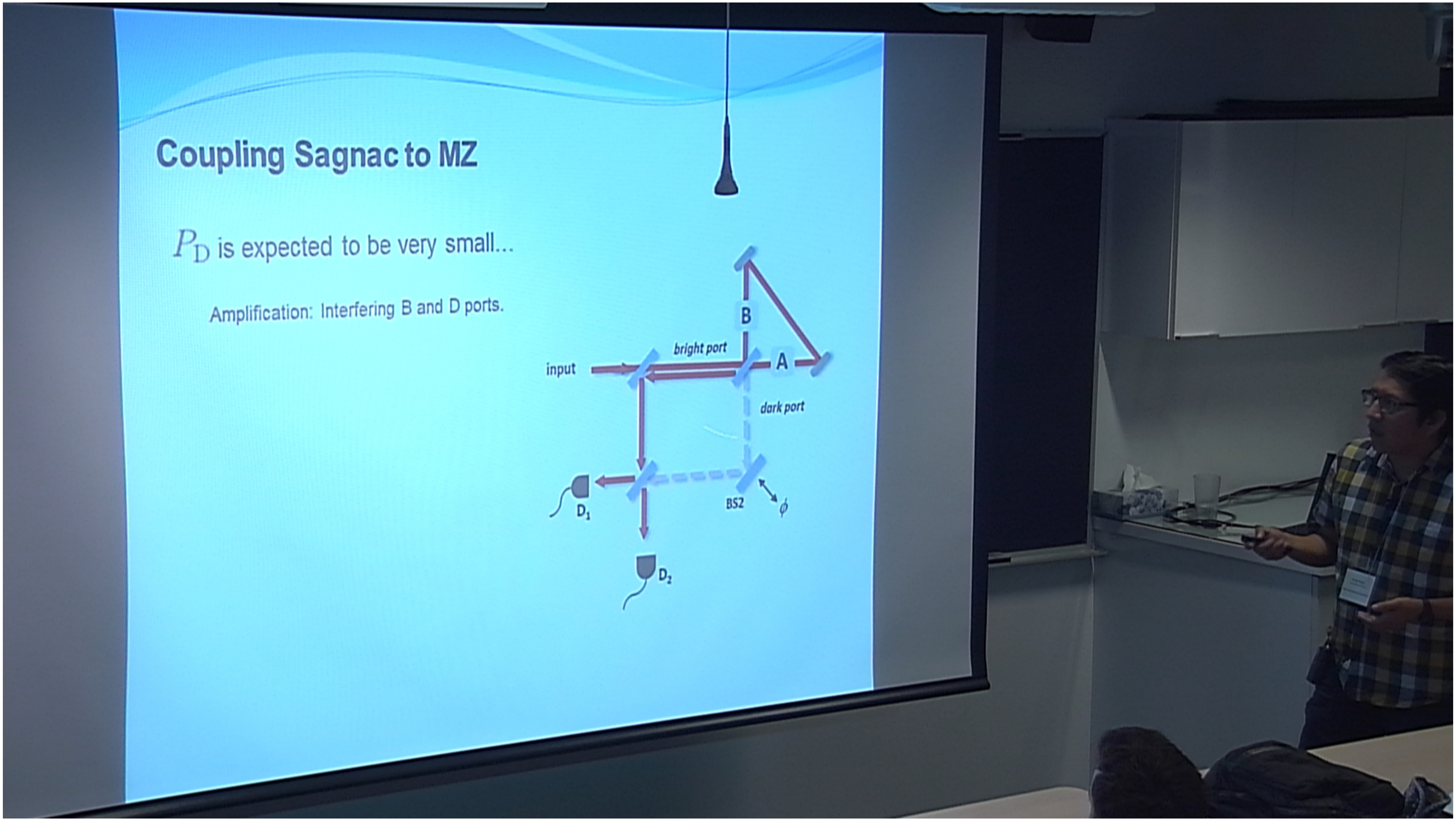
$$P_{\mathrm{D}} = \frac{1}{2} - \frac{v\Gamma}{2}$$

Visibility Sagnac

$$\Gamma = 1 - \frac{|[\alpha, \beta]|^2}{2}$$

$P_{\mathrm{D}}^{\mathrm{ideal}} = 0$ CQM

$P_{\mathrm{D}}^{\mathrm{ideal}} = \frac{|[\alpha, \beta]|^2}{4}$ QQM

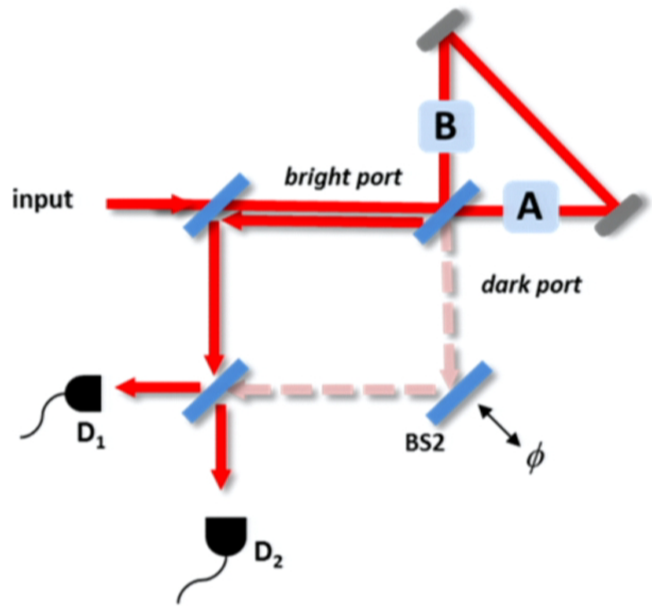

Coupling Sagnac to MZ
P_D is expected to be very small...
Amplification: Interfering B and D ports.
B
bright port
A
input
dark port
D_1
BS2
ϕ
D_2

Coupling Sagnac to MZ

P_{D} is expected to be very small…

Amplification: Interfering B and D ports.

$$P_{\mathrm{MZ}\sim} = \frac{1}{2} + \frac{1}{2} V \cos\phi$$



Our Goal:

$$V = \sqrt{1 - v^2\Gamma^2}$$

MZ

Sagnac

Commutation relation $\Gamma = 1 - \frac{|[\alpha,\beta]|^2}{2}$

Our phases

Peres:

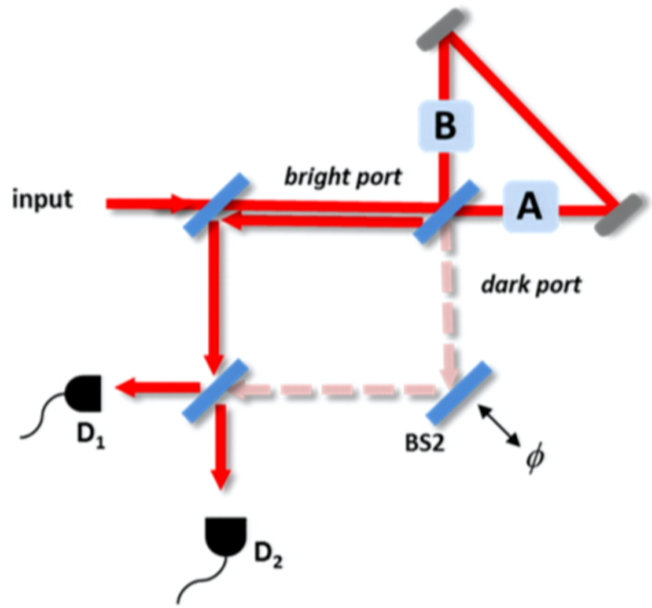
- Complex scaterring amplitudes (more likely to have quaternionic phases)

Kaiser *et al.*

- Phase shift = $-\lambda NbD$

Positive scattering length

Negetive scattering lengh

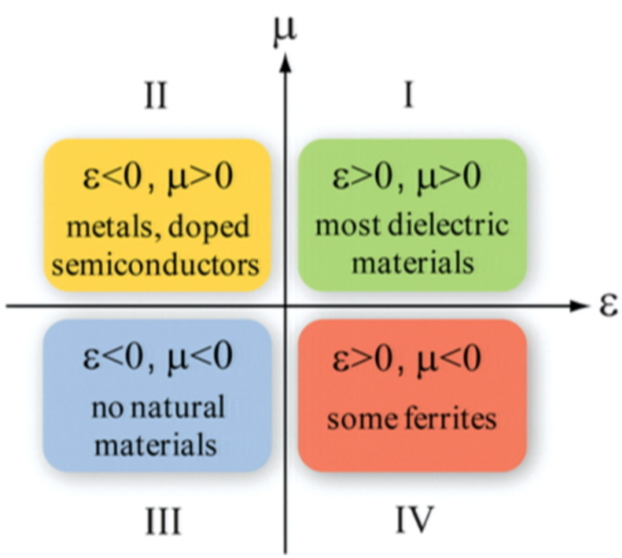


Optical analog:

- Positive refractive index A → Liquid crystal
- Negative refractive index B → Metamaterial

Metamaterials

Metamaterials consist of periodically or randomly distributed structured elements, whose size and spacing are much smaller than the wavelength of EM waves.



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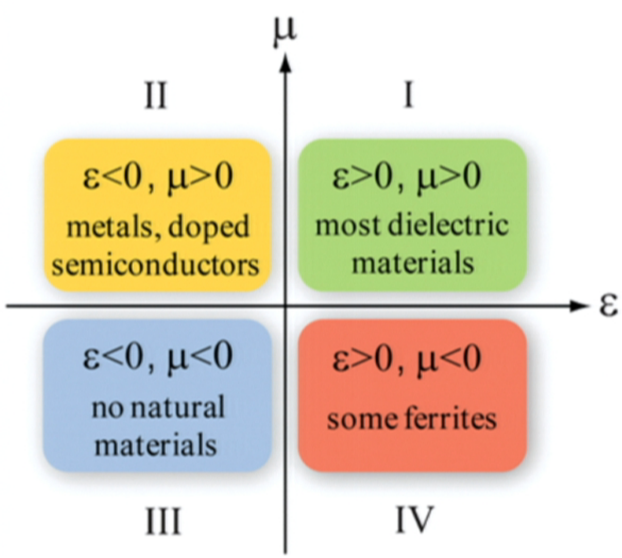
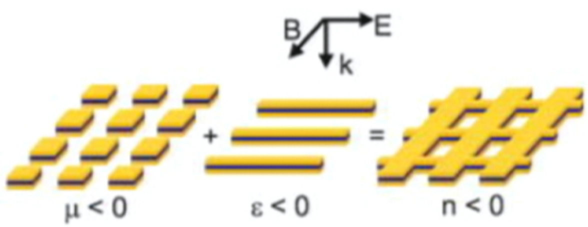




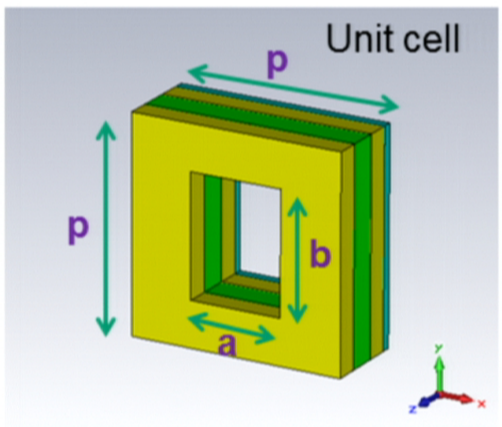
Negative phase shift

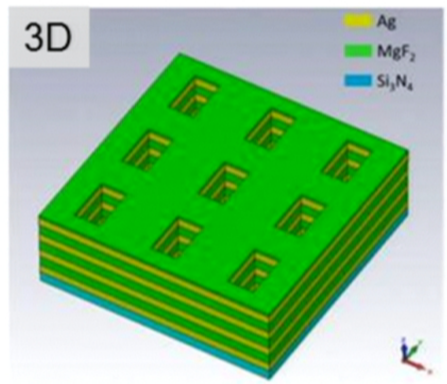
ZHANG LAB
DEPARTMENT OF MECHANICAL ENGINEERING

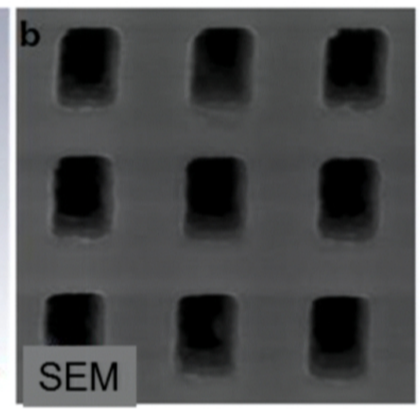
Berkeley
UNIVERSITY OF CALIFORNIA

Negative index metamaterial (NIM)

(Fishnet structure)



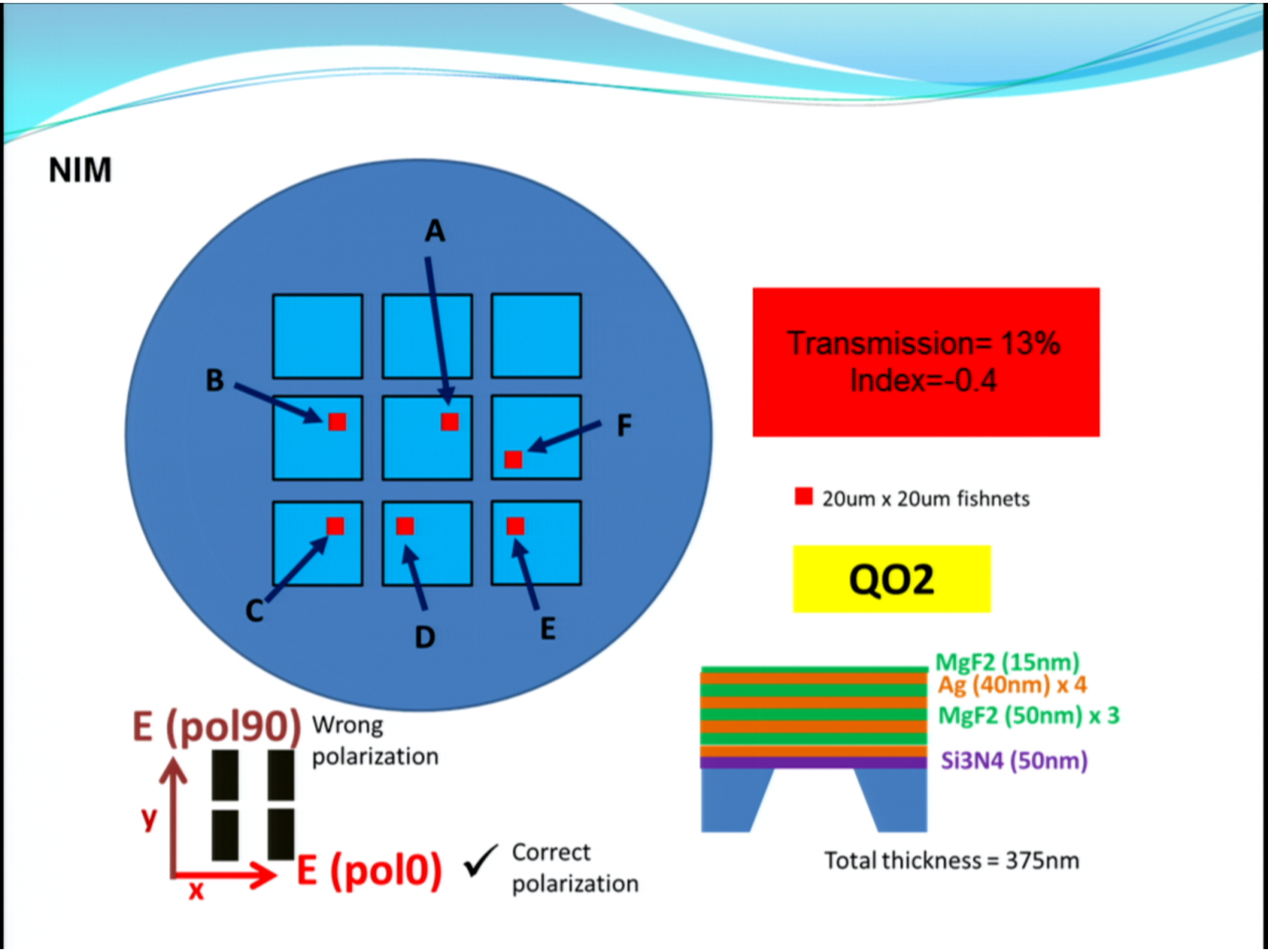




p = 350 nm
a = 150 nm
b = 200 nm

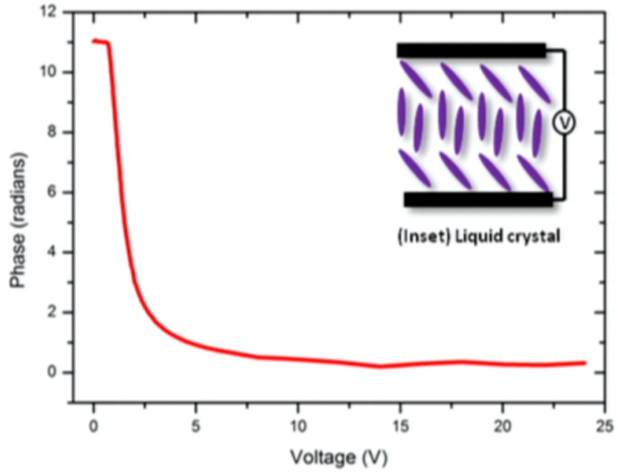
Silver / magnesium fluoride / silver / silicon nitride

Thickness = 40nm / 50nm / 40nm / 15nm

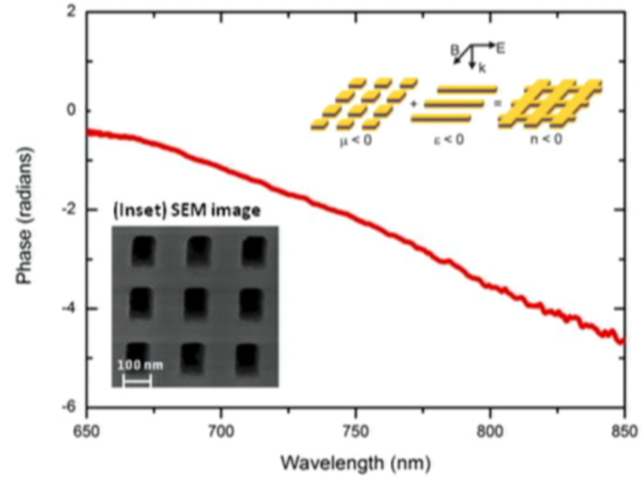


NIM
A
B
F
C
D
E
Transmission= 13%
Index=-0.4
20um x 20um fishnets
QO2
MgF2 (15nm)
Ag (40nm) x 4
MgF2 (50nm) x 3
Si3N4 (50nm)
Total thickness = 375nm
E (pol90)
Wrong polarization
y
x
E (pol0)
✓ Correct polarization

Our phases

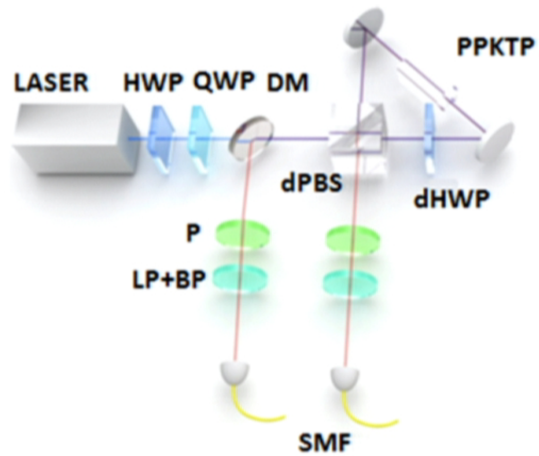


Standard Liquid Phase retarder
Phase shift= +π



Negative index Metamaterial
Phase shift= -π

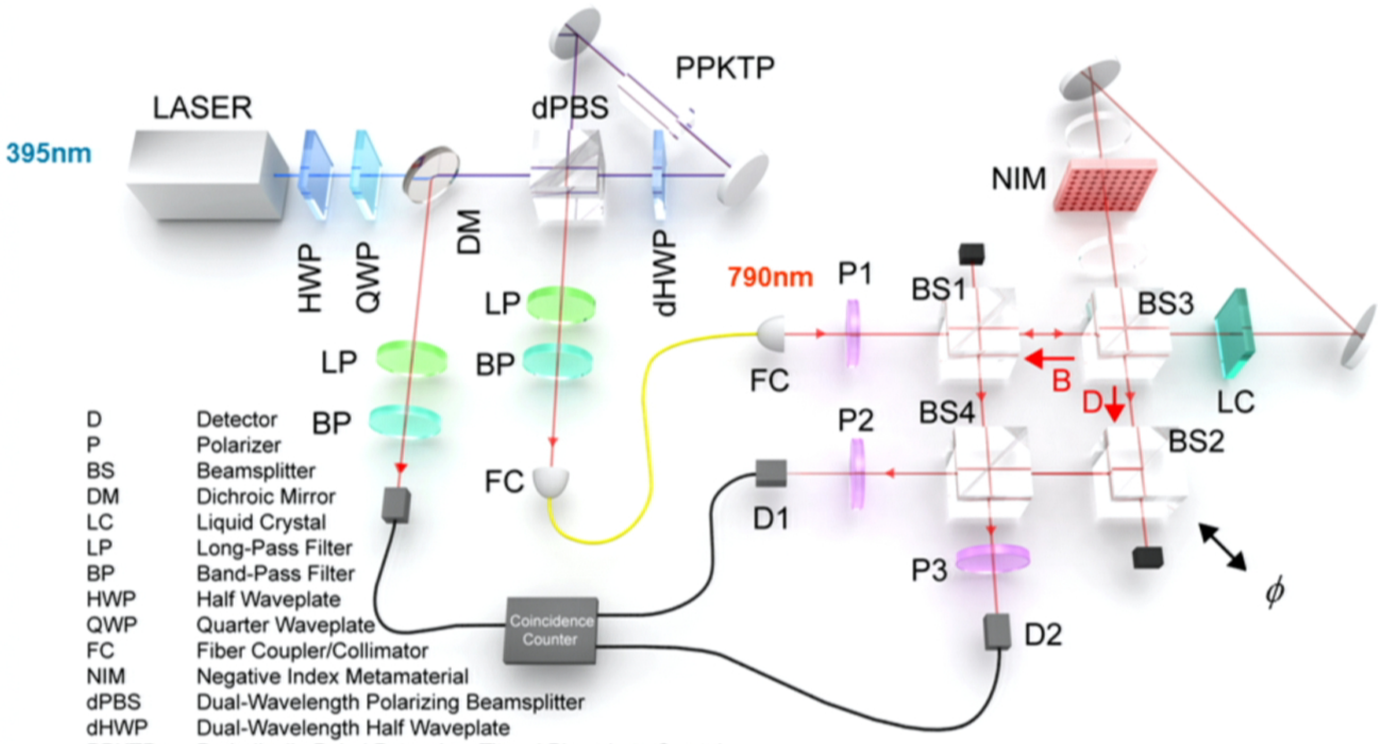
Sagnac scheme



- Nonlinear crystal type-II, 20-mm-length PPKTP
- Pump laser 23.7mW at 395 nm
- Degenerate case at 790 nm
- Down-converted photons in a separable polarization state $|H\rangle|V\rangle$
- 2 millions of single

PPKTP: periodically-poled potassium titanyl phosphate
HWP(QWP): Half wave-plate(Quarter wave-plate)
DM: Dichroic Mirror
SMF: Single-mode fiber
dPBS: dual polarizer beam splitter
P:Polorizer

Our setup



D	Detector
P	Polarizer
BS	Beamsplitter
DM	Dichroic Mirror
LC	Liquid Crystal
LP	Long-Pass Filter
BP	Band-Pass Filter
HWP	Half Waveplate
QWP	Quarter Waveplate
FC	Fiber Coupler/Collimator
NIM	Negative Index Metamaterial
dPBS	Dual-Wavelength Polarizing Beamsplitter
dHWP	Dual-Wavelength Half Waveplate
PPKTP	Periodically-Poled Potassium Titanyl Phosphate Crystal

Lorenzo Procopio *et al.* arXiv:1602.01624, under review at *Nat. Comm.*

Our measurements

Our Goal

$$V = \sqrt{1 - v^2\Gamma^2}$$

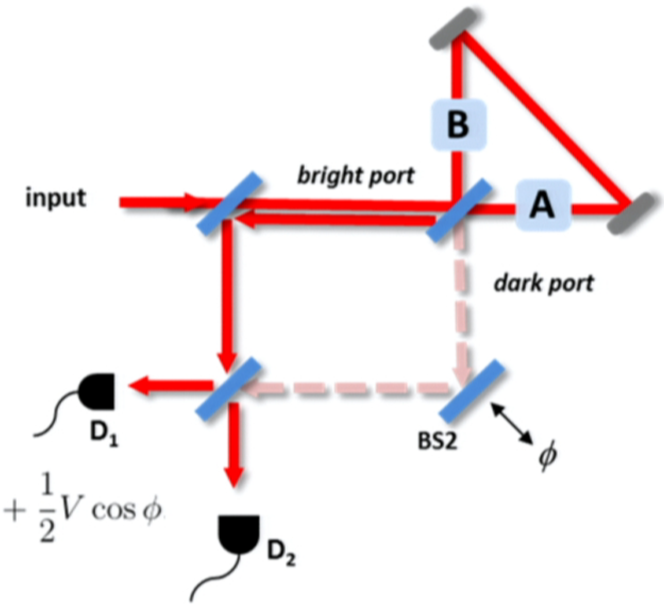
Four settings:

Characterization of apparatus

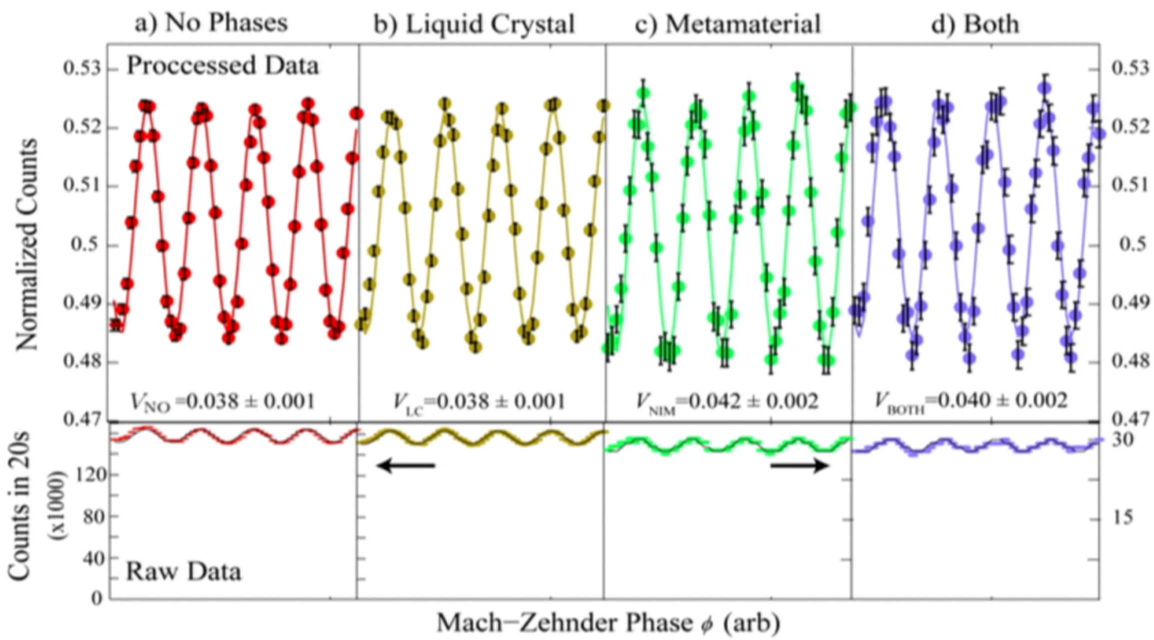
a) No phases V_{NO}

b) Positive Phase V_{LC}

$$P_{\mathrm{MZ}\sim} = \frac{1}{2} + \frac{1}{2} V \cos\phi$$



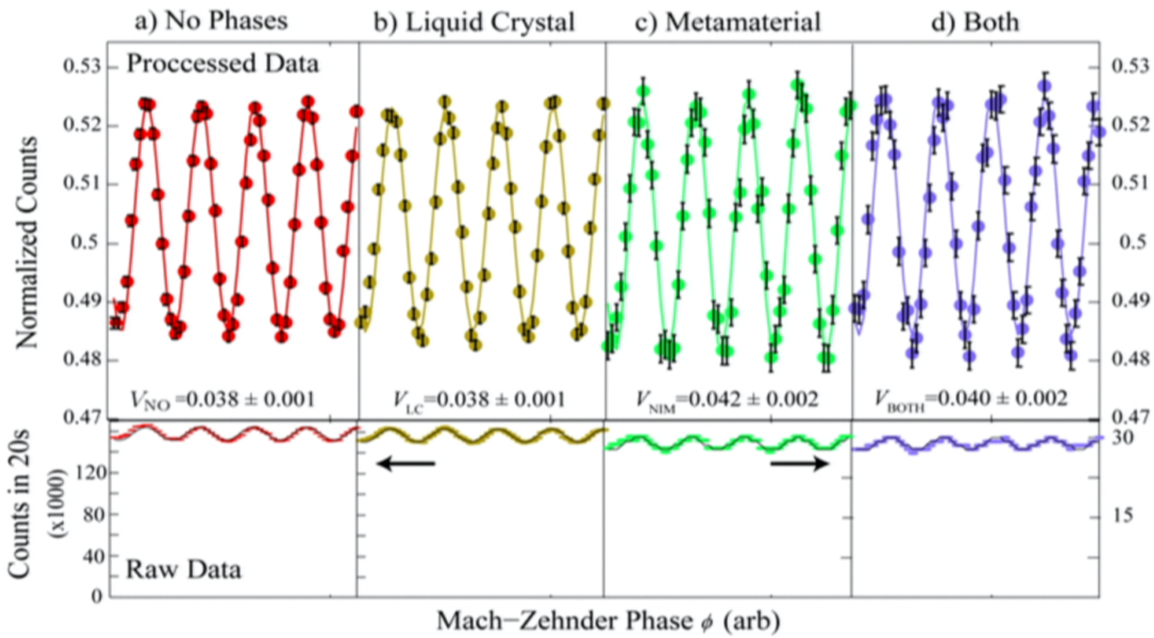
Results



Characterization of apparatus

On a single run: V_{NO}=V_{LC}

Results

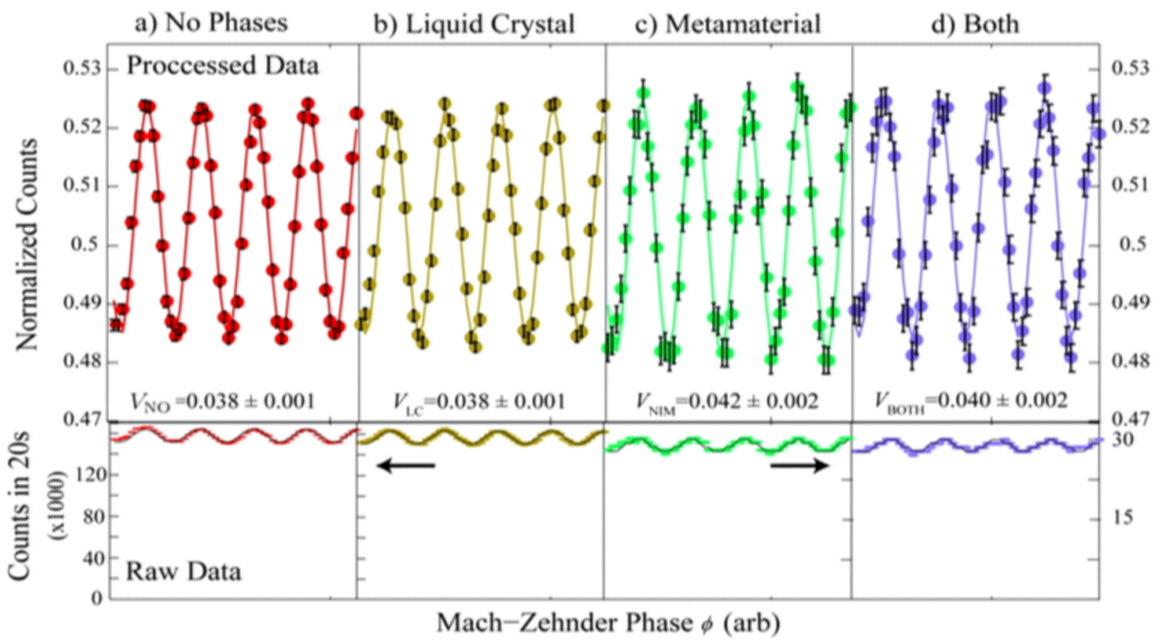


Characterization of apparatus

On a single run: $V_{NO}=V_{LC}$

After 402 times: $\Delta_{LC} = V_{NO}-V_{LC}$ = 0.002 ± 0.003

Results



Characterization of apparatus

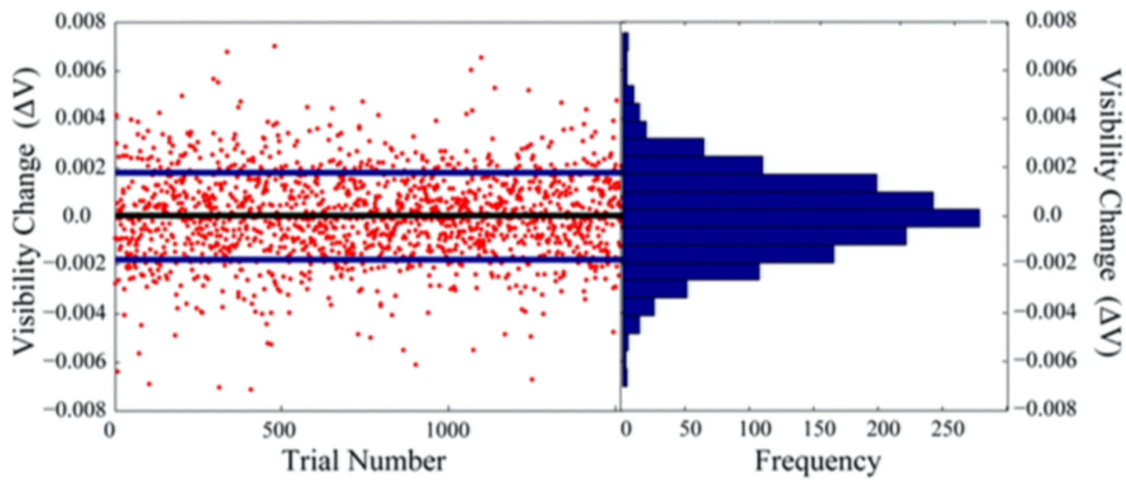
On a single run: V_{NO}=V_{LC}

After 402 times: Δ_{LC} =V_{NO}-V_{LC} = 0.002 ± 0.003

Testing QQM

On a single run: V_{NIM}=V_{BOTH}

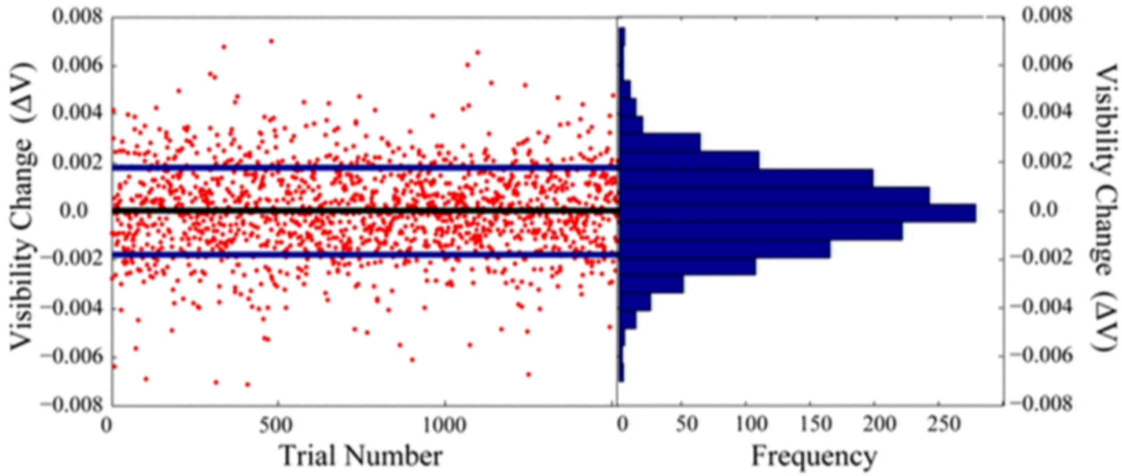
Visibility change distribution



Testing QQM

After 1522 times: $\Delta V = V_{BOTH} - V_{NIM}$ = 0.0006 ± 0.005

Visibility change distribution



Testing QQM

After 1522 times: $\Delta V = V_{BOTH} - V_{NIM}$ = 0.0006 ± 0.005 → Sagnac effect: 10^{-4} Faraday effect: 10^{-6} → Decrease v

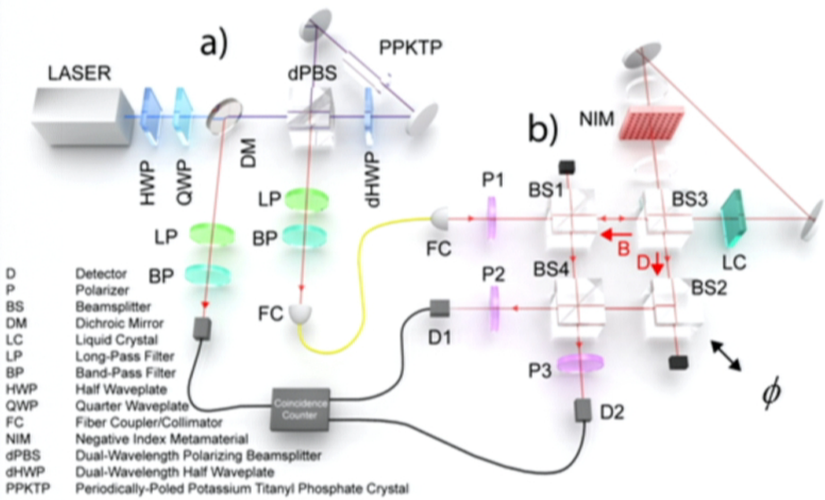
But…

Does the Peres experiment using photons test for hyper-complex (quaternionic) quantum theories?

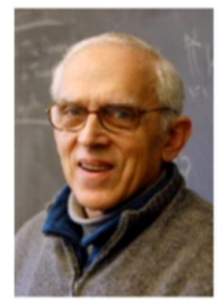
Stephen L. Adler

(Submitted on 18 Apr 2016)

Assuming the standard axioms for quaternionic quantum theory and a spatially localized scattering interaction, the S-matrix in quaternionic quantum theory is complex valued, not quaternionic. Using the standard connections between the S-matrix, the forward scattering amplitude for electromagnetic wave scattering, and the index of refraction, we show that the index of refraction is necessarily complex, not quaternionic. This implies that the recent optical experiment of Procopio et al. based on the Peres proposal does not test for hyper-complex or quaternionic quantum effects arising within the standard Hilbert space framework. Such a test requires looking at near zone fields, not radiation zone fields.



Hey guys, your experiment will never see quaternions



Stephen L. Adler

S.L.A , arXiv:1604.04950

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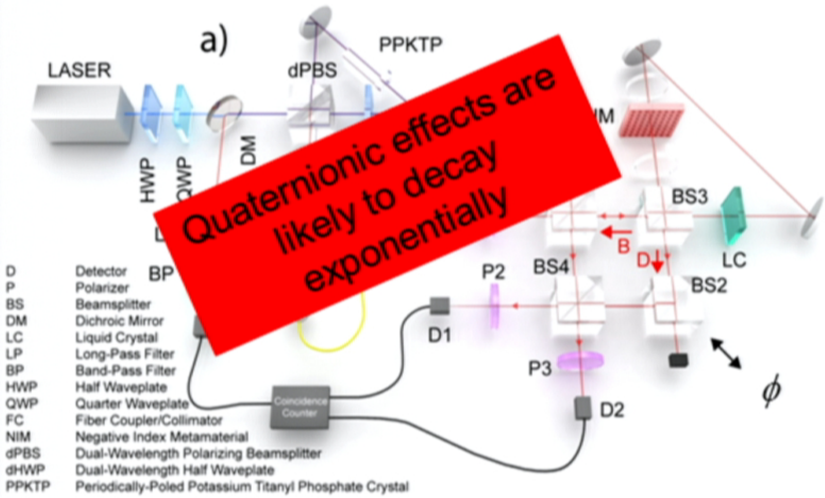

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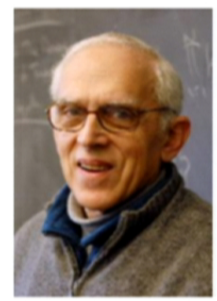


Stephen L. Adler

S.L.A , arXiv:1604.04950

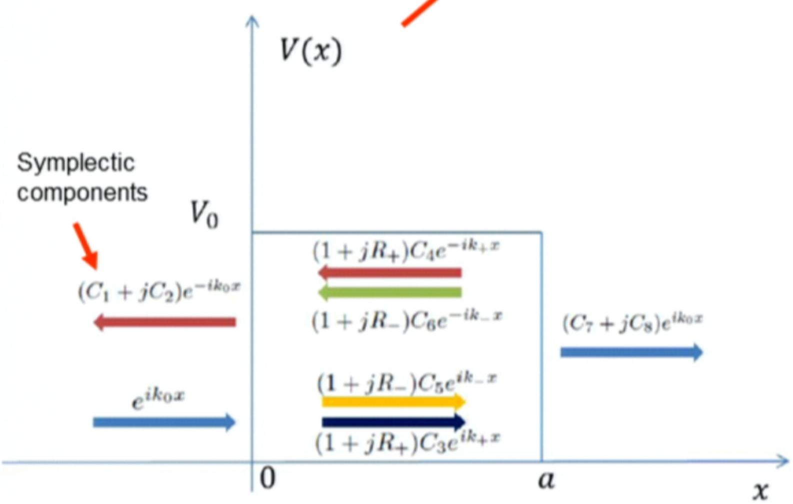
$$\Psi = \Psi_\alpha + j\Psi_\beta \longleftarrow \Psi_\beta \sim e^{-p|\mathbf{x}|}$$

Counterexample

Klein-Gordon Equation

Massless relativistic particles m=0

$$\left[-\left(\frac{\partial}{\partial t} - iV(x)\right)^2 + \frac{\partial^2}{\partial x^2}\right]\phi(x,t) = m^2\phi(x,t).$$



Rectangular potential

We found that a non-decaying quaternionic phase remains

C_8 , $C_2 \neq 0$

L.M. Procopio *et. al.*, arXiv:1607.01648

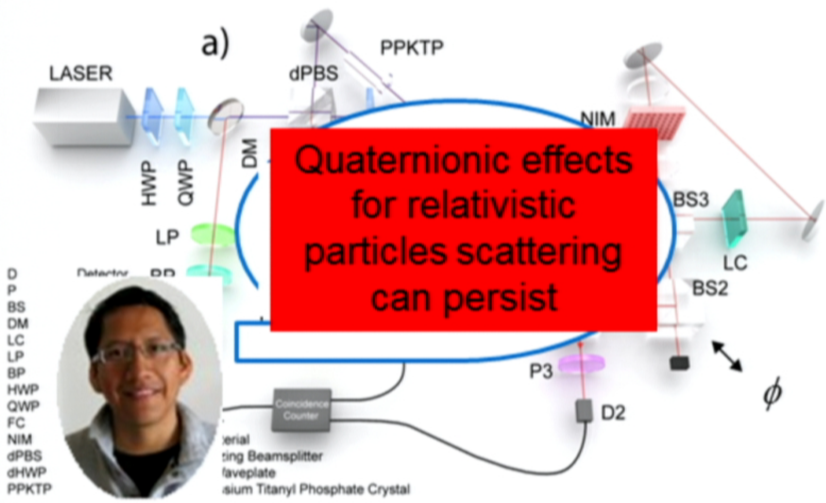
Thus…

Comment on Adler's "Does the Peres experiment using photons test for hyper-complex (quaternionic) quantum theories?"

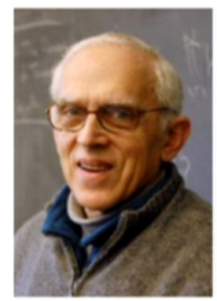
Lorenzo M. Procopio,[1] Lee A. Rozema,[1] Borivoje Dakić,[1,2] and Philip Walther[1]

[1] *Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria*
[2] *Institute of Quantum Optics and Quantum Information, Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria*

(Dated: July 7, 2016)



Oh I see



Stephen L. Adler

L.M. Procopio *et al.*, arXiv:1607.01648

S.L.A , arXiv:1604.04950

Summary and Outlook

- Our experiment is the first direct search for QQM using massless particles
- Quaternionic effects for relativistic Klein-Gordon scattering can persist
- Our work was enabled by the combination of novel negative-index metamaterial with standard optical photonic technology
- Further tests of QQM can be performed within optics using other methods, regimes, for instance, near-field measurements.