

Title: Higher-order interference and phase transformations in operational theories

Date: Aug 04, 2016 02:00 PM

URL: <http://pirsa.org/16080027>

Abstract:

Higher order interference and phase in operational theories

John H. Selby & Ciarán M. Lee
arXiv: 1510.03860, 1510.04699

Motivation:

Quantum mechanics as quantum measure theory, R. Sorkin, 1994,
arXiv:9401003

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Quantum mechanics as quantum measure theory, R. Sorkin, 1994,
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“The surprising thing (once one has gotten used to the fact of interference itself) is that this violation of the classical probability sum-rules is in a certain sense so mild...”

Motivation:

Quantum mechanics as quantum measure theory, R. Sorkin, 1994,
arXiv:9401003

“If some more general form of dynamics than quantum mechanics is at work in nature, it should show itself in a failure of the sum rule for which the three-slit discussion is a prototype. [...] It might be worthwhile looking for experimentally realizable situations of this type...”

Operational framework:

L. Hardy, 2011, arXiv:1104.2066

G. Chiribella, M. D'Ariano & P. Perinotti, 2010, arXiv:1011.6451

Operational framework:

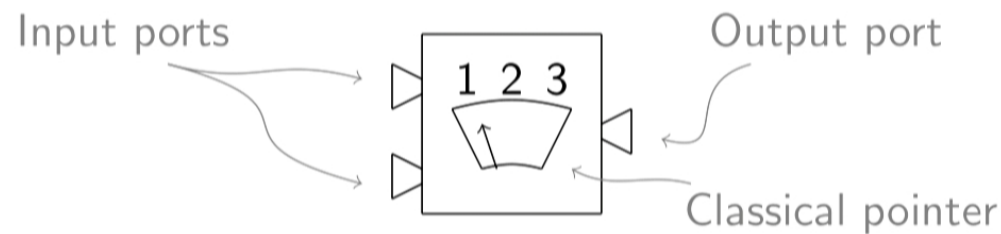
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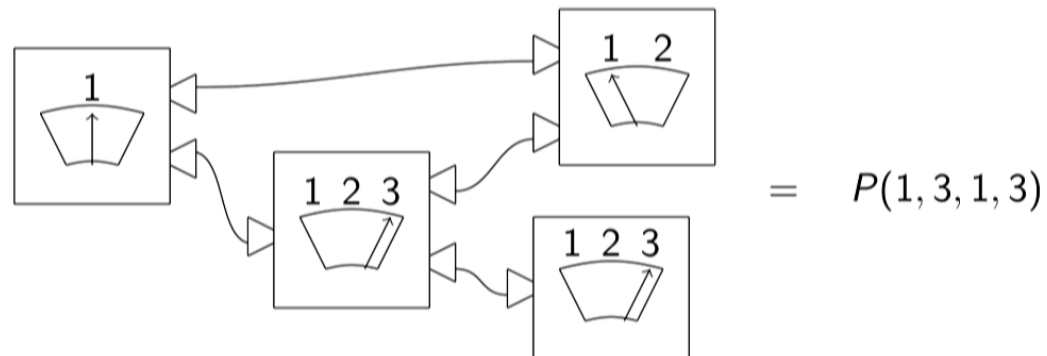
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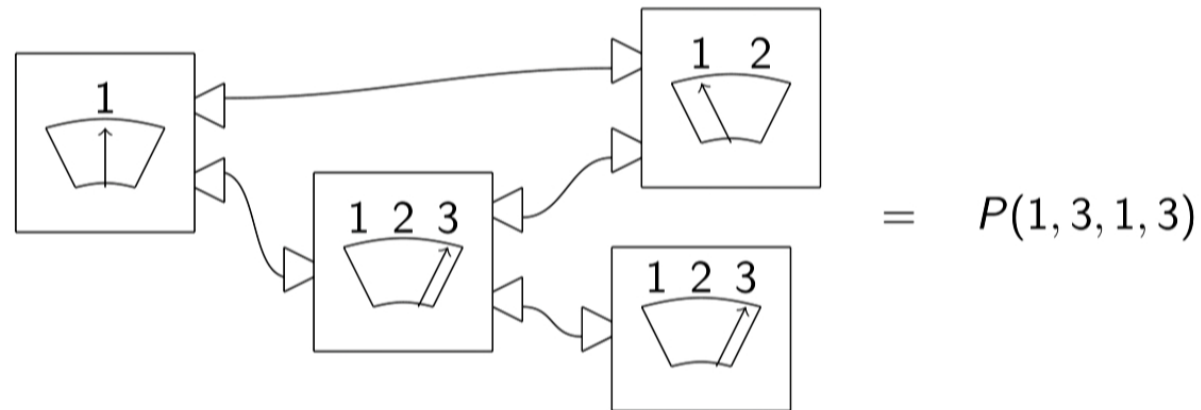
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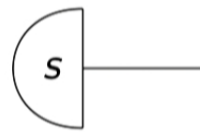
Operational framework:



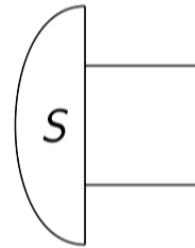
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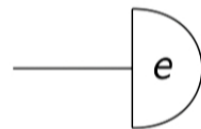
Example processes:



States



Bipartite states



Effects



Scalars

Assumption: Finite tomography

*Processes can be characterised
by a finite set of experiments each
with a finite number of outcomes.*

Outline

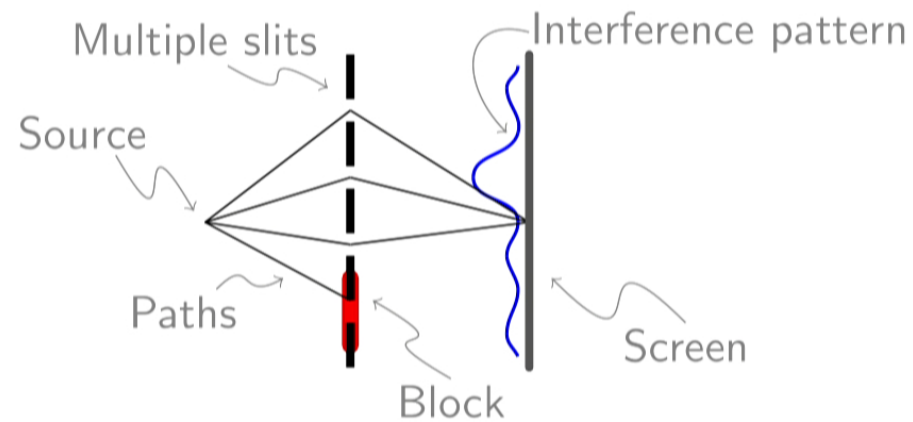
Defining higher order interference

Interference and phase

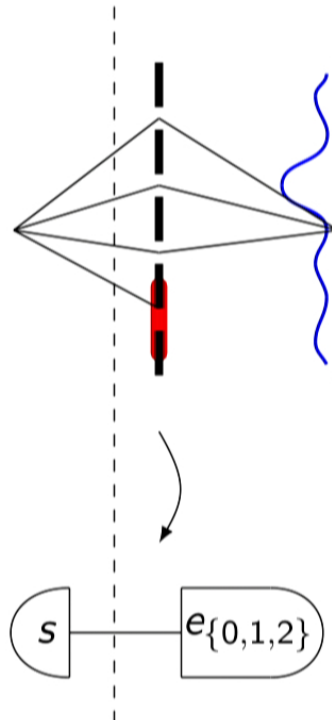
Generalised phase kickback

Consequences

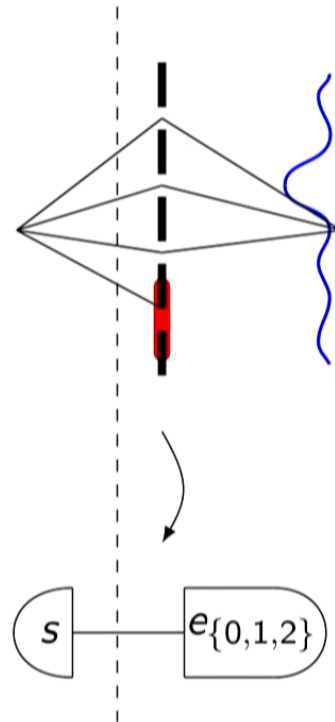
An interference experiment



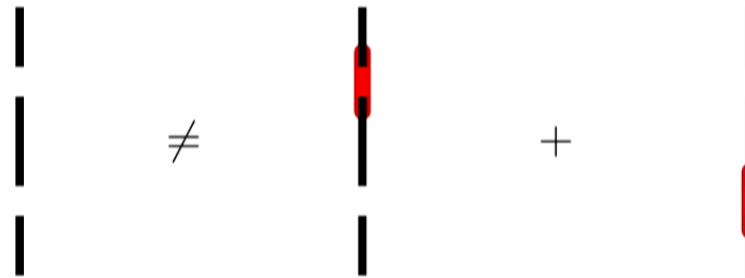
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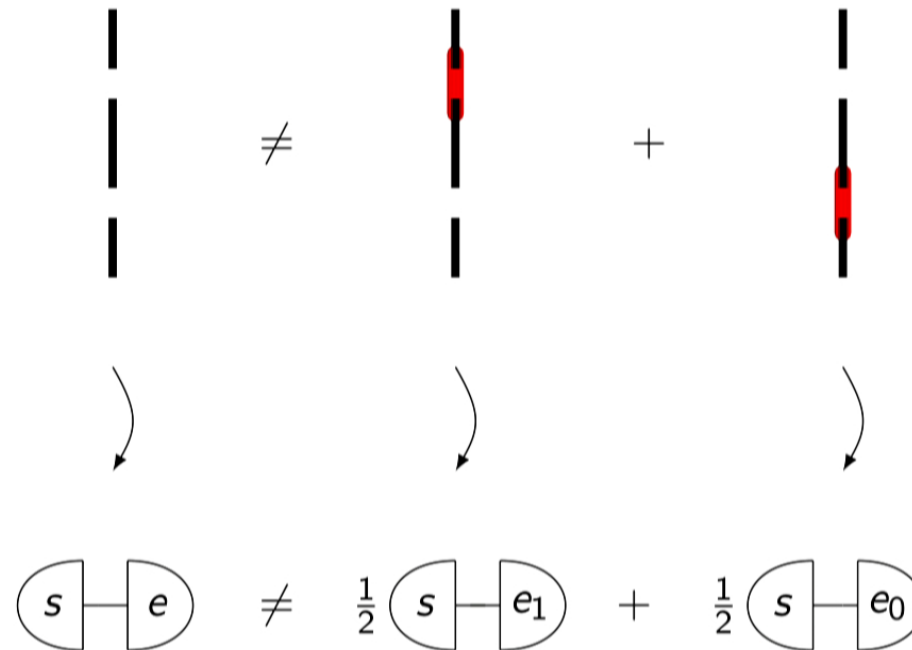
An interference experiment



Second order interference in quantum theory



Second order interference in quantum theory



Higher order interference experiment

Third order:

$$\begin{aligned}
 \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right) s \text{---} e \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right) &\neq a \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right) s \text{---} e_{01} \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right) + a \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right) s \text{---} e_{12} \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right) + a \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right) s \text{---} e_{20} \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right) \\
 &\quad - b \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right) s \text{---} e_0 \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right) - b \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right) s \text{---} e_1 \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right) - b \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right) s \text{---} e_2 \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right)
 \end{aligned}$$

Higher order interference experiment

Third order:

$$\begin{aligned} \left(\begin{array}{|c|} \hline s \\ \hline \end{array} \right) \left(\begin{array}{|c|} \hline e \\ \hline \end{array} \right) &\neq a \left(\begin{array}{|c|} \hline s \\ \hline \end{array} \right) \left(\begin{array}{|c|} \hline e_{01} \\ \hline \end{array} \right) + a \left(\begin{array}{|c|} \hline s \\ \hline \end{array} \right) \left(\begin{array}{|c|} \hline e_{12} \\ \hline \end{array} \right) + a \left(\begin{array}{|c|} \hline s \\ \hline \end{array} \right) \left(\begin{array}{|c|} \hline e_{20} \\ \hline \end{array} \right) \\ &\quad - b \left(\begin{array}{|c|} \hline s \\ \hline \end{array} \right) \left(\begin{array}{|c|} \hline e_0 \\ \hline \end{array} \right) - b \left(\begin{array}{|c|} \hline s \\ \hline \end{array} \right) \left(\begin{array}{|c|} \hline e_1 \\ \hline \end{array} \right) - b \left(\begin{array}{|c|} \hline s \\ \hline \end{array} \right) \left(\begin{array}{|c|} \hline e_2 \\ \hline \end{array} \right) \end{aligned}$$

Order h :

$$\left(\begin{array}{|c|} \hline s \\ \hline \end{array} \right) \left(\begin{array}{|c|} \hline e \\ \hline \end{array} \right) \neq \sum_{I: |I| < h} c_{|I|} (-1)^{h-|I|} \left(\begin{array}{|c|} \hline s \\ \hline \end{array} \right) \left(\begin{array}{|c|} \hline e_I \\ \hline \end{array} \right)$$

Higher order interference theory

Higher order interference theory

There exists an experiment,

$$\left(\begin{array}{|c|} \hline s \\ \hline \end{array} \right) \text{---}, \text{---} \left(\begin{array}{|c|} \hline e \\ \hline \end{array} \right) \text{ \& } \left\{ \text{---} \left(\begin{array}{|c|} \hline e_l \\ \hline \end{array} \right) \right\}$$

such that,

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Higher order interference theory

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$$\left(\begin{array}{c} \text{---} \\ \text{---} \end{array} \right) s, \quad \left(\begin{array}{c} \text{---} \\ \text{---} \end{array} \right) e \quad \& \quad \left\{ \left(\begin{array}{c} \text{---} \\ \text{---} \end{array} \right) e_I \right\}$$

such that,

$$\left(\begin{array}{c} \text{---} \\ \text{---} \end{array} \right) s \quad \left(\begin{array}{c} \text{---} \\ \text{---} \end{array} \right) e \quad \neq \quad \sum_{I: |I| < h} c_{|I|} (-1)^{h-|I|} \left(\begin{array}{c} \text{---} \\ \text{---} \end{array} \right) s \quad \left(\begin{array}{c} \text{---} \\ \text{---} \end{array} \right) e_I$$

Problem: How do we know that s , e and $\{e_I\}$ are a valid experiment?

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Higher order interference experiment

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Quartic quantum theory

K. Życzkowski, 2008, arXiv:0804.1247

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$$K = N^r$$

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- r=1 Classical theory
- r=2 Quantum theory
- r=4 Quartic quantum theory

QQT States

N -level QQT = restricted N^2 -level quantum

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Pure states:

$$\left\{ \begin{array}{c} \text{meter} \\ |0\rangle \\ \text{unitary } U \end{array} \right\} \quad \text{i.e.} \quad \left\{ U_{AB} |0\rangle \langle 0|_A \otimes \frac{\mathbb{I}_B}{d} U_{AB}^\dagger \right\}$$

QQT Effects

Effects, e must satisfy, for all U :

The diagram shows a quantum circuit with two input lines on the left and one output line on the right. The leftmost input line is labeled $0 \leq$ and has a control symbol (a vertical line with two short horizontal bars) and a target symbol (a semi-circle labeled o). The second input line is labeled ≤ 1 and has a control symbol (a vertical line with two short horizontal bars) and a target symbol (a semi-circle labeled e). Both control and target symbols are connected to a central rectangular box labeled U . The output line on the right is labeled ≤ 1 and has a target symbol (a semi-circle labeled e) connected to the box U .

QQT States

N -level QQT = restricted N^2 -level quantum

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QQT Effects

Effects, e must satisfy, for all U :

$$0 \leq \text{Diagram: a box labeled } U \text{ with a meter symbol (a semi-circle with '0' inside) on the top input and a battery symbol on the bottom input} \leq 1$$

For example,

$$\left\{ \text{Diagram: a meter symbol with 'e' inside} \right\} = d \left\{ \text{Diagram: a meter symbol with '0' inside} \right\} \quad \text{i.e. } d |0\rangle \langle 0|_A \otimes |0\rangle \langle 0|$$

QQT States

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Interference in QQT

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Quantum:

$$\left(s^q \right) \left(e^q \right) = \sum_{I: |I| \leq 2} c_{|I|} (-1)^{2-|I|} \left(s^q \right) \left(e_I^q \right)$$

Interference in QQT

QQT:

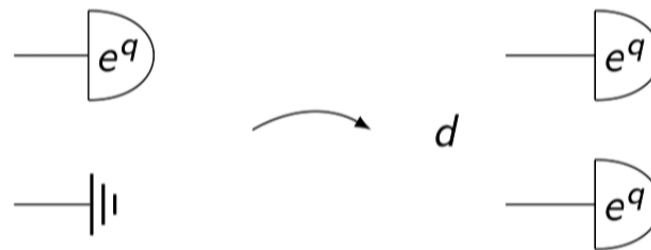
$$= \sum_{I: |I| \leq 2} c_{|I|} (-1)^{2-|I|} \left(\text{Diagram with } s, e_I^q, \text{ and } || \right)$$

Interference in QQT

QQT:

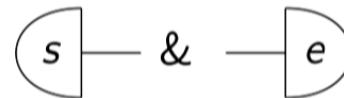
$$= \sum_{I: |I| \leq 2} c_{|I|} (-1)^{2-|I|} \left(\text{Diagram with } s, e_I^q, \text{ and } || \right)$$

Replace, for example:

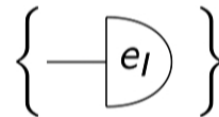


Refined definition

There exists an experiment,



such that for all,

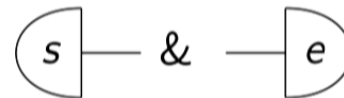


we have,

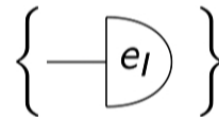
$$\begin{array}{|c|} \hline s \\ \hline \end{array} \begin{array}{|c|} \hline e \\ \hline \end{array} \neq \sum_{I: |I| < h} c_{|I|} (-1)^{h-|I|} \begin{array}{|c|} \hline s \\ \hline \end{array} \begin{array}{|c|} \hline e_I \\ \hline \end{array}$$

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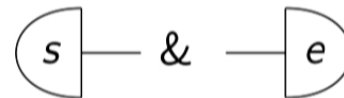


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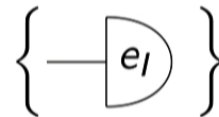
$$\left(s \text{ --- } e \right) \neq \sum_{I: |I| < h} c_{|I|} (-1)^{h-|I|} \left(s \text{ --- } e_I \right)$$

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There exists an experiment,



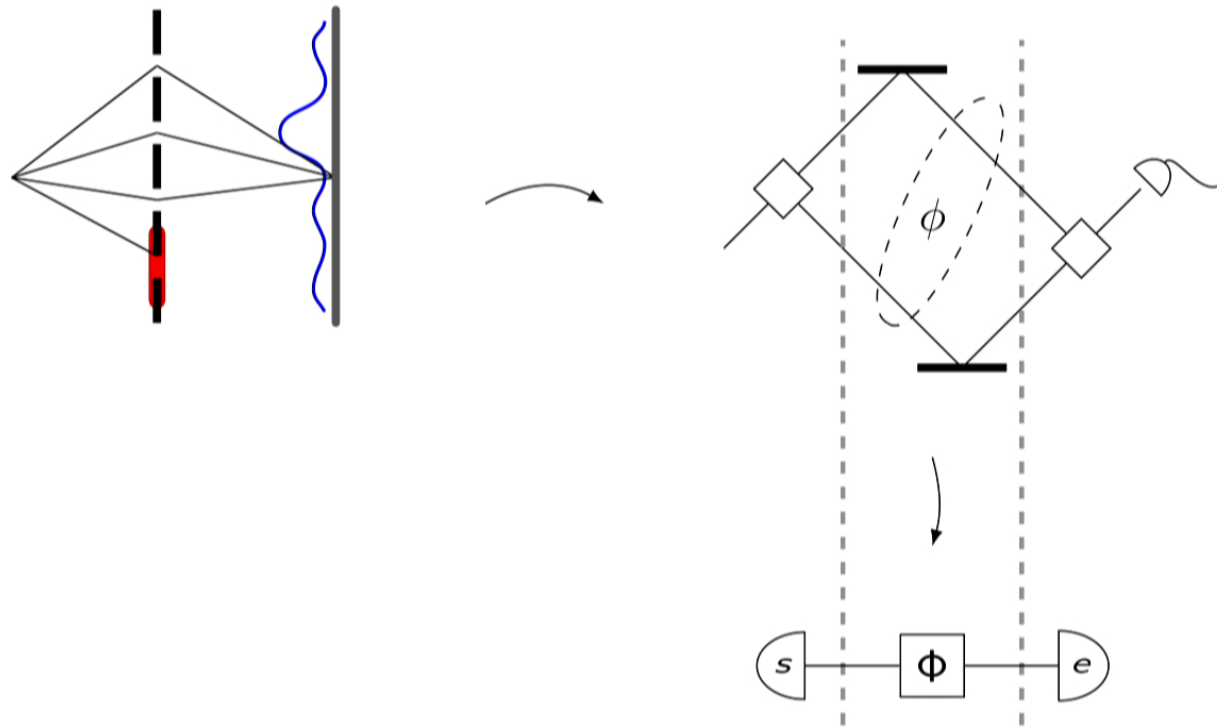
such that for all,



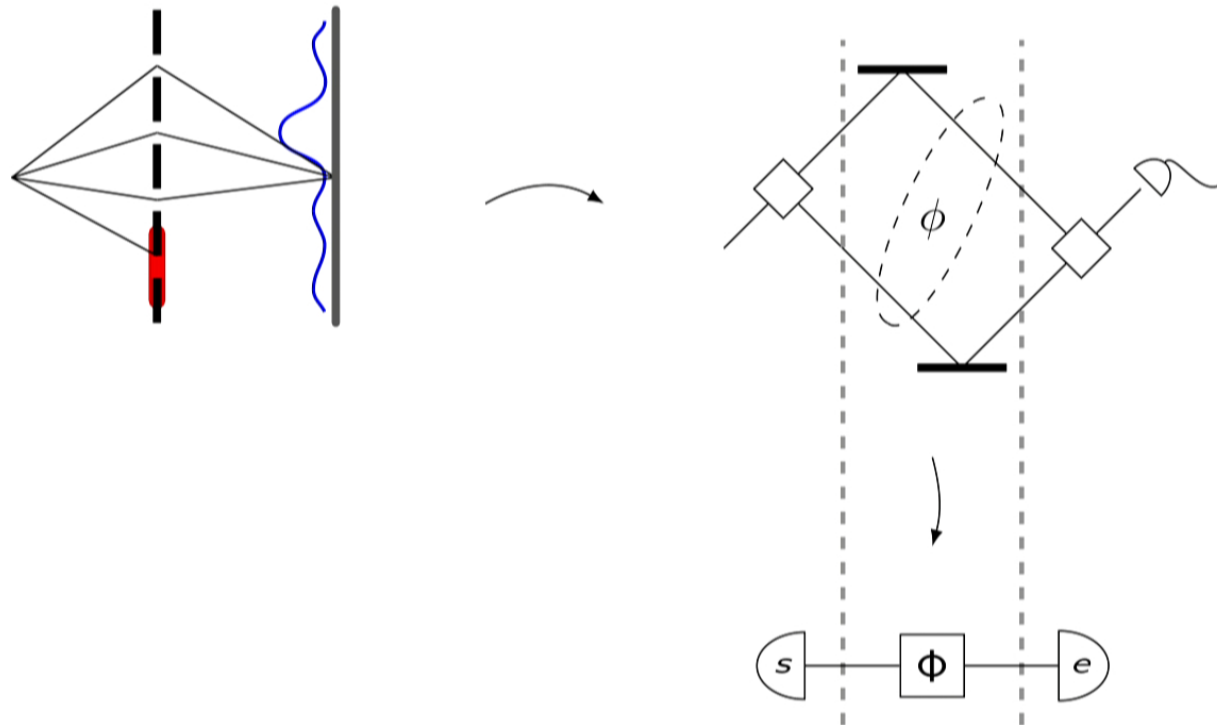
we have,

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Interference and phase



Interference and phase



How do we operationally define Φ ?

Phase transformations

Definition:

$$\begin{array}{c} \text{---} \boxed{\Phi} \text{---} \text{D}^t = \text{---} \text{D}^t \\ \text{---} \boxed{\Phi} \text{---} \text{D}^b = \text{---} \text{D}^b \end{array}$$

Phase transformations guarantee interference in a theory

Phase transformations guarantee interference in a theory

For any phase transformation there are s and e such that,

$$\left(\begin{array}{c} \text{---} s \end{array} \right) \text{---} \boxed{\Phi} \text{---} \left(\begin{array}{c} \text{---} e \end{array} \right) \neq \left(\begin{array}{c} \text{---} s \end{array} \right) \text{---} \left(\begin{array}{c} \text{---} e \end{array} \right)$$

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Consider an interference experiment for s and e ,

$$\left(\begin{array}{c} \text{---} s \end{array} \right) \text{---} \left(\begin{array}{c} e \text{---} \end{array} \right) \stackrel{?}{=} \frac{1}{2} \left(\begin{array}{c} \text{---} s \end{array} \right) \text{---} \left(\begin{array}{c} t \text{---} \end{array} \right) + \frac{1}{2} \left(\begin{array}{c} \text{---} s \end{array} \right) \text{---} \left(\begin{array}{c} b \text{---} \end{array} \right)$$

Phase transformations guarantee interference in a theory

For any phase transformation there are s and e such that,

$$\langle s | \Phi | e \rangle \neq \langle s | e \rangle$$

Consider an interference experiment for s and e ,

$$\begin{aligned} \langle s | e \rangle &= \frac{1}{2} \langle s | t \rangle + \frac{1}{2} \langle s | b \rangle \\ &\neq \\ \langle s | \Phi | e \rangle &= \frac{1}{2} \langle s | \Phi | t \rangle + \frac{1}{2} \langle s | \Phi | b \rangle \end{aligned}$$

Phase transformations guarantee interference in a theory

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$\Rightarrow$ Theory has interference

Higher order phases?

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Definition:

$$\forall I \text{ with } |I| < h \quad \text{---} \boxed{\Phi} \text{---} \text{---} e_I = \text{---} e_I$$

Higher order phases?

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$$\forall I \text{ with } |I| < h \quad \text{---} \boxed{\Phi} \text{---} \text{---} e_I \text{---} = \text{---} e_I \text{---}$$

h -order phase $\implies h$ -order interference

Higher order phases?

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h -order phase $\implies h$ -order interference

Generalised phase kickback algorithm

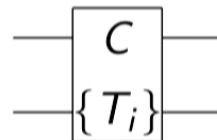
Generalised phase kickback algorithm

Axioms:

- ▶ Causality
- ▶ Purification
- ▶ Strong symmetry

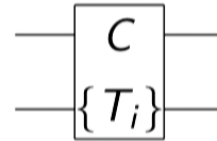
Reversible controlled transformations

For all $\{T_i\}$ there exists,

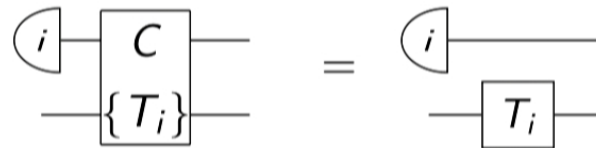


Reversible controlled transformations

For all $\{T_i\}$ there exists,



such that for all i we have,



Phase kickback

If we have a state s such that for all i ,

$$\begin{array}{|c} \text{---} \end{array} \left(\begin{array}{|c} s \end{array} \right) \begin{array}{|c} \text{---} \end{array} \left[T_i \right] \begin{array}{|c} \text{---} \end{array} = \begin{array}{|c} \text{---} \end{array} \left(\begin{array}{|c} s \end{array} \right) \begin{array}{|c} \text{---} \end{array}$$

Phase kickback

If we have a state s such that for all i ,

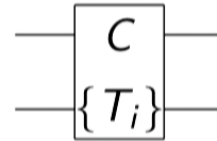
$$\begin{array}{c} \text{---} \\ | \\ \text{---} \end{array} \begin{array}{|c|} \hline s \\ \hline \end{array} \begin{array}{|c|} \hline T_i \\ \hline \end{array} \text{---} = \begin{array}{c} \text{---} \\ | \\ \text{---} \end{array} \begin{array}{|c|} \hline s \\ \hline \end{array} \text{---}$$

Then we get a phase kicked back as,

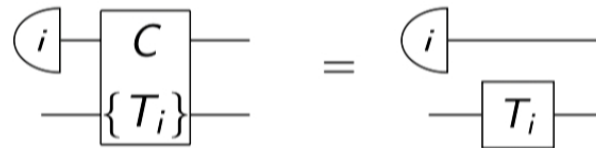
$$\begin{array}{c} \text{---} \\ | \\ \text{---} \end{array} \begin{array}{|c|} \hline C \\ \hline \end{array} \begin{array}{|c|} \hline \{T_i\} \\ \hline \end{array} \text{---} = \begin{array}{c} \text{---} \\ | \\ \text{---} \end{array} \begin{array}{|c|} \hline \mathcal{P}_s \\ \hline \end{array} \begin{array}{c} \text{---} \\ | \\ \text{---} \end{array} \begin{array}{|c|} \hline s \\ \hline \end{array} \text{---}$$

Reversible controlled transformations

For all $\{T_i\}$ there exists,



such that for all i we have,



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Any phase – including higher order – can be reached in this way!

Consequences

- Computation in operational theories

Consequences

- ▶ Computation in operational theories
- ▶ Particle exchange symmetries in operational theories

Particle Symmetries

O. Dahlsten et al., 2013, arXiv:1307.2529

In quantum theory we have a close connection between:

$$- \boxed{R_z(\phi)} - \sim e^{i\phi} \sim \text{Particle types}$$

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How do we measure these phases?

Detecting particle types: Quantum theory

$$SWAP |\bullet \bullet\rangle = |\bullet \circlearrowleft \bullet\rangle = e^{i\phi} |\bullet \bullet\rangle$$

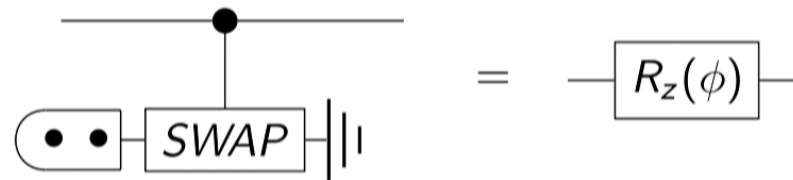
... undetectable global phase

Detecting particle types: Quantum theory

$$SWAP |\bullet \bullet\rangle = |\bullet \bullet\rangle = e^{i\phi} |\bullet \bullet\rangle$$

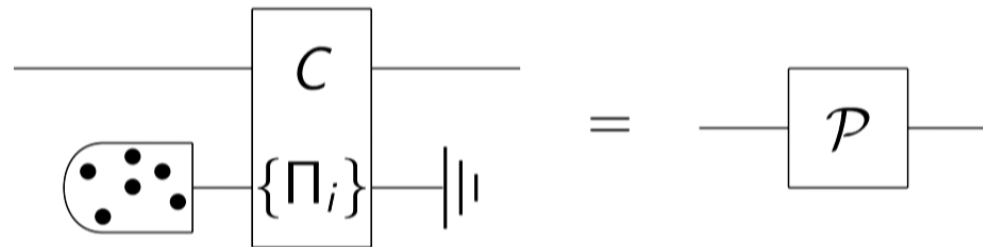
... undetectable global phase

Using phase kickback...

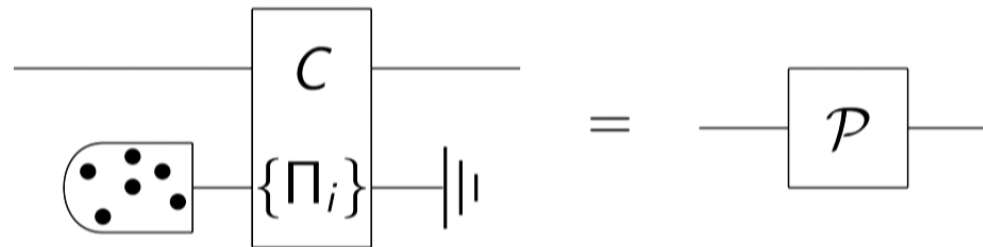


...detectable phase transformation!

Detecting particle types: General theories

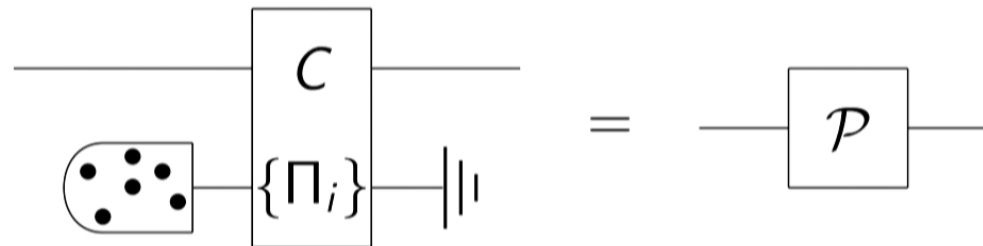


Detecting particle types: General theories



Can we get any phase from such an experiment?

Detecting particle types: General theories



Can we get any phase from such an experiment?
Which state and permutations to use?

Summary

- Why consider GPTs?

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- ▶ Why consider GPTs?
 - ▶ Implausible theoretical consequences?
 - ▶ Potential experimental implications?
- ▶ Operational definition of higher order interference

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 - ▶ Implausible theoretical consequences?
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- ▶ Operational definition of higher order interference
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 - ▶ Accessed via generalised phase kick-back
- ▶ Particle symmetries

Thanks!