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Group: Neutron interferometry
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Direct extraction of path weak values from interferograms without auxiliary qubits

Content

Content

- **Part 1:** Motivation and goal

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- **Part 2:** Introduction to weak values and weak measurements

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- **Part 1:** Motivation and goal
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- **Part 3:** Weak values based description of a Mach-Zehnder interferometer

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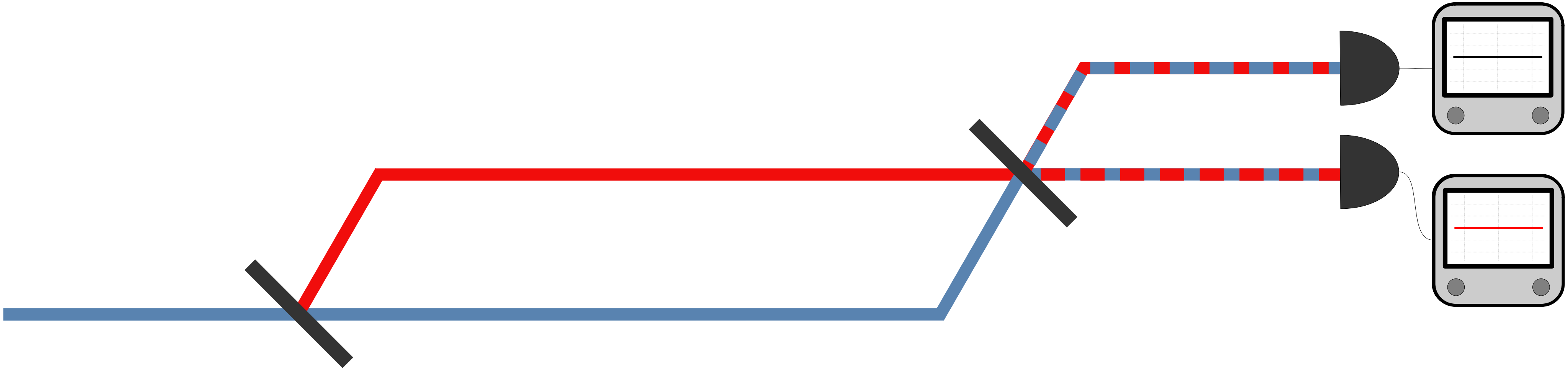
- **Part 1:** Motivation and goal
- **Part 2:** Introduction to weak values and weak measurements
- **Part 3:** Weak values based description of a Mach-Zehnder interferometer
- **Part 4:** Experimental measurement of path weak values directly from interferograms

Part 1: Motivation and goal

Motivation

Mach-Zehnder interferometry:



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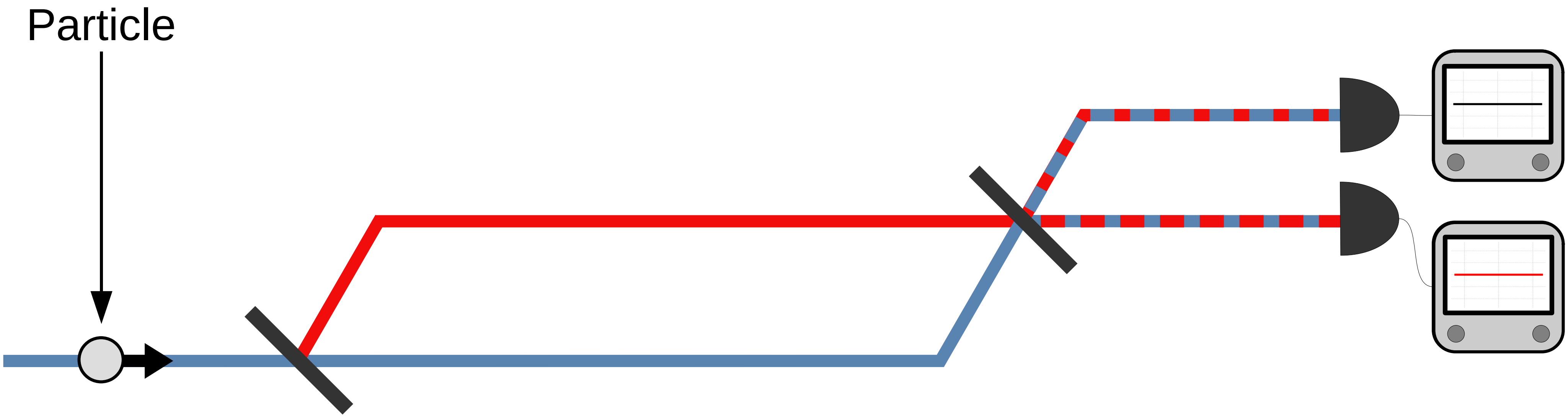
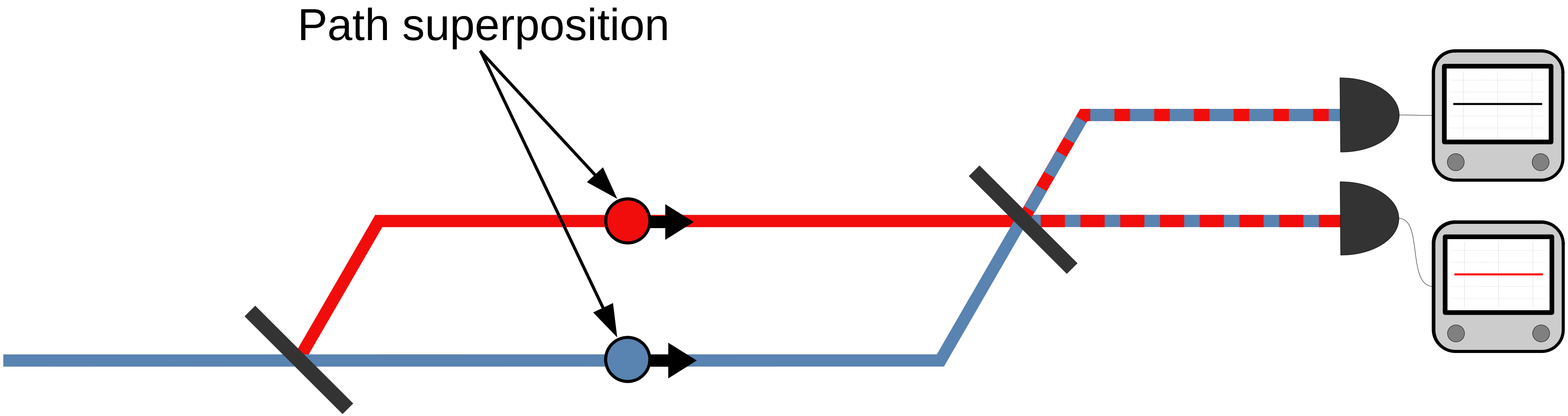
Motivation

Mach-Zehnder interferometry:



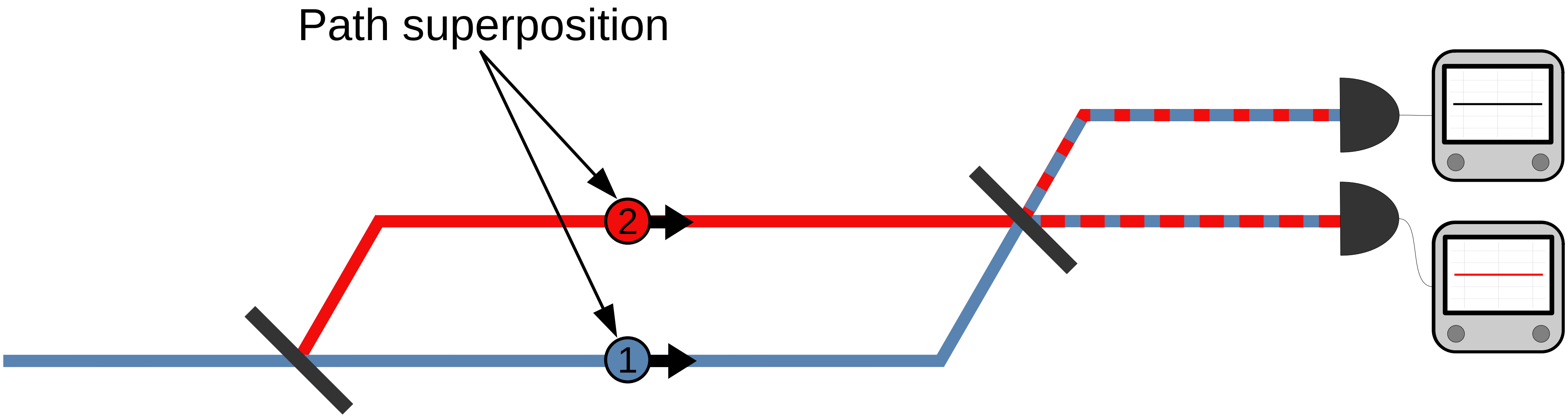
Motivation

Mach-Zehnder interferometry:



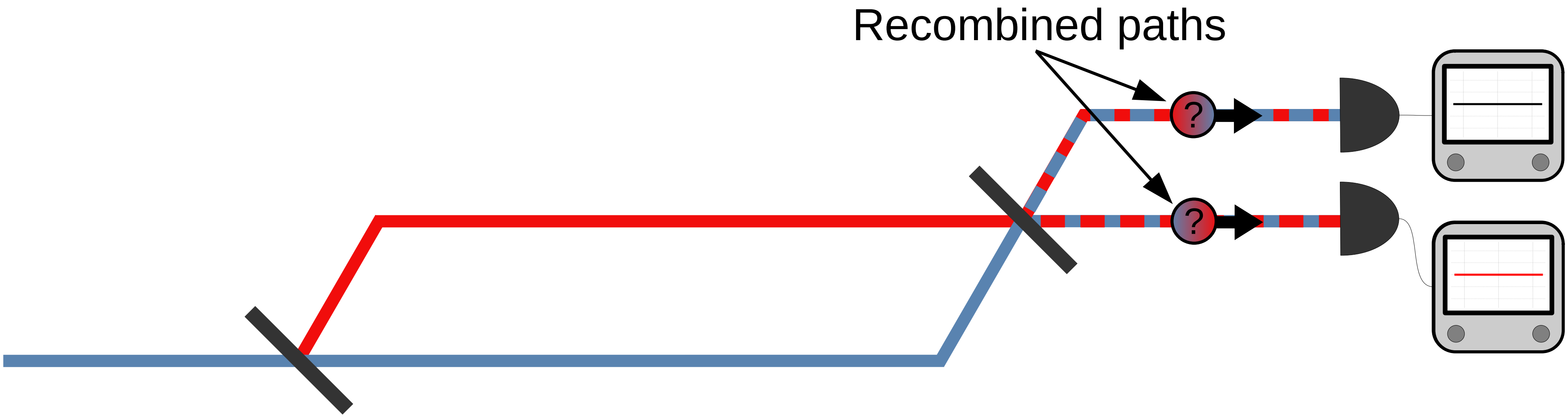
Motivation

Mach-Zehnder interferometry:



Motivation

Mach-Zehnder interferometry:



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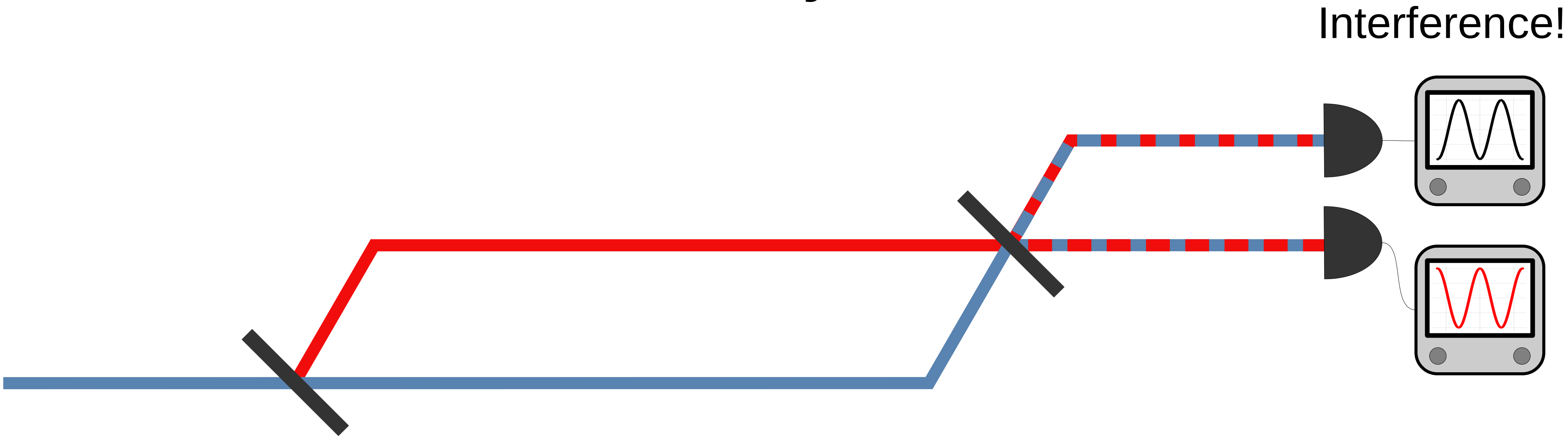
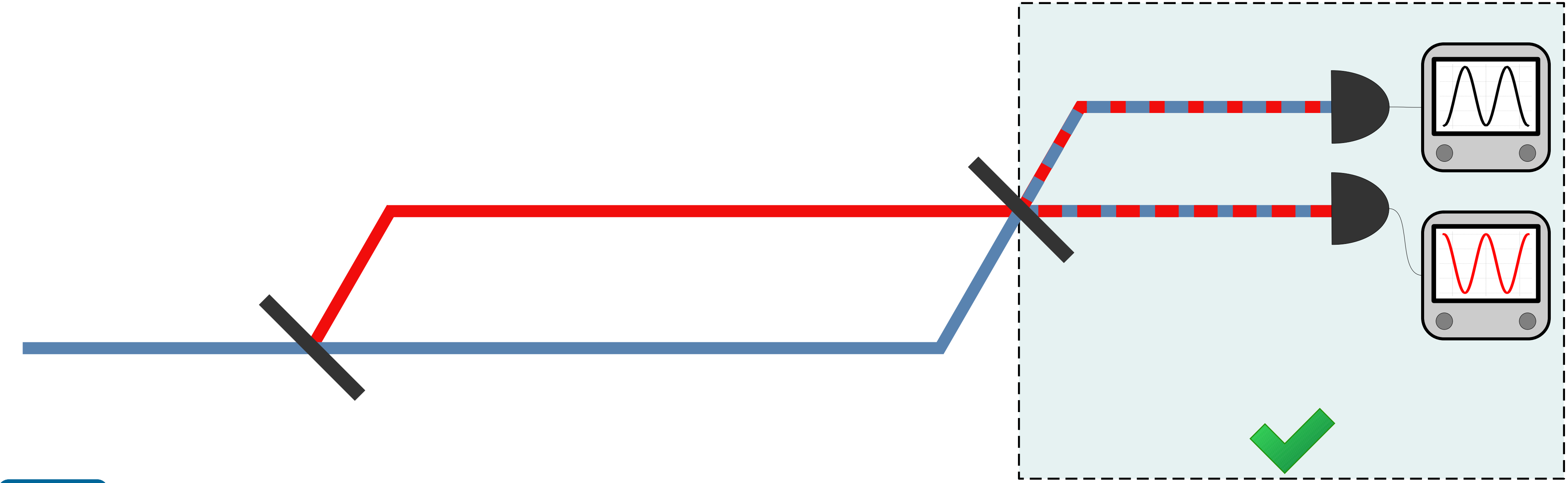
Motivation

Mach-Zehnder interferometry:



Motivation

Mach-Zehnder interferometry:



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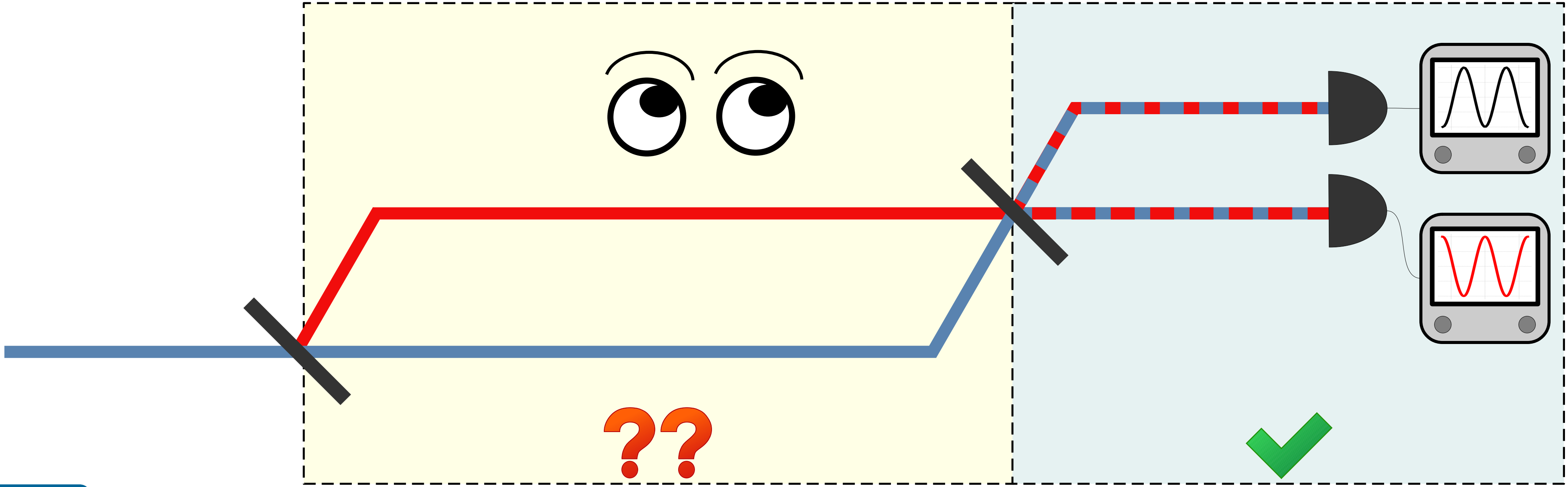
Motivation

Mach-Zehnder interferometry:



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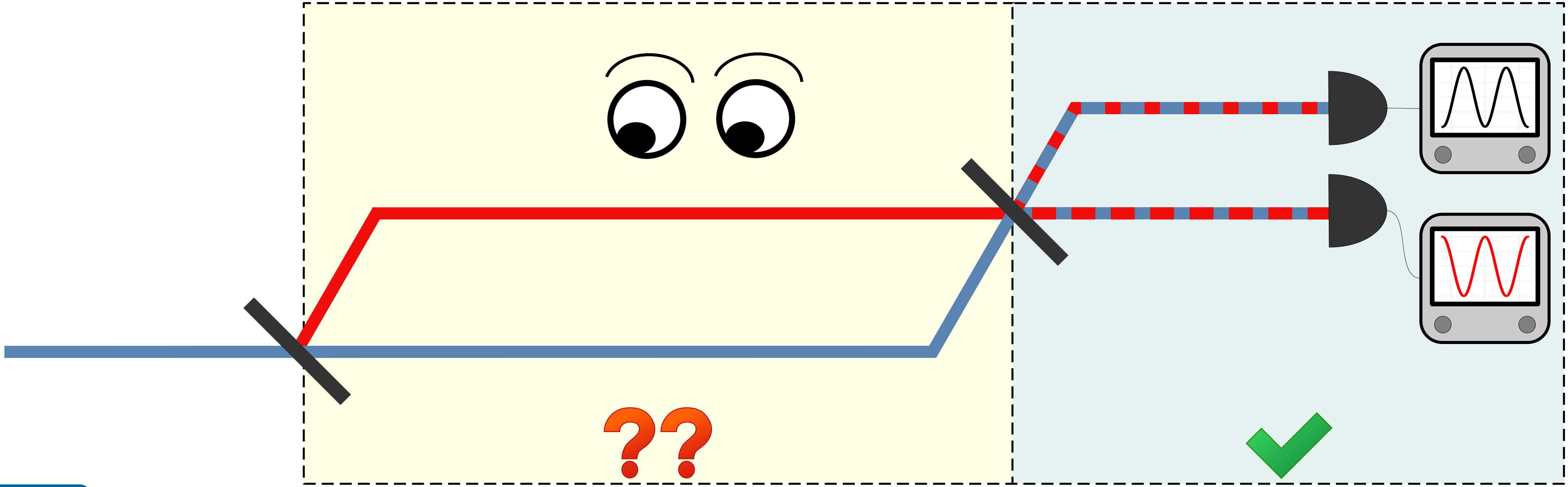
Motivation

Mach-Zehnder interferometry:



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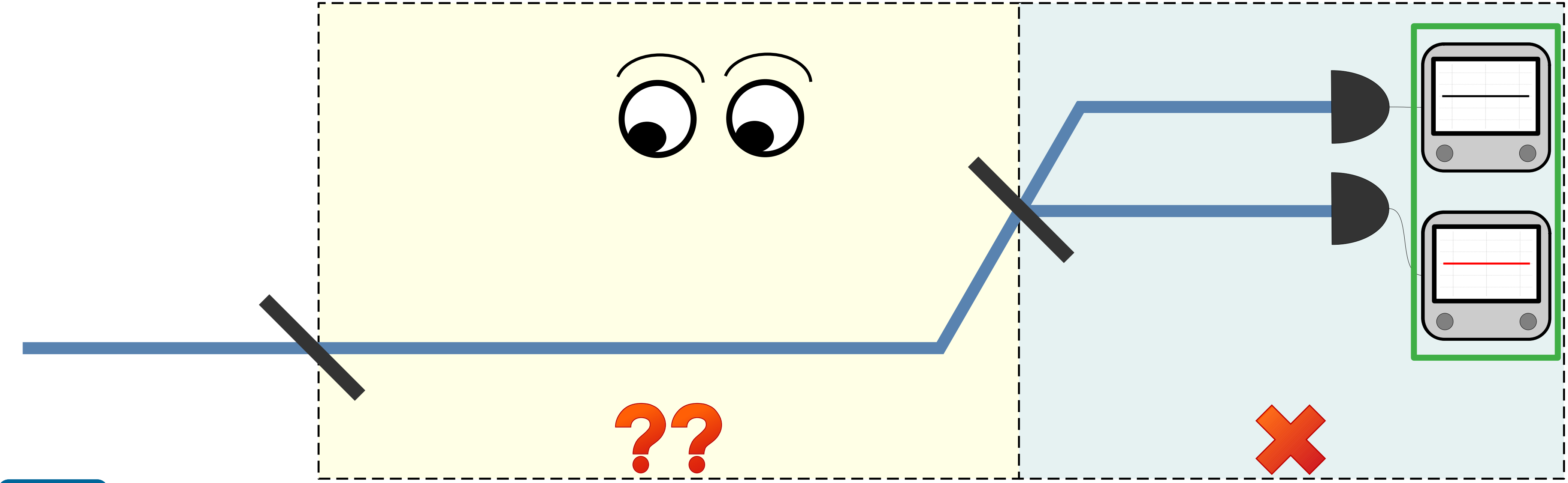

Motivation

Weak values carry information about an observable in between states
in the limit of minimum disturbance

Goal

Use weak values for a new perspective on interferometry and hopefully gain some new insights!

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Part 2: Introduction to weak values and weak measurement

Weak value

Definition:

$$A_w = \frac{\langle \psi_{\mathrm{f}} | \hat{A} | \psi_{\mathrm{in}} \rangle}{\langle \psi_{\mathrm{f}} | \psi_{\mathrm{in}} \rangle}$$

Weak value

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Weak value

Definition:

$$A_w = \frac{\langle\psi_\mathrm{f}|\hat{A}|\psi_\mathrm{in}\rangle}{\langle\psi_\mathrm{f}|\psi_\mathrm{in}\rangle}$$

- Observable: $\hat{A}$
- Pre-selected state: $|\psi_\mathrm{in}\rangle$
- Post-selected state: $|\psi_\mathrm{f}\rangle$

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Weak value

Definition:

$$A_w = \frac{\langle \psi_{\mathrm{f}} | \hat{A} | \psi_{\mathrm{in}} \rangle}{\langle \psi_{\mathrm{f}} | \psi_{\mathrm{in}} \rangle}$$

Expectation value:

$$\langle \hat{A} \rangle = \frac{\langle \psi | \hat{A} | \psi \rangle}{\langle \psi | \psi \rangle}$$

- Observable: $\hat{A}$
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Weak value

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$$A_w = \frac{\langle\psi_{\mathrm{f}}|\hat{A}|\psi_{\mathrm{in}}\rangle}{\langle\psi_{\mathrm{f}}|\psi_{\mathrm{in}}\rangle}$$

Expectation value:

$$\langle\hat{A}\rangle = \frac{\langle\psi|\hat{A}|\psi\rangle}{\langle\psi|\psi\rangle}$$

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- Not bounded by eigenvalues

Weak value

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- Observable: $\hat{A}$
- Pre-selected state: $|\psi_\mathrm{in}\rangle$
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- Not bounded by eigenvalues
- Complex number

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Weak value

$$A_w = A_w^{\Re} + \mathrm{i} A_w^{\Im}$$

Real Imaginary

- Observable: $\hat{A}$
- Pre-selected state: $|\psi_{\mathrm{in}}\rangle$
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- Not bounded by eigenvalues
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Weak value

$$A_w = A_w^{\Re} + \mathrm{i} A_w^{\Im}$$

Real

Imaginary

Describes the observable in the limit of minimum disturbance

- Observable: $\hat{A}$
- Pre-selected state: $|\psi_{\mathrm{in}}\rangle$
- Post-selected state: $|\psi_{\mathrm{f}}\rangle$
- Not bounded by eigenvalues
- Complex number

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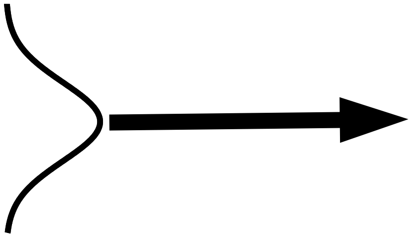
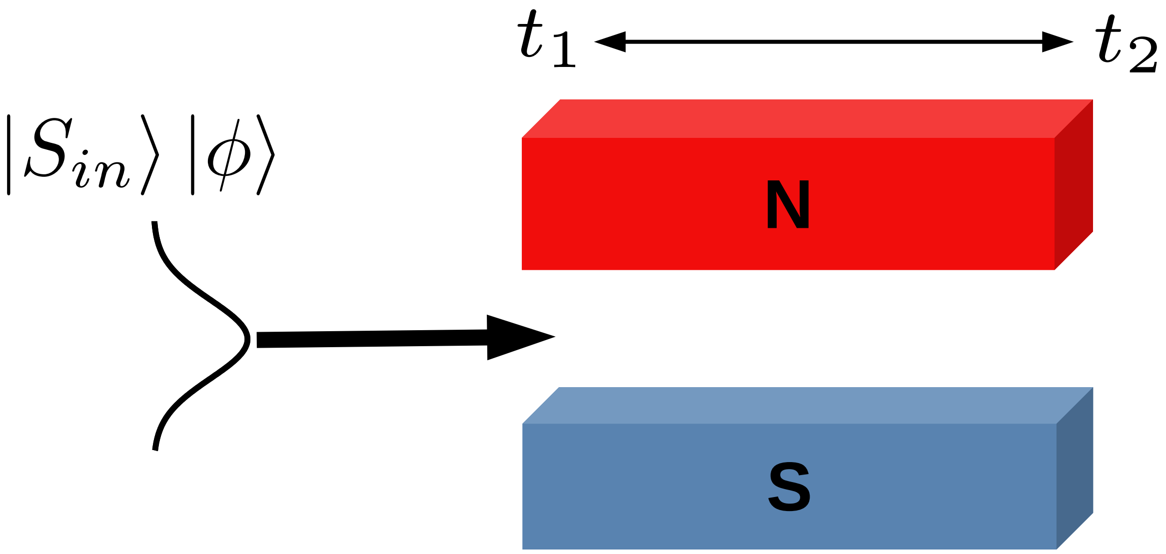
Stern-Gerlach

$$\overset{\text{Spin}}{\downarrow}\qquad\overset{\text{Position}}{\downarrow}$$

$$|S_{in}\rangle\,|\phi\rangle$$

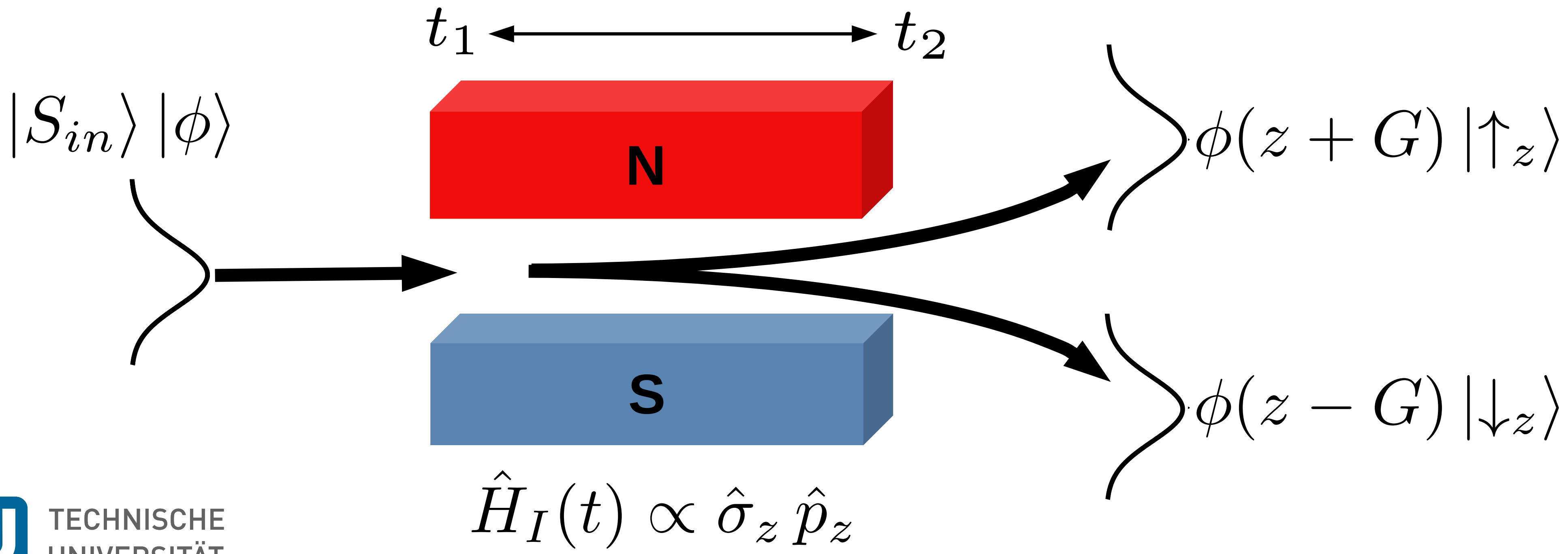


Stern-Gerlach



$$\hat{H}_I(t) \propto \hat{\sigma}_z\,\hat{p}_z$$

Stern-Gerlach



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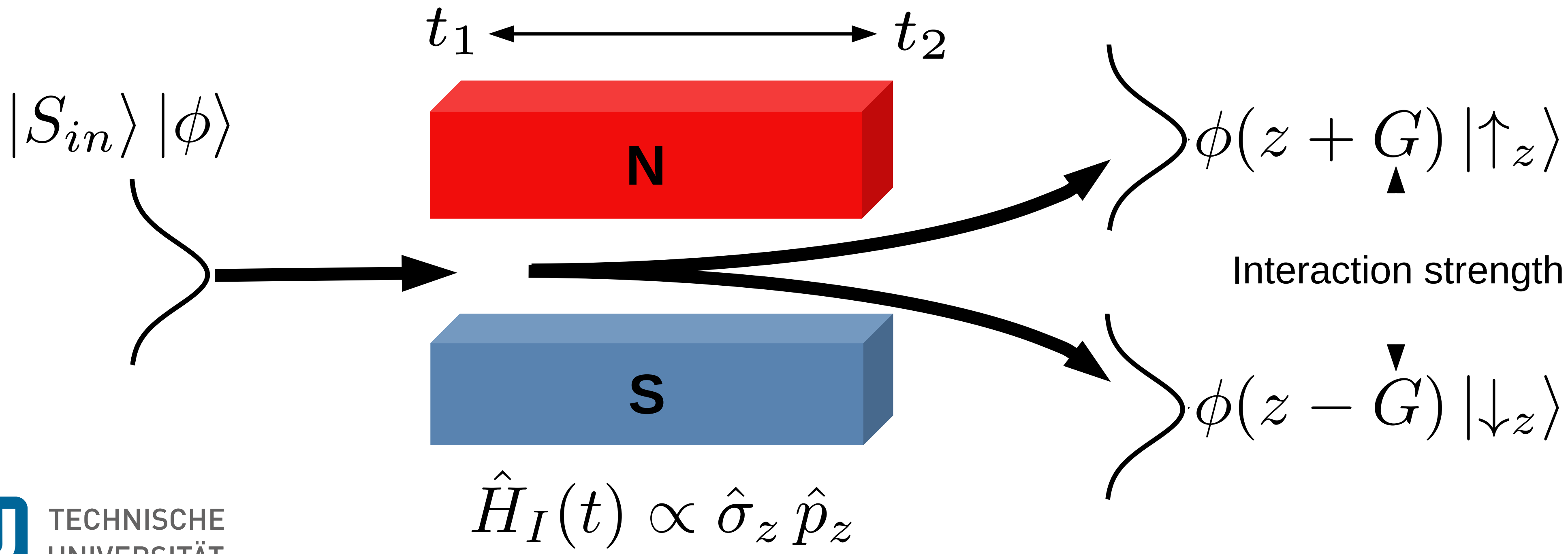
Stern-Gerlach



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Example of standard measurement (Von Neumann scheme)

Example of standard measurement (Von Neumann scheme)

Two quantum states

$$|\psi_{\mathrm{in}}\rangle_{\mathrm{s}}\,|\phi\rangle_{\mathrm{m}}$$

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Example of standard measurement (Von Neumann scheme)

Two quantum states

System $\longrightarrow$ $|\psi_{\mathrm{in}}\rangle_{\mathrm{s}}\,|\phi\rangle_{\mathrm{m}}$ $\longleftarrow$ Meter / Auxiliary

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Example of standard measurement (Von Neumann scheme)

Two quantum states

System $\longrightarrow$ $|\psi_{\mathrm{in}}\rangle_{\mathrm{s}}\,|\phi\rangle_{\mathrm{m}}$ $\longleftarrow$ Meter / Auxiliary

System observable $\hat{A}_s$

$$\hat{A}_s\,|a\rangle_{\mathrm{s}} = a\,|a\rangle_{\mathrm{s}}\;,\;\;\{|a\rangle_{\mathrm{s}}\}$$

Example of standard measurement (Von Neumann scheme)

Two quantum states

System $\longrightarrow$ $|\psi_{\mathrm{in}}\rangle_{\mathrm{s}}\,|\phi\rangle_{\mathrm{m}}$ $\longleftarrow$ Meter / Auxiliary

System observable $\hat{A}_s$

$$\hat{A}_s\,|a\rangle_{\mathrm{s}} = a\,|a\rangle_{\mathrm{s}}\ ,\ \{|a\rangle_{\mathrm{s}}\}$$

Interaction Hamiltonian

$$\hat{H}_I(t) \propto \hat{A}_{\mathrm{s}}\,\hat{p}_{\mathrm{m}}$$

Example of standard measurement (Von Neumann scheme)

Effect of the interaction Hamiltonian

$$\mathrm{e}^{-\mathrm{i}\int_{t_1}^{t_2}\hat{H}_I(t)\mathrm{d}t} = \mathrm{e}^{-\mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}}$$

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Example of standard measurement (Von Neumann scheme)

Effect of the interaction Hamiltonian

$$e^{-\mathrm{i}\int_{t_1}^{t_2} \hat{H}_I(t)\mathrm{d}t} = e^{-\mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}}$$

Interaction strength

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Example of standard measurement (Von Neumann scheme)

Effect of the interaction Hamiltonian

$$e^{-\mathrm{i}\int_{t_1}^{t_2} \hat{H}_I(t)\mathrm{d}t} = e^{-\mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}}$$

$$\hat{\mathbb{I}} = \sum_a |a\rangle_\mathrm{s}\,\langle a|_\mathrm{s}$$

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Example of standard measurement (Von Neumann scheme)

Effect of the interaction Hamiltonian

$$\mathrm{e}^{-\mathrm{i}\int_{t_1}^{t_2}\hat{H}_I(t)\mathrm{d}t} = \mathrm{e}^{-\mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}}$$

$$= \sum_a \mathrm{e}^{-\mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}}\,|a\rangle_\mathrm{s}\,\langle a|_\mathrm{s}$$

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Example of standard measurement (Von Neumann scheme)

Effect of the interaction Hamiltonian

$$
\begin{aligned}
\mathrm{e}^{-\mathrm{i}\int_{t_1}^{t_2}\hat{H}_I(t)\mathrm{d}t} &= \mathrm{e}^{-\mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}} \\
&= \sum_a \mathrm{e}^{-\mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}}\,|a\rangle_\mathrm{s}\,\langle a|_\mathrm{s} \\
&= \sum_a \mathrm{e}^{-\mathrm{i}Ga\hat{p}_\mathrm{m}}\,|a\rangle_\mathrm{s}\,\langle a|_\mathrm{s}
\end{aligned}
$$

Example of standard measurement (Von Neumann scheme)

Effect of the interaction Hamiltonian

$$
\begin{aligned}
\mathrm{e}^{-\mathrm{i}\int_{t_1}^{t_2}\hat{H}_I(t)\mathrm{d}t} &= \mathrm{e}^{-\mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}} \\
&= \sum_a \mathrm{e}^{-\mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}} \left|a\right\rangle_\mathrm{s} \left\langle a\right|_\mathrm{s} \\
&= \sum_a \mathrm{e}^{-\mathrm{i}G\boxed{a}\hat{p}_\mathrm{m}} \left|a\right\rangle_\mathrm{s} \left\langle a\right|_\mathrm{s}
\end{aligned}
$$

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Example of standard measurement (Von Neumann scheme)

Effect of the interaction Hamiltonian

$$e^{-i\int_{t_1}^{t_2}\hat{H}_I(t)\mathrm{d}t} = e^{-iG\hat{A}_\mathrm{s}\hat{p}_\mathrm{m}}$$

$$= \sum_a e^{-iG\hat{A}_\mathrm{s}\hat{p}_\mathrm{m}} |a\rangle_\mathrm{s}\langle a|_\mathrm{s}$$

$$= \sum_a \boxed{e^{-iGa\hat{p}_\mathrm{m}}} |a\rangle_\mathrm{s}\langle a|_\mathrm{s}$$

Translation operator

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Example of standard measurement (Von Neumann scheme)

Overall effect

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Example of standard measurement (Von Neumann scheme)

Overall effect

Eigenvalue

$$\phi_{\mathrm{m}}(x) \rightarrow \phi_{\mathrm{m}}(x + Ga)$$

Interaction strength

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Weak measurement

Effect of the interaction Hamiltonian

$$\mathrm{e}^{-\mathrm{i}G\hat{A}_{\mathrm{s}}\,\hat{p}_{\mathrm{m}}}\,|\psi_{\mathrm{in}}\rangle_{\mathrm{s}}\,|\phi\rangle_{\mathrm{m}}$$

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Weak measurement

Effect of the interaction Hamiltonian

$$e^{-\mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}} \left|\psi_\mathrm{in}\right\rangle_\mathrm{s} \left|\phi\right\rangle_\mathrm{m} \approx \left(\hat{\mathbb{I}} - \mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}\right) \left|\psi_\mathrm{in}\right\rangle_\mathrm{s} \left|\phi\right\rangle_\mathrm{m}$$

$$G \ll 1$$

Weak measurement

Effect of the interaction Hamiltonian

$$\langle\psi_{\mathrm{f}}|_s \, \mathrm{e}^{-\mathrm{i}G\hat{A}_{\mathrm{s}}\,\hat{p}_{\mathrm{m}}} \, |\psi_{\mathrm{in}}\rangle_{\mathrm{s}} \, |\phi\rangle_{\mathrm{m}} \approx \langle\psi_{\mathrm{f}}|_s \left(\hat{\mathbb{I}} - \mathrm{i}G\hat{A}_{\mathrm{s}}\,\hat{p}_{\mathrm{m}}\right) |\psi_{\mathrm{in}}\rangle_{\mathrm{s}} \, |\phi\rangle_{\mathrm{m}}$$

Post-selection

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Weak measurement

Effect of the interaction Hamiltonian

$$\langle\psi_\mathrm{f}|_s\, \mathrm{e}^{-\mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}}\, |\psi_\mathrm{in}\rangle_\mathrm{s}\, |\phi\rangle_\mathrm{m} \approx \langle\psi_\mathrm{f}|_s \left(\hat{\mathbb{I}} - \mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}\right) |\psi_\mathrm{in}\rangle_\mathrm{s}\, |\phi\rangle_\mathrm{m}$$

$$= \langle\psi_\mathrm{f}|\psi_\mathrm{in}\rangle \left(\hat{\mathbb{I}} - \mathrm{i}G\frac{\langle\psi_\mathrm{f}|\hat{A}_\mathrm{s}|\psi_\mathrm{in}\rangle}{\langle\psi_\mathrm{f}|\psi_\mathrm{in}\rangle}\hat{p}_\mathrm{m}\right) |\phi\rangle_\mathrm{m}$$

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Weak measurement

Effect of the interaction Hamiltonian

$$\langle\psi_{\mathrm{f}}|_s\, \mathrm{e}^{-\mathrm{i}G\hat{A}_{\mathrm{s}}\,\hat{p}_{\mathrm{m}}}\, |\psi_{\mathrm{in}}\rangle_{\mathrm{s}}\, |\phi\rangle_{\mathrm{m}} \approx \langle\psi_{\mathrm{f}}|_s \left(\hat{\mathbb{I}} - \mathrm{i}G\hat{A}_{\mathrm{s}}\,\hat{p}_{\mathrm{m}}\right) |\psi_{\mathrm{in}}\rangle_{\mathrm{s}}\, |\phi\rangle_{\mathrm{m}}$$

$$= \langle\psi_{\mathrm{f}}|\psi_{\mathrm{in}}\rangle \left(\hat{\mathbb{I}} - \mathrm{i}G\underbrace{\boxed{\frac{\langle\psi_{\mathrm{f}}|\hat{A}_{\mathrm{s}}|\psi_{\mathrm{in}}\rangle}{\langle\psi_{\mathrm{f}}|\psi_{\mathrm{in}}\rangle}}}_{\text{Weak value of } \hat{A}_s}\hat{p}_{\mathrm{m}}\right) |\phi\rangle_{\mathrm{m}}$$

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Weak measurement

Effect of the interaction Hamiltonian

$$\langle\psi_\mathrm{f}|_s \, \mathrm{e}^{-\mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}} \, |\psi_\mathrm{in}\rangle_\mathrm{s} \, |\phi\rangle_\mathrm{m} \approx \langle\psi_\mathrm{f}|_s \left(\hat{\mathbb{I}} - \mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}\right) |\psi_\mathrm{in}\rangle_\mathrm{s} \, |\phi\rangle_\mathrm{m}$$

$$= \langle\psi_\mathrm{f}|\psi_\mathrm{in}\rangle \left(\hat{\mathbb{I}} - \mathrm{i}GA_w\hat{p}_\mathrm{m}\right) |\phi\rangle_\mathrm{m}$$

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Weak measurement

Effect of the interaction Hamiltonian

$$\langle\psi_\mathrm{f}|_s \, \mathrm{e}^{-\mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}} \, |\psi_\mathrm{in}\rangle_\mathrm{s} \, |\phi\rangle_\mathrm{m} \approx \langle\psi_\mathrm{f}|_s \left(\hat{\mathbb{I}} - \mathrm{i}G\hat{A}_\mathrm{s}\,\hat{p}_\mathrm{m}\right) |\psi_\mathrm{in}\rangle_\mathrm{s} \, |\phi\rangle_\mathrm{m}$$

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$$\approx \langle\psi_\mathrm{f}|\psi_\mathrm{in}\rangle \left(\underbrace{\boxed{\mathrm{e}^{-\mathrm{i}GA_w\hat{p}_\mathrm{m}}}}_{\text{Translation operator}}\right) |\phi\rangle_\mathrm{m}$$

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Weak measurement

Overall effect

Weak measurement

Overall effect

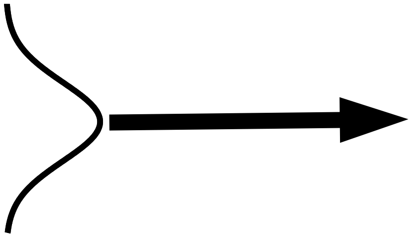
Weak value

$$\phi(x) \rightarrow \phi\left(x + G A_w\right)$$

Interaction strength

Stern-Gerlach weak measurement

$$|S_{in}\rangle \, |\phi\rangle$$



Stern-Gerlach weak measurement

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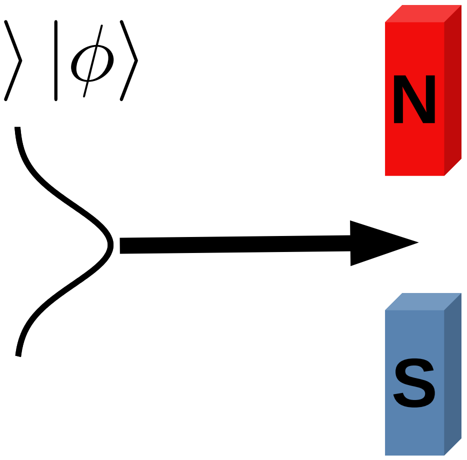

$$\hat{H}_I(t) \propto \hat{\sigma}_z\, \hat{p}_z$$

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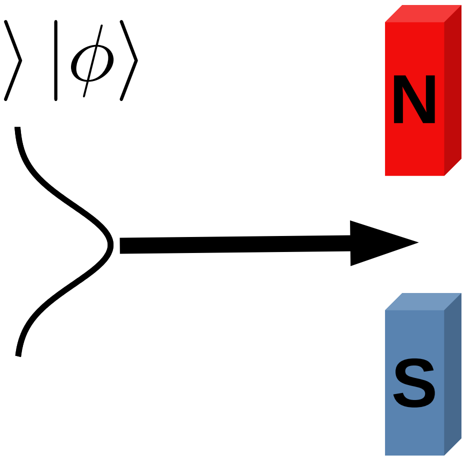
Stern-Gerlach weak measurement

Weak interaction

$G \ll 1$

$|S_{in}\rangle\,|\phi\rangle$



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Stern-Gerlach weak measurement

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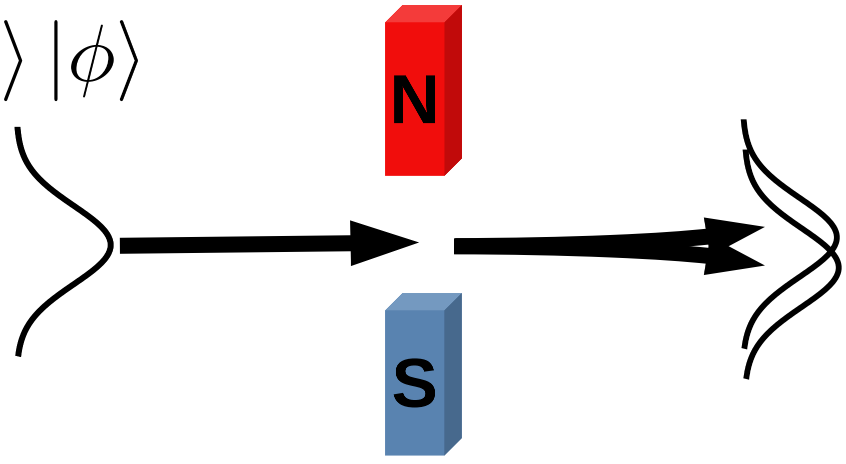


$$\phi(z+G)$$
$$\phi(z-G)$$

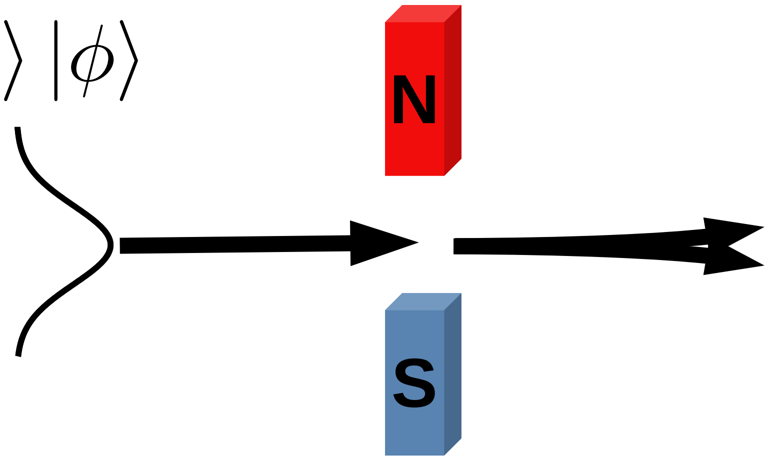
$$\hat{H}_I(t) \propto \hat{\sigma}_z\,\hat{p}_z$$

Stern-Gerlach weak measurement

Weak interaction

$G \ll 1$

$|S_{in}\rangle\,|\phi\rangle$



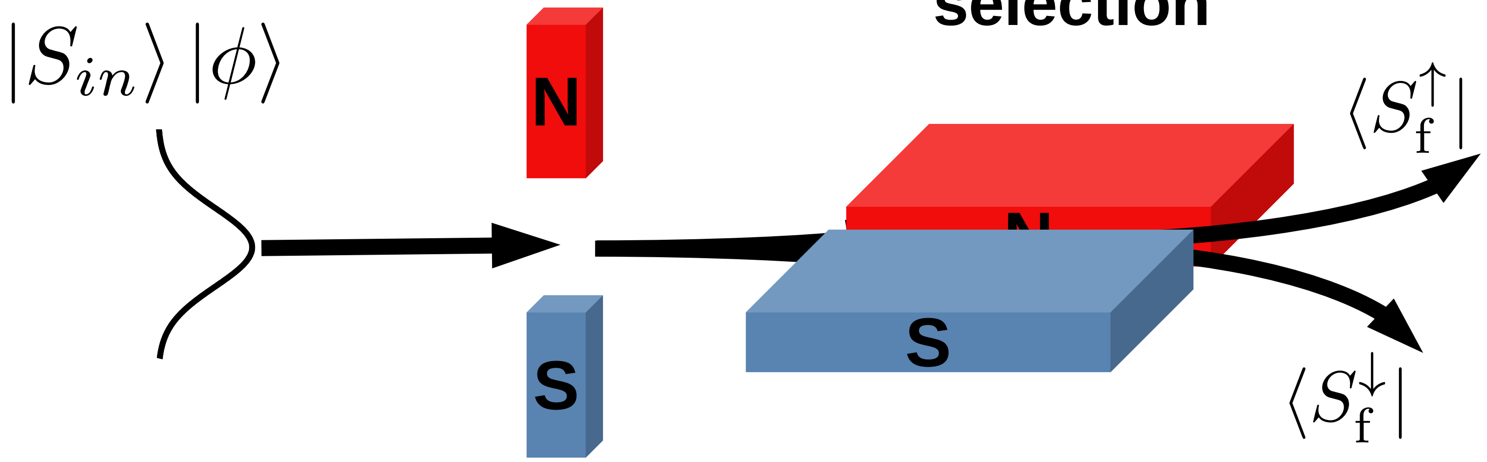
$\hat{H}_I(t) \propto \hat{\sigma}_z\,\hat{p}_z$

Stern-Gerlach weak measurement

Weak interaction

$G \ll 1$

Post-selection



$$\hat{H}_I(t) \propto \hat{\sigma}_z\,\hat{p}_z$$

Stern-Gerlach weak measurement

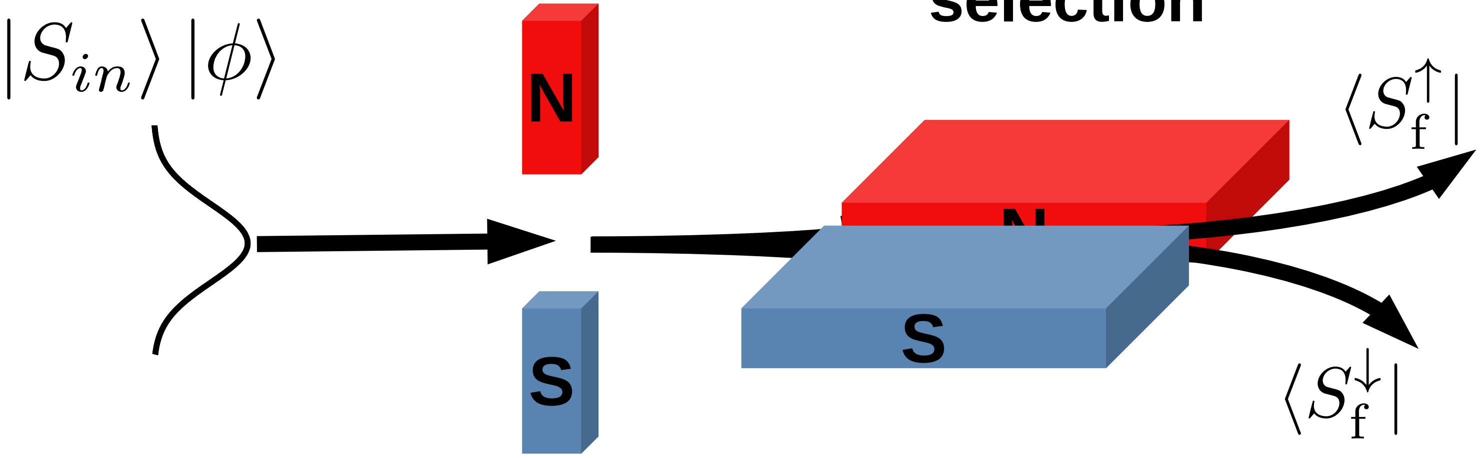
Weak interaction

$G \ll 1$

Post-selection

Spin weak value:

$$\sigma^{\updownarrow}_{z,w} = \frac{\langle S^{\updownarrow}_{\mathrm{f}} | \hat{\sigma}_z | S_{\mathrm{in}} \rangle}{\langle S^{\updownarrow}_{\mathrm{f}} | S_{\mathrm{in}} \rangle}$$



$$\hat{H}_I(t) \propto \hat{\sigma}_z\, \hat{p}_z$$

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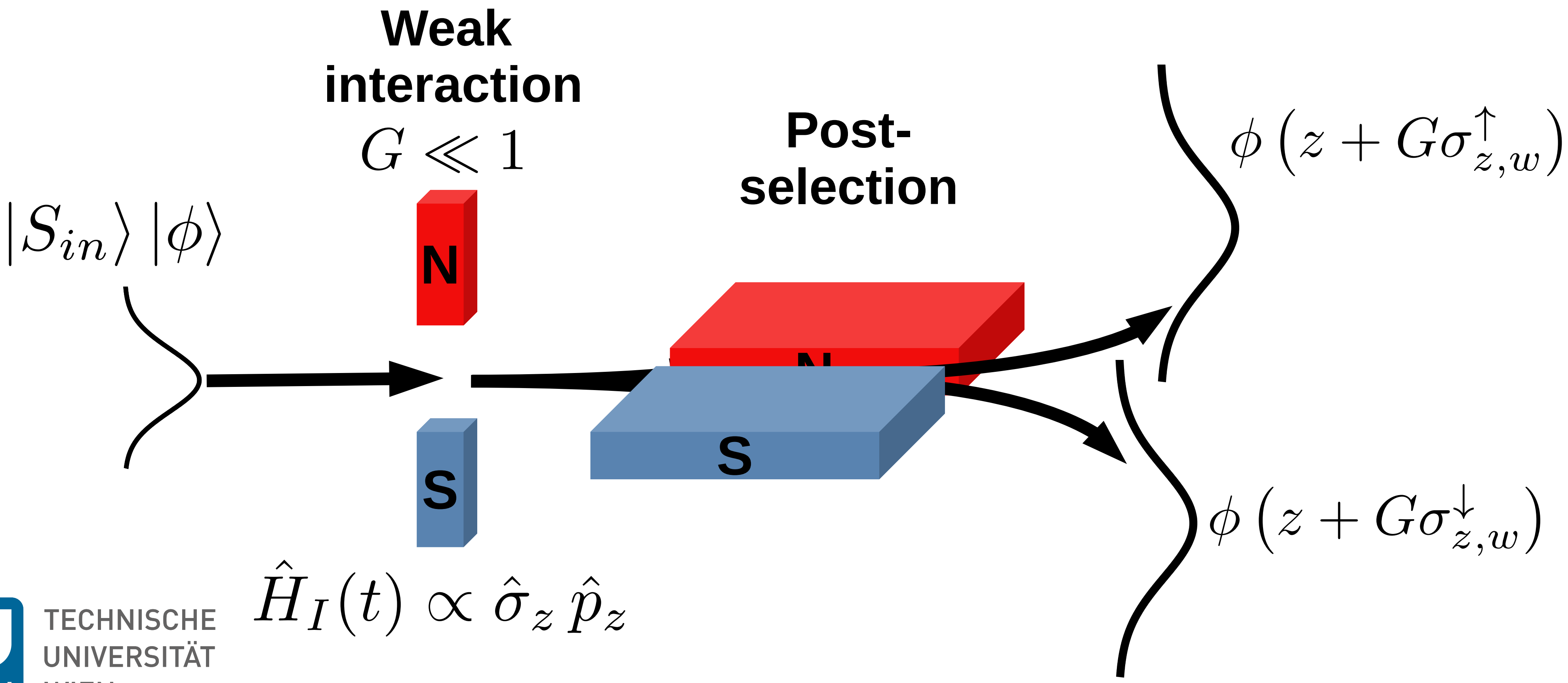
Stern-Gerlach weak measurement



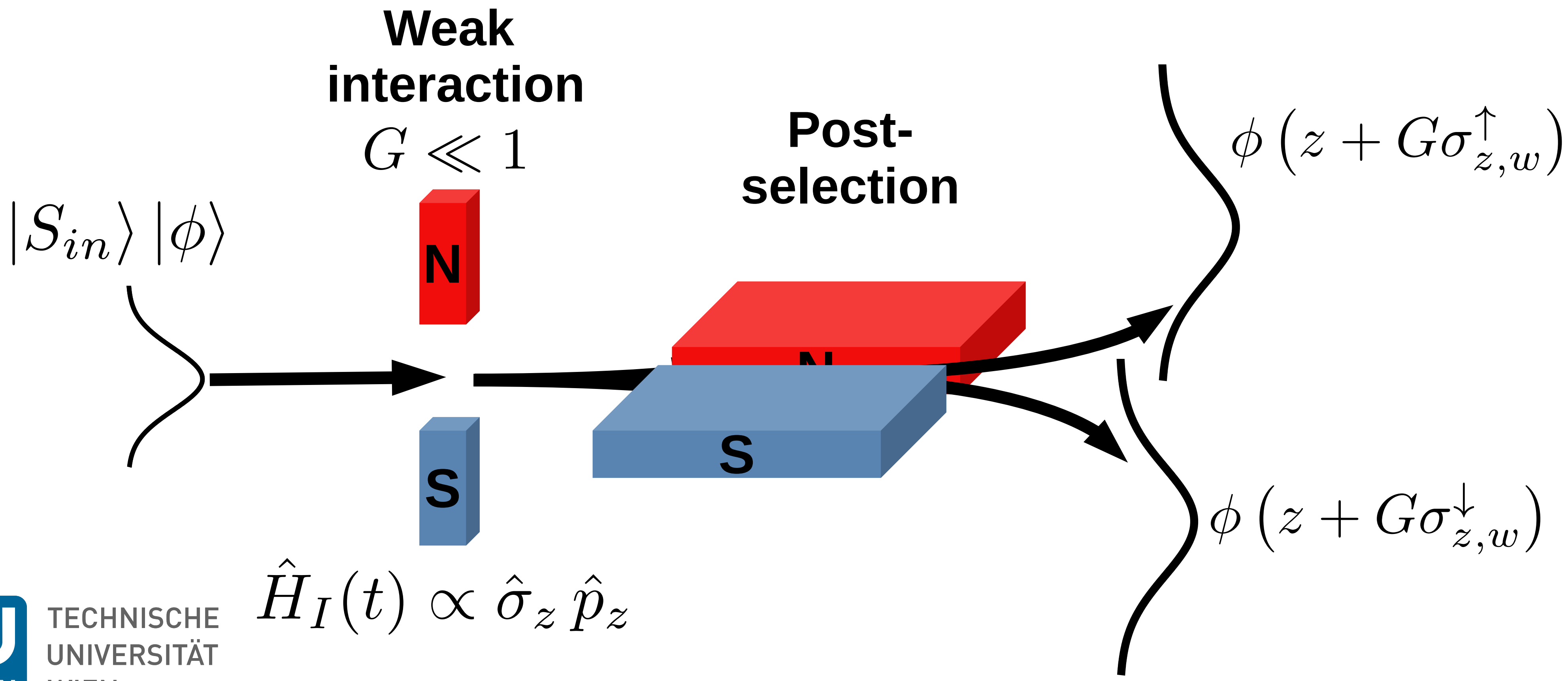
First paper on weak values

VOLUME 60, NUMBER 14 PHYSICAL REVIEW LETTERS 4 APRIL 1988

How the Result of a Measurement of a Component of the Spin of a Spin-$\frac{1}{2}$ Particle Can Turn Out to be 100

Yakir Aharonov, David Z. Albert, and Lev Vaidman

Stern-Gerlach weak measurement



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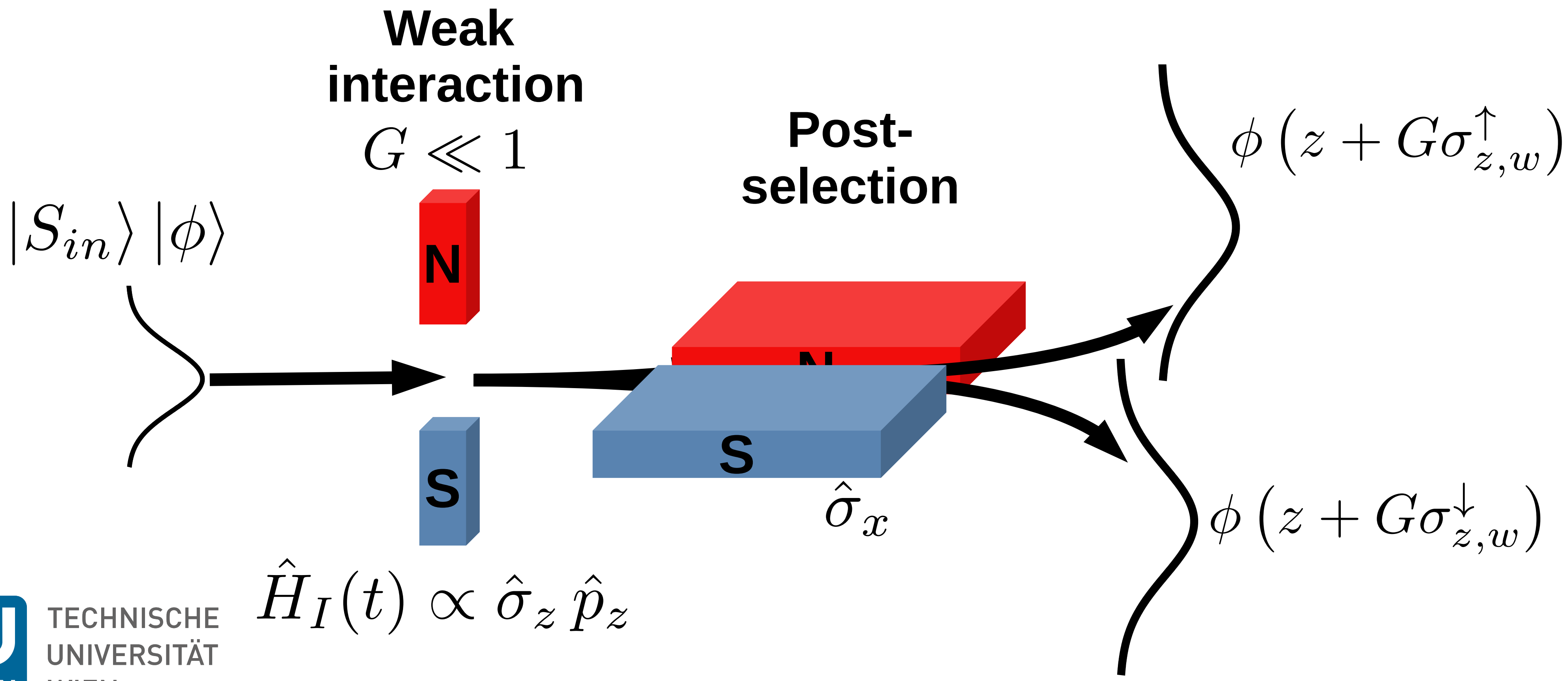
Stern-Gerlach weak measurement



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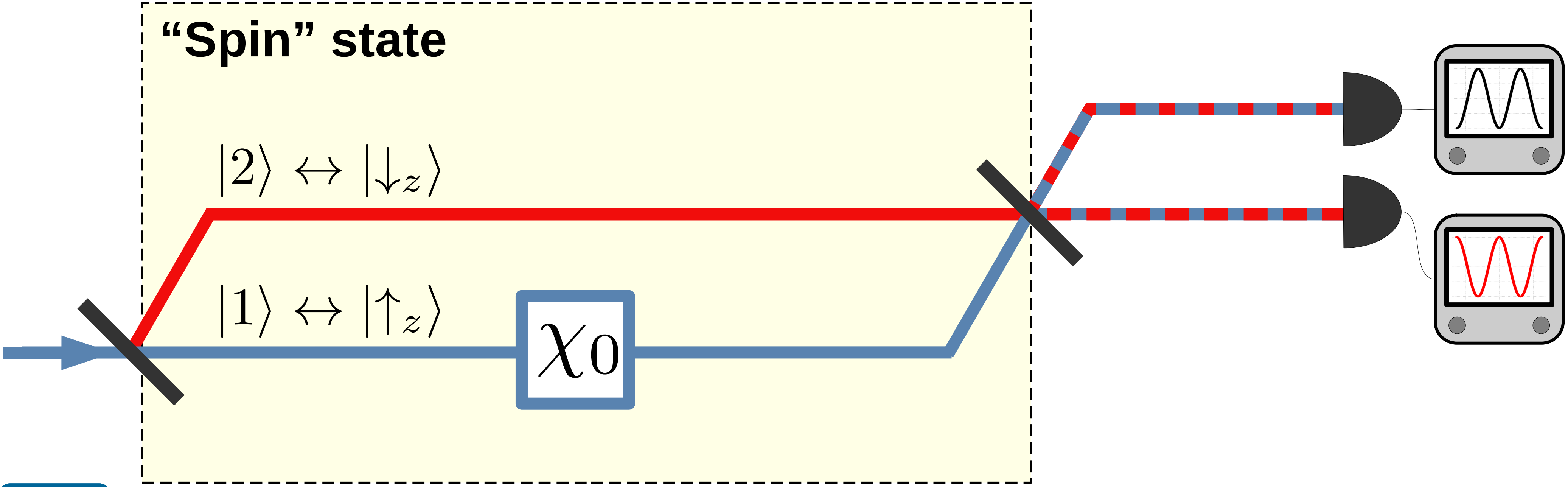
Interferometry

Two level system = spinor



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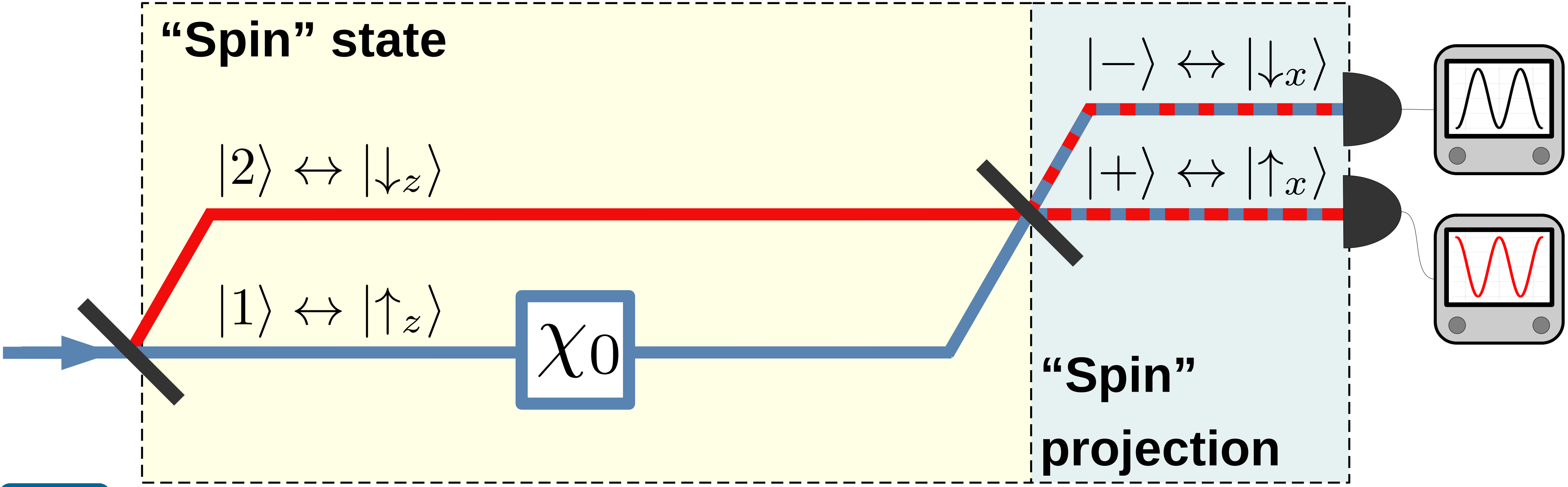

Do we actually need a weak measurement and/or an auxiliary state?

Weak value

Definition:

$$A_w = \frac{\langle \psi_{\mathrm{f}} | \hat{A} | \psi_{\mathrm{in}} \rangle}{\langle \psi_{\mathrm{f}} | \psi_{\mathrm{in}} \rangle}$$

Weak value

Definition:

$$A_w = \frac{\langle \psi_\mathrm{f} | \hat{A} | \psi_\mathrm{in} \rangle}{\langle \psi_\mathrm{f} | \psi_\mathrm{in} \rangle}$$

- No mention of interaction strength
- No mention of meter/auxiliary state

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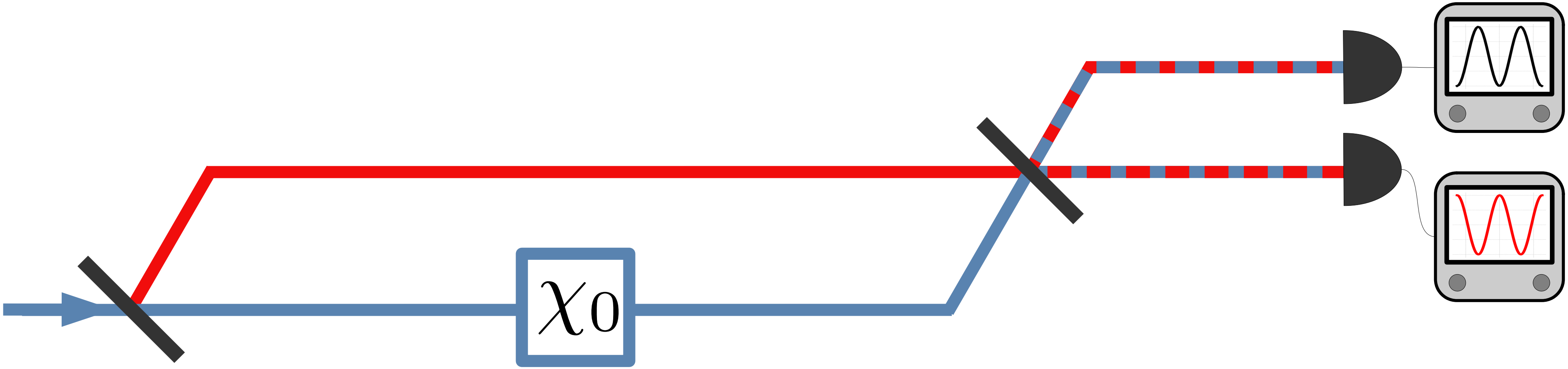
Part 3: Weak values based description of interferometry

Standard interferometry formalism



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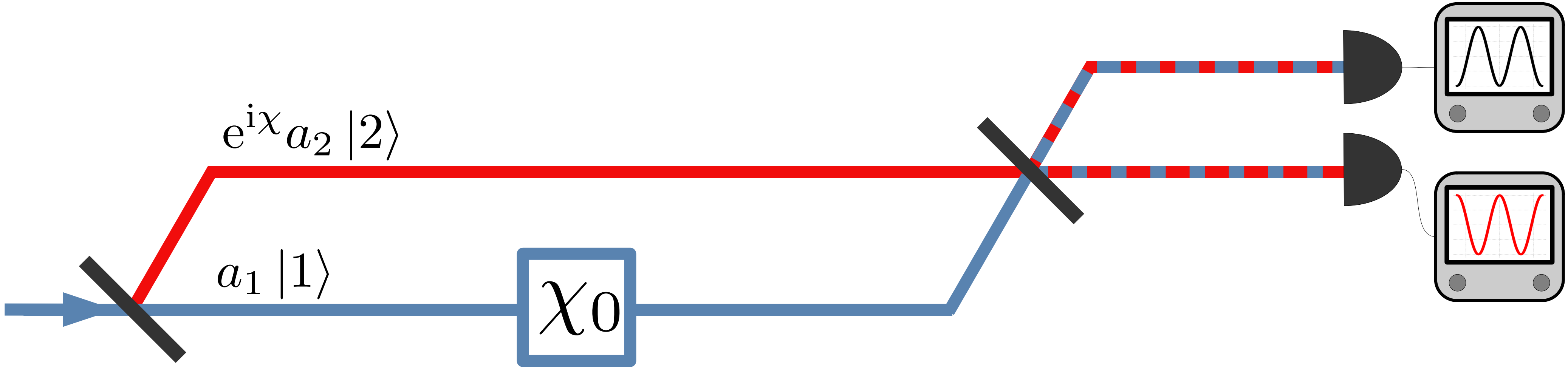
Standard interferometry formalism



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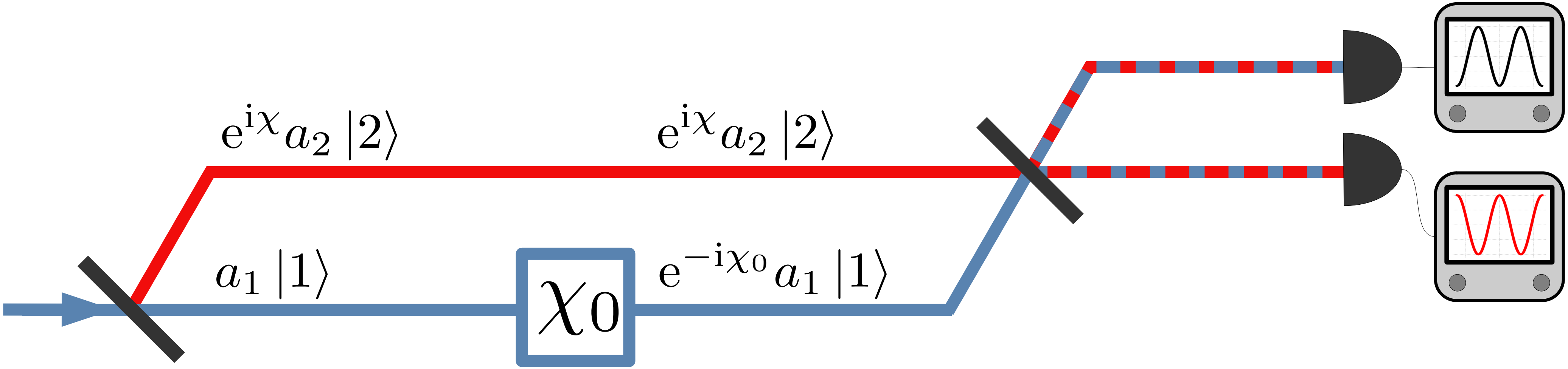
Standard interferometry formalism



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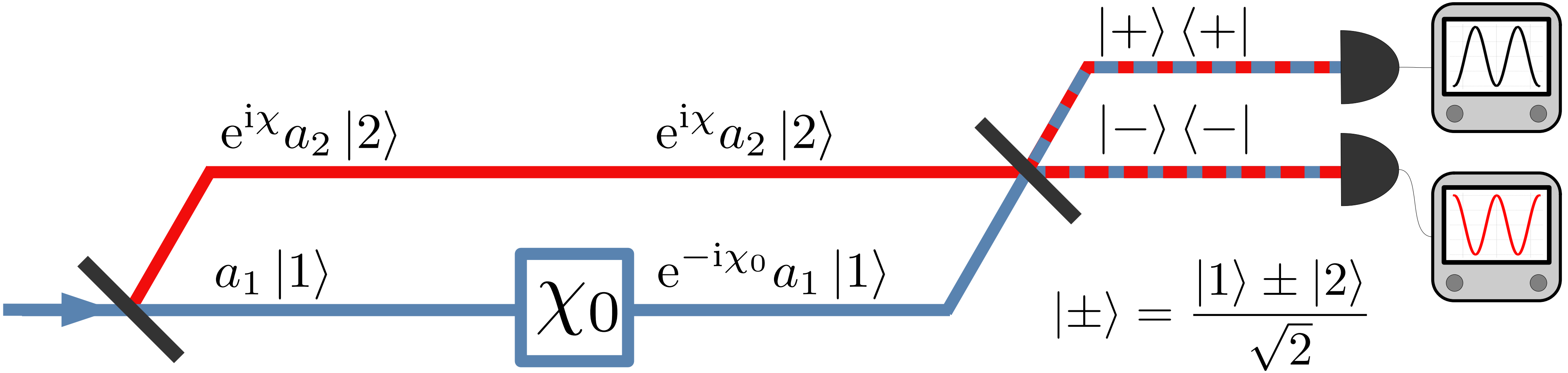
Standard interferometry formalism



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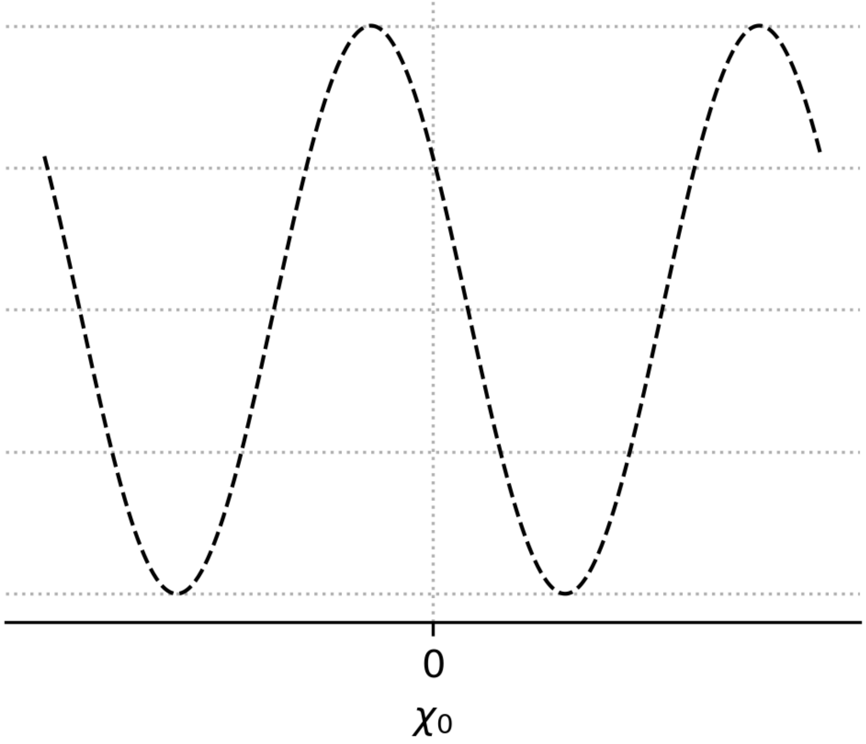
Standard interferometry formalism

Measured intensity

$$I_{\pm,1}(\chi, \chi_0) = \frac{1}{2} \pm a_1 a_2 \cos(\chi + \chi_0)$$



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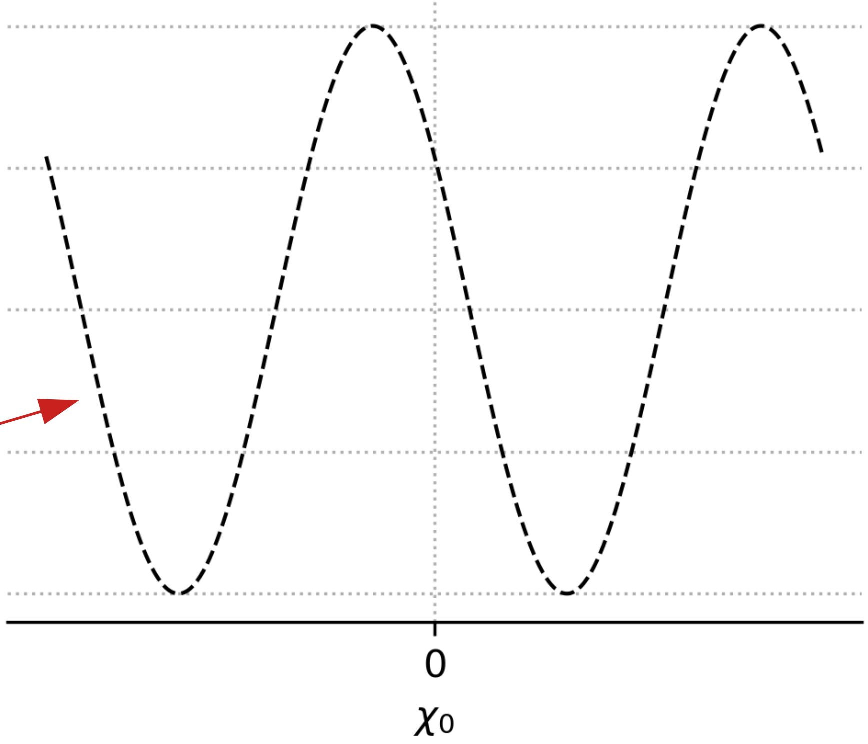
Standard interferometry formalism

Measured intensity

$$I_{\pm,1}(\chi, \chi_0) = \frac{1}{2} \pm a_1 a_2 \cos(\chi + \chi_0)$$

Interferogram



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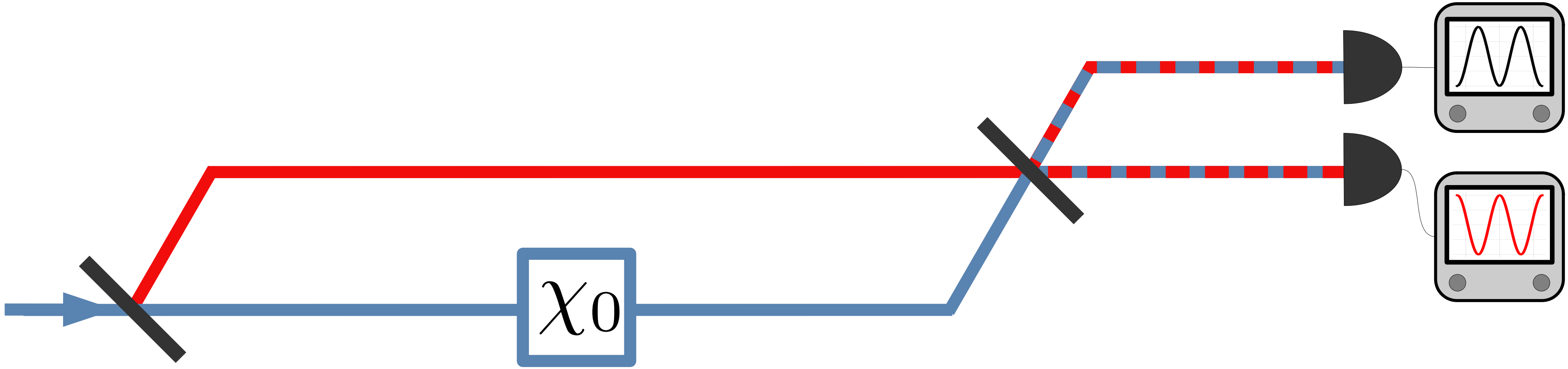
Weak value picture



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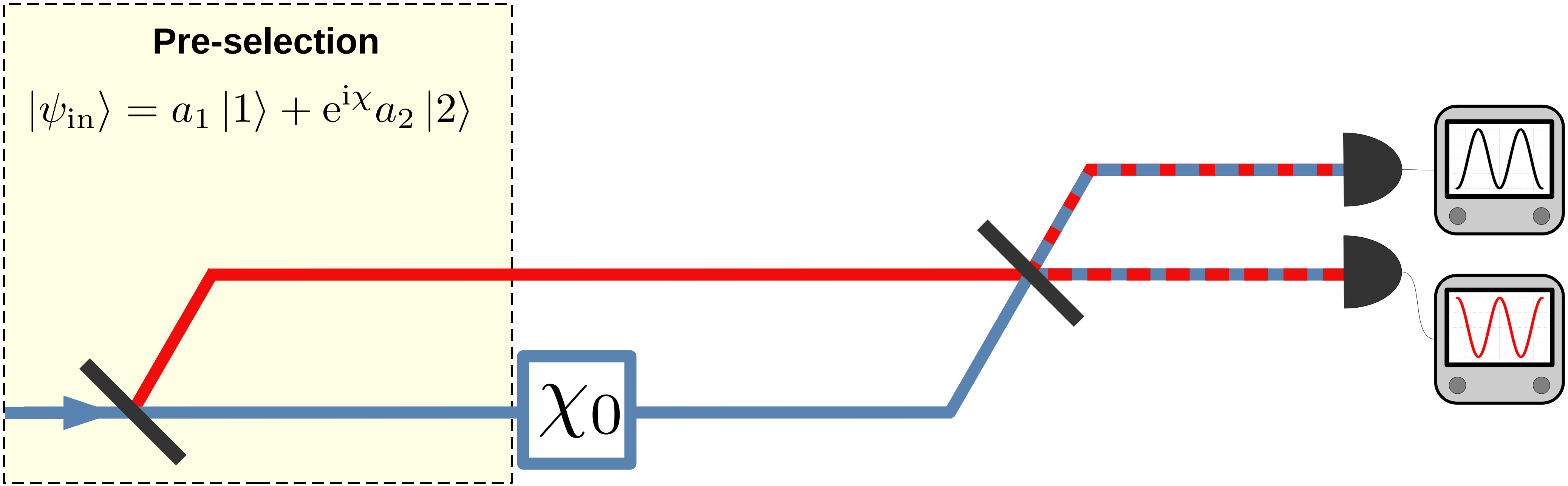
Weak value picture



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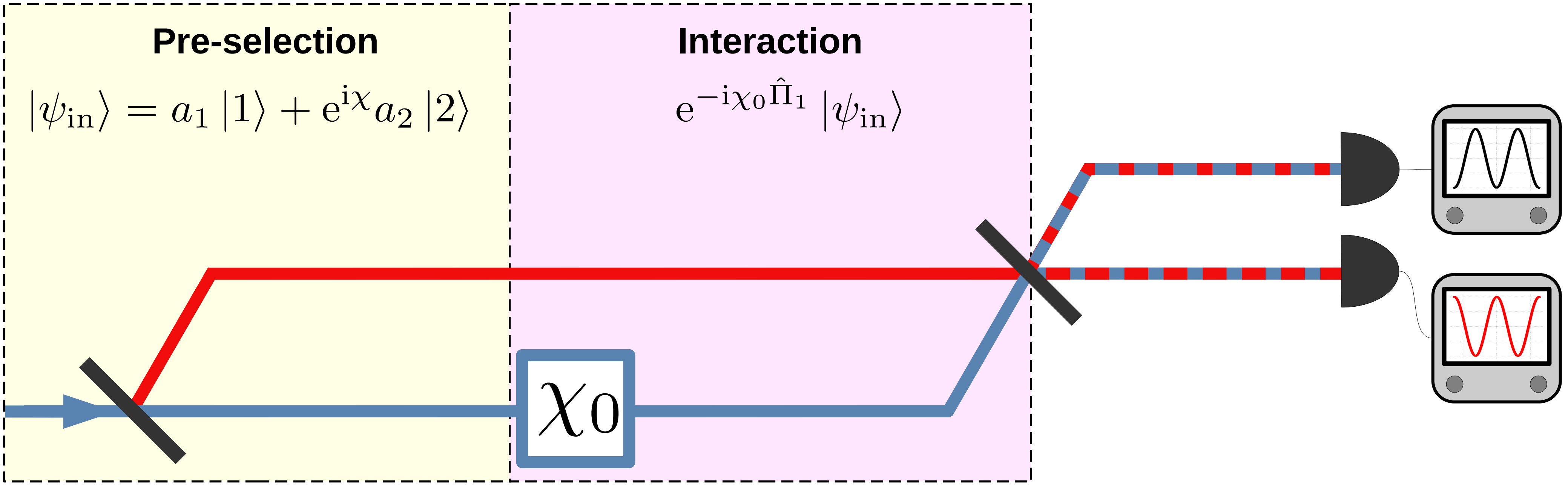
Weak value picture



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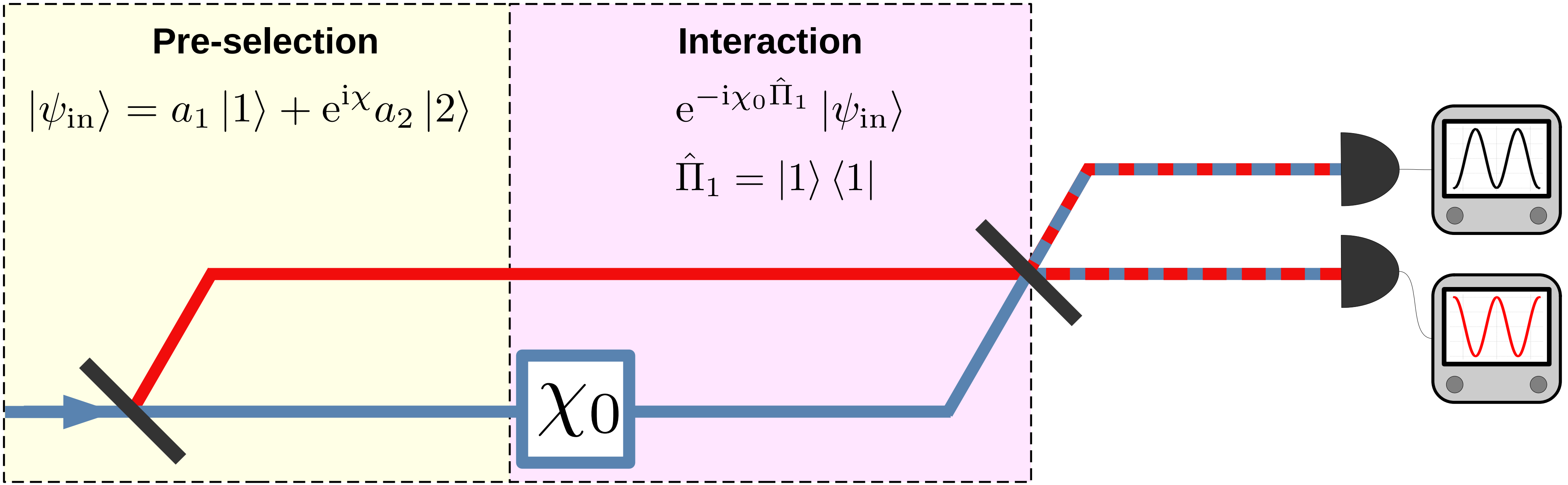
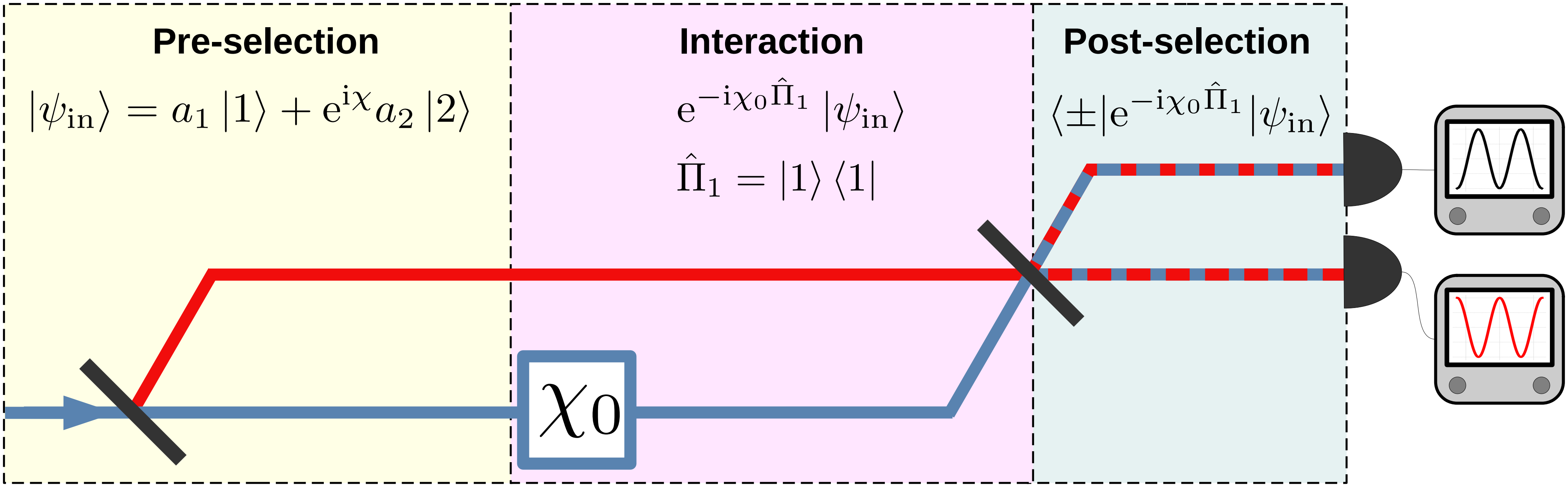
Weak value picture



Weak value picture



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Weak value picture

Path weak value

$$w_{\pm,1} = \frac{\langle \pm | \hat{\Pi}_1 | \psi_{\text{in}} \rangle}{\langle \pm | \psi_{\text{in}} \rangle}$$

Weak value picture

Measured intensity

$$I_\pm(\chi,\chi_0) = |\langle\pm|\psi_{\text{in}}\rangle|^2 \left[1 + 2\left(|w_{\pm,1}|^2 - w^{\Re}_{\pm,1}\right)(1-\cos\chi_0) + 2w^{\Im}_{\pm,1}\sin\chi_0\right]$$

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Weak value picture

Measured intensity

$$I_{\pm}(\chi,\chi_0) = |\langle \pm|\psi_{\text{in}}\rangle|^2 \left[1 + 2\left(\boxed{|w_{\pm,1}|^2} - w^{\Re}_{\pm,1}\right)(1-\cos\chi_0) + 2w^{\Im}_{\pm,1}\sin\chi_0\right]$$

Amplitude square

Weak value picture

Measured intensity

Real part

$$I_{\pm}(\chi, \chi_0) = |\langle \pm | \psi_{\text{in}} \rangle|^2 \left[1 + 2\left(\boxed{|w_{\pm,1}|^2} - \boxed{w^{\Re}_{\pm,1}}\right)(1 - \cos\chi_0) + 2 w^{\Im}_{\pm,1} \sin\chi_0\right]$$

Amplitude square

Weak value picture

Measured intensity

Real part

$$I_\pm(\chi,\chi_0) = |\langle \pm|\psi_{\text{in}}\rangle|^2 \left[1 + 2\left(\boxed{|w_{\pm,1}|^2} - \boxed{w^{\Re}_{\pm,1}}\right)(1-\cos\chi_0) + 2\boxed{w^{\Im}_{\pm,1}}\sin\chi_0\right]$$

Amplitude square

Imaginary part

Weak value picture

Measured intensity

$$I_\pm(\chi,\chi_0) = |\langle\pm|\psi_{\text{in}}\rangle|^2 \left[1 + 2\left(|w_{\pm,1}|^2 - w^{\Re}_{\pm,1}\right)\left(1 - \cos\boxed{\chi_0}\right) + 2w^{\Im}_{\pm,1}\sin\boxed{\chi_0}\right]$$

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Weak value picture

Measured intensity

$$I_\pm(\chi,\chi_0) = \boxed{|\langle\pm|\psi_{\text{in}}\rangle|^2}\left[1 + 2\boxed{\left(|w_{\pm,1}|^2 - w^{\Re}_{\pm,1}\right)}(1-\cos\boxed{\chi_0}) + 2\boxed{w^{\Im}_{\pm,1}}\sin\boxed{\chi_0}\right]$$

$$\boxed{I_\pm(\chi,0) = |\langle\pm|\psi_{\text{in}}\rangle|^2}$$

$$\boxed{\frac{I_\pm(\chi,\pi) - I_\pm(\chi,0)}{4I_\pm(\chi,0)} = |w_{\pm,1}|^2 - w^{\Re}_{\pm,1}}$$

$$\boxed{\frac{I_\pm(\chi,\frac{\pi}{2}) - I_\pm(\chi,\frac{3\pi}{2})}{4I_\pm(\chi,0)} = w^{\Im}_{\pm,1}}$$

Weak value picture

Almost there...

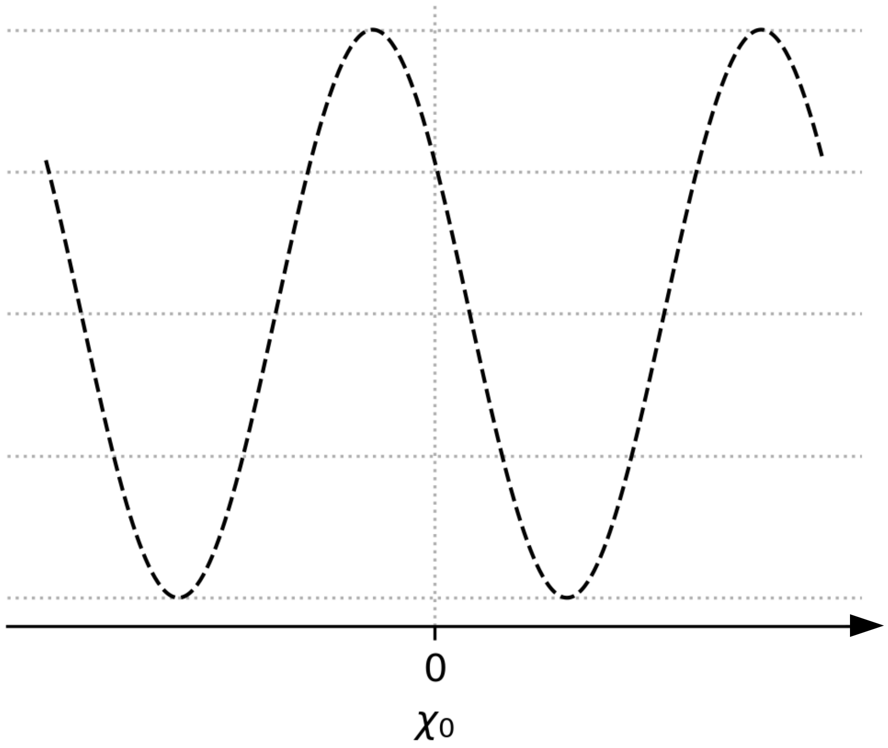
$$\frac{I_{\pm}(\chi,\frac{\pi}{2})-I_{\pm}(\chi,\frac{3\pi}{2})}{4I_{\pm}(\chi,0)}=w^{\Im}_{\pm,1}$$

Weak value picture

Almost there...

$$\frac{I_\pm(\chi,\frac{\pi}{2}) - I_\pm(\chi,\frac{3\pi}{2})}{4I_\pm(\chi,0)} = w^{\Im}_{\pm,1}$$

Interferogram



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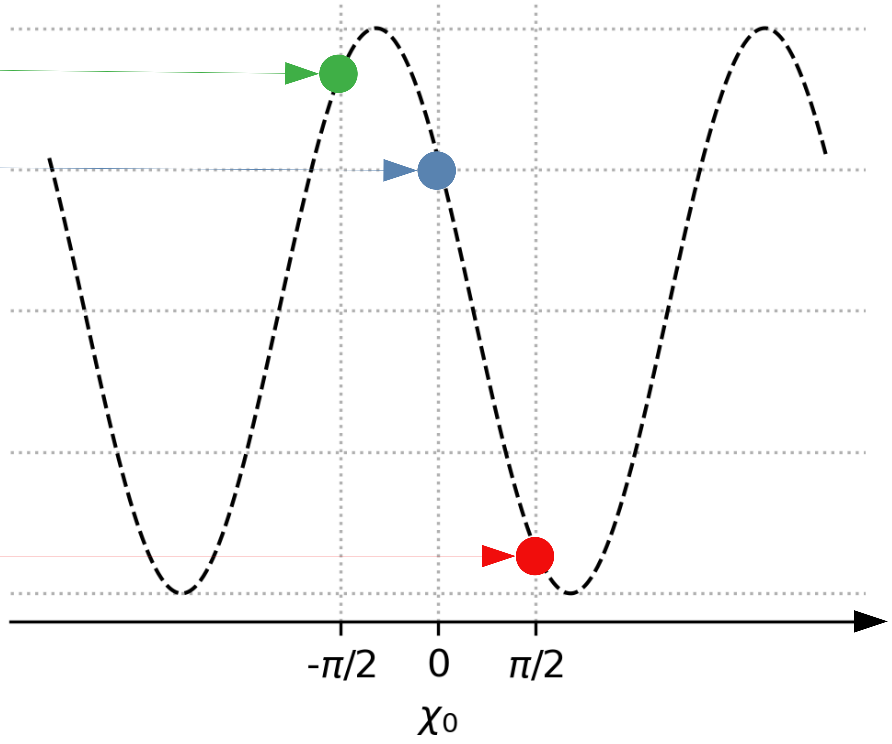
Weak value picture

Almost there...

$$\frac{\boxed{I_\pm(\chi, \frac{\pi}{2})} - \boxed{I_\pm(\chi, \frac{3\pi}{2})}}{4\boxed{I_\pm(\chi, 0)}} = w^{\Im}_{\pm,1}$$

Interferogram



Weak value picture

Almost there...

$$\frac{I_\pm(\chi,\frac{\pi}{2}) - I_\pm(\chi,\frac{3\pi}{2})}{4I_\pm(\chi,0)} = w^{\Im}_{\pm,1}$$ ✔

Weak value picture

Almost there…

$$\frac{I_\pm(\chi,\frac{\pi}{2}) - I_\pm(\chi,\frac{3\pi}{2})}{4I_\pm(\chi,0)} = w^{\Im}_{\pm,1}$$

$$\frac{I_\pm(\chi,\pi) - I_\pm(\chi,0)}{4I_\pm(\chi,0)} = |w_{\pm,1}|^2 - w^{\Re}_{\pm,1}$$

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Weak value picture

Almost there...

$$\frac{I_\pm(\chi,\frac{\pi}{2}) - I_\pm(\chi,\frac{3\pi}{2})}{4I_\pm(\chi,0)} = w^{\Im}_{\pm,1}$$

$$\frac{I_\pm(\chi,\pi) - I_\pm(\chi,0)}{4I_\pm(\chi,0)} = \boxed{\left|w_{\pm,1}\right|^2} - w^{\Re}_{\pm,1}$$

$$\boxed{{w^{\Re}_{\pm,1}}^2 + {w^{\Im}_{\pm,1}}^2}$$

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Weak value picture

Almost there...

$$\frac{I_\pm(\chi,\frac{\pi}{2}) - I_\pm(\chi,\frac{3\pi}{2})}{4I_\pm(\chi,0)} = w^{\Im}_{\pm,1}$$

$$\frac{I_\pm(\chi,\pi) - I_\pm(\chi,0)}{4I_\pm(\chi,0)} = \underbrace{\boxed{\left|w_{\pm,1}\right|^2}}_{\boxed{{w^{\Re}_{\pm,1}}^2 + {w^{\Im}_{\pm,1}}^2}} - w^{\Re}_{\pm,1}$$

Quadratic equation

Weak value picture

Almost there…

$$\frac{I_\pm(\chi,\frac{\pi}{2}) - I_\pm(\chi,\frac{3\pi}{2})}{4I_\pm(\chi,0)} = w^{\Im}_{\pm,1}$$

$$\frac{I_\pm(\chi,\pi) - I_\pm(\chi,0)}{4I_\pm(\chi,0)} = \boxed{\left|w_{\pm,1}\right|^2} - w^{\Re}_{\pm,1}$$

$$\boxed{{w^{\Re}_{\pm,1}}^2 + {w^{\Im}_{\pm,1}}^2}$$

Quadratic equation

2 solutions

Weak value picture

Almost there...

$$\frac{I_\pm(\chi,\frac{\pi}{2}) - I_\pm(\chi,\frac{3\pi}{2})}{4I_\pm(\chi,0)} = w^{\Im}_{\pm,1}$$

$$\frac{I_\pm(\chi,\pi) - I_\pm(\chi,0)}{4I_\pm(\chi,0)} = \boxed{\left|w_{\pm,1}\right|^2} - w^{\Re}_{\pm,1}$$

Weak value picture

Almost there...

$$\frac{I_\pm(\chi,\frac{\pi}{2}) - I_\pm(\chi,\frac{3\pi}{2})}{4I_\pm(\chi,0)} = w^{\Im}_{\pm,1}$$

$$-\frac{I_\pm(\chi,\pi) - I_\pm(\chi,0)}{4I_\pm(\chi,0)} + |w_{\pm,1}|^2 = w^{\Re}_{\pm,1}$$

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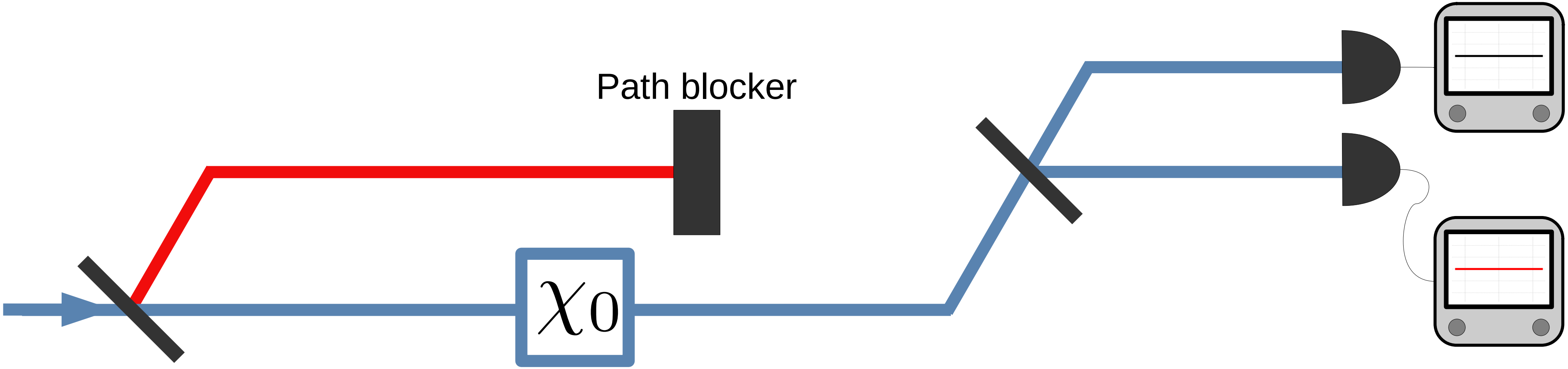
Weak value picture



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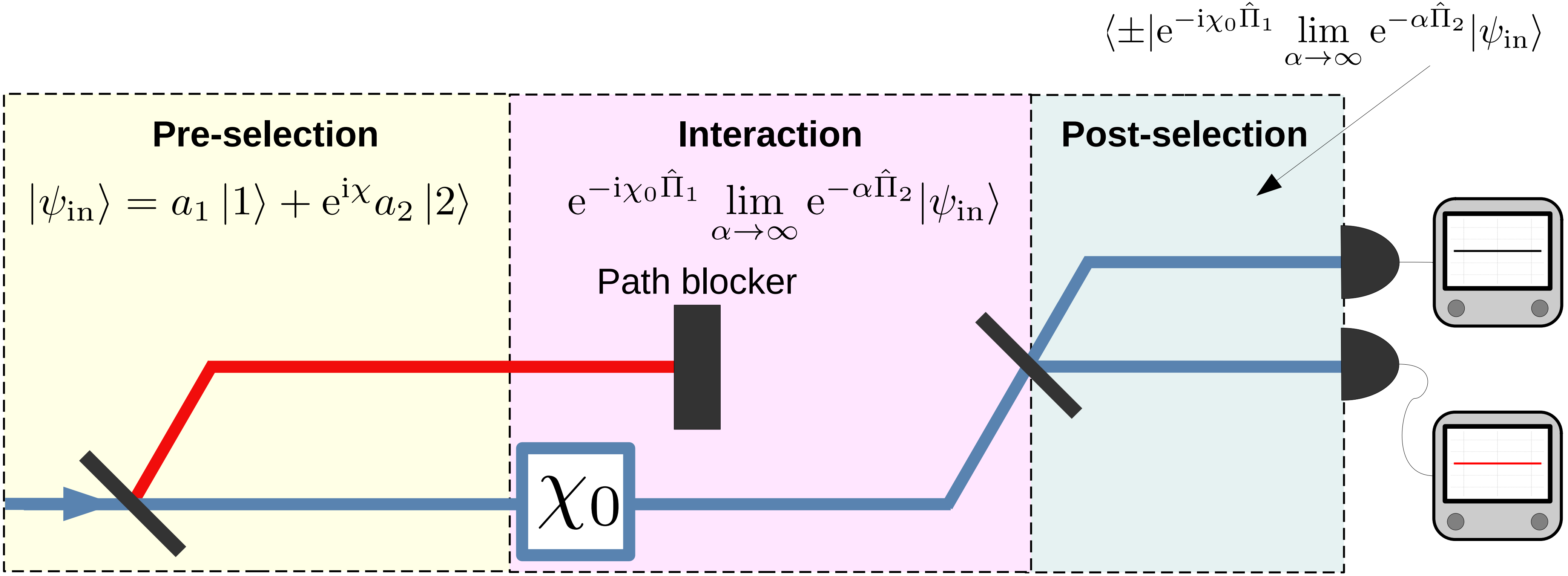
Weak value picture



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Weak value picture

Measured intensity

$$
\begin{aligned}
I_{\pm}^{Bl.\,2} &= \left| \langle \pm | \mathrm{e}^{-\mathrm{i}\chi_0 \hat{\Pi}_1} \lim_{\alpha \to \infty} \mathrm{e}^{-\alpha \hat{\Pi}_2} | \psi_{\mathrm{in}} \rangle \right|^2 \\
&= \left| \langle \pm | \mathrm{e}^{-\mathrm{i}\chi_0} \hat{\Pi}_1 | \psi_{\mathrm{in}} \rangle \right|^2 = \left| \langle \pm | \hat{\Pi}_1 | \psi_{\mathrm{in}} \rangle \right|^2 \\
&= \left| \langle \pm | \psi_{\mathrm{in}} \rangle \right|^2 \left| w_{\pm,1} \right|^2
\end{aligned}
$$

Weak value picture

Measured intensity

$$
\begin{aligned}
I_{\pm}^{Bl.\,2} &= \left| \langle \pm | \mathrm{e}^{-\mathrm{i}\chi_0 \hat{\Pi}_1} \lim_{\alpha \to \infty} \mathrm{e}^{-\alpha \hat{\Pi}_2} | \psi_{\mathrm{in}} \rangle \right|^2 \\
&= \left| \langle \pm | \mathrm{e}^{-\mathrm{i}\chi_0} \hat{\Pi}_1 | \psi_{\mathrm{in}} \rangle \right|^2 = \left| \langle \pm | \hat{\Pi}_1 | \psi_{\mathrm{in}} \rangle \right|^2 \\
&= \left| \langle \pm | \psi_{\mathrm{in}} \rangle \right|^2 \boxed{\left| w_{\pm,1} \right|^2}
\end{aligned}
$$

Weak value picture

Measured intensity

$$
\begin{aligned}
I_{\pm}^{Bl.\,2} &= \left|\langle\pm|\mathrm{e}^{-\mathrm{i}\chi_0\hat{\Pi}_1}\lim_{\alpha\to\infty}\mathrm{e}^{-\alpha\hat{\Pi}_2}|\psi_{\mathrm{in}}\rangle\right|^2 \\
&= \left|\langle\pm|\mathrm{e}^{-\mathrm{i}\chi_0}\hat{\Pi}_1|\psi_{\mathrm{in}}\rangle\right|^2 = \left|\langle\pm|\hat{\Pi}_1|\psi_{\mathrm{in}}\rangle\right|^2 \\
&= \boxed{\left|\langle\pm|\psi_{\mathrm{in}}\rangle\right|^2}\boxed{\left|w_{\pm,1}\right|^2}
\end{aligned}
$$

Weak value picture

We got there!

$$\frac{I_\pm(\chi,\frac{\pi}{2}) - I_\pm(\chi,\frac{3\pi}{2})}{4I_\pm(\chi,0)} = w^{\Im}_{\pm,1}$$ ✔

$$-\frac{I_\pm(\chi,\pi) - I_\pm(\chi,0)}{4I_\pm(\chi,0)} + |w_{\pm,1}|^2 = w^{\Re}_{\pm,1}$$ ✔

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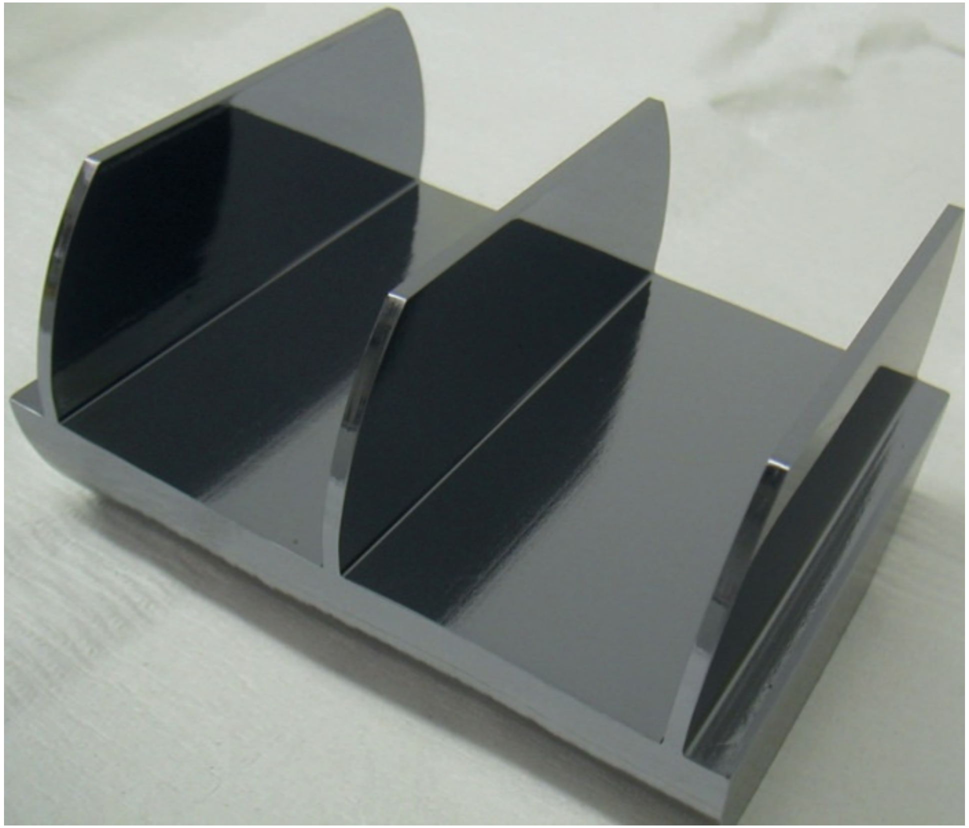
Part 4: Experimental measurement of path weak value from interferograms

Neutron interferometer



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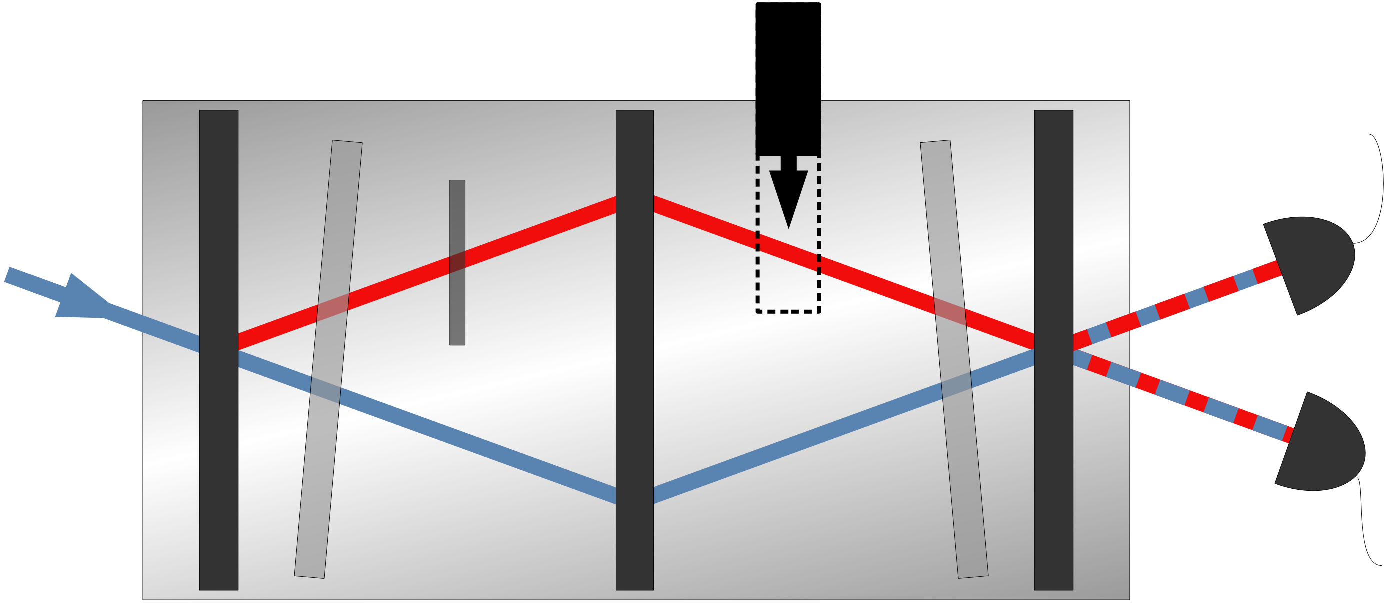
Setup



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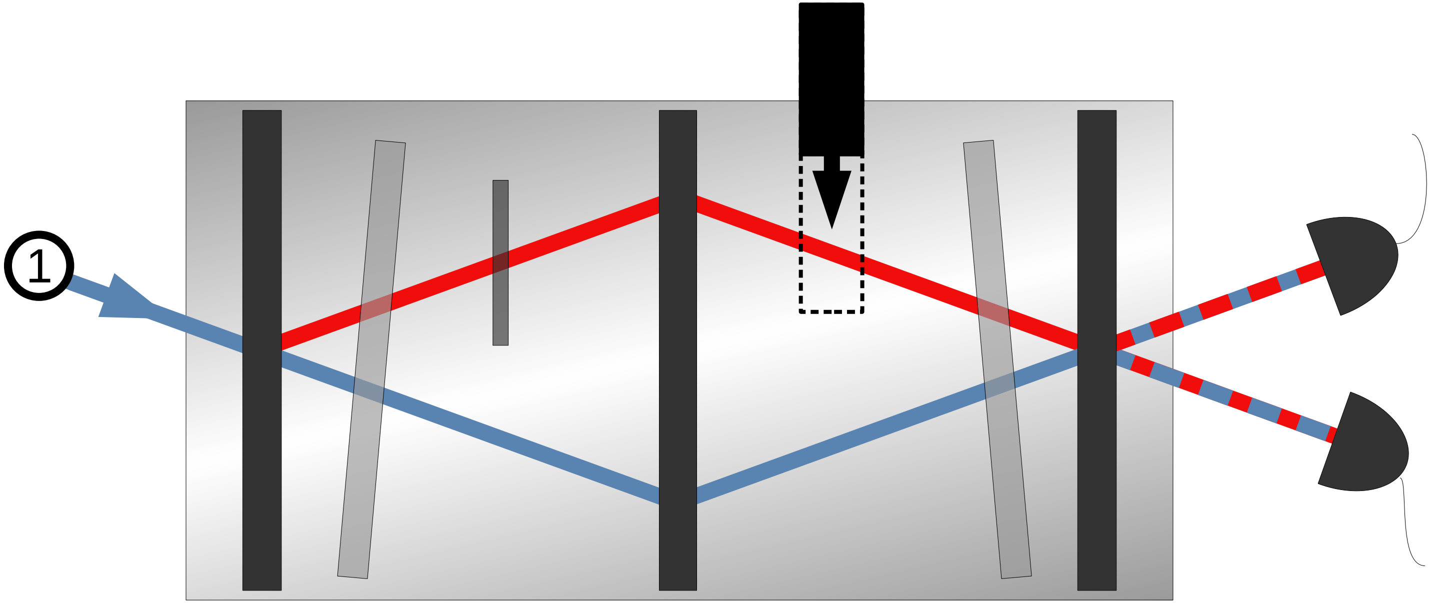
Setup

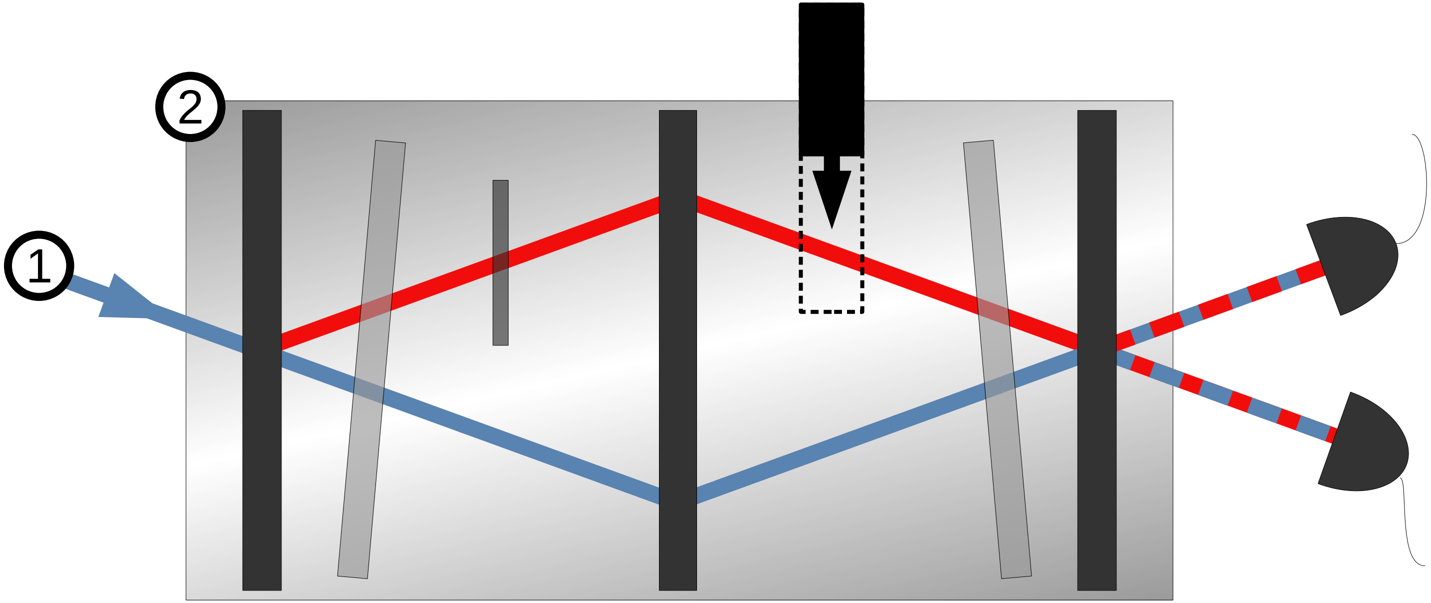
1 Unpolarised neutron beam
$\lambda = 1.92Å$
$\delta\lambda/\lambda \approx 0.02$



Setup

1 Unpolarised neutron beam
$\lambda = 1.92 \mathring{A}$
$\delta\lambda/\lambda \approx 0.02$

2 Neutron interferometer

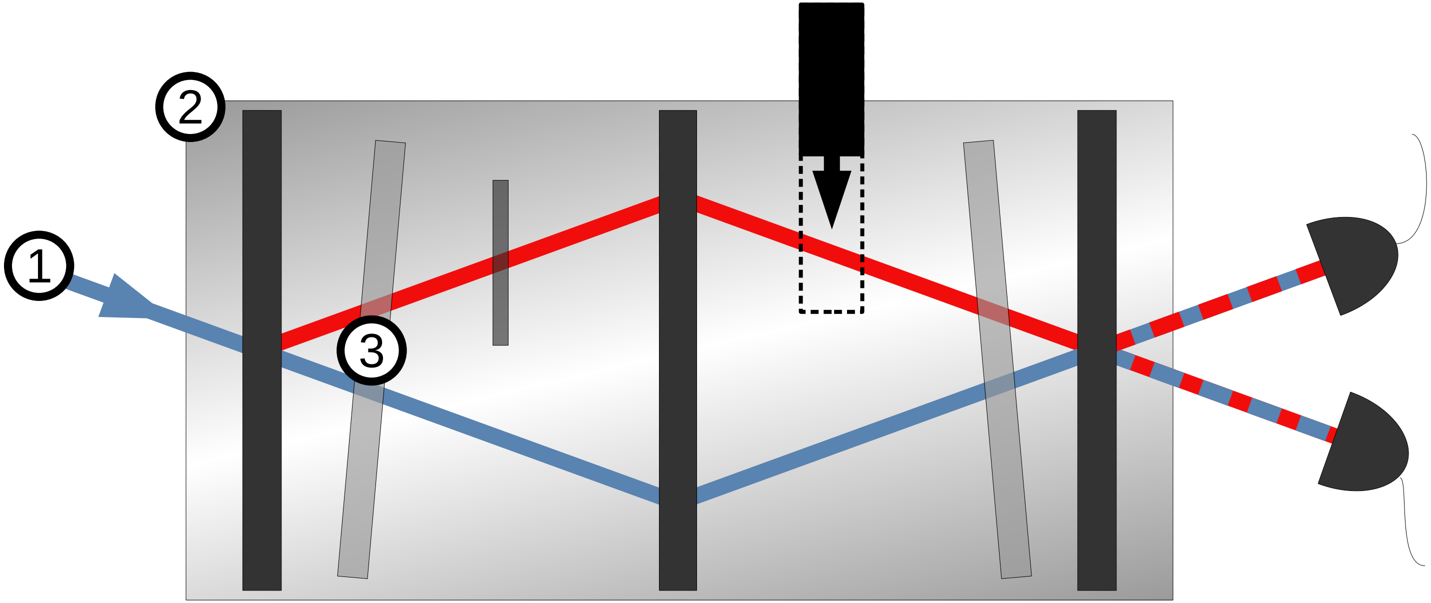


Setup

1 Unpolarised neutron beam
$\lambda = 1.92\AA$
$\delta\lambda/\lambda \approx 0.02$

2 Neutron interferometer

3 Phase-shifter
χ



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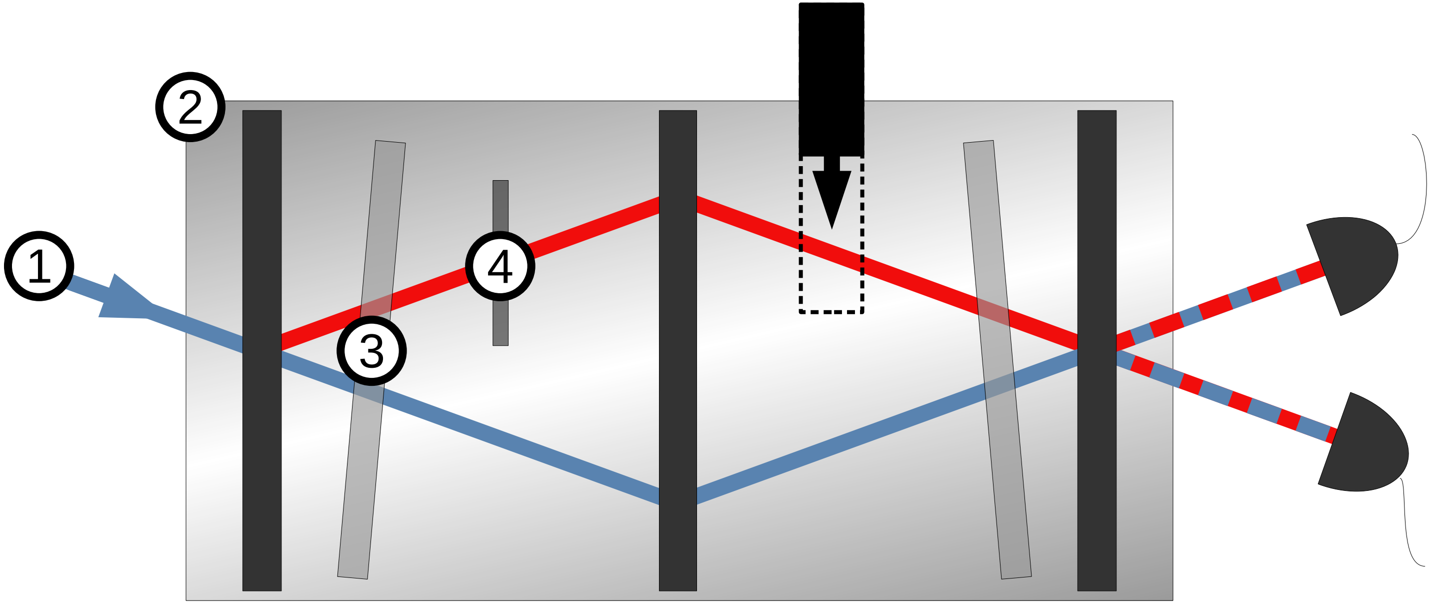
Setup

1 Unpolarised neutron beam
$\lambda = 1.92 Å$
$\delta\lambda/\lambda \approx 0.02$

2 Neutron interferometer

3 Phase-shifter
χ

4 Indium foils to adjust path amplitudes
$a_2/a_1 \approx 0.59$



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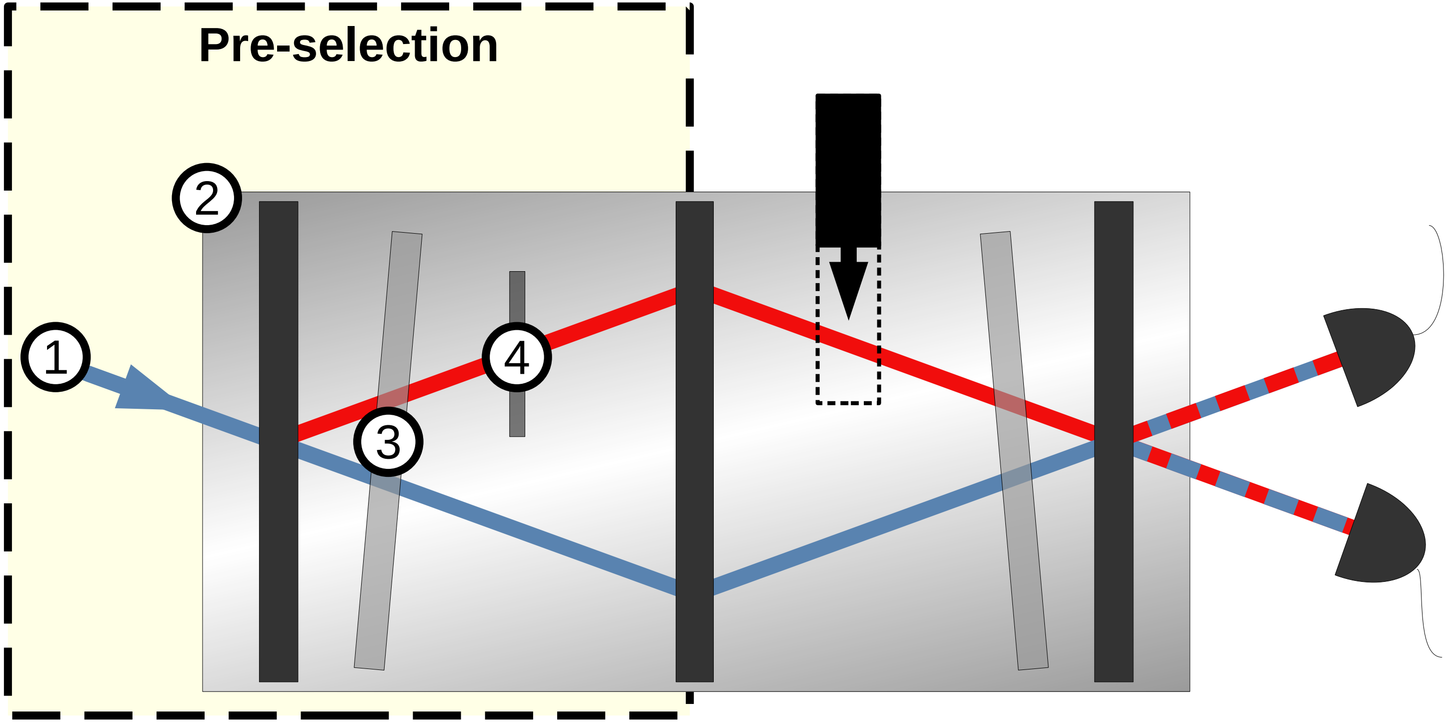
Setup

1. Unpolarised neutron beam
   $\lambda = 1.92 \mathring{A}$
   $\delta\lambda/\lambda \approx 0.02$
2. Neutron interferometer
3. Phase-shifter
   χ
4. Indium foils to adjust path amplitudes
   $a_2/a_1 \approx 0.59$



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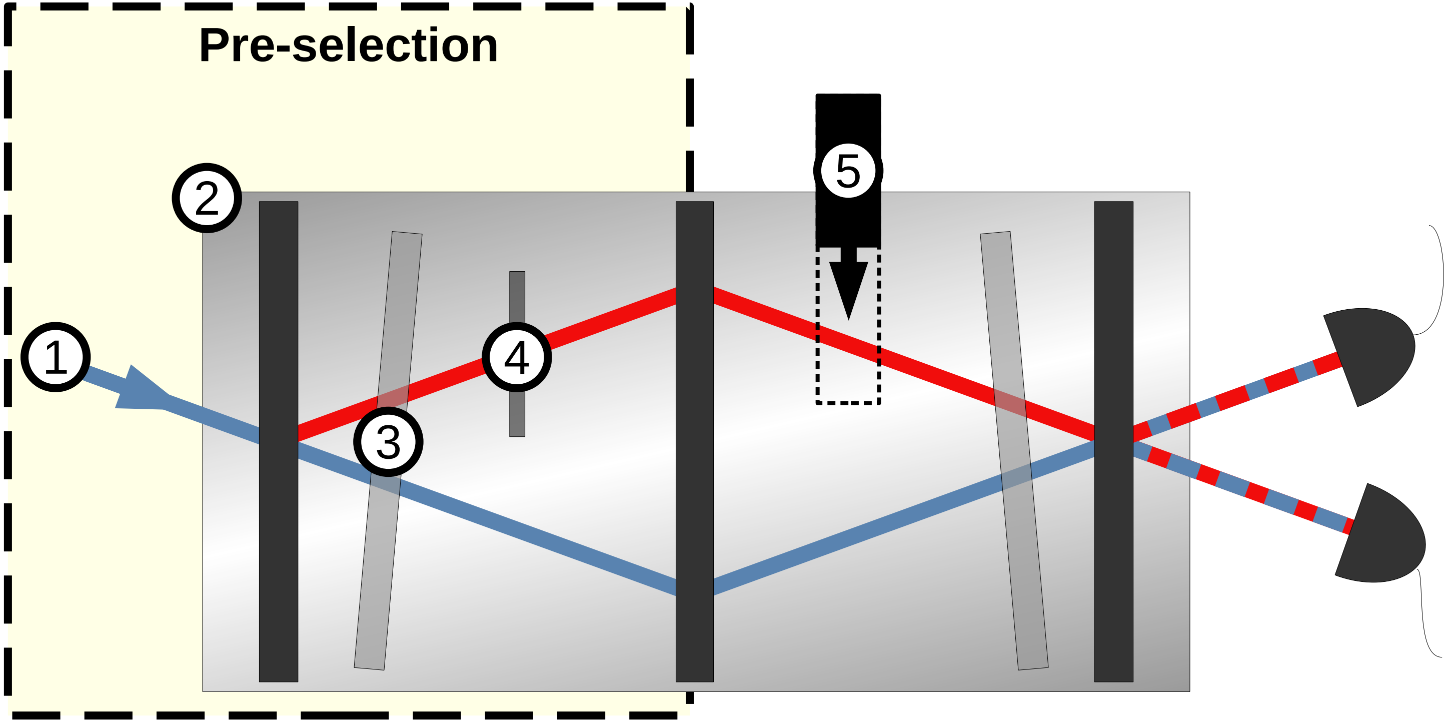
Setup

1 Unpolarised neutron beam
$\lambda = 1.92\text{Å}$
$\delta\lambda/\lambda \approx 0.02$

2 Neutron interferometer

3 Phase-shifter
χ

4 Indium foils to adjust path amplitudes
$a_2/a_1 \approx 0.59$



5 Cadmium path blocker

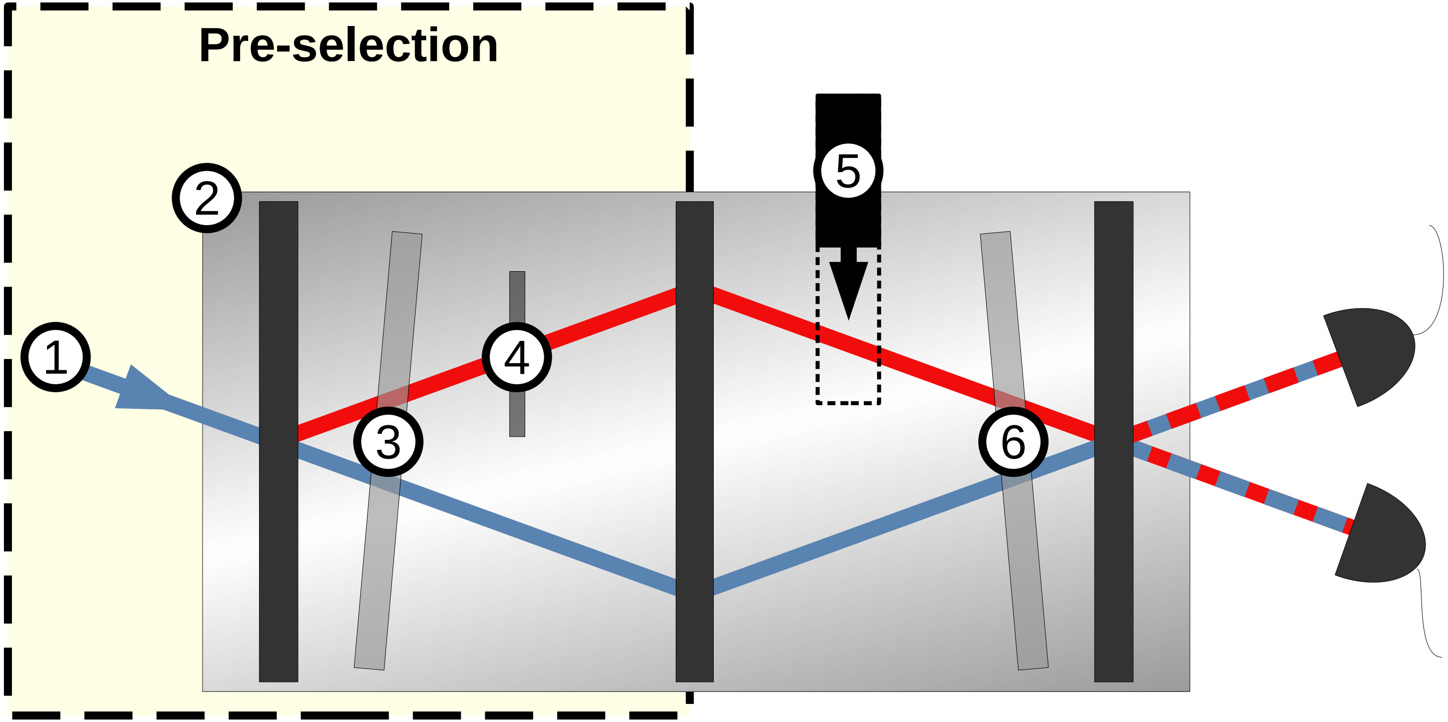
Setup

1 Unpolarised neutron beam
$\lambda = 1.92 \mathring{A}$
$\delta\lambda/\lambda \approx 0.02$

2 Neutron interferometer

3 Phase-shifter
χ

4 Indium foils to adjust path amplitudes
$a_2/a_1 \approx 0.59$



5 Cadmium path blocker

6 Phase-shifter
χ_0

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Setup

1 Unpolarised neutron beam
$\lambda = 1.92 \AA$
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2 Neutron interferometer

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χ

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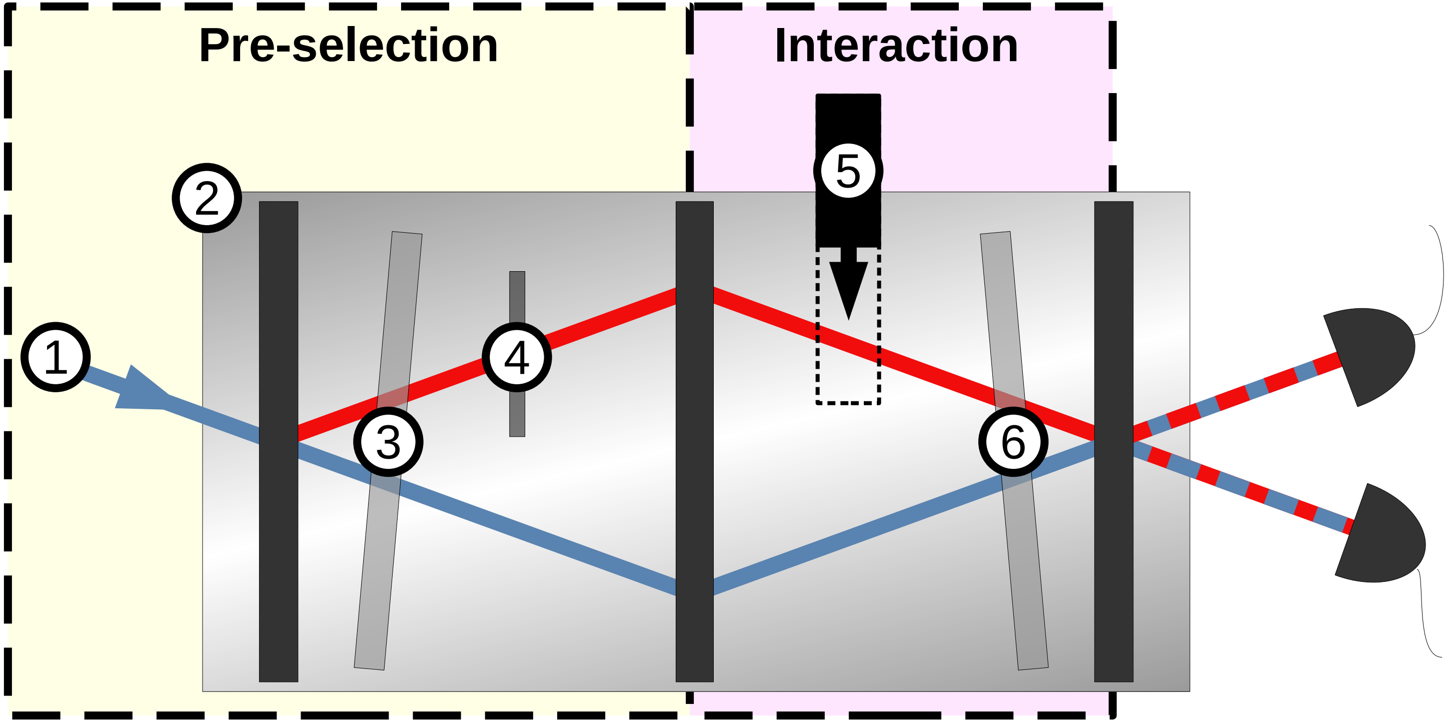

5 Cadmium path blocker

6 Phase-shifter
χ_0

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Setup

1 Unpolarised neutron beam
$\lambda = 1.92\text{Å}$
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3 Phase-shifter
χ

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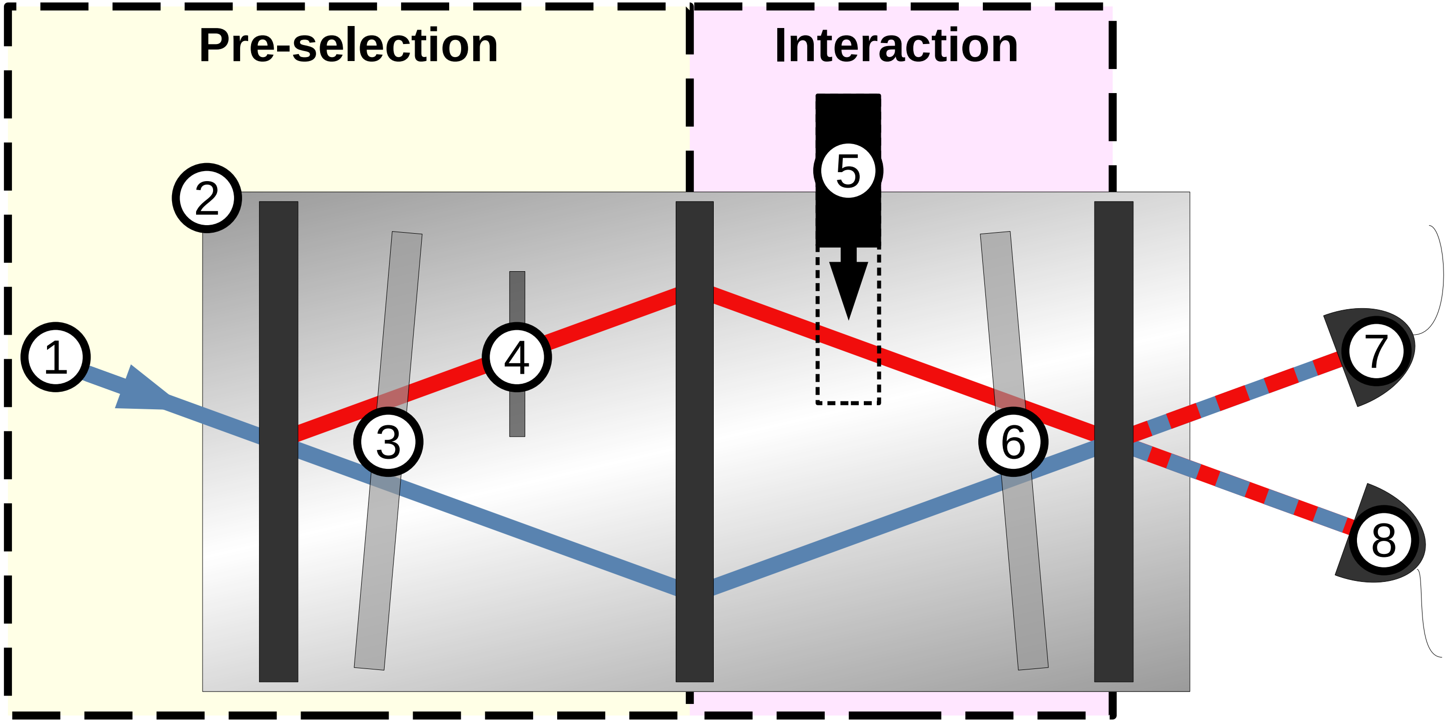


5 Cadmium path blocker

6 Phase-shifter
χ_0

8 $|+\rangle$-detector

7 $|-\rangle$-detector

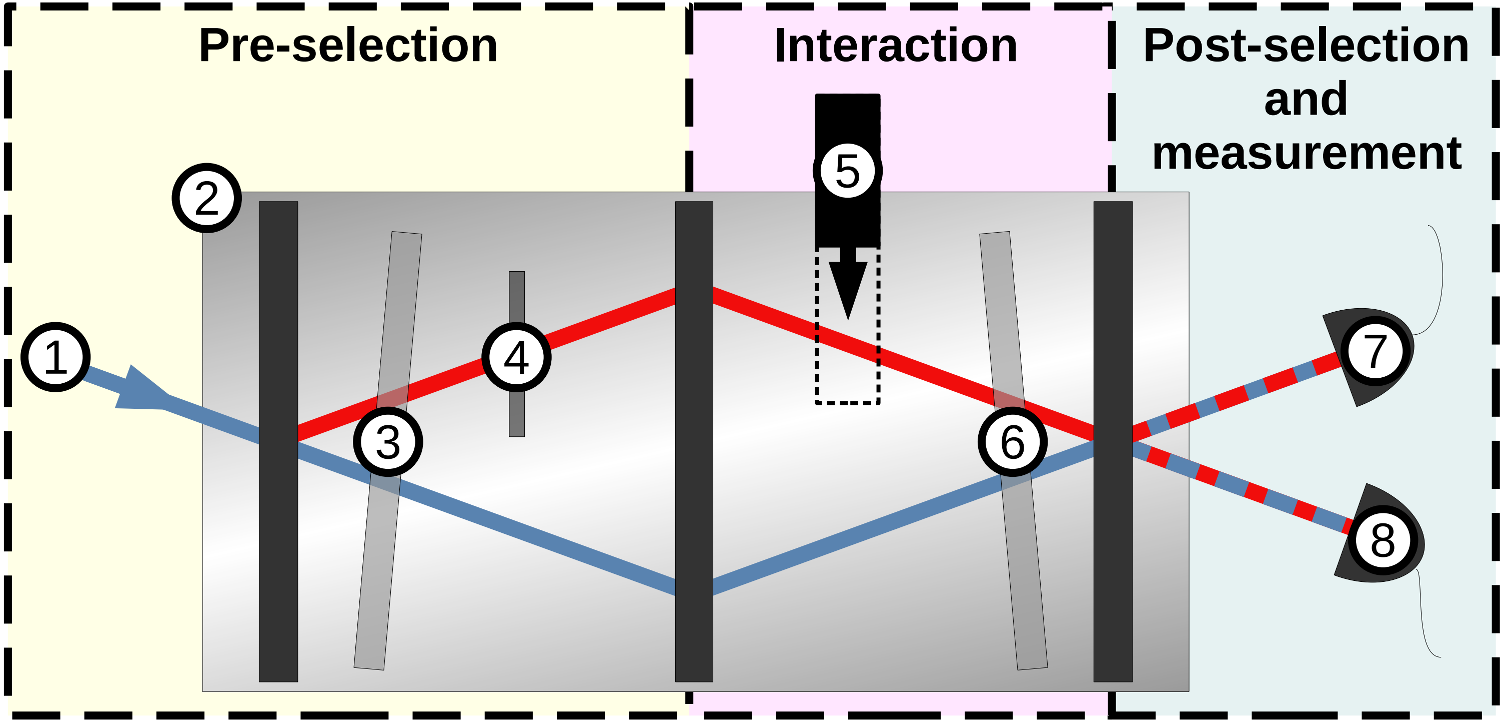
Setup

1 Unpolarised neutron beam
$\lambda = 1.92\text{Å}$
$\delta\lambda/\lambda \approx 0.02$

2 Neutron interferometer

3 Phase-shifter
χ

4 Indium foils to adjust path amplitudes
$a_2/a_1 \approx 0.59$



5 Cadmium path blocker

6 Phase-shifter
χ_0

8 $|+\rangle$-detector

7 $|-\rangle$-detector

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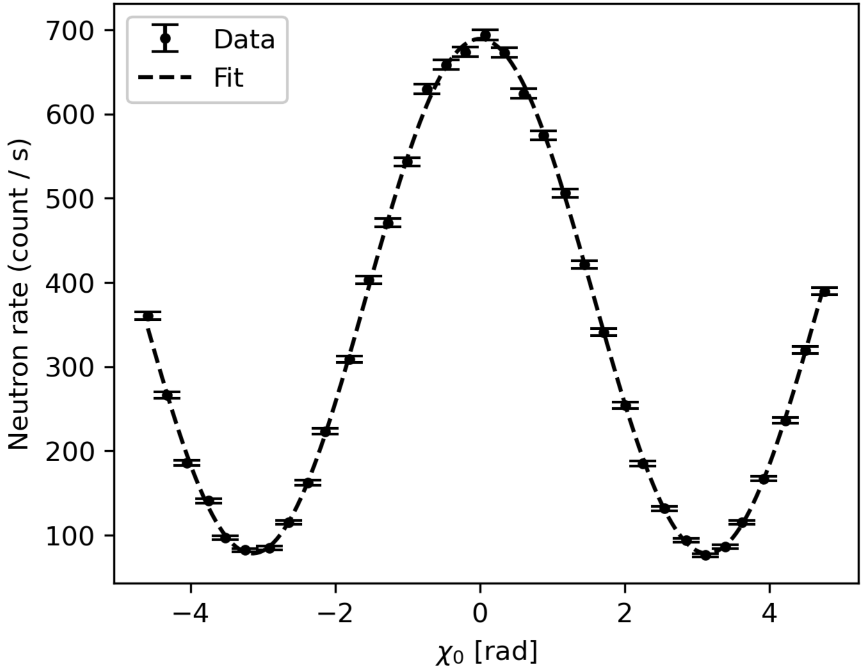
Example of interferogram



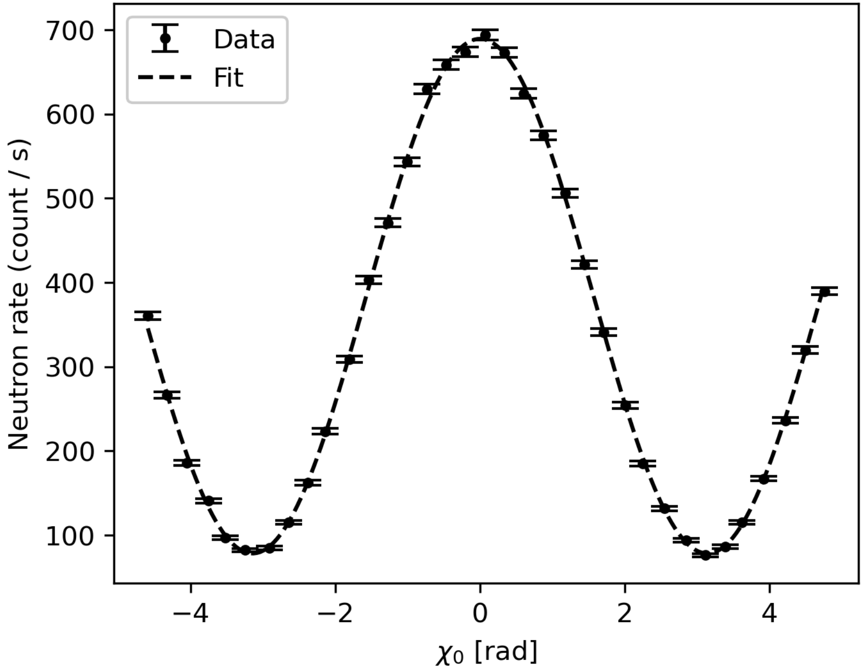
Example of interferogram

Real part

$$-\frac{I_{\pm}(\chi,\pi)-I_{\pm}(\chi,0)}{4I_{\pm}(\chi,0)}+|w_{\pm,1}|^2=w^{\Re}_{\pm,1}$$

Imaginary part

$$\frac{I_{\pm}(\chi,\frac{\pi}{2})-I_{\pm}(\chi,\frac{3\pi}{2})}{4I_{\pm}(\chi,0)}=w^{\Im}_{\pm,1}$$



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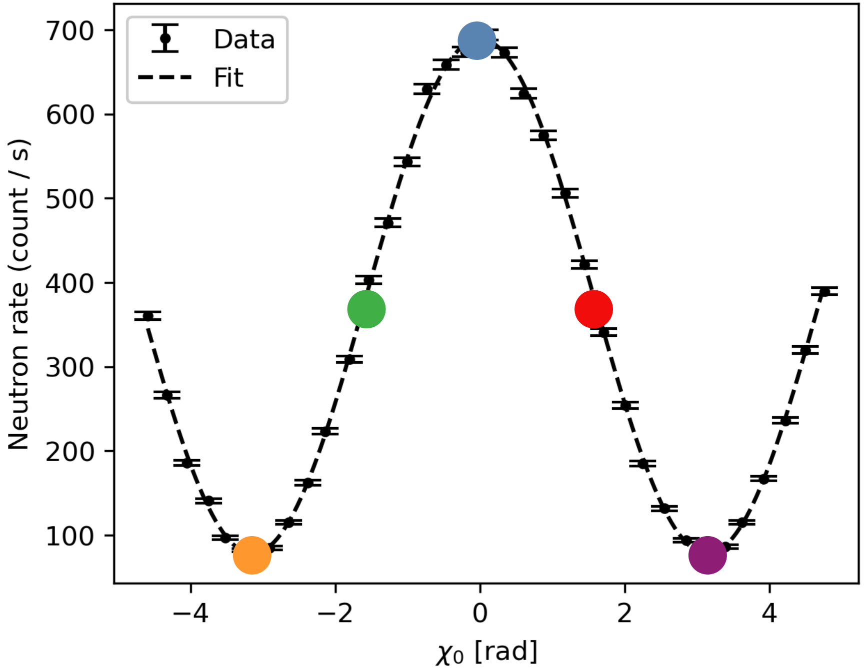
Example of interferogram

Real part

$$-\frac{\boxed{I_\pm(\chi,\pi)} - \boxed{I_\pm(\chi,0)}}{4\boxed{I_\pm(\chi,0)}} + |w_{\pm,1}|^2 = w^{\Re}_{\pm,1}$$

Imaginary part

$$\frac{\boxed{I_\pm(\chi,\frac{\pi}{2})} - \boxed{I_\pm(\chi,\frac{3\pi}{2})}}{4\boxed{I_\pm(\chi,0)}} = w^{\Im}_{\pm,1}$$



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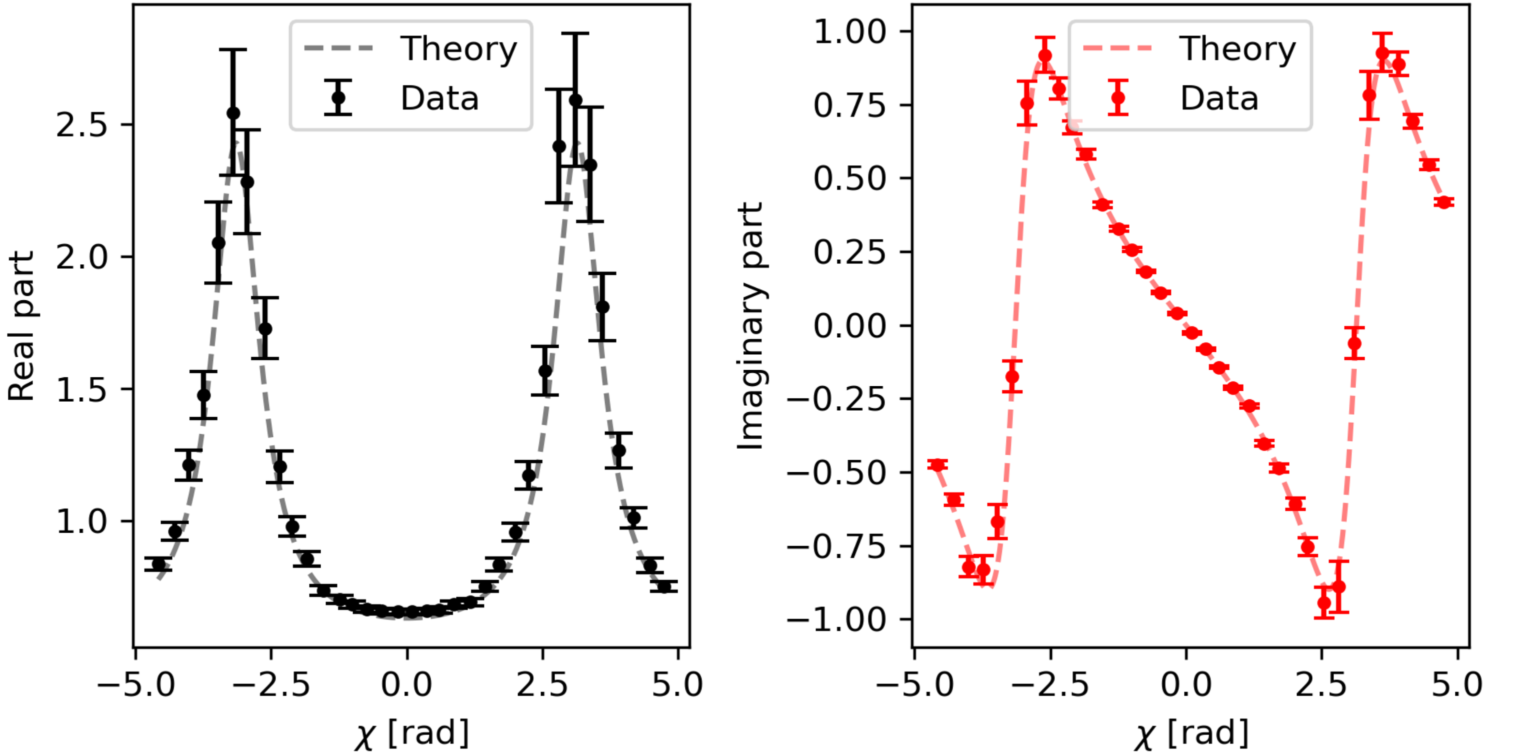
Results: Weak value of path 1



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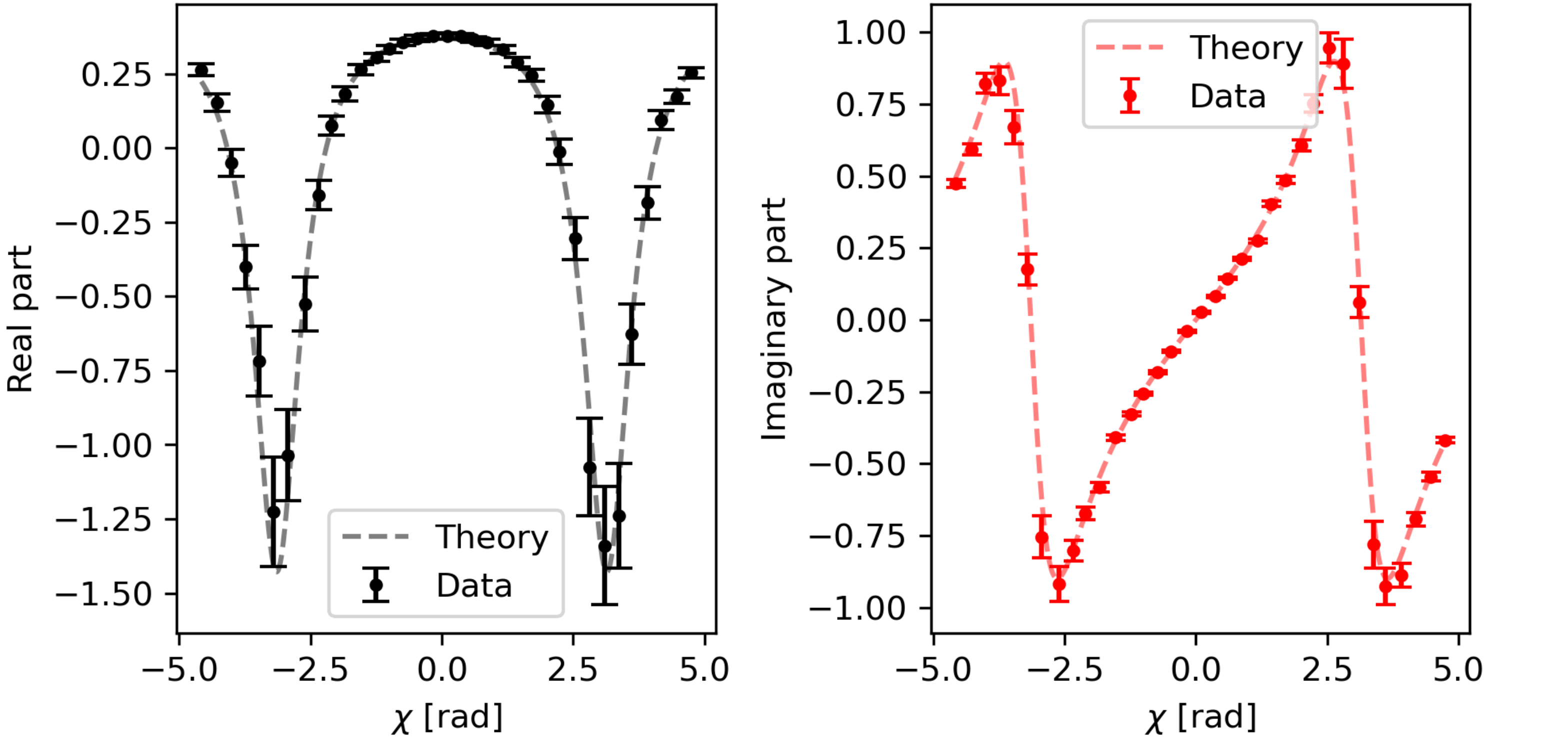
Results: Weak value of path 2



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Interpretation of the results

Interpretation of the results

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General idea

Weak values are related to different fundamental aspects of quantum mechanics, such as:

- Observables in the limit of minimum disturbance
- Negative quasi-probability distributions (quantumness)
- Uncertainty relations
- And more…

General idea

Now we have a direct link to **interferometry and the which way information**.

General idea

Now we have a direct link to **interferometry and the which way information**.

Can we put everything together in a more general picture and maybe understand something new?

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General idea

Now we have a direct link to **interferometry and the which way information**.

Can we put everything together in a more general picture and maybe understand something new?

How is the which way information changing throughout an interferogram?

General idea

Now we have a direct link to **interferometry and the which way information**.

Can we put everything together in a more general picture and maybe understand something new?

How is the which way information changing throughout an interferogram?

Is asking questions a good way to finish a presentation?

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Aknowledgements

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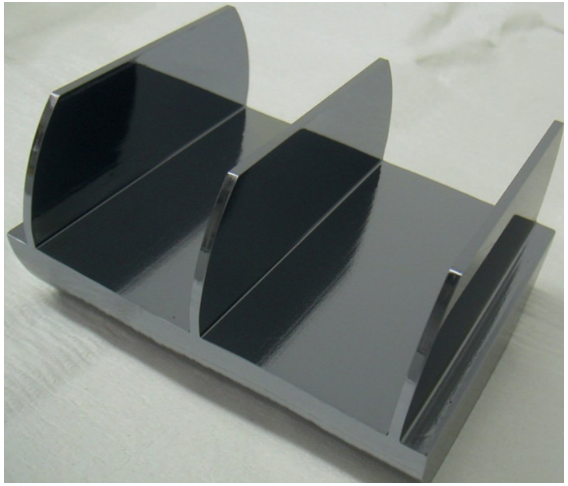
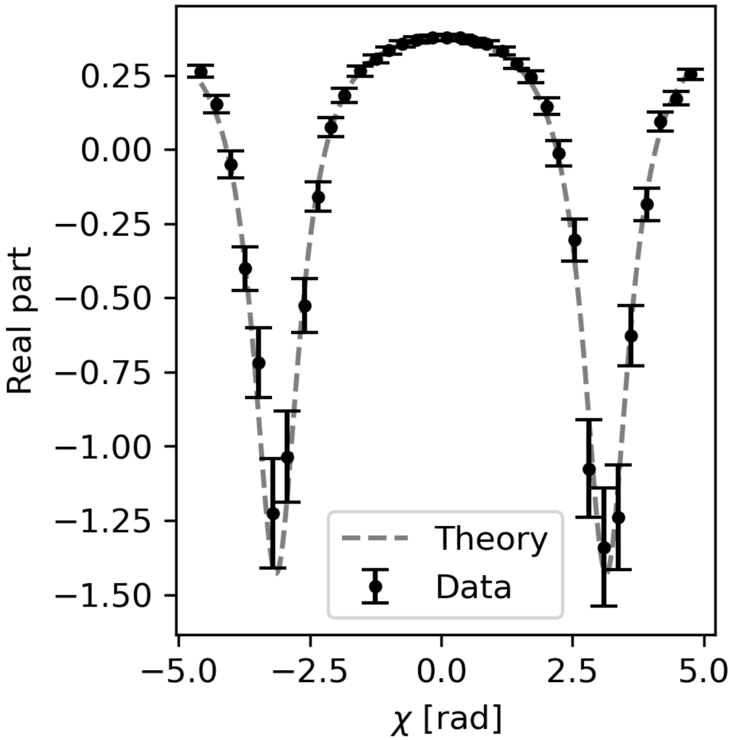
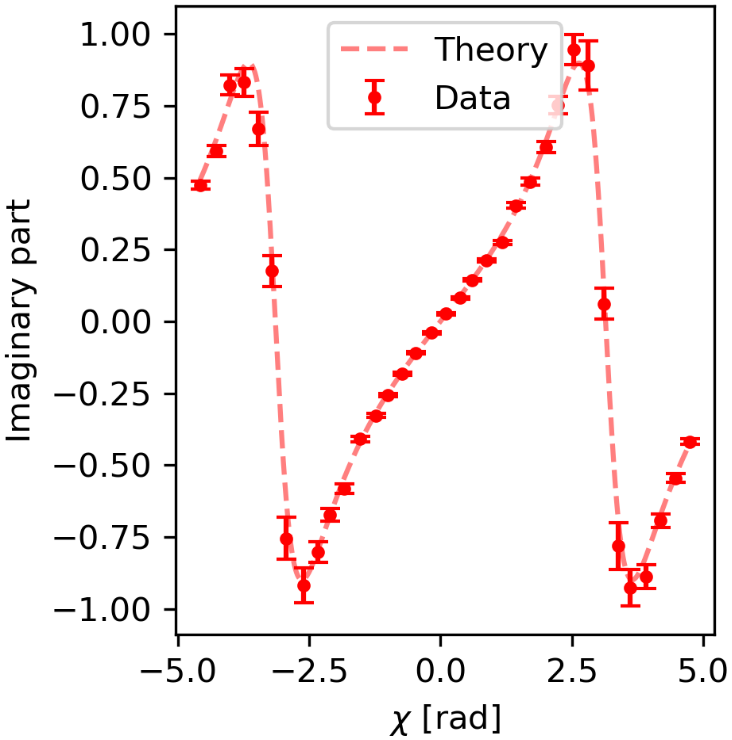
Thanks for your time!







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