

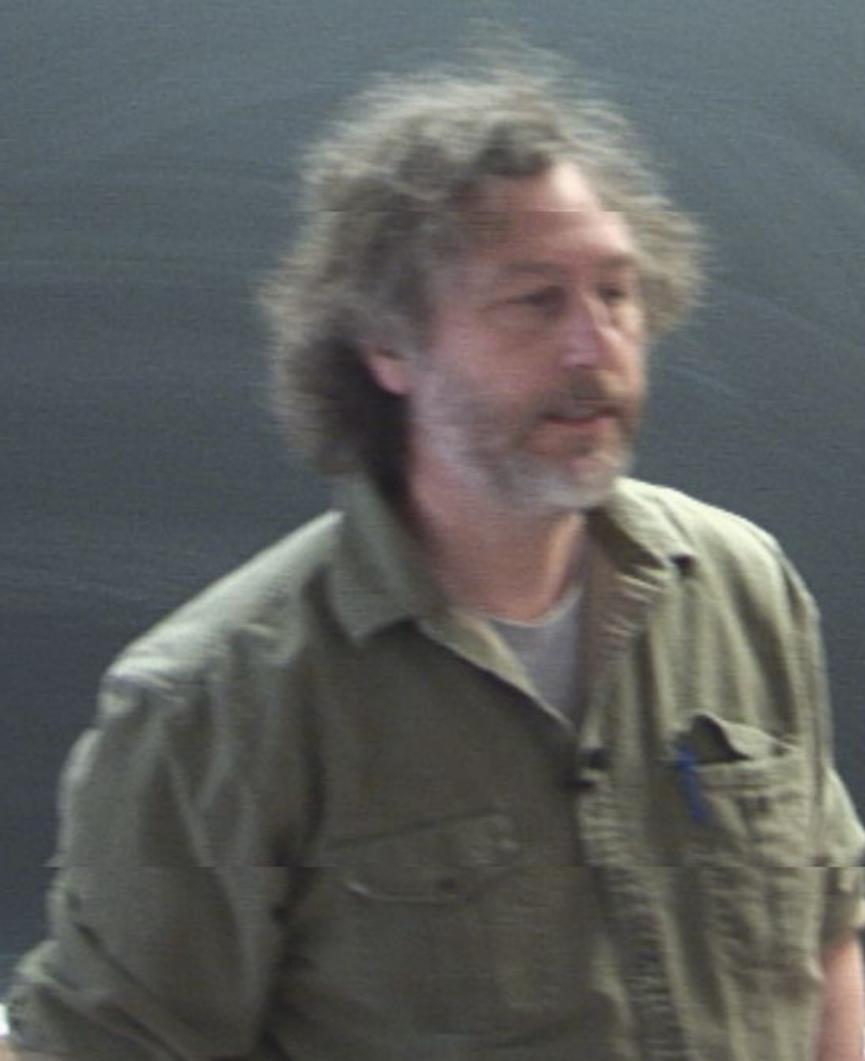
Title: Explorations in Quantum Info. (PHYS 641) - Lecture 1

Date: Feb 16, 2010 09:00 AM

URL: <http://pirsa.org/10020084>

Abstract:

Neutron Interferometry



Magnetic Resonance
nuclear

Magnetic Resonance
nuclear
electron

Magnetic Resonance
nuclear
electron
optics
P(FQ)

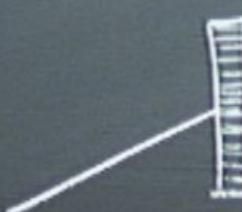
Magnetic Resonance
nuclear
electron
optics
P(FQ)

Neutron Interferometry

Rewritten

Neutron Interferometry

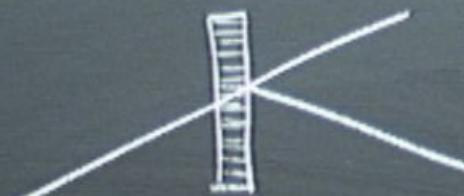
MZ



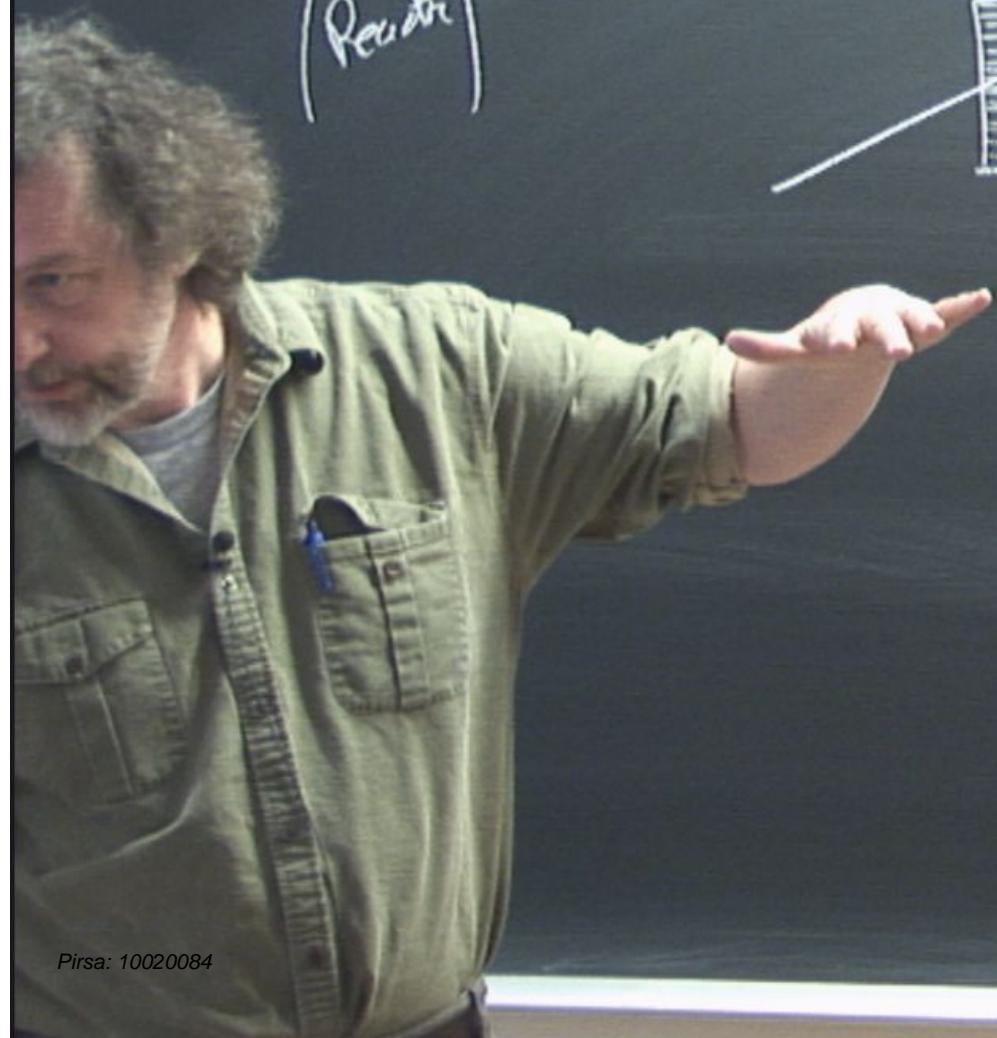
Neutron Interferometry

MZ

Bragg, Laue



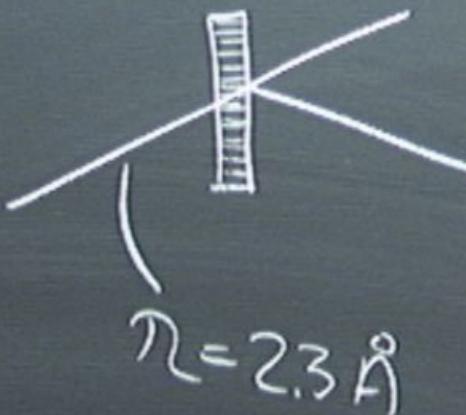
Reuter



Neutron Interferometry

MZ

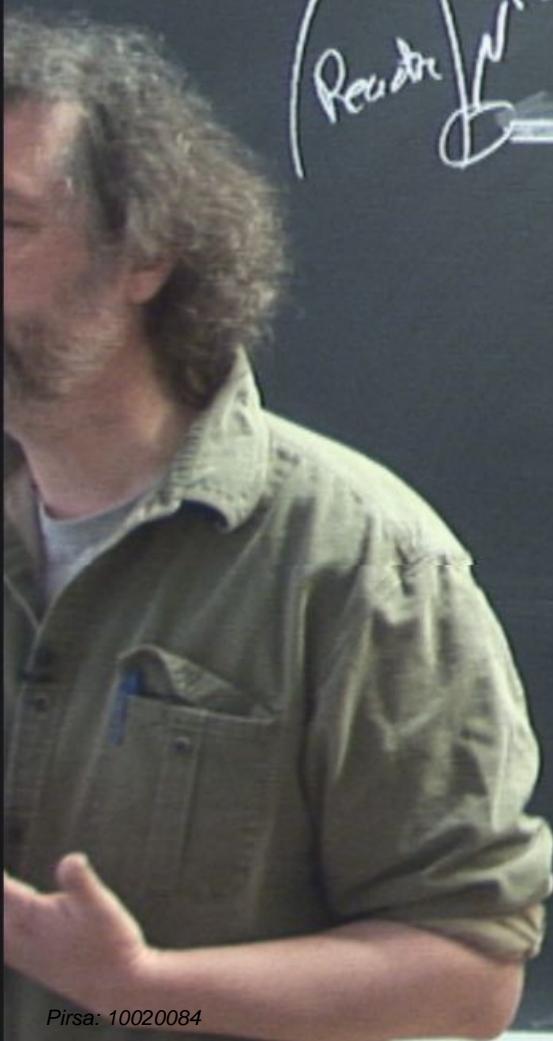
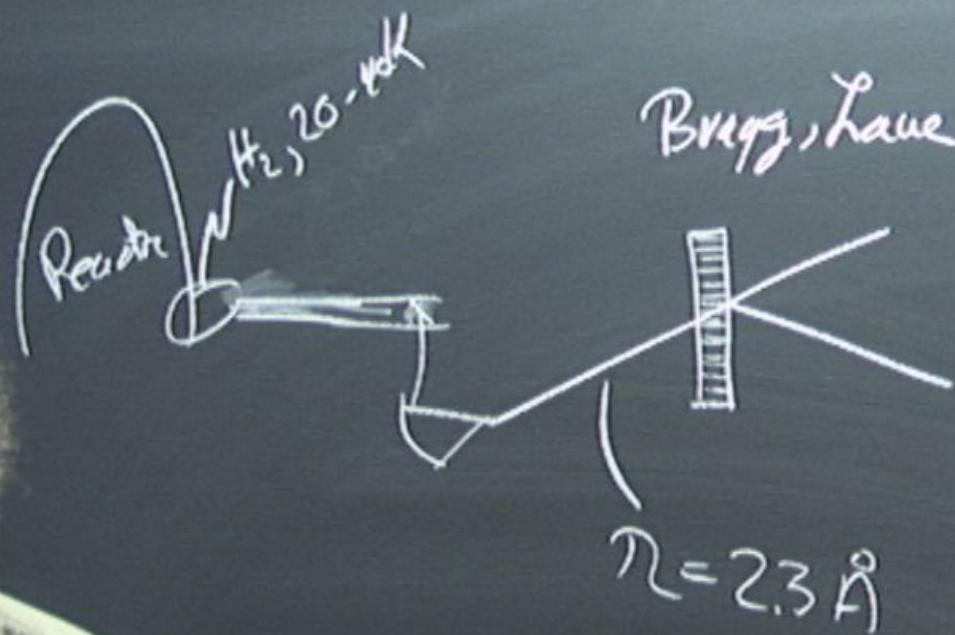
Bragg, Laue



Reuter

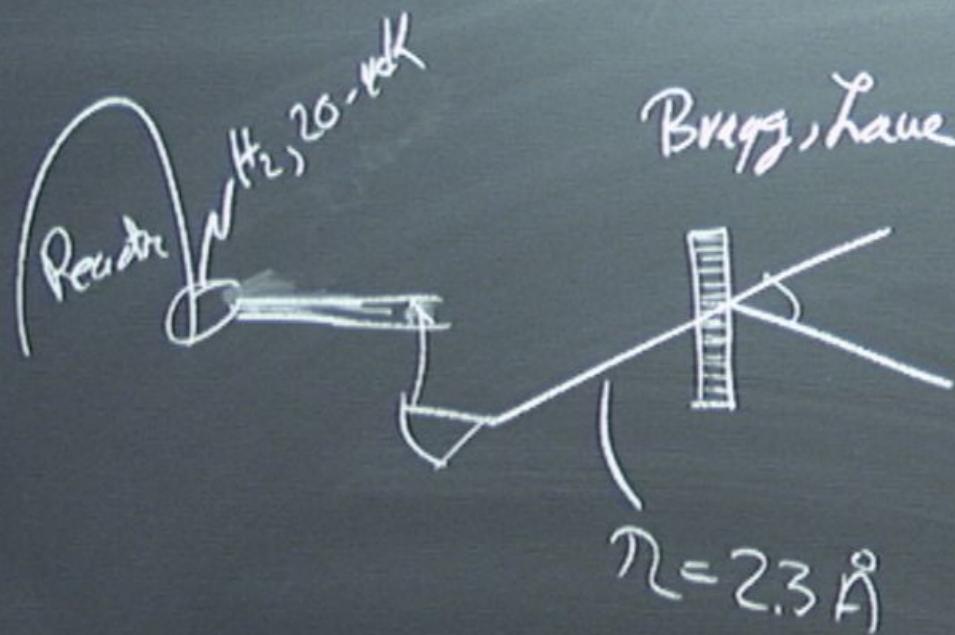
Neutron Interferometry

MZ



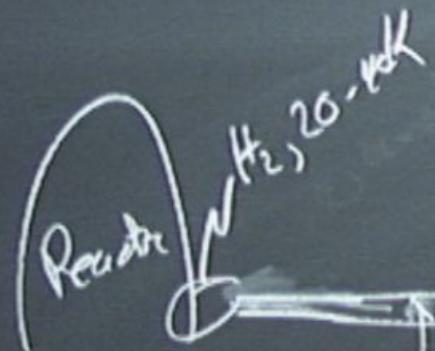
Neutron Interferometry

MZ

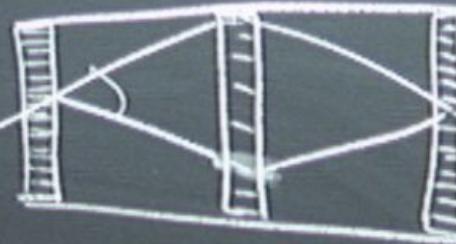


Neutron Interferometry

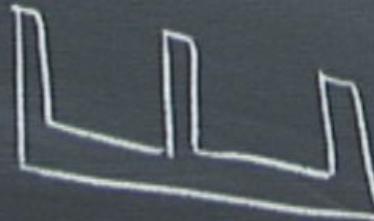
MZ



Bragg, Laue

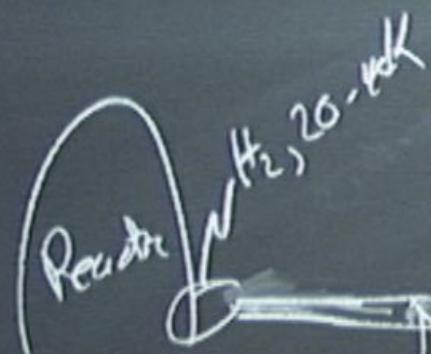


$$\lambda = 2.3 \text{ \AA}$$

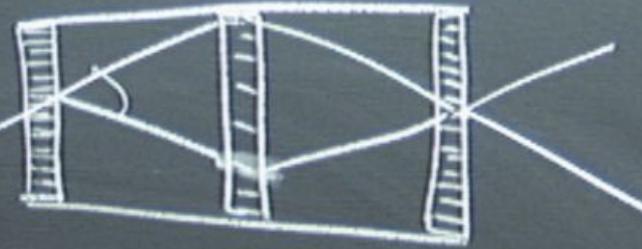


Neutron Interferometry

MZ

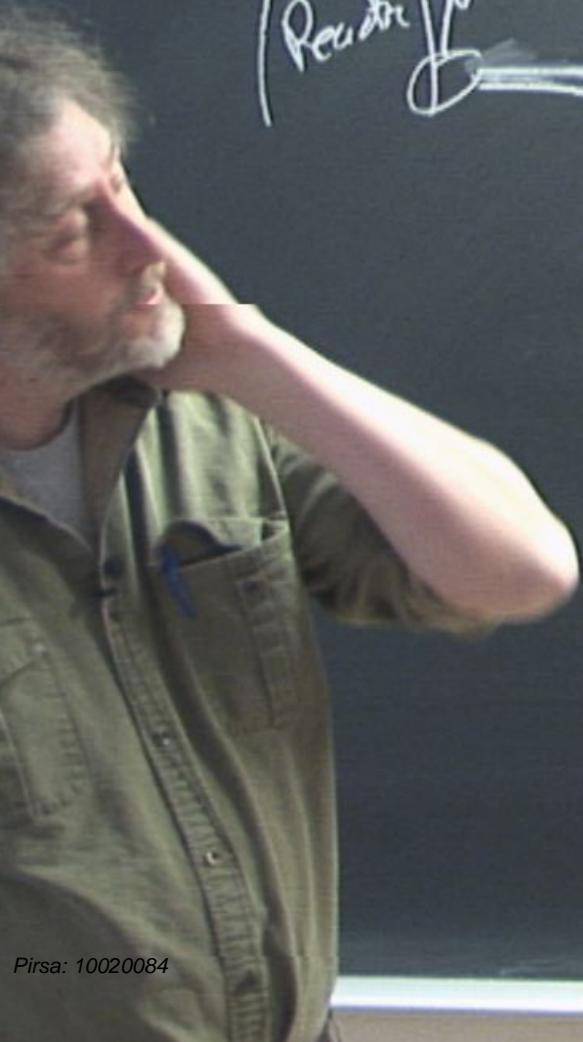
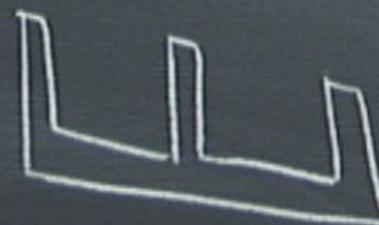


Bragg, Laue



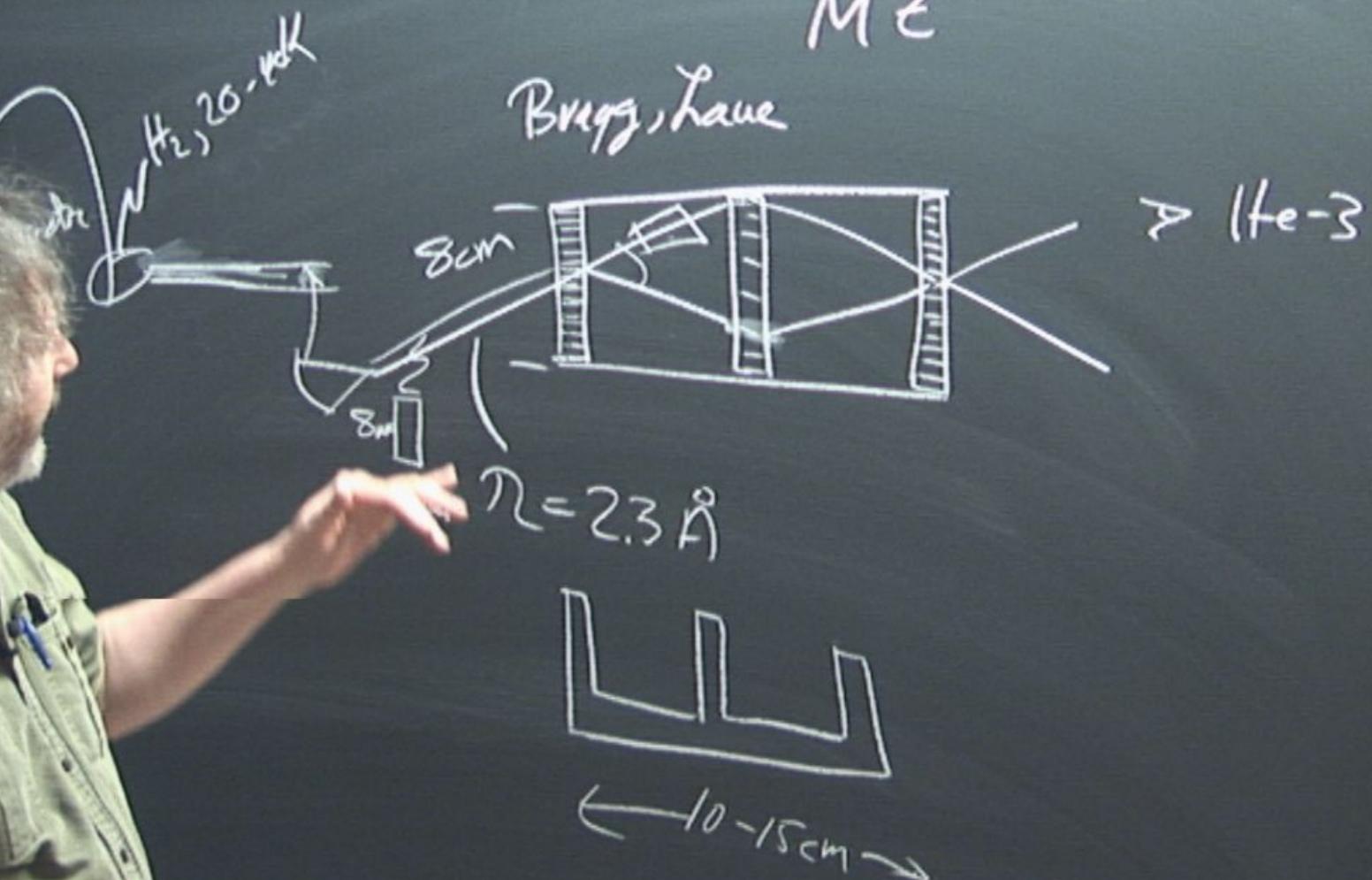
$\sigma_{\text{He-3}}$

$\lambda = 2.3 \text{ \AA}$



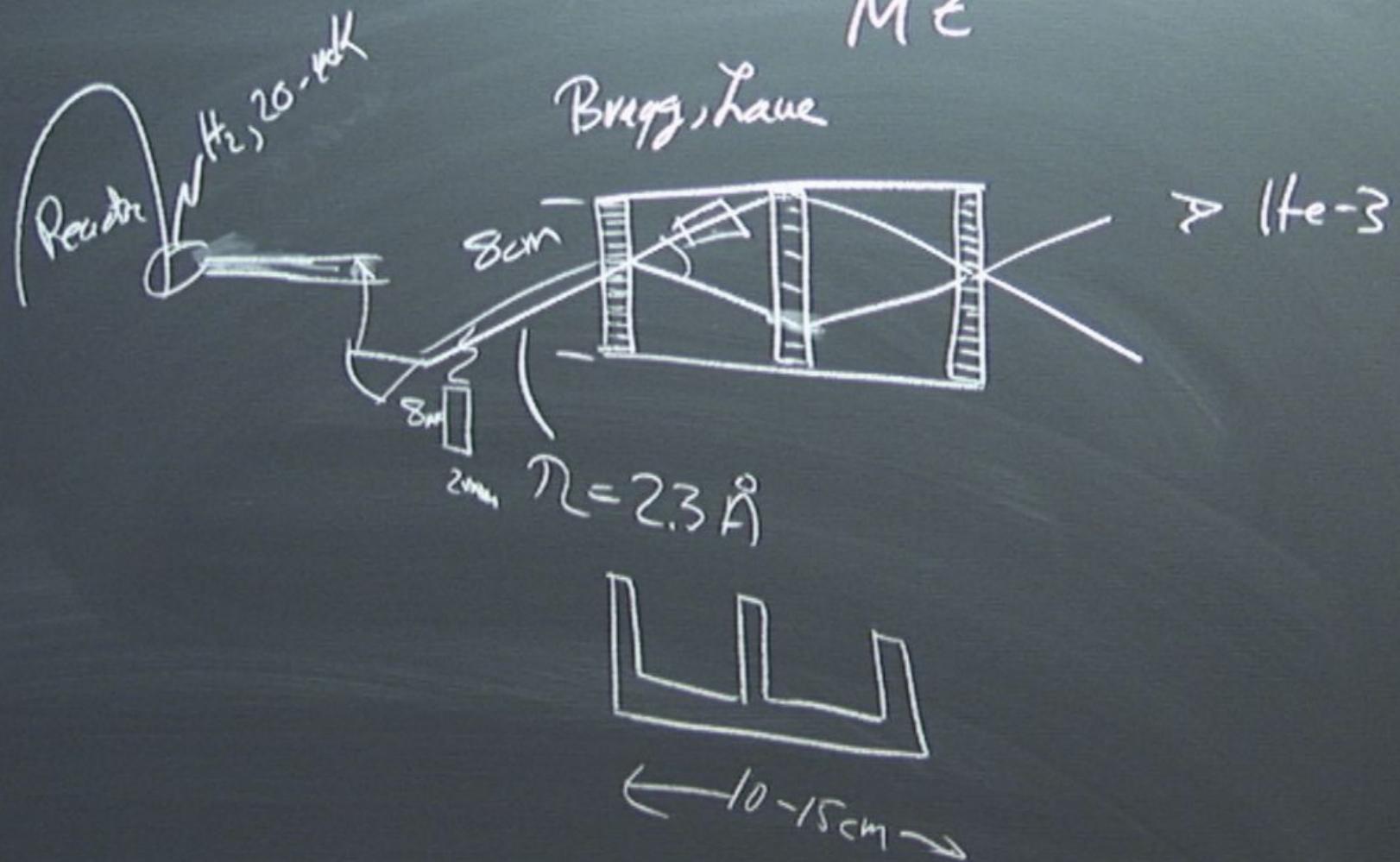
Neutron Interferometry

MZ



Neutron Interferometry

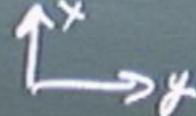
M2



Neutron Interferometry

M2

Bragg, Laue



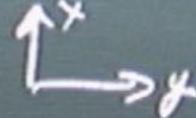
σ He-3



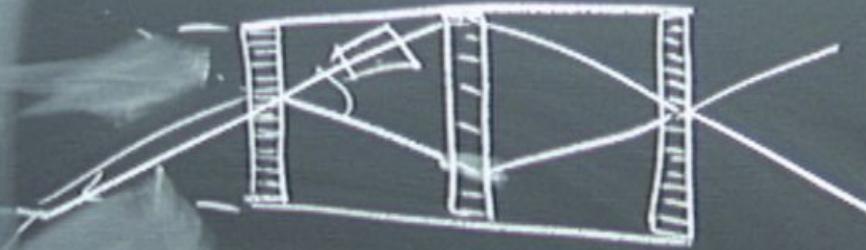
Neutron Interferometry

MZ

Bragg, Laue



σ (He-3)



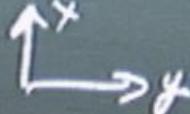
$$|0\rangle \in k_x \text{ positive}$$

$$|1\rangle \in k_x \text{ negative}$$

Neutron Interferometry

M2

Bragg, Laue



? He-3

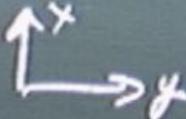
$$|0\rangle \in k_x \text{ positive}$$

$$|1\rangle \in k_x \text{ negative}$$

Neutron Interferometry

MZ

Bragg, Laue



$|0\rangle \langle 0|$

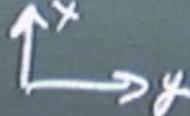
$|0\rangle \in k_x \text{ positive}$

$|1\rangle \in k_x \text{ negative}$

Neutron Interferometry

MZ

Bragg, Laue



σ (He-3)

$|0\rangle \langle 0|$

$$U = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$

$|0\rangle \in k_x \text{ positive}$

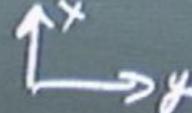
$|1\rangle \in k_x \text{ negative}$



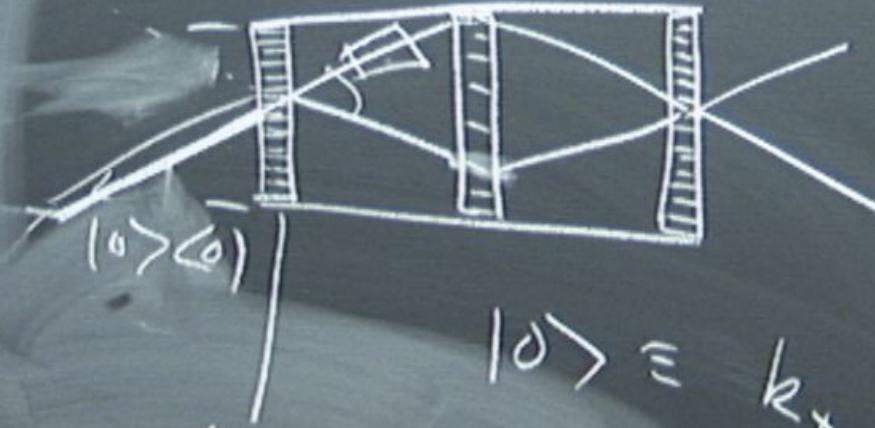
Neutron Interferometry

MZ

Bragg, Laue



$\geq \text{He-3}$



$$U_{\text{plate}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$

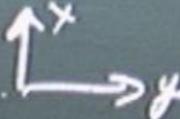
$|0\rangle \in k_x \text{ positive}$

$|1\rangle \in k_x \text{ negative}$

Neutron Interferometry

MZ

Bragg, Laue



> He-3

$|0\rangle \langle 0|$

$$U_{\text{blade}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$

$$|0\rangle \equiv k_x \text{ pos. up}$$

$$|1\rangle \equiv k_x \text{ neg. up}$$

$$U_0 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$

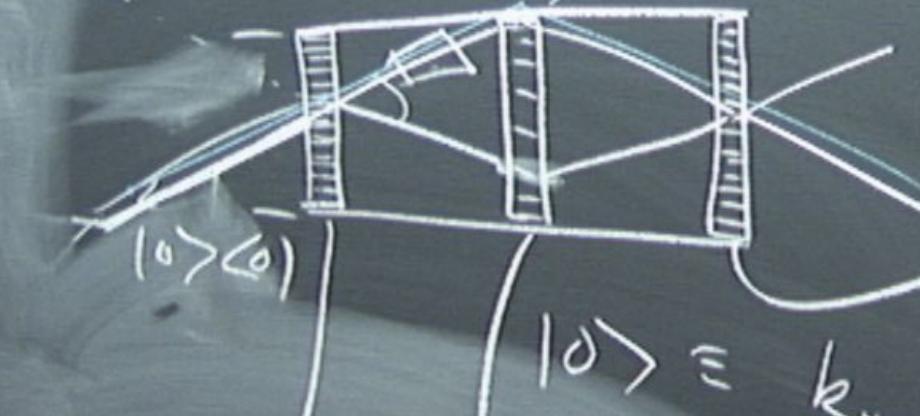
Neutron Interferometry

MZ

Bragg, Laue



σ He-3



$$u_{\text{blade}} = \frac{1}{\sqrt{2}}$$

k_x positive

$$u_{\text{blade}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \\ -1 \\ 1 \end{pmatrix}$$

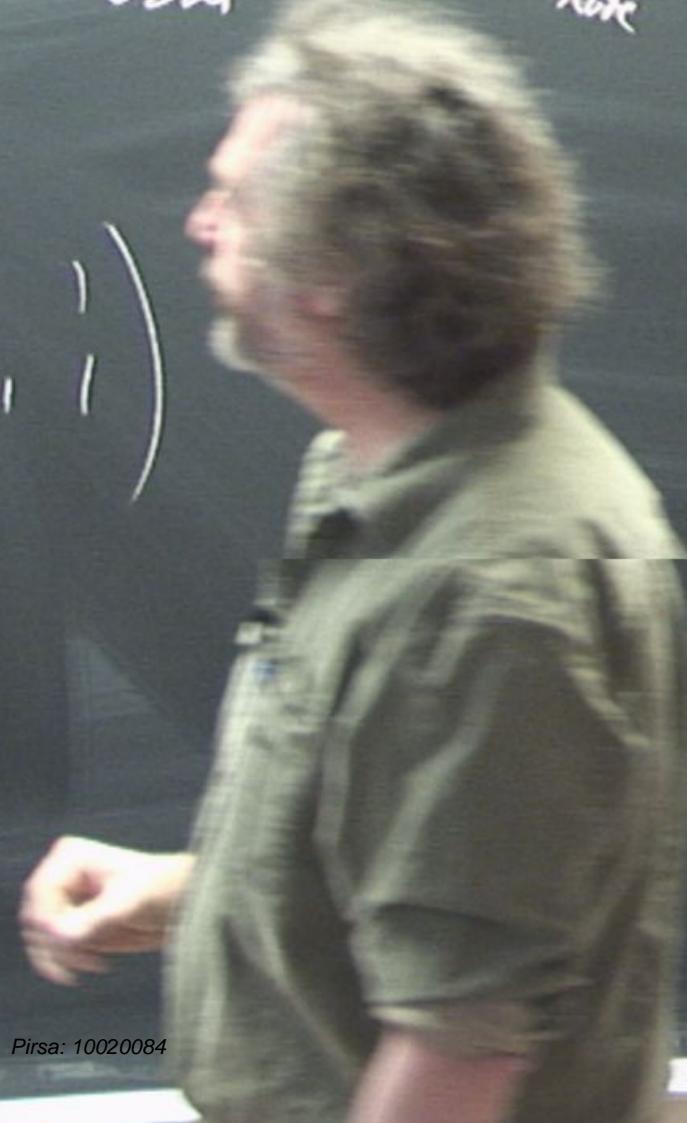
$$|10\rangle \equiv \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

k_x negative

$$u_n = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

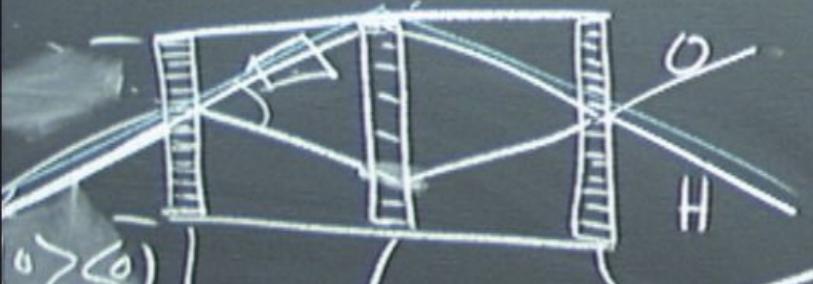
$$\begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$

$$S_{out} = U_{blue} U_{red} U_{blue} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} U_{blue}^{-1} U_{red}^{-1} U_{blue}^{-1}$$



Neutron Interferometry

MZ
Bragg, Laue



$$S \propto (He-3)$$

$$|0\rangle\langle 0|$$

$$|1\rangle = k_x \text{ positive}$$

$$\frac{1}{\sqrt{2}}(|1\rangle\langle 1| - |0\rangle\langle 0|)$$

$$|2\rangle = k_x \text{ negative}$$

$$U_0 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$

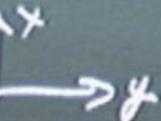
$$U_{\text{block}} = \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$

$$S_{\text{out}} = U_{\text{total}}$$

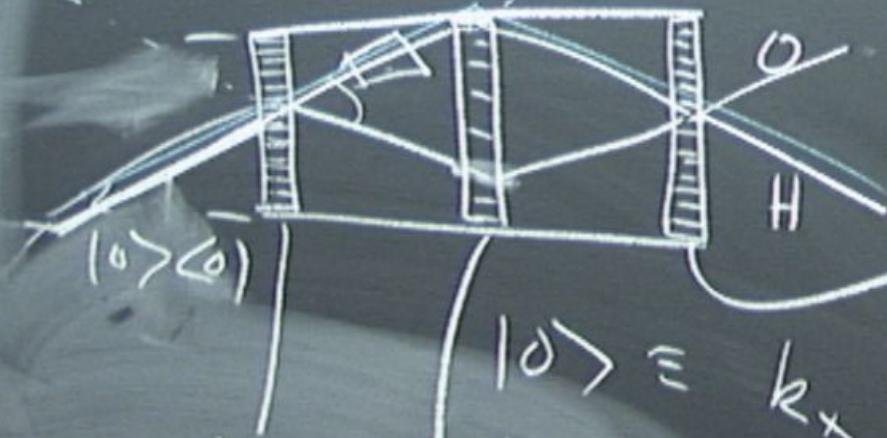
Neutron Interferometry

M2

Bragg, Laue



$\geq 1/\epsilon - 3$



$$U_{\text{blade}} = \frac{1}{\sqrt{2}}$$

$|0\rangle \in k_x \text{ positive}$

$$U_{\text{blade}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \quad \begin{pmatrix} |1\rangle \in k_x \text{ negative} \end{pmatrix}$$

$$U_0 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$

S_{out}

$$\begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$

Neutron Interferometry

MZ

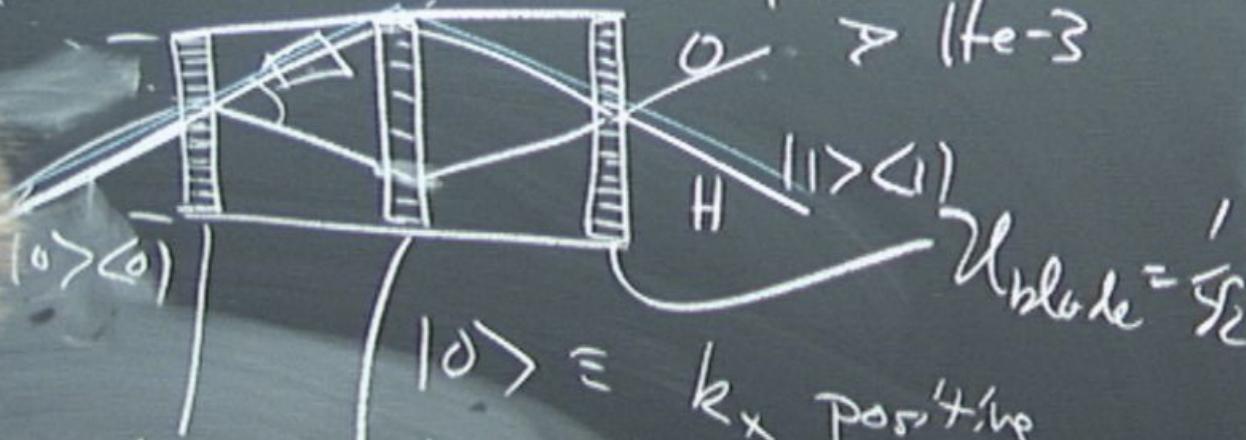
Bragg, Laue



$$|0\rangle < 0 |$$



$$|1\rangle \gtrsim 1 \text{ Fe-3}$$



$$U_{\text{blade}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$

$$|0\rangle \equiv k_x \text{ positive}$$

$$|1\rangle \equiv k_x \text{ negative}$$

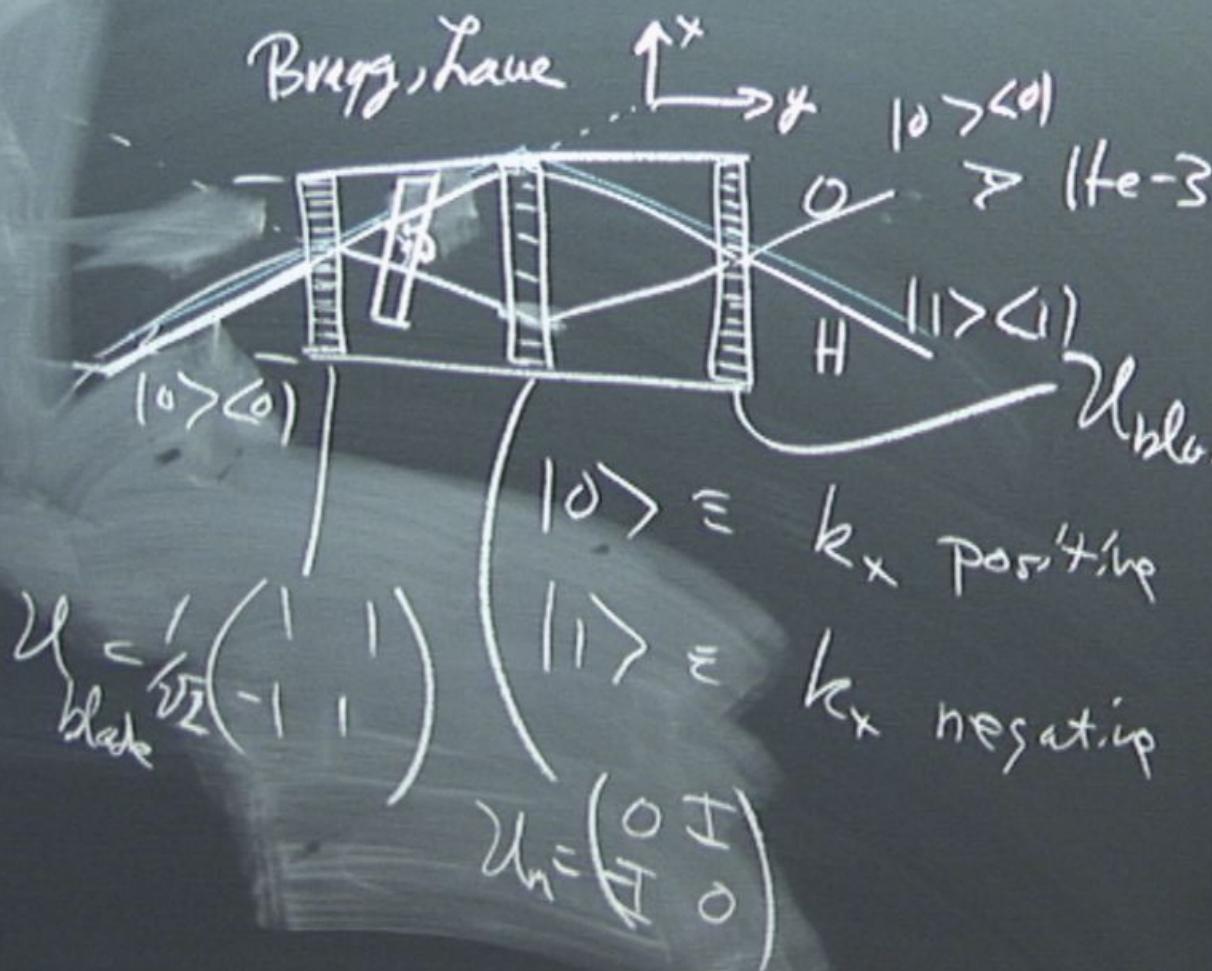
$$U_n = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$

S_{out}

$$\begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$

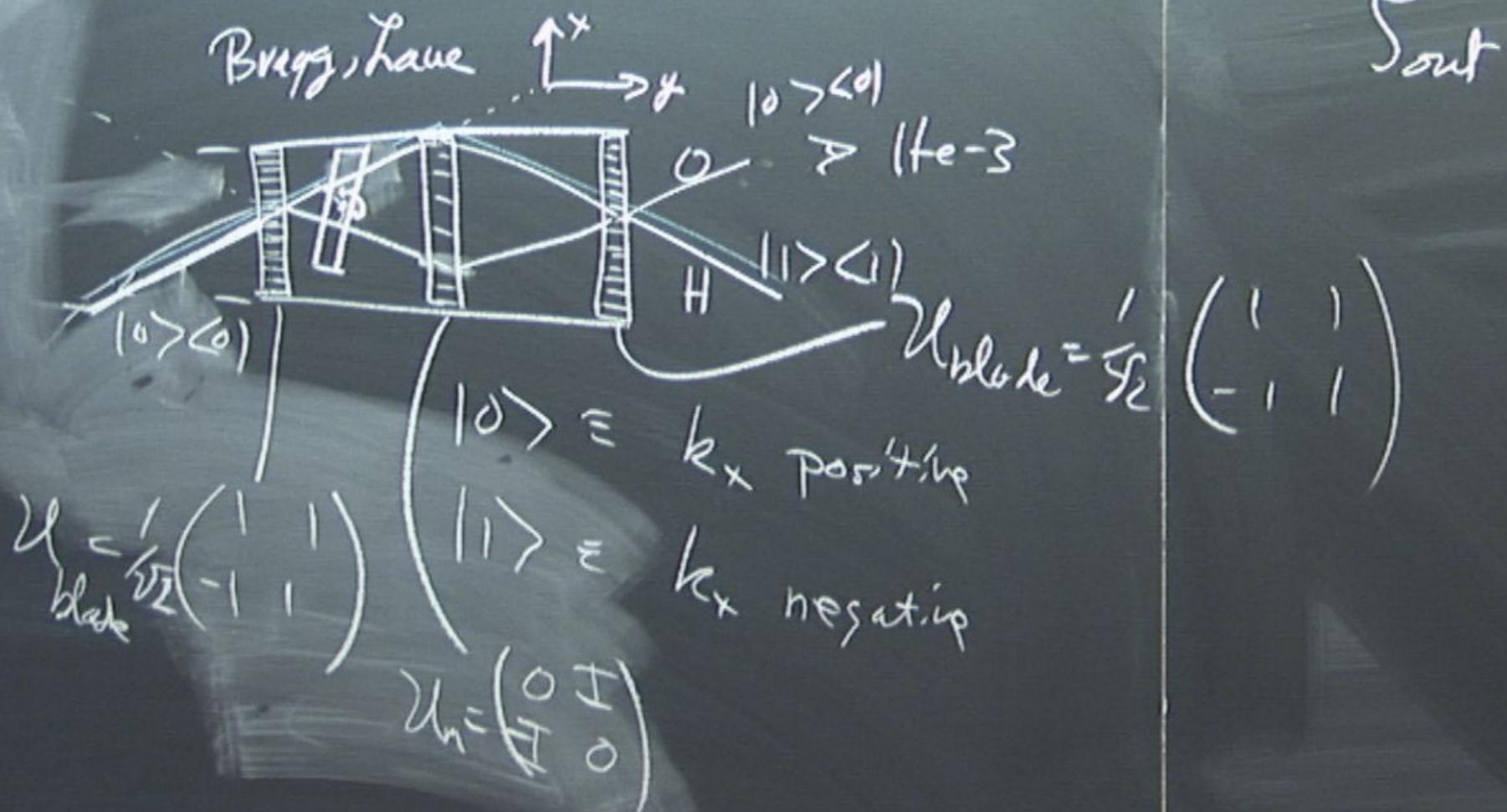
Neutron Interferometry

M2



Neutron Interferometry

M2

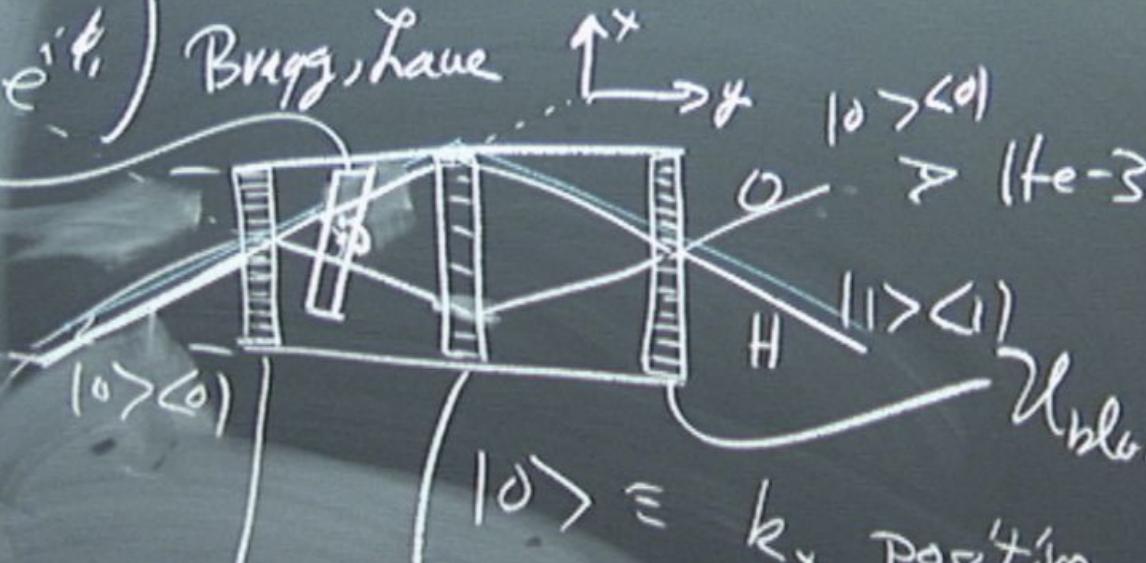


Neutron Interferometry

$$U_{\text{phase}} = \begin{pmatrix} e^{i\phi_0} & 0 \\ 0 & e^{i\phi_1} \end{pmatrix}$$

MZ

Bragg, Laue



$|10\rangle <01\rangle$

$\Sigma (\text{He-3})$

$|11\rangle <11\rangle$

$U_{\text{blade}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$

$\begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$

$|10\rangle \in k_x \text{ positive}$

$|11\rangle \in k_x \text{ negative}$

$$U_{\text{blade}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$

$$U_n = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$

Neutron Interferometry

MZ

$$U_{\text{phase}} = \begin{pmatrix} e^{i\phi_0} & 0 \\ 0 & e^{i\phi_1} \end{pmatrix}$$

Bragg, Laue

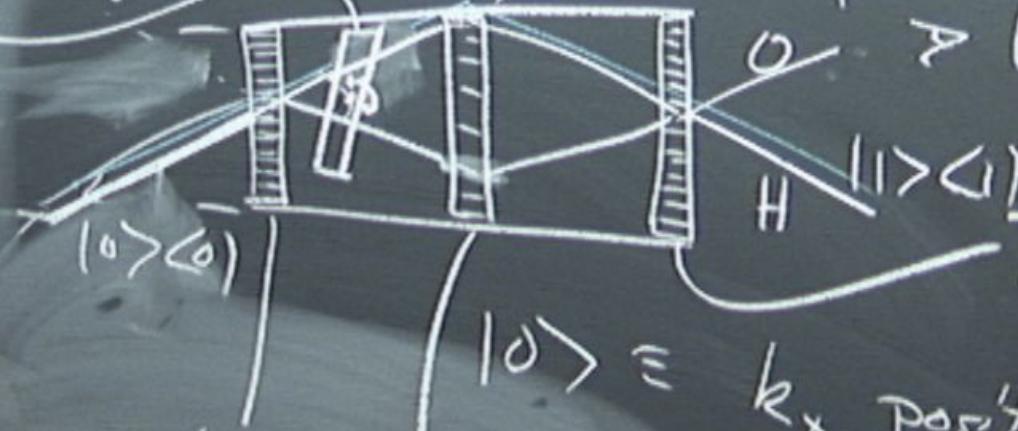
\uparrow^x

$|0\rangle\langle 0|$

$\sigma \approx 1/\epsilon - 3$

$$\nabla(r) = \sum b_c r^2 \delta(r)$$

$$\phi = -Nb_c \pi D$$



$$U_{\text{blade}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$

$|0\rangle \in k_x \text{ positive}$

$|1\rangle \in k_x \text{ negative}$

$$U_n = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$

Neutron Interferometry

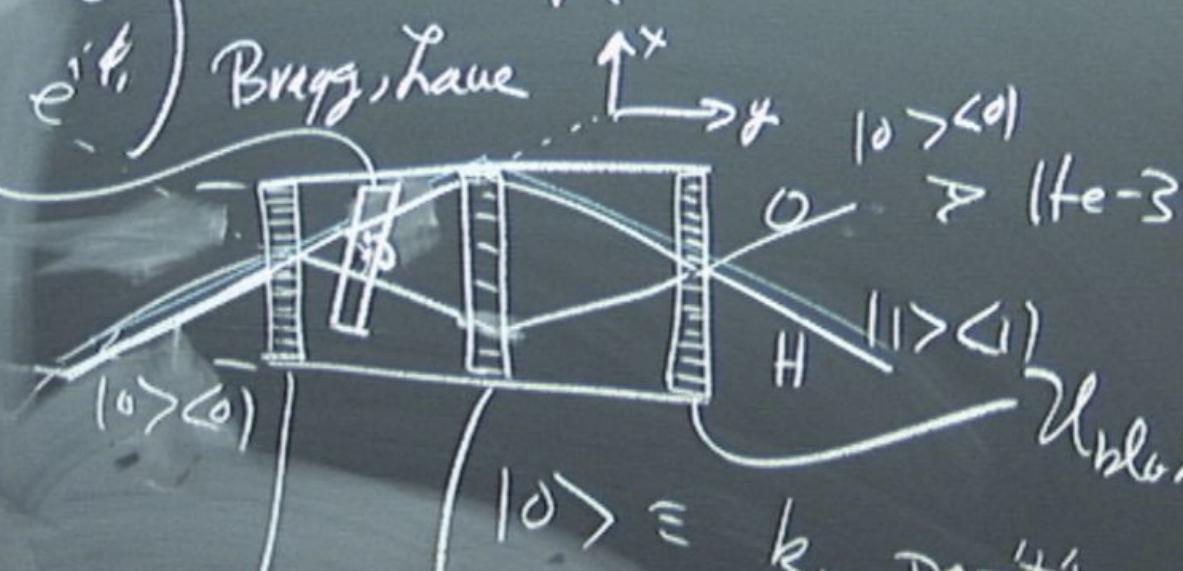
$$U_{\text{phase}} = \begin{pmatrix} e^{i\phi_0} & 0 \\ 0 & e^{i\phi_f} \end{pmatrix}$$

$$\nabla(r) = \sum b_c \delta(r)$$

$$\phi = -Nb_c \pi D$$

Path length

$$U_{\text{blade}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$



$$U_{\text{blade}} = \frac{1}{\sqrt{2}}$$

$|0\rangle \in k_x \text{ positive}$

$|1\rangle \in k_x \text{ negative}$

$$U_n = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$

$$V_{mag} \propto MB$$

$$U_{phase} = \begin{pmatrix} e^{i\phi_0} & 0 \\ 0 & e^{i\phi_1} \end{pmatrix}$$

Neutron Interferometry

MZ

Bragg, Laue

\uparrow^x

$$|0\rangle<\!\!\phi\!\!|$$

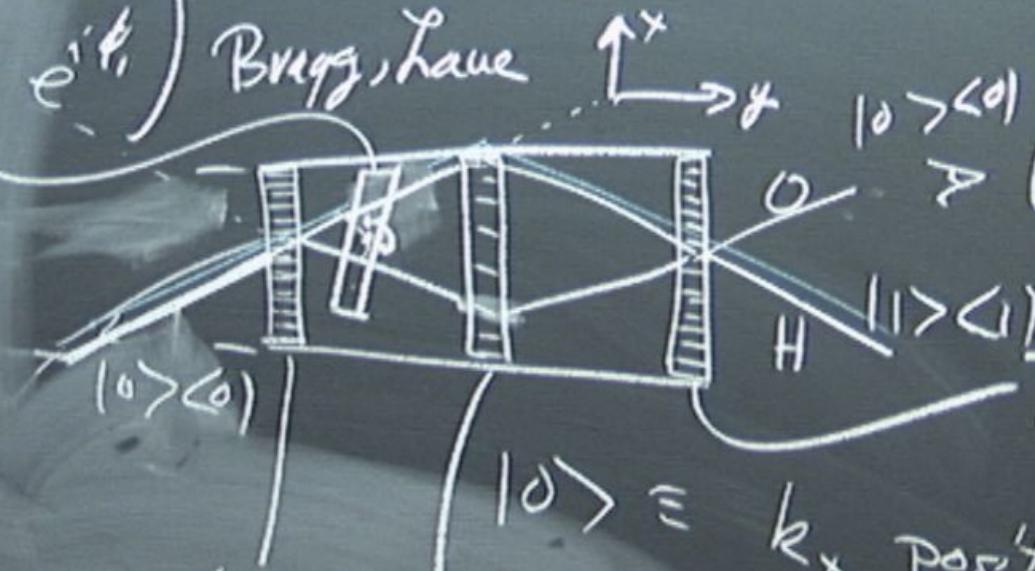
$$\sigma \approx 10^{-3}$$

$$V(r) = \sum b_c \delta(r)$$

$$\phi = -Nb_c \pi D$$

Path length

$$U_{blade} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$



$|0\rangle \equiv k_x \text{ positive}$

$|1\rangle \equiv k_x \text{ negative}$

$$U_n = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$$

$$\rho_{\text{out}} = U_{\text{blue}} U_{\text{mix}} U_{\text{blue}} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} U_{\text{blue}}^{-1} U_{\text{mix}}^{-1} U_{\text{blue}}^{-1}$$

$$I_0 = \text{Tr} \left\{ |0\rangle\langle 0| \rho_{\text{out}} \right\} \quad (2) = \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle)$$

$$\rho_{\text{out}} = U_{\text{chz}} U_{\text{mix_blue}}^{\downarrow} \underbrace{U_{\text{phase}}(\alpha) \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} U_{\text{chz}}^{-1}}_{U_{\text{mix}} \text{ Unitary}} U_{\text{blue}}^{\dagger}$$

$$I_0 = \text{Tr} \left\{ |0\rangle\langle 0| \rho_{\text{out}} \right\} \quad (2) = \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle)$$

(1) (2)

$$\rho_{\text{out}} = U_{\text{chir}} U_{\text{mix}}^{\dagger} U_{\text{blue}} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} U_{\text{blue}}^{-1} U_{\text{mix}}^{-1} U_{\text{chir}}^{\dagger}$$

U_{phase}(α)

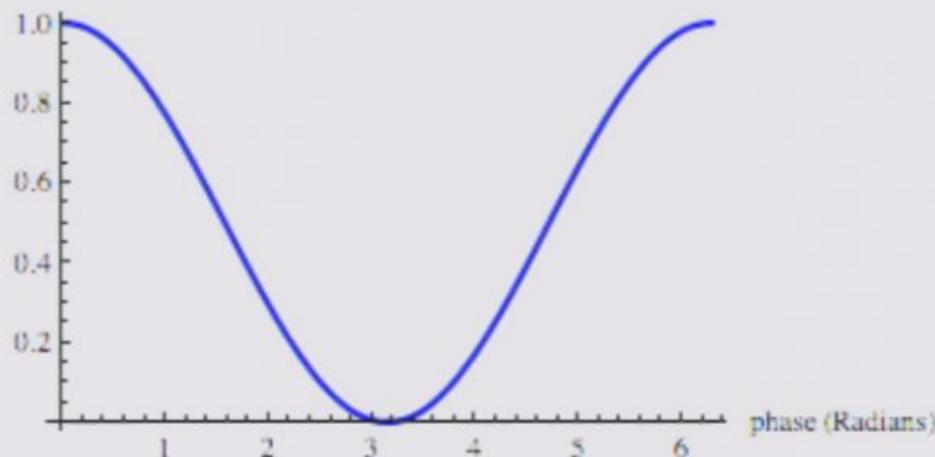
$$I_0 = \text{Tr} \left\{ |0\rangle\langle 0| \rho_{\text{out}} \right\} \quad (2) = \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle)$$

$$\rho_{\text{out}}(\alpha) = \frac{1}{2} \begin{pmatrix} 1 + \cos\alpha & \gamma' \sin\alpha \\ -\gamma' \sin\alpha & 1 - \cos\alpha \end{pmatrix}$$

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#1.nb

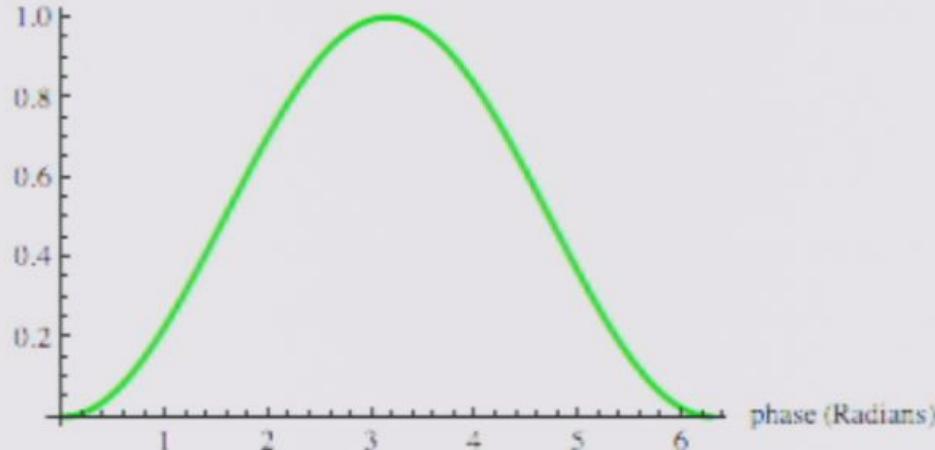
O-beam intensity



```
MLH[a_] := Tr[Ezm . resl[a]]
```

```
Plot[MLH[a], {a, 0, 2 π}, {AxesLabel -> {"phase (Radians)", "O-beam intensity"},  
PlotStyle -> {RGBColor[0, 1, 0], Thickness[0.01]}]}
```

O-beam intensity



#1.nb

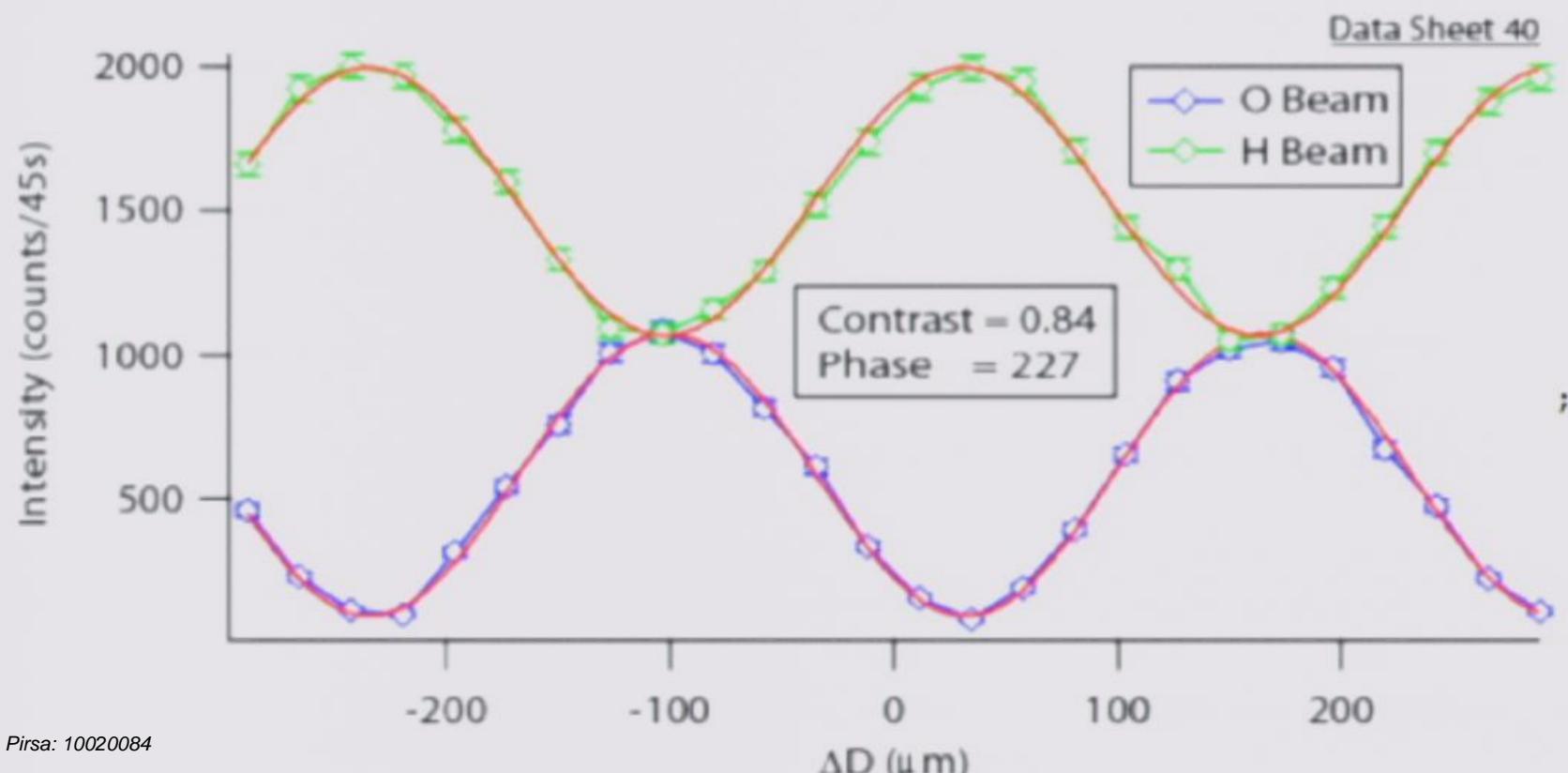


xpected the sum of the O and H-beam intensities is 1

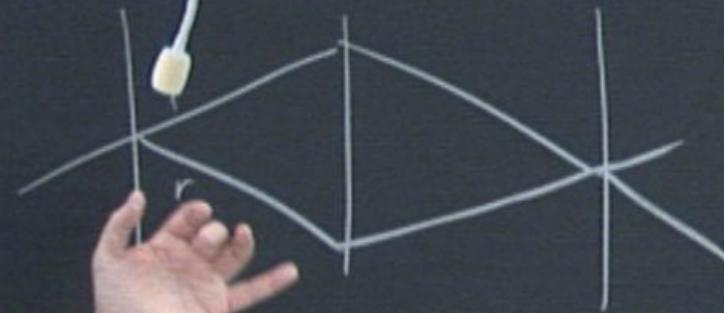
Simplify[M1O[a] + M1H[a]]

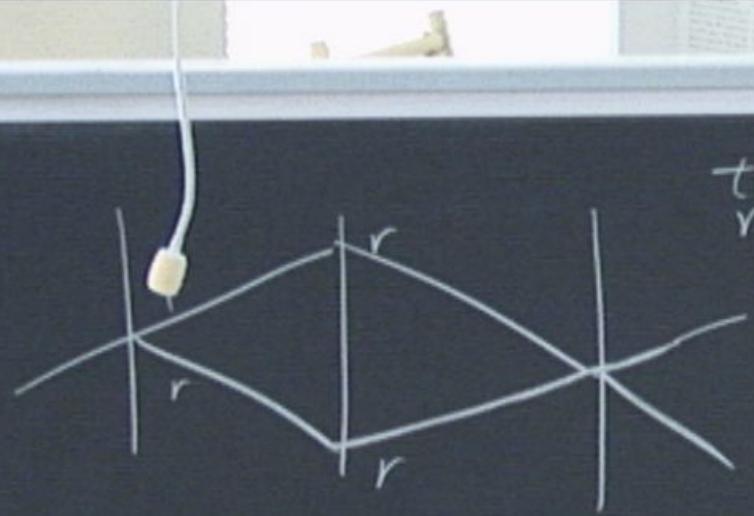
1

- Problem 11: Here is a set of experimental data. The horizontal axis is given in terms of the difference in path length of silica blades placed in the two paths. What width of silica corresponds to a π phase shift in this experiment? Suggest a few possible reasons for the differences between the experiment and theory. We will explore some of these next.



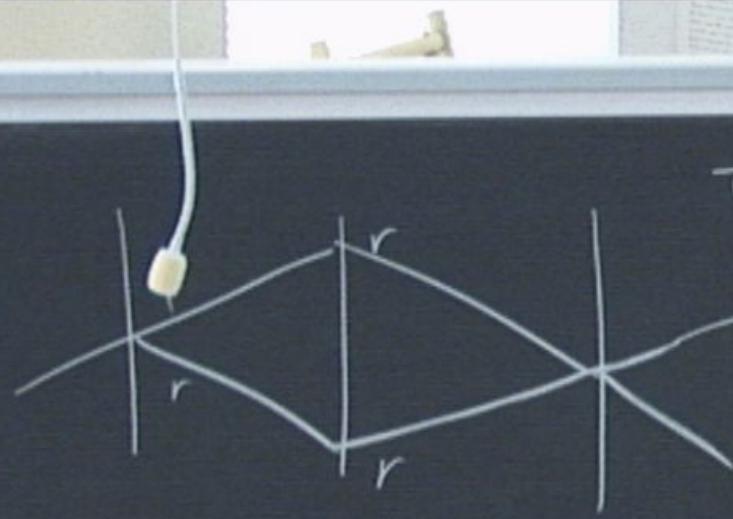
Magneti
nuclear
electron
optics
PCFQ





t r r
 v r t \downarrow \uparrow
 O -heat

Magneti
nuclear
electron
optics
PCFQ



trr
rrt up
O-beam

H-beam

trt up
rrr down

Magnetic
nuclear
electron
optics
PCFQ

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#1.nb

$$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

ade with different transmission and reflection coefficients

Since the probabilities of transmission and reflection add to 1 we can completely describe the action with only one parameter. $t = \text{Cos}^2[a]$ and $r = \text{Sin}^2[a]$

```
Ubladeg[a_] := {{Cos[a], Sin[a]}, {-Sin[a], Cos[a]}}
Ubladeginv[a_] := Transpose[Conjugate[Ubladeg[a]]];
Simplify[Refine[Ubladeg[a] . Ubladeginv[a], Element[a, Reals]]] // MatrixForm
```

$$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

- Problem 2: We give the propagator for the general blade, give a Hamiltonian description for an infinitesimally thin blade. Show that this integrates to the correction action for a thick blade.
- Problem 3: Give an interpretation for the Hamiltonian. Note that we are describing a set of physics where there is at most one scatter event in a single blade.
- Problem 4: The blades have a finite thickness. Show that the reflected beam is spread relative to the incoming beam.

Middle blade

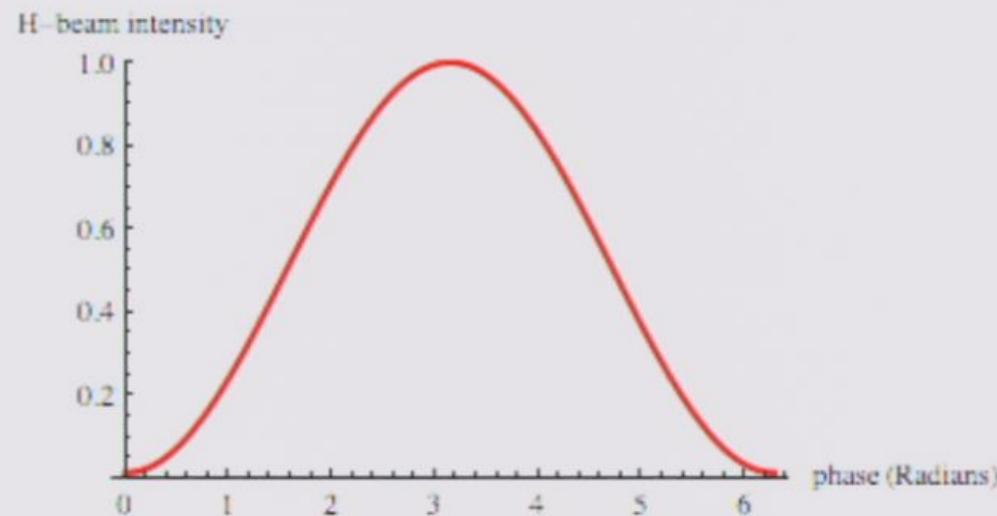
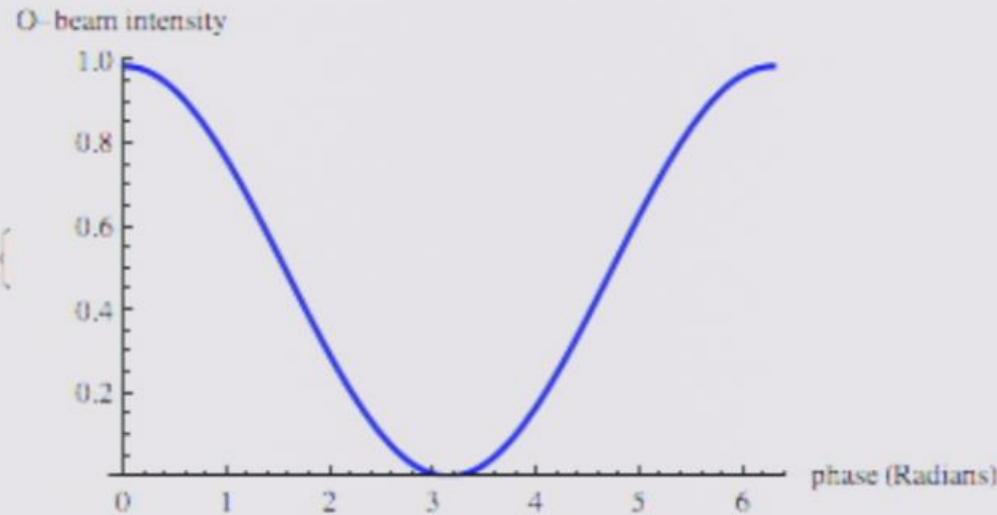
propagator for the mirror is its own inverse.

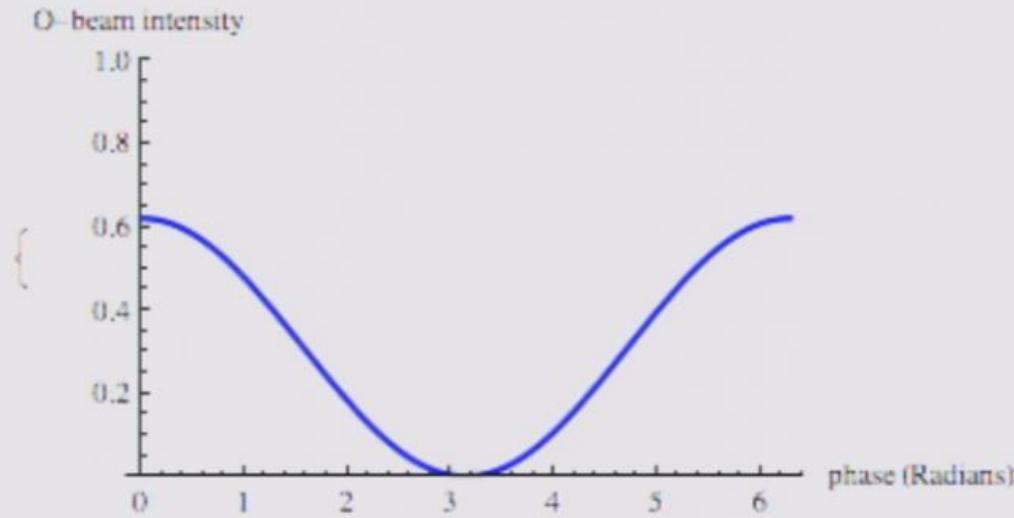
```
Um = {{0, 1}, {-1, 0}};
UmInv = Um;
UmInv // MatrixForm
```

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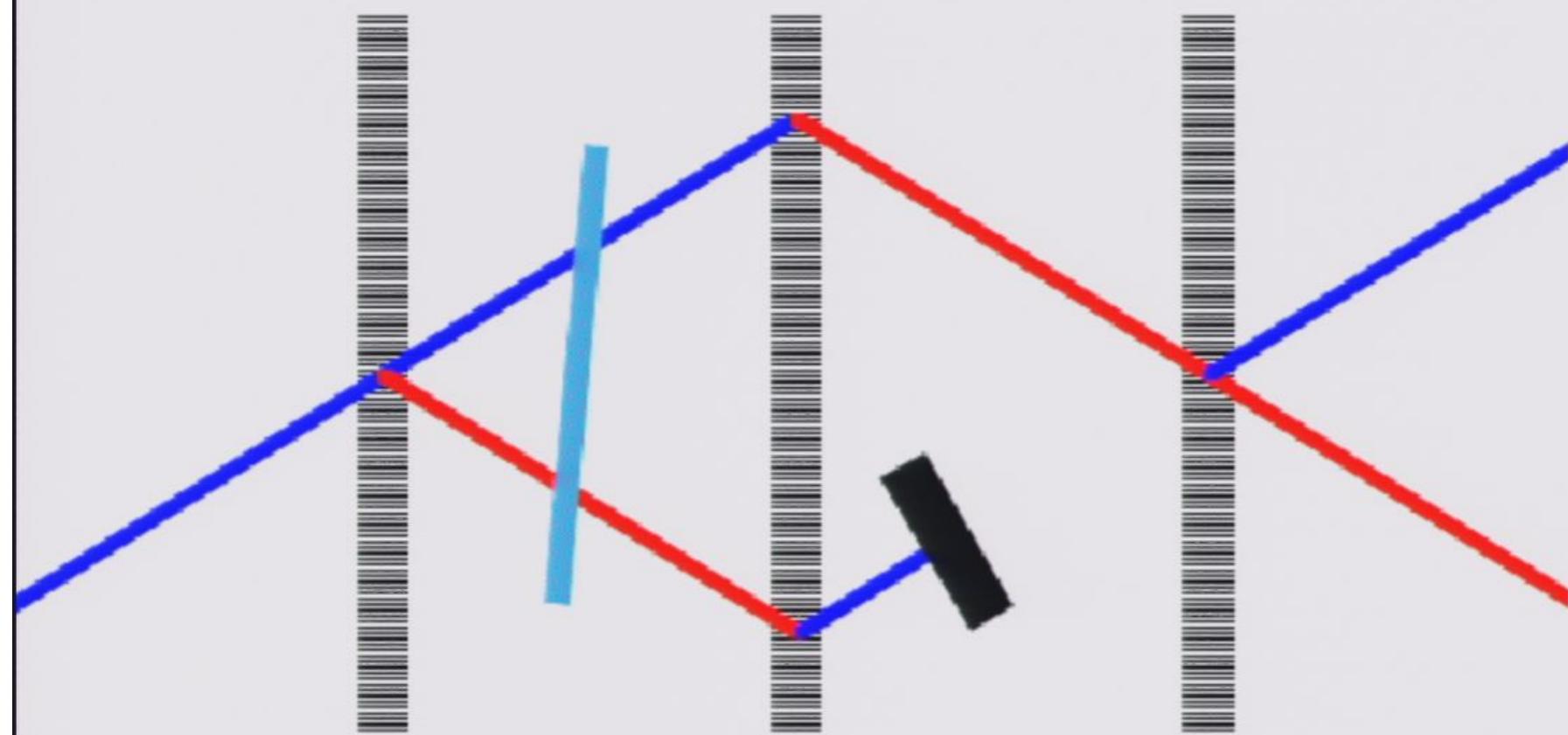
#1.nb







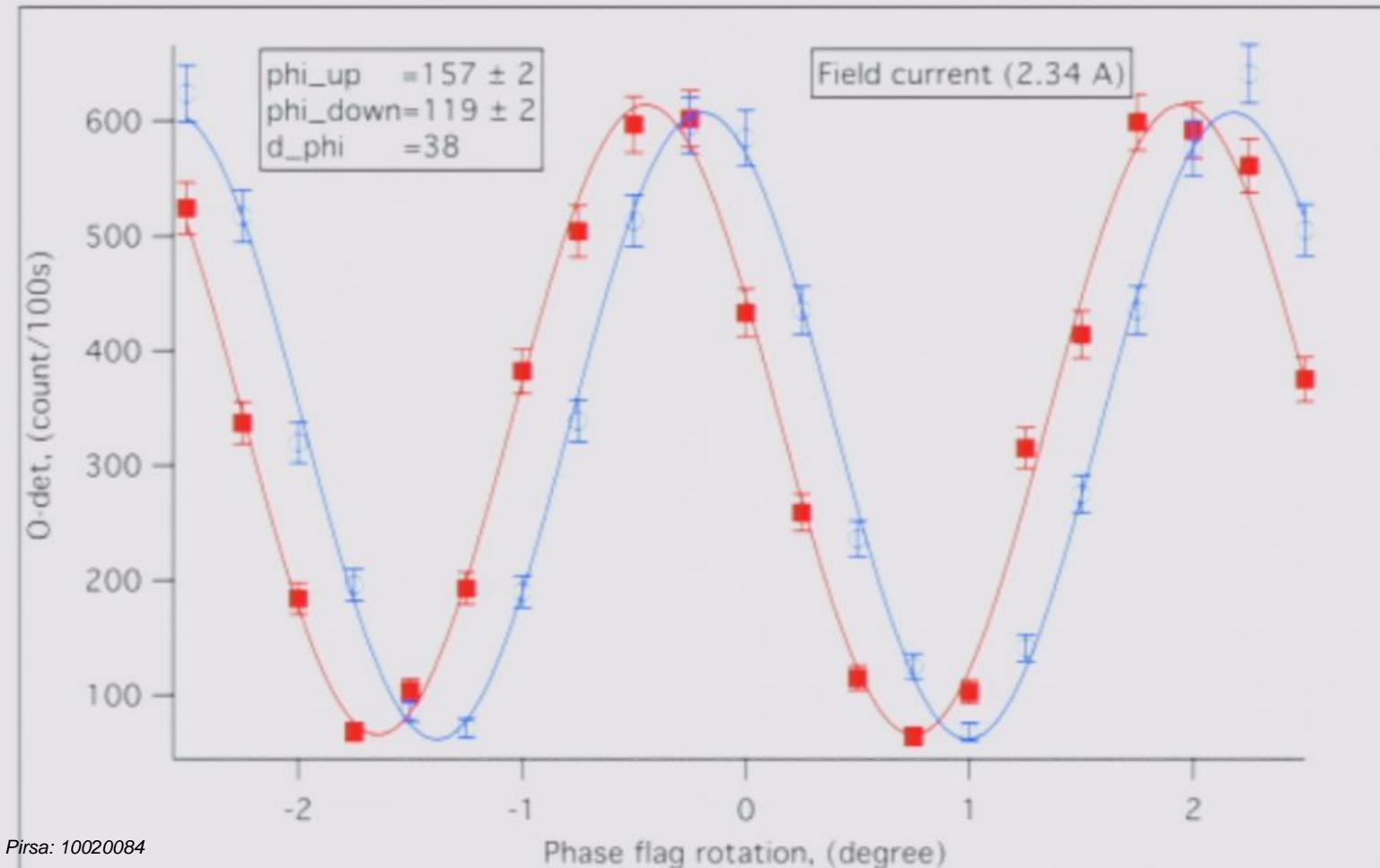
ourth experiment: Block one path

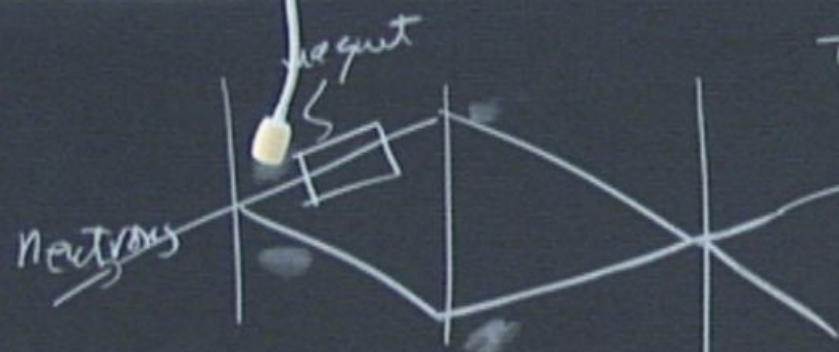


we look at the intensities at the O- and H-detectors for a perfect single crystal interferometer when we block beam in the upward direction between the 2nd and 3rd blade. We will compute this by projecting the state between these blades.

```
res4[a_] :=  
TrigReduce[ExpToTrig[Simplify[Ublade . Ezp . Um . Uphase[b, a] . Ublade . in .  
Ubladeinv . Uphaseinv[b, a] . Uminv . Ezp . Ubladeinv]]]
```

phase flag can be magnetic and since the neutrons have spin we expect the contrast to be a function of this mag-
field. Here we look at a simple example where the spin degree of freedom remains separable throughout the
riment and thus we do not need to expand the Hilbert space to describe the experiment. Latter we will look at
riments where the spin and path degrees of freedom become entangled.



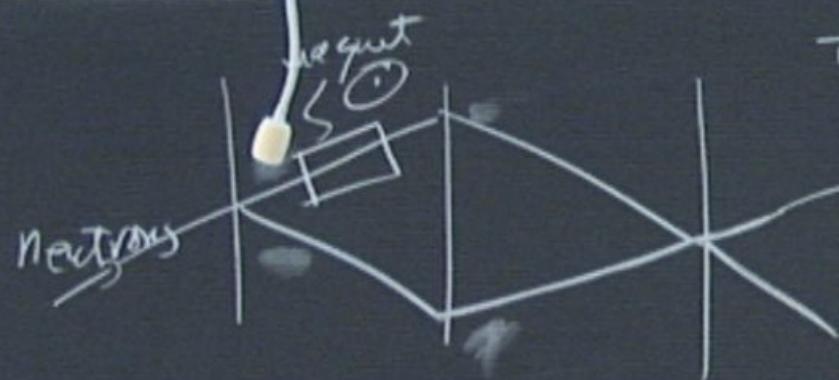


trr up
rrt down
O-beam

H-beam

trt up
rrr down

Magneti
nuclear
electron
optics
PCFQ

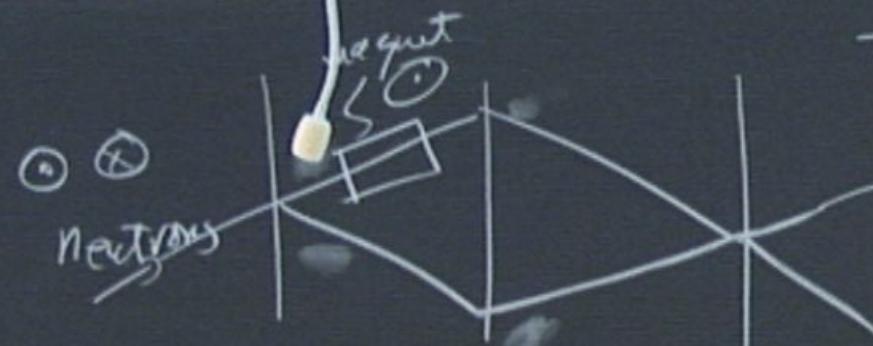


trr up
vnt down
O-beam

H-beam

trt up
rrr down

Magnetic
nuclear
electron
optics
PCFQ



trr up
rrt down

O-beat

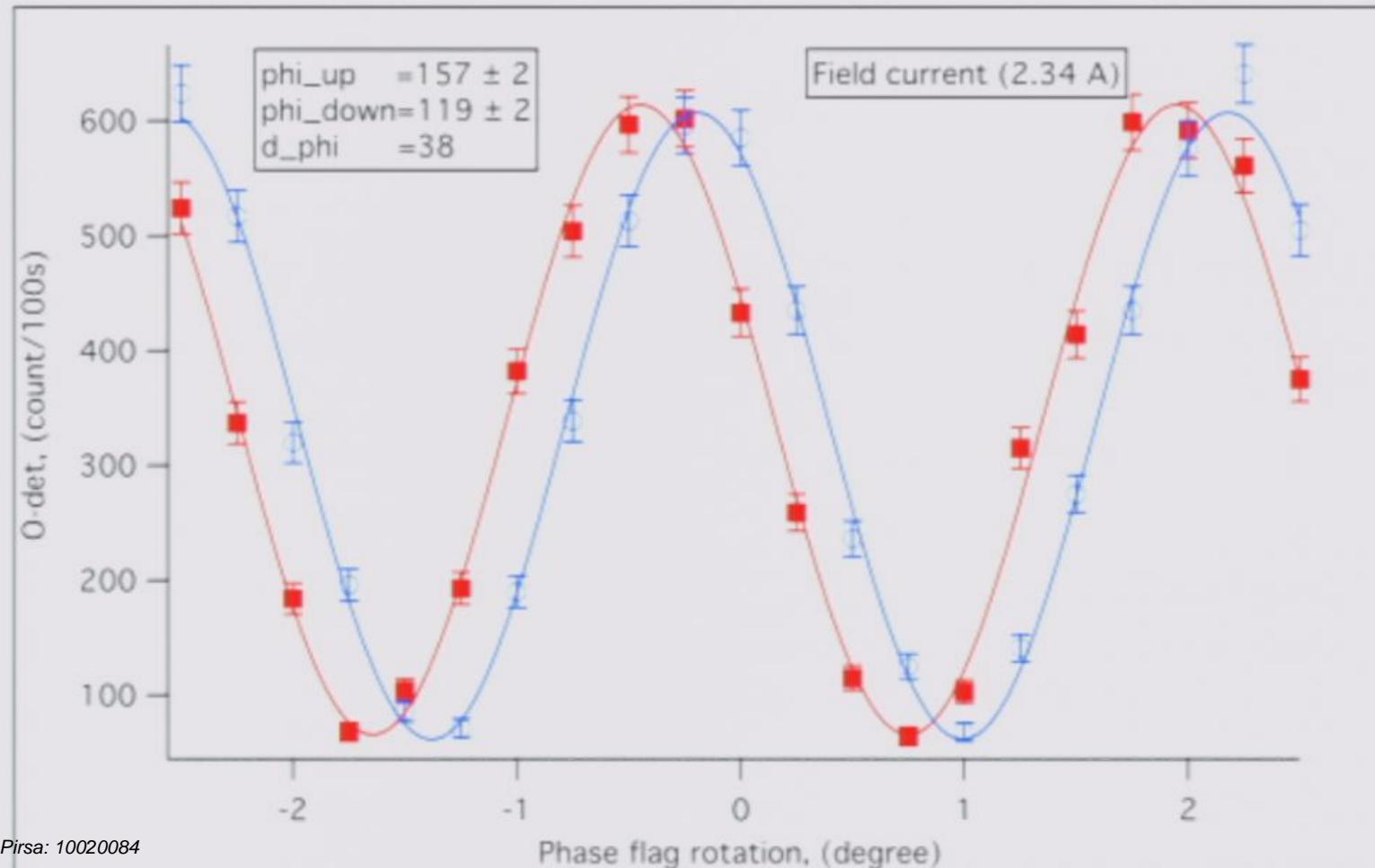
H-beat

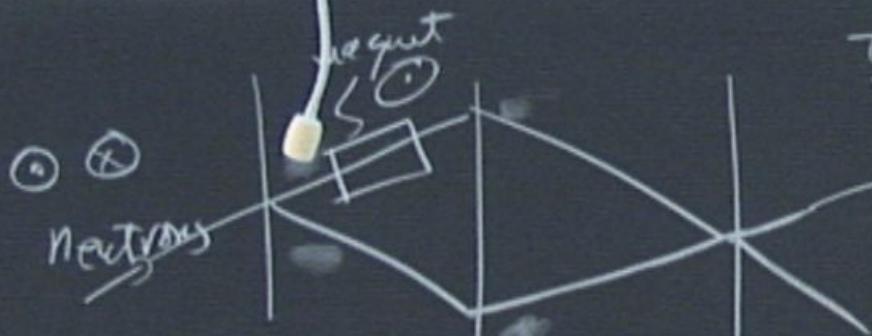
trt up
rrr down

M
nucle
electro
opt
P



phase flag can be magnetic and since the neutrons have spin we expect the contrast to be a function of this mag-
field. Here we look at a simple example where the spin degree of freedom remains separable throughout the
riment and thus we do not need to expand the Hilbert space to describe the experiment. Latter we will look at
riments where the spin and path degrees of freedom become entangled.





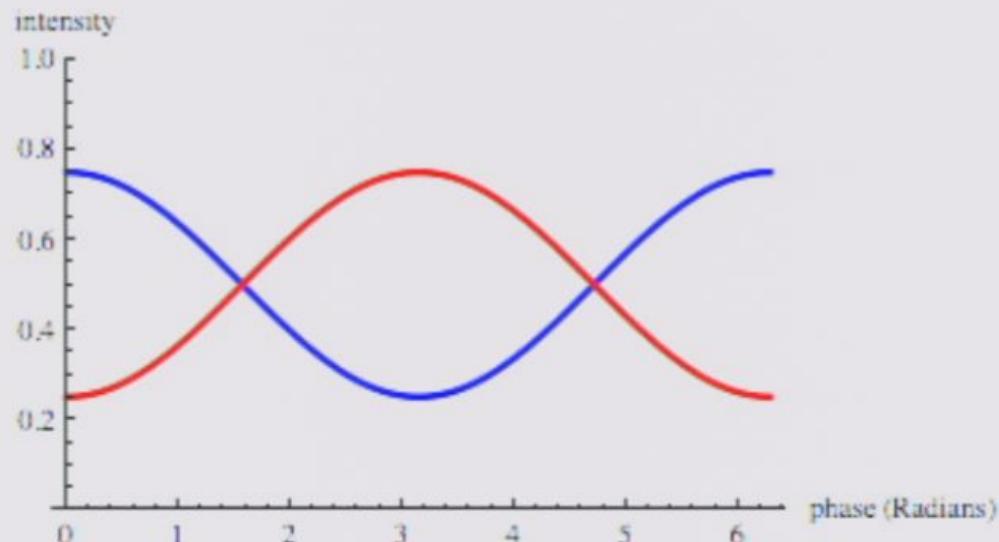
trr up
rrt down
O-beam

H-beam

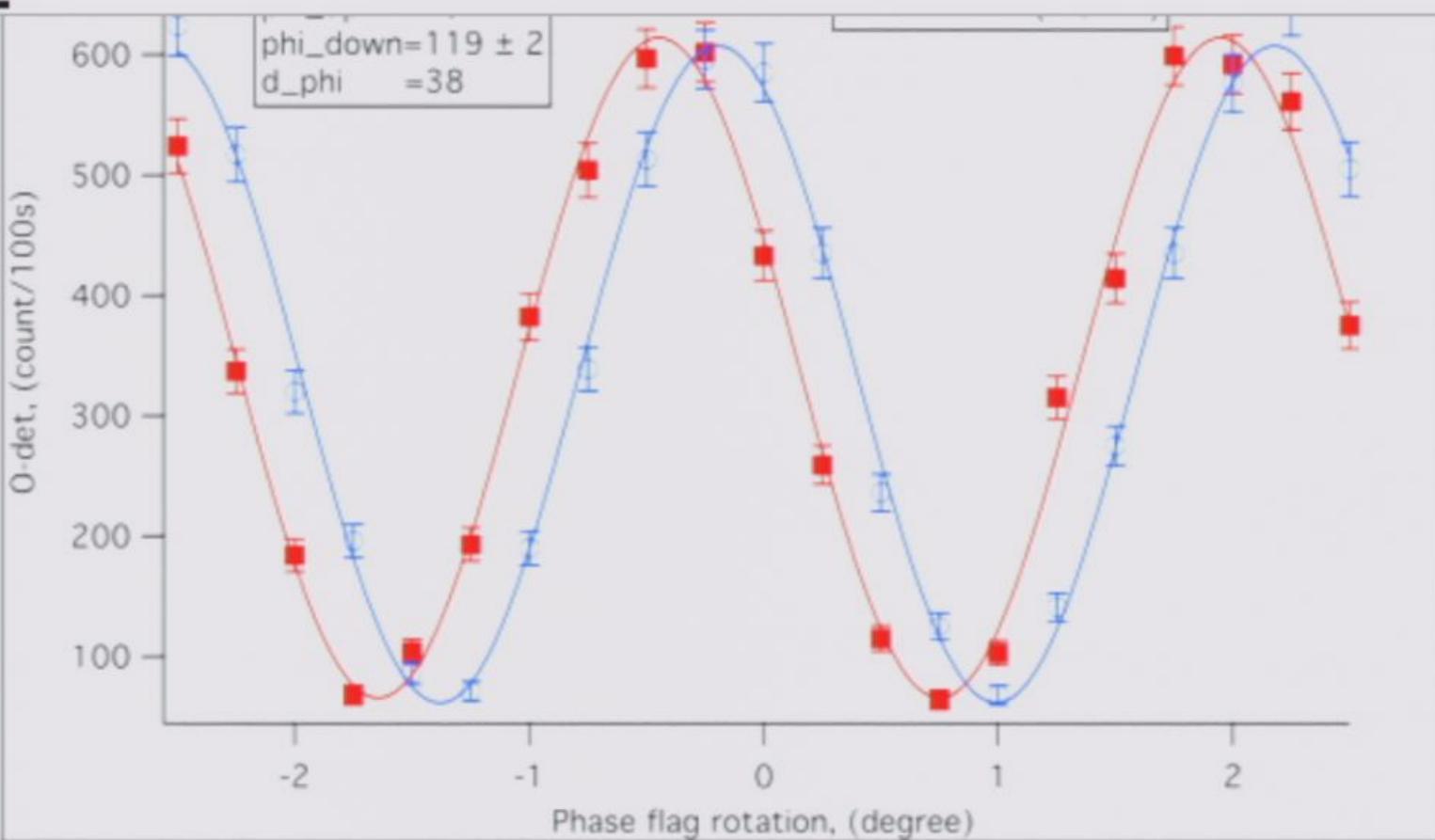
trt up
rrr down

Magnetic
nuclear
electron
optics
PCFQ

```
Animate[  
 Show[Plot[M5O[a, b], {a, 0, 2 π}, {AxesLabel -> {"phase (Radians)", "intensity"},  
 PlotStyle -> {RGBColor[0, 0, 1], Thickness[0.01]}, PlotRange -> {0, 1}}],  
 Plot[M5H[a, b], {a, 0, 2 π}, {AxesLabel -> {"phase (Radians)", "intensity"},  
 PlotStyle -> {RGBColor[1, 0, 0], Thickness[0.01]}, PlotRange -> {0, 1}}]],  
 {b, 0, 2 π}, AnimationRunning -> False]
```



plot what happens to the two spin states then the total picture is easier to see. Of course we can do this experiment by either preparing the neutrons in a particular state or by using a spin polarized detector. Does it matter which state?



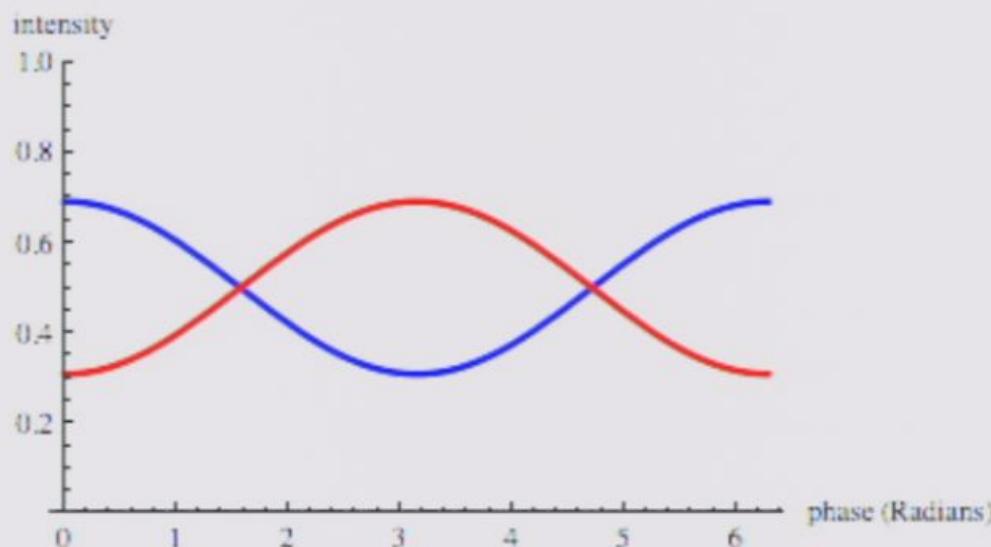
we must add a new description where we run two experiments one for each neutron spin state. Note the neutron is a spin 1/2 and the magnetic field in the sample is assumed to be uniform.

```
res5up[a_, b_] :=
TrigReduce[ExpToTrig[Simplify[Ublade.Um.Uphase[0, a].Usample[b].Ublade.
in.Ubladeinv.Uphaseinv[0, a].Usampleinv[b].Uminv.Ubladeinv]]]

res5down[a_, b_] :=
TrigReduce[ExpToTrig[Simplify[Ublade.Um.Uphase[0, a].Usample[-b].Ublade.
in.Ubladeinv.Uphaseinv[0, a].Usampleinv[-b].Uminv.Ubladeinv]]]
```

```
M5O[a_, b_] := (M5Oup[a, b] + M5Odown[a, b]) / 2
M5H[a_, b_] := (M5Hup[a, b] + M5Hdown[a, b]) / 2

Animate[
 Show[Plot[M5O[a, b], {a, 0, 2 π}, {AxesLabel → {"phase (Radians)", "intensity"}},
 PlotStyle → {RGBColor[0, 0, 1], Thickness[0.01]}, PlotRange → {0, 1}]],
 Plot[M5H[a, b], {a, 0, 2 π}, {AxesLabel → {"phase (Radians)", "intensity"}},
 PlotStyle → {RGBColor[1, 0, 0], Thickness[0.01]}, PlotRange → {0, 1}]],
 {b, 0, 2 π}, AnimationRunning → False]
```

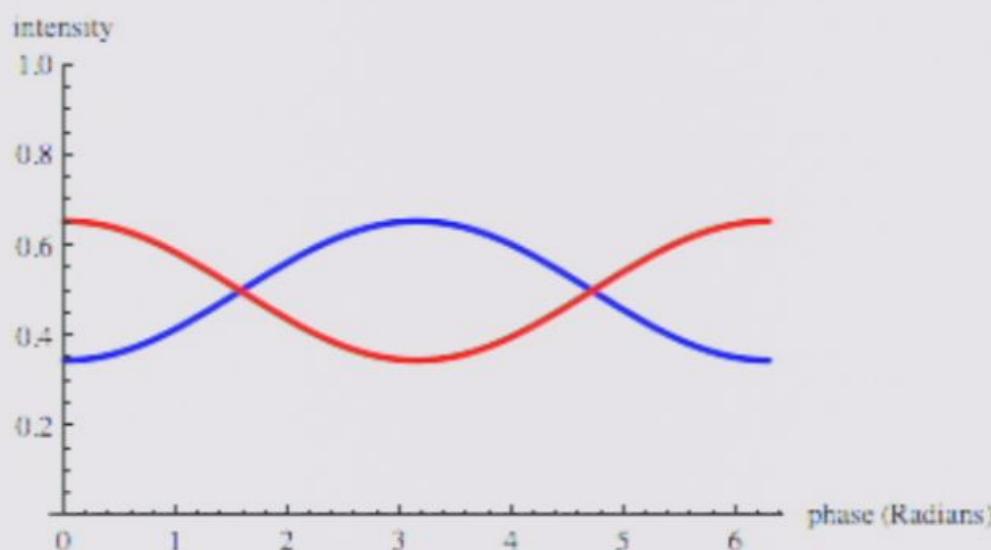


Mathematica File Edit Insert Format Cell Graphics Evaluation Palettes Window Help

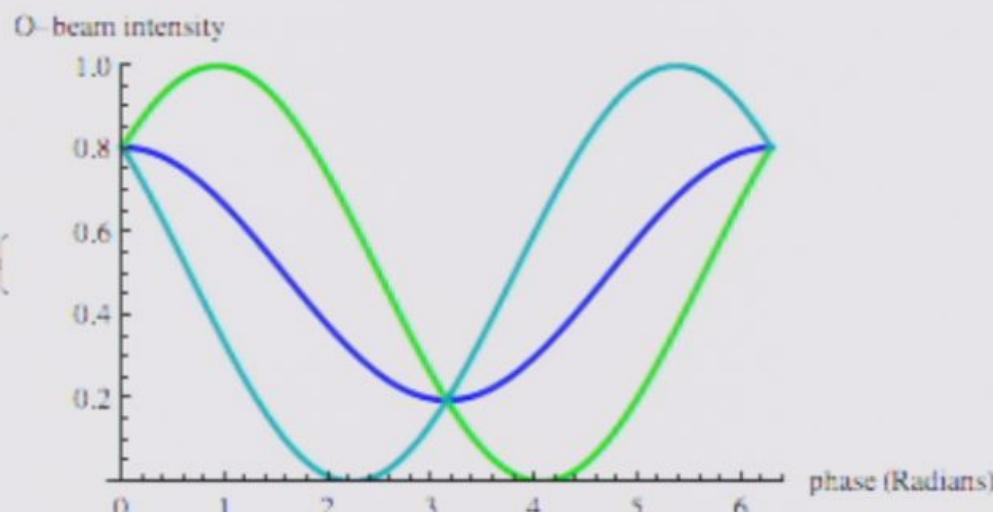
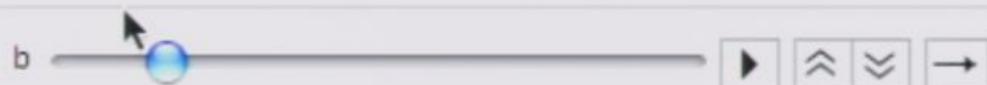
#1.nb

```
M5O[a_, b_] := (M5Oup[a, b] + M5Odown[a, b]) / 2
M5H[a_, b_] := (M5Hup[a, b] + M5Hdown[a, b]) / 2

Animate[
 Show[Plot[M5O[a, b], {a, 0, 2 π}, {AxesLabel → {"phase (Radians)", "intensity"}},
 PlotStyle → {RGBColor[0, 0, 1], Thickness[0.01]}, PlotRange → {0, 1}]],
 Plot[M5H[a, b], {a, 0, 2 π}, {AxesLabel → {"phase (Radians)", "intensity"}},
 PlotStyle → {RGBColor[1, 0, 0], Thickness[0.01]}, PlotRange → {0, 1}]],
 {b, 0, 2 π}, AnimationRunning → False]
```

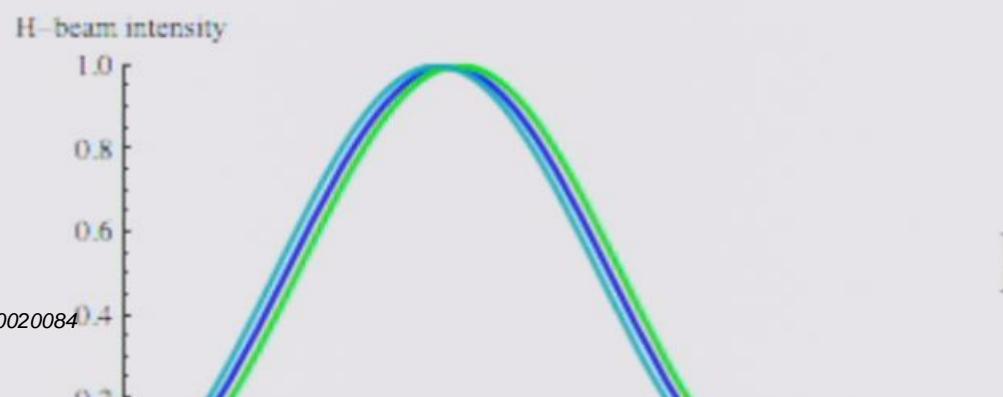
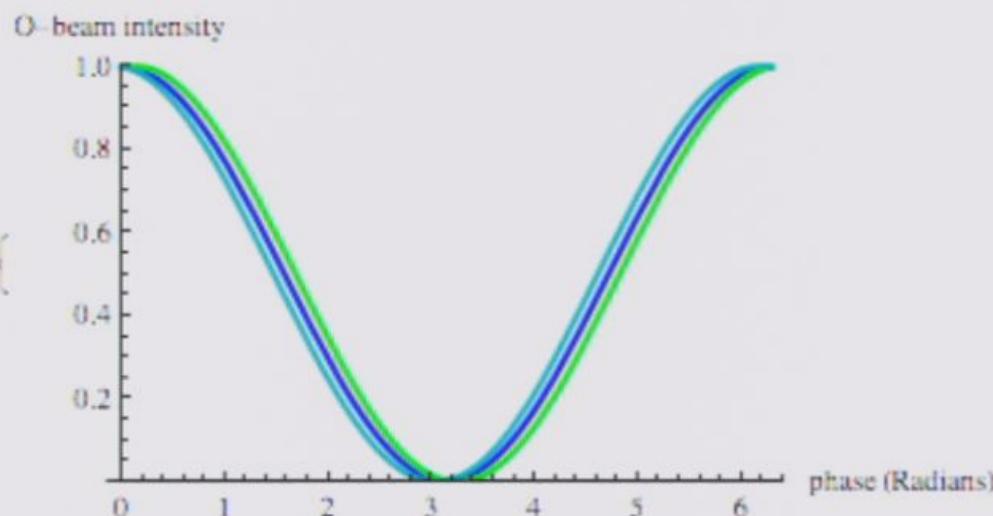


```
PlotStyle -> {RGBColor[0, 1, 0], Thickness[0.01]}, PlotRange -> {0, 1}],  
Plot[M5Hdown[a, b], {a, 0, 2 π}, {AxesLabel -> {"phase (Radians)", "intensity"},  
PlotStyle -> {RGBColor[0, 0.5, 0.5], Thickness[0.01]}, PlotRange -> {0, 1}}]],  
{b, 0, 2 π}, AnimationRunning -> False]
```



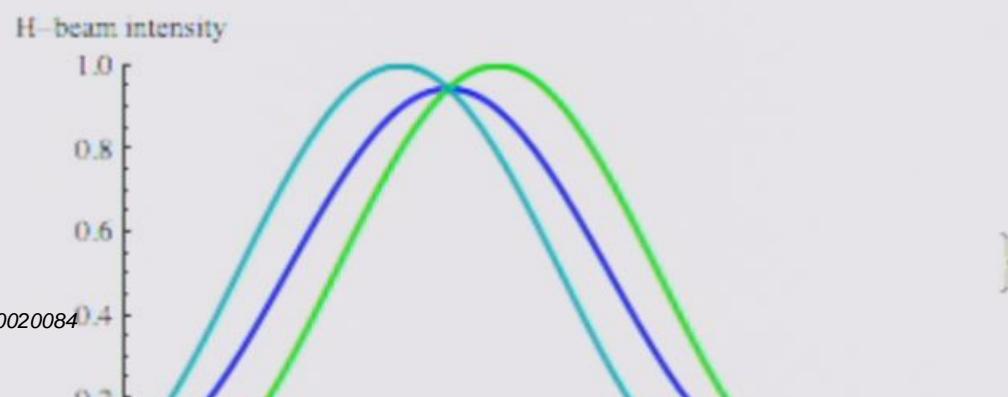
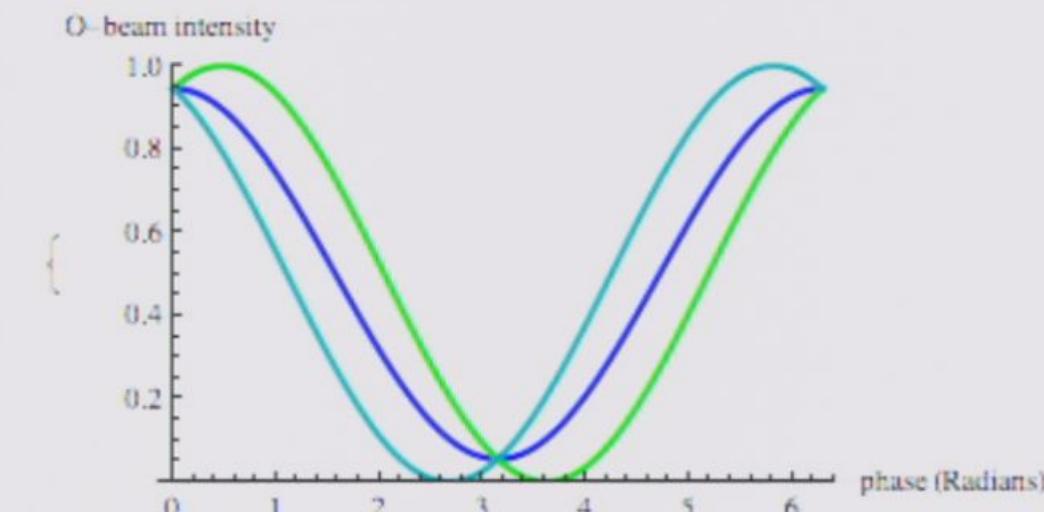
```
PlotStyle -> {RGBColor[0, 1, 0], Thickness[0.01]}, PlotRange -> {0, 1}}],  
Plot[M5Hdown[a, b], {a, 0, 2 π}, {AxesLabel -> {"phase (Radians)", "intensity"},  
PlotStyle -> {RGBColor[0, 0.5, 0.5], Thickness[0.01]}, PlotRange -> {0, 1}}]],  
{b, 0, 2 π}, AnimationRunning -> False]
```

b



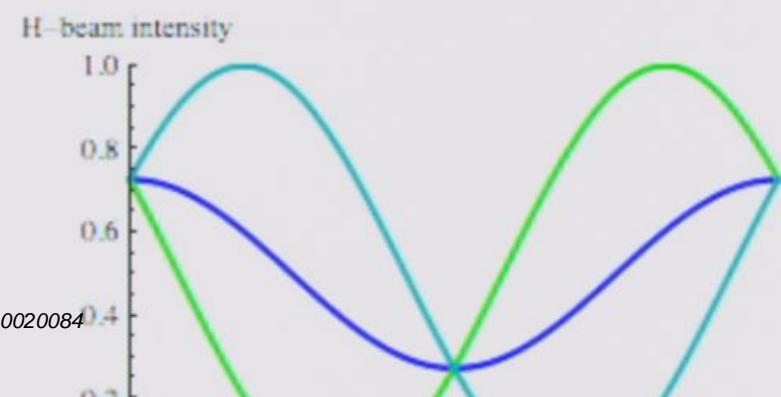
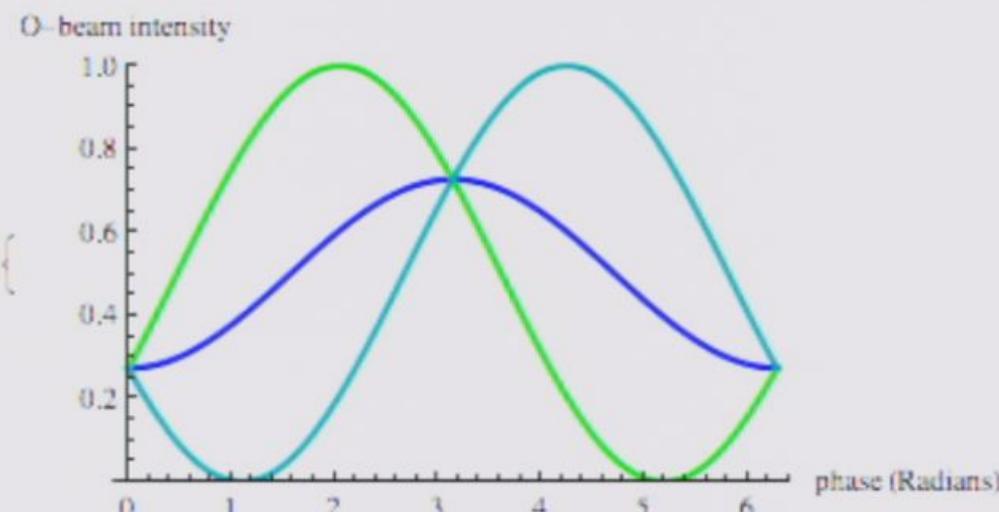
```
PlotStyle -> {RGBColor[0, 1, 0], Thickness[0.01]}, PlotRange -> {0, 1}}],  
Plot[M5Hdown[a, b], {a, 0, 2 π}, {AxesLabel -> {"phase (Radians)", "intensity"},  
PlotStyle -> {RGBColor[0, 0.5, 0.5], Thickness[0.01]}, PlotRange -> {0, 1}}]],  
{b, 0, 2 π}, AnimationRunning -> False]
```

b



```
PlotStyle -> {RGBColor[0, 1, 0], Thickness[0.01]}, PlotRange -> {0, 1}],  
Plot[M5Hdown[a, b], {a, 0, 2 π}, {AxesLabel -> {"phase (Radians)", "intensity"},  
PlotStyle -> {RGBColor[0, 0.5, 0.5], Thickness[0.01]}, PlotRange -> {0, 1}}]],  
{b, 0, 2 π}, AnimationRunning -> False]
```

b 



$$\rho_{\text{out}} = \sum U_{\text{chirp}} U_{\text{mix, blue}}^{\dagger} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} U_{\text{chirp}}^{-1} U_{\text{unmix}}^{\dagger} U_{\text{decode}}$$

\$U_{\text{phase}}(\alpha)\$

\$U_{\text{phase}}^{\dagger}(\alpha)\$

$$I_0 = \text{Tr} \left\{ |0\rangle\langle 0| \rho_{\text{out}} \right\} \quad (B) = \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle)$$

$$\rho_{\text{out}}(\alpha) = \frac{1}{2} \begin{pmatrix} 1 + \cos\alpha & \gamma \sin\alpha \\ -\gamma \sin\alpha & 1 - \cos\alpha \end{pmatrix}$$

$$\rho_{out} = \sum_{i=1}^4 U_{hole} U_{in_blue} \underbrace{U_{phase}(\alpha_i)}_{\downarrow} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} U_{hole}^{-1} U_{in_blue}^{-1} U_{phase}(\alpha)$$

$$I_\phi = \text{Tr} \left\{ |0\rangle\langle 0| \rho_{out} \right\} \quad (4) = \frac{1}{2} (|0\rangle + |1\rangle)$$

$$\rho_{out}(\alpha) = \frac{1}{2} \begin{pmatrix} 1+\cos\alpha & -i\sin\alpha \\ -i\sin\alpha & 1-\cos\alpha \end{pmatrix}$$

Neutron Interferometry

MZ

S_{out}

1
 σ_x
 σ_y
 σ_z



Interferometry
M2

Mlibert Sme.

$$S_{out} = \sum_{n=1}^{\infty} U_{n,d} U_{n,d}$$

$$\tilde{U}_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad I_0 = T$$

$$\tilde{U}_x = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$\tilde{U}_y = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

$$\tilde{U}_z = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$S_{out}(Q)$$

Newton Interferometry

MZ

Möller-Stern

$$P_{\text{out}} = \sum_{k=1}^{\infty} U_{kk}$$

$$\tilde{U} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \quad I_0 =$$

$$\tilde{U}_x = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\tilde{U}_y = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

$$\tilde{U}_z = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$P_{\text{out}}$$

Neutron Interferometry

MZ

$$\$ = \text{Tr} \{$$

Möller-Sone.

$$S_{\text{out}} = \sum_{k=1}^{\infty} U_{kk}$$

$$S_0 = \tilde{U} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad I_0 =$$

$$S_1 = \tilde{U}_X = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$S_2 = \tilde{U}_Y = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

$$S_3 = \tilde{U}_Z - \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Neutron Interferometry

M2

$$\$ = \text{Tr} \left\{ \mathcal{U}_1 \sum U_{\text{eff}} \mathcal{U}_1^\dagger; U_{\text{eff}}^\dagger \right\}$$

Alibert Sme.

$$S_{\text{out}} = \sum_i U_{\text{out},i}$$

$$S_0 = \tilde{\mathbb{I}} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$S_1 = \tilde{\sigma}_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$S_2 = \tilde{\sigma}_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$S_3 = \tilde{\sigma}_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Neutron Interferometry

MZ

$$\$ = \text{Tr} \left\{ \mathcal{I}_0 \sum_k U_{\text{eff}}^k \mathcal{I}_0 ; U_{\text{eff}}^k \right\}$$

Möller-Some

$$S_{\text{out}} = \sum_{i=1}^{\infty} U_{i,i}$$

$$S_0 = \tilde{I} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad I_0 =$$

$$S_1 = \tilde{J}_X = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$S_2 = \tilde{J}_Y = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

$$S_3 = \tilde{J}_Z - \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

Neutron Interferometry

MZ

classical probability

$$\$ = \text{Tr} \left\{ \mathcal{S}_1 \sum_k U_{\text{loss}}^k \mathcal{S}_1 ; U_{\text{eff}}^k \right\}$$

Möller-Sone.

$$S_{\text{out}} = \sum_{i=1}^{\infty} U_{i,i}$$

$$\mathcal{S}_0 = \tilde{I} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad I_0 =$$

$$\mathcal{S}_1 = \tilde{J}_X = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$\mathcal{S}_2 = \tilde{J}_Y = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

$$\mathcal{S}_3 = \tilde{J}_Z - \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

Neutron Interferometry

MZ

$$\$ = \text{Tr} \left\{ \mathcal{S}_1 \sum_k \mathcal{U}_{\text{loss}}^k \mathcal{S}_1 ; \mathcal{U}_{\text{eff}}^k \right\}$$

classical probability

Momentum Space.

$$P_{\text{out}} = \sum_{i=1}^n U_{i,i}$$

$$\mathcal{S}_0 = \tilde{\mathcal{U}} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad I_0 =$$

$$\mathcal{S}_1 = \tilde{\mathcal{U}}_X = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$\mathcal{S}_2 = \tilde{\mathcal{U}}_Y = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

$$\mathcal{S}_3 = \tilde{\mathcal{U}}_Z = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

P_{out}