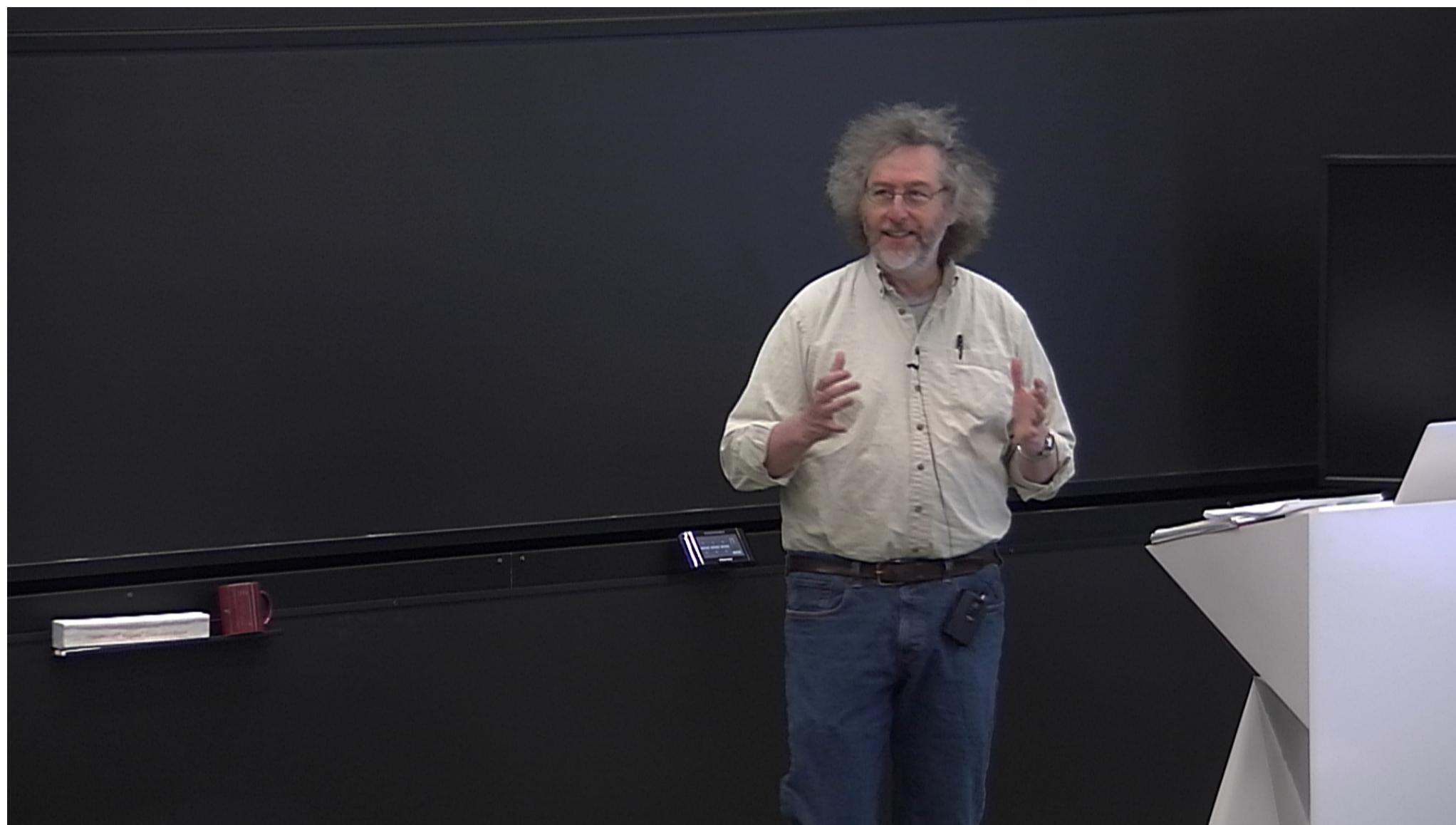


Title: 12/13 PSI - Explorations on Quantum Information Lecture 1

Date: Mar 18, 2013 09:00 AM

URL: <http://pirsa.org/13030054>

Abstract:



# Neutron Interferometer



Neutron Interferometer  
2 qubits



- Neutron Interferometer  
2 qubits
- Magnetic Resonance



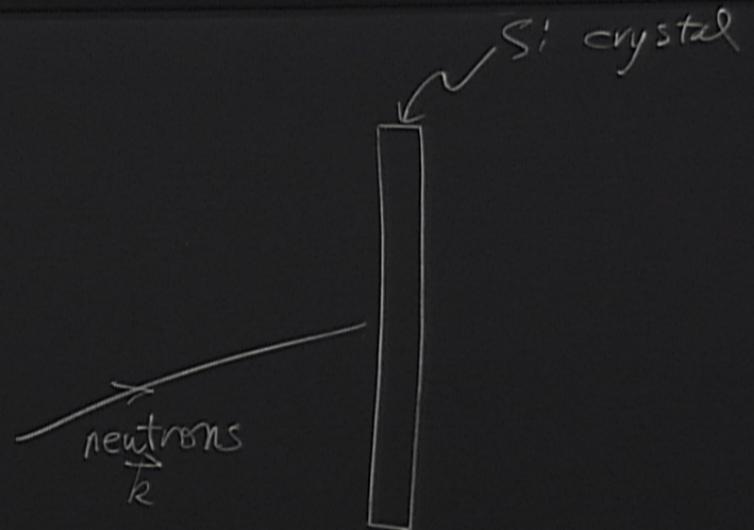
- Neutron Interferometer  
2 qubits
- Magnetic Resonance
  - Hilbert Space
- Diamond NV

- Neutron Interferometer  
2 qubits
- Magnetic Resonance
  - Hilbert Space
- Diamond NV

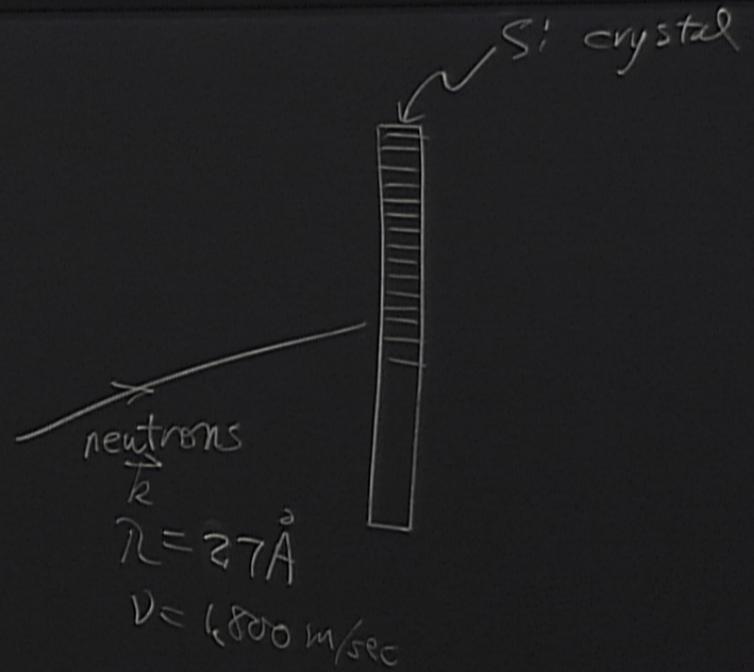
- Neutron Interferometer  
2 qubits
- Magnetic Resonance
  - Hilbert Space
- Diamond NV



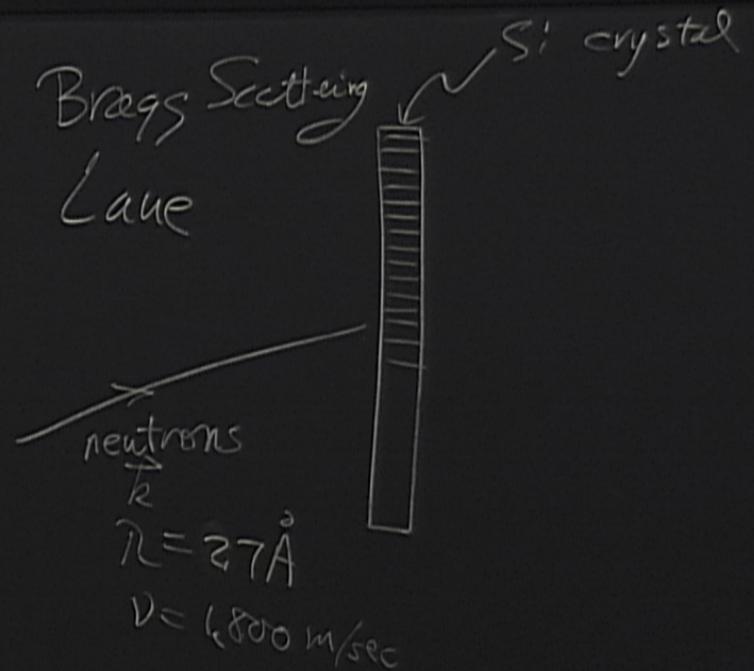
- Neutron Interferometer
- Magnetic Resonance in Space
- D...

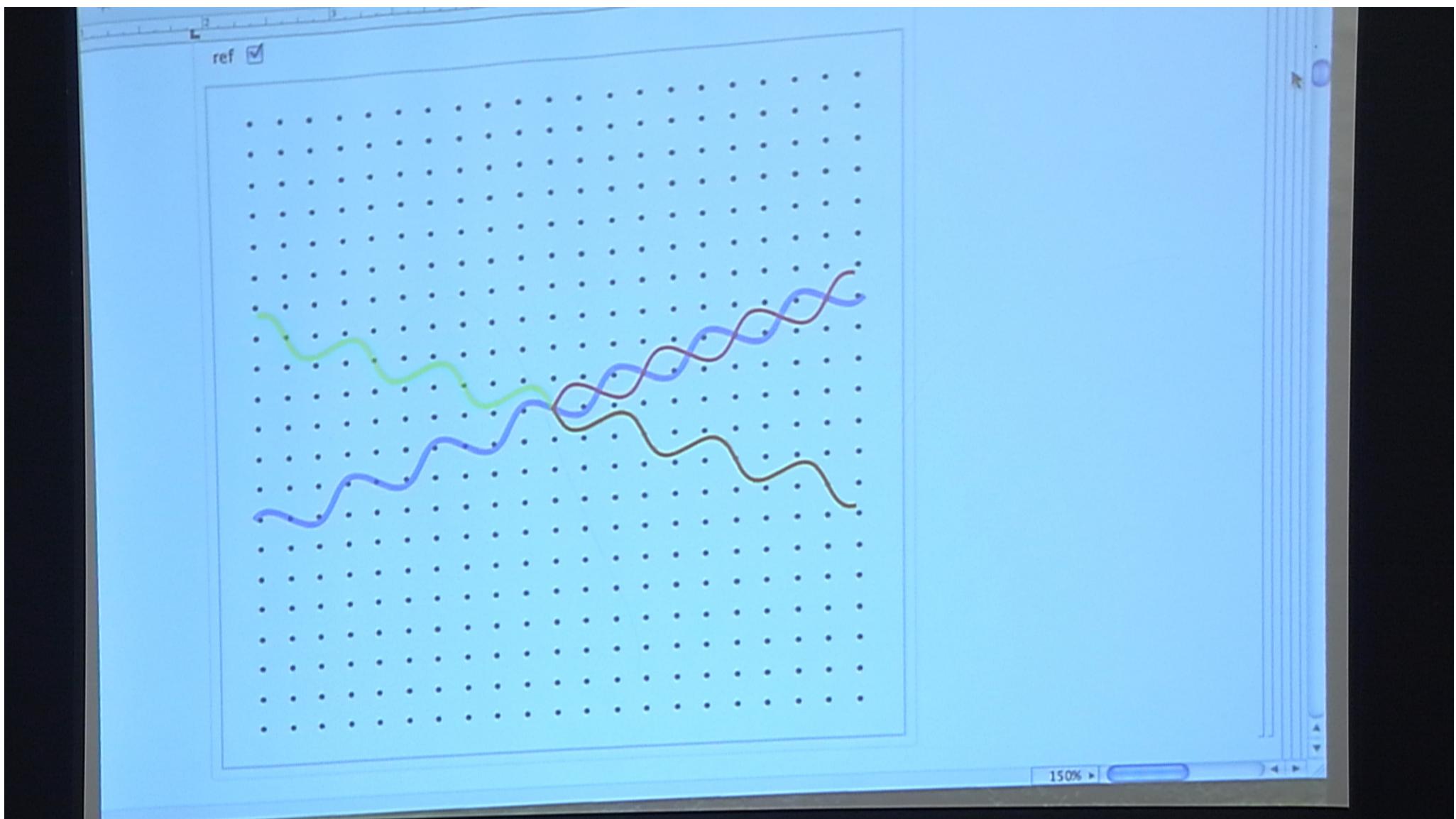


- Neutron Interferometer  
2 qubits
- Magnetic Resonance
  - Hilbert Space
- Diamond NV

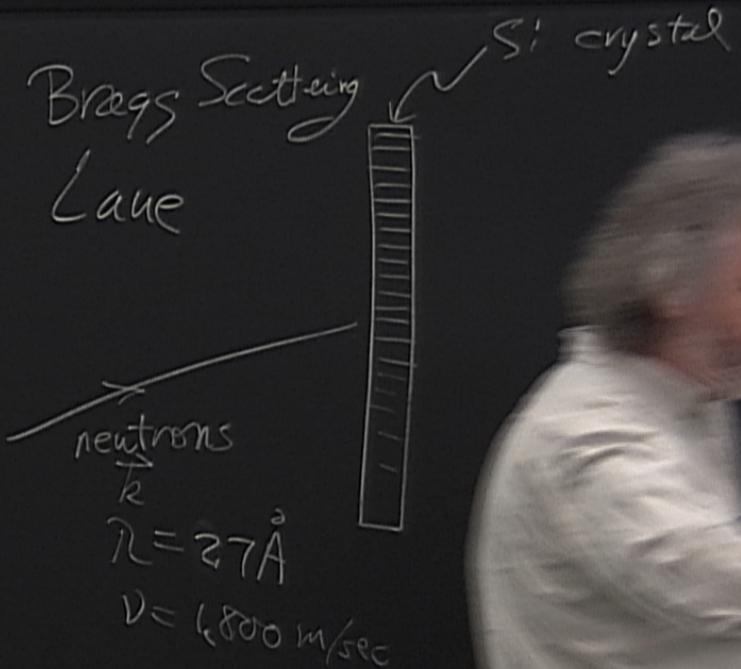


- Neutron Interferometer  
2 qubits
- Magnetic Resonance  
- Hilbert Space
- Diamond NV

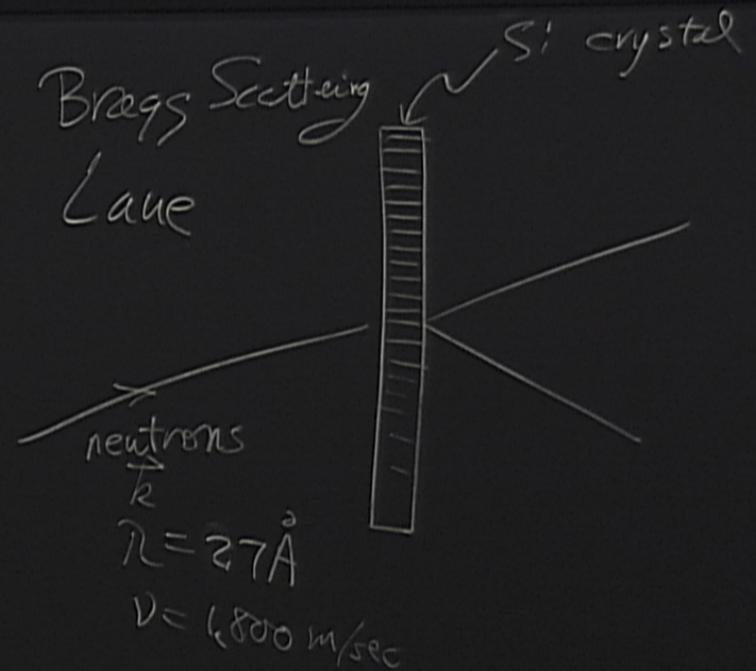




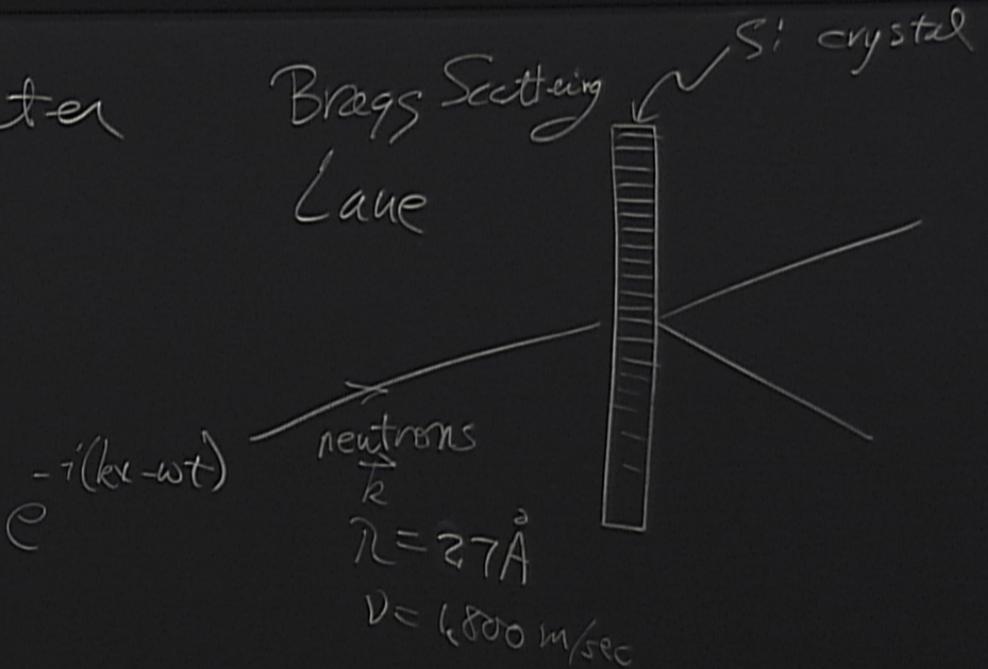
- Neutron Interferometer  
2 qubits
- Magnetic Resonance
  - Hilbert Space
- Diamond NV

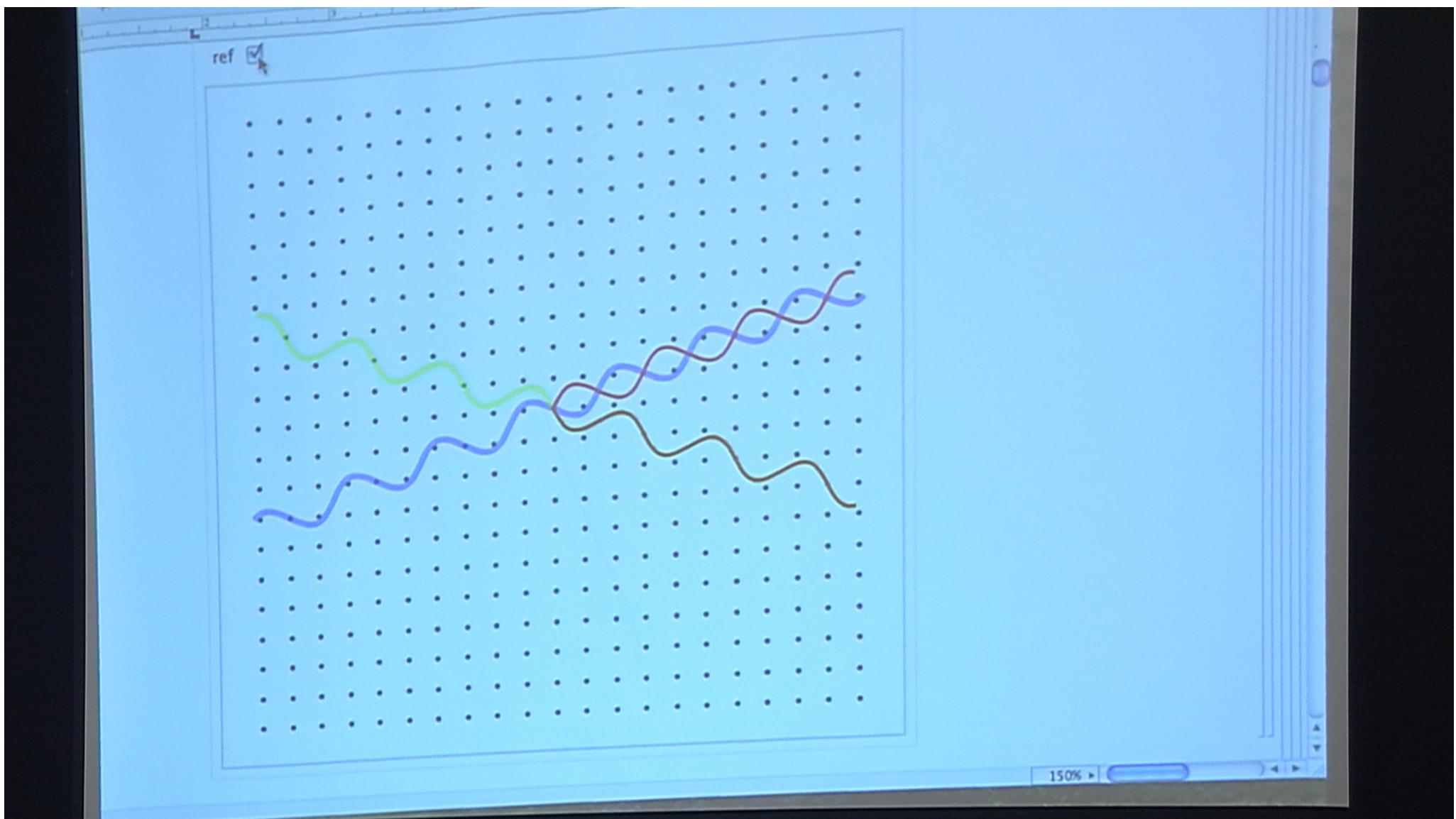


- Neutron Interferometer  
2 qubits
- Magnetic Resonance  
- Hilbert Space
- Diamond NV

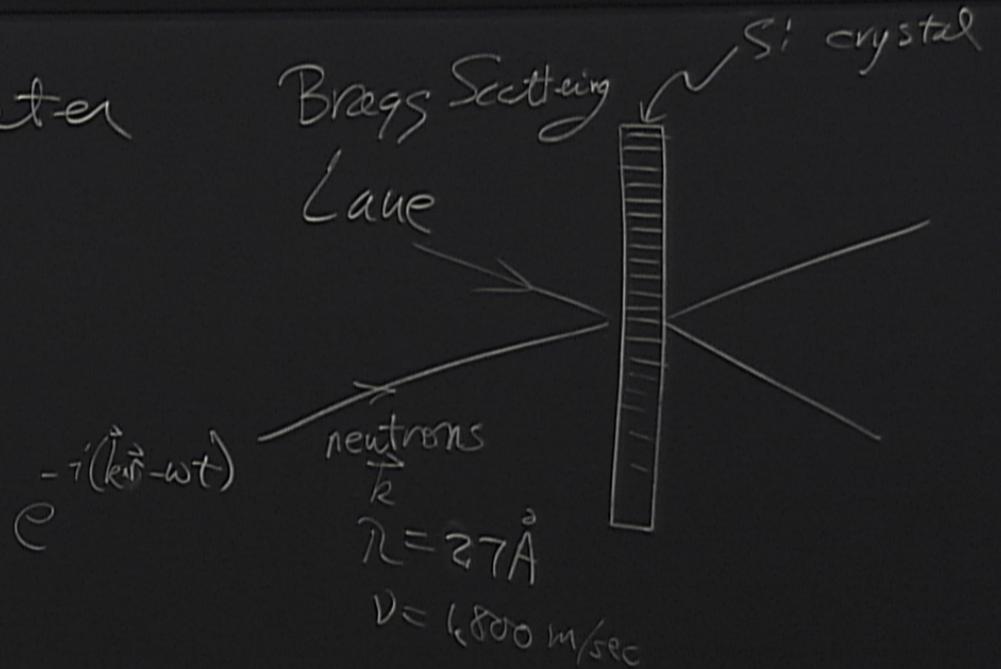


- Neutron Interferometer  
2 qubits
- Magnetic Resonance  
- Hilbert Space
- Diamond NV

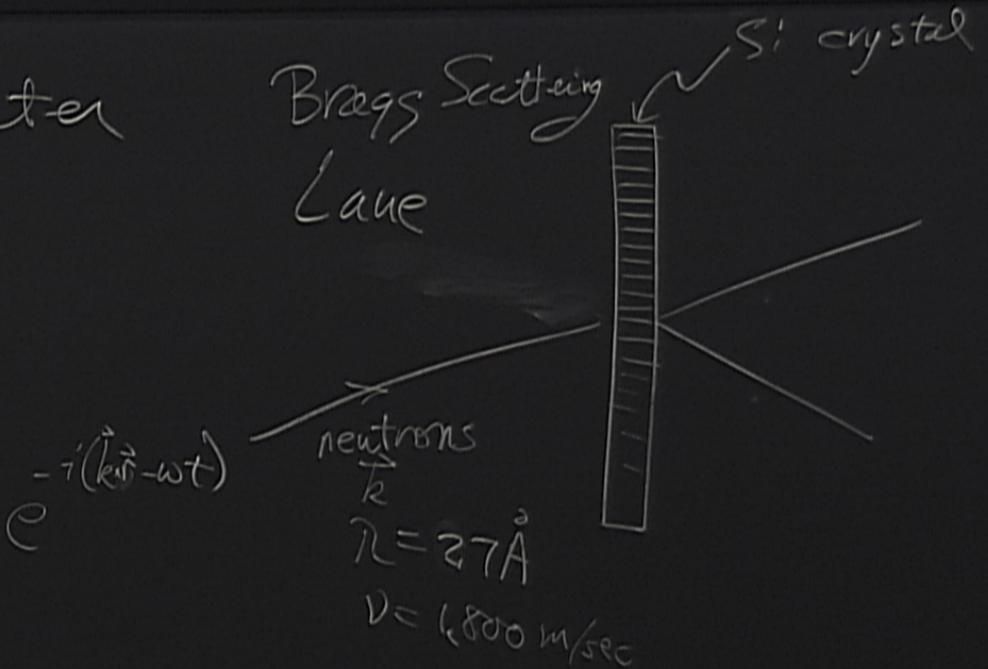


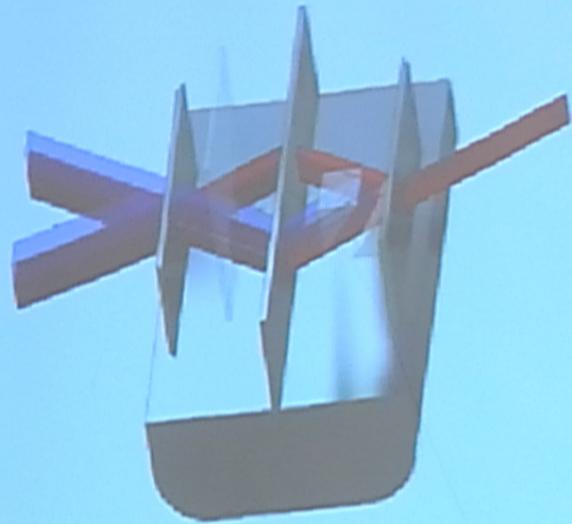


- Neutron Interferometer  
2 qubits
- Magnetic Resonance  
- Hilbert Space
- Diamond NV



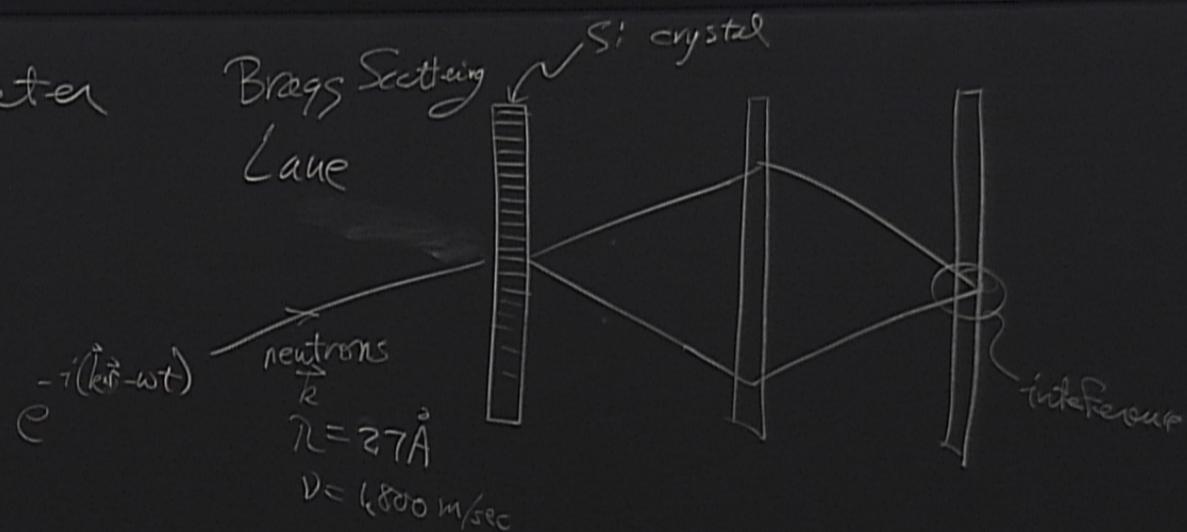
- Neutron Interferometer  
2 qubits
- Magnetic Resonance  
- Hilbert Space
- Diamond NV



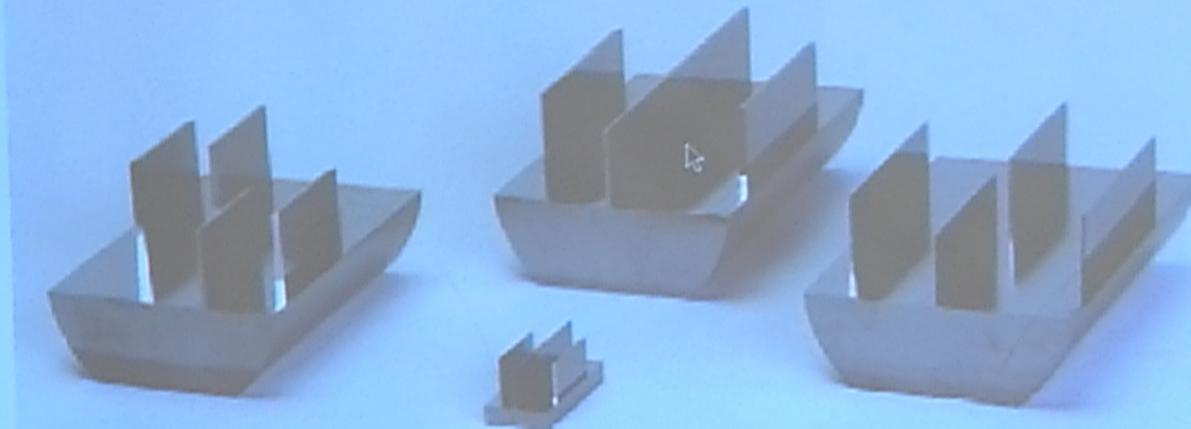


The three blade interferometer is shown above. The neutron beam enters at right and is a well collimated and mono-energetic beam. The beam interacts with the first blade and exits in a coherent superposition over two paths. The middle blade acts as a beam splitter and the beams recombine at the third blade. There are two neutron beams of interest leaving the crystal. We can conveniently detect the neutrons in either of these beams with a He-3 detector. A phase flag and set of prisms are shown inside the interferometer. We will describe the actions of these latter.

- Neutron Interferometer  
2 qubits
- Magnetic Resonance  
- Hilbert Space
- Diamond NV



phase mask and set of prisms are shown inside the interferometer.



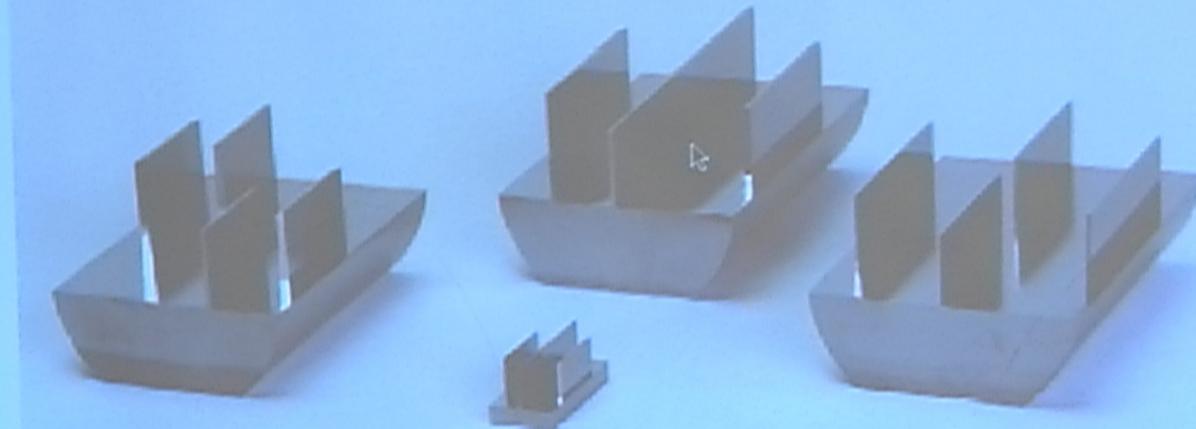
Picture of a variety of single crystal neutron interferometers. All are examples of Mach-Zehnder interferometers.

### ■ He-3 detector

We use a gas filled detector to measure neutrons. The gas is helium-3 which has a high absorption cross section of 5333 barns for 2200 m/s neutrons. 1 barn is  $10^{-28} \text{ m}^2$  or 100 square femtometers ( $\text{fm}^2$ ). Since the absorption cross-

150% ► | ← ◀ ▶

phase mask and set of prisms are shown inside the interferometer.



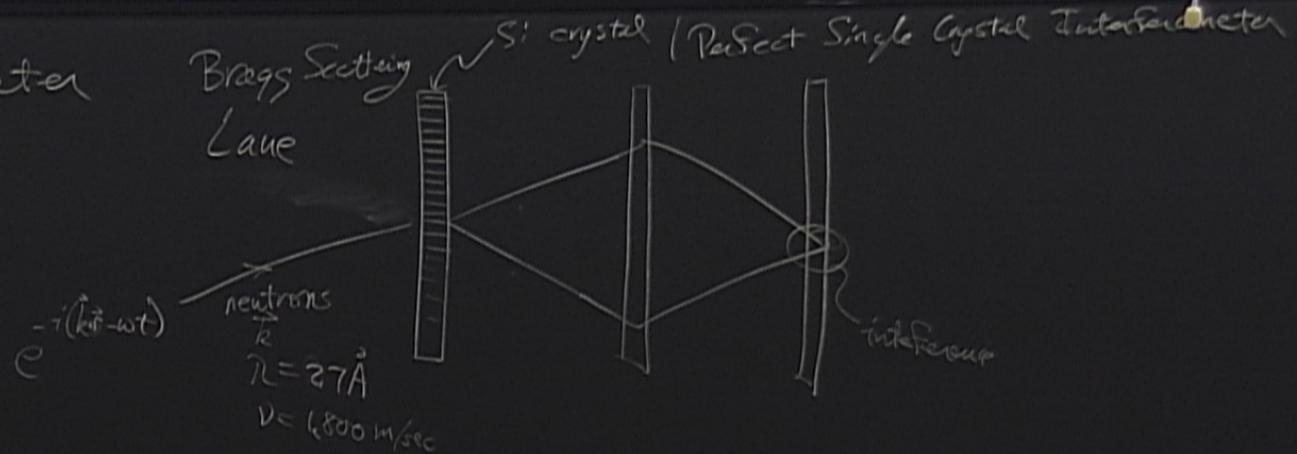
Picture of a variety of single crystal neutron interferometers. All are examples of Mach-Zehnder interferometers.

### ■ He-3 detector

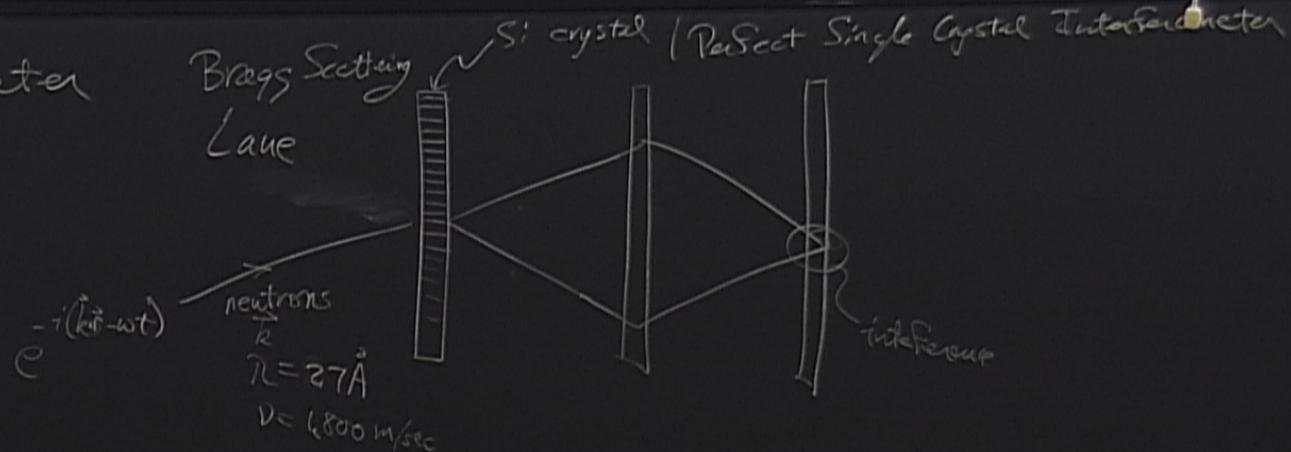
We use a gas filled detector to measure neutrons. The gas is helium-3 which has a high absorption cross section of 5333 barns for 2200 m/s neutrons. 1 barn is  $10^{-28} \text{ m}^2$  or 100 square femtometers ( $\text{fm}^2$ ). Since the absorption cross-

150% ►

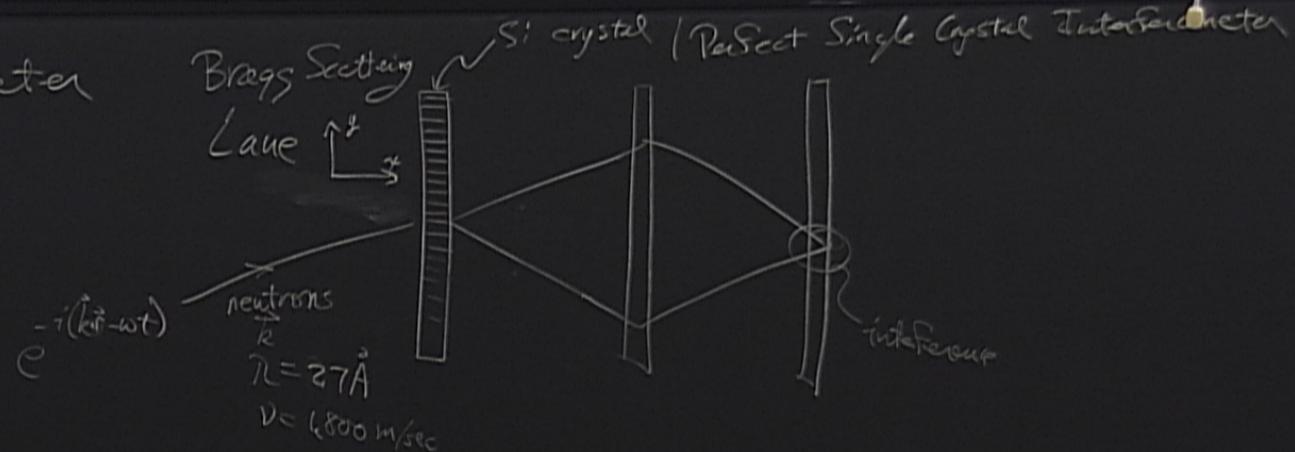
- Neutron Interferometer
- 2 qubits
- Sc Resonance
- $\Delta D \parallel$  bit Space
- NV



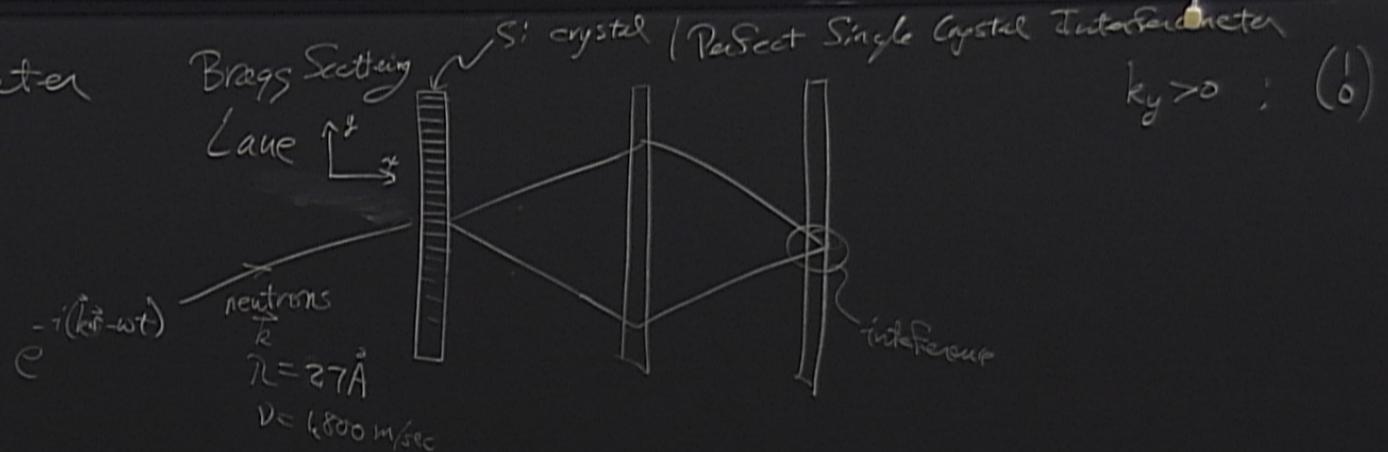
- Neutron Interferometer
- 2 qubits
- Magnetic Resonance
- Hilbert Space
- Diamond NV



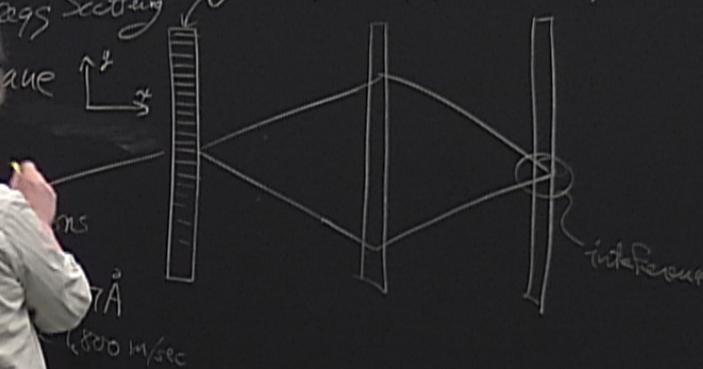
- Neutron Interferometer  
2 qubits
- Magnetic Resonance  
- Hilbert Space
- Diamond NV



- Neutron Interferometer  
2 qubits
- Magnetic Resonance  
- Hilbert Space
- Diamond NV



- Neutron Interferometer  
2 qubits
  - Magnetic Resonance
    - Hilbert Space
  - Diamond NV



$$\mathcal{U}_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix}$$



$$U_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix}$$

$$|\psi_1\rangle = U_1 |\psi_{in}\rangle$$
$$= \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

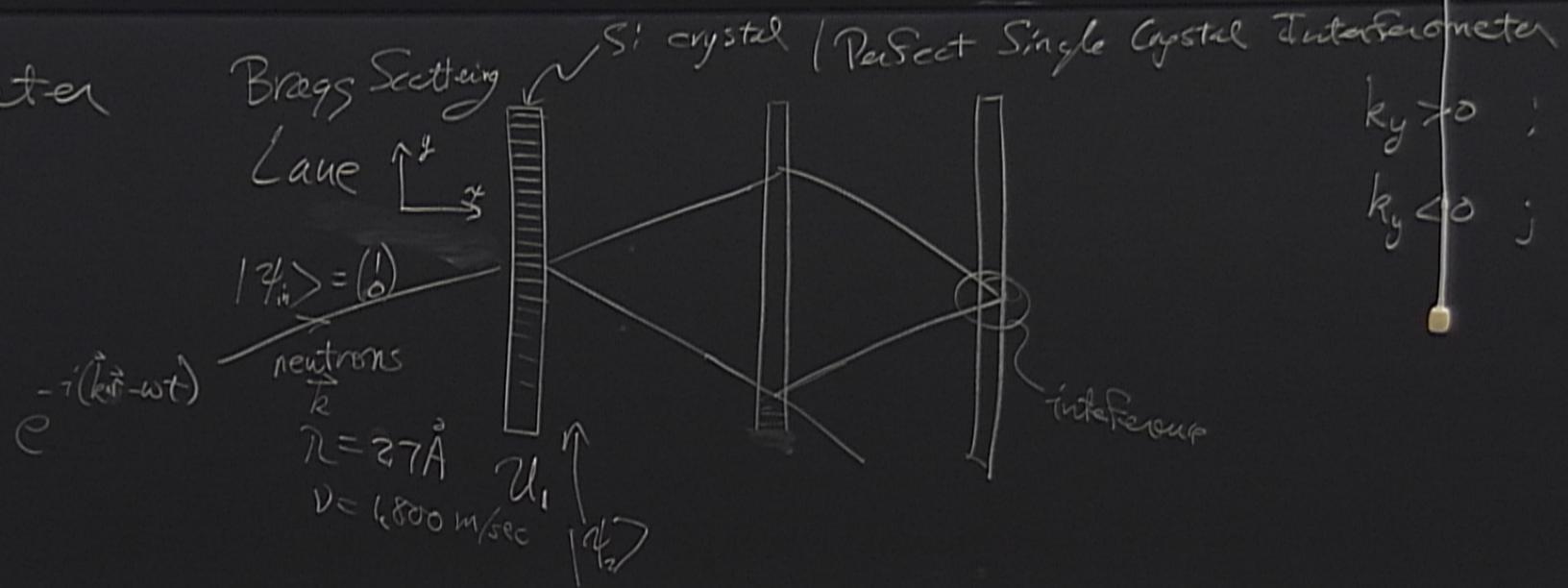
$$I = 47A$$
$$V = 1800 \text{ m/sec}$$
$$\mathcal{U}_1 \begin{pmatrix} | \psi_1 \rangle \\ | \psi_2 \rangle \end{pmatrix}$$

$$\mathcal{U}_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} ; \quad |\psi_2\rangle = \mathcal{U}_1 |\psi_{in}\rangle$$

$$(\alpha) = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

Interferometer  
ubits

Resonance  
Gilbert Space  
NV



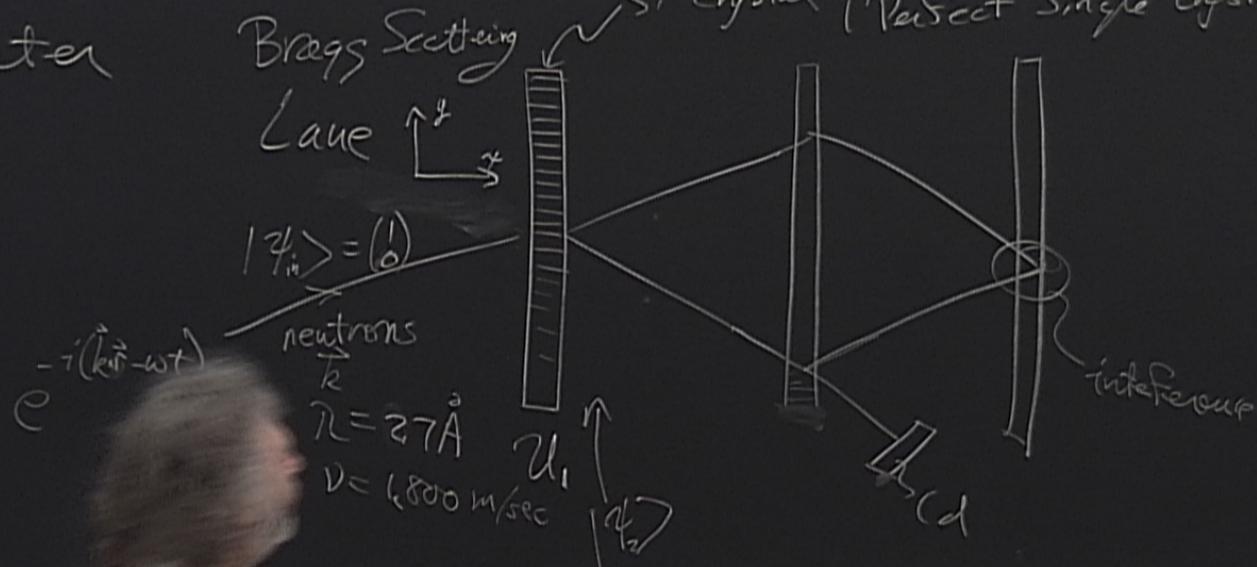
$$k_y > 0 : (0)$$
$$k_y < 0 : (1)$$

Interferometer  
ubits

Resonance  
elbert Space

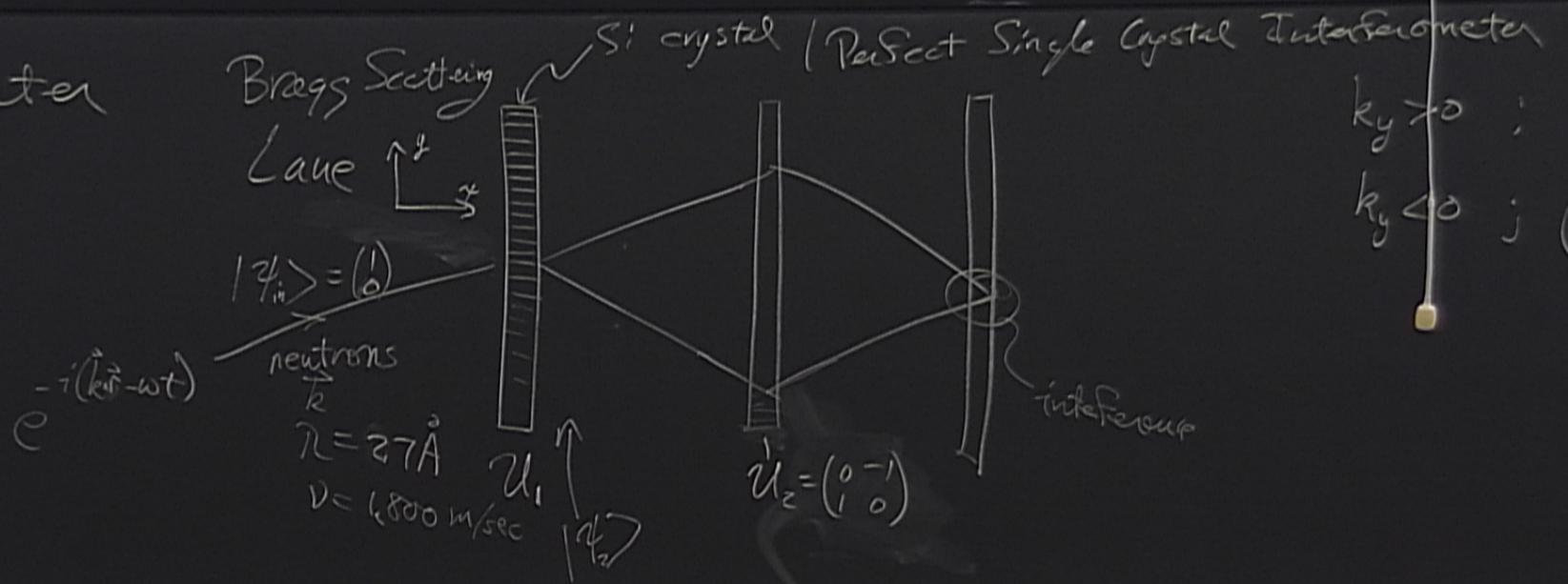
NV

Si crystal / Perfect Single Crystal Interferometer

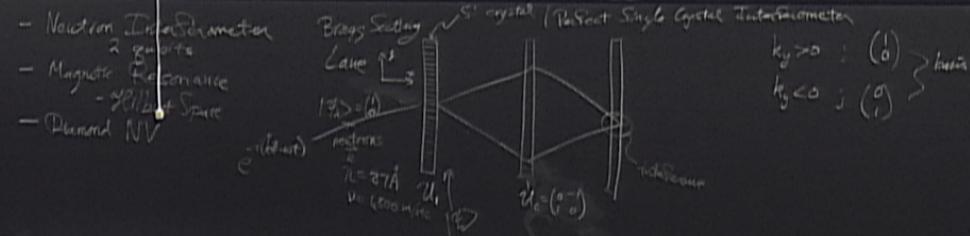


$$k_y > 0 : (0)$$
$$k_y < 0 : (1)$$

Interferometer  
ubits  
Resonance  
 Gilbert Space  
NV

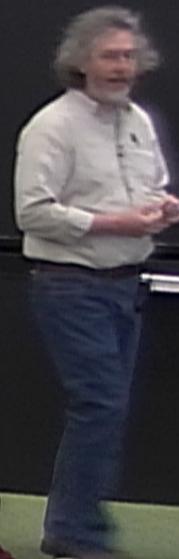


- Neutron Interferometer
- Magnetic Resonance
- Diamond NV



$$k_y > 0 : (0) \rightarrow \text{holes}$$

$$k_y < 0 : (0) \rightarrow \text{holes}$$

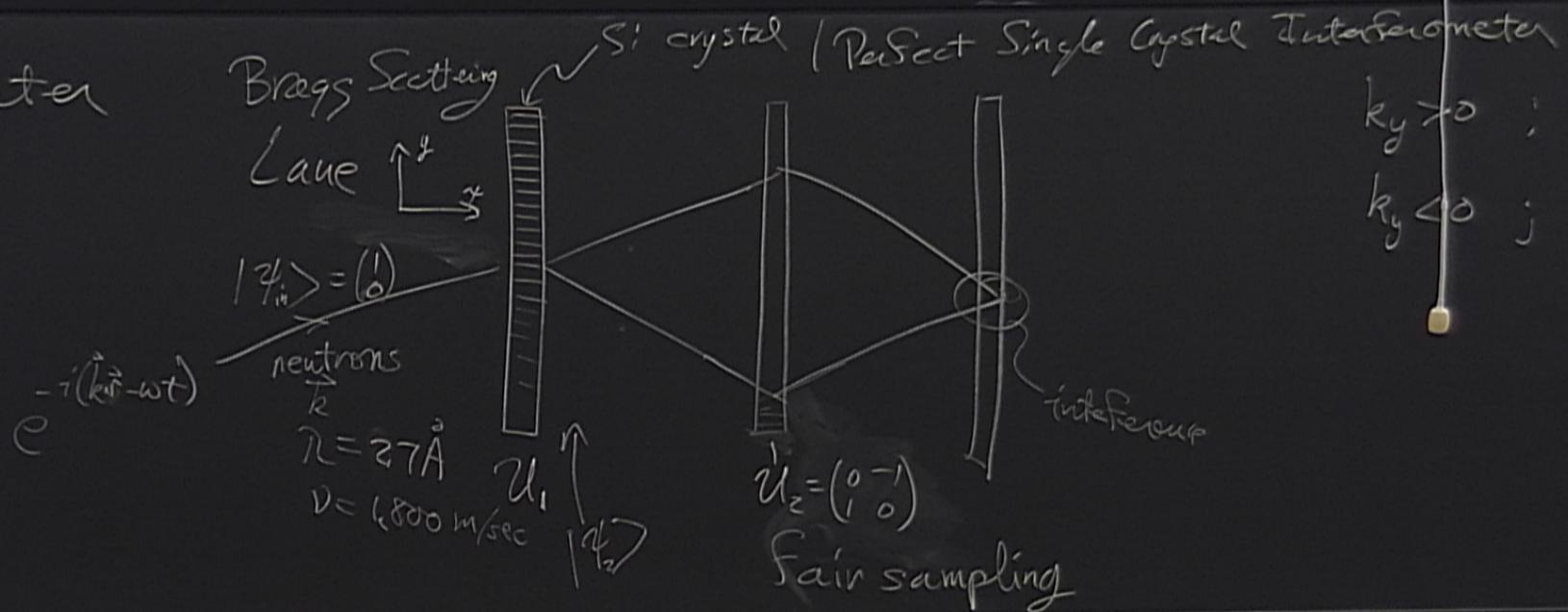


Interferometer  
qubits

Resonance

Gibbs Space

NV

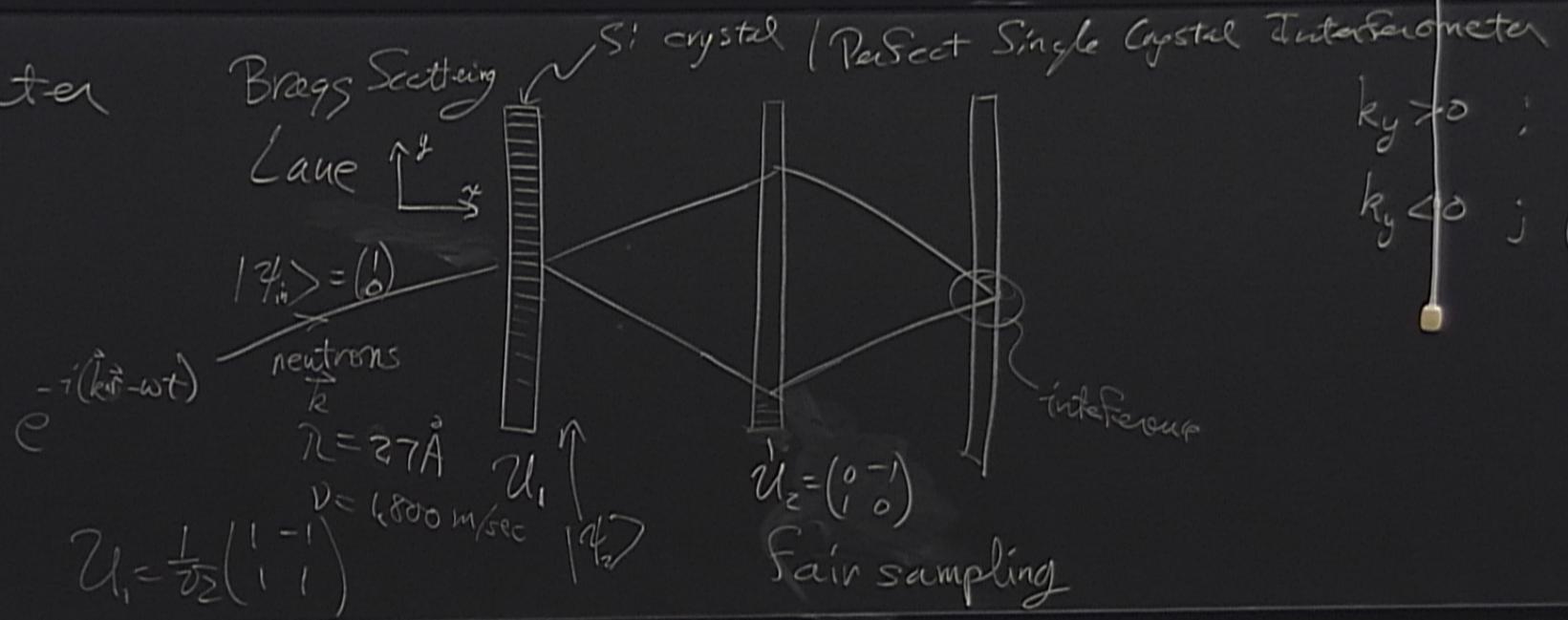


Interferometer  
qubits

Resonance

Gilbert Space

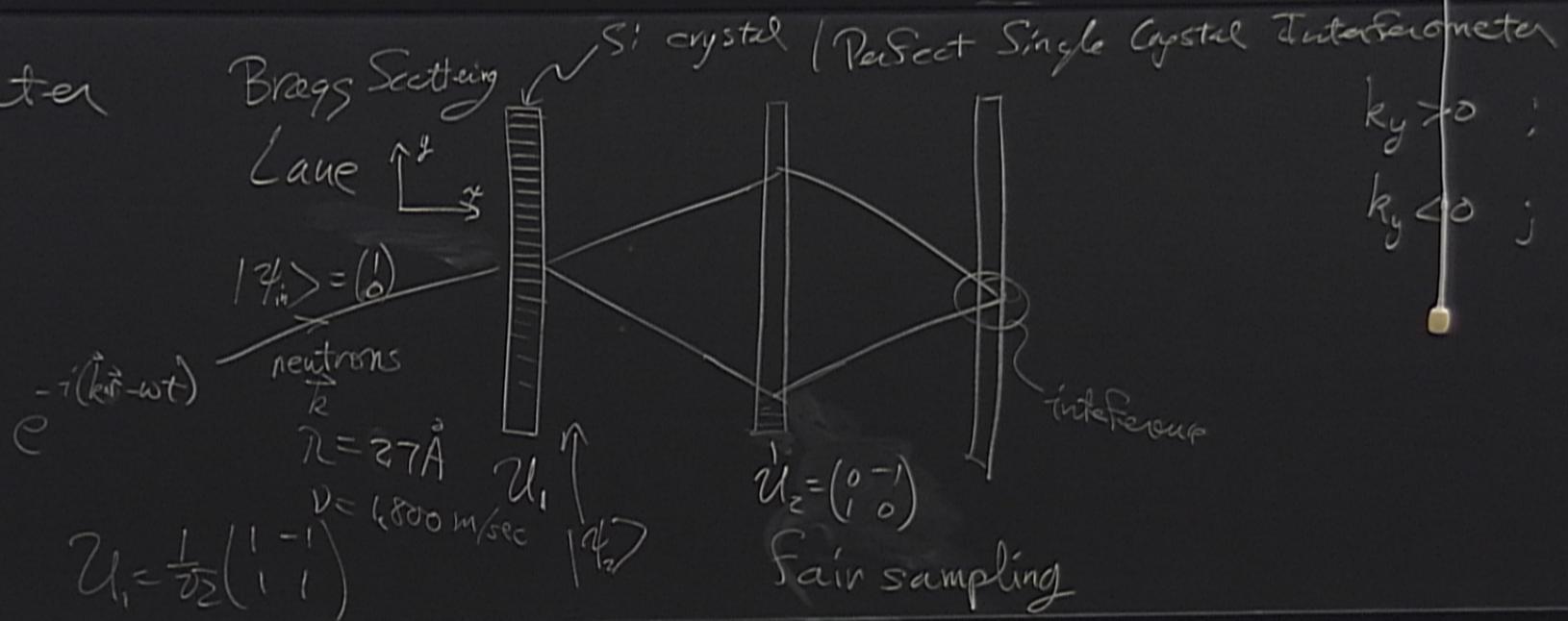
NV



Interferometer  
qubits

Resonance  
Silent Space

NV



$$U_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \quad ; \quad U_2 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad ; \quad U_3 = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

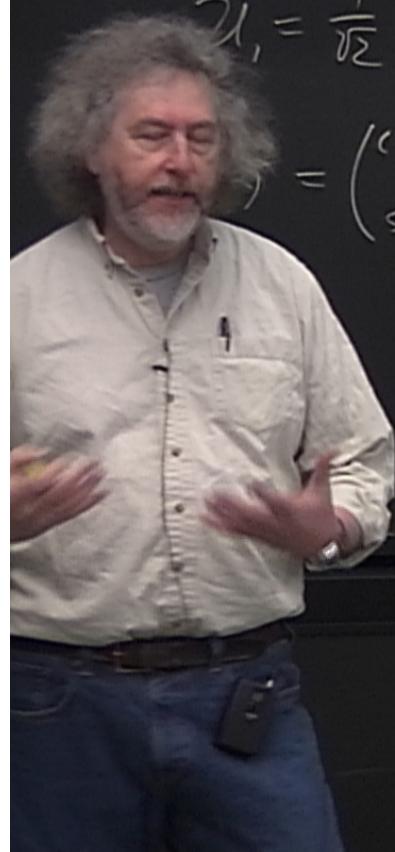
$v = 1800 \text{ m/sec}$

Fair sampling

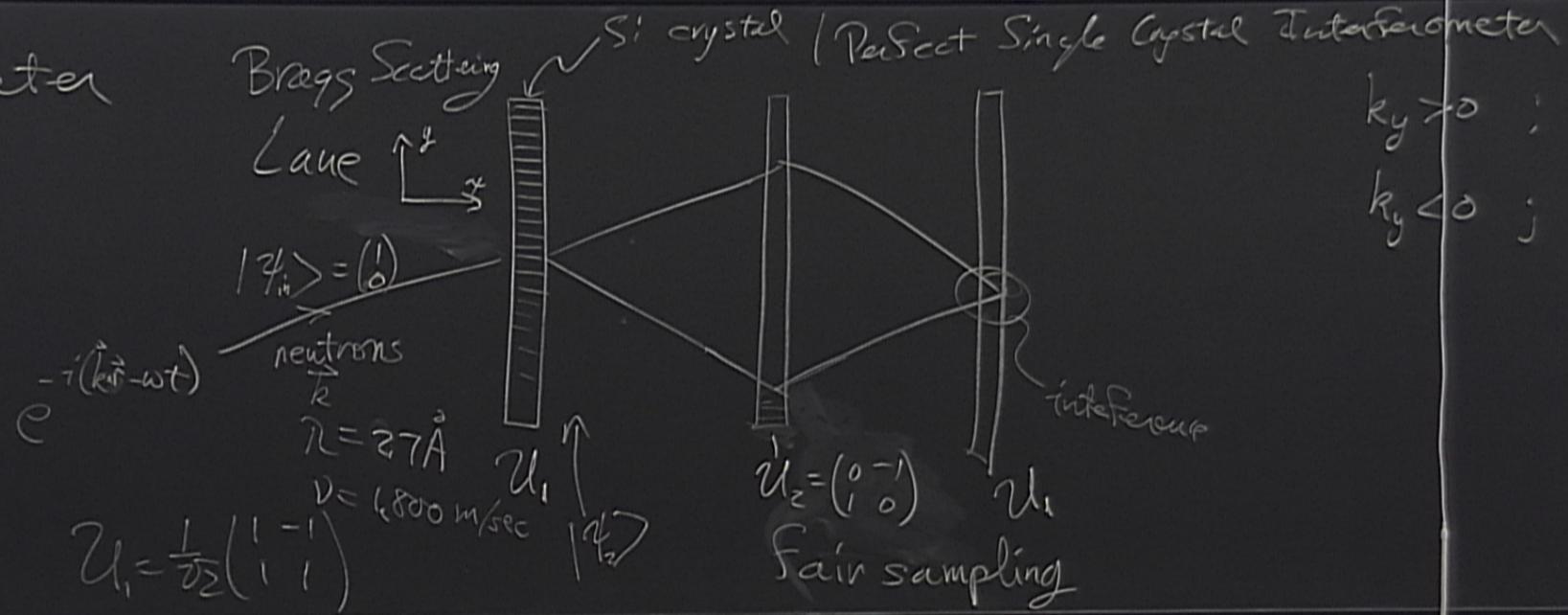
$$U_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \quad ; \quad |\Psi_1\rangle = U_1 |\Psi_{in}\rangle ; \quad |\Psi_2\rangle = U_2 U_1 |\Psi_{in}\rangle$$

$$= \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \quad = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

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

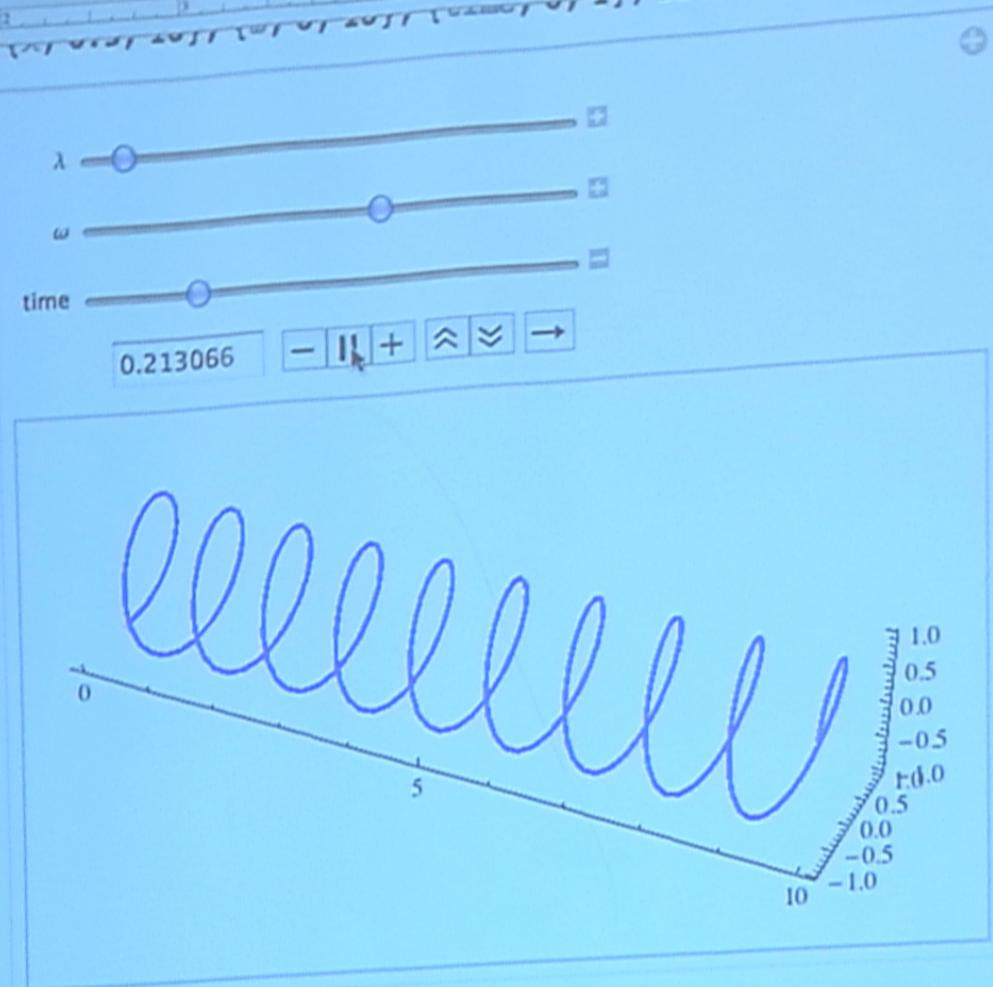


1 Interferometer  
 2 qubits  
 Resonance  
 Hilbert Space  
 NV



$$\begin{aligned}
 ; \quad | \Psi_2 \rangle &= U_1 | \Psi_{in} \rangle ; \quad | \Psi_3 \rangle = U_2 U_1 | \Psi_{in} \rangle \\
 &= \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \\
 &\quad \left( \begin{array}{l} \sin \alpha \\ \cos \alpha \end{array} \right) \quad = \frac{1}{\sqrt{2}} \begin{pmatrix} -1 \\ 1 \end{pmatrix}
 \end{aligned}$$

For the neutron interferometer we will need also the solution when the incoming beam is from above

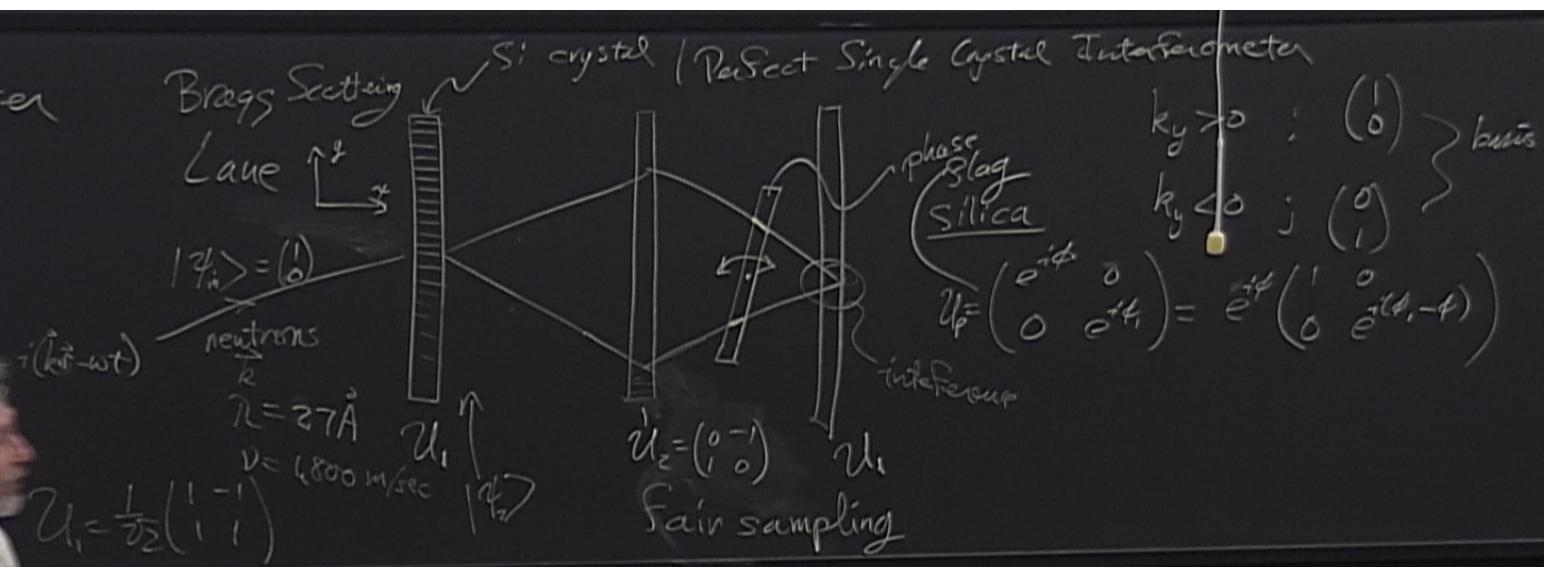


interparameter  
ubits

resonance

bet Space

V

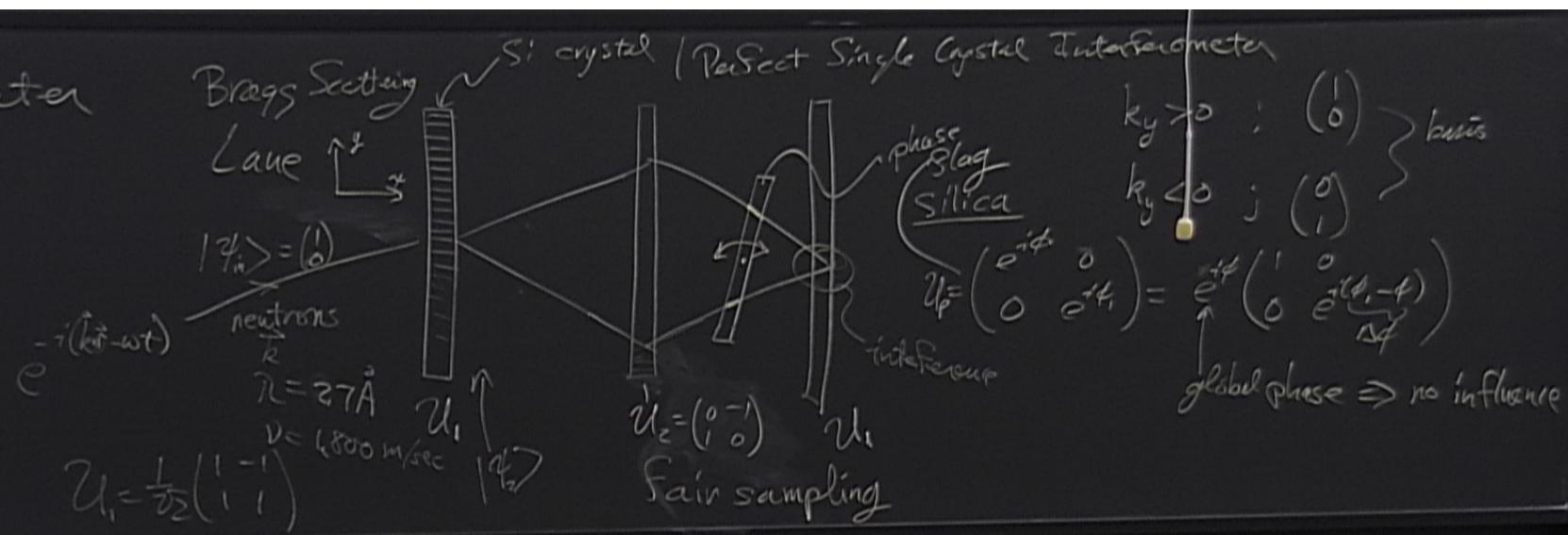


interparameter  
ubits

resonance

bit Space

V



$$U_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix}$$

$\vec{U}_1$

$v = 6800 \text{ m/sec}$

$$\vec{U}_2 = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

$\vec{U}_1$

Fair sampling

global phase  $\Rightarrow$  no influence

$$|4_2\rangle = U_1 |4_{in}\rangle ; |4_3\rangle = U_2 U_1 |4_{in}\rangle ; |4_4\rangle = U_3 U_2 U_1 |4_{in}\rangle$$

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

$$= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

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

$$U_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix}$$

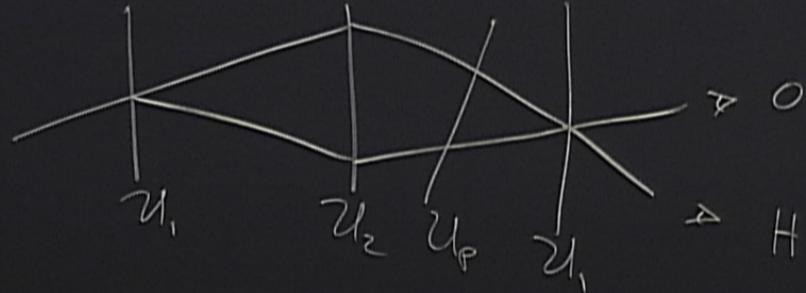
$v = 6800 \text{ m/sec}$

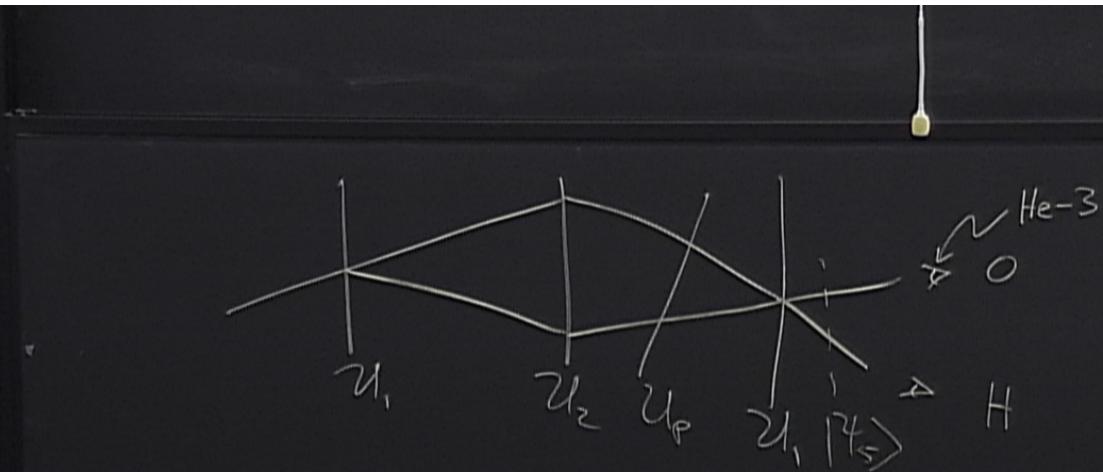
$$U_2 = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

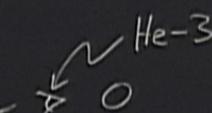
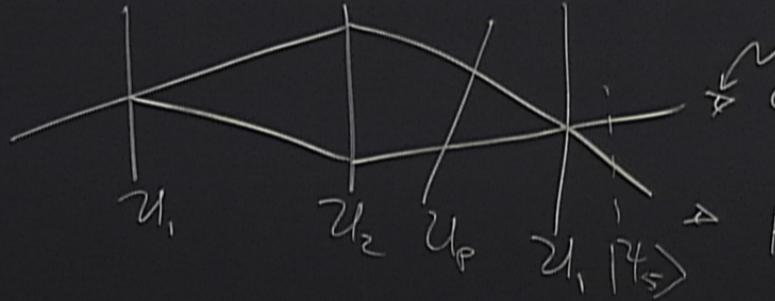
Fair sampling

global phase  $\Rightarrow$  no influence

$$\begin{aligned}
 |4_2\rangle &= U_1 |4_{in}\rangle ; \quad |4_3\rangle = U_2 U_1 |4_{in}\rangle ; \quad |4_4\rangle = U_1 U_2 U_1 |4_{in}\rangle \\
 &= \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad &= \frac{1}{\sqrt{2}} \begin{pmatrix} -1 \\ e^{-i\phi} \end{pmatrix} \\
 &= \frac{1}{\sqrt{2}} \begin{pmatrix} -1 \\ -1 \end{pmatrix} \quad &|4_5\rangle = U_1 |4_4\rangle = \frac{1}{2} \begin{pmatrix} -1 - e^{-i\phi} \\ -1 + e^{-i\phi} \end{pmatrix}
 \end{aligned}$$





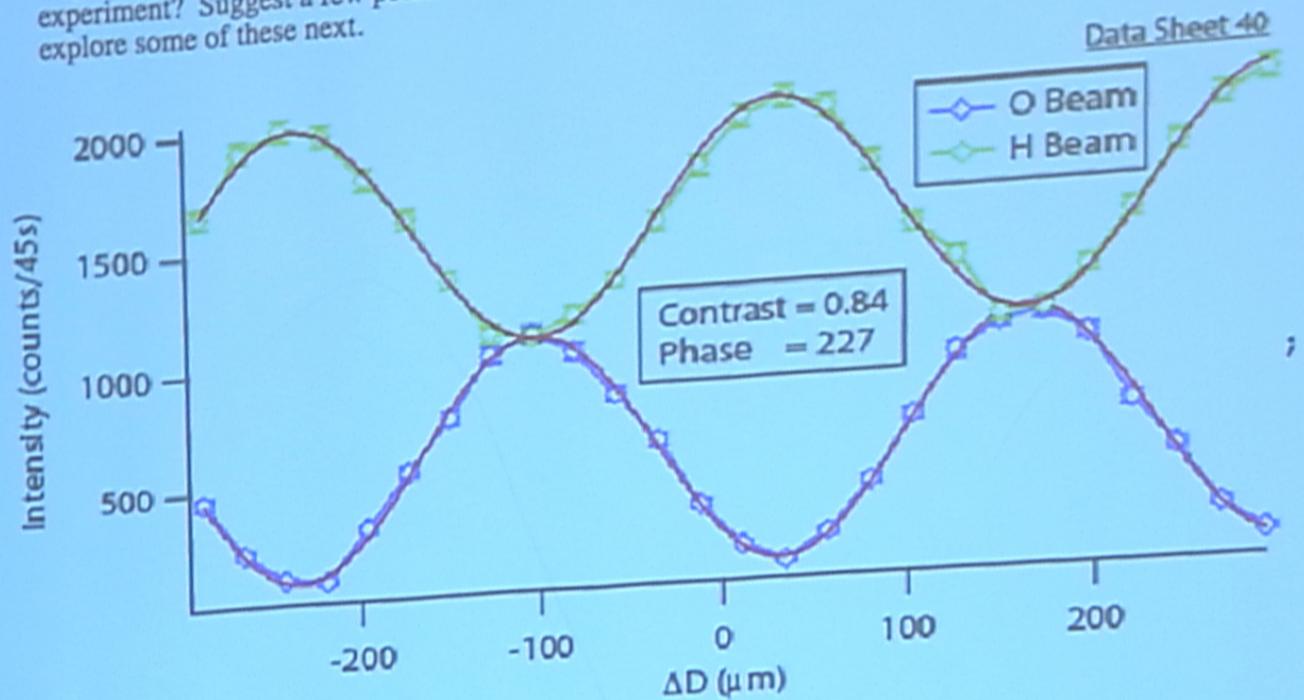


$\rightarrow O$

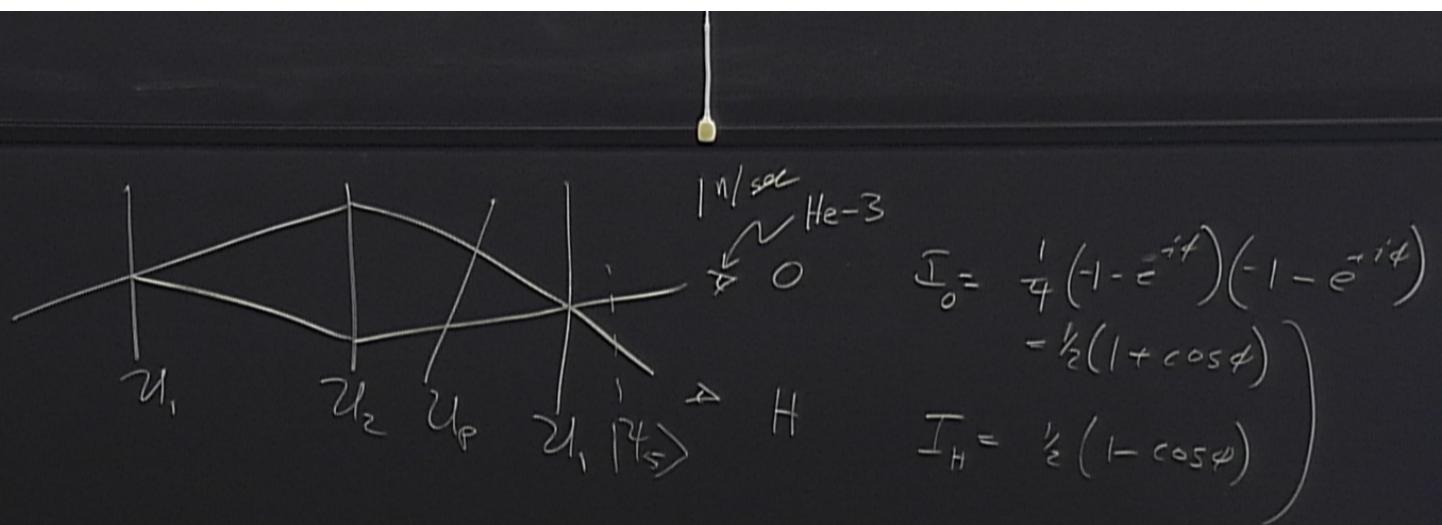
$H$

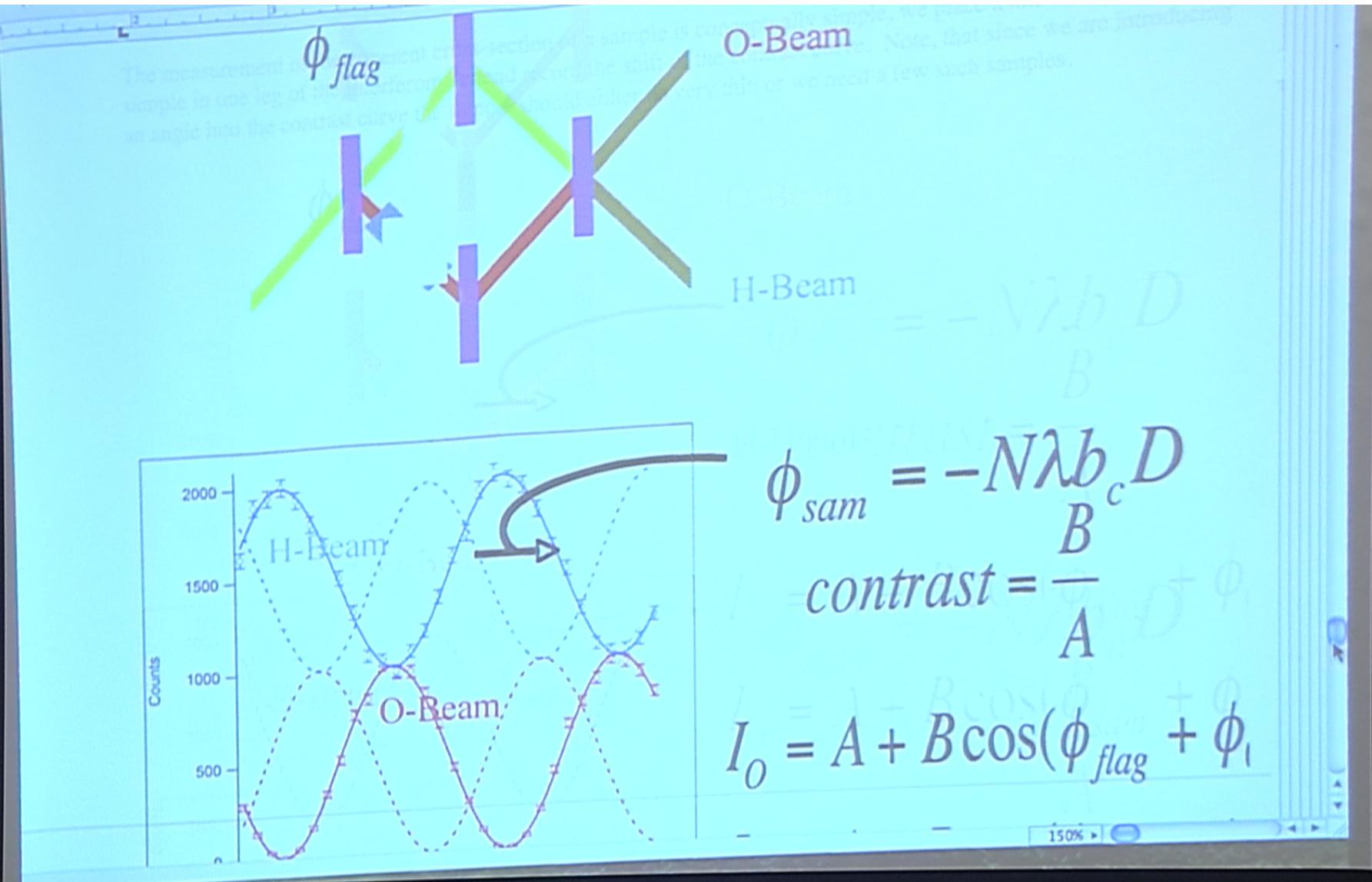
$$\begin{aligned}I_o &= \frac{1}{4} (-1 - e^{-i\phi}) (-1 - e^{+i\phi}) \\&= \frac{1}{2} (1 + \cos \phi) \\I_H &= \frac{1}{2} (1 - \cos \phi)\end{aligned}$$

- Problem 10: Here is a set of experimental data. The horizontal axis is given in micrometers. What width of silica corresponds to a  $\pi$  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.



Note, all of the data on neutron interferometry was collected by Dr. Dmitry Pushin with the NIST setup.

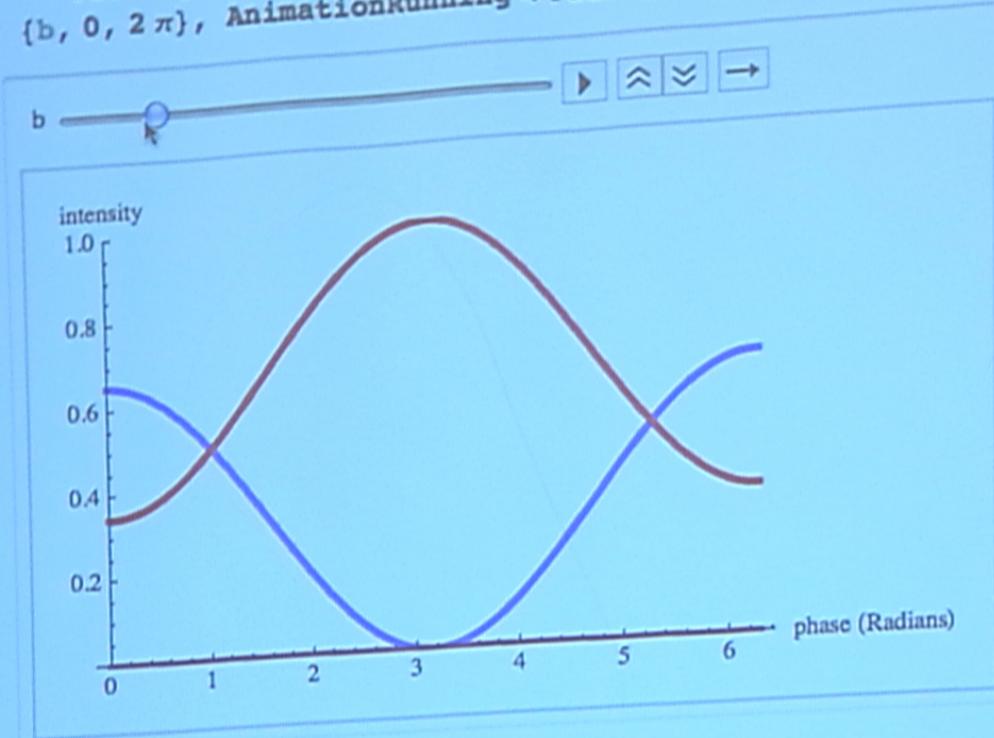




```

{AxesLabel -> {"phase (Radians)", "intensity"}, 
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 Plot[M3H[a, b], {a, 0, 2 \pi}, 
 {AxesLabel -> {"phase (Radians)", "intensity"}, 
 PlotStyle -> {RGBColor[1, 0, 0], Thickness[0.01]}, PlotRange -> {0, 1}]], 
 {b, 0, 2 \pi}, AnimationRunning -> False, SaveDefinitions -> True]

```

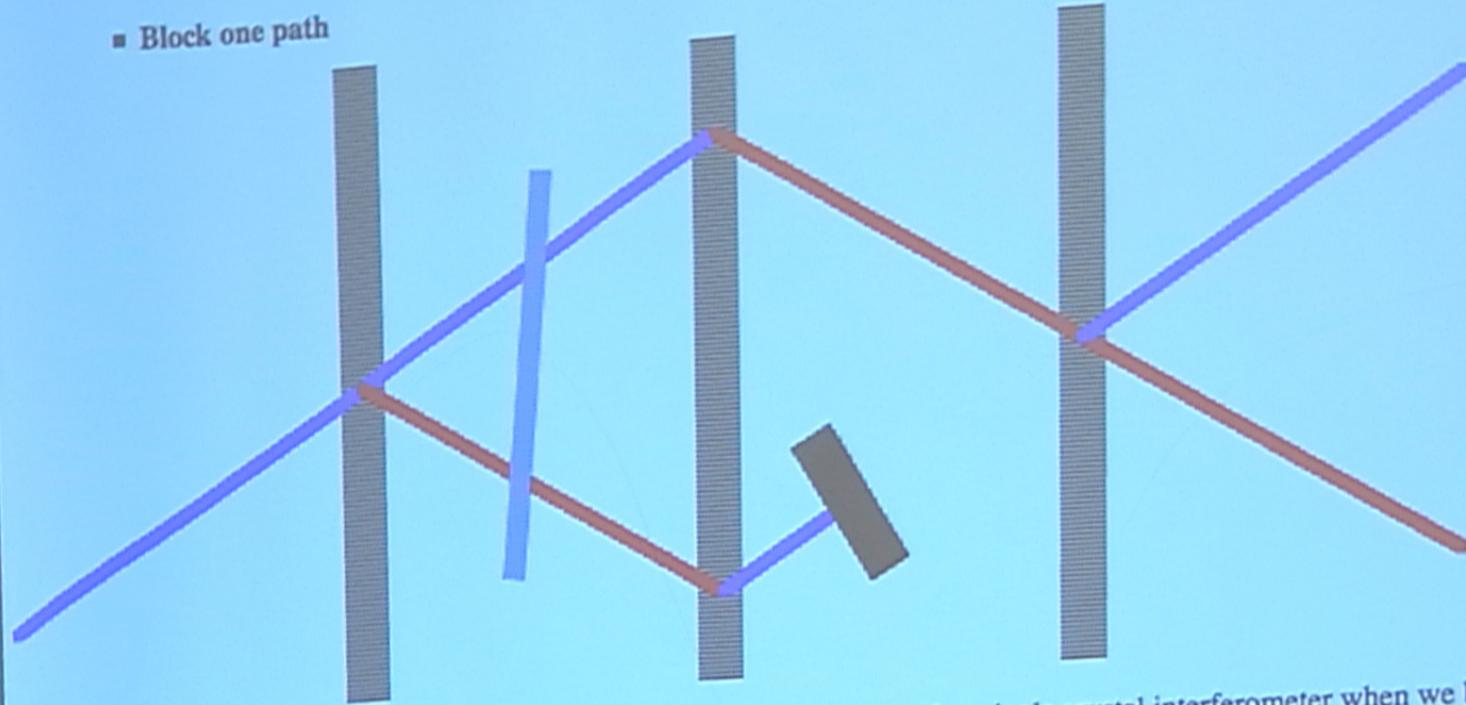


The slider changes the sample induced phase shift. Note that this effect alone is not sufficient to describe the experimental result.

A diagram on a chalkboard illustrating the centers of two ellipses. The top ellipse is centered at the origin with its center labeled  $(0)$ . The bottom ellipse is centered at  $(1)$ . A vector from the origin to the center of the top ellipse is labeled  $\sqrt{2} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ . A vector from the origin to the center of the bottom ellipse is labeled  $\sqrt{2} \begin{pmatrix} 1 \\ e^{-i\pi/4} \end{pmatrix}$ .

1

■ Block one path



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

- Discussion: This is a simple example that helps to show that the intensities are governed by probability amplitudes. Notice that there is a change in the normalization. How did the phase flag become a global phase and thus its influence vanish? What if you allowed the neutrons that leave the interferometer to carry away information, could you then use this resource to make the outcome compatible with a probabilistic interpretation of the paths?

150%