

GEST 011, Newton's Clock & Heisenberg's Dice, Fall 2013

Dancing Light

(Polarization, a Quantum Cousin of Coin)

Mahn-Soo Choi (Korea University)

November 7, 2013 (v5.4)

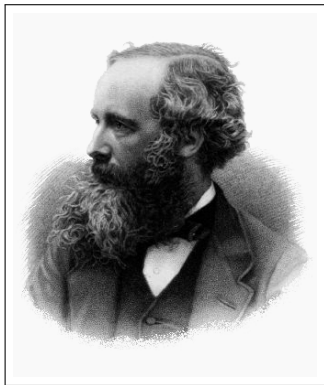
So Weird?

$$\psi = \frac{\text{100 won coin} + \text{100 won coin}}{\sqrt{2}}$$

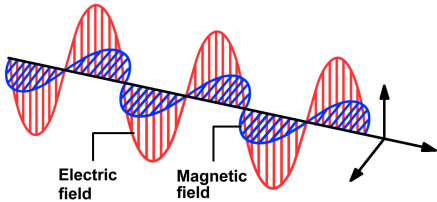
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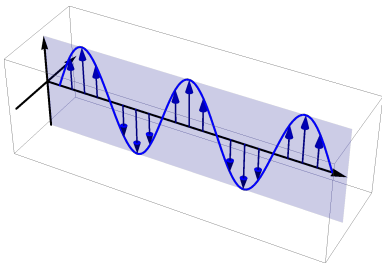
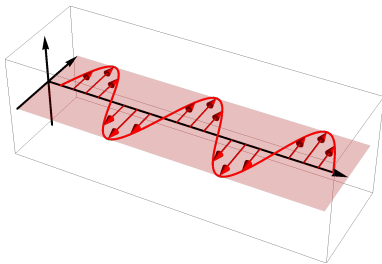
Light Again!



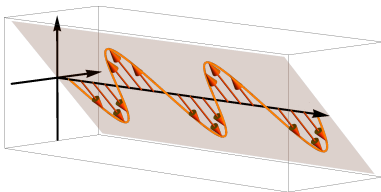
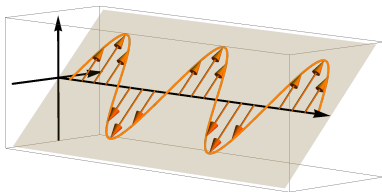
James C. Maxwell (1831-1879)



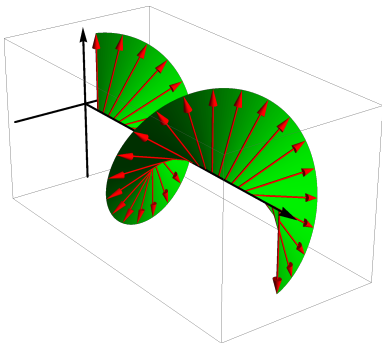
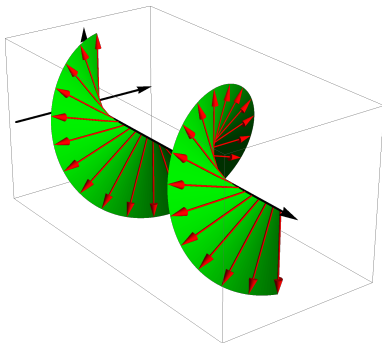
Linear Polarization



Linear Polarization



Circular Polarization



Symbols and the Abstract

꽃

김춘수 (金春洙, 1922-2004)

내가 그의 이름을 불러 주기 전에는
그는 다만
하나의 몸짓에 지나지 않았다.

내가 그의 이름을 불러 주었을 때,
그는 나에게로 와서
꽃이되었다.

내가 그의 이름을 불러준 것처럼
나의 이 빛깔과 향기(香氣)에 알맞은
누가 나의 이름을 불러다오.
그에게로 가서 나도
그의 꽃이 되고 싶다.

우리들은 모두
무엇이 되고 싶다.
너는 나에게 나는 너에게
잊혀지지 않는 하나의 눈짓이 되고 싶다



<http://busan.com>

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<http://busan.com>

도덕경 (道德經)

道可道, 非常道. 名可名, 非常名.
無名, 天地之始. 有名, 萬物之母.

故常無欲以觀其妙. 常有欲以觀其.
此兩者, 同出而異名, 同謂之玄,
玄之又玄, 衆妙之門.



도덕경 (道德經)

노자 (老子), Author; Lin Yutang (林語堂), Translator

道可道, 非常道. 名可名, 非常名.
無名, 天地之始. 有名, 萬物之母.

도라 이룰 수 있는 도는
진정한 도가 아니요,
부를 수 있는 이름은
진정한 이름이 아니다.

이름 없는 것은 천지의 처음이고
이름 있는 것은 만물의 어머니다.

The Tao that can be told of
Is not the Absolute Tao;
The Names that can be given
Are not Absolute Names.

The Nameless is the origin of
Heaven and Earth;
The Named is the Mother of All Things.

도덕경 (道德經)

노자 (老子), Author; Lin Yutang (林語堂), Translator

故常無欲以觀其妙. 常有欲以觀其.
此兩者, 同出而異名, 同謂之玄,
玄之又玄, 衆妙之門.

그러므로 항상 사심 없이
미묘한 본체를 살피고, 항상
욕심이 있는 것으로 그
순환하는 현상을 살핀다.

이 둘은 같이 나와 이름을
달리하며 둘다 현묘한
것이라고 한다.

현묘하고 또 현묘하여 모든
미묘한 것이 나오는 문이다.

Therefore:

Oftentimes, one strips oneself of passion
In order to see the **Secret of Life**;
Oftentimes, one regards life with passion,
In order to see its **manifest forms**.

**These two (the Secret and its manifestations)
Are (in their nature) the same;**

They are given different names
When they become manifest.
They may both be called the Cosmic Mystery.

**Reaching from the Mystery into the Deeper Mystery
Is the Gate to the Secret of All Life.**

양자경 (量子經)

작자 미상 (作者 未詳)

형체가 없다하여 두려워 말라!
Don't be afraid of **abstract objects**!

“Quantum” States of a Penny



$\Rightarrow \psi_H(x) \Rightarrow |H\rangle$



$\Rightarrow \psi_T(x) \Rightarrow |T\rangle$

Why Symbols?

(abstract objects)

Why Symbols?

(abstract objects)

귀찮으니즘!!

Why Symbols?

(abstract objects)

귀찮으니즘!!

☉	日	日	日	日	日
☾	月	月	月	月	月
山	山	山	山	山	山
水	水	水	水	水	水
雨	雨	雨	雨	雨	雨
木	木	木	木	木	木
禾	禾	禾	禾	禾	禾
人	人	人	人	人	人

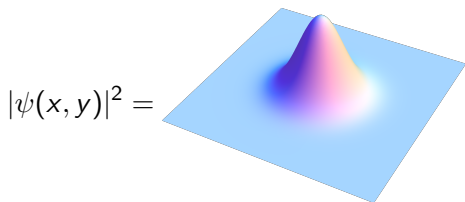
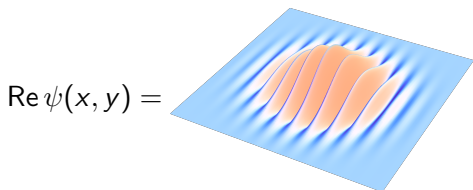
Symbols make life easier and simpler!

Why not just “ H ” or “ T ”?

Why not just “ H ” or “ T ”?

깔끄미즘!?
까칠리즘!?

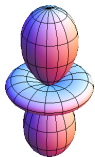
Wave Packet in 2D



$$|\bar{x}, \Delta x; \bar{p}, \Delta p\rangle \quad |0, 1 \text{ nm}; 8 \times 10^9 \hbar, 0.5 \times 10^9 \hbar\rangle$$

Atomic Orbitals

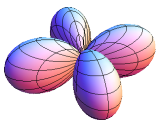
$|d_{z^2}\rangle$



$|d_{x^2-y^2}\rangle$



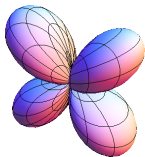
$|d_{xy}\rangle$



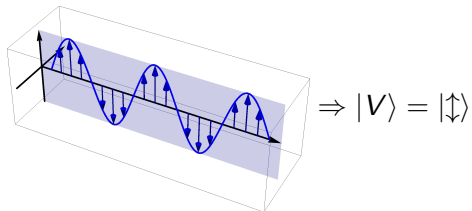
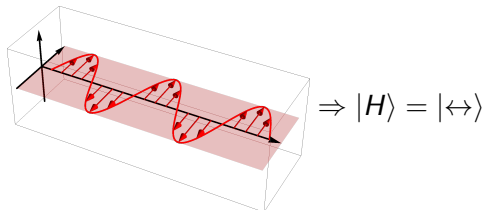
$|d_{yz}\rangle$

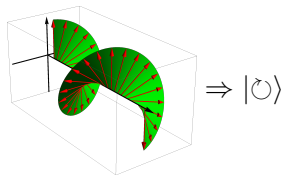
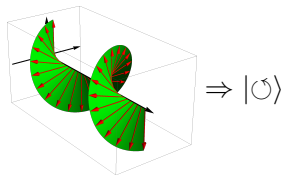
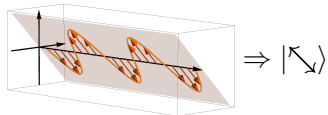
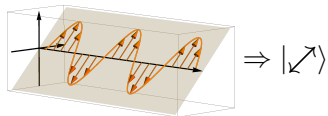


$|d_{zx}\rangle$



Polarization States of Light

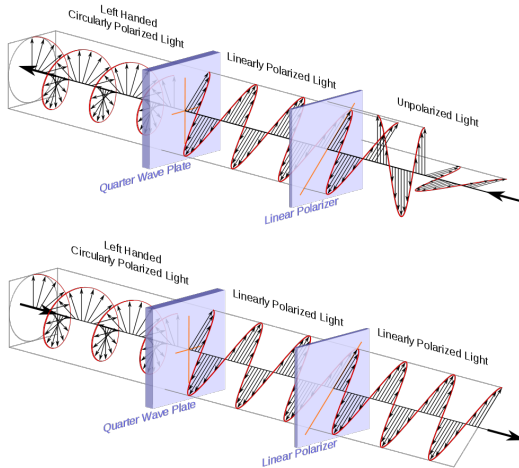




Manipulation of Polarization States

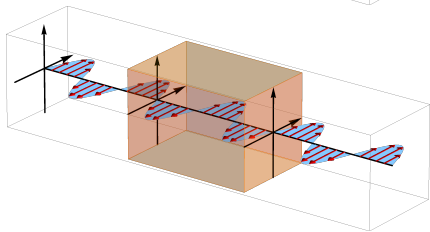
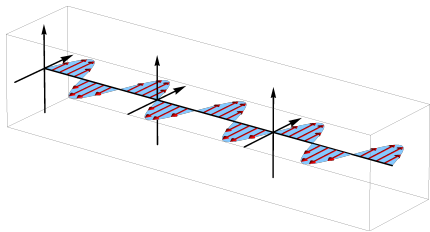
Polarizers

(classical light)

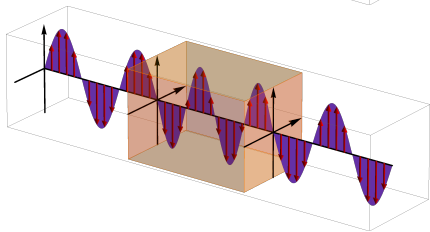
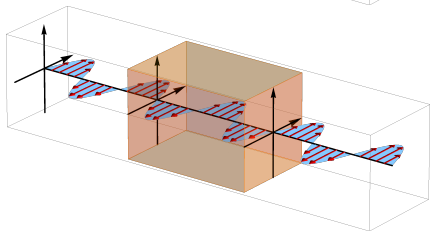
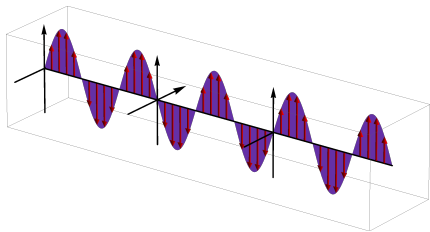
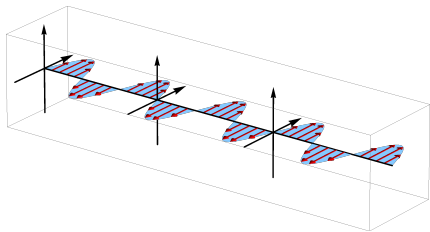


(Images from Wikipedia)

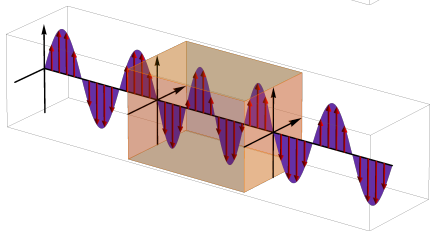
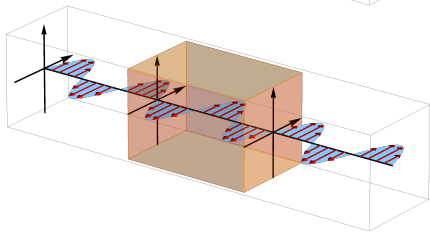
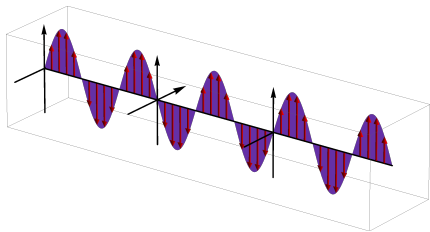
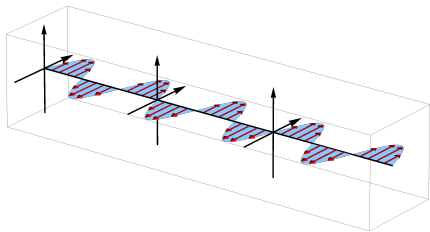
Half-Wave Plates



Half-Wave Plates



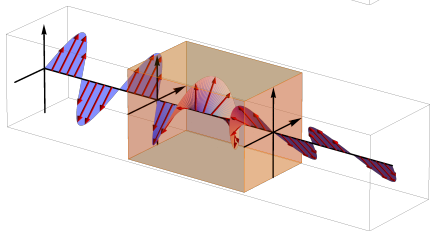
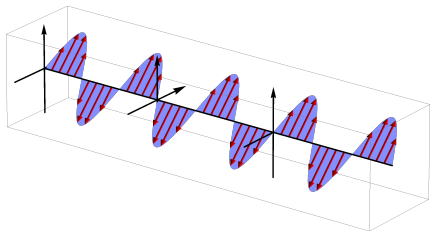
Half-Wave Plates



$$|\leftrightarrow\rangle \Rightarrow |\leftrightarrow\rangle$$

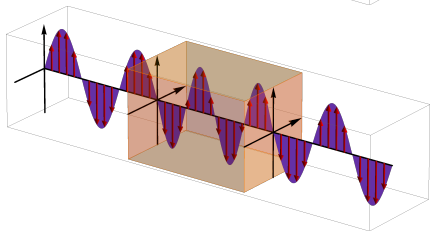
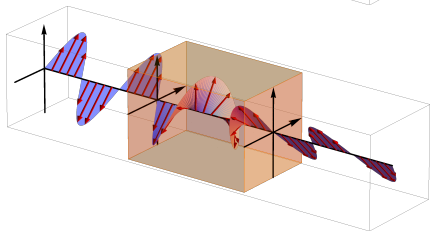
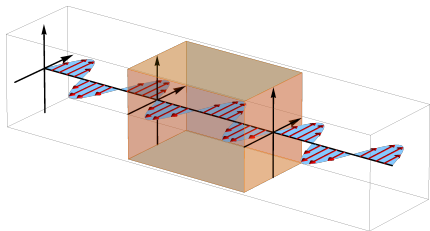
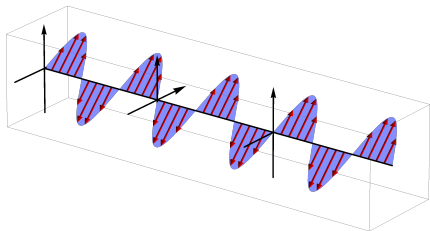
$$|\updownarrow\rangle \Rightarrow -|\updownarrow\rangle$$

Half-Wave Plates



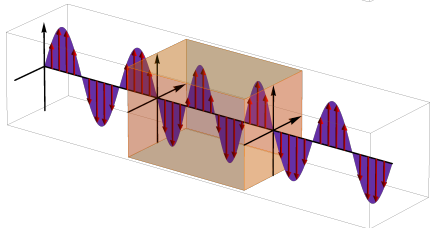
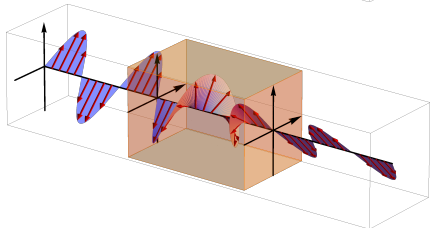
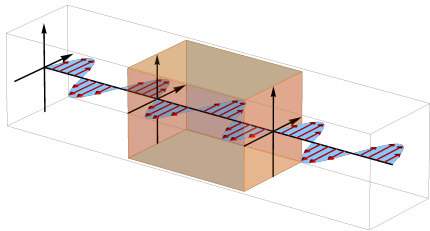
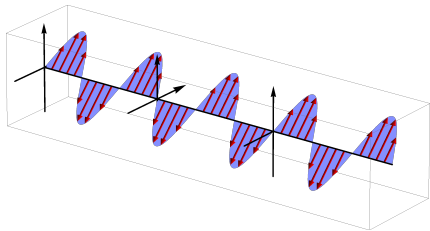
$$|\nearrow\rangle \Leftrightarrow |\searrow\rangle$$

Half-Wave Plates



$$|\nearrow\rangle \Leftrightarrow |\searrow\rangle$$

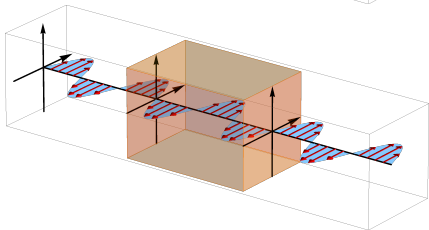
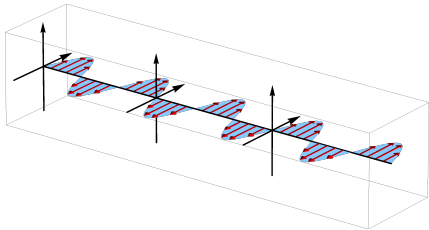
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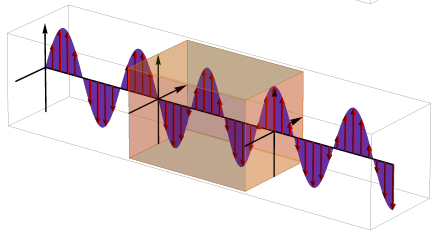
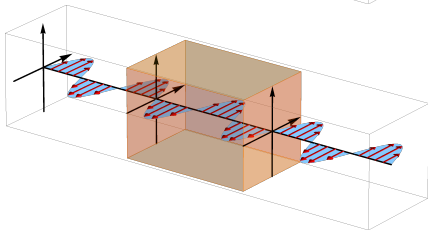
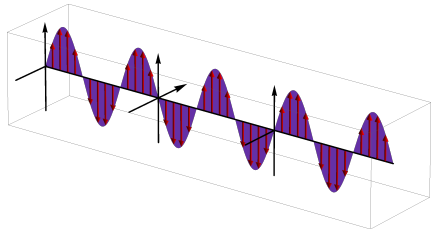
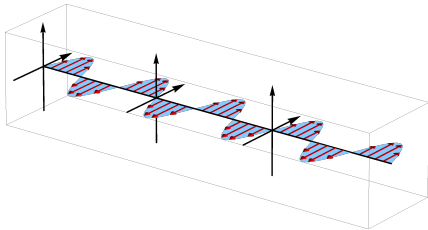
$$\frac{|\leftrightarrow\rangle + |\updownarrow\rangle}{\sqrt{2}} \Leftrightarrow \frac{|\leftrightarrow\rangle - |\updownarrow\rangle}{\sqrt{2}}$$

$$|\leftrightarrow\rangle \Rightarrow |\leftrightarrow\rangle, \quad |\updownarrow\rangle \Rightarrow -|\updownarrow\rangle$$

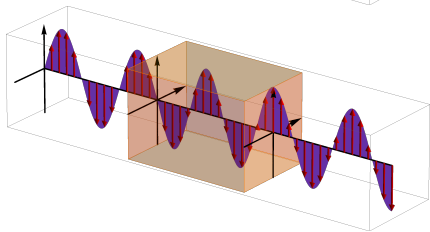
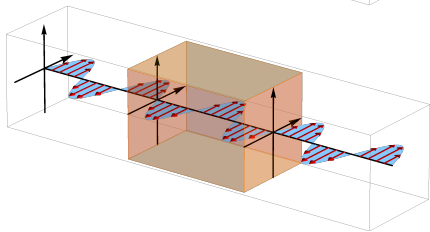
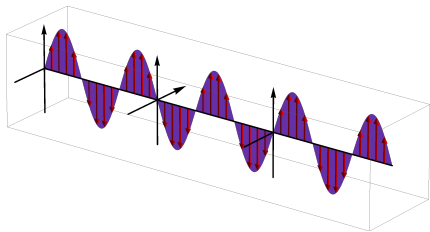
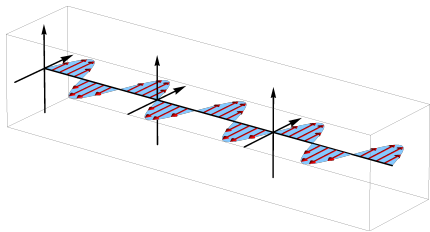
Quarter-Wave Plates



Quarter-Wave Plates



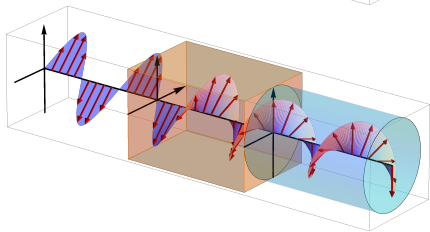
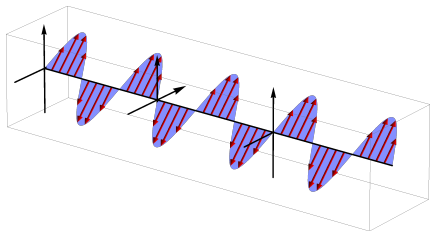
Quater-Wave Plates



$$|\leftrightarrow\rangle \Rightarrow |\leftrightarrow\rangle$$

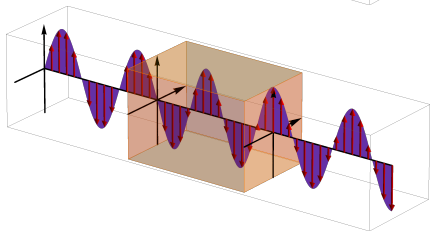
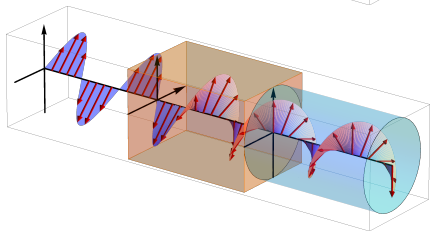
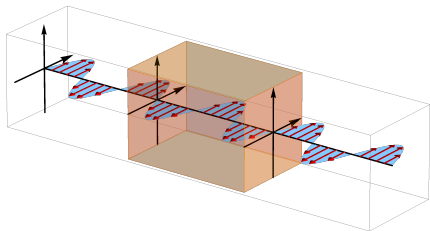
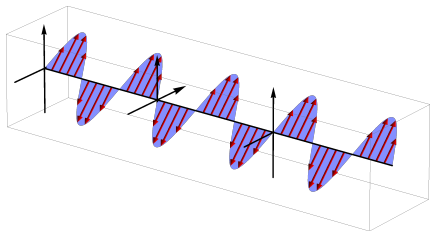
$$|\updownarrow\rangle \Rightarrow i|\updownarrow\rangle$$

Quarter-Wave Plates



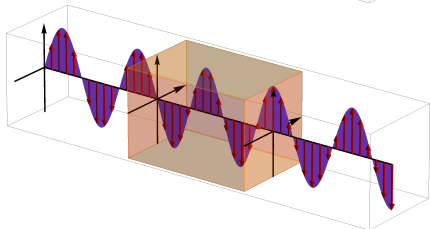
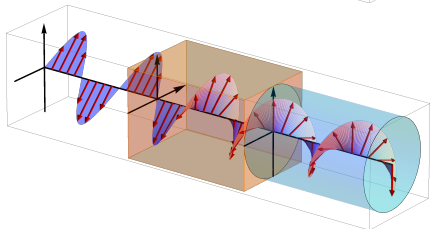
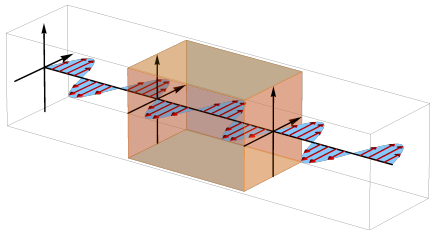
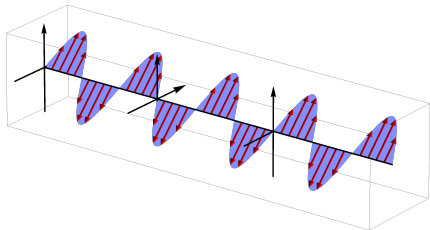
$$|\nearrow\rangle \Rightarrow |\circ\rangle$$

Quarter-Wave Plates



$$|\nearrow\rangle \Rightarrow |\circ\rangle$$

Quarter-Wave Plates



$$\frac{|\leftrightarrow\rangle \pm |\updownarrow\rangle}{\sqrt{2}} \Rightarrow \frac{|\leftrightarrow\rangle \pm i|\updownarrow\rangle}{\sqrt{2}}$$

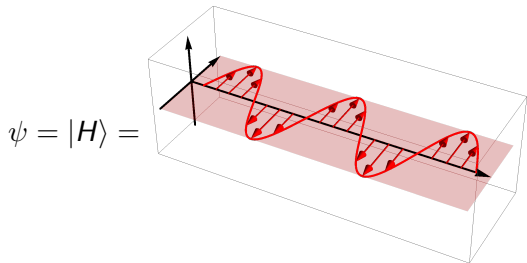
$$|\leftrightarrow\rangle \Rightarrow |\leftrightarrow\rangle, \quad |\updownarrow\rangle \Rightarrow i|\updownarrow\rangle$$

Polarization Measurement

(single photons)

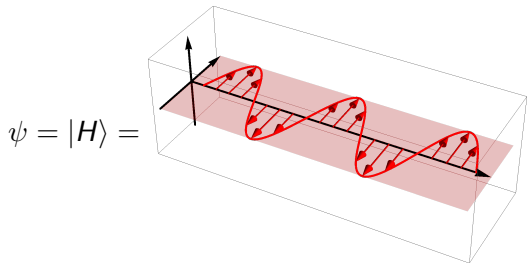
Polarization Measurement

(single photons)



Polarization Measurement

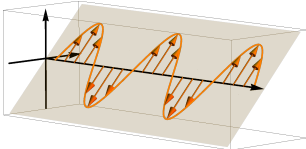
(single photons)



I_{\leftrightarrow}	Probability
0	0
1	1

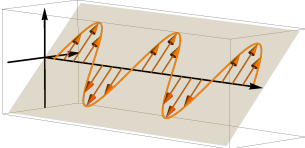
Polarization Measurement

(single photons)

$$\psi = \frac{|H\rangle + |V\rangle}{\sqrt{2}} =$$
A 3D diagram showing a rectangular prism representing a volume of space. A horizontal black line with an arrow at the end represents the direction of photon propagation. A vertical black line with an arrow at the top represents the vertical axis. Two orange elliptical loops are drawn around the horizontal line, representing the electric field oscillations. The loops are oriented vertically, indicating vertical polarization. The diagram illustrates the physical interpretation of the quantum state $\psi = \frac{|H\rangle + |V\rangle}{\sqrt{2}}$, which is a superposition of horizontal and vertical polarization states.

Polarization Measurement

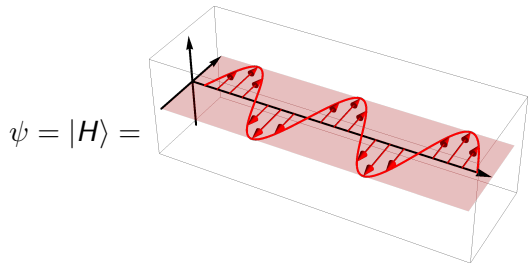
(single photons)

$$\psi = \frac{|H\rangle + |V\rangle}{\sqrt{2}} =$$


I_{\leftrightarrow}	Probability
0	$\frac{1}{2}$
1	$\frac{1}{2}$

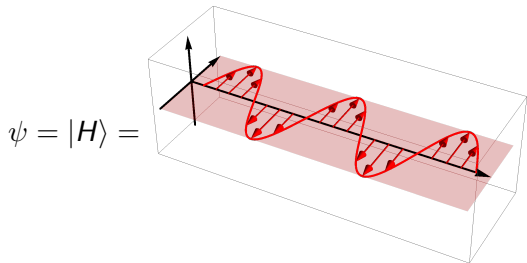
Polarization Measurement

(single photons)



Polarization Measurement

(single photons)

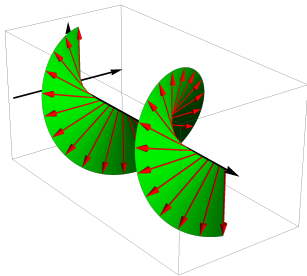


I_{\nearrow}	Probability
0	$\frac{1}{2}$
1	$\frac{1}{2}$

Polarization Measurement

(single photons)

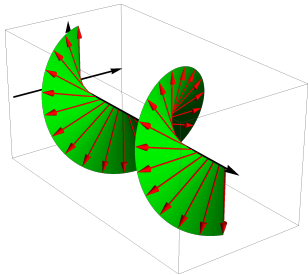
$$\psi = \frac{|H\rangle + i|V\rangle}{\sqrt{2}} =$$



Polarization Measurement

(single photons)

$$\psi = \frac{|H\rangle + i|V\rangle}{\sqrt{2}}$$



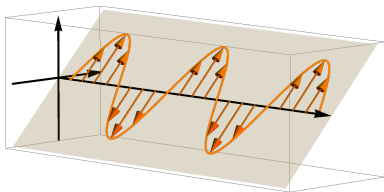
I_{\leftrightarrow}	Probability
0	$\frac{1}{2}$
1	$\frac{1}{2}$

I_{\circlearrowleft}	Probability
0	0
1	1

Polarization Measurement

(single photons)

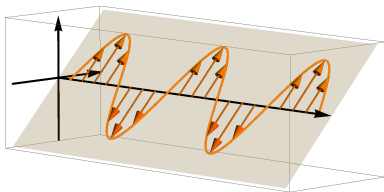
$$\frac{|H\rangle + |V\rangle}{\sqrt{2}} =$$



Polarization Measurement

(single photons)

$$\frac{|H\rangle + |V\rangle}{\sqrt{2}} =$$



I_{\leftrightarrow}	Probability
0	$\frac{1}{2}$
1	$\frac{1}{2}$

I_{\circlearrowleft}	Probability
0	??
1	??

$|H\rangle$, $|V\rangle$

$$|\nearrow\rangle = \frac{|H\rangle + |V\rangle}{\sqrt{2}} , \quad |\nwarrow\rangle = \frac{|H\rangle - |V\rangle}{\sqrt{2}}$$

$$|\circ\rangle = \frac{|H\rangle + i|V\rangle}{\sqrt{2}} , \quad |\ominus\rangle = \frac{|H\rangle - i|V\rangle}{\sqrt{2}}$$

Summary

- 1 The **polarization** of single photons is a **quantum two-state system**.
- 2 The polarization states can be manipulated by means of linear optics (wave plates).

References