PHYS543000

Principle and Application of Quantum Technology

Chung-Yu Mou

email: mou@phys.nthu.edu.tw

phone: 574-2537, Room 514

Course Information

Lecture room: Phys Dept 019

Time: 2:20PM – 5:10PM

Homework and course outline:

http://w3.phys.nthu.edu.tw/~mou/teach.html

Feb. 27, March 20 no class (due to conference)
March 13, April 24 speaker lecture

- TA:

Shih-Si Hsiao (蕭世熙)
email: tousiotousio@gmail.com

•Grading scheme:

•Homework (4, 60%) and final report (40%)

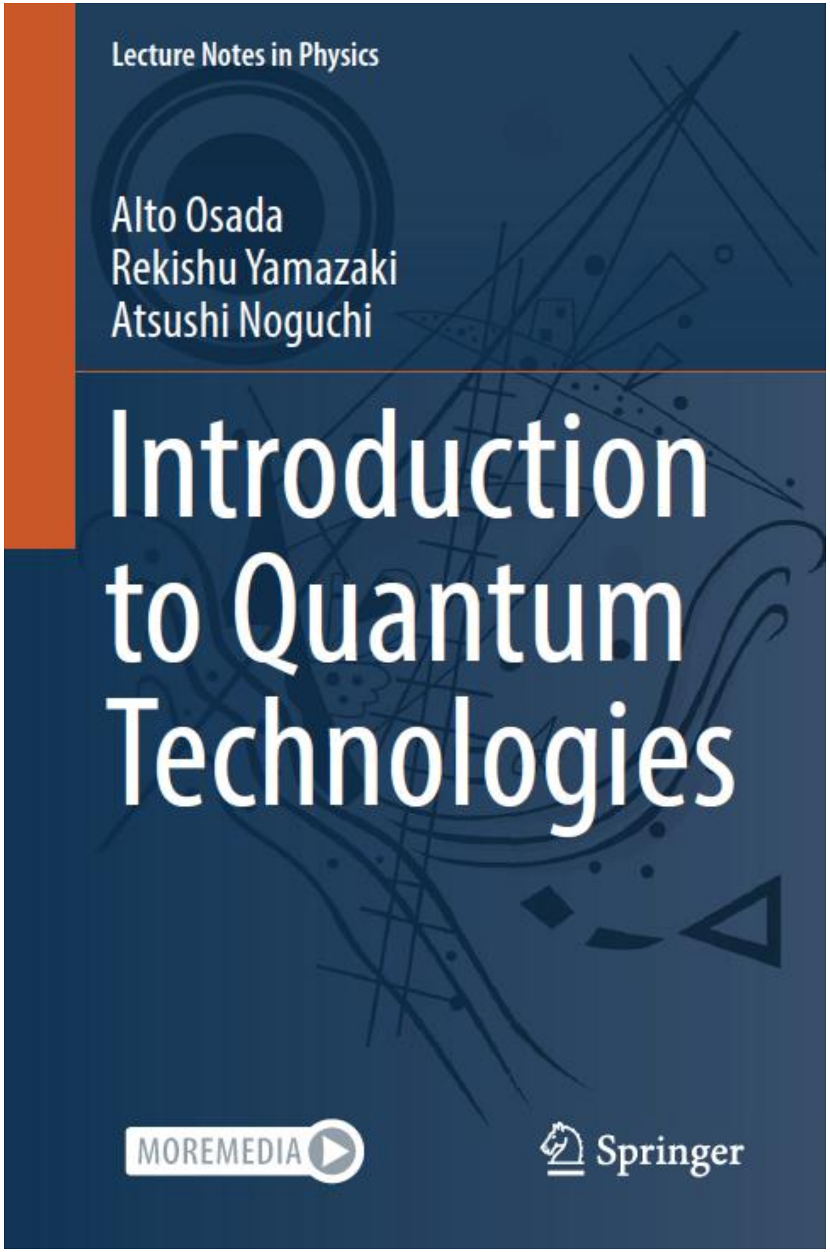
Textbooks
1. Introduction to Quantum Technologies, Alto Osada, Rekishu Yamazaki, and Atsushi Noguchi, Springer 2022.
2. eBook: Understanding Quantum Technologies 2021, 4th edition, Oliviar Ezratty
https://www.oezratty.net/wordpress/2021/understanding-quantum-technologies-2021/

References:
Quantum Computation and Quantum Information, Michael Nielsen and Isaac Chuang, Cambridge University press, 2000.

Topics for final report:

1. Status report of quantum computation to break RSA (including methods using method of quantum simulation such as the preprint arXiv 2212.12372)
2. Quantum radar and quantum illumination
3. Status report of most recent quantum error corrections code
4. Status report on photonic quantum computer
5. Status report on Si-based quantum computer
6. Status report on trap-ion based quantum computer
7. Status report on Satellite-based quantum communication and quantum network

More accurate syllabus: following



Part I Quantum States and Quantum Mechanics

Part II Harmonic Oscillator, Qubit and Coupled Quantum Systems

Overview of Quantum Technology

Two important technologies that are being developed started from the beginning of the 21th century unesco

INTERNATIONAL YEAR OF Quantum Science and Technology

100 years of quantum is just the beginning...

On June 7, 2024, the United Nations proclaimed 2025 as the International Year of Quantum Science and Technology (IYQ). According to the proclamation, this year-long, worldwide initiative will "be observed through activities at all levels aimed at increasing public awareness of the importance of quantum science and applications."

The year 2025 was chosen for this International Year as it recognizes 100 years since the initial development of quantum mechanics. Join us in engaging with quantum science and technology education and celebration throughout 2025!

It takes times for a technology to be fully developed…

The Nobel Prize in Physics 2022

Ill. Niklas Elmehed © Nobel Prize Outreach

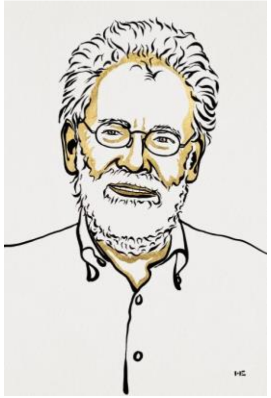
Alain Aspect

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

John F. Clauser

Prize share: 1/3



Ill. Niklas Elmehed © Nobel Prize Outreach

Anton Zeilinger

Prize share: 1/3

The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

量子糾纏發展年表:

*1935年

愛因斯坦(Einstein)、波多爾斯基(Podolsky)、羅森(Rosen)共同發表一篇論文，提出了量子糾纏之思想實驗，來反駁哥本哈根學派所詮釋的“偶然論”。這著名的EPR思想實驗(EPR Paradox)主張量子力學裡面應仍有“隱藏變數”，來維護古典的“必然論”，並聲稱量子力學尚未完備。

*1964年

貝爾(John Bell, 1928~1990)為了證實EPR所主張的“必然論”，設計了一個思想實驗，表明糾纏粒子的狀態如果有隱藏變數，則應遵守所謂的“貝爾不等式”(Bell Inequality)。然而以當時的技術很難做出此實驗。

貝爾不等式被認為是當代最具深邃的理論物理上的見解。

*1972年

美國的克勞澤(John Clauser, 1942~)改進了貝爾定理，並提出了產生糾纏光子的方法（紫外線照射鈣原子），然後在1972年首次做出實驗。該實驗結果是貝爾不等式並不成立。當時克勞澤所做的實驗被認為仍有許多漏洞，所以貝爾不等式成立與否尚未能定音於一錘。

*1982年

之後的十年間法國的阿思佩克特(Alain Aspect, 1947~)不斷改進克勞澤的實驗，例如改用雷射激發鈣原子來產生更有效率的糾纏光子對，也改善了偵測的精準度，並也設計出更為古怪的“量子延遲實驗”。這一連串的實驗結果都大幅偏離貝爾不等式。

然而這些實驗裡還有一個瑕疵是設備中的亂數產生器被認為非真正隨機；這讓糾纏光子對仍有機會暗通款曲。

*2010s

奧地利的蔡林格(Anton Zeilinger, 1945~)利用遙遠星系所發出了訊號作為控制訊號，讓糾纏實驗的進行真正處於隨機狀態。蔡林格早在1997做出了單光子量子態傳送(Quantum Teleport)，也奠定了量子計算、量子通訊的基礎。

*2022

瑞典皇家科學院稱，2022年諾貝爾物理獎表彰了法國的阿思佩克特、美國的克勞澤和奧地利的蔡林格等三人「展示了對『糾纏狀態』的粒子進行考察和控制的潛力」。

npj | digital medicine

News & Views

Published in partnership with Seoul National University Bundang Hospital

https://doi.org/10.1038/s41746-024-01345-9

Artificial Intelligence awarded two Nobel Prizes for innovations that will shape the future of medicine

Ben Li & Stephen Gilbert

Check for updates

John J. Hopfield and Geoffrey E. Hinton were awarded the 2024 Nobel Prize in Physics for developing machine learning technology using artificial neural networks. In Chemistry it was awarded to Demis Hassabis and John M. Jumper for developing an AI algorithm that solved the 50-year protein structure prediction challenge. This highlights AI's impact on science, medicine and society; however, the winners acknowledge ethical aspects of AI that must be considered.

In October 2024, the Nobel Committees in Stockholm announced that the prizes in Physics and Chemistry were awarded to work related to artificial intelligence (AI)[1,2]. The prize in Physics was awarded to John J. Hopfield and Geoffrey E. Hinton (formerly of Google) for "foundational discoveries and inventions that enable machine learning with artificial neural networks[1]." The prize in Chemistry was awarded one-half to David Baker for "computational protein design" and one-half to Demis Hassabis and John M. Jumper (of DeepMind) for "protein structure prediction[2]." The historic announcement of these Nobel Prizes for AI-related work has been widely

aggregation with other ML methods and architectures brought us to the ML technologies of today, including the overlapping concepts and implementations of deep learning, convolution neural networks, transformer and attention-based architectures (advanced neural networks that excel at, for example, natural language processing), large language models and large multimodal models[11]. This is an evolving landscape of multipurpose foundation technologies, that some have compared to the printing press or the Internet in terms of reach and impact[12]. As an example of this, and maybe as a portent of what is to come, the ML of the 2024 Nobel Prize in Physics even enabled the groundbreaking discovery associated with the 2024 Nobel Prize in Chemistry[2].

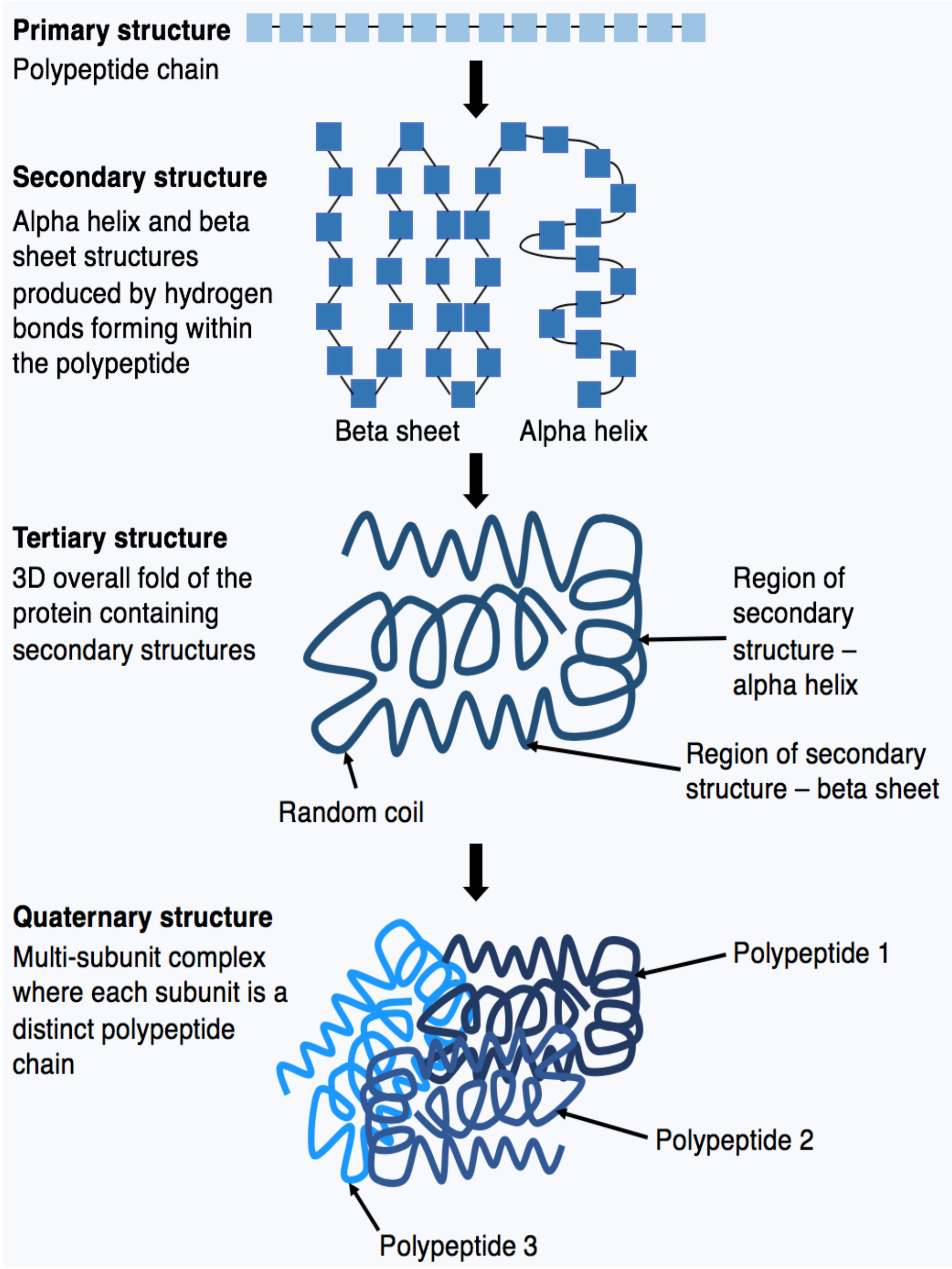
2024 Nobel Prize in Chemistry

Hassabis and Jumper developed an AI model that accurately predicts protein structures from their amino acid sequences, which is one of the most intriguing and famous scientific challenges of the last 50 years[2]. As every biology student learns in school, a gene codes simply for the amino acid sequence, (with a few exceptions), and based on the environment of the cell, this sequence folds and assembles into a definitive and complex three-dimensional structure that dictates its function[13]. The 3D protein (again, with a few exceptions) is always the same, and thus, it should be possible to predict its structure just from the gene sequence, and perhaps knowledge of the cell environment[13]. Over 200 million amino acid sequences have been identified, yet less than 1% of their corresponding three-dimensional pro-

AlphaFold is an artificial intelligence (AI) program developed by DeepMind, a subsidiary of Alphabet, which performs predictions of protein structure. It is designed using deep learning techniques.

AlphaFold has two versions: AlphaFold 1 (2018) and AlphaFold 2 (2020).

AlphaFold 1 (2018) was placed first in the overall rankings of the 13th Critical Assessment of Structure Prediction (CASP) in December 2018. It was particularly successful at predicting the most accurate structures for targets rated as most difficult by the competition organizers.



It is foreseeable that successful combination of quantum technology and artificial intelligence will be the next milestone!

Recent Breakthrough of Quantum Technology

量子電腦 [qubit, 量子位元]

之前: 幾個量子位元

HARDWARE > NEWS

IBM Inches Closer To Quantum Supremacy With 16- And 17-Qubit Quantum Computers

by Lucian Armasu May 17, 2017 at 9:00 AM

IBM Raises the Bar with a 50-Qubit Quantum Computer

by Will Knight November 10, 2017

ScienceNews
MAGAZINE OF THE SOCIETY FOR SCIENCE & THE PUBLIC

Google moves toward quantum supremacy with 72-qubit computer

Google contends its Bristlecone chip demoes 1% error rates for readout, 0.1% for single-qubit gates, and 0.6% for two-qubit gates.

CES 2018: Intel's 49-Qubit Chip Shoots for Quantum Supremacy

By Jeremy Hsu (/author/jeremy-hsu)
Posted 9 Jan 2018 | 0:00 GMT

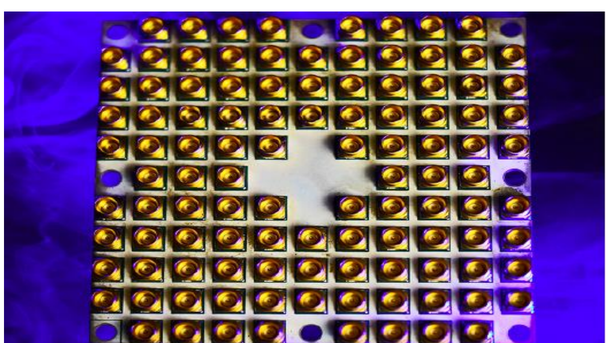
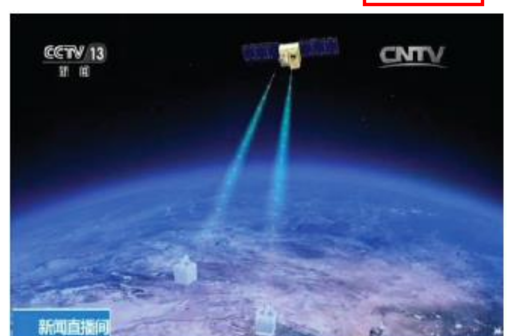


Photo: Intel
Intel's new 49-qubit superconducting quantum test chip is named Tangle Lake.

Intel Roadmap: 1000 qubits 5-7 years

(中央社台北18日電) 2017/06/18 13:52

陸首顆量子衛星墨子號 可全球秘密通訊



光子: 飛行量子位元

2017年09月07日 07:51 中時電子報

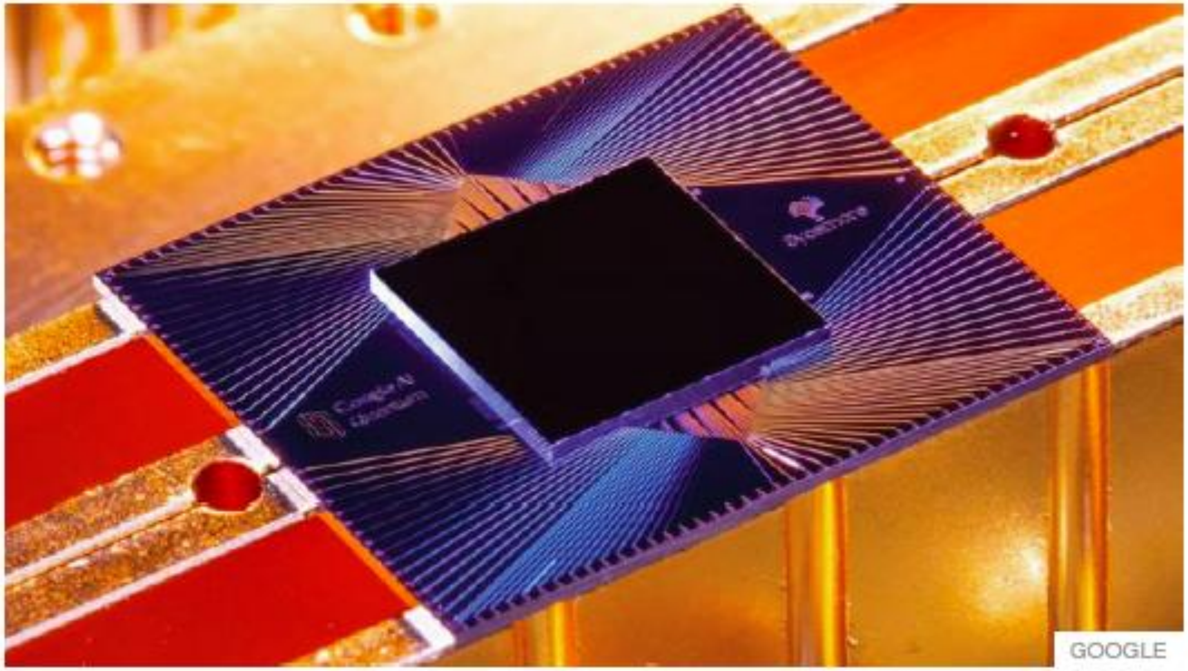
陸量子雷達再突破 F35隱形戰機藏不住

Google claims 'quantum supremacy' for computer

By Paul Rincon
Science editor, BBC News website

23 October 2019

Share



GOOGLE

The technology giant's Sycamore quantum processor was able to perform a specific task in 200 seconds that would take the world's best supercomputer 10,000 years to complete.

Early development

- 1982 R. P. Feynman proposed the idea of a 'quantum computer', a computer that uses the effects of quantum mechanics

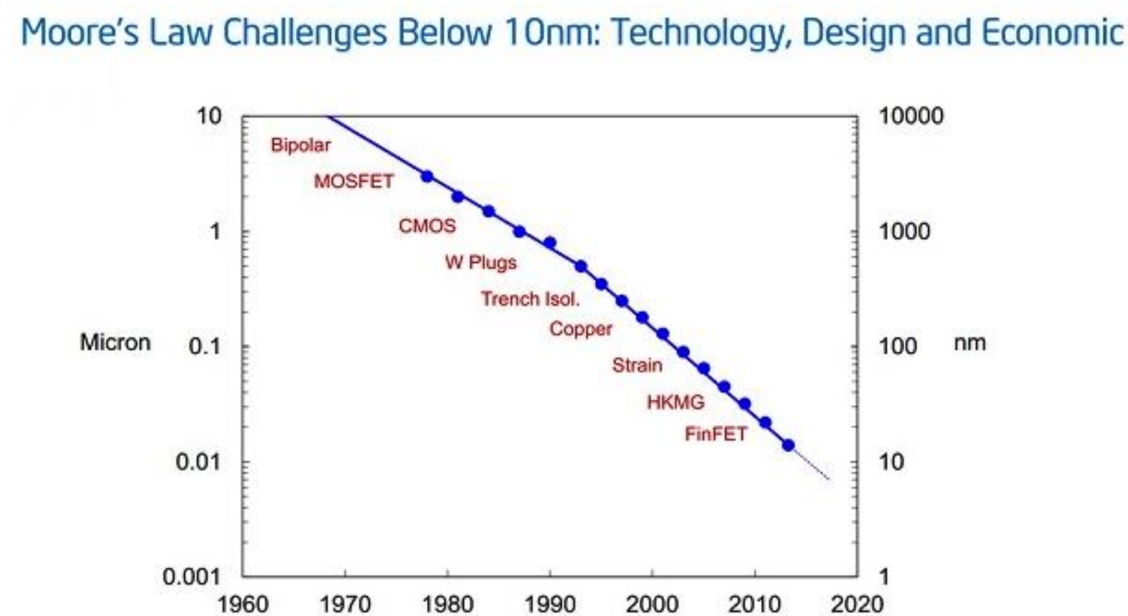
- 1984 BB84 Quantum key distribution

- 1994 Shor’s algorithm (fast prime factorization)

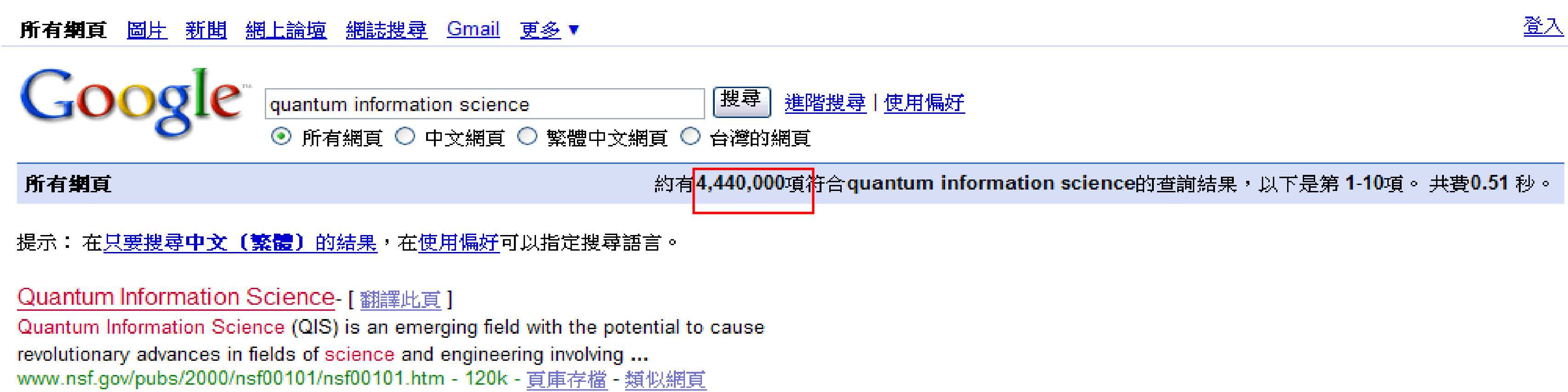
- 1995 Quantum error correction (Shor and Steane)

- 1996 Grover’s searching algorithm
- …

Promoted by Nano-technology

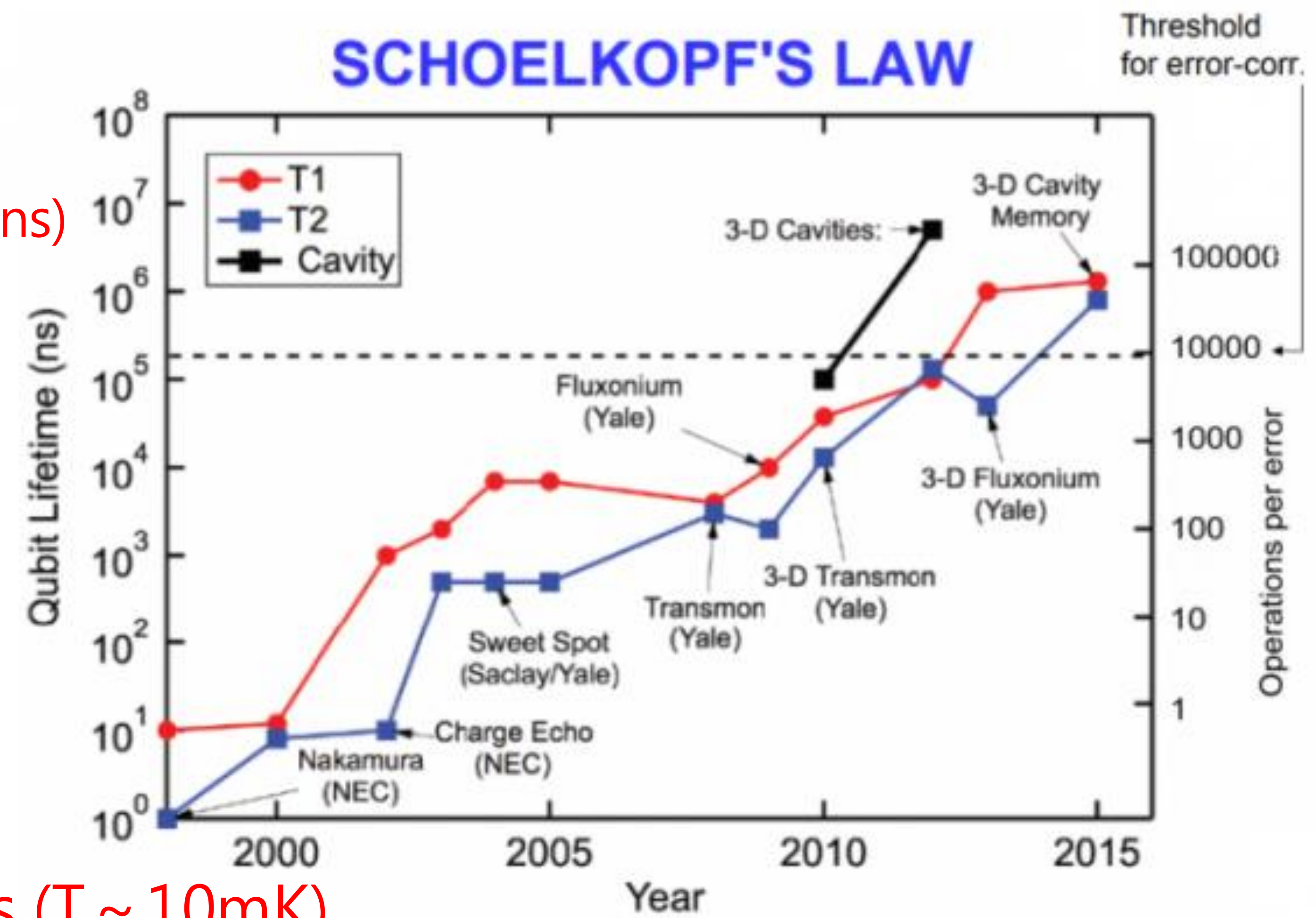


Find post-semiconducting technology platform ➡ 量子資訊 (quantum information science) (~2000)



Breakthrough in Superconducting Qubit (2015)

存活時間(ns)



30-140 μs (T ~ 10mK)

Devoret & Schoelkopf, Science 339, 1169 (2013)

10^5 improvement：

Ignite the technology community's hope for quantum technology!

Developing Critical Point of Quantum Technology

Quantum Technology： Technology that directly utilizes the properties of quantum wave functions for information processing and calculation. The realization of quantum computers can be used to solve problems that are difficult for traditional computers Absolutely secure communication networks, research and development of new drugs, design of new materials, and new forms of artificial intelligence may bring about revolutionary changes

Berkeley Lab Supercomputer Breaks New Ground in Quantum Computing Simulation
Michael Feldman | April 12, 2017 11:26 CEST

Cori, the fifth fastest supercomputer in the world, has been used to model a 45-qubit circuit

Classical computers 50 qubit Quantum supremacy

→ Qubit number

50 qubit ➡ Second quantum revolution

Facing the arrival of possible second quantum revolution

A number of projects are initiated such as Europe Quantum Manifesto, UK National Quantum Technologies Programme, Centre for Quantum Technologies in Singapore, USA DARPA call program ,…)

426 | NATURE | VOL 532 | 28 APRIL 2016

A €1-billion (US$1.1-billion) European flagship project could advance the state of quantum computing.

FUNDING

Billion-euro boost for quantum tech

Microsoft just upped its multi-million bet on quantum computing

Microsoft pours millions into a new Station Q outpost in Copenhagen.

By Liam Tung | September 7, 2017 -- 13:38 GMT (21:38 GMT+08:00) | Topic: Innovation

The DOE Is Giving Berkeley Lab $3 Million Annually for Quantum Computing Research

繼施堯耘之後，又一重量級量子計算學者入職阿里巴巴達摩院

作者 雷鋒網 | 發布日期 2018 年 01 月 18 日 17:35 | 分類 AI 人工智慧，人力資源，科技教育 Follow G+ 讚 5 分享

The Quantum Manifesto calls upon Member States and the European Commission to launch a €1 billion Flagship-scale Initiative in Quantum Technology, preparing for a start in 2018 within the European H2020 research and innovation framework programme.

This initiative aims to place Europe at the forefront of the second quantum revolution now

UNSW SYDNEY Newsroom

Australia's first quantum computing company launches at UNSW

23 AUG 2017 | UNSW MEDIA

Australia's first quantum computing company, Silicon Quantum Computing Pty Ltd, has been launched to advance the development and commercialisation of UNSW Sydney's world-leading quantum computing technology.

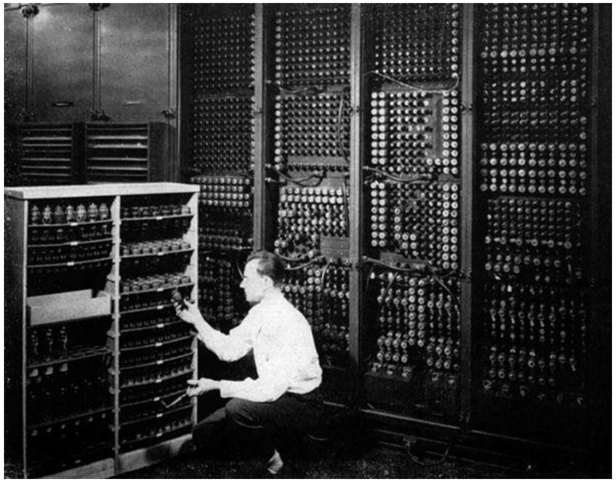
2018年03月08日 10:17 時報資訊 綜合外電報導

新浪財經消息，百度今日宣布成立量子計算研究所，開展量子計算軟件和信息技術應用業務研究，百度計畫在五年內組建世界一流的量子計算研究所，並逐步將量子計算融入到業務中。

量子計算機在金融、醫藥、化學、材料、人工智能等領域具有廣闊的應用空間，有望應用於人工智能（如自動駕駛軟件）等領域。

Promise of quantum technology ?

Eniac 1943



Quantum Technology

?

?

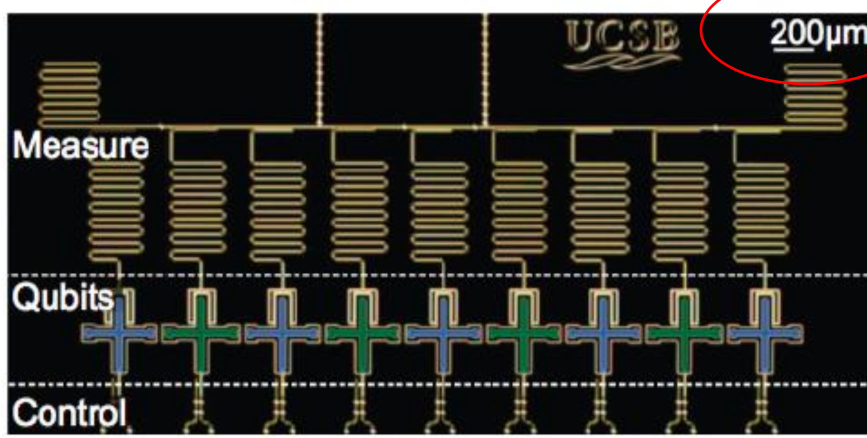
Typical Misunderstanding

台積電3奈米赴美？關鍵在量子電腦

發稿時間：2017/03/20 14:40　最新更新：2017/03/20 15:18

（中央社記者鍾榮峰台北20日電）台積電傳出考量3奈米赴美設廠。工研院IEK主任室計畫副組長楊瑞臨指出，台積電3奈米選址非常關鍵，牽涉布局量子電腦1奈米以下的次奈米新技術和材料。

UCSB/Google nine X-mon qubit processor



Need to understand What Quantum Mechanics can do?

Quantum Technology

Quantum information Science

Applications and Programming:
Quantum Algorithms, Programming, Protocols

量子裝置
Quantum Device

量子電腦
Universal quantum computer

量子模擬器
Quantum simulator

量子退火機
Quantum annealer

量子感測器
Quantum sensor

量子通訊/網路
Quantum network

量子裝置
Quantum Device

量子材料
Quantum Material

Status and Challenge

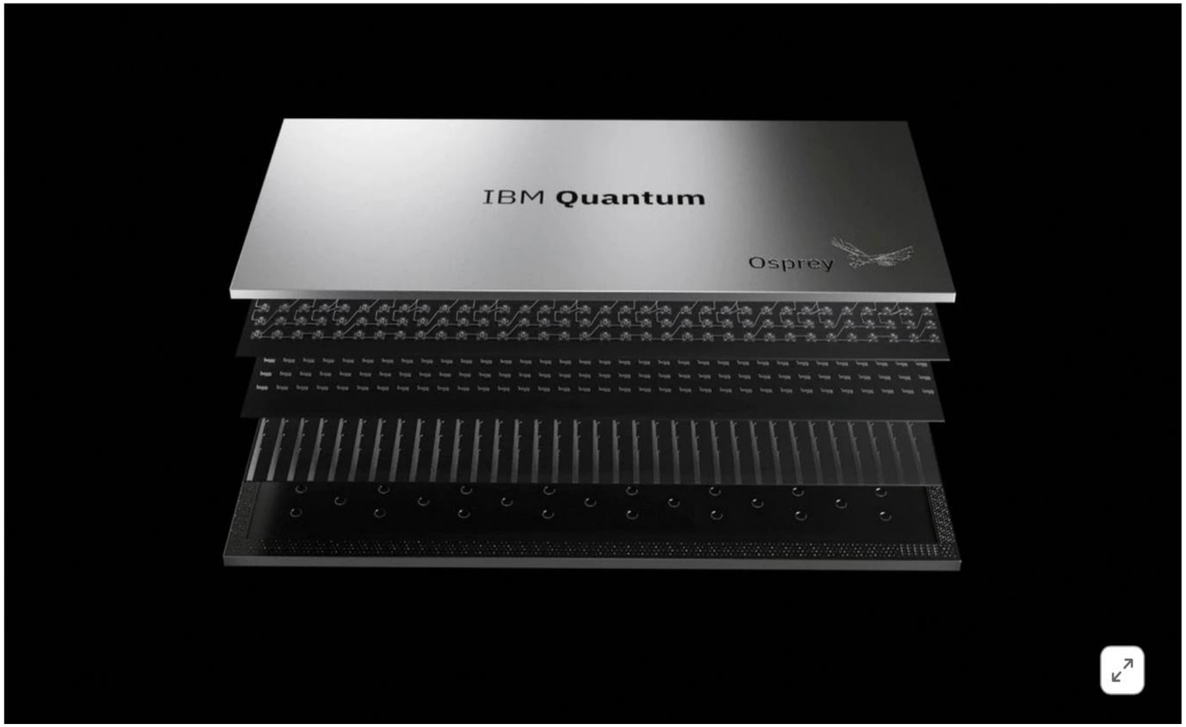
REUTERS® World Business Legal Markets Breakingviews Technology Investigations More My View Sign In Register

2 minute read · November 9, 2022 10:07 PM GMT+8 · Last Updated a day ago

IBM launches its most powerful quantum computer with 433 qubits

2022

By Jane Lanhee Lee



algorithms that harness these indicators to estimate a person's 'biological age', which can be higher or lower than their chronological age[3].

Another hallmark of ageing is a shift in the proteins that the body produces. To explore how organs age, Oh and his colleagues first analysed nearly 5,000 proteins in blood samples from 1,398 healthy adults. They identified about 850 proteins that originated mainly from a single organ and trained a machine-learning algorithm to predict a person's age on the basis of the levels of these proteins. They validated their model using blood samples from more than 4,000 other people.

The results showed that an organ's biological age is linked to disease risk. For example, roughly 2% of participants had accelerated heart ageing — that is, their levels of blood proteins relating to heart ageing differed substantially from those of other people of the same age. Having a prematurely old heart was linked to a 250% increased risk of heart failure, the authors found.

Marking time

Researchers have used epigenetic markers to show that the pace of organ ageing varies between individuals[4]. But the link between epigenetic changes and ageing is unclear, says Matt Kaeberlein, a specialist in the biology of ageing and chief executive of Optispan, a biotechnology company in Seattle, Washington. Proteins are "much closer to the downstream mechanisms that might be driving ageing", he says.

Combining various hallmarks of ageing could lead to more-robust tests of organ age

IBM RELEASES FIRST-EVER 1,000-QUBIT QUANTUM CHIP

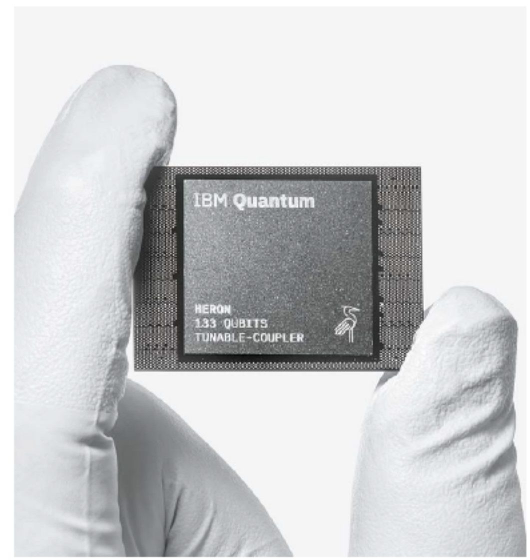
The company will now focus on developing smaller, more reliable processors.

By Davide Castelvecchi

IBM has unveiled the first quantum computer with more than 1,000 qubits — the equivalent of the digital bits in an ordinary computer. But the company says that it will now shift gears and focus on making its machines more error-resistant rather than larger.

For years, IBM has been following a quantum-computing road map that roughly doubled the number of qubits every year. The chip unveiled on 4 December, called Condor, has 1,121 superconducting qubits arranged in a honeycomb pattern. It follows on from IBM's other record-setting, bird-named machines, including a 127-qubit chip called Eagle, released in 2021 and a 433-qubit one called Osprey, announced last year.

Quantum computers promise to perform certain computations that are beyond the reach of classical computers. They will do so by exploiting uniquely quantum phenomena, such as entanglement and superposition, which allow multiple qubits to exist in multiple collective states at once.



IBM's Heron quantum processor.

RYAN LAVINE FOR IBM

2023). The company says that it will now focus on building chips designed to hold a few qLDPC-corrected qubits in just 400 or so physical qubits, and then networking those chips together.

The IBM preprint is "excellent theoretical work", says Mikhail Lukin, a physicist at

大陸第三代自主超導量子電腦 「本源悟空」上線運行

12:57 2024/01/06 | 中時 | 李文輝

大陸第三代自主超導量子電腦「本源悟空」上線運行。（翻攝自大陸央視）

Development assessment

?

Status

50 -100 qubits | 1000 | 1000-10,000 | 1000,000…

Near-term applications that are beyond the capability of classical computers

Noisy Intermediate quantum computing regime、quantum simulation、optimization

Intermediate scale & rate quantum communication

Probably 5-10 years

Universal Quantum computing

?

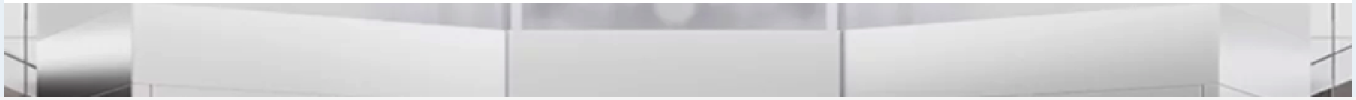
global quantum network

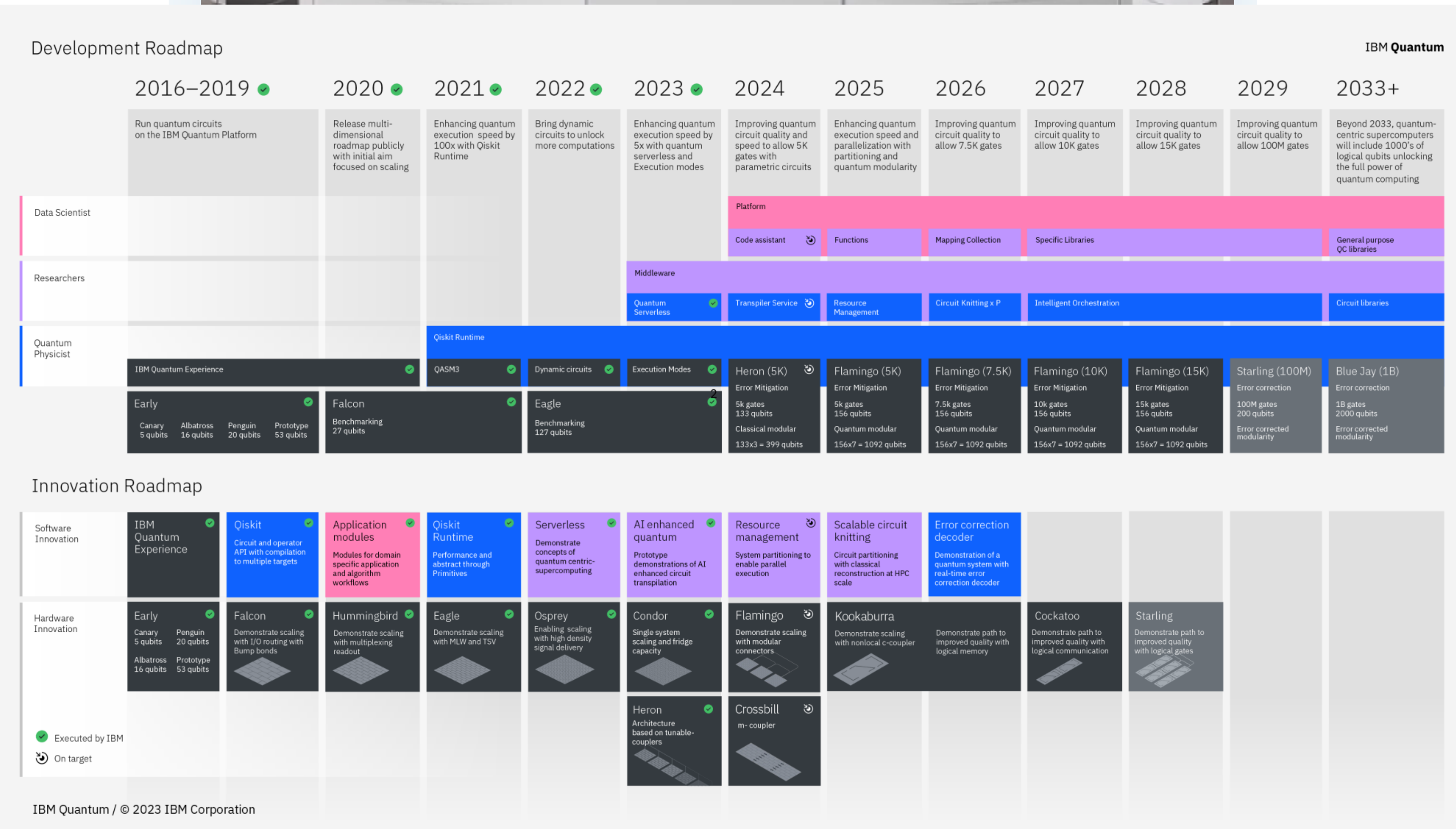
200km | 1000km

IBM Aims For 100,000-Qubit Machine By 2033, Pioneering 'Quantum-Centric Supercomputing'

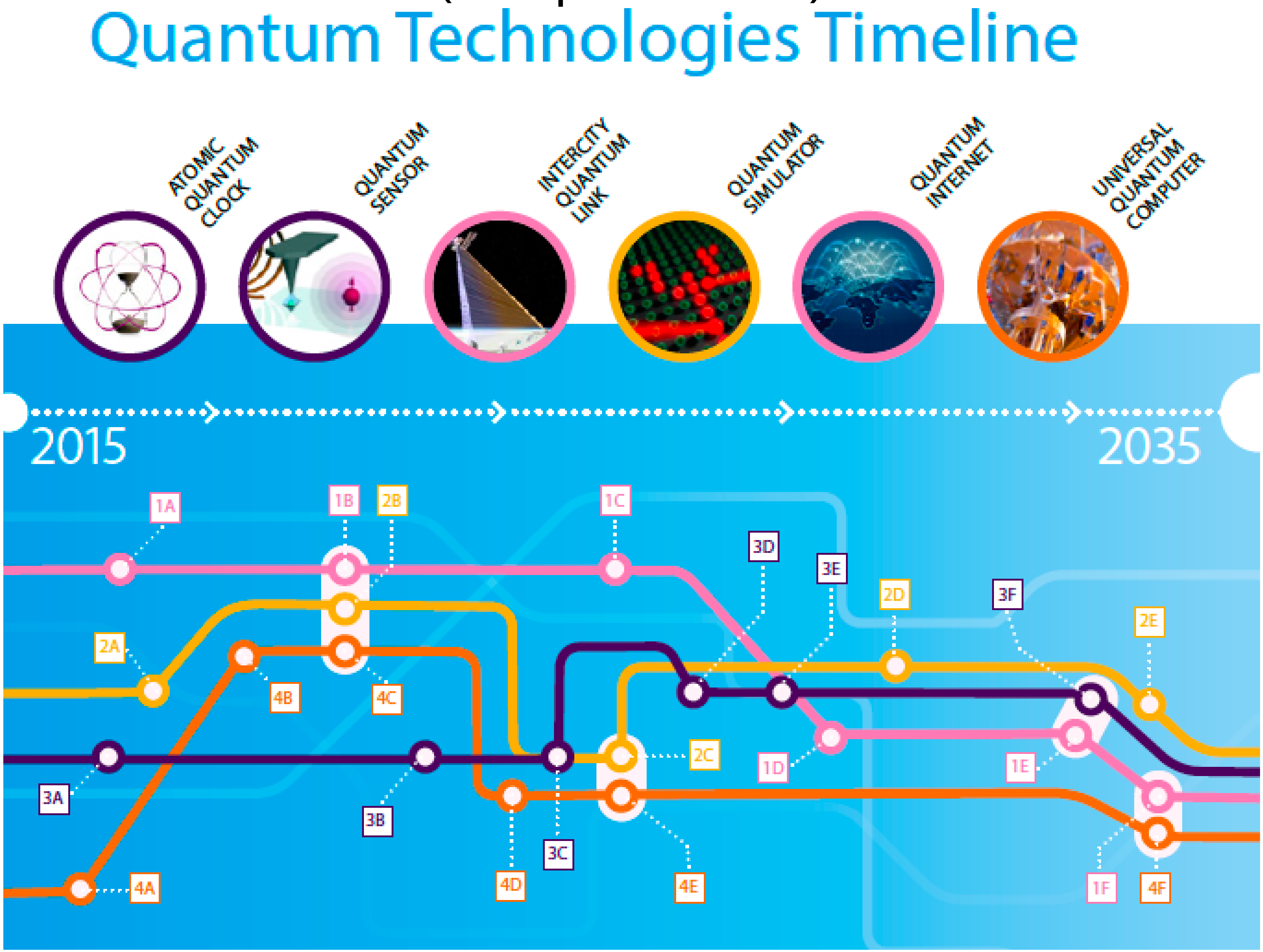
Quantum Computing Business

Matt Swayne • May 23, 2023





Quantum Manifesto (European union)



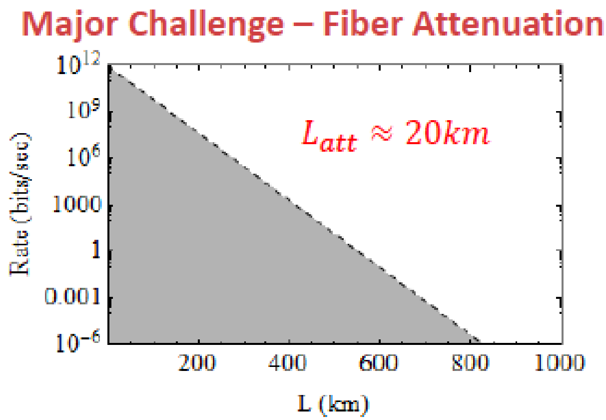
Effort for establishing quantum network

DiVincenzo criteria

- A scalable physical system with well characterized qubits. ?
- The ability to initialize the state of the qubits to a simple fiducial state. √
- Long relevant decoherence times (>10^4 operation time) √
- A "universal" set of quantum gates. √
- A qubit-specific measurement capability. √
- The ability to interconvert stationary and flying qubits.
- The ability to faithfully transmit flying qubits

Challenge for quantum communication and n

Decay in optical fibre



No clone theorem !

（量子態無法複製）

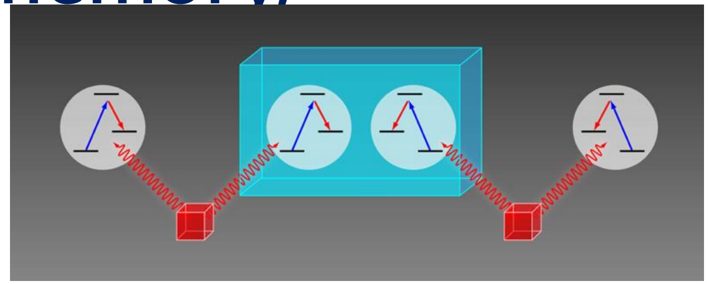
Need to develop quantum repeater (quantum repe

to break through the 200km limit

Key technologies: quantum memory,

quantum teleportation,

entanglement swapping



Credit: Alan Stonebraker

photon： flying qubit, decay length 200km

➡ satellite quantum communication

European scientists propose world's largest quantum network, between Earth and the ISS

April 9, 2013 at 8:50 am

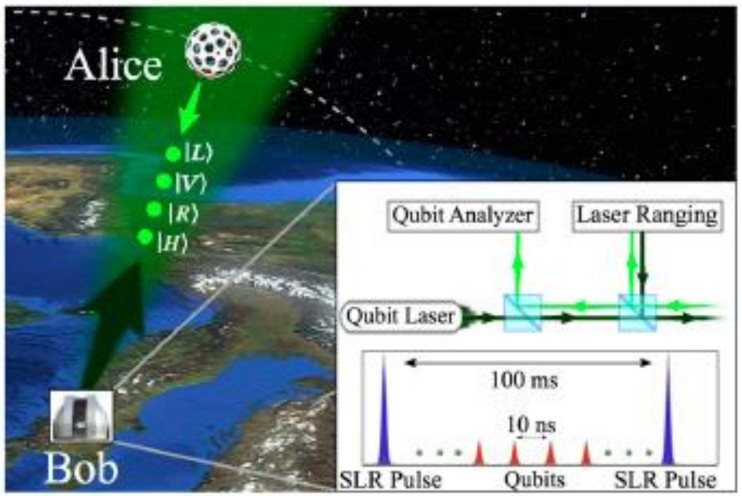


FIG. 1 (color online). Scheme of the satellite QKD demonstration. Qubit pulses are sent at a 100 MHz repetition rate and are reflected back to the single photon level from the satellite, thus mimicking a QKD source in space. Synchronization was performed by using the bright SLR pulses at a repetition rate of 10 Hz.

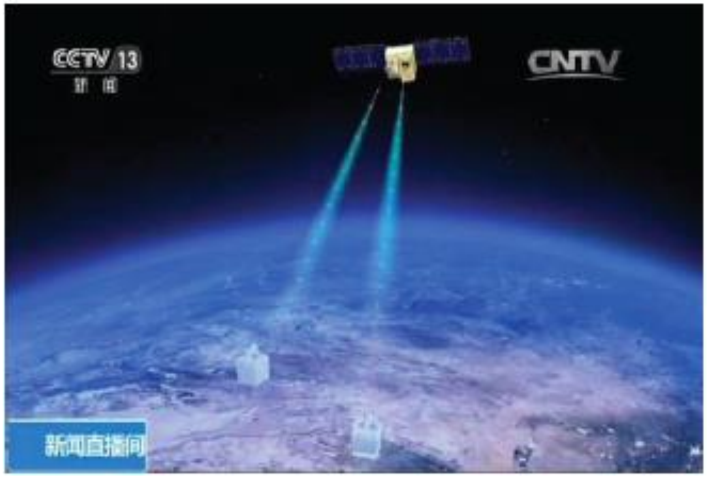
Phys. Rev. Lett. 115, 040502 (2015)

Itallian group, **qubit error ratio 4.6%**

The world's first quantum communication satellite (China), viable for 300s

(中央社台北18日電) 2017/06/18 13:52

陸首顆量子衛星墨子號 可全球秘密通訊



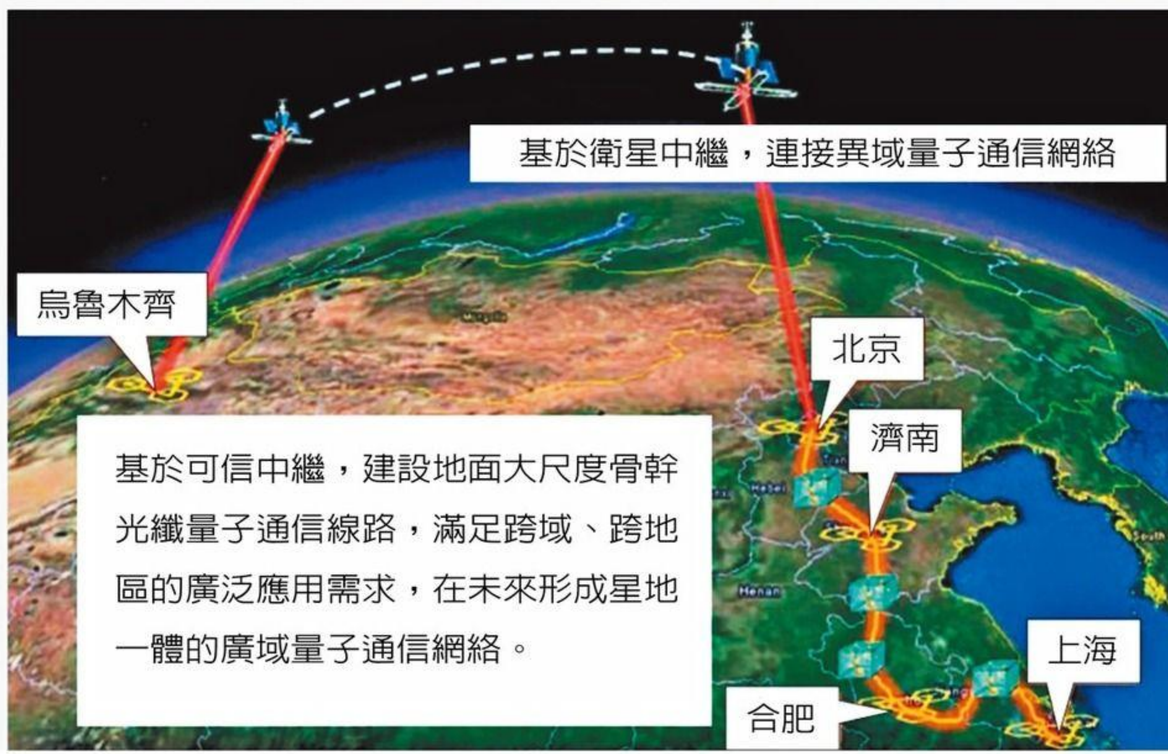
Phys. Rev. Lett. **120**, 030501(2018)

量子保密通信 京滬幹線開通

全長逾2000公里的量子保密通信骨幹網絡「京滬幹線」2017/09/29 開通，是世界首條量子保密通信幹線。中科院院長白春禮昨日到「京滬幹線」北京控制中心，用量子加密視頻會議系統與合肥、濟南、上海、新疆南山等地的科研人員對話，**並通過「墨子號」量子衛星與奧地利地面站的衛星量子通信，與奧地利科學院院長塞林格(Anton Zeilinger)作了世界首次洲際量子保密視頻通話。交通銀行、工商銀行、阿里徵信已開始使用此幹線加密實時交易和數據傳輸。**

量子通信是迄今唯一被嚴格證明無條件的安全通信方式，可以有效解決信息安全問題。「中國量子通信技術已經走在了世界前列，並持續保持著其優勢地位。我們的量子保密通信技術比國外領先了4-5年。」潘建偉說。

京滬幹線 示意圖



資料來源：中科院 （美編王欣琬／製表）

Source: MOST_量子科技研究與發展規劃案報告(管希聖)

The world's first commercial quantum communication network successfully tested in Jinan

世界首個大型商用量子通信專網於2017年7月在濟南完成第一階段黨政機關量子通信專網測試，與周邊數百平方公里的，近200個終端進行保密通信。它是目前世界上規模最大、功能最全的城域量子通信網路，業務可涵蓋政務、金融、政法、科研、教育等五大領域，能為用戶提供基於量子加密的電話、傳真、文件和文本通信業務。

Source: MOST_量子科技研究與發展規劃案報告(管希聖)

Recent developments of quantum communication n

UK

QKD network integrated with commercial communication

Austria

QKD network of 8 nodes demonstrated

China

2,000 km QKD network between Shanghai and Beijing is underway

USA

Installing QKD network

Japan

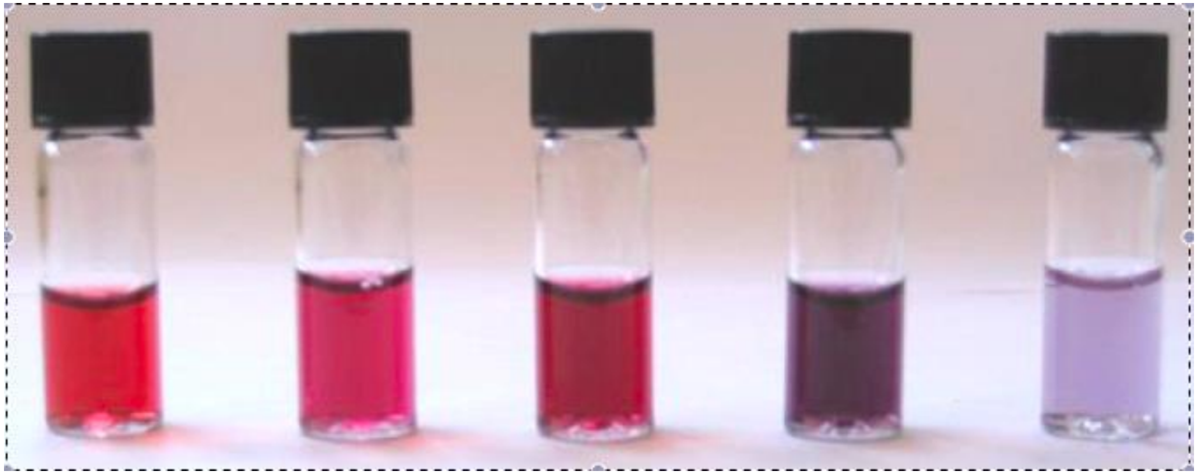
QKD network to transmit sensitive Genome data

Source: MOST_量子科技研究與發展規劃案報告(褚志崧)

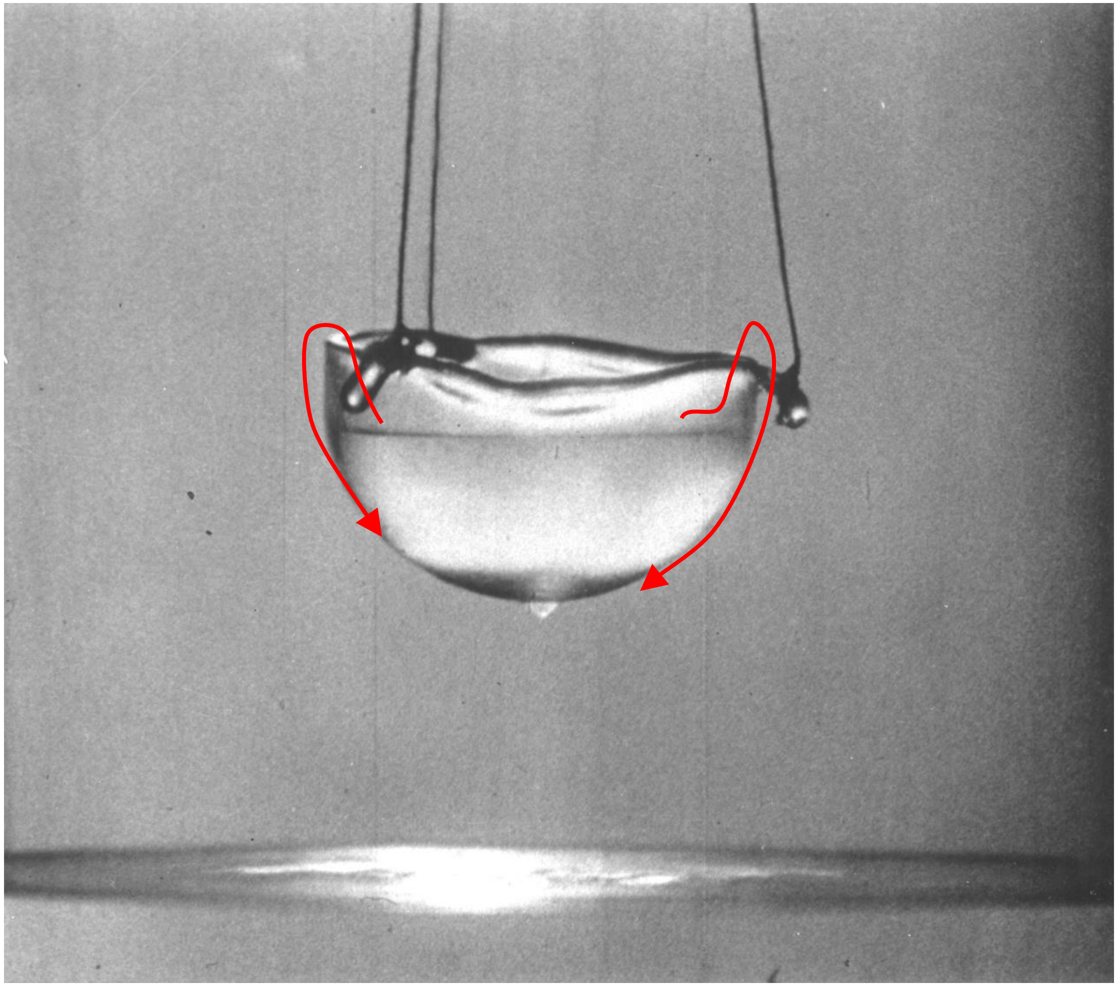
- What is quantum technology? Quantum Computer? Quantum Phenomenon?

Typical Quantum Phenomenon

Gold is not shining



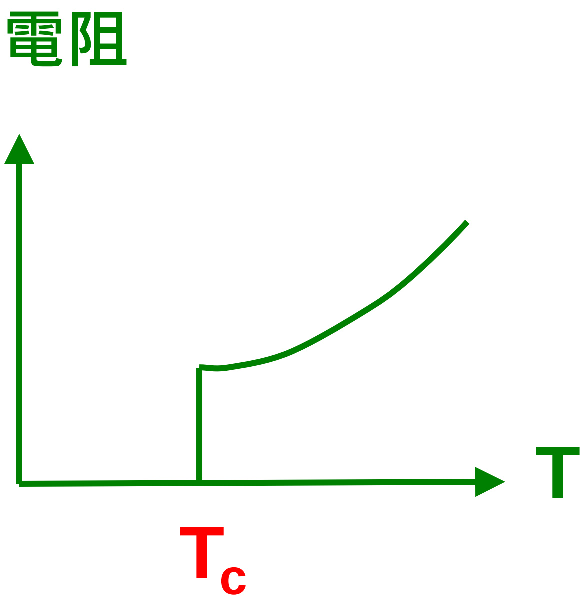
Macroscopic quantum phenomena : usually require low T and coherence

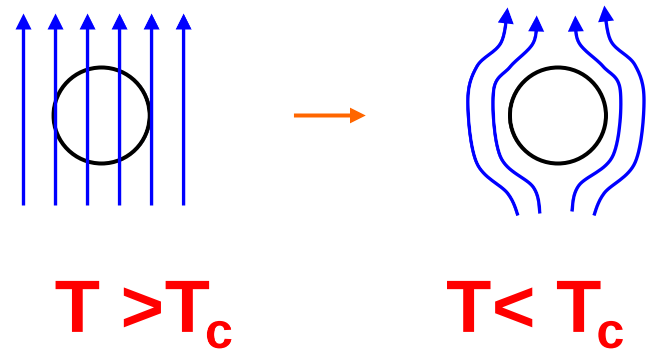


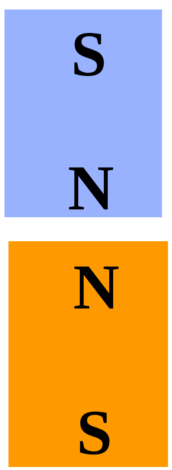
Creeping of liquid helium

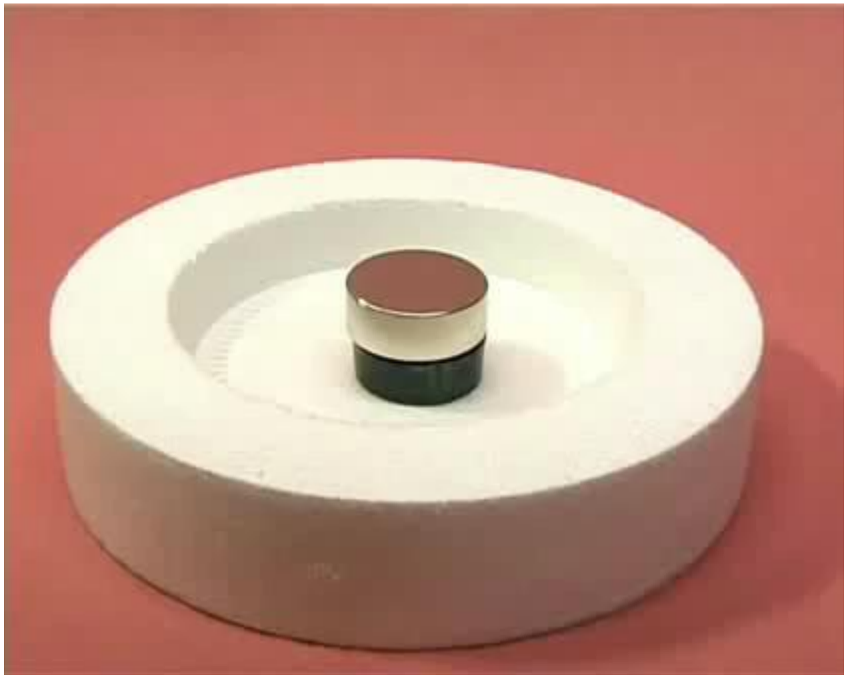
http://www.youtube.com/watch?v=2Z6UJbwxBZI https://youtu.be/2Z6UJbwxBZI

Macroscopic quantum phenomenon: superconduc





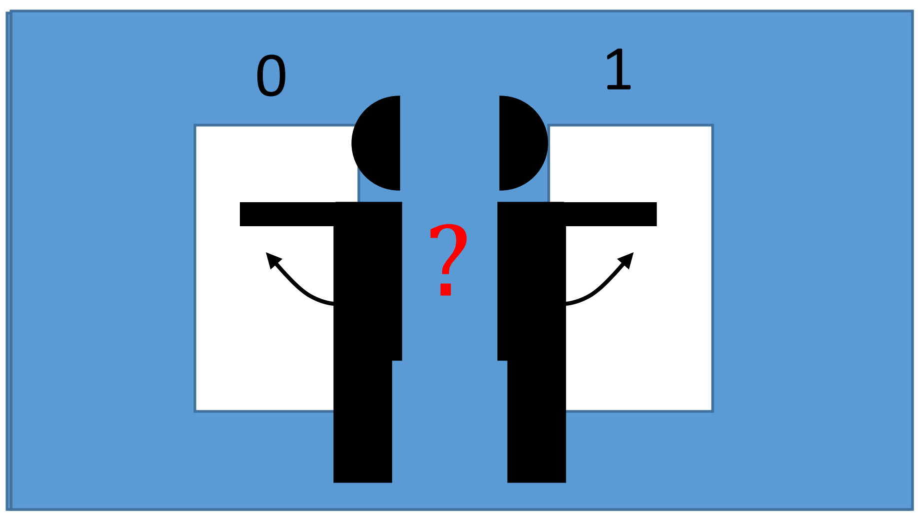




https://www.youtube.com/watch?v=D3koi9jfI7M

Essential of Quantum Mechanics

A way to describe a particle that pass two doors (qubit) at the same time.

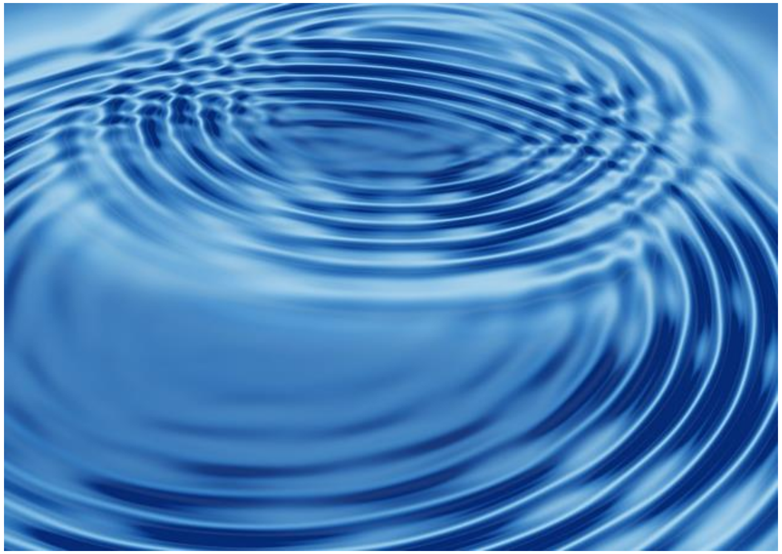


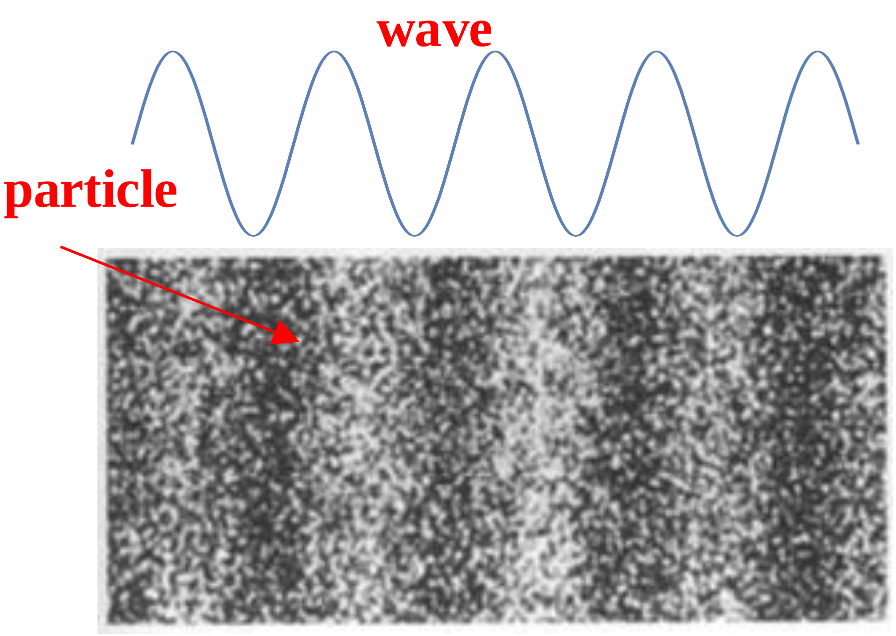
Rechard Feynman
(1965 Nobel Prize)

I think that it is fair to say that no one understands the quantum theory…

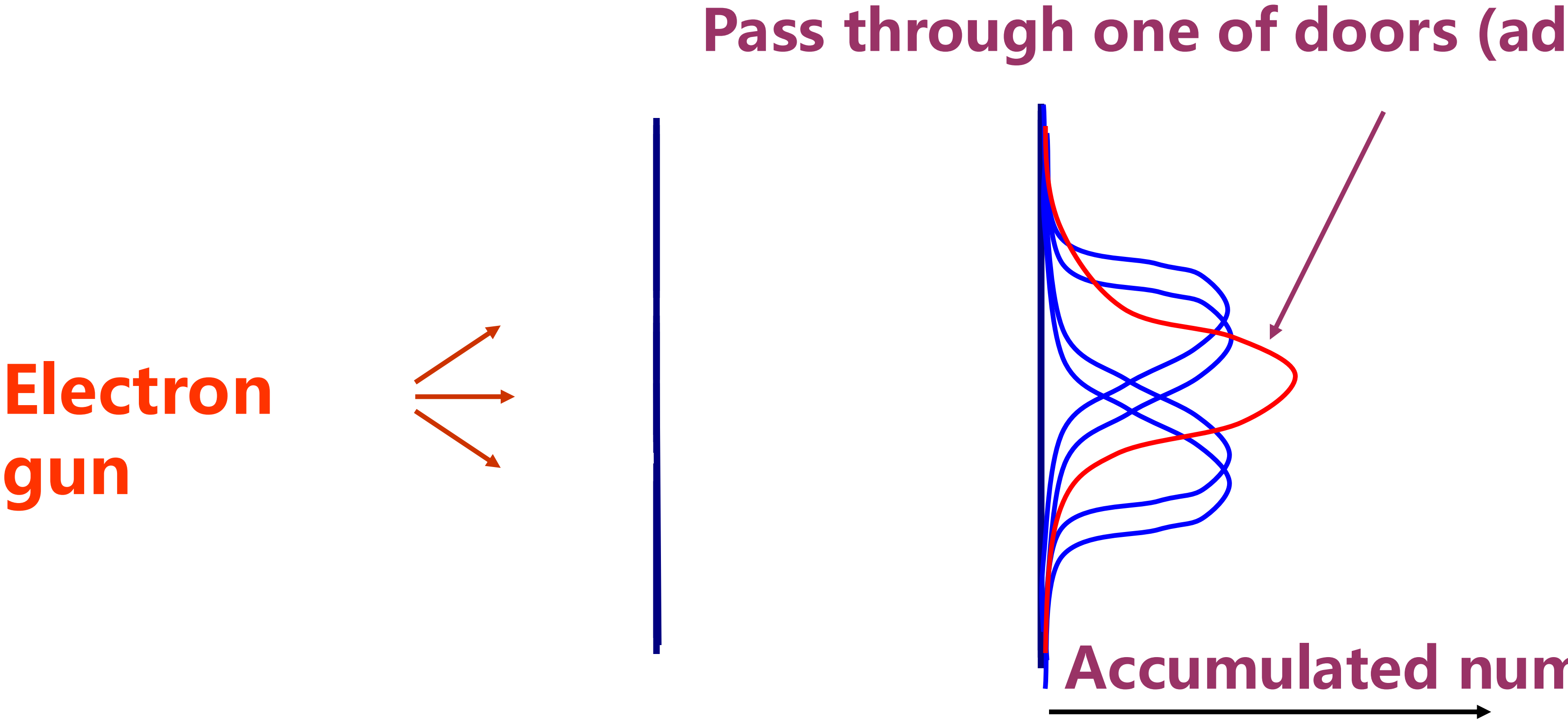
Quantum Mechanics: wave and particle duality, matter needs to be described using both concept of particle and wave:

Matter wave dictates where the particle goes to, but when it is measured, one piece of particle is found.



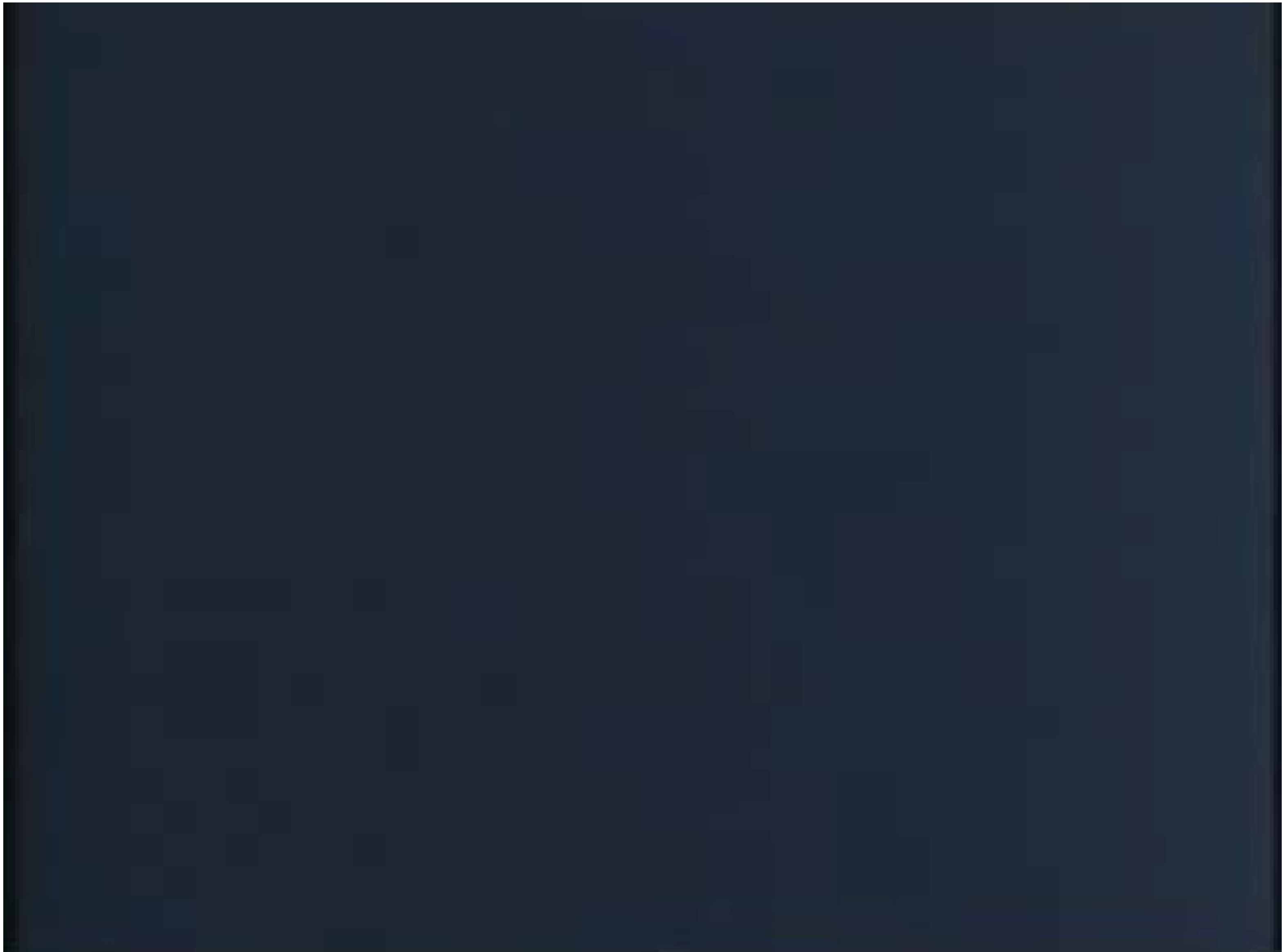


Let us examine the statement “passing two door at the same time”



Shooting one electron each time

(Tonomura et al, 1989)



Number of events ⇔ probability

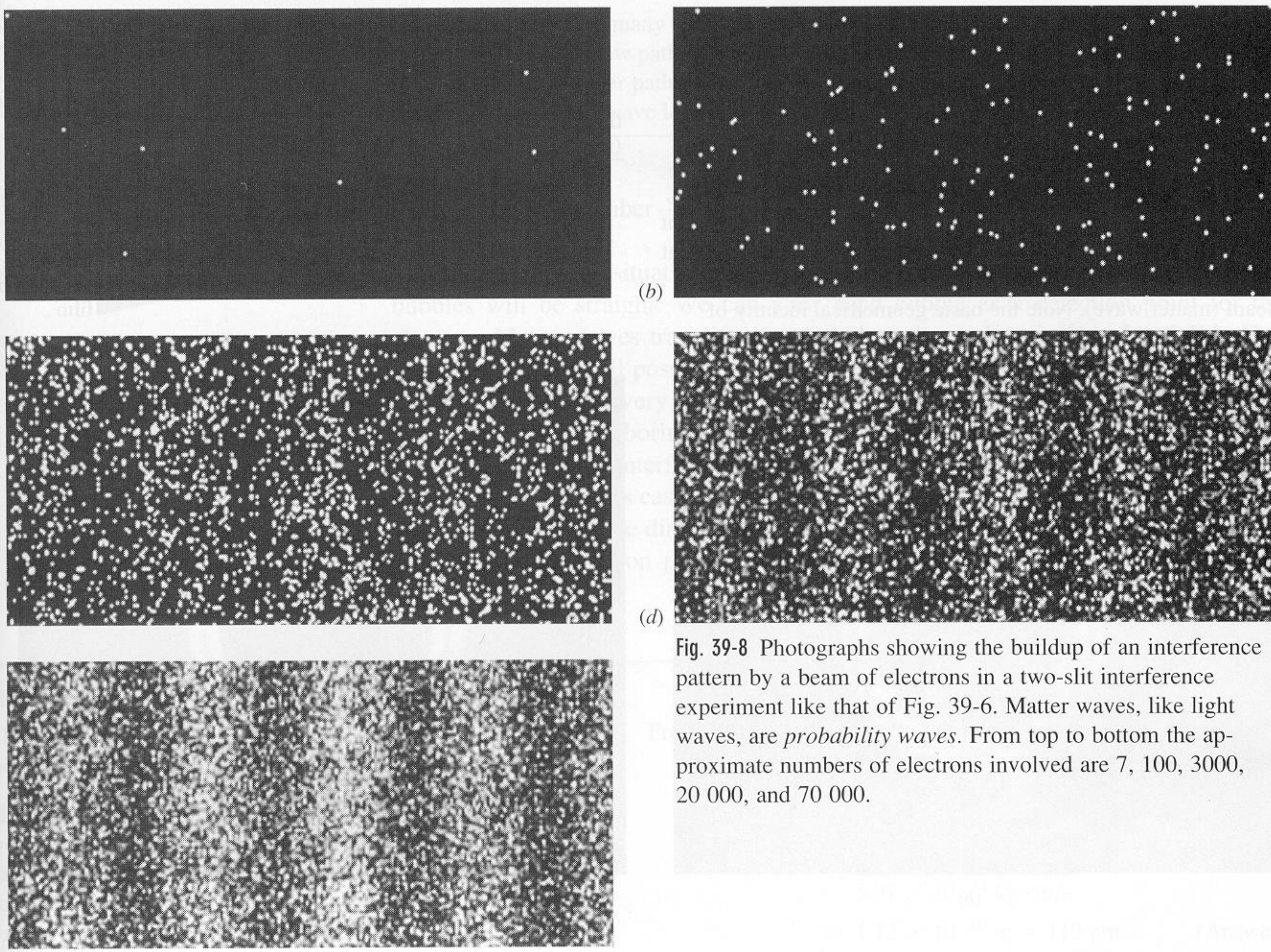
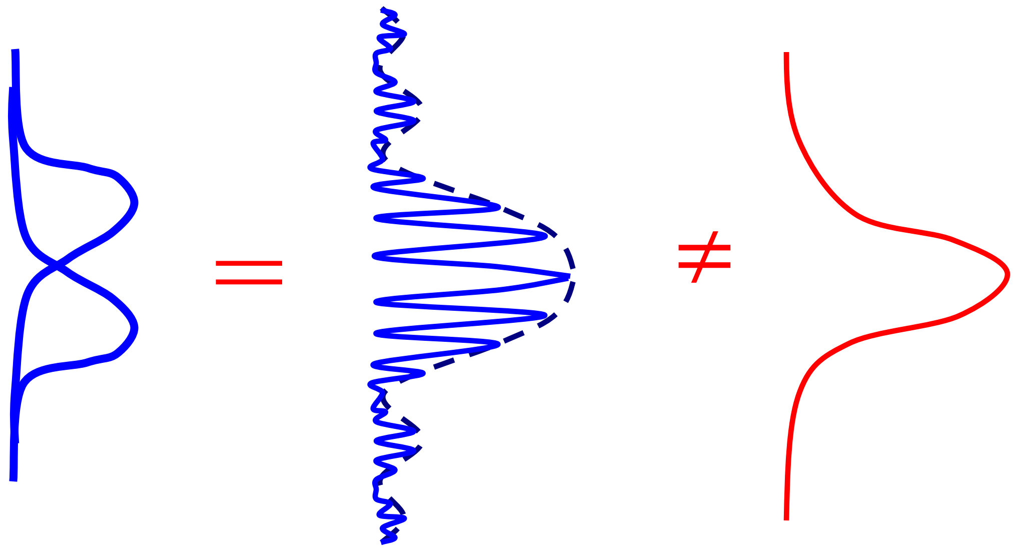
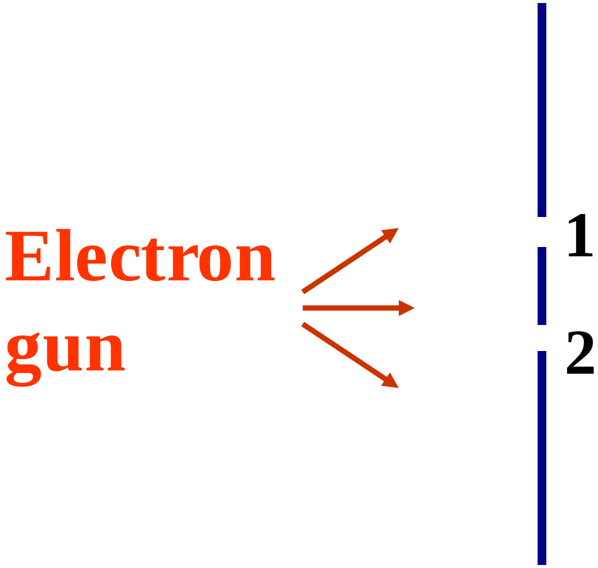


Fig. 39-8 Photographs showing the buildup of an interference pattern by a beam of electrons in a two-slit interference experiment like that of Fig. 39-6. Matter waves, like light waves, are *probability waves*. From top to bottom the approximate numbers of electrons involved are 7, 100, 3000, 20 000, and 70 000.

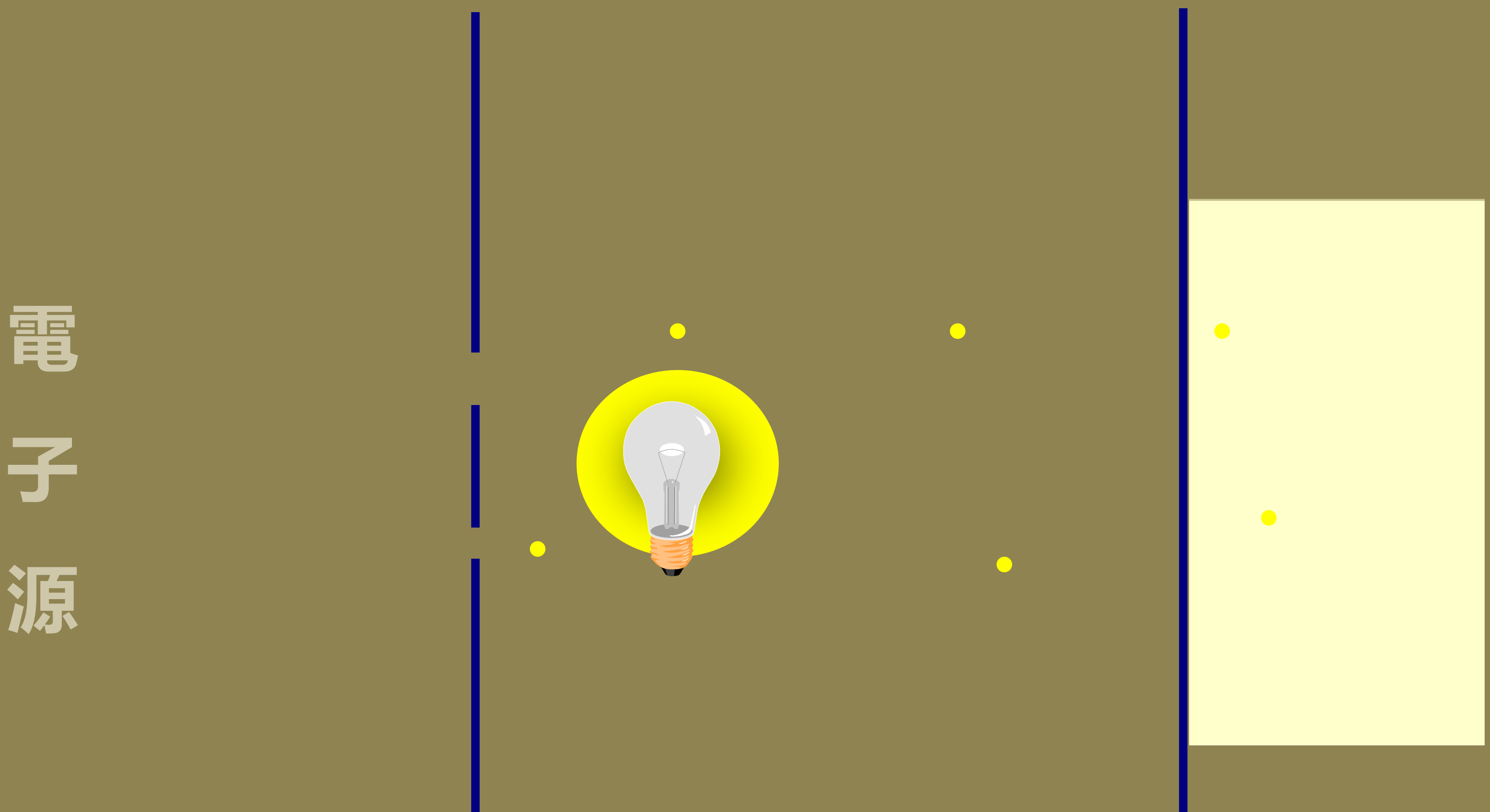
A great puzzle





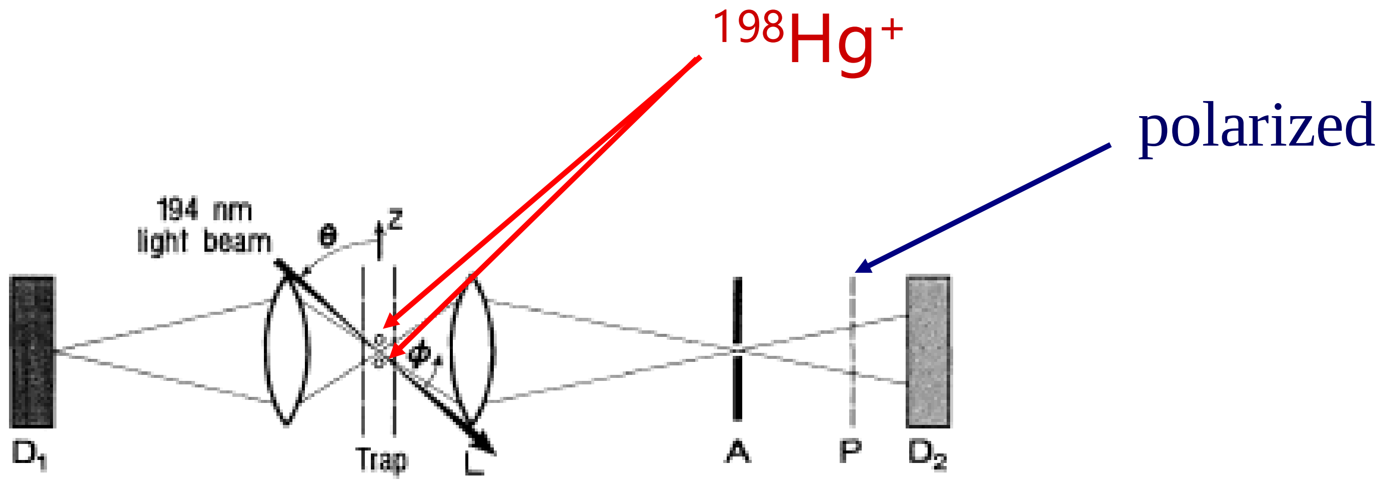
Electron is not passing 1 or 2, Instead it passes through 1 and 2 at the same time.

Which-way experiment



Nature 395, 33(1998)
PRL70,2359(1993)

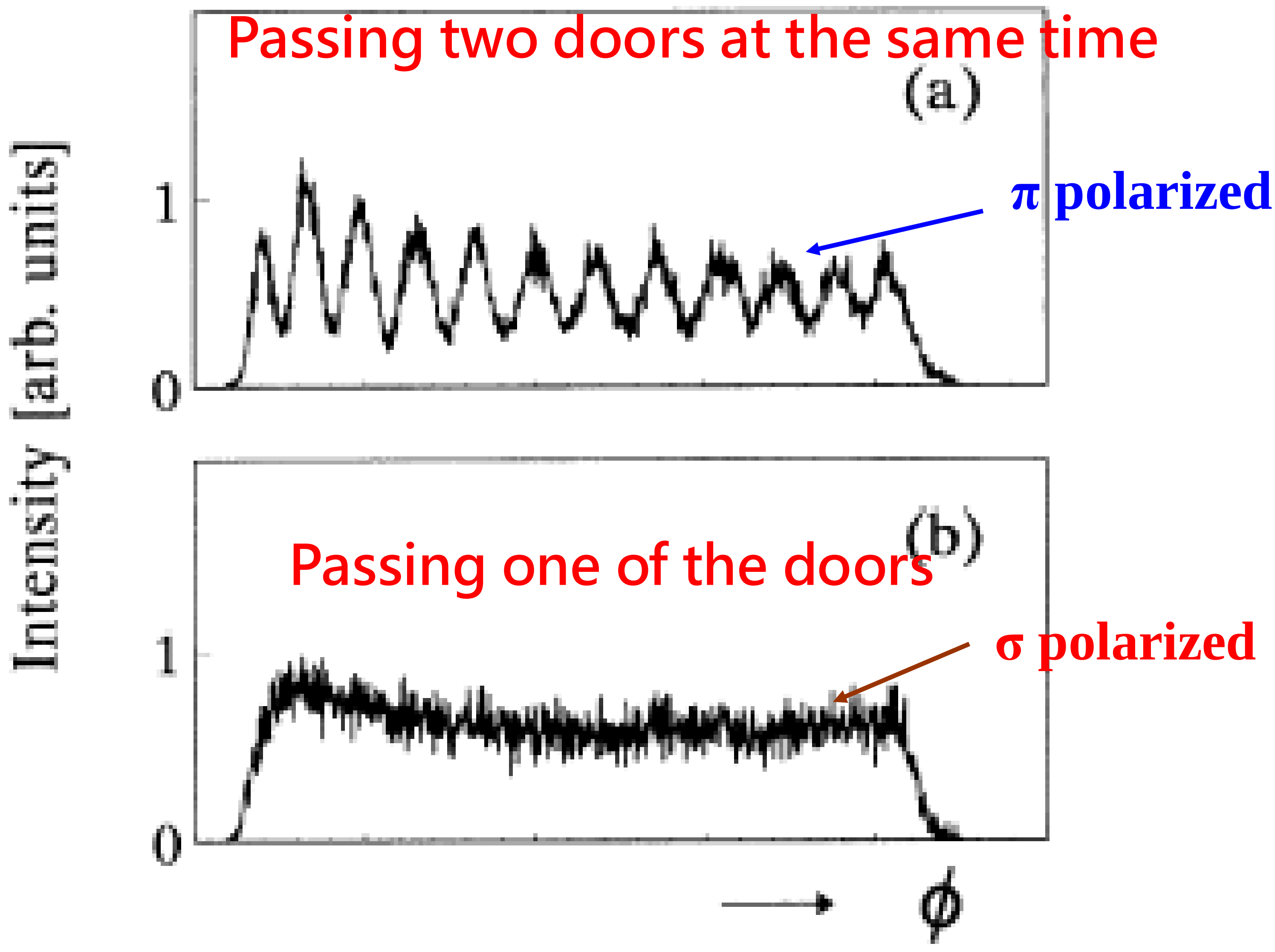
Which way expt. by using photons



Phys. Rev. Lett. 70,2359(1993)

Ground state: $6s^2S_{1/2}$, Excited state: $6p^2P_{1/2}$
degenerate: m_J

Photons: σ&π polarized
π: $\Delta m_J=0$ two atoms are in the same state
σ: $\Delta |m_J|=1$ two atoms are not in the same state



Electron version: Applied Physics Letters 97, 263101 (2010)

Concept of quantum bit (qubit)

$1 \rightarrow 0, |0\rangle$

$2 \rightarrow 1, |1\rangle$

Class bit: 0 or 1

qubit: can be 0 and at the same tim

When it is measured, only 0 or 1 is
Obtained (collapse of state)

double slit $\Rightarrow \dfrac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ ⇔ superposition $\boldsymbol{\Psi} = \boldsymbol{\Psi}_1 + \boldsymbol{\Psi}$

Advantage of qubit

*** 0 and 1 can be input at once**

0 or 1 can only be input separately

Classical computer — 1 — 0 —

Quantum computer — $\alpha|0\rangle + \beta|1\rangle$ —

*** more manipulation space:**

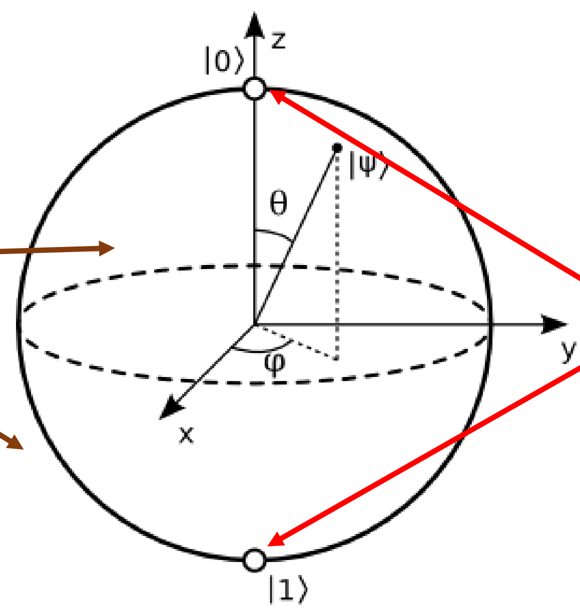
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle = \cos\frac{\theta}{2}|1\rangle + e^{i\phi}\sin\frac{\theta}{2}|0\rangle$$

$|\alpha|^2$ is the probability for finding 0

$|\beta|^2$ is the probability for finding 1

$$|\alpha|^2 + |\beta|^2 = 1$$

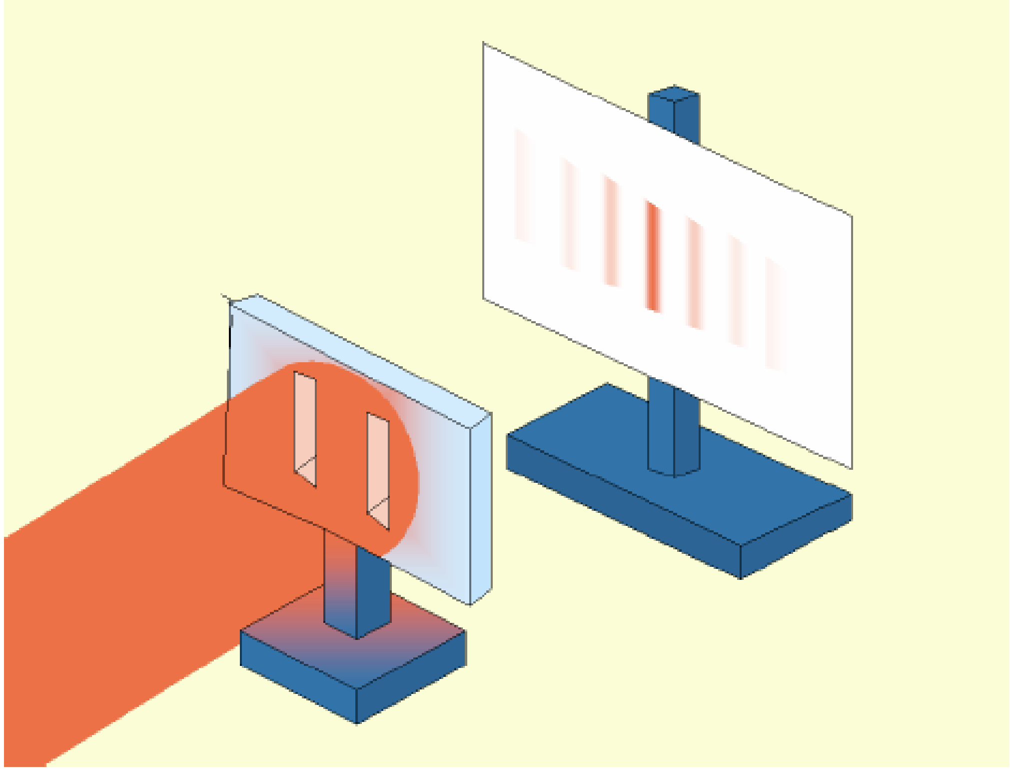
Quantum: whole sphere



classical: 2 point

Puzzles in Double-slit quantum eraser experim

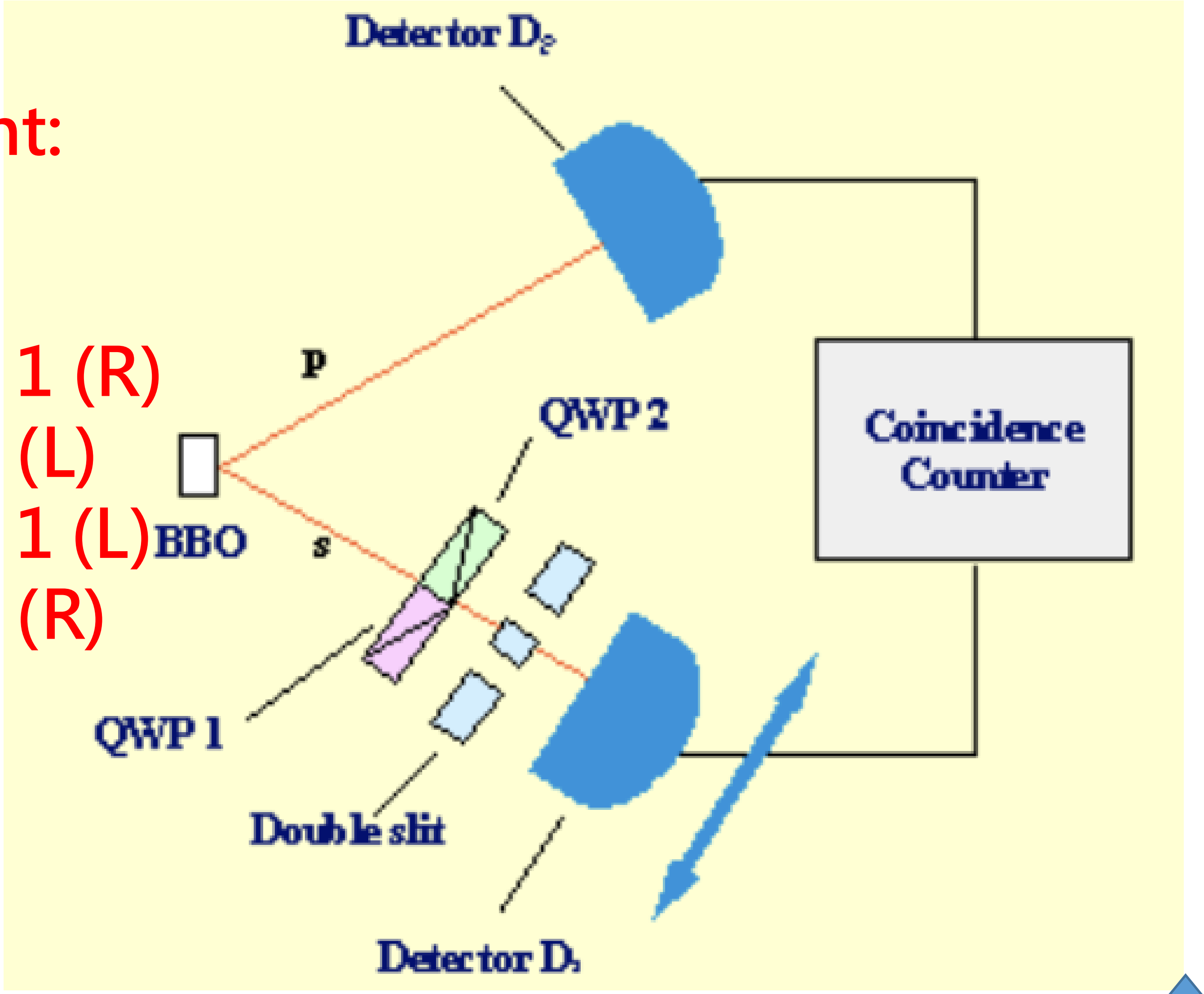
Using photons



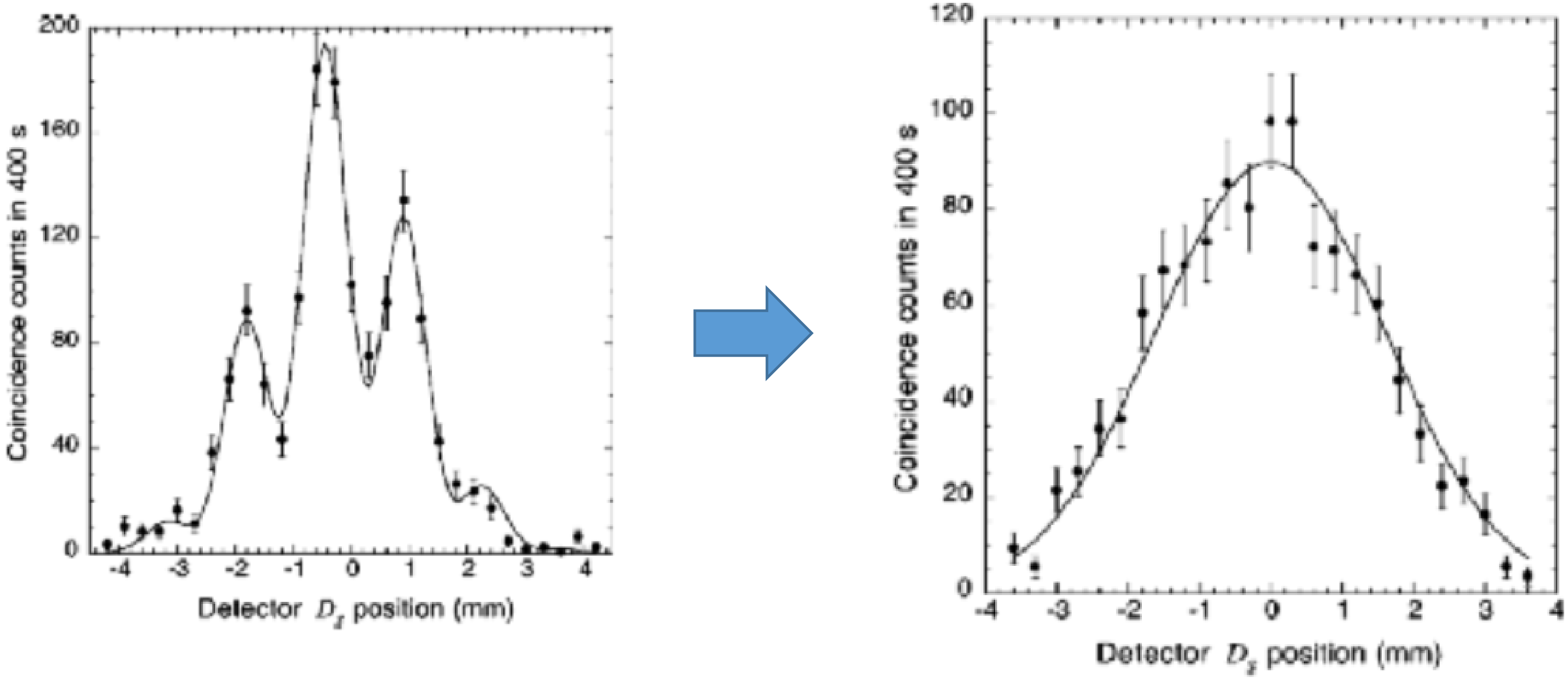
Which way experiment by using entangled photon s

Polarization Entanglement:

p s
x y => QWP 1 (R)
QWP 2 (L)
y x => QWP 1 (L)
QWP 2 (R)



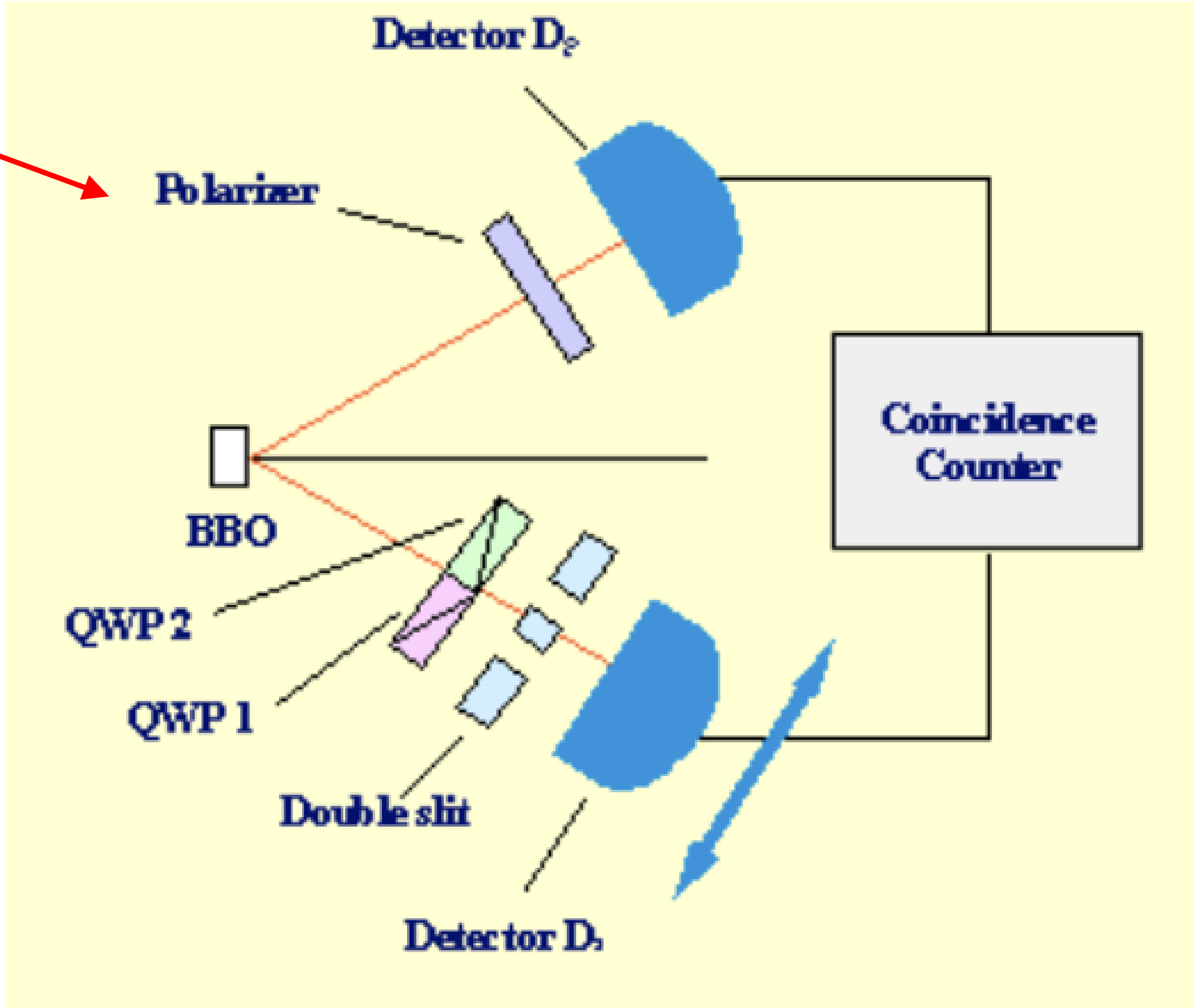
Which way experiment by detecting polariza



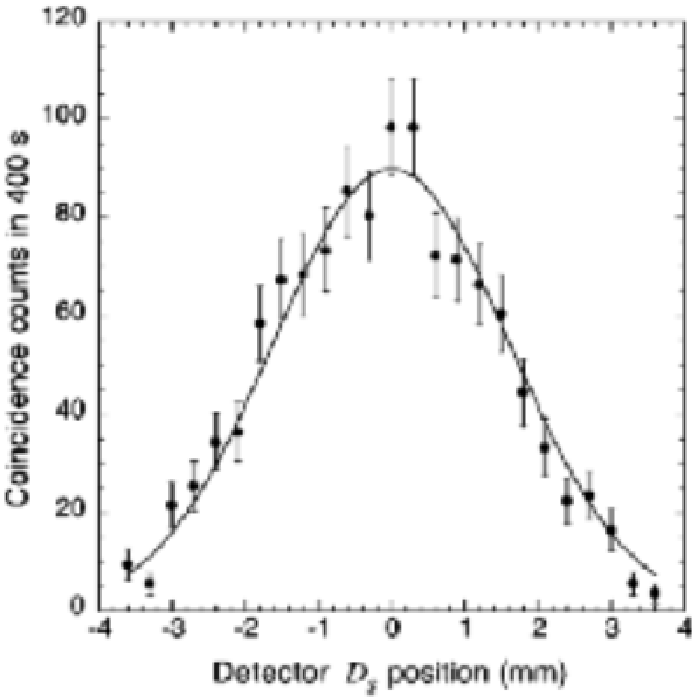
Quantum eraser

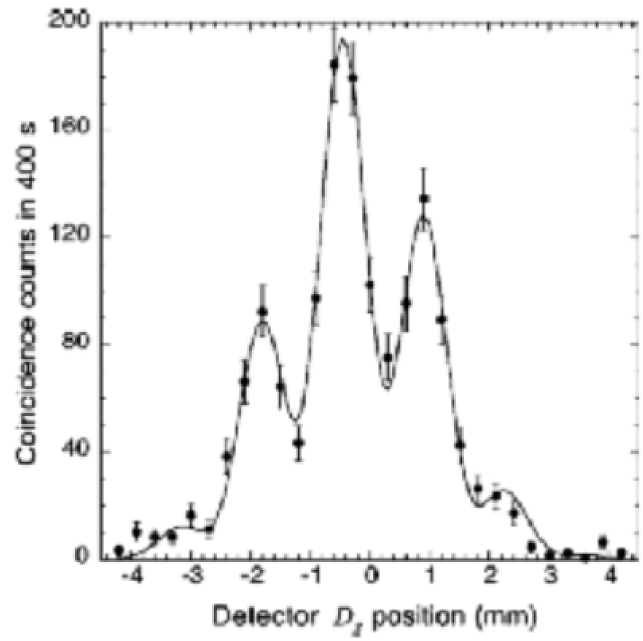
Linear polarized along $\frac{\pi}{4}$

$$\frac{1}{\sqrt{2}}(E, E)e^{(i\omega t - kz)}$$



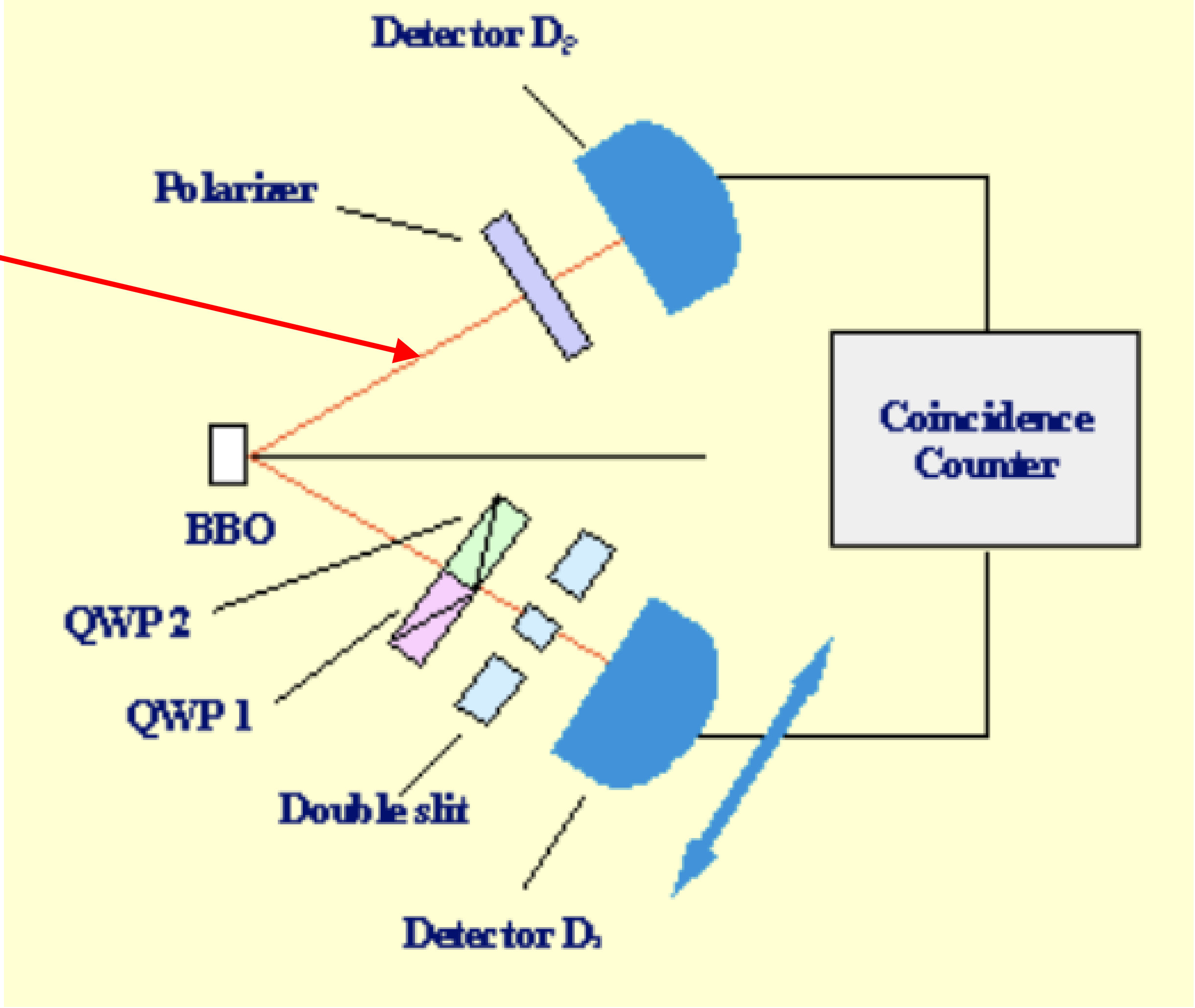
Quantum eraser



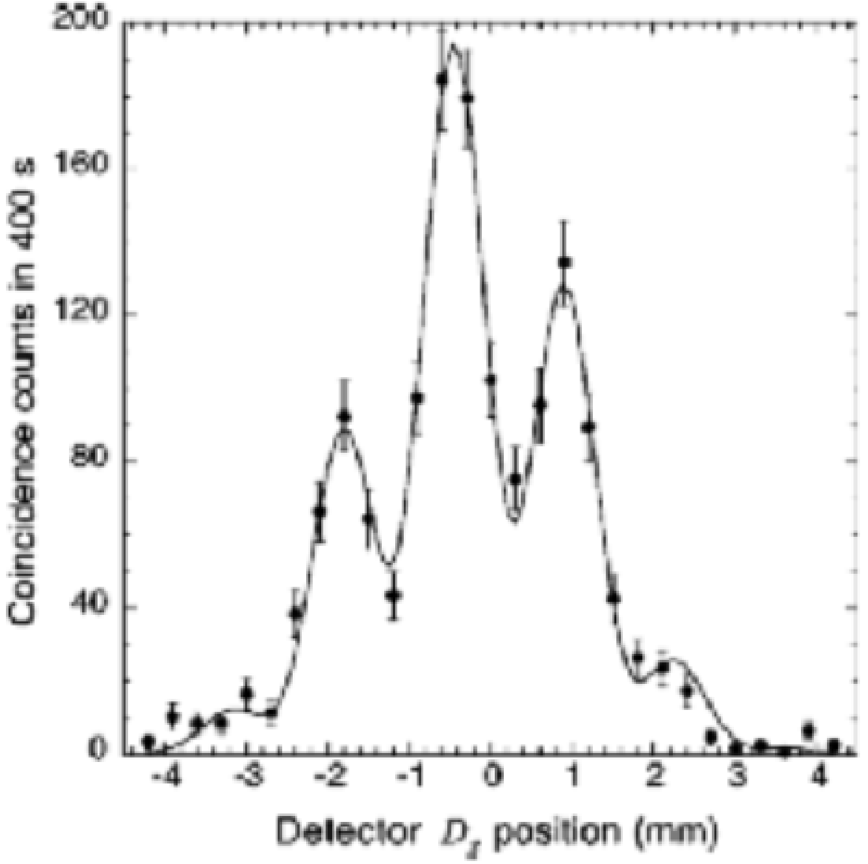


Delayed Quantum eraser

Make it very long
Before p photon encounter the polarizer, s photon will be detected first.



Future affects past?



Safari 檔案 編輯 顯示方式 瀏覽記錄 書籤 視窗 輔助說明 75% 2月19日 週三 下午9:25

w3.phys.nthu.edu.tw/~mou/teach.html

teach

- 奈米科技與量子的魔力

有趣的物理問題

- 打水漂兒的簡化模型
- 雲的形成
- 家用電表的簡化模型
- 有質量彈簧的振盪

電磁學(I)(II) 2014-2015

- 課程大綱(Syllabus)

筆記

- **Introduction and Vector Analysis**
- **Electrostatics: description and basic properties**
- **Electric potentials and methods of their evaluation**
- **Electric fields in matter**
- **Magnetostatitics**
- **Magnetic fields in matter**
- **Electrodynamics**
- **Conservation Laws**
- **Electromagnetic waves**
- **Special relativity and electrodynamics**
- **Potentials and fields**
- **Radiation**

習題 (I)

- 第3版與第4版習題對照表

Principle and Applicaton of Quantum Technology (量子科技的原理與應用) 2025 Spring

- **課程大綱(Syllabus)**

習題

- **Homework 1**

Slides

牟中瑜
Chung-Yu Mou 03-5742537 office: Department of Physics Room 514

教學 Teaching E-mail

Principle and Application of Quantum Technology
2023 Spring **Chung-Yu Mou**
Syllabus
Teaching Assistant : Shih-Si Hsiao
email: tousiotousio@gmail.com
phone:

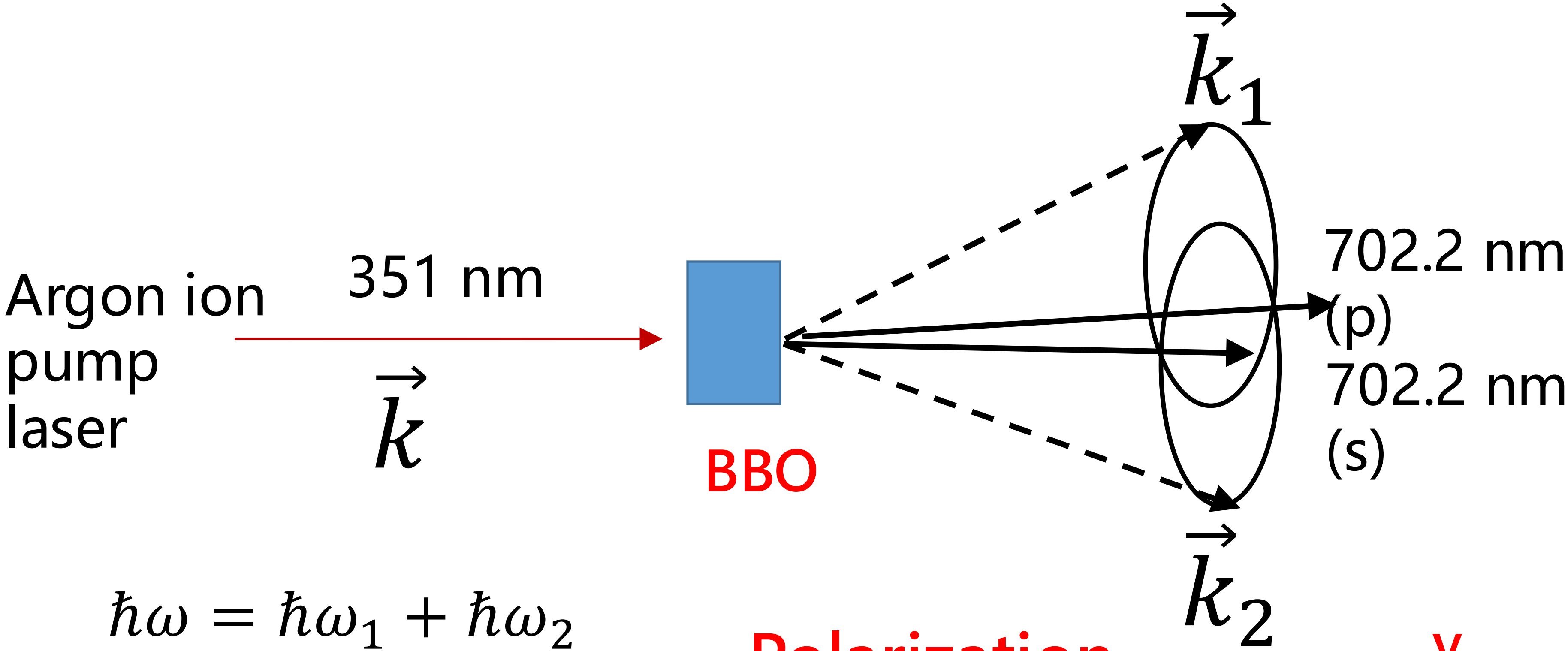
Course description

This course is designed for students with a background in science and engineering. Through detailed and systematic explanations, graduate students can master the basic principles of quantum technology. The main goal is to introduce the principles behind the operation of quantum devices and their possible applications, especially the manufacture and processes involved in making these devices. For those technologies that are still under development, we shall point it out at appropriate places and guide students to study in reports of final.

- Introduction to quantum phenomena and quantum mechanics
  - interfere and basic quantum mechanics
  Double-slit and related experiments
  (Hamiltonian and Schrodinger Equation, Dirac Notation Operators in Quantum Mechanics, Heisenberg Uncertainty Wave Particle Duality, Coherence)
  - quantization
  - tunneling effect
  - two-level system and spin
  (quantum bit and measurement, Rabi. Oscillation, Ramsey oscillation)
  - Many-particle state and entanglement (density matrix and decoherence)
  -Quantum measurement and quantum bit
- Typical applications of quantum technology
  - Quantum algorithm and universal quantum computer
  - Quantum communication
  - Quantum simulation and method of quantum annealing
  - Quantum sensing
- Technique of quantum qubit
  - Construction and manipulation of superconducting transmon qubit
  - Construction and manipulation of qubit based on ion trap
  - Construction and manipulation of silicon-based qubit
  - Principle, construction and manipulation of topological qubit
  - Principle and technique of photon-based qubit
  - Other relevant qubit technique such as vacancy-based qubit in diamond
- Quantum communication
  -Protocols of quantum key distributions and relevant technique for their realizations
  - Single photon source, entangled-photon source, and single photon detector

Entangled photon source

Nonlinear crystal: BBO (beta-barium borate)



$$\hbar\omega = \hbar\omega_1 + \hbar\omega_2$$

(energy conservation)

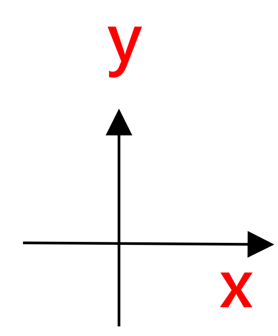
$$\hbar\vec{k} = \hbar\vec{k}_1 + \hbar\vec{k}_2$$

(momentum conservation)

Polarization Entanglement:

p s   s p

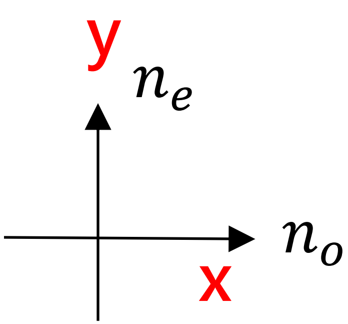
x y + y x



Quarter wavelength plate (QWP)

Convert linearly polarized light into circularly polarized light and vice versa

Using birefringent material (different indices of refraction associated with different crystallographic directions.)

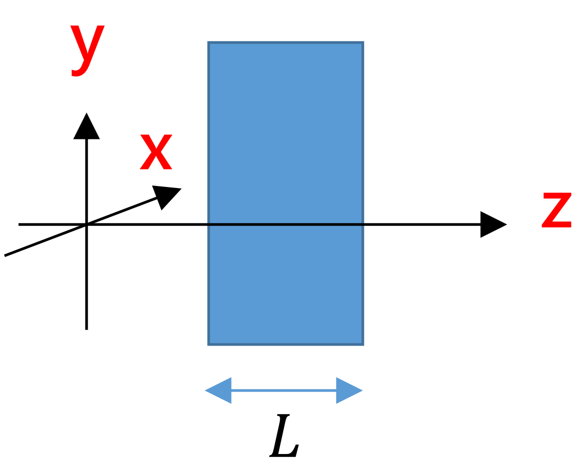


Linear Polarized along x

$$(\boldsymbol{E}, \boldsymbol{0})e^{i(\omega t - kz)}$$

Circular polarized

$$\frac{1}{\sqrt{2}}(\boldsymbol{E}, \pm i\boldsymbol{E})e^{(i\omega t - kz)} \text{ (+ right – left)}$$



Phase difference: $\Gamma = \frac{2\pi \Delta n L}{\lambda_0}$

Quarter wave: $\Gamma = \frac{\pi}{2}$

Route and obstacles to large scale quantum computing

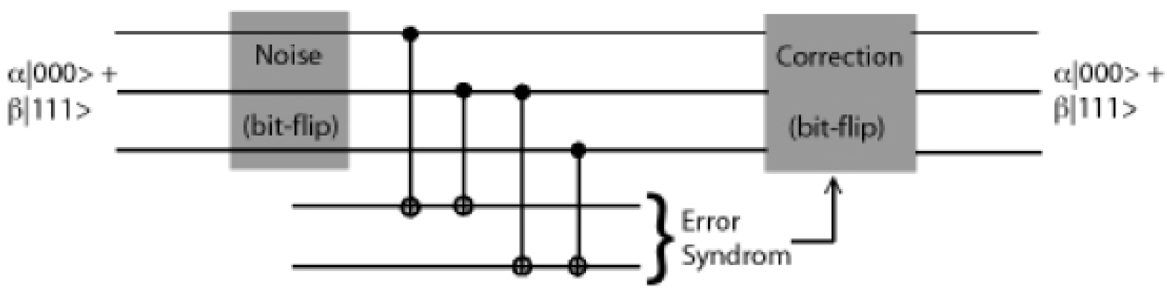
Quantum error correction (量子除錯)

Classical error correction: repeat bits & majority vote $0 \rightarrow 000,\ 1 \rightarrow 111$

Quantum: no clone theorem

$$\alpha\,|0\rangle + \beta\,|1\rangle \mapsto \alpha\,|000\rangle + \beta\,|111\rangle$$

+ two ancillary qubits



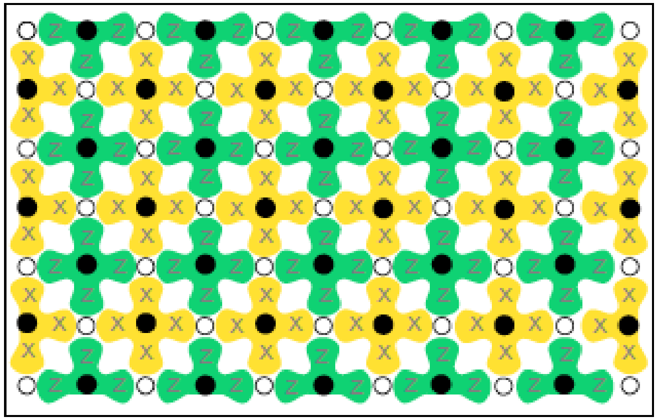
Error Location	Final State, $|\text{data}\rangle\,|\text{ancilla}\rangle$
No Error	$\alpha\,|000\rangle\,|00\rangle + \beta\,|111\rangle\,|00\rangle$
Qubit 1	$\alpha\,|100\rangle\,|11\rangle + \beta\,|011\rangle\,|11\rangle$
Qubit 2	$\alpha\,|010\rangle\,|10\rangle + \beta\,|101\rangle\,|10\rangle$
Qubit 3	$\alpha\,|001\rangle\,|01\rangle + \beta\,|110\rangle\,|01\rangle$

Need more physical qubits than the logical qubits!

Stabilizer codes (surface code)

Best code for tolerance of error (up to 1%): surface code (one of stabilizer codes)

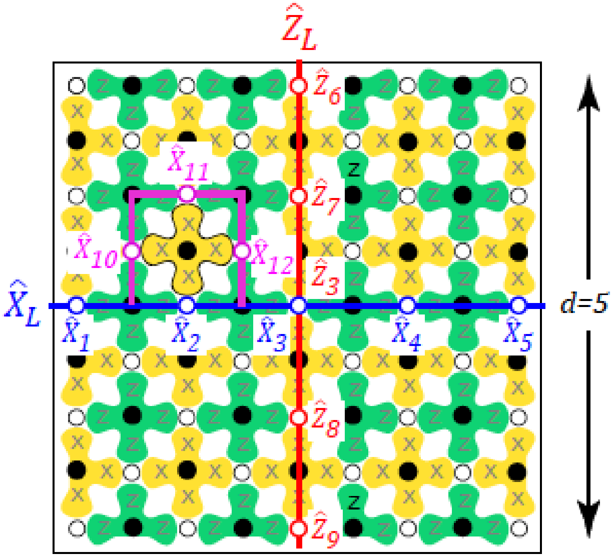
Repeat measurement of a quantum system using a complete set of commuting stabilizer (operators), the system is forced to be simultaneous and unique eigenstate of all stabilizers.



(open circles: data qubits,
filled circles: measurement qubits)

$X = \sigma_x, Z = \sigma_z$

(Fowler et al .Phys. Rev. A 86, 032324, 2012)



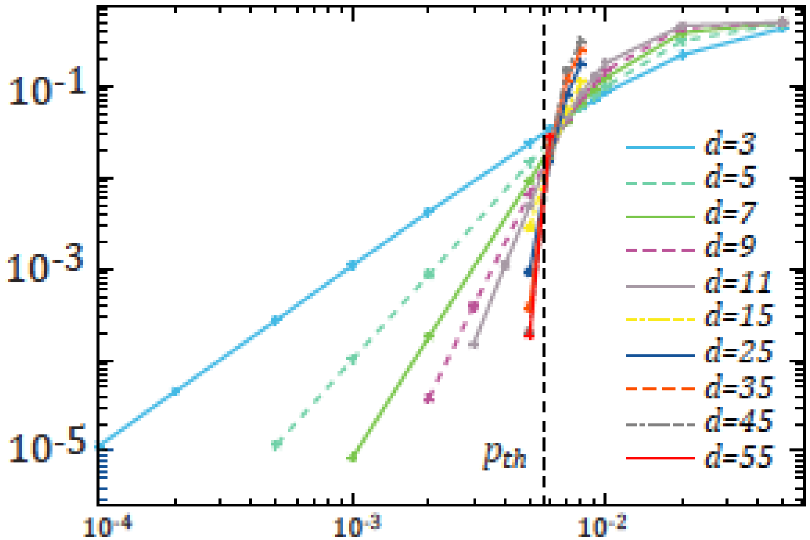
41 data qubits but only 40 stabilizers X and Z

$X_L = X_1X_2X_3X_4X_5$
$Z_L = Z_6Z_7Z_3Z_8Z_9$

Thresholds for large scale quantum computation

Best code for tolerance of error (up to 1%): surface code

However, this is at the sacrifice of many physical qubits for logical qubits: one logical qubit needs 10^3-10^4 physical qubits



Error probability $p < p_{th}$, P_L decreases with increasing number (d) of of physical qubits that define operator of logical qubit.

(Fowler et al .Phys. Rev. A 86, 032324, 2012)

Factorize a number of 6000 bits (~ 600 decimal digits)

$\Rightarrow$ 4000 logical qubits and 130 Millions physical qubits, roughly 26.7 hours to do (100ns gate time) (classical THz computer, >150000years)

Reference: Google 72 qubit and strategy