看圖片說奈米
量子物理與奈米的憧憬

清華大學物理系牟中瑜
http://www.phys.nthu.edu.tw/~mou
何謂奈米？

奈米 (nm) 就是 $1/1000000000 \ (10^{-9})$ 公尺

精密外科手術：$1/10000$ 公尺 = 0.1 公釐

假想你變成與台灣島 (~100公里~100000公尺) 一般巨大，來為正常人動精密外科手術。
4th Century, Roman glassmaker: the color of glasses can be changed by mixing in metal particles
• 1883, Films containing silver halides for photography were invented by George Eastman, founder of Kodak
• 1908, Gustay Mie first provided the explanation of the size dependence of color
• Vision from Feynman in 1959: “There is plenty room at the bottom”, and also recognized there are plenty of nature-given nanostructures in biological systems
• 1950-1960, small metal particles were investigated by physicists
• 1957, Ralph Landauer realized the importance of quantum mechanics plays in devices with small scales
• Before 1997 => mesoscopic (or low dimensional) physics: quantum dots, wells, wires...are known already
There’s Plenty of Room at the Bottom

An Invitation to Enter a New Field of Physics

by Richard P. Feynman

This transcript of the classic talk that Richard Feynman gave on December 29th, 1959, at the annual meeting of the American Physical Society at the California Institute of Technology (Caltech) was first published in the February 1960 issue of Caltech’s Engineering and Science, which owns the copyright. It has been made available on the web at http://www.zyvex.com/nanotech/feynman.html with their kind permission.

Information on the Feynman Prizes

Links to pages on Feynman


I imagine experimental physicists must often look with envy at men like Kamerlingh Onnes, who discovered a field like low temperature, which seems bottomless and in which one can go down and down. Such a man is then a leader and has some temporary monopoly in a scientific adventure. Percy Bridgman, in designing a way to obtain higher pressures, opened up another new field and was able to move into it and to lead us all along. The development of ever higher vacuum was a continuing development of the same kind.

I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle. This field is not quite the same as the others in that it will not tell us much of fundamental physics (in the sense of, "What are the strange particles?") but it is more like solid-state physics in the sense that it might tell us much of great interest about the strange phenomena that occur in complex situations. Furthermore, a point that is most
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What I want to talk about is the problem of manipulating and controlling things on a small scale.

As soon as I mention this, people tell me about miniaturization, and how far it has progressed today. They tell me about electric motors that are the size of the nail on your small finger. And there is a device on the market, they tell me, by which you can write the Lord's Prayer on the head of a pin. But that's nothing: that's the most primitive, halting step in the direction I intend to discuss. It is a staggeringly small world that is below. In the year 2000, when it looks back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction.

Why cannot we write the entire 24 volumes of the Encyclopedia Britannica on the head of a pin?

Let's see what would be involved. The head of a pin is a sixteenth of an inch across. If you magnify it by 25,000 diameters, the area of the head of the pin is then equal to the area of all the pages of the Encyclopaedia Britannica. Therefore, all it is necessary to do is to reduce in size all the writing in the Encyclopaedia by 25,000 times. Is that possible? The resolving power of the eye is about 1/120 of an inch—that is roughly the diameter of one of the little dots on the fine half-tone reproductions in the Encyclopaedia. This, when you demagnify it by 25,000 times, is still 80 angstroms in diameter—32 atom across, in an ordinary metal. In other words, one of these dots still would contain in its area 1,000 atoms. So, each dot can easily be adjusted in size as required by the photoengraving, and there is no question that there is enough room on the head of a pin to put all of the Encyclopaedia Britannica.

Furthermore, it can be read if it is so written. Let's imagine that it is written in raised letters of metal; that is, where the black is in the Encyclopedia, we have raised letters of metal that are actually 1/25,000 of their ordinary size. How would we read it?

If we had something written in such a way, we could read it using techniques in common use today. (They will undoubtedly find a better way when we actually have it written, but to make my point conservatively I shall just take techniques we know today.) We would press the metal into a plastic materi and make a mold of it, then peel the plastic off very carefully, incorporate silica into the plastic to get a very thin film, then shadow it by evaporating gold
Information on a small scale

Suppose that, instead of trying to reproduce the pictures and all the information directly in its present form, we write only the information content in a series of dots and dashes, or something like that, to represent the various letters. Each letter represents six or seven “bits” of information; that is, you need only about six or seven dots or dashes for each letter. Now, instead of writing everything, as I did before, on the surface of the head of a pin, I am going to use the interior of the material as well.

Let us represent a dot by a small spot of one metal, the next dash, by an adjacent spot of another metal, and so on. Suppose, to be conservative, that a bit of information is going to require a little cube of atoms 5 times 5 times 5—that is 125 atoms. Perhaps we need a hundred and some odd atoms to make sure the information is not lost through diffusion, or through some other process.

I have estimated how many letters there are in the Encyclopaedia, and I have assumed that each of my 24 million books is as big as an Encyclopaedia volume, and have calculated, then, how many bits of information there are (10^15). For each bit I allow 100 atoms. And it turns out that all of the information that man has carefully accumulated in all the books in the world can be written in this form in a cube of material one two-hundredth of an inch wide—which is the barest piece of dust that can be made out by the human eye. So there is plenty of room at the bottom! Don’t tell me about microfilm.

This fact—that enormous amounts of information can be carried in an exceedingly small space—is, of course, well known to the biologists, and resolve a mystery which existed before we understood all this clearly, of how it could be that, in the tiniest cell, all of the information for the organization of a complex creature such as ourselves can be stored. All this information—whether we have brown eyes, or whether we think at all, or that in the embryo the jawbone should first develop with a little hole in the side so that later a nerve can grow through it—all this information is contained in a very tiny fraction of the cell in the form of long-chain DNA molecules in which approximately 50 atoms are used for one bit of information about the cell.

Better electron microscopes

If I have written in a code, with 5 times 5 times 5 atoms to a bit, the question is: How could I read it today? The electron microscope is not quite good enough, with the greatest care and effort, it can only resolve about 10 angstroms. I would like to try and impress upon you while I am talking about all of these things on a small scale, the importance of improving the electron microscope by a hundred times. It is not impossible; it is not against the laws of diffraction of the electron. The wavelength of the electron in such a microscope is only 1/20 of an angstrom. So it should be possible to see the individual atoms. What good would it be to see individual atoms distinctly?

We have friends in other fields—in biology, for instance. We physicists often look at them and say, “You know the reason you fellows are making so little progress?” (Actually I don’t know any field where they are making more rapid progress than they are in biology today.) “You should use more mathem
The marvelous biological system

The biological example of writing information on a small scale has inspired me to think of something that should be possible. Biology is not simply writing information; it is doing something about it. A biological system can be exceedingly small. Many of the cells are very tiny, but they are very active; they manufacture various substances; they walk around; they wiggle; and they do all kinds of marvelous things—all on a very small scale. Also, they store information. Consider the possibility that we too can make a thing very small which does what we want—that we can manufacture an object that maneuvers at that level.

There may even be an economic point to this business of making things very small. Let me remind you of some of the problems of computing machines: computers we have to store an enormous amount of information. The kind of writing that I was mentioning before, in which I had everything down as a distribution of metal, is permanent. Much more interesting to a computer is a way of writing, erasing, and writing something else. (This is usually because we don’t want to waste the material on which we have just written. Yet if we could write it in a very small space, it wouldn’t make any difference; it could just be thrown away after it was read. It doesn’t cost very much for the material).

Miniaturizing the computer

I don’t know how to do this on a small scale in a practical way, but I do know that computing machines are very large; they fill rooms. Why can’t we make them very small, make them of little wires, little elements—and by little, I mean little. For instance, the wires should be 10 or 100 atoms in diameter, and circuits should be a few thousand angstroms across. Everybody who has analyzed the logical theory of computers has come to the conclusion that the possibilities of computers are very interesting—if they could be made to be more complicated by several orders of magnitude. If they had millions of times as many elements, they could make judgments. They would have time to calculate what is the best way to make the calculation that they are about to make. They could select the method of analysis which, from their experience, is better than the one that we would give to them. And in many other ways, they would have new qualitative features.

If I look at your face I immediately recognize that I have seen it before. (Actually, my friends will say I have chosen an unfortunate example here for the subject of this illustration. At least I recognize that it is a man and not an apple.) Yet there is no machine which, with that speed, can take a picture of a face and say even that it is a man; and much less that it is the same man that you showed it before—unless it is exactly the same picture. If the face is changed I am closer to the face; if I am further from the face; if the light changes—I recognize it anyway. Now, this little computer I carry in my head is easily able to do that. The computers that we build are not able to do that. The number of elements in this bone box of mine are enormously greater than the number of
Chemical Vapor Deposition and Molecular Beam Epitaxial Growth

But there is plenty of room to make them smaller. There is nothing that I can see in the physical laws that says the computer elements cannot be made enormously smaller than they are now. In fact, there may be certain advantages.

**Miniaturization by evaporation**

How can we make such a device? What kind of manufacturing processes would we use? One possibility we might consider, since we have talked about writing by putting atoms down in a certain arrangement, would be to evaporate the material, then evaporate the insulator next to it. Then, for the next layer evaporate another position of a wire, another insulator, and so on. So, you simply evaporate until you have a block of stuff which has the elements—cc and condensers, transistors and so on—of exceedingly fine dimensions.

But I would like to discuss, just for amusement, that there are other possibilities. Why can't we manufacture these small computers somewhat like we manufacture the big ones? Why can't we drill holes, cut things, solder things, stamp things out, mold different shapes all at an infinitesimal level? What the limitations as to how small a thing has to be before you can no longer mold it? How many times when you are working on something frustratingly tiny like your wife's wrist watch, have you said to yourself, "If I could only train an ant to do this!" What I would like to suggest is the possibility of training an ant to train a mite to do this. What are the possibilities of small but movable machines? They may or may not be useful, but they surely would be fun to make.

Consider any machine—for example, an automobile—and ask about the problems of making an infinitesimal machine like it. Suppose, in the particular design of the automobile, we need a certain precision of the parts; we need an accuracy, let's suppose, of 4/10,000 of an inch. If things are more inaccurate than that in the shape of the cylinder and so on, it isn't going to work very well. If I make the thing too small, I have to worry about the size of the atom; I can't make a circle of "balls" so to speak, if the circle is too small. So, if I make the error, corresponding to 4/10,000 of an inch, correspond to an error of an atom, it turns out that I can reduce the dimensions of an automobile 4,000 times, approximately—so that it is 1 mm. across. Obviously, if you redesign the car so that it would work with a much larger tolerance, which is not at all impossible, then you could make a much smaller device.

It is interesting to consider what the problems are in such small machines. Firstly, with parts stressed to the same degree, the forces go as the area you are reducing, so that things like weight and inertia are of relatively no importance. The strength of material, in other words, is very much greater in proportion. The stress is expansion of the flywheel from centrifugal force, for example, would be the same proportion only if the rotational speed is increased in the same proportion as we decrease the size. On the other hand, the metals that we use have a grain structure, and this would be very annoying at small scale because the material is not homogeneous. Plastics and glass and things of this amorphous nature are very much more homogeneous, and so we would have to make our machines out of such materials.

There are problems associated with the electrical part of the system—with the copper wires and the magnetic parts. The magnetic properties on a very sm
But it is interesting that it would be, in principle, possible (I think) for a physicist to synthesize any chemical substance that the chemist writes down. Give the orders and the physicist synthesizes it. How? Put the atoms down where the chemist says, and so you make the substance. The problems of chemistry and biology can be greatly helped if our ability to see what we are doing, and to do things on an atomic level, is ultimately developed—a development which I think cannot be avoided.

Now, you might say, "Who should do this and why should they do it?" Well, I pointed out a few of the economic applications, but I know that the reason that you would do it might be just for fun. But have some fun! Let's have a competition between laboratories. Let one laboratory make a tiny motor which sends to another lab which sends it back with a thing that fits inside the shaft of the first motor.

**High school competition**

Just for the fun of it, and in order to get kids interested in this field, I would propose that someone who has some contact with the high schools think of making some kind of high school competition. After all, we haven't even started in this field, and even the kids can write smaller than has ever been written before. They could have competition in high schools. The Los Angeles high school could send a pin to the Venice high school on which it says, "How's this?" They get the pin back, and in the dot of the 'i' it says, "Not so hot."

Perhaps this doesn't excite you to do it, and only economics will do so. Then I want to do something; but I can't do it at the present moment, because I haven't prepared the ground. It is my intention to offer a prize of $1,000 to the first guy who can take the information on the page of a book and put it on a 1/25,000 smaller in linear scale in such manner that it can be read by an electron microscope.

And I want to offer another prize—if I can figure out how to phrase it so that I don't get into a mess of arguments about definitions—of another $1,000 to the first guy who makes an operating electric motor—a rotating electric motor which can be controlled from the outside and, not counting the lead-in wires, only 1/64 inch cube.

I do not expect that such prizes will have to wait very long for claimants.
Top-down approach dominates....

**BASIC CHIPMAKING PROCESS**

1. Steam oxidizes surface (red layer)
2. Photoresist (dark blue layer) coats oxidized wafer
3. Lithography transfers desired pattern from mask to wafer

**REFINEMENTS IN CHIPMAKING**

- Strained silicon
- Silicon-germanium blend
- Oxide
- Silicon substrate

- Pattern on mask
- Pattern on wafer
近來大力推動奈米科技的背景

來自微電子學可能遭遇瓶頸的考慮

Moore's Law:

a 30% decrease in the size of printed dimensions every two years
### Table: Actual vs. Forecast for Transistor Generations

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<td>50</td>
<td>35</td>
<td>20nm</td>
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</table>

*Peter Silverman, Intel, July, 2001*

---

**Diagram: Heading toward 1 billion transistors in 2007**

- 4004
- 8008
- 8080
- 8086
- 286
- 386™ Processor
- Pentium® II Processor
- Pentium® Processor
- Pentium® IV Processor
- Pentium® III Processor
- Itanium™ Processor (McKinley)

*Y. Borodovsky, Intel, April, 2002 in PMJ 2002*
到底會發生??事

預估以現行的半導體技術縮小的速度，在2015左右，device大小達50nm以下。電子的波動性不可再被忽略...

Refs.
• Fowler, Physics Today Oct. 50-54(1997)
• Glattii, Nature 393, 516(1998)
可能遭遇的問題

•需要製造更小的pattern的技術（advanced lithographic techniques，如 e-beam, x-ray, ..）

•電子量子特性的重要性??

•記憶元件運作原理的不適用

• .. etc.
跨領域最小單位逐漸重疊

電機工程
生物
材料
奈米
奈米科技的起源

1996-1998年間，以美國NSF為主要贊助者，由World Technology Evaluation Center (WTEC)出面組織的委員對奈米尺度下之可能的科技作了仔細的評估

結論是奈米科技極具潛力，發展它有可能有重要且影響廣泛的技術突破..
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nanotechnology

nanotechnology is an expected future manufacturing technology that will make most products lighter, stronger, cleaner, less expensive and more precise. ... More Information.


www.zyvex.com/nano/ - 33k - 2004年4月17日 - 頁庫存檔 - 類似網頁

nanotechnology

nanotechnology, ... What's new? Turpion Ltd: Institute of Physics Publishing acquires a 9% share Nanotechnology now clustered by subject. Journal history. 1990-present, nanotechnology. Recommend this journal ISSN 0957-4484 (Print) ISSN 1361-6528 online) e-mail alerts. An easy way to keep up to date ... www.iop.org/EJ/journal/0957-4484 - 類似網頁

nanotechnology - Foresight Institute - Molecular Nanotech


友站連結

奈米商機
作成完美投資決策的關鍵
讀者可瀏覽他的網站

nanotechnology Stock News

Nanotechnology Jobs
New jobs posted continuously. Numerous options for employers www.nanorex.com
Assemble & material preparation: physics, chemistry and engineering

An important direction
Bottom-up approach?

Quantum & statistical mech

Communication & design

SPM: probe & manipulation
First Lesson

塊材到奈米的轉變

(bulk-to-nano transition)
例: size-dependence of melting temperature

例：size-dependence of color

powered cadmium selenide

larger

smaller
例：size-dependence of magnetism

超順磁現象 (superparamagnetism)

Dependence of the coercive field $B_c$ (i.e., $H_c$) on the granular particle size $d$ of a Nd–B–Fe permanent magnet. [Adapted from A. Manaf et al., J. Magn. Magn. Mater. 101, 360 (1991).]
Conventional magnetic recording is limited by the superparamagnetic limit.
例: 邊界態 (edge mode) 的重要性增加

M=1

(a) $L_y = 4, U = 1$

(b) $L_y = 6, U = 1$

量子物理的重要
尺度變化的起源

• 邊界的影響
  • 邊界佔有比例的增加
  • 邊界態(surface/edge modes)的存在
  • 幾何結構的重整
• 粒子數的減少(束縛減弱, 說動增加, 連續性的不適用..)
• 不同物理量有不同的尺度變化
• 量子效應 => 最有可能產生新的突破
奈米尺寸的物性/應用

以電子為基礎
(如：奈米電子學)

以原子/離子為基礎
物質波與力學性質的聯繫

\[ h = \text{Planck constant} \]
\[ (6.626 \times 10^{-34} \text{ joule-sec}) \]

DeBroglie:
\[ \lambda = \frac{h}{p} \]

Einstein:
\[ E = h\nu = \frac{p^2}{2m} \]

自由電子: \( \lambda_{th}(300K) = 6.2\text{nm} \)
(半導體中 \( 10\text{nm} \leq \lambda \leq 100\text{nm} \))
原子: \( \lambda_{th}(300K) \leq 0.2\text{nm} \)
塊材極限 ↔ 奈米極限

\[ L \gg \lambda \]

\[ L \approx \lambda \]
奈米尺度的五大量子效應
(I) 干渉
(Interference)
神奇的電子波動性

古典粒子的期待

= ?
電子波動性
電子的雙狹縫干涉
$dsin\theta = (m+1/2)\lambda$

建设性干涉

$\Delta y = \frac{L}{d}\lambda$

破坏性干涉

$d\frac{\Delta y}{L} = \lambda$
\[ L \approx 1\, m \]

\[ \lambda \approx 700\, nm \]

\[ \lambda \approx 0.17\, nm \]

\[ d \approx 10^{-1}\, mm = 10^{-4}\, m \]

\[ \Delta y = \frac{L}{d} \lambda \]

\[ = 7\, mm \]

\[ \Delta y = 1.7\, \mu m \]
...This experiment has never been done in just this way. The trouble is that the apparatus would have to be made on an impossible small scale ... We are doing a “thought experiment”...

參考值:
Davisson and Germer 之電子繞射實驗
電子波長為0.165nm(1.65 Å, 50eV)
Tonomura et al.

\[
\lambda = 0.054 \text{Å (50kV), } V_a = 10\text{V} \\
a = 0.5 \mu\text{m, } b = 5\text{mm} \\
\text{spacing = 700nm}
\]
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.
The double-slit experiment

Who performed the most beautiful experiment in physics?

What is the most beautiful experiment in physics? This is the question that Robert Crease asked Physics World readers in May - and more than 200 replied with suggestions as diverse as Schrödinger's cat and the Trinity nuclear test in 1945. The top five included classic experiments by Galileo, Millikan, Newton and Thomas Young. But uniquely among the top 10, the most beautiful experiment in physics - Young's double-slit experiment, applied to the interference of single electrons - does not have a name associated with it.

Most discussions of double-slit experiments with particles refer to Feynman's quote in his lectures: "We choose to examine a phenomenon which is impossible, absolutely impossible, to explain..."
量子柵欄 (Quantum Corral)

Crommue, Luts, and Eigler, Science 262, 218-220, 1993
Quantum Mirage

IBM Almaden Research Center, 2000
害羞的電子與 which-way experiment

PRL 70, 2359(1993)
一旦知道 which-way...
=>粒子性 (complimentary)
Which-way (welcher Weg) experiment

$^{198}\text{Hg}^+$

polarizer


利用 polarizer 選擇所要觀察光子的 polarization
One atom spin flip

Intensity [arb. units]
Matter Wave of Large Molecules

http://www.quantum.univie.ac.at/research/c60/index.html
Other atoms: Na, Phys. Rev. 66, 2693 (1991)
Biomolecules

3D structure of tetraphenylporphyrin $\text{C}_{44}\text{H}_{30}\text{N}_4$(TPP)
Interference between condensates

Science 275, 637 (1997): $\sim 10^6$ Sodium atoms
(II) Quantumization
物質波的束縛

駐波

量子化
量子柵欄 (Quantum Corral)

Crommues, Luts, and Eigler, Science 262, 218-220, 1993
能量的量子化

\[ L = \frac{n}{2} \lambda \]

\[ p = \frac{h}{\lambda} = \frac{nh}{2L} \]

\[ E_n = \frac{p^2}{2m} = \frac{n^2 h^2}{8mL^2} \]

\[ \delta E \propto \frac{1}{L^2} \]
束縛結構的分類

依被束縛方向的數目分類：

量子井 (quantum well): 1個束縛方向

MOSFET:

二維電子氣

AlGaAs

GaAs

$E_F$

e

AlGaAs

GaAs
SEM images of MoOx nanowires on graphite surfaces
奈米碳管

\[
\begin{align*}
\sigma & \quad \text{bond} \\
\pi & \quad \text{bond}
\end{align*}
\]
DNA 線

DNA 可以拿來當電線嗎？
量子點 (quantum dot): 3個束縛方向
用電壓把電子關起來 -- 量子點
不同形狀的量子點
powered cadmium selenide

larger

smaller

\[ \lambda \]

\[ E = \frac{hc}{\lambda} \propto \frac{1}{L^2} \]
部分束縛 (partial confinement) 與“奈米捷運線”

量子線

\[ G = \frac{I}{\Delta V} \]

流量和截面積成正比嗎？
Partial confinement

\[ E = \frac{p_z^2}{2m} + \varepsilon_n \]

\[ E \propto \frac{1}{L^2} \]

不同橫向的駐波為不同的頻道
以電壓控制參與電導之頻道數
傳導係數量子化

Science 289, 2323 (2000)
直接観察頻道

Science **289**, 2323 (2000)
(III) 穿隧效应
(Tunneling)
**Classical Picture**

in classical physics, the electron is repelled by an electric field as long as energy of electron is below energy level of the field

**Quantum Picture**

in quantum physics, the wave function of the electron encounters the electric field, but has some finite probability of tunneling through
穿隧效應是電晶體尺寸變小時可能失敗的主因
但穿隧效應卻被物理學家用以觀看奈米結構

Nature 409, 304(2001)
STM中的共振式穿隧效应

用途：可以用來察看奈米結構的能譜
観測条件

$T > 0$

維持peak的條件: $\delta \ll k_B T$
例一: 3.2nm InAs 奈米晶體的能譜

T=4.2K
DT= hexane dithiol molecules

Nature 400, 542(1999)
例二: 奈米碳管中的頻道

Nature 391,49(1998)
zig-zag (16,0) tube
例三: 奈米碳管端點的電子能態

(13,-2) tube
單電子電晶體 (SET) 組態
Coulomb Blockade 現象
--- 單電子傳導的基礎

even-odd effect

\[ \delta + \Delta_c \]
回顧 InAs 奈米晶體的能譜

\[ E_c = \Delta_c \]
以奈米碳管為基礎的室溫SET

利用AFM製造兩個彎曲(buckle)點

Henk et al. Science 293, 76 (2001)
Gate Voltage
(IV) Quantum Spin
自旋（spin）與科技的關係
自旋為磁性的最小單位，源自於量子力學
以往主要被用来作记忆使用如：硬碟...(magnetic recording)有300亿市场

现在的努力重点是希望能以自旋的组态作控制：

spintronics ⇔ electronics

自旋电子学！
基本的GRM結構

ΔR/R -5% - 10%
saturation field
10-30 Oe
新一代電腦

運算儲存一次完成

Fig. 7. A schematic representation of RAM that is constructed of magnetic tunnel junctions connected together in a point contact array. The conducting wires provide current to the junctions and permit voltage measurements to be made. They also enable the manipulation of the magnetization of the elements by carrying currents both above and below the magnetic junctions to create magnetic fields.

電源一開電腦就好
磁鐵的量子行為
- 以自旋為量子位元 (qubit)

\[ \frac{\hbar}{2} = |0\rangle + |1\rangle \]

\( qubit = \alpha |0\rangle + \beta |1\rangle \)

Due to superposition
More information!
(V) 量子心電感應
(Entanglement/糾纏)
Interference with Entangled photons
Dopfer, B., 1998
\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|ab\rangle + |a'b\rangle) \neq 1000\text{個光子對中} \]

有500對在\(|ab\rangle\)而另500對在\(|a'b\rangle\)

正如:

電子不是通過1或通過2，而是“同時通過1與2”
bit versus qubit

\[
\begin{align*}
1 & \rightarrow |0\rangle \\
2 & \rightarrow |1\rangle
\end{align*}
\]

\[
\text{qubit} = \alpha |0\rangle + \beta |1\rangle
\]

Due to superposition, get more information!

Quantum Information Science
Journal of Quantum Information

Journal of Quantum Information, a multijournal compilation, contains articles that focus on quantum information, including quantum computing, cryptography, error correction, and theoretical and experimental investigations of entanglement. ... Search Quantum Information. Recent Review Articles. ...

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Many applications, 如量子密码...

(Ekert scheme, using entangled photons)
Summary

奈米尺度的五大量子效應

• Interference
• Quantization
• Tunneling
• Quantum Spin
• Entanglement

這些效應對人類生活的衝擊正在發展進行中！