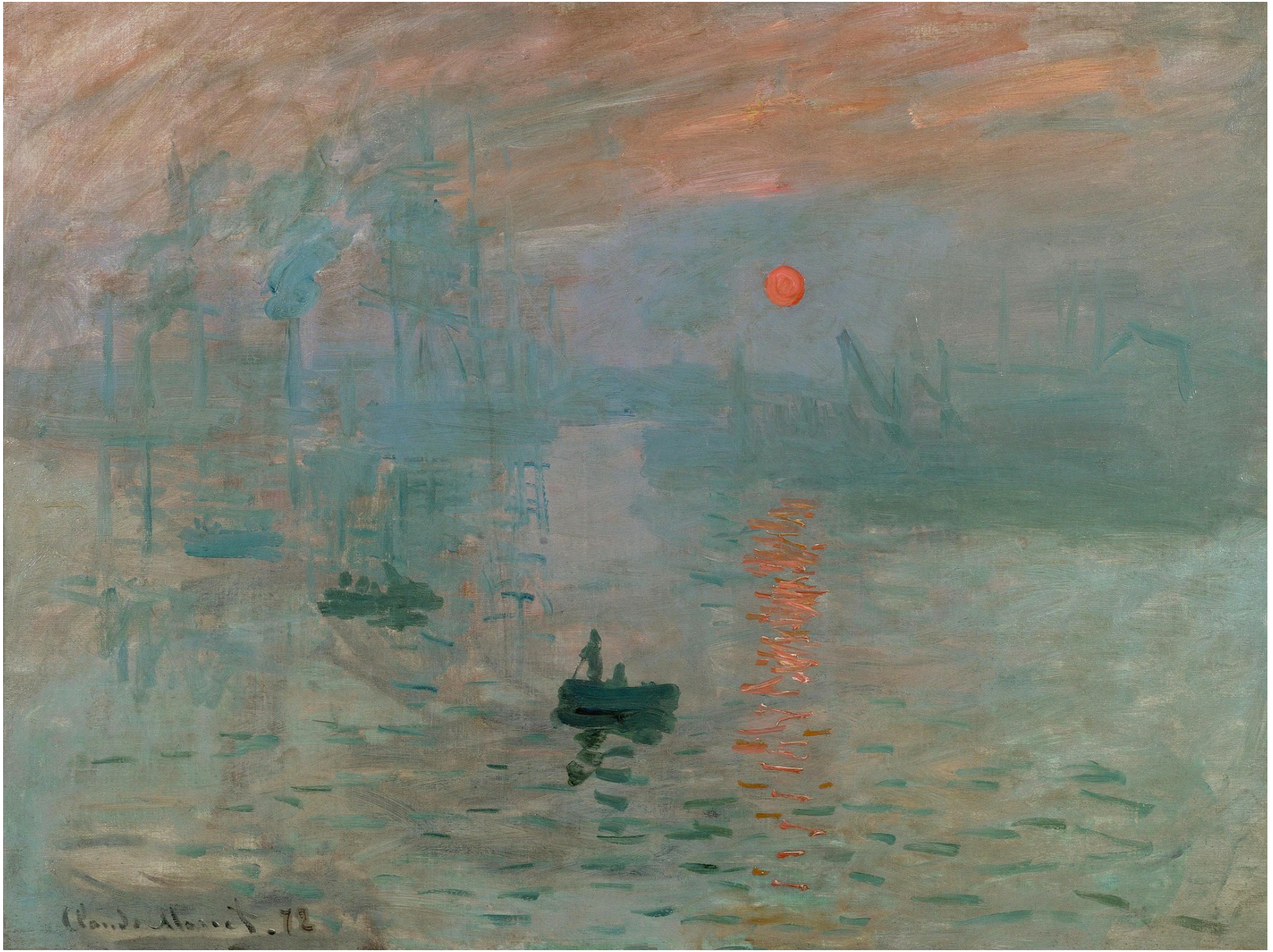

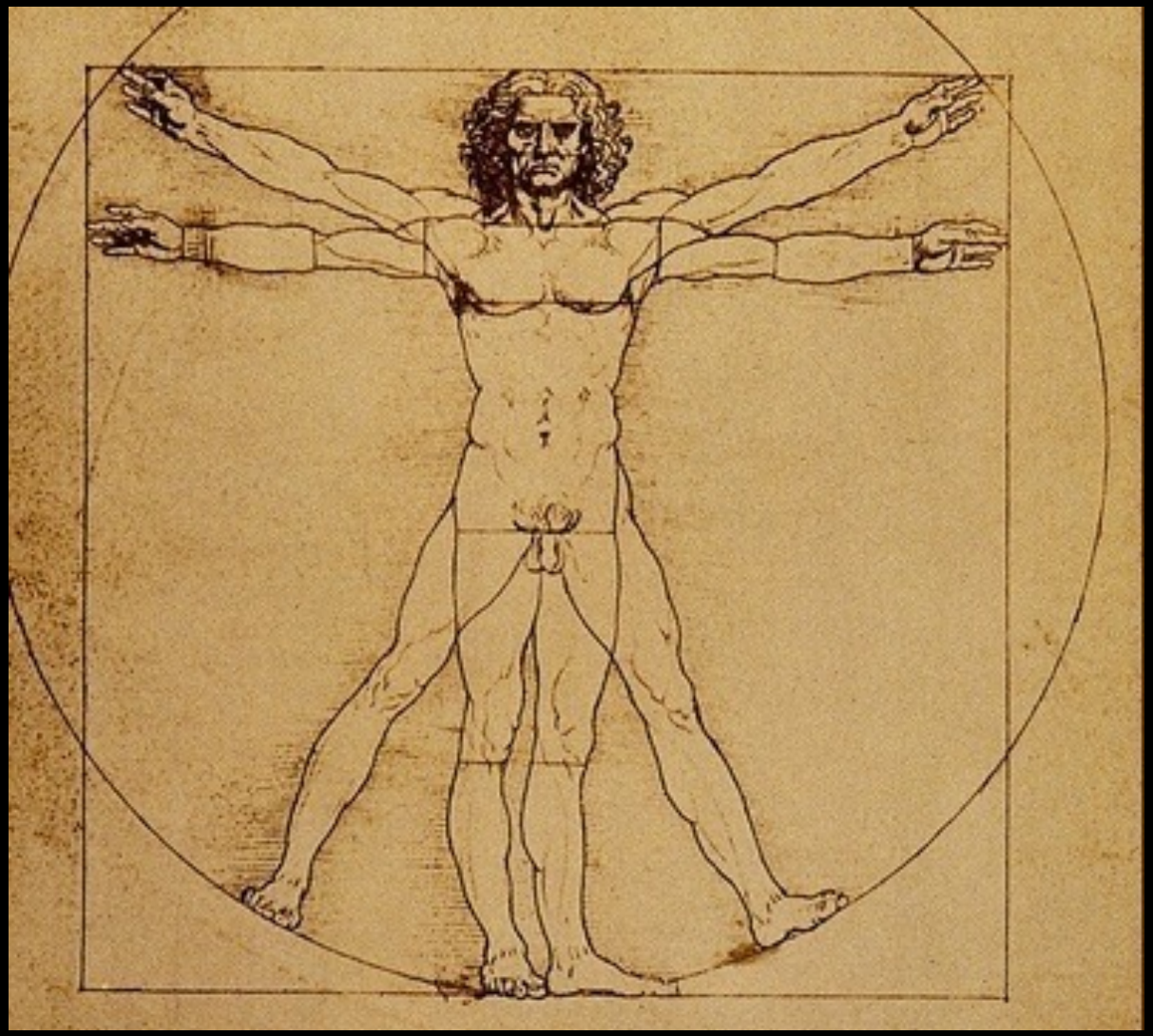

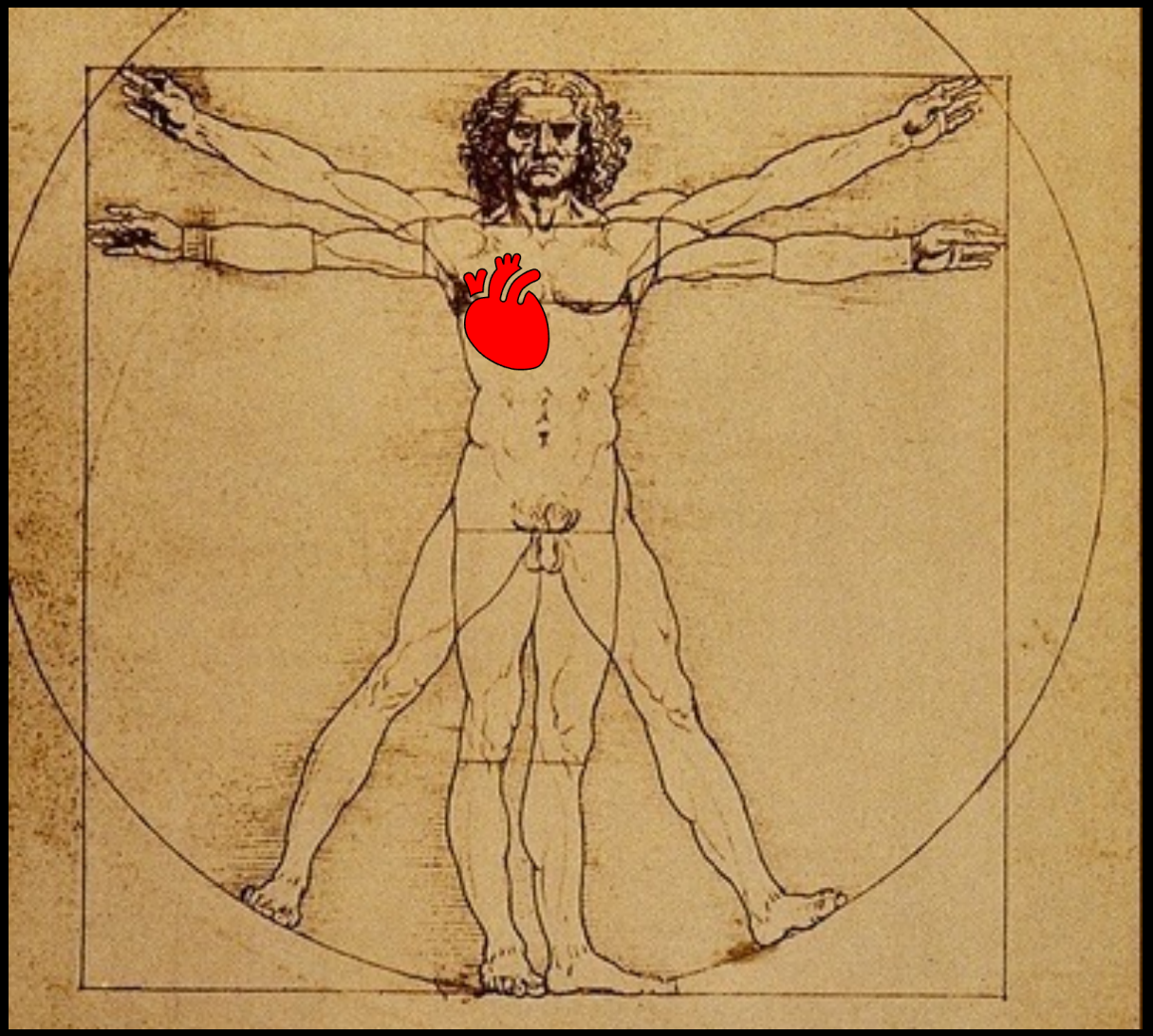

這是鏡子裡面的影像，不是真實的。

人體不是完美的對稱形狀！





美與對稱似乎被直接連接在一起。





我們說一個影像是對稱的：無法分辨鏡中的影像與真實的影像！鏡射不變性。



我在日常生活看到的鍋牛，從中心起都是順時鐘旋，右旋。







這個逆時鐘旋，左旋的鍋牛顯然是鏡中的影像。

真的嗎？





A Rare, Left-Coiling Snail Needs Help Finding a Mate. New Zealanders Are Looking for Its 1-in-40,000 Match

Known as Ned, the creature needs a fellow left-coiling garden snail to reproduce—but the species almost always has shells that coil on their right side



Sarah Kuta | Daily Correspondent

September 18, 2025

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左旋鍋牛雖然稀少，但是存在而且生長、生活一切正常。

左旋鍋牛稀少，只是偶然，就生物的原理與功能來說，完全與右旋無異。

A Rare, Left-Coiling Snail Needs Help Finding a Mate. New Zealanders Are Looking for Its 1-in-40,000 Match

Known as Ned, the creature needs a fellow left-coiling garden snail to reproduce—but the species almost always has shells that coil on their right side



Sarah Kuta | Daily Correspondent

September 18, 2025

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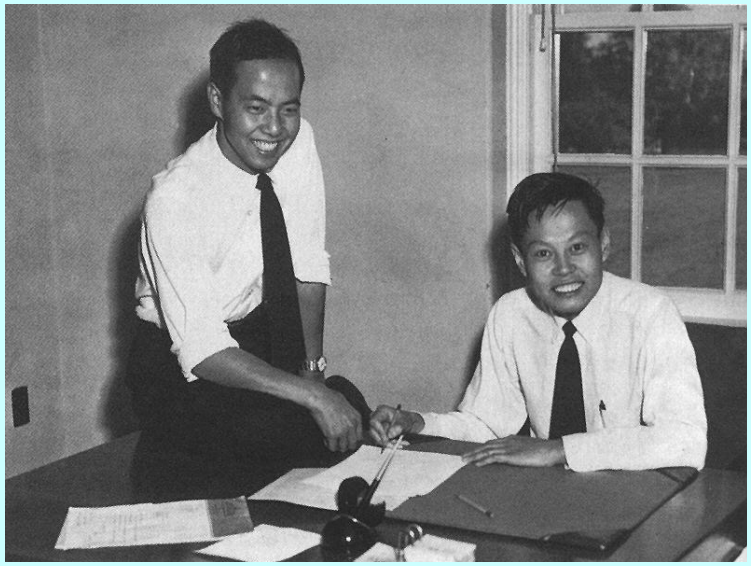
左旋鍋牛如此稀少是因為先天基因的偶然變異！

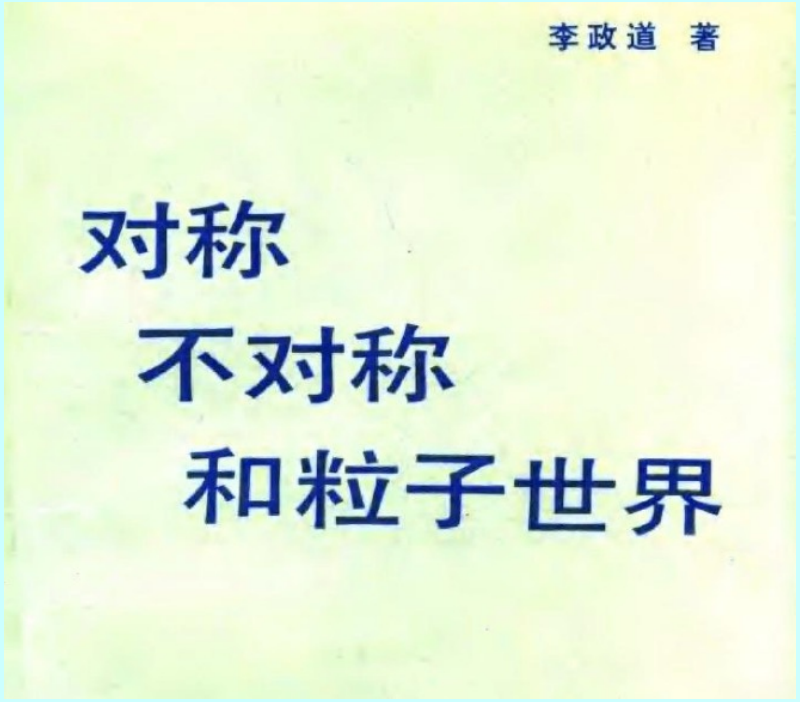
生物機制的左右對稱，可能表面上看不出來，被左旋鍋牛稀少性隱藏了。

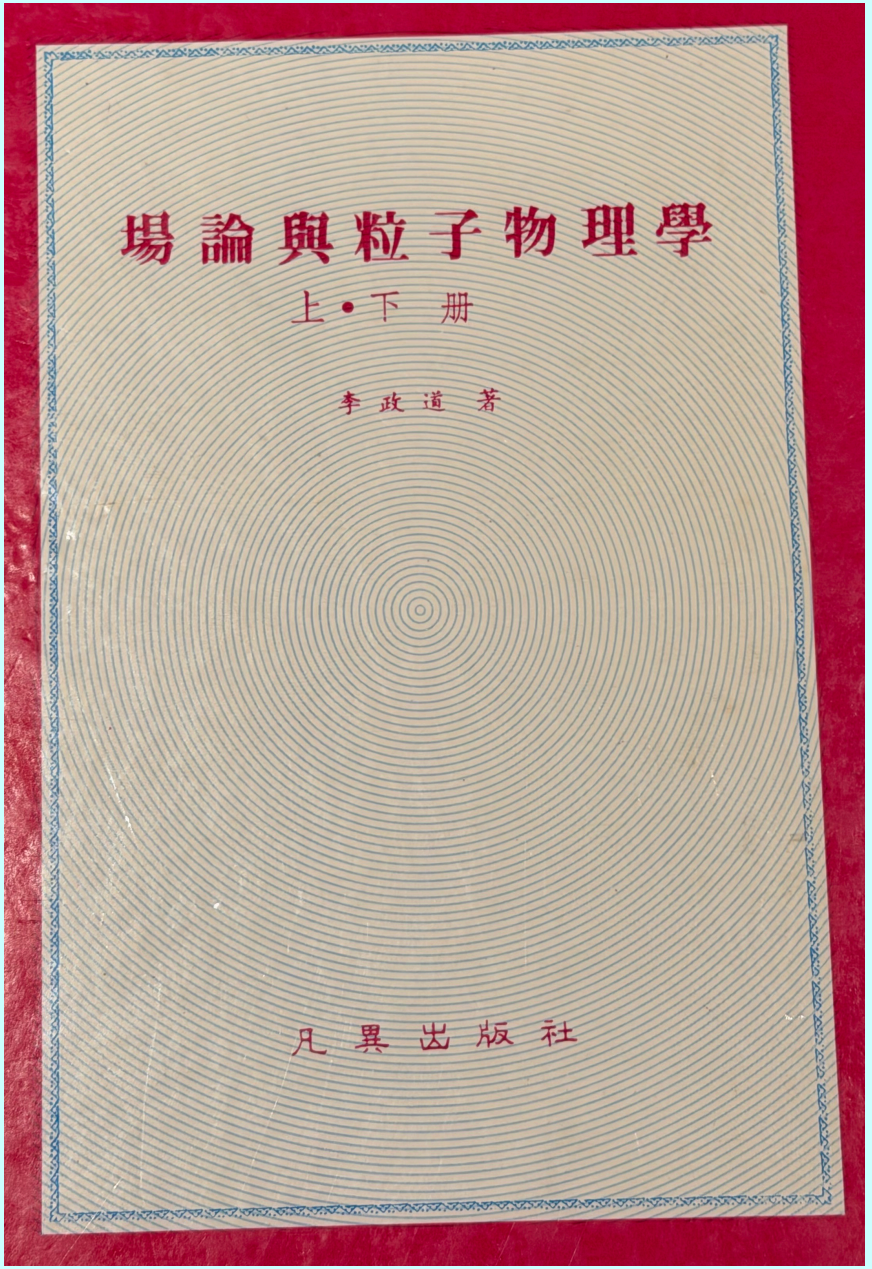




生物原理、觀察、實驗無法讓我們辨別影像是鏡中世界、還是真實世界。




李政道 著
对称
不对称
和粒子世界


場論與粒子物理學
上·下 册
李政道 著
凡異出版社

當然鏡中世界不是真的存在，

以上的暗室與鏡中世界的思辨，其實是在說明真實世界的一個特質：

我們無法觀測左與右的絕對分別！

左與右只是隨興的名詞，隨時可以交換。

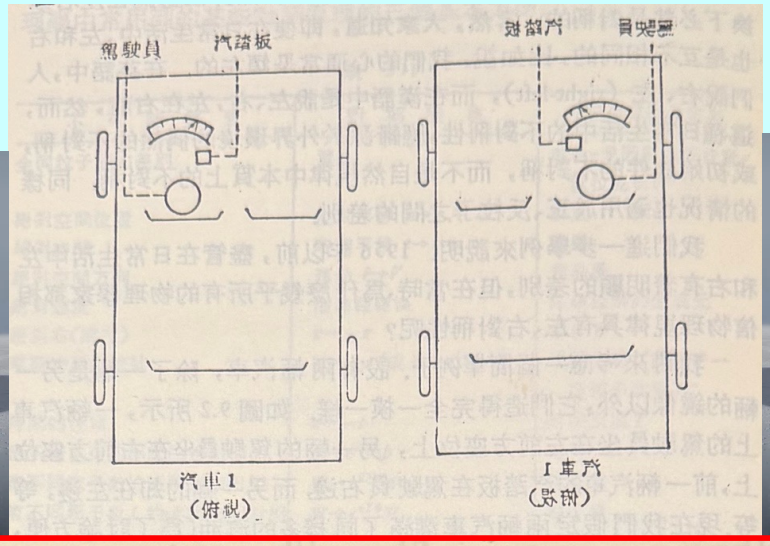
§9.2 不可觀察量;對稱變換和守恒律

物理學的一切對稱性原理，均植根於下述假設：某些基本量(下面將稱之爲“不可觀察量”)是不可能觀察到的.

当我们说左右对称时，我们暗示了不能观测到左右之间的绝对差别

當然，大家知道，即使在日常生活中，左和右也是互不相同的，比如說，我們的心通常是傾左的. 在英語中，人們說右、左 (right-left)，而在漢語中是說左、右，左在右前，然而，這種日常生活中的不對稱性，應歸源於外界環境的偶然的不對稱，或初始條件的不對稱，而不是自然規律中本質上的不對稱.







我們來考慮一個簡單例子. 設有兩輛汽車, 除了一輛是另一輛的鏡像以外,它們造得完全一模一樣. 如圖 9.2 所示, 一輛汽車上的駕駛員坐在左前方座位上, 另一輛的駕駛員坐在右前方座位上,前一輛汽車的汽踏板在駕駛員右邊, 而另一輛的却在左邊, 等等.現在我們假定兩輛汽車灌滿了同樣多的汽油(爲了討論方便, 我們暫不考慮汽油分子並不是完全鏡像對稱這一事實). 假定一個駕駛員順時針地開動點火鑰,把汽車發動起來,並用右脚放在汽踏板上, 使得汽車以一定速度向前駛去. 另一個駕駛員做完全一樣的動作,只是左右交換一下: 他反時針地開動點火鑰把汽車發動起來,並把左脚放在汽踏板上,但使汽踏板與前一輛汽車一樣保持相同的傾斜度. 現在我們問: 如果第一輛汽車每小時向前開 40 華里,第二輛汽車將怎麼行駛呢? 你們可以試着猜一猜.

從常識角度看來,你們大概會認爲,第二輛汽車將以完全一樣的速度向前行駛. 如果那樣的話,你們就和 1956 年以前的物理學

常識會覺得左右應該沒差，兩台車會一樣好開。







按照同樣的常識，那時的物理學家相信自然規律具有左、右對稱性：“如果兩個裝置，其中一個是另一個的鏡像，除此以外，完全一樣，那末除了這一左、右差別外，在所有其他方面這兩個裝置將有完全同樣的行動”。

依照鏡中汽車形象製造的真實汽車，在真實世界照樣可以運作！

想像的鏡中的世界的物理定律與真實世界相同，

我們就說這樣的真實世界的物理定律是對稱的！

鏡中世界的想法太好用了，所以乾脆更具體一點。

最後還有一種說法： 鏡射不變性





想像有另一個世界，在那裏.....

想像有另一個世界，那裏是此世界左右對調後的映像 。

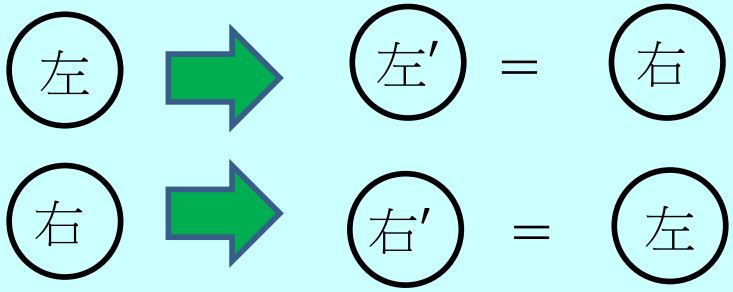
左右稱左′右′，′是提醒那是在另一世界 Another world。

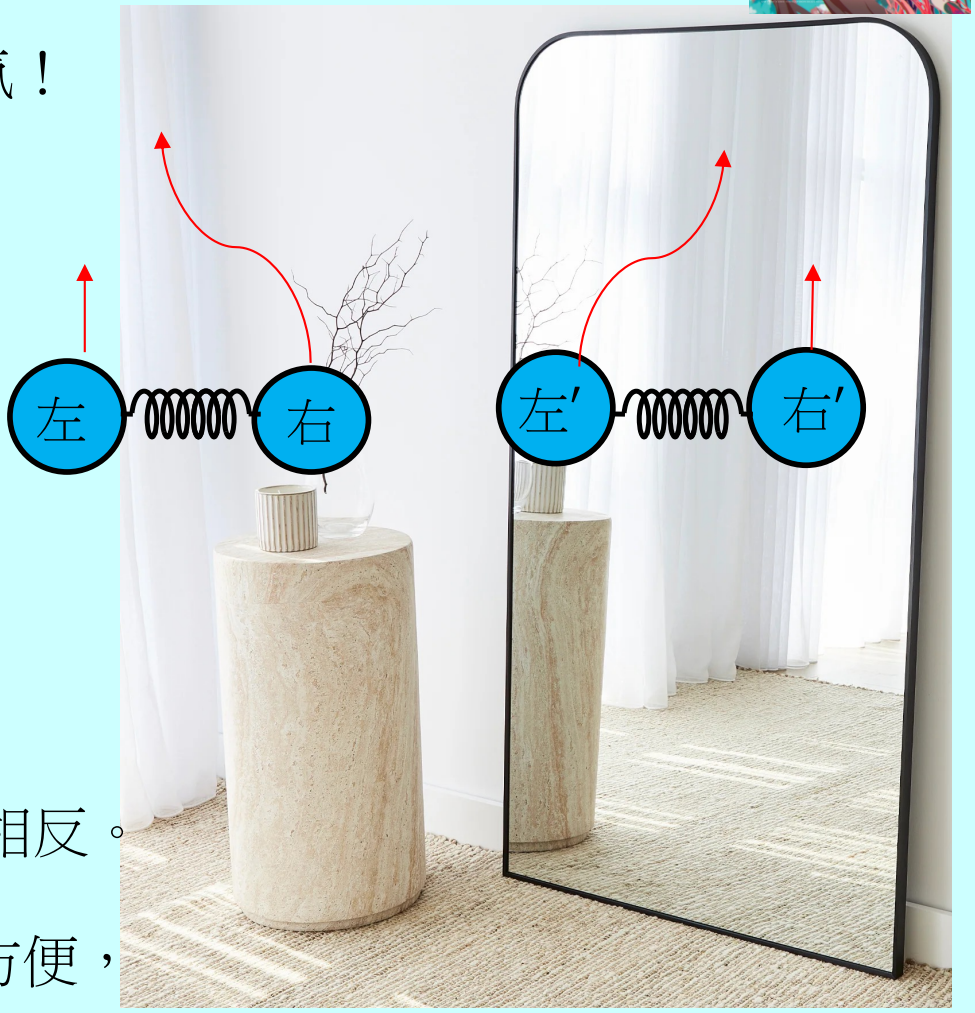
那裡的右′，其實是這裡的左的映像。反之亦然。



可以想像氫分子的左氫與右氫！







注意：兩個圖像是不同的。

左行直線、右行曲線，鏡中相反。

但如果左右的差別只是命名方便，

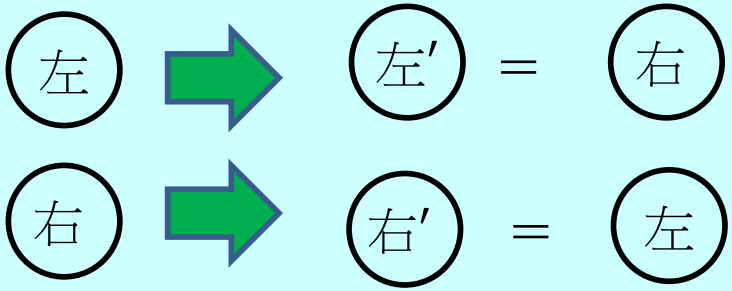
鏡中的氫分子′也符合物理定律。反正就是有一個行直線、一個行曲線！

任意這樣的想像世界，術語稱為變換，

此一變換稱為鏡射變換，宛如射入一個新世界。

變換後的氫分子′也是定律允許的，

稱我們的世界有鏡射不變性、或鏡射對稱。





針對一個變換，我們無法以物理方法分辨所看到現象是變換前或後，

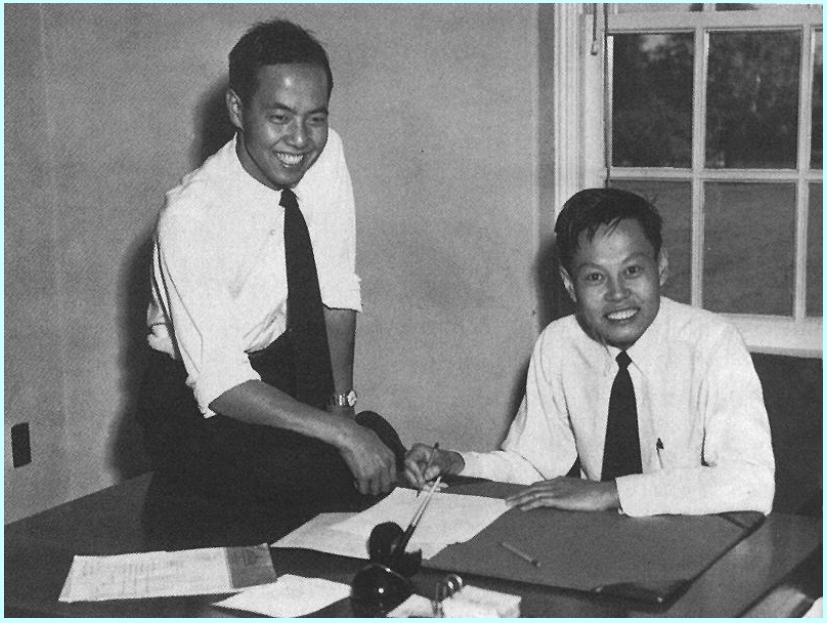
就稱物理定律有此不變性、或對稱。

大部分物理學家原本都相信

我們的世界有鏡射不變性、或鏡射對稱。

I do not believe that the Lord is a weak left-hander.

I am ready to bet a very large sum. Pauli







Parity symmetry is violated (broken) in weak interaction.

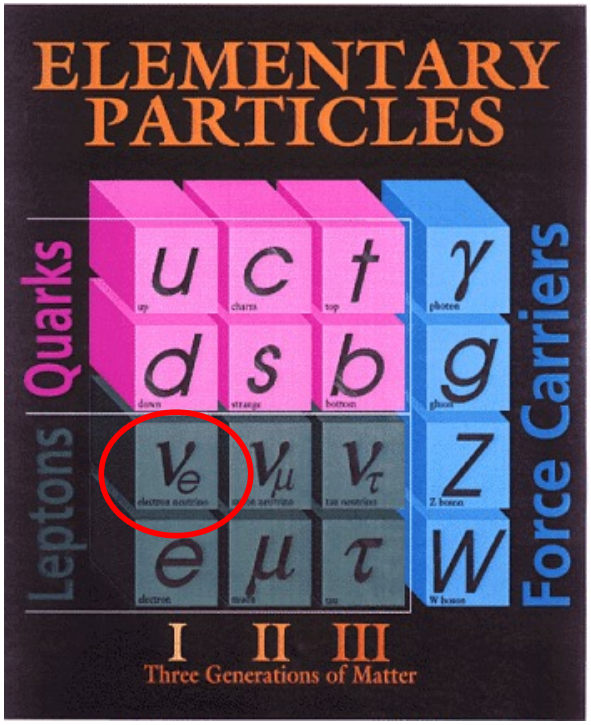
弱交互作用不遵守鏡射不變性、或鏡射對稱。

Nobel Prize in Physics 2026



Francis Halzen

Prize share: 1/1



無法再分割的基本粒子

The Nobel Prize in Physics 2026 was awarded to Francis Halzen "for decisive contributions to the IceCube Neutrino Observatory and the discovery of high-energy neutrinos of astrophysical origin"

The Nobel Prize in Physics 2015



Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2



Photo: K. MacFarlane, Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2



The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

已經至少有五個諾貝爾獎是頒給微中子。

微中子 Neutrino 是一個甚麼樣的基本粒子？

微中子有一首自己的詩！



Neutrinos, they are very small.
They have no *charge* and have no *mass*
And do not interact at all.

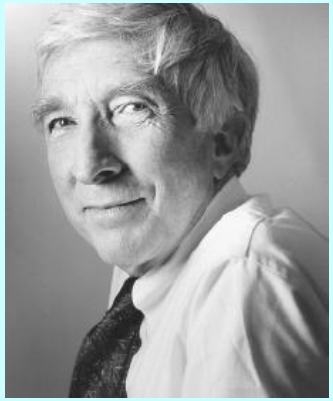
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids (女僕) through a drafty (空蕩) hall
Or photons through a sheet of glass.

They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.

At night, they enter at Nepal
And pierce the lover and his lass



COSMIC GALL (莽撞)- John Updike



因為微中子與大部分物質幾乎都不作用，因此有極大的穿透能力。



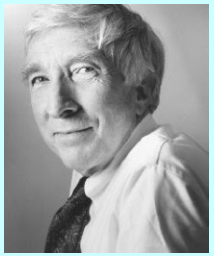
要阻擋他.....需要多厚的盾牌？

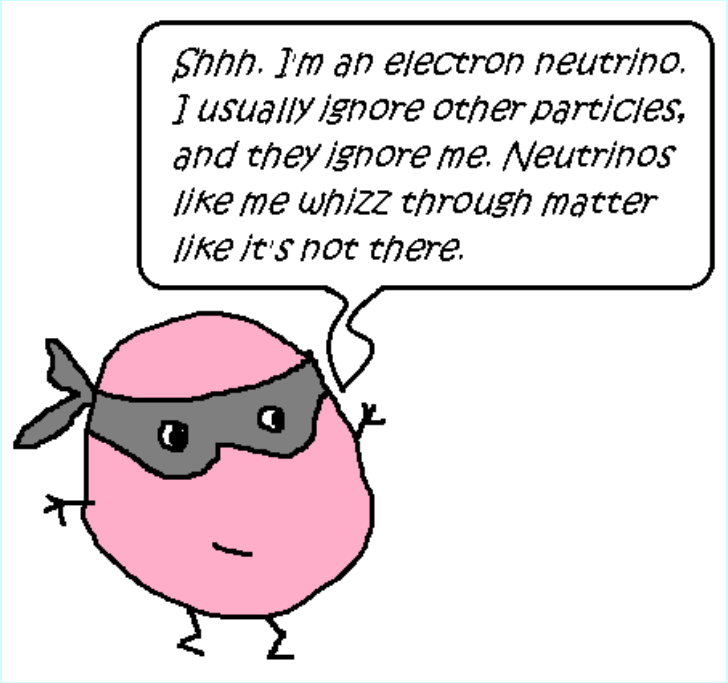
要好幾個光年厚！





The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids through a drafty hall
Or photons through a sheet of glass.





In 1957 we found neutrino has only one helicity.

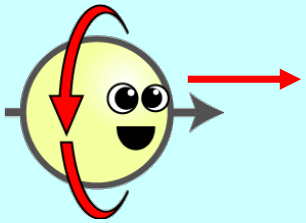
Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] $0-$, we find that the neutrino is "left-handed," i.e., $\sigma_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

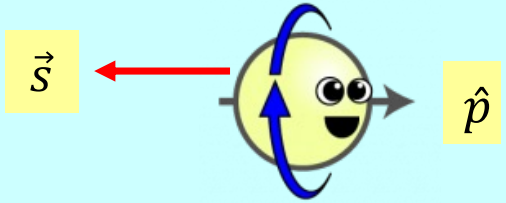
Our method may be illustrated by the following simple example: take a nucleus A (spin $I=0$) which decays by allowed orbital electron capture, to an excited state of a nucleus $B(I=1)$, from which a γ ray is emitted to the ground state of $B(I=0)$. The conditions necessary for resonant scattering are best fulfilled for those γ rays which are emitted opposite to the neutrino, which have an energy comparable to that of the neutrino, and which are emitted before the recoil energy is lost. Since the orbital electrons captured by a nucleus are almost entirely s electrons (K, L_{I}, $\cdots$ electrons of spin $S=\frac{1}{2}$), the substates of the daughter nucleus

Helicity 螺旋性



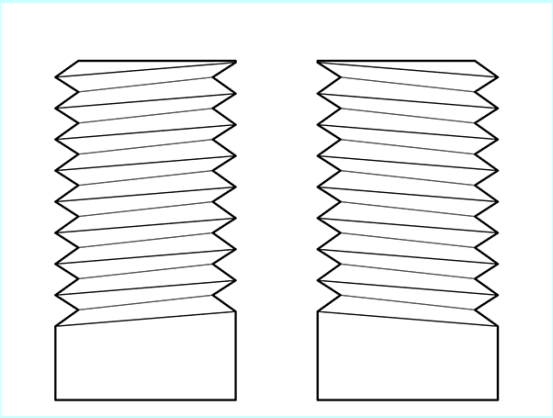
自旋$\vec{s}$與動量$\vec{p}$同向，右手旋 right-handed

$$\vec{s}\cdot\hat{p}=\frac{\hbar}{2}$$

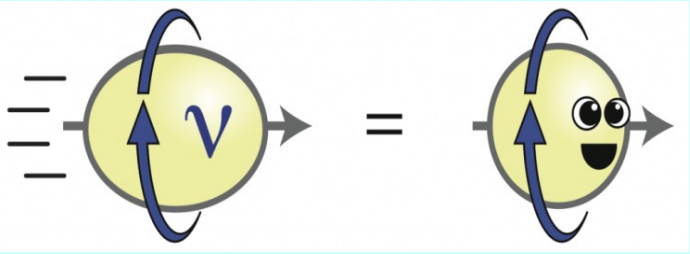


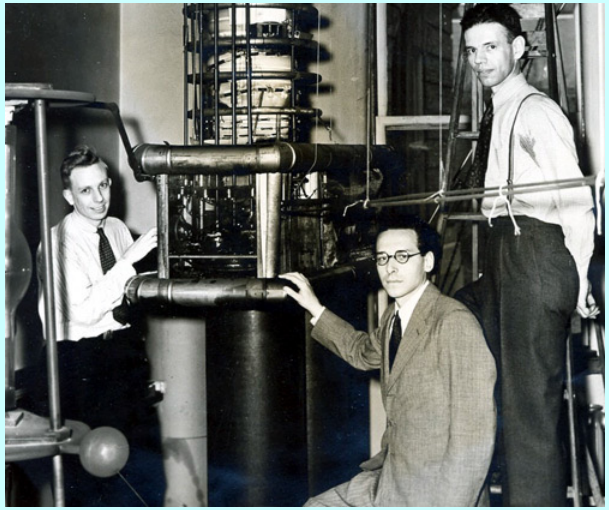
自旋$\vec{s}$與動量$\vec{p}$反向，左手旋 left-handed

$$\vec{s}\cdot\hat{p}=-\frac{\hbar}{2}$$



A 1958 ex. by Goldhaber et al measured the helicity of neutrino!

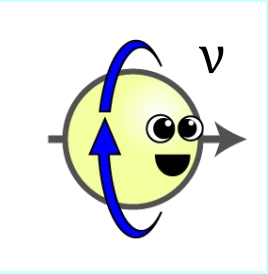




所有微中子都是左手旋！

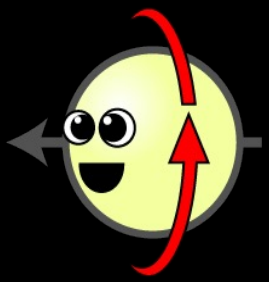
沒有右手旋的微中子！

左旋微中子











當你看到一個右旋的微中子，你知道你看到的是鏡中的世界。

在鏡射變換下左右旋態會互換

I don’t believe that the Lord is a weak left-hander, and I am ready to bet a very large sum that the experiments will give symmetric results.

Pauli’s letter to Weisskopf 3 days before he was told the news



Now after the first shock is over, I begin to collect myself. I was to give a lecture at 8:15PM on the “past and recent history of the neutrino”. At 5:00PM the mail brought me the three experimental papers. Now where shall I start? It is good that I did not make a bet

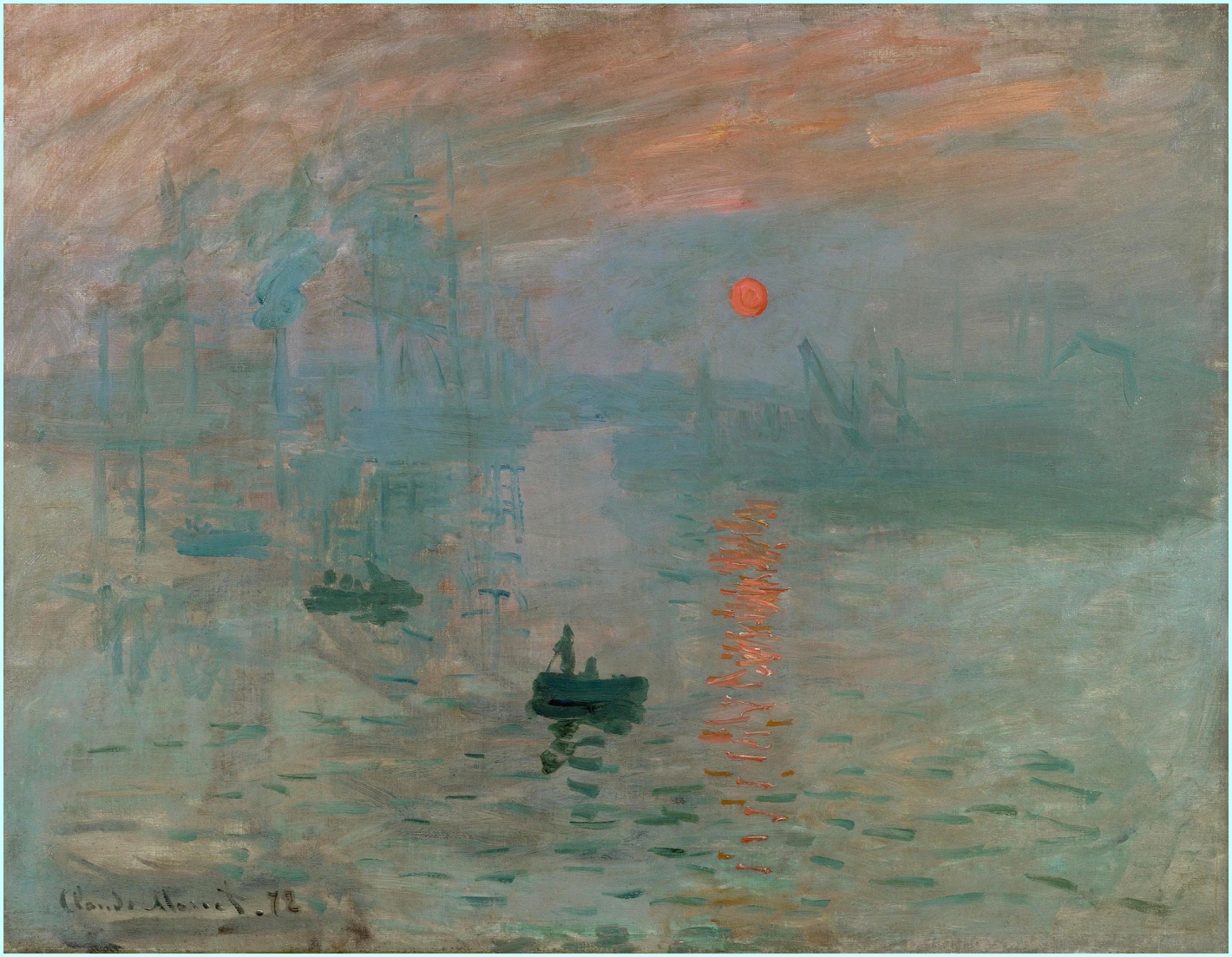
Pauli’s letter to Weisskopf 10 days later

與微中子相關的物理定律，不遵守左右對稱。

弱交互作用破壞了自然(電磁力、重力、強力)的左右對稱。

The Lord is indeed a weak left-hander.





印象、日出，莫內 Le Havre 勒哈芙

上與下：量子雙胞胎的連續對稱



上與下：由質子中子雙人組的同位旋對稱，到電磁與弱力的統一

如何優雅地隱藏物理的美

連續對稱與對稱破壞、真空中希格斯場幹的好事！

連續對稱



平移變換：在想像的世界(非鏡)，將所有物體平移一個距離。

想像的世界會如真實世界，遵守一樣的規則嗎？



我們似乎不能任意將粒子的位置做平移，而不讓它感覺到嗎。



如果將兩個粒子的位置一起做平移，這相當於原點倒著走一樣的距離！

很顯然兩者都不會有感覺，

空間沒有絕對的原點！

觀察者需要原點才能量測位置，但原點的選擇無關現實的結果。

絕對的原點選擇是無法觀測的。這種任意性就稱為平移對稱！





平移不變性有什麼後果？

考慮太陽與地球的平移變換：



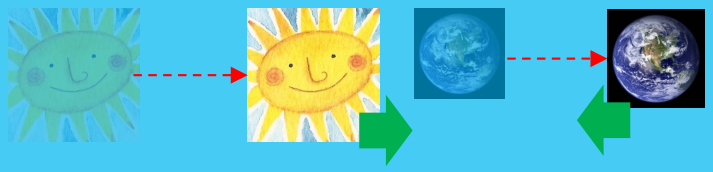
力



力

$x \to x + a$



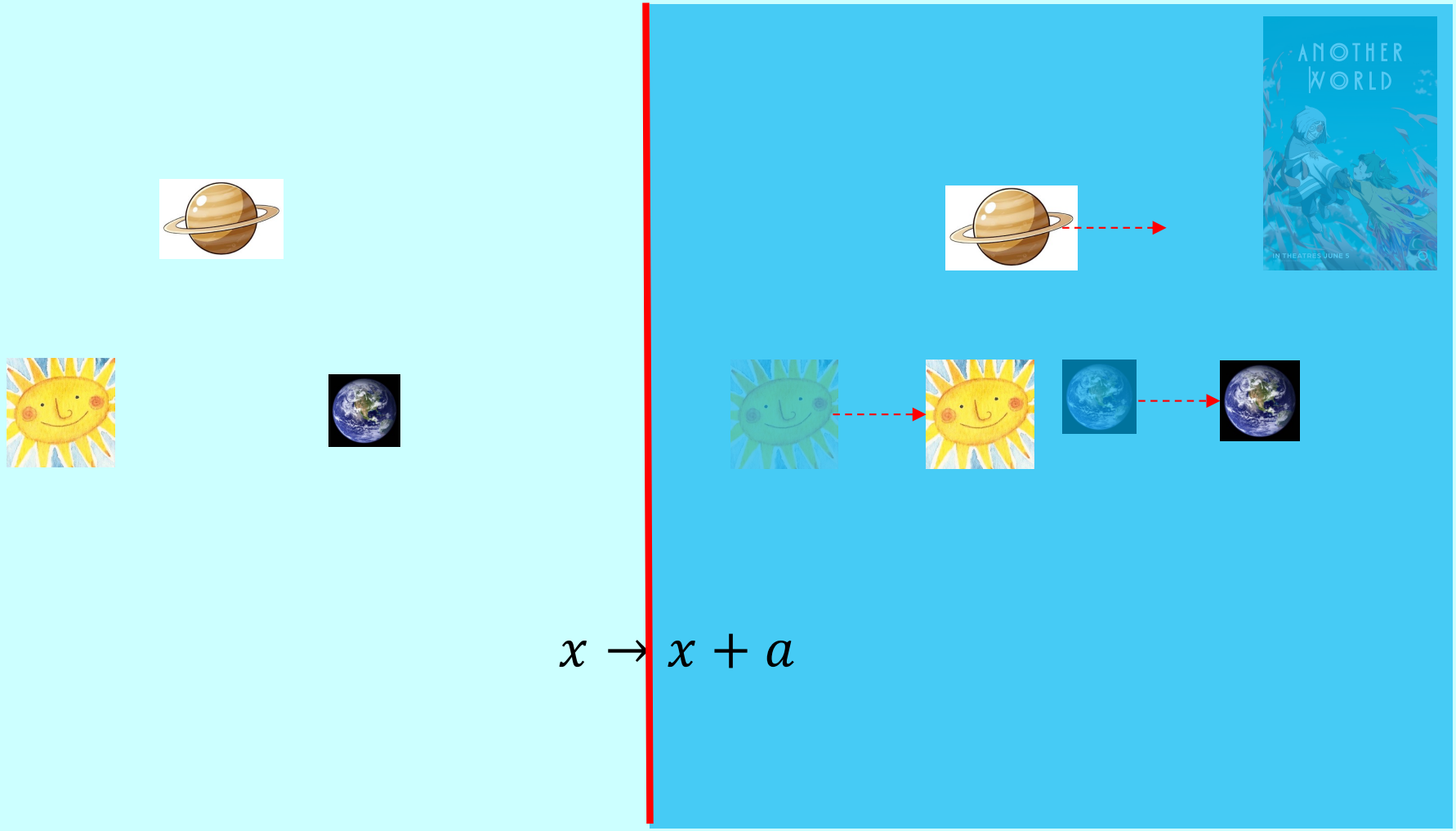


運用於力學，個別粒子位能在平移後的變化率，即是該粒子的受力。

地球與太陽的總位能在平移後不變，代表地球與太陽的總受力為零，

地球對太陽的施力，與太陽對地球施力，大小相等、方向相反。

總動量守恆定律就是平移對稱的結果。



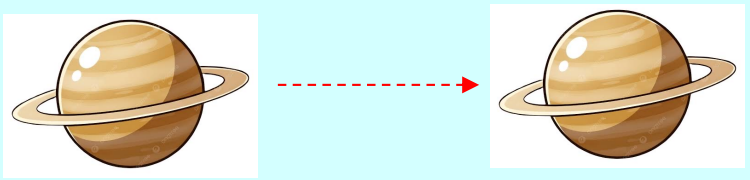
如果還有一顆土星呢？

地球與太陽平移後，跟土星的距離都變了！太陽與地球總動量就不守恆。

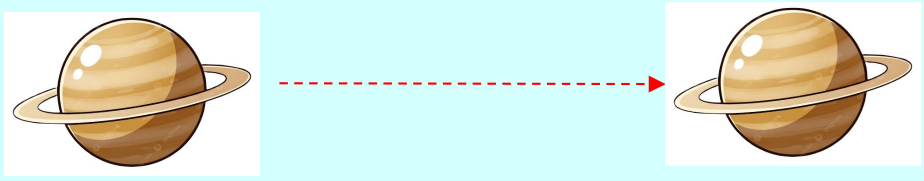
但如果土星也跟著以同樣方式平移。太陽、土星與地球總動量也是守恆的。

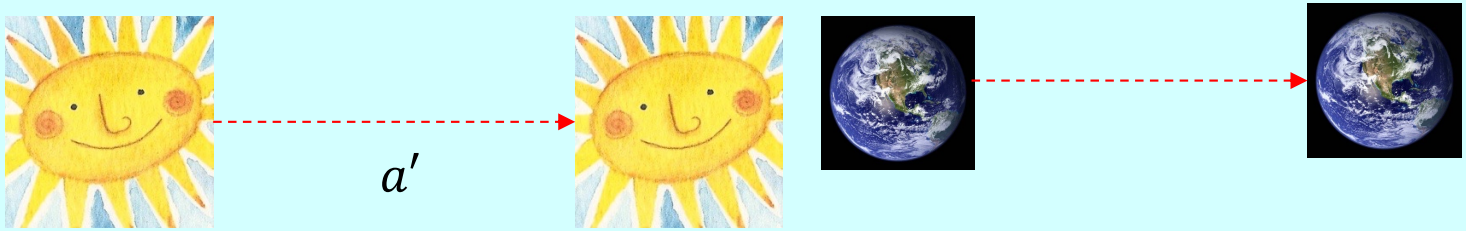
$x \to x + a$

若有平移對稱：









位置的平移量a，是可以任意選擇，而且選擇的可能是連續的，

一個平移量a，就對應一個對稱！因此這是一系列的連續對稱！



位置的平移量a

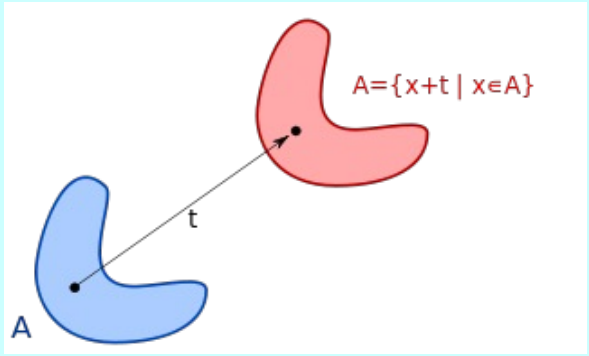
$\cdots\cdots$

$\cdots a$

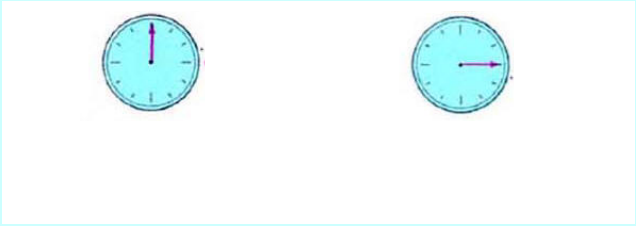
$= (-\infty, \infty)$

我們有一系列與真實世界對稱的想像世界！想像世界是不可數而連續分布的！

這與鏡射左右交換對稱的單一想像世界是有差距的！



平移對稱 $x \to x + a$，對應動量守恆定律！



時間沒有原點！$t \to t + t_0$

由時間平移對稱可以導出能量守恆。

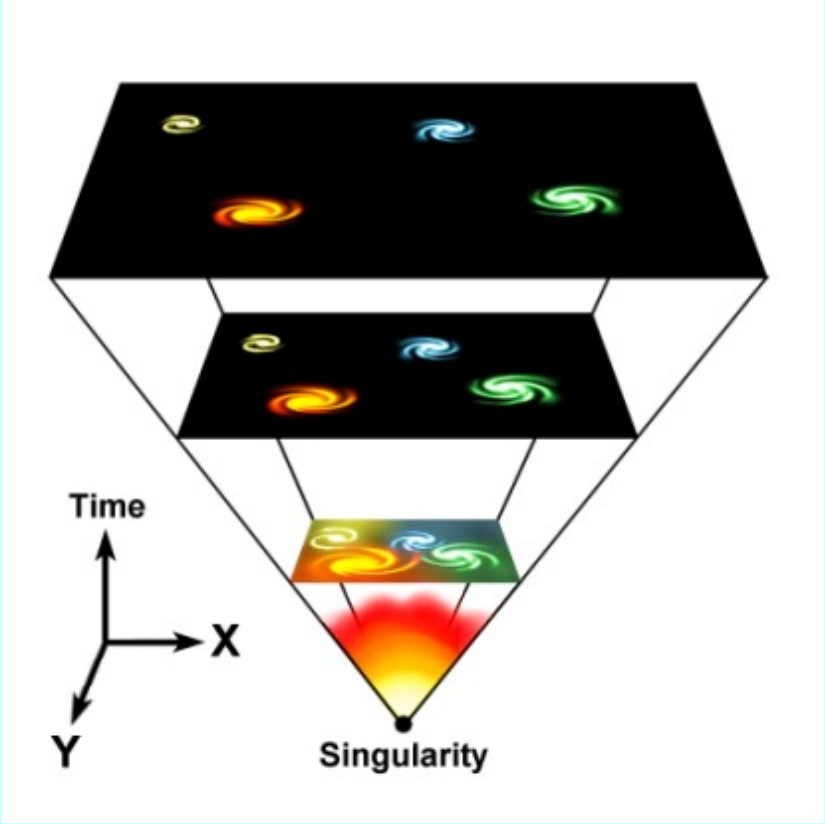


座標軸旋轉對稱可以導出角動量守恆。

當然時間是有起點的，不過……

如果時間範圍離起點太遠，起點也可以被忽略！

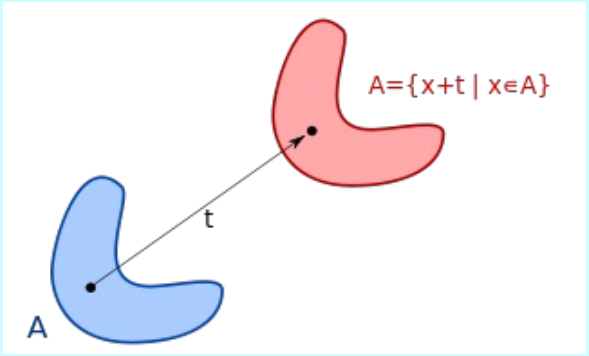
可以說是近似的時間平移對稱。



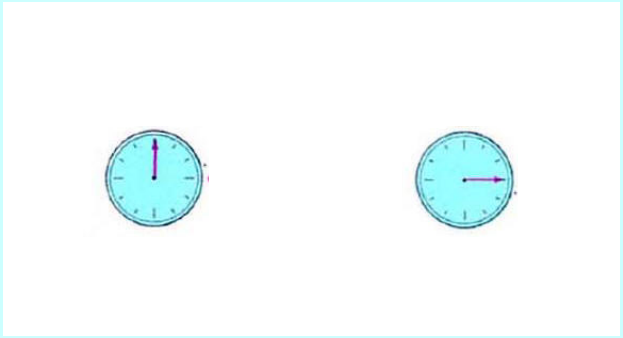
一個連續的對稱性、就對應一個守恆律。



在許多物理問題，我們很容易可以找到identify其中的孤立系統。
位置測量的原點、時間的起點、坐標軸的方向是必須但無關緊要的。
因此都是不可觀測量，各自就對應一個對稱性、以及一個守恆律。



平移對稱可以導出動量守恆定律！

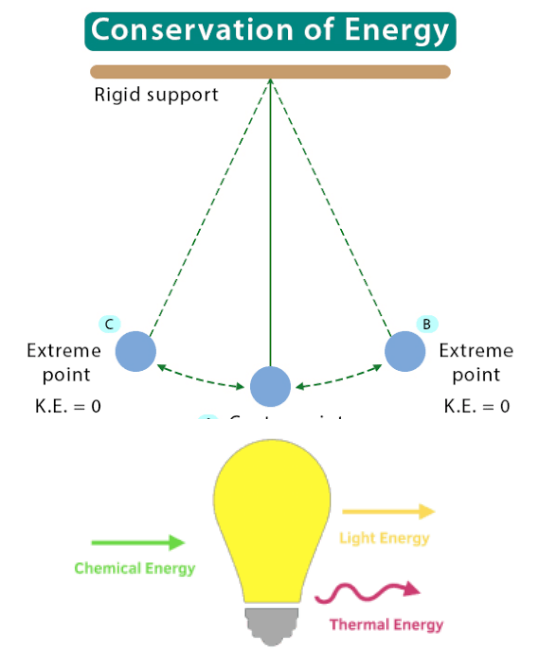


時間平移對稱可以導出能量守恆。

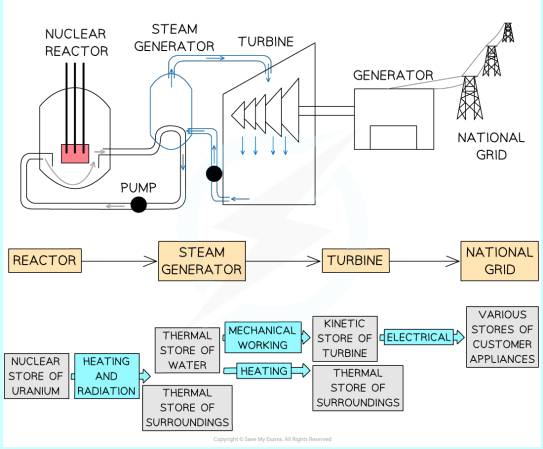


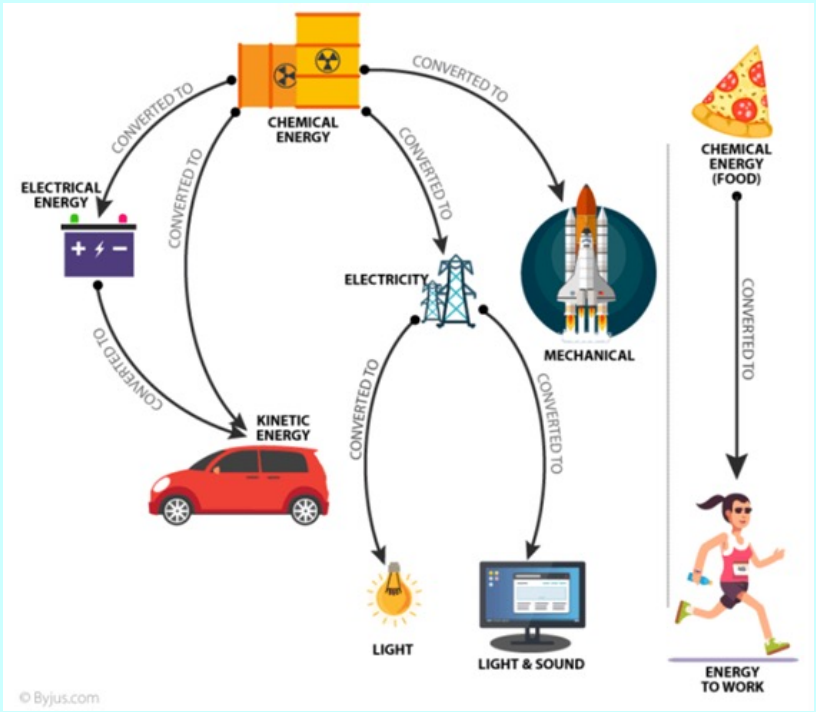
座標軸旋轉對稱可以導出角動量守恆。

難怪我們有跨主題、應用廣泛、普遍的能量守恆定









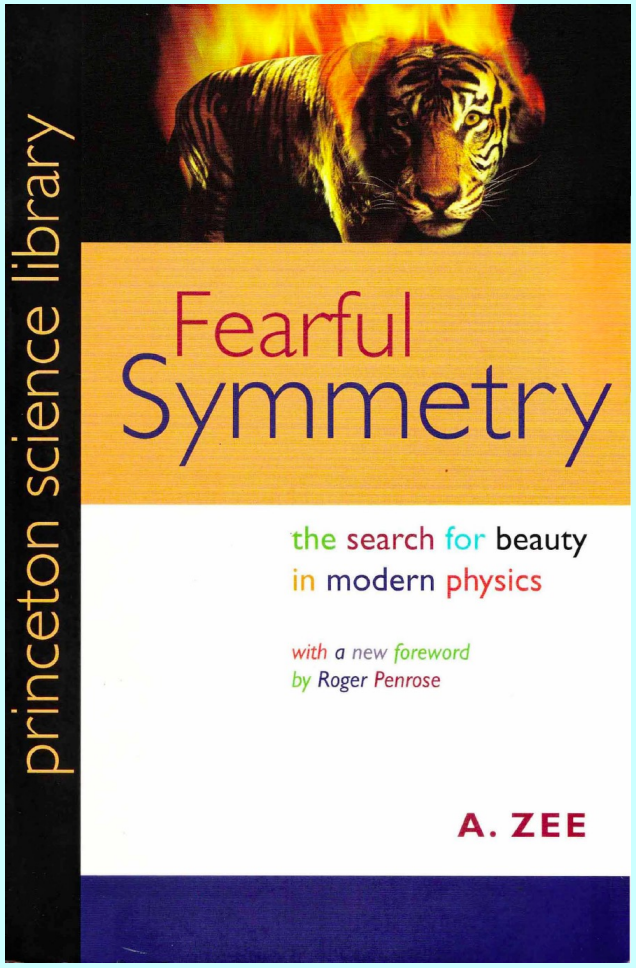
在幾乎所有物理問題，都可以找到identify其中的孤立系統，遵守時間平移對稱

對稱可以得出嚴格的、普遍的定律！特別是守恆定律。

你可以說它很優美地、給這些定律一個深刻的理由！

也可以說它很嚴苛、很可怕！但總之的確很厲害！

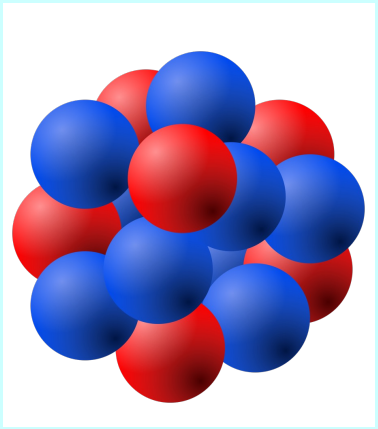
連續對稱又比互換對稱嚴苛一點。



上與下：雙胞胎的交換對稱，在量子力學下升級為連續對稱



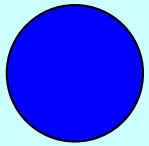
Atomic nucleus 原子核由核子組成。



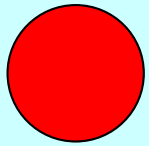
A nucleon 核子 is either a proton or a neutron.







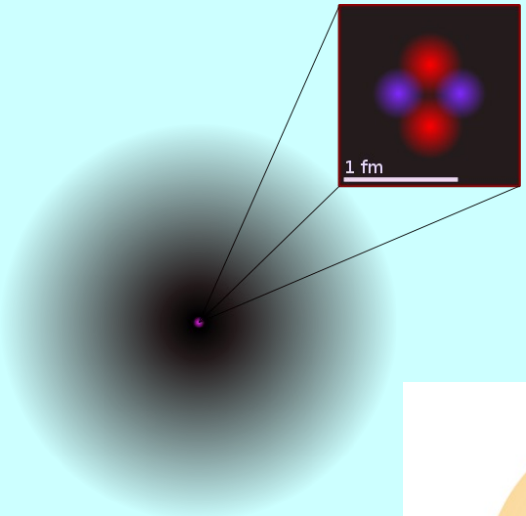
Neutron



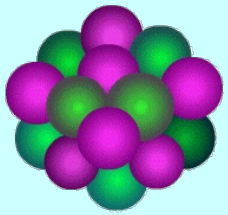
Proton

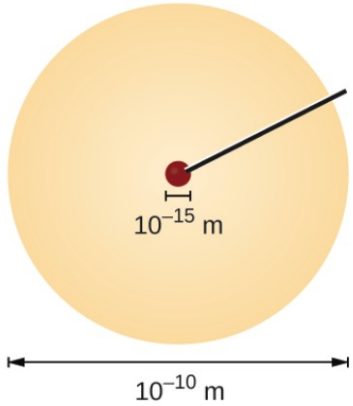
原子核比電子重非常多。

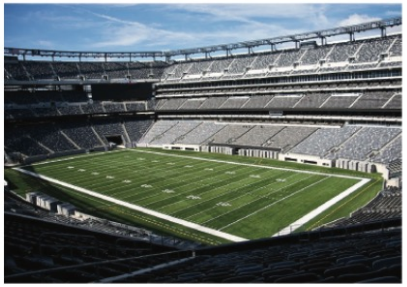
原子内的正電與大部分的質量集中於極小的原子核 Nucleus



1 Ångström (=100,000 fm)



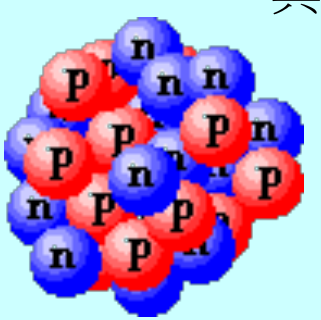






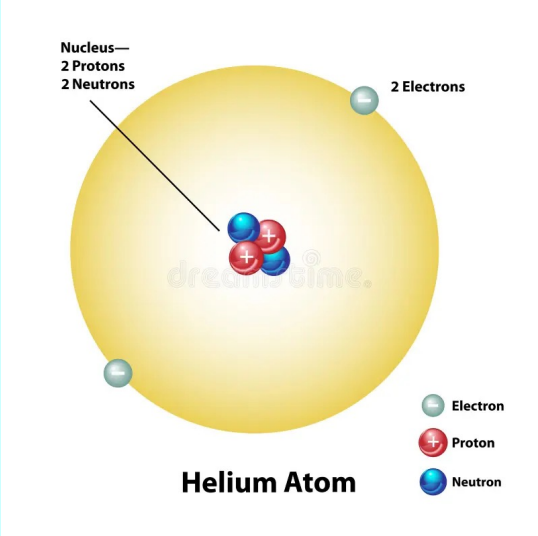
If an atom could be expanded to the size of a football stadium, the nucleus would be the size of a single blueberry. (credit middle: modification of work by "babyknight"/Wikimedia Commons; credit right: modification of work by Paxson Woelber)



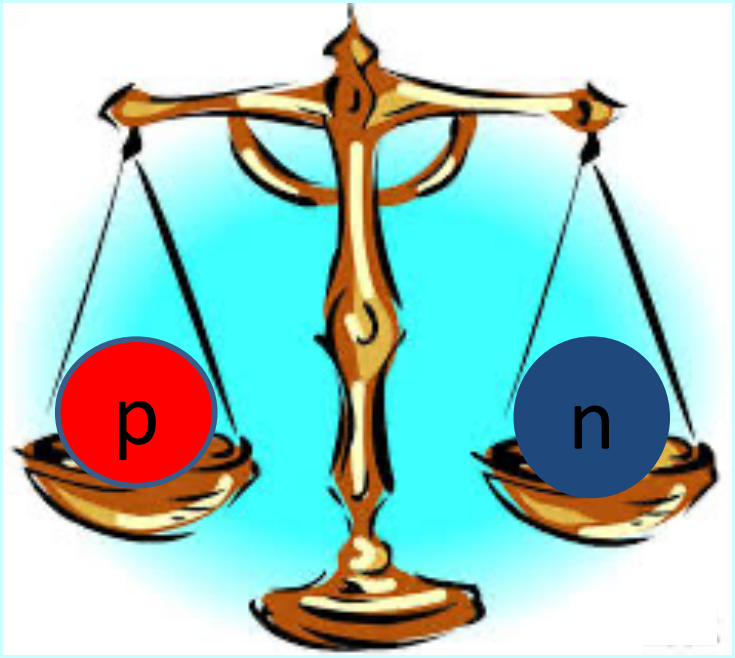


與質子等數目的電子圍繞著原子核就形成原子。

氦 He



這三種粒子就構成了我們的整個自然世界！



中子與質子幾乎等重！質量差只有 10^{-3}

p $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 938.272046 \pm 0.000021$ MeV [a]

n $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 939.565379 \pm 0.000021$ MeV [a]

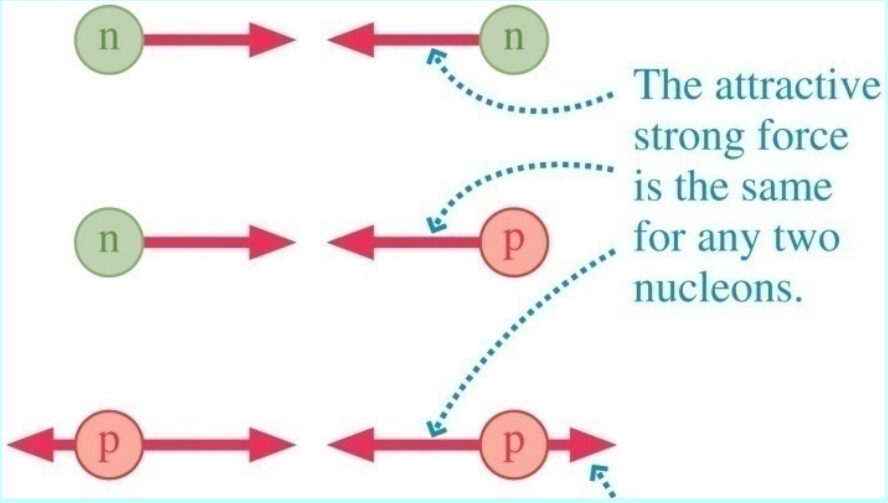
$$m_n - m_p = 1.2933322 \pm 0.0000004 \text{ MeV}$$

物理學家相信自然是沒有巧合的，巧合必定有深意。

質子與中子不只質量相似，兩者的核力、就是強交互作用也相同。

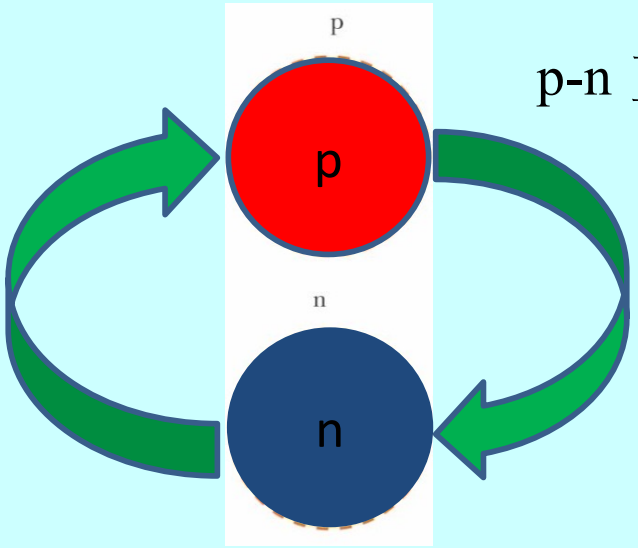
許多原子核的性質非常接近 $^{7}_{3}\mathrm{Li}\approx{}^{7}_{4}\mathrm{Be}$ $^{11}_{5}\mathrm{B}\approx{}^{11}_{6}\mathrm{C}$ 它們差別只是交換了質子與中子。

同時散射實驗顯示 p-p, p-n, n-n之間的核力完全相等！

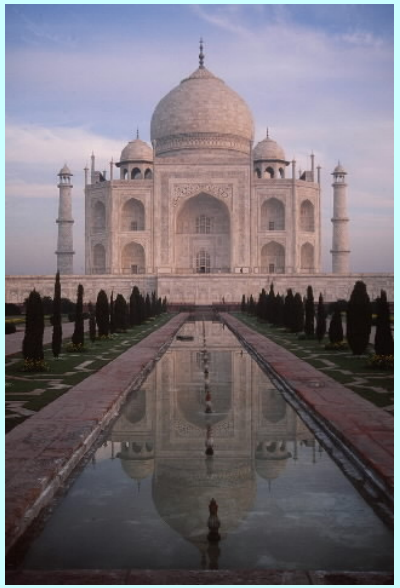


當然質子與中子電荷不同。

假想我們將電磁力關掉，然後將所有的質子與中子互換，



p-n 互換



質子與中子質量幾乎相等！

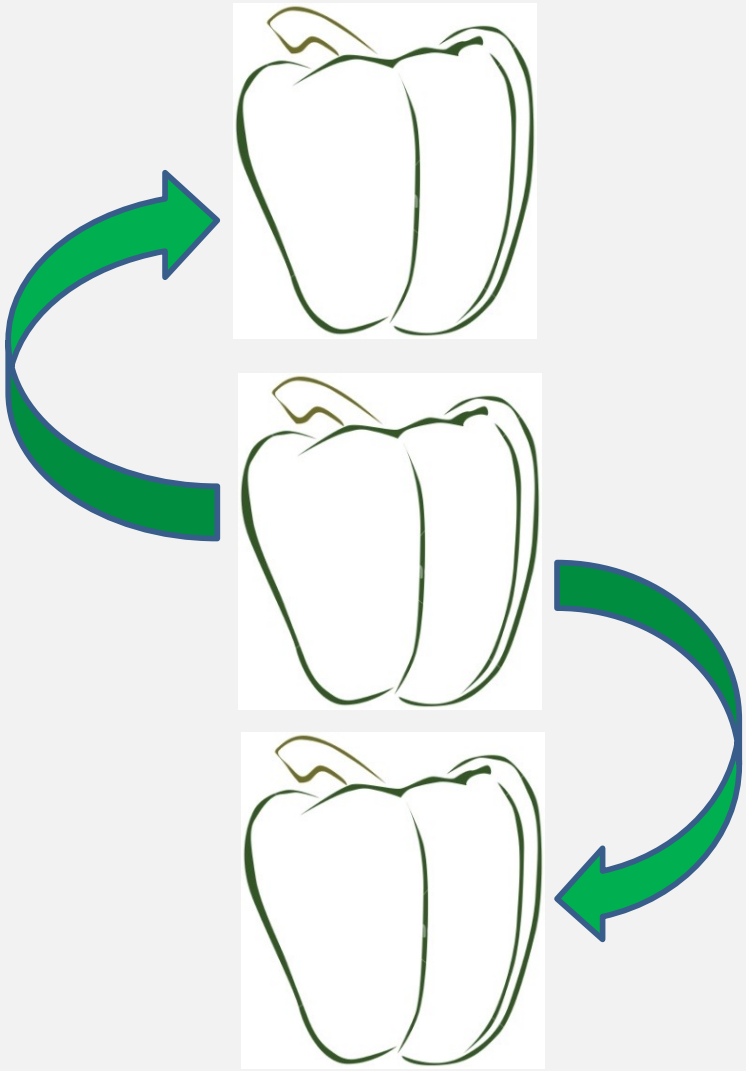
此時宇宙中僅存的作用：核力也相同。

在 p-n 互換之後，整個自然世界將運作如常，並沒有變化！

透過物理實驗，你無法辨別互換是否已經發生！

類似鏡射左右互換對稱。

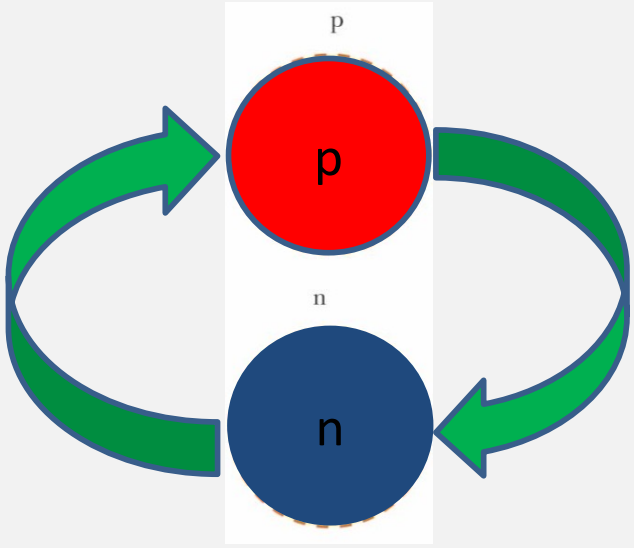




色盲將無法分辨青椒與紅黃椒，將其中兩者互換，他將不會發覺。

關閉對顏色的感知(將電磁弱力關掉)，你才會發現它們在形狀上的相似！

這樣的p-n互換不變性是一個近似不變性，或部分不變性，只有核力遵守！





對愛因斯坦來說，不變性、對稱是物理世界美的代表！ 海森堡實用主義者！

質子與中子的世界是部分美麗的！

但質子與中子並不是基本粒子，而是由基本粒子夸克組成。



把與質子及中子性質(質量)相近的粒子收集起來。

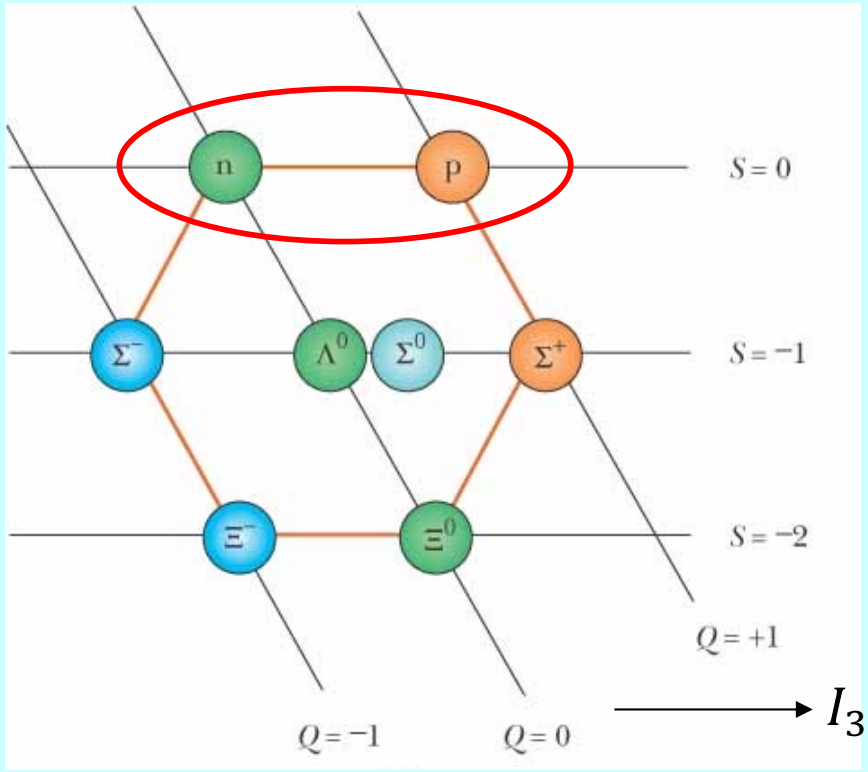
這樣的樣式源自它們有類似的組成成分。

我們現在知道質子是由三個夸克uud構成。

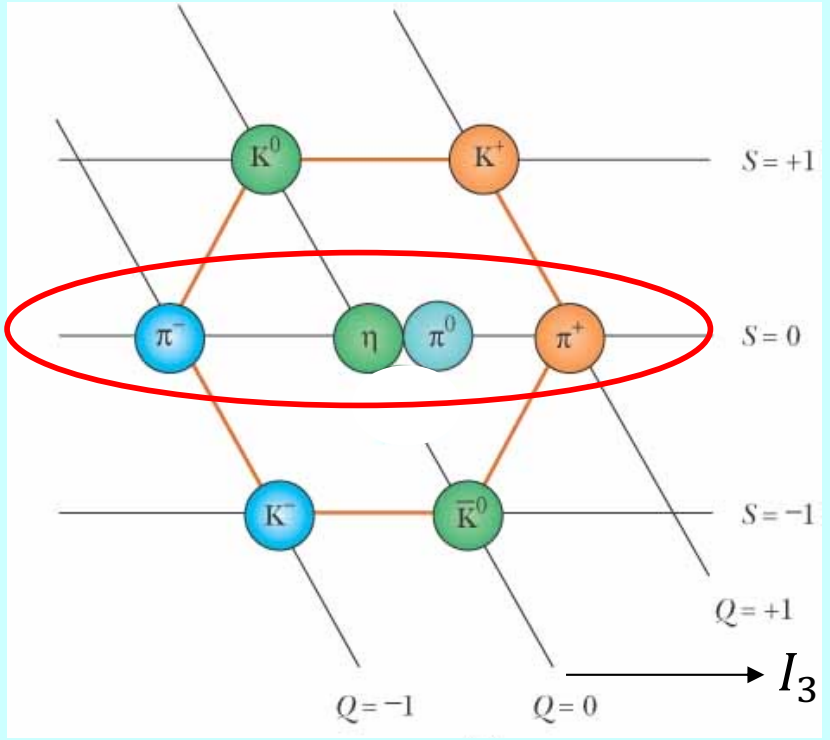


同樣的樣式竟然一再出現！

質量相近的重子（自旋為 1/2）



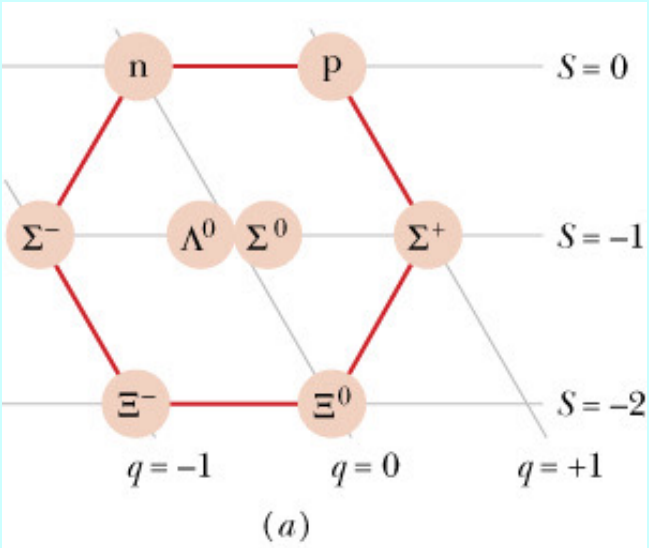
質量相近的介子（自旋為 0）

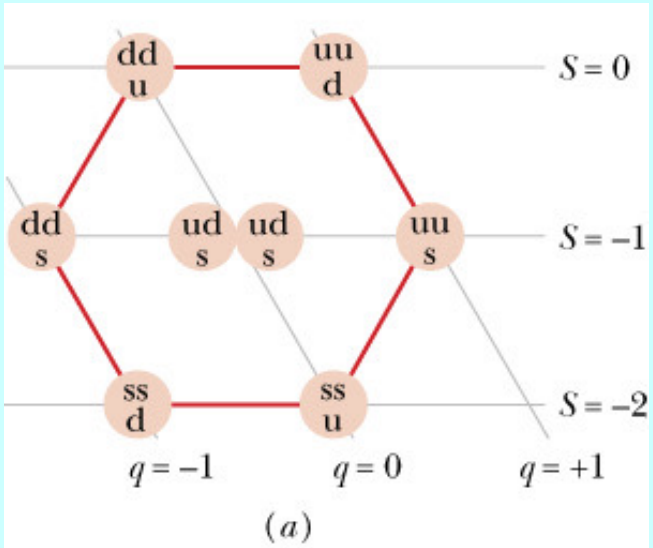


Fortune telling diagrams? 八卦圖？紫微斗數？

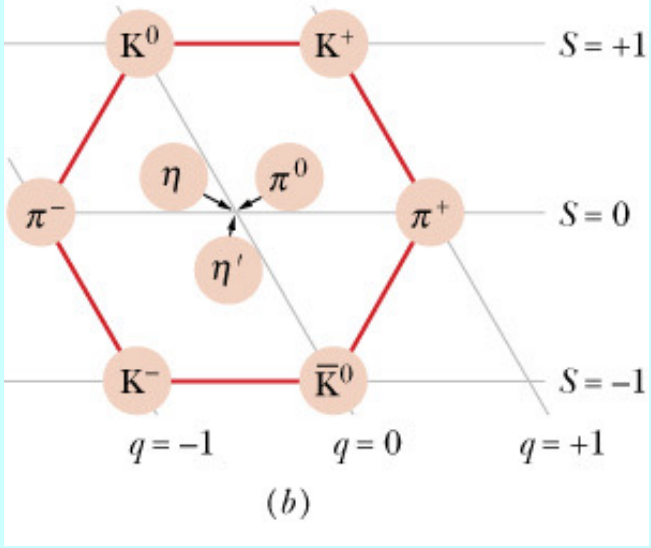
Octet可以看成這三個性質相似物件u, d, s，所作以下兩種組合的所有可能：

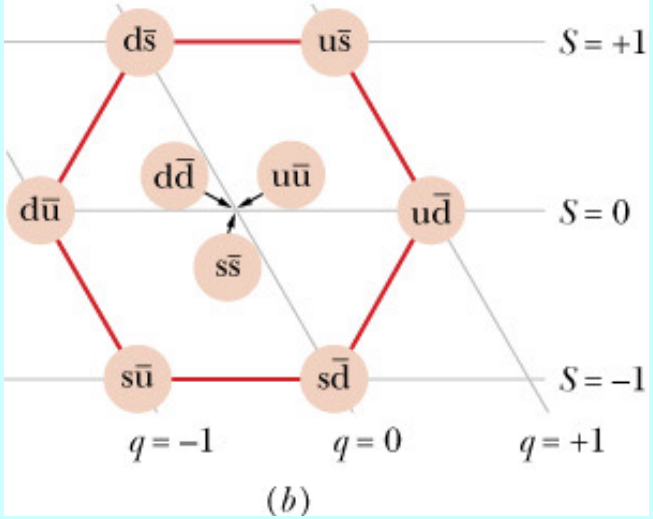
三個物體的組合

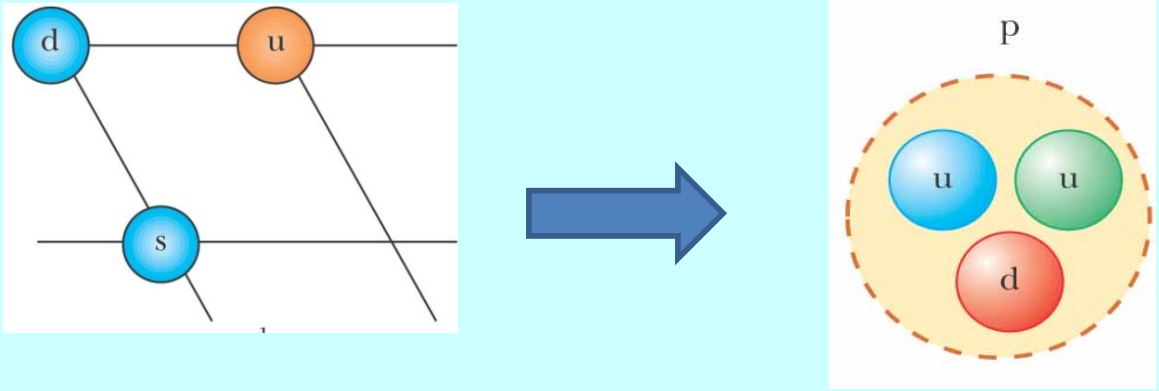




物體與反物體的組合





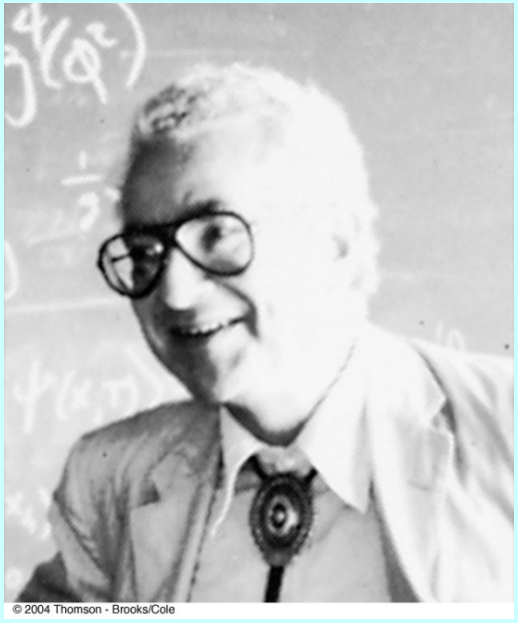


這三個相似物件原本只是數學上的抽象觀念。

但Gell-mann 現在提議：這三個相似物件就是質子及中子的組成成分！

這個組合成份被命名為 **Quarks 夸克.**





"three quarks for Muster Mark" in James Joyce's novel, Finnegan's Wake

The opening line of *Finnegans Wake* continues from the book's unfinished closing line



riverrun, past Eve and Adam's, from swerve of shore to bend of bay, brings us by a commodius vicus of recirculation back to Howth Castle and Environs.—

A way a lone a last a loved a long the / riverrun,

---

past Eve and Adam's, from swerve of shore to bend of bay, brings us by a commodius vicus of recirculation back to Howth Castle and Environs.

-- Three quarks for Muster Mark!
Sure he hasn't got much of a bark
And sure any he has it's all beside the mark.

But O, Wreneagle Almighty, wouldn't un be a sky of a lark
To see that old buzzard whooping about for uns shirt in the dark
And he hunting round for uns speckled trousers around by
Palmerstown Park?
Hohohoho, moulty Mark!

In 1963, when I assigned the name "quark" to the fundamental constituents of the nucleon, I had the sound first, without the spelling, which could have been "kwork". Then, in one of my occasional perusals of Finnegans Wake, by James Joyce, I came across the word "quark" in the phrase "Three quarks for Muster Mark". Since "quark" (meaning, for one thing, the cry of the gull) was clearly intended to rhyme with "Mark", as well as "bark" and other such words, I had to find an excuse to pronounce it as "kwork". But the book represents the dream of a publican named Humphrey Chimpden Earwicker. Words in the text are typically drawn from several sources at once, like the "portmanteau" words in Through the Looking-Glass. From time to time, phrases occur in the book that are partially determined by calls for drinks at the bar. I argued, therefore, that perhaps one of the multiple sources of the cry "Three quarks for Muster Mark" might be "Three quarts for Mister Mark", in which case the pronunciation "kwork" would not be totally unjustified. In any case, the number three fitted perfectly the way quarks occur in nature.

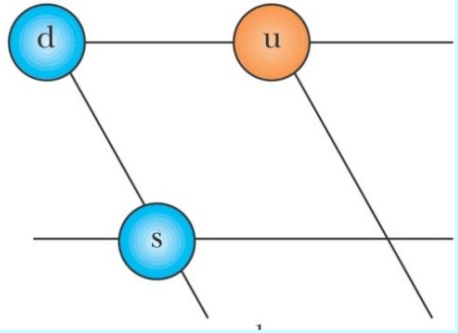


Three **flavors** 口味 of quarks:

上

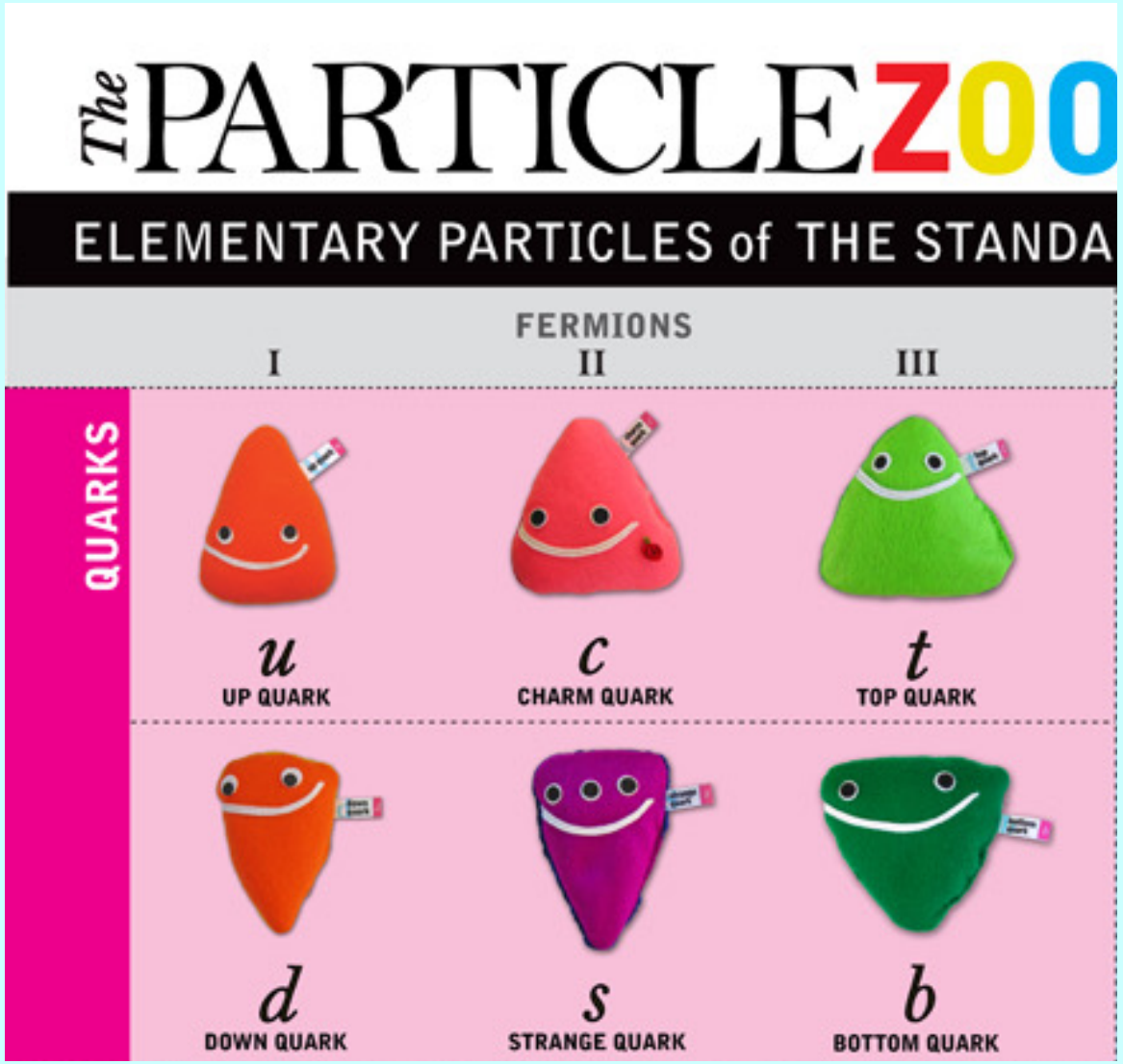
下





夸克有三種口味！他們的質量相似，強作用完全相同。

因此由它們組合出來的強子（介子與重子）質量相似。


The PARTICLE ZOO
ELEMENTARY PARTICLES of THE STANDA
FERMIONS
I
II
III
QUARKS
u
UP QUARK
c
CHARM QUARK
t
TOP QUARK
d
DOWN QUARK
s
STRANGE QUARK
b
BOTTOM QUARK

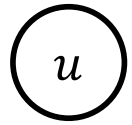
QUARKS

u

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$m_u = 2.3^{+0.7}_{-0.5}$ MeV　　Charge $= \frac{2}{3}\,e$　　$I_z = +\frac{1}{2}$

$m_u/m_d = 0.38$–0.58



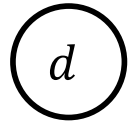
d

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

$m_d = 4.8^{+0.5}_{-0.3}$ MeV　　Charge $= -\frac{1}{3}\,e$　　$I_z = -\frac{1}{2}$

$m_s/m_d = 17$–22

$\overline{m} = (m_u+m_d)/2 = 3.5^{+0.7}_{-0.2}$ MeV



注意夸克的電荷量是電子的分數倍！



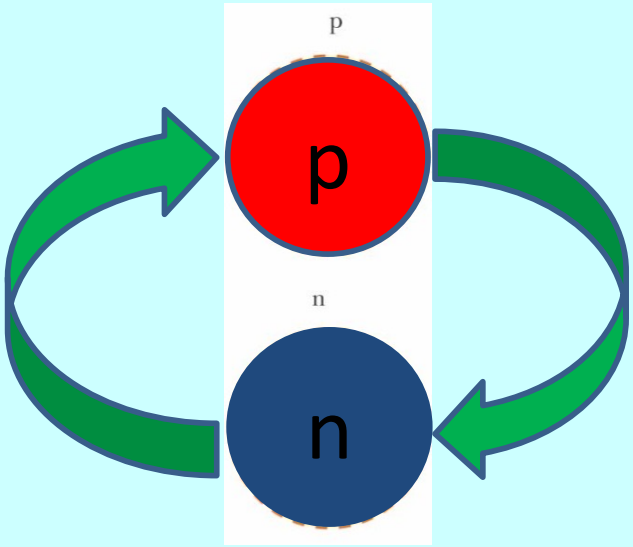


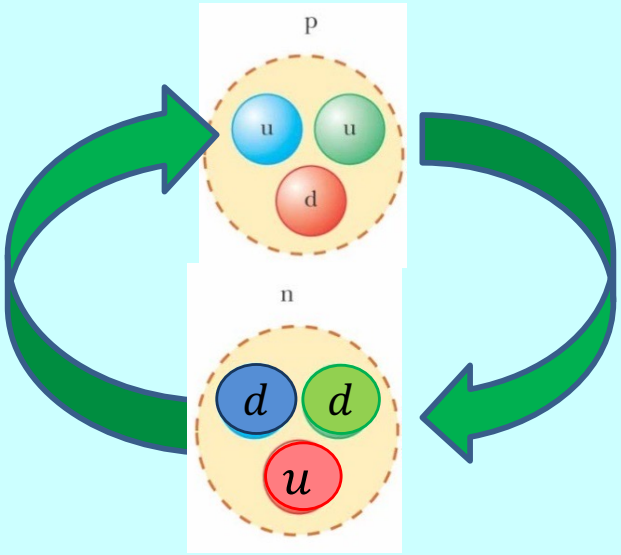
中子是由兩個下夸克、一個上夸克組成。

質子是由兩個上夸克、一個下夸克組成。

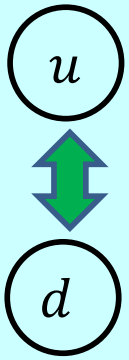
組成的束縛機制完全相同！可見上下交換不會有影響。

p,n 的差別在其中一個 u夸克換成了 d夸克





p-n 互換不變性其實是 u-d 互換不變性



u-d 互換不變性

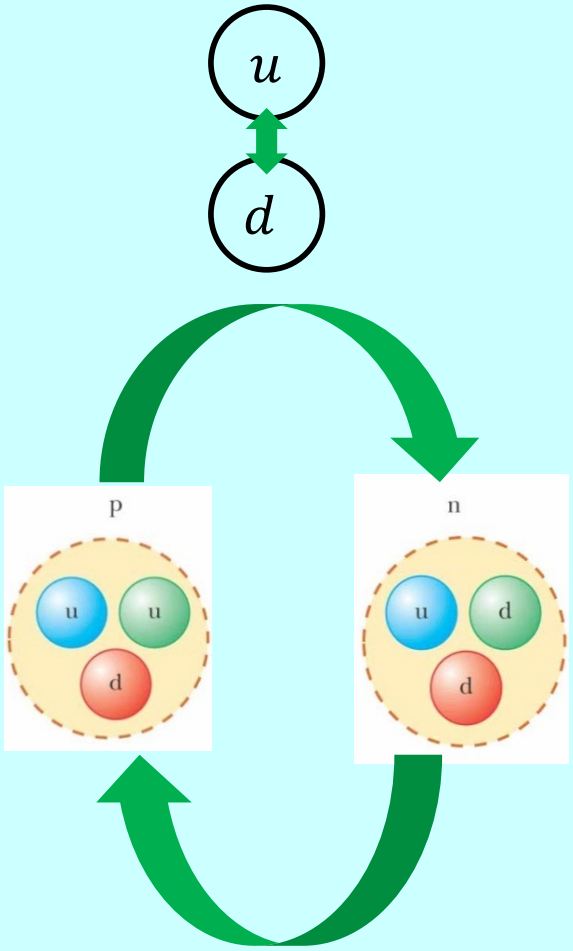


上夸克與下夸克的質量與核力都相同：上與下的分別只是人造的命名，

你無法測量絕對的上與下，因此互換不應影響物理結果！

u-d 互換不變性

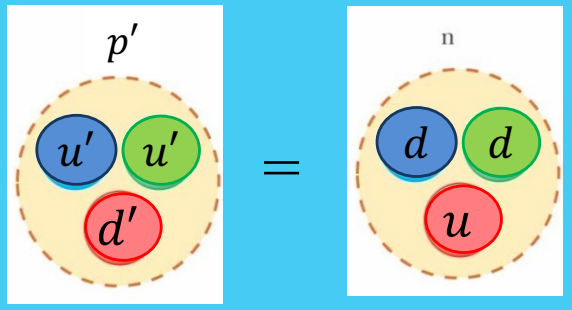
可以想像的世界來思考：





u' = d

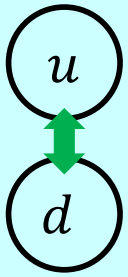
d' = u



變換後、想像世界的u'其實是d，d'其實是u，

u與d可以互換，因此我們無法分辨變換前的世界、與變換後的想像世界。







$$u' = d + u$$

$$d' = u - d$$

u'可不可以是u與d的疊加？

如果u與d性質類似，u換成u與d的疊加，d換成另一個u與d的疊加。

宇宙應該不會察覺吧？我們應該依舊無法分辨變換的前後？

首先解釋一下量子態的疊加。

疊加在某些時候非常自然，我們會說一個人的心情悲喜交加，

悲與喜是相反不相容的心情，但我們並不覺得悲喜交加很奇怪。

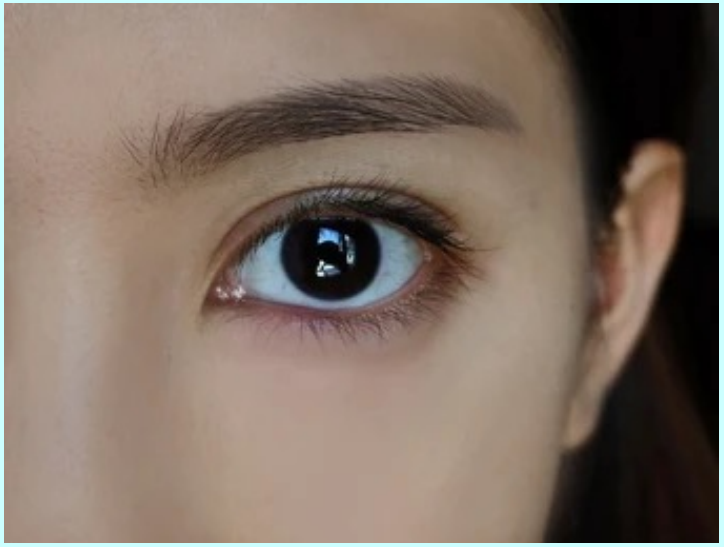


但如果我們說一個人的眼珠既是黑的，也是藍的，

是黑與藍的疊加，就有點怪了。

眼珠是藍就不會是黑，是黑就不會是藍。一看就知道。







or

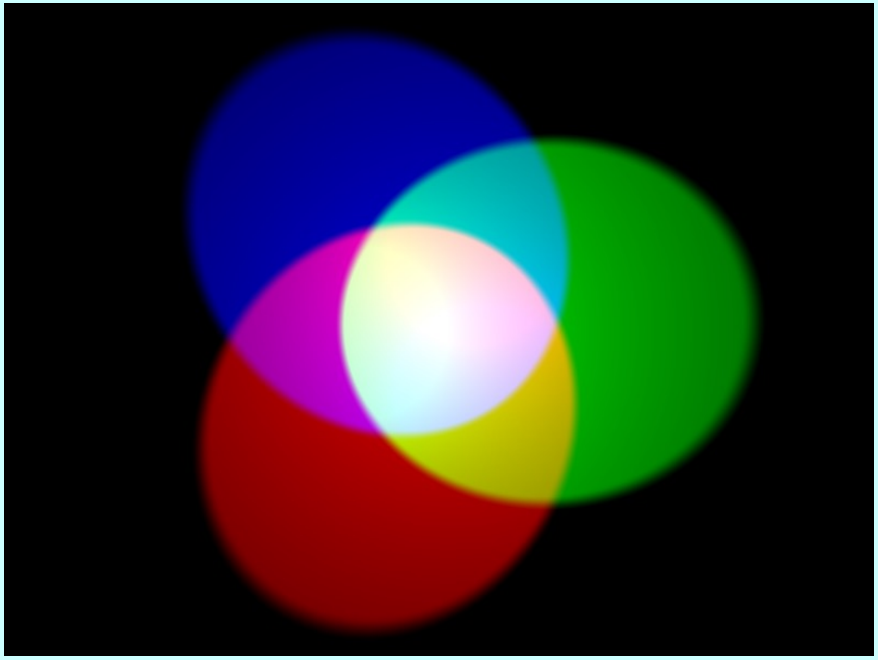


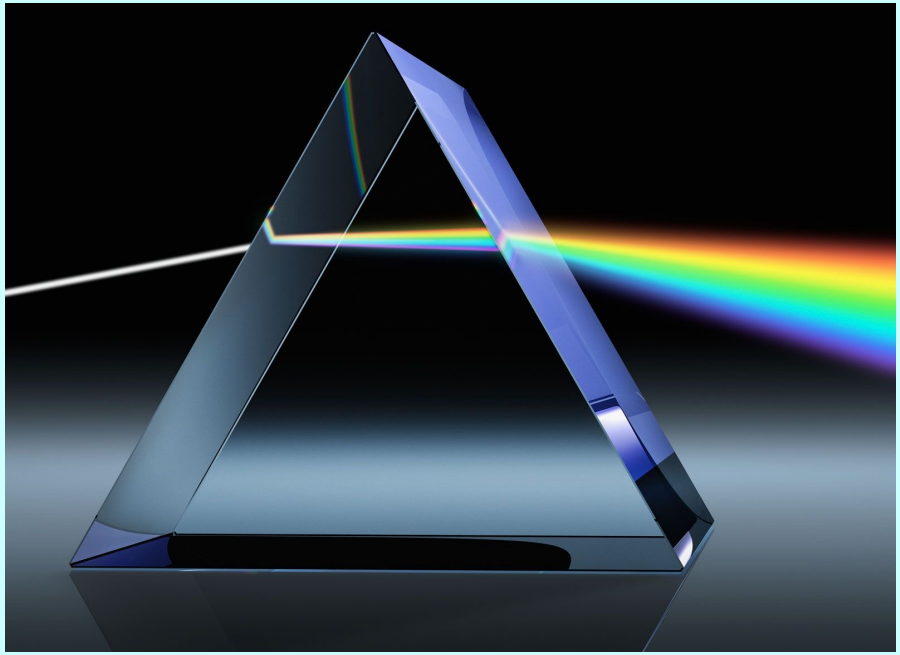
同理，是上夸克就不會是下夸克，是下夸克就不會是上夸克。兩者不相容。

u d

但光可以又綠又藍！

白光是七色光波的疊加，但又不同於任一單色光線。

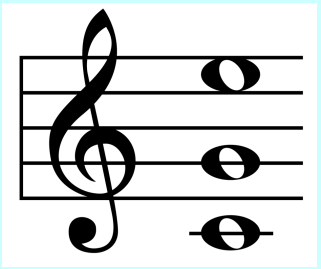


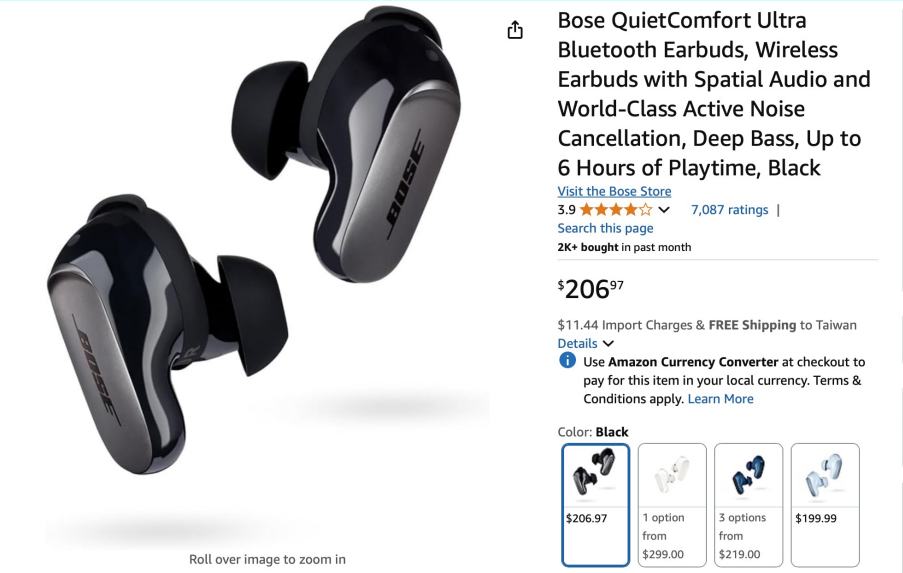


疊加 superposition 的概念在波是很自然的！

合聲也是一樣的道理，我們聽到的聲音是四個個別發出的音波的疊加。







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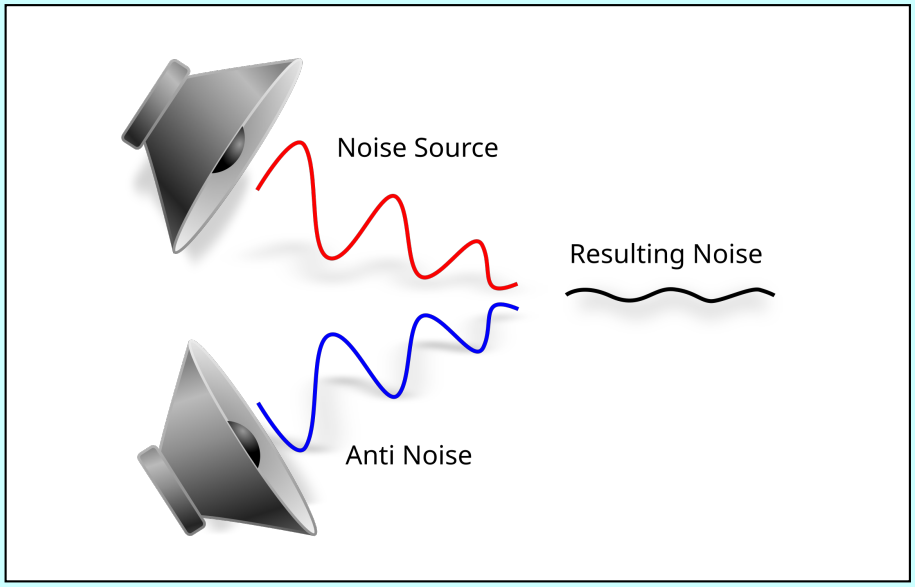


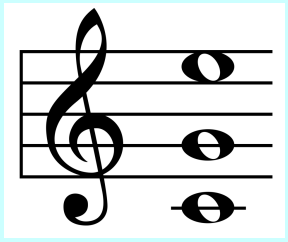
物體不相容的狀態不會同時發生。



or





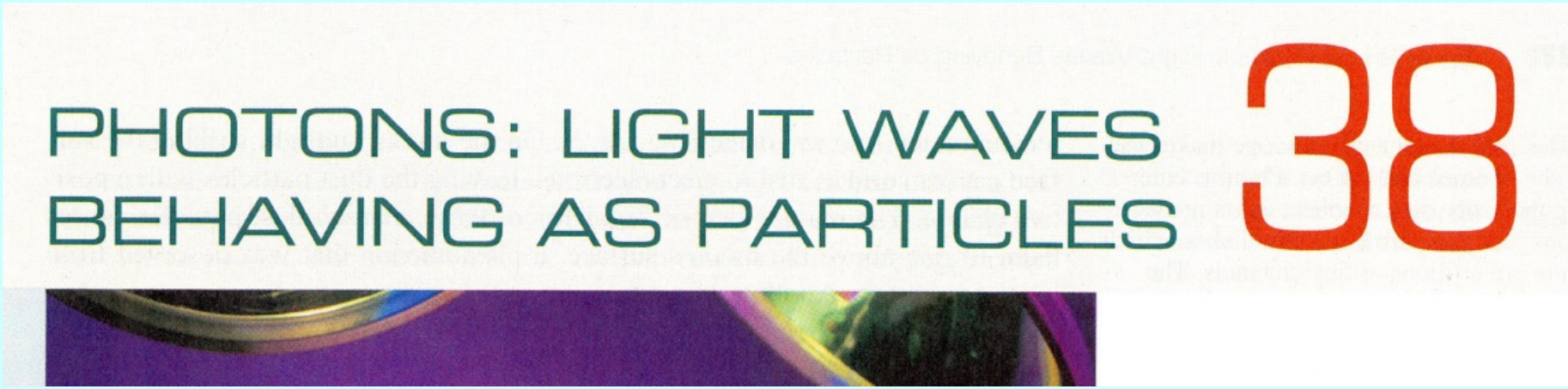


疊加

Do and So and Mi

但波的不相容的狀態卻可以疊加！

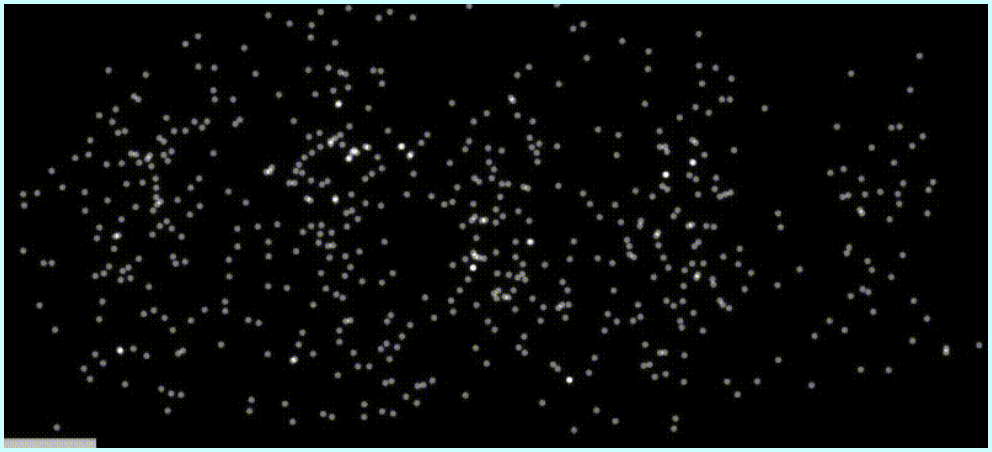
粒子與波的二重性

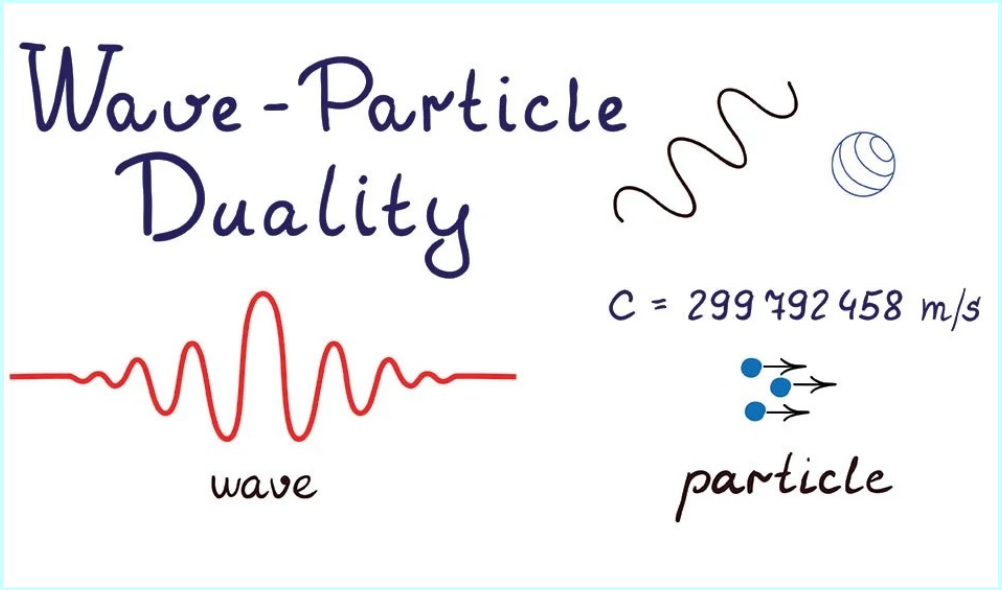






光既是波，也是粒子 (1905)。





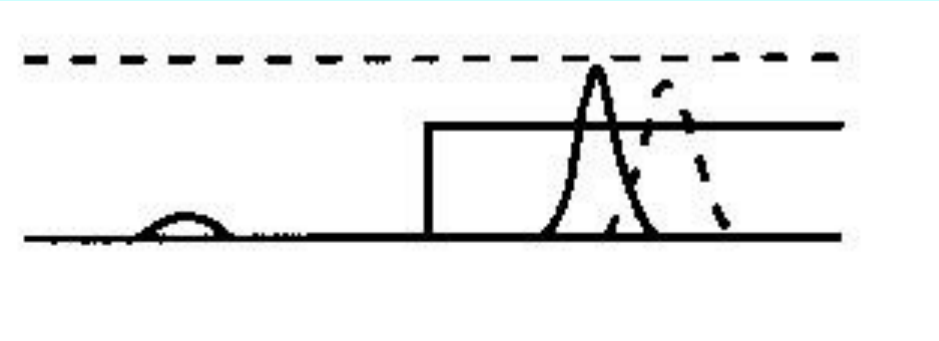
電子既是粒子，也是波 (1924)。

電子與夸克的狀態可以疊加！因為電子、夸克是波。

電子、夸克的狀態可以是兩個古典情況下彼此互不相容的狀態的疊加！

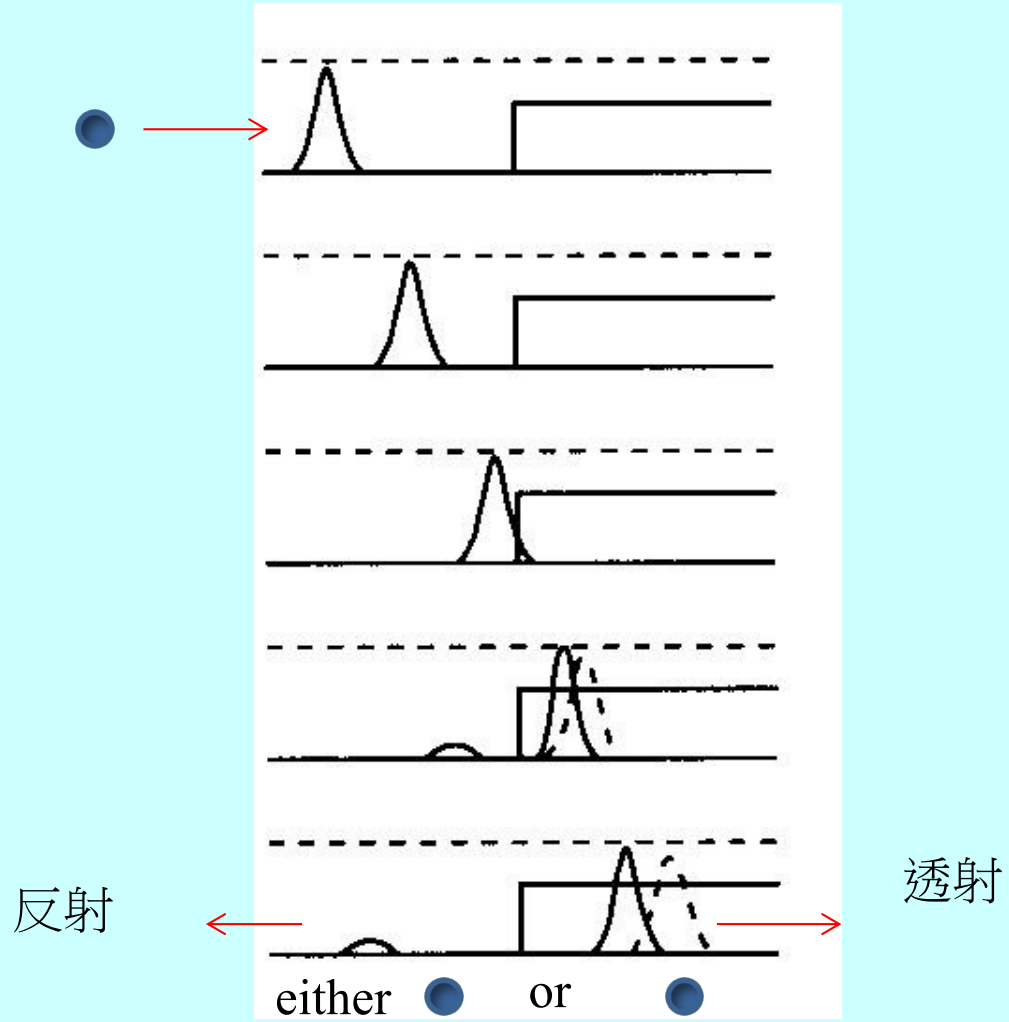
$$\psi = a\psi_1 + b\psi_2$$

觀察時看到狀態 1 與看到狀態 2 的機率比正好是 $|a|^2 : |b|^2$



d + u

單一電子的波，很容易就被散射、分裂為兩個分立的波。



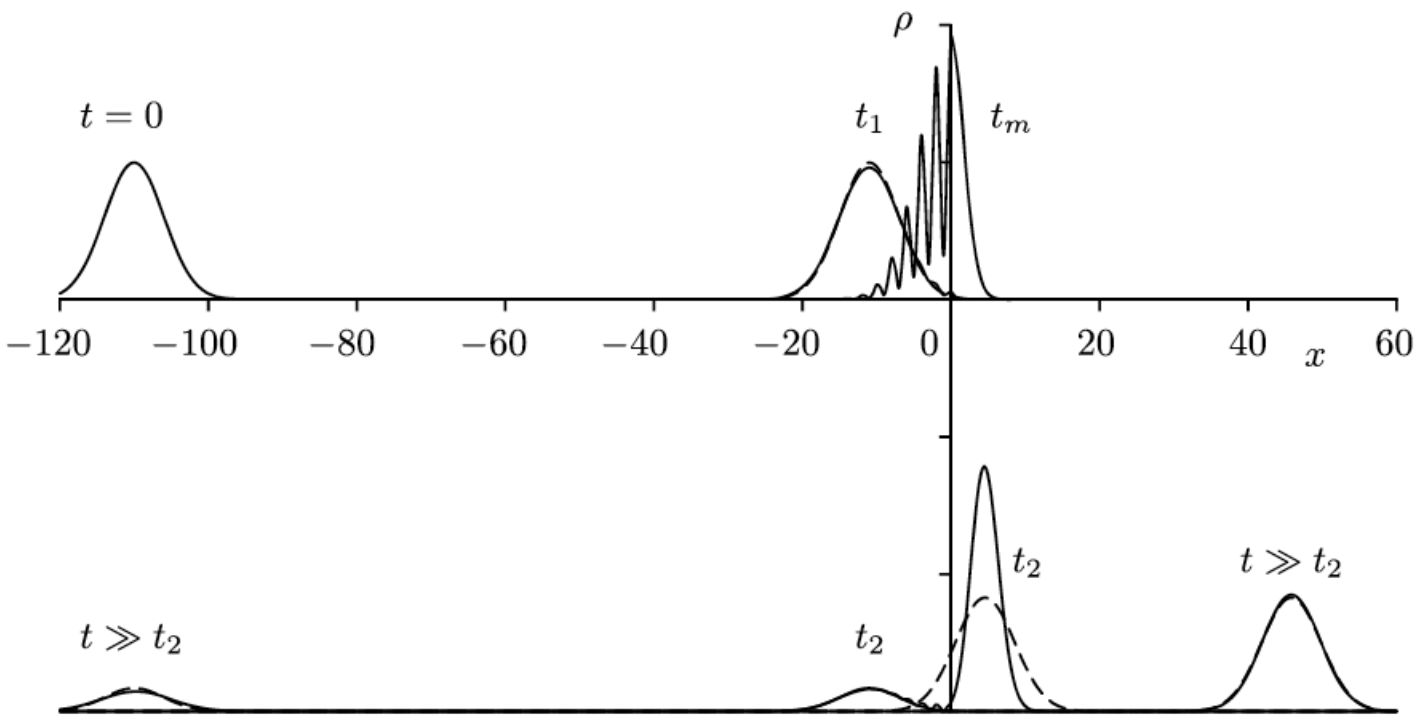
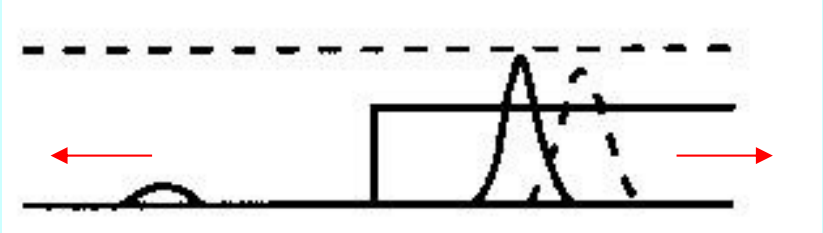
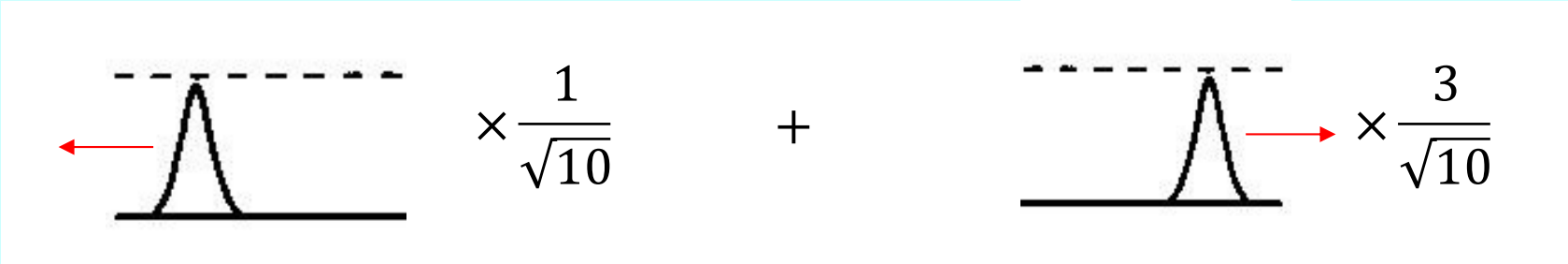


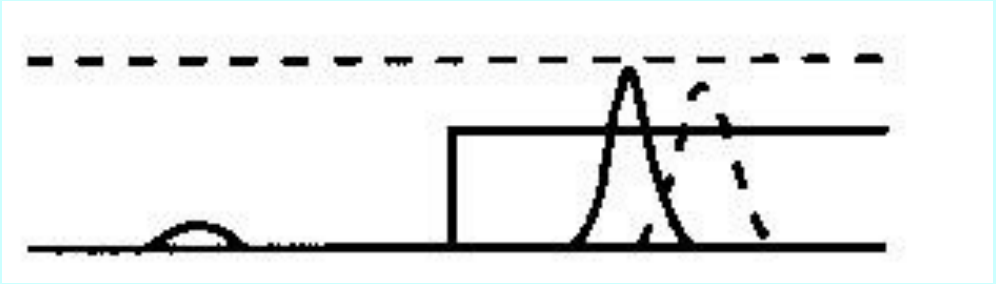
Fig. 7.5 Evolution of the probability density of a wave packet in the presence of a step potential with an energy $E > V_0$ (solid lines). The parameters of the potential and the initial Gaussian wave packet are the same as in Fig. 7.4, except $k_0 = 11 > k_V$ and $x_0 = -110$. The evolution of the packet using the approximations (7.6.25), (7.6.37) and (7.6.40) is represented by dashed lines

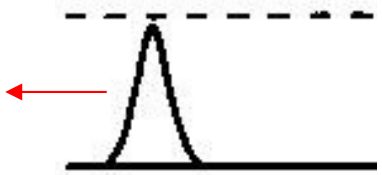




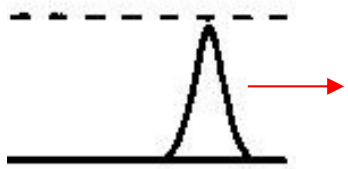
這個雙波，顯然就是一個向右行波，與向左行波的疊加！

向左、向右、就粒子來說，是不相容的！

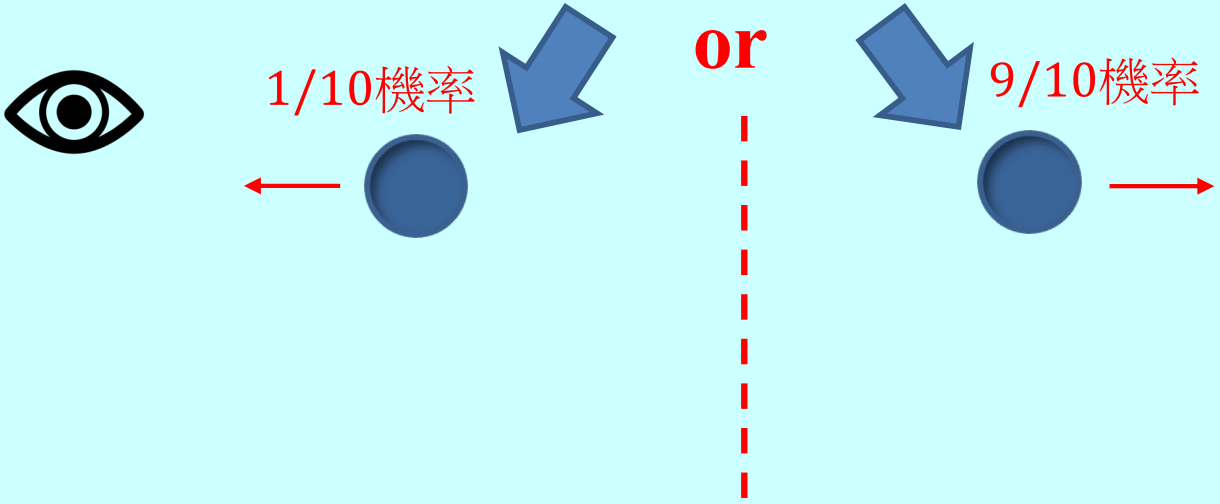




$$\times \frac{1}{\sqrt{10}} + \times \frac{3}{\sqrt{10}}$$



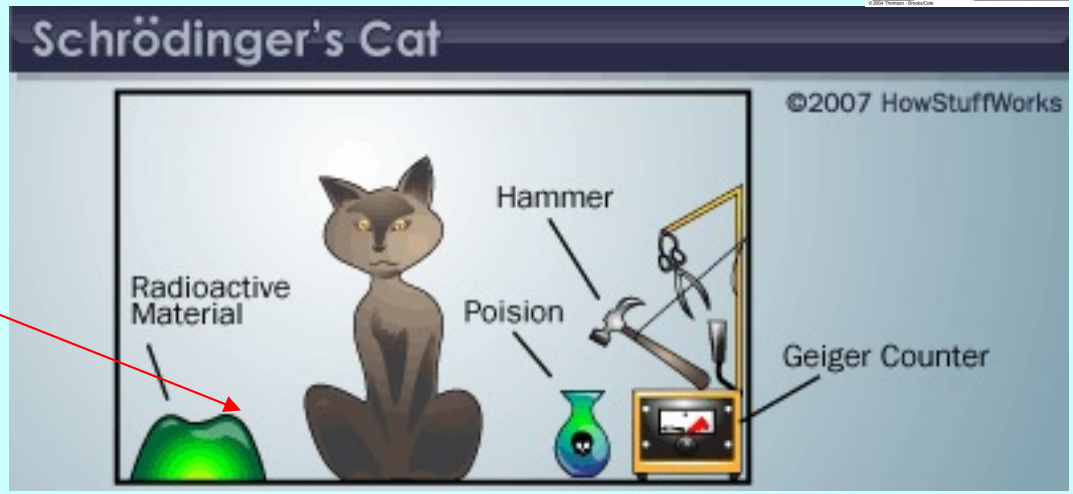
To observe this one electron, there is 9/10 probability it is moving right, 1/10 left!



薛丁格的貓故事中，

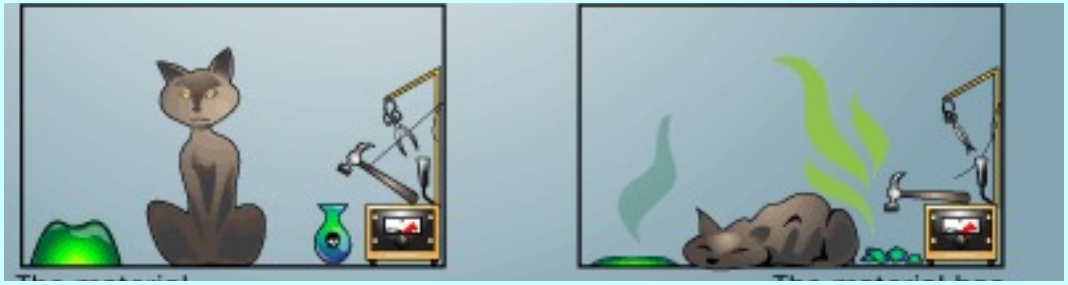


「讓我們安排一個非常可笑的情況。將一隻貓，與放射性原子核一起放進一封閉鐵箱內，再放入一個啟動裝置，但要小心防止貓咪破壞它。在這裝置中有一測放射性的蓋格計數器。」



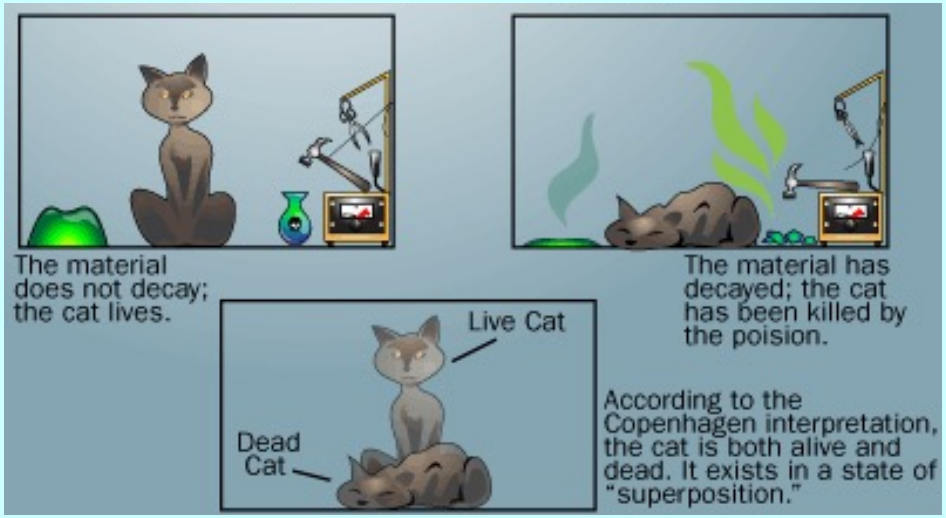
若放射性原子核未衰變，貓會活著，

若已衰變，則貓會中毒而死



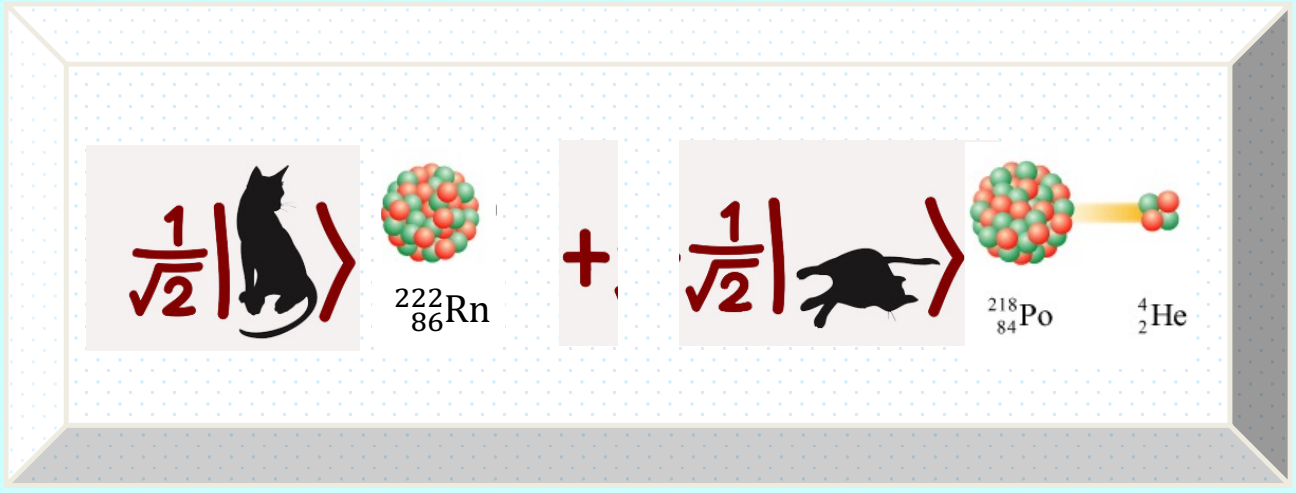
當初薛丁格很隨性的說：

「我們密封鐵箱一個小時後，整個系統的狀態波函數，就會是放射性原子核未衰變而貓活，同時也可能是已衰變而貓死。」



現代術語就會說是這時的整個鐵箱，是兩個狀態的疊加

"還活著的貓配未衰變的原子核"，加，"已死去的貓配已衰變的原子核"。





量子力學還預測如果不去打開來看，鐵箱會繼續維持此狀態。

量子態可以做線性疊加



推廣u', d'為兩個彼此互相垂直的u與d的疊加狀態！

就是u與d分別換成兩個正交的u, d疊加！

如果u與d性質類似：

u', d'的性質與滿足的物理定律，還是會和u, d一樣。這就稱為$SU(2)$對稱。

$u \Rightarrow u' = d$

$d \Rightarrow d' = u$

古典

古典的 u-d 互換

$u \Rightarrow u' = a \cdot u + b \cdot d$

$d \Rightarrow d' = c \cdot u + d \cdot d$

量子

量子力學推廣的 u-d $SU(2)$變換

u-d 互換不變性

u

d



$$u' = a \cdot u + b \cdot d$$

$$d' = c \cdot u + d \cdot d$$

只要滿足適當條件的四個複數 a, b, c, d 就給定一個變換！

疊加的成份加總必需固定！

$|a|^2 + |b|^2 = 1$ $|c|^2 + |d|^2 = 1$

兩種疊加組合必需純粹的不同。

$ac^* + bd^* = 0$

u

d



$$u' = a \cdot u + b \cdot d$$

$$d' = c \cdot u + d \cdot d$$

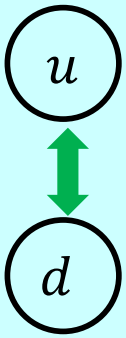
以矩陣來描寫這些變換更加方便，若將夸克寫成一個1×2的行向量：$\begin{pmatrix} u \\ d \end{pmatrix}$

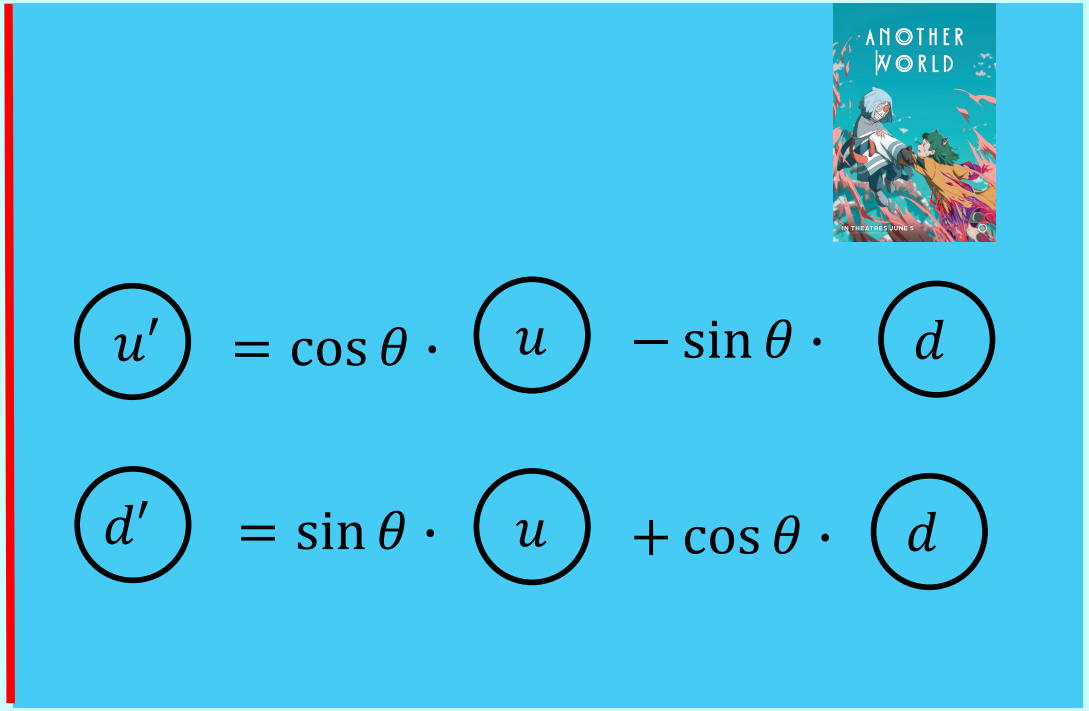
$$\begin{pmatrix} u' \\ d' \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix} \equiv U \begin{pmatrix} u \\ d \end{pmatrix}$$

只要滿足適當條件的2×2矩陣就給定一個變換！ $UU^{\dagger} = I$

這樣的矩陣 U 稱為unitary么正。任一unitary 2×2 矩陣就給定一個變換。

例如以下的選擇就符合條件：





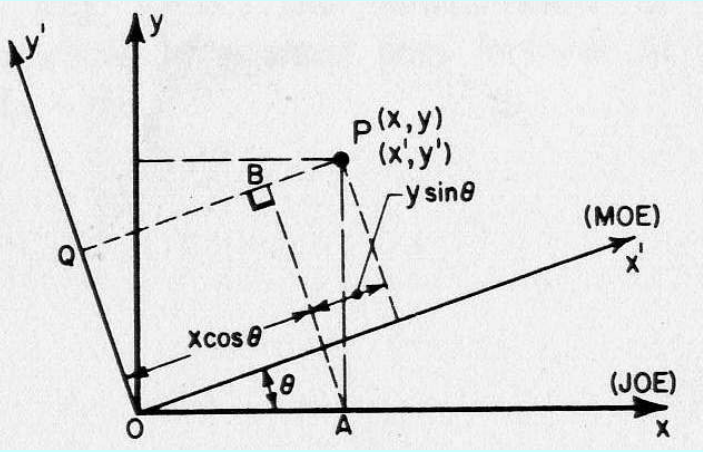
$|a|^2 + |b|^2 = 1$ $|c|^2 + |d|^2 = 1$

$$\begin{pmatrix} u' \\ d' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix}$$

$ac^* + bd^* = 0$

注意：這一系列變換有連續分布的無限多個，由一個連續變數θ標定。

如同平移對稱一般，是一個連續對稱！互換不變性升級為連續對稱！



這與向量的座標軸選轉變換非常類似！

因為座標軸的選取是任意的。

將座標軸旋轉 θ 角，就得到一組新座標軸。

$$\begin{pmatrix} x \\ y \end{pmatrix} \rightarrow \begin{pmatrix} x' \\ y' \end{pmatrix}$$

$$x' = x\cos\theta - y\sin\theta$$
$$y' = x\sin\theta + y\cos\theta$$



u

d

$u' = \cos\theta \cdot u - y\sin\theta \cdot d$

$d' = \sin\theta \cdot u + y\cos\theta \cdot d$

這些連續分布的2×2的Special Unitary矩陣的集合組成一個群，稱為$SU(2)$！

請注意：我們的推導其實普遍適用於任意兩個可分辨但相似的物件。

當我們要說兩個東西相似，量力的版本就是$SU(2)$對稱！

應用於u與d 夸克就稱為同位旋 Isospin $SU(2)$。

除了θ，我們其實還有兩個、共三個獨立的連續變數可以選擇！



$UU^\dagger = I$ $\det U = 1$

2×2的矩陣有四個複數元素a, b, c, d，special unitary 2×2 matrix滿足五個條件。

因此變換由三個連續實數來標訂。那三個？

定義U的對數矩陣A：

$$U = e^{-iA} = 1 - iA + \frac{1}{2!}(-iA)^2 + \cdots \qquad e^x = 1 + x + \frac{1}{2!}x^2 + \cdots$$

$$-iA \equiv \ln U = (U-1) - \frac{1}{2}(U-1)^2 + \frac{1}{3}(U-1)^3 + \cdots$$

U矩陣是 unitary： $U^\dagger = U^{-1}$， $\left(e^{-iA}\right)^\dagger = e^{iA^\dagger} = e^{iA}$

A矩陣必須是Hermitian： $A^\dagger = A$

$\mathrm{Det}\, U = e^{-i\,\mathrm{tr}A} = 1$ A矩陣必須是Traceless： $\mathrm{tr}A = 0$

符合這兩個條件的矩陣A就一對一地對應一個U矩陣。

$A^\dagger = A$ $\quad$ $\mathrm{tr}A = 0$

符合這兩個條件的矩陣A就一對一地對應一個U矩陣。

$$A = \begin{pmatrix} a_{\mathrm{re}} & c_{\mathrm{re}} - ic_{\mathrm{im}} \\ c_{\mathrm{re}} + ic_{\mathrm{im}} & d_{\mathrm{re}} \end{pmatrix} \equiv \frac{1}{2}\begin{pmatrix} \alpha_3 & \alpha_1 - i\alpha_2 \\ \alpha_1 + i\alpha_2 & -\alpha_3 \end{pmatrix}$$

$\alpha_{1,2,3}$任意連續變數。

矩陣A、因此U矩陣也是，是以三個連續變數標定的空間！

A一般可以用三個標準矩陣的線性組合描述：

$$A = -i\left(\frac{\tau_1}{2}\alpha_1 + \frac{\tau_2}{2}\alpha_2 + \frac{\tau_3}{2}\alpha_3\right)$$

$$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Pauli Matrices

$\frac{\alpha_{1,2,3}}{2}$ 就稱為Isospin SU(2) 的Generators。A矩陣是Generators的線性組合。

任一Generators的線性組合都可以是A矩陣，取指數後就是一個U矩陣：

$$U(\alpha_1, \alpha_2, \alpha_3) = e^{-iA} = e^{-i\left(\frac{\tau_1}{2}\cdot\alpha_1 + \frac{\tau_2}{2}\cdot\alpha_2 + \frac{\tau_3}{2}\cdot\alpha_3\right)} = \exp\left(-i\sum_{i=1}^{3}\frac{\tau_i}{2}\cdot\alpha_i\right)$$

當我們要說兩個東西相似，量力的版本就是$SU(2)$對稱！

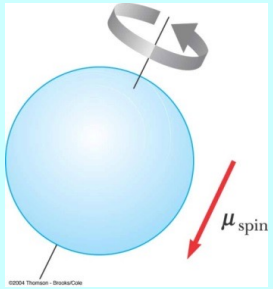
因此U矩陣是以三個連續變數$\alpha_{1,2,3}$標定的空間！



$\cdots \alpha_1 = (-\infty, \infty)$

$\vdots$

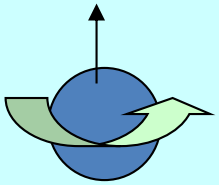
α_2



舉一個例子：

靜止的電子基本上是一個帶電的磁鐵！

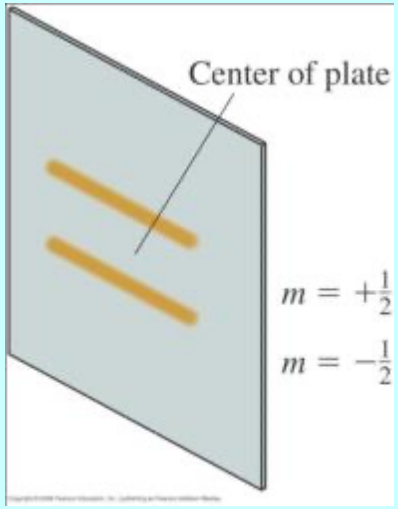
電子有一個內在的自旋世界！

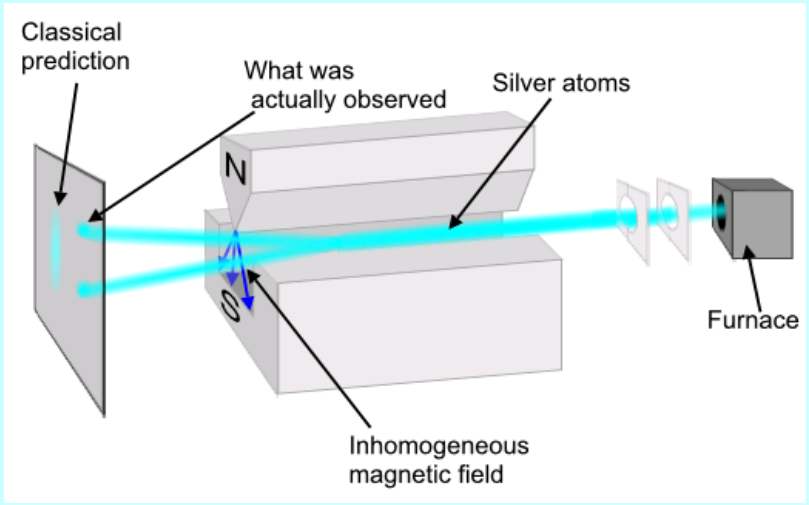


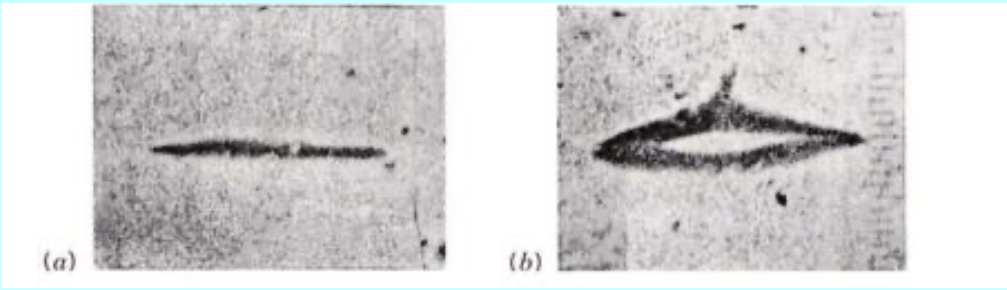




The postcard sent by Stern to Bohr showing the results of the Stern–Gerlach experiment. The left image shows the rectangular beam in the absence of the magnetic field gradient; the right-hand image shows the splitting of the beam into two components. The greatest field gradient occurs in the centre of the beam.







實驗顯示，只量到兩個分離的軌跡，電子磁鐵只能指向上或下！



電子這兩個狀態，一般稱為自旋向上及自旋向下。

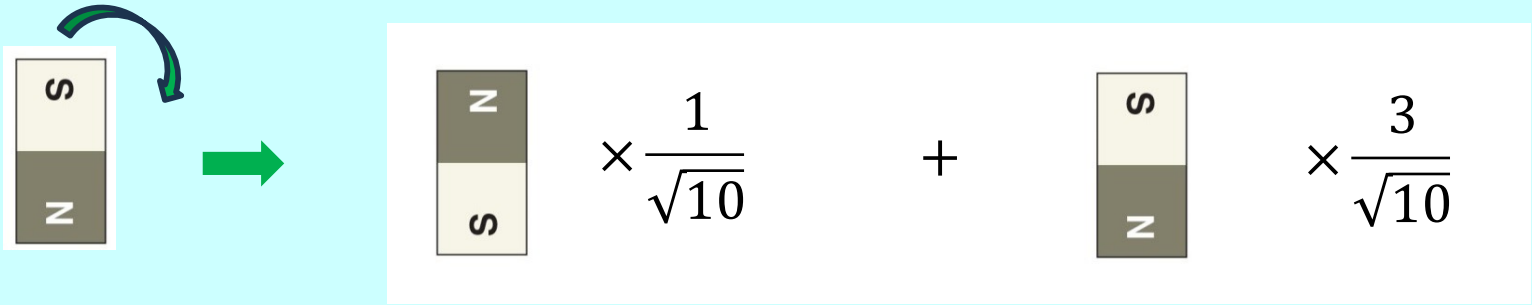
若無磁場，這兩個狀態的性質就沒有差異。

當我們要說兩個東西相似，量力的版本就是$SU(2)$對稱！

例如：可以將鐵轉一個方向，

就會得到自旋向上狀態及自旋向下狀態的疊加，

旋轉前與旋轉後，電子狀態的性質相似！



所有可能的旋轉方式，就是$SU(2)$對稱！

這樣的討論對了解材料的磁性很重要。

$SU(2)$的變換在數學結構上等於3D 旋轉。

(完全等於自旋1/2 的電子態的3D 旋轉)。

$SU(2) \sim SO(3)$

$SU(2)$ **is locally isomorphic to** $SO(3)$

但並不是真的旋轉，而是一個Internal Space的變換。

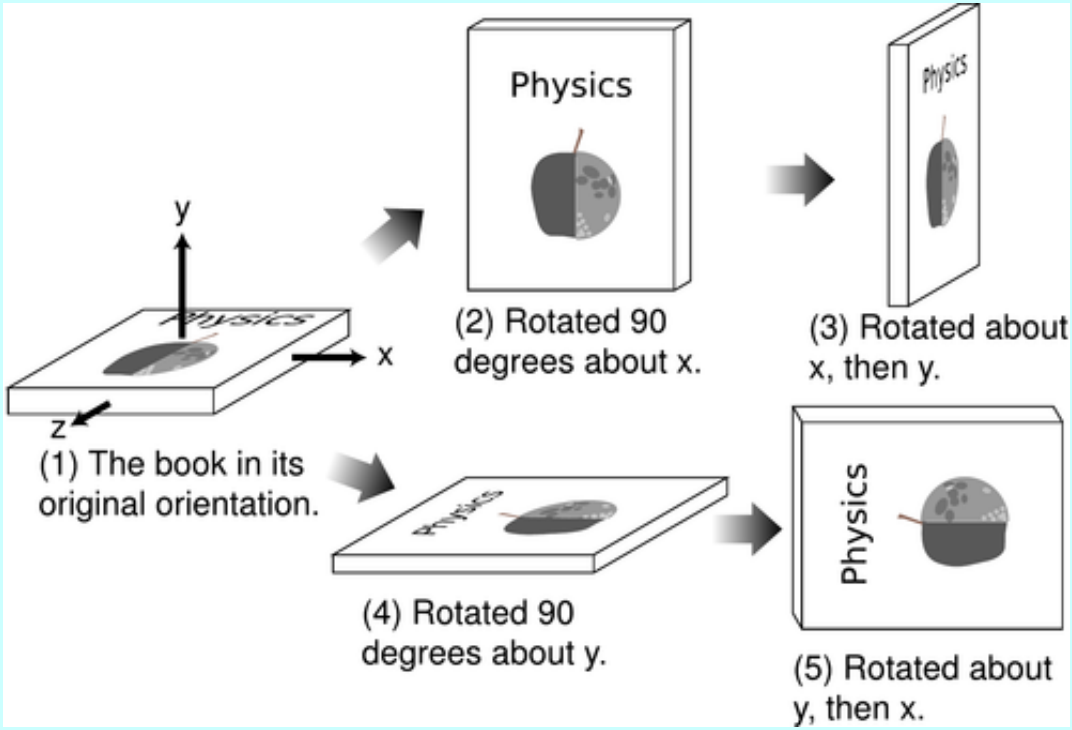
強交互作用在對應的 Isospin “旋轉” 變換下是不變的！





Isospin $SU(2)$如同3D 旋轉是不commute的。

稱為non-abelian Group or non-commutative group。



上與下：雙胞胎的交換離散對稱，在量子力學下升級為連續對稱

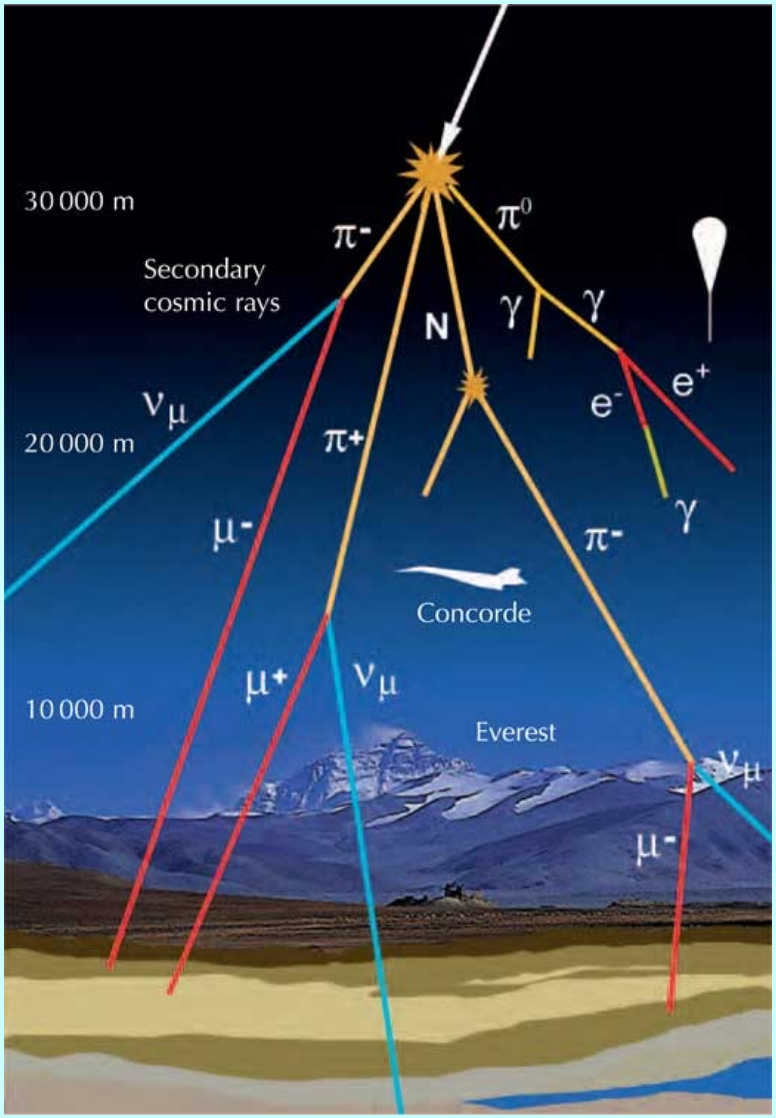


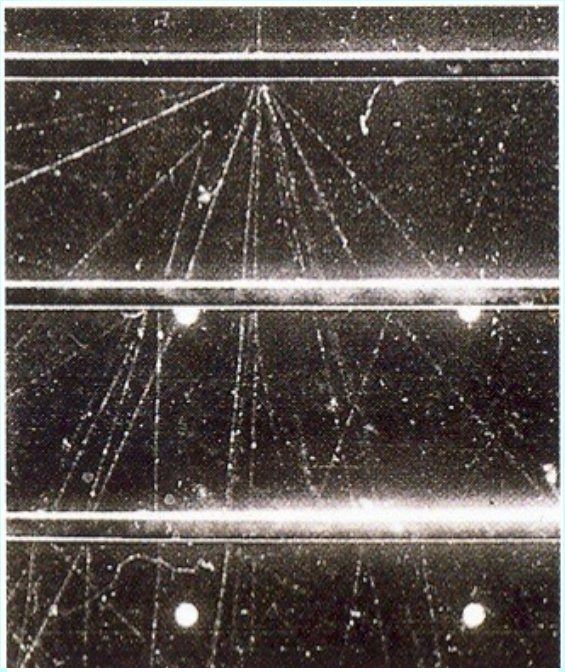
這樣的連續對稱有什麼用處？當然，有三個守恆定律。

再舉兩個粒子物理的例子。

π子的故事

高速宇宙射線打擊高空氣體分子，產生新的粒子：π子。

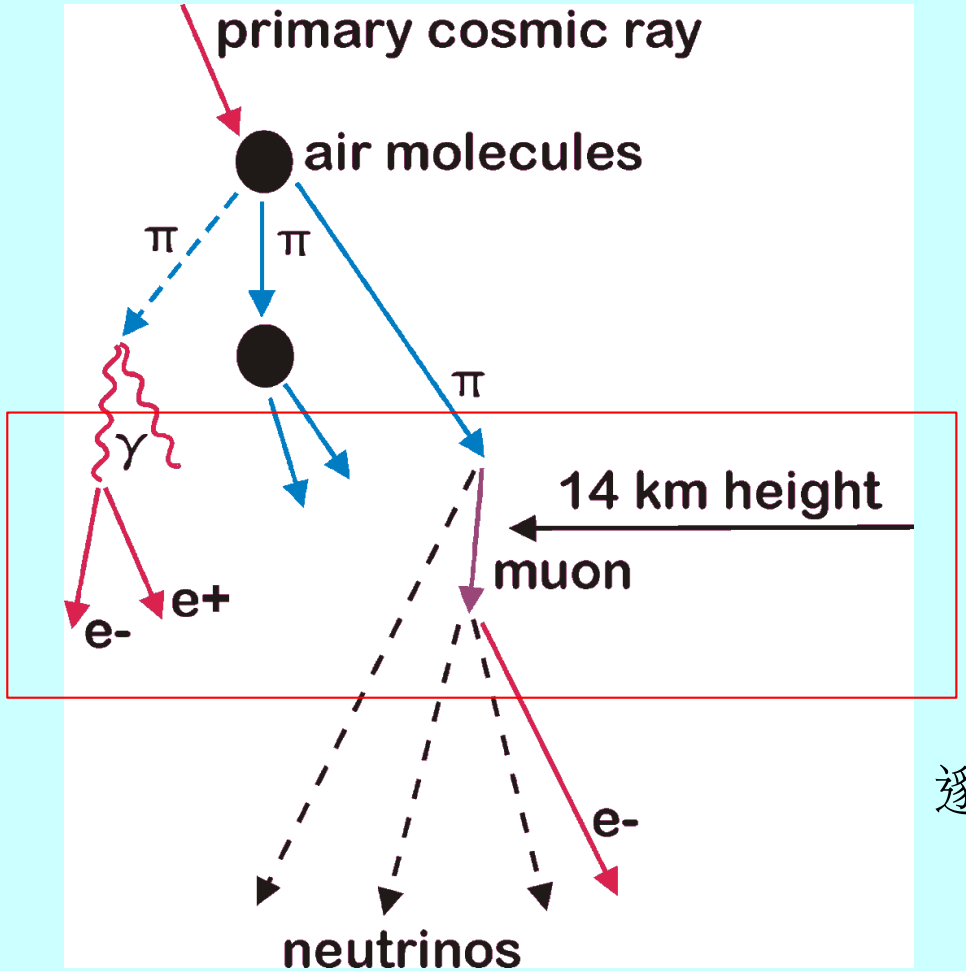


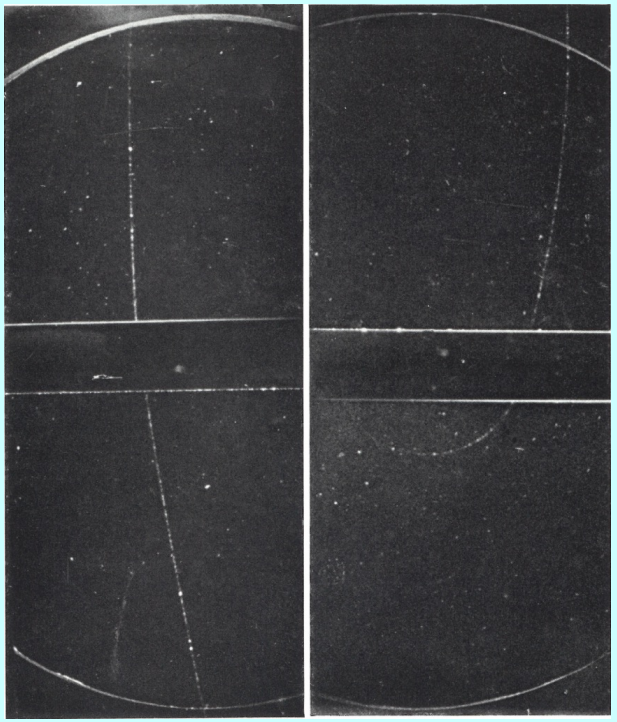




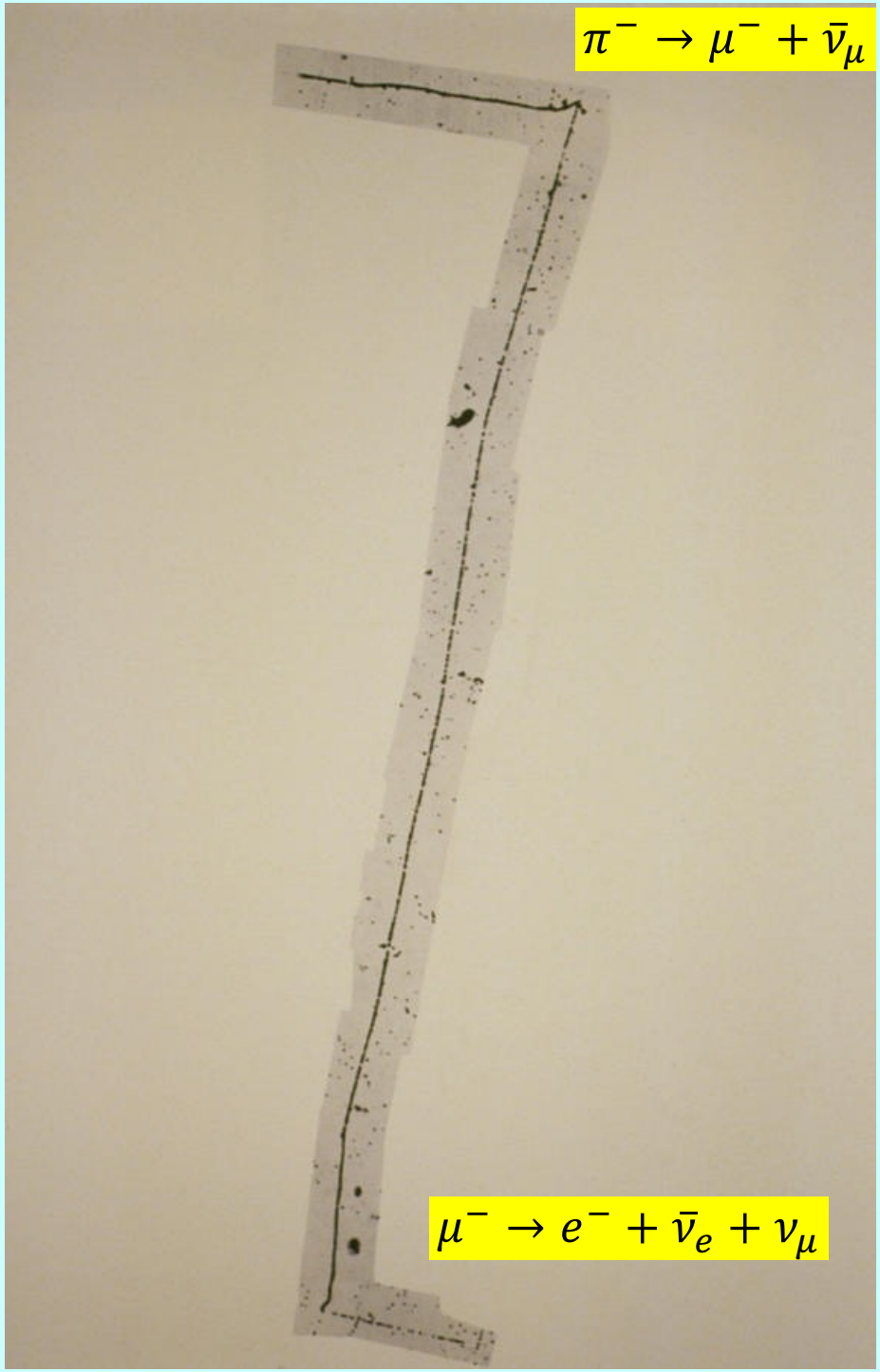
粒子π會衰變，衰變產物主要就是邊子μ。

在地面已幾乎看不到π Pion，邊子則可飛行到達地面，速度都是近光速等級。





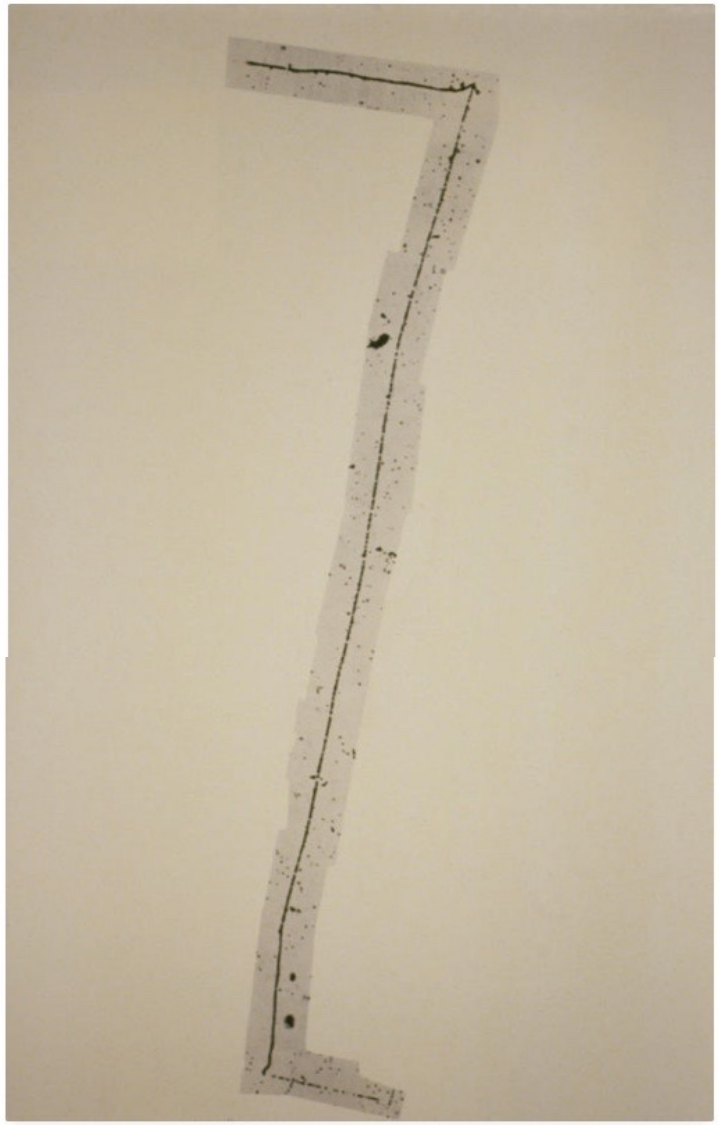
邊子μ壽命只有百萬分之一秒衰變為電子。



C. F. Powell



Emulsion photograph showing the classic pion-muon- electron (pi-mu-e) decay chain of a charged cosmic ray pion. The pion enters the picture at top left; it soon decays to a muon, which travels down the picture, & a neutrino, which is neutral & so leaves no track. At the bottom of the picture, the muon decays to an electron - the faint track heading to the right - & another neutrino. The muon's track, which is about 0.6 mm long, becomes denser as the muon slows down before decaying. The picture was taken in 1948 by Cecil Powell, the English physicist who pioneered the use of photo-graphic emulsions to record particle tracks.



Pion-muon-electron (pi-mu-e) Decay Chain is a photograph by C. Powell, P. Fowler & D. Perkins which was uploaded on May 2nd, 2013.

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0 0 0

Pion-muon-electron (pi-mu-e) Decay Chain

Emulsion photograph showing the classic pion-muon- electron (pi-mu-e) decay chain of a charged cosmic ray pion. The pion enters the picture at top... more

by C. Powell, P. Fowler & D. Per...

Canvas Print $95
Framed Print $94
Print $45
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Metal Print $75
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Title
Pion-muon-electron (pi-mu-e) Decay Chain

Artist
C. Powell, P. Fowler & D. Perkins

Medium
Photograph - Photograph

Description
Emulsion photograph showing the classic pion-muon- electron (pi-mu-e) decay chain of a charged cosmic ray pion. The pion enters the picture at top left; it soon decays to a muon, which travels down the picture, & a neutrino, which is neutral & so leaves no track. At the bottom of the picture, the muon

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LIGHT UNFLAVORED MESONS
($S = C = B = 0$)

For $I = 1$ (π, b, ρ, a): $u\overline{d}$, $(u\overline{u}-d\overline{d})/\sqrt{2}$, $d\overline{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\overline{u} + d\overline{d}) + c_2(s\overline{s})$

$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
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F_V slope parameter $a = 0.10 \pm 0.06$
$R = 0.059^{+0.009}_{-0.008}$

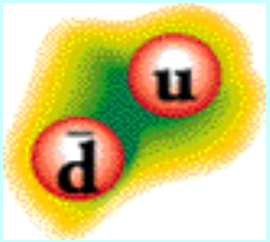
質量介於輕子與重子之間，稱為介子 Meson

π^- modes are charge conjugates of the modes below.

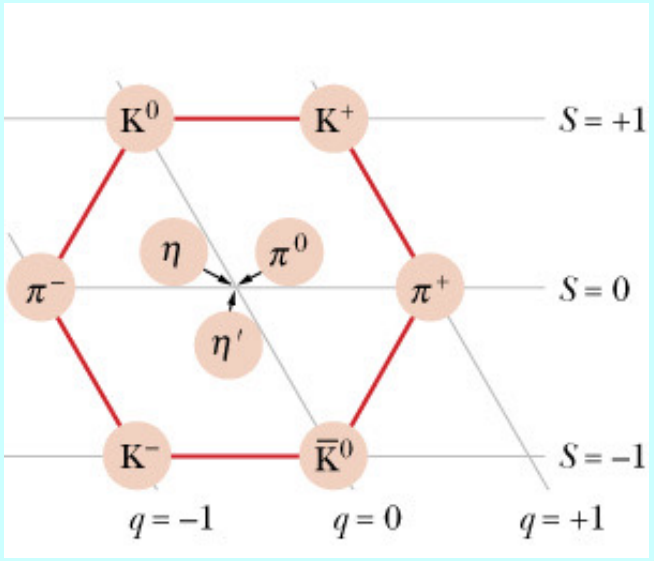
For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

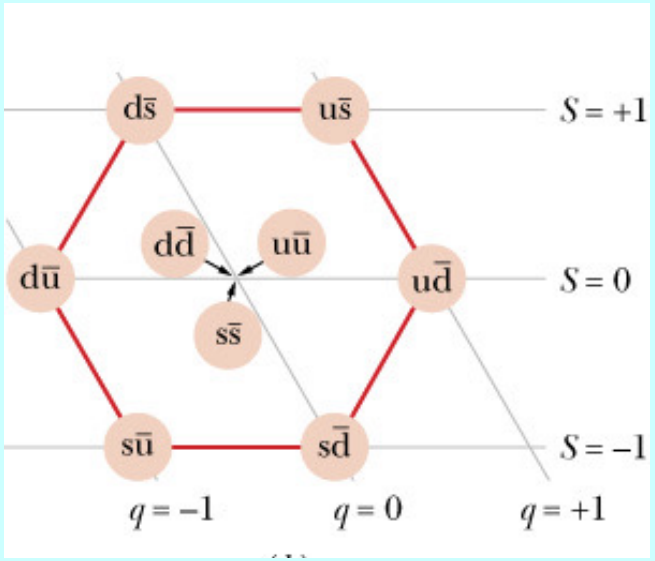
π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	(2.00 ± 0.25) $\times 10^{-4}$		30
$e^+\nu_e$	[b]	(1.230 ± 0.004) $\times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	(7.39 ± 0.05) $\times 10^{-7}$		70
$e^+\nu_e\pi^0$		(1.036 ± 0.006) $\times 10^{-8}$		4
$e^+\nu_e e^+ e^-$		(3.2 ± 0.5) $\times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$		$< 5 \times 10^{-6}$	90%	70

$\pi^+ = u\bar{d}$



$\pi^- = du$





Pion $u\bar{d}$ 在同位旋 Isospin $SU(2)$變換下會變換爲什麼？



u

d

$$u' = \cos\theta \cdot u - \sin\theta \cdot d$$

$$d' = \sin\theta \cdot u + \cos\theta \cdot d$$

$\pi^+ = u\bar{d}$

u'

?

$\pi^- = d\bar{u}$

注意：如果只是u-d互換變換，π^+與反粒子π^-會互換，如此而已。

同位旋$SU(2)$變換下則是一個連續的變換。

$$u' = u\cos\theta - d\sin\theta \qquad \bar{u}' = \bar{u}\cos\theta - \bar{d}\sin\theta$$

$$d' = u\sin\theta + d\cos\theta \qquad \bar{d}' = \bar{u}\sin\theta + \bar{d}\cos\theta$$

$$u\bar{d} \to u'\bar{d}' = (u\cos\theta - d\sin\theta)(\bar{u}\sin\theta + \bar{d}\cos\theta)$$

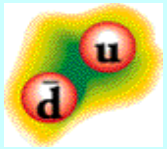
$$= -\cos^2\theta\, u\bar{d} - \sin^2\theta\, d\bar{u} + \cos\theta\sin\theta\,(u\bar{u} - d\bar{d})$$

$$u'\bar{d}' = -\cos^2\theta\, u\bar{d} - \sin^2\theta\, d\bar{u} + \cos\theta\sin\theta\,(u\bar{u} - d\bar{d})$$

$\pi^+ = u\bar{d}$

$\pi^+ = u\bar{d}$ $\pi^- = d\bar{u}$ $u\bar{u} - d\bar{d}$

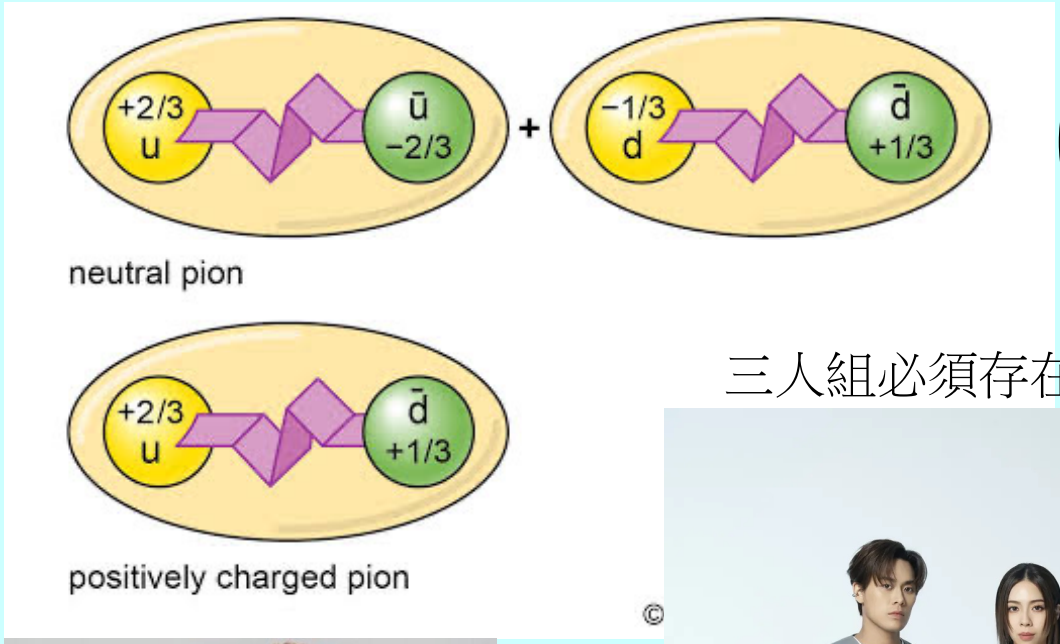




$u\bar{u} - d\bar{d}$

為了維持同位旋 Isospin $SU(2)$對稱，

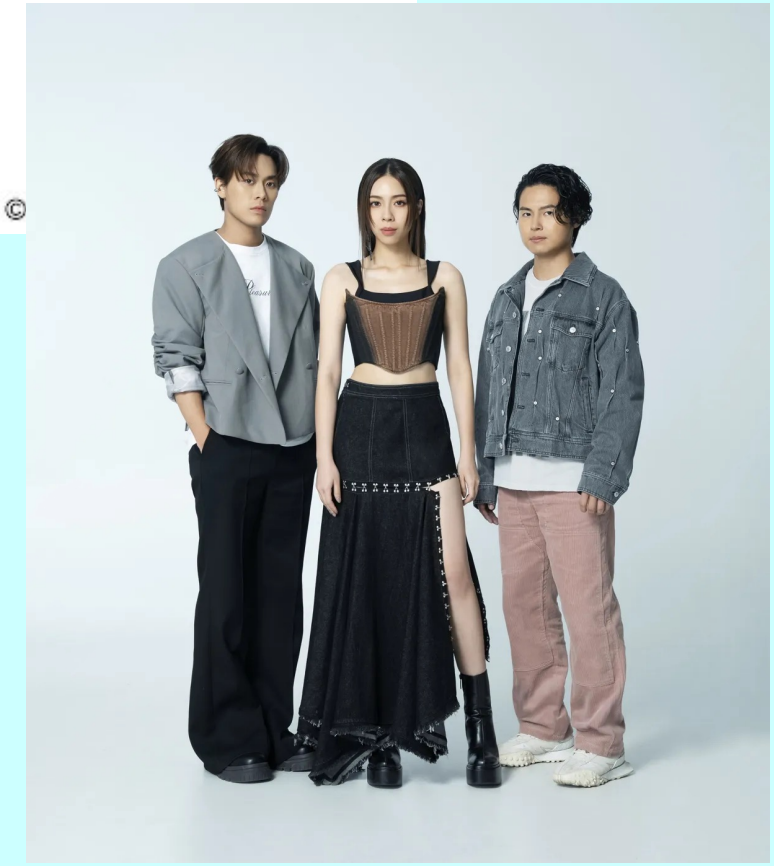
這樣一個電中性粒子一定要存在。



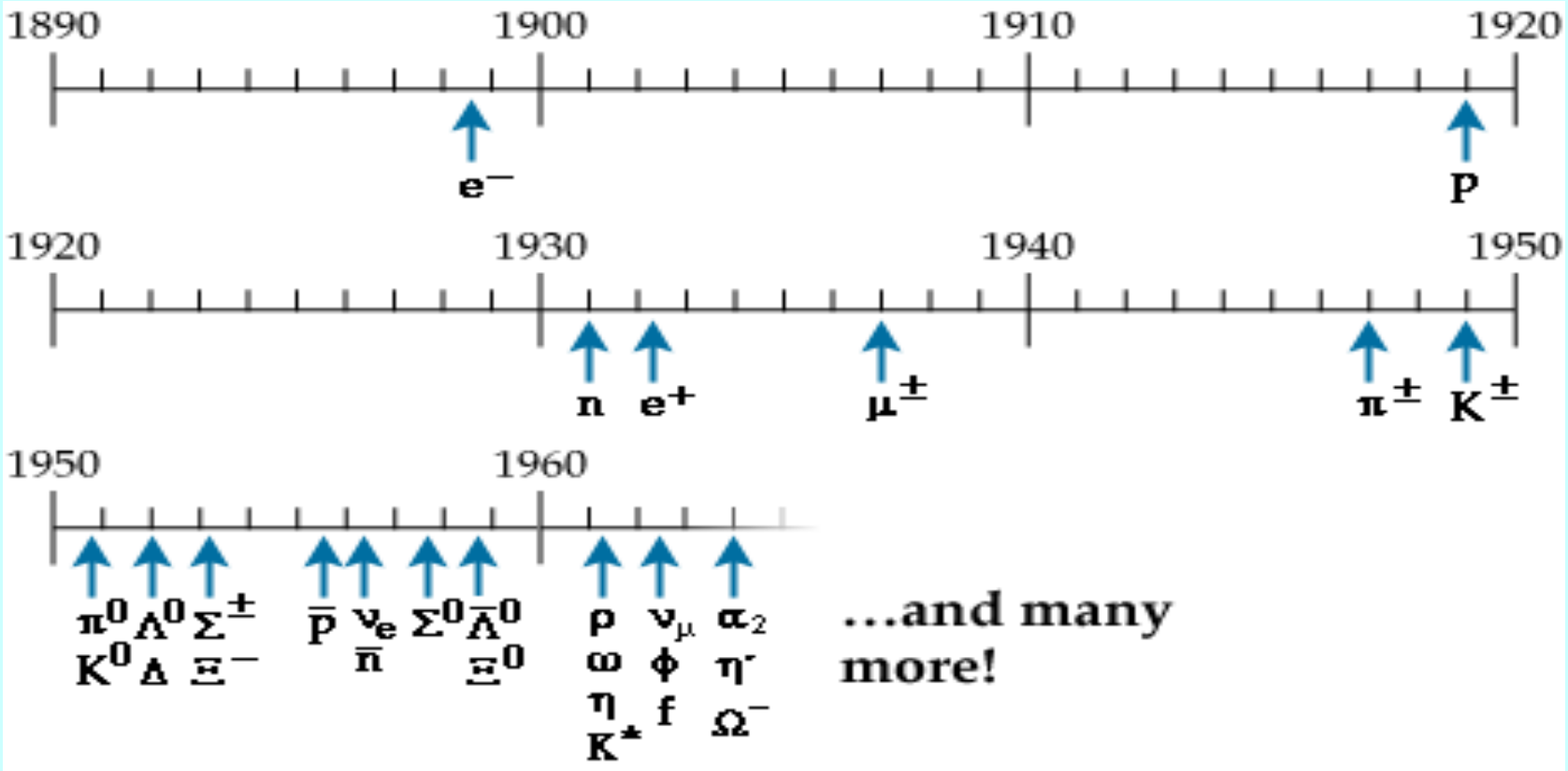
$$\pi^0$$
$$u\bar{u} - d\bar{d}$$

三人組必須存在，性質相似！

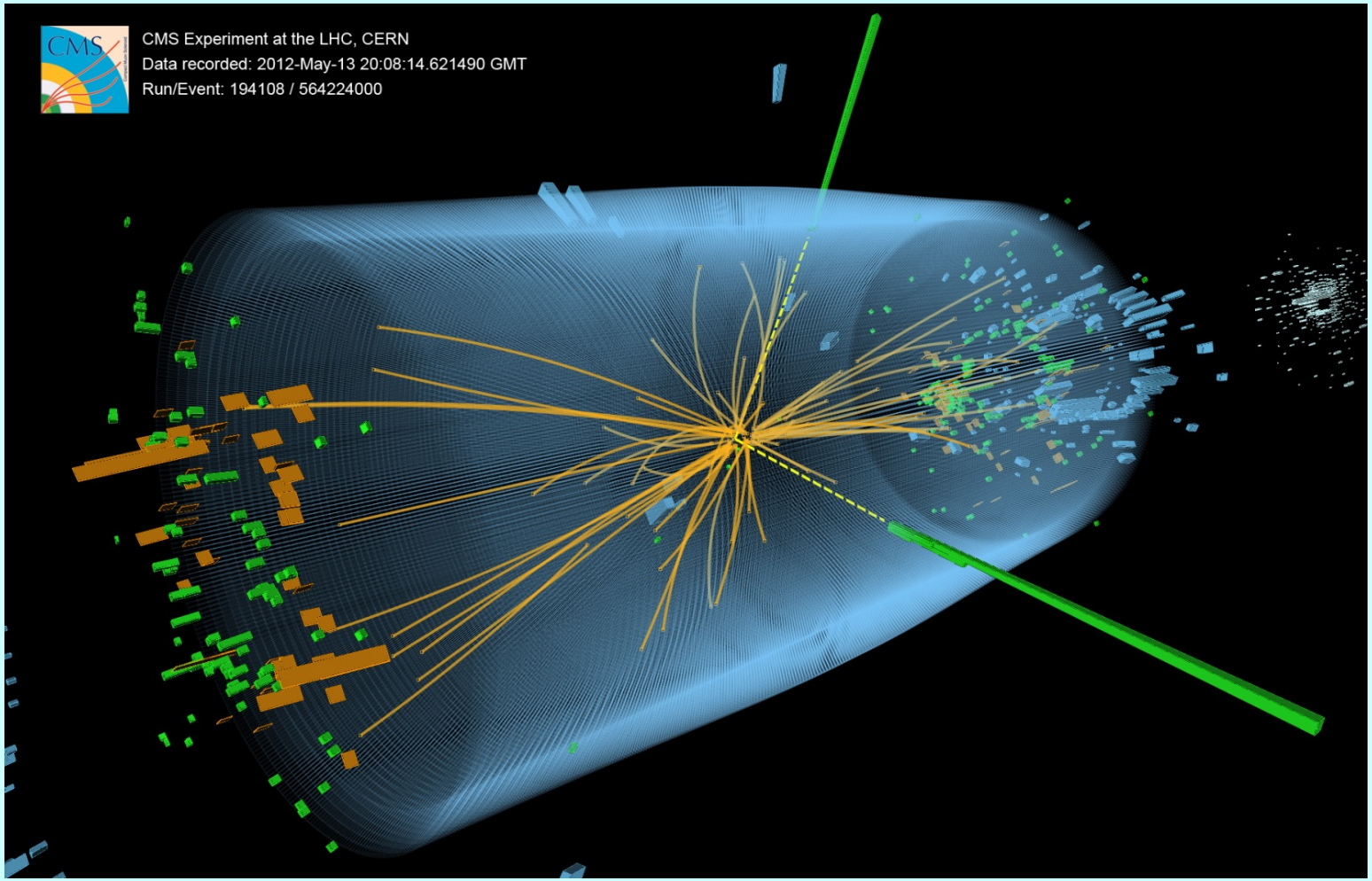


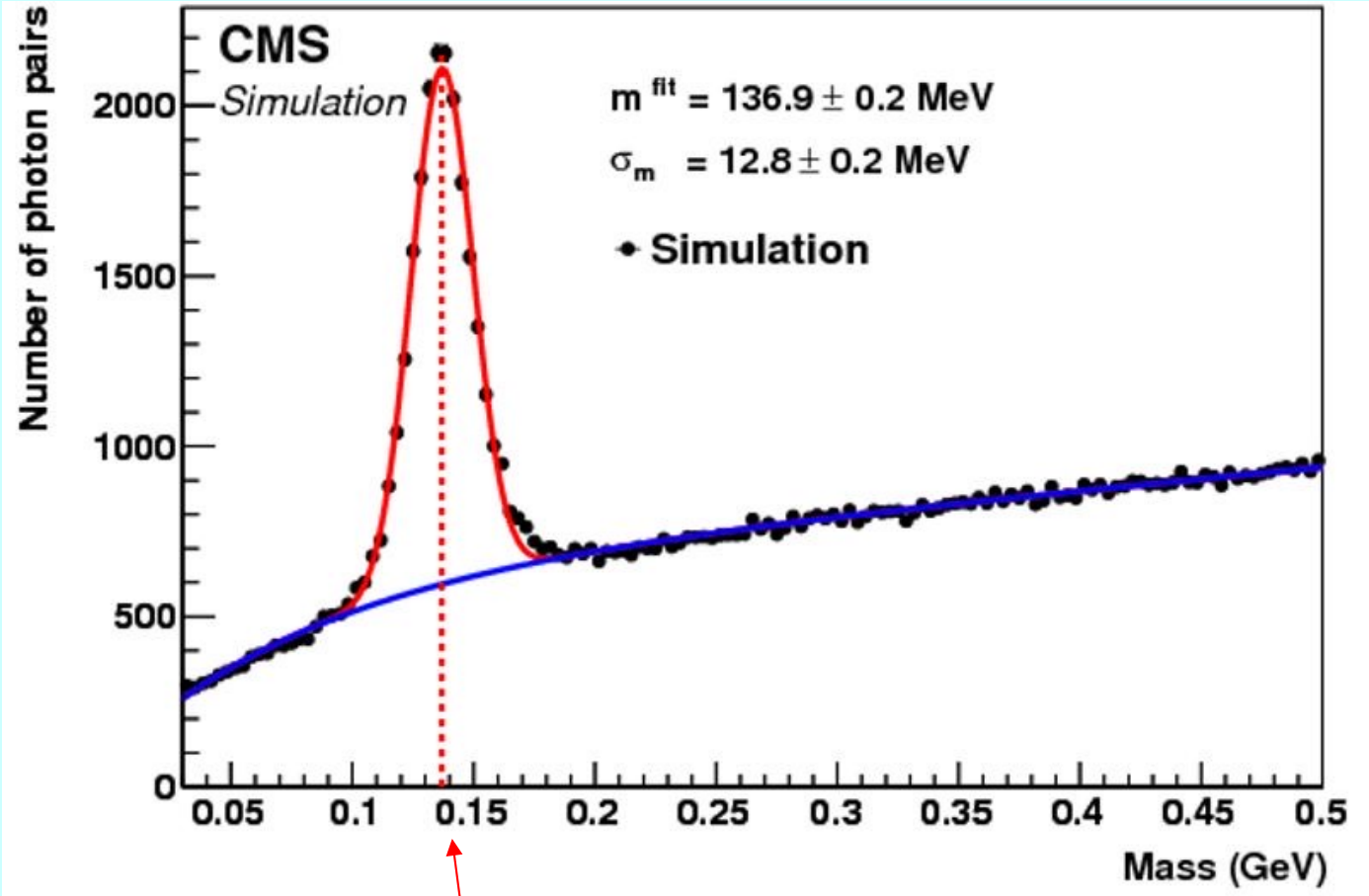


π^0晚一點才發現。


1890
1900
1910
1920
e⁻
p
1920
1930
1940
1950
n
e+
μ±
π±
K±
1950
1960
π0 Λ0 Σ±
K0 Δ Ξ−
p̄ νe
n̄
Σ0 Λ̄0
Ξ̄0
ρ νμ α2
ω φ η′
η f Ω−
K*
...and many more!

電中性的π^0不留下軌跡，只能從其衰變產物看出。





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$\pi^+ = u\bar{d}$

$\pi^- = du$

π^0
$u\bar{u} - d\bar{d}$

三人組必須存在，性質相似！





同位旋$SU(2)$對稱要求所有粒子必須成組、一人、二人、三人.....

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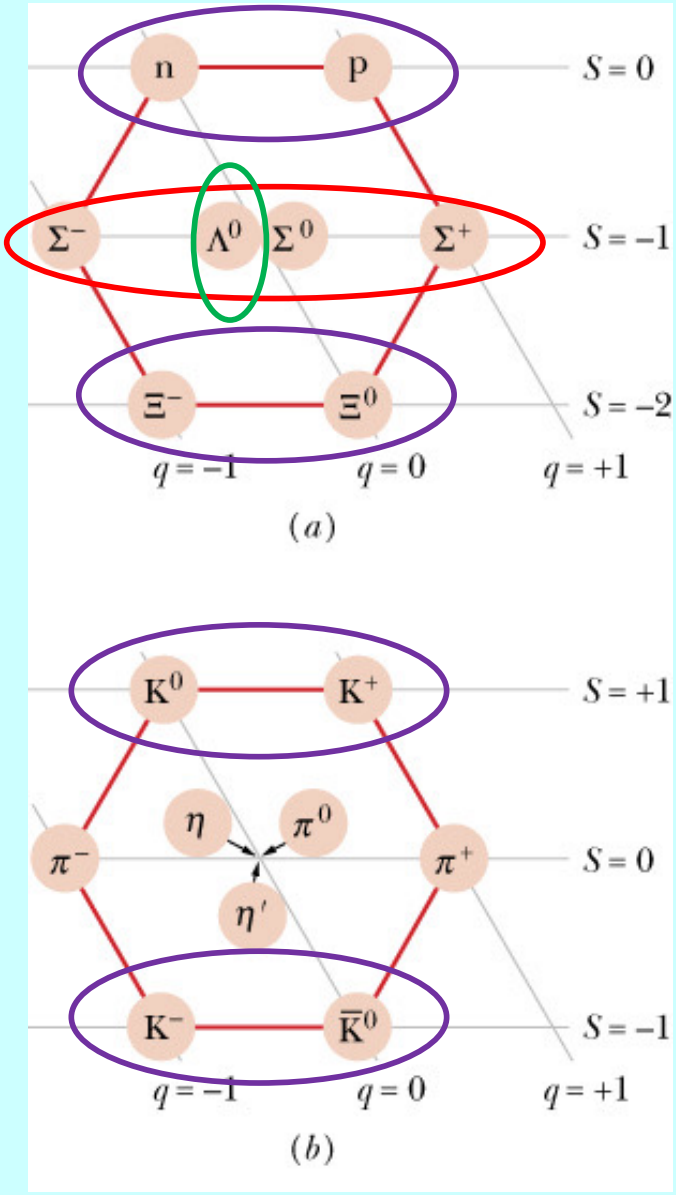
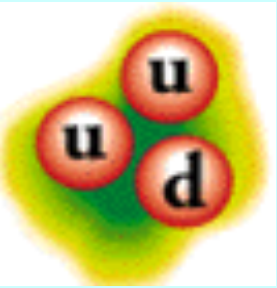
每個組型(例如所有每個二人組)樣式要相同：例如粒子的電荷差要相等。

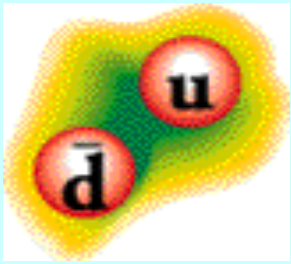


重子



由三個夸克構成

介子

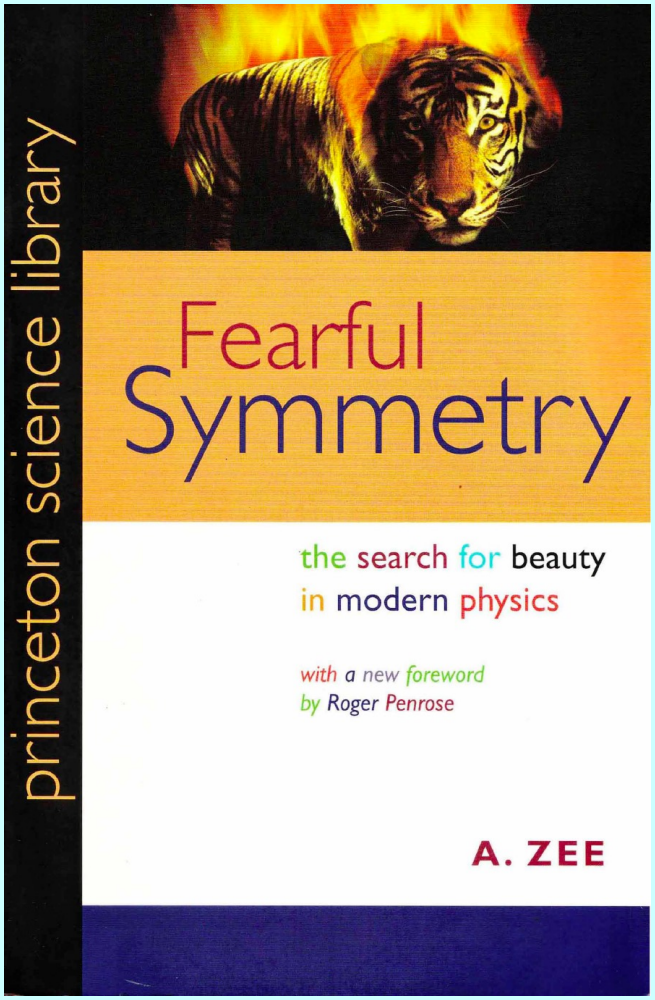


由一個夸克及一個反夸克構成

同位旋$SU(2)$對稱要求所有粒子必須成組、一人、二人、三人.....

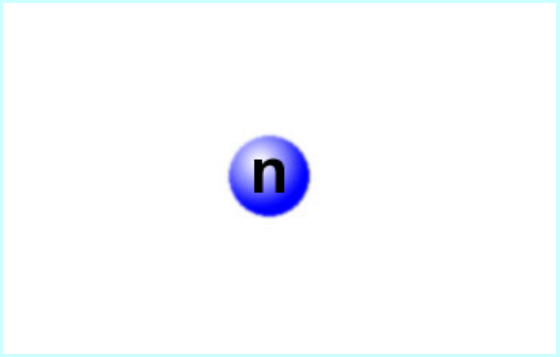
每個組型(例如所有每個二人組)樣式要相同：例如粒子的電荷差要相等。

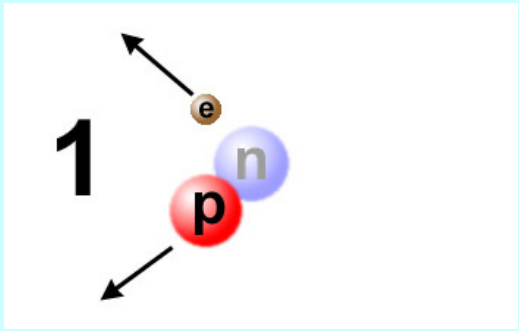
規則非常嚴苛、可怕！但的確厲害！

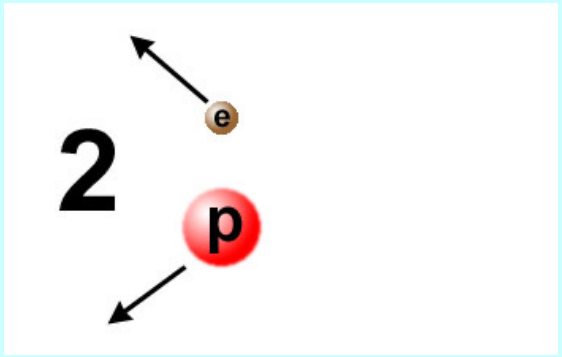


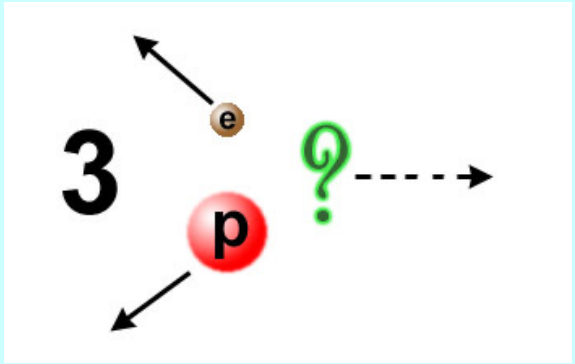
弱作用的故事

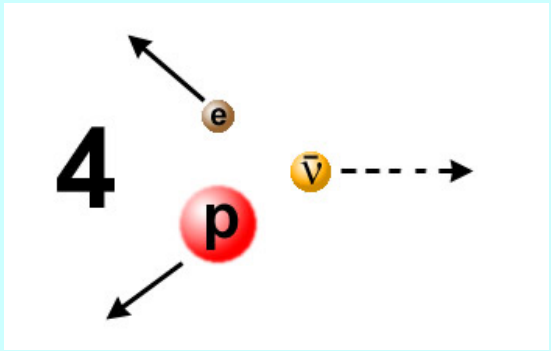
β Beta Decay $n^0 \rightarrow p^+ + e^- + \bar{\nu}_e$







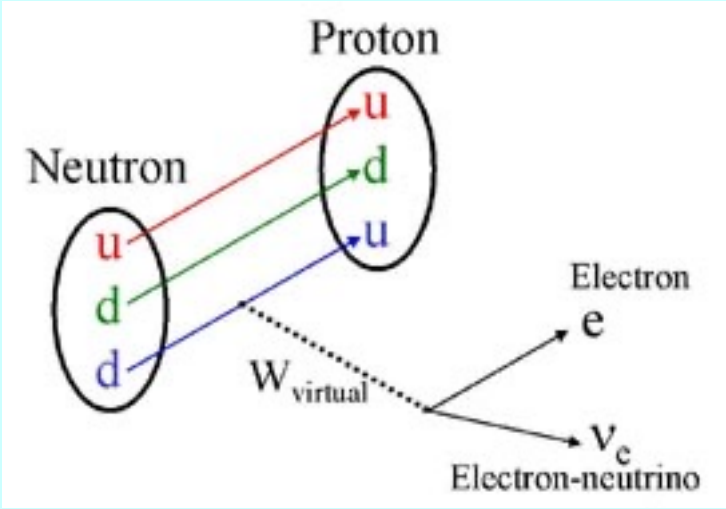


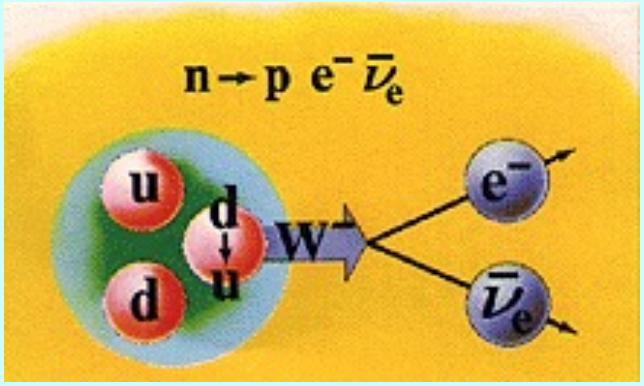




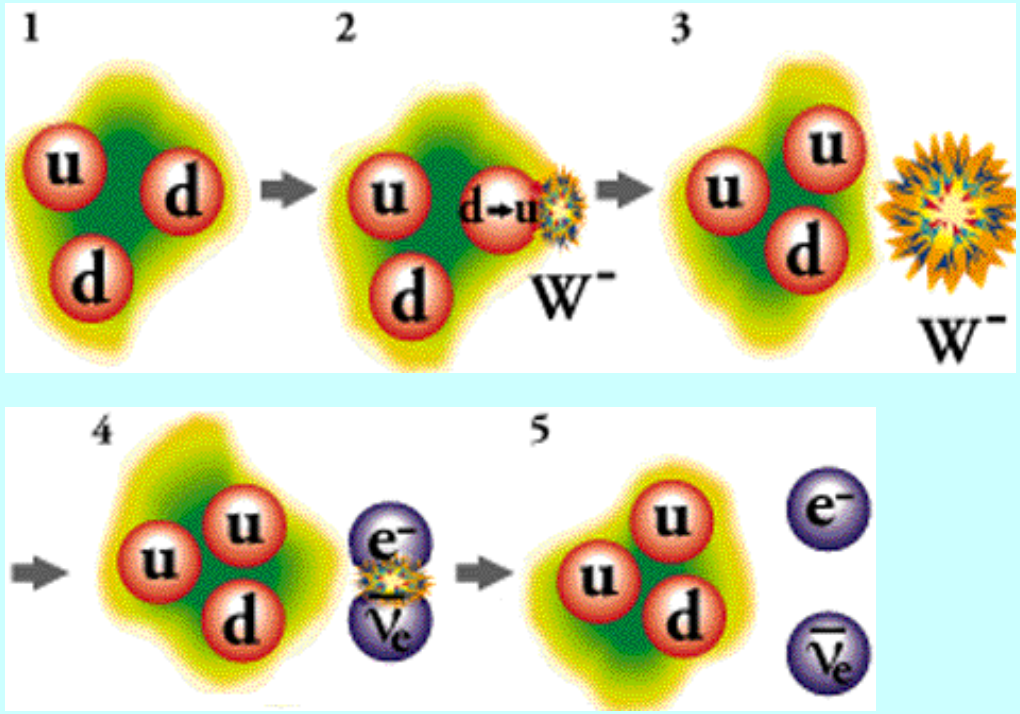
質子中子都是由夸克組成，差別在一個 d 夸克換成了 u 夸克，

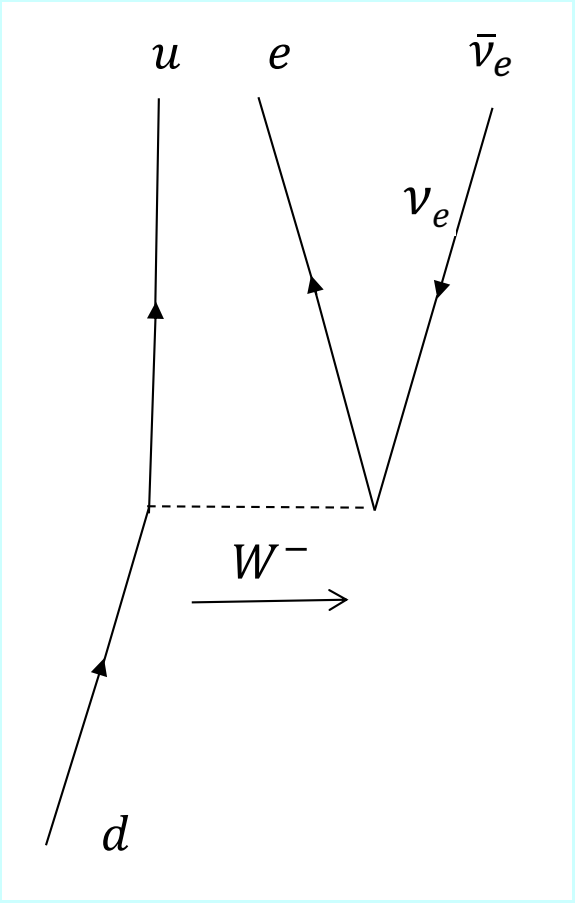
因此 β 衰變應該看成是 d 夸克換成了 u 夸克的衰變：

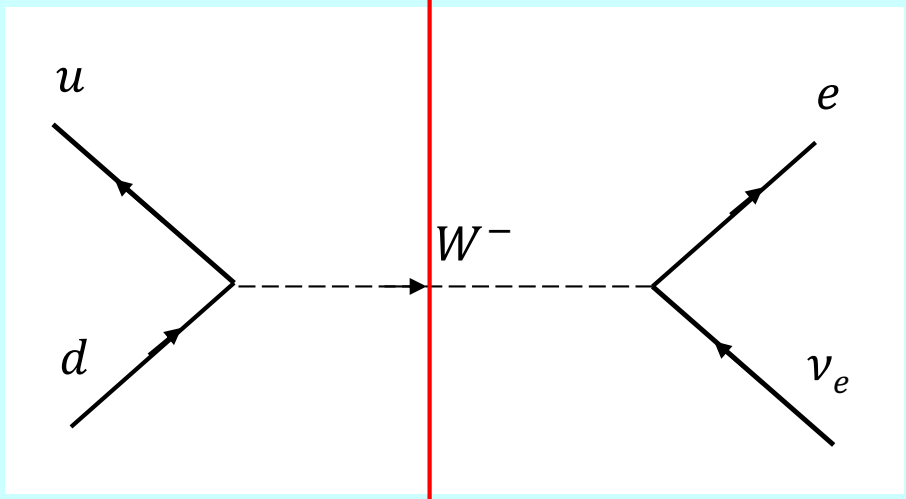




$$d \rightarrow u + e^- + \bar{\nu}_e$$

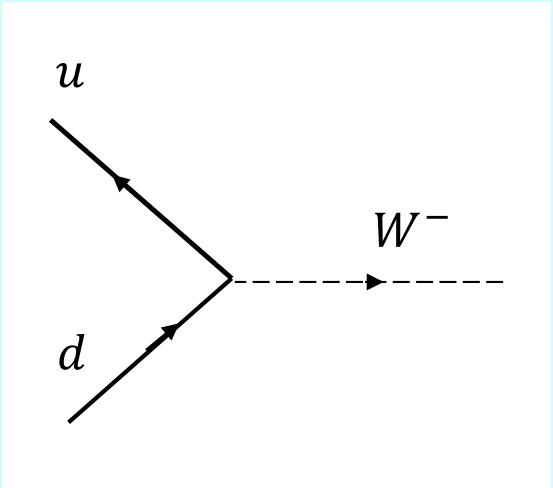

1
2
3
u
d
d
u
d
d→u
W⁻
u
u
d
W⁻
4
5
u
u
d
e⁻
ν̄e
u
u
d
e⁻
ν̄e

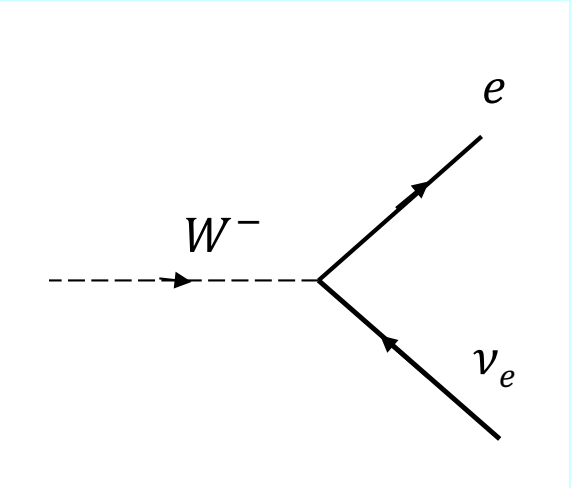

u
e
$\bar{\nu}_e$
ν_e
W^-
d

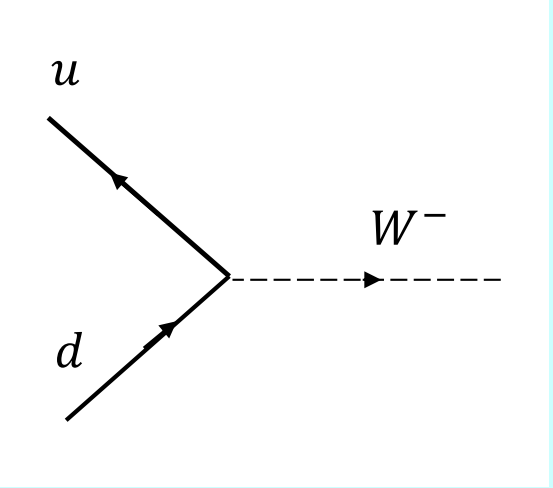


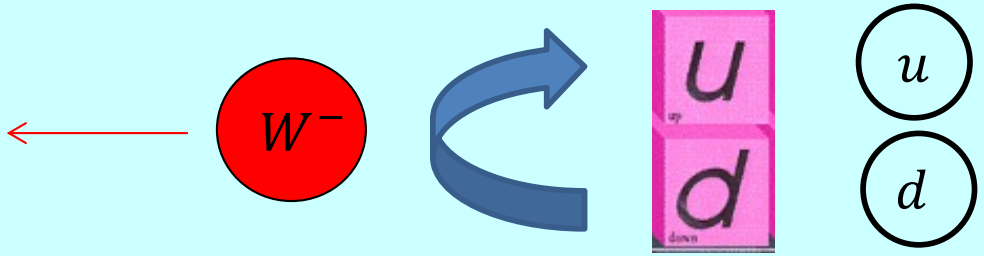
左手邊是新的夸克的圖

右手邊是已知的圖

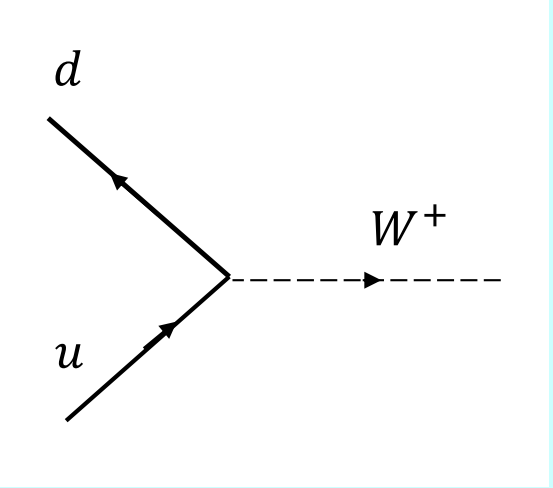


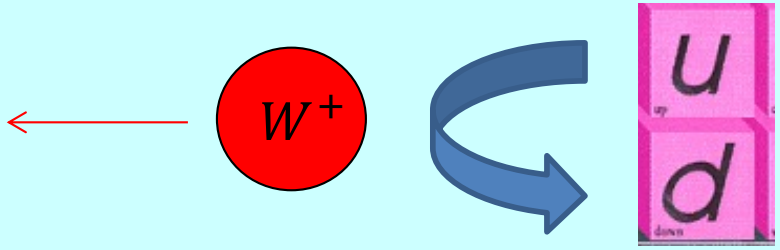






放出 W^-（或吸收 W^+）後，成對的粒子可以由下方升到上方！





放出W^+（或吸收W^-）後，成對的粒子可以由上方降到下方！

W $J = 1$

Charge $= \pm 1$ e

Mass $m = 80.377 \pm 0.012$ GeV

W/Z mass ratio $= 0.88145 \pm 0.00013$

$m_Z - m_W = 10.811 \pm 0.012$ GeV

$m_{W^+} - m_{W^-} = -0.029 \pm 0.028$ GeV

Full width $\Gamma = 2.085 \pm 0.042$ GeV

$\langle N_{\pi^\pm} \rangle = 15.70 \pm 0.35$

$\langle N_{K^\pm} \rangle = 2.20 \pm 0.19$

$\langle N_p \rangle = 0.92 \pm 0.14$

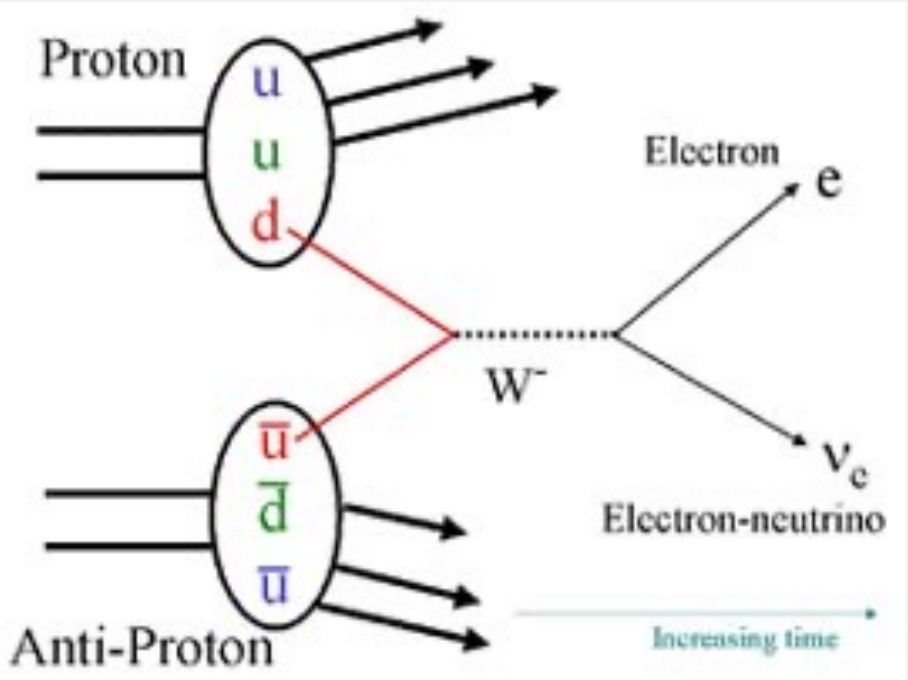
$\langle N_{\text{charged}} \rangle = 19.39 \pm 0.08$

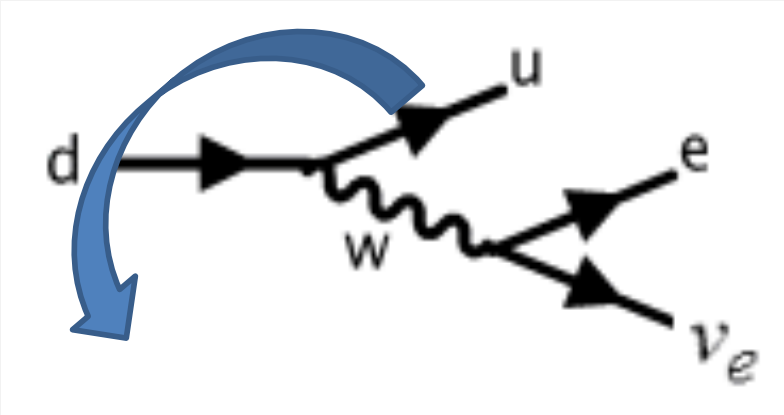
W^- modes are charge conjugates of the modes below.

W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\ell^+ \nu$	[b]	(10.86 ± 0.09) %		–



W 粒子可以由質子與反質子的碰撞來產生



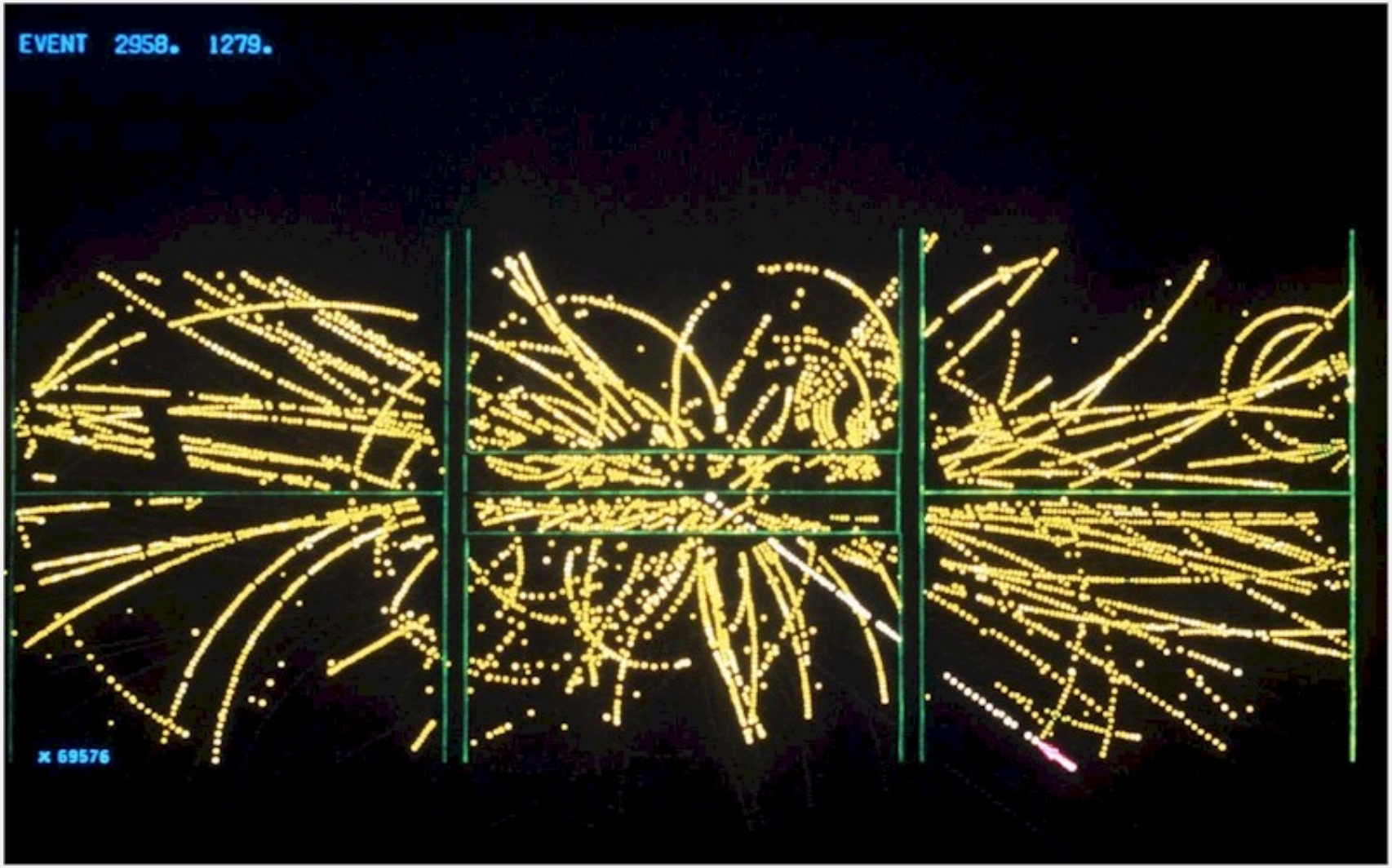


往後的外線扭成往前的外線後，
就變成反粒子！

$d + \bar{u} \rightarrow W^- \rightarrow e^- + \bar{\nu}_e$

$p + \bar{p} \rightarrow W^- + \text{other} \rightarrow e^- + \bar{\nu}_e + +\text{other}$

高速飛出的電子是W 的主要跡象



The first observation of W boson at $P\bar{P}$ collider, UA1, CERN 1983



The Nobel Prize in Physics 1984

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"



Carlo Rubbia

1/2 of the prize

Italy

CERN
Geneva, Switzerland



Simon van der Meer

1/2 of the prize

the Netherlands

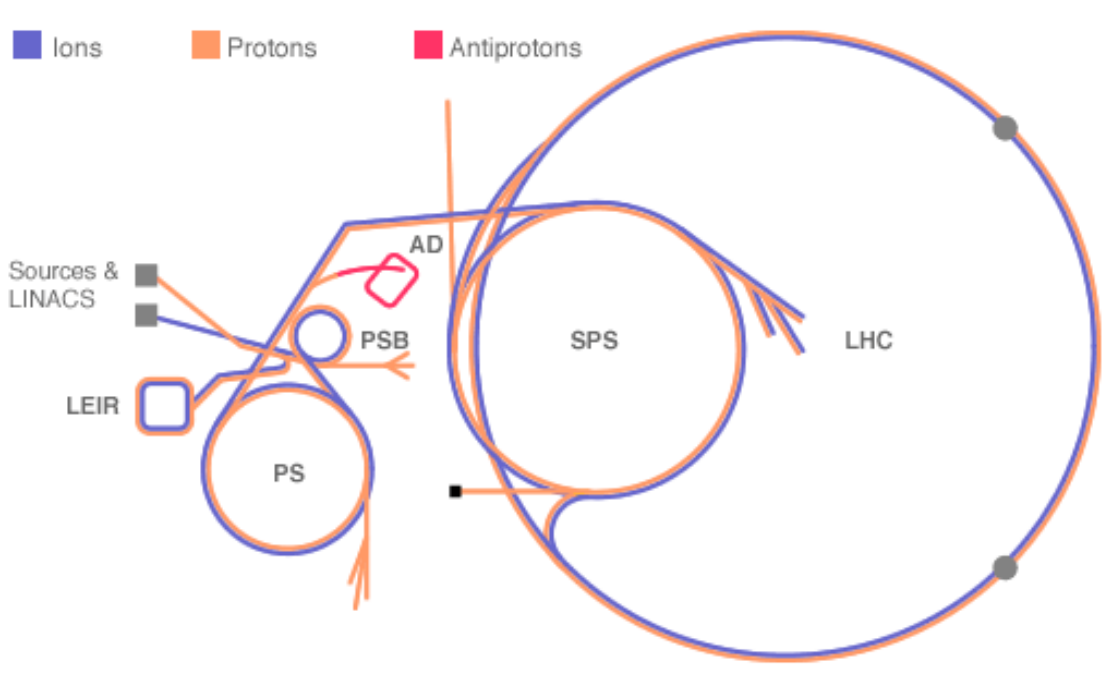
CERN
Geneva, Switzerland



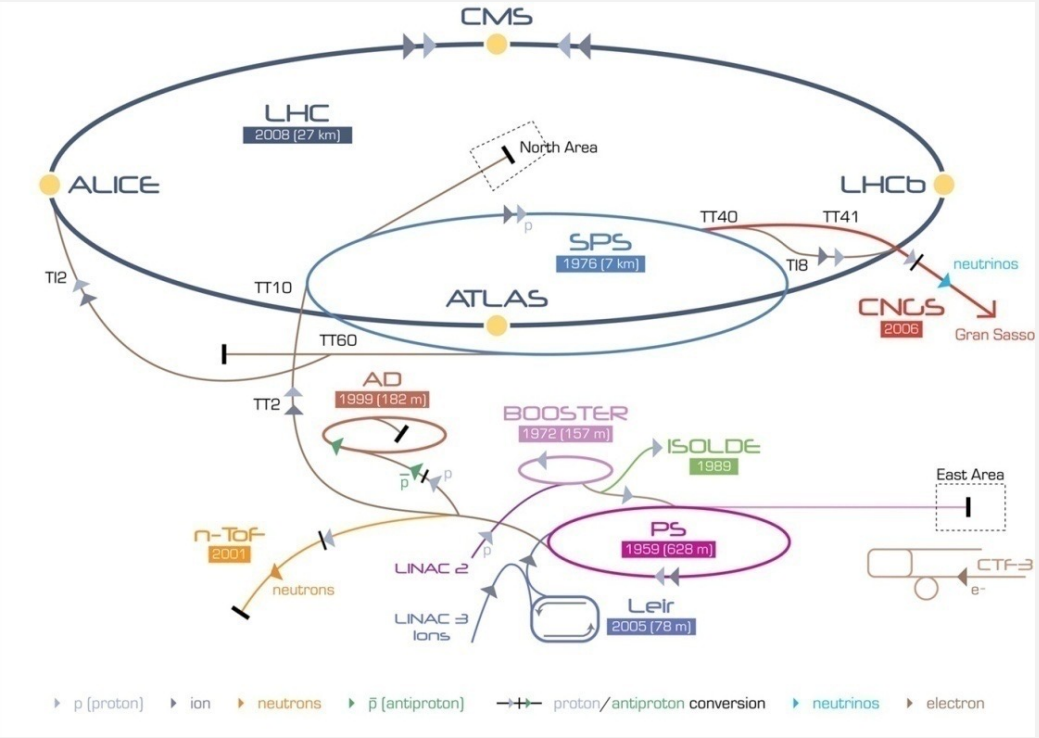


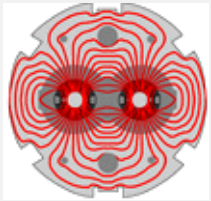


CERN


Ions
Protons
Antiprotons
Sources &
LINACS
AD
PSB
SPS
LHC
LEIR
PS

W 在 SPS 找到！


CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
n-ToF
2001
PS
1959 (628 m)
neutrons
LINAC 2
CTF-3
LINAC 3
Ions
Leir
2005 (78 m)
p (proton)
ion
neutrons
p̄ (antiproton)
proton/antiproton conversion
neutrinos
electron

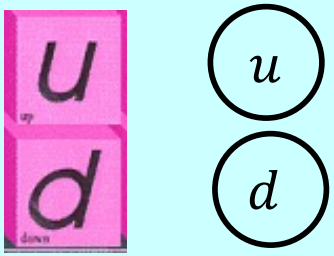



CERN

同位旋$SU(2)$對稱要求所有粒子必須成組、一人、二人、三人.....

$$(W^+ \quad W^-)$$

典型二人組：



$$(u^{2/3} \quad d^{-1/3})$$

每個組型內粒子的電荷差要相等。

二人組的電荷是差一，$W^{\pm}$不是二人組！

是不是如同π，還有一個未到？

$$(W^+ \quad W^- \quad W^0)$$

或是已到、而我們沒有察覺？

W^0是不是就是電中性的電磁波的光子？





ANNALS OF PHYSICS: **2**, 407–434 (1957)

A Theory of the Fundamental Interactions

JULIAN SCHWINGER

Harvard University, Cambridge, Massachusetts

"The axiomatic basis of theoretical physics cannot be extracted from experience but must be freely invented."

A. Einstein.

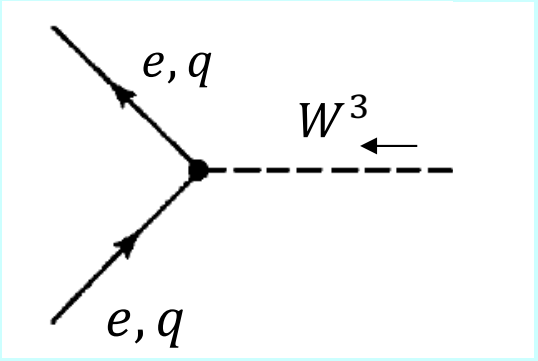
This note is an account of some developments in an effort to find a description of the present stock of elementary particles within the framework of the theory of quantized fields[1].

The theory of fields suggests that the spin values of ½ for F(ermi)-D(irac) fields, and of 0 and 1 for B(ose)-E(instein) fields are not only exceptional in their simplicity but are likely to be unique in the possibility of constructing a con-

Schwinger first suggested the existence of an "isotopic" triplet of vector fields whose universal couplings would generate both the weak interactions and electromagnetism — the two oppositely charged fields mediate weak interactions and the neutral field is light [2]). A certain ambiguity beclouds the self-

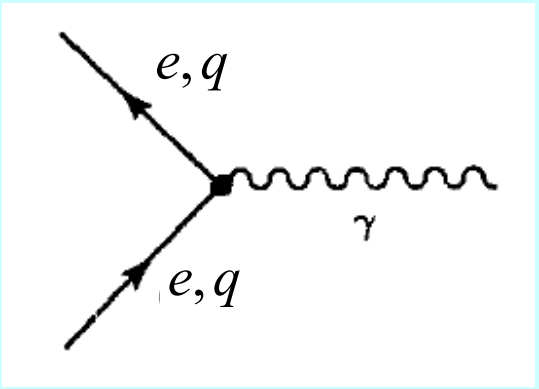


統一的電弱理論



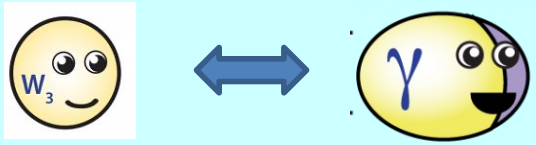
$(W^+ \quad W^0 \quad W^-)$

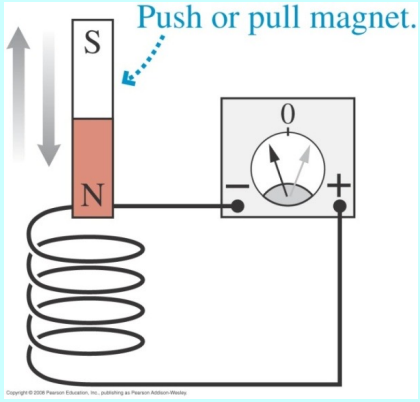






他主張電中性的W^0就是光子！





磁場變化產生感應電場！

磁力與電力是內在地聯繫在一起，

必須以統一的電磁力來對待。







或許電磁力與弱作用力也是同一個力的兩個面向

電磁作用與弱作用或許可以統一成為電弱交互作用Electroweak。

這些粒子都是規範波色子！





Yang and Mills

$SU(2)$ global symmetry

$$\Psi(x) \rightarrow \exp\left(-\frac{i}{2}\boldsymbol{\tau}\cdot\boldsymbol{\alpha}\right)\Psi(x)$$

$$\boldsymbol{\alpha} = (\alpha^1, \alpha^2, \alpha^3)$$

$$\boldsymbol{J}^{\mu} = (J^1, J^2, J^3)$$

Current conservation



Globalization

$SU(2)$ local symmetry 規範對稱 Gauge symmetry

$$\Psi(x) \rightarrow \exp\left(-\frac{i}{2}\boldsymbol{\tau}\cdot\boldsymbol{\alpha}(x)\right)\Psi(x)$$

$$\boldsymbol{\alpha}(x) = \left(\alpha^1(x), \alpha^2(x), \alpha^3(x)\right)$$

A^{μ} ? $\left(W_{\mu}^1, W_{\mu}^2, W_{\mu}^2\right) \equiv \boldsymbol{W}_{\mu}$

規範場、電磁場





在地化 Localization

為了使 $\mathcal{L}$ 是 gauge invariant，對應於每一個連續變數α_i，即每一個generator，
必須引進一個如電磁場的向量規範場$A_\mu(x)$，
也就是一個如光子一樣，自旋為1的規範粒子Gauge Boson!

$U(1)$ local 規範對稱 Gauge symmetry		$SU(2)$ local 規範對稱 Gauge symmetry	
θ	$\psi(x) \to e^{-i\theta(x)}\psi(x)$	$\alpha_1, \alpha_2, \alpha$	$\Psi' = \exp\left(-\frac{i}{2}\boldsymbol{\tau}\cdot\boldsymbol{\alpha}(x)\right)\Psi$
1		$\frac{\tau_1}{2}, \frac{\tau_2}{2}, \frac{\tau_3}{2}$	
⇩		⇩	
A^μ	電磁場	$A_1^\mu, A_2^\mu, A_3^\mu$	
		⇩	
		W_1, W_2, W_3	

例如：媒介弱作用的W波色子就是$SU(2)$的規範粒子Gauge Boson。

光的存在是有道理的！

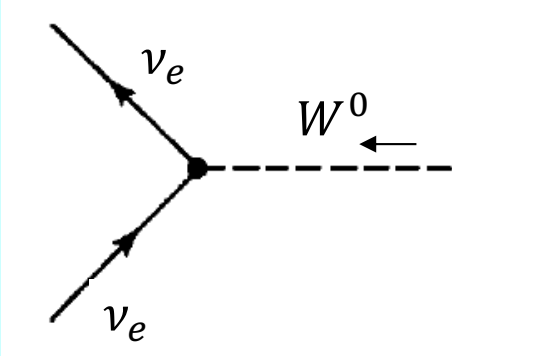


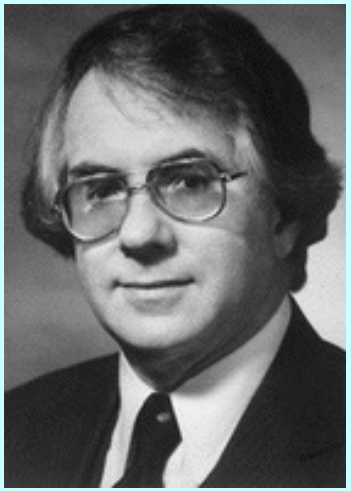
Let there be light!

In the name of gauge symmetry! 為了在地的規範對稱！

可惜，It doesn’t work!

W^0與微中子的交互作用是光子沒有的！





PARTIAL-SYMMETRIES OF WEAK INTERACTIONS

SHELDON L. GLASHOW †

Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

Received 9 September 1960

Abstract: Weak and electromagnetic interactions of the leptons are examined under the hypothesis that the weak interactions are mediated by vector bosons. With only an isotopic triplet of leptons coupled to a triplet of vector bosons (two charged decay-intermediaries and the photon) the theory possesses no partial-symmetries. Such symmetries may be established if additional vector bosons or additional leptons are introduced. Since the latter possibility yields a theory disagreeing with experiment, the simplest partially-symmetric model reproducing the observed electromagnetic and weak interactions of leptons requires the existence of at least four vector-boson fields (including the photon). Corresponding partially-conserved quantities suggest leptonic analogues to the conserved quantities associated with strong interactions: strangeness and isobaric spin.

1. Introduction

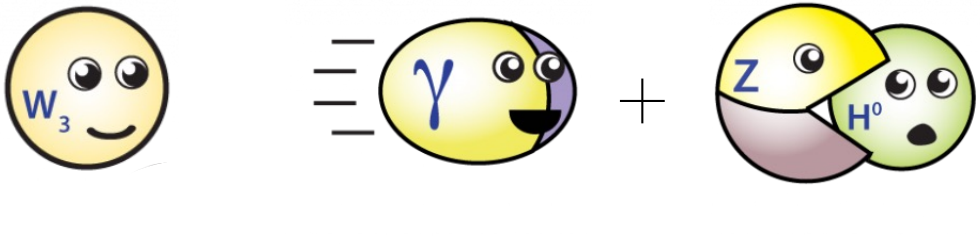
At first sight there may be little or no similarity between electromagnetic effects and the phenomena associated with weak interactions. Yet certain remarkable parallels emerge with the supposition that the weak interactions are mediated by unstable bosons. Both interactions are universal, for only a single coupling constant suffices to describe a wide class of phenomena: both interactions are generated by vectorial Yukawa couplings of spin-one fields ††. Schwinger first suggested the existence of an "isotopic" triplet of vector fields whose universal couplings would generate both the weak interactions and electromagnetism — the two oppositely charged fields mediate weak interactions and the neutral field is light [2]). A certain ambiguity beclouds the self-interactions among the three vector bosons; these can equivalently be interpreted as weak or electromagnetic couplings. The more recent accumulation of experimental evidence supporting the $\Delta I = \frac{1}{2}$ rule characterizing the non-leptonic decay modes of strange particles indicates a need for at least one additional neutral intermediary [3]).

The mass of the charged intermediaries must be greater than the K-meson mass, but the photon mass is zero — surely this is the principal stumbling block in any pursuit of the analogy between hypothetical vector mesons and photons. It is a stumbling block we must overlook. To say that the decay intermediaries

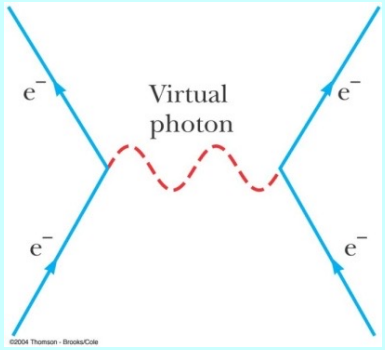
The reader may wonder what has been gained by the introduction of another neutral vector meson. Neither Z_3 nor Z_S interacts with the electrical current so that neither interaction may be identified with electromagnetism. (To have chosen $J_\mu{}^S$ to be the electrical current would have violated (4.1) and lost partial-symmetry.) However, both the neutral fields have the same CP property so that linear combinations of the two fields may correspond to "particles."

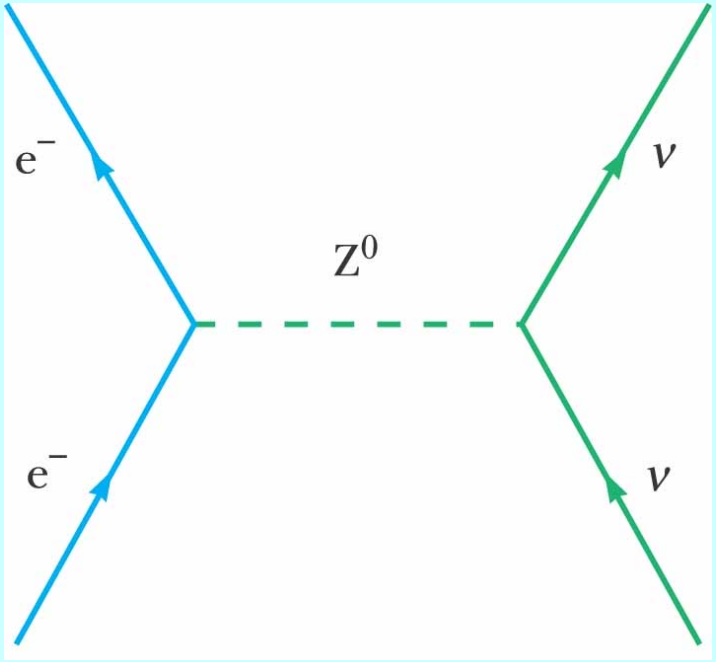
Glashow提議：W^0是光子γ與另一個尚未觀察到的粒子Z的疊加。

$$W^0 = \sin\alpha\,\gamma + \cos\alpha\,Z$$



Weak Interaction through Z particle



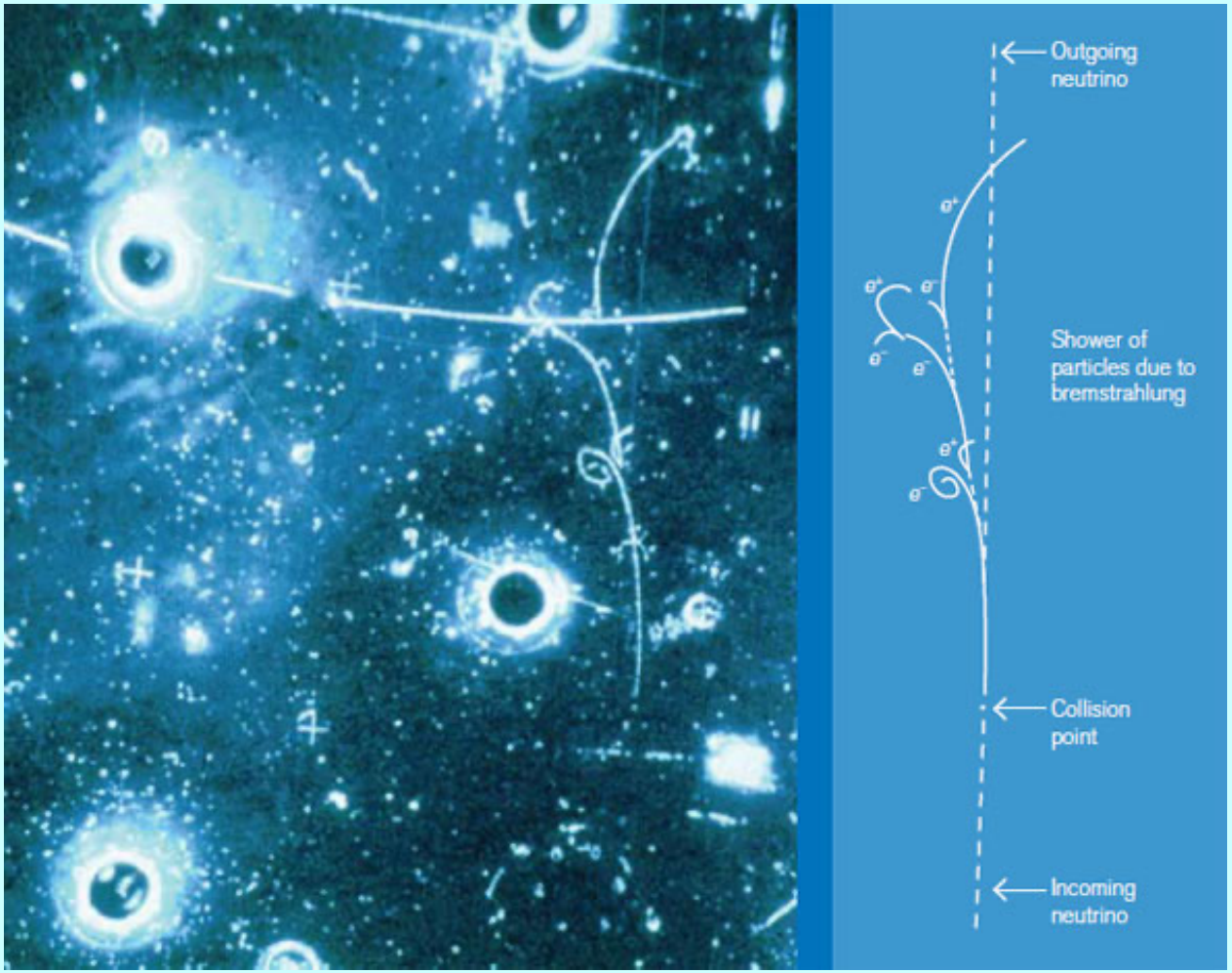


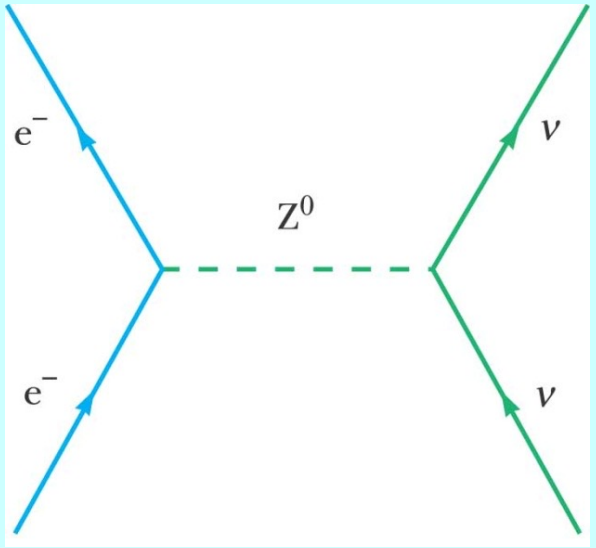
Beta衰變只需要W即可，Z的存在是依據規範對稱的原則在

60年代即預測出來，70年代間接證實，80年代才直接找到。

Z^0與光子的作用很接近，難區分，但只有Z^0與微中子是有作用的！

$$\nu + e^- \rightarrow \nu + e^-$$





Garmamelle CERN 1973

Z $J = 1$

Charge $= 0$

Mass $m = 91.1876 \pm 0.0021$ GeV [d]

Full width $\Gamma = 2.4952 \pm 0.0023$ GeV

$\Gamma(\ell^+\ell^-) = 83.984 \pm 0.086$ MeV [b]

$\Gamma(\text{invisible}) = 499.0 \pm 1.5$ MeV [e]

$\Gamma(\text{hadrons}) = 1744.4 \pm 2.0$ MeV

$\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-) = 1.0009 \pm 0.0028$

$\Gamma(\tau^+\tau^-)/\Gamma(e^+e^-) = 1.0019 \pm 0.0032$ [f]


Z BOSON
Z
Z boson
The Z BOSON is a very massive carrier particle for the weak force. Unlike its siblings the W-/W+ particles, the Z is neutrally charged. Living only 10^{-25} second, the Z quickly decays into other particles. Discovered in 1983, the Z has allowed physicists to further study electroweak theory.
Wool felt with gravel fill for maximum mass.
LIGHT
HEAVY
$10.49 PLUS SHIPPING
GLUON PHOTON NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK TAU NEUTRINO MUON UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON Z BOSON NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK TAU NEUTRINO MUON UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON PHOT

電磁作用與弱作用統一成為電弱Electroweak交互作用。

部分是光子的W^0、與負責弱衰變的$W^{\pm}$形成三人組！

疊加統一了兩個彼此分不開的交互作用。







這樣的統一建議雖然美好，但還沒起飛就已墜落！



Gauge Bosons are massless, by gauge symmetry.

Gauge Bosons mass term is not gauge invariant, hence will ruin renormalization.

$m_W W_\mu^+ W^{-\mu}$ $m_Z Z_\mu Z^\mu$

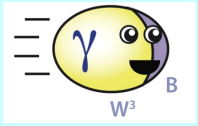
在$SU(2)$變換之下 $(W^+ \quad W^3 \quad W^-)$

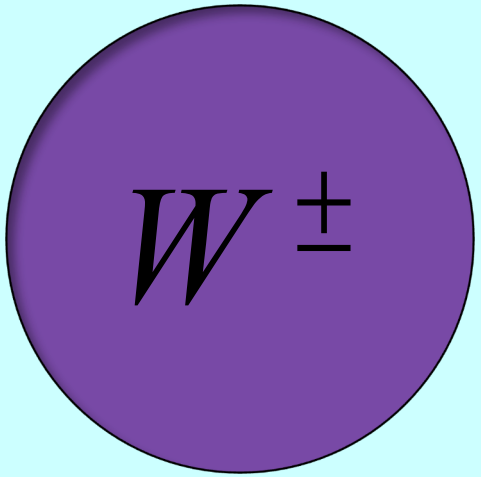
$$\delta \boldsymbol{W}_\mu = \frac{1}{g}\partial_\mu \boldsymbol{\alpha} + \boldsymbol{\alpha} \times \boldsymbol{W}_\mu$$

是屬於一個 Representation。

一個Representation中的所有基本粒子性質（質量）相等。

因此對稱性要求三個波色子性質相同！

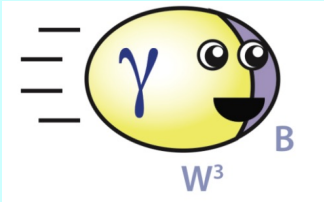


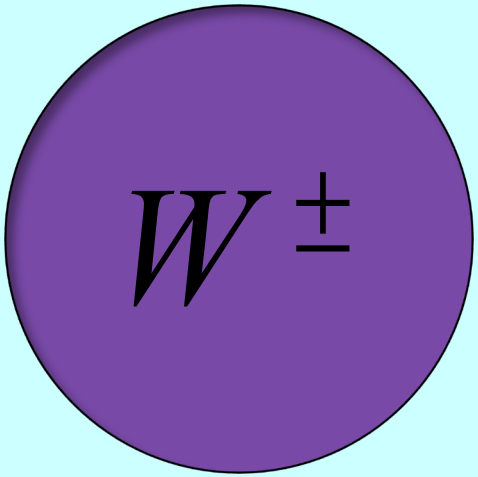


光子中有W^3的成分

$W^\pm$與W^3三者性質相似！

為什麼 $W^\pm$ 會比 γ 重如此之多？





$W^{\pm}$會比 γ 重如此之多！

規範波色子必須無質量，但$W^{\pm}$是很重的！

$SU(2)$ 對稱已經被破壞！

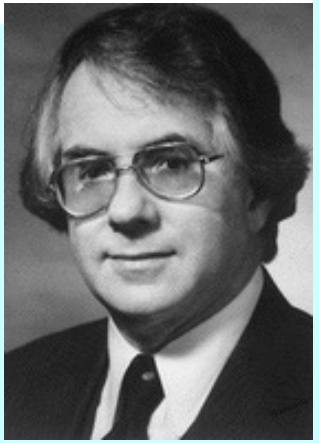
規範對稱已經被破壞！

如何優雅而不粗暴地破壞理論優美的對稱呢？



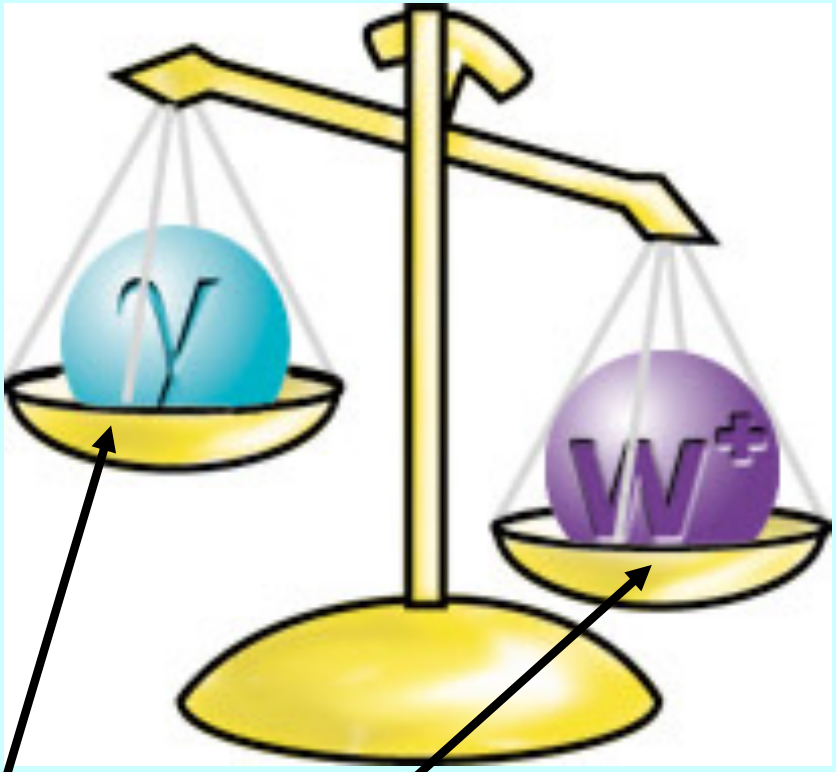
你可以暴力地直接破壞對稱：就直接容許某些項就是不是不變的。

is well known. We recently introduced the notion of "partial-symmetry" — invariance of only part of the Lagrange function under a group of infinitesimal transformations [4]). The part of the Lagrange function bilinear in the field variables which produces masses of the elementary particles need not be invariant under a partial-symmetry. Corresponding "partial-conservation laws" become conservation laws only with the neglect of appropriate masses or mass differences. This is the only sort of symmetry which could relate the massive decay intermediaries to the massless photon.



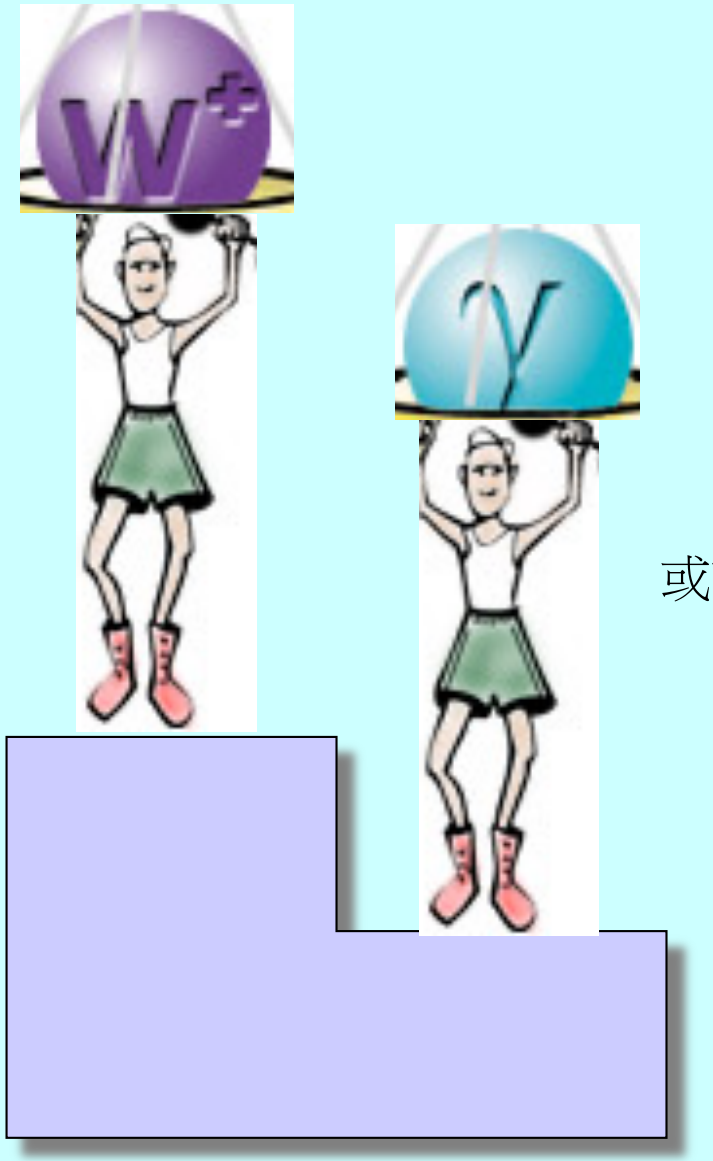
這樣的作法會使理論無法重整化 renormalizable。

為什麼 W 比 γ 重?



或許是 W 的基礎與 γ 的基礎不同!!!!!!! 基礎就是真空。

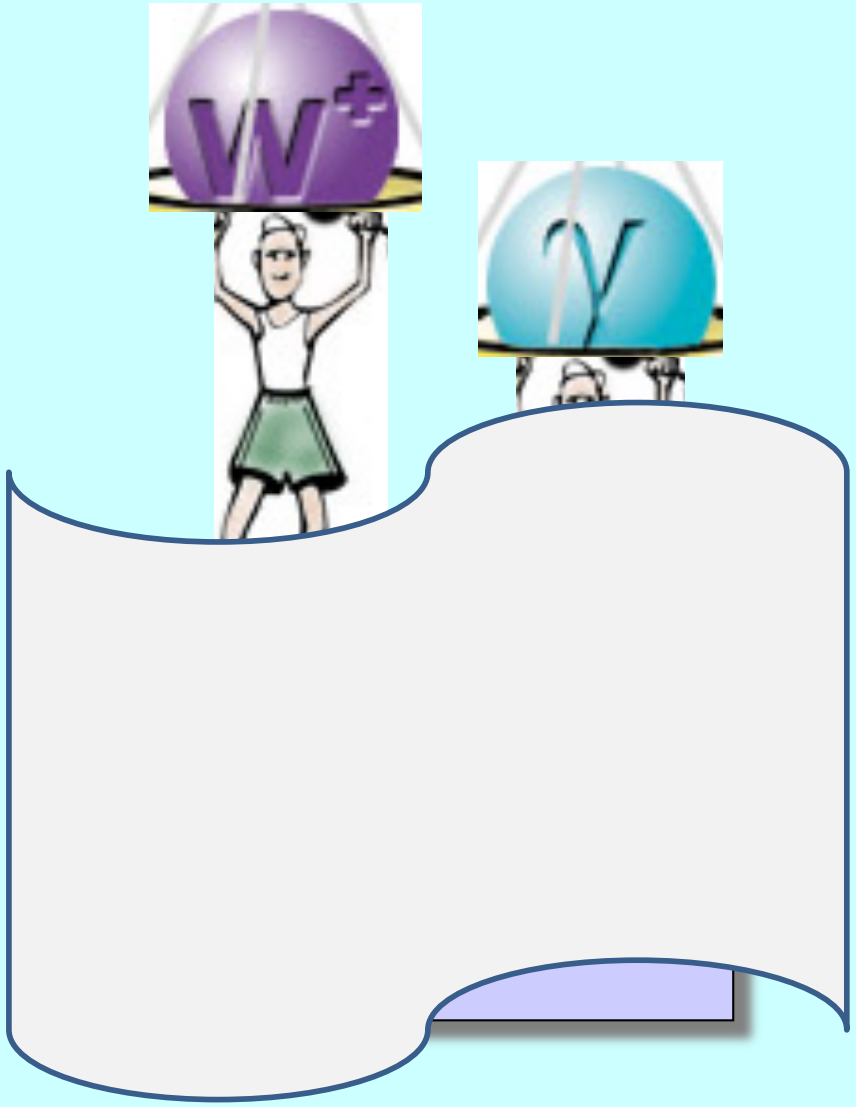
真空只有一個，但兩個粒子對真空的感覺不同。



或許是作為基礎的真空使兩者質量不同！

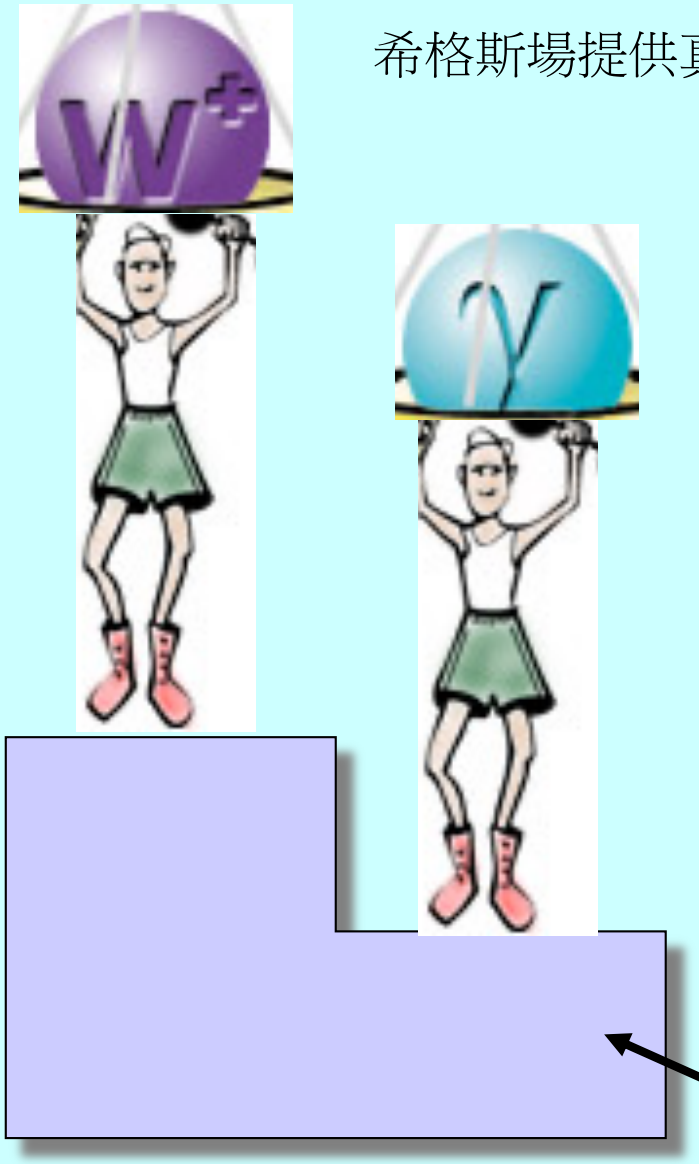
對稱的能量所得出不對稱的真空破壞了弱力與電磁力的對稱！

對稱的能量，得出不對稱的最低能量真空，將能量的對稱性隱藏起來：



Symmetry is hidden!

希格斯場提供真空一個結構，使得真空中的 W 比 γ 重.



Spontaneous Symmetry Breaking



Higgs Fields in Vacuum



Steven Weinberg

A MODEL OF LEPTONS*

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(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

We will restrict our attention to symmetry groups that connect the observed electron-type leptons only with each other, i.e., not with muon-type leptons or other unobserved leptons or hadrons. The symmetries then act on a left-handed doublet

$$L \equiv [\tfrac{1}{2}(1+\gamma_5)]\begin{pmatrix}\nu_e\\ e\end{pmatrix} \tag{1}$$

and on a right-handed singlet

$$R \equiv [\tfrac{1}{2}(1-\gamma_5)]e. \tag{2}$$

The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu\partial_\mu L-\bar{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{\mathbf{T}}$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q=T_3-N_R-\frac{1}{2}N_L$, and the electron number $N=N_R+N_L$. But the gauge field corresponding to an unbroken symmetry will have zero mass,[4] and there is no massless particle coupled to N,[5] so we must form our gauge group out of the electronic isospin $\vec{\mathbf{T}}$ and the electronic hypercharge $Y\equiv N_R+\frac{1}{2}N_L$.

Therefore, we shall construct our Lagrangian out of L and R, plus gauge fields $\vec{A}_\mu$ and B_μ coupled to $\vec{\mathbf{T}}$ and Y, plus a spin-zero doublet

$$\varphi = \begin{pmatrix}\varphi^0\\ \varphi^-\end{pmatrix} \tag{3}$$

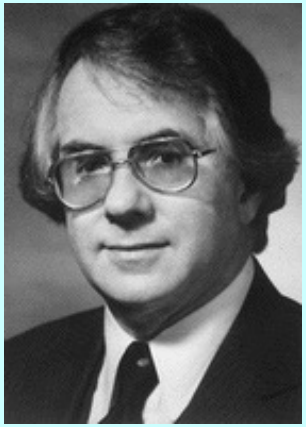
whose vacuum expectation value will break $\vec{\mathbf{T}}$ and Y and give the electron its mass. The only renormalizable Lagrangian which is invariant under $\vec{\mathbf{T}}$ and Y gauge transformations is

$$\mathfrak{L} = -\tfrac{1}{4}(\partial_\mu\vec{A}_\nu-\partial_\nu\vec{A}_\mu+g\vec{A}_\mu\times\vec{A}_\nu)^2-\tfrac{1}{4}(\partial_\mu B_\nu-\partial_\nu B_\mu)^2-\bar{R}\gamma^\mu(\partial_\mu-ig'B_\mu)R-L\gamma^\mu(\partial_\mu igt\cdot\vec{A}_\mu-i\tfrac{1}{2}g'B_\mu)L$$

$$-\tfrac{1}{2}|\partial_\mu\varphi-ig\vec{A}_\mu\cdot\vec{t}\varphi+i\tfrac{1}{2}g'B_\mu\varphi|^2-G_e(\bar{L}\varphi R+\bar{R}\varphi^\dagger L)-M_1{}^2\varphi^\dagger\varphi+h(\varphi^\dagger\varphi)^2. \tag{4}$$

We have chosen the phase of the R field to make G_e real, and can also adjust the phase of the L and Q fields to make the vacuum expectation value $\lambda\equiv\langle\varphi^0\rangle$ real. The "physical" φ fields are then φ^-

的確，W 和 Z 得到該有的質量，而光子仍是無質量！





Glashow, Weinberg and Salem:

Standard Model



Twins



Different aspects of the same interaction.



Electromagnetic and weak interactions are unified into **Electroweak**.

結論

針對一個變換，我們無法以物理方法分辨所看到現象是變換前或後，
就稱物理定律有此不變性、或對稱。通常對應一無法絕對觀測的物理量。

一個連續的對稱性、可以推導出一個守恆律。

當我們要說2個東西相似可以互換，量子的版本就是$SU(2)$連續對稱！
上夸克u與下夸克d互換不變性，量子版本就是同位旋$SU(2)$對稱。

同位旋$SU(2)$對稱要求所有粒子必須成組、一人、二人、三人.....
每種組型樣式要相同。

電磁作用與弱作用統一成為電弱Electroweak交互作用。
部分是光子的W^0、與負責弱衰變的$W^{\pm}$形成三人組！