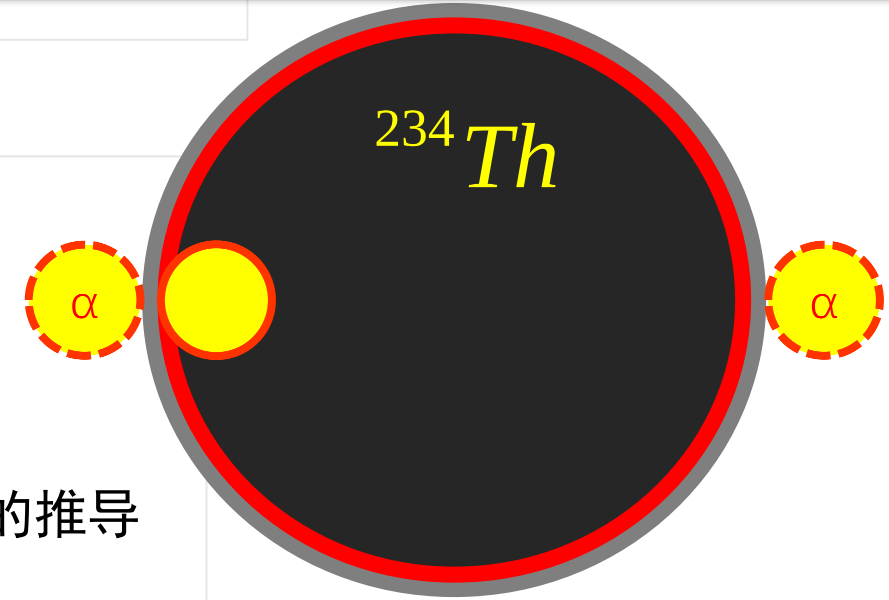
➢上节回顾：

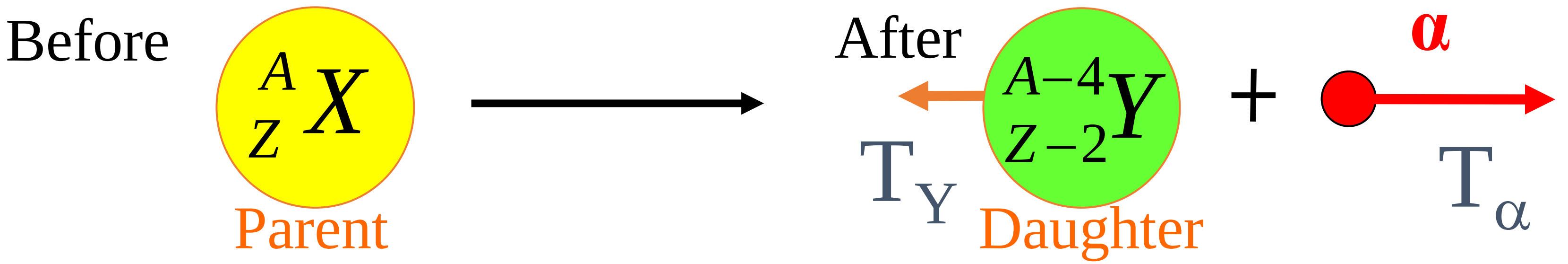
- 活度修正、决定放射源制备活度的5个因素（时间足够长，退化为3个因素）
- 原子核的三种衰变方式
- α衰变概述

α衰变的过程，就是一场α粒子摆脱子核束缚的“越狱史”



➢本节提要：

- α衰变能→原子核的能级结构
- **One-body model ——Gamow**的势垒穿透模型，α衰变常数的推导
- α衰变中的角动量守恒vs宇称守恒
- β衰变初步



视衰变前母核为 **“静止”**，则：

$$\underbrace{m_X c^2}_{\text{衰变前静止质量}} = \underbrace{m_Y c^2 + m_\alpha c^2}_{\text{衰变后静止质量}} + \underbrace{T_\alpha + T_Y}_{\text{衰变后动能}}$$

定义：α衰变能

α衰变能等于**子核Y**和**α粒子**的**动能之和**，对应衰变前后静止质量之差，记作E_0。

$$E_0 = T_\alpha + T_Y = [m_X - (m_Y + m_\alpha)]c^2$$

以**原子质量M**代替**原子核的质量m**，并忽略电子结合能的差异，则：

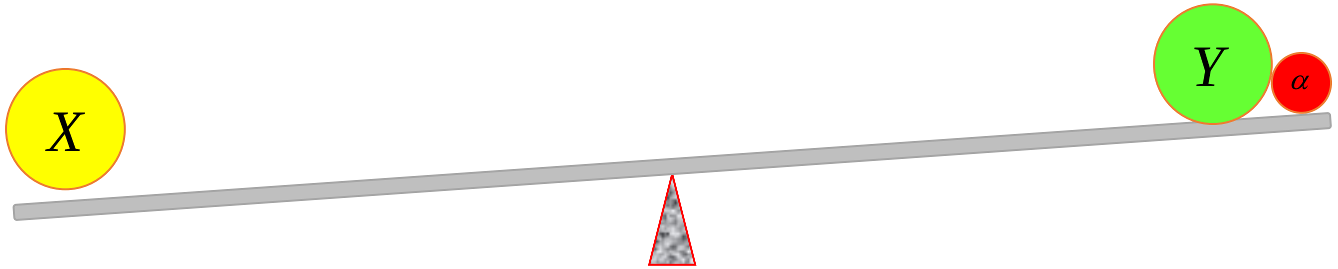
$$E_0 = M(Z,A)c^2 - [M(Z-2,A-4) + M(2,4)]c^2$$

$$E_0 = \Delta(Z,A) - [\Delta(Z-2,A-4) + \Delta(2,4)]$$

$$E_0 = B(Z-2,A-4) + B(2,4) - B(Z,A)$$

α衰变发生的条件：

$$E_0 > 0$$



$$M_X(Z,A) > M_Y(Z-2,A-4) + M_{^4He}(2,4)$$

$$^{210}Po \rightarrow ^{206}Pb + \alpha$$

$$\Delta_{^{210}Po} - (\Delta_{^{206}Pb} + \Delta_{^4He})$$
$$= -15.9531 - (-23.7855 + 2.4249)$$
$$= 5.4075 MeV$$

E_0>0，**可以**发生α衰变。

$$^{64}Cu \rightarrow ^{60}Co + \alpha$$

$$\Delta_{^{64}Cu} - (\Delta_{^{60}Co} + \Delta_{^4He})$$
$$= -65.4245 - (-61.6503 + 2.4249)$$
$$= -6.1991 MeV$$

E_0<0，**不可能**发生α衰变。

投票 最多可选1项

设置

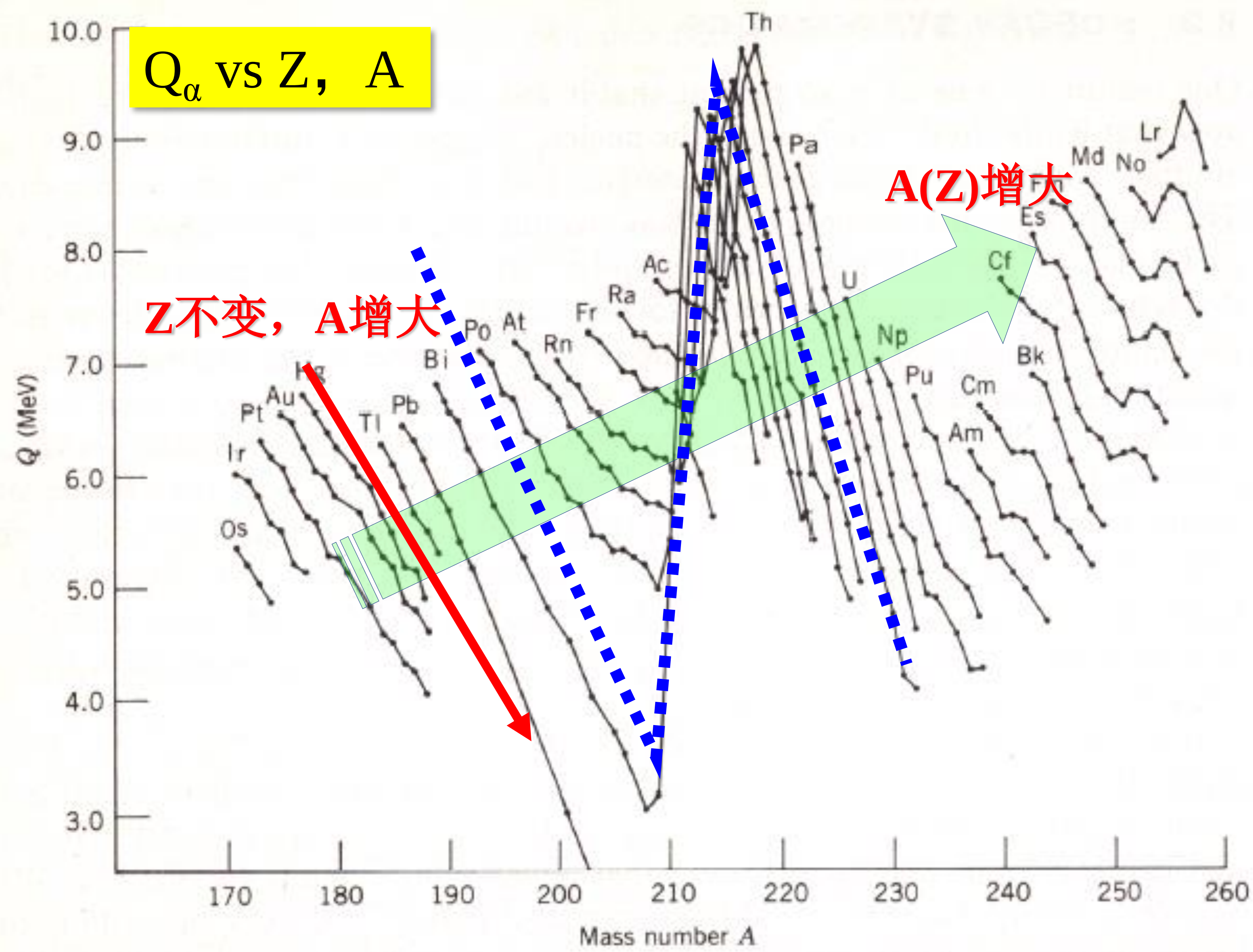
$E_0 > 0$是α衰变能够发生的什么条件?

A 充分条件

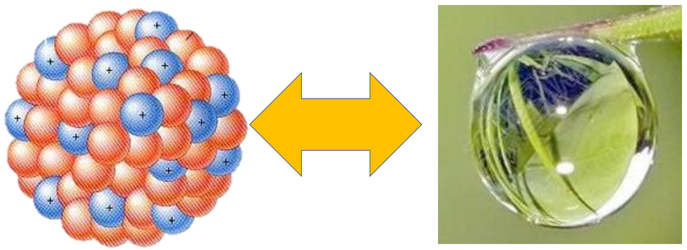
B 必要条件

C 充要条件

提交



$$B_c = \frac{-3e^2}{20\pi\varepsilon_0}\cdot\frac{Z(Z-1)}{R}$$
$$\approx -a_C \cdot Z^2 A^{-1/3}$$



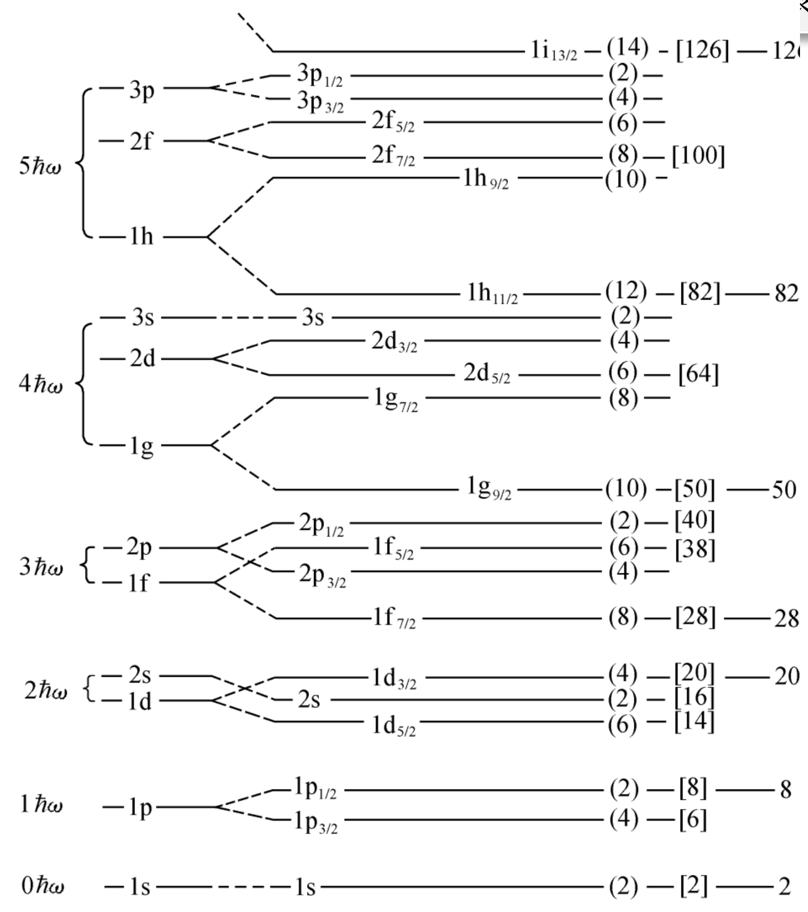


图 1.19　考虑自旋－轨道耦合后的核子能级[2]

Bi	83	206	−20.028	6(+)	6.243 d(ε)
		207	−20.054	9/2−	32.9 a(ε)
		208	−18.870	(5)+	3.68×10^5 a(ε)
		209	−18.258	9/2−	100%
		210	−14.792	1−	5.012 d(β^-)
		211	−11.858	9/2−	2.14 min(α99.7%, β^-)
		212	−8.117	1(−)	60.55 min(β^- 64%, α)

$^{211}Bi_{128}$: α, $T_{1/2}$=2.15min

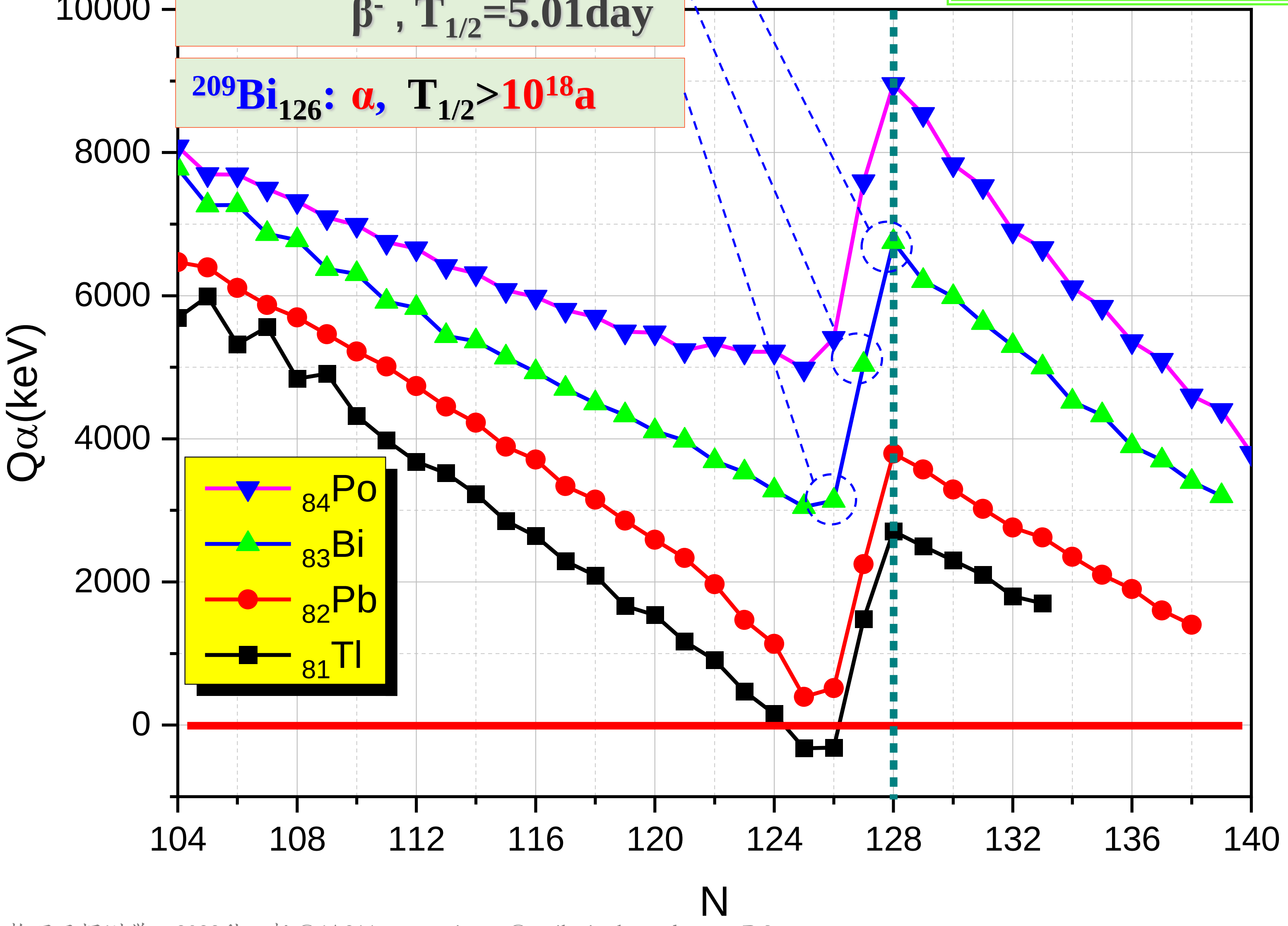
$^{210}Bi_{127}$: α, $T_{1/2}=3\times10^6$a

β^-, $T_{1/2}$=5.01day

$^{209}Bi_{126}$: α, $T_{1/2}>10^{18}$a

中子幻数：126

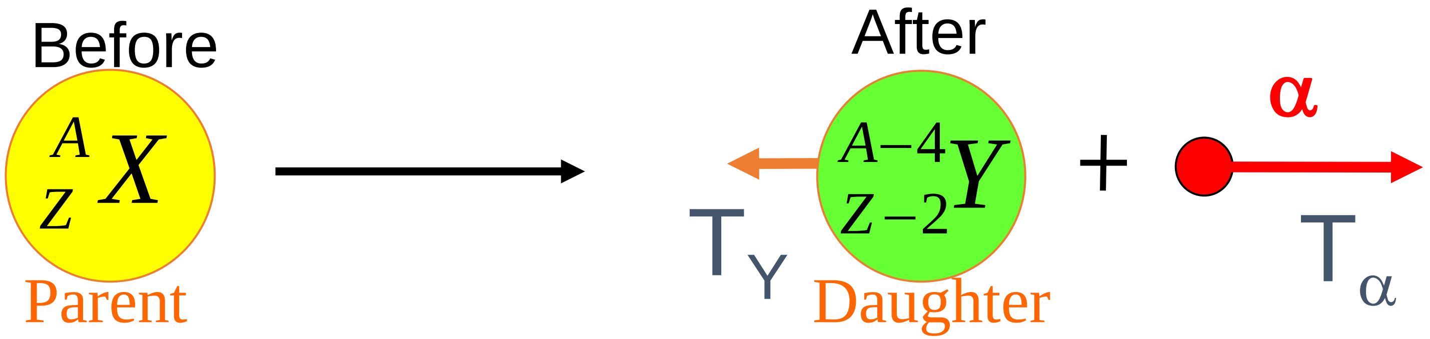
壳层结构

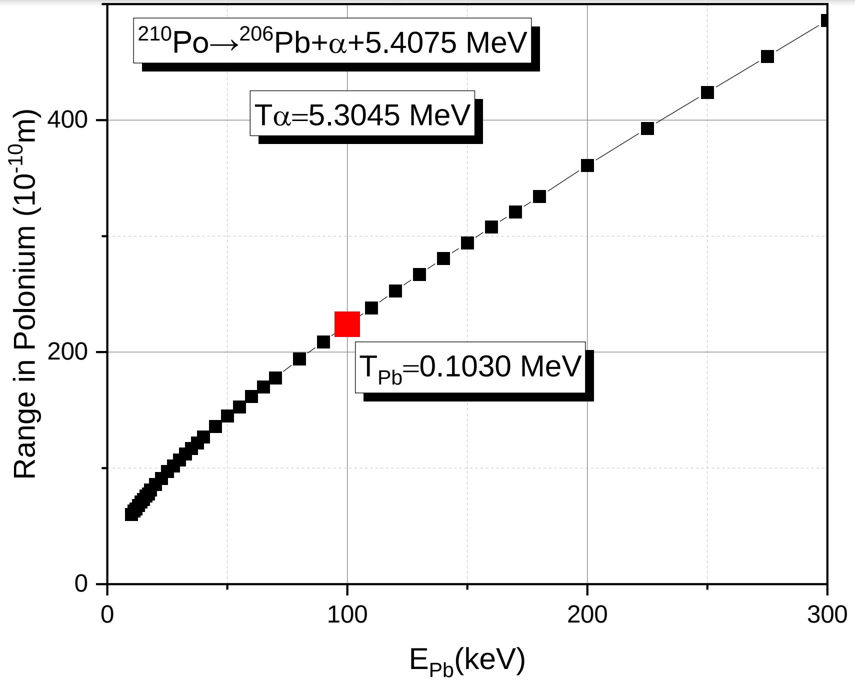


- 虽然是原子核的衰变，我们仍用原子质量来开展讨论。分析的是母核原子质量与子核原子质量、^{4}He原子质量之和之间的关系。

- 只有当母核原子的质量>子核原子与^{4}He原子质量之和时，即衰变能E_0>0时，α衰变才有可能发生；
  - **A（Z）越大，α衰变能就越大**；但对于**同位素（Z同）**，则是**A越大，α衰变能却越小**；这可由液滴模型给出的结合能公式进行解释。
  - 当母核的中子数是126时，α衰变能很小；而当子核的中子数是126时，α衰变能是局部极大。这是壳层结构的缘故，导致了“邻居”之间，半衰期有巨大的差别。

- 但这只是必要条件！除此之外，还要看其它约束条件是否满足。





反应前，母核静止

能量守恒

$$E_0 = T_\alpha + T_Y = [m_X - (m_Y + m_\alpha)]c^2$$

$$E_0 = \frac{m_Y + m_\alpha}{m_Y} T_\alpha \approx \frac{A}{A-4} T_\alpha$$

动量守恒

$$m_Y v_Y = m_\alpha v_\alpha$$

$$T_Y = \frac{m_\alpha}{m_Y} T_\alpha$$

可否把T_Y也测出来，然后直接求和呢？

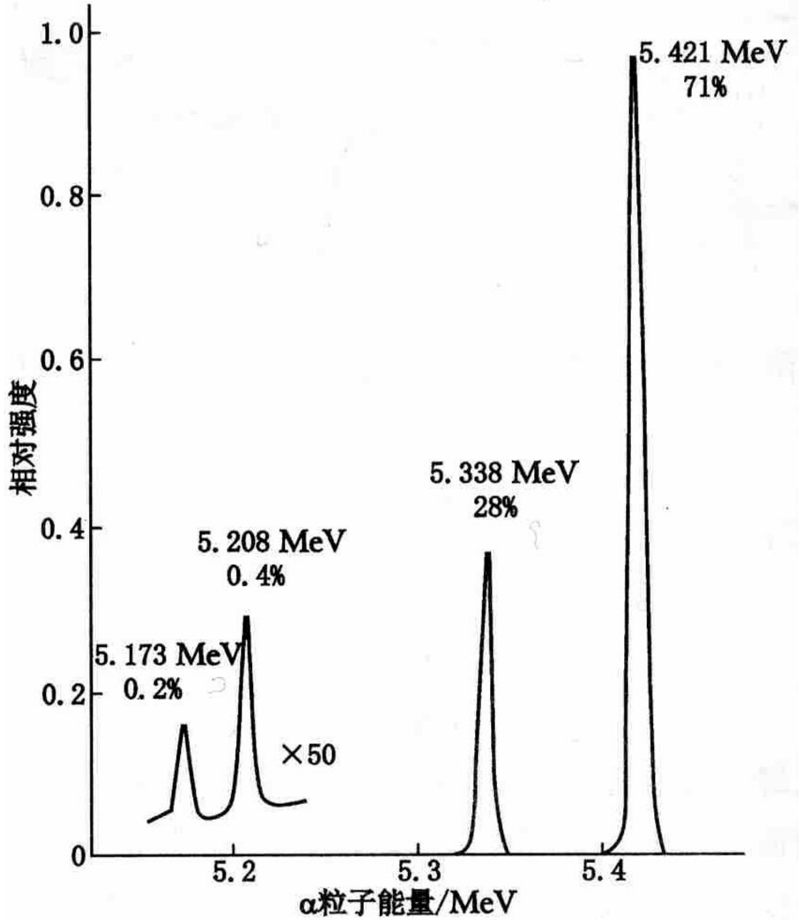
可以通过测量α粒子的能量T_α来得到**α衰变能E_0（Q_α）**

T_α看起来是个单值函数，它有可能取多值吗？

^{228}Th的α能谱

$$^{228}_{90}Th \xrightarrow{T_{1/2}=1.91year} {}^{224}_{88}Ra+\alpha$$

在^{228}Th的α能谱中，可以发现4个α粒子能量。

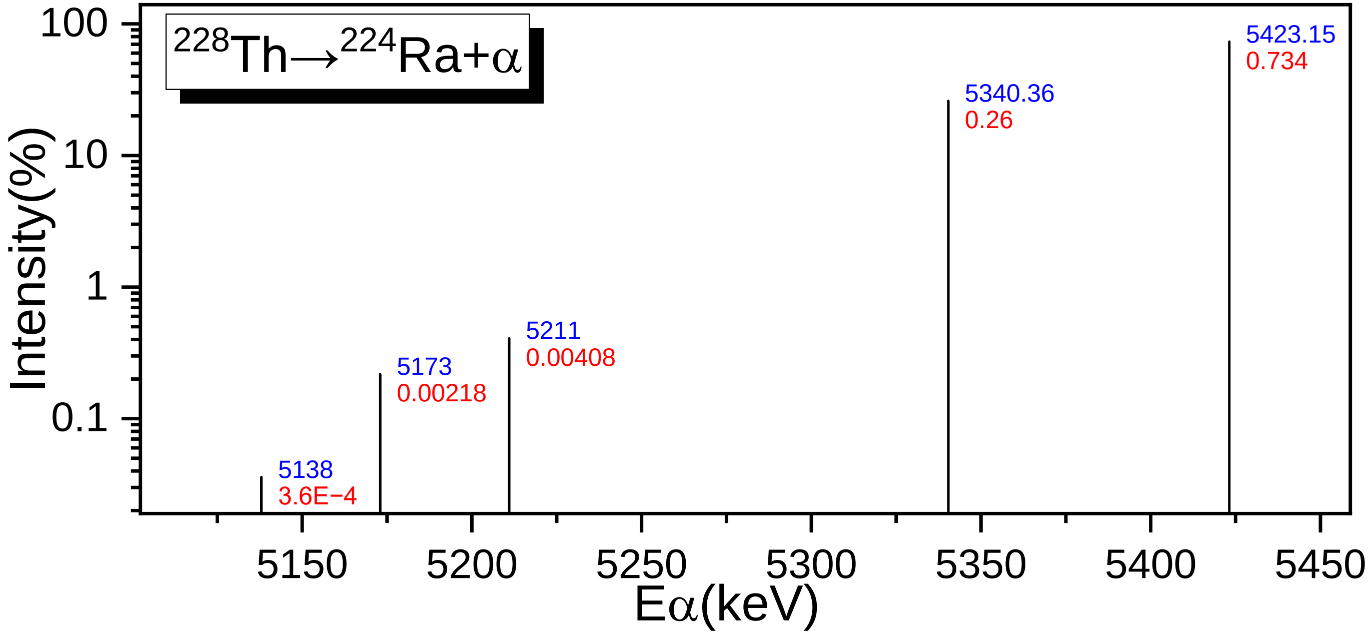


粒子能量 vs 强度？

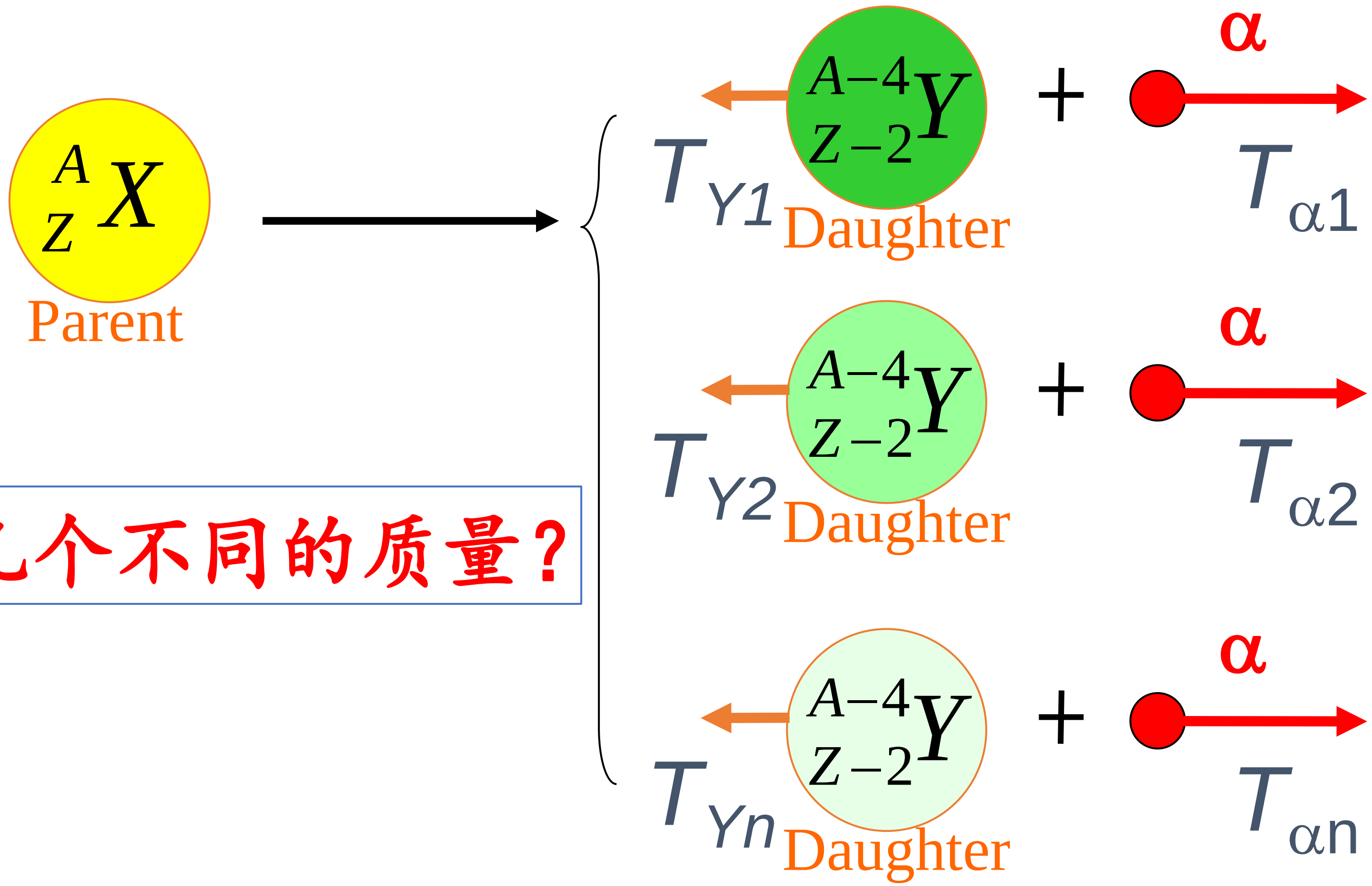
能量不确定？

$$\Gamma \cdot \tau = \hbar = 6.6\times10^{-22}\,MeV\cdot s$$

$$T_{1/2}=1.91year \rightarrow \tau = 6\times10^{7}s$$



单一能级衰变的母核的不同α衰变能反映了**子核**有**多个能级**，且能级能量可以由 **α 衰变能**求出。



这里有几个不同的质量?

示例：^{212}Bi 的α粒子能量→衰变能

$$ {}^{212}_{83}Bi \rightarrow {}^{208}_{81}Tl + \alpha $$

	T_α (MeV)	E_0 (MeV)
α_0	6.084	6.201
α_1	6.044	6.161
α_2	5.763	5.874
α_3	5.621	5.730
α_4	5.601	5.709
α_5	5.480	5.585

在衰变纲图中要写出来

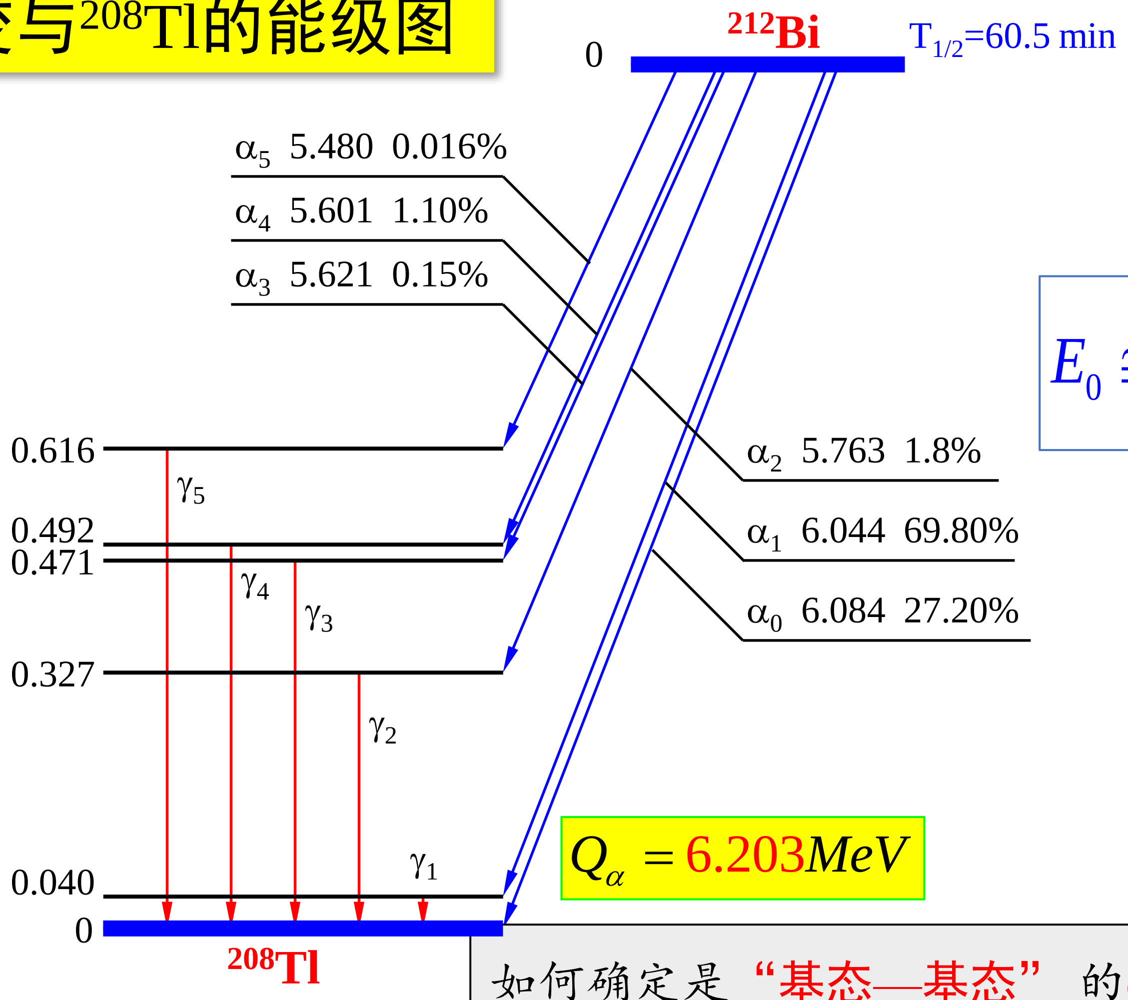
$$ T_\alpha \times \frac{212}{208} \cong E_0 $$

? 谁是**直接**观测量？

? 谁是**推算**出来的？

? 谁在**衰变纲图**中出现？

示例：^{212}Bi的α衰变与^{208}Tl的能级图



$$E_0 \cong \frac{A}{A-4} T_\alpha$$

$$Q_\alpha = 6.203MeV$$

如何确定是“基态—基态”的α衰变？

$$\Delta(^{212}Bi) - \left[\Delta(^{208}Tl) + \Delta(^{4}He)\right]$$
$$= -8.135MeV - \left[-16.763MeV + 2.425MeV\right]$$
$$= 6.203MeV$$

$$E_{05} = 5.585MeV$$
$$E_{04} = 5.709MeV$$
$$E_{03} = 5.730MeV$$
$$E_{02} = 5.874MeV$$
$$E_{01} = 6.161MeV$$
$$E_{00} = 6.201MeV$$

$$E_{00} - E_{05} = 0.616MeV$$
$$E_{00} - E_{04} = 0.492MeV$$
$$E_{00} - E_{03} = 0.471MeV$$
$$E_{00} - E_{02} = 0.327MeV$$
$$E_{00} - E_{01} = 0.040MeV$$

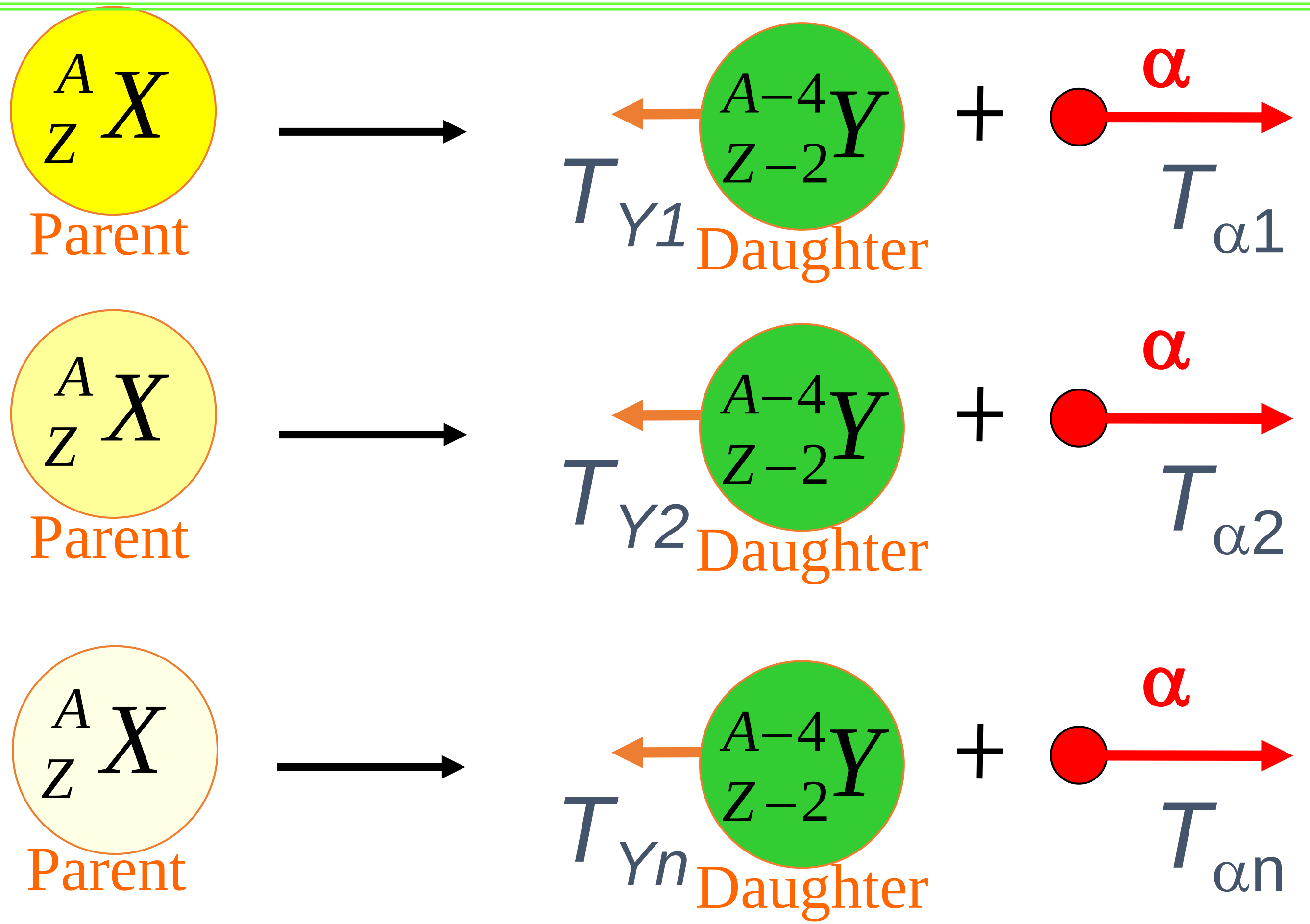
衰变能与子核激发态

$$E_0 = [m_X - (m_{Y^*} + m_\alpha)]c^2$$

母核原子质量过剩（MeV/c²）	⁴He原子质量过剩（MeV/c²）	子核激发能（MeV）	子核原子质量过剩（MeV/c²）	衰变能（MeV）	备注
-8.135	2.425	0	-16.763	6.203	子核基态
-8.135	2.425	0.04	-16.723	6.163	子核第一激发态
-8.135	2.425	0.327	-16.436	5.876	子核第二激发态
-8.135	2.425	0.471	-16.292	5.732	子核第三激发态
-8.135	2.425	0.492	-16.271	5.711	子核第四激发态
-8.135	2.425	0.616	-16.147	5.587	子核第五激发态

多能级母核到子核基态的不同α衰变能反映了**母核**的**多个能级**，且能级能量可以求出。

这里有几个不同的质量？



示例：^{212}Po的α衰变及其能级图

$$E_0 \cong \frac{A}{A-4} T_\alpha$$

$T_{\alpha 3} = 10.550MeV$

$T_{\alpha 2} = 10.432MeV$

$T_{\alpha 1} = 9.499MeV$

$T_{\alpha 0} = 8.785MeV$

$E_{30} = 10.753MeV$

$E_{20} = 10.633MeV$

$E_{10} = 9.682MeV$

$E_{00} = 8.954MeV$

1.799MeV

1.679MeV

0.728MeV

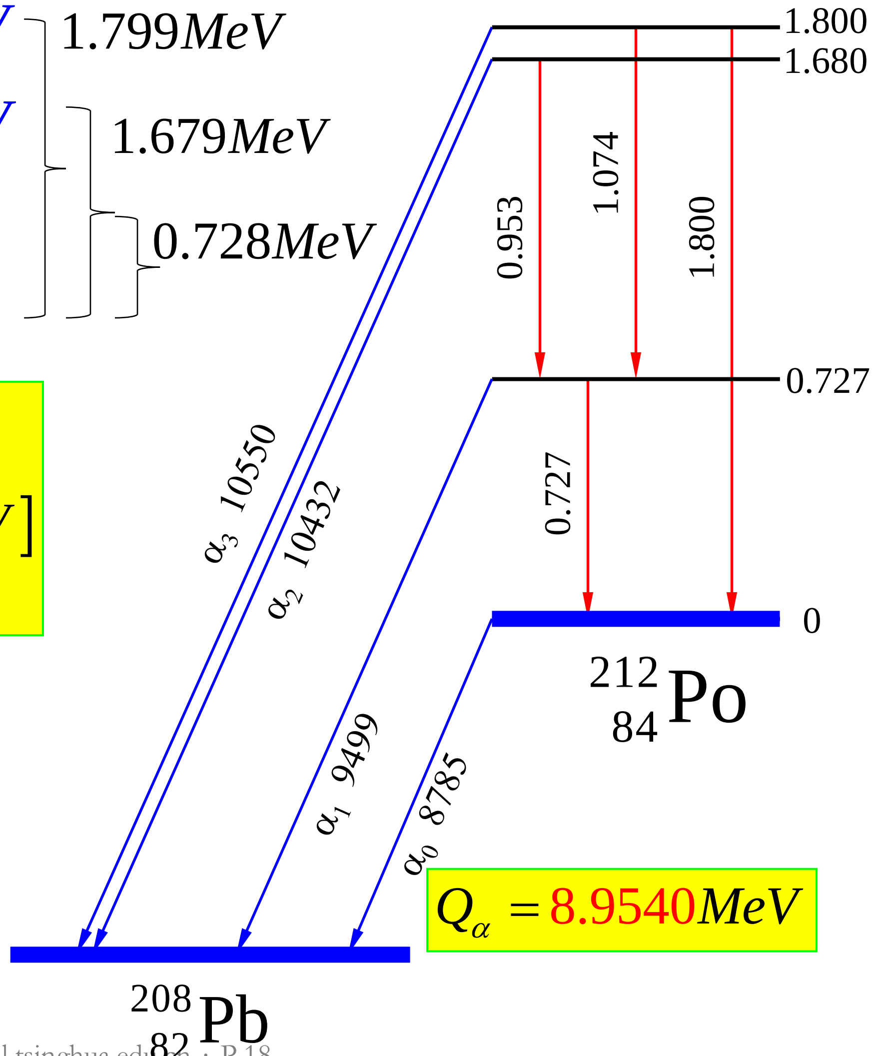
$$\Delta(^{212}Po) - \left[\Delta(^{208}Pb) + \Delta(^{4}He)\right]$$
$$= -10.3702MeV - \left[-21.7492MeV + 2.425MeV\right]$$
$$= 8.9540MeV$$

$E_{30} - E_{00} = 1.799MeV$

$E_{30} - E_{10} = 1.071MeV$

$E_{20} - E_{10} = 0.951MeV$

$E_{10} - E_{00} = 0.728MeV$



$Q_\alpha = 8.9540MeV$

衰变能与母核激发态

$$E_0 = [m_{X^*} - (m_Y + m_\alpha)]c^2$$

母核激发能（MeV）	母核原子质量过剩（MeV/c²）	⁴He原子质量过剩（MeV/c²）	子核原子质量过剩（MeV/c²）	衰变能（MeV）	备注
0	-10.3702	2.425	-21.7492	8.954	母核基态
0.727	-9.6432	2.425	-21.7492	9.681	母核第一激发态
1.68	-8.6902	2.425	-21.7492	10.634	母核第二激发态
1.80	-8.5702	2.425	-21.7492	10.754	母核第三激发态

- 母核X在发生α衰变时，有可能使子核Y处在几种不同的能态上（不同的核素），子核的能态不同，其质量就不同，则衰变能也不同。

"衰变纲图中α粒子后面跟的是我，实验测量值"

"衰变纲图中基态→基态的衰变能要写出来"

- 根据这几种情况下α粒子的动能T_α，$\times \frac{A}{A-4}$得到其各自的衰变能E_0。这些衰变能之间的差异，对应的就是子核Y的质量差，进而可知其能级结构。

- 最大的衰变能，很有可能对应的就是子核的基态。但在确信之前，一定要进行验证——计算出$M(X_{基态})-M(Y_{基态})-M(^4He_{基态})$，看它是否和最大衰变能对应？

- 当然也有可能是子核处于基态，而母核自己处在不同的能态上，此时，根据衰变能的差异可了解母核的能级结构。但这时最小衰变能通常对应于母核的基态。

重要的一句话：计算$M(X_{基态})-M(Y_{基态})-M(^4He_{基态})$，看它跟哪个衰变能相等，这是画α衰变纲图的第一步！！

一．α衰变概述

二．α衰变的衰变能

三．α衰变能与核能级图

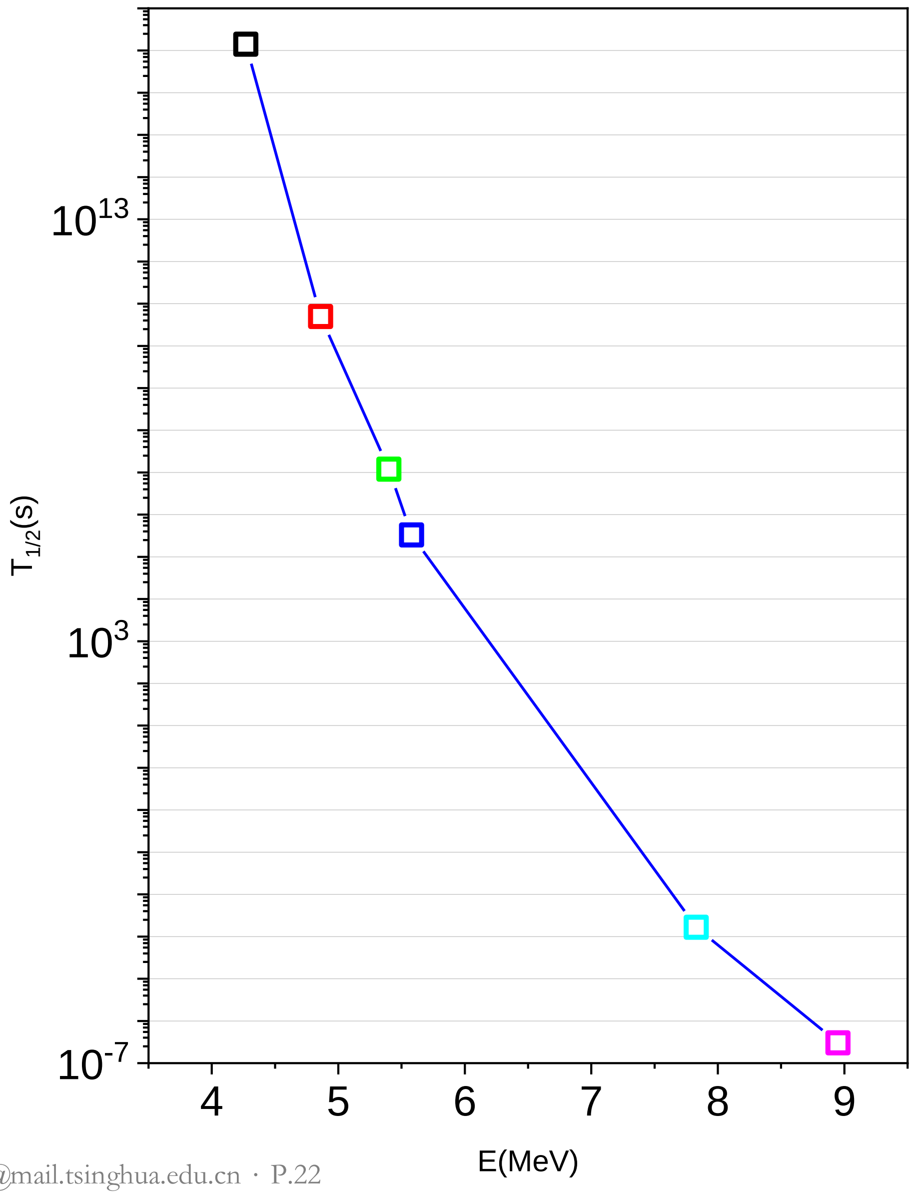
✓ 四．α衰变的衰变常数

五．*α衰变的禁戒：宇称与角动量

六．其它重粒子衰变

实验发现，α衰变能与衰变常数之间有密切的关系：

α放射性核	E_0 (MeV)	$T_{1/2}$	$\lambda(s^{-1})$
^{238}U	4.27	$4.468\times10^9 a$	4.9×10^{-18}
^{226}Ra	4.86	$1.60\times10^3 a$	1.4×10^{-11}
^{210}Po	5.40	$1.384\times10^2 d$	5.8×10^{-8}
^{222}Rn	5.58	$3.824 d$	2.1×10^{-6}
^{214}Po	7.83	$1.64\times10^{-4} s$	4.2×10^3
^{212}Po	8.95	$3.0\times10^{-7} s$	2.3×10^6



Enrico Fermi: Nuclear Physics Course Notes

Geiger Nuttall rule——1911年，盖格（H.Geiger）与努塔尔（J.M.Nuttall）发现α衰变常数λ与α粒子在空气中的射程R之间存在关系：

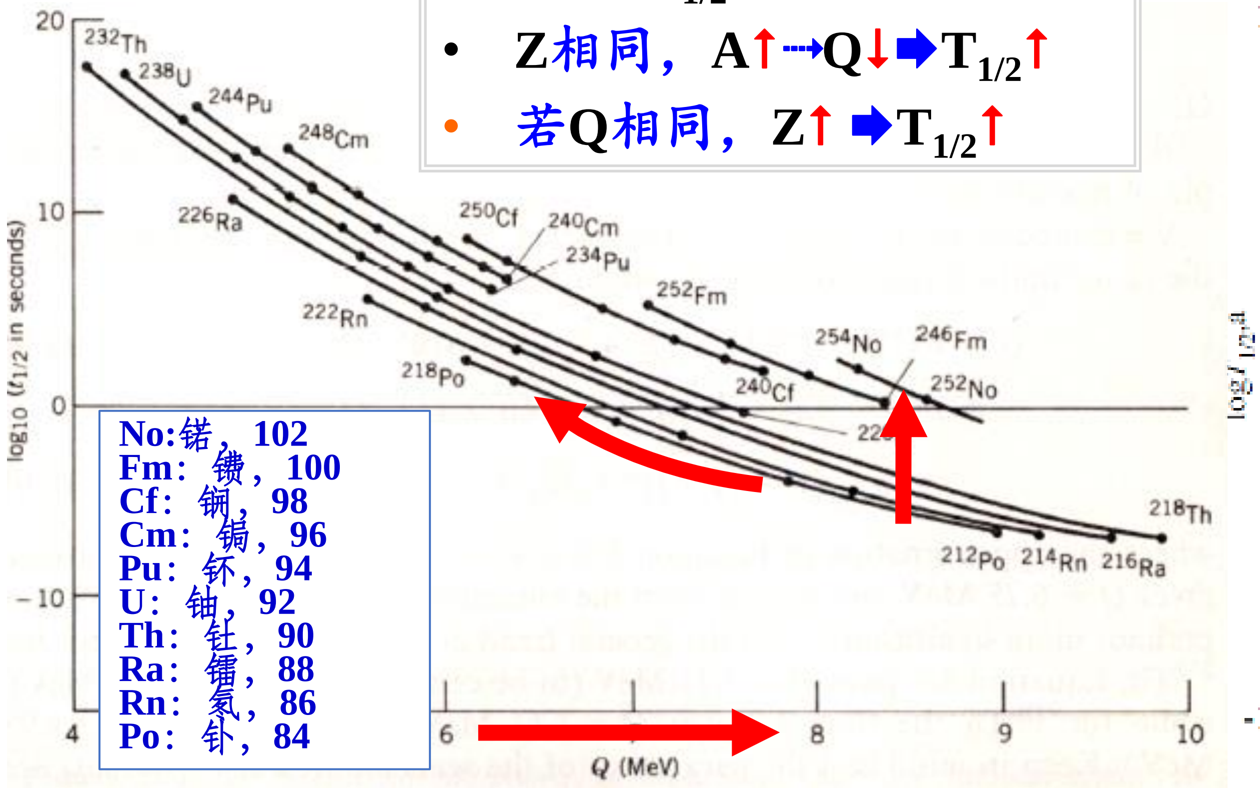
$$\lambda = \text{constant} \cdot R^{57.5}$$

$$\text{constant} = \begin{cases} 10^{-42.3} & \text{for Uranium family} \\ 10^{-44.2} & \text{for Thorium} \\ 10^{-46.3} & \text{for Actinium} \end{cases}$$

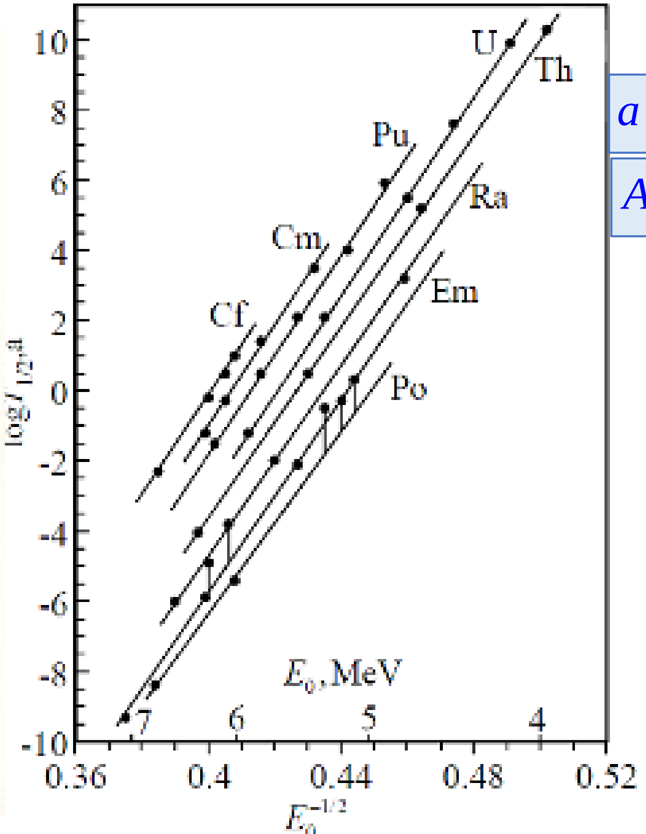
由经验公式：$R(cm) \propto E_\alpha^{1.5}(MeV)$ 有：$\lambda \propto E_\alpha^{86.25}$

实验数据表明，衰变常数与α衰变能、原子序数有关。偶偶核同位素的点在一条平滑的线上，并且：

- Q↑ ➡ $T_{1/2}$↓
- Z相同，A↑⇢Q↓➡$T_{1/2}$↑
- 若Q相同，Z↑ ➡$T_{1/2}$↑



No：锘，102
Fm：镄，100
Cf：锎，98
Cm：锔，96
Pu：钚，94
U：铀，92
Th：钍，90
Ra：镭，88
Rn：氡，86
Po：钋，84



$$\log T_{1/2} = a + bE_0^{-1/2}$$

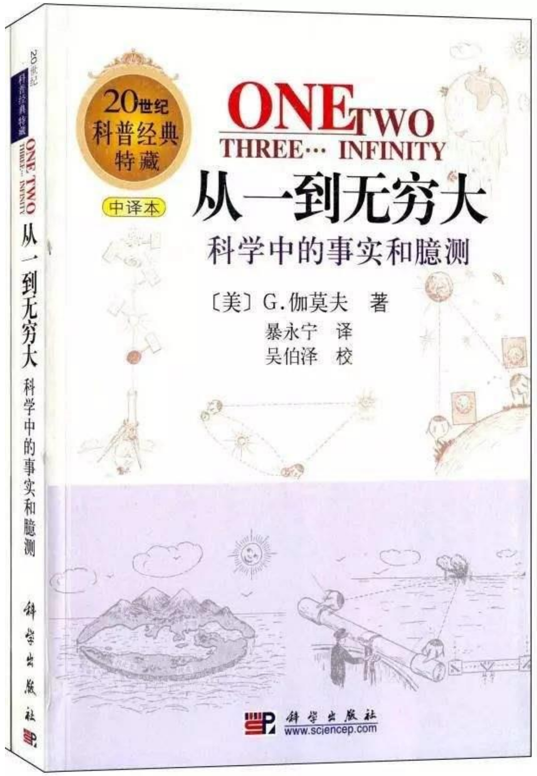
$$a = -1.61Z_Y^{2/3} - 21.4$$

$$b = B = 1.61 \times Z_Y$$

$$A = 1.61Z_Y^{2/3} - 21.03$$

$$\log \lambda = A - BE_0^{-1/2}$$

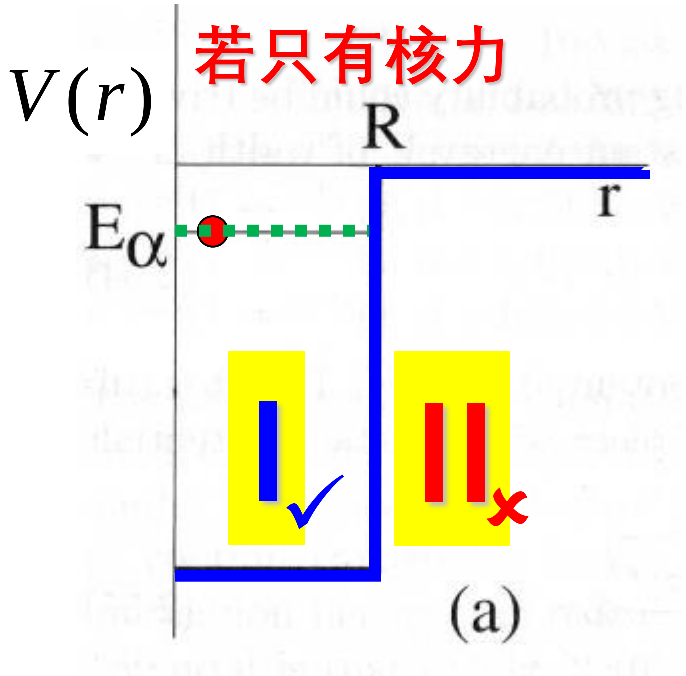
George Gamow (1904–1968), born and educated in Russia, did his first important work at Göttingen in 1928 when he developed the theory of alpha decay, the first application of quantum mechanics to nuclear physics. (Edward U. Condon and Ronald W. Gurney, working together, arrived at the same theory independently of Gamow at about the same time). In 1929 he proposed the liquid-drop model of the nucleus. After periods in Copenhagen, Cambridge, and Leningrad, Gamow went to the United States in 1934 where he was first at George Washington University and later at the University of Colorado. In 1936 Gamow collaborated with Edward Teller on an extension of Fermi's theory of beta decay. Much of his later research was concerned with astrophysics, notably on the evolution of stars, where he showed that as a star uses up its supply of hydrogen in thermonuclear reactions, it becomes hotter, not cooler. Gamow also did important work on the origin of the universe (he and his students predicted the 2.7-K remnant radiation from the Big Bang) and on the formation of the elements. His books for the general public introduced many people to the concepts of modern physics.

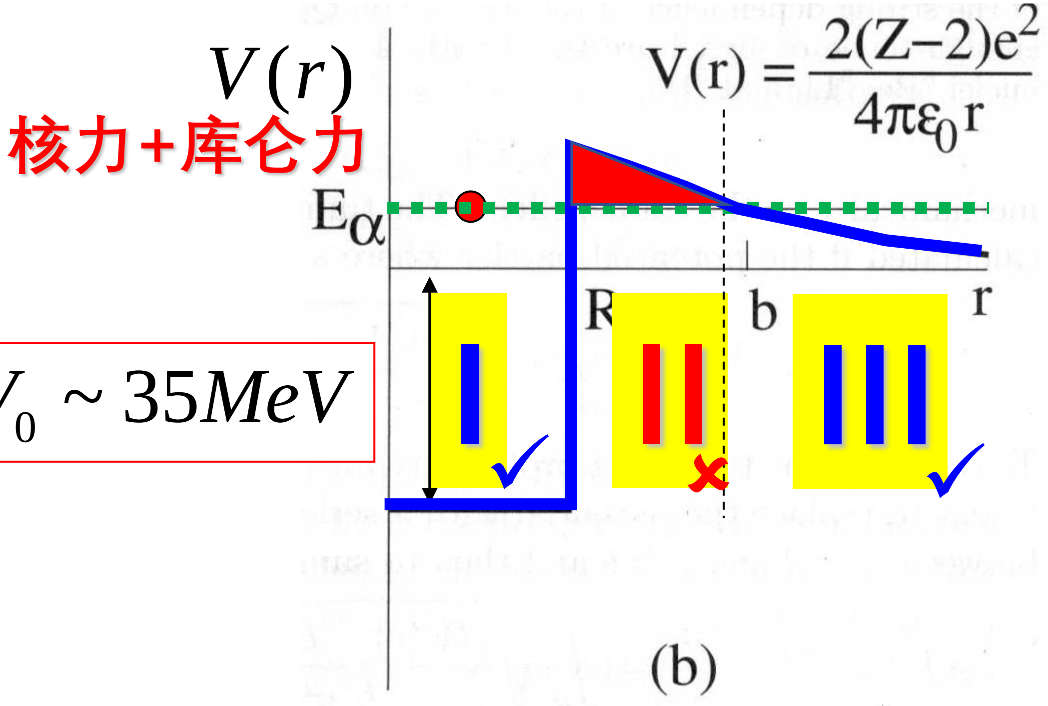


(1904-1968)

Russian-American physicist who worked out the theory of alpha decay in terms of tunneling through the nucleus's potential barrier. Gamow showed that, as a star burns hydrogen, the star heats up. He supported the "big bang" theory of Lemaître. He was also a popularizer of science, publishing many works including *Mr. Tompkins in Wonderland* (1937) and *Thirty Years that Shook Physics* (1966).

- α粒子在**核内**主要感受两种力：**核力**和**库仑力**。
- α粒子在**核内**所受合力平衡➡在核内**自由地高速运动**。
- 在**核边界**处受到很强的向核心的**吸引力**。
- 在**核外**，α粒子与子核之间**核力消失**，**库仑力**成为**主导**。





$V_0 \sim 35MeV$

量子力学的成功范例之一：α衰变的隧道穿透理论——

“……*one of the first triumphs* *of quantum mechanics.*”，由Gamow与Gurney、Condon几乎同时在1928年提出。

One-body model:

- α粒子事先存在于母核中
- 并在子核构成的球形区域内运动

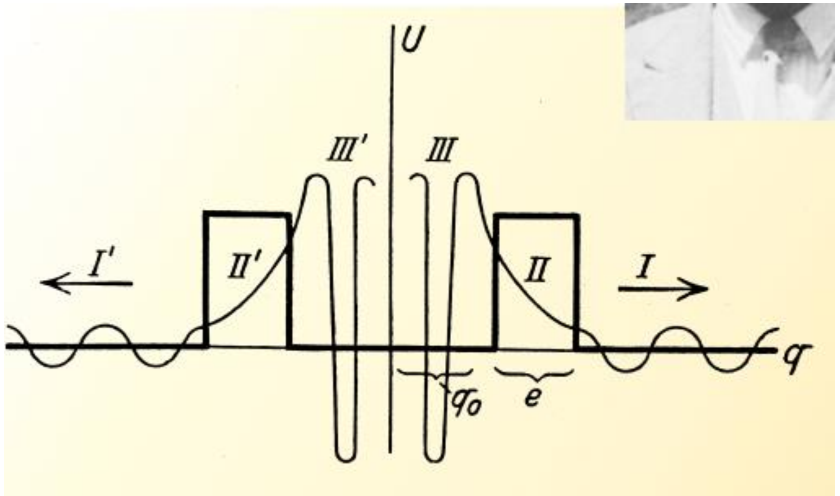
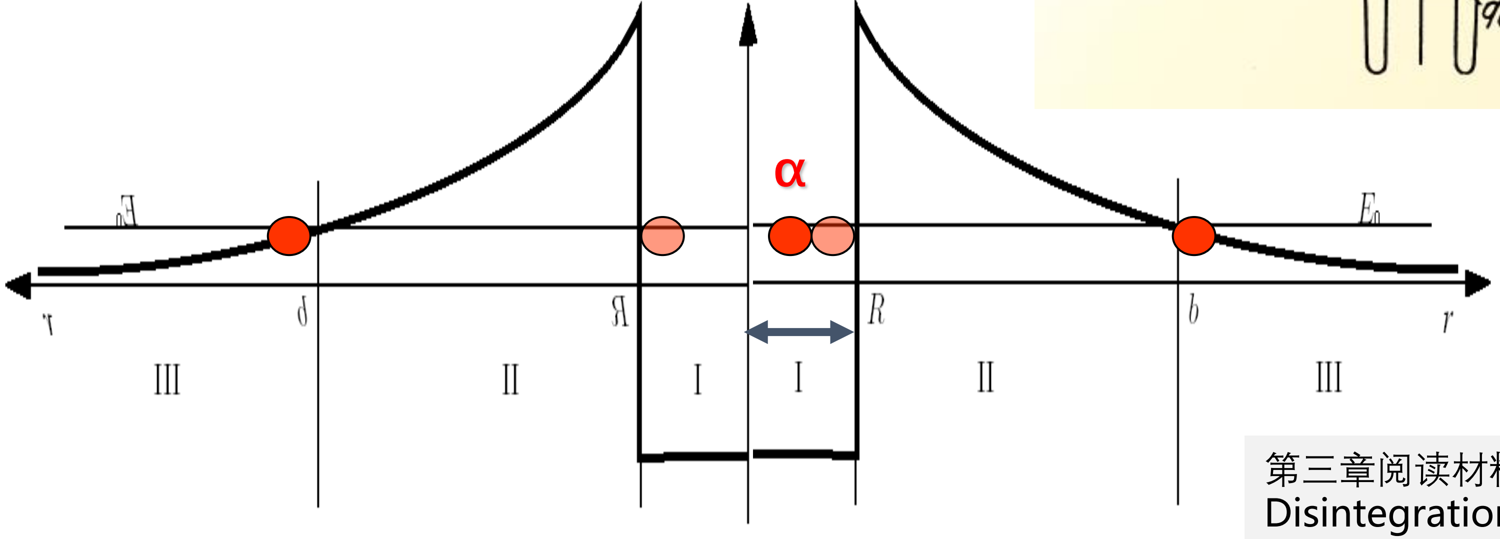


FIGURE 5. ONE-DIMENSIONAL POTENTIAL used by George Gamow to illustrate the tunneling of alpha particles. A wavefunction is sketched for an alpha particle of energy E near the bottom of the well in regions III and III′, each of width q_0, within the nucleus. In regions I and I′ outside the nucleus, the wavefunction amplitude is suppressed by an exponential factor, with exponent proportional to $\ell(U_0 - E)^{1/2}$, where ℓ and U_0 are the width and height of the barrier (regions II and II′). (From ref. 12.) The photo shows Gamow in the early 1930s (courtesy AIP Emilio Segrè Visual Archives, Frenkel Collection).



^{238}U：α粒子平均要“撞”10^{38}次，每秒10^{21}次，～10^{9}年

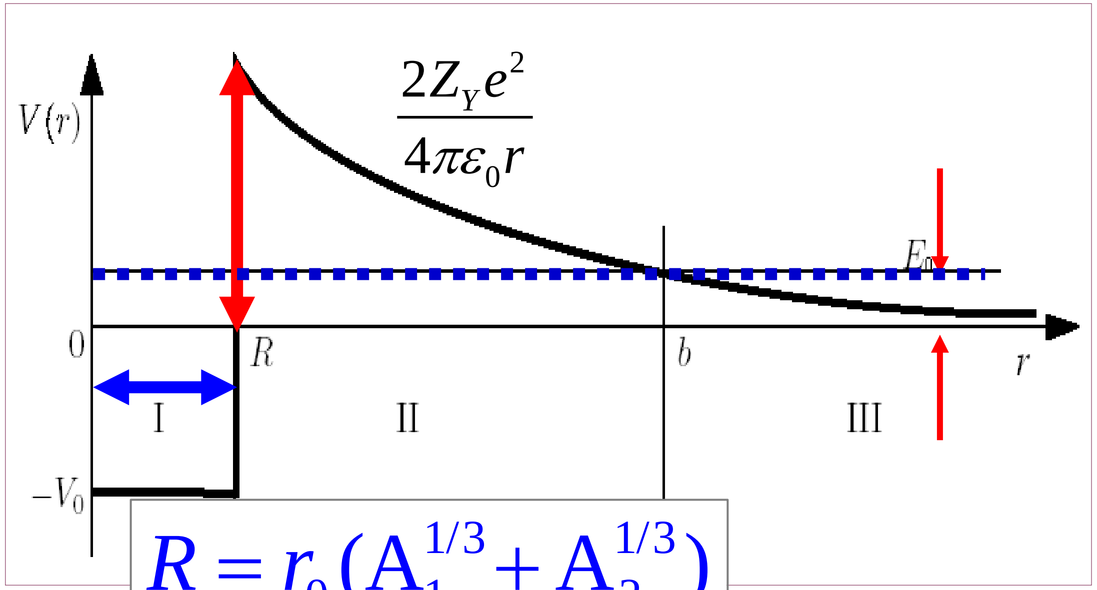
第三章阅读材料1：1_Wave Mechanics and Radioactive Disintegration.pdf
第三章补充阅读材料——The Early History of Quantum Tunneling.pdf

α粒子相对于子核的势能为：

$$V(r)=\begin{cases} -V_0 & r<R \\ \dfrac{2(Z-2)e^2}{4\pi\varepsilon_0 r} & r>R \end{cases}$$

当 $r=R$ 时，势垒高度：

$$\boxed{V_c=V(\mathrm{R})}$$



$$R=r_0(\mathrm{A}_1^{1/3}+\mathrm{A}_2^{1/3})$$

^{212}Po的α衰变，势垒高度为：

$$V_c(R)=26.2\,\mathrm{MeV}$$

$$\bigvee$$

^{212}Po的α衰变能

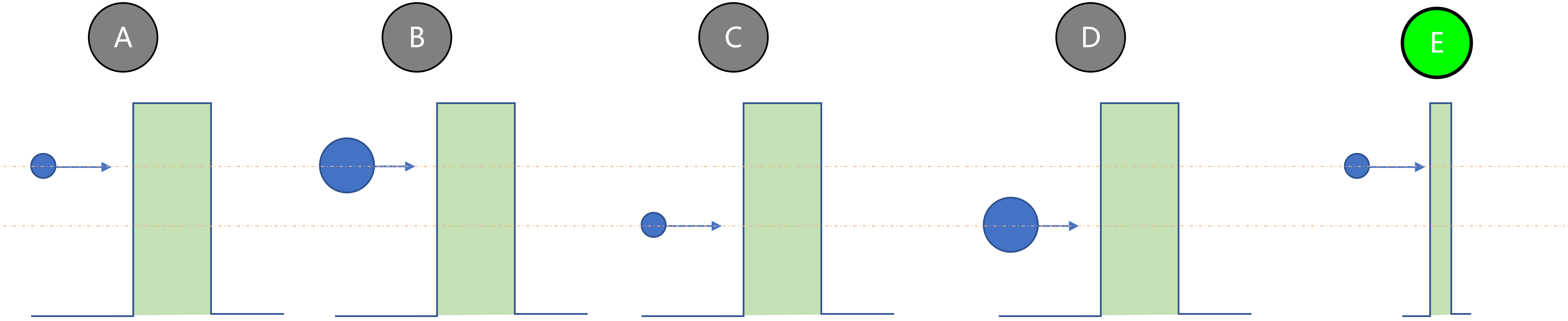
$$E_0=8.95\,\mathrm{MeV}$$

α能出去吗？概率？

单选题 1分

设置

哪种情况下，” 粒子” 穿越势垒的概率最大?



提交

隧穿效应： 微观粒子以一定概率穿透势垒的现象，

概率依赖于：

1. **m：粒子质量**
2. **a：势垒宽度**
3. **(V_0-E)**

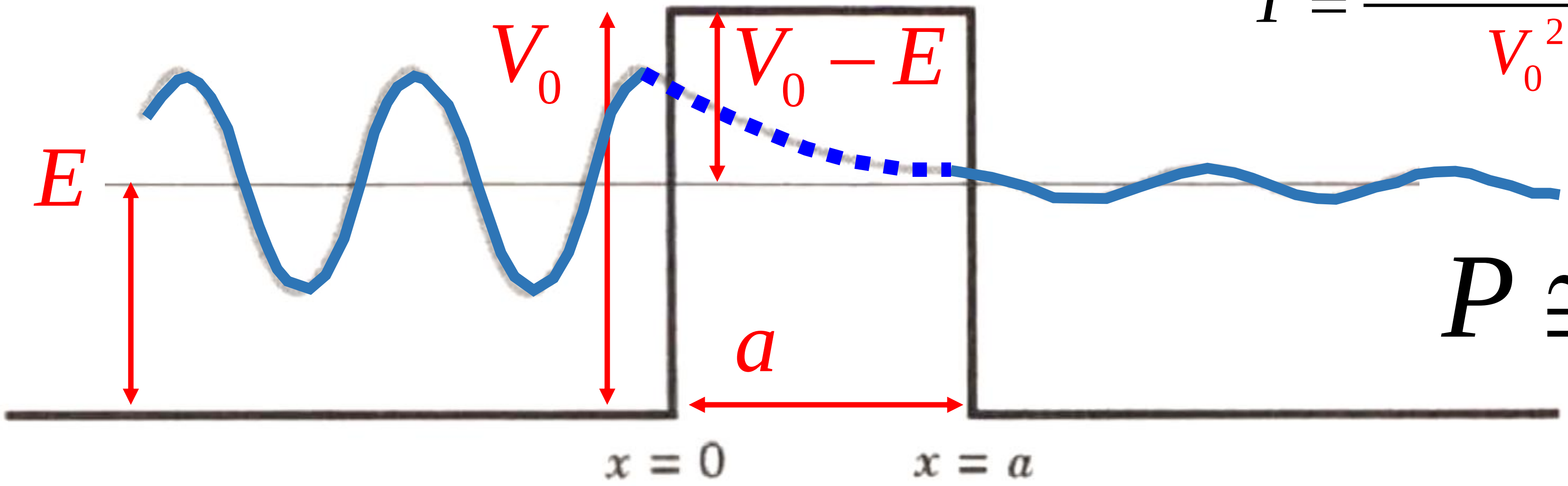
$$\kappa=\frac{\sqrt{2m(V_0-E)}}{\hbar}$$

$$T=\frac{1}{1+\dfrac{1}{\dfrac{4E}{V_0}\left(1-\dfrac{E}{V_0}\right)}\sinh^2\kappa a}$$

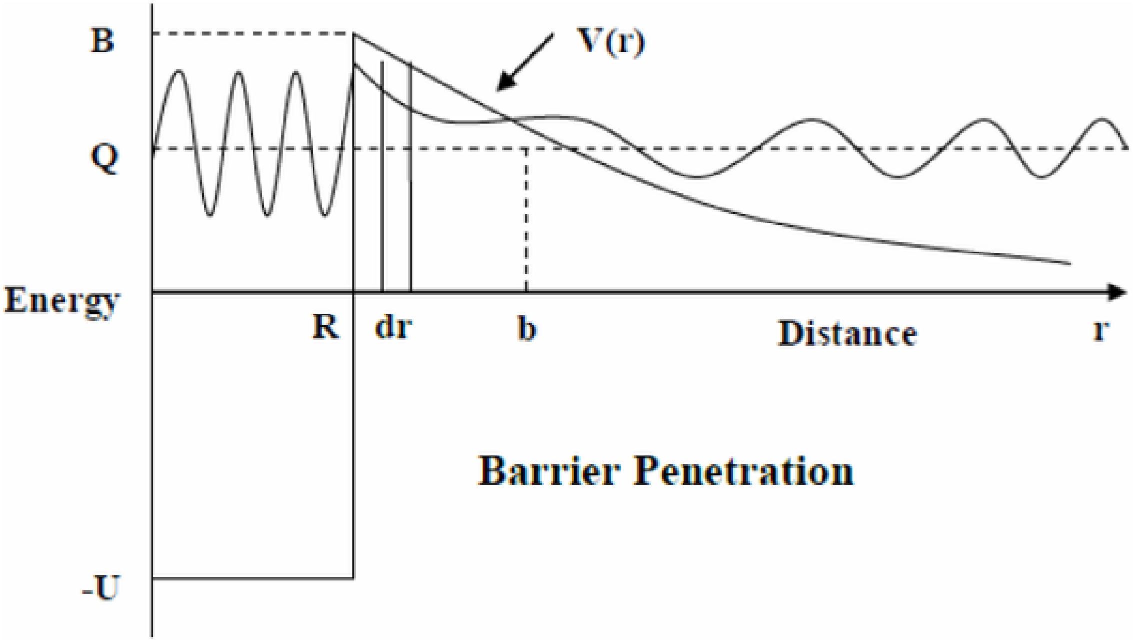
$$\kappa a\gg 1$$

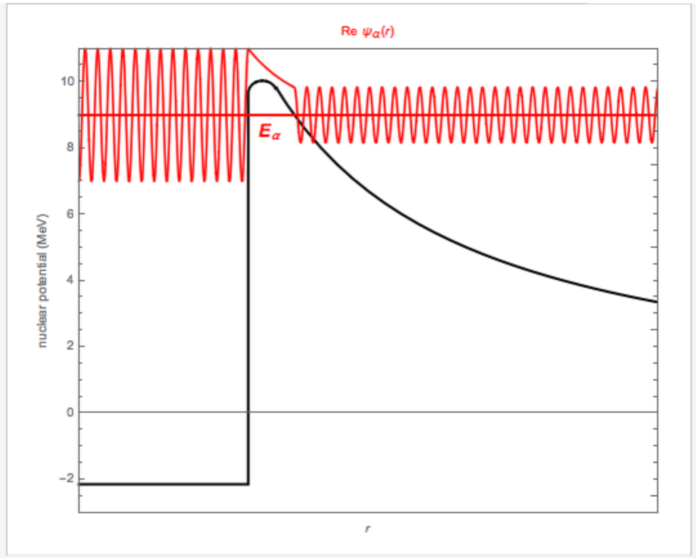
$$\sinh\kappa a=\frac{e^{\kappa a}-e^{-\kappa a}}{2}\approx\frac{e^{\kappa a}}{2}$$

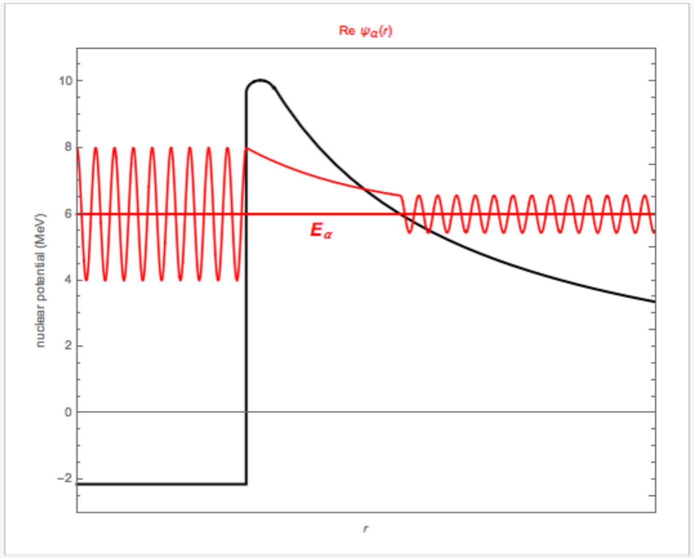
$$T=\frac{16E\left(V_0-E\right)}{V_0^{\,2}}e^{-2\kappa a}$$

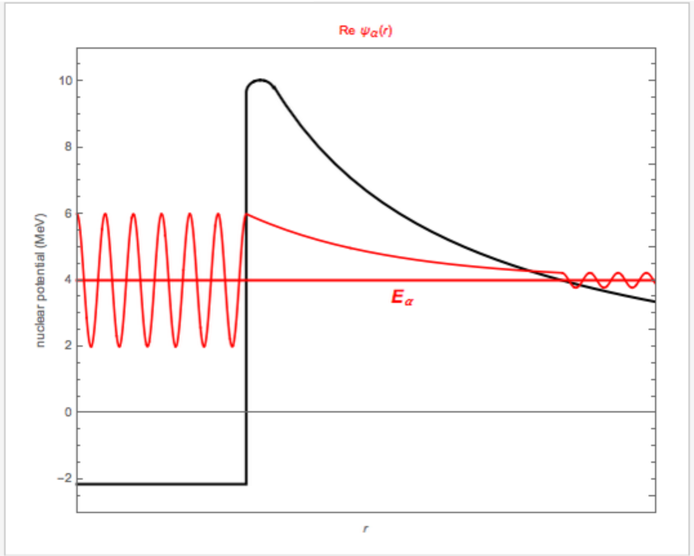


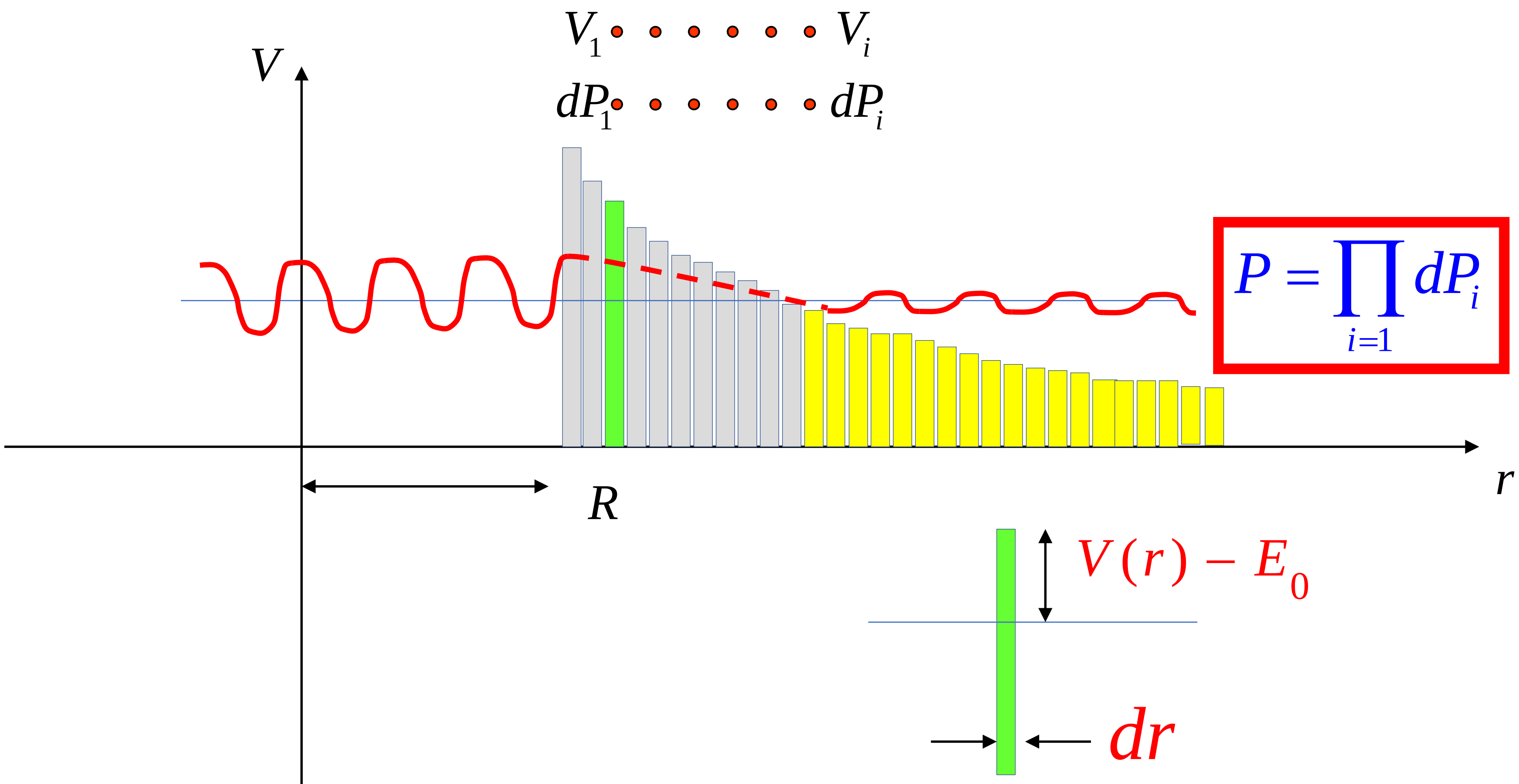
$$P\cong e^{-2a\frac{\sqrt{2m(V_0-E)}}{\hbar}}$$


B
Q
Energy
-U
V(r)
R
dr
b
Distance
r
Barrier Penetration


Re ψα(r)
nuclear potential (MeV)
Eα
r


Re ψα(r)
nuclear potential (MeV)
Eα
r


Re ψα(r)
nuclear potential (MeV)
Eα
r



$$\boxed{P = \prod_{i=1} dP_i}$$

$$dP_i = e^{-2\cdot dr\cdot\frac{\sqrt{2\mu(V(r)-E_0)}}{\hbar}}$$

$$\mu = \frac{m_Y m_\alpha}{m_Y + m_\alpha}$$

$$P = e^{-2\cdot\frac{\sqrt{2\mu}}{\hbar}\int_R^b \sqrt{V(r)-E_0}\,dr} = e^{-2G}$$

Gamow factor

其中 $\mu = \dfrac{m_\alpha m_Y}{m_\alpha + m_Y}$

$R = R_Y + R_\alpha$

$b = \dfrac{2Z_Y e^2}{4\pi\varepsilon_0 E_0}$

对厚垒（即 b>>R）有(自行推导):

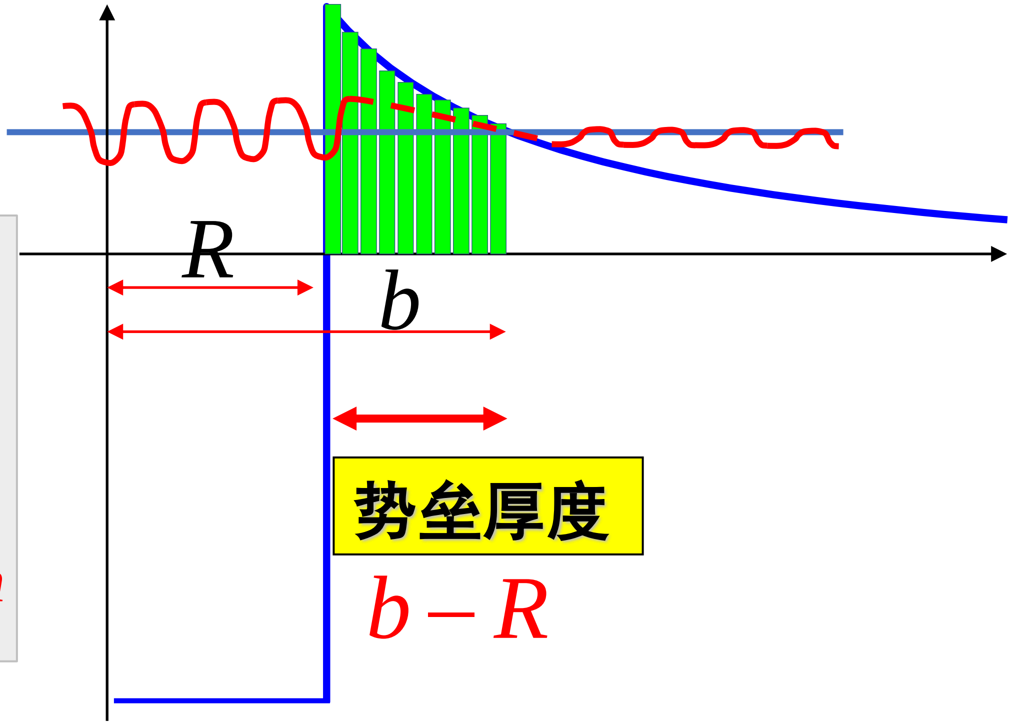
$$P = e^{-2G} = \exp\left\{-\frac{Z_Y e^2\sqrt{2m_\alpha}}{2\varepsilon_0\hbar\sqrt{E_0}} + \frac{4e\sqrt{m_\alpha R Z_Y}}{\sqrt{\pi\varepsilon_0}\hbar}\right\}$$

$^{212}Po \longrightarrow {}^{208}Pb + {}^{4}He$

$E_0 = 8.95\,MeV, Z_Y = 82$

$R = 1.2\,fm\times(208^{1/3} + 4^{1/3}) = 9\,fm$

$b = \dfrac{2\times 82\times 1.44\,MeV\cdot fm}{8.95\,MeV} = 26.4\,fm$



$$-\frac{Z_Y e^2\sqrt{2m_\alpha}}{2\varepsilon_0\hbar\sqrt{E_0}} = -\frac{Z_Y}{\sqrt{E_0}}\cdot\frac{e^2}{4\pi\varepsilon_0}\cdot\frac{\sqrt{2m_\alpha c^2}}{\hbar c}\cdot 2\pi$$

$$= -\frac{Z_Y}{\sqrt{E_0}}\cdot\frac{1.44\cdot\sqrt{7454MeV}}{197}\cdot 2\pi = -3.9653\frac{Z_Y}{\sqrt{E_0}}$$

$$\frac{4e\sqrt{m_\alpha RZ_Y}}{\sqrt{\pi\varepsilon_0}\hbar} = 8\cdot\sqrt{\frac{e^2}{4\pi\varepsilon_0}}\cdot\frac{\sqrt{m_\alpha c^2 RZ_Y}}{\hbar c}$$

$$= 8\cdot\frac{\sqrt{1.44MeV\cdot fm}\cdot\sqrt{3727MeV\cdot RZ_Y}}{197MeV\cdot fm}$$

$$= 2.975\sqrt{RZ_Y}$$

$$P = e^{-\frac{Z_Y e^2\sqrt{2m_\alpha}}{2\varepsilon_0\hbar\sqrt{E_0}} + \frac{4e\sqrt{m_\alpha RZ_Y}}{\sqrt{\pi\varepsilon_0}\hbar}} = e^{-3.9653\frac{Z_Y}{\sqrt{E_0}} + 2.975\sqrt{RZ_Y}}$$

$(E_0: MeV, R: fm)$

$$P = e^{-108.7+80.8} = e^{-27.9} = 7.64\times 10^{-13}$$

$$P = e^{-172.7+86.1} = e^{-86.6} = 2.46\times 10^{-38}$$

$${}^{212}Po \xrightarrow{T_{1/2}=0.299\mu s} {}^{208}Pb + {}^{4}He$$

$E_0 = 8.95MeV, Z_Y = 82$

$R = 1.2\,fm\times(208^{1/3} + 4^{1/3}) = 9\,fm$

$V_c(R) = 26.2MeV \rightarrow V_c(R) - E_0 = 17.25MeV$

$b = 26.4\,fm \rightarrow$ 垒厚$b - R = 17.4\,fm$

$m_\alpha = 3727\,MeV/c^2, V_0 = 35MeV$

P是衰变常数λ吗？

$${}^{238}U \xrightarrow{T_{1/2}=4.468E9\,y} {}^{234}Th + {}^{4}He$$

$E_0 = 4.269MeV, Z_Y = 90$

$R = 1.2\,fm\times(234^{1/3} + 4^{1/3}) = 9.3\,fm$

$V_c(R) = 27.9MeV \rightarrow V_c(R) - E_0 = 23.63MeV$

$b = 60.7\,fm \rightarrow$ 垒厚$b - R = 51.5\,fm$

$m_\alpha = 3727\,MeV/c^2, V_0 = 35MeV$

λ是单位时间内发生α衰变的几率：$\lambda = n \cdot P$

n是α粒子“访问边界”的频率

$$n = \frac{v}{2R} = \frac{1}{2R}\sqrt{\frac{2E_k}{\mu}} \approx \frac{1}{2R}\sqrt{\frac{2(E_0+V_0)}{m_\alpha}} \approx \frac{4.4\times10^7\, m/s}{18\times10^{-15}\, m} = 2.44\times10^{21}/s$$

代入得

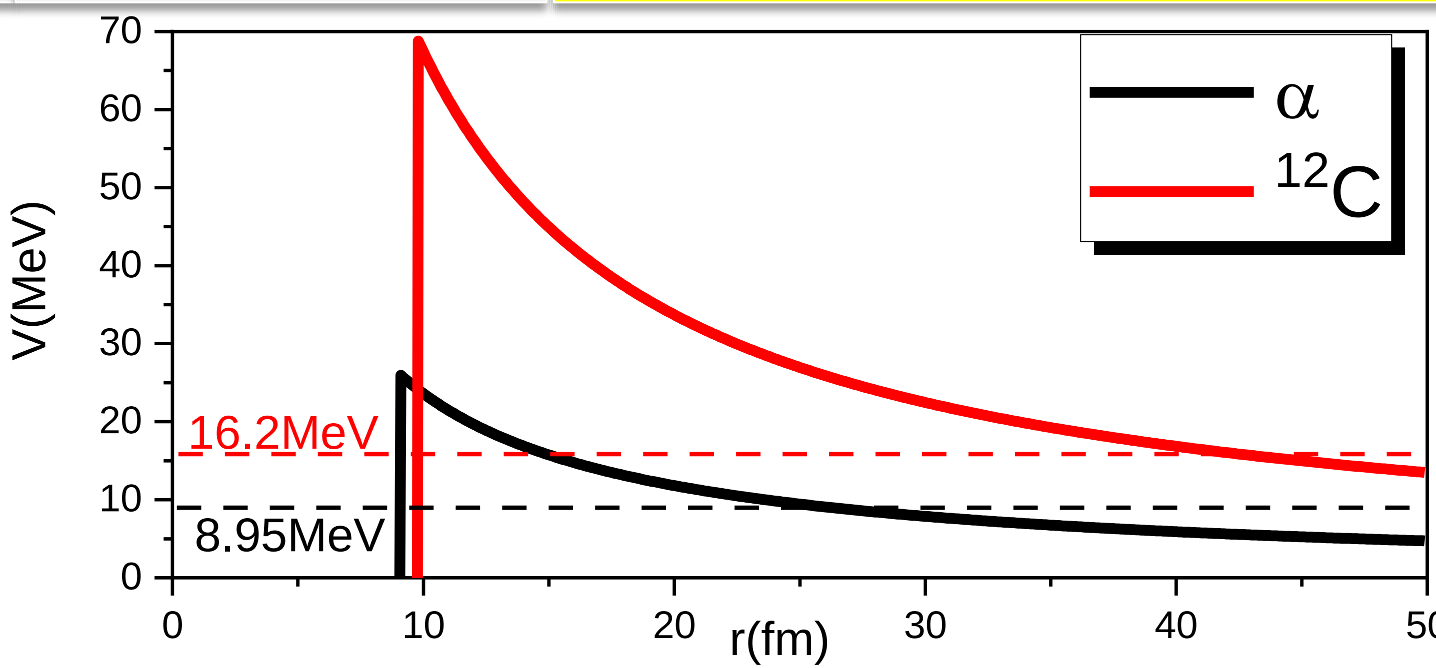
$$\boxed{\lambda = \frac{1}{2R}\sqrt{\frac{2(E_0+V_0)}{m_\alpha}}\exp\left\{-\frac{Z_Y e^2\sqrt{2m_\alpha}}{2\varepsilon_0\hbar\sqrt{E_0}} + \frac{4e\sqrt{m_\alpha R Z_Y}}{\sqrt{\pi\varepsilon_0}\hbar}\right\}}$$

$$\boxed{\log\lambda = A - B\cdot E_0^{-1/2}}$$

$$A = \log\left(\frac{1}{2R}\sqrt{\frac{2(E_0+V_0)}{m_\alpha}}\right) + \frac{4e\sqrt{m_\alpha R\, Z_Y}}{2.3\sqrt{\pi\varepsilon_0}\hbar}$$

$$B = \frac{\sqrt{2m_\alpha}Z_Y e^2}{4.6\varepsilon_0\hbar} = 1.72\times Z_Y$$

为什么是α 而不是^{12}C？



$$^{212}Po \xrightarrow{T_{1/2}=0.299\,\mu s} {}^{208}Pb + {}^{4}He$$

$$Z_Y = 82, m_\alpha = 3727\ MeV/c^2$$

$$R = 1.2\ fm \times (208^{1/3} + 4^{1/3}) = 9\ fm$$

$$b = 26.4\ fm \rightarrow \text{垒厚} b - R = 17.4\ fm$$

$$E_0 = 8.95 MeV, V_c(R) = 26.2 MeV$$

$$V_c(R) - E_0 = 17.25 MeV$$

$$^{212}Po \longrightarrow {}^{200}Pt + {}^{12}C$$

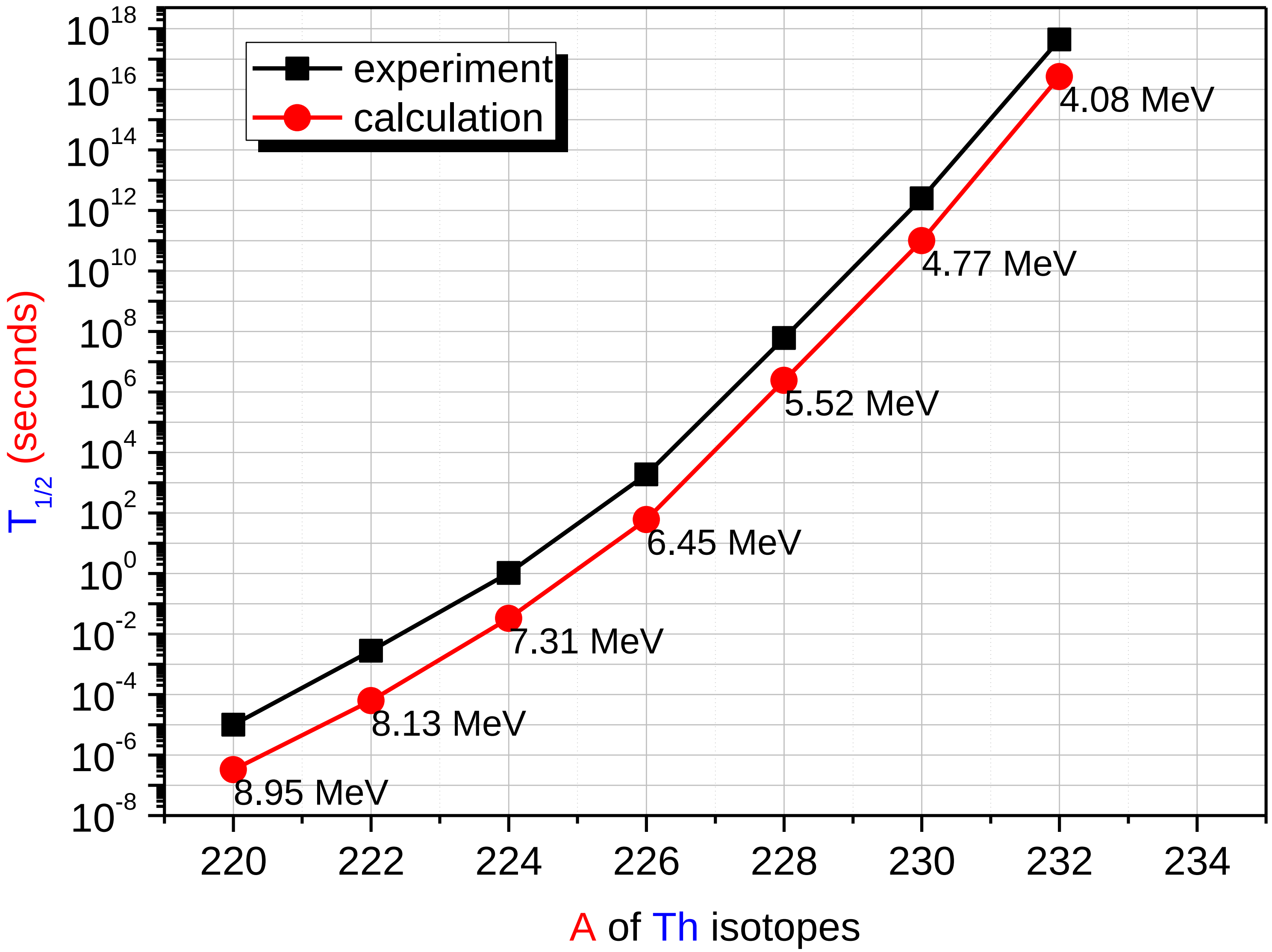
$$Z_Y = 78, m_{^{12}C} = 11175\ MeV/c^2$$

$$R = 1.2\ fm \times (200^{1/3} + 12^{1/3}) = 9.77\ fm$$

$$b = 41.6\ fm \rightarrow \text{垒厚} b - R = 31.83\ fm$$

$$E_0 = 16.2 MeV, V_c(R) = 69.0 MeV$$

$$V_c(R) - E_0 = 52.78 MeV$$

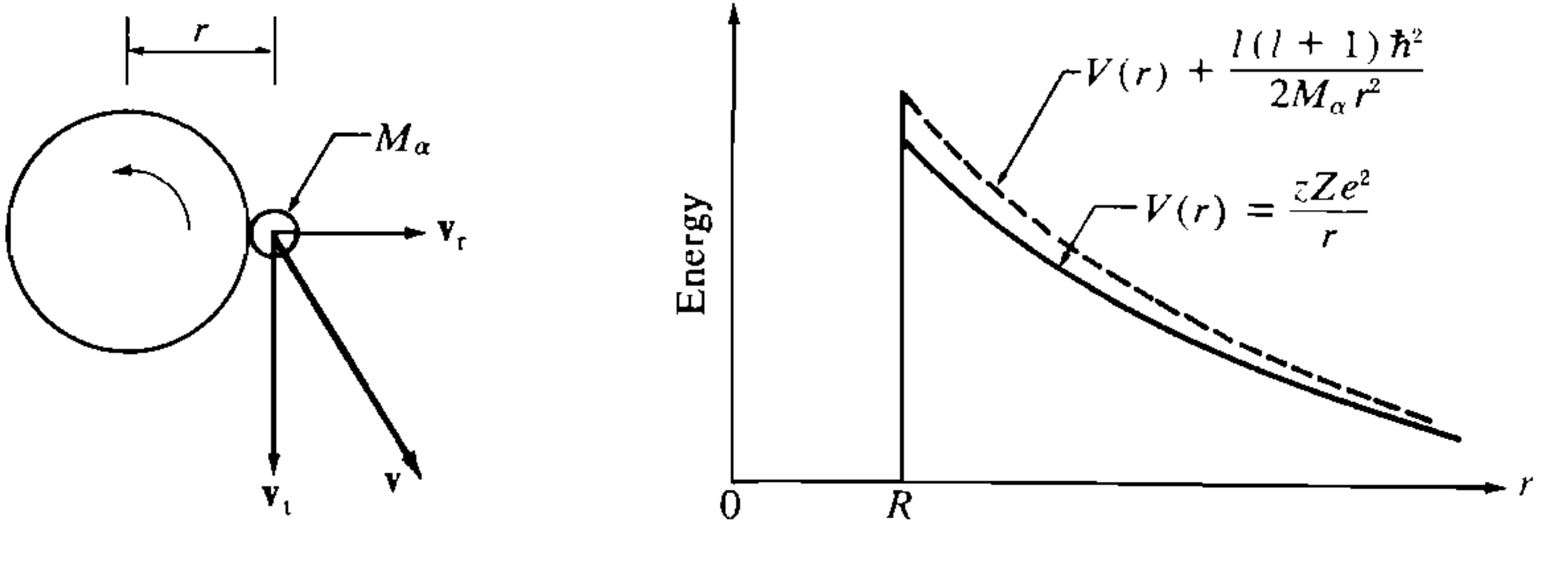

experiment
calculation
4.08 MeV
4.77 MeV
5.52 MeV
6.45 MeV
7.31 MeV
8.13 MeV
8.95 MeV
$T_{1/2}$ (seconds)
10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
220
222
224
226
228
230
232
234
A of Th isotopes

人们引入阻碍因子(Hindrance Factor)来解释这种差别，考虑：

- 形成因子：α粒子并非早已存在，是在衰变过程中产生的。
- 角动量≠0：离心势的存在使势垒加高变厚，更难穿透。
  - 偶偶核的基态角动量为0。

？但仍有矛盾……

$$F = \frac{T_{exp}}{T_{th}} = \frac{\lambda_{th}}{\lambda_{exp}}$$



(a) (b)