



核物理概论

第一章：原子核整体性质

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中山大学物理与天文学院
School of Physics and Astronomy
Sun Yat-sen University





课程介绍

▶ 参考书籍

1、主讲教材（**主讲教材尽量使用“马工程”和国家规划教材**）

《原子核物理》 杨福家、王炎森、陆福全，复旦大学出版社，2002年

2、辅助教材

《原子核物理》 卢希庭，原子能出版社，2002年

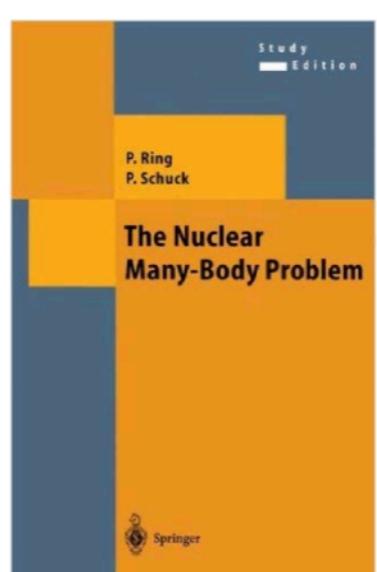
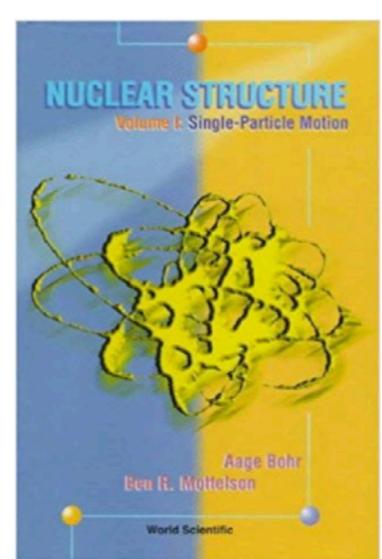
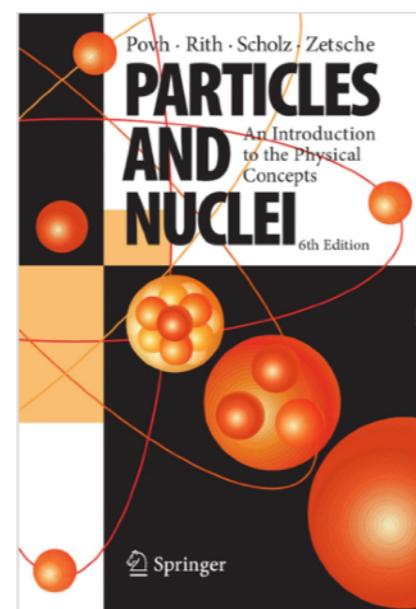
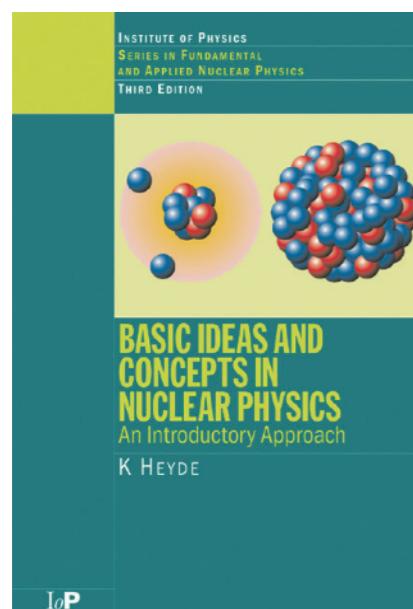
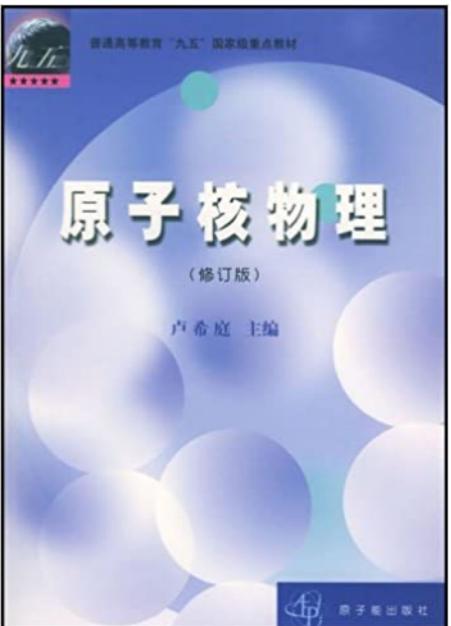
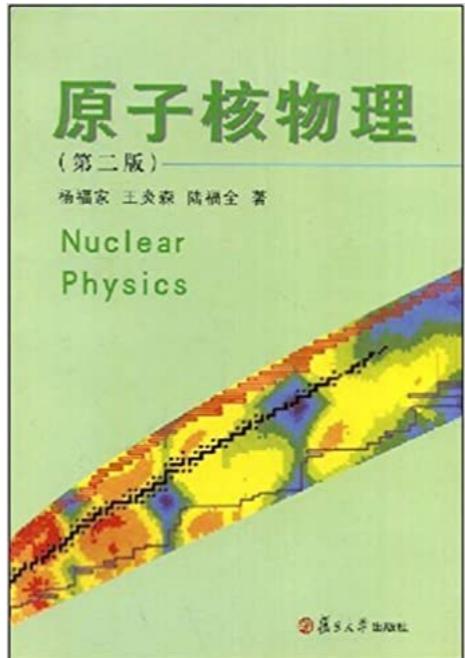
▶ Books

1. 《**Particles and Nuclei: An Introduction to the Physical Concepts**》, Bogdan Povh,

Klaus Rith, Christoph Scholz, Frank Zetsche, Werner Rodejohann,
Springer-Verlag Berlin Heidelberg, 2008

2. 《**Basic ideas and concepts in nuclear physics: An introductory approach**》, K.

Heyde, CRC Press; 3rd edition, 2004



Bohr-Mottelson

Ring-Schuck

中山大学物理与天文学院



课程介绍

► 成绩

占比：平时考核（40%）、期中作业（30%）、期末作业（30%）

平时考核：作业、课堂讨论、小组学习汇报（分工明确）



关于核物理，我们知道什么？



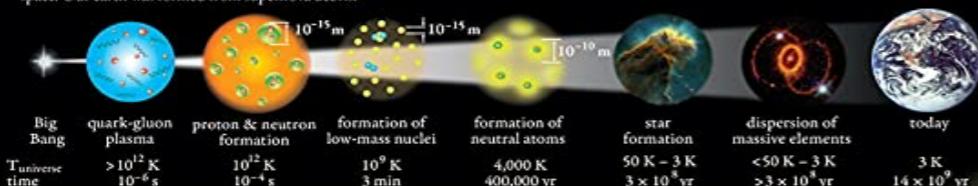


关于核物理，我们知道什么？

Nuclear Science

Expansion of the Universe

After the Big Bang, the universe expanded and cooled. At about 10^{-4} second, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. When the temperature of the Universe, $T_{universe}$, cooled to about 10^9 K, this soup coalesced into protons, neutrons, and electrons. As time progressed, some of the protons and neutrons formed deuterium, helium, and lithium nuclei. Still later, electrons combined with protons and these low-mass nuclei to form neutral atoms. Due to gravity, clouds of atoms contracted into stars, where hydrogen and helium fused into more massive chemical elements. Exploding stars (supernovae) form the most massive elements and disperse them into space. Our earth was formed from supernova debris.

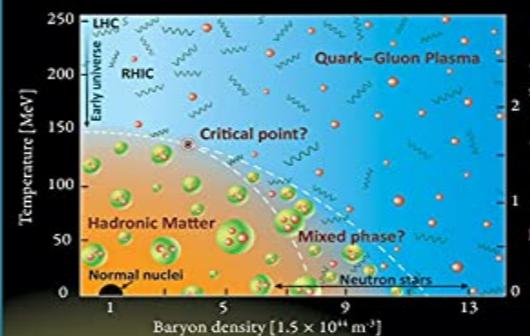


Nuclear Science is the study of the structure, properties, and interactions of the atomic nuclei. Nuclear scientists calculate and measure the masses, shapes, sizes, and decays of nuclei at rest and in collisions. They ask questions, such as: Why do nucleons stay in the nucleus? What combinations of protons and neutrons are possible? What happens when nuclei are compressed or rapidly rotated? What is the origin of the nuclei found on Earth?

Legend	electron (e^-)	quark	A mass number
proton	p	q	14 C
neutron	n	\bar{q}	Z atomic number
positron (e^+)	e^+	g	N neutron number
antineutrino ($\bar{\nu}$)	$\bar{\nu}$	γ	$A = Z + N$

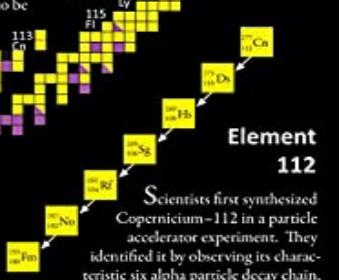
Phases of Nuclear Matter

Nuclear matter can exist in several phases. When nuclei collide at high energies, individual protons and neutrons (baryons) may evaporate from the produced nuclear fluid. At sufficiently high temperature and/or density, a gas of nucleons (orange background) forms. At even more extreme conditions, individual nucleons may cease to have meaningful identities, merging into the quark-gluon plasma (blue background). Experiments suggest the quark-gluon plasma has remarkable liquid properties.

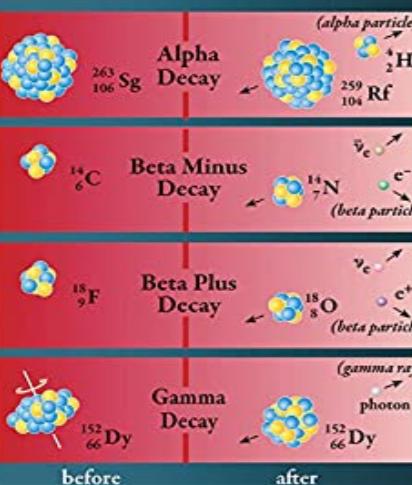


Unstable Nuclei

Stable nuclides form a narrow white band on the Chart of the Nuclides. Scientists produce unstable nuclides far from this band and study their decay, thereby learning about the extremes of nuclear conditions. In its present form, this chart contains about 2500 different nuclides. Nuclear theory predicts that there are at least 4000 more to be discovered with $Z \leq 118$.

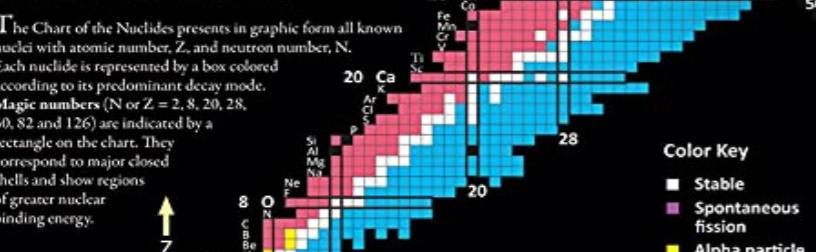


Radioactivity



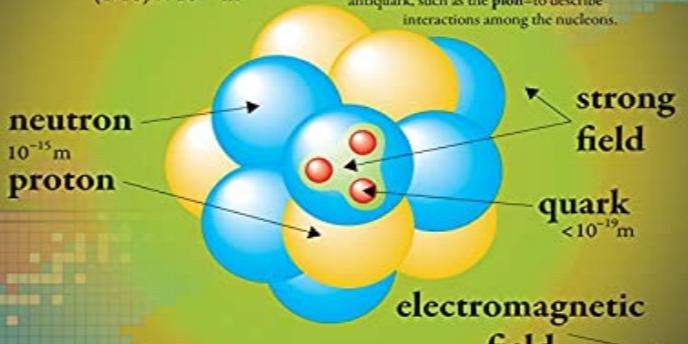
Radioactive decay transforms a nucleus by emitting different particles. In alpha decay, the nucleus releases a ${}^4_2\text{He}$ nucleus – an alpha particle. In beta decay, the nucleus either emits an electron and antineutrino (or a positron and neutrino) or captures an atomic electron and emits a neutrino. A positron is the name for the antiparticle of the electron. Antimatter is composed of anti-particles. Both alpha and beta decays change the original nucleus into a nucleus of a different chemical element. In gamma decay, the nucleus lowers its internal energy by emitting a photon – a gamma ray. This decay does not modify the chemical properties of the atom.

Chart of the Nuclides



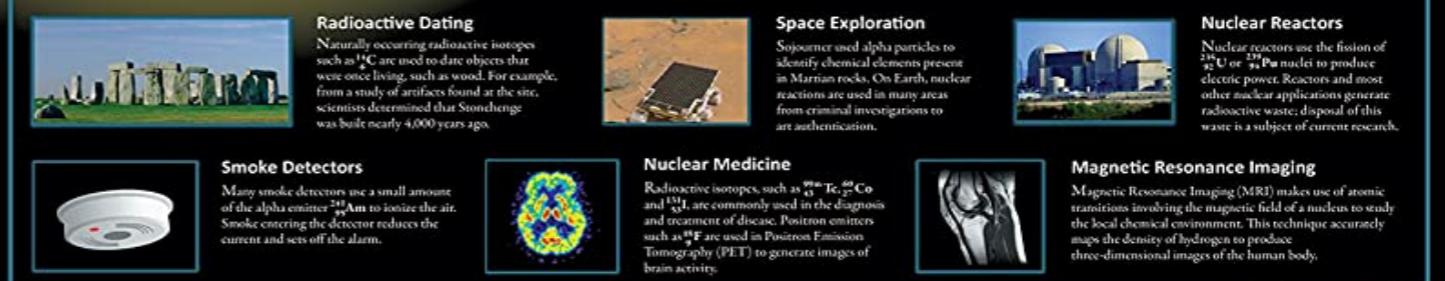
www.CPEPhysics.org

The Nucleus



In an atom, electrons range around the nucleus at distances typically up to 10,000 times the nuclear diameter. If the electron cloud were shown to scale, this chart would cover a small town.

Applications



Nuclear Reactors

Nuclear reactors use the fission of ${}^{235}\text{U}$ or ${}^{239}\text{Pu}$ nuclei to produce electric power. Reactors and most other nuclear applications generate radioactive waste; disposal of this waste is a subject of current research.



关于核物理，我们知道什么？

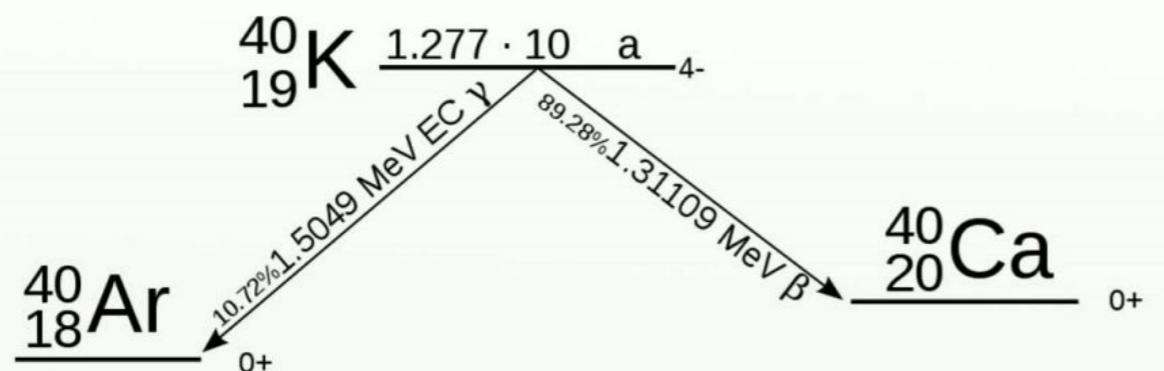
- ▶ 原子核基本组分？如何得知？
- ▶ 原子核多大？如何测定？
- ▶ 原子核哪来的？太阳与核电站都提供能源，有什么共同点和不同点？
- ▶ 自然界稳定原子核有多少？为什么只有这些？为什么“金”贵”铁“便宜？
- ▶ “点石成金”可能实现吗？
- ▶ 原子核中核子数目有上限吗？为什么？
- ▶ 核子有内部结构吗？如何知道？
- ▶ 自然界都有哪些基本粒子，参与哪些基本相互作用？
- ▶ 恒星燃烧后变成什么？他们与核物理有什么关系？
- ▶ 引力波探测项目与核物理学研究有关系吗？
- ▶ . . .



身边的核物理 (举例)



Potassium-40 →



从上面这张图中您了解到什么信息?

Calcium Ca²⁺ is found in food in different heavy isotopes, e.g. ⁴²Ca or ⁴⁴Ca.

Nutrition Facts		
Bananas		Sources include: USDA
Amount Per 100 grams ▾		
Calories 89		% Daily Value*
Total Fat 0.3 g	0%	
Saturated fat 0.1 g	0%	
Polyunsaturated fat 0.1 g		
Monounsaturated fat 0 g		
Cholesterol 0 mg	0%	
Sodium 1 mg	0%	
Potassium 358 mg	10%	
Total Carbohydrate 23 g	7%	
Dietary fiber 2.6 g	10%	
Sugar 12 g		
Protein 1.1 g	2%	
Vitamin A 1%	Vitamin C 14%	
Calcium 0%	Iron 1%	
Vitamin D 0%	Vitamin B-6 20%	
Cobalamin 0%	Magnesium 6%	

*Per cent Daily Values are based on a 2,000 calorie diet.



身边的核物理 (举例)

全身受照射剂量可能发生的效应：

(1) 0-0.25希伏没有显著的伤害；

(2) 0.25-0.50希伏可以引起血液的变化，但无严重伤害；

(3) 0.50-1.0希伏血球发生变化且有一些损害，但无疲劳感；

(4) 1.0-2.0希伏有损伤，而且可能感到全身无力；

(5) 2.0-4.0希伏有损伤，全身无力，体弱者可能死亡；

(6) 4.0希伏50%的致命伤；

(7) 6.0希伏以上可能因此而死亡。 [2]

辐射剂量 (mSv)	影响和标准
0.001	手足X射线照相
0.001	骨密度X射线检查
0.005–0.01	口腔X射线照相
0.01	四肢X射线照相
0.02–0.1	做一次X射线胸部摄影的剂量。另说为0.9mSv [7]
0.2	乘飞机从东京到纽约之间往返一次的剂量（宇宙射线和飞行高度有关）。
0.4	筛查乳腺癌的钼靶检查 (MAMMOGRAM)
0.54	腹部X射线照相
0.66	骨盆X射线照相
1.0	一般公众一年工作所受人工放射剂量 (ICRP推荐) 从事辐射相关工作的妇女从被告知怀孕到临产所受人工放射剂量上限。

10 个香蕉

1000个香蕉

1.2	与1天平均吸1.5盒 (30支) 纸烟同居的被动吸烟者一年累计辐射 [8]。
1.5	日本人一年累计所受自然辐射。
1.5	腰椎X射线照相
1.5	胸部低剂量CT筛查
2.0	从事辐射相关工作的妇女从被告知怀孕到临产腹部表面所受人工放射剂量极限。
2.0	1次头部CT检查
2.4	地球人平均一年累计所受辐射 (宇宙射线0.4, 大地0.5, 氡1.2, 食物0.3)
2.5–4	一次胃部X射线钡餐透视的剂量。
5	从事辐射相关的妇女工作者一年累计所受辐射法定极限。
6	上消化道X射线检查
6.9	1次胸部CT检查
7.1	做一次X射线胸部透视的剂量。 [7]
8	下消化道X射线检查
10	日本原子力安全委员会所制定「室内避难」的辐射剂量。
10	一次腹腔骨盆CT检查
10 – 20	全身CT检查
13 – 60	1天平均吸1.5盒 (30支) 纸烟者一年累计 [8][9]。
20	放射性职业工作者一年累积全身受职业照射的上限 (ICRP推荐)
50	从事辐射相关工作者 (非女性) 一年累计所受辐射旧标准规定的上限。 日本原子力安全委员会所制定「避难」的辐射剂量。 自卫队员, 消防员, 警察 (妇女除外) 一年累计所受辐射法定极限。
100	已证明对人健康明显有害的辐射剂量极限 从事辐射相关工作者 (非女性) 五年累计所受辐射法定极限。 从事辐射相关工作者 (非女性) 在紧急情况下从事一次作业所受辐射法定极限 [10]。
250	福岛第一核电站事故 现场人员暂定辐射剂量上限。 白细胞减少。
500	淋巴细胞减少。 国际放射防护委员会 规定除人命救援外所能承受的辐射极限。
500	放射性职业工作者一年累积局部 (如皮肤、手、足) 受职业照射的上限 (ICRP推荐)
1,000	出现被辐射症状。恶心, 呕吐。水晶体浑浊。
2,000	细胞组织遭破坏, 内部出血, 脱毛脱发。死亡率5%。
3,000 – 5,000	死亡率50% (局部被辐射时3,000 : 脱毛脱发、4,000 : 失去生育能力、5,000 : 白内障、皮膚出現紅斑) [11]。
7,000 – 10,000	死亡率99%。
10,001以上	死亡率99.9%。
50,000	死亡率100%。

10次胸透

100次胸透

15次全身CT

100次全身CT



主要内容

◆ 原子核的结合能

- ▶ 原子核基本组分
- ▶ 原子核的结合能
- ▶ 液滴模型

◆ 原子核的状态量子数

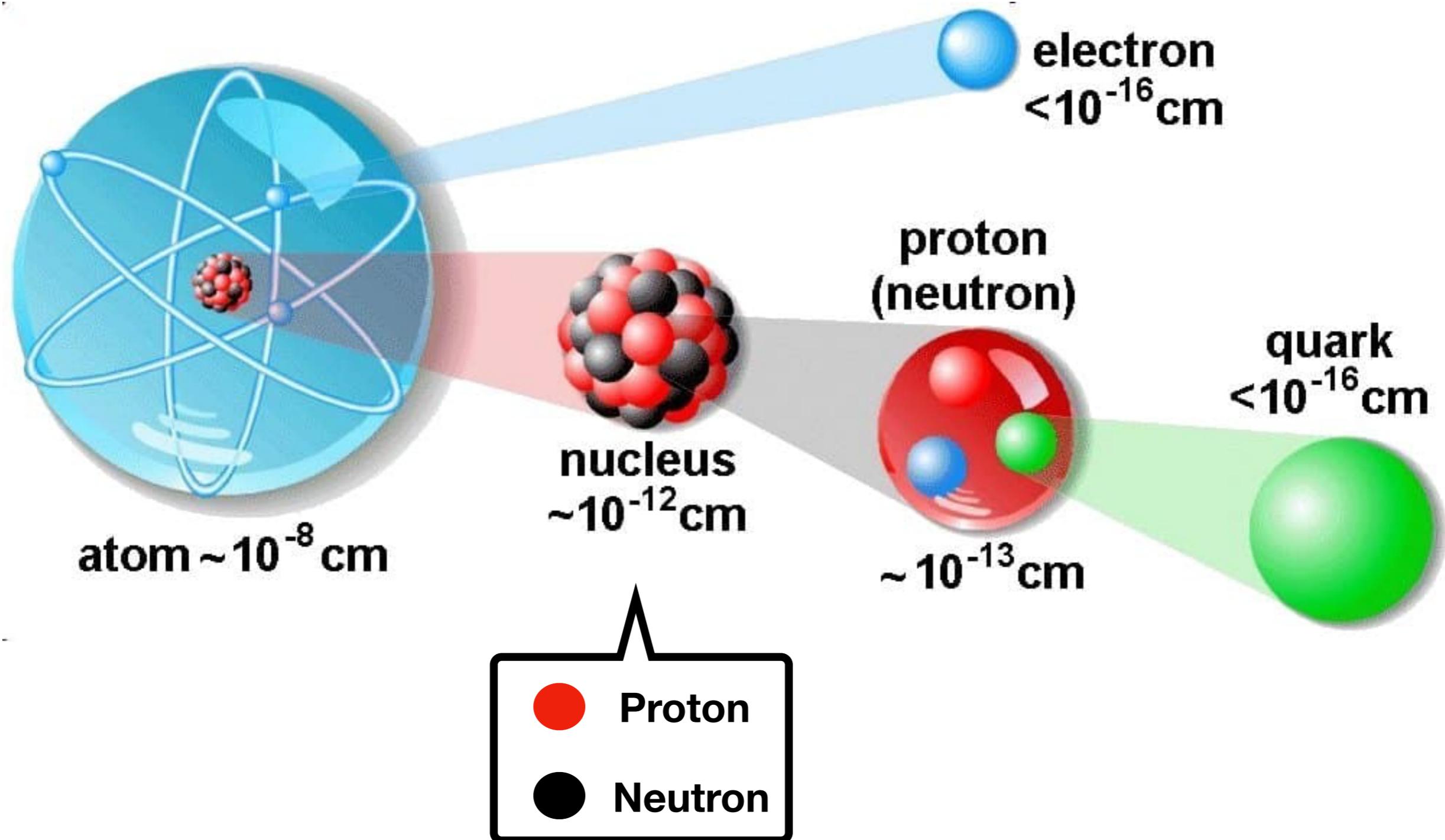
- ▶ 原子核的自旋宇称
- ▶ 原子核的同位旋

◆ 原子核的电磁矩

- ▶ 原子核的电多极矩
- ▶ 原子核的磁多极矩

原子核的基本组分

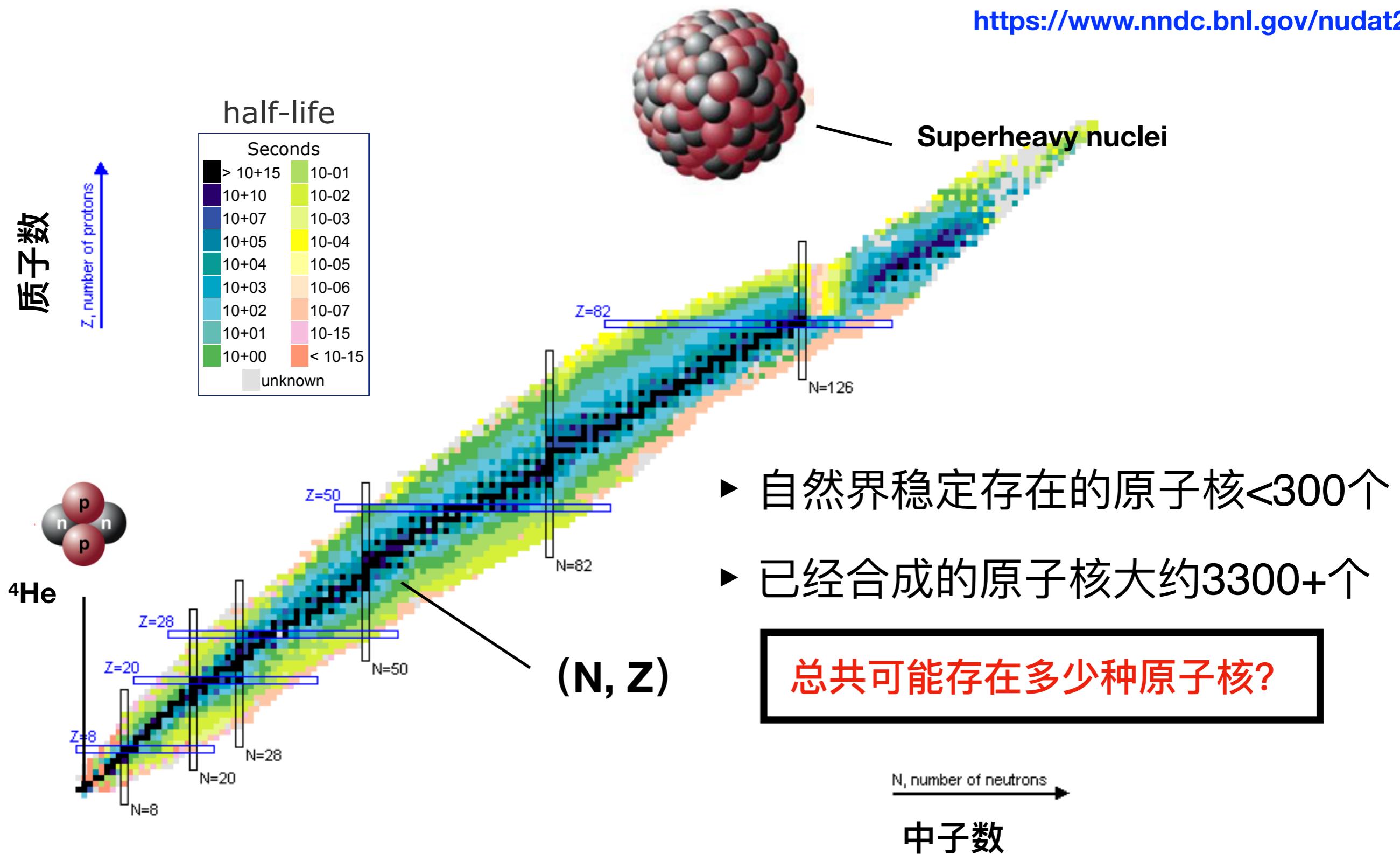
- ▶ 原子核由核子（质子、中子）组成



原子核的基本组分

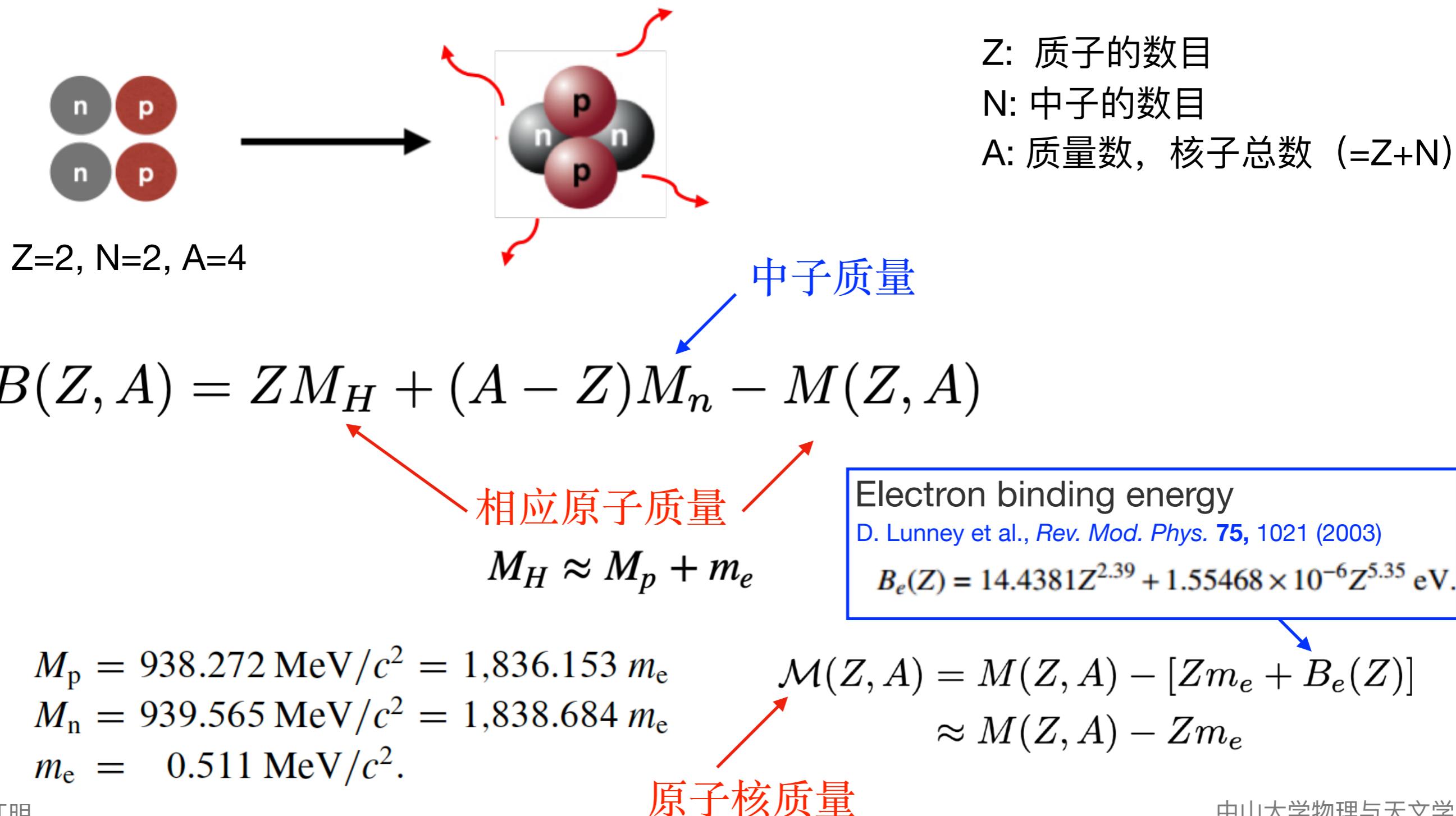


<https://www.nndc.bnl.gov/nudat2/>



原子核的结合能

► 原子核结合能：核子由自由状态结合成束缚的原子核放出的能量





原子核的结合能

- ▶ 原子（核）质量（Nuclear Mass）：

$$M(Z, A) = ZM_H + (A - Z)M_n - B(Z, A)$$

- ▶ 原子（核）质量过剩（Mass excess）：

$$\Delta M(Z, A) = M(A, Z) - Am_u$$

Atomic Mass for ^{12}C : 11177.926272 [MeV]

1 u : 931.493856 [MeV]

Mass excess for ^{12}C : 0.0 [MeV]

<http://amdc.impcas.ac.cn/web/masseval.html>

原子质量单位 (u): ^{12}C 原子质量/12

For ^{12}C , $\Delta M(Z, A) = 0$



Atomic Mass Evaluation - AME 2020

in [Chinese Phys. C 45, 030002 \(2021\)](#) and [Chinese Phys. C 45, 030003 \(2021\)](#).

原子核的结合能

► 原子核结合能实验数据



<https://www.nndc.bnl.gov>



<https://waww-nds.iaea.org/amdc/>



<http://www.nuclear.csdb.cn>

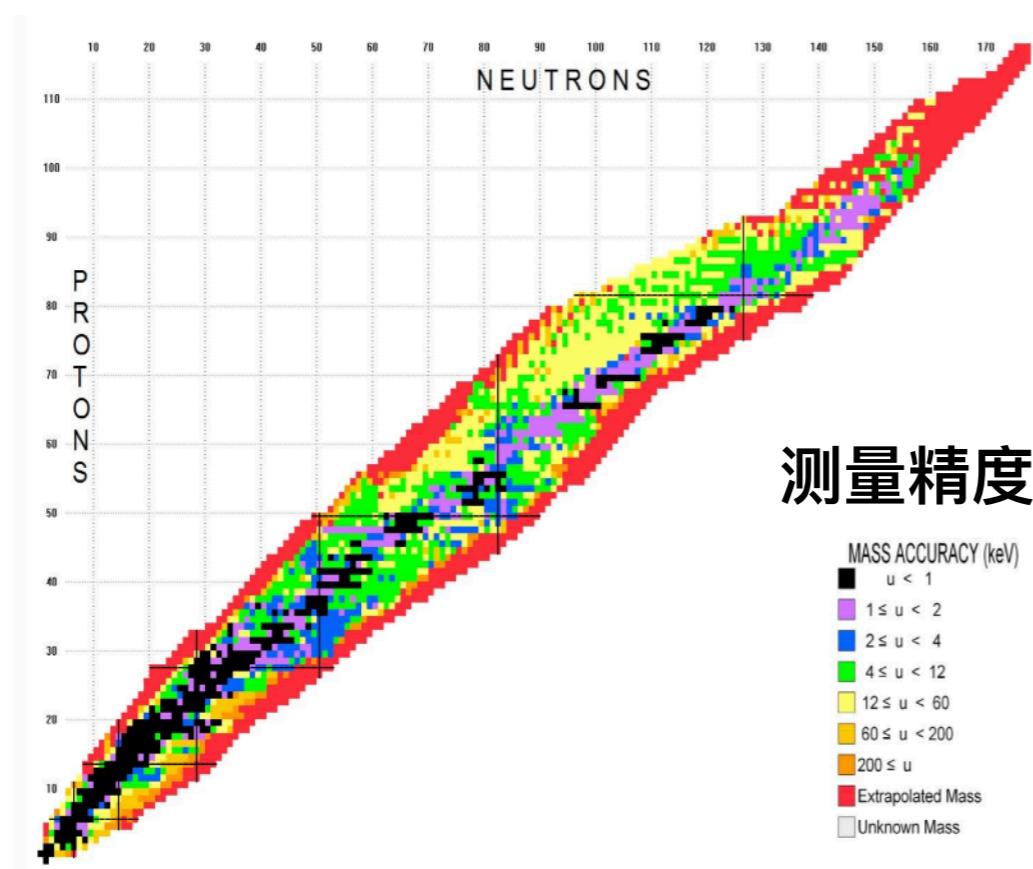
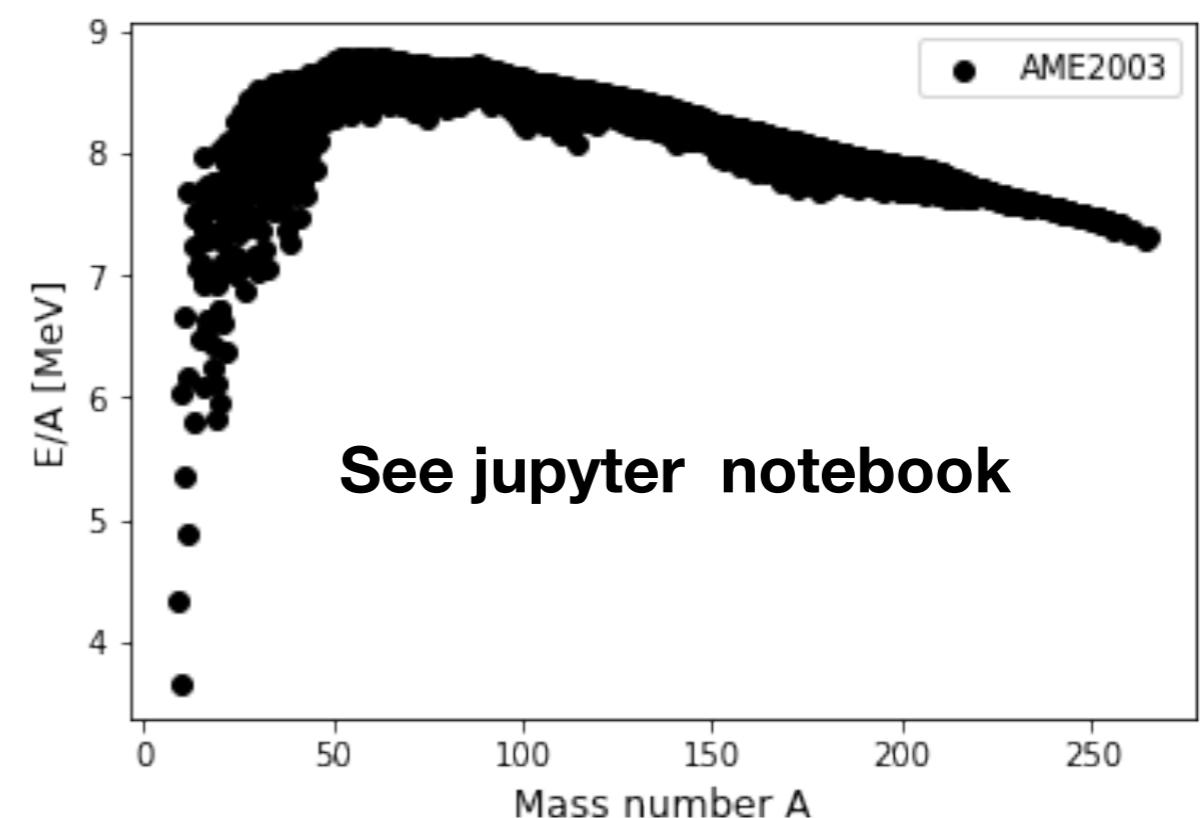


Figure 1. Chart of the nuclides displaying the accuracy 'u' of masses (created by NUCLEUS-AMDC).



原子核的结合能

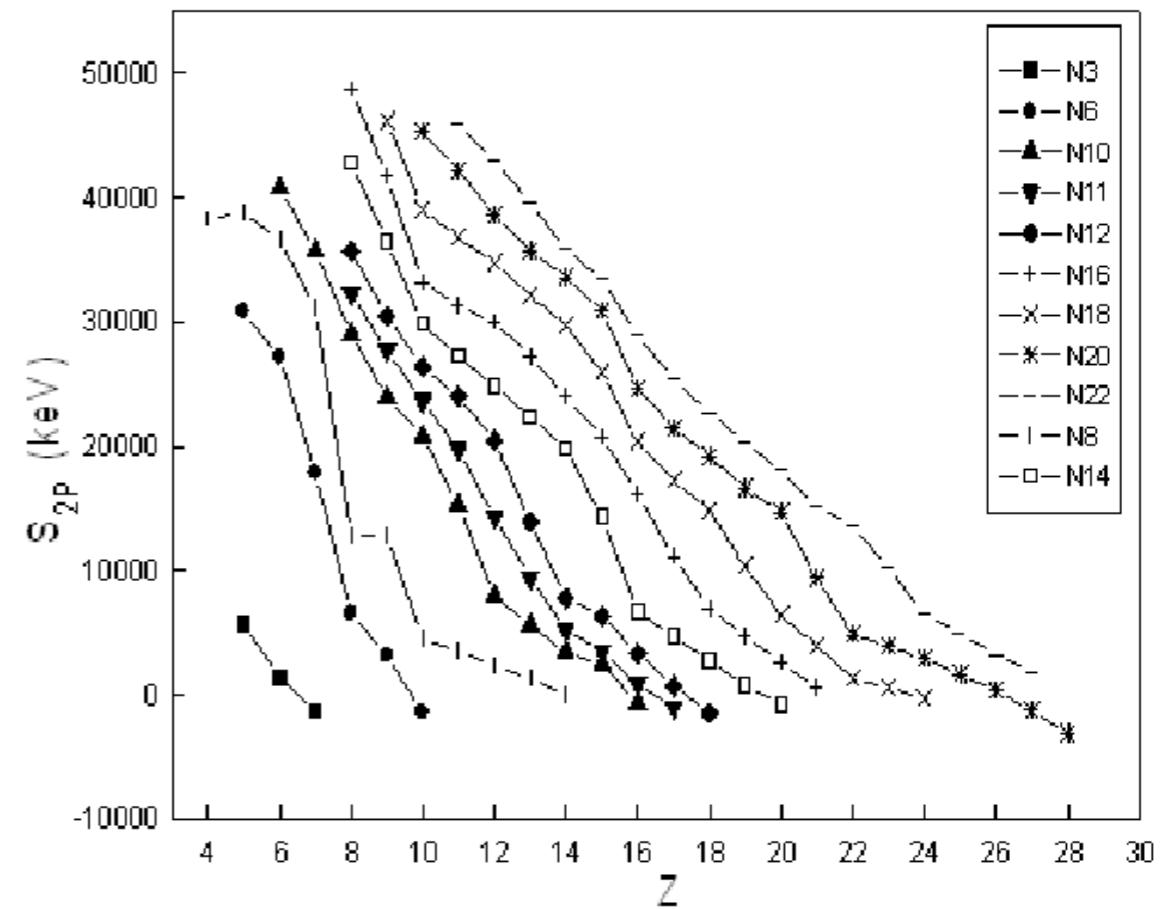
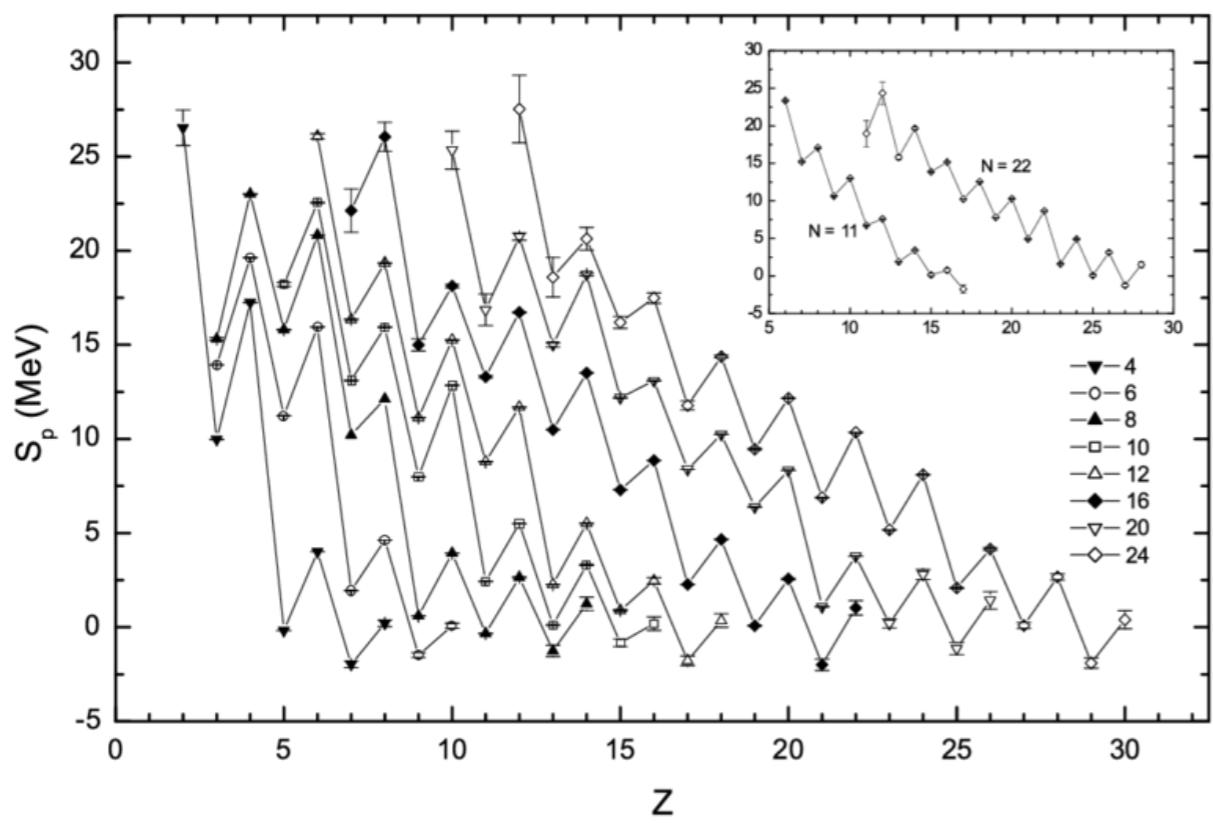
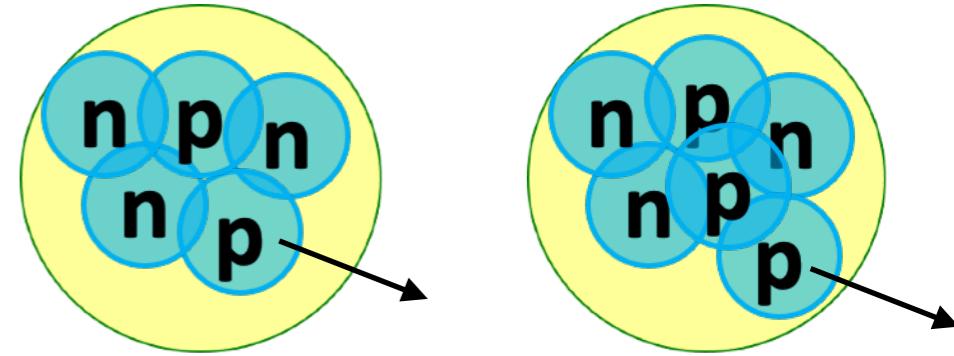
► 质子分离能

单质子分离能 S_p :

$$S_p = B(A, Z) - B(A - 1, Z - 1)$$

双质子分离能 S_{2p} :

$$S_{2p} = B(A, Z) - B(A - 2, Z - 2)$$



- Z 为偶数原子核的单质子 $>$ Z 为奇数原子核的单质子 (配对效应)。
- 双质子分离能在原子核具有某些 Z 数值时下降迅速 (壳结构效应)。

原子核的结合能

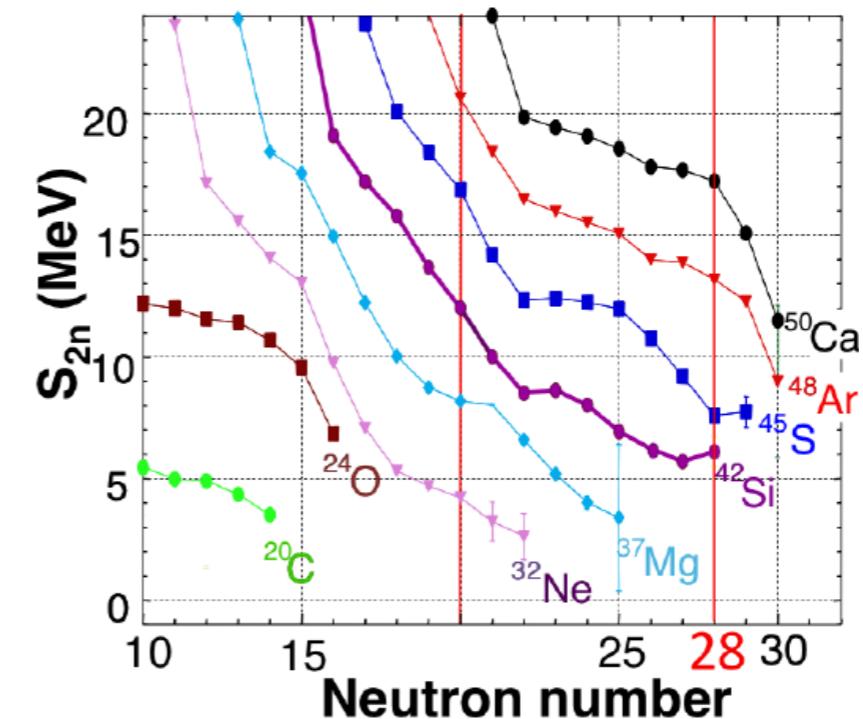
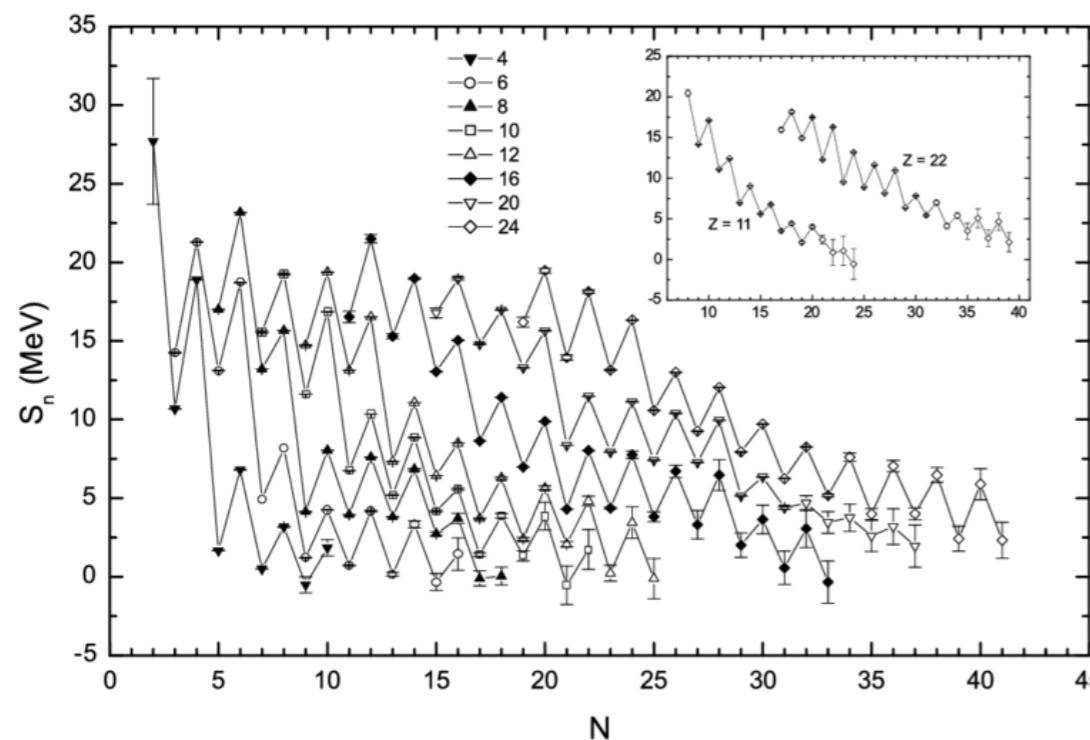
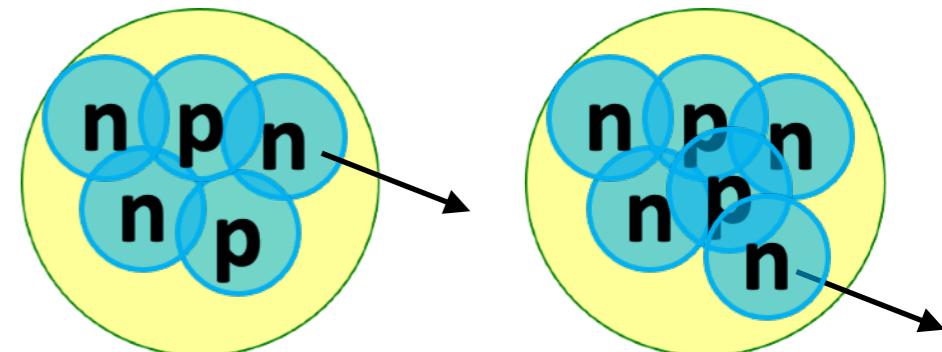
► 中子分离能

单中子分离能 S_n :

$$S_n = B(A, Z) - B(A - 1, Z)$$

双中子分离能 S_{2n} :

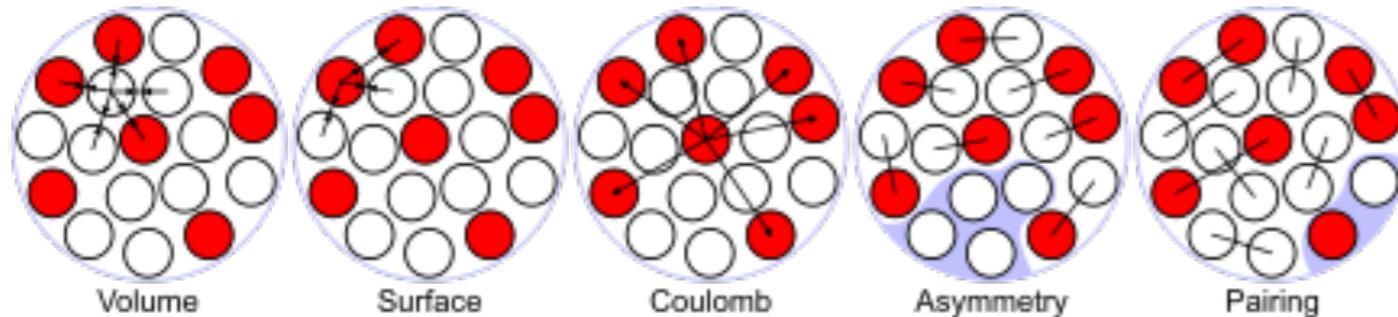
$$S_{2n} = B(A, Z) - B(A - 2, Z)$$



- N 为偶数原子核的单中子 $>$ N 为奇数原子核的单中子 (配对效应)。
- 双中子分离能在原子核具有某些 N 数值时下降迅速 (壳结构效应)。

原子核的液滴模型

► Weizsäcker 公式 (半经验质量公式) :

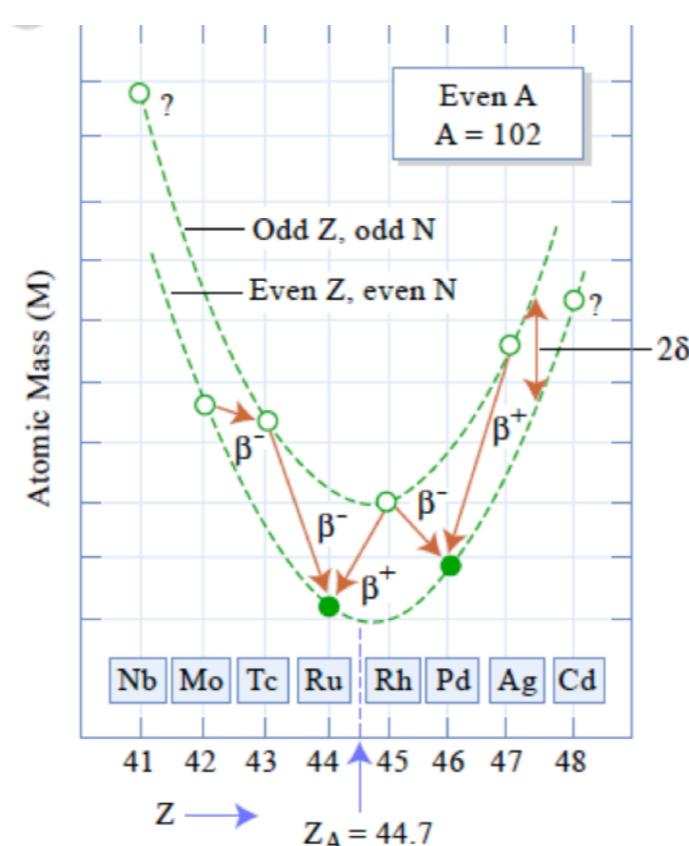


The Semi-Empirical Mass Formula

$$B(A, Z) = a_V \cdot A - a_S \cdot A^{2/3} - a_C \cdot \frac{Z \cdot (Z - 1)}{A^{1/3}} - a_{asym} \cdot \frac{(A - 2Z)^2}{A} + a_{pair} \cdot \frac{\delta}{A^{1/2}}$$

参数化:

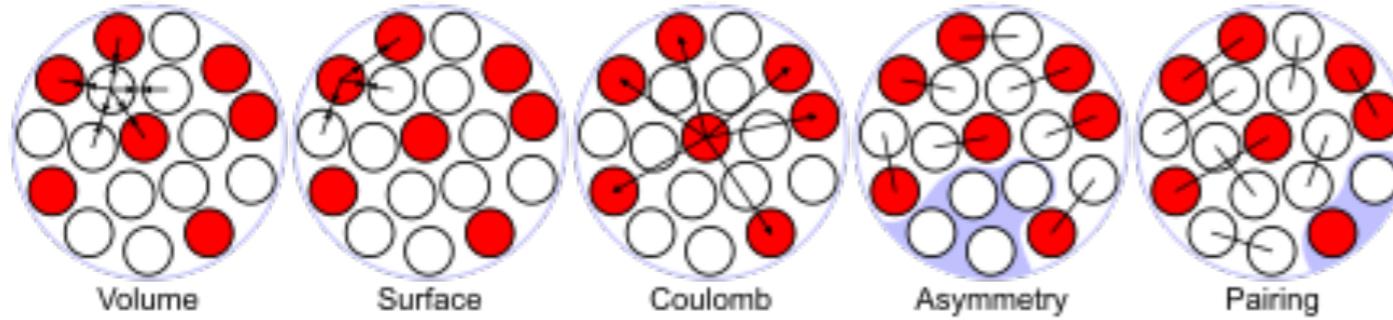
a_V	15.85 MeV
a_S	18.34 MeV
a_C	0.71 MeV
a_{asym}	23.21 MeV
a_{pair}	12 MeV



$$\delta = \begin{cases} +1 & \text{for even-even nuclei} \\ 0 & \text{for odd-even nuclei} \\ -1 & \text{for odd-odd nuclei} \end{cases}$$

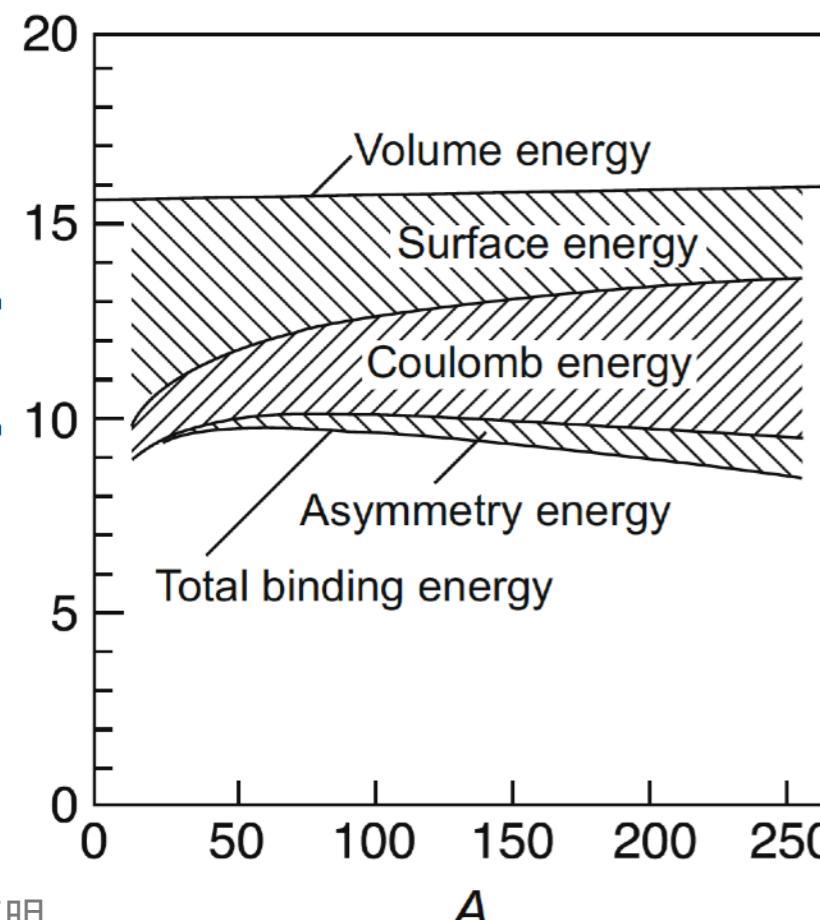
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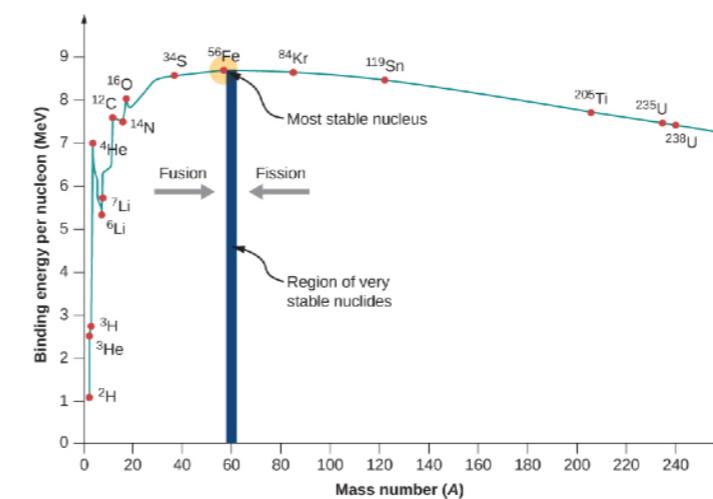
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体积能
表面能
库伦能
对称能
总能量

$$\delta = \begin{cases} +1 & \text{for even-even nuclei} \\ 0 & \text{for odd-even nuclei} \\ -1 & \text{for odd-odd nuclei} \end{cases}$$



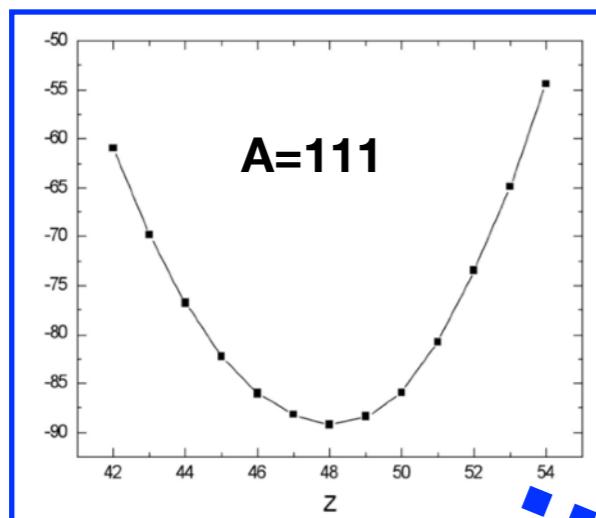
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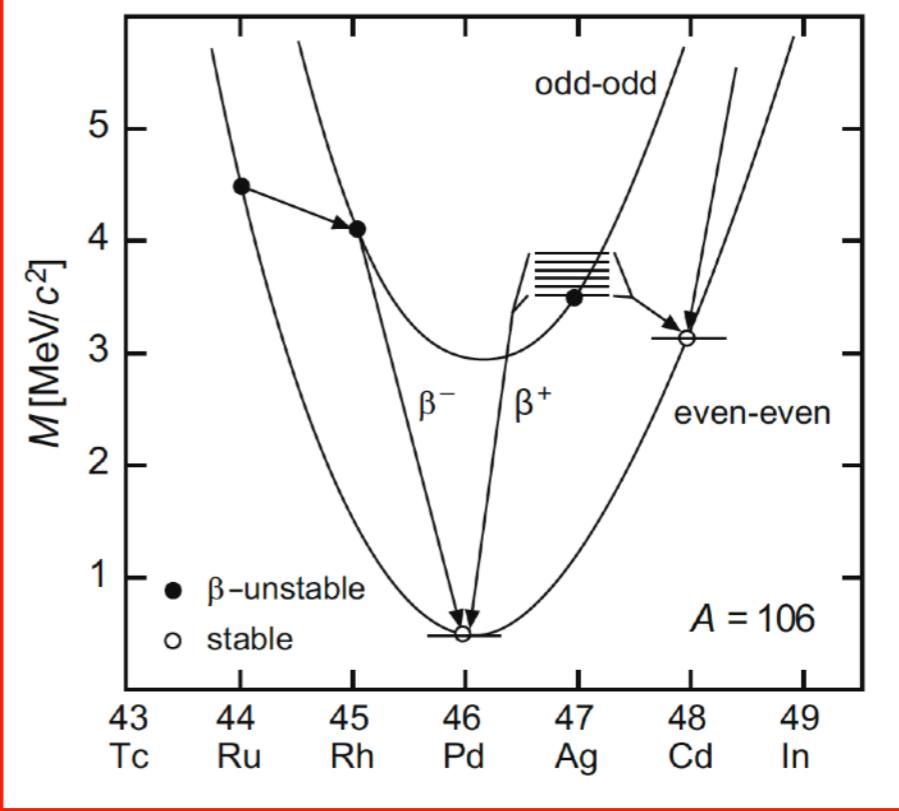
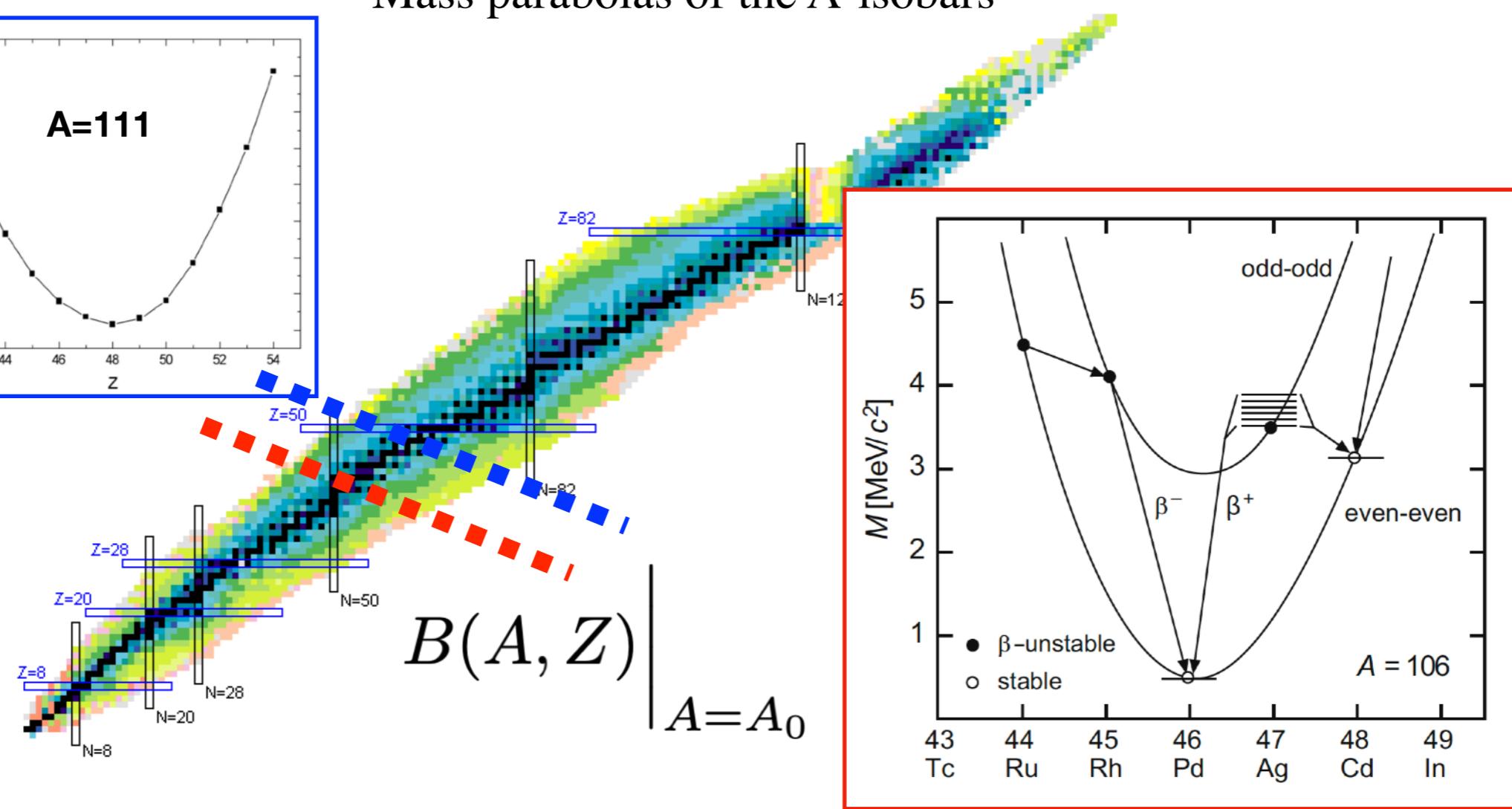
The Semi-Empirical Mass Formula

$$B(A, Z) = a_V \cdot A - a_S \cdot A^{2/3} - a_C \cdot \frac{Z \cdot (Z - 1)}{A^{1/3}} - a_{asym} \cdot \frac{(A - 2Z)^2}{A} + a_{pair} \cdot \frac{\delta}{A^{1/2}}$$

Odd-even nuclei



Mass parabolas of the A-isobars



原子核的液滴模型

► Weizsäcker 公式 (半经验质量公式) :

The Semi-Empirical Mass Formula

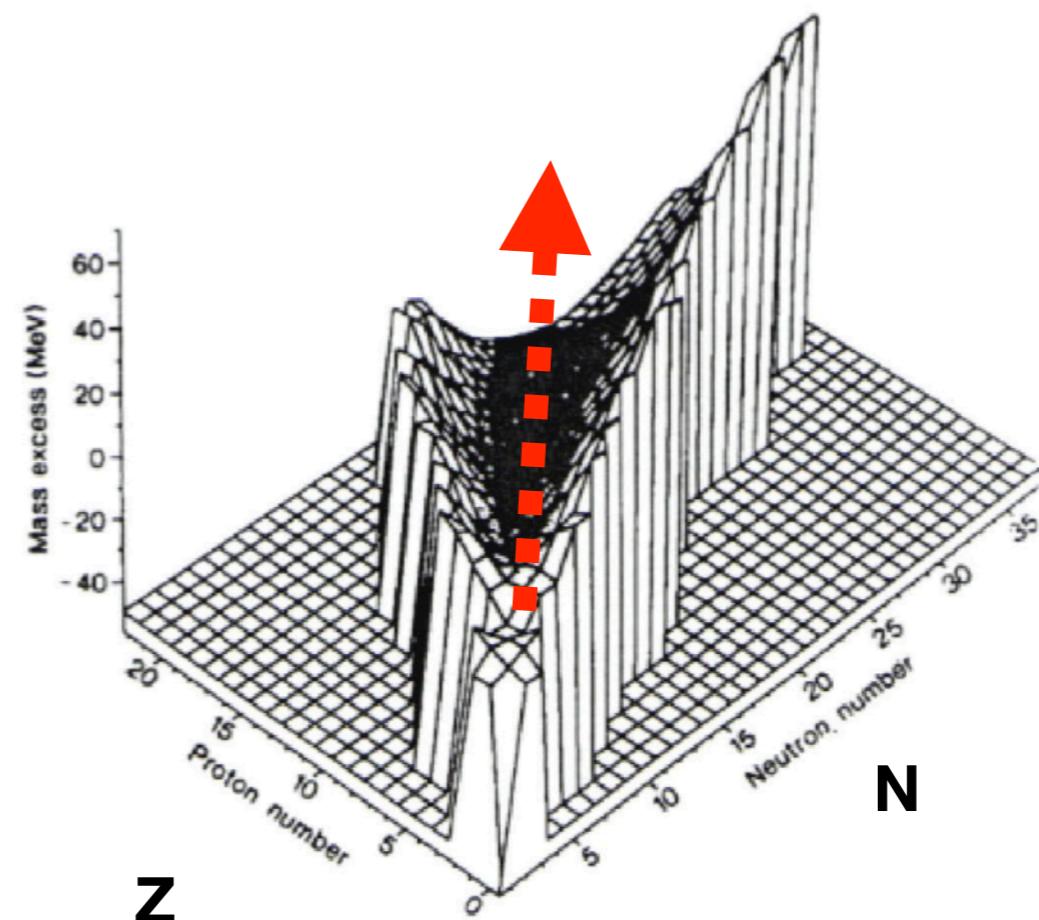
$$B(A, Z) = a_V \cdot A - a_S \cdot A^{2/3} - a_C \cdot \frac{Z \cdot (Z - 1)}{A^{1/3}} - a_{asym} \cdot \frac{(A - 2Z)^2}{A} + a_{pair} \cdot \frac{\delta}{A^{1/2}}$$

$$\left. \frac{\partial B(A, Z)}{\partial Z} \right|_{A=A_0} = 0$$

Beta-stability line

$$Z = \frac{A_0}{1.98 + 0.0155A_0^{2/3}}$$

Depends on parameterization
(Homework)





原子核的液滴模型

The most tightly bound nucleus

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In many textbooks,^{1,2} we are told that ⁵⁶Fe is the nuclide with the greatest binding energy per nucleon, and therefore is the most stable nucleus, the heaviest that can be formed by fusion in normal stars.

But we calculate the binding energy per nucleon BE/A , for a nucleus of mass number A , by the usual formula,

$$BE/A = (1/A)(Zm_H + Nm_n - M_{atom})c^2. \quad (1)$$

where m_H is the hydrogen atomic mass and m_n is the neutron mass, for the nuclides ⁵⁶Fe and ⁶²Ni (both are stable) using data from Wapstra and Audi.³ The results are 8.790 MeV/nucleon for ⁵⁶Fe and 8.795 MeV/nucleon for ⁶²Ni. The difference,

$(0.005 \text{ MeV/nucleon})(\approx 60 \text{ nucleons}) = 300 \text{ keV}. \quad (2)$

is much too large to be accounted for as the binding energy of the two extra electrons in ⁶²Ni over the 26 electrons in ⁵⁶Fe.

⁵⁶Fe is readily produced in old stars as the end product of the silicon-burning series of reactions.⁴ How, then, do we explain the relative cosmic deficiency of ⁶²Ni compared with ⁵⁶Fe? In order to be abundant, it is not enough that ⁶²Ni be the most stable nucleus. To be formed by charged-particle fusion (the energy source in normal stars), a reaction must be available to bridge the gap from ⁵⁶Fe to ⁶²Ni.

To accomplish this with a single fusion requires a nuclide with $Z = 2$, $A = 6$. But no such stable nuclide exists. The other possibility is two sequential fusions with ¹H, producing first ⁵⁹Co then ⁶²Ni. However, the ¹H nucleus is unstable and is not expected to be present in old stars synthesizing heavy elements. We are aware that there are element-generating processes other than charged-particle fusion, such as processes involving neutron capture, which could generate nickel. However, these processes apparently do not occur in normal stars, but rather in supernovas and post-supernova phases, which we do not address.

We conclude that ⁵⁶Fe is the end product of normal stellar fusion not because it is the most tightly bound nucleus, which it is not, but that it is in close, but unbridgeable, proximity to ⁶²Ni, which is the most tightly bound nucleus.

¹Arthur Beiser, *Concepts of Modern Physics* (McGraw-Hill, New York, 1987), 4th ed., p. 421

²Frank Shu, *The Physical Universe* (University Science Books, Mill Valley, CA, 1982), 1st ed., pp. 116–117

³Donald D. Clayton, *Principles of Stellar Evolution and Nucleosynthesis* (McGraw-Hill, New York, 1968), p. 518

⁴A. H. Wapstra and G. Audi, *Nucl. Phys. A* **432**, 1 (1985).

⁵William K. Rose, *Astrophysics* (Holt, Rinehart and Winston, New York, 1973), p. 186



核物理概论：原子核整体性质



原子核的状态量子数

► 原子核的自旋、宇称 J^π

$$\hat{J} = \sum_{i=1}^A \hat{j}_i,$$

单个核子自旋矢量叠加 $\hat{j} = \hat{\ell} + \hat{s},$

$$\pi = (-1)^{\sum_i l_i}$$

基态自旋宇称：

偶偶核：0+

奇偶核：半整数自旋

奇奇核：整数自旋

$$\hat{J} = \hat{j}_p + \hat{j}_n.$$

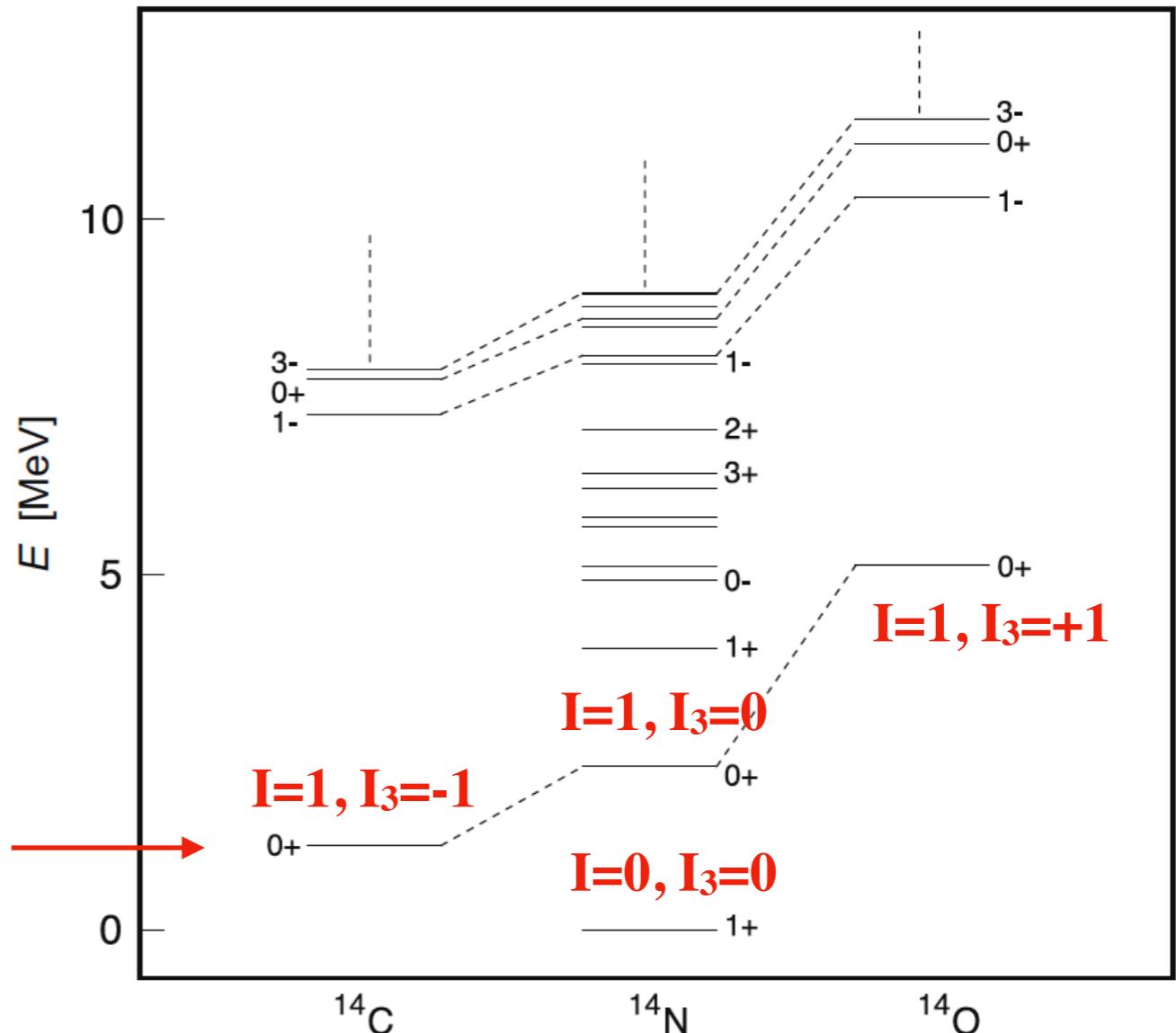
原子核的状态量子数

► 原子核的同位旋 $|II_3\rangle$

$$I_3^{\text{nucleus}} = \sum I_3^{\text{nucleon}} = \frac{Z-N}{2}.$$

Nucleon : $I = 1/2$ $\begin{cases} \text{proton} : I_3 = +1/2 \\ \text{neutron} : I_3 = -1/2. \end{cases}$

A=14 同质异位素 (isobars)



I=1 同位旋三重态

原子核的电磁矩

► 原子核的磁偶极矩

- 经典物理，环型电流产生磁矩

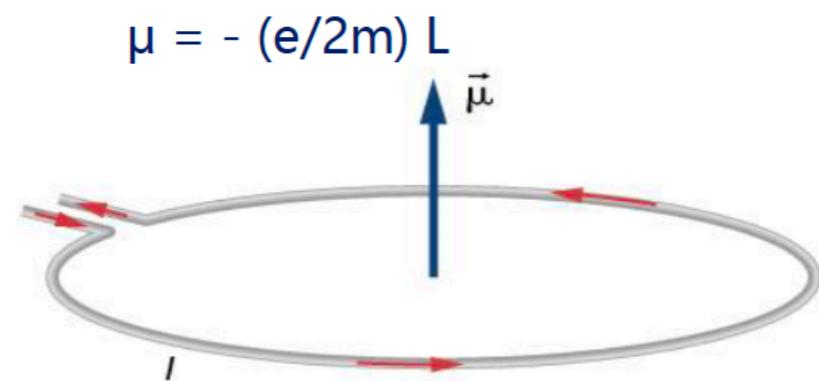
$$\mu = I A \quad I - \text{环型电流}, \quad A - \text{电流包围的面积}$$

- 考虑电荷 q 的粒子做圆周运动 (角动量 $L = r \times p$)，电流

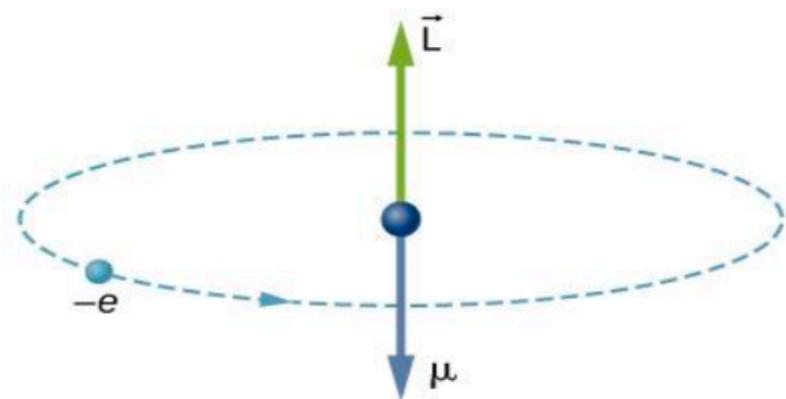
$$I = \frac{q}{t} = \frac{q}{2\pi r/v} = \frac{qv}{2\pi r}$$

$$\mu = IA = \frac{qv}{2\pi r} \pi r^2 = \frac{qvr}{2} = \frac{q}{2m} (mv r) = \frac{q}{2m} L$$

- 电子轨道磁矩



(a) Current-carrying loop



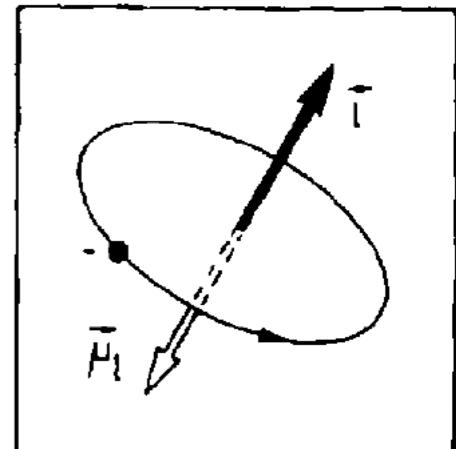
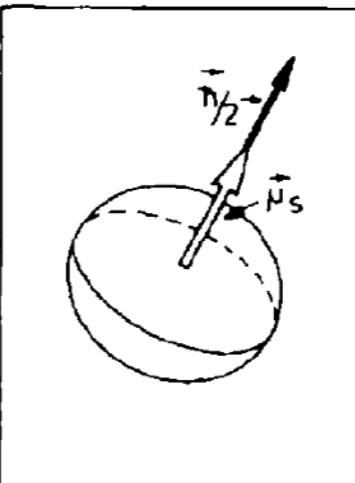
(b) Hydrogen atom

原子核的电磁矩

► 原子核的磁偶极矩

- 电子轨道磁矩

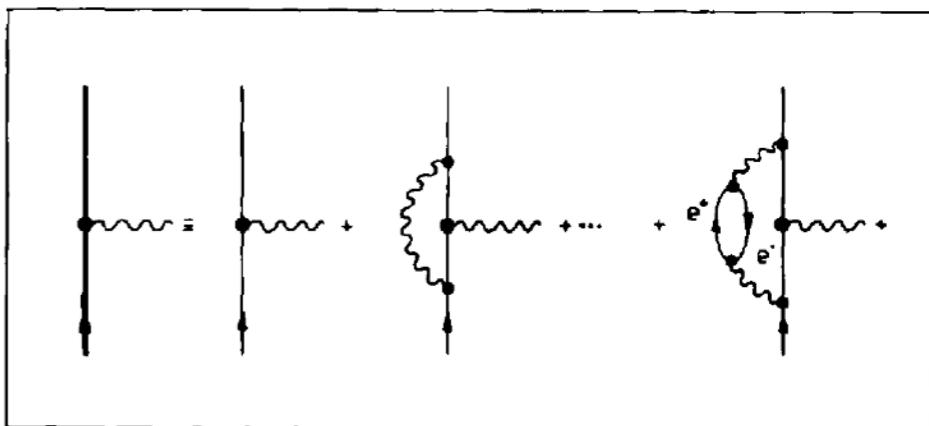
$$\mu = - (e/2m) \mathbf{L}$$



- 电子自旋磁矩

$$\mu = - (e/2m) g \mathbf{S}$$

In the QED leading order, $g=2$



- 电子反常磁矩 (anomalous magnetic moment)

$$a = (g-2)/2$$

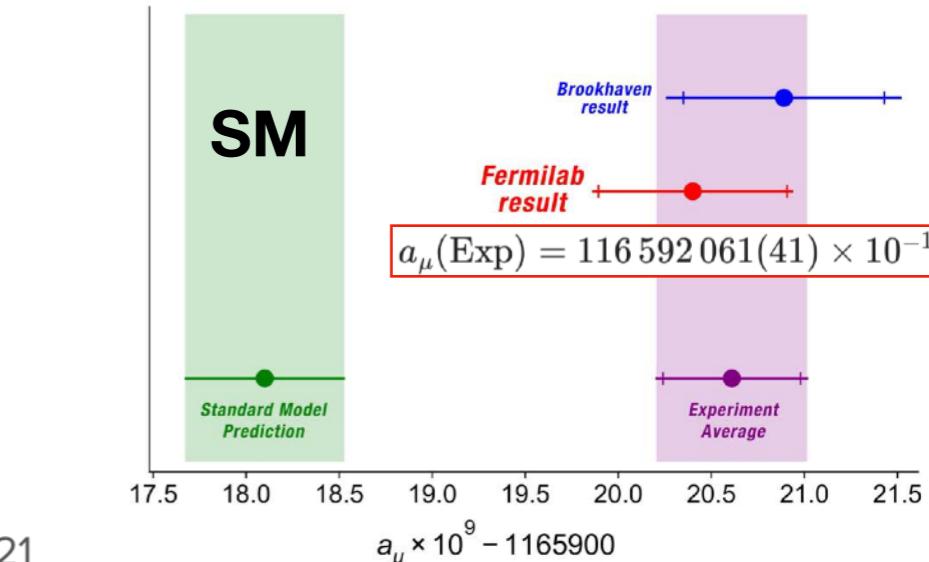
$$a_e^{\text{th}} = \frac{1}{2} \left(\frac{\alpha}{\pi} \right) - 0.328479 \left(\frac{\alpha}{\pi} \right)^2 + 1.29 \left(\frac{\alpha}{\pi} \right)^3.$$

- QED最大成就: $a_e(\text{SM}) = 1.15965218188(78) \times 10^{-3}$

$$a_e(\text{exp}) = 1.15965218073(28) \times 10^{-3}$$

- Muon g-2 $a_\mu(\text{SM}) = 116591802(2)(42)(26) \times 10^{-11}$

$$a_\mu(\text{exp}) = 11659208.9(5.4)(3.3) \times 10^{-10}$$



原子核的电磁矩

► 原子核的磁偶极矩

电子磁矩 $\vec{\mu}_e = -\frac{e\hbar}{2m_e c} (g_{e,l}\vec{L} + g_{e,s}\vec{S}) \approx -\mu_B(\vec{L} + 2\vec{S})$

$g_{e,s} - 2 \neq 0$ 点粒子

核磁矩 $\vec{\mu}_p = \frac{e\hbar}{2m_p c} (\vec{L} + g_{p,s}\vec{S}) = \mu_N(\vec{L} + g_{p,s}\vec{S})$

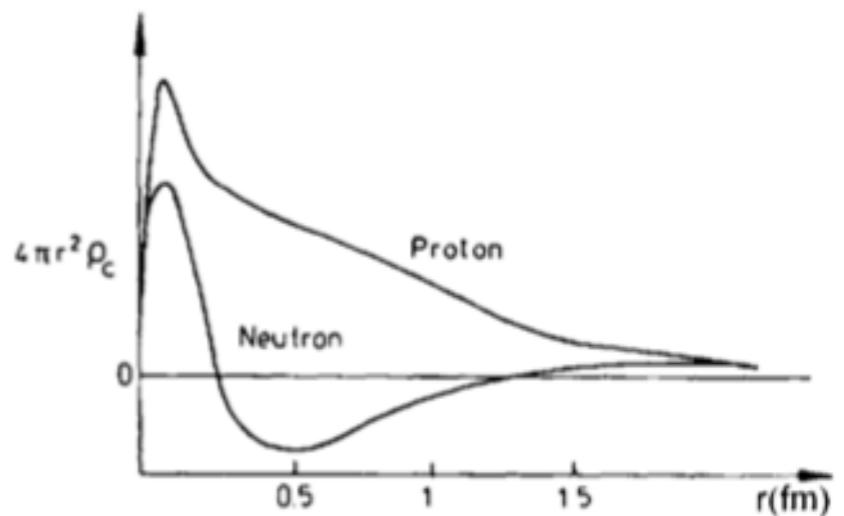
$g_{p,s} = 5.58, \quad g_{n,s} = -3.82$ 内部结构

对比电子与核子磁矩大小：

$$\mu_B = \frac{e\hbar}{2m_e c} = 5.7883826 \times 10^{-5} \text{ eV/T} \quad \text{玻尔磁子 Bohr magneton}$$

$$\mu_N = \frac{e\hbar}{2m_p c} = 3.15245 \times 10^{-8} \text{ eV/T} \quad \text{核磁子 nucleon magneton}$$

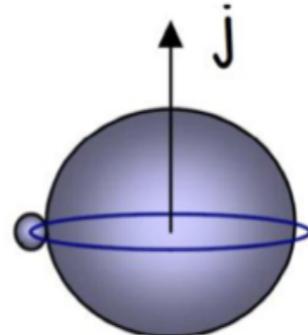
$$\mu_B \approx 10^3 \mu_N$$



原子核的电磁矩

- 奇A原子核的磁偶极矩

(假设) 基态自旋由未配对核子决定



$$\langle jm|\mathbf{A}|jm'\rangle = \langle jm|\mathbf{j}|jm'\rangle \frac{\langle jj|\mathbf{A}\mathbf{j}|jj\rangle}{j(j+1)},$$

$$\mu = \mu_N \frac{1}{j+1} \langle jj| g' \mathbf{l}\mathbf{j} + g^s \mathbf{s}\mathbf{j} | jj \rangle$$

$$= \mu_N \frac{1}{2(j+1)} [g' (j(j+1) + l(l+1) - \frac{3}{4}) + g^s (j(j+1) + \frac{3}{4} - l(l+1))].$$

For $j = l \pm \frac{1}{2}$ we get

Schmidt 公式

$$\mu = \mu_N \left\{ \begin{array}{l} g' (j - \frac{1}{2}) + \frac{1}{2} g^s \\ [g' (j + \frac{3}{2}) - \frac{1}{2} g^s] \frac{j}{j+1} \end{array} \right\} \text{ for } \begin{cases} j = l + \frac{1}{2} \\ j = l - \frac{1}{2} \end{cases}.$$

Ring & Schuck, 1980

原子核的电磁矩

► 奇A原子核的磁偶极矩

For $j = l \pm \frac{1}{2}$ we get

Schmidt 公式

$$\mu = \mu_N \left\{ \begin{array}{l} g'(j - \frac{1}{2}) + \frac{1}{2} g^s \\ [g'(j + \frac{3}{2}) - \frac{1}{2} g^s] \frac{j}{j+1} \end{array} \right\} \text{ for } \begin{cases} j = l + \frac{1}{2} \\ j = l - \frac{1}{2} \end{cases}$$

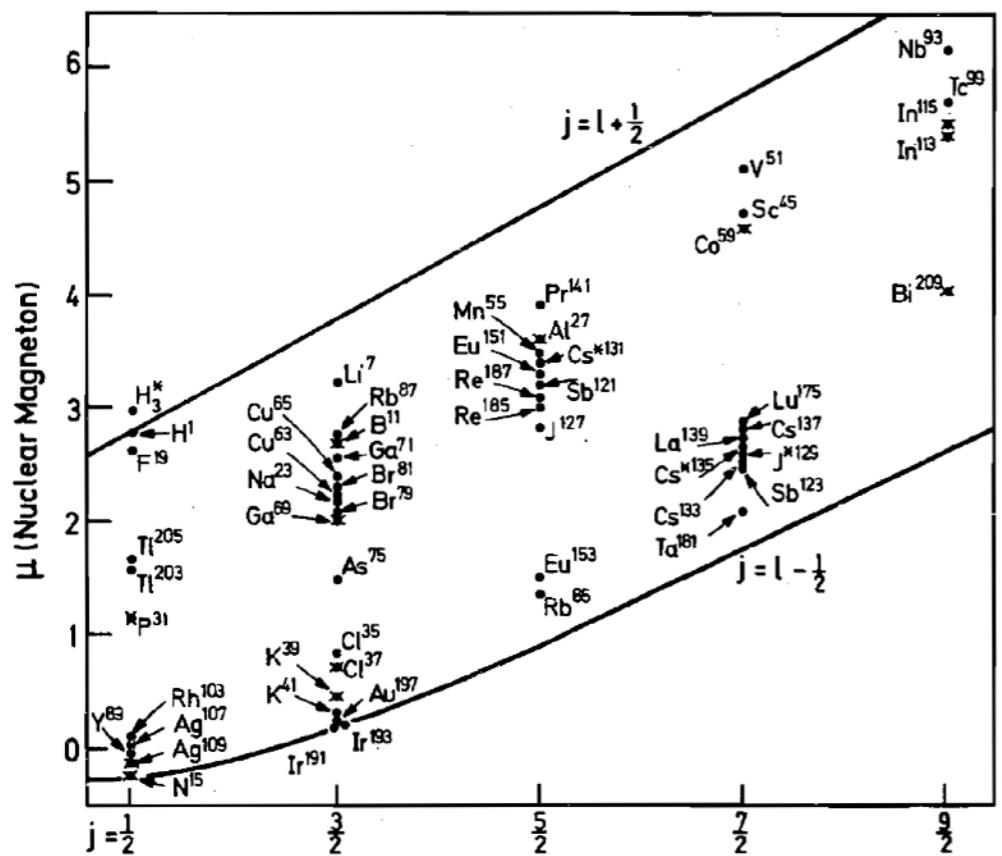


Figure 2.16. Magnetic moments for Z-odd nuclei as a function of angular momentum. (From [MJ 55].)

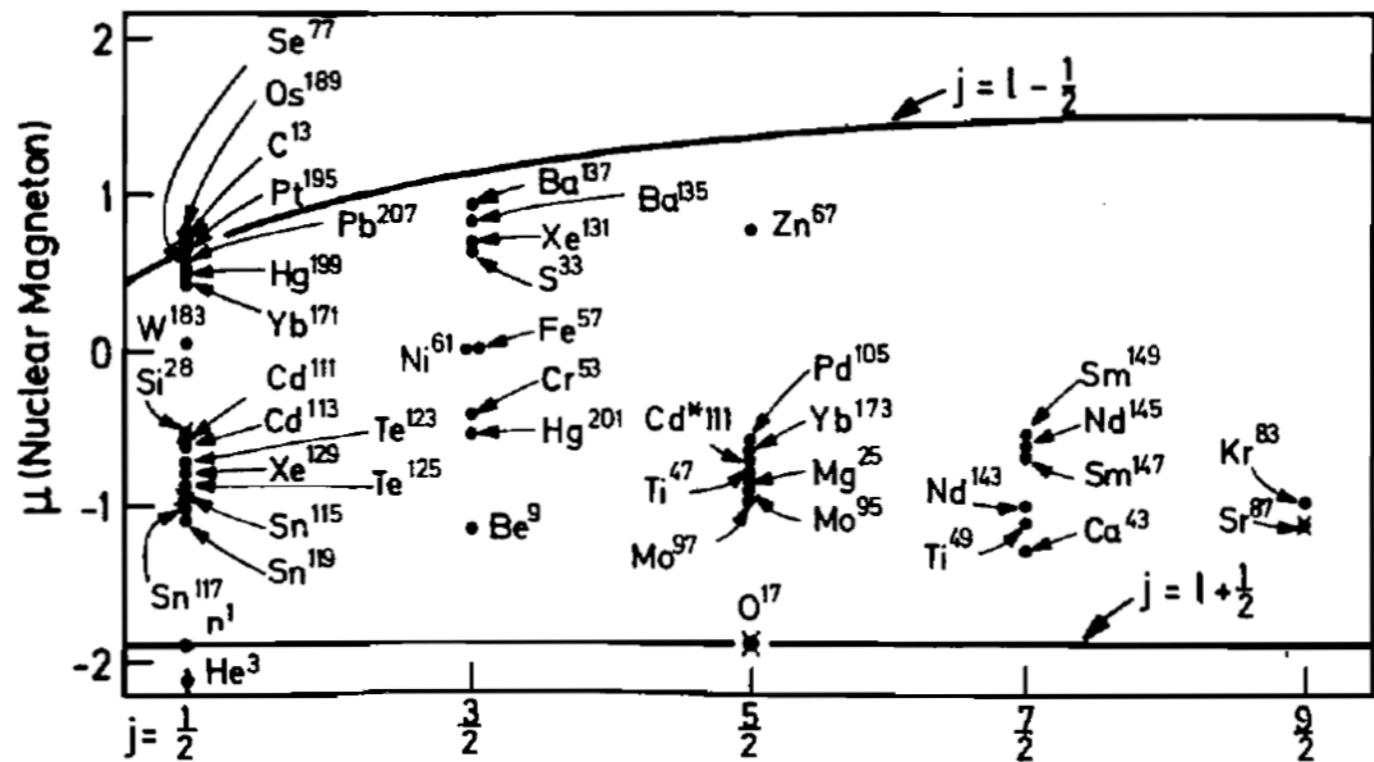


Figure 2.17. Magnetic moments of N-odd nuclei as a function of angular momentum. (From [MJ 55].)

实验数据与Schmidt 公式偏差：极端单粒子模型近似缺陷

Ring & Schuck, 1980

原子核的电磁矩

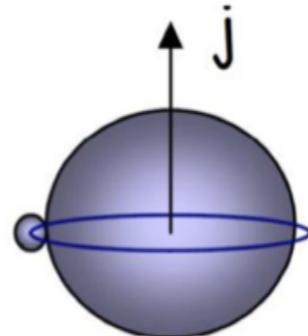
► 奇A原子核的电四极矩

(假设) 基态电四极矩完全由未配对核子贡献

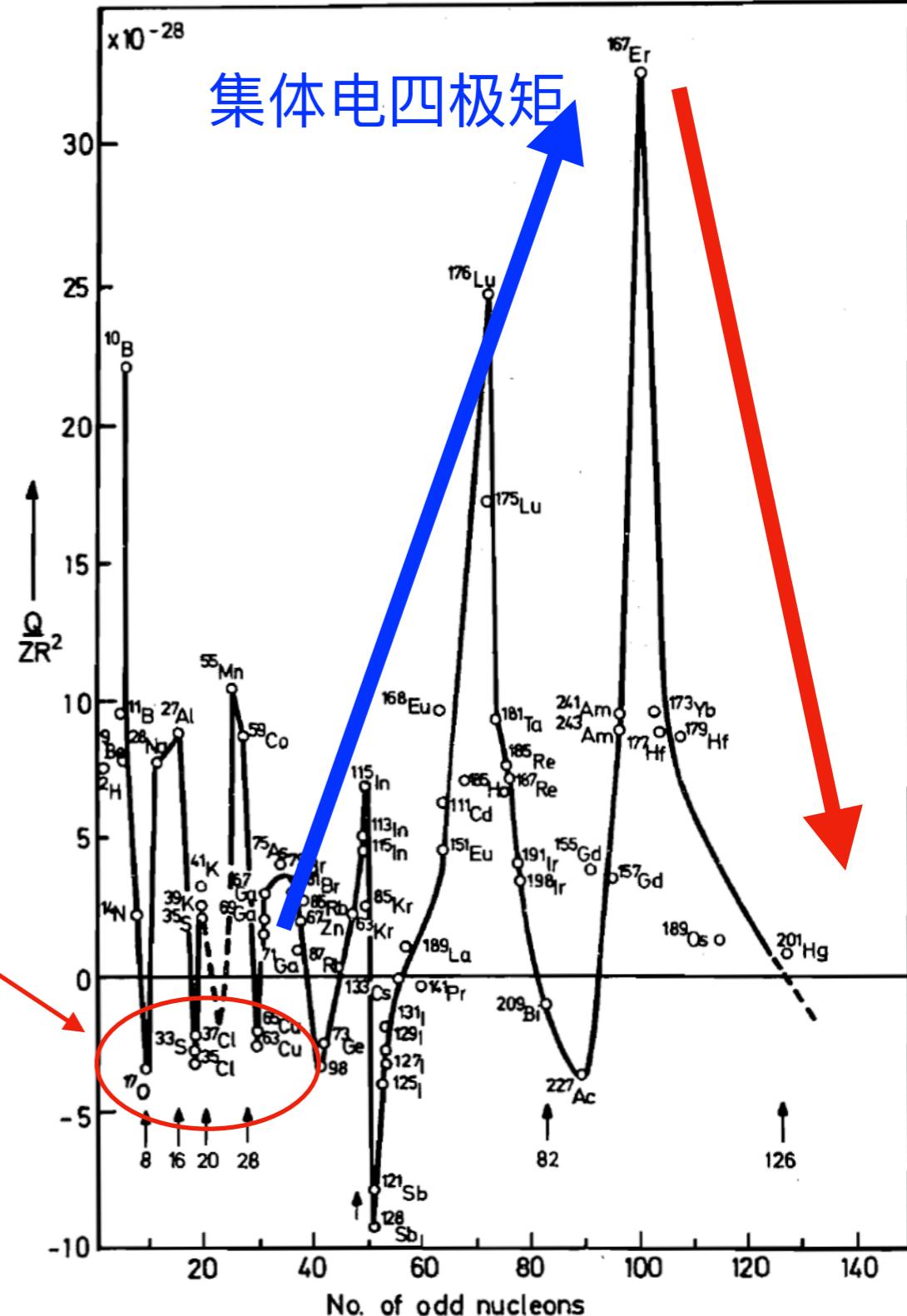
$$Q = e \sqrt{\frac{16\pi}{5}} \langle nljj | r^2 Y_{20} | nljj \rangle = -e \langle r^2 \rangle \frac{2j-1}{2j+2},$$

价核子电四极矩

$Q < 0$ for $j > 1/2$



Ring & Schuck, 1980



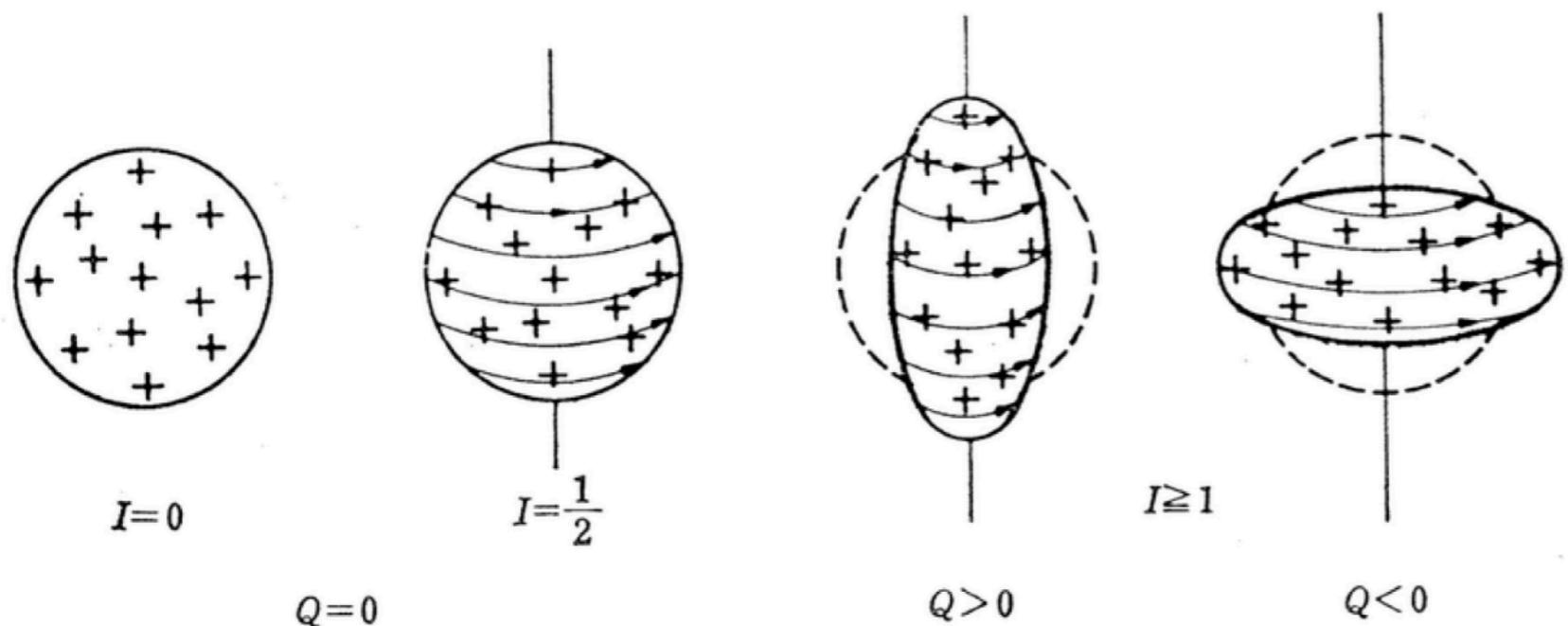
where $\langle r^2 \rangle$ is the average square radius of a particle in the state $|nljm\rangle$. For $j > 1/2$, the quadrupole moments turn out to be negative, that is, the probability distribution looks like a pancake in the plane perpendicular to the z-axis. For holes we have the opposite (i.e., prolate probability distributions). In Fig. 2.18, we see that this picture is qualitatively right in the neighborhood of magic numbers. However, as one fills the next shell with more and more nucleons, we soon find experimentally a transition to positive quadrupole moments with very large values. We shall see in the next chapter that in this case the average field of the nucleons is no longer spherical and we obtain a deformed density distribution. Only at the end of the shell, when nearly all levels are occupied, does one again get the picture of one or a few holes in a spherical core.

Figure 2.18. Quadrupole moments for odd-*A* nuclei against the number of odd nucleons. Arrows indicate closed shells. (From [Se 64].)

原子核的电磁矩

▶ 原子核的电四极矩

- 液滴模型/壳模型：大部分原子核接近球形
- 形变：轴对称椭球→电四极矩



原子核的电磁矩

► 原子核的电多极展开

$$\Phi(\vec{R}) = \frac{1}{4\pi\epsilon_0} \int_{\text{Vol}} \frac{\rho(\vec{r})}{|\vec{R} - \vec{r}|} d\vec{r},$$

in a series for (r/R) . 展开

$$\begin{aligned} \Phi(\vec{R}) &= \frac{1}{4\pi\epsilon_0} \frac{q}{R} + \frac{1}{4\pi\epsilon_0} \int \frac{\rho(\vec{r}) r \cos \theta d\vec{r}}{R^2} \\ &\quad + \frac{1}{2} \cdot \frac{1}{4\pi\epsilon_0} \int \frac{\rho(\vec{r})(3\cos^2 \theta - 1)r^2 d\vec{r}}{R^3} + \dots \end{aligned}$$

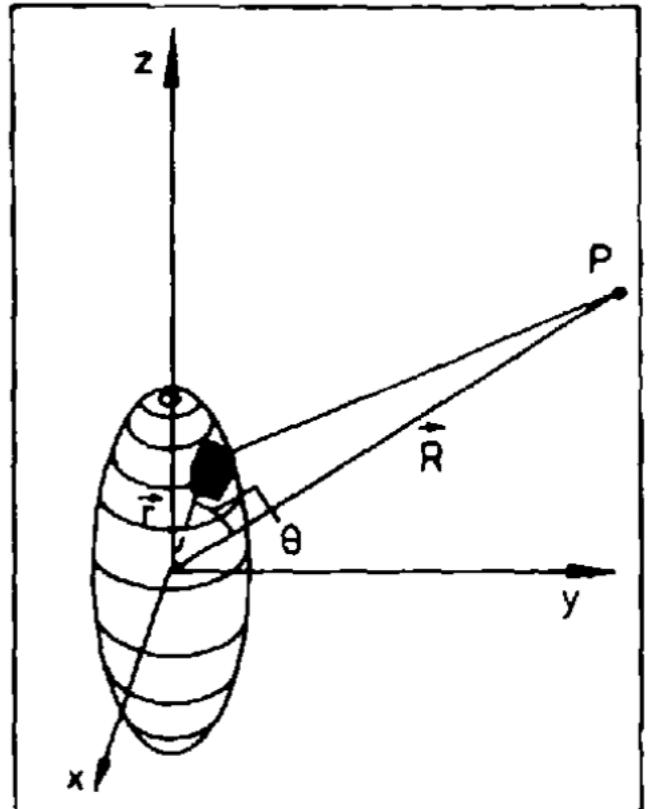
$$= \frac{1}{4\pi\epsilon_0} q/R + \sum_i \frac{p_i}{4\pi\epsilon_0} \frac{\mathbf{X}_i}{R^3} + \sum_{ij} \frac{1}{2} \frac{1}{4\pi\epsilon_0} \frac{Q_{ij}}{R^5} \mathbf{X}_i \mathbf{X}_j + \dots$$

电偶极矩

$$p_i = \int \rho(\vec{r}) x_i d\vec{r},$$

电四极矩

$$Q_{ij} = \int \rho(\vec{r})(3x_i x_j - r^2 \delta_{ij}) d\vec{r}.$$



$$r \cos \theta = \vec{r} \cdot \vec{R}/R = \sum_i x_i X_i / R,$$

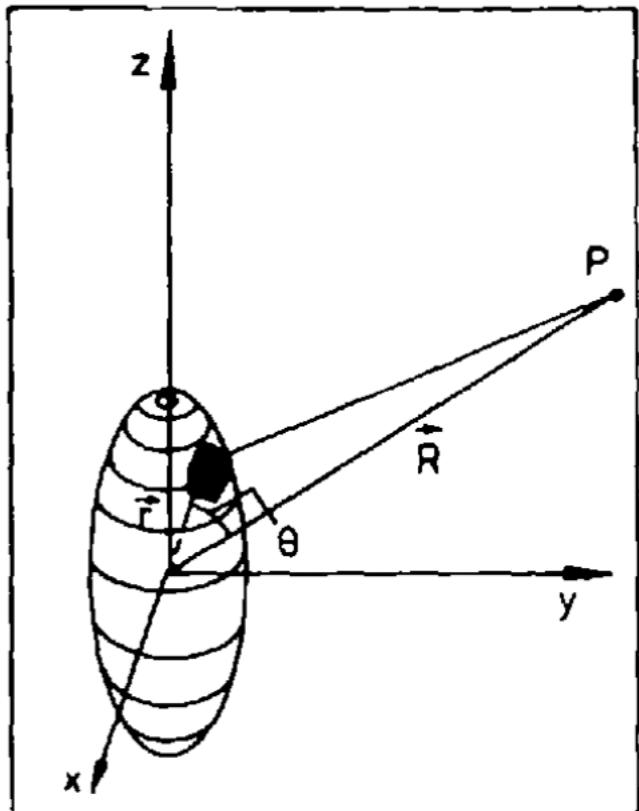
原子核的电磁矩

► 原子核的电四极矩

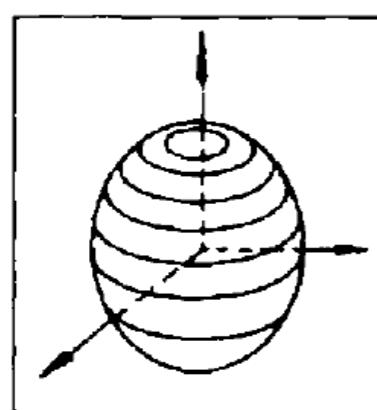
$$Q(J, M) = \int \psi_J^* M(\vec{r}_i) \sum_i (3z_i^2 - r_i^2) \psi_J^M(\vec{r}_i) d\vec{r}_i,$$

$$Q_{\text{lab}} = \frac{1}{2} (3 \cos^2 \beta - 1) Q_{\text{intr}},$$

$$\int \rho(\vec{r}) (3\vec{z}^2 - r^2) d\vec{r},$$

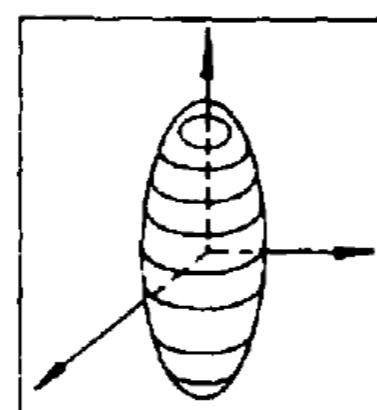


$$r \cos \theta = \vec{r} \cdot \vec{R} / R = \sum_i x_i X_i / R,$$



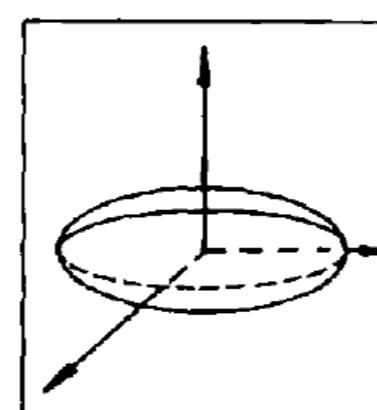
$$Q=0$$

球形



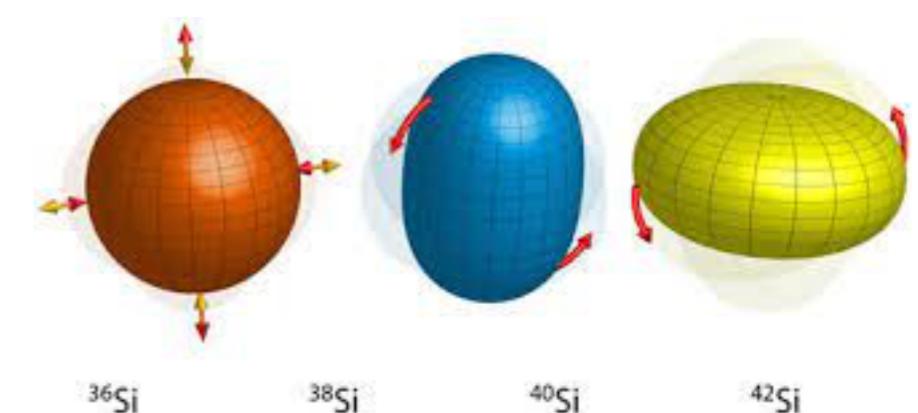
$$Q>0$$

长椭球



$$Q<0$$

扁椭球





小结

◆ 主要内容

- ▶ 结合能、液滴模型、基态量子数、电偶极矩以及电四极矩

◆ 基本概念

- ▶ 结合能、分离能、自旋宇称、同位旋、磁矩、电四极矩

◆ 重点、难点

- ▶ 液滴模型各项的物理意义

The End