Part III: Modern Physics

Chapter 44

Nuclear Structure

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LECTURE OUTLINE

- **44.1** Some Properties of Nuclei
- **44.2** Nuclear Binding Energy
- **44.4** Radioactivity
- **44.5** The Decay Processes
- **44.6** Natural Radioactivity
- **44.7** Nuclear Reactions

Some Properties of Nuclei

- the **atomic number** *Z*, which equals the number of protons in the nucleus (sometimes called the *charge number*)
- the **neutron number** *N*, which equals the number of neutrons in the nucleus
- the **mass number** $A = Z + N$, which equals the number of **nucleons** (neutrons plus protons) in the nucleus

A **nuclide** is a specific combination of atomic number and mass number that represents a nucleus. In representing nuclides, it is convenient to use the symbol $^{A}_{Z}X$ to convey the numbers of protons and neutrons, where X represents the chemical symbol of the element. For example, $^{56}_{26}Fe$(iron) has mass number 56 and atomic number 26; therefore, it contains 26 protons and 30 neutrons. When no confusion is likely to arise, we omit the subscript *Z* because the chemical symbol can always be used to determine *Z.* Therefore, $^{56}_{26}Fe$ is the same as ^{56}Fe and can also be expressed as "iron-56" or "Fe-56."

Some Properties of Nuclei

Table 44.1 Masses of Selected Particles in Various Units

Particle	Mass kg	u	MeV/c^2
Proton	$1.672\,62 \times 10^{-27}$	1.007 276	938.27
Neutron	$1.674\,93 \times 10^{-27}$	1.008 665	939.57
Electron (β particle)	$9.109\,38 \times 10^{-31}$	$5.485\,79 \times 10^{-4}$	0.510 999
$^{1}_{1}$H atom	$1.673\,53 \times 10^{-27}$	1.007 825	938.783
$^{4}_{2}$He nucleus (α particle)	$6.644\,66 \times 10^{-27}$	4.001 506	3 727.38
$^{4}_{2}$He atom	$6.646\,48 \times 10^{-27}$	4.002 603	3 728.40
$^{12}_{6}$C atom	$1.992\,65 \times 10^{-27}$	12.000 000	11 177.9

It is often convenient to express the atomic mass unit in terms of its *rest-energy equivalent.* For one atomic mass unit,

$$E_R = mc^2 = (1.660\,539 \times 10^{-27}\ \text{kg})(2.997\,92 \times 10^{8}\ \text{m/s})^2 = 931.494\ \text{MeV}$$

where we have used the conversion

$$1\ \text{eV} = 1.602\,176 \times 10^{-19}\ \text{J}.$$

Some Properties of Nuclei

1 u= 1.660566 × 10^{-27} Kg

$$m_p = 1.672648 \times 10^{-27} kg = 1.007276u$$

$$m_n = 1.674955 \times 10^{-27} kg = 1.008665u$$

$$m_e = 9.109 \times 10^{-31} kg = 0.000549u$$

$$E = mc^2 = (mass of\, 1u) \times c^2$$

$$E = 1.660566 \times 10^{-27} kg \times (3 \times 10^8 m/s)^2$$

$$= 0.149 \times 10^{-9} J$$

$$E = \frac{0.149 \times 10^{-9}}{1.6 \times 10^{-19}} = 9.315 \times 10^8 eV = 931.5 MeV$$

1u= 931.5 MeV

The Size and Structure of Nuclei

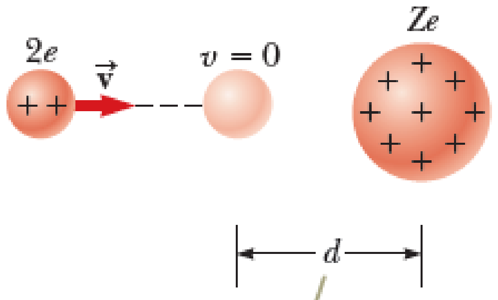
conservation of energy principle, to the system gives

$$\Delta K + \Delta U = 0$$

$$\left(0 - \tfrac{1}{2}mv^2\right) + \left(k_e \frac{q_1 q_2}{d} - 0\right) = 0$$

where m is the mass of the alpha particle and v is its initial speed. Solving for d gives

$$d = 2k_e \frac{q_1 q_2}{mv^2} = 2k_e \frac{(2e)(Ze)}{mv^2} = 4k_e \frac{Ze^2}{mv^2}$$



Because of the Coulomb repulsion between the charges of the same sign, the alpha particle approaches to a distance d from the nucleus, called the distance of closest approach.

where Z is the atomic number of the target nucleus.

$$1 \text{ fm} \equiv 10^{-15} \text{ m}$$

$$r = aA^{1/3}$$

where a is a constant equal to 1.2×10^{-15} m and A is the mass number.

- وباعتبار أن النواة كرة فإن حجمها يعطى بالعلاقة:

$$V = \frac{4}{3}\pi r^3 = \frac{4}{3}\pi\left(r_0 A^{\frac{1}{3}}\right)^3 = \frac{4}{3}\pi\left(r_0^3 A\right)$$

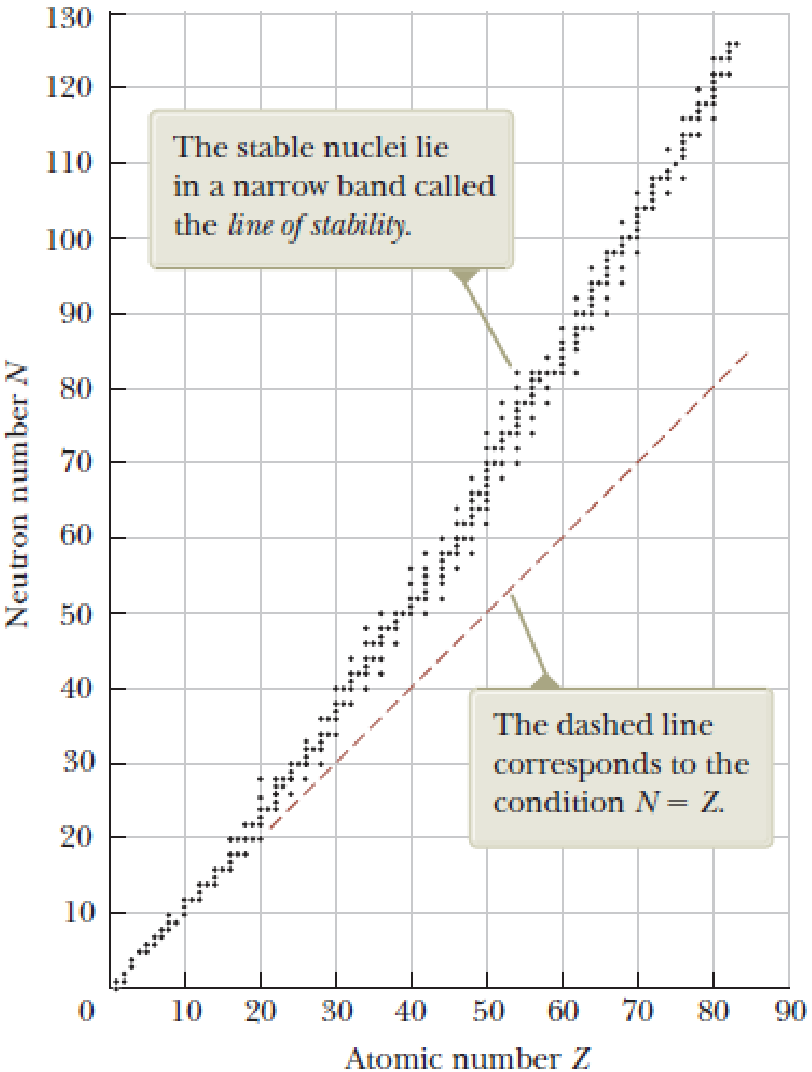
- مثال: احسب حجم نواة ذرة الكربون وكثافتها حيث A=12.

$$V = \frac{4}{3}\pi\left(r_0^3 A\right) = \frac{4}{3}\pi\left(1.2\times10^{-15}\right)^3 \times 12 = 8.6859\times10^{-44}\, m^3$$

$$\rho = \frac{M}{V} \approx \frac{12\times1.660566\times10^{-27}}{8.6859\times10^{-44}} = 2.3\times10^{17}\, kg/m^3$$

وهي قيمة عالية جدا تدل على أن المادة النووية مضغوطة جدا داخل النواة.

Nuclear Stability



Nuclear Binding Energy

Conservation of energy and the Einstein mass–energy equivalence relationship show that the binding energy E_b in MeV of any nucleus is

$$E_b = [ZM(\mathrm{H}) + Nm_n - M(^A_Z\mathrm{X})] \times 931.494 \text{ MeV/u}$$

where M (H) is the atomic mass of the neutral hydrogen atom, m_n is the mass of the neutron, M $(^A_Z X)$ represents the atomic mass of an atom of the isotope $^A_Z X$, and the masses are all in atomic mass units. The mass of the Z electrons included in M (H) cancels with the mass of the Z electrons included in the term $M(^A_Z X)$ within a small difference associated with the atomic binding energy of the electrons.

The atomic binding energies are typically several electron volts and nuclear binding energies are several million electron volts, so, this difference is negligible.

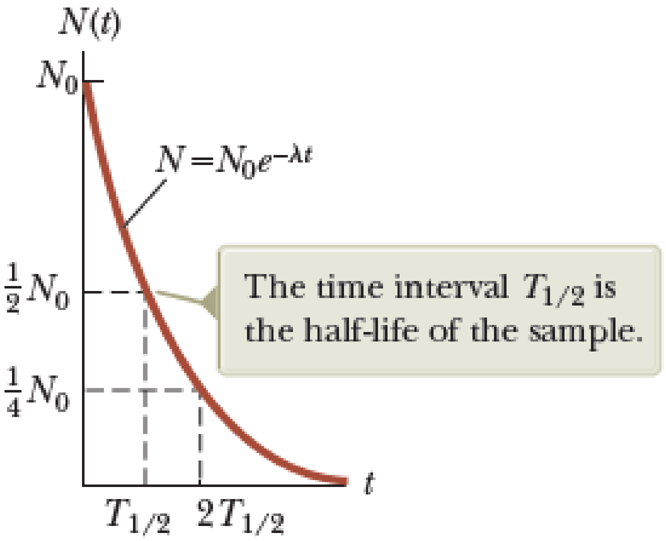
Radioactivity

If N is the number of undecayed radioactive nuclei present at some instant, the rate of change of N with time is

$$\frac{N-N_0}{t-t_0}=\frac{\Delta N}{\Delta t}=-\lambda N$$

$$N=N_0e^{-\lambda t}$$

where the constant N_0 represents the number of undecayed radioactive nuclei at $t=0$.



$$\frac{N_0}{2}=N_0e^{-\lambda T_{1/2}}$$

$$\therefore 2=e^{\lambda T_{1/2}}\Rightarrow T_{1/2}=\frac{\ln 2}{\lambda}=\frac{0.693}{\lambda}$$

Radioactivity

The **decay rate** *R*, which is the number of decays per second

$$R = \left|\frac{dN}{dt}\right| = \lambda N = \lambda N_0 e^{-\lambda t} = R_0 e^{-\lambda t}$$

where $R_0 = \lambda N_0$ is the decay rate at *t* 5 0. The decay rate *R* of a sample is often referred to as its **activity.** Note that both *N* and *R* decrease exponentially with time.

$$\frac{dN}{dt} = -\lambda N$$

$$\therefore R = \left|\frac{dN}{dt}\right| = \lambda N = \lambda N_0 e^{-\lambda t}$$

$$\therefore R = R_0 e^{-\lambda t}, R_0 = \lambda N_0$$

Another parameter useful in characterizing nuclear decay is the **half-life** $T_{1/2}$:

1 Ci= $3.7\text{x}10^{10}$ decay/sec

1 Bq= 1 decay/sec,
1 Ci= $3.7\text{x}10^{10}$ Bq

❑ التحلل بانبعاث ألفا Alpha decay

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$$

$$Example: {}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

الطاقة المتحررة نتيجة التحلل التلقائي تسمى طاقة التحلل ويرمز لها عادة ب Q أي أن:

$$Q = [M(x) - (M(y) + M_{\alpha})] \times 931.5 MeV$$

ولكي تكون النواة باعثة لجسيمات ألفا يجب أن يكون Q>0 .

مثال: هل البولونيوم 210 باعث لجسيمات ألفا إذا علم أن:

$$M(^{210}Po) = 209.98285u$$

$$M(^{206}Pb) = 205.97440u$$

$$M_{\alpha} = 4.002603u$$

الحل: معادلة التحلل هي:

$$^{210}_{84}Po \rightarrow ^{206}_{82}Pb + ^{4}_{2}He$$

$$\therefore Q = \left[M(^{210}Po) - \left(M(^{206}Pb) + M_{\alpha}\right)\right] \times 931.5MeV$$

$$= \left[209.98285 - (205.97440 + 4.002603\right] \times 931.5$$

$$= 5.45MeV \succ 0$$

إذن يمكن للبولونيوم 210 أن يتحلل بانبعاث جسيمات ألفا

❑ التحلل بانبعاث بيتا β- decay

هناك نوعين من هذا التحلل هما :

أ- بيتا السالب : $${}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + \beta^{-} + \overline{\nu}$$

هذا التحول يحدث عندما تكون نسبة النيوترونات إلى البروتونات في النواة أكبر من قيمتها في منطقة الاستقرار،

فلكي يحدث استقرار يتحول النيوترون إلى بروتون وينطلق جسيم بيتا السالب من النواة:

$${}_{0}^{1}n \rightarrow {}_{+1}^{1}p + {}_{-1}^{0}e + \overline{\nu}$$

طاقة تحلل بيتا السالب يعطى بالعلاقة:

$$Q = [M(x) - (M(y) + m_e)] \times 931.5 MeV$$

- نحصل على أعلى قيمة لطاقة تحلل جسيمات بيتا السالبة بأخذ الكتل الذرية بدل النووية:

$$Q = [M(x) - M(y)] \times 931.5 MeV$$

مثال : تحلل الكربون 14: $${}_{6}^{14}C \rightarrow {}_{7}^{14}N + \beta^{-} + \overline{\nu}$$

ب- بيتا الموجب : $$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + \beta^{+} + \nu$$

فلكي يحدث استقرار يتحول البروتون إلى نيوترون وينطلق جسيم بيتا الموجب (البوزيترون) من النواة:

$$^{1}_{+1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + \nu$$

- طاقة تحلل بيتا الموجب يعطى بالعلاقة:

$$Q = [M(x) - (M(y) + m_e)] \times 931.5 MeV$$

- نحصل على أعلى قيمة لطاقة تحلل جسيمات بيتا الموجبة بأخذ الكتل الذرية بدل النووية:

$$Q = [M(x) - (M(y) + 2m_e)] \times 931.5 MeV$$

مثال : تحلل النيتروجين 13: $$^{13}_{7}N \rightarrow {}^{13}_{6}C + \beta^{+} + \nu$$

- **هناك جسيمين يصاحبان تحلل بيتا السالب والموجب هما نيوترينو v وضد نيوترينو $\bar{V}$ ، وهما بدون شحنة وبلا كتلة ولكن وجودهما ضروري لكي تبقى الطاقة والزخم الخطي والزاوية قبل وبعد التحلل محفوظة حسب مبدأ حفظ الطاقة والزخم.**

Natural Radioactivity

Radioactive nuclei are generally classified into two groups: (1) unstable nuclei found in nature, which give rise to **natural radioactivity,** and (2) unstable nuclei produced in the laboratory through nuclear reactions, which exhibit **artificial radioactivity.**

Nuclear Reactions

$$a + X \rightarrow Y + b$$

Sometimes this reaction is written in the more compact form

$$X(a, b)Y$$

Q value, or disintegration energy, of a radioactive decay was defined as the rest energy transformed to kinetic energy as a result of the decay process. Likewise, we define the **reaction energy** *Q* associated with a nuclear reaction as *the difference between the initial and final rest energies resulting from the reaction:*

$$Q = (M_a + M_X - M_Y - M_b)c^2$$

Nuclear Reactions

The minimum energy necessary for such a reaction to occur is called the **threshold energy.**

➢ التفاعلات النووية Nuclear reactions

$$ {}_{2}^{4}He + {}_{7}^{14}N \rightarrow \left[{}_{9}^{18}F \right] \rightarrow {}_{8}^{17}O + {}_{1}^{1}H $$

← عملية تحول العناصر

مستقر مشع مستقر

- ويمكن التعبير عن التفاعلات النووية بالمعادلة الآتية: x+ X→Y + y

الطاقة المحررة تساوي:

$$ Q = [M(x) + M(X) - (M(Y) + M(y))] \times c^2 \, joule $$

حيث الكتل بوحدة الكيلو جرام(kg).

أو:

$$ Q = [M(x) + M(X) - (M(Y) + M(y))] \times 931.5 MeV $$

حيث الكتل بوحدات الكتل الذرية (u).

α+ N →F →O + P Q = -1.19 MeV

ونظرا لأن قيمة الطاقة المحررة المحسوبة سالبة فإنه لحدوث التفاعل لابد ان يكون لجسيم ألفا طاقة حركية تتحول إلى كتلة ليصبح الطرف الأيسر مساويا أو أكبر من مجموع الكتل في الطرف الأيمن لكي يتم التفاعل.

Thank You

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