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Chapter 15

Chapter 15
Nuclear Physics

Brief history

1896 Becqueral. discovery of radioactivity

Rutherford classified the radioactivity into α, β, γ decay.

Rutherford scattering ⇒ atomic nuclei 1911
↓
massive nucleus has a radius of 1-10 fermi
(1 fermi $= 10^{-15}$ m)

Application of quantum mechanical tunneling
⇒ explanation of α-decay.
Gamow, Curney, and Condon 1928

1932
Discovery of neutron by Chadwick (nucleus is made of proton and neutron)
positron by Anderson
↕
Dirac's electron theory

First nuclear reaction using artificially accelerated particles (protons) was observed by Cockcroft and Walton

Major Areas in Nuclear Physics

Radioactivity
Structure
Reaction.

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Antoine-Henri Becquerel (1852–1908) was born and educated in Paris. His grandfather, father, and son were also physicists, all of them in turn professors at the Paris Museum of Natural History. Like his grandfather and father, Becquerel specialized in fluorescence and phosphorescence, phenomena in which a substance absorbs light at one frequency and reemits it at another, lower frequency.

In 1895 Roentgen had detected x-rays by the fluorescence they cause in an appropriate material. When he learned of this early in 1896, Becquerel wondered whether the reverse process might not occur, with intense light stimulating a fluorescent material to give off x-rays. He placed a fluorescent uranium salt on a photographic plate covered with black paper, exposed the arrangement to the sun, and indeed found the plate fogged when he had developed it. Becquerel then tried to repeat the experiment, but clouds obscured the sun for several days. He developed the plates anyway, expecting them to be clear, but to his surprise they were just as fogged as before. In a short time he had identified the source of the penetrating radiation as the uranium in the fluorescent salt. He was also able to show that the radiation ionized gases and that part of it consisted of fast charged particles.

Although Becquerel's discovery was accidental, he realized its importance at once and explored various aspects of the radioactivity of uranium for the rest of his life. He received the Nobel Prize in physics in 1903.

Marie Curie-Sklodowska (1867–1934) and her husband **Pierre Curie** (1859–1906). Together they discovered that there were elements besides uranium that were radioactive (a term introduced by Marie), notably polonium (named after Marie's country of birth) and radium. Radium, occurring in minute quantities in pitchblende, actually produces heat (nuclear energy): 1 g of radium can heat about 1.3 g of water from the melting point to the boiling point in one hour. The Curies analyzed large amounts of pitchblende, supposedly a worthless residue from mining operations. Pierre died rather young in a traffic incident, which caused intense grief to Marie. Her extended work with radioactive materials was probably part of the cause of her death, 28 years after her husband.

Not only was Marie the first woman to receive the Nobel prize for physics (in 1903, with Becquerel and her husband Pierre), she was also the first person to receive a second Nobel prize (chemistry, 1911: for her services to the advancement of chemistry by the discovery of the elements radium and polonium, by the isolation of radium and the study of the nature and compounds of this remarkable element). The only other woman to receive the physics Nobel prize (1963) is Maria Goeppert-Mayer for her work in nuclear physics. It has remained something of a scandal that Lise Meitner (1878–1968) did not share the 1944 Nobel chemistry prize given to Otto Hahn (1879–1968) for, in fact, their work on nuclear fission (this initiated atomic reactors and nuclear bomb research). It was a clear case of male chauvinism that makes the Swedes blush to this day.

There is also the case of Marietta Blau, see vignette on Powell in Chapter 2.

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• **Figure 15–6** Marie Curie, one of the handful of people to have won two Nobel prizes.

α - decay
↓
we have encountered early.
↓
quantum tunneling
$M_{^4He} c^2 \sim 4 \cdot 10^3$ MeV

α has energy
$\sim$ few MeV
⇒ non-relativistic

β - decay

$n \to p + \beta^- + \bar{\nu}_e$
↓ electron; ↳ neutrino

discovery of neutrino

$^{198}Au \to {}^{198}Hg + \beta^- + \bar{\nu}_e$

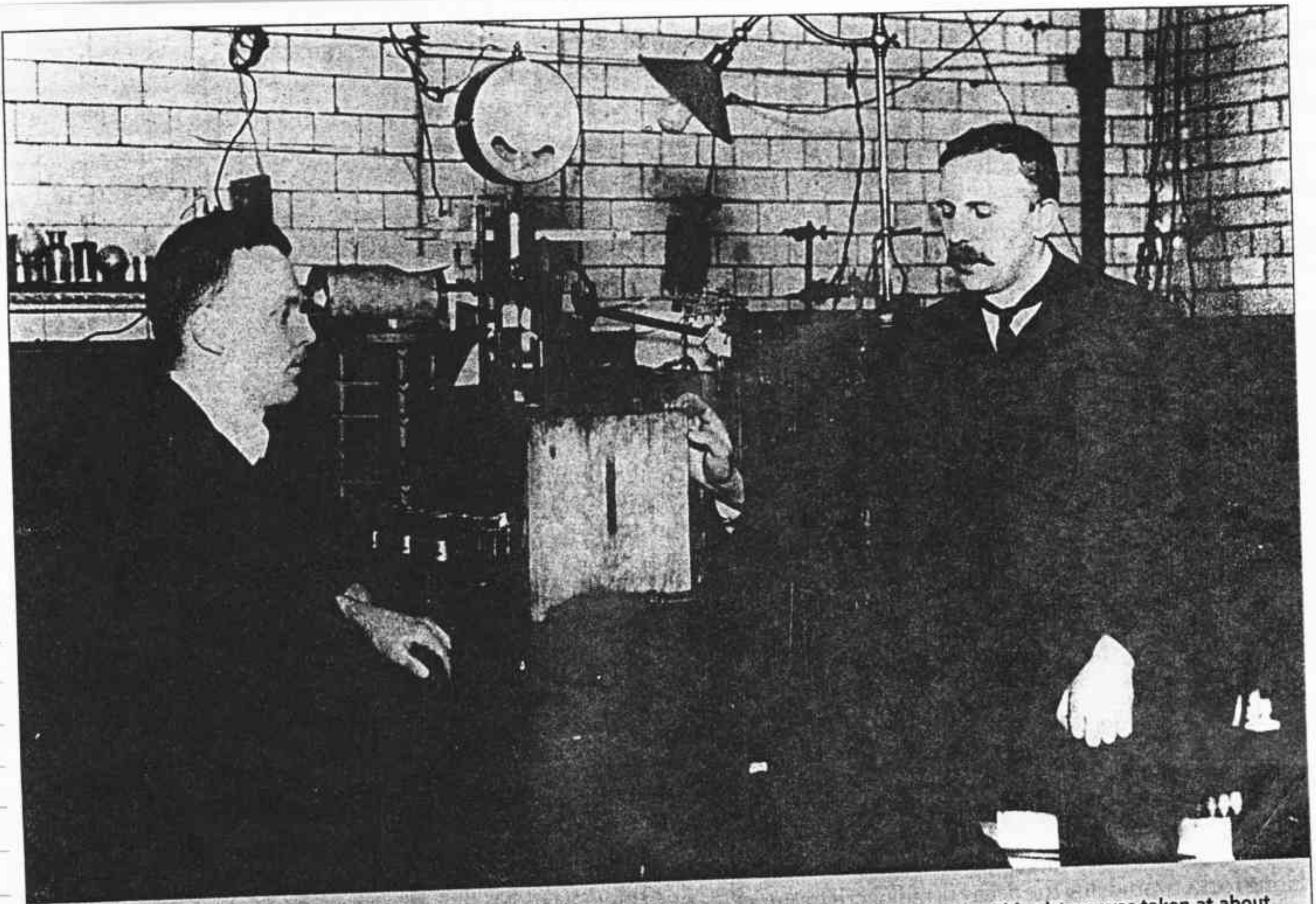
β^+ decay

$^{13}_{7}N \to {}^{13}_{6}C + \beta^+ + \nu_e$
↓
positron

weak interaction

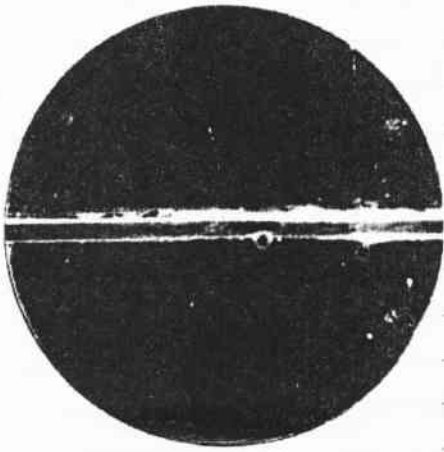
The discovery of e^+
↓
anti-particles
for electron
⇓
positron.

New interaction: strong and weak interaction.



Hans Geiger, 1882–1947, left, with Ernest Rutherford, 1871–1937, in Rutherford's laboratory in Manchester. This picture was taken at about the time of the discovery of the nucleus. (Science Museum/Science and Society Picture Library.)

James Chadwick, 1891–1974. His discovery of the neutron in 1932 was a turning point in nuclear physics. Chadwick was well aware that the neutron had been predicted by Rutherford in 1920. (Copyright the Nobel Foundation.)



The first evidence for the positron, the anti-particle of the electron. The cloud chamber track bends the wrong way in a magnetic field for it to be caused by an electron, and it is not a proton track. Anderson's unprecedented discovery was highly controversial until it was confirmed a year later. (Courtesy C.D. Anderson.)

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Carl Anderson (1905–1991).

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Irene and Frederic Joliot-Curie

(1897–1956 and 1900–1958, French)

Irène Joliot-Curie was the daughter of Pierre and Marie Curie. She met her husband, Frédéric Joliot, when they were both working as assistants to her mother. After they were married, they took the name Joliot-Curie and continued to work together. They narrowly missed discovering the neutron (losing out to Chadwick) and the positron (losing out to Anderson). In 1934 they identified the first man-made radioactive nucleus, an isotope of phosphorus, which they created by bombarding aluminum with alpha particles; and for this discovery, they won the Nobel Prize for chemistry in 1935. Irène was refused admission to the American Chemical Society in 1954 because of her left-leaning politics.

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John Cockcroft (1879–1967) and **Ernest Walton** (1903–1995), Nobel prize 1951. They constructed the first accelerator useful for doing nuclear physics experiments; their first observed reaction was the splitting of a lithium nucleus by means of a proton. The lithium nucleus contains 3 protons and four neutrons, and together with the incident proton one obtains a pair of alpha particles, each alpha particle containing 2 protons and 2 neutrons. It is amusing to read how they established this reaction. They had to demonstrate that a reaction gave rise to two alpha particles being emitted simultaneously. They did that using two observers each watching a screen that would light up if hit by an alpha particle. If they saw such a light flash they would tap a key. Two coincident keystrokes would indicate a lithium nucleus disintegration.

The machine they used for this experiment accelerated protons to about 700 000 Volts (700 keV). By today's standard this is of course a rather low energy, but it is already a quite useful energy for the purposes of the study of atomic nuclei. Optimistically, Walton thought as late as 1951 (see his Nobel lecture) that this method could be used to acceleration of protons to about 10 GeV (i.e. 10 000 MeV or 10 000 000 keV), but that was certainly a vain hope. Circular accelerators such as cyclotrons etc. are better suited for proton acceleration. Interestingly, a Cockcroft-Walton type voltage generator (cascade generator) can be found in most TV sets, to generate the required voltage of 10–30 keV. Also, Cockcroft-Walton machines are used to this day as an initial accelerator just following the ionization chamber of large proton accelerators.

Composition of Nuclei

Proton and neutron → nucleons

Properties of Nucleons

Nucleon	Mass	Spin	Magnetic Moment
Proton	938.28 MeV/c^2	$\frac{1}{2}$	2.792846 $\frac{e\hbar}{2M_p}$
Neutron	939.57 MeV/c^2	$\frac{1}{2}$	-1.913042 $\frac{e\hbar}{2M_p}$

Remarks — nuclear magneton

· Nuclei are made of protons and neutrons
↓
Heisenberg

· Chadwick : $\alpha + {}^{9}Be \rightarrow {}^{12}C + n$

Notation ${}^{A}_{Z}X$ ${}^{12}_{6}C$
(6 ↓ may be omitted.)

{ Irene Curie and Frederic Joliot missed the discovery "n" → γ

Neutrons are unstable particle

$$n \rightarrow p + e^- + \bar{\nu} \qquad \beta\text{-decay}$$

the electron and the anti-neutrino are ejected with a (shared) energy of roughly 1 MeV

$$m_e c^2 = 0.511 \text{ MeV.}$$

↓
relativistic kinematics may be important

Nuclei with a given Z and N are nuclides

Nuclei with the same A but different Z's and N's are called isobars.

Nuclei with a given Z but different N's are isotopes

deuteron stable bound state of a neutron and a proton

deuterium

triton two neutrons and one proton

tritium

Discovery of the neutron

Nucleus cannot contain electron
↓
Uncertainty relation argument

Spin argument

^{14}N 7 p   7 n ⇒ bosons
          14 p   7 e^- ⇒ fermions

spin = 1

Discovery of neutron

$A = N + Z$

Some important Isotopes

Symbol	Nucleus
^{1}H	ordinary hydrogen
^{2}H	deuterium (heavy hydrogen)
^{3}H	tritium (radioactive hydrogen)
^{4}He	helium (alpha particle)
^{12}C	carbon, commonest isotope
^{14}C	rare radioactive isotope, used for dating
^{16}O	oxygen, common isotope
^{56}Fe	iron, common isotope
^{235}U	uranium, rare isotope
^{238}U	uranium, most common isotope

Nuclear notation

^{12}C

A nucleus is denoted by the chemical symbol of its element along with a number denoting the sum of the number of protons and neutrons it contains. Thus ^{12}C (you read it as carbon-twelve) is a nucleus with 6 protons (the signature of carbon) and 6 neutrons whereas the isotope ^{14}C, which also contains 6 protons, has two extra neutrons. Atomic and nuclear masses are often given in atomic mass units (amu), where one amu (or 1.66×10^{-27} kg) is defined as one twelfth of the mass of the neutral ^{12}C atom. The total number of nucleons is known as the atomic mass number, or just mass number.

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Nuclei are made of protons and neutrons

Z → atomic number

A → mass number

$A = N + Z$

N ↓ number of neutrons

Z ↳ number of protons

Nuclides with the same atomic number Z
⇒ isotopes.

Compare the mass of a nucleus with the sum of the masses of its constituent protons and neutrons
⇒ the mass of the nucleus is smaller than the masses of its constituents.
↓
the difference is called the mass defect

$$(\text{mass defect}) = Z M_p + N M_N - m$$

↳ m: mass of the nucleus

$$B = \text{binding energy} = (\text{mass defect})\, c^2 = (Z M_p + N M_n - m) c^2$$

⇒ B energy needed to break the nucleus into its constituent nucleons.

Size and Shape of Nuclei

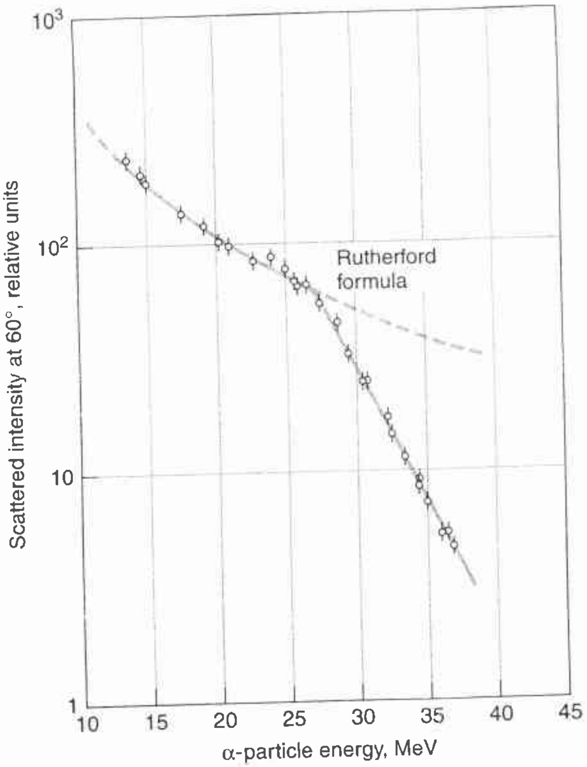

Fig. 11-2 Rutherford's α scattering formula (Equation 4-6) is shown by the dashed line. α particles of increasing energy incident on the nuclei of a Pb target scatter as would be expected by the Rutherford formula until their energy reaches about 27 MeV. At greater energies the α particles approach the Pb nuclei closely enough so that the nucleons of the α and the Pb interact via the attractive nuclear force and the scattered intensity falls below that predicted by the Rutherford equation. [*Data from R. M. Eisberg and C. E. Porter,* Rev. Mod. Phys., ***33****, 190 (1961).*]

Deviation from Rutherford formula
↓
nuclei are not point particles

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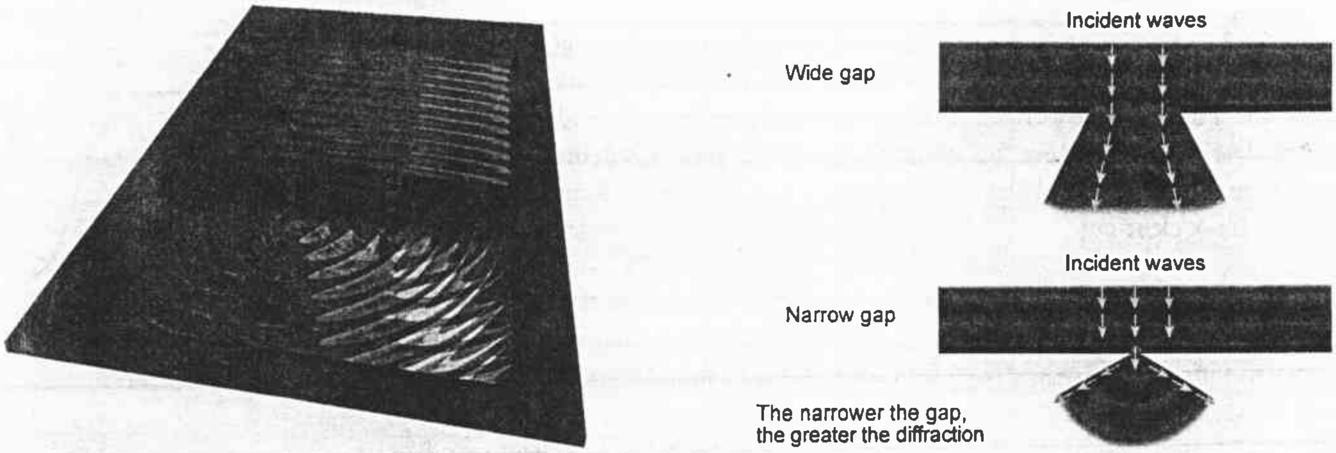

Waves 'diffract' (spread out) when they strike objects or pass through holes or slits in barriers. On the right is shown how the smaller the object or the hole relative to the wavelength, the stronger the diffraction, provided the object or hole is not much smaller than the wavelength. To study nuclei, we need much shorter wavelengths than can be achieved with an electron microscope.

Measure the charge distribution through diffraction

Particle has wave property
⇓
e

$$\lambda = \frac{h}{p}$$

Robert Hofstadter, 1915–1990, pioneered the use of electrons for studying the size and density of nuclei and of the nucleons they are made of. (Copyright the Nobel Foundation.)

Robert L. Hofstadter. Born 1915 in New York. He received his Ph.D. from Princeton in 1938. In 1948 Hofstadter showed that sodium iodide, activated by thallium, made an excellent scintillation counter. In the 1950s at Stanford University he and his colleagues carried out a series of classic experiments to investigate the scattering of electrons from nucleons and nuclei. These led to a rather detailed knowledge of the charge and magnetic-moment distributions of protons, neutrons, and nuclei. In 1961 he shared the Nobel Prize with Rudolf Mössbauer. (*Photograph from the Meggers Gallery of Nobel Laureates, American Institute of Physics.*)

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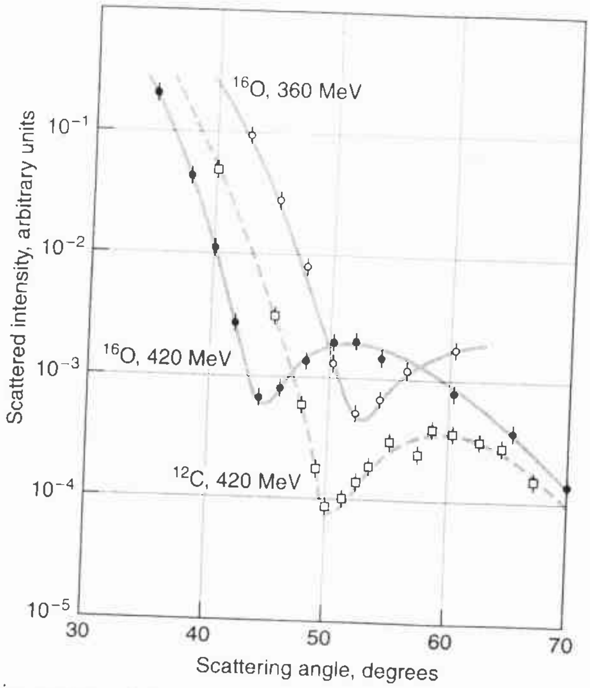
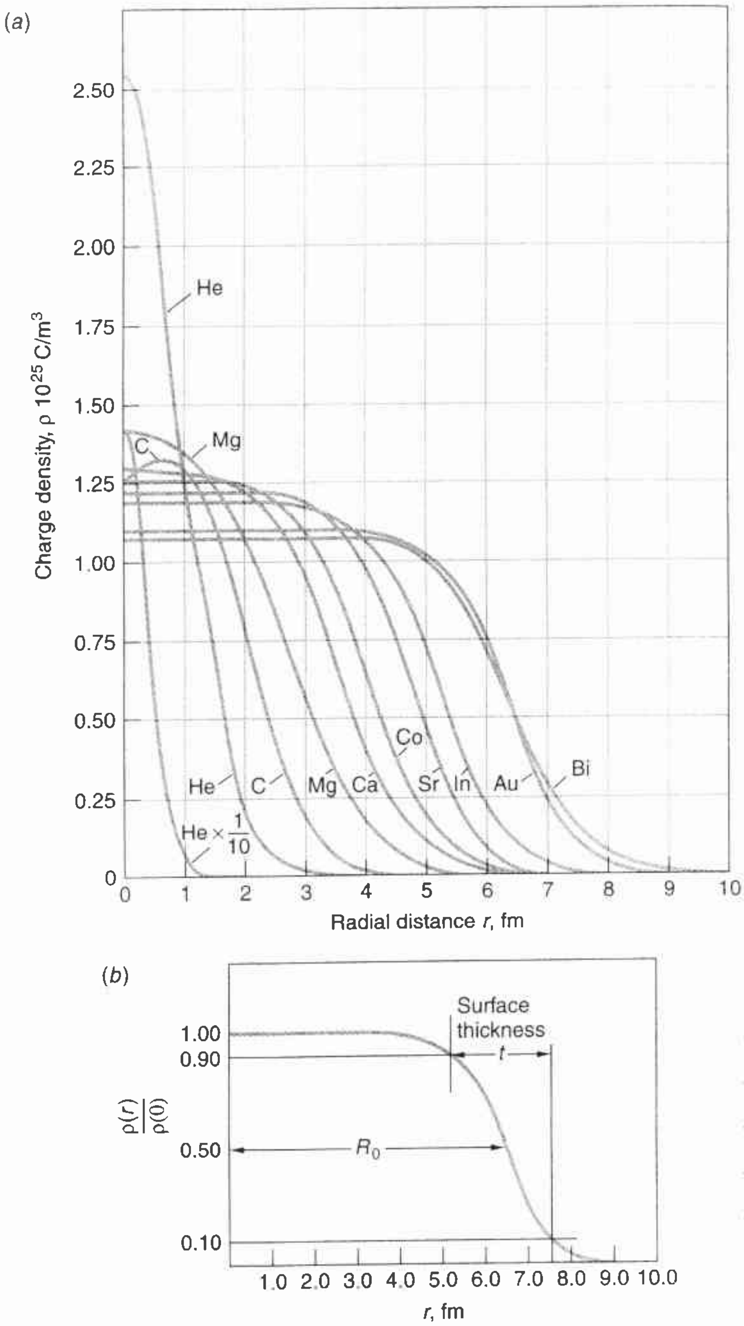


Fig. 11-4 Diffraction pattern of high-energy electrons scattered by ^{16}O and ^{12}C. The angle at which the minimum occurs in each pattern is given by Equation 11-4.

Fig. 11-5 (*a*) Charge density versus distance for several nuclei as determined by high-energy electron scattering experiments. (*b*) Definitions of parameters R_0 and t used to describe nuclear charge density. The skin thickness t is measured from 10 percent to 90 percent of the central core density. [*From R. Hofstadter,* Annual Review of Nuclear Science, *7, 231 (1957).*]



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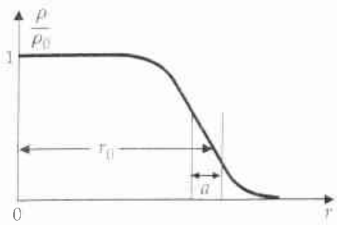

• **Figure 15–3** For large enough nuclei ($Z > 10$, say) the nuclear density is well described by the formula

$$\rho(r) = \frac{\rho_0}{\{1 + \exp[(r - r_0)/a]\}},$$

where $\rho_0 = 0.17$ nucleon/fm^3, $r_0 = (1.2A^{1/3} - 0.48)$ fm, and $a = 0.55$ fm. This formula is obtained from electron–nucleus collision experiments, on the assumption that the nuclear density is the same as the electric charge density—that is, that the protons and neutrons are distributed in the same way. It is the charge density that is actually measured by the electron-scattering experiments.

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$R = (1.07 \pm 0.02) A^{\frac{1}{3}}$ fm

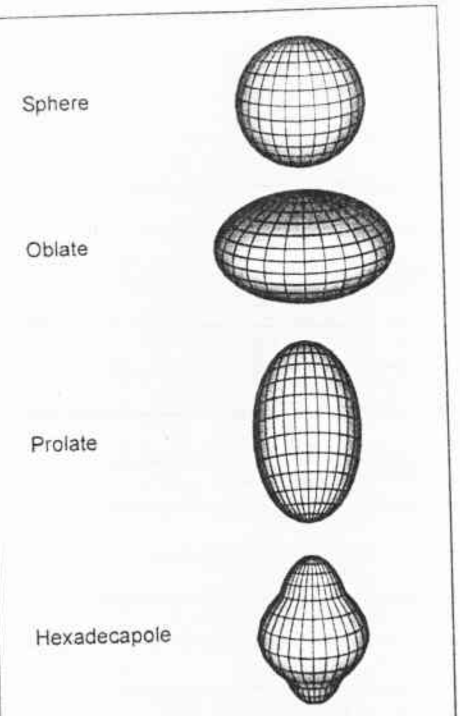
$\downarrow$

r_0 $\quad 1\ fm = 10^{-15}\ m$

$t = 2.4 \pm 0.3$ fm

$\downarrow$

a



Not all nuclei are spheres. A few are 'oblate', that is, flattened at the poles, and a great many are 'prolate', lengthened in the direction of the poles, like an American football. Quite subtle shapes can be measured, like the bottom figure which shows a 'hexadecapole' variant of prolate.

^{176}Lu

Nuclei has also been explored by scattering experiments with neutrons and protons

The results of these experiments are difficult to interpret because the neutrons and protons interact with the nucleus via the nuclear force, whose dependence on distance is not very well known.

Most nuclei are spherical, but some nuclei are deformed.
Example ^{176}Lu prolate ellipsoidal
from analysis of isotope shifts of spectral lines

Nuclear Force

· It is different from gravitational, electromagnetic interaction

· It has a very short range
  · the central density of nuclear matter is ~ constant
    ↓
    each additional nucleon feels a force only from its nearest neighbor
  · binding energy per nucleon is almost constant.

· Two nucleons in the same state

$$V_{nn} = V_{np} = V_{pp}$$

charge symmetry, charge independent

See the figure for binding energy per nucleon

The qualitative discussion of the dependence on distance of the strong force.
↓
strong force has a very complicated dependence on distance

See the following figure (roughly)

· Strongly attractive in the range 1-2 fm
· A repulsive core at a distance < 0.8 fm
· U(r) is given by Yukawa potential

$$U(r) \sim 10.46 \text{ MeV} \frac{e^{-r/b}}{r/b} \quad (r \gtrsim 1 fm)$$

with $b \simeq 1.43$ fm. ($b = R$)

Note: the unit it appears here.

The nucleon-nucleon potential is determined by fitting the scattering data and the binding energy of deuteron (bound state of p and n

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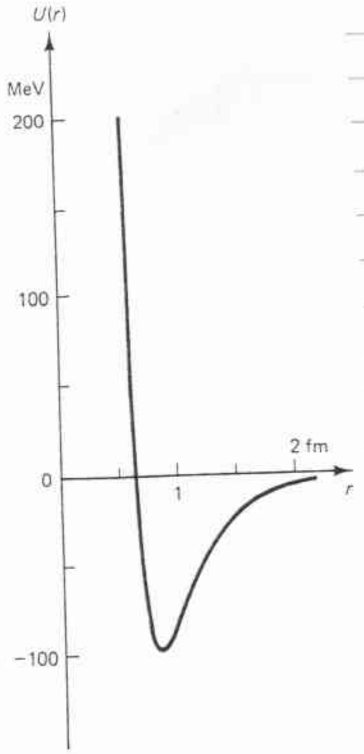

Fig. 9.6 Potential of the strong force for two nucleons of antiparallel spin and zero orbital angular momentum ($^1S_0$ state). [After R. V. Reid, *Ann. Phys.* **50,** 411 (1968).]

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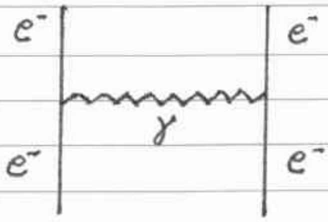
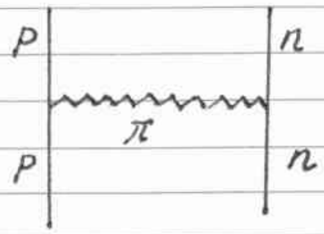
Yukawa potential

Electromagnetic interaction between two electrons
↓
through the exchange of a photon



Strong interaction between two nucleons
↓
through the exchange of a pion



In the rest system of p, after the pion is emitted and before it is absorbed by n, the energy is violated by $\Delta E \gtrsim m_\pi c^2$

Uncertainty relation $\Delta E \, \Delta t \sim \hbar$

$\Rightarrow$ the violation of energy conservation will not be detected if

$$\Delta t \lesssim \frac{\hbar}{\Delta E} \sim \frac{\hbar}{m_\pi c}$$

In this time interval, the particle travel a distance

$$\frac{c\hbar}{m_\pi c^2}$$

After a pion is emitted by P, it can at most travel a distance $R = \frac{\hbar}{m_\pi c}$ before it is absorbed by n.
↓ identify

$$R = \frac{\hbar}{m_\pi c}$$

Based on the nuclear force having a range of $\sim 1\,fm$

$\Rightarrow$ $m_\pi c^2 \sim 200\ MeV$.

Discovery of π with $m_\pi c^2 = 140$ MeV

More detailed calculation ⇒ Yukawa potential

$$A \frac{e^{-r/R}}{r}$$

$$R = \frac{\hbar}{m_\pi c}$$

With $m_\gamma = 0$ ⇒ Coulomb potential $A' \frac{1}{r}$

Yukawa potential give a good description of the tail end of the potential ($r > 1\,fm$)

↓

To fit the experimental data precisely, the nucleon-nucleon potential become very messy

↓ (messy) many terms and spin dependent etc.

↓ related to the fact the nucleons are composite themselve.

Magnetic moment of nucleons differ from that predicted by Dirac

↓ suggest

nucleons are composite

1961 Hofstadter measured the electromagnetic structure of the nucleons

Quark model

p	uud
n	udd

Nuclear force → similar to forces among atoms

15-17

Hideki Yukawa. Born 1907 in Tokyo. He received a D.Sc. from Osaka University in 1938. In 1935 he proposed that the force responsible for nuclear binding was a new type of force, neither electromagnetic nor gravitational in origin. To account for the finite range of this force, he postulated that there must be associated with it a new particle with a mass approximately 200 times that of the electron. The π meson, whose existence was confirmed in 1947, proved to be the "Yukawa particle." Yukawa was awarded the Nobel Prize in 1949 for his prediction of the existence of mesons. (*Photograph from the Niels Bohr Library, American Institute of Physics.*)

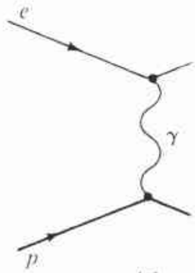


Figure 3-12 (a) S
vertical axis is the
is transferred from
(b) Elastic nucleo
with nonzero rest

We shall return
e-p scattering. W
the N-N force.
scattering as due t
rest mass (Fig. 3-1
particle from the r
The energy violati
is $\sim m_X c^2$. From
exist for a time

In this time it ca
velocity of light.
action, we obtain
particle,[1]

(Yukawa's predict

[1] In units convenient
A compilation of use

The Semiempirical Mass Formula.

$$E(A, Z) = (Z M_p + N M_n) c^2 - A b_{vol} + A^{2/3} b_{surf}$$
$$+ \frac{0.2 Z^2}{A^{1/3}} \text{MeV} + \frac{(N-Z)^2}{2A} + \Delta mc^2$$

Weizsaker - Bethe
semi-empirical mass formula.

Volume term: accounts for the binding energy of all the the nucleons as if every one were entirely surrounded by other nucleons

Surface term: corrects the volume energy term for the fact that not all nucleons are surrounded by other nucleons but may lie in or near the surface.

Coulomb term: give the contribution to the energy of the nucleus due to Coulomb repulsion

Asymmetry term: accounts for the fact that if all other factors were equal, the most strongly bound nucleus of a given A is that closest to have $Z = N$

Pairing term: accounts for the fact that a pair of like nucleons is more strongly bound than is pair of unlike nucleons

$$\Delta mc^2 \quad \begin{cases} \frac{b_{pair}}{\sqrt{A}} & \text{for } N \text{ and } Z \text{ even} \\ 0 & \text{for } N \text{ even or } Z \text{ odd or for } N \text{ odd and } Z \text{ even} \\ -\frac{b_{pair}}{\sqrt{A}} & \text{for } N \text{ and } Z \text{ odd} \end{cases}$$

$b_{vol} = 16$ MeV, $b_{surf} = 17$ MeV, $b_{pair} = 12$ MeV.

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Magic Numbers: 2, 8, 14, 20, 28, 50, 82 or 126

↓

shell model

The curve of binding energy

$B(A,Z)/A$

↓

energy per nucleon required to disassemble the nucleus into A seperated nucleons

$$= b_{vol} - \frac{b_{surf}}{A^{1/3}} - \frac{(0.7\,\text{MeV})Z^2}{A^{4/3}} - \frac{(N-Z)^2}{2A^2}B_{symm} - \frac{\Delta mc^2}{A}$$

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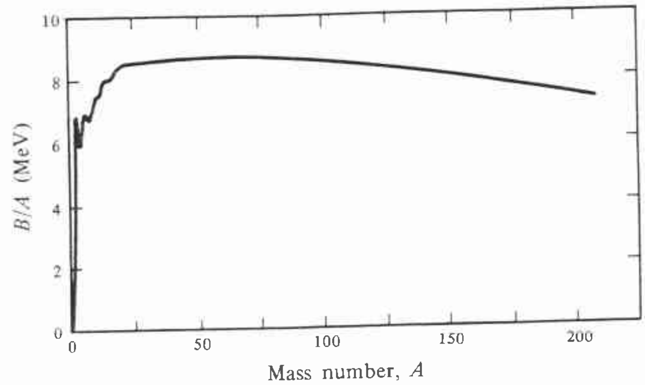

Fig. 14.1. Binding energy per particle for nuclei.

2. B/A reaches its maximum in the region of iron ($A \approx 60$). It drops off slowly toward large A and more steeply toward small A. This behavior is crucial for nuclear power production: If a nucleus of, say, $A = 240$ is split into two parts with $A \approx 120$, the binding of the two parts is stronger than that of the original nuclide, and energy is set free. This process is responsible for energy production in fission. At the other end, if two light nuclides are fused, the binding of the fused system will be stronger, and energy will again be set free. This energy release is the base for energy production in fusion.

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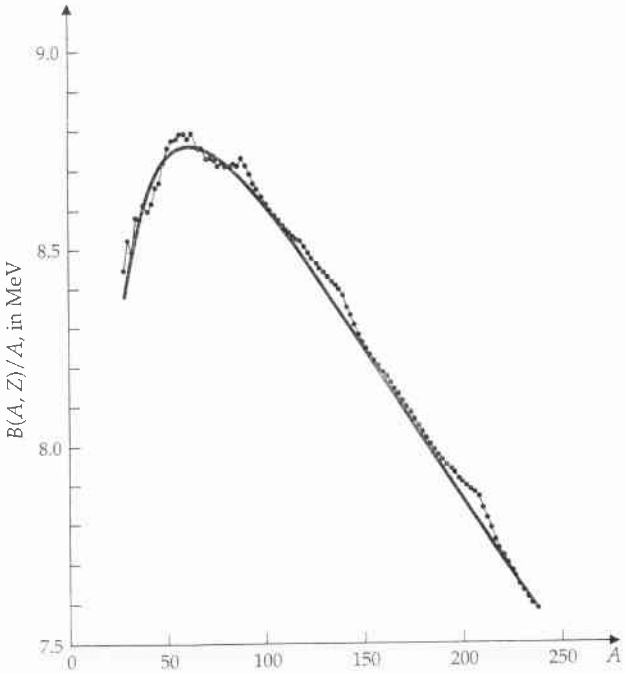
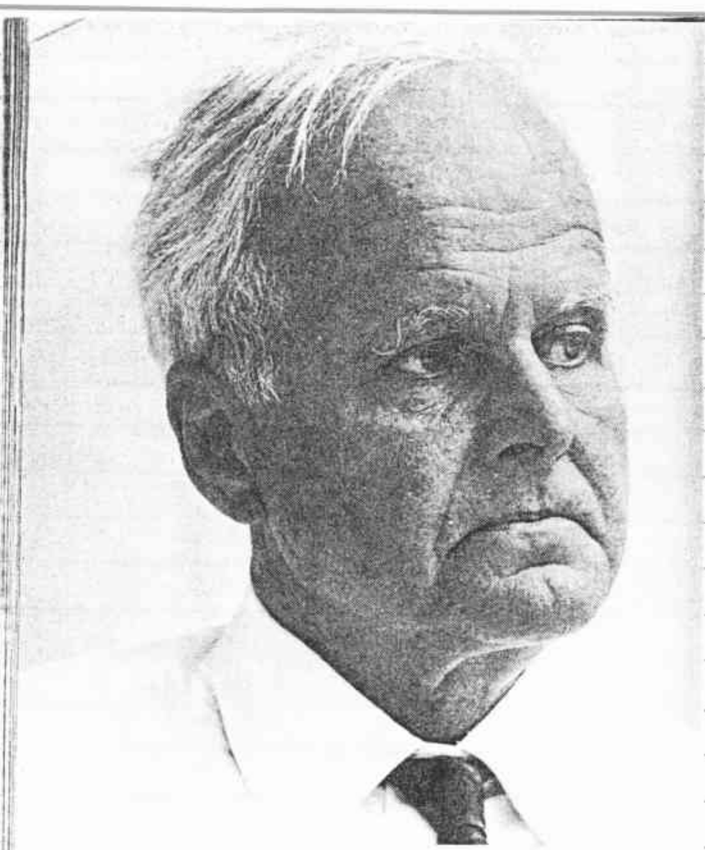


• **Figure 15–4** The comparison of the experimental binding energy per nucleon, $B(A, Z)/A$, given by the line connecting the dots, with the value of the binding energy per nucleon obtained from the semiempirical mass formula, shown by the smooth curve. The peaks in the experimental distribution signal closed-shell effects not included in the mass formula.

[5] There are no naturally occurring nuclei for which $Z = 126$, although $N = 126$ is realized.



Carl Friedrich Freiherr von Weizsäcker

Hans Bethe

(Born 1906, German-American)

After postdoctoral work with Rutherford in Cambridge and Fermi in Rome, Bethe taught in Germany for a few years before coming to the United States in 1935. Among many contributions to atomic and nuclear physics, he is best known for finding the two nuclear cycles by which most stars get their energy. For this discovery, he won the 1967 Nobel Prize in physics.

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The Liquid-drop Model

Bohr and Wheeler

A picture of a uniformly charged fluid held together by surface tension in spite of the repulsive electrostatic interaction that lends to break up the fluid.

Dominant excitations of an electrically charged liquid drop.
↓
vibrational excitation.

Semi-empirical formula → incompressibility
volume remain the same under deformation

Oscillating liquid drop
↕
fission

surface tension → tends to make the spherical shape stable
Coulomb repulsion > surface tension for large Z
⇒ oscillation becomes unstable.

Fisson fragment diagram.

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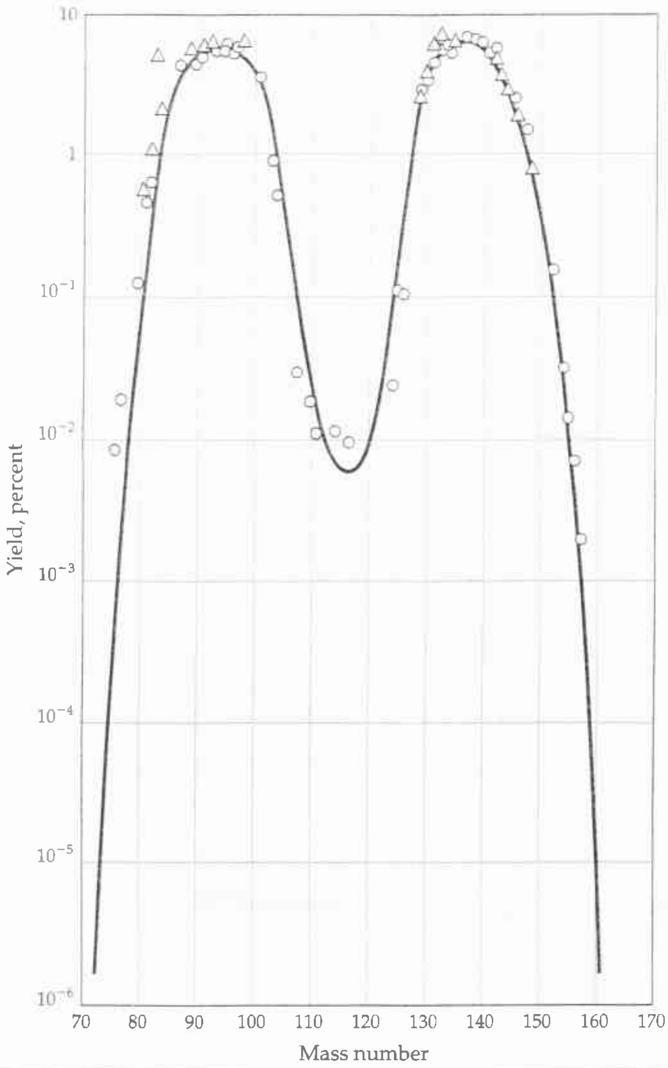
• **Figure 15–7** The sequence of shapes assumed by a charged oscillating liquid drop. The last stage is at the point of fission into two smaller drops.



• **Figure 15–8** The mass distribution of fission products of ^{235}U when the fission is induced by thermal neutrons. The result of a theoretical calculation is drawn as a solid line.

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Table 8.1 Nuclear properties not described by the liquid drop model.

(1) Ground state spins and parities
(2) Excited state spins and parities
(3) Existence of magic numbers
(4) Magnetic moments
(5) Density
(6) Values of coefficients in semi-empirical mass formula (apart from Coulomb)

分類：
編號：
總號：

Ulli Steltzer

Eugene P. Wigner

Compound nucleus

Wigner

$$n_1 + N \rightarrow N^* \rightarrow n_2 + N_2 \qquad \text{nuclear reaction}$$

N^* ↓ compound nucleus.

long lived compared with the time it takes to cross the nuclear diameter

the compound nucleus "forget" how it was formed.

$$R(n_1 + N_1 \rightarrow n_2 + N_2) = R(n_1 + N \rightarrow N^*)\, R(N^* \rightarrow n_2 + N)$$

Example

(i) $\alpha + {}^{60}Ni \rightarrow n + {}^{63}Zn$ $\qquad R(\alpha + Ni^{60} \rightarrow {}^{64}Zn)\, R({}^{64}Zn \rightarrow n + {}^{63}Zn)$

(ii) $\alpha + {}^{60}Ni \rightarrow 2n + {}^{62}Zn$ $\qquad R(\alpha + Ni^{60} \rightarrow {}^{64}Zn)\, R({}^{64}Zn \rightarrow 2n + {}^{62}Zn)$

(iii) $\alpha + {}^{60}Ni \rightarrow n + p + {}^{62}Cu$ $\qquad R(\alpha + {}^{60}Ni \rightarrow {}^{64}Zn)\, R(\ ' \rightarrow n + p + {}^{62}Cu)$

(iv) $p + {}^{63}Cu \rightarrow n + {}^{63}Zn$ $\qquad R(\ + {}^{63}Cu \rightarrow {}^{64}Zn\ )\, R({}^{64}Zn \rightarrow n + {}^{63}Zn)$

(v) $p + {}^{63}Cu \rightarrow 2n + {}^{62}Zn$ $\qquad R(p + {}^{63}Cu \rightarrow {}^{64}Zn)\, R({}^{64}Zn \rightarrow 2n + {}^{62}Zn)$

(vi) $p + {}^{63}Cu \rightarrow n + p + {}^{62}Zn$ $\qquad R(p + {}^{63}Cu \rightarrow {}^{64}Zn)\, R({}^{64}Zn \rightarrow n + p + {}^{62}Cu)$

$$\Rightarrow \quad \frac{(i)}{(ii)} = \frac{(iv)}{(v)}$$

Other relations can be derived using the same method.

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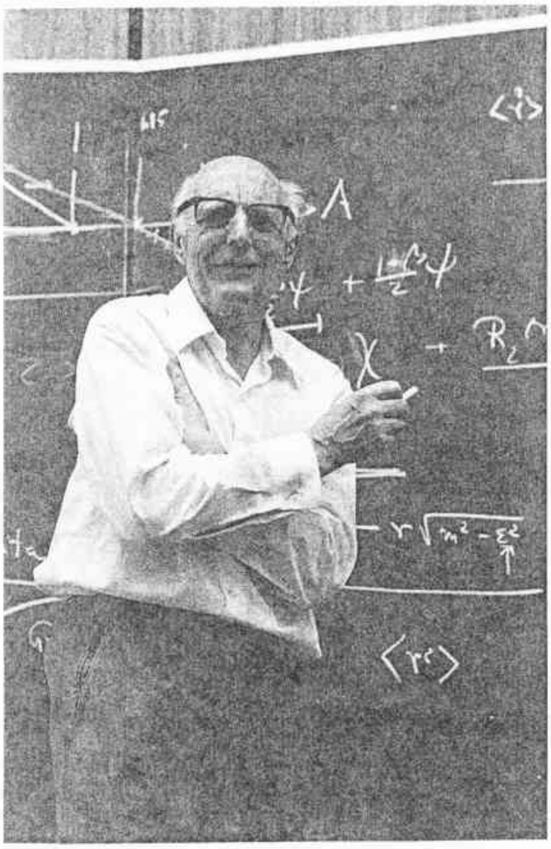

Figure 11.7 J. Hans D. Jensen, 1972. (1907–1973)

Figure 13.4 Maria Mayer studying a chart of nuclei at the University of Chicago. This systematic study led her to create a shell model of the nucleus that is reminiscent of Bohr's atomic model and explains many nuclear regularities. (Photo University of Chicago.)

Maria Goeppert-Mayer (1906–1972) was the daughter of the pediatrician of Max Born's children, and she studied at Göttingen under Born. As Born recalled, "She went through all my courses with great industry and conscientiousness, yet remained at the same time a gay and witty member of Göttingen society, fond of parties, of laughter, dancing, and jokes. . . . After she got her doctor's degree with a very good thesis on a problem of quantum mechanics, she married a young American, Joseph Mayer, who worked with me on problems of crystal theory. Both had brilliant careers in the U.S.A., always remaining together." At the University of Chicago in 1948 Goeppert-Mayer reopened the question of periodicities in nuclear stability, which had remained a mystery since their discovery in the early 1930s, and devised a shell model that agreed with the data. J. H. D. Jensen in Germany published a similar theory independently at the same time, and both received the Nobel Prize in 1963 for their work.

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The Shell Model

Maria Goeppert - Mayer and Hans Jensen

Magic number

Either Z or N the values 2, 8, 20, 28, 50, 82 and for N alone 126 are particularly stable.
↓
See the figure.

In atomic physics
↓
atom has a shell structure
See the figure

But the magic numbers are not the same.

The physical picture.

A single nucleon moves in a potential is the average of the effect of all the other nucleons and that this potential varies smoothly.

Nucleon moves in a potential wells.

The picture is possible only when exclusion principle is taken into account
↓
increase the mean free path for the physical picture to be viable.

Steps.

- Propose some simple potential
- Solve the Schrodinger equation
- Fill the energy level
- Look for the magic number

Square well, Harmonic oscillator, Saxon-Woods

⇒ do not give the correct magic numbers

Add a strong spin-orbit interaction

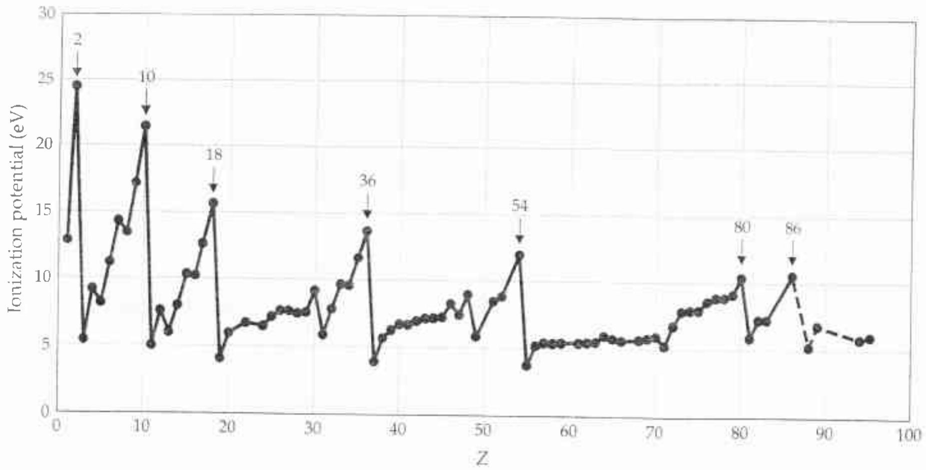
$$V(r) \Rightarrow V(r) + W(r)\,\vec{L}\cdot\vec{S}$$

⇓

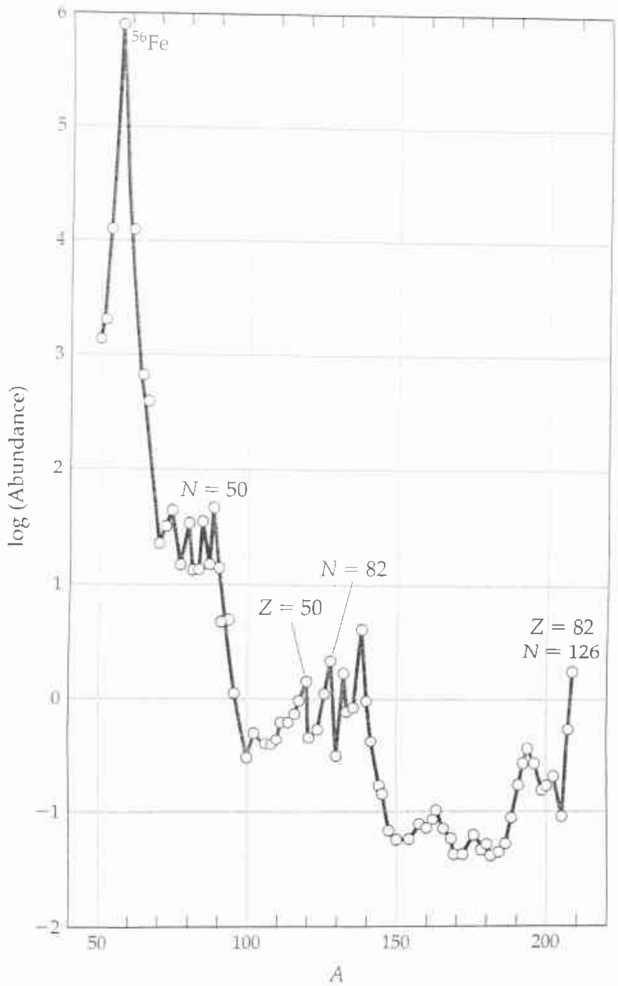
the correct magic number.

Additional predictions.

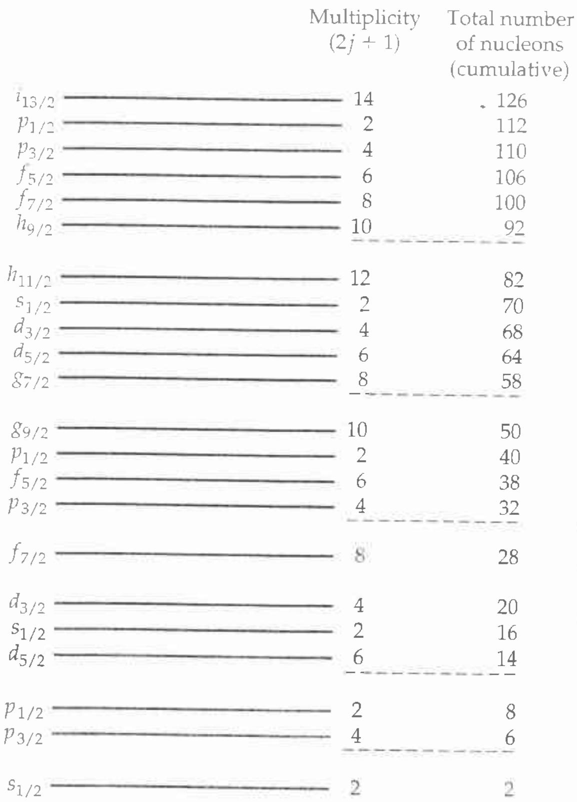
- nuclear spin, parity
- magnetic dipole moment
- electromagnetic moment
- excited states.



• **Figure 15–9** Atomic ionization potentials as a function of Z, showing that the atom has a shell structure, from data compiled by C. E. Moore (1970). (From *Subatomic Physics*, 2nd ed., by Hans Frauenfelder and Ernest Henley. Copyright © 1991 by Prentice-Hall, Inc., Upper Saddle River, NJ.)



• **Figure 15–10** Relative abundances of even–even nuclides, from data compiled by A. G. W. Cameron (1968). The abundances are measured relative to that of Si. The pattern of shell structure, similar to that shown in •Fig. 15–9, is manifest. (From *Subatomic Physics*, 2nd ed., by Hans Frauenfelder and Ernest Henley. Copyright © 1991 by Prentice-Hall, Inc., Upper Saddle River, NJ.)



• **Figure 15–11** The experimental ordering of nuclear shells for protons. The levels are labeled by (ℓ, j). The energy gaps, characterized by the "magic numbers" 2, 8, 28, 50, 82, and 126, are impressionistically drawn. The shell structure for neutrons differs slightly from that for protons at the higher levels. We ignore the difference.

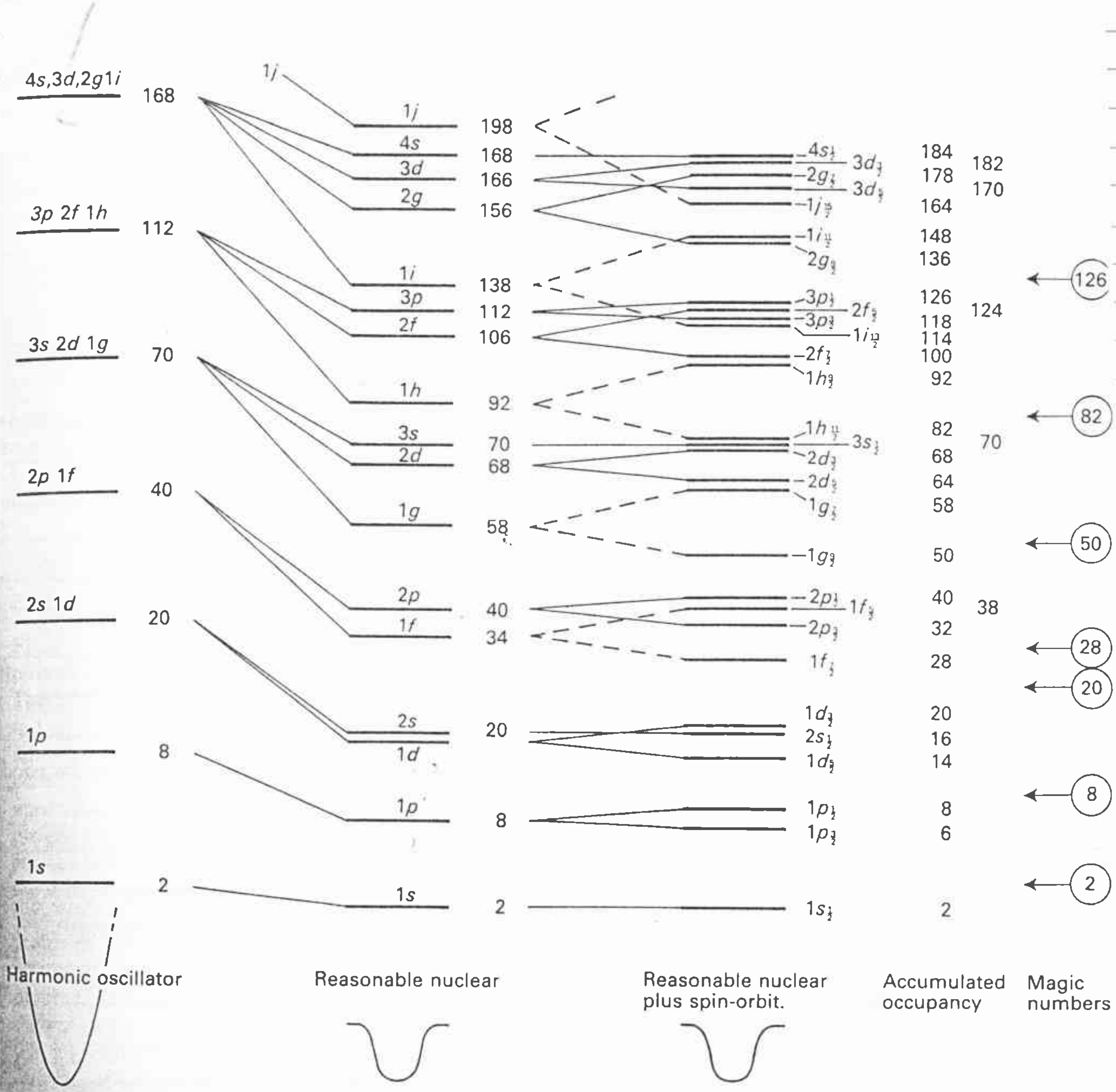


Fig. 8.6 A schematic representation of the change in single-particle level ordering in moving from (a) the harmonic oscillator to (b) a reasonable nuclear potential to (c) the same with an inverted spin-orbit interaction added. On the right of each are shown the accumulated occupancy numbers. An ordering is given in (c) which gives the magic numbers. Between these numbers the residual interactions between nucleons will alter the ordering as the levels are filled. The splittings caused by the spin–orbit interaction which are vital to the explanation of the observed magic numbers are emphasized by heavy broken lines: they are $1f \rightarrow 1f_{7/2} + 1f_{5/2}$, $1g \rightarrow 1g_{9/2} + 1g_{7/2}$, $1h \rightarrow 1h_{11/2} + 1h_{9/2}$, and $1i \rightarrow 1i_{13/2} + 1i_{11/2}$. These are the splittings mainly responsible for the gaps defining the magic numbers.

1975

原子結構理論的突破—集體模型

科學月刊編輯部

波耳（Aage Bohr, 1922-）

莫特森（Ben R. Mottelson, 1926-）

雷恩沃特（James Rainwater, 1917-1986）

發現原子核內集體運動與粒子運動的關連，

並以此發展原子核的結構理論。

波耳

莫特森

雷恩沃特

15-24

「由於發現原子核內集體運
原子核的結構理論」，波耳（
Mottelson）及雷恩沃特（James
年的諾貝爾物理獎。1949年秋
耳及莫特森則從那時開始即全力

雷恩沃特是美國哥倫比亞大
1975年諾貝爾獎的消息時，起
是由於他在1953年做的實驗證
出的X光，最後當他得知波耳及
眞正原因。他的貢獻是首先提出
地承認，這方面百分之九十的工
森兩人二十幾年來所做的。

殼層模型

在1949年時，關於原子核的
model）及殼層模型（shell moc
綜合。所謂液滴模型，顧名思義
子組成的液滴。這模型在1939
的父親，量子力學的大師，192
A. Wheeler）發表的論文中曾子
核有表面張力和均勻的密度，會
（核分裂），就像普通水滴一樣。

殼層模型由於顏森（J.
Goeppert-Mayer）的貢獻，在19
並共同得到1963年的諾貝爾獎
爲其中每一中子或質子（通稱核

分類：
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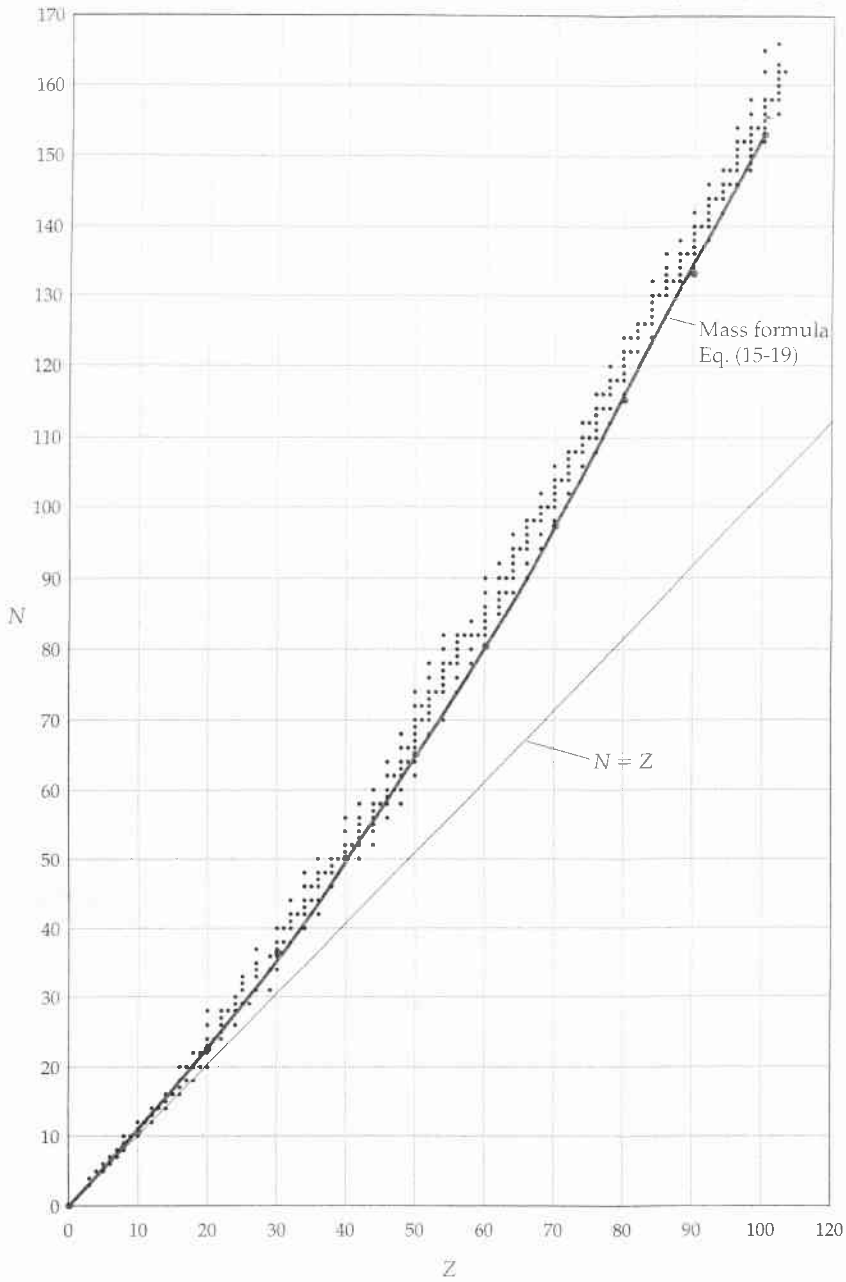
The discovery of the connection between collectective motion and particle motion in atomic nuclei and for the structure of the atomic nucleus based on this connection. earned

Aage Bohr
Ben R. Mottleson
L. James Rainwater
Nobel prize in physics
1975

Ben Mottelson, 1926–, American-born physicist living in Denmark. He was awarded the Nobel Prize in 1975 with James Rainwater, 1917–1986, and Aage Bohr, 1922 –, the son of Niels Bohr, for work on vibrations and rotations of nuclei. (Copyright the Nobel Foundation.)



• **Figure 15–5** The experimental distribution of nuclides as a function of N and Z. The data are given by the round points; the prediction derived from Eq. (15–19) is shown as a heavy line. The experimental distribution shows the expected excess of neutrons above the line $N = Z$.

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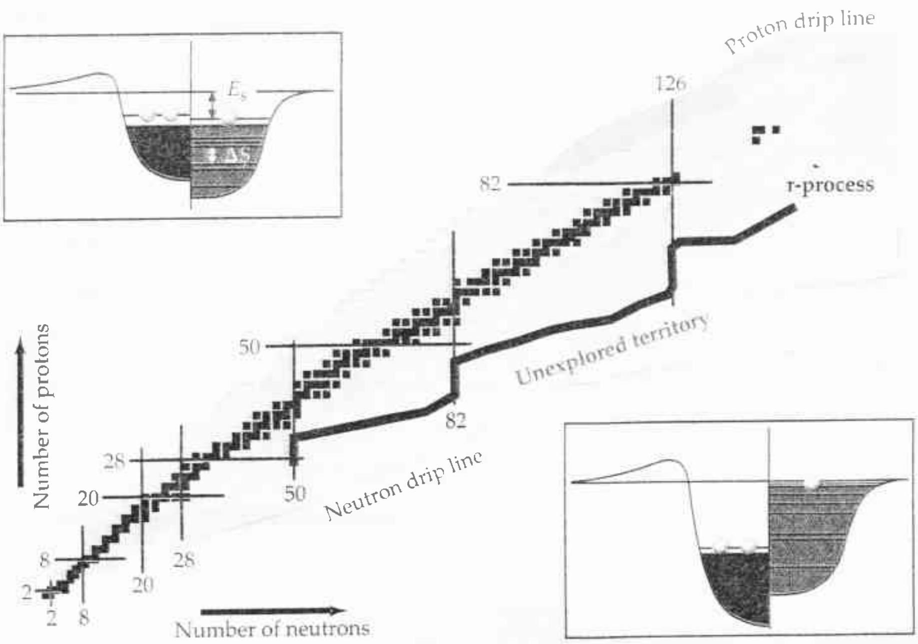

Figure 1. The nuclear landscape depicted here is a chart of nuclides in a plane arranged by neutron and proton number. The black squares represent stable nuclei; the orange region, measured nuclei; and the green region, nuclei that are stable according to calculation but otherwise have not been explored. Red lines indicate magic numbers. The rapid neutron-capture (r-process) path, which describes an important stellar nucleosynthesis chain, lies almost entirely in unexplored territory. The insets show nuclear potentials for protons (red) and neutrons (blue) in a stable nucleus (top) and a neutron-rich weakly bound nucleus (bottom) whose binding or separation energy E_s is rather small. The energy separating major nuclear shells is denoted by ΔS.

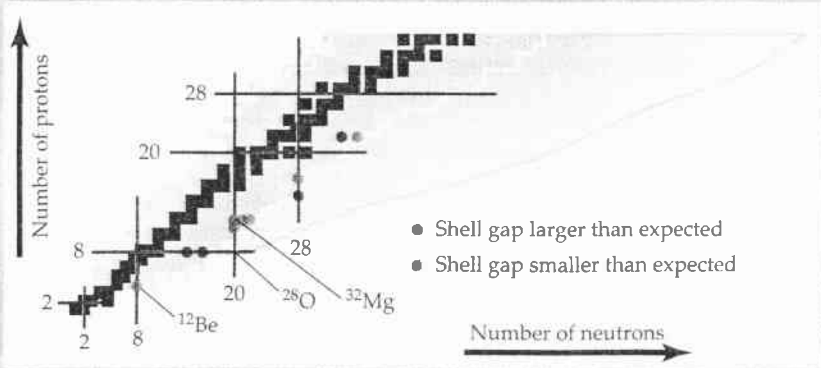

Figure 2. New magic numbers are emerging through accurate measurements of nuclear masses. This enlarged view of the low-mass region of the nuclear landscape indicates several nuclei with unexpected energy gaps between nuclear shells.

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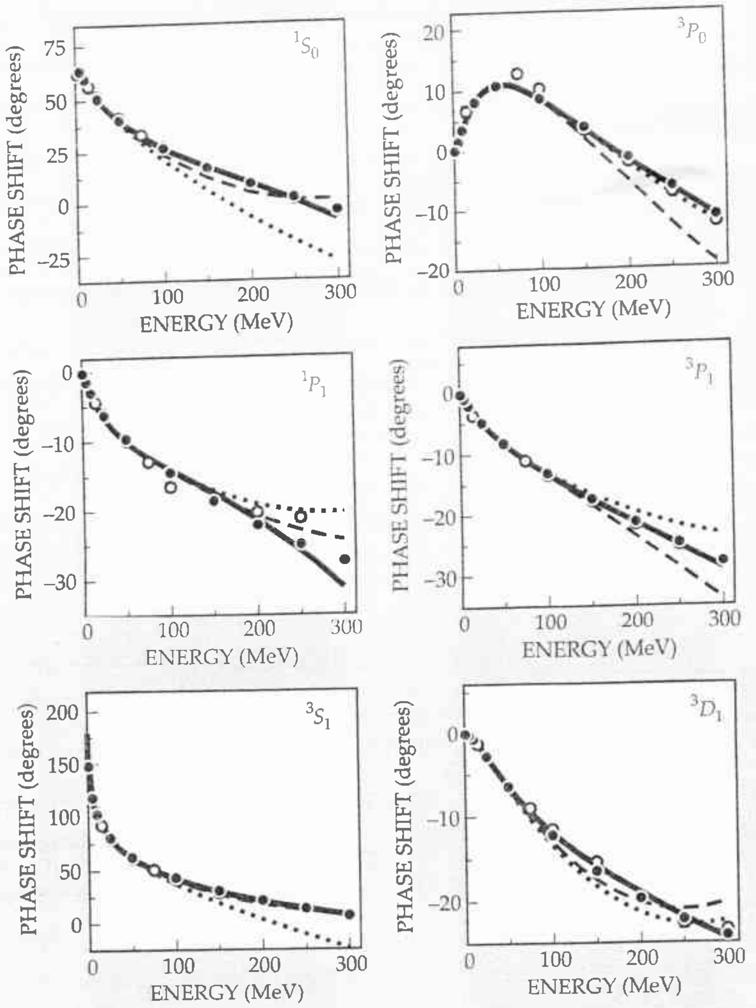

Figure 3. Nucleon–nucleon scattering phase shifts are well predicted by effective field theories. The plots show experimental data (filled and unfilled points) and calculated values (curves) for the phase shifts of several scattering channels as a function of energy. The dotted lines represent second-order EFT calculations; dashed lines, third order; solid lines, fourth order. Increasing the order allows for a more complete and accurate description of the phase shifts. (Adapted from ref. 10.)

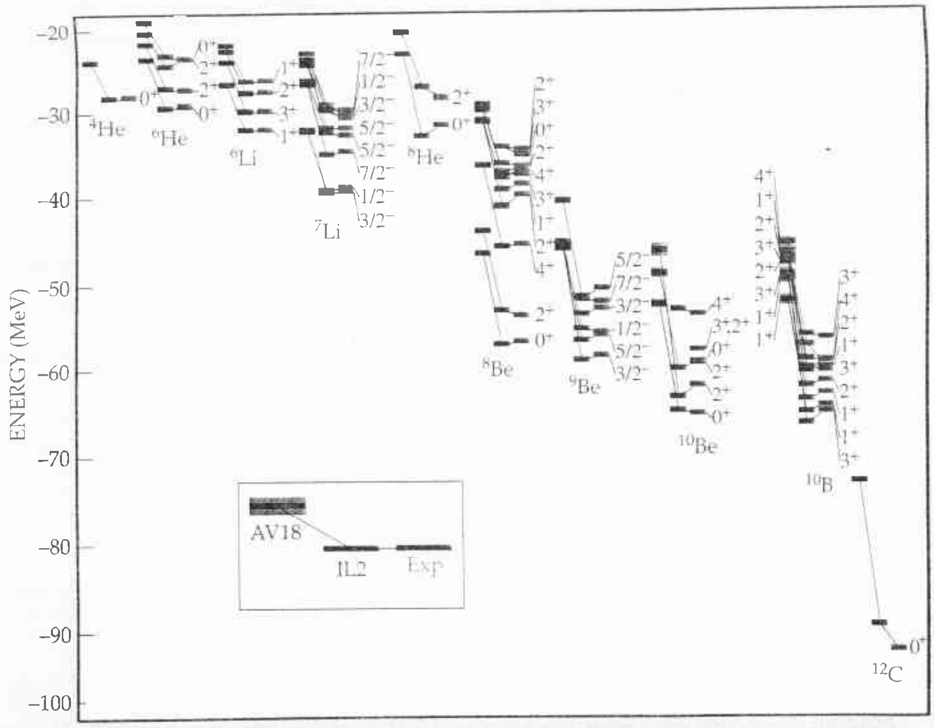

Figure 4. Green's function Monte Carlo techniques have been applied to a number of light nuclei, ranging from helium-4 to carbon-12. The Argonne v_{18} (AV18) calculation includes only two-body forces. The Illinois-2 (IL2) calculation adds three-body forces. Once those attractive interactions are included, theory and experiment are in beautiful agreement. The yellow and lighter blue rectangles indicate theoretical error; light green rectangles indicate resonance widths. (Courtesy of Steven Pieper, Argonne National Laboratory.)

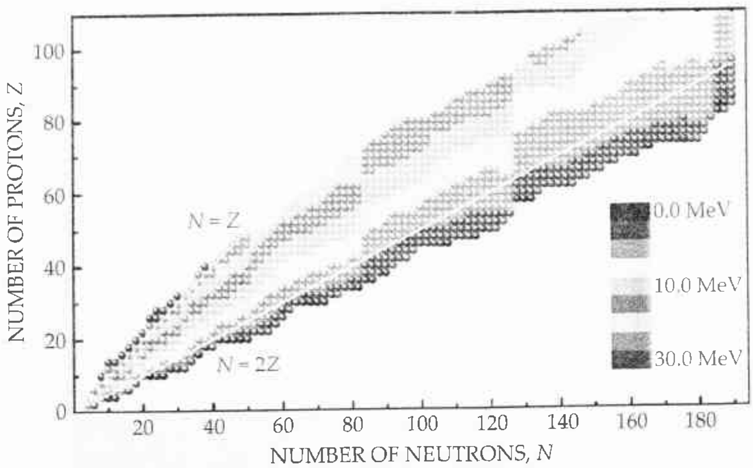

Figure 6. A single energy-density functional predicts the energies needed to separate two neutrons from 1553 different bound nuclei. The results shown here include nuclei with even numbers of both protons and neutrons and allow for nuclear deformations. Clearly visible are neutron shell closures at N = 82, 126, and 184. (Courtesy of Mario Stoitsov, University of Tennessee.)

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Radioactivity

Time dependence in quantum mechanical decay

$$\frac{dN(t)}{dt} = -R\,N(t)$$

R ↓ decay rate ↕ Fermi golden rule.

$$N(t) = N_0\, e^{-Rt} = N_0\, e^{-t/\tau}$$

$$\tau = \frac{1}{R}$$

τ ↓ mean lifetime

$$R = R_1 + R_2 + R_3 + \cdots$$

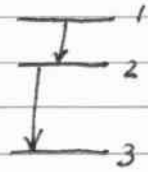
R ↳ decay

R_i partial decay rate into ith channal

Decay in series

$$\frac{dN_1}{dt} = -R_{12}\, N_1(t)$$

$$\frac{dN_2}{dt} = R_{12} N_1(t) - R_{23} N_2(t)$$



$R_{12} N_1(t)$: gain; $R_{23} N_2(t)$: loss

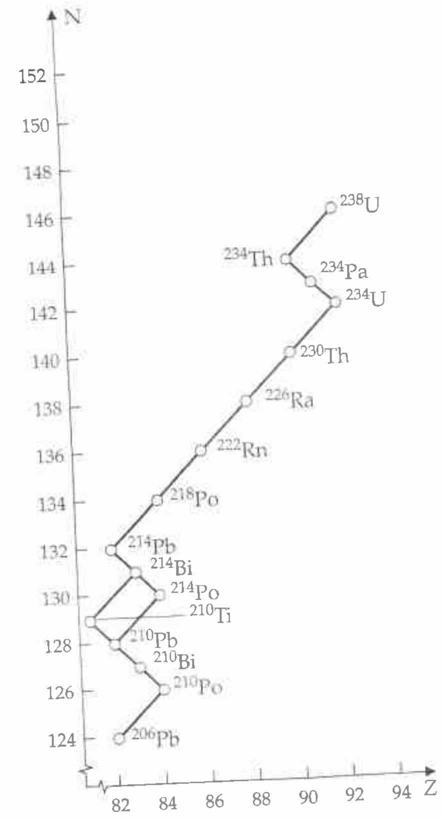
$$N_1(t) = N_1(0)\, e^{-R_{12}t}$$

$$\Rightarrow \frac{dN_2}{dt} = R_{12} N_1(0)\, e^{-R_{12}t} - R_{23} N_2(t)$$

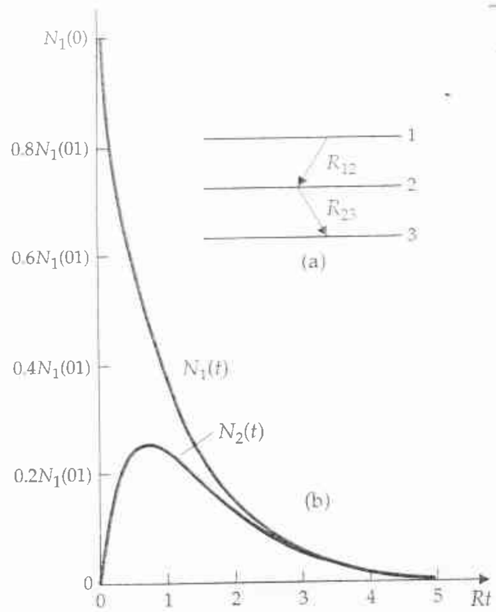
↓ equation for $N_2(t)$ alone

$$\Rightarrow N_2(t) = N_1(0) R_{12} \frac{e^{-R_{23}t} - e^{-R_{12}t}}{R_{12} - R_{23}}$$

↓ can be show that it satisfies the differential equation by direct substition.



• **Figure 15–12** Decay series leading from ^{238}U to ^{206}Pb by steps involving alpha decay (a drop in Z and N by two units each) and beta decay (a drop in N by one and an increase in Z by one).



• **Figure 15–13** (a) Schematic picture of the nuclear decay sequence $N_1 \rightarrow N_2 \rightarrow N_3$ with rates R_{12} and R_{23}, respectively. (b) Plot of Eq. (15–27) in arbitrary time units for the parameters $R_{23} = 2R_{12}$.

α- decay

We have already discuss this problem in quantum tunneling.

Gamow

The two figures follows
↓
Fig. 15-14 , 15- 15

George Gamow, 1904–1968, whose work in 1928 showed that alpha particles can behave as waves. In so doing, he solved the long-standing puzzle about the half-life of alpha decay. This demonstrated for the first time that quantum mechanics applies to nuclei. (AIP Emilio Segrè Visual Archives.)

β - Decay

$n \to p + \beta^- + \bar{\nu}$ simplest β - decay
($\beta^- \to e^-$)

Closely related process

$p \to n + \beta^+ + \nu$
$\beta^- + p \to n + \nu$
$\bar{\nu} + p \to n + \beta^+$

$^A[Z] \to {}^A[Z-1] + \beta^+ + \nu$

Q
↓
Q - value
$= (M_Z - Zm_e)c^2 - (M_{Z-1} - (Z-1)m_e)c^2 - m_e c^2$

$= M_Z c^2 - M_{Z-1} c^2 - 2m_e c^2$

M_Z = mass of the atom

Example: $^{13}_{7}N \to {}^{13}_{6}C + \beta^+ + \nu_e$

$^{40}_{19}K \to {}^{40}_{18}Ar + \beta$

Discovery of Neutrino

Original thought to be $n \to p + e^-$

Difficulty: $A \to B + C$
In the center of mass system (from energy-momentum conservation

$$M_A c^2 = \sqrt{\vec{P}_c^2 c^2 + M_B^2 c^4} + \sqrt{\vec{P}_c^2 c^2 + M_c^2 c^4}$$

$\Rightarrow$ ~~$|\vec{P}_e|$ is uniquely determined~~

Experimentally, the energy spectrum of the electron is continuous
(P. 407 of Ohanian)

Furthermore, angular momentum conservation can not be maintained

Resolution: Pauli proposed the existence of ν.

Fermi construct a model (4 fermion interaction) based on quantum field theory for

$$n \to p + e^- + \bar{\nu}_e$$

which give a good description of the experimental result.

ν has the following properties

$m_\nu = 0$, spin $= \frac{1}{2}$, $Q = 0$

only interact weak

↓

it is very difficult to detect.

ν was detected by F. Reines and C. L. Cowan

1928 Dirac relativistic spin $\frac{1}{2}$ wave equation

↓

Dirac equation

↙

prediction the existence of e^+ positron.

↓

having the same mass, spin but opposite charge of e^-

$e^- \leftrightarrow e^+$ are anti-particle of each other

e^+ was discovered by Anderson in 1932

Now: all particles have their anti-particle

$p \leftrightarrow \bar{p}$, $n \leftrightarrow \bar{n}$

in special case, a particle may be its own anti-particle.

$\gamma \leftrightarrow \gamma$, $\pi^0 \leftrightarrow \pi^0$

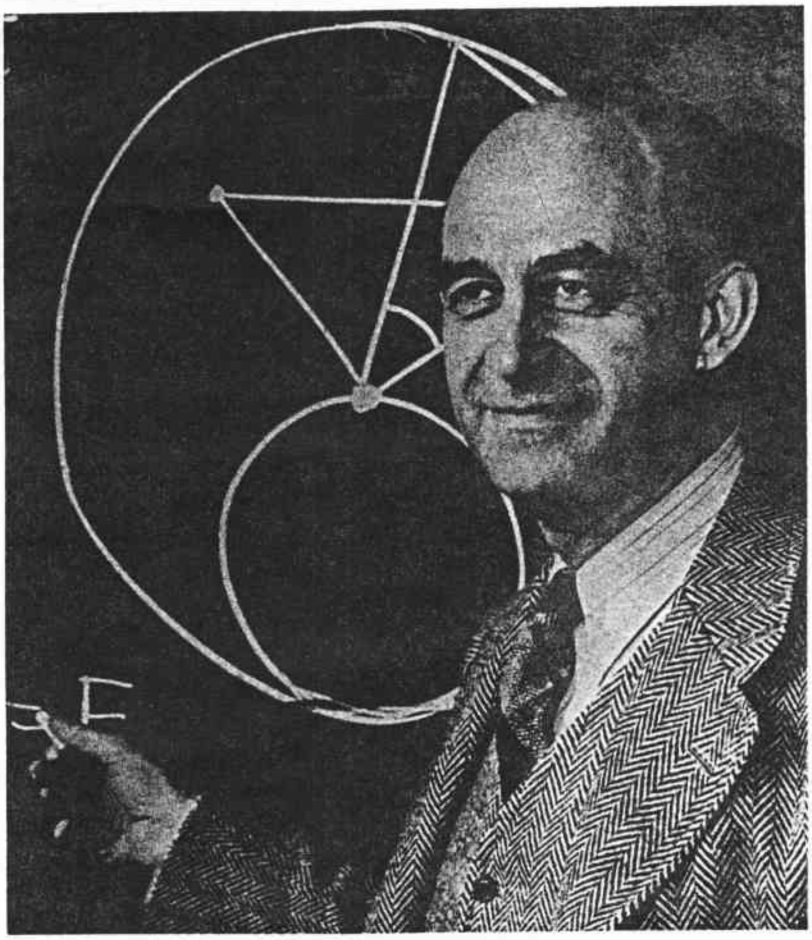
$\bar{\nu}_e \longleftrightarrow \nu_e$

$\bar{\nu}_e$ ↓ produced with e^-

ν_e ↓ produced with e^+

Wolfgang Pauli, 1900–1958, and Niels Bohr, 1885–1962. One of Pauli's many contributions to quantum physics concerned the spin of elementary particles such as electrons. The spin of much larger objects like this top was clearly also of great interest. (AIP Emilio Segrè Visual Archives.)

15-31



Enrico Fermi. Born 1901 in Rome; died 1954. His early work included discovery of the so-called Fermi-Dirac statistics for particles with half-integer spin (fermions). While at the University of Rome, he and his group carried out a series of classic experiments to study artificial radioactivity induced by neutron bombardment for which he later received the Nobel Prize. The theory of β decay that he proposed in 1934 was the basis for the current theory of weak interactions. In 1939 he emigrated to the United States. His contributions to the development of the first chain-reacting pile during the war are well known. After the war he and his group at the University of Chicago started a series of experiments to study pion-nucleon scattering with pion beams from the Chicago cyclotron. Fermi also made significant contributions to astrophysics. He was one of the very few physicists who have done outstanding work in both theory and experiment. He was a superb teacher and writer; his books and papers are noted for their clarity. Element 100 in the periodic table is named in his honor. *(Photograph from the Niels Bohr Library, American Institute of*

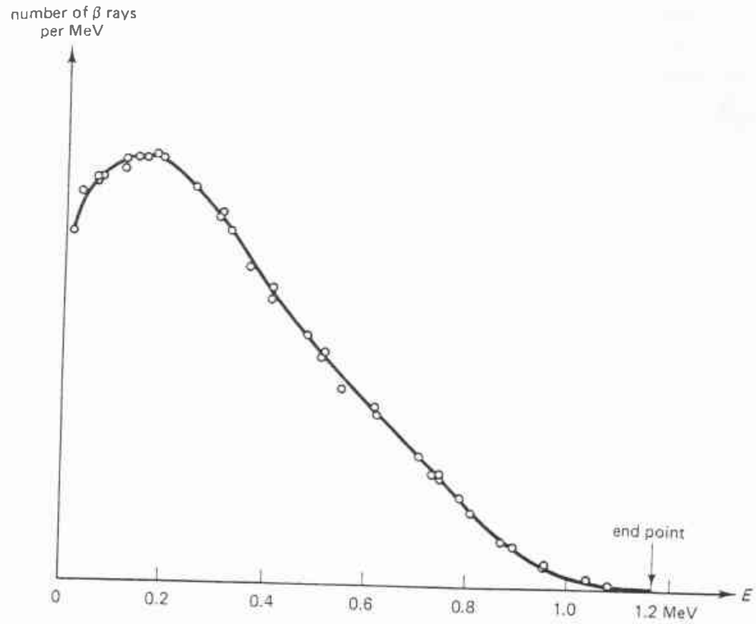


Fig. 10.6 Energy spectrum of β rays ejected by the radioactive decay of a sample of ^{210}Bi. [After G. J. Neary, *Proc. Roy. Soc.* (London) **A175,** 71 (1940).]

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C. S. Wu made enoromous contributions to β-decay.

β-decay differ from strong, electromagnetic interaction

↓

first of a new class of interactions

↓

weak interaction.

short range

weak

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6-1 Estimate the probability of a neutrino's passing directly through the earth without interacting. Take the neutrino total cross section to be $\sim 10^{-14}$ of that for high-energy neutrons. (The radius of the earth is $\approx 6.4 \times 10^6$ m; its mass is $\approx 6 \times 10^{24}$ kg.) Repeat for a high-energy neutron. The earth is constantly being bombarded by a flux of neutrinos $\sim 4 \times 10^{10}$ cm^{-2}/sec from the sun. Make a rough estimate of the number of neutrino-induced reactions in our bodies per day.

$\sigma_{\nu N} \sim 10^{-38}$ cm^2 at 1 GeV/c incident momentum

$$l = \frac{1}{n\sigma}$$

n = number of nucleons per unit volume

$M_N \sim 1000$ MeV/c^2

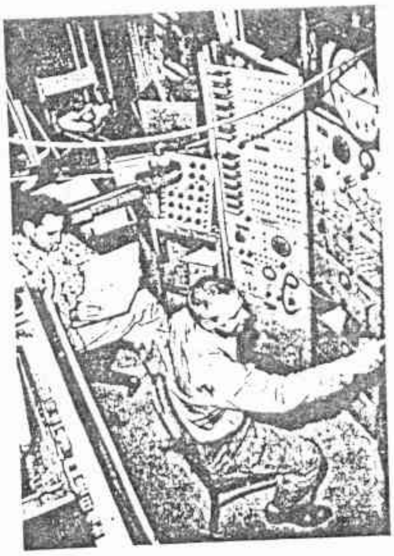
strong interaction

$\pi^- + p \to K^0 + \Lambda$ at 1 GeV/c incident momentum

$\sigma \sim 1$ mb $= 10^{-27}$ cm^2

Figure 12.8 Chien Shiung Wu (right) and W. Pauli. Wu, who did fundamental studies on weak interactions, is photographed here with the inventor of the neutrino hypothesis. The neutrino plays an important role in weak interactions.

Reines takes notes while Cowan reads dial settings.



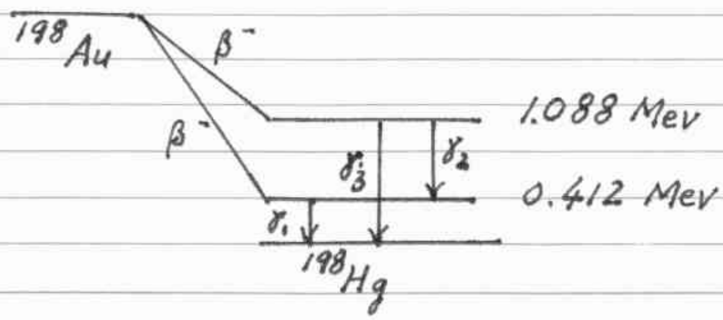
Some of the researchers: left to right, Lt. P. Powell, USN, Dr. F. N. Hayes, Mr. K. Perkins, Dr. F. Reines, Dr. E. C. Anderson, and Dr. C. L. Cowan.

γ - Decay

The nucleus will reach its ground state after emitting one or more photons → nuclear γ - rays.

The energy of each photon is the energy difference between the final nuclear states less the recoil kinetic energy of the nucleus

Example



Typical energy level diagram of excited nuclear states

Selection rules are established

Nuclear spectroscopy
↓
important tool for physicists to understand the nuclear structure.

Half-lives of the excited states $\sim 10^{-9}$ to 10^{-12} sec.

Occassionally it happens, the half-lives of some excited nuclear state is very long (hours or even days) ⇒ such states are known as isomeric states.

Internal conversion:

An excited state A^* of a nucleus can decay electromagnetically to the ground state A without emission of a photon.

The energy difference is used to eject an electron from one of the inner shells of atom containing the nucleus.

The Mössbauer effect occurs when a radioactive nucleus is embedded in crystal.
Nuclear γ decays can occur without nuclear recoil resulting in extremely narrow line widths.

Mössbauer effect was discovered in 1957
Nobel prize 1961

An elementary discussion of Mössbauer effect will be given in Appendix A
(Rohlf , P. 322 - 326)

Fission

Binding energy per nucleon is in the vicinity of 8 MeV

In heavy nuclei (i.e. $A > 200$) the binding energy is somewhat smaller.

↓

the decrease is due to the increasing importance of electrostatic repulsion.

It is energetically favorable for a heavy nucleus to split up into two fragments, forming two lighter nuclei

$$^{238}U \rightarrow {}^{119}Pd + {}^{119}Pd$$

Potential energy as a function of deformation.

↓

the intermediate stage of deformation

↓

potential barrier

↓

quantum mechanical tunneling is needed to have spontaneous fission.

⇒ In the case of ^{238}U spontaneous fission is a rare occurrence → one nucleus in 10^{-6} will decay by spontaneous fission, others will decay via α - emission

Fission releases energy in the form of kinetic energy of fission fragments.

^{238}U is susceptible to induced fission

$$n + {}^{238}U \rightarrow {}^{145}Ba + {}^{94}Kr$$

↓

discovery of fission by O. Hahn and F. Strassman

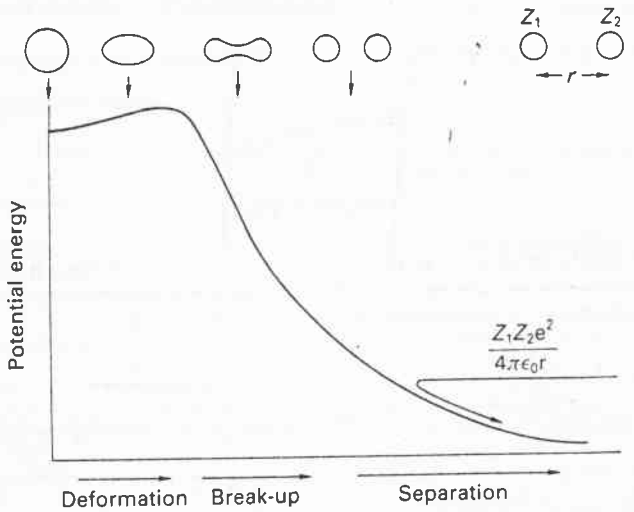


Fig. 6.7 The fission barrier. The expected form of the potential energy curve as a nucleus deforms, breaks up, and the products separate during the process of fission. The abscissa is not well defined until the fission products are well separated, when we can expect it to vary Coulomb-wise. At zero abscissa the nucleus has an energy greater than that at infinite separation of the products at rest, by the energy released in fission. There is a barrier to fission which is probably about 6–8 MeV higher than the undeformed energy in nuclei near uranium. This height is the activation energy and it decreases as Z^2/A increases and may reach zero near $Z=115$. (The heaviest nucleus so far observed has $Z=106$.) This barrier determines the spontaneous fission transition rate.

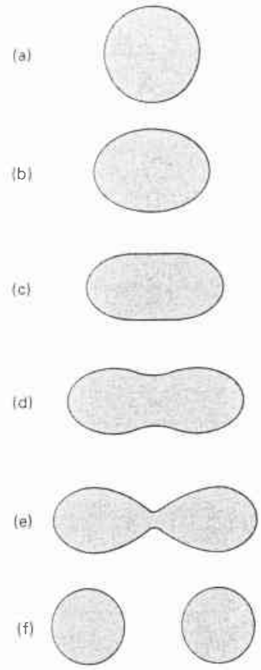


Fig. 10.14 Fission of a drop of nuclear fluid. [After D. L. Hill and J. A. Wheeler, *Phys. Rev.* **89,** 1102 (1953).]

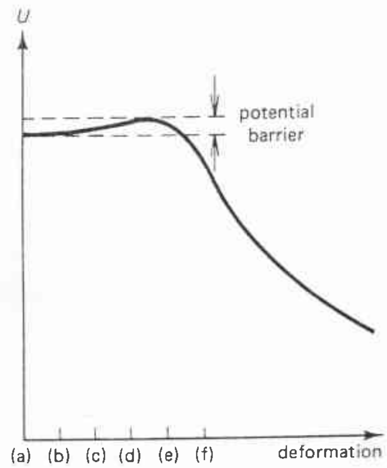


Fig. 10.15 Potential energy as a function of deformation (the letters give a rough correspondence with Fig. 10.14.)

Both the fission fragments are very neutron rich.
↓
almost immediately eject two or three neutrons.

$$n + {}^{238}U \rightarrow \text{fission fragments} + 2n \text{ or } 3n.$$

Practical applications of fission rely on the neutrons released in this reaction to induce further fission reaction
↓
chain reaction

If there is no neutrons, or only few neutron, are lost from the chain ⇒ avalanche of neutrons and of fissions.

Problem with ${}^{238}U$

The cross section for neutron induced fission reaction depends on the neutron energy
In the cases of ${}^{238}U$, the minimum neutron energy required for initiating the fission reaction is 1.2 MeV
↓
fast neutron.

The neutrons released in fission of ${}^{238}U$ are initially fast
↓ likely suffering several consecutive inelastic collision
↓
neutrons lose most of their kinetic energy

inelastic collisions effectively remove neutrons from the fission chain
↓
inhibit the chain reaction

${}^{238}U$ tends to soak up neutrons without undergoing fission and it will not sustain a chain reaction

分類：
編號： 15-36
總號：

^{235}U is a fissible material

No minimum neutron energy required for fission.
For low energy neutron σ (for induced fission) $\propto \frac{1}{v}$
because the slowest neutron spend the longest time passing through nucleus.

Natural uranium ores

99.3% ^{238}U
0.7% ^{235}U

↓

isotope seperation is needed.

Multiplication factor k

↓

the factor by which the number of neutrons increases in successive step along the fission chain.

If no neutron is lost k = average number of neutrons released per fission.
But if some neutrons are loss k is smaller

$k = 1$ → critical condition.

$k > 1$ → supercritical condition.

Neutron loss

- absorbed by impurities such as ^{238}U
  $n + {}^{238}U \rightarrow {}^{239}U$
  ↓ low energy
- escape from the volume of the fissile material
  ↓ To reach critical condition.
  critical volume
  ↓ given density
  critical mass

A simple "atomic" bomb consists of two pieces of ^{235}U such that seperately their masses are less than the critical mass, but jointly their masses add up to more than the critical mass

To detonate such a bomb, the pieces of ^{235}U, initially at safe distance from one another, are suddenly brought closely together.

In a nuclear reactor, the fission proceeds under controlled conditions, at a constant rate rather than at an explosively increasing rate

The fissile material in the reactor is in a critical rather than a supercritical condition

Most reactors operate with "enriched" uranium.

↓

consisting of few % ^{235}U
~90 % ^{238}U

Such uranium mixture cannot by itself sustain a chain reaction. - the ^{238}U absorbs too many of neutron

If the uranium is surrounded by substance (moderator) capable of slow down fast neutrons, then a chain reaction becomes viable.

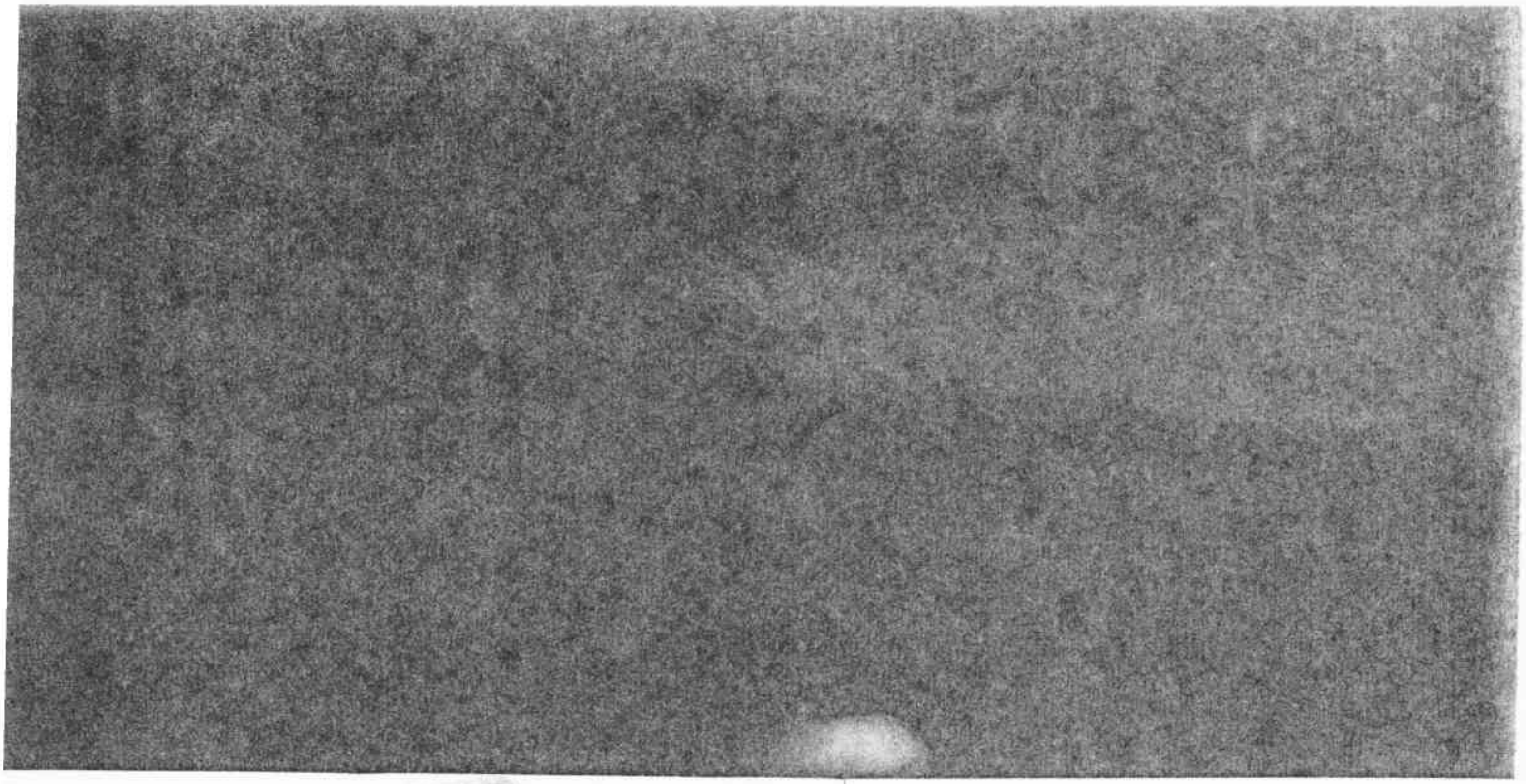
Slower neutron has higher cross section to induce fission.

分類：
編號：15-38
總號：

Fission O. Hahn, F. Strassman
L. Meitner, O. Frish

Chain reaction Fermi

Atomic bomb Manhatten project.

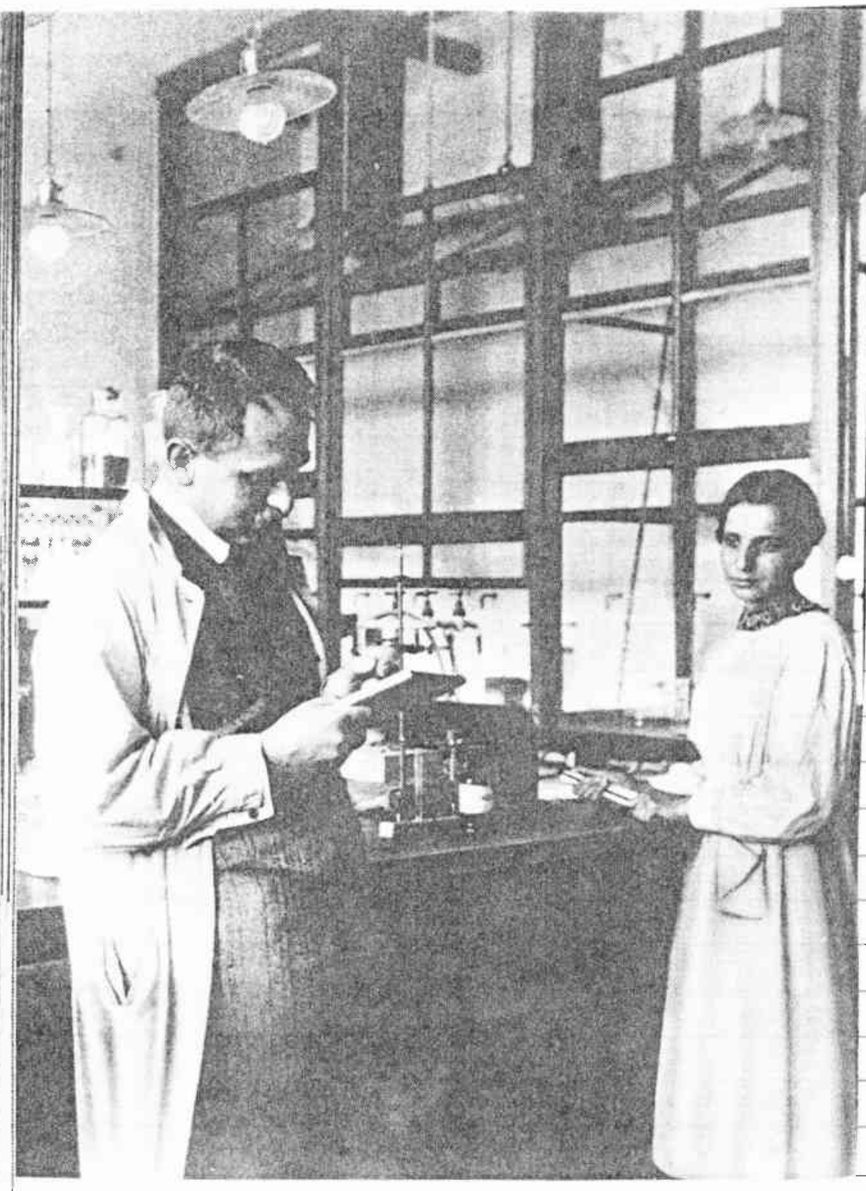


KINDHEIT UND JUGEND

Der Großvater väterlicherseits war Weinbauer und Landwirt a
Hof in Gundersheim bei Worms. Er betrieb daneben eine Glase
sterrahmenschreinerei, weil der Grundbesitz durch die dam
Erbteilung bereits so klein geworden war, daß eine größere Fa
allein nicht mehr ausreichend leben konnte. Ihm wurde 184
Heinrich Hahn geboren, der wenig Interesse für die landwir
Tätigkeit hatte und deshalb nach den Regeln der Zunft das G
werk erlernte. Dem damaligen Brauch folgend ging Heinrich
Geselle auf Wanderschaft. Obwohl er von Haus aus noch eine
germaßen versorgt gewesen wäre, versuchte er doch sehr bald,
zu werden. In der Schweiz arbeitete er als junges, schmächtig
chen mit stämmigen älteren Gesellen im Akkord. Otto Hahn b
der gekrümmte Rücken den Vater für den Rest seines Leb
schwere Arbeit in den Jugendjahren erinnerte. Im Jahre 1868
ließ sich Heinrich Hahn in der Freien Reichsstadt Frankfurt an
der und heiratete dort die junge Witwe Charlotte Stutzmann
Giese, die für einen Sohn Karl aus erster Ehe zu sorgen hatte.
war in Norddeutschland, in der Mark Brandenburg und
beheimatet. Unter ihren Vorfahren finden wir eine Reihe nam
demiker. Mit ihrer Mutter wohnte sie in der Nachbarschaft
schen Glaserei, in der Heinrich Hahn arbeitete. Beide Frauen fü
Mittagstisch, der vor allem von alleinstehenden, gebildete
Kaufleuten besucht wurde. Dort war auch Heinrich Hahn stä
und lernte auf diese Weise seine spätere Ehefrau kennen. Si
1875. Dem Ehepaar wurden in kurzer Folge drei Söhne geboren
ner, 1877 Julius und als jüngster am 8. März 1879 Otto Hahn
vom Vater Hahn adoptiert, und so wuchsen in Frankfurt am M
Gebrüder Hahn heran. Strebsamkeit, Treue und Fleiß schaffte
bald eine gutbürgerliche Existenz. Mit 26 Jahren ergriff der Va
lichkeit, die Glaserei von seinem Prinzipal käuflich zu erwerbe
auszubauen. Durch eine Reihe von äußeren Ereignissen kon
bescheidene Handwerksbetrieb zu einem gewichtigen Untern
wickeln: Die Annexion der Freien Reichsstadt Frankfurt am
die Preußen und der wirtschaftliche Aufschwung nach dem De
zösischen Krieg 1870/71 führten zu einer lebhaften Bautät
Handwerker, die ihren Fleiß einsetzten, konnten Vermögen er
ursprünglichen Glaserei wurde ein Spiegel- und Bilderrahm
mit Vergolderei angegliedert. Heute noch besteht die Firm
Heinrich Hahn» als bekanntes Unternehmen in Frankfurt an
Geburtshaus Otto Hahns in der Bockgasse [1*] wurde für die
sende Familie bald zu klein. In der Töngesgasse 21 [2] war ein Ha
worden, das sich sowohl als Wohn- wie auch als Geschäftsh
Aus den ersten Kindheitsjahren berichtet Otto Hahn: *An die S*
Geburt erinnere ich mich nur noch von einigen späteren Be

---

* Die hochgestellten Ziffern verweisen auf die Anmerkungen S



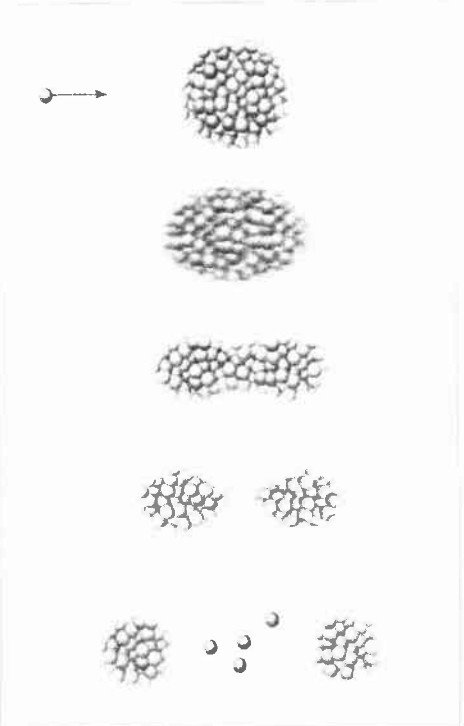
Mit Lise Meitner im Labor, Berlin, 1913

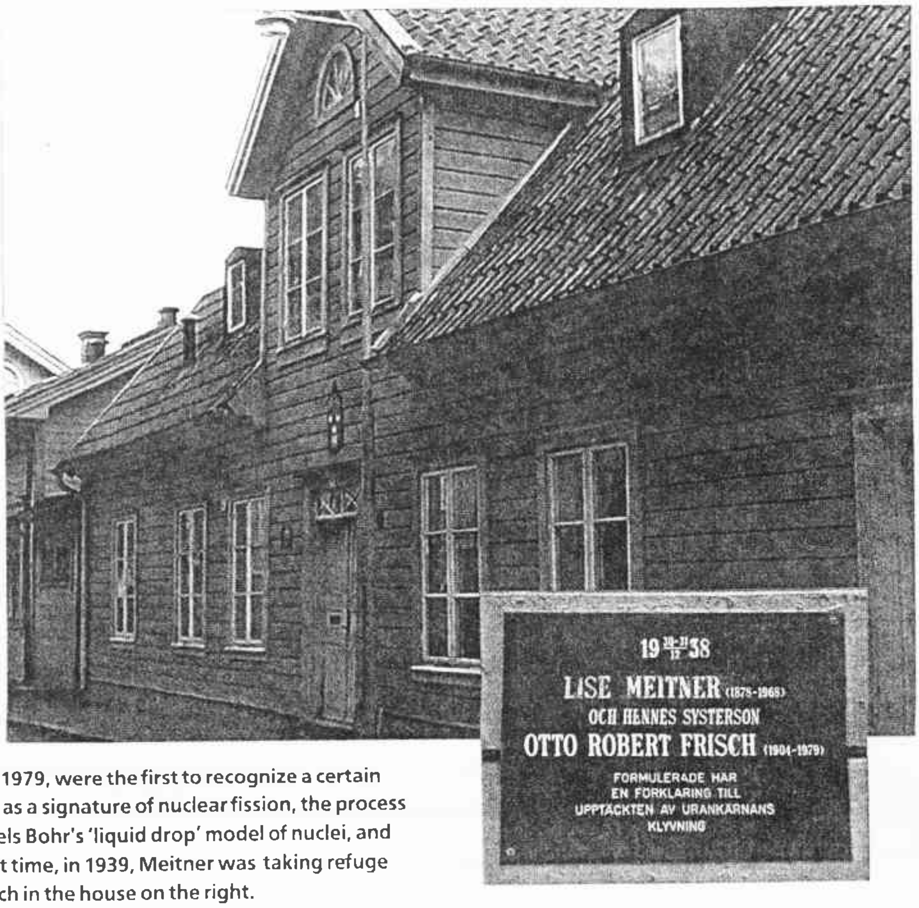
Lise Meitner

(1878–1968, Austrian)

One of the first women to attend the University of Vienna, Meitner was a brilliant student and decided to enter the new field of nuclear physics. Despite continuing discrimination, she eventually became a full professor in Berlin, where she was recognized as one the most skilled nuclear experimentalists in the world. Prior to World War II, she had a long and fruitful collaboration with the chemist Otto Hahn, but she was forced to flee Nazi Germany in 1938. Shortly after her exile, Hahn and his colleague Fritz Strassman, using equipment built by Meitner and with her continuing guidance, discovered that the uranium nucleus can split into two much lighter nuclei. Within weeks of the discovery, Meitner and her nephew, Otto Frisch, developed a theoretical understanding of this new process, which they named fission. Hahn and Strassman were awarded the 1944 Nobel Prize in physics for the discovery of fission, but many historians believe Meitner should have shared the honor. Element 109, Meitnerium (Mt), is named in her honor.

Lise Meitner, 1878–1968. Born in Vienna, she worked for many years in Berlin doing research in radioactivity. Element 109, meitnerium, is named after her. (AIP Emilio Segrè Visual Archives.)





Meitner and her nephew Otto Robert Frisch, 1904–1979, were the first to recognize a certain phenomenon discovered by Hahn and Strassmann as a signature of nuclear fission, the process shown above. Their fission model was based on Niels Bohr's 'liquid drop' model of nuclei, and predicted that fission releases much energy. At that time, in 1939, Meitner was taking refuge in Sweden. She spent her winter holidays with Frisch in the house on the right.

分類：
編號：15-39
總號：

Fusion

In light nuclei (A < 20), the binding energy is small.

Light nuclei released energy when they are brought together and are made to fuse into a heavier nucleus.

Substantial energy would be released
↓
fusion.

In order to fuse ⇒ two nuclei must be smashed together at high speed; otherwise their Coulomb repulsion would push them apart before the strong attraction has a chance to act.

To achieve fusion reactions on a large scale, we need a gas at extremely high temperature
↓
provide the energy source for the Sun

Proton-Proton cycle. (e^+: annihilate with e^-; ν: escape as solar neutrino)

$p + p \rightarrow d + e^+ + \nu + 0.41$ MeV (7×10^9 year)

$d + p \rightarrow {}^3He + \gamma + 5.51$ MeV (4 s)

${}^3He + {}^3He \rightarrow {}^4He + p + p + \gamma + 12.98$ MeV (4×10^5 year)

Carbon cycle

$${}^{12}C + p \rightarrow {}^{13}N + \gamma + 1.93 \text{ MeV} \quad (10^6 \text{ yr})$$
$${}^{13}N \rightarrow {}^{13}C + e^+ + \nu + \gamma + 1.20 \text{ MeV} \quad (10 \text{ min})$$
$${}^{13}C + p \rightarrow {}^{14}N + \gamma + 7.60 \text{ MeV} \quad (2\times10^5 \text{ year})$$
$${}^{14}N + p \rightarrow {}^{15}O + \gamma + 1.71 \text{ MeV} \quad (<3\times10^7 \text{ year})$$
$${}^{15}O \rightarrow {}^{15}N + e^+ + \nu + \gamma + 1.71 \text{ MeV} \quad (2 \text{ min})$$
$${}^{15}N + p \rightarrow {}^{12}C + {}^4He + 4.99 \text{ MeV} \quad (10^4 \text{ year})$$

Bethe 1939

In the Sun, the predominant fusion process is the proton-proton cycle.

Star hotter than the Sun ⇒ carbon cycle.

appropriate to the conditions in the Sun

central temperature $\sim 1.4 \times 10^7$ K

$$p + p \to d + e^- + \nu + 0.41\ \text{MeV} \qquad (7 \times 10^9\ \text{yr});$$
$$d + p \to {}^3\text{He} + \gamma + 5.51\ \text{MeV} \qquad (4\ \text{s});$$
$${}^3\text{He} + {}^3\text{He} \to {}^4\text{He} + p + p + \gamma + 12.98\ \text{MeV} \qquad (4 \times 10^5\ \text{yr}).$$

$$6p \to 2p + 2e^- + {}^4\text{He} + \text{photons} + \text{neutrinos}$$

Carbon cycle

$${}^{12}\text{C} + p \to {}^{13}\text{N} + \gamma + 1.93\ \text{MeV} \qquad (10^6\ \text{yr});$$
$${}^{13}\text{N} \to {}^{13}\text{C} + e^+ + \nu + \gamma + 1.20\ \text{MeV} \qquad (10\ \text{min});$$
$${}^{13}\text{C} + p \to {}^{14}\text{N} + \gamma + 7.60\ \text{MeV} \qquad (2 \times 10^5\ \text{yr});$$
$${}^{14}\text{N} + p \to {}^{15}\text{O} + \gamma + 7.39\ \text{MeV} \qquad (< 3 \times 10^7\ \text{yr});$$
$${}^{15}\text{O} \to {}^{15}\text{N} + e^+ + \nu + \gamma + 1.71\ \text{MeV} \qquad (2\ \text{min});$$
$${}^{15}\text{N} + p \to {}^{12}\text{C} + {}^4\text{He} + 4.99\ \text{MeV} \qquad (10^4\ \text{yr}).$$

$$4p \to {}^4\text{He} + 2e^+ + \text{photons} + \text{neutrinos}$$

分類：
編號：15-40
總號：

On Earth:

Hydrogen bomb
↓
deuterium and tritium are made to fuse into Helium.

High temperature required to trigger the fusion reaction are generated by exploding an ordinary atomic bomb.

Produce energy
- use deuterium and small amount of lithium and berryllium
- through DT cycle
  ↓
  nuclei are made to fuse and release of 9 MeV per deuterium nucleus consumed.
- temperature $\sim 1.1 \times 10^5$ K

Problem is the confinement of the plasma.

magnetic confinement → tokamak

inertial confinement

Pictures Blatt P. 388-389

Advantages:

Fuels are plentiful
No nuclear waste problem.

分類：
編號：
總號：

Hans Bethe

(Born 1906, German-American)

After postdoctoral work with Rutherford in Cambridge and Fermi in Rome, Bethe taught in Germany for a few years before coming to the United States in 1935. Among many contributions to atomic and nuclear physics, he is best known for finding the two nuclear cycles by which most stars get their energy. For this discovery, he won the 1967 Nobel Prize in physics.

Carbon Dating

$dN(t) = -\lambda N(t)\,dt$

$\Rightarrow \quad N(t) = N_0 e^{-\lambda t}$

Activity $\equiv -\frac{dN}{dt} = \lambda N_0 e^{-\lambda t}$

↓

number of decays per second.

^{14}C

Produced through

$n + {}^{14}N \rightarrow {}^{14}C + {}^{1}H$

↓

cosmic ray

Decay through

$^{14}C \rightarrow {}^{14}N + \beta^- + \bar{\nu}$ lifetime 5730 ± 30 years

Knowing the neutral flux, half-life of ^{14}C

$\Rightarrow \frac{^{14}C}{^{12}C} \rightarrow \frac{1}{7.6} \cdot 10^{11}$

^{14}C does occur naturally in the atmosphere in the form of CO_2

Carbon dioxide, used by plants in photosynthesis, enters all organisms that live off plants

Living plant containing one ^{14}C for every 7.6×10^{11} ^{12}C atom

Once organism dies, there is no more further uptake of atomospheric carbon.

^{14}C nuclei in the organism decay to ^{14}N

$\Rightarrow$ 5730 following death, $^{14}C/^{12}C$ will be 3.8×10^{11} ^{12}C

A measurement of the ^{14}C activity can be used to ascertain how long ago that organism ceased to metabolize atomspheric carbon.

William F. Libby won the Nobel prize in chemistry (1961)

↓

radioisotopes in archeology

Determine the rock age.

^{204}Pb , ^{206}Pb , ^{207}Pb , and ^{208}Pb

↓

lifetime $1.4 \cdot 10^{17}$ years

^{206}Pb , ^{207}Pb , ^{208}Pb are the end product of uranium or thorium

Sample : ^{238}U and ^{206}Pb ; no ^{204}Pb

↓

^{206}Pb originated from the decay of ^{238}U

Originally, when the rock is formed

↓

only uranium, no lead.

$^{206}Pb / ^{238}U$ gives the age of the rock.

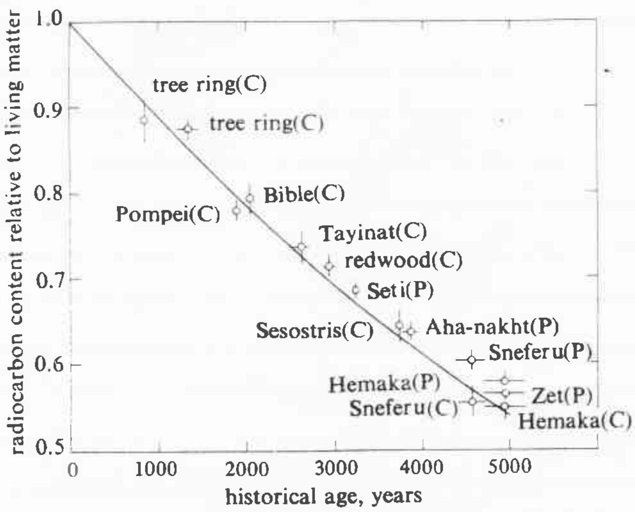
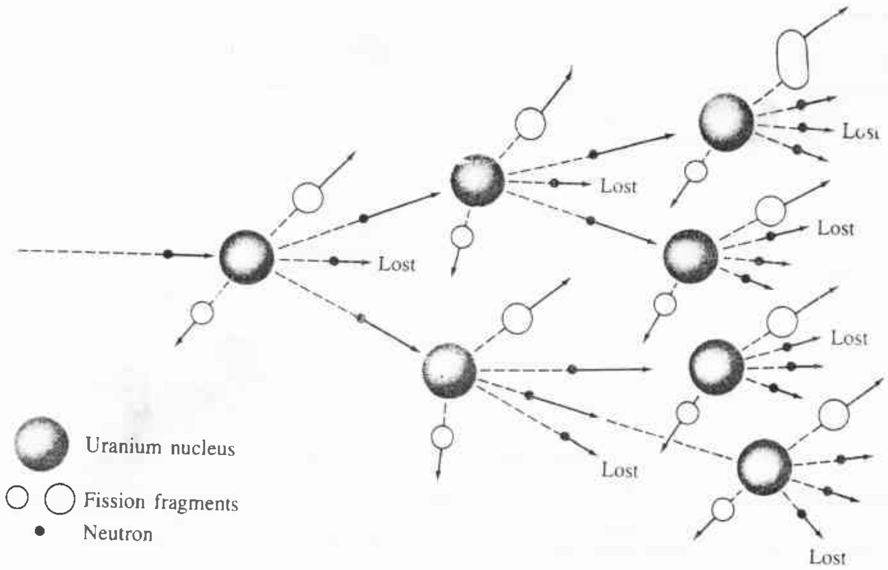


Figure 5-11 Calibration curve of ^{14}C method. Curve calculated from $T_{1/2}=$ 5568 yr. Key: Samples of known age; (C), Chicago dates; (P), Pennsylvania dates (Ralph). [W. F. Libby, in *Les Prix Nobel en 1960*, Stockholm, 1961.] The presently accepted half-life of ^{14}C is 5730 ± 30 yr.

Figure 15.21 A fission chain reaction (schematic diagram). The reproduction constant $k = 2$; the moderator is not shown.



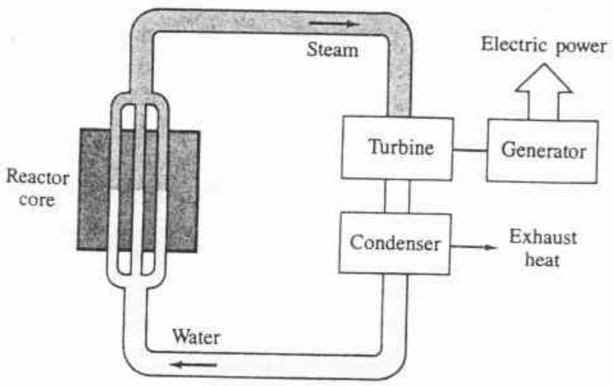


Figure 15.22 Schematic diagram of a boiling-water reactor.

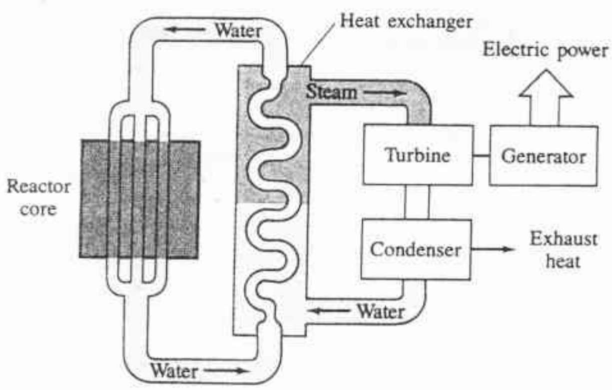


Figure 15.23 Schematic diagram of a pressurized-water reactor.

Nuclear radiation in medicine

Diagnosis

radiopharmaceutical is administered to the patient
compound used is determined by the organ to be examined.
↓
for example, for investigating thyroid function, radioactive iodine is used
because
the body concentrate this element in the thyroid.

Use of short-lived radioisotope is advantage in that it reduces the radiation dose to the patient.

Therapy

Use charged particle beam from accelerator to treat cancer

Advantage: energy loss, (hence their efficacy in producing biological damage) reaches a fairly sharp maximum near the end of their range, the so called Bragg peak.

(See P. 395 of Blatt)

Of course, NMR is perhap the most exciting advance in medical diagonostics since the discovery of X-rays
We have already discussed NMR in earlier sections.

分類：
編號：
總號：

Rosalind Yalow (1921–, United States). After receiving her Ph.D. in nuclear physics, she researched the medical applications of radioactive isotopes. She developed the technique of radioimmunoassay, which uses radioactive tracers to measure small amounts of substances in the blood or other fluids. She first applied this technique to study insulin in the blood of diabetics. Her development of this technique was recognized with the award of the Nobel prize in medicine in 1977.

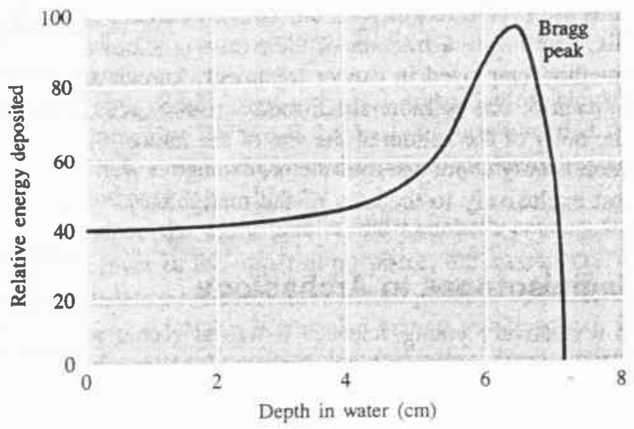


Figure 15.31 Energy loss of a high-energy α particle as a function of penetration. Note the pronounced peak (Bragg peak) at the end of the range.

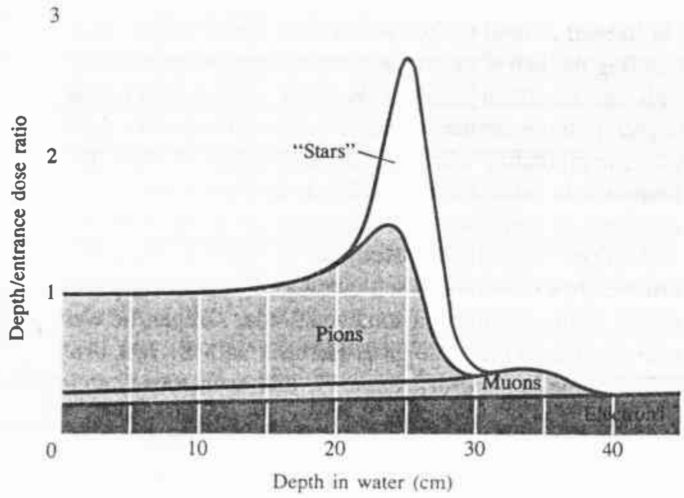


Figure 15.32 Energy deposited by 95-MeV π^- particles as a function of penetration. The normal Bragg peak is further enhanced by the energy deposited due to capture of the π^- by a nucleus and the subsequent nuclear reaction (star).

Appendix A

11-7 THE MÖSSBAUER EFFECT

Consider an atomic transition from a state with energy E_2 to a state with energy E_1. We usually write the energy of the emitted photon (E_{photon}) as

$$E_{photon} = E_2 - E_1. \qquad (11.104)$$

The foregoing equation is an excellent approximation but it is not *exact* because momentum must be conserved. The atom must recoil with the same magnitude of momentum as the photon. The recoil momentum (p) of the atom is

$$p = \frac{E_{photon}}{c}. \qquad (11.105)$$

The kinetic energy of the atom is

$$E_k = \frac{p^2}{2M} = \frac{(pc)^2}{2Mc^2}, \qquad (11.106)$$

where M is the atomic mass. The energy scale of a photon emitted from an electronic transition between outer energy levels is electronvolts. The mass energy of the atom is much larger than the photon energy ($Mc^2 >> pc$). This means that even for a light atom like hydrogen, the recoil kinetic energy of the atom is small because the mass is large. For an iron atom ($Mc^2 \approx 50$ GeV), the recoil kinetic energy is

$$E_k = \frac{(1\,\mathrm{eV}/c)^2}{100\,\mathrm{GeV}} \approx 10^{-11}\ \mathrm{eV}. \qquad (11.107)$$

Since the atom gains this energy, the photon energy is smaller than E_2–E_1 by an amount E_k. We usually can neglect such a small energy correction! Notice, however, that because the photon energy is slightly smaller than E_2-E_1, we might expect that the emitted photon could not be readily reabsorbed by the same type of atom because the photon energy is a bit too small. The emitted photons *are* observed to be reabsorbed, however. This phenomenon is called *resonance absorption*. Resonance absorption occurs because of the natural width of the photon energy distribution, corresponding to the finite lifetime of the atomic state. The natural width and atomic lifetime are related by the uncertainty principle. The typical lifetime of an atomic transition is 10^{-8} seconds, corresponding to an energy width (Γ) of

$$\Gamma = \frac{\hbar}{\tau} = \frac{6.6\times10^{-16}\ \mathrm{eV\cdot s}}{10^{-8}\ \mathrm{s}} \approx 10^{-7}\ \mathrm{eV}. \qquad (11.108)$$

The natural width is much larger than the recoil energy:

$$\Gamma >> E_k. \qquad (11.109)$$

The natural spread in photon energies allows atoms to reabsorb the radiation.

Now consider the case of photons emitted from an excited nucleus (gamma transitions). The nuclear lifetimes are of the same order of magnitude as the atomic lifetimes because the same force, electromagnetism, is responsible for the decays. The photon energies from nuclear transitions, however, are about 10^5 times greater than photons from atomic transitions between outer electron levels. The recoil energy of the nucleus, again taking the iron mass, is

$$E_k = \frac{(pc)^2}{2Mc^2} = \frac{(10^5\ \mathrm{eV})^2}{100\,\mathrm{GeV}} \approx 10^{-1}\ \mathrm{eV}. \qquad (11.110)$$

In nuclear systems, the kinetic energy of the recoil nuclei are typically much greater than the width:

$$E_k >> \Gamma. \qquad (11.111)$$

This means that photons emitted in nuclear decay ordinarily do not have enough energy to be reabsorbed by the same type of nucleus. Resonance absorption cannot readily occur in nuclei.

The phenomenon of resonance absorption is illustrated in Figure 11-18. A transition occurs between two energy levels causing a photon of energy (E) to be emitted. The average emitted photon energy is smaller than the energy difference between the energy levels (E_0), but the photon has an energy width given by the uncertainty principle. For a photon to be absorbed, it must have an energy to allow for the recoil. The absorption spectrum has the same shape as the emission spectrum. The amount of overlap determines the amount of resonance absorption. For atomic systems, the overlap is complete. For nuclear systems, the overlap is zero.

In 1957, Rudolf Mössbauer discovered that nuclear transitions may occur with negligible nuclear recoil if the decaying nucleus is embedded in a crystal lattice. In this case the entire lattice takes up the recoil momentum. Since the mass of the crystal (M_c) can be huge, the crystal as a whole conserves momentum and gains essentially zero kinetic energy. The kinetic energy gained by the recoiling crystal is

$$E_k = \frac{(pc)^2}{2M_c c^2} \approx 0. \qquad (11.112)$$

This means that like the atomic system, there can be complete overlap between the emission and absorption energy spectra, and resonance absorption can occur. The nuclear system first studied by Mössbauer was ^{191}Ir. The nuclear energy levels of ^{191}Ir are indicated in Figure 11-19.

EXAMPLE 11-16

Estimate the size of the crystal necessary to cause nuclear resonance absorption in ^{191}Ir. The lifetime of the ^{191}Ir* state is 1.9×10^{-10}s and the emitted photon has an energy of 129 keV.

SOLUTION:

From the uncertainty principle, the width of the ^{191}Ir* state is

$$\Gamma = \frac{\hbar}{\tau} = \frac{6.6 \times 10^{-16}\ \text{eV} \cdot \text{s}}{1.3 \times 10^{-10}\ \text{s}} \approx 3.5 \times 10^{-6}\ \text{eV}.$$

A significant amount of resonance absorption will occur when the recoil kinetic energy is

$$E_k \approx \Gamma.$$

The recoil kinetic energy may be found from

$$E_k = \frac{(pc)^2}{2M_c c^2} \approx \Gamma,$$

so the mass of the crystal is given by

$$M_c c^2 = \frac{(pc)^2}{2\Gamma} = \frac{(129\,\text{keV})^2}{(2)(3.5 \times 10^{-6}\ \text{eV})}$$

$$\approx 2 \times 10^{15}\ \text{eV} = 2 \times 10^{6}\ \text{GeV}.$$

The mass energy of ^{191}Ir is about 178 GeV. Therefore, the number of atoms in the crystal necessary to cause resonance absorption is

$$N \approx \frac{2 \times 10^6\ \text{GeV}}{178\,\text{GeV}} \approx 10^4.$$

Only a small crystal is necessary. ■

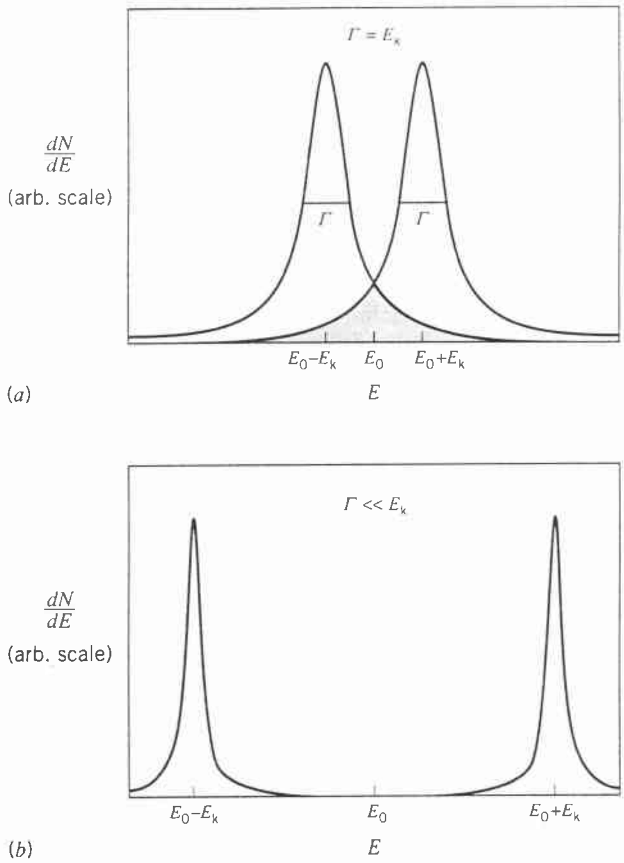


FIGURE 11-18 Resonance absorption.
A transition occurs between two energy levels, causing a photon of energy (E) to be emitted. The photon energy is slightly different from the difference between the energy levels due to the recoil energy (E_k) and the natural width due to the uncertainty principle. (a) Photon energy distribution for the case $\Gamma = E_k$. The resonance absorption probability is proportional to the amount of overlap of the two curves. (b) Photon energy distribution for the case $\Gamma << E_k$.

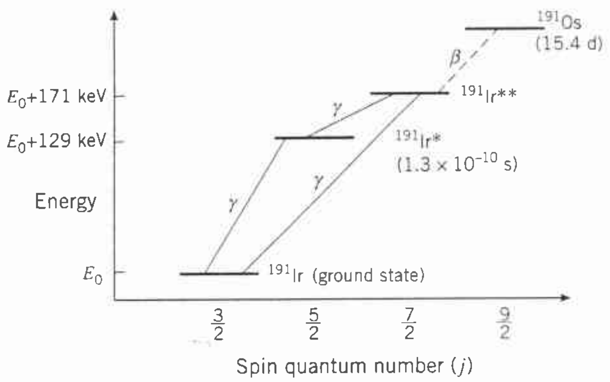


FIGURE 11-19 Nuclear energy levels for ^{191}Ir.

The experimental setup of Mössbauer is shown in Figure 11-20. The radioactive source is ^{191}Os, which beta decays into ^{191}Ir:

$$^{191}\text{Os} \to {}^{191}\text{Ir}^* + e^- + \bar{\nu}_e, \qquad (11.113)$$

and the excited iridium decays by gamma emission

$$^{191}\text{Ir}^* \to {}^{191}\text{Ir} + \gamma. \qquad (11.114)$$

The energy of the photon is 129 keV. The half-life of the ^{191}Ir* decay is 1.3×10^{-10}s, corresponding to a natural fractional width of

$$\frac{\Gamma}{E} = 4 \times 10^{-11}. \qquad (11.115)$$

Normally, the energy shift due to the motion of the nucleus will be larger than the natural width by several orders of magnitude. Mössbauer discovered that if the ^{191}Os is embedded in a crystal, then a small fraction of the decays have a negligible nuclear recoil. The recoilless photon emission produces an extremely narrow photon "line." The photons from the decay of ^{191}Ir* were detected by Mössbauer by resonance absorption in an iridium absorber. The process in the absorber is

$$^{191}\text{Ir} + \gamma \to {}^{191}\text{Ir}^*. \qquad (11.116)$$

The absorber must also be a crystal for resonance absorption to occur (see Figure 11-18).

In the Mössbauer experiment, the width of the photon source may be measured by giving the source some motion so that the line is broadened by the Doppler effect. The absorption fraction is then measured as a function of the speed of the source. When the photon has the wrong energy, its absorption probability is reduced. The data of Mössbauer are shown in Figure 11-21. A speed of only a few centimeters per second is sufficient to destroy the absorption.

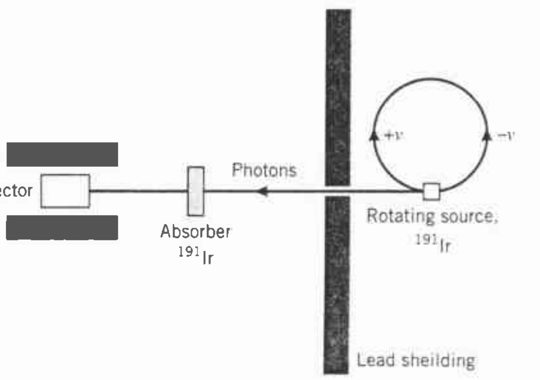


FIGURE 11-20 Experimental arrangement of Mössbauer.

EXAMPLE 11-17

Calculate the speed of the source necessary to destroy the resonance absorption in ^{191}Ir.

SOLUTION:

The natural line width is

$$\Gamma = \frac{\hbar}{\tau} = \frac{6.6 \times 10^{-16}\ \text{eV}\cdot\text{s}}{1.3 \times 10^{-10}\ \text{s}} = 3.5 \times 10^{-6}\ \text{eV}.$$

The fractional width is

$$\frac{\Gamma}{E} = \frac{3.5 \times 10^{-6}\ \text{eV}}{129\,\text{keV}} = 2.7 \times 10^{-11}.$$

The motion of the decaying ^{191}Ir* nucleus causes a Doppler broadening of the photon. Consider motion of the ^{191}Ir* in the direction of the emitted photon. The Doppler formula for the Lorentz boosted photon energy (E') is

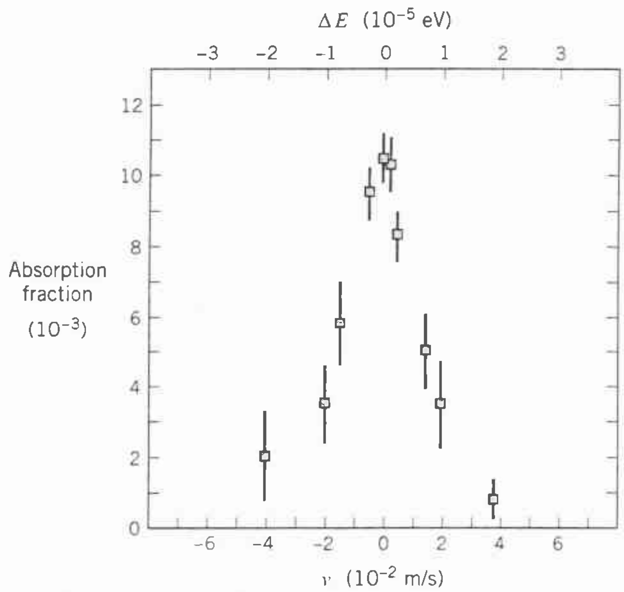


FIGURE 11-21 Recoilless gamma emission and absorption from ^{191}Ir.

From R. L. Mössbauer, *Naturwissenschaften* **45**, 538 (1958).

$$E' = E\sqrt{\frac{1+\beta}{1-\beta}} = E\gamma(1+\beta) \approx E(1+\beta).$$

The fractional change in the photon energy is

$$\frac{E' - E}{E} = \beta.$$

The resonance absorption is destroyed when β is equal to a few times Γ/E. For $\beta = \Gamma/E$, we have

$$\beta = \frac{v}{c} = 2.7\times10^{-11}.$$

This corresponds to a speed of

$$v = (3\times10^8 \text{ m/s})(2.7\times10^{-11}) \approx 10^{-2} \text{ m/s}.$$

Speeds of centimeters per second destroy the resonance absorption! ■

The unprecedented resolution of the Mössbauer technique has many interesting applications in physics. Perhaps the most ingenious of these is contained in the work of Robert V. Pound and Glen A. Rebka, Jr. The resolution in the original experiment of Mössbauer is limited by the natural width of the $^{191}Ir^*$ state due to its short lifetime. Pound and Rebka studied the Mössbauer effect in ^{57}Fe, which has an excited state with a much longer lifetime. An energy level diagram of ^{57}Fe is shown in Figure 11-22. The 14.4-keV photon originates from the decay of the $^{57}Fe^*$ state, which has a lifetime of about 10^{-7}s. This lifetime corresponds to a natural width of about $\Gamma \approx 10^{-8}$ eV. The fractional width is

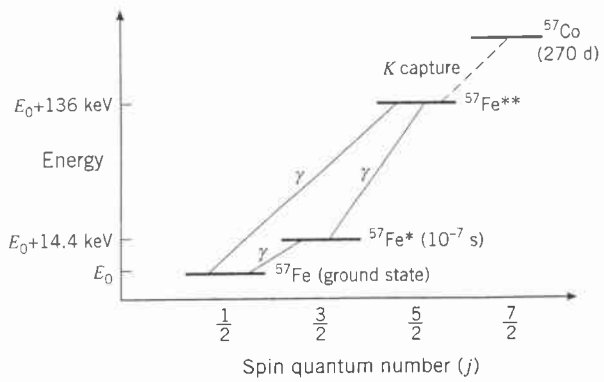


FIGURE 11-22 Energy levels of the ^{57}Fe nucleus.

$$\frac{\Gamma}{E} \approx 10^{-12}. \qquad (11.117)$$

Pound and Rebka realized that if they could achieve this resolution, then they could measure the change in energy of the 14.4-keV photon caused by its gravitational interaction with the earth! This experiment provided an important fundamental test of the theory of general relativity.

In 1959, Pound and Rebka set out to fabricate a high-resolution Mössbauer source appropriate for detection of the gravitational interaction of the photon. In this section we shall describe the ^{57}Fe source; the results of the gravitational experiment will be discussed in Chapter 19. The key to high resolution is to make a source and absorber that have identical energy levels. In the case of ^{57}Fe, a shift in energy levels caused by the intrinsic angular momentum of the nuclei is enough to cause significant broadening of the photon line observed by resonant absorption. The experimenters made an ^{57}Fe source by electroplating ^{57}Co atoms onto one face of a thin sheet of iron. The source was then heated to 1220 K for an hour. The heat treatment caused diffusion of the cobalt into the iron to a mean distance of about 300 nanometers or about 1000 atomic distances. The absorber consisted of a thin (about 14 μm) sheet of iron that was also annealed. The heat treatment was discovered to be a crucial step for achieving high resolution. The source was cemented on a moving-coil magnetic transducer (a "loudspeaker") that was driven at 10 Hz. The resulting Mössbauer spectrum obtained by Pound and Rebka is shown in Figure 11-23. The resonant absorption is a maximum of about 17.5% (compare to Figure 11-21). The line shape fits that of a Breit-Wigner with a full width of

$$\Gamma = 1.6\times10^{-8} \text{ eV}, \qquad (11.118)$$

or

$$\frac{\Gamma}{E} = 1.1\times10^{-12}. \qquad (11.119)$$

The contribution to the width of the photon line from finite lifetime of the $^{57}Fe^*$ state is twice the natural width, or about 9×10^{-8} eV. Thus, the experimental resolution is only about a factor of 2 greater than the contribution from the natural width.

The resolution of the Pound-Rebka apparatus was good enough to observe hyperfine splitting, as shown in Figure 11-23*b*. Hyperfine splitting is caused by the interaction of the magnetic moment of the nucleus with the internal magnetic field caused by the electrons. The intrinsic angular momentum quantum number of $^{57}Fe^*$ is $j = 3/2$. Thus, $^{57}Fe^*$ is expected to be split into four states by the nuclear hyperfine interaction. The intrinsic angular momentum quantum number of ^{57}Fe is $j = 1/2$. The ground state, ^{57}Fe, is expected to be split into two states by the nuclear hyperfine interaction. Thus, six photon transitions may be expected to be present from

$$^{57}\text{Fe}^* \rightarrow {}^{57}\text{Fe} + \gamma . \qquad (11.120)$$

The observed spectrum can be quite complicated because it depends on how the energy levels in the source and absorber overlap. The data of Figure 11-23*b* show that the splitting between the states is about 1.3×10^{-7} eV. This technique provided unprecedented resolution for the study of nuclear structure.

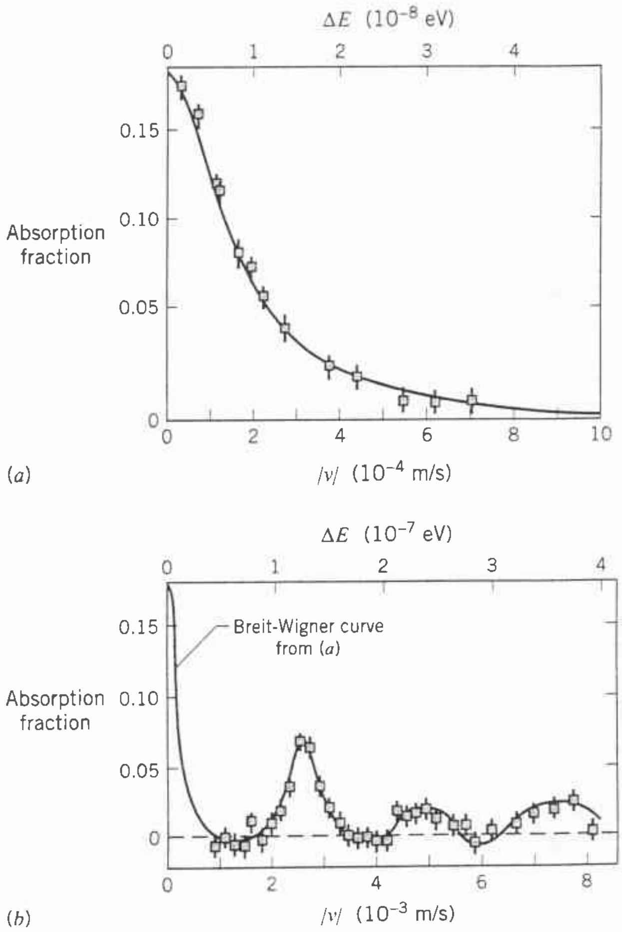


FIGURE 11-23 Mössbauer effect in ^{57}Fe.
(*a*) Principal line. (*b*) Satellite lines are observed due to the interaction of the nuclear magnetic moment with the internal magnetic field generated by electrons. From R. V. Pound and G. A. Rebka Jr., *Phys. Rev. Lett.* **3**, 554 (1959).