Chapter 42

Nuclear Physics

42.6: Radioactive Dating:

A fragment of the Dead Sea scrolls and the caves from which
The scrolls were recovered. (*www.BibleLandPictures.comAlamy)*

The decay of very long-lived nuclides can be used to measure the time that has elapsed since they were formed. Such measurements for rocks from Earth and the Moon, and for meteorites, yield a consistent maximum age of about 4.5×10^9 y for these bodies.

Example, Radioactive dating of a moon rock:

In a Moon rock sample, the ratio of the number of (stable) ^{40}Ar atoms present to the number of (radioactive) ^{40}K atoms is 10.3. Assume that all the argon atoms were produced by the decay of potassium atoms, with a half-life of 1.25×10^9 y. How old is the rock?

KEY IDEAS

(1) If N_0 potassium atoms were present at the time the rock was formed by solidification from a molten form, the number of potassium atoms now remaining at the time of analysis is

$$N_K = N_0 e^{-\lambda t}, \tag{42-29}$$

in which t is the age of the rock. (2) For every potassium atom that decays, an argon atom is produced. Thus, the number of argon atoms present at the time of the analysis is

$$N_{Ar} = N_0 - N_K. \tag{42-30}$$

Calculations: We cannot measure N_0; so let's eliminate it from Eqs. 42-29 and 42-30. We find, after some algebra, that

$$\lambda t = \ln\left(1 + \frac{N_{Ar}}{N_K}\right), \tag{42-31}$$

in which N_{Ar}/N_K *can* be measured. Solving for t and using Eq. 42-18 to replace λ with $(\ln 2)/T_{1/2}$ yield

$$t = \frac{T_{1/2}\ln(1 + N_{Ar}/N_K)}{\ln 2}$$

$$= \frac{(1.25 \times 10^9\text{ y})[\ln(1 + 10.3)]}{\ln 2}$$

$$= 4.37 \times 10^9\text{ y.} \qquad \text{(Answer)}$$

Lesser ages may be found for other lunar or terrestrial rock samples, but no substantially greater ones. Thus, the oldest rocks were formed soon after the solar system formed, and the solar system must be about 4 billion years old.

42.7: Measuring Radiation Dosage:

Absorbed Dose.

This is a measure of the radiation dose (as energy per unit mass) actually absorbed by a specific object, such as a patient's hand or chest.
Its SI unit is the **gray (Gy).** An older unit, the rad (from radiation absorbed dose) is still used.
1 Gy =1 J/kg =100 rad.

Dose Equivalent.

Although different types of radiation (gamma rays and neutrons, say) may deliver the same amount of energy to the body, they do not have the same biological effect. The dose equivalent allows us to express the biological effect by multiplying the absorbed dose (in grays or rads) by a numerical ***RBE factor*** (from relative biological effectiveness).

For x rays and electrons, RBE 1; for slow neutrons, RBE 5; for alpha particles, RBE 10; and so on.

Personnel-monitoring devices such as film badges register the dose equivalent.
The SI unit of dose equivalent is the **sievert (Sv)**. An earlier unit, the rem, is still used.
1 Sv =100 rem.

42.8: Nuclear Models: The Collective Model:

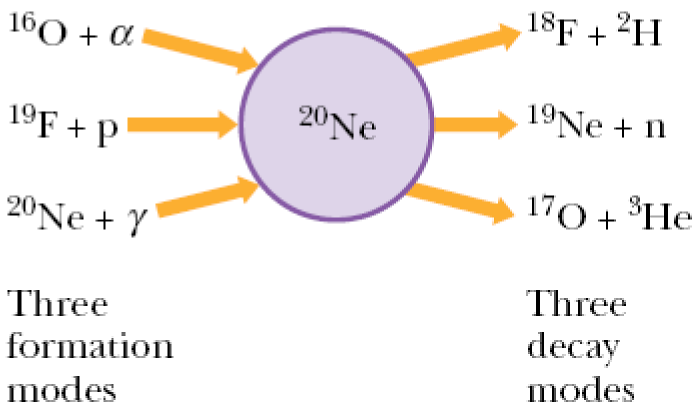

Fig. 42-14 The formation modes and the decay modes of the compound nucleus ^{20}Ne.

In the *collective model,* formulated by Niels Bohr, the nucleons, moving around within the nucleus at random, are imagined to interact strongly with each other, like the molecules in a drop of liquid.

A given nucleon collides frequently with other nucleons in the nuclear interior, its mean free path as it moves about being substantially less than the nuclear radius.

This model permits us to correlate many facts about nuclear masses and binding energies; it is useful in explaining nuclear fission. It is also useful for understanding a large class of nuclear reactions.

42.8: Nuclear Models: The Independent Particle Model:

The ***independent particle model*** is based on the assumption that each nucleon remains in a well-defined quantum state within the nucleus and makes hardly any collisions at all!

The nucleus, unlike the atom, has no fixed center of charge; we assume in this model that each nucleon moves in a potential well that is determined by the smeared-out (time-averaged) motions of all the other nucleons.

If two nucleons within the nucleus are to collide, the energy of each of them after the collision must correspond to the energy of an *unoccupied state.* If no such state is available, the collision simply cannot occur.

Some nuclei can show "closed-shell effects" such as the case of electrons in noble gases, associated with certain ***magic nucleon numbers*:** 2, 8, 20, 28, 50, 82, 126, ...
Any nuclide whose proton number Z or neutron number N has one of these values turns out to have a special stability.

42.8: Nuclear Models: The Combined Model:

Consider a nucleus in which a small number of neutrons (or protons) exist outside a core of closed shells that contains magic numbers of neutrons or protons.

The outside nucleons occupy quantized states in a potential well established by the central core, thus preserving the central feature of the ***independent-particle model***.

These outside nucleons also interact with the core, deforming it and setting up "tidal wave" motions of rotation or vibration within it. These collective motions of the core preserve the central feature of the ***collective model***.

Such a model of nuclear structure thus succeeds in combining the irreconcilable points of view of the collective and independent- particle models. It has been remarkably successful in explaining observed nuclear properties.

Example, Lifetime of a compound nucleus made by neutron capture:

Consider the neutron capture reaction

$$^{109}\mathrm{Ag} + \mathrm{n} \rightarrow {}^{110}\mathrm{Ag} \rightarrow {}^{110}\mathrm{Ag} + \gamma, \qquad (42\text{-}35)$$

in which a compound nucleus (^{110}Ag) is formed. Figure 42-15 shows the relative rate at which such events take place, plotted against the energy of the incoming neutron. Find the mean lifetime of this compound nucleus by using the uncertainty principle in the form

$$\Delta E \cdot \Delta t \approx \hbar. \qquad (42\text{-}36)$$

Here ΔE is a measure of the uncertainty with which the energy of a state can be defined. The quantity Δt is a measure of the time available to measure this energy. In fact, here Δt is just t_{avg}, the average life of the compound nucleus before it decays to its ground state.

Reasoning: We see that the relative reaction rate peaks sharply at a neutron energy of about 5.2 eV. This suggests that we are dealing with a single excited energy level of the compound nucleus ^{110}Ag. When the available energy (of the incoming neutron) just matches the energy of this level above the ^{110}Ag ground state, we have "resonance" and the reaction of Eq. 42-35 really "goes."

However, the resonance peak is not infinitely sharp but has an approximate half-width (ΔE in the figure) of about 0.20 eV. We can account for this resonance-peak width by saying that the excited level is not sharply defined in energy but has an energy uncertainty ΔE of about 0.20 eV.

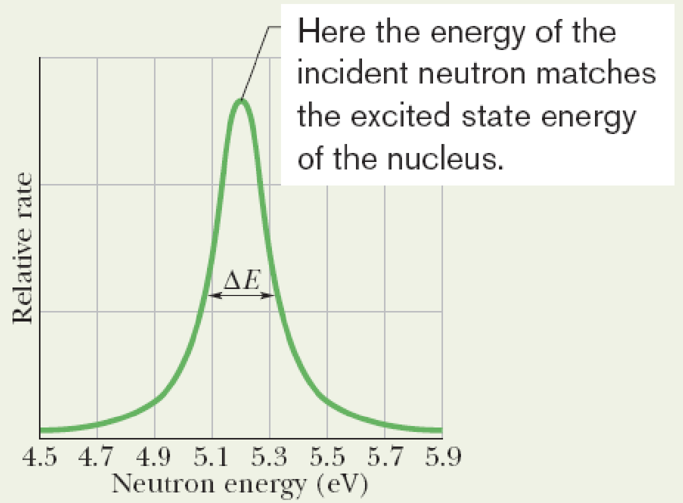

Fig. 42-15 A plot of the relative number of reaction events of the type described by Eq. 42-35 as a function of the energy of the incident neutron. The half-width ΔE of the resonance peak is about 0.20 eV.

Calculation: Substituting that uncertainty of 0.20 eV into Eq. 42-36 gives us

$$\Delta t = t_{avg} \approx \frac{\hbar}{\Delta E} \approx \frac{(4.14 \times 10^{-15}\ \mathrm{eV \cdot s})/2\pi}{0.20\ \mathrm{eV}}$$

$$\approx 3 \times 10^{-15}\ \mathrm{s}. \qquad \text{(Answer)}$$

This is several hundred times greater than the time a 0.20 eV neutron takes to cross the diameter of a ^{109}Ag nucleus. Therefore, the neutron is spending this time of 3×10^{-15} s *as part of* the nucleus.