NUCLEAR FISSION

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NUCLEAR FISSION

Fission is a special type of nuclear reaction in which a nucleus frequently breaks into two comparable size fragments and a large amount of energy (~200 MeV) is emitted in each fission.

The fission can be caused not only by slow neutrons, but also by fast neutrons, charged particles, and gamma rays.

The capture of a neutron by a nucleus may result either in fission or in the emission of a gamma ray. The later process is called radiative capture and is a complete loss of a neutron, as far as fission is concerned.

The best nuclei for fission are those for which the fission cross-section is very high and, for thermal neutrons, the radiative capture cross-section is very small.

FISSIONABLE MATERIALS

There are a large number of isotopes of $_{90}Th$, $_{91}Pa$, $_{92}U$, $_{93}Np$, $_{94}Pu$, and $_{95}Am$ that are fissionable. With the exception of three isotopes, $_{92}U^{233}$, $_{92}U^{235}$, and $_{94}Pu^{239}$, the others have either very short half-lives or have very small fission cross-sections for thermal neutrons.

$_{92}U^{235}$ occurs naturally and has a half-life of 7.1×10^8 y. $_{92}U^{233}$ and $_{94}Pu^{239}$ can be produced artificially in large quantities and decay with half-lives of 1.62×10^5 y and 2.44×10^4 y, respectively.

The fission cross-sections of U^{233} , U^{235} , and Pu^{239} for thermal neutrons are 525 b, 584 b, and 742 b, while their total absorption cross-sections are 578 b, 683 b, and 1028 b, respectively.

FISSIONABLE MATERIALS

The fission cross-sections for U^{233} and U^{235} vary as *1/v* at low energies to about 0.5 MeV.

As an alternative to alpha decay, some heavy nuclei decay by spontaneous fission, but their half-lives are very long. For examples, U^{235} , U^{238}, and Pu^{240} have half-lives 1.8×10^{17} y, 8×10^{15} y and 5.5×10^{15} y, respectively for spontaneous fission decay.

Many nuclei like U^{234} , U^{236}, and U^{238} undergo fission only by fast neutrons. The threshold energy for these reactions is about 1 MeV and the fission cross section increases with increasing energy up to a few MeV and levels off.

FISSIONABLE MATERIALS

It may be pointed out that besides the emission of two large fragments in fission, neutrons and gamma rays are also emitted. For example, in the case of fission of U^{233} , U^{235} and Pu^{239}, caused by thermal neutrons, on the average 2.51, 2.44, and 2.89 neutrons are emitted per fission, respectively. Besides the emission of different particles, an energy release of about 200 MeV per fission takes place, which plays an important part in the application of fission reactions.

Because of its natural occurrence and a very long half-life U^{235} is commonly used for fission by thermal neutrons. It is also important to note that natural uranium consists of only 0.72 percent of the U^{235} isotope. A complete separation of U^{235} from other U isotopes is a difficult and costly process. Usually natural uranium enriched in isotope U^{235} is used for fission and to obtain a chain reaction.

THE MASS AND ENERGY DISTRIBUTION OF FISSION FRAGMENTS

The fission of U^{235} by slow neutrons results in the emission of a large number of different products varying from A=70, Z=30 (Zinc); to A=160, Z=65 (Terbium). The fission fragments produced have always an excess of neutrons, and they are unstable.

In order to get rid of excess neutrons, most of the fission fragments decay by β^- emission.

Because of the short half-lives of the fission fragments, it is difficult to separate and identify them. Most of these fragments go through many β^- decays before becoming stable isotopes. A series of products with the same mass number A is a fission chain. One of the longest chains is the following

$$_{54}Xe^{143} \xrightarrow{\beta^-(1s)} {}_{55}Cs^{143} \xrightarrow{\beta^-(<1s)} {}_{56}Ba^{143} \xrightarrow{\beta^-(<0.5\,\mathrm{m})} {}_{57}La^{143} \xrightarrow{\beta^-(\sim 19m)}$$

$$_{58}Ce^{143} \xrightarrow{\beta^-(33h)} {}_{59}\mathrm{Pr}^{143} \xrightarrow{\beta^-(13.8d)} {}_{60}Nd^{143}\,(stable)$$

THE MASS AND ENERGY DISTRIBUTION OF FISSION FRAGMENTS

One of the shortest chains is the following

$$_{42}Mo^{99} \xrightarrow{\beta^-(66h)} {}_{43}Tc^{99} \xrightarrow{\beta^-(2.2x10^5 y)} {}_{44}Ru^{99}\left(stable\right)$$

The fission of U^{235} by slow neutrons is completely asymmetric. Most of the fission products are divided into two groups, a light group, with mass number A from 85 to 104, and a heavy group, with mass number A from 130 to 149. These two groups account for 97 percent of the fission. The most probable type of fission corresponds to the two peaks in the two groups. The mass numbers of these two are 95 and 139 and occur in about 7 percent of the total fission.

Almost identical yield curves are obtained from the fission of U^{233} , and Pu^{239} by thermal neutrons. At these neutron energies the fission is asymmetric, and the symmetric fission, division into two equal fragments, takes place in less than 0.01 percent of the fissions.

THE MASS AND ENERGY DISTRIBUTION OF FISSION FRAGMENTS

In order to get some idea of the energy release in a fission process, consider the following:

The binding energy per nucleon for U^{235} is about 7.6 MeV. The average binding energy of the fission fragments is about 8.5 MeV/nucleon. Thus the energy released in a single fission is

$$2 \times 118 \times 8.5 - 236 \times 7.6 \simeq 212 \text{ MeV}$$

More careful calculations show it to be about 200 MeV. This energy appears in the form of kinetic energy of fission fragments, kinetic energy of fission neutrons, γ-rays emitted in the fission, β and γ-decay energies, and the energy taken away by the neutrinos.

THE MASS AND ENERGY DISTRIBUTION OF FISSION FRAGMENTS

ENERGY RELEASE IN THE FISSION OF U235 BY THERMAL NEUTRONS	
Kinetic energy of fission fragments	162 Mev
Kinetic energy of fission neutrons (2.5 neutrons per fission each carry 2 MeV on the average)	5 MeV
Prompt γ-rays	7 MeV
β^- and γ-decay energies (5 MeV each)	10 MeV
Neutrinos energy	11 MeV
Total energy per fission	195 MeV

THE MASS AND ENERGY DISTRIBUTION OF FISSION FRAGMENTS

The measurements of the energy distribution of the fission fragments from the fission of U^{233} , U^{235}, and Pu^{239} by thermal neutrons has been made by several experimentalists. Assuming that the nucleus undergoing fission is initially at rest, the conservation of momentum gives

$$M_1 V_1 = M_2 V_2 \qquad (1)$$

where M_1 , M_2 are the masses and V_1, V_2 are the velocities of the two fission fragments, respectively. The energies of the fission fragments are given by

$$E_1 / E_2 = \frac{1}{2} M_1 V_1^2 / \frac{1}{2} M_2 V_2^2 \qquad (2)$$

Combining Eq. 1 and 2, we get

$$E_1 / E_2 = M_2 / M_1 \qquad (3)$$

NEUTRON EMISSION

As mentioned earlier, 2.5 neutrons, on the average, are emitted per fission. The average number of neutrons emitted per fission is denoted by ν. The value of ν has been measured for different fissionable materials for various neutron energies. When the fission of U^{233}, U^{235}, and Pu^{239} is caused by thermal neutrons, the average value of ν is 2.5, 2.44, and 2.9 respectively.

The neutrons emitted in fission can be divided into two categories: prompt neutrons and delayed neutrons.

Prompt Neutrons: Prompt neutrons are those that are emitted within a very short interval after the fission takes place ($\sim 10^{-14}$ sec). The prompt neutrons account for more than 99 percent of the total neutrons emitted in fission.

NEUTRON EMISSION

The prompt neutrons are emitted from the fission fragments and not directly in the fission process. This is possible because the fission fragments are very unstable due to a high neutron-to-proton ratio and the availability of excess energy for neutron emission.

Delayed Neutrons: Only about 0.64 percent of the total fission neutrons are delayed neutrons. These are called delayed neutrons because they are emitted with decreasing intensity for several minutes.

Though the delayed neutrons form a very small fraction of the total neutrons emitted in fission, they play a very important part in the control of nuclear reactors.

THEORY OF FISSION

There is no theory in existence at present that can explain all the different aspects of fission, especially asymmetric fission. Many features can be explained by the liquid-drop model of the nucleus.

In the ground state of the nucleus, the liquid drop is perfectly spherical. The two terms in the semiempirical mass formula that are responsible for the shape of the nucleus are the surface tension and the coulomb repulsion. For a nucleus of radius R, the total energy due to these two terms is

$$E = 4\pi R^2 O + 3Z^2 e^2 / 5R \qquad (4)$$

where O is the surface tension coefficient. The coulomb repulsion causes distortion of the nucleus and tries to deform its shape, but the surface tension effect overcomes this repulsion and keeps the nucleus in a perfectly spherical shape.

THEORY OF FISSION

An addition of a small amount of energy to the spherically-shaped liquid-drop causes its deformation, and the nucleus is then in an excited state. These low lying excited states are due to the rotation of the nucleus along an axis perpendicular to its axis of symmetry. Mathematically, the deformed shape of the nucleus is represented by

$$R(\theta) = R_0\left[1 + a_1 P_1(\cos\theta) + a_2 P_2(\cos\theta) + ...\right] \qquad (5)$$

or, by neglecting higher terms

$$R(\theta) = R_0\left[1 + a_2 P_2(\cos\theta)\right] \qquad (6)$$

where R(θ) and θ are as defined in Fig. 13.14 and a_2 is a constant that is a function of the degree of deformation of the otherwise spherical nucleus of radius R_0 . See Fig 13.14 in Fundamentals of Nuclear Physics by Atam P. Arya for different shapes of the fissionable nucleus for different degrees of excitation, according to liquid-drop model.

THEORY OF FISSION

The first odd term $a_1P_1(\cos\theta)$ has been omitted because it represents only the translation motion of the nucleus while the terms higher than $a_2P_2(\cos\theta)$ are unimportant for a low degree of excitation. Once the nucleus is excited, it can take different deformed shapes for different values of a_2 as shown in Fig. 13.14.

It can be shown that fission will not only be spontaneous, but instantaneous as well for nuclei for which the surface-tension effect is equal to or less then the coulomb repulsion. This happens for

$$Z^2 / A > 50 \qquad (7)$$

for nuclei with A>390 and Z>140. For U^{238}, $Z^2/A=36$, and the fission is certainly not instantaneous.

THEORY OF FISSION

Why some nuclei undergo fission by thermal neutrons while others do so by fast neutrons only?

The potential energy of the drop for different degrees of deformation has been calculated according to the Bohr-Wheeler theory. The plots of E_p (the potential energy) and R (the separation or deformation) for different types of nuclei are shown in Fig 13.15 in Fundamentals of Nuclear Physics in Atam P. Arya. Curve (a) belongs to nuclei of the type with A~100, curve (b) to A~235, and curve (c) to A~390.

Suppose the nucleus (Z,A) has undergone fission and produced two fragments (Z_1,A_1) and (Z_2,A_2). The potential energy between these two fragments, which are spherical in shape, is zero when $R=\infty$ and increases as they are brought together.

THEORY OF FISSION

The Coulomb energy E_c between the two drops when they are just touching is given by

$$E_C = \frac{Z_1 Z_2 e^2}{R_1 + R_2} \quad (8)$$

If the drops are brought still closer, the potential energy is a complicated function of coulomb and surface tension. The variation of E_p between R=0 and $R=R_1+R_2$ depends on the type of the nucleus as shown in Fig 13.15 for three different cases.

The nuclei of the type (a) lie about 50 MeV below E_c, the type (b) are about 6 MeV below E_c, and the type (c) lie above E_c and will undergo spontaneous fission. The type (b) are the nuclei such as U, Pu, or Th and need a few MeV energies to undergo fission.

THEORY OF FISSION

The energy needed by a nucleus to undergo fission is called the *activation energy* and is equal to E_c-E_0 where E_0 is defined as the energy of the compound nucleus formed by the capture of a neutron in the ground state.

$$E_0 = \left[M\left(A,Z\right) - M\left(A_1,Z_1\right) - M\left(A_2,Z_2\right) \right] c^2 \qquad (9)$$

E_0 does not include the excitation energy resulting from the capture of a neutron. Now it can be made clear why some nuclei may undergo fission by the capture of thermal neutrons. In those cases the excitation energy resulting from the capture of slow neutrons (thus forming a compound nucleus in the excited state) is more than the activation energy, and , therefore fission will take place. If the excitation energy is less than the activation energy, fast neutrons are used to make up for this difference in order to cause fission.

THEORY OF FISSION

When ^{235}U captures a neutron to form the compound state $^{236}U^*$, the *excitation energy* is

$$E_{ex} = \left[m\left({}^{236}U^* \right) - m\left({}^{236}U \right) \right] c^2 \qquad (10)$$

The energy of the compound state can be found directly from the mass energies of ^{235}U and n, if we assume the neutron's kinetic energy is so small (i.e., in the thermal region) that it is negligible

$$\begin{aligned} m\left({}^{236}U^* \right) &= m\left({}^{235}U \right) + m_n \\ &= \left(235.043924\,u + 1.008665\,u \right) \\ &= 236.052589\,u \\ E_{ex} &= \left(236.052589\,u - 236.045563\,u \right) 931.502\,MeV/u \\ &= 6.5\,MeV \end{aligned}$$

THEORY OF FISSION

The activation energy (energy needed to overcome the fission barrier) for ^{236}U is calculated also to be 6.2 MeV. Thus, the energy needed to excite ^{236}U into a fissionable state (the activation energy) is exceeded by the energy we get by adding a neutron to ^{235}U.

This means that ^{235}U can be fissioned with zero-energy neutrons, consistent with its large observed fission cross section in the thermal region.

A similar calculation for $^{238}U + n \rightarrow {}^{239}U^*$ gives $E_{ex} = 4.8$ MeV, which is far smaller than the calculated activation energy of ^{239}U, 6.6 MeV.

Neutrons of at least MeV energy are therefore required for fission of ^{238}U, which is consistent with the observed threshold for neutron-induced fission of ^{238}U.

REFERENCES

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