NUCLEAR FISSION OF URANIUM-238 BY ELECTROMAGNETIC ACCELERATION OF NEUTRONS

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1 Introduction

Nuclear Fission is a nuclear reaction or a radioactive decay process in which a heavy nucleus of an atom splits into two or more smaller, lighter nuclei. Most of the fission reactions are binary and about 0.4% are ternary. This process releases gamma photons and releases a very large amount of energy. The credit for the discovery of Nuclear Fission of heavy elements goes to Dr. Otto Hahn and his assistant at the time Fritz Strassmann in 1938.

For heavy nuclides, Nuclear Fission an exothermic reaction which releases large amounts of energy both as electromagnetic radiation and as kinetic energy of the fragments (heating the bulk material where fission takes place)

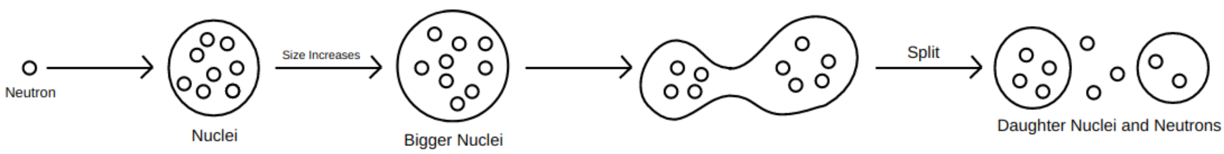

Figure 1: General Fission Reaction Mechanism

In case of Nuclear Fission of Uranium, we are going to talk about the two isotopes of Uranium, $^{235}U\ and\ ^{238}U$. Uranium-235 being fissile by thermal neutrons and Uranium-238 can't sustain a chain reaction in a thermal neutron generator although it is fissile by fast neutrons. Uranium-238 is also fertile which means it can be transmuted to fissile plutonium-239. Uranium-238 can't support a chain reaction because inelastic scattering of neutrons reduces the energy below the range where fast fission of one or more nuclei is probable.

For Nuclear Fission usually the 235 isotope (^{235}U) is used. The natural abundance of Uranium-238 is 99.28% which has a half life of 14.1×10^{16} seconds (4.468×10^{9} years, or 4.468 billion years) and that of Uranium-235 (which has a half life of about 703.8 million years) is 0.71%. So only 0.71% of the available Uranium is only available for controlled chain fission reaction for energy and power generation.

In this paper I'll try to explore on to how Uranium-238 can be used for controlled chain fission. Using the remaining 99.28% of the resource. We are going to be talking about Induced Nuclear Fission by neutrons

2 Fission of Uranium-235

Fission of one nucleus of Uranium-235 (about $3.9029 \times 10^{-22} g$) releases about 201.5 MeV (3.24×10^{-11} J) inside the reactor. After the $^{235}_{92}U$ nucleus is hit by a neutron ($^{1}_{0}n$) it turns into $^{236}_{92}U$ atom, which is unstable.

$$^{1}_{0}n \ + \ ^{235}_{92}U \rightarrow \ ^{236}_{92}U$$

Inside the reactor the following fission reactions take place

$$^{236}_{92}U \ \rightarrow \ ^{144}_{66}Ba \ + \ ^{89}_{36}Kr \ + \ 3\ ^{1}_{0}n$$

$$^{236}_{92}U \ \rightarrow \ ^{133}_{51}Sb \ + \ ^{99}_{41}Nb \ + \ 4\ ^{1}_{0}n$$

$$^{236}_{92}U \ \rightarrow \ ^{140}_{54}Xe \ + \ ^{99}_{38}Sr \ + \ 2\ ^{1}_{0}n$$

Fission of Uranium-235 requires a slow neutron (energy of about 1 eV) or a thermal neutron (energy of about 0.025 eV). After the fission reaction the neutron that gets released has energy near the levels of 2 MeV. We have to slow these neutrons down to lower the energy so that they can cause further fission starting a chain reaction of Nuclear Fission. If the neutron used to cause the fission reaction with Uranium-238 is of higher energy than that of thermal neutrons then the neutron just passes through the ^{238}U atom and no fission reaction takes place. So for ^{235}U we use a neutron of about 0.025 Joules of energy.

The neutron strikes the surface and is absorbed. The absorbed neutron causes the nucleus to undergo deformation. In about 10^{-14} second (a hundred-million-millionth of a second), one of the deformation is so drastic that the nucleus can't recover. The nucleus fissions, releasing an average of 2-3 neutrons. In about 10^{-12} second (a million-millionth of a second), the fission fragments lose their kinetic energy and come to rest, emitting a number of γ-rays. Now the fragments are called fission products. The fission products lose their excess energy by radioactive decay, emitting particles over a lengthy time period (seconds to years)

Fission of Uranium-235 has also been hypothesized to be used for propulsion engines. Figure 2[1] shows a concept for a fission propulsion engine.

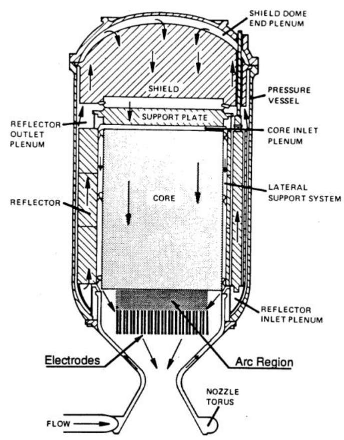

Figure 2: Fission Propulsion Engine

Uranium-235 has many uses such as fuel for nuclear power plants, and nuclear weapons such as nuclear bombs. Some artificial satellites, such as the SNAP-10A and the RORSATs were powered by nuclear reactors fueled with uranium-235.

2.1 Uncontrolled Fission of Uranium-235

Uncontrolled Fission of Uranium-235 is basically a chain of fission reactions where one fission reaction causes more than one fission.

In this type of fission chain reaction, energy multiplies in millisecond. Atom Bomb work on this principle.

The Little Boy gun type atomic bomb dropped on Hiroshima on August 6, 1945 was made of highly enriched Uranium with a large tamper. The nominal spherical critical mass for an untampered Uranium-235 nuclear weapon is 56 kilograms (123 lb), a sphere 17.32 centimetres (6.82 in) in diameter. The material must be 85% or more of 235U and is known as weapons grade uranium, though for a crude, inefficient weapon, 20% is sufficient (called weapon(s)-usable). Even lower enrichment can be used, but then the required critical mass rapidly increases.

The energy blast of uncontrolled chain nuclear fission reaction is about the order of 10^5 J by using just about 56 kg of Uranium-235.

The average energy released in this fission is divided among kinetic energies of fission fragments, prompt neutrons and the energy carried by γ-rays and anti-neutrinos

Source	Energy Released [MeV]
Kinetic energy of fission fragments	168.1
Kinetic energy of prompt neutrons	4.8
Energy carried by prompt γ-rays	7.0
Energy of β-particles	6.5
Energy of delayed γ-rays	7.3
Energy released from non-fission prompt neutrons	8.8
Total heat energy in thermal nuclear reactor	**202.5**
Energy of anti-neutrinos	8.7
Sum	210.2

Table 1: Sources of Energy in fission of Uranium-235

Table 1[2] shows the sources of energy released along with the amount each source release. The total heat energy released on fusion of 1 nucleus of Uranium-235 is about 202.5 MeV

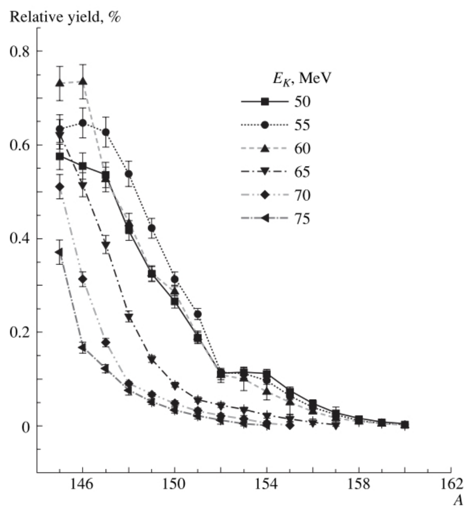

Figure 3: Mass Distribution of Fission Fragments

Figure 3[3] shows the mass distribution of fragments by energies E_k = 50-75 MeV in fission reaction of ^{235}U induced by thermal neutrons

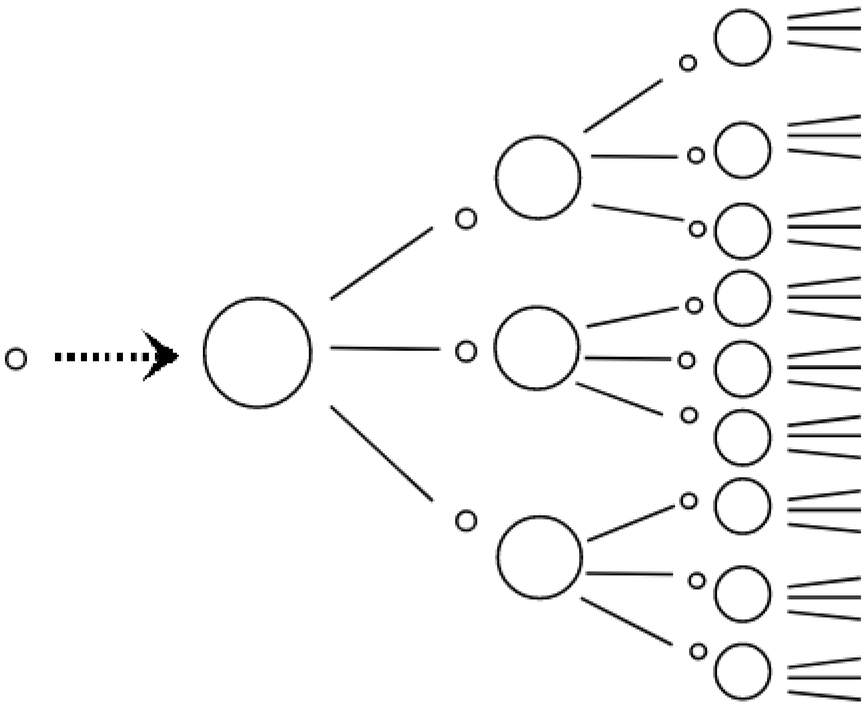

Figure 4: General Uncontrolled Fission Reaction

Figure 4 represents uncontrolled nuclear fission chain reaction. The bigger circles represents the ^{235}U atoms and the smaller circles represent the neutrons. Here the first Uranium-235 atoms is hit by a thermal neutron and releases 3 neutrons which hit 3 different ^{235}U atoms and thus one fission reaction leads to more than one chain fission reactions.

Atomic bombs work on the principle of Uncontrolled Chain Fission Reaction. The mass-energy equivalence formula

$$E = \Delta mc^2 \tag{1}$$

applies to atomic bombs for calculating the amount of energy released. Here the motion of the ^{235}U atom is also considered to increase the mass by the following equation

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{2}$$

This change in mass is considered for calculating the energy released because of the high speeds of the particles involved in the fission reaction (even slow neutrons move at 8 times the speed of sound). The energy of released in uncontrolled fission reaction is increased exponentially as compared to controlled fission chain reactions.

2.2 Controlled Fission of Uranium-235

Controlled Fission of Uranium-235 is basically when one fission reaction causes only a single fission reaction. Energy is liberated at a constant rate.

When the fission of one ^{235}U atom occurs it releases 3 neutrons out of which 2 are not used for further nuclear fission reaction thus a single neutron is used to carry forward the chain fission reaction.

Figure 5 represents controlled nuclear fission chain reaction. The bigger circles represent the ^{235}U atoms and the smaller circles represent the neutrons. Here the first Uranium-235 atom is hit by a thermal neutron releasing 3 neutrons out of which two are eliminated from the reaction and only one neutron carries the fission reaction forward with another ^{235}U atom which then again releases 3 neutrons and thus creating a chain reaction using only one emitted neutron from each fission reaction

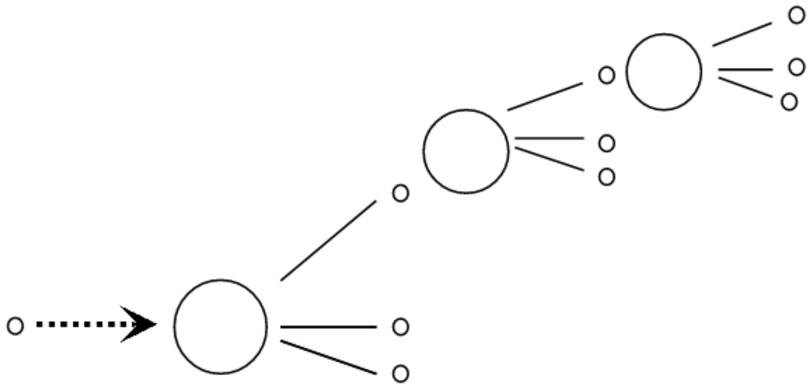

Figure 5: General Controlled Fission Reaction

Controlled Fission Reaction is used in Nuclear Reactors for energy generation and for electricity production

3 Fission of Uranium-238

Uranium-238 is non-fissile by a thermal neutron but it can carry forward chain fission reaction by a fast neutron. ^{238}U atom can only be carry forward fission reactions with high energy neutrons (approximately 1 MeV to 20 MeV). On fission reaction of ^{238}U atom the neutrons released are slow neutrons (with about 1 to 10 eV of energy) because of inelastic scattering.

Instead these slow neutrons are absorbed by the ^{238}U nucleus and β decay occurs from the reaction

As explained earlier Uranium-238 is the most abundant isotope found in nature (99.28%) and Uranium-235 with an abundance of 0.71% is used as the main fuel for power generation through fission reaction.

For fission reaction of ^{238}U with a fast neutron (^1_0n) (energy of about 1 MeV to 20 MeV) to produce $^{239}_{92}U$ atom, which is unstable

$$^{238}_{92}U \;+\; ^1_0n \;\rightarrow\; ^{239}_{92}U$$

The $^{239}_{92}U$ undergoes the following reaction inside the reactor

$$^{239}_{92}U \;\rightarrow\; ^{239}_{93}Np \;+\; ^{239}_{94}Pu$$

The reaction produces Plutonium-239 ($^{239}_{94}Pu$) which is a fissile isotope. The

Plutonium-239 can thus sustain a chain fission reaction when hit by a thermal neutron (energy of about 0.025 eV) releasing energy of the magnitudes of 207.1 MeV per atom.

After the ^{239}Pu atom is hit by a thermal neutron it forms ^{240}Pu atom which is unstable and undergoes a fission reaction releasing Zirconium ($^{103}_{40}Zr$) and Xenon ($^{134}_{54}Xe$) along with three fast neutrons

$$^{239}_{94}Pu \; + \; ^{1}_{0}n \; \rightarrow \; ^{240}_{94}Pu$$

$$^{240}_{94}Pu \; \rightarrow \; ^{103}_{40}Zr \; + \; ^{134}_{54}Xe \; + \; 3\; ^{1}_{0}n$$

The difficulty in fission of Uranium-238 is the fast neutron part, now neutrons are neutral particles so they can't be accelerated by an electric field but they do have a spin magnetic moment because of which they can be accelerated by a magnetic field.

It has been shown[4] that a magnetic dipole in homogeneous magnetic and electric fields must undergo an acceleration both classically and quantum mechanically. This a consequence of the Hamiltonian

$$H = \frac{p^2}{2m} - \mu \cdot [\vec{B} - \frac{p \times \vec{E}}{mc}] \tag{3}$$

Here p and m refer to the momentum and mass respectively of the particle. The magnetic moment is $\mu = \frac{\gamma\sigma}{2}$ with σ being the set of Pauli spin matrices and E and B are uniform and time independent. Further we get

$$\ddot{x} = \frac{\gamma}{mc}\vec{E} \times (\mu \times \vec{B}) + O(E^2) \tag{4}$$

Thus there is a nonvanishing acceleration proportional in lowest order to both $|E|$ and $|B|$. For E = 10^7 V/m and B = 1T this can be as big as 6 cm/sec^2 increasing the energy of the neutron.

It's shown here[5] that the wave packet

$$\Psi(x,0) = \psi(x)\phi \tag{5}$$

acquires a shift in velocity of $-\frac{\mu}{mc}\langle\sigma\rangle \times \vec{E}$ and an acceleration of

$$-\frac{2\mu^2}{mc}(\langle\sigma\rangle \times \vec{B}) \times \vec{E} \tag{6}$$

With a sufficiently powerful Electromagnetic Field the slow neutrons released by fission of ^{238}U with energy of 1 to 10 eV can be accelerated to become a fast neutron (with energy of 1 MeV to 20 MeV) carrying forward a chain reaction increasing at an exponential rate producing more amounts of $^{239}_{94}Pu$ atoms.

This Plutonium-239 can be used for further chain fission reactions, producing energy (207.1 MeV per nucleus of $^{239}_{94}Pu$) which can be converted to other purposes such as energy generation thus utilizing the 99.28% of Uranium-238 found in nature instead of relying on a source with an abundance of about 0.71%, Uranium-235.

4 References

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3. V. P. Pikul, U. Yu. Jovliev, Yu. N. Koblik, A. V. Khugaev, A. I. Muminov, K. V. Pavliy and B. S. Yuldashev, "Analysis of Fragment Mass Distribution in Asymmetric Area at Fission of ^{235}U Induced by Thermal Neutrons", June 26, 2004

4. J. Anandan and C. R. Hagen, "Neutron Acceleration in Uniform Electromagnetic Fields", January 26, 1993

5. J.A[4] and C.R.H[4] further discuss the spatial motion of a polarized neutron, whose initial spatial wave function and spin polarization are arbitrary, in constant electric and magnetic fields