# Nuclear Thermal Rockets:
# The Physics of the Fission Reactor

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## 1 Introduction

In exploring the outer planets of the solar system, humankind will want to do more than send unmanned probes that merely fly rapidly by, snapping a few pictures. Eventually, we will want to send spacecraft that go into orbit around the gas giants or land on their moons, perhaps even returning samples to Earth. And one day, we will follow those pioneering probes ourselves, sending astronauts to explore and eventually colonize the far reaches of our stellar neighborhood.

For missions such as these, we will need rockets that are more efficient than the current chemical rockets. A likely alternative to rockets powered chemical combustion are those powered by nuclear fission.

**Comparison of Chemical and Nuclear Rockets.** Most existent rockets are thermally driven gas devices in which heat energy is added to the gas. The heat energy ejects the gas propellant from the engine, giving the desired thrust. The energy can come from any number of sources. In chemical rockets, the propellant itself releases energy through chemical combustion (e.g., hydrogen and oxygen). In a nuclear rocket, or more precisely, a *nuclear thermal rocket*, the propellant heats up when it passes through a nuclear reactor, where controlled fission of some fissionable material (e.g., uranium) is taking place. Figure 1.1 shows a schematic of a nuclear thermal rocket.

To make the performance comparison quantitative, chemical rockets have a low maximum velocity increment, or $\Delta V$, which means that their exhaust velocities, $u_e$ (and consequently, their specific impulses $I_{sp}$), are not high enough to impart very high speeds to the rocket. The best chemical rockets, based on combustion of hydrogen and oxygen, can impart a maximum $\Delta V$ of about 10 km/s to a spacecraft departing from Earth orbit. In contrast, nuclear thermal rockets could impart a maximum $\Delta V$ of about 22 km/s. This would, for example, reduce the travel time to Saturn from 7 years to 3 years. Additionally, nuclear thermal rockets have engine thrust to weight ratios comparable to chemical rockets. Thus, for launch vehicles from Earth's surface to low Earth orbit (roughly 250-1000 km altitude), a nuclear thermal rocket could carry 4-6 times more payload than a chemical rocket because of its higher specific impulse.

**Fission Propulsion.** The energy available from a unit mass of fissionable material is approximately $10^7$ times larger than that available from the most energetic chemical reactions. Attempts to harness this energy have taken three general approaches: fission reactors, bomb detonation, and direct use of fragments from the fission reaction.

As already mentioned, the reactor approach uses the thermal energy from a fission reactor to heat a propellant working fluid, and then expand the heated fluid through a nozzle to produce thrust. Thus,

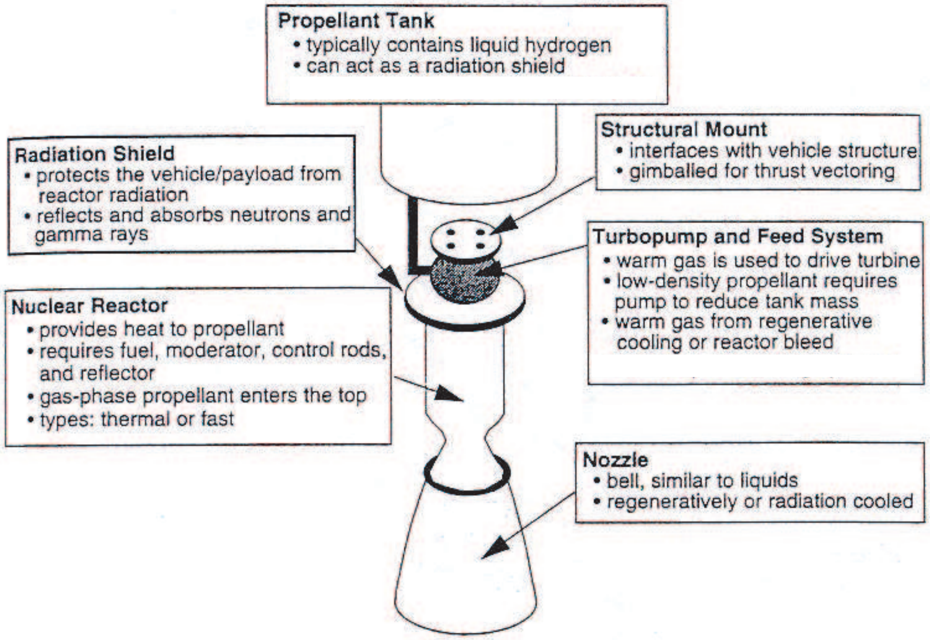

Figure 1.1: **Schematic of a Nuclear Rocket**. A nuclear rocket operates as a monopropellant liquid system, with the nuclear fission reactor as a heat source [Lawrence, Witter, and Humble, 1992].

it works essentially the same as a chemical rocket, but with the reactor as the heat source, rather than chemical combustion of the propellant. Since the propellant need not provide the energy, a wider choice of propellant is possible. To have a high $I_{sp}$ (and therefore high exhaust velocity $u_e$), the propellant should have a low molecular weight $\mathcal{M}$ and a high stagnation temperature $T_0$. Recall the relationship

$$u_e \propto \sqrt{\frac{T_0}{\mathcal{M}}}. \tag{1.1}$$

Thus hydrogen, with the lowest molecular weight of any molecule, would be the best propellant, and would provide the highest exhaust velocity for a given stagnation temperature. One might think that with a reactor, very high $T_0$ could be achieved, but this is not so. The reactors used to date are all solid reactors (known as the *reactor core*), and must be kept below their melting temperature, which keeps their $T_0$ around 3000 K, similar to chemical rockets. Thus, the specific impulse of nuclear thermal rockets are limited to about 1000 s, but this is about twice that of the best chemical rockets, and therefore a great advantage.

There has been much study and testing over the past half century into nuclear thermal propulsion concepts and prototypes have even been built and tested (e.g., NERVA). But there are other uses of fission for propulsion. A reactor core containing a fissioning gaseous plasma could achieve an $I_{sp}$ of about 7000 s. Even higher specific impulses can be achieved by using the actual fission products as expellant, eliminating the need for a reactor core. For example, the ORION concept uses explosion debris from a small atomic bomb to drive the vehicle. And in the fission fragment approach, daughter nuclei from the fission reaction are used as the expellant. But these concepts are of uncertain feasibility, and the construction of actual rockets using these concepts may be years away.

# 2 Physics of Fission

If a very heavy nucleus has a neutron added to it (which it will absorb without any intermediate electric repulsioa), the nucleus may become so unstable that it wants to split into two more-or-less equal pieces, a process called nuclear *fission*. If the fission process itself releases more free neutrons (because heavy nuclei tend to be more neutron-rich than small fragments), then obviously one could produce a self-sustaining *chain reaction* if a critical mass of the fissionable material is gathered together. See Figure 2.1. Uncontrolled fission chain reactions lead to an A-bomb; controlled fission chain reactions, to a nuclear reactor.

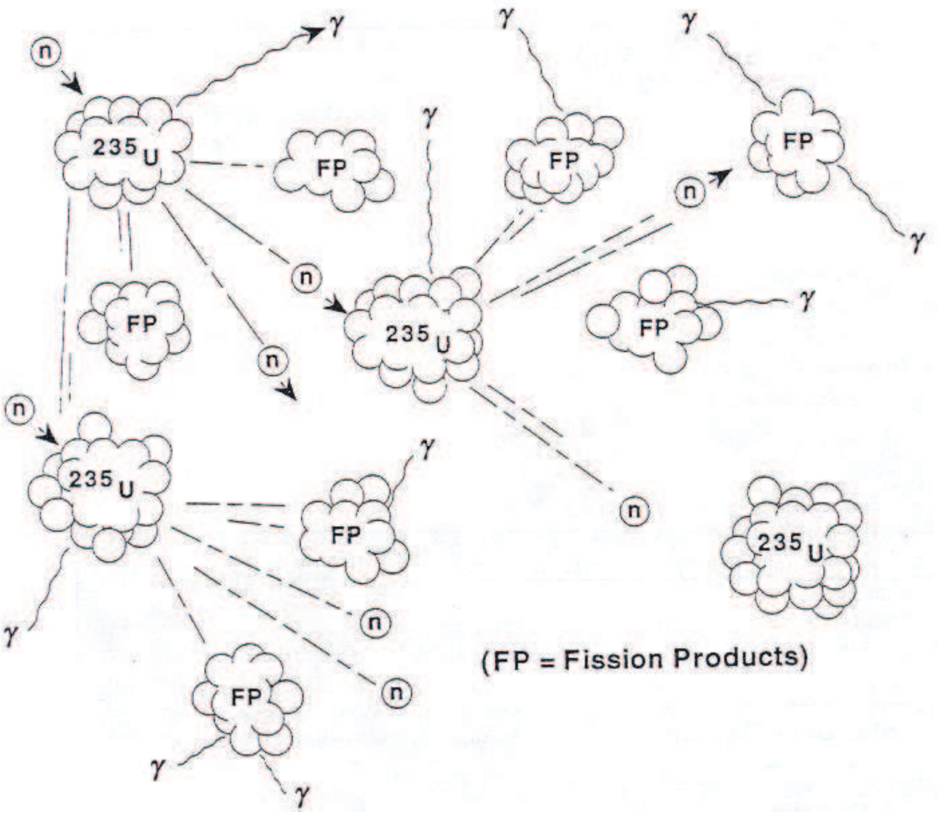

Figure 2.1: **The Fission Chain Reaction.** Uranium ($^{235}$U) splits to give two products of the nuclear fission (FP), several neutrons (n), and gamma rays ($\gamma$) [Lawrence, Witter, and Humble, 1992].

The fission fragments have high kinetic energy from the release of nuclear binding energy, which is a release of a million times more energy per reaction than a chemical combustion reaction. This energy becomes thermal energy through collisions and interactions with other surrounding atoms. If neutrons are also produced during the fission event, they can interact with nearby nuclei by either scattering of a nucleus, being absorbed by a nucleus, or causing another fission event, which releases more neutrons and so on. Thus, if each fission results in another fission event in a reactor, the reactor core is said to be *critical.*

To understand the physics going on in a reactor, we need to review the basics of nuclear physics, the study of the nucleus of atoms. The goal is to present a good picture of the forces and energies involved in fission.

## 2.1 Atomic Structure

The nuclei of ordinary atoms are made up of protons and neutrons in a space of about $10^{-15}$ m across. In an uncharged atom, the nucleus can be pictured as surrounded by a cloud of orbiting electrons at a distance of about $10^{-10}$ m from the nucleus. The atom has the same number ($Z$) of protons and electrons, and is therefore electrically neutral. It is the electron number $Z$ which determines the chemical identity and properties of an atom and its location on the periodic table. See Table 1 to get an initial feel for the atom's configuration. The atomic mass number ($A$) gives the total number of protons and neutrons in the nucleus. Atoms having nuclei containing the same number of protons, but different numbers of neutrons are called isotopes. For example, three different isotopes of uranium ($^{233}$U, $^{235}$U, $^{238}$U) all have 92 protons with 141, 143, and 146 neutron, respectively. Isotopes with $A$ in the range $2Z$ to $2.6Z$ are stable, and all isotopes outside that range (excluding hydrogen and helium-3) are unstable and decay quickly.

Table 1: **Atomic Particles.** The mass, charge, and size of particles are given in the following table. Note that mass is given in atomic mass units (1 amu equal to $1.66 \times 10^{-27}$ kg) and charge is given in terms of the fundamental charge ($e$ is equal to $1.602\times10^{-19}$ coulomb).

| **Particle** | **Mass (amu)** | **Charge ($e$)** | **Radius (m)** |
|---|---|---|---|
| Electron | 0.00055 | -1 | $1.88\times10^{-15}$ |
| Proton | 1.00759 | 1 | $10^{-18}$ |
| Neutron | 1.00898 | 0 | $10^{-18}$ |
| Nucleus | $\approx A$ | $Z$ | $10^{-15}$ |
| Atom | $\approx A$ | 0 | $10^{-10}$ |

The neutrons and protons in the nucleus are held together by the *strong nuclear force.* Within the nucleus, the strong nuclear force is a very strong, short-range, attractive force[1]. This force is considered to be the same between two neutrons, two protons, or a neutron and a proton. The negatively-charged electrons stay in their orbits around the nucleus because of the Coulomb attraction with the positively-charged protons. The strong nuclear force overrides the Coulomb repulsive force between the protons to bind them (along with the uncharged neutrons) into the compact nucleus. The range of the attractive strong nuclear force is about $10^{-15}$ m, roughly the size of the nucleus.

A free neutron, one not bound to a nucleus, such as would initiate or be the product of a fission event, does not feel the Coulomb force. It therefore travels through vacuum, in a straight line, until it "strikes" a nucleus, by which we mean it gets within the $10^{-15}$–meter range of nucleus and feels the strong nuclear force. The neutron is thus much better for causing fission reactions than a proton, which would have to overcome the Coulomb repulsion of a positively-charged nucleus.

## 2.2 Nuclear Reactions as Energy Sources

A chemical reaction entails a rearrangement of the electron structures of atoms. In contrast, a nuclear reaction entails the rearrangement of the protons and neutrons in nuclei, sometimes bringing about a change in chemical identity (changing $Z$) and sometimes creating more than one product atom.

In nuclear reactions, the energy may be related to the change in mass of the material undergoing reaction. From the special theory of relativity, the energy release $\Delta E$ accompanying a decrease of mass $\Delta m$ is

$$\Delta E = c^2 \Delta m, \tag{2.1}$$

where $c$ is the speed of light in vacuum ($2.998\times10^{8}$ m/s).

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[1] The strong force is a bit complicated, and not always attractive. For example, it is known to become repulsive at sufficiently small separation distances. Thus, the strong nuclear force between protons and neutrons has an attractive-repulsive duality that is reminiscent of the der Waals force between molecules. But over the distance of a nucleus, about $10^{-15}$ m, it is attractive, and this is how we will usually view it for out purposes.

The energy $\Delta E$ can be thought of as the amount of energy released when free nucleons (as protons and neutrons are referred to) coalesce to form the nucleus. It is also referred to as the *binding energy* required to separate all of the nucleons to a distance at which they no longer exert the strong nuclear force on each other. The binding energy can be related to the *mass defect* $\Delta m$. The mass of an atom is always less than the sum of the masses of the individual constituents. When the particles are assembled together ("from infinity," where all forces go to zero), the product atom has "missing mass", the mass defect given by

$$\Delta m = [Z(m_p + m_e) + (A - Z)m_n] - m_{atom} \tag{2.2}$$

where $m_p, m_e, m_n$, and $m_{atom}$ are the masses of the proton, electron, neutron, and atom, respectively. The mass defect converts into energy when the nucleus forms according to equation 2.1. For example, in the case of $^{235}$U, which consists of 92 protons, 143 neutrons, and 92 electrons, the total of the free particle masses is 237.03293 amu (atomic mass unit, equal to $1.66 \times 10^{-27}$ kg), while the mass of the atom is 235.124 amu. This leaves a mass defect of 1.909 amu and a binding energy of 1777 MeV (where eV is an electron volt, equal to $1.602 \times 10^{-19}$ joules).

It is more important to examine the average binding energy *per nucleon.* For $^{235}$U, it is 1777/235 = 7.56 MeV. In Figure 2.2, we plot the binding energy per nucleon as a function of atomic mass number.

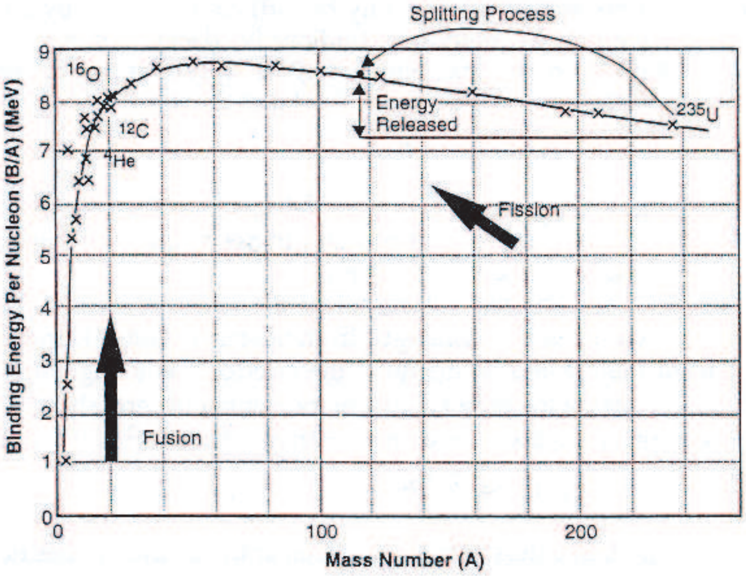

Figure 2.2: **The Average Binding Energy Per Nucleon for Various Nuclei.** Uranium ($^{235}$U) splits to give two nuclei with average masses of 117 amu, releasing the energy shown (200 MeV/2 × 117 = 0.855 MeV/nucleon) [Lawrence, Witter, and Humble, 1992].

Figure 2.2 illustrates that, on average, nuclei in the center of the range are more tightly bound than those of very low or high mass. We see two competing trends. First, starting from the low mass end, we see the general tendency for the binding energy per nucleon to become greater as we go to heavier nuclei. However, this tendency reverses past iron-56, $^{56}$Fe. Beyond iron, the binding energy per nucleon decreases as we go to heavier nuclei.[2]

The general tendency for the binding energy per nucleon to increase until iron and to decrease thereafter illustrates the existence of both fusion and fission. Nuclear *fusion* is the assembling of two nuclei into a single nucleus. For low mass nuclei, there is a release of energy when two nuclei combine to form a

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[2] The two competing trends can be understood roughly as the balance between the attractive and repulsive parts of the strong nuclear force between the protons and neutrons, modified by the Coulomb repulsion between the protons. But we will not go into the details here.

larger nucleus. For example, when two deuterons $^2$H combine to form helium-4 $^4$He, there is an increase in the binding energy per nucleon of 6 MeV, and a corresponding release of energy, mostly in the form of kinetic energy imparted to the helium-4 nucleus. Reactions of this type are the source of energy for stars and *fusion reactors*.

On the other hand, if a very heavy nucleus, like uranium, has a neutron added to it (which it will absorb without any intermediate Coulomb repulsion), the nucleus may become so unstable that it wants to split into two roughly equal sized pieces, which we call fission. Note from Figure 2.2 that we can increase the binding energy per nucleon in a nucleus with A=235 (e.g., $^{235}$U) by nearly 1 MeV if we split it into two fragments of about A=117. Because 235 nucleons are involved, a total of about 235 MeV of energy is available to cause such a transition to take place. Compared to nuclei of half its mass, the $^{235}$U nucleus is relatively weakly bound. Energy must be released to split the loosely bound $^{235}$U into two tightly bound fragments. This energy (really it's closer to $\approx$ 200 MeV) mostly goes into kinetic energy, heating up surrounding material through collisions.

## 2.3 Neutron Interactions with Nuclei

As can be seen from Figure 2.2, fission occurs most readily in nuclei with high mass or too many neutrons (recall the $A > 2.6Z$ relationship we saw earlier). We will look at the example of a neutron interacting with a $^{235}_{92}$U nucleus to better understand the processes involved.

Suppose we have free *thermal* neutrons colliding about. "Thermal" means that the neutrons have achieved thermal equilibrium with the surrounding material through repeated collisions. They typically have kinetic energies which are much smaller than 1 MeV, usually around 0.25 eV, corresponding to a thermal speed of about 2200 m/s. Upon capture of a thermal neutron by $^{235}_{92}$U, the excited compound nucleus $[^{236}_{92}\text{U}]$ is formed. The excitation energy in this case would be just equal to the binding energy of the captured neutron, since its initial kinetic (thermal) energy is negligible. The compound nucleus may react in a variety of ways.

- *Fission*: the excited nucleus $[^{236}_{92}\text{U}]$ splits into two roughly equal mass nuclei and releases, on average, 2.5 neutrons.
- *Absorption*: the nucleus absorbs the neutron and de-excites itself to the ground state of $^{236}_{92}$U by emitting a charged particle ($\alpha$- or $\beta$-particle) or a $\gamma$-ray.
- *Scattering*: the nucleus may eject the neutron to return to $^{235}_{92}$U. In the process, the neutron imparts some of its momentum and kinetic energy to the nucleus, and moves off in a different direction from its original path.

The probability of each of these reactions can be expressed in terms of a reaction *cross section*, which is measured in barns, a unit of area equal to $10^{-24}$ cm$^2$. The cross sections of $^{235}_{92}$U are: fission (577 barns); absorption (106 barns); scattering (9 barns). For our purposes, only the relative cross sections are important, and it can be seen that, of the interactions of thermal neutrons with $^{235}_{92}$U nuclei, 80% [577/(577 + 106 + 9)] result in fission.

## 2.4 Products of Fission

Fission results in two heavy products or *fission fragments*, which carry most of the energy released in the form of kinetic energy. Nuclear stability usually causes one of the fission fragments to be larger than the other. Figure 2.3 shows the characteristic "double-humped" distribution for thermal fission of $^{235}$U. About 97% of the fission fragments fall into either a "light" group having mass numbers near 95 or a "heavy" group having mass numbers near 139.

Most fission fragments contain too many neutrons, since the heavy nuclei such as uranium generally have a much higher neutron-proton ratio than the stable lighter nuclei. Thus the fission fragments are

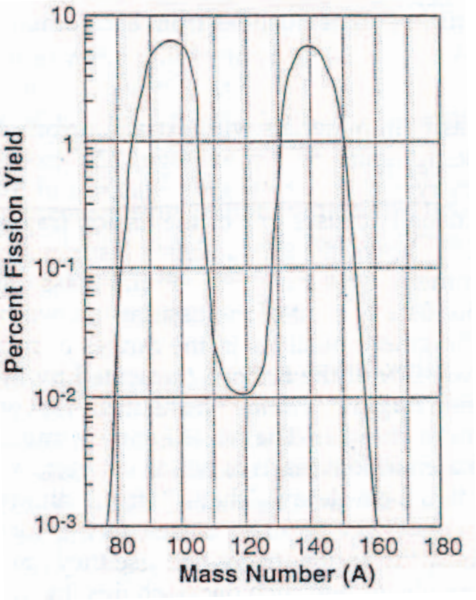

Figure 2.3: **Mass Yield Curve for Fission of $^{235}$U by Thermal Neutrons**. This curve shows that fission fragments fall into either a "light" group having mass numbers near 95 or a "heavy" group having mass numbers near 139. The sum of these numbers is 234, showing that, on average, roughly two neutrons are released to bring the total mass to 236 (mass sum of $^{235}$U plus the original neutron) [Lawrence, Witter, and Humble, 1992].

highly radioactive. Most emit $\beta$-particles (electrons), which converts a neutron to a proton, but some emit neutrons directly. Figure 2.4 shows two $\beta$-decay "chains" from different fissions. The $\gamma$-rays are emitted whenever a $\beta$-particle leaves the nucleus in an excited state. The total fission energy release includes that released in these various product decay processes.

A very important feature of the fission process is the emission of neutrons. More than 99% are emitted during fission or shortly thereafter, while some originate in the decay of fission fragments. These neutrons, if captured by additional fissionable nuclei, can cause further fissions. Thus, under the proper circumstances, a self-sustaining chain reaction can occur in which the fissioning material releases enough neutrons to cause continued fission of remaining material at the same rate. On average, thermal fission of $^{235}$U is accompanied by release of about 2.5 neutrons.

## 2.5 Fission Energy

Most of the fission energy appears in the form of kinetic energy of the fission fragments. The two fragments created by the split original nucleus (see Figure 2.4) quickly re-form into roughly spherical shapes. At this point, they are separated by a distance greater than the range of the nuclear force ($> 10^{-15}$ m) and are charged, thus a very large Coulomb repulsive force pushes them apart. As they pick up tremendous speed, they go careening through the medium. Being relatively massive and usually very highly ionized, the fragments collide with other charged nuclei (through Coulomb interaction) and so quickly transmit their kinetic energy to the surrounding medium. As a result, the initial kinetic energy of these fragments ($\approx$ 168 MeV) cascades, through Coulomb interaction, to the nuclei near the site where the original fission took place. Thus, the average kinetic energy (temperature) of the neighboring medium increases from collisions nearly instantaneously. About 84% of the energy released in thermal fission of $^{235}$U converts into an increase in local temperature in this manner.

The rest of the energy released in fission is summarized in Table 2. This table shows a typical distribution of energy, in which the term "prompt" denotes immediate release during the fission event

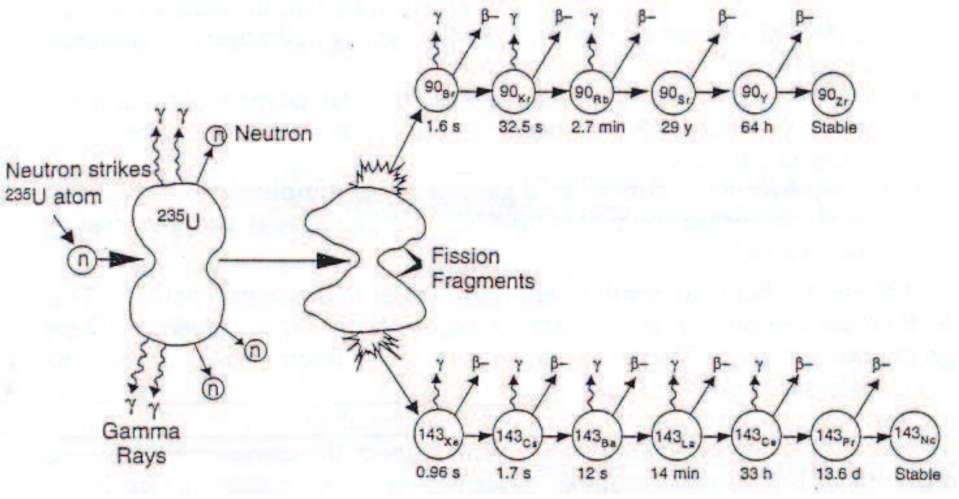

Figure 2.4: **Nuclear Fission and Subsequent Decay**. A thermal neutron strikes the nucleus of the $^{235}$U atom, causing it to split. Fission releases neutrons, $\gamma$-rays, and two fission fragments. The masses of the fission fragments depend on a probability distribution (Figure 2.3). The resulting fission fragments decay radioactively as shown, releasing more energy [Lawrence, Witter, and Humble, 1992].

(within nanoseconds), in contrast to gradual decay (see Figure 2.4).

Table 2: **Energy Release in the Fission of $^{235}$U by Thermal Neutrons**. Most of the energy is in the fission fragments (84%), but some other particles take up some additional energy. Note, energy is measured in millions of electron volts (1 MeV is equal to $1.602 \times 10^{-13}$ joules).

| **Energy Source** | **Fission Energy (MeV)** |
|---|---|
| Fission fragments | 168 |
| Neutrons | 5 |
| Prompt $\gamma$-rays | 7 |
| $\beta$-decay | 8 |
| $\gamma$-decay | 7 |
| Radiative capture $\gamma$-rays | 5 |
| Total | 200 |

Fission converts mass energy into kinetic energy of the fission fragments, prompt neutrons, and the radiation energy of $\gamma$-rays. The fission fragments subsequently decay, as in Figure 2.4, further converting mass energy into $\gamma$-rays and into kinetic energy of released $\beta$-particles and delayed neutrons. The energy spectrum for neutrons produced in fission is shown in Figure 2.5. The neutrons transmit their energy to charged particles by direct collisions with nuclei, through $\gamma$-rays, and by electromagnetic interactions. In this manner, all the energy released from fission quickly transmits to charged particles. The energy is eventually transmitted to the nuclei of the medium through Coulomb interaction in a cascade effect, raising the average temperature of the material comprising the medium.

## 3 Conclusion

Fission is the energy source for nuclear thermal rockets, a monopropellant liquid fuel rocket concept which has been studied and tested on the ground, but has not yet flown. Nuclear thermal rockets, which

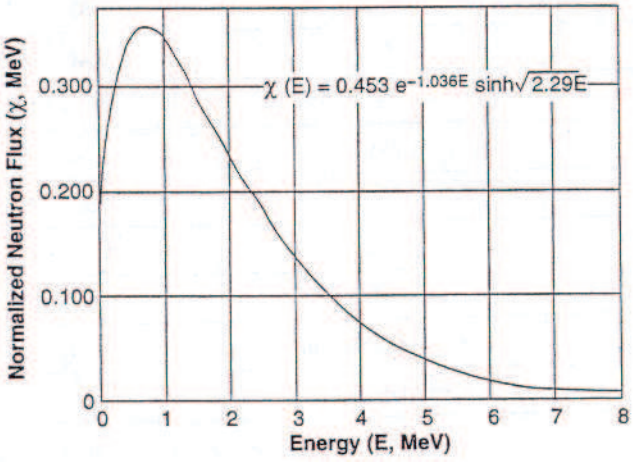

Figure 2.5: **Empirical Energy Spectrum for Fission Neutron from the Thermal Fission of $^{235}$U**. A thermal neutron (kinetic energy of about 0.25 eV) creates a nuclear fission. Fission releases more neutrons with an energy distribution as shown. Most of the neutrons have energies much greater than the thermal level and do not support fission. "Moderators" must slow them down so they are useful for future fission reactions [Lawrence, Witter, and Humble, 1992].

use a solid-core fission reactor to heat a propellant, are capable of twice the $I_{sp}$ of the best chemical rockets, which use chemical combustion to heat the propellant. Of the high efficiency alternatives to current chemical rockets, only nuclear thermal rockets are capable of the high engine thrust to weight ratios necessary to launch payloads from the Earth's surface into low Earth orbit.

In this paper, we have reviewed some basic concepts of nuclear physics involved in nuclear fission, especially fission of $^{235}$U. The energy in a fission reaction is nearly instantaneously converted into increased temperature in the medium containing the fissionable nuclei. A fission reaction releases about a million times the energy of a chemical reaction, and is therefore a very efficient energy source.

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