Nuclear Reactions

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1 Introduction

"The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars ... The cosmos is within us. We are made of star-stuff. We are a way for the universe to know itself." - Carl Sagan, 'Cosmos', 1980.

We saw last week that mass and energy are not separate things, but just a different way of looking at the same thing. We saw that they are related via the equation $E = mc^2$. Rather than having a law of conservation of mass, we must now work instead with a law of conservation of mass-energy, remembering that we can convert between forms.

The speed of light is very big, it's about $3 * 10^8$ m/s. Because of this, a very small amount of mass is equivalent to a lot of energy.

We are now ready to look closer at nuclear reactions.

2 Cockcroft & Watson's Experiment

While Einstein predicted energy-mass equivalence in his 1905 special relativity paper, it wasn't experimentally confirmed until 19932 by Cockcroft and Walton, who produced the first disintegration of a nucleus using an accelerated charged particle.

Fun Fact: Ernest Walton was from Waterford, and is the only Irish person to ever win a Nobel Prize for Physics. He won it in 1951 alongside Cockcroft for verifying $E = mc^2$.

The particle involved using an electrostatic generator to accelerate protons to energies of 600keV. They showed that when lithium is bombarded with protons, two alpha particles are emitted in opposite directions. This shows that momentum of the system is conserved, but the mass of the lithium and the protons before impact is greater than that of the two alpha particles produced. The

KE of the alpha particles after the impact was equal, according to energy-mass equivalence, to the mass lost.

3 Fission

The discovery of nuclear fission is a groundbreaking scientific achievement that revolutionized our understanding of atomic physics and energy production. It was first observed and confirmed by German scientists Otto Hahn and Fritz Strassmann, with significant contributions from Austrian physicist Lise Meitner, in late 1938.

The discovery came as a result of their experiments involving the bombardment of uranium atoms with neutrons. They noticed that the uranium nuclei were splitting into smaller fragments, releasing a substantial amount of energy in the process. This unexpected phenomenon was termed "nuclear fission."

Hahn and Strassmann initially believed they had witnessed the formation of transuranium elements, but Lise Meitner, who had fled Nazi Germany to Sweden, correctly interpreted their results. She theorized that the uranium nucleus had actually split into two smaller nuclei, accompanied by the release of energy. This groundbreaking insight, proposed by Meitner and her nephew Otto Frisch, laid the foundation for our understanding of nuclear fission.

The scientific community recognized the significance of this discovery, and its potential for both destructive and constructive applications became apparent. Subsequent research by scientists such as Enrico Fermi, Leo Szilard, and others led to the development of the first controlled nuclear chain reaction in December 1942, known as the Chicago Pile-1.

The implications of nuclear fission were soon realized in the form of nuclear weapons. The first atomic bomb was successfully detonated in 1945 during the Manhattan Project, leading to the end of World War II. However, nuclear fission also paved the way for the development of peaceful applications, such as nuclear power generation. Nuclear reactors harness the controlled release of energy through fission, producing electricity on a large scale.

The discovery of nuclear fission marked a pivotal moment in scientific history, unveiling the immense power hidden within the atomic nucleus and ushering in a new era of both destructive capabilities and energy possibilities.

3.1 Uranium Fission

Most practical fission reactions use uranium. The most common uranium isotopes are U-238(99.2%), U-235(0.7%), and U-234(0.006%). Different isotopes behave differently during fission.

3.1.1 Radiative Capture

To start the fission process, the nucleus is bombarded with neutrons. There is a chance, when struck with a neutron, that a nucleus will undergo fission. If not, it will simply emit the neutron in a process known as radiative capture.

Typically, its very difficult to induce fission in U-238. It tends to go with radiative capture the majority of the time, unless the neutron it is hit with is faster than 1MeV. Most neutrons are not this fast.

On the other hand, U-235 undergoes very little radiative capture and tends to undergo fission very easily. When this happens, the uranium nucleus splits into two fragments: one krypton atom and barium atom, with two neutrons emitted.There is also immense amounts of energy released in this process.

3.2 Chain reactions & Nuclear Weapons

When a nuclear fission process emits two fragments and two neutrons, those neutrons usually have a substantial amount of energy. If they strike the nuclei of other surrounding atoms, they themselves can cause nuclear fission. This is called a chain reaction.

It is rare to see a chain reaction in natural uranium. You will need lots of U-235 (Pu-239 will also work) for start a chain reaction of nuclear fission. If this chain reaction occurs in an uncontrolled way, with the excess energy simply being expelled into the surroundings, we call this a nuclear bomb.

Nuclear weapons can cause loss of life and livelihoods on scales never seen before with any other kinds of technology. During WWII, the Allied powers put a lot of effort into creating nuclear bombs in what was called **The Manhattan Project**. The Manhattan Project was centered in Los Alamos, New Mexico. Many prominent scientists worked on the Manhattan Project: Einstein himself, Richard Feynman and Oppenheimer just to name a few. The result of the Manhattan project was that two nuclear bombs were dropped on two Japanese cities within days of each other: Hiroshima and Nagasaki. The past century has been shaped by political efforts to make these the last nuclear weapons dropped on civilians.

4 Nuclear Reactors

It is possible to use nuclear reactions for peaceful purposes. For instance, if we could harness all of the energy released in a fission reaction, we could harvest it as a clean source of energy, without needing any fossil fuels. This is the idea behind nuclear power.

To control the fission process, we can use something called a **Nuclear Reactor**. To control the nuclear fission process, the reactor has control rods made of materials like boron or cadmium. These control rods are inserted or withdrawn into the reactor core to absorb some of the extra neutrons and slow down or speed up the fission process. By adjusting the position of the control rods, the reactor's power output can be regulated.

As the atoms split and release heat, the surrounding water in the reactor core absorbs that heat and turns into steam. This steam then travels through pipes to a turbine, a large spinning machine. The high-pressure steam causes the turbine blades to spin, and the turbine is connected to a generator. As the turbine spins, it generates electricity.

After passing through the turbine, the steam cools down and turns back into water. It goes through a cooling system, usually using water from a nearby river or ocean, and then returns to the reactor core to be reheated and turned into steam again.

4.1 Dangers of fission reactors

Fission reactors are generally very safe. If all correct safety protocols are followed, nothing should go wrong. However, if shortcuts are taken, the consequences can be literally disastrous.

The Chernobyl nuclear disaster, which occurred on April 26, 1986, was the result of a combination of design flaws, human errors, and a series of unfortunate events during a safety test.

At the Chernobyl nuclear power plant in Ukraine, the test involved shutting down the reactor and assessing its ability to provide electrical power to the cooling system during a potential blackout. However, the reactor design, specifically the RBMK-1000 reactor, had inherent stability issues and a positive void coefficient, meaning that as the coolant water heated up and turned into steam, it would actually accelerate the nuclear reaction instead of slowing it down.

During the test, the operators made a critical mistake by lowering the power level of the reactor to a point where it became too unstable. To compensate, they inserted the control rods too far, which had graphite tips that further increased the reactivity. Additionally, the emergency shutdown system was deactivated as part of the test protocol.

A sudden power surge occurred due to a combination of these factors, causing a steam explosion and the rupture of the reactor vessel. This explosion led to a fire that lasted for days and released massive amounts of radioactive material into the atmosphere.

The absence of a proper containment structure around the reactor exacerbated the situation, allowing the radioactive debris and gases to spread over a wide area. The radioactive plume carried by the wind contaminated large regions of Ukraine, Belarus, and other neighboring countries.

The Chernobyl disaster was a wake-up call for the nuclear industry, highlighting the importance of strict safety measures, robust containment structures, and operator training. The event led to significant improvements in nuclear safety worldwide and a reevaluation of reactor designs and emergency response procedures.

5 Fusion

We have briefly discussed nuclear fusion before. Recall that the immense pressures at the core of stars and supernovae are the only way to create elements heavier than hydrogen. That's why I've included the Carl Sagan quote at the top of this document; to say that 'we are star stuff' is not metaphor.

What happens inside stars is an uncontrolled fusion reaction. Akin to uncontrolled fission reactions, uncontrolled fusion reactions can also be used as weaponry.

One of the Holy Grails of 20th/21st century physics has been the search for the development of fusion energy, in the same way that we have fission reactors. The advantage of fusion over fission is that fusion doesn't involve any radioactive substance, and is therefore safer and cleaner.

The problem is that it has yet to be developed in such a way that it is both energy positive (that is, the reaction gives out more energy than it needs to start the reaction) and easy to mass produce. A few weeks ago (in 2023), a paper was published announcing the development of the first energy positive fusion reactor. It is still far away from being commercially available in the same way fission energy is, but it's not out of the question that in the future, we may have fusion reactors for clean, renewable energy.