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Nuclear Physics

Radioactivity, Fission, and Fusion

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Chapter 1: What Is Nuclear Physics?

Nuclear physics is the study of the atomic nucleus, the tiny core at the center of every atom. The nucleus contains protons and neutrons, held together by the strongest force in nature. Understanding the nucleus has changed the world. It gave us nuclear power, nuclear medicine, and the knowledge that stars shine by nuclear fusion.

Nuclear physics is the science of the most powerful forces in the universe, operating in the tiniest spaces.

The field of nuclear physics began in 1896, when Henri Becquerel discovered that uranium salts emitted a form of radiation that could pass through paper and darken photographic plates. This discovery, made by accident while investigating phosphorescence, opened a window into a world that no one had suspected existed — the world inside the atom.

Within a decade, Marie and Pierre Curie had isolated two new radioactive elements, polonium and radium, and Ernest Rutherford had begun a systematic investigation of the nature of the radiation that Becquerel had discovered. Rutherford found that the radiation consisted of two types, which he called alpha and beta, and that alpha particles were deflected by electric and magnetic fields, which meant they were charged.

This work led to the discovery of the atomic nucleus in 1911, when Rutherford's gold foil experiment showed that the positive charge of an atom was concentrated in a tiny central region, not spread throughout the atom as had been previously believed. The discovery of the nucleus transformed physics. Before 1911, atoms were thought to be the smallest particles of matter, indivisible and fundamental.

After 1911, the atom was recognized as a structure — a nucleus surrounded by electrons — and the nucleus itself became the new frontier. What was the nucleus made of? How was it held together? What forces operated within it?

These questions drove the development of nuclear physics for the next century, and the answers that were found — the proton, the neutron, the strong force, fission, fusion — are the foundation of modern nuclear science.

Nuclear physics is not a single discipline but a collection of related fields, each focused on a different aspect of the nucleus. Nuclear structure physics studies the organization of protons and neutrons within the nucleus and the forces that hold them together. Nuclear reaction physics studies what happens when nuclei collide or are bombarded with particles.

Nuclear astrophysics studies the nuclear processes that occur in stars and that create the elements of the periodic table.

Applied nuclear physics includes nuclear power, nuclear medicine, and nuclear

weapons. Each of these fields is connected to the others through the shared study of the nucleus, and each has contributed to our understanding of the physical world. The impact of nuclear physics on human society has been enormous. Nuclear power generates approximately 10 percent of the world's electricity, providing a low-carbon energy source that is used in more than 30 countries.

Nuclear medicine uses radioactive isotopes for diagnosis and treatment, and millions of medical procedures involving nuclear technology are performed each year. Nuclear weapons have shaped international relations since 1945, and the threat of nuclear war remains one of the greatest dangers facing humanity.

The discovery of nuclear fission and fusion changed the world, and the continuing development of nuclear technology — including the effort to achieve practical nuclear fusion — is one of the most important scientific and engineering projects of the current era.

The discovery of the nucleus also raised a question that has driven nuclear physics ever since: what holds the nucleus together? The protons in the nucleus are all positively charged, and the electromagnetic force causes like charges to repel. The repulsion between protons in a nucleus is enormous — at the scale of the nucleus, the electromagnetic repulsion is one of the strongest forces in nature.

And yet the nucleus does not fly apart.

The protons are held together by a force that is stronger than the electromagnetic force, a force that operates only at very short range, and a force that was unknown to physics before the discovery of the nucleus. This force — the strong nuclear force — is the subject of Chapter 3, and it is one of the most important discoveries in the history of physics.

The search for the strong force was the search for the glue that holds the nucleus together, and the discovery of the strong force was one of the great achievements of twentieth-century physics.

While the work on radioactivity by Becquerel and Marie Curie predates this, an explanation of the source of the energy of radioactivity would have to wait for the discovery that the nucleus itself was composed of smaller constituents, the nucleons.

In 1906, Ernest Rutherford published "Retardation of the a Particle from Radium in passing through matter." Hans Geiger expanded on this work in a communication to the Royal Society with experiments he and Rutherford had done, passing alpha particles through air, aluminum foil and gold leaf. More work was published in 1909 by Geiger and Ernest Marsden, and further greatly expanded work was published in 1910 by Geiger.

In 1911–1912 Rutherford went before the Royal Society to explain the experiments and propound the new theory of the atomic nucleus as we now understand it. Published in 1909, with the eventual classical analysis by Rutherford published May 1911, the key preemptive experiment was performed during 1909, at the University of Manchester.

Ernest Rutherford's assistant, Professor Johannes "Hans" Geiger, and an undergraduate, Marsden, performed an experiment in which Geiger and Marsden under Rutherford's supervision fired alpha particles (helium 4 nuclei) at a thin film of gold foil. The plum pudding model had predicted that the alpha particles should come out of the foil with their trajectories being at most slightly bent.

But Rutherford instructed his team to look for something that shocked him to observe: a few particles were scattered through large angles, even completely backwards in some cases. He likened it to firing a bullet at tissue paper and having it bounce off.

Chapter 2: Inside the Nucleus

Every atom has a nucleus at its center. The nucleus is incredibly small, about 100,000 times smaller than the atom itself.

If an atom were the size of a football stadium, the nucleus would be a pea on the field. Despite its tiny size, the nucleus contains almost all the atom's mass. It is made of protons, which have positive charge, and neutrons, which have no charge. The number of protons determines which element the atom is.

The nucleus was discovered by Ernest Rutherford in 1911 in one of the most famous experiments in the history of science.

Rutherford and his assistants, Hans Geiger and Ernest Marsden, bombarded a thin sheet of gold foil with alpha particles — positively charged particles emitted by radioactive materials. Most of the alpha particles passed straight through the foil, but a small number were deflected at large angles, and some bounced back toward the source.

Rutherford described this result as remarkable — the only explanation was that the positive charge of the atom was concentrated in a tiny, dense central region — the nucleus.

The structure of the nucleus was further revealed in the following decades. The proton was identified by Rutherford in 1919 as the nucleus of the hydrogen atom, and the neutron was discovered by James Chadwick in 1932. The proton has a positive electric charge equal in magnitude to the electron's negative charge, and the neutron has no electric charge.

Both protons and neutrons have approximately the same mass — about 1.67×10^{-27} kilograms, or 1 atomic mass unit — and both are classified as nucleons. The number of protons in a nucleus is the atomic number, which determines the element, and the number of neutrons determines the isotope. A nucleus with 6 protons and 6 neutrons is carbon-12, the most common isotope of carbon.

Add two more neutrons instead and the result is carbon-14, a radioactive isotope used in radiocarbon dating.

The size of the nucleus is remarkable. A typical nucleus has a diameter of about 1 to 10 femtometers, where a femtometer is 10^{-15} meters. The diameter of an atom is

about 100 picometers, or 10^{-10} meters, which means the nucleus is approximately 100,000 times smaller than the atom.

Nuclear volume shrinks further still: roughly 10^{15} times more compact than the atom as a whole, and yet the nucleus contains more than 99.9 percent of the atom's mass.

The density of nuclear matter is approximately 2.3×10^{17} kilograms per cubic meter, which is about 100 trillion times the density of water. A cube of nuclear matter one centimeter on each side would weigh approximately 230 million tons. This enormous density is a consequence of the strong nuclear force, which packs the nucleons together with extraordinary tightness.

The nucleus is not a solid sphere but a dynamic system in which protons and neutrons are in constant motion, interacting through the strong force and the electromagnetic force. The protons, being positively charged, repel each other through the electromagnetic force, and the neutrons, being neutral, do not participate in this repulsion.

The strong nuclear force, which is about 100 times stronger than the electromagnetic force at the distance of the nucleus, overcomes the electromagnetic repulsion and holds the nucleus together.

The balance between the strong force and the electromagnetic force determines which nuclei are stable and which are radioactive. The discovery of the nucleus also led to the development of nuclear models — theoretical descriptions of how the nucleus is organized and how it behaves.

The first model was the liquid drop model, proposed by Niels Bohr and John Wheeler in 1939, which describes the nucleus as a drop of incompressible fluid, with protons and neutrons behaving like molecules in a liquid.

The liquid drop model explains the gross properties of nuclei — their binding energies, their shapes, and their fission behavior — and it was the basis for the understanding of nuclear fission. More detailed models, such as the shell model and the collective model, were developed later to explain the finer details of nuclear structure, but the liquid drop model remains a useful description of the nucleus as a whole.

The nucleus also exhibits quantum mechanical properties that are not present in macroscopic objects.

The protons and neutrons in the nucleus are fermions — particles with half-integer spin — and they obey the Pauli exclusion principle, which forbids two identical fermions from sharing a single quantum state. The Pauli principle has a profound effect on nuclear structure: it determines the arrangement of nucleons in energy levels, the stability of nuclei, and the existence of magic numbers.

Without the Pauli principle, all the nucleons in a nucleus would collapse to the lowest energy state, and the rich structure of nuclear physics would not exist. The quantum mechanical nature of the nucleus is one of the reasons why nuclear physics is so different from classical physics, and the study of the nucleus was, in turn, a proving

ground for the development of quantum mechanics.

The discovery, with Rutherford's analysis of the data in 1911, led to the Rutherford model of the atom, in which the atom had a very small, very dense nucleus containing most of its mass, and consisting of heavy positively charged particles with embedded electrons in order to balance out the charge (since the neutron was unknown).

As an example, in this model (which is not the modern one) nitrogen-14 consisted of a nucleus with 14 protons and 7 electrons (21 total particles) and the nucleus was surrounded by 7 more orbiting electrons. Around 1920, Arthur Eddington anticipated the discovery and mechanism of nuclear fusion processes in stars, in his paper The Internal Constitution of the Stars.

At that time, the source of stellar energy was a complete mystery; Eddington correctly speculated that the source was fusion of hydrogen into helium, liberating enormous energy according to Einstein's equation E = mc2. This was a particularly remarkable development since at that time fusion and thermonuclear energy, and even that stars are largely composed of hydrogen (see metallicity), had not yet been discovered.

The Rutherford model worked quite well until studies of nuclear spin were carried out by Franco Rasetti at the California Institute of Technology in 1929. By 1925 it was known that protons and electrons each had a spin of ±+1⁄2.

In the Rutherford model of nitrogen-14, 20 of the total 21 nuclear particles should have paired up to cancel each other's spin, and the final odd particle should have left the nucleus with a net spin of 1⁄2.

Rasetti discovered, however, that nitrogen-14 had a spin of 1. In 1932 Chadwick realized that radiation that had been observed by Walther Bothe, Herbert Becker, Irène and Frédéric Joliot-Curie was actually due to a neutral particle of about the same mass as the proton, that he called the neutron (following a suggestion from Rutherford about the need for such a particle).

Chapter 3: The Strong Nuclear Force

Protons all have positive charge, so they should repel each other.

But the nucleus does not fly apart. Something stronger than the electric repulsion holds it together. This is the strong nuclear force, the strongest of the four fundamental forces. It out-muscles the electromagnetic force by a factor of about 100 but only works at very short range, about the diameter of the nucleus itself. Without the strong force, no atom heavier than hydrogen could exist.

The strong nuclear force is one of the four fundamental forces of nature, along with the electromagnetic force, the weak nuclear force, and gravity. The strong force is the most powerful of the four — approximately 100 times stronger than the electromagnetic force, 10^6 times stronger than the weak force, and 10^{38} times stronger than gravity.

Despite its enormous strength, the strong force has a very short range — it operates

only at distances of about 1 to 3 femtometers (10^{-15} meters), which is approximately the diameter of the nucleus. Beyond this range, the strong force drops to zero, and the electromagnetic repulsion between protons becomes the dominant force.

The strong force was proposed in the 1930s as a theoretical necessity — something had to hold the nucleus together despite the electromagnetic repulsion between protons — but its nature was not understood until the development of quantum chromodynamics (QCD) in the 1970s. QCD describes the strong force as the interaction between quarks and gluons, the fundamental particles that make up protons and neutrons.

According to QCD, protons and neutrons are each made of three quarks, and the quarks are held together by gluons, which are the carriers of the strong force. The strong force that holds the nucleus together is actually a residual force — a leftover of the much stronger force that holds the quarks together within each proton and neutron. The properties of the strong force have profound consequences for nuclear physics.

The short range of the force means that large nuclei, in which protons are far apart, are less stable than small nuclei, in which all the protons are within the range of the force. This is why heavy elements like uranium and plutonium are radioactive — the electromagnetic repulsion between the protons in a large nucleus eventually overcomes the strong force, and the nucleus decays.

That same strong-versus-electric contest also fixes the ratio of neutrons to protons in stable nuclei. In light nuclei, the ratio is approximately 1:1, but in heavy nuclei, more neutrons are needed to provide additional strong force attraction without adding electromagnetic repulsion. The strong force is also responsible for the energy released in nuclear reactions.

In nuclear fission, a heavy nucleus splits into two lighter nuclei, and the total mass of the products is less than the mass of the original nucleus.

The missing mass is converted to energy through Einstein's equation $E = mc^2$, and the energy comes from the strong force — the products are more tightly bound by the strong force than the original nucleus, and the difference in binding energy is released as energy.

In nuclear fusion, two light nuclei combine to form a heavier nucleus, and the same principle applies. The strong force, by holding the nucleus together, is the source of the energy that powers stars and nuclear reactors. The strong force is also remarkable for a property called confinement.

Unlike the electromagnetic force and gravity, which decrease with distance but never reach zero, the strong force between quarks actually increases with distance — the further apart two quarks are pulled, the stronger the force between them becomes.

This means that quarks can never be separated — if you try to pull two quarks apart, the energy required increases until it is sufficient to create new quark-antiquark pairs, and the new quarks bind with the original quarks to form new particles.

This property, called color confinement, means that quarks are never observed as free particles — they are always confined within protons, neutrons, and other hadrons. Confinement is one of the most distinctive features of the strong force, and it is a large part of what separates the strong force from its three cousins.

The experimental observation of confinement and the theoretical explanation of why it occurs are active areas of research in nuclear and particle physics.

In the same year Dmitri Ivanenko suggested that there were no electrons in the nucleus — only protons and neutrons — and that neutrons were spin 1⁄2 particles, which explained the mass not due to protons.

The neutron spin immediately solved the problem of the spin of nitrogen-14, as the one unpaired proton and one unpaired neutron in this model each contributed a spin of 1⁄2 in the same direction, giving a final total spin of 1.

With the discovery of the neutron, scientists could at last calculate what fraction of binding energy each nucleus had, by comparing the nuclear mass with that of the protons and neutrons which composed it. Differences between nuclear masses were calculated in this way. When nuclear reactions were measured, these were found to agree with Einstein's calculation of the equivalence of mass and energy to within 1% as of 1934.

Alexandru Proca was the first to develop and report the massive vector boson field equations and a theory of the mesonic field of nuclear forces. Proca's equations were known to Wolfgang Pauli who mentioned the equations in his Nobel address, and they were also known to Yukawa, Wentzel, Taketani, Sakata, Kemmer, Heitler, and Fröhlich who appreciated the content of Proca's equations for developing a theory of the atomic nuclei in Nuclear Physics.

In 1935 Hideki Yukawa proposed the first significant theory of the strong force to explain how the nucleus holds together. In the Yukawa interaction a virtual particle, later called a meson, mediated a force between all nucleons, including protons and neutrons.

This force explained why nuclei did not disintegrate under the influence of proton repulsion, and it also gave an explanation of why the attractive strong force had a more limited range than the electromagnetic repulsion between protons.

Later, the discovery of the pi meson showed it to have the properties of Yukawa's particle. With Yukawa's papers, the modern model of the atom was complete. The center of the atom contains a tight ball of neutrons and protons, which is held together by the strong nuclear force, unless it is too large.

Unstable nuclei may undergo alpha decay, in which they emit an energetic helium nucleus, or beta decay, in which they eject an electron (or positron).

Chapter 4: Radioactivity

Some atomic nuclei are unstable. They spontaneously break apart or change,

releasing energy and particles. This is radioactivity, discovered by Henri Becquerel in 1896. There are three main types: alpha particles, which are two protons and two neutrons, beta particles, which are electrons, and gamma rays, which are high-energy light. Radioactivity is natural. The Earth itself is radioactive, and the heat from radioactive decay keeps the planet's interior molten. Henri Becquerel's discovery of radioactivity was accidental.

He was investigating phosphorescence — the ability of certain materials to glow after exposure to light — and he had placed uranium salts on a photographic plate wrapped in black paper, intending to expose them to sunlight. The sky was overcast, so he put the materials in a drawer.

When he later developed the plate, he found that the uranium had produced a clear image through the wrapping, even though it had not been exposed to light.

Becquerel realized that the uranium was emitting a form of radiation that was not related to phosphorescence and that could pass through opaque materials. This was the discovery of radioactivity, and it earned Becquerel a share of the 1903 Nobel Prize in Physics with Marie and Pierre Curie. The three types of radiation are distinguished by their properties.

Alpha particles, identified by Rutherford, are the nuclei of helium atoms — two protons and two neutrons — and they are the heaviest and least penetrating type of radiation. Alpha particles can be stopped by a sheet of paper or a few centimeters of air, but they are also the most ionizing — they can cause significant damage to living tissue if alpha-emitting materials are ingested or inhaled.

Beta particles are electrons emitted by the nucleus during beta decay, a process in which a neutron converts to a proton and an electron. Beta particles are lighter and more penetrating than alpha particles but can be stopped by a thin sheet of aluminum. Gamma rays are high-energy photons — packets of electromagnetic energy — emitted by the nucleus during transitions between energy states.

Gamma rays are the most penetrating type of radiation and require thick lead or concrete shielding to stop.

The process of radioactive decay follows a statistical pattern. It is impossible to predict when any individual nucleus will decay, but the decay rate of a large sample is predictable and constant. The probability of decay per unit time is characterized by the half-life, which is the time it takes for half of the nuclei in a sample to decay.

Half-lives range from fractions of a second to billions of years, and the wide range of half-lives is a reflection of the wide range of nuclear stabilities. Some nuclei are only slightly unstable and decay slowly, while others are highly unstable and decay rapidly. Radioactivity is a natural phenomenon.

The Earth itself is radioactive — the interior of the planet is heated by the radioactive decay of uranium, thorium, and potassium isotopes in the crust and mantle, and this heat is what drives plate tectonics, volcanism, and the Earth's magnetic field. Without radioactive decay, the Earth's interior would have cooled long ago, and the planet

would be geologically dead.

Radioactivity is also present in the environment — in rocks, soil, water, and even in the food we eat.

The human body contains radioactive potassium-40, and the radiation from this isotope is a natural part of human biology. The discovery of radioactivity also led to a profound change in the understanding of matter and energy. Before Becquerel's discovery, atoms were thought to be permanent, unchanging, and stable.

After the discovery of radioactivity, it became clear that atoms could change — that one element could transform into another, releasing energy in the process.

This was the first evidence that the elements are not permanent but can be created and destroyed, and it led to the understanding that the elements are products of nuclear processes — processes that occur in stars, in the early universe, and in nuclear reactors.

The discovery of radioactivity was not just the discovery of a new phenomenon but the discovery of a new principle: that matter is not static but dynamic, and that the elements that make up the world are the products of processes that have been operating since the beginning of the universe.

After one of these decays the resultant nucleus may be left in an excited state, and in this case it decays to its ground state by emitting high-energy photons (gamma decay). The study of the strong and weak nuclear forces (the latter explained by Enrico Fermi via Fermi's interaction in 1934) led physicists to collide nuclei and electrons at ever higher energies.

This research became the science of particle physics, the crown jewel of which is the standard model of particle physics, which describes the strong, weak, and electromagnetic forces. A heavy nucleus can contain hundreds of nucleons. This means that with some approximation it can be treated as a classical system, rather than a quantum-mechanical one.

In the resulting liquid-drop model, the nucleus has an energy that arises partly from surface tension and partly from electrical repulsion of the protons.

The liquid-drop model is able to reproduce many features of nuclei, including the general trend of binding energy with respect to mass number, as well as the phenomenon of nuclear fission. Superimposed on this classical picture, however, are quantum-mechanical effects, which can be described using the nuclear shell model, built largely through the work of Mayer and of Jensen.

Nuclei with certain "magic" numbers of neutrons and protons are particularly stable, because their shells are filled.

Other more complicated models for the nucleus have also been proposed, such as the interacting boson model, in which pairs of neutrons and protons interact as bosons. Ab initio methods try to solve the nuclear many-body problem from the ground up, starting from the nucleons and their interactions. Much of current research in nuclear

physics relates to the study of nuclei under extreme conditions such as high spin and excitation energy.

Nuclei may also have extreme shapes (similar to that of Rugby balls or even pears) or extreme neutron-to-proton ratios. Experimenters can create such nuclei using artificially induced fusion or nucleon transfer reactions, employing ion beams from an accelerator.

Chapter 5: Half-Life

Radioactive atoms decay at a steady rate. The half-life is the interval in which half of a radioactive sample decays away.

Half-lives stretch from under a second to many billions of years.

Uranium-238 has a half-life of 4.5 billion years, about the age of the Earth. Carbon-14 has a half-life of 5,730 years, which makes it useful for dating ancient artifacts. The concept of half-life allows scientists to measure the age of rocks, fossils, and the Earth itself. The concept of half-life was introduced by Ernest Rutherford in 1904, and it remains among nuclear physics's most consequential ideas.

The half-life of a radioactive isotope is a measure of its stability — a long half-life means the isotope is nearly stable and decays slowly, while a short half-life means the isotope is highly unstable and decays rapidly. The half-life is a statistical measure — it does not predict when any individual atom will decay, but it describes the behavior of a large sample.

If you have 1 million atoms of an isotope with a half-life of 1 year, after 1 year approximately 500,000 will have decayed, after 2 years approximately 250,000 will have decayed, and so on. The decay follows an exponential curve, and the number of remaining atoms approaches zero but never reaches it. The range of half-lives in nature is enormous.

The longest known half-life is that of tellurium-128, which is approximately 2.2×10^{24} years — more than 100 trillion times the age of the universe. Such an isotope is effectively stable. The shortest known half-lives are those of certain isotopes that exist for only fractions of a second before decaying. Between these extremes, there are isotopes with half-lives of seconds, minutes, days, years, centuries, and millennia.

The practical applications of half-life are diverse and important.

Radiocarbon dating, developed by Willard Libby in the 1940s, uses the half-life of carbon-14 (5,730 years) to determine the age of organic materials. Carbon-14 is produced in the atmosphere by cosmic rays and is incorporated into living organisms through photosynthesis and the food chain. When an organism dies, it stops taking in carbon-14, and the carbon-14 that is already present decays at its characteristic rate.

By measuring the ratio of carbon-14 to carbon-12 in a sample, scientists can determine how long ago the organism died.

ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.