SAMPLE

Nuclear Physics

Radioactivity, Fission, and Fusion

Aira Astralis

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Introduction

This book provides a comprehensive exploration of chapter 01: what is nuclear physics?, covering its fundamental concepts, historical development, key discoveries, and significance in our understanding of the universe. The chapters that follow build progressively, introducing core ideas before advancing to more complex topics.

Nuclear physics is the field of physics that studies atomic nuclei and their constituents and interactions, in addition to the study of other forms of nuclear matter. Nuclear physics should not be confused with atomic physics, which studies the atom as a whole, including its electrons.

Discoveries in nuclear physics have led to applications in many fields such as nuclear power, nuclear weapons, nuclear medicine and magnetic resonance imaging, industrial and agricultural isotopes, ion implantation in materials engineering, and radiocarbon dating in geology and archaeology.

Such applications are studied in the field of nuclear engineering. Particle physics evolved out of nuclear physics and the two fields are typically taught in close association. Nuclear astrophysics, the application of nuclear physics to astrophysics, is crucial in explaining the inner workings of stars and the origin of the chemical elements.

The history of nuclear physics as a discipline distinct from atomic physics, starts with the discovery of radioactivity by Henri Becquerel in 1896, made while investigating phosphorescence in uranium salts.

The discovery of the electron by J. J. Thomson a year later was an indication that the atom had internal structure. At the beginning of the 20th century the accepted model of the atom was J. J. Thomson's "plum pudding" model in which the atom was a positively charged ball with smaller negatively charged electrons embedded inside it.

In the years that followed, radioactivity was extensively investigated, notably by Marie Curie, a Polish physicist whose maiden name was Sklodowska, Pierre Curie, Ernest Rutherford and others.

By the turn of the century, physicists had also discovered three types of radiation emanating from atoms, which they named alpha, beta, and gamma radiation. Experiments by Otto Hahn in 1911 and by James Chadwick in 1914 discovered that the beta decay spectrum was continuous rather than discrete.

That is, electrons were ejected from the atom with a continuous range of energies, rather than the discrete amounts of energy that were observed in

gamma and alpha decays.

This was a problem for nuclear physics at the time, because it seemed to indicate that energy was not conserved in these decays. The 1903 physics Nobel honored Becquerel for the discovery itself and Marie and Pierre Curie for the research that followed it.

Rutherford was awarded the Nobel Prize in Chemistry in 1908 for his "investigations into the disintegration of the elements and the chemistry of radioactive substances". In 1905, Albert Einstein formulated the idea of mass-energy equivalence.

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.

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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.