INVESTIGATORY PROJECT REPORT

NUCLEUS

NAME

CLASS XII

RUTHERFORD'S TEAM DISCOVERS THE NUCLEUS

In 1906 Ernest Rutherford published "Retardation of the α 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 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.

The key experiment behind this announcement was performed in 1910 at the University of Manchester. Ernest Rutherford's team performed a remarkable experiment in which Geiger and Ernest Marsden under Rutherford's supervision fired alpha particles (helium 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. 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.

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 ½. 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 ½. Rasetti discovered, however, that nitrogen-14 had a spin of 1.

JAMES CHADWICK DISCOVERS THE NEUTRON

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). In the same year Dmitri Ivanenko suggested that there were no electrons in the nucleus — only protons and neutrons — and that neutrons were spin ½ 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 ½ 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.

YUKAWA'S MESON POSTULATED TO BIND NUCLEI

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). 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.

PROCA'S EQUATION OF MASSIVE VECTOR BOSON

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.

MODERN NUCLEAR PHYSICS

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-dropmodel, the nucleus has an energy which 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, developed in large part by Maria Goeppert Mayer and J. Hans D. Jensen. Nuclei with certain numbers of neutrons and protons (the magic numbers 2, 8, 20, 28, 50, 82, 126, ...) 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, analogously to Cooper pairs of electrons.

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. Beams with even higher energies can be used to create nuclei at very high temperatures, and there are signs that these experiments have produced a phase transition from normal nuclear matter to a new state, the quark–gluon plasma, in which the quarks mingle with one another.

NUCLEAR DECAY

Nuclear decay, is the process by which the nucleus of an unstable atom loses energy by emitting radiation, including alpha particles, beta particles, gamma rays and conversion electrons.

Nuclear decay is a random process at the level of single atoms, in that, according to quantum theory, it is impossible to predict when a particular atom will decay. The chance that a given atom will decay never changes, that is, it does not matter how long the atom has existed. The decay rate for a large collection of atoms, however, can be calculated from their measured decay constants or half-lives. This is the basis of radiometric dating. The half-lives of radioactive atoms have no known lower or upper limit of duration.

The first decay processes to be discovered were alpha decay, beta decay, and gamma decay. Alpha decay occurs when the nucleus ejects an alpha particle (helium nucleus). This is the most common process of emitting nucleons, but in rarer types of decays, nuclei can eject protons, or in the case of cluster decay specific nuclei of other elements. Beta decay occurs when the nucleus emits an electron or positron and a neutrino, in a process that changes a proton to a neutron or the other way about. The nucleus may capture an orbiting electron, causing a proton to convert into a neutron in a process called electron capture.

By contrast, there are radioactive decay processes that do not result in a nuclear transmutation. The energy of an excited nucleus may be emitted as a gamma ray in a process called gamma decay, or be used to eject an orbital electron by its interaction with the excited nucleus, in a process called internal conversion.

Another type of radioactive decay results in products that are not defined, but appear in a range of "pieces" of the original nucleus. This decay, called spontaneous fission, happens when a large unstable nucleus spontaneously splits into two (and occasionally three) smaller daughter nuclei, and generally leads to the emission of gamma rays, neutrons, or other particles from those products.

NUCLEAR FUSION

In nuclear physics, nuclear fusion is a nuclear reaction in which two or more atomic nuclei come close enough to react and form one or more different atomic nuclei and subatomic particles. During this process, matter is not conserved because some of the matter of the fusing nuclei is converted to photons. Fusion is the process that powers active or main sequence stars.

The fusion of two nuclei with lower masses than iron-56 generally releases energy, while the fusion of nuclei heavier than iron requires energy input. The opposite is true for the reverse process, nuclear fission. This means that only lighter elements are fusable, such as hydrogen and helium, and likewise, that only heavier elements are fissionable, such as uranium and plutonium. There are, however, extreme astrophysical events that can lead to short periods of fusion with heavier nuclei. This is the process that gives rise to the creation of the heavy elements during events such as a supernova.

Following the discovery of quantum tunneling by physicist Friedrich Hund, in 1929 Robert Atkinson and Fritz Houtermans used the measured masses of light elements to predict that large amounts of energy could be released by fusing small nuclei. Building upon the nuclear transmutation experiments by Ernest Rutherford, carried out several years earlier, the laboratory fusion of hydrogen isotopes was first accomplished by Mark Oliphant in 1932. During the remainder of that decade the steps of the main cycle of nuclear fusion in stars were worked out by Hans Bethe. Research into fusion for military purposes began in the early 1940s as part of the Manhattan Project. Fusion was accomplished in 1951 with the Greenhouse Item nuclear test. Nuclear fusion on a large scale in an explosion was first carried out on November 1, 1952, in the Ivy Mike hydrogen bomb test.

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NUCLEAR FISSION

In nuclear physics and nuclear chemistry, nuclear fission is either a nuclear reaction or a radioactive decay process in which the nucleus of an atom splits into smaller parts. The fission process often produces free neutrons and gamma photons, and releases a very large amount of energy even by the energetic standards of radioactive decay.

Nuclear fission of heavy elements was discovered on December 17, 1938 by German Otto Hahn and his assistant Fritz Strassmann, and explained theoretically in January 1939 by Lise Meitner and her nephew Otto Robert Frisch. Frisch named the process by analogy with biological fission of living cells. It is an exothermic reaction which can release large amounts of energy both as electromagnetic radiation and as kinetic energy of the fragments. In order for fission to produce energy, the total binding energy of the resulting elements must be less negative (higher energy) than that of the starting element.

Fission is a form of nuclear transmutation because the resulting fragments are not the same element as the original atom. The two nuclei produced are most often of comparable but slightly different sizes, typically with a mass ratio of products of about 3 to 2, for common fissile isotopes. Most fissions are binary fissions (producing two charged fragments), but occasionally three positively charged fragments are produced, in a ternary fission. The smallest of these fragments in ternary processes ranges in size from a proton to an argon nucleus.

The unpredictable composition of the products (which vary in a broad probabilistic and somewhat chaotic manner) distinguishes fission from purely quantum-tunneling processes such as proton emission, alpha decay, and cluster decay, which give the same products each time. Nuclear fission produces energy for nuclear power and drives the explosion of nuclear weapons. Both uses are possible because certain substances called nuclear fuels undergo fission when struck by fission neutrons, and in turn emit neutrons when they break apart.