**Neutron**

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*This article is about the subatomic particle. For other uses, see Neutron (disambiguation).*

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| ***Neutron*** |
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| The quark structure of the neutron. |
| **Classification:** | Baryon |
| **Composition:** | 1 up quark, 2 down quarks |
| **Statistical behavior:** | Fermion |
| **Group:** | Hadron |
| **Interaction:** | Gravity, Weak, Strong |
| **Symbol(s):** | n, n0, N0 |
| **Antiparticle:** | Antineutron |
| **Theorized:** | Ernest Rutherford (1920) |
| **Discovered:** | James Chadwick[1] (1932) |
| **Mass:** | 1.67492729(28)×10−27 kg939.565560(81) MeV/c21.0086649156(6) u |
| **Mean lifetime:** | 885.7(8) s (free) |
| **Electric charge:** | 0 e0 C |
| **Electric dipole moment:** | <2.9×10−26 e cm |
| **Electric polarizability:** | 1.16(15)×10−3 fm3 |
| **Magnetic moment:** | −1.9130427(5) μN |
| **Magnetic polarizability:** | 3.7(20)×10−4 fm3 |
| **Spin:** | 1⁄2 |
| **Isospin:** | 1⁄2 |
| **Parity:** | +1 |
| **Condensed:** | *I*(*JP*) = 1⁄2(1⁄2+) |

The **neutron** is a subatomic particle with no net electric charge and a mass slightly larger than that of a proton.

Neutrons are usually found in atomic nuclei. The nuclei of most atoms consist of protons and neutrons, which are therefore collectively referred to as nucleons. The number of protons in a nucleus is the atomic number and defines the type of element the atom forms. The number of neutrons is the neutron number and determines the isotope of an element. For example, the carbon-12 isotope has 6 protons and 6 neutrons, while the carbon-14 isotope has 6 protons and 8 neutrons.

While bound neutrons in stable nuclei are stable, free neutrons are unstable; they undergo beta decay with a mean lifetime of just under 15 minutes (885.7 ± 0.8 s). Free neutrons are produced in nuclear fission and fusion. Dedicated neutron sources like research reactors and spallation sources produce free neutrons for use in irradiation and in neutron scattering experiments.

Even though it is not a chemical element, the free neutron is sometimes included in tables of nuclides. It is then considered to have an atomic number of zero and a mass number of one.

**[edit] Discovery**

In 1931 Walther Bothe and Herbert Becker in Germany found that if the very energetic alpha particles emitted from polonium fell on certain light elements, specifically beryllium, boron, or lithium, an unusually penetrating radiation was produced. At first this radiation was thought to be gamma radiation, although it was more penetrating than any gamma rays known, and the details of experimental results were very difficult to interpret on this basis. The next important contribution was reported in 1932 by Irène Joliot-Curie and Frédéric Joliot in Paris. They showed that if this unknown radiation fell on paraffin or any other hydrogen-containing compound it ejected protons of very high energy. This was not in itself inconsistent with the assumed gamma ray nature of the new radiation, but detailed quantitative analysis of the data became increasingly difficult to reconcile with such a hypothesis.

In 1932 physicist James Chadwick at the University of Liverpool performed a series of experiments showing that the gamma ray hypothesis was untenable. He suggested that the new radiation consisted of uncharged particles of approximately the mass of the proton, and he performed a series of experiments verifying his suggestion. These uncharged particles were called *neutrons*, apparently from the Latin root for *neutral* and the Greek ending *-on* (by imitation of *electron* and *proton*).

The discovery of the neutron explained a puzzle involving the spin of the nitrogen-14 nucleus, which had been experimentally measured to be 1 basic unit of angular momentum. It was known that atomic nuclei usually had about half as many positive charges as if they were composed completely of protons, and in existing models this was often explained by proposing that nuclei also contained some "nuclear electrons" to neutralize the excess charge. Thus, nitrogen-14 would be composed of 14 protons and 7 electrons to give it a charge of +7 but a mass of 14 atomic mass units. However, it was also known that both protons and electrons carried an intrinsic spin of 1/2 unit of angular momentum, and there was no way to arrange 21 particles in one group, or in groups of 7 and 14, to give a spin of 1. All possible pairings gave a net spin of 1/2. However, when nitrogen-14 was proposed to consist of 3 pairs of protons and neutrons, with an additional unpaired neutron and proton each contributing a spin of 1/2 in the same direction for a total spin of 1, the model became viable. Soon, nuclear neutrons were used to naturally explain spin differences in many different nuclides in the same way, and the neutron as a basic structural unit of atomic nuclei was accepted.

**Intrinsic properties**

**Stability and beta decay**



The Feynman diagram of the neutron beta decay process

Because the neutron consists of three quarks, the only possible decay mode without a change of baryon number requires the flavor changing of one of the quarks via the weak nuclear force. The neutron consists of two down quarks with charge −1/3 and one up quark with charge +2/3, and the decay of one of the down quarks into a lighter up quark can be achieved by the emission of a W boson. By this means the neutron decays into a proton (which contains one down and two up quarks), an electron, and an electron antineutrino (antineutrino).

Outside the nucleus, free neutrons are unstable and have a mean lifetime of 885.7±0.8 s (about 14 minutes, 46 seconds); the half-life for this process is 613.9±0.8 s (about 10 minutes, 14 seconds). Free neutrons decay by emission of an electron and an antineutrino to become a proton:

n0 → p+ + e− + νe

This decay mode, known as beta decay, can also transform the character of neutrons within unstable nuclei.

Bound inside a nucleus, protons can also transform via inverse beta decay into neutrons. In this case, the transformation occurs by emission of a positron (antielectron) and a neutrino (instead of an antineutrino):

p+ → n0 + e+ + νe

The transformation of a proton to a neutron inside of a nucleus is also possible through electron capture:

p+ + e− → n0 + νe

Positron capture by neutrons in nuclei that contain an excess of neutrons is also possible, but is hindered because positrons are repelled by the nucleus, and quickly annihilate when they encounter electrons.

When bound inside of a nucleus, the instability of a single neutron to beta decay is balanced against the instability that would be acquired by the nucleus as a whole if an additional proton were to participate in repulsive interactions with the other protons that are already present in the nucleus. As such, although free neutrons are unstable, bound neutrons are not necessarily so. The same reasoning explains why protons, which are stable in empty space, may transform into neutrons when bound inside of a nucleus.

Beta decay and electron capture are types of radioactive decay and are both governed by the weak interaction.

**Electric dipole moment**

Main article: Neutron electric dipole moment

The Standard Model of particle physics predicts a tiny separation of positive and negative charge within the neutron leading to a permanent electric dipole moment. The predicted value is, however, well below the current sensitivity of experiments. From several unsolved puzzles in particle physics, it is clear that the Standard Model is not the final and full description of all particles and their interactions. New theories going beyond the Standard Model generally lead to much larger predictions for the electric dipole moment of the neutron. Currently, there are at least four experiments trying to measure for the first time a finite neutron electric dipole moment.

**Anti-neutron**

Main article: anti-neutron

The antineutron is the antiparticle of the neutron. It was discovered by Bruce Cork in the year 1956, a year after the antiproton was discovered. CPT-symmetry puts strong constraints on the relative properties of particles and antiparticles and, therefore, is open to stringent tests. The fractional difference in the masses of the neutron and antineutron is 9±5×10−5. Since the difference is only about 2 standard deviations away from zero, this does not give any convincing evidence of CPT-violation.

**Geometry**

An article published in 2007 featuring a model-independent analysis concluded that the neutron has a negatively charged exterior, a positively charged middle, and a negative core. The negatively charged exterior of the neutron gives an intuitive explanation for why more neutrons are required in atoms with large numbers of protons, as the neutrons' negatively charged surfaces attract the positively charged protons to stay clumped together in the atom.

**Neutron compounds**

**Dineutrons and tetraneutrons**

Main articles: Dineutron and Tetraneutron

The existence of stable clusters of four neutrons, or tetraneutrons, has been hypothesized by a team led by Francisco-Miguel Marqués at the CNRS Laboratory for Nuclear Physics based on observations of the disintegration of beryllium-14 nuclei. This is particularly interesting because current theory suggests that these clusters should not be stable.

The dineutron is another hypothetical particle.

**Neutronium and neutron stars**

Main articles: Neutronium and Neutron Star

At extremely high pressures and temperatures, nucleons and electrons are believed to collapse into bulk neutronic matter, called neutronium. Presumably this is what happens in neutron stars.

**Detection**

Main article: Neutron detection

The common means of detecting a charged particle by looking for a track of ionization (such as in a cloud chamber) does not work for neutrons directly. Neutrons that elastically scatter off atoms can create an ionization track that is detectable, but the experiments are not as simple to carry out; other means for detecting neutrons, consisting of allowing them to interact with atomic nuclei, are more commonly used.

A common method for detecting neutrons involves converting the energy released from such reactions into electrical signals. The nuclides 3He, 6Li, 10B, 233U, 235U, 237Np and 239Pu are useful for this purpose. A good discussion on neutron detection is found in chapter 14 of the book *Radiation Detection and Measurement* by Glenn F. Knoll (John Wiley & Sons, 1979).

**Uses**

The neutron plays an important role in many nuclear reactions. For example, neutron capture often results in neutron activation, inducing radioactivity. In particular, knowledge of neutrons and their behavior has been important in the development of nuclear reactors and nuclear weapons. The fissioning of elements like uranium-235 and plutonium-239 is caused by their absorption of neutrons.

*Cold*, *thermal* and *hot* neutron radiation is commonly employed in neutron scattering facilities, where the radiation is used in a similar way one uses X-rays for the analysis of condensed matter. Neutrons are complementary to the latter in terms of atomic contrasts by different scattering cross sections; sensitivity to magnetism; energy range for inelastic neutron spectroscopy; and deep penetration into matter.

The development of "neutron lenses" based on total internal reflection within hollow glass capillary tubes or by reflection from dimpled aluminum plates has driven ongoing research into neutron microscopy and neutron/gamma ray tomography.

A major use of neutrons is to excite delayed and prompt gamma rays from elements in materials. This forms the basis of neutron activation analysis (NAA) and prompt gamma neutron activation analysis (PGNAA). NAA is most often used to analyze small samples of materials in a nuclear reactor whilst PGNAA is most often used to analyze subterranean rocks around bore holes and industrial bulk materials on conveyor belts.

Another use of neutron emitters is the detection of light nuclei, particularly the hydrogen found in water molecules. When a fast neutron collides with a light nucleus, it loses a large fraction of its energy. By measuring the rate at which slow neutrons return to the probe after reflecting off of hydrogen nuclei, a neutron probe may determine the water content in soil.

**Sources**

Because free neutrons are unstable, they can be obtained only from nuclear disintegrations, nuclear reactions, and high-energy reactions (such as in cosmic radiation showers or accelerator collisions). Free neutron beams are obtained from neutron sources by neutron transport. For access to intense neutron sources, researchers must go to specialist facilities, such as the ISIS facility in the United Kingdom, which is currently the world's most intense pulsed neutron and muon source.

Neutrons' lack of total electric charge prevents engineers or experimentalists from being able to steer or accelerate them. Charged particles can be accelerated, decelerated, or deflected by electric or magnetic fields. However, these methods have no effect on neutrons except for a small effect of an inhomogeneous magnetic field because of the neutron's magnetic moment.

**Protection**

Exposure to free neutrons can be hazardous, since the interaction of neutrons with molecules in the body can cause disruption to molecules and atoms, and can also cause reactions which give rise to other forms of radiation (such as protons). The normal precautions of radiation protection apply: avoid exposure, stay as far from the source as possible, and keep exposure time to a minimum. Some particular thought must be given to how to protect from neutron exposure, however. For other types of radiation, e.g. alpha particles, beta particles, or gamma rays, material of a high atomic number and with high density make for good shielding; frequently lead is used. However, this approach will not work with neutrons, since the absorption of neutrons does not increase straightforwardly with atomic number, as it does with alpha, beta, and gamma radiation. Instead one needs to look at the particular interactions neutrons have with matter (see the section on detection above). For example, hydrogen rich materials are often used to shield against neutrons, since ordinary hydrogen both scatters and slows neutrons. This often means that simple concrete blocks or even paraffin-loaded plastic blocks afford better protection from neutrons than do far more dense materials. After slowing, neutrons may then be absorbed with an isotope which has high affinity for slow neutrons without causing secondary capture-radiation, such as lithium-6.

Hydrogen-rich ordinary water affects neutron absorption in nuclear fission reactors: usually neutrons are so strongly absorbed by normal water that fuel-enrichment with fissionable isotope is required. The deuterium in heavy water has a very much lower absorption affinity for neutrons than does protium (normal light hydrogen). Deuterium is therefore used in CANDU-type reactors, in order to slow (moderate) neutron velocity, to increase the probability of nuclear fission compared to neutron capture.

**Production**

Various nuclides become more stable by expelling neutrons as a decay mode; this is known as neutron emission, and happens commonly during spontaneous fission.

Cosmic radiation interacting the Earth's atmosphere continuously generates neutrons that can be detected at the surface. Even stronger neutron radiation is produced at the surface of Mars where the atmosphere is thick enough to generate neutrons from cosmic ray spallation, but not thick enough to provide significant protection from the neutrons produced. These neutrons not only produce a Martian surface neutron radiation hazard from direct downward-going neutron radiation, but also a significant hazard from reflection of neutrons from the Martian surface, which will produce reflected neutron radiation penetrating upward into a Martian craft or habitat from the floor.

Nuclear fission reactors naturally produce free neutrons; their role is to sustain the energy-producing chain reaction. The intense neutron radiation can also be used to produce various radioisotopes through the process of neutron activation, which is a type of neutron capture.

Experimental nuclear fusion reactors produce free neutrons as a waste product. However, it is these neutrons that possess most of the energy, and converting that energy to a useful form has proved a difficult engineering challenge. Fusion reactors which generate neutrons are likely to create around twice the amount of radioactive waste of a fission reactor, but the waste is composed of neutron-activated lighter isotopes, which have relatively short (50–100 years) decay periods as compared to typical half-lives of 10,000 years for fission waste, which is long primarily due to the long half-life of alpha-emitting transuranic actinides.

**Neutron temperature**

Main article: Neutron temperature

**Thermal neutron**

A thermal neutron is a free neutron that is Boltzmann distributed with kT = 0.024 eV (4.0×10−21 J) at room temperature. This gives characteristic (not average, or median) speed of 2.2 km/s. The name 'thermal' comes from their energy being that of the room temperature gas or material they are permeating. (see *kinetic theory* for energies and speeds of molecules). After a number of collisions (often in the range of 10–20) with nuclei, neutrons arrive at this energy level, provided that they are not absorbed.

In many substances, thermal neutrons have a much larger effective cross-section than faster neutrons, and can therefore be absorbed more easily by any atomic nuclei that they collide with, creating a heavier — and often unstable — isotope of the chemical element as a result.

Most fission reactors use a neutron moderator to slow down, or *thermalize* the neutrons that are emitted by nuclear fission so that they are more easily captured, causing further fission. Others, called fast breeder reactors, use fission energy neutrons directly.

**Cold neutrons**

These neutrons are thermal neutrons that have been equilibrated in a very cold substance such as liquid deuterium. These are produced in neutron scattering research facilities.

**Ultracold neutrons**

Ultracold neutrons are produced by equilibration in substances with a temperature of a few kelvins, such as solid deuterium or superfluid helium. An alternative production method is the mechanical deceleration of cold neutrons.

**Fission energy neutron**

A fast neutron is a free neutron with a kinetic energy level close to 2 MeV (20 TJ/kg), hence a speed of 28,000 km/s. They are named *fission energy* or *fast* neutrons to distinguish them from lower-energy thermal neutrons, and high-energy neutrons produced in cosmic showers or accelerators. Fast neutrons are produced by nuclear processes such as nuclear fission.

Fast neutrons can be made into thermal neutrons via a process called moderation. This is done with a neutron moderator. In reactors, typically heavy water, light water, or graphite are used to moderate neutrons.

**Fusion neutron**



The fusion reaction rate increases rapidly with temperature until it maximizes and then gradually drops off. The DT rate peaks at a lower temperature (about 70 keV, or 800 million kelvins) and at a higher value than other reactions commonly considered for fusion energy.

For more details on this topic, see Nuclear fusion#Criteria and candidates for terrestrial reactions.

D-T (deuterium-tritium) fusion is the fusion reaction that produces the most energetic neutrons, with 14.1 MeV of kinetic energy and traveling at 17% of the speed of light. D-T fusion is also the easiest fusion reaction to ignite, reaching near-peak rates even when the deuterium and tritium nuclei have only a thousandth as much kinetic energy as the 14.1 MeV that will be produced.

14.1 Mev neutrons have about 10 times as much energy as fission neutrons, and are very effective at fissioning even non-fissile heavy nuclei, and these high-energy fissions produce more neutrons on average than fissions by lower-energy neutrons. 14.1 MeV neutrons can also produce neutrons by knocking them loose from nuclei. On the other hand, these very high energy neutrons are less likely to simply be captured without causing fission or spallation. For these reasons, nuclear weapon design extensively utilizes D-T fusion 14.1 MeV neutrons to cause more fission.

Other fusion reactions produce much less energetic neutrons. D-D fusion produces a 2.45 MeV neutron and helium-3 half of the time, and produces tritium and a proton but no neutron the other half of the time. D-3He fusion produces no neutron.

**Intermediate-energy neutrons**



Transmutation flow in LWR which is a thermal-spectrum reactor

A fission energy neutron that has slowed down but not yet reached thermal energies is called an epithermal neutron.

Cross sections for both capture and fission reactions often have multiple resonance peaks at specific energies in the epithermal energy range. These are of less significance in a fast neutron reactor where most neutrons are absorbed before slowing down to this range, or in a well-moderated thermal reactor where epithermal neutrons mostly interact with moderator nuclei, not with either fissile or fertile actinide nuclides. However, in a partially moderated reactor with more interactions of epithermal neutrons with heavy metal nuclei, there are greater possibilities for transient changes in reactivity which might make reactor control more difficult.

Ratios of capture reactions to fission reactions are also worse (more captures without fission) in most nuclear fuels such as plutonium-239, making epithermal-spectrum reactors using these fuels less desirable, as captures not only waste the one neutron captured but also usually result in a nuclide which is not fissile with thermal or epithermal neutrons, though still fissionable with fast neutrons. The exception is uranium-233 of the thorium cycle which has good capture-fission ratios at all neutron energies.

**High-energy neutrons**

These neutrons have more energy than fission energy neutrons and are generated in accelerators or in the atmosphere from cosmic particles. They can have energies as high as tens of joules per neutron.