

Nuclear Science

Nuclear Science is the study of the structure, properties, and interactions of the atomic nuclei. Nuclear scientists calculate and measure the masses, shapes, sizes, and decays of nuclei at rest and in collisions. They ask questions, such as: Why do nucleons stay in the nucleus? What combinations of protons and neutrons are possible? What happens when nuclei are compressed or rapidly rotated? What is the origin of the nuclei found on Earth?

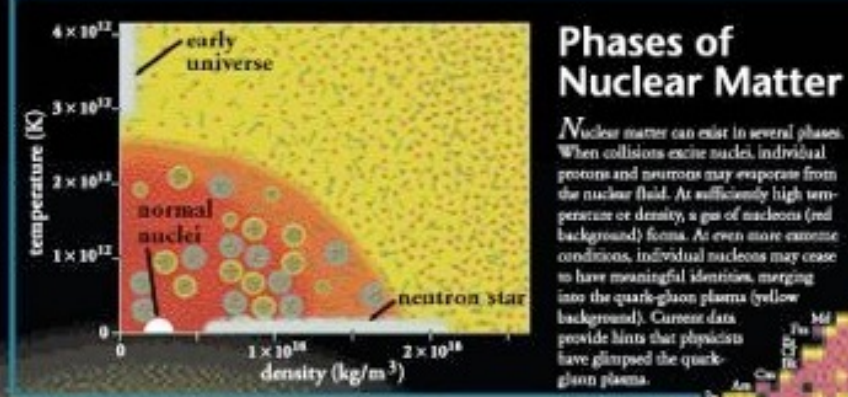
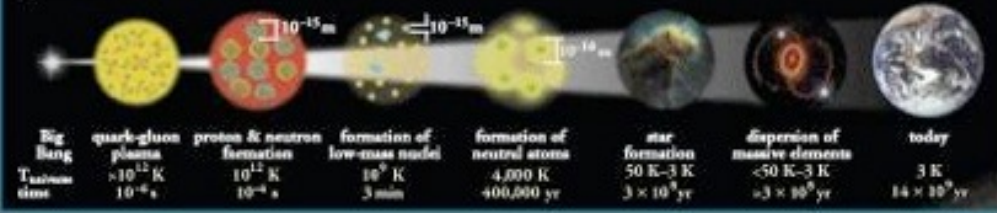
Legend

- electron (e^-)
- quark
- gluon field
- photon
- positron (e^+)
- gluon
- neutrino (ν)
- antineutrino ($\bar{\nu}$)
- photon (γ)

Atomic Number Z
Mass Number A
Neutron Number $N = A - Z$

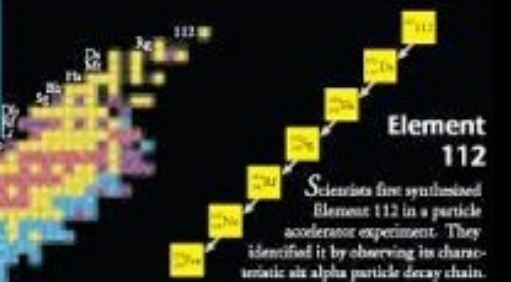
Expansion of the Universe

After the Big Bang, the universe expanded and cooled. At about 10^{-4} second, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. When the temperature of the Universe, $T_{universe}$, cooled to about 10^{12} K, this soup coalesced into protons, neutrons, and electrons. As time progressed, some of the protons and neutrons formed deuterium, helium, and lithium nuclei. Still later, electrons combined with protons and these low-mass nuclei to form neutral atoms. Due to gravity, clouds of atoms contracted into stars, where hydrogen and helium fused into more massive chemical elements. Exploding stars (supernovas) form the most massive elements and disperse them into space. Our earth was formed from supernova debris.



Unstable Nuclei

Stable nuclides form a narrow white band on the Chart of the Nuclides. Scientists produce unstable nuclides far from this band and study their decays, thereby learning about the extremes of nuclear conditions. In its present form, this chart contains about 2500 different nuclides. Nuclear theory predicts that there are at least 4000 more to be discovered with $Z \leq 112$.



Radioactivity

Alpha Decay
 $^{238}_{92}\text{U} \rightarrow ^{234}_{90}\text{Th} + ^4_2\text{He}$

Beta Minus Decay
 $^{14}_6\text{C} \rightarrow ^{14}_7\text{N} + e^- + \bar{\nu}_e$

Beta Plus Decay
 $^{18}_9\text{F} \rightarrow ^{18}_8\text{O} + e^+ + \nu_e$

Gamma Decay
 $^{152}_{64}\text{Dy}^* \rightarrow ^{152}_{64}\text{Dy} + \gamma$

Radioactive decay transforms a nucleus by emitting different particles. In alpha decay, the nucleus releases a ^4_2He nucleus—an alpha particle. In beta decay, the nucleus either emits an electron and antineutrino (or a positron and neutrino) or captures an atomic electron and emits a neutrino. A positron is the name for the antiparticle of the electron. Antimatter is composed of antiparticles. Both alpha and beta decays change the original nucleus into a nucleus of a different chemical element. In gamma decay, the nucleus lowers its internal energy by emitting a photon—a gamma ray. This decay does not modify the chemical properties of the atom.

The Nucleus

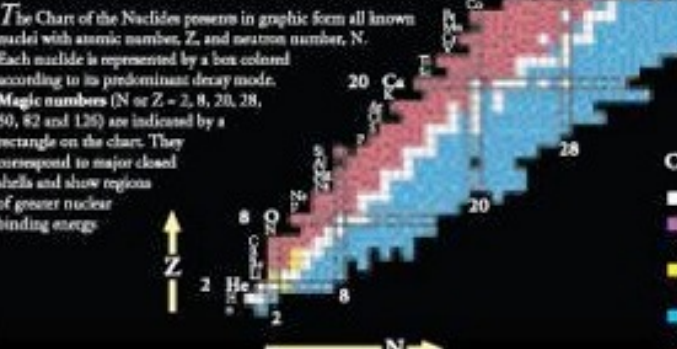
$(1-10) \times 10^{-15}$ m

neutron 10^{-16} m
proton 10^{-16} m
quark $<10^{-17}$ m
strong field
electromagnetic field

At the center of the nucleus are two kinds of nucleons: protons and neutrons. Each nucleon is made from three quarks held together by their strong interactions, which are mediated by gluons. In turn, the nucleus is held together by the strong interactions between the protons and quarks constituting its constituent nucleons. Nuclear physicists often use the radiation of various particles which consist of a quark and an antiquark, such as the pion, to describe interactions among the nucleons.

In an atom, electrons surround the nucleus at distances typically up to 10^{-10} times the nuclear diameter. If the electron cloud were drawn to scale, this distance would cover a football field.

Chart of the Nuclides



Color Key

- Stable
- Spontaneous fission
- Alpha particle emission
- Beta minus emission
- Beta plus emission or electron capture

Nuclear Energy

Fission
 $^{235}_{92}\text{U} + ^1_0\text{n} \rightarrow ^{141}_{54}\text{Xe} + ^{92}_{38}\text{Sr} + 3^1_0\text{n}$

Fusion
 $^2_1\text{H} + ^3_1\text{H} \rightarrow ^4_2\text{He} + ^1_0\text{n}$

126 Nuclear reactions release energy when the total mass of the products is less than the sum of the masses of the initial nuclei. The "lost mass" appears as kinetic energy of the products ($E = mc^2$). In fission, a massive nucleus splits into two major fragments that usually eject one or more neutrons. In fusion, low mass nuclei combine to form a more massive nucleus plus one or more ejected particles—neutrons, protons, photons, or alpha particles.

In the early stages of stellar evolution of our sun and other stars, hydrogen fuses to form helium, releasing energy in the form of photons (light) and neutrinos. During the later stages of stellar evolution, more massive nuclei up to and beyond uranium are synthesized by fusion. By measuring the number of neutrinos that come from the Sun, scientists recently have demonstrated that neutrinos must have a mass greater than zero.

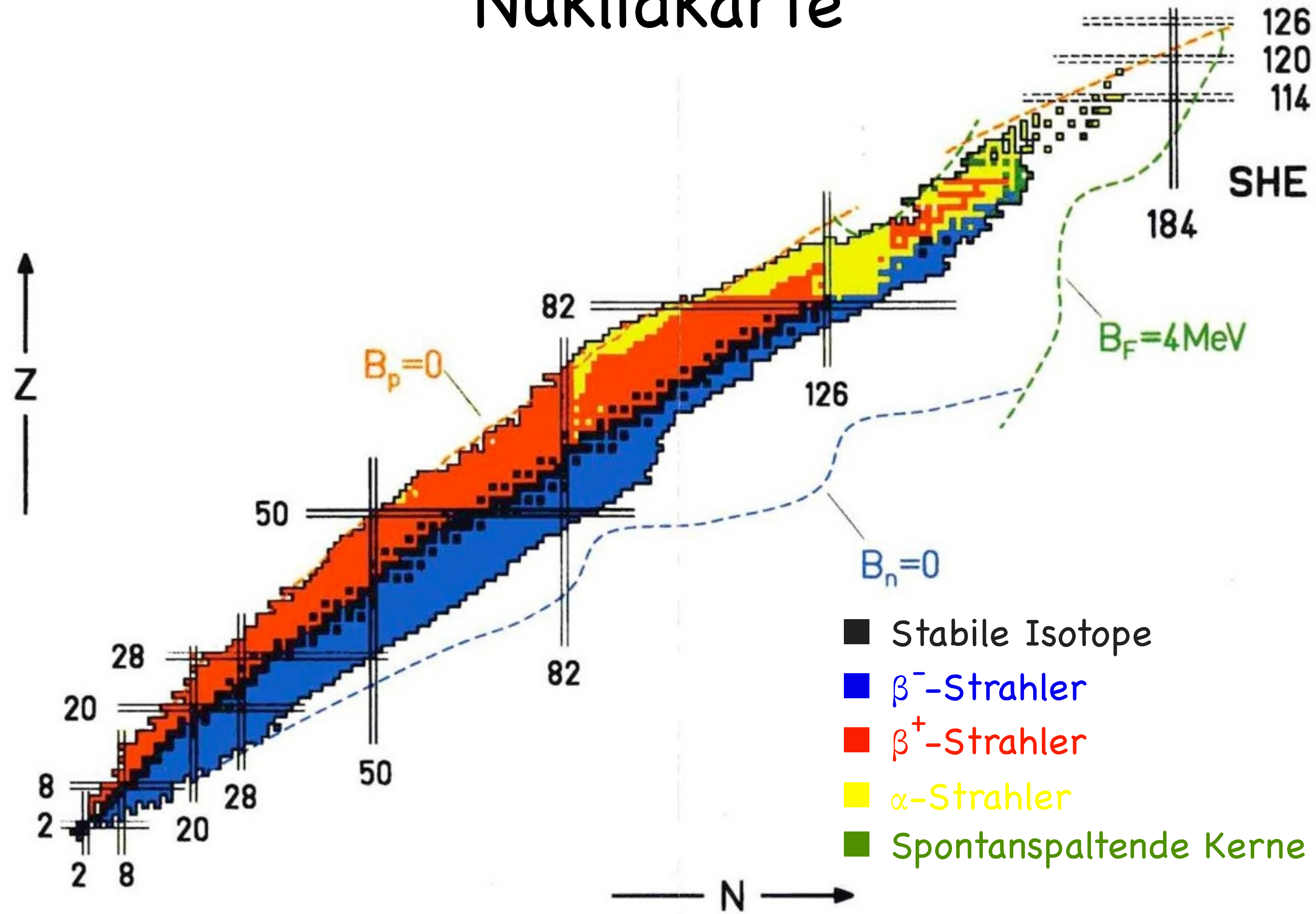
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Applications

- Radioactive Dating**
Naturally occurring radioactive isotopes such as ^{14}C are used to date objects that were once living, such as wood. For example, from a study of artifacts found at the site, scientists determined that Stonehenge was built nearly 4,000 years ago.
- Smoke Detectors**
Many smoke detectors use a small amount of the alpha emitter ^{241}Am to ionize the air. Smoke entering the detector reduces the current and sets off the alarm.
- Nuclear Medicine**
Radioactive isotopes, such as ^{59}Fe , ^{57}Co , and ^{67}Ga , are commonly used in the diagnosis and treatment of disease. Positron emitters such as ^{18}F are used in Positron Emission Tomography (PET) to generate images of brain activity.
- Space Exploration**
Satellites use alpha particles to identify chemical elements present in Martian rocks. On Earth, nuclear reactions are used in many areas from criminal investigations to arc authentication.
- Nuclear Reactors**
Nuclear reactors use the fission of ^{235}U or ^{239}Pu nuclei to produce electric power. Reactors and many other nuclear applications generate radioactive waste; disposal of this waste is a subject of current research.
- Magnetic Resonance Imaging**
Magnetic Resonance Imaging (MRI) makes use of atomic transitions involving the magnetic field of a nucleus to study the local chemical environment. This technique accurately maps the density of hydrogen to produce three-dimensional images of the human body.

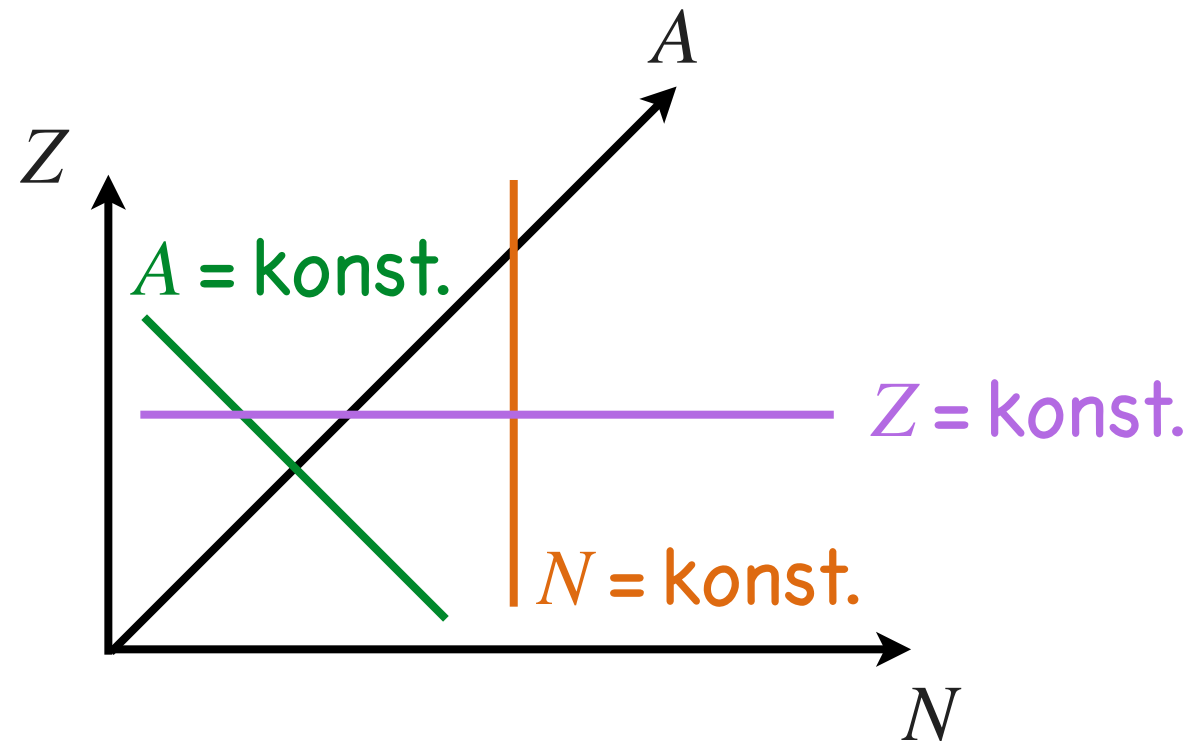
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Nuklidkarte



Nuklidkarte

Nuklidkarte = Verzeichnis aller bekannten Kerne („Nuklide“)
(vgl. Periodensystem in Atomphysik)



Nuklide mit $A = \text{konst.}$: **Isobare**

Nuklide mit $Z = \text{konst.}$: **Isotope**

Nuklide mit $N = \text{konst.}$: **Isotone**

Nuklide mit $(A, Z) = \text{konst.}$: **Isomere**
(Grundzustand & angeregte Zustände)

Z ... Kernladung = Anzahl von Protonen im Kern

N ... Anzahl von Neutronen im Kern