

# Nuclear Science

## 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  $10^9$  K, this soup condensed 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, these atoms contracted into stars, where hydrogen and helium fused into more massive chemical elements. Exploding stars (supernovae) form the most massive elements and disperse them throughout the universe. The elements from supernovae debris.



Nuclear Science is the study of the structure, properties, and interactions of the atomic nucleus. Nuclear scientists explore and measure the masses, shapes, sizes, and decays of nuclei at rest and in collisions. They ask questions about: Why do nuclei exist in the nucleus? What combinations of protons and neutrons are possible? What happens when nuclei are compressed to rapidly rotate? What is the origin of the nuclei found on Earth?

Legend: electron (e<sup>-</sup>), proton (p), neutron (n), quark (q), gluon (g), photon (γ), neutrino (ν), antineutrino (ν̄), alpha particle (α), beta particle (β), gamma ray (γ), X-ray (X), ultraviolet (UV), visible light (vis), infrared (IR), radio (radio), microwave (microw), cosmic ray (CR), dark matter (DM), dark energy (DE).

## Phases of Nuclear Matter



## Unstable Nuclei

Stable nuclei form a narrow white band on the Chart of the Nuclides. Scientists produce unstable nuclei 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  $Z \leq 112$ .

Scientists first synthesized Element 112 in a particle-accelerator experiment. They identified it by observing its characteristic six alpha particle decay chains.

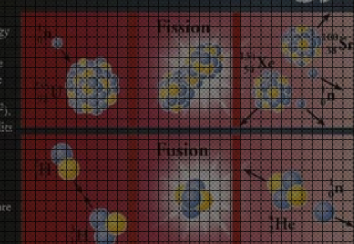
## Radioactivity



Radioactive decay transforms a nucleus by emitting different particles. In alpha decay, the nucleus releases a  $^4\text{He}$  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 positron. A positron is the name for the antiparticle of the electron. Antimatter is composed of anti-particles. 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.

Michael Cherney  
Creighton University

## Nuclear Energy



In the early stages of stellar evolution, low mass and cool 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 fuse 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.

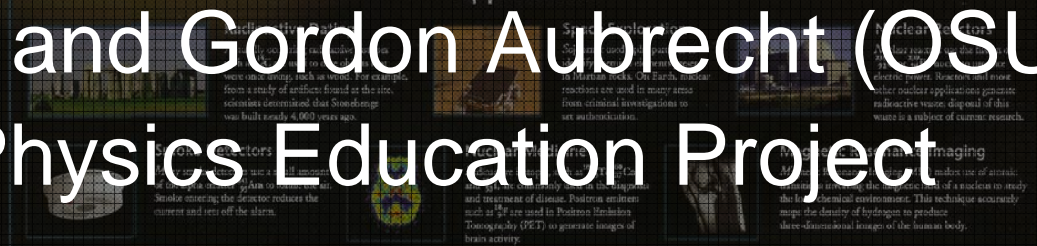
## Chart of the Nuclides

The Chart of the Nuclides presents in graphic form all known nuclei with atomic number,  $Z$ , and neutron number,  $N$ . Each nuclide is represented by a box colored according to its predominant decay mode.

Magic numbers ( $N$  or  $Z = 2, 8, 20, 28, 50, 82$  and  $126$ ) are indicated by a



## Applications



Howard Matis (LBL) and Gordon Aubrecht (OSU)  
Contemporary Physics Education Project

www.CPEPweb.org



# Nuclear Science

## Nuclear Science in High School

- At Creighton we have done multiple 5 hr mini-courses in nuclear science with high school students, gifted junior high students and boy scouts
- High school students (and gifted junior high students) outperform university astronomy students in nuclear physics problem solving

Calculus-based physics students do better  
Boy scouts were not assessed

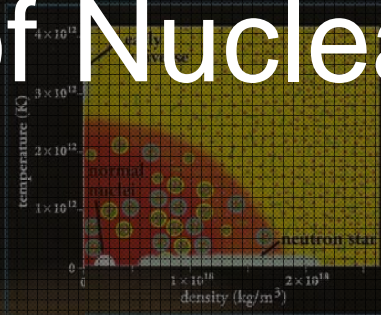
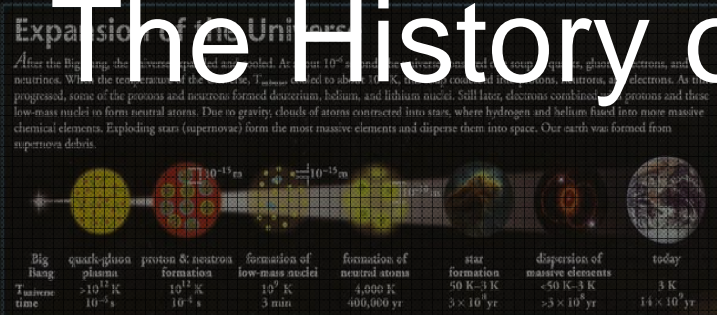
Cherney, I. D., Winter, J., & Cherney, M. G. (2005). Nuclear physics problem solving: A case study of expert-novice differences. *Transactions of the Nebraska Academy of Sciences*, 30, 9-15.



# The History of Nuclear Science

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**Nuclear Science** is the study of the structure, properties, and interactions of the atomic nuclei. Nuclear scientists create and measure the masses, shapes, sizes, and decays of nuclei at rest and in collisions. They ask questions, like: 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?



Nucleons after can exist in several phases. When collisions excite nuclei, individual protons and neutrons may evaporate from the nuclear fluid. At sufficiently high temperature or density, a gas of nucleons (red background) forms. At even more extreme conditions, individual nucleons may cease to have meaningful identities, merging into the quark-gluon plasma (yellow background). Current data from RHIC provide hints that physicists have glimpsed the quark-gluon plasma.

# ence



# • Nuclei

Radioactive decay transforms a nucleus by emitting different particles. In alpha decay, the nucleus releases a  ${}^4\text{He}$  nucleus—an alpha particle. In beta decay, the nucleus either emits an electron and/or neutrino (or a positron and neutrino) or captures an atomic electron and emits a neutrino and a positron. Gamma and X-ray emissions are composed of high-energy photons. 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—as it does not move to a different chemical element. The physical properties of the atom,

# The Nucleus

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

PROTO

[illegible]

electromagnetic  
field

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 fusion, a massive nucleus splits into two major fragments that usually eject one or more particles. In fission, a massive nucleus combines with a smaller nucleus to produce two major fragments, plus one or more ejected particles—neutrons, protons, photons, or alpha particles.

# Nuclear Energy

Fiss

on

## Applications

## Radioactive Dating

Naturally occurring radioactive isotopes such as  $^{14}\text{C}$  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  $^{241}\text{Am}$  as a source. The alpha particles ionize the air. Smoke entering the detector reduces the current and sets off the alarm.

Nuclear Medicine

Radioactive isotopes, such as  $^{99\text{m}}_{43}\text{Tc}$ ,  $^{67}_{30}\text{Ga}$  and  $^{201}_{81}\text{Tl}$ , are commonly used in the diagnosis and treatment of disease. Positron emitters such as  $^{18}\text{F}$  are used in Positron Emission Tomography (PET) to generate images of brain activity.

Nuclear reactors use the fission of  $^{235}_{92}\text{U}$  or  $^{239}_{94}\text{Pu}$  nuclei to produce electric power. Reactors and most 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.

Astronomical observations courtesy NASA/UT/Caltech and AURA/STScI.

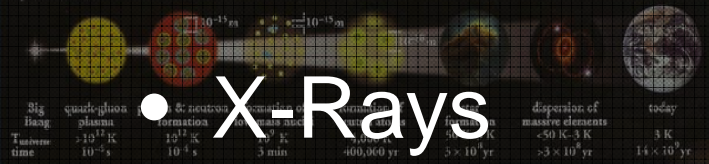


# Nuclear Science

## Particles and Waves

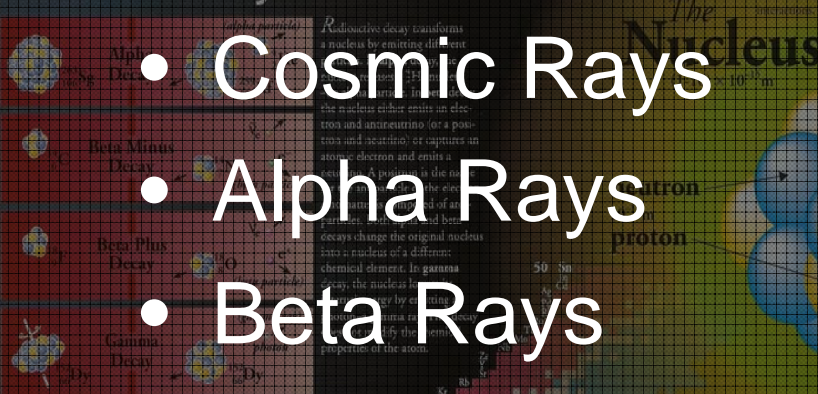
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- X Rays
- Cathode Rays
- Cosmic Rays
- Alpha Rays
- Beta Rays
- Gamma Rays

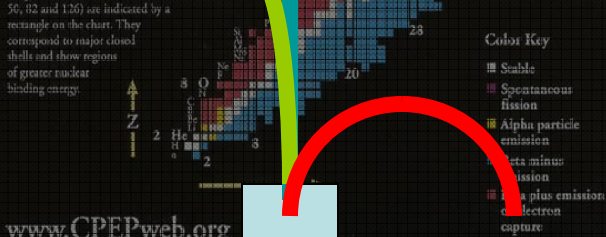
### Radioactivity



### Chart of the Nuclei

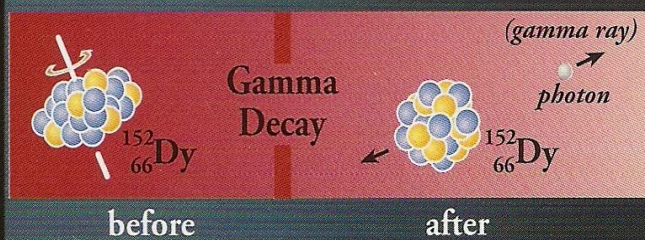
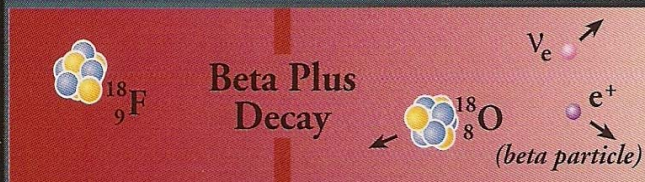
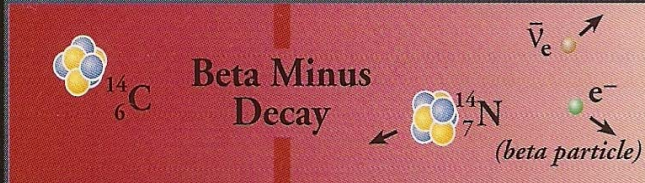
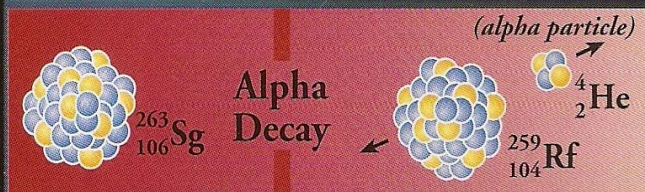
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Magic numbers ( $N$  or  $Z = 2, 8, 20, 28, 50, 82$  and  $126$ ) are indicated by a rectangle on the chart. They correspond to major closed shells and these regions of greater nuclear binding energy.



www.CPEPweb.org

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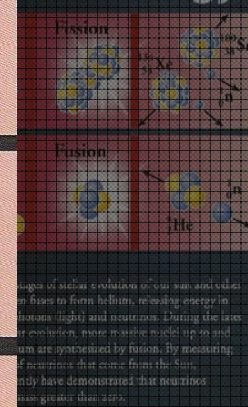


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### Nuclear Energy



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### Magnetic Resonance Imaging

Magnetic Resonance Imaging (MRI) makes use of atomic nuclei in the magnetic field of a nucleus to study chemical environments. This technique accurately determines the structure of the human body.

pictures courtesy NASA/JPL/Caltech and AURA/STScI



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# Nuclei

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- Structure
- Chart of the Nuclides

## Radioactivity



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## The Nucleus

(10<sup>-16</sup> m)

neutron  
10<sup>-16</sup> m  
proton  
10<sup>-16</sup> m

strong field  
quark  
10<sup>-16</sup> m  
electromagnetic field

electron  
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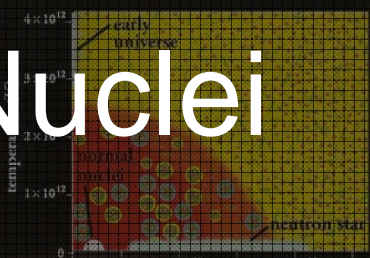
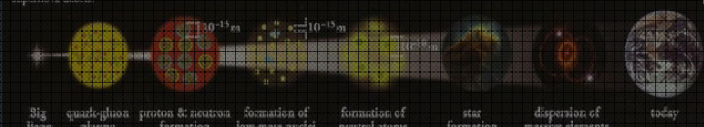
# Nuclear Science

## Building Up and Breaking Down Nuclei

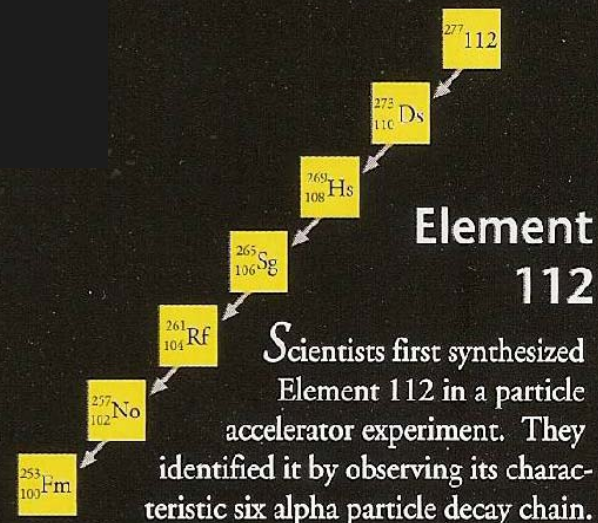
- Identifying the Super-heavy Nuclei from Decay Chains
- Nuclear Decay Applications

### 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,  $T_{univ}$ , cooled to about  $10^9$  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 (supernovae) form the most massive elements and disperse them into space. Our earth was formed from supernovae debris.



### Unstable Nuclei



### Radioactive Dating

Naturally occurring radioactive isotopes such as  $^{14}\text{C}$  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  $^{241}\text{Am}$  to ionize the air. Smoke entering the detector reduces the current and sets off the alarm.



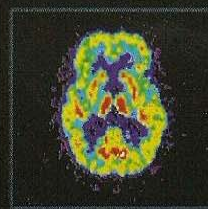
### Space Exploration

Sojourner used alpha particles to identify chemical elements present in Martian rocks. On Earth, nuclear reactions are used in many areas from criminal investigations to art authentication.



### Nuclear Medicine

Radioactive isotopes, such as  $^{99\text{m}}\text{Tc}$ ,  $^{60}\text{Co}$  and  $^{131}\text{I}$ , are commonly used in the diagnosis and treatment of disease. Positron emitters such as  $^{18}\text{F}$  are used in Positron Emission Tomography (PET) to generate images of brain activity.



### Chart of the Nuclei

The Chart of the Nuclei plots nuclei with atomic number,  $Z$ , and mass number,  $A$ . Each nucleus is represented by a dot. The dots are arranged in a grid according to their atomic number,  $Z$ , and mass number,  $A$ . Magic numbers (2, 8, 20, 28, 50, 82, and 126) are indicated by red dots on the chart. They correspond to major closed shells and these regions of greater nuclear binding energy.

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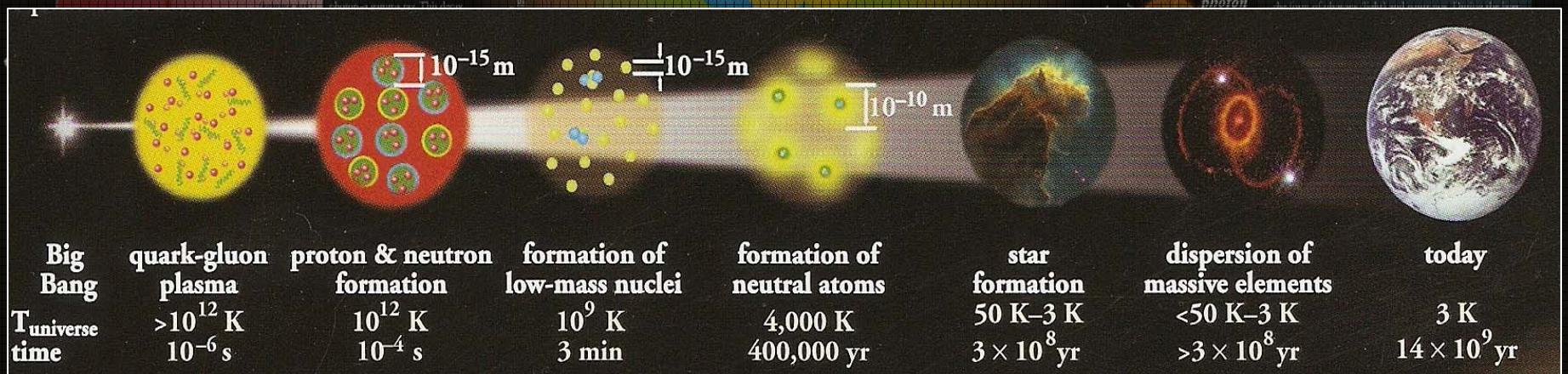
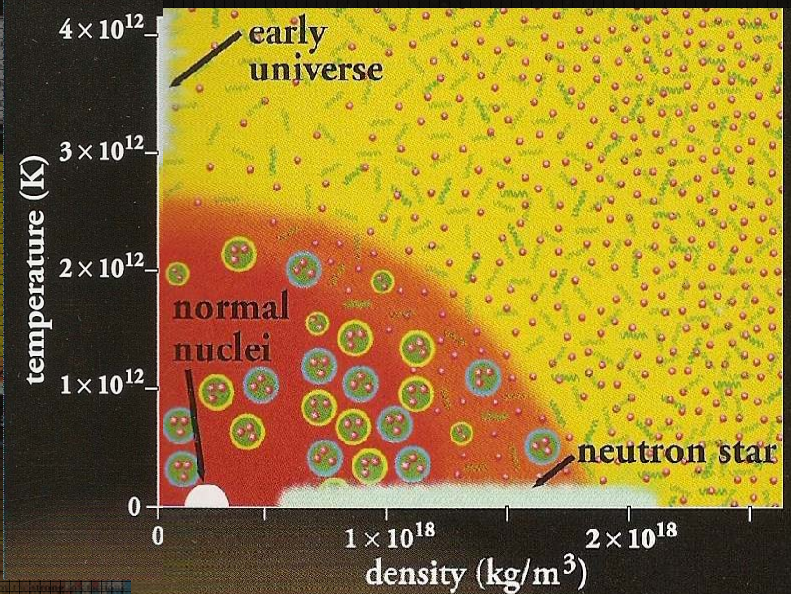




# Nuclear Science

# Nuclear Thermodynamics

- Phase Diagram
- Particles of the Big Bang
  - kinetic energy vs. binding energy



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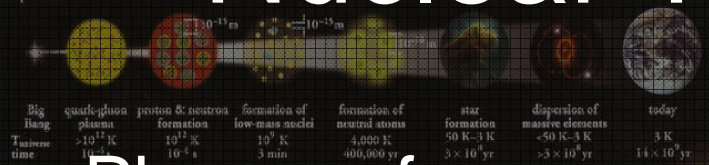


# Nuclear Science

# Heavy Ion Physics Probing Nuclear Thermodynamics

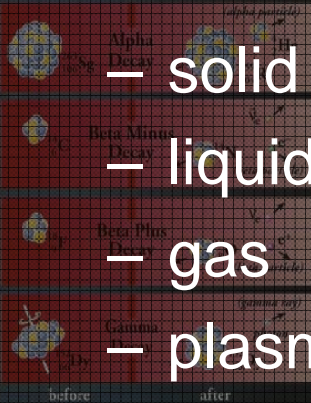
## Expansion of the Universe

After the Big Bang, the universe expanded and cooled. At about  $10^{-43}$  second, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. When the temperature of the Universe,  $T$ , cooled to about  $10^{12}$  K, these particles began to combine into protons, neutrons, and electrons. As time progressed, some of the protons and neutrons combined to form deuterium, helium, and lithium. These light elements are the primary constituents of the universe. In its present form, this chart contains information about the different phases of nuclear matter. Nuclear theory predicts that there are about 100 more to be discovered with  $Z \leq 112$ .



- Phases of Atomic Matter
  - solid
  - liquid
  - gas
  - plasma of constituents

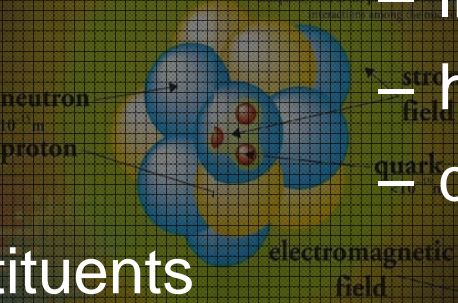
## Radioactive Decay



Radioactive decay transforms a nucleus by emitting different particles. In alpha decay, the nucleus releases a  $^4\text{He}$  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 positron. 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 composition of the nucleus.

## The Nucleus

$(1.0 \times 10^{-14})$  m



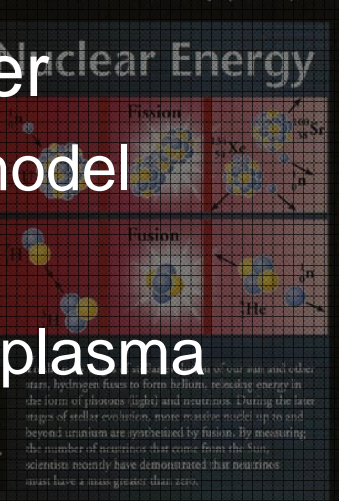
## Phases of Nuclear Matter

Nuclear matter can exist in several phases. At low temperatures and densities, it forms a solid lattice of nuclei. As temperature and density increase, it transitions through a liquid phase to a gas phase. At extremely high temperatures and densities, it becomes a quark-gluon plasma, where individual nucleons cease to have meaningful identities, merging into a fluid of quarks and gluons. Current data provide hints that physicists have glimpsed the quark-gluon plasma.

- Phases of Nuclear Matter
  - liquid drop model
  - hadron gas
  - quark-gluon plasma

## Unstable Nuclei

Stable nuclei 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 forces. In its present form, this chart contains information about the different phases of nuclear matter. Nuclear theory predicts that there are about 100 more to be discovered with  $Z \leq 112$ .



## Chart of the Nuclides

The Chart of the Nuclides presents in graphic form all known nuclei with atomic number,  $Z$ , and neutron number,  $N$ . Each nuclide is represented by a box colored according to its predominant decay mode. Magic numbers ( $N$  or  $Z = 2, 8, 20, 28, 50, 82$  and  $126$ ) are indicated by a rectangle on the chart. They correspond to major closed shells and are associated with greater binding energy.

Nearest neighbor forces govern the binding

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Color Key

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

Spherical Water Drops

Spherical Nucleus



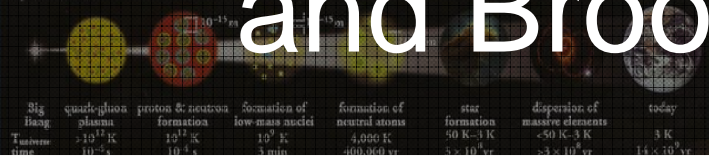


# Nuclear Science

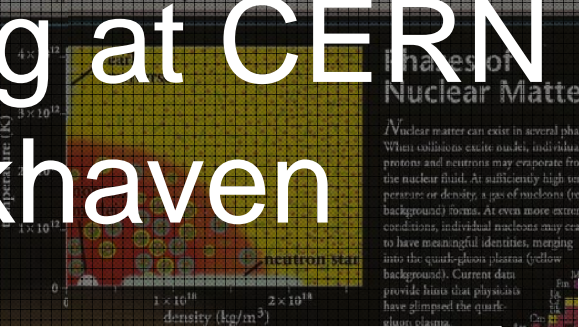
## The Little Bang at CERN and Brookhaven

### Expansion of the Universe

After the Big Bang, the universe expanded and cooled. At first, it was a soup of quarks, gluons, photons, and neutrinos. When the temperature of the Universe,  $T_{univ}$ , cooled to about  $10^{12}$  K, this soup condensed 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 (supernovae) form the most massive elements and disperse them. Our earth was formed from supernova debris.



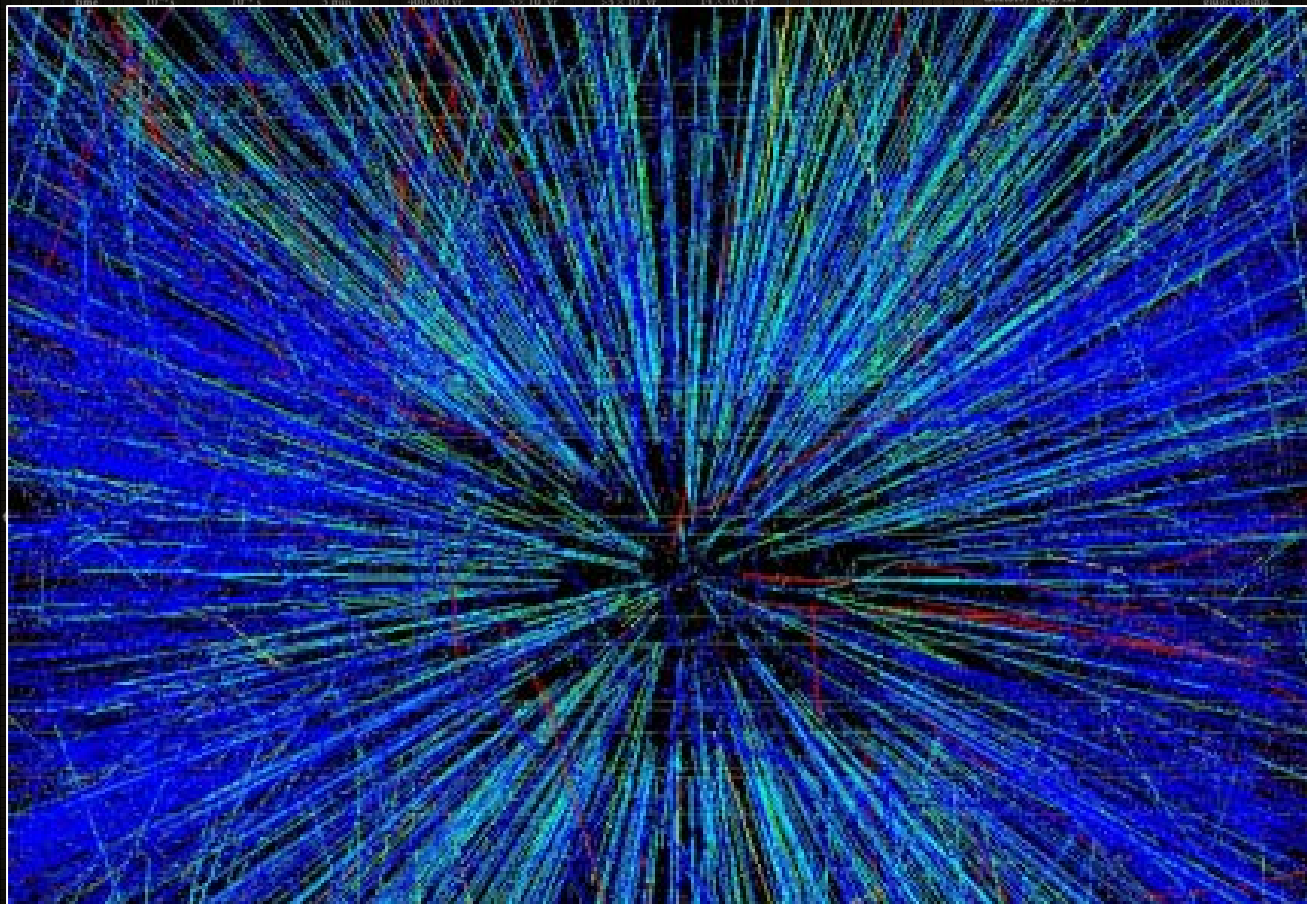
Nuclear Science is the study of the structure, properties, and interactions of the atomic nuclei. Nuclear scientists explore the structure, properties, and interactions of nuclei at rest and in motion. They ask questions about why do nuclei exist in the nucleus? What combinations of protons and neutrons are possible? What happens when nuclei are ionized or excited?



Nuclear matter can exist in several phases. When collisions excite nuclei, individual protons and neutrons may evaporate from the nuclear fluid. At sufficiently high temperature or density, a gas of nucleons (red background) forms. At even more extreme conditions, individual nucleons may cease to have meaningful identities, merging into the quark-gluon plasma (yellow background). Current data provide hints that physicists have glimpsed the quark-gluon plasma.

### Unstable Nuclei

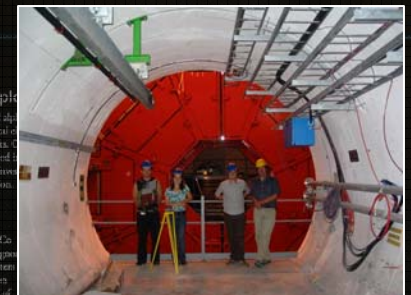
Stable nuclei form a narrow white band on the Chart of the Nuclides. Scientists produce unstable nuclides far from this band and study their decays, thereby learning about the extremes of nuclear conditions. In its present form, this chart contains about 2500 different nuclides. Nuclear theory predicts that there are at least 6000 more to be discovered with  $Z \leq 112$ .



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Capture

Beam activity



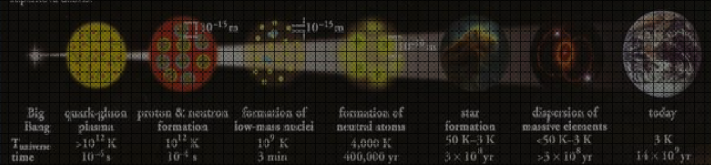
Astrophysical pictures courtesy NASA/JPL/Caltech and AURA/STScI.



# Nuclear Science

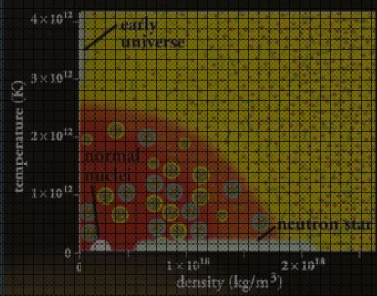
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Nuclear Science is the study of the structure, properties, and interactions of the atomic nuclei. Nuclear scientists explore and measure the masses, shapes, sizes, and decays of nuclei at rest and in collisions; they ask questions about why do nuclei exist in the nucleus? What combinations of protons and neutrons are possible? What happens when nuclei are compressed to rapidly rotated? What is the origin of the nuclei found on Earth?

Legend: electron (e<sup>-</sup>), proton (p), neutron (n), quark (q), gluon (g), photon (γ), neutrino (ν), antineutrino (ν̄), alpha particle (α), beta particle (β), gamma ray (γ), X-ray (X), ultraviolet (UV), visible light (vis), infrared (IR), radio wave (radio).



## Phases of Nuclear Matter

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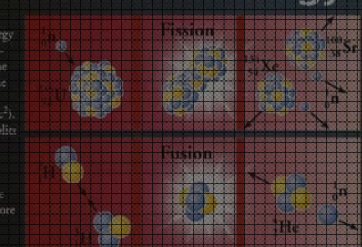
## Radioactivity



Radioactivity is the process by which a nucleus emits a particle. In alpha decay, the nucleus releases a <sup>4</sup>He nucleus—an alpha particle. In beta decay, the nucleus either emits an electron and an antineutrino (or a positron and a neutrino) or captures an atomic electron and emits a neutrino. A positron is the name for the antiparticle of the electron. Antineutrinos are composed of anti-particles. Both alpha and beta decays change the original nucleus into a nucleus of a different chemical element. In gamma decay, the nucleus lowers its energy by emitting a gamma ray. This does not change the chemical properties of the atom.

neutron  
proton  
strong field  
quark  
electromagnetic field

## Nuclear Energy



Nuclear reactions release energy. In fission, a heavy nucleus splits into two lighter nuclei, releasing energy in the form of gamma rays and neutrons. During the late stages of stellar evolution, more massive nuclei are formed and beyond uranium are synthesized by fusion. By measuring the number of neutrons that come from the Sun, scientists recently have demonstrated that the Sun is a nuclear reactor.

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Color Key

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

## Applications



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Astrophysical pictures courtesy NASA/JPL/Caltech and AURA/STScI.