Nuclear Reactions
with respect to other changes

Energy drives all reactions, physical, chemical, biological, and nuclear.

Physical reactions change states of material among solids, liquids, gases, solutions. Molecules of substances remain the same.

Chemical reactions change the molecules of substances, but identities of elements remain the same.

Biological reactions are combinations of chemical and physical reactions.

Nuclear reactions change the atomic nuclei and thus the identities of nuclides. They are accomplished by bombardment using subatomic particles or photons.

Nuclear Reactions

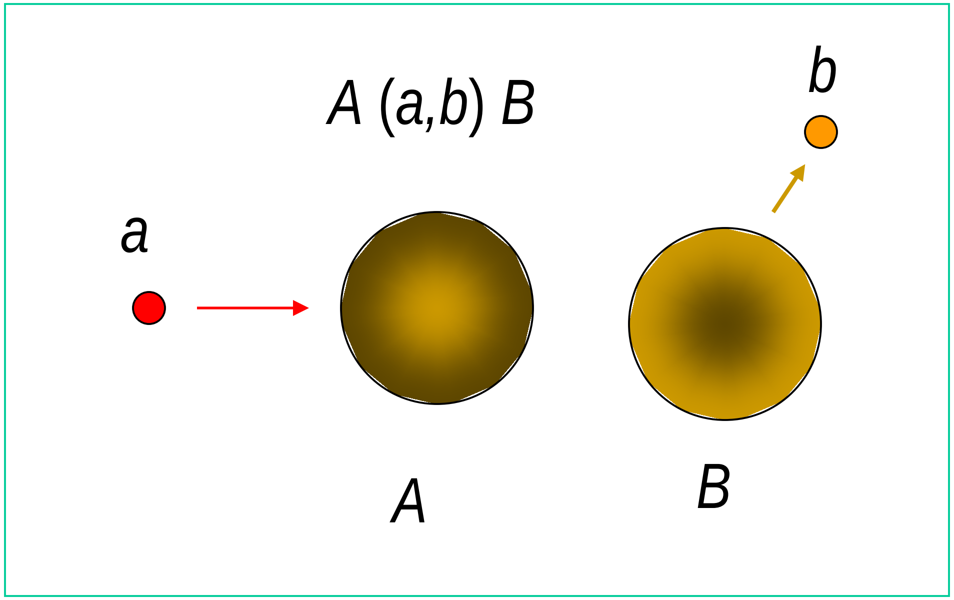
changing the hearts of atoms

Nuclear reactions, usually induced by subatomic particles *a*, change the energy states or number of nucleons of nuclides.

After bombarded by *a*, the nuclide *A* emits a subatomic particle *b*, and changes into *B*.

$$a + A \rightarrow B + b$$

or written as *A* (*a*,*b*) *B*



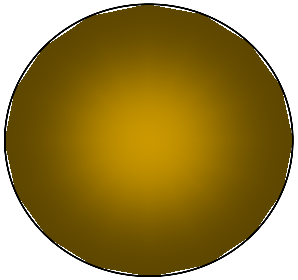
Describe nuclear reactions

Subatomic Particles for and from Nuclear Reactions

Subatomic particles used to bombard or emitted in nuclear reactions:

γ	photons
β	electrons
p or ^{1}H	protons
n	neutrons
d or ^{2}D	deuterons
t or ^{3}T	tritons
α or ^{4}He	alpha particles
^{n}E	atomic nuclei

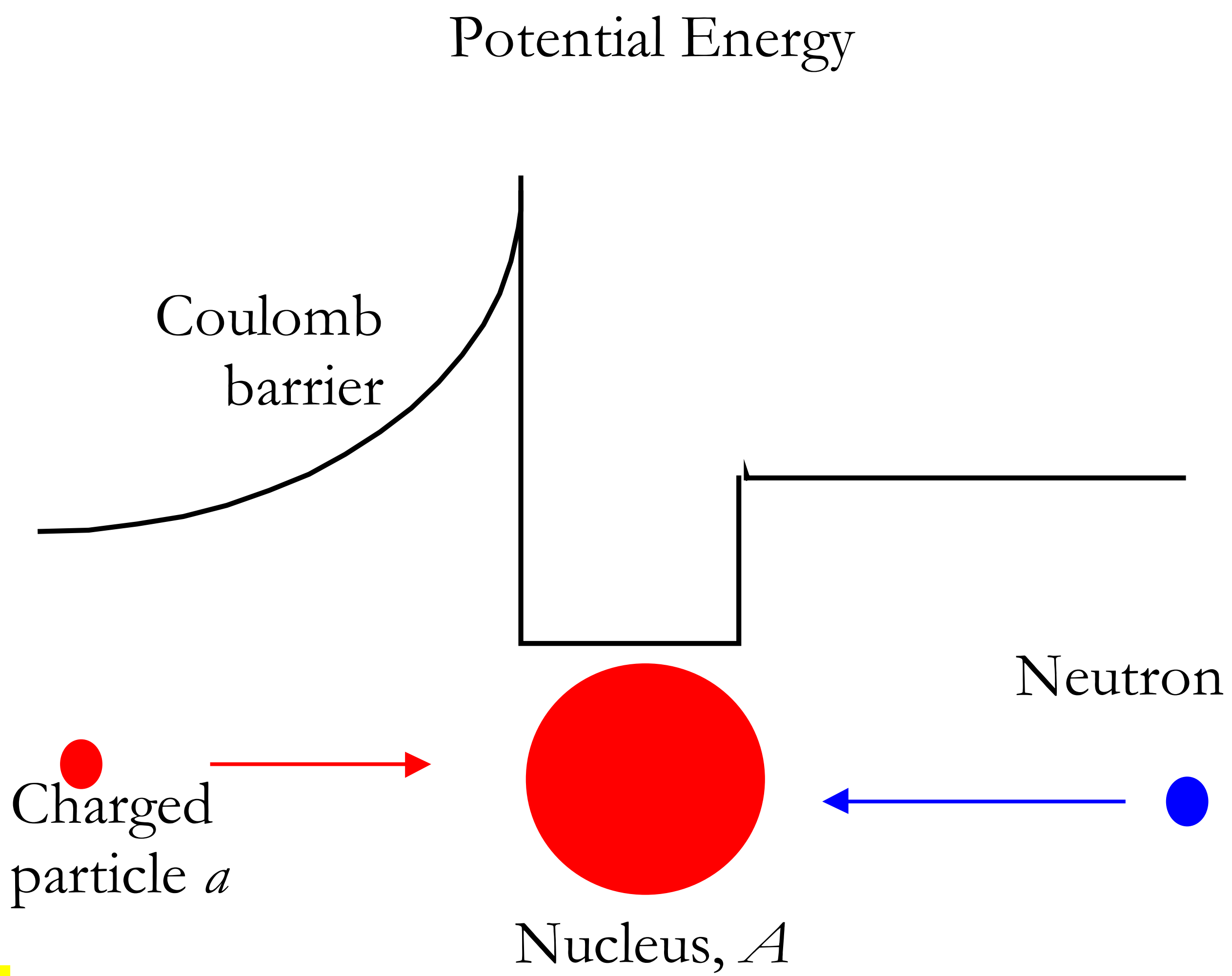
Endothermic reactions require energy.



exothermic reactions release energy.

The Potential Energy of a Positively Charged Particle as it Approaches a Nucleus.

Potential Energy of Nuclear Reactions



Explain interaction of particle with nuclei

Estimate Energy in Nuclear Reactions

The energy Q in a reaction A (a, b) B is evaluated according to

$$m_a + m_A = m_b + m_B + Q, \qquad \text{(}Q\text{ differs from enthalpy)}$$

where m_i means mass of i etc

$$Q = m_a + m_A - (m_b + m_B) \qquad \text{(difference in mass before and after the reaction)}$$

The Q is positive for exothermic (energy releasing at the expense of mass) or negative for endothermic (requiring energy) reactions.

For endothermic reactions, the energy can be supplied in the form of kinetic energy of the incident particle. Energy appear as kinetic energy of the products in exothermic reactions.

Endothermic and Exothermic Reactions

These two examples illustrate endothermic and exothermic reactions.

Example: Energy for the reaction

$$^{14}N + {}^{4}He \rightarrow {}^{17}O + {}^{1}H + Q$$

$$14.00307 + 4.00260 = 16.99914 + 1.007825 + Q$$

$$Q = 14.00307 + 4.00260 - (16.99914 + 1.007825) = -0.001295 \text{ amu}$$

$$= -1.21 \text{ MeV}$$

endothermic, kinetic energy of α must be greater than 1.21 MeV

Example: The energy Q for the reaction $^{11}B(\alpha, n)\,^{14}N$, given masses: ^{11}B, 11.00931; n, 1.0086649.

$$Q = 11.00931 + 4.00260 - (1.0086649 + 14.00307) = 0.000175 \text{ amu}$$

$$= 0.163 \text{ MeV}$$

exothermic reaction

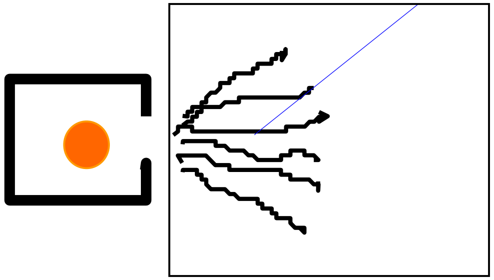
Discoveries of Nuclear Reactions

In 1914, Marsden and Rutehrford saw some thin tracks and spots among those due to α particles. They attributed them to protons and suggested the nuclear reaction:

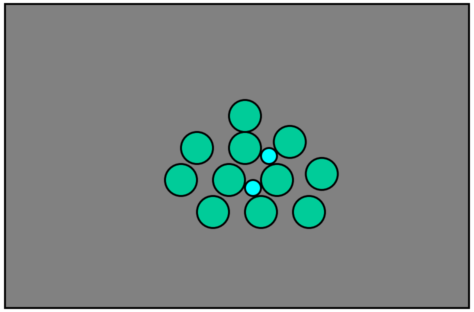
$$^{14}N + {}^{4}He \rightarrow {}^{17}O + {}^{1}H \quad \text{or} \quad {}^{14}N\,(\alpha, p)\,{}^{17}O$$

F. Joliot and I. Curie discovered the reaction

$$^{27}Al\,(\alpha, n)\,{}^{30}P\,(, \beta^{+} \text{ or EC})\,{}^{30}Si, \quad \text{half life of } {}^{30}P \text{ is 2.5 min}$$



α source & tracks with thin proton track



α and thin proton spots on fluorescence screen

Smashing the Atoms

In 1929, John Cockroft and Ernest Walton used 700,000 voltage to accelerate protons and bombarded lithium to induce the reaction,

$$^{7}\text{Li} + \text{p} \rightarrow 2\,\alpha$$

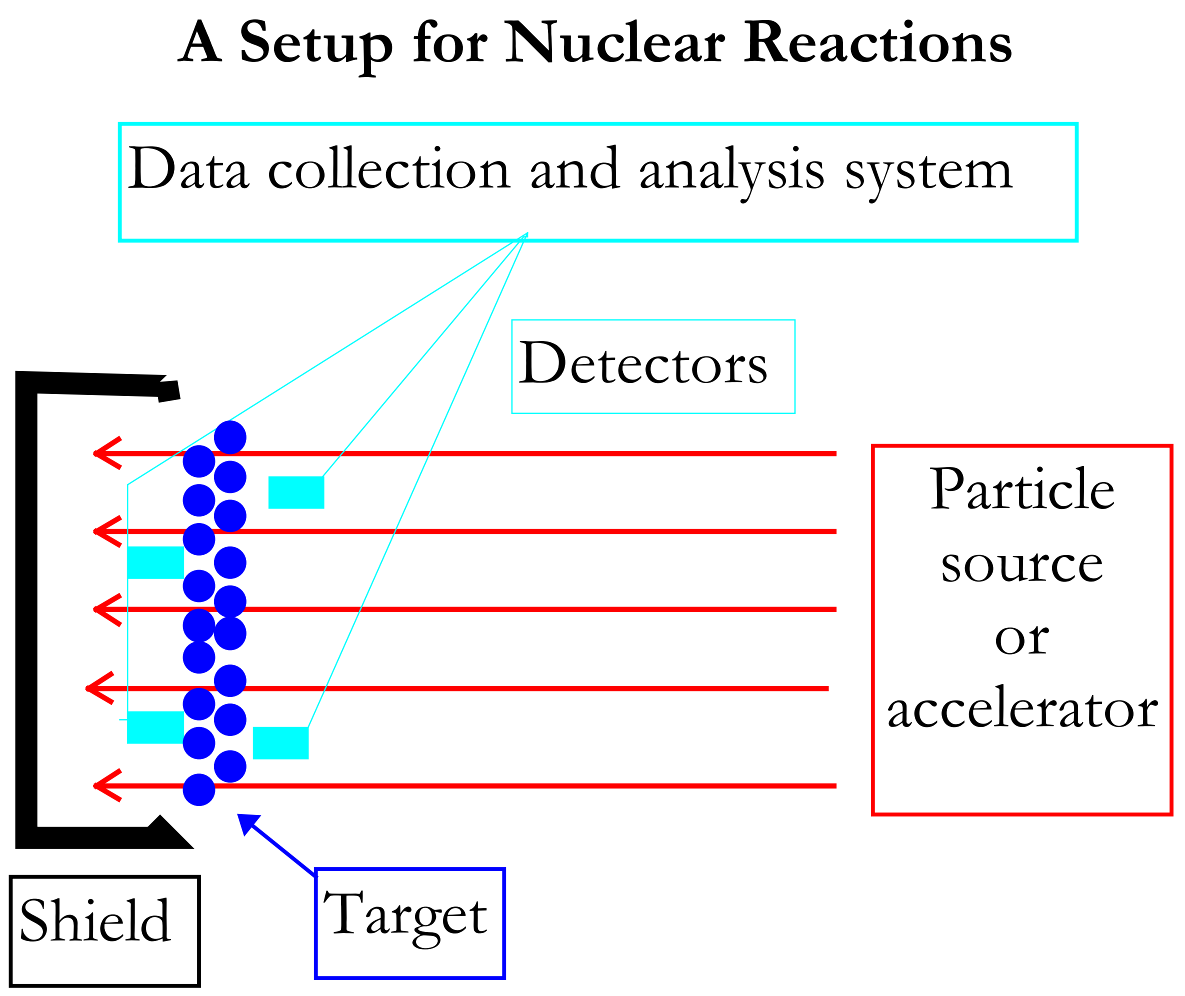
They called it smashing the atoms, a mile stone in the discovery of nuclear reaction. This reaction is also a proton induced fission, and illustrates the stability of the helium nuclide.

They received the Nobel prize for physics in 1951.

Nuclear Reaction Experiments

Basic Components

particle source
target
shield
detectors
data collection
data analysis system



Neutron Sources for Nuclear Reactions

Neutrons are the most important subatomic particles for inducing nuclear reactions. These sources are:

Neutrons from α induced nuclear reactions

Neutrons from γ-photon excitations

Neutrons from nuclear reactions induced by accelerated particles

Neutrons from spontaneous and n-induced fission reactions (nuclear reactors)

Neutrons from α Induced Reactions

The discovery of neutron by James Chadwick in 1932 by reaction

^{9}Be (α, n) ^{12}C,

was applied to supply neutrons for nuclear reactions by mixing α-emitting nuclides with Be and other light nuclides.

Mixtures used as neutron sources

Source	Reaction	n energy / MeV
Ra & Be	^{9}Be(α, n)^{12}C	up to 13
Po & Be	^{9}Be(α, n)^{12}C	up to 11
Pu & B	^{11}B(α, n)^{14}N	up to 6
Ra & Al	^{27}Al (α, n)^{31}P	

Neutrons by γ Excitation

High-energy photons excites light nuclides to release neutrons. To avoid α- and β-ray excitation, radioactive materials are separated from these light nuclides in these two-component neutron sources to supply low energy neutrons for nuclear reactions.

Two-component neutron sources

Source	Reaction	n energy / MeV
^{226}Ra, Be	$^{9}Be(\gamma, n)^{12}C$	0.6
^{226}Ra, D_2O	$^{2}D(\gamma, n)^{1}H$	0.1
^{24}Na, Be	$^{9}Be(\gamma, n)^{8}Be$	0.8
^{24}Na, H	$^{2}D(\gamma, n)^{1}H$	0.2

Neutrons from Accelerators and Reactors

Neutrons are produced from nuclear reaction using energetic particles from accelerators.

^{2}D (d, n) ^{3}He

^{3}T (d, n) ^{4}He

Neutrons from nuclear fission reactions

^{252}Cf spontaneous fission to yield 3 or more neutrons

^{235}U and ^{239} Pu induced fission reactions release 2 to 3 neutrons in each fission

Neutron Induced Radioactivity

Using neutrons from the reaction, $^{27}Al\ (\alpha, n)^{31}P$, Fermi's group in Italy soon discovered these reactions:

$^{19}F\ (n, \alpha)\ ^{16}N$

$^{27}Al\ (n, \alpha)\ ^{24}Na\ (, \beta)\ ^{24}Mg$.

They soon learned that almost all elements became radioactive after the irradiation by neutrons, in particular

$^{10}B\ (n, \alpha)\ ^{7}Li$ releasing 2.3-2.8 MeV energy

is used in classical neutron detectors. Now, detectors use,

$^{3}He\ (n, p)\ ^{3}H$

Nuclear Reactions Induced by Cosmic Rays

Cosmic rays consist of mainly high energy protons, and they interact with atmospheres to produce neutrons, protons, alpha particles and other subatomic particles.

One particular reaction is the production of ^{14}C,

$^{14}N(n, p)^{14}C$ - β emitting, half-life 5730 y

Ordinary carbon active in exchange with CO_2 are radioactive with 15 disintegration per minute per gram of C.

Applying decay kinetics led to the ^{14}C-dating method.

Simple Theories on Nuclear Reactions

Theories on nuclear reactions involve theory of nuclei, collision theory, and high-energy particles etc.We can only talk about some simple concepts of nuclear reactions.

Energy Consideration of Nuclear Reactions (giving earlier)

Cross Sections of Nuclear Reactions

Rate of Nuclear Reactions

Types of Nuclear reactions

Give an overall look at n.r.

Nuclear Reaction Cross Sections

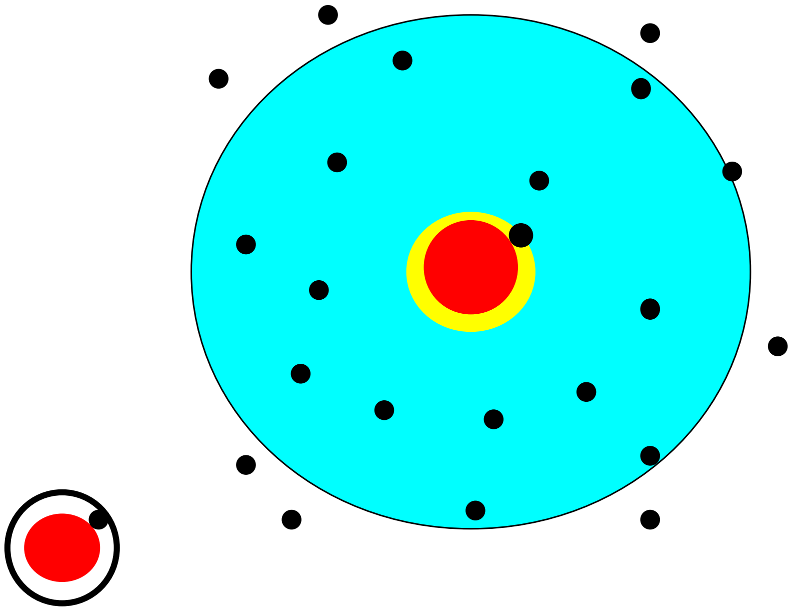
Cross section with unit barn (1 b=1e-28 m^2) comes from target area consideration, but it is a parameter (σ) indicating the probability leading to a reaction,

$$rate = \sigma N I$$

N is the number of target nuclei per unit area;
I is the beam intensity

Cross Section of the Target and the Random Target Shooting

(Don't be too serious about the crossection)



Differentiate the concept and reality of cross section

Cross Sections and *Rate*

A large copper (^{65}Cu) foil with a surface density of 0.01g cm^{-2} is irradiated with a fast neutron beam with an intensity 2.0e10 n s^{-1} cm^{-2}. A total width of the beam is 0.5 cm^{-2}. After irradiation for 1 min, a total of 6.0e7 ^{64}Cu has been formed. Estimate the cross section for the reaction, ^{65}Cu (n, 2n) ^{64}Cu. Ignore the ($t_{1/2}$ 12.7 h) ^{64}Cu nuclei decayed during the irradiation.

Solution: ($rate = \sigma N I$)

rate = 6e7/60 =1e6 ^{64}Cu s^{-1}.

N = 6.022e23*0.01 cm^{-2}*0.5 cm^2/ 65 = 9.26e19 ^{65}Cu.

1e6 s^{-1} = σ * 9.26e19 * 2.0e10 s^{-1} cm^{-2}

σ = 1.08e-24 cm^2 = 1.08 b

The cross section is 1.08 b for ^{65}Cu (n, 2n) reaction.

Cross Sections and *Rate*

The cross section for neutron capture of cobalt is 17 b. Estimate the rate of nuclear reaction when 1.0 g of ^{59}Co is irradiated by neutrons with an intensity of 1.0e15 n s^{-1} cm^{-2} in a reactor.

Solution:

In a nuclear reactor, the entire sample is bathed in the neutron flux.

N = 6.022e23 *1.0 / 59 = 1.02e22 ^{59}Co

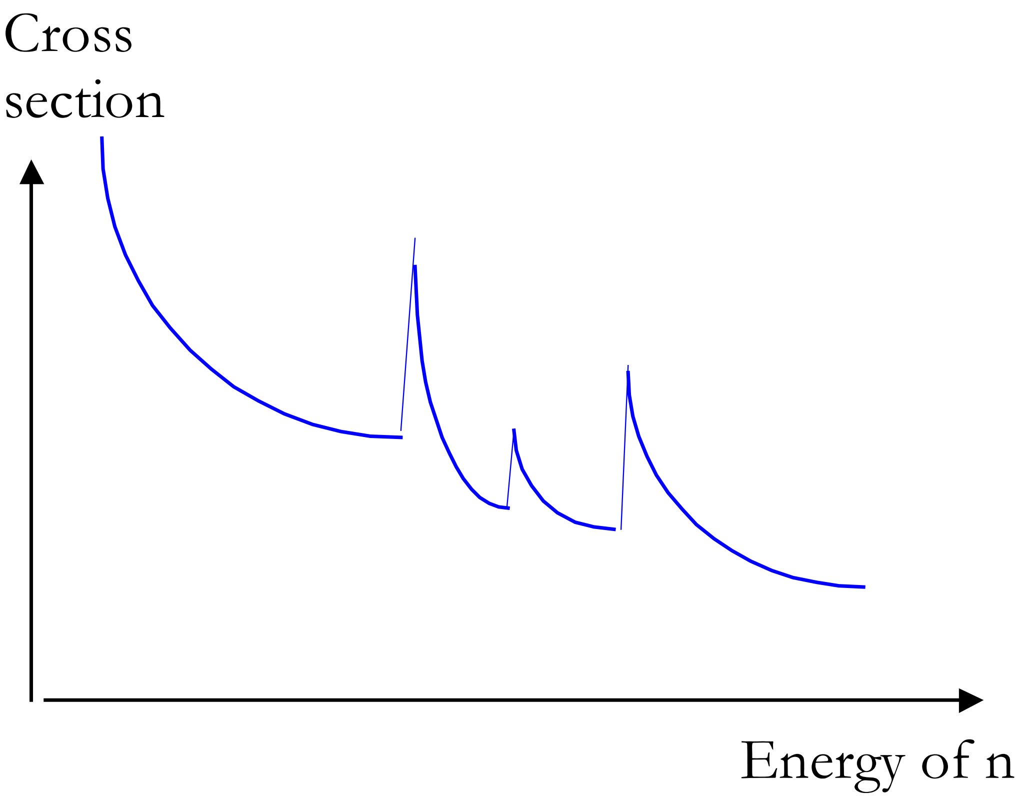
rate = $\sigma\, N\, I$

= 17e-24 * 1.02e22 * 1.0e15 = 1.74e14 ^{60}Co s^{-1}

Estimate the radioactivity of ^{60}Co, half life = 5.27 y.

Energy Dependence of Cross Section

A Typical Variation of Neutron Cross Section against the Energy of Neutrons.



Cross sections depend on the nuclide, the reaction, and energy.

The neutron capture cross sections usually decrease as energy of the neutron increase.

The sharp increases are due to resonance absorption.

Cross Sections of Multi-reaction Modes

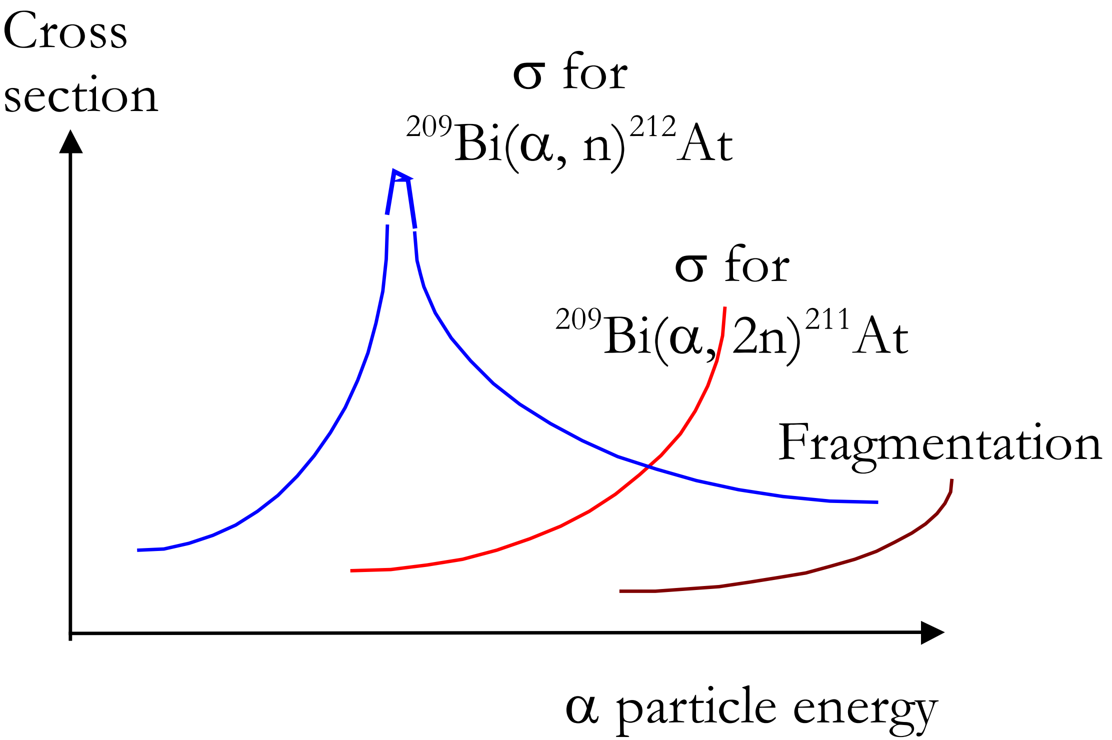
Reactions of ^{4}He and ^{209}Bi serve as an example of multiple reaction modes.

The variation of partial σs as functions of energy of ^{4}He is shown to illustrate the point.

$\sigma_{total} = \Sigma\ \sigma_i$

for total consumption of nuclei.

Cross Section of Multiple Reaction Modes



Types of Nuclear Reactions

Elastic scattering (n, n) no energy transfer

Inelastic scattering (n, n) energy transferred

Capture reactions (n, γ)

Photon excitation (γ,)

Rearrangement reactions (n, x)

Fission reactions

Fusion reactions

Elastic and Inelastic Scattering

When the incident and emitted particles are the same, the process is scattering. If energy is transferred between the particle and the target nuclei the process is inelastic, otherwise, elastic.

Elastic scattering example:

^{208}Pb (n, n) ^{208}Pb, but the two n's may not be the same particle

Inelastic scattering examples:

^{40}Ca (α, α) ^{40m}Ca excitation

^{208}Pb (^{12}C, ^{12m}C) ^{208m}Pb mutual excitation

Capture Reactions

The incident particle is retained by target nuclei in capture reactions. Prompt and delayed γ emission usually follow.

$^{197}Au^{79}$ (p, γ) $^{198}Hg^{80}$
^{238}U (n, γ) ^{239}U
^{2}D (n, γ) ^{3}T
^{9}Be (n, γ) ^{10}Be
^{12}C (n, γ) ^{13}C
^{14}N (n, γ) ^{15}N

Rearrangement Nuclear Reactions

After absorption of a particle, a nuclide rearranges its nucleons resulting in emitting another particle. For example:

$^{197}Au\ (p, d)\ ^{196m}Au$

$^{4}He\ (^{4}He, p)\ ^{7}Li$

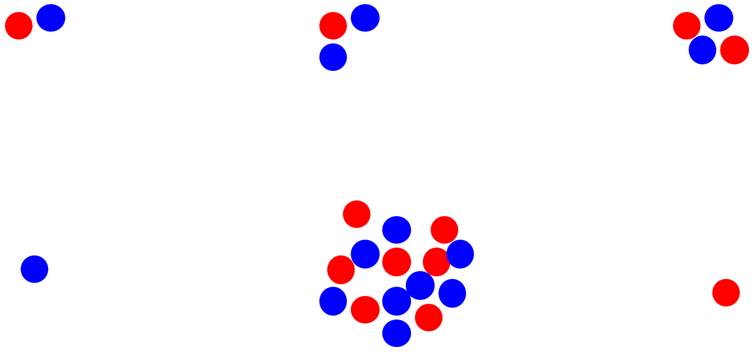
$^{27}Al\ (^{4}He, n)\ ^{30}P$

$^{54}Fe\ (^{4}He, 2\ n)\ ^{56}Ni$

$^{54}Fe\ (^{4}He, d)\ ^{58}Co$

$^{54}Fe\ (^{32}S, ^{28}Si)\ ^{58}Ni$

Particles or nuclides



Transformation of Nuclides in Nuclear Reactions

No. of protons

(^{3}He, 2n) (α, 3n)	(^{3}He, n), (d, β), (α, 2n)	(^{3}He, γ) (α, n), (t, β)	(α, γ)
(p, n) (d, 2n)	(p, γ), (n, β) (^{3}t, 2n), (d, n) (^{3}He, d) (α, t)	(d, γ) (^{3}t, n) (^{3}He, p) (α, d)	(^{3}t, γ) (α, p)
(γ, n) (n, 2n) (p, d) (^{3}He, α)	**Original Nuclide** *Scattering, elastic & inelastic*	(n, γ) (d, p) (^{3}t, d) (^{3}He, 2p) (α, ^{3}He)	(^{3}t, p) (α, 2p)
(γ, d) (n, ^{3}t) (d, α)	(γ, p) (^{3}t, α)	(n, p) (d, 2p) (^{3}He, 3p)	(^{3}t, 2p) (α, 3p)

No. of neutrons

Some Nuclear Reactions

Types of Nuclear Reactions

Nuclear Fission and Fusion

A nuclide splits into two pieces with the emission of some neutrons is nuclear fission. Nuclides such as ^{254}Fm undergo spontaneous fission, whereas neutrons induce ^{238}U and ^{239}Pu fission.

Fusion on the other hand combines two light nuclides into one, and may also be accompanied by the emission of one or more nucleons. An important fusion is

$$^{2}D + {}^{3}T \rightarrow {}^{4}He + n$$

Two chapters are devoted to these nuclear reactions.

Applications of Nuclear Reactions

Based on nuclide productions:

synthesis of radioactive nuclides - for various applications

synthesis of missing elements Tc, Pm and At

synthesis of transuranium (93-102) elements

synthesis of transactinide (103 and higher) elements

Activation analyses

non-destructive methods to determine types and amounts of elements

Syntheses of Radioactive Isotopes

Over 1300 radioactive nuclides have been made by nuclear reactions. The most well known is the production of ^{60}Co, by neutron capture,

^{59}Co (100%) (n, γ) ^{60m}Co and ^{60}Co - β and γ emission $t_{1/2}$ = 5.24 y

The sodium isotope for study of Na transport and hypertension is produced by

^{23}Na (n, γ) ^{24}Na (β emission, $t_{1/2}$ = 15 h)

For radioimmunoassay, ^{131}I is prepared by

^{127}I (n, γ) ^{128}I (β^+, β^- EC, $t_{1/2}$ = 25 m)

There are many other production methods.

Syntheses of Tc, Pm, and At

In 1937, Perrier and Segré synthesized the missing element 43 using deuteron from cyclotron,

$^{96}Mo + {}^{2}D \rightarrow {}^{97}Tc + n$, (Tc, EC, $t_{1/2}$ = 2.6e6 y)

In 1940, Segré and Mackenzie synthesized and named element 85 astatine (Greek astatos - unstable) At by the reaction,

$^{209}Bi^{83}$ (α, xn) $^{(213-x)}At^{85}$, (x = 1, 2, 3 etc)

The missing element promethium was made by

$^{144}Sm^{62}$ (n, γ) ^{145}Sm (, EC) $^{145}Pm^{61}$ (EC, $t_{1/2}$ = 17.7 y)

Many more isotopes of these elements have been made.

Syntheses of Transuranium Elements

From 1940 to 1962, about 11 radioactive transuranium elements (almost 100 nuclides) have been synthesized, about one every two years. Representative isotopes of the 11 elements are neptunium (Np^{93}), plutonium (Pu^{94}), americium (Am^{95}), curium (Cm^{96}), berklium (Bk^{97}), californium (Cf^{98}), einsteinium (Es^{99}), fermium (Fm^{100}), mendelevium (Md^{101}), nobelium (No^{102}), and lawrencium (Lw^{103}).

La^{57} , Ce, Pr^{59}, Nd, Pm^{61}, Sm, Eu^{63} , Gd, Tb^{65} , Dy, Ho^{67}, Er, Tm^{69}, Yb, Lu^{71}
Ac^{89}, Th, Pa^{91}, U^{92}, Np^{93} , Pu , Am^{95}, Cm, Bk^{97}, Cf, Es^{99}, Fm, Md, No, Lw^{103}

Among these, tons of ^{239}Np, and its decay products ^{239}Pu have been made for weapon and reactor fuel. Successive neutron capture reactions are major methods, but accelerators are involved. . . continue =>

Syntheses of Transuranium Elements -continue

Very heavy elements are synthesized using accelerated nuclides,

$$^{246}Cm + ^{12}C \rightarrow \; ^{254}No^{102} + 4\ n,$$

$$^{252}Cf + ^{10}B \rightarrow \; ^{247}Lw^{103} + 5\ n,$$

$$^{252}Cf + ^{11}B \rightarrow \; ^{247}Lw^{103} + 6\ n.$$

These syntheses completed the analogous of rare-earth elements. These elements were made during the cold war, and results from the former USSR were not available to us.

Syntheses of Transactinide Elements

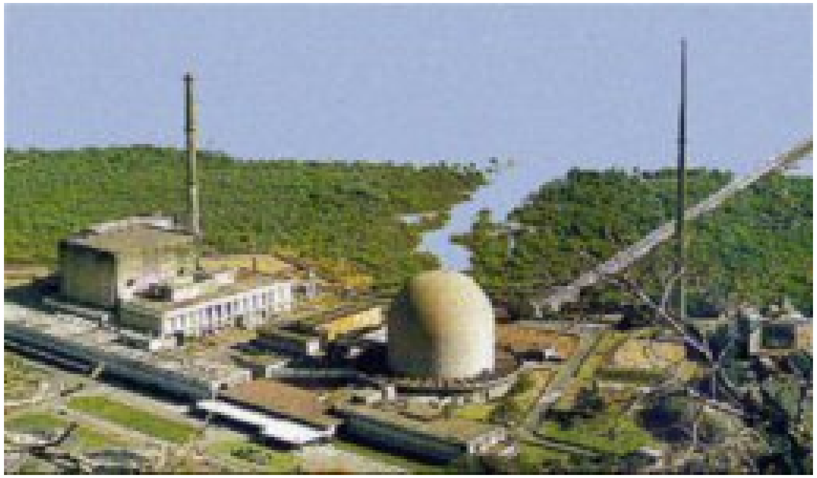
$^{242}Pu\ (^{22}Ne, 4n)\ ^{260}Rf^{104}$	rutherfordium
$^{249}Cf^{98}\ (^{12}C^{6}, 4n)\ ^{257}Rf^{104}$	
$^{249}Cf\ (^{15}N, 4n)\ ^{260}Ha^{105}$	hahnium
$^{249}Cf\ (^{18}O, 4n)\ ^{263}Sg^{106}$	seaborgium
$^{268}Mt^{109}\ (, \alpha)\ ^{264}Ns^{107}$	nielsbohrium
$^{209}Bi\ (^{55}Mn, n)\ ^{263}Hs^{108}$	hassium
$^{208}Pb\ (^{58}Fe, n)\ ^{265}Hs^{108}$	
$^{272}E^{111}\ (, \alpha)\ ^{268}Mt^{109}$	meitnerium
$^{208}Pb\ (^{64}Ni, n)\ ^{271}Uun^{110}$	ununnilium
$^{209}Bi\ (^{64}Ni, n)\ ^{272}Uuu^{111}$	unununium

Elements with Z > 103 are transactinides. Some results from both the USA and the former USSR are known, and some of the syntheses are given here.

Additional Interests

Isotope production and distribution facilities:
The U.S. Department of Energy's (DOE) national laboratories offer unique isotope production and separation facilities and processes such as reactors, associated hot cells, accelerators, and calutrons.

The 250-megawatt Advanced Test Reactor (ATR) at Idaho



CANDU reactors can also produce useful isotopsCanada now produces approximately 85 percent of the world's supply of Co-60 and more than 50 percent of the Co-60 medical therapy devices and medical device sterilizers. It also produces most of the world's supply of molybdenum-99, the precursor of Technetium-99m, the isotope that is the most widely used radioactive pharmaceutical.