

Физика на ядрото и елементарните частици

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Introductory Nuclear Physics

Kenneth S. Krane, John Wiley&Sons, Inc. New York, 1988.

Basic Ideas and Concepts in Nuclear Physics

K. Heyde, IoP publishing, Bristol&Philadelphia, 2004

Nuclear structure from a simple perspective

R.F. Casten, Oxford University Press, 2000

Физика на атомните ситеми

Петър Райчев, издателство ЛОДОС, София 2006

Физика на ядрото и елементарните частици

У.С.С. Уилямс, Университетско издателство “Св. Кл. Охридски”, София 2000

Увод в теоретичната ядрена физика

Б. Славов, Университетско издателство “Св. Кл. Охридски”, София 2002, 1992

Електронни ресурси

Тиймс (Teams)

<https://teams.microsoft.com/l/team/19%3AyMOHC87-m3i4OFACnu-XJ5-zO47KsJm7aib5vxa6Ew1%40thread.tacv2/conversations?groupId=0673b203-1e27-4f67-83ef-4d59e9e13268&tenantId=9d05c5fb-e448-4700-8a58-e15b93c84ea9>



Страница на курса

<https://nucleus.phys.uni-sofia.bg/riglectures/>



Физика на ядрото и елементарните частици

Изпит:

Крайна оценка = $0.10 \cdot (\text{Тест 1}) + 0.10 \cdot (\text{Тест 2}) + 0.20 \cdot (\text{Задачи}) +$
 $+ 0.20 \cdot (2 \text{ въпроса}) + 0.40 \cdot (\text{Практикум})$

(+ 0.5 към оценката при изпълнени над 85% от електроните тестове)

НО

При липса на оценка от практикума максималната крайна оценок

НЕ МОЖЕ да бъде по-висока от СРЕДЕН (3.0)

По важни събития от историята на ядрената физика

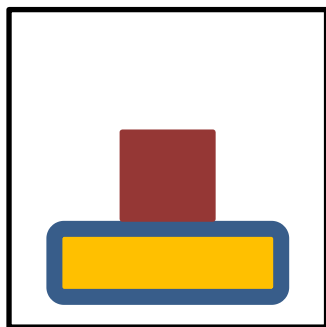
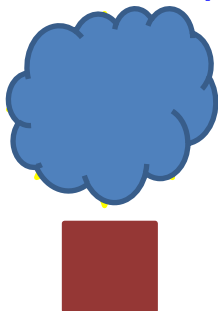
- 1896 – Becquerel – открива радиоактивността;

Има ли флуоресциращи материали, които излъчват X – лъчи?

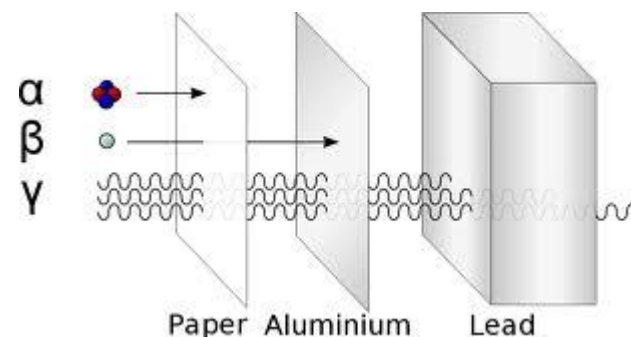
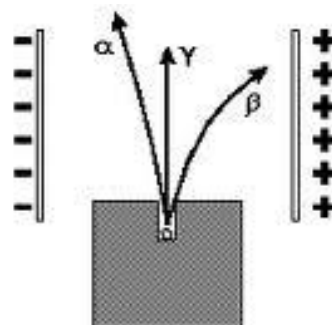
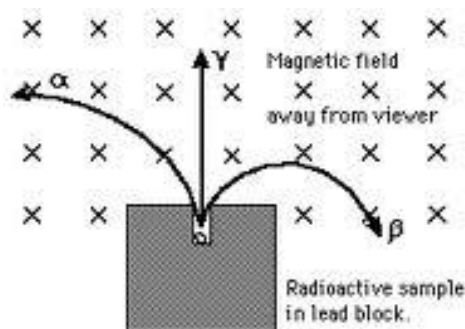


Систематични измервания!

Нов тип лъчение
спонтанна радиация



S.P. Thompson, Lord Kelvin



- 1898 – Marie and Pierre Curie – термина радиоактивност и изолират Ra и Po;

По важни събития от историята на ядрената физика

- 1911 – Rutherford – открива атомното ядро

- 1917 – Rutherford, Mardsen протона;



- 1919 – Rutherford – открива ядрените превръщания при ядрени реакции;

- 1919 – Aston – разработва първия мас спектрометър;

- 1925 – Goudsmit, Uhlenbeck – собствен спин;

- 1928 – Gamov, Gurney, Condon – теория на α - разпада;

- 1930 – Pauli – неутринна хипотеза;

- 1931 – Van de Graaff – първи електростатичен ускорител;

- 1931 – Sloan, Lawrence – първи линеен ускорител;

- 1932 – Lawarence, Livingston – първи циклотрон;

- 1932 – Anderson – открива поситрона;

По важни събития от историята на ядрената физика

- 1932 – Chadwick – открива неутрона;



- 1932 – Cockcroft, Walton – ядрени реакции, чрез използване на ускорител;



- 1934 – I. Curie, F. Joliot – откриват изкуствената радиоактивност;



- 1934 – E. Fermi – теория на β -разпада;
- 1935 – Yukawa – мезонна хипотеза;
- 1935 – Bothe – предлага техниката на съвпадение;
- 1936 – N. Bohr – теория на съставното ядро;

По важни събития от историята на ядрената физика

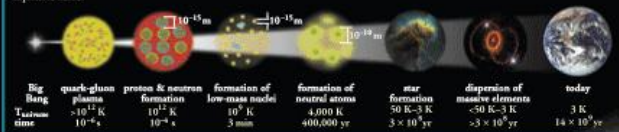
- 1938 – Hahn, Strassmann/Meitner, Frisch – откриват ядреното делене;
- 1938 – Bethe – ядреното сливане е енергетичния източник на звездите;
- 1939 – Borh, Wheeler – първи модел описващ ядреното делене;
- 1940 – McMillan, Seaborg – получават първия изкуствено създаден елемент;
- 1942 – E. Fermi – първи ядрен реактор;
- 1945 – първа ядрена бомба;
- 1946 – Gamow – Big Bang космология;
- 1946 – Bloch, Purcell – ядрено-магнитен резонанс;
- 1947 – Libby – радиоактивно датиране;
- 1949 – Mayer, Jensen, Haxel, Suess – слоест модел на атомното ядро;
- 1952 – първа термоядрена бомба;
- 1953 – A. Borh, B. Mottelson – колективен модел на атомното ядро;
- 1955 – Nilsson – деформиран слоест модел;

Ядрена физика

Nuclear Science

Expansion of the Universe

After the Big Bang, the universe expanded and cooled. At about 10^{-36} second, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. When the temperature of the 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, clumps 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 supernova debris.



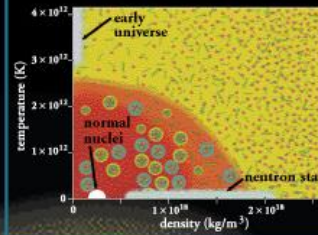
Nuclear Science is the study of the structure, properties, and interactions of the atomic nuclei. Nuclear scientists calculate and measure the masses, shapes, sizes, and decays of nuclei at rest and in collisions. They ask questions, such as: Why do nuclei stay in the nucleus? What combinations of protons 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^-)
- positron (e^+)
- neutrino (ν)
- antineutrino ($\bar{\nu}$)
- quark
- gluon field
- gluon
- photon (γ)

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

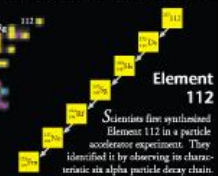
Phases of Nuclear Matter



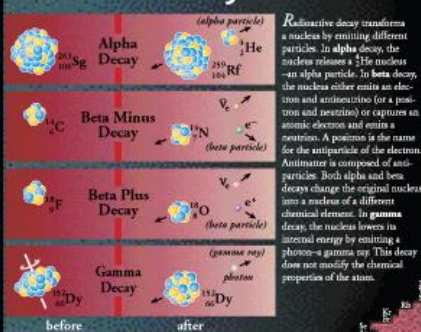
Nuclear matter can exist in several phases. When collisions excite nuclei, individual protons and neutrons may evaporate from the nuclear fluid. At sufficiently high temperature or density, a gas of nucleons (red background) forms. At even more extreme conditions, individual nucleons may cease to have 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 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 $Z \leq 112$.

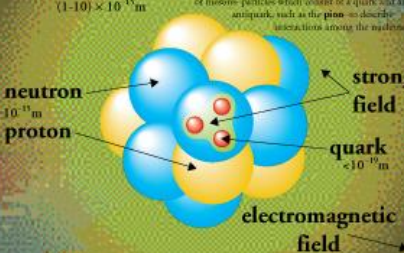


Radioactivity



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 (for 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 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.

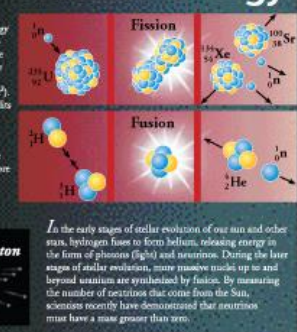
The Nucleus



At the center of the atom is a tiny, dense nucleus. The nucleus is made of protons and neutrons. Each nucleon is made from three quarks held together by strong interactions, which are mediated by gluons. In turn, the nucleus is held together by the strong interaction between the gluon and quark constituents of adjacent nucleons. Nuclear physics often uses the exchange of meson particles which consist of a quark and an antiquark, such as the pion, to describe interactions among the nucleons.

In an atom, electrons orbit the nucleus at distances typically up to 10,000 times the nuclear diameter. If the electron cloud were shrunk to the size of a small room, the nucleus would be a small speck.

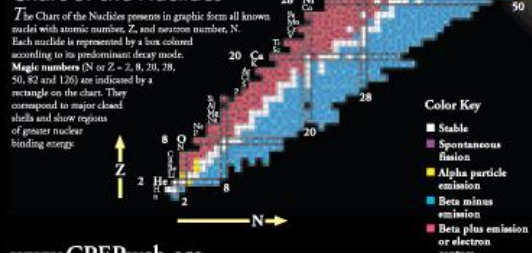
Nuclear Energy



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 give off 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.

Chart of the Nuclides



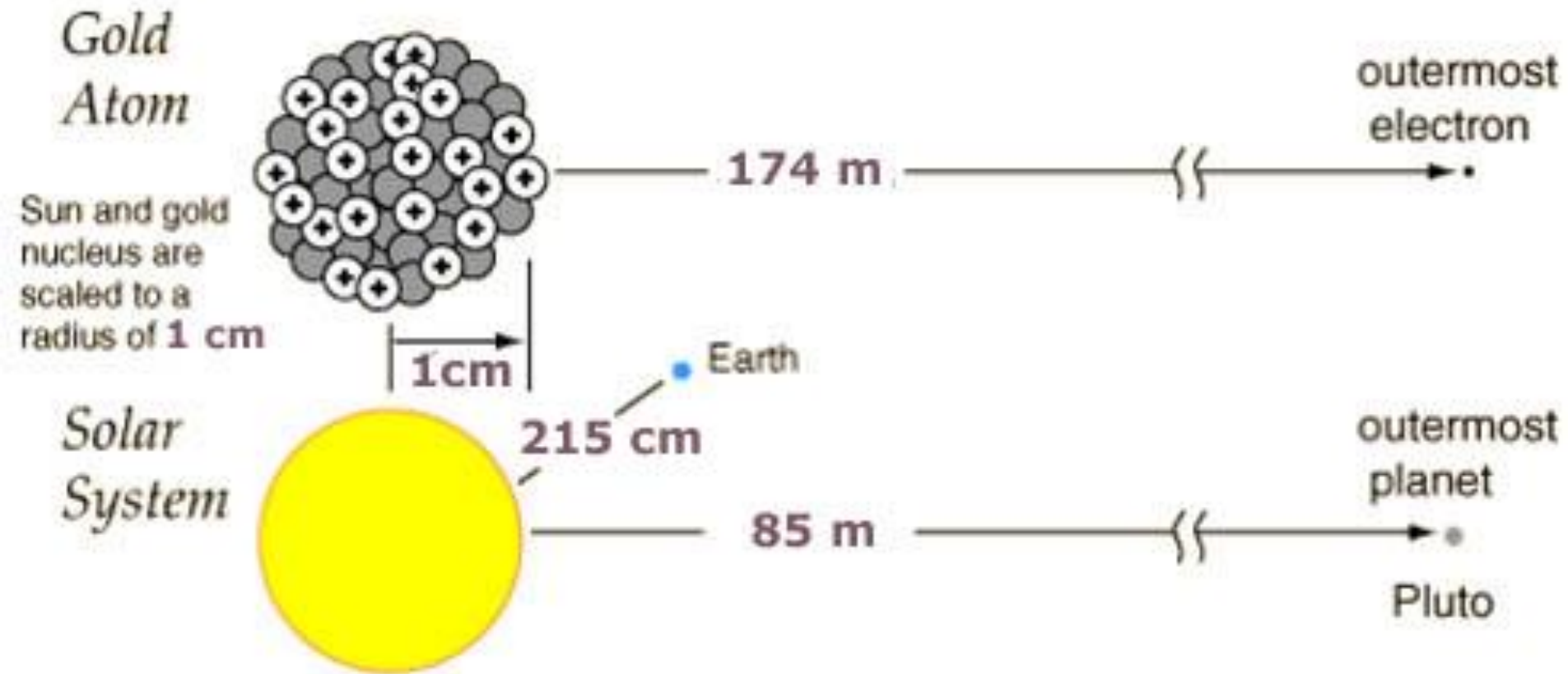
www.CPEPweb.org

Applications



Основни термини,
величини и размерности в
ядрената физика.

Скала на размерите в микросвета



Ако приемем че дължината на футболен стадион (~100 м) е равна на диаметъра на атома, то диаметъра на ядрото е колкото костилка от череша (~6 мм)

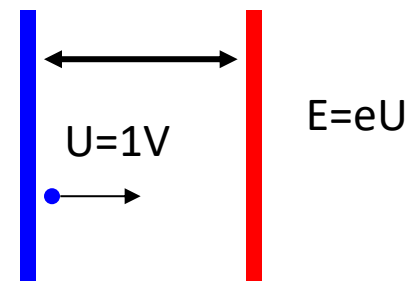
Единици за енергия

SI prefixes

1000^m	10^n	Prefix	Symbol	Since ^[1]	Short scale	Long scale	Decimal
1000^8	10^{24}	yotta-	Y	1991	Septillion	Quadrillion	1 000 000 000 000 000 000 000 000
1000^7	10^{21}	zetta-	Z	1991	Sextillion	Trilliard	1 000 000 000 000 000 000 000
1000^6	10^{18}	exa-	E	1975	Quintillion	Trillion	1 000 000 000 000 000 000
1000^5	10^{15}	peta-	P	1975	Quadrillion	Billiard	1 000 000 000 000 000
1000^4	10^{12}	tera-	T	1960	Trillion	Billion	1 000 000 000 000
1000^3	10^9	giga-	G	1960	Billion	Milliard	1 000 000 000
1000^2	10^6	mega-	M	1960	Million		1 000 000
1000^1	10^3	kilo-	k	1795	Thousand		1 000
$1000^{2/3}$	10^2	hecto-	h	1795	Hundred		100
$1000^{1/3}$	10^1	deca-	da	1795	Ten		10
1000^0	10^0	(none)	(none)	NA	One		1
$1000^{-1/3}$	10^{-1}	deci-	d	1795	Tenth		0.1
$1000^{-2/3}$	10^{-2}	centi-	c	1795	Hundredth		0.01
1000^{-1}	10^{-3}	milli-	m	1795	Thousandth		0.001
1000^{-2}	10^{-6}	micro-	μ	1960 ^[2]	Millionth		0.000 001
1000^{-3}	10^{-9}	nano-	n	1960	Billionth	Milliardth	0.000 000 001
1000^{-4}	10^{-12}	pico-	p	1960	Trillionth	Billionth	0.000 000 000 001
1000^{-5}	10^{-15}	femto-	f	1964	Quadrillionth	Billiardth	0.000 000 000 000 001
1000^{-6}	10^{-18}	atto-	a	1964	Quintillionth	Trillionth	0.000 000 000 000 000 001
1000^{-7}	10^{-21}	zepto-	z	1991	Sextillionth	Trilliardth	0.000 000 000 000 000 000 001
1000^{-8}	10^{-24}	yocto-	y	1991	Septillionth	Quadrillionth	0.000 000 000 000 000 000 000 001

- Енергия; $1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$

Типичните γ и β разпадания са $\sim 1 \text{ MeV}$



100 W ел. Крушка, за 1 час ще отдели:

$$E = P \cdot t = 100 \text{ W} (60 \times 60) \text{ s} = 360000 \text{ J}$$

$$= (3.6 \times 10^5 \text{ J}) / (1.602 \times 10^{-19} \text{ J / eV}) = 2.25 \times 10^{24} \text{ eV}$$

$$= 2.25 \text{ YeV}$$

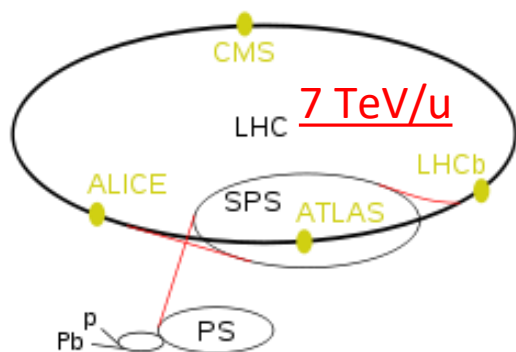
- Температурен еквивалент

$$\frac{1 \text{ eV}}{k_B} = \frac{1.60217653(14)10^{-19} \text{ J}}{1.3806505(24)10^{-23} \text{ J/K}}$$

$$= 11604.505(20) \text{ K} \propto 10^4 \text{ K}$$

Единици за енергия

Large Hadron Collider
протони до 7 TeV



Мравка тежаща 1 g се движи със скорост 5 cm/s

$$E = \frac{m v^2}{2} = \frac{(10^{-3} \text{ kg}) (5 \times 10^{-2} \text{ m / s})^2}{2} = 1.25 \times 10^{-6} \text{ J}$$

$$= \frac{1.25 \times 10^{-6} \text{ J}}{1.602 \times 10^{-19} \text{ J / eV}} = 0.78 \times 10^{13} \text{ eV} = 7.8 \text{ TeV}$$

Колко нуклеона има в една мравка (от C)?

$$\# (\text{C}) = \frac{1 \text{ g}}{12} 6.022 \times 10^{23} \text{ mol / g} = 5 \times 10^{22}$$

$$E / \text{нук} = 1.6 \times 10^{-9} \text{ eV / u}$$

$$\# (\text{p}) + \# (\text{n}) = (6 + 6) \times \# (\text{C}) = 5 \times 10^{23} \text{ u}$$

$$N_A = 6.022 \times 10^{23} \text{ mol / g}$$

- 210 MeV – средната енергия отделяна при деленето едно ядро ^{239}Pu
- 200 MeV – средната енергия отделяна при деленето едно ядро ^{235}U

Тропилов еквивалент: $\mu\text{t}(\text{gTNT})$, $\text{mt}(\text{kgTNT})$, $\text{t}(\text{tTNT})$, $\text{kt}(\text{ktTNT})$

$$1 \text{ gram TNT} = 4184 \text{ J}$$

- 13.6 eV – йонизационната енергия на водорода
- 1/40 eV – топлината енергия при стайна температура

Единици за енергия

Температурен ефект на освободената при разпад енергия



Колко грама ^{238}U са необходими за да се загрее даденото количество вода до 100°C ? Каква е плътността на отделяната топлинна енергия за единица време?

$$Q = \Delta T c(\text{H}_2\text{O}) m(\text{H}_2\text{O}) \quad c(\text{H}_2\text{O}) = 4.1855 \text{ J/gK} \quad Q = 6.7 \times 10^4 \text{ J}$$
$$\Delta T = (100 - 20)^{\circ} \text{ C} \quad E_{\alpha} = 4 \text{ MeV} = 4 \times 1.6 \times 10^{-13} \text{ J} = 6.4 \times 10^{-13} \text{ J}$$
$$\frac{Q}{E_{\alpha}} = \frac{6.7 \times 10^4}{6.4 \times 10^{-13}} = 10^{17} \alpha' \text{s} \quad \rightarrow 10^{17} \text{ } ^{238}\text{U} \quad \frac{m}{\mu} = \frac{N}{N_A} \quad m = \frac{10^{17}}{6.022 \times 10^{23}} \times 238 = 40 \times 10^{-6} \text{ g} = 40 \text{ } \mu\text{g}$$

$$1\text{kg H}_2\text{O} \rightarrow 200 \text{ } \mu\text{g } ^{238}\text{U}$$

$$1\text{t H}_2\text{O} \rightarrow 200 \text{ mg } ^{238}\text{U}$$

$$5\text{t H}_2\text{O} \rightarrow 1 \text{ g } ^{238}\text{U}$$

$$N(t) = N_0 e^{-\lambda t}$$

$$\lambda = \frac{1}{\tau} = \frac{\ln 2}{T_{1/2}}$$

$$T_{1/2}(^{238}\text{U}) = 4.468 \times 10^9 \text{ y}$$

$$\lambda(^{238}\text{U}) = 1.5 \times 10^{-8} \text{ y}^{-1}$$

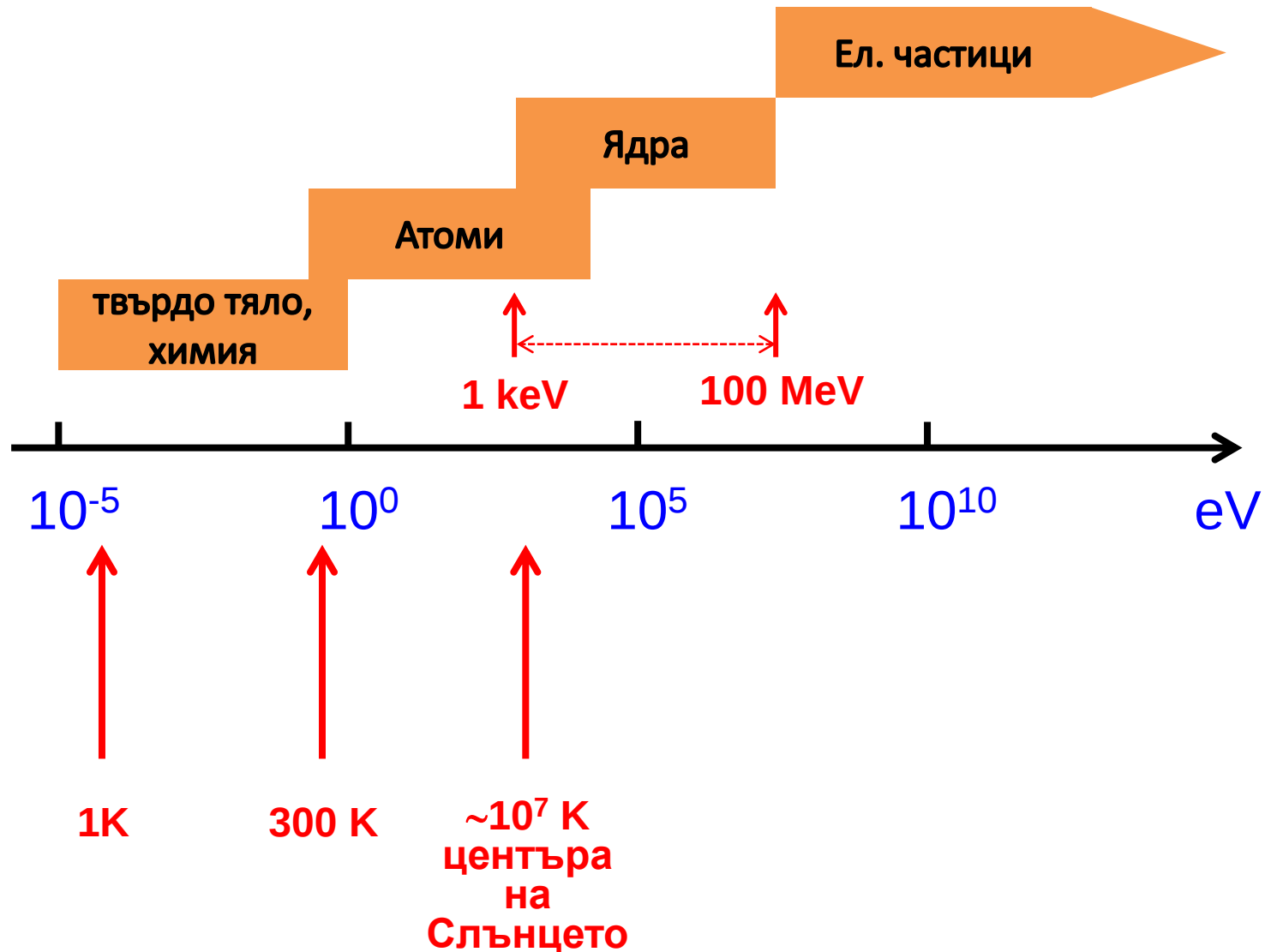
$$A = \lambda N = 1.5 \times 10^{-8} \text{ y}^{-1} 10^{17} = 1.5 \times 10^9 \text{ r/y}$$

$$\rightarrow 6 \times 10^9 \text{ MeV/y} \approx 1 \times 10^{-3} \text{ J/y}$$

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$

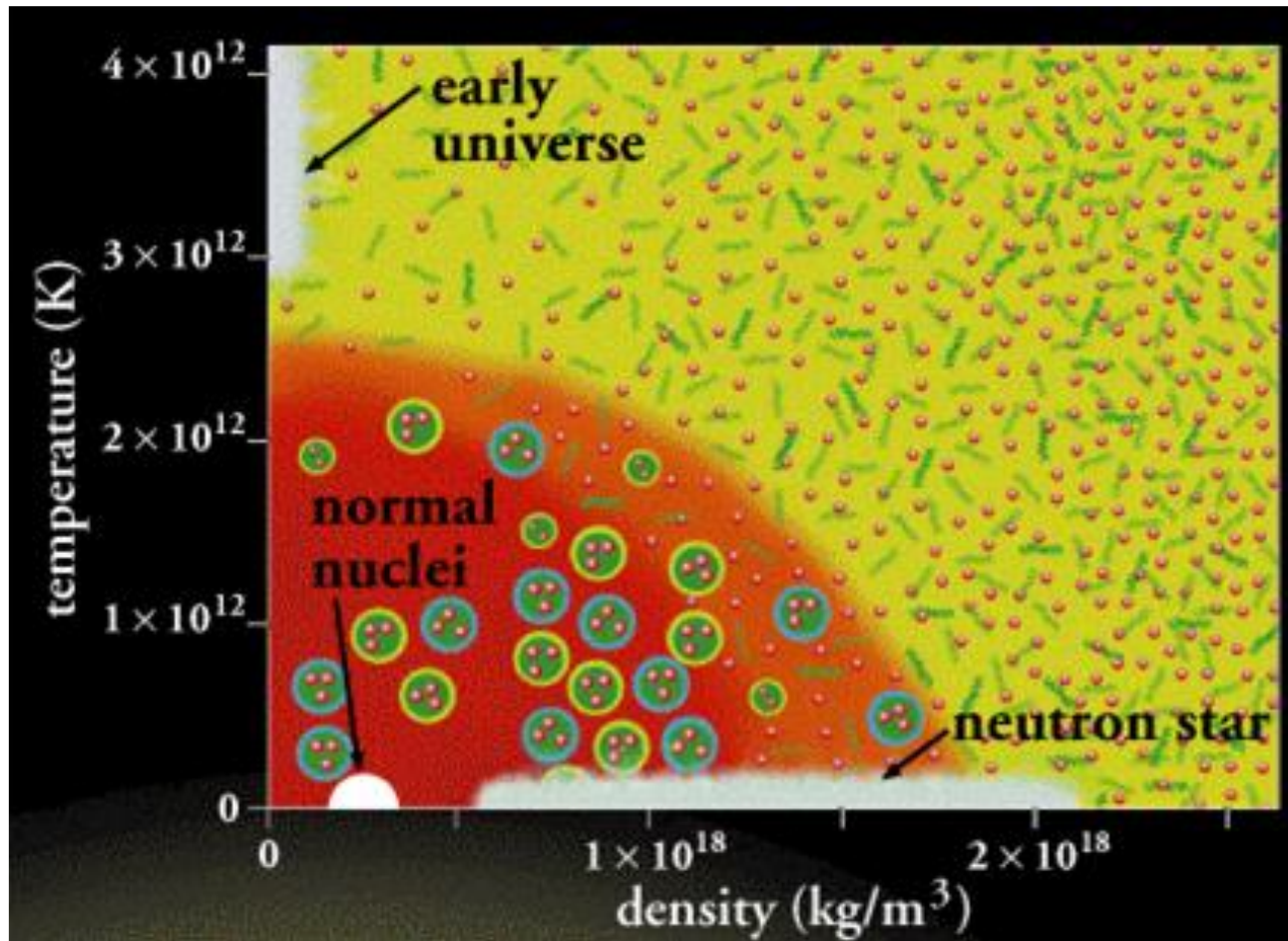
$$t = 6.7 \times 10^7 \text{ y}$$

Енергетична скала в ядрената физика



Плътност на ядрената материя

$$\rho = \frac{M_N}{\frac{4\pi}{3} R_N^3} = \frac{Am_n}{\frac{4\pi}{3} (1.2\text{fm } A^{1/3})^3} = \frac{m_n}{7.2\text{fm}^3} = \frac{1.66 \times 10^{-27} \text{kg}}{7.2 \times 10^{-45} \text{m}^3} = 2.3 \times 10^{17} \text{kg/m}^3$$



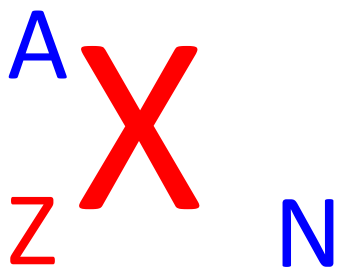
Основни означения

1932 - Chadwick – открива нейтрона – **електрически неутрална частица** с маса

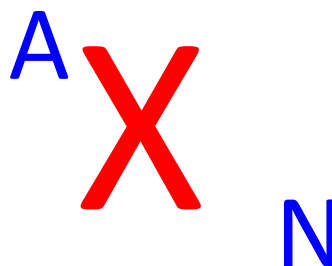
$$m_n \approx m_p \quad (m_p = 938.272 \text{ MeV}, m_n = 939.566 \text{ MeV}, \Delta m = 1.293 \text{ MeV})$$

{**протон**, **неутрон**} $\equiv$ **нуклеон**

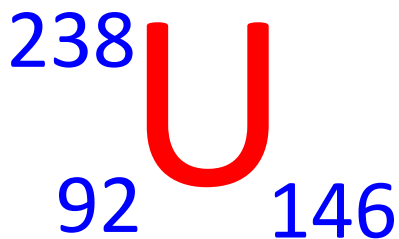
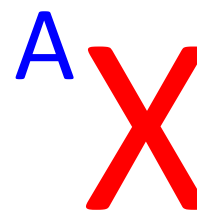
$$\text{ЯДРО} \equiv Z, N, A = N + Z$$



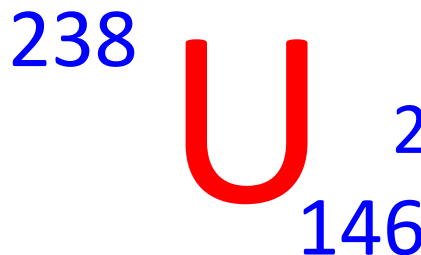
$$X \equiv Z$$



$$A = N + Z$$



$$U \equiv 92$$



$$238 = 146 + 92$$



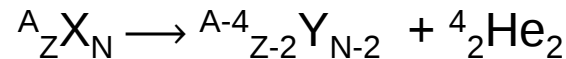
Z – константа – **ИЗОТОПИ** (^{112}Sn , ^{114}Sn , ^{115}Sn , ^{116}Sn , ^{118}Sn , ^{120}Sn)

N – константа – **ИЗОТОНИ** (^{132}Te , ^{134}Xe , ^{136}Ba , ^{138}Ce)

Основни свойства на ядрата

- маса – измерва се в обобщени атомни маси (относителна единица):
 $m(^{12}\text{C}) = 12\text{u} \Rightarrow 1\text{u} = 931.502 \text{ MeV}$;
- радиус – типичните разстояния в ядрото $\propto 10^{-15} \text{ m} = 1 \text{ fm}$ (1 Fermi);
- относително разпространение на изотопите (за стабилните нуклиди);
- канали на разпад и времена на полуразпад (за радиоактивните нуклиди):

➤ α разпад -



$$E_\alpha \approx 5 \text{ MeV}, T_{1/2} \approx \text{min} \div \mu\text{s}, \text{ но}$$

$$T_{1/2}(^{238}\text{U}) = 4.46 \times 10^9 \text{ y}, T_{1/2}(^{232}\text{Th}) = 1.4 \times 10^{10} \text{ y}$$

➤ β разпад - ${}^A_Z\text{X}_N \longrightarrow {}^A_{Z+1}\text{Y}_{N-1} + e^- + \tilde{\nu}_e$ β - минус ${}^{140}_{54}\text{Xe}_{86} \longrightarrow {}^{140}_{55}\text{Cs}_{85} + e^- + \tilde{\nu}_e$



$$E_\beta \leq 1 \text{ MeV}, T_{1/2} \approx \text{ms} \div \text{days},$$

Основни свойства на ядрата

- **γ разпад** - електромагнитно лъчение

$$E_{\gamma} \approx 0.05 \div 20 \text{ MeV}, T_{1/2} \approx \text{ns} \div \text{fs}, \text{ но}$$

съществуват и така наречените ядрени изомери:

$$T_{1/2}({}^{99}\text{Tc}) = 6.02 \text{ h}, T_{1/2}({}^{95}\text{Tc}) = 61 \text{ days}$$

$$T_{1/2}({}^{180}\text{Ta}) = 1.2 \times 10^{15} \text{ y}, T_{1/2}({}^{178}\text{Hf}) = 31 \text{ y}$$

α разпад
**силно ядрено
взаимодействие**

β разпад
**слабо ядрено
взаимодействие**

γ разпад
**електромагнитно
взаимодействие**

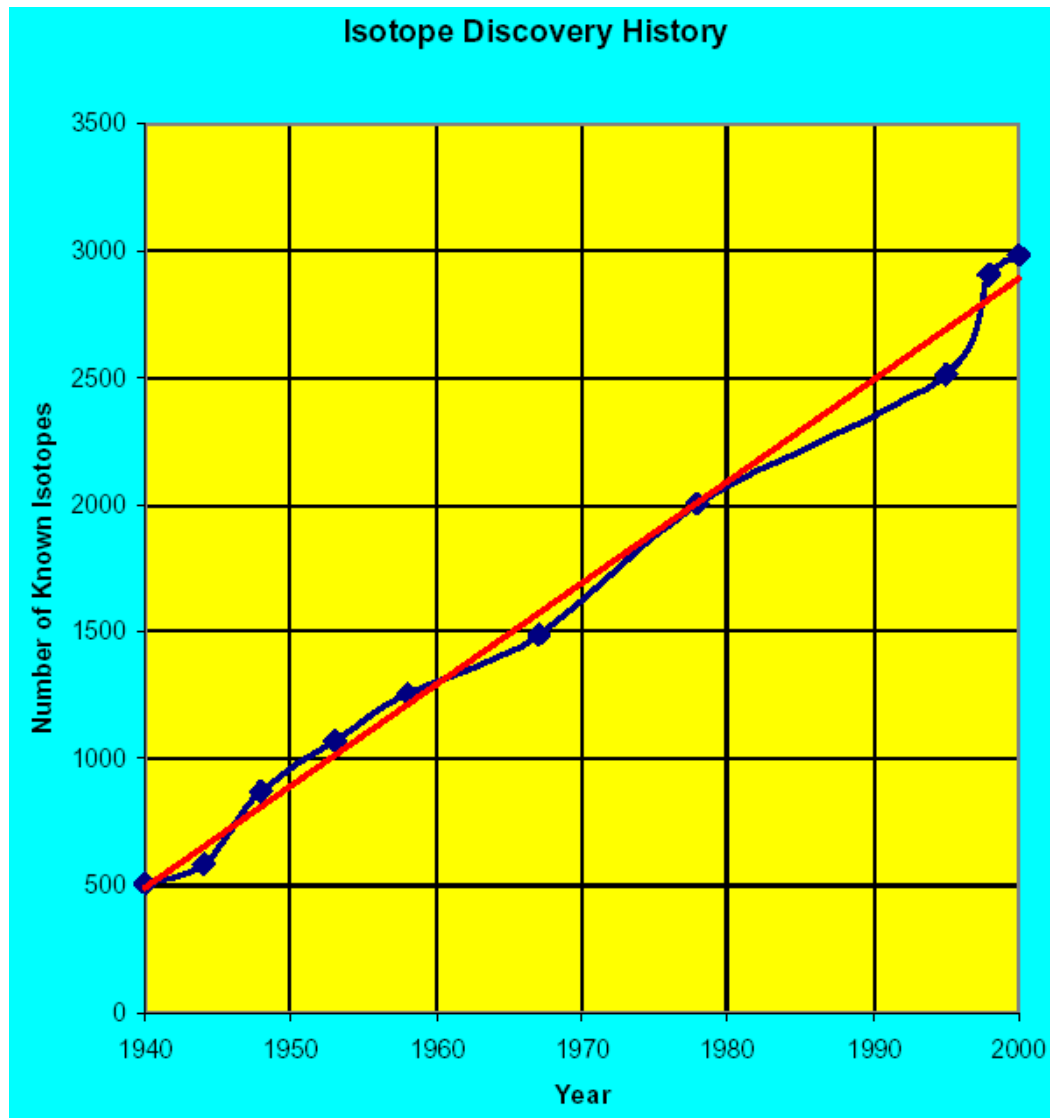
- **спонтанно делене** - ${}^A\text{X} \longrightarrow {}^{A_1}\text{Y} + {}^{A_2}\text{Z} + \text{Nn}, A > 230$
- **редки разпади** - с излъчване на един, два протона (${}^{113}\text{Cs} \longrightarrow {}^{112}\text{Xe} + \text{p}$),
неутрон (${}^{13}\text{Be} \longrightarrow {}^{12}\text{Be} + \text{n}$), ядрени клъстери ${}^8\text{Be}, {}^{12}\text{C}, {}^{16}\text{O}$ (${}^{114}\text{Ba} \longrightarrow {}^{102}\text{Sn} + {}^{12}\text{C}$);

- възможни реакции и сечения за тях
- възбудени състояния – енергия на възбуждане, спин, вероятности за електромагнитни преходи между тях, мултиполни моменти;

Фундаментални взаимодействия

Взаимодействие	Проявление	Сила	Обсег	Преносител
Силно ядрено	Свързва протоните и неутроните в ядро	1	10^{-15} m	глюони m=0 spin=1
Електромагнитно	Обуславя взаимодействиет о м/у заредени частици	1/137	∞	Фотон m = 0 spin = 1
Слабо ядрено	β -разпад	10^{-6}	10^{-18} m (0.1%D(p))	Векторни бозони W^+ , W^- , Z^0 m > 80 GeV spin = 1
Гравитация	Обуславя взаимодействиет о м/у масови обекти	6×10^{-34}	∞	гравитон(??) $m_g < 1.2 \times 10^{-22}$ eV spin = 2

Карта на нуклидите



- До днес са идентифицирани около 3000 нуклида;
- От тях само 284 са стабилни;
- Известни са 118 химични елемента:
 - 116 – Livermorium
 - 117 – Tennessine
 - 118 – Oganesson