

Bulgarian Teacher Programme CERN 2017

УЧИТЕЛСКИ КВАЛИФИКАЦИОНЕН КУРС ЦЕРН 2017

Атомни ядра: основни градивни клетки на материята

Георги Райновски

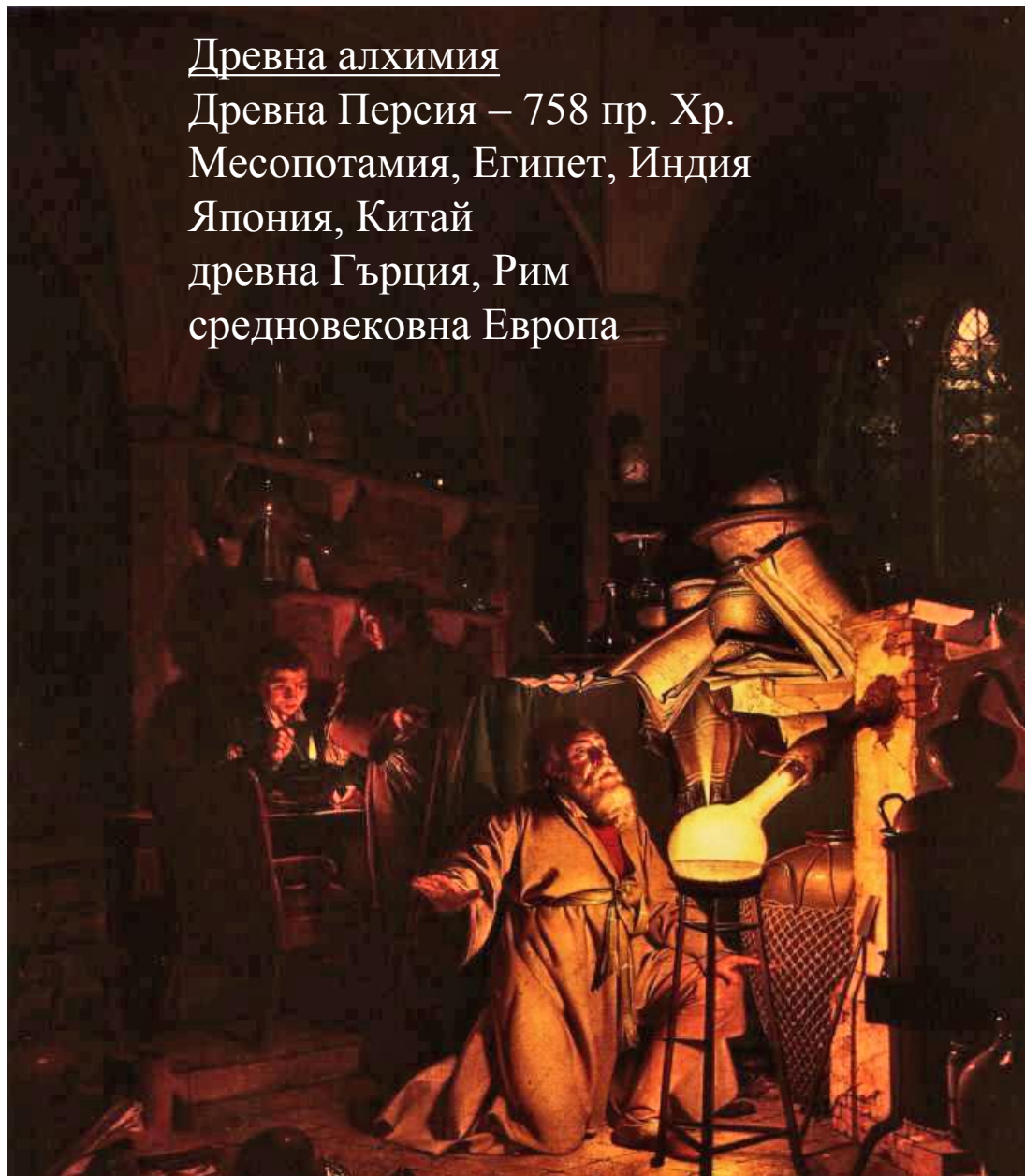


**Софийски Университет
Св. Климент Охридски**

От какво е изграден светът?

Древна алхимия

Древна Персия – 758 пр. Хр.
Месопотамия, Египет, Индия
Япония, Китай
древна Гърция, Рим
средновековна Европа



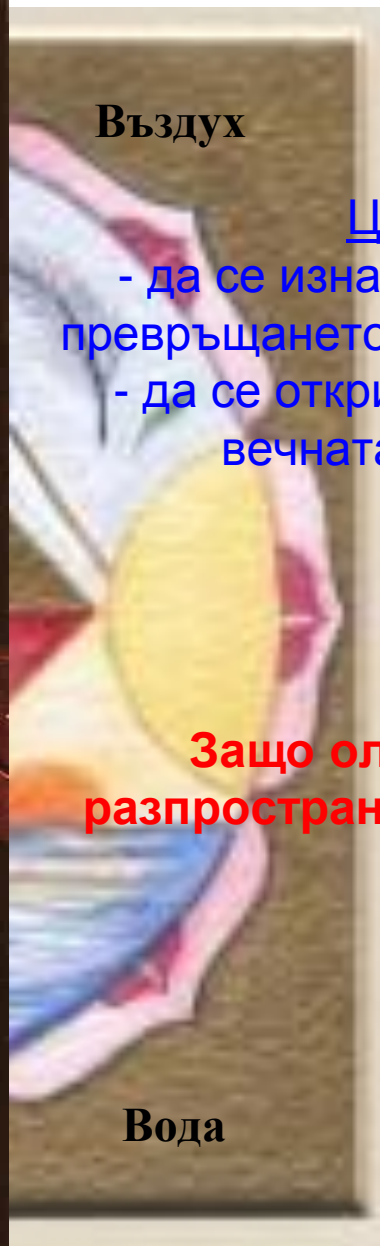
Въздух

Цели:

- да се изнамери метод за превръщането оловото в злато
- да се открие еликсира на вечната младост

Защо оловото е по-разпространено от златото?

Вода



Какъв е произхода на химичните елементите

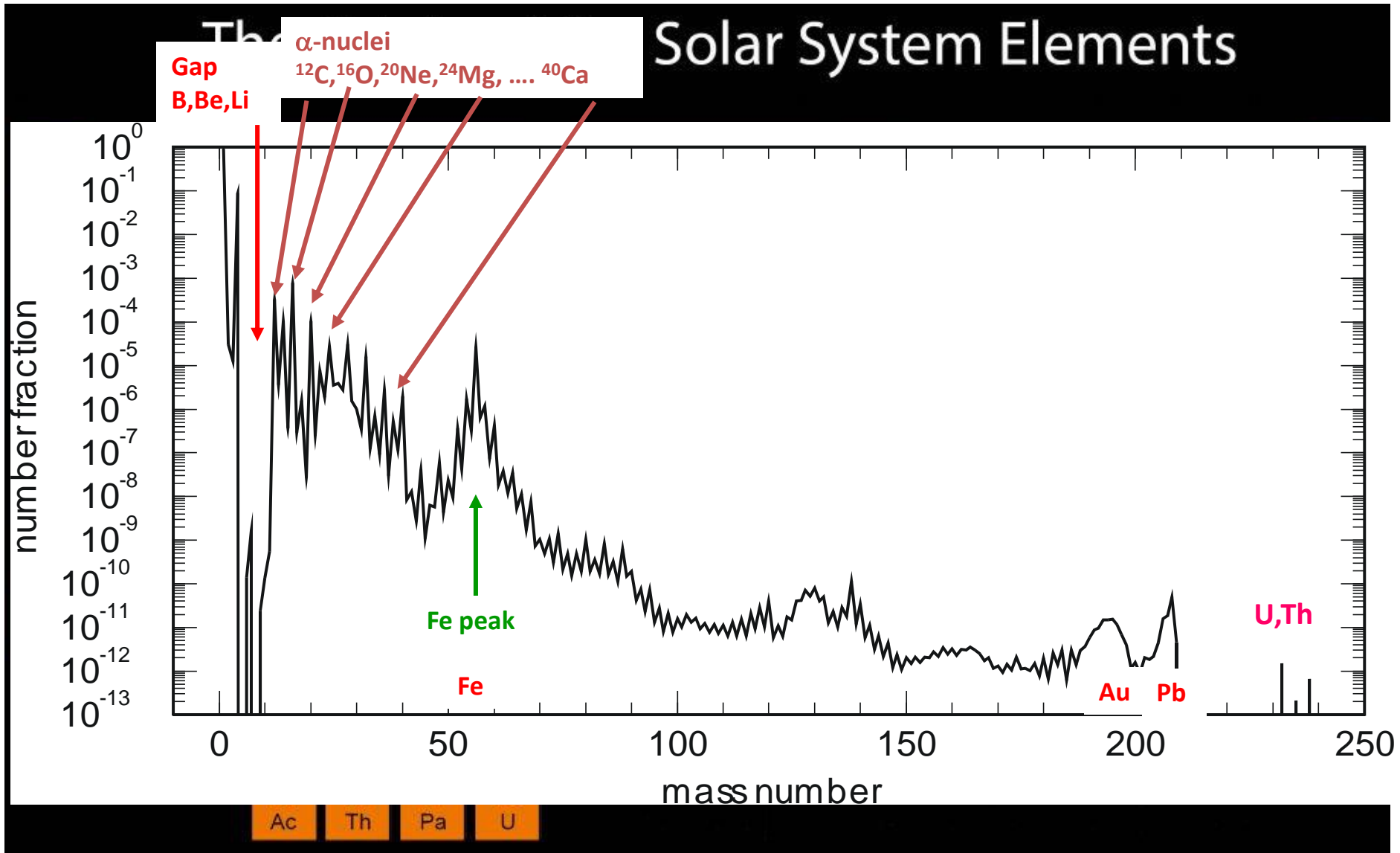
Periodic Table of the Elements

1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.384	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [209]	86 Rn Radon [222]
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Nh Nihonium unknown	114 Fl Flerovium [289]	115 Mc Moscovium unknown	116 Lv Livermorium [293]	117 Ts Tennessine unknown	118 Og Oganesson unknown

57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

- Alkali Metal
- Alkaline Earth
- Transition Metal
- Basic Metal
- Semimetal
- Nonmetal
- Halogen
- Noble Gas
- Lanthanide
- Actinide

Какъв е произхода на химичните елементи



Ядрена физика

Expansion of the Universe

Radioactivity

Alpha Decay
 ${}_{106}^{263}\text{Sg} \rightarrow {}_{104}^{259}\text{Rf} + {}_2^4\text{He}$ (alpha particle)

Beta Minus Decay
 ${}_{6}^{14}\text{C} \rightarrow {}_{7}^{14}\text{N} + e^{-} + \bar{\nu}_e$ (beta particle)

Beta Plus Decay
 ${}_{9}^{18}\text{F} \rightarrow {}_{8}^{18}\text{O} + e^{+} + \nu_e$ (beta particle)

Radioactive decay transforms a nucleus by emitting different particles. In **alpha** decay, the nucleus releases a ${}_{2}^4\text{He}$ 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 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



6 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.

Nuclear Energy

Fission
 ${}_{92}^{235}\text{U} + {}_0^1\text{n} \rightarrow {}_{54}^{134}\text{Xe} + {}_{38}^{100}\text{Sr} + {}_0^1\text{n}$

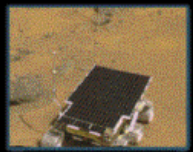
Fusion
 ${}_{1}^2\text{H} + {}_{1}^3\text{H} \rightarrow {}_{2}^4\text{He} + {}_0^1\text{n}$

In the early stages of stellar evolution of our sun and other

Applications



Radioactive Dating
 Naturally occurring radioactive isotopes such as ${}_{6}^{14}\text{C}$ 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.



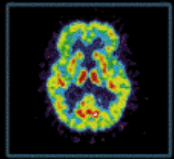
Space Exploration
 Sojourner used alpha particles to identify chemical elements present in Martian rocks. On Earth, nuclear reactions are used in many areas from criminal investigations to art authentication.



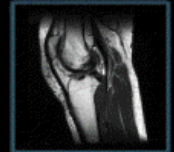
Nuclear Reactors
 Nuclear reactors use the fission of ${}_{92}^{235}\text{U}$ or ${}_{94}^{239}\text{Pu}$ nuclei to produce electric power. Reactors and most other nuclear applications generate radioactive waste; disposal of this waste is a subject of current research.



Smoke Detectors
 Many smoke detectors use a small amount of the alpha emitter ${}_{95}^{241}\text{Am}$ to ionize the air. Smoke entering the detector reduces the current and sets off the alarm.



Nuclear Medicine
 Radioactive isotopes, such as ${}_{43}^{99m}\text{Tc}$, ${}_{27}^{60}\text{Co}$ and ${}_{53}^{131}\text{I}$, are commonly used in the diagnosis and treatment of disease. Positron emitters such as ${}_{9}\text{F}^{18}$ are used in Positron Emission Tomography (PET) to generate images of brain activity.



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.

Основни величини и задачи в ядрената физика

- Енергия – маса на ядрата, енергия на възбудени ядрени състояния;
- Пространствено разпределение на ядрената материя – ядрени радиуси, моменти и ориентация;
- Вероятности – за разпад (времена живот \leftrightarrow закон за радиоактивното разпадане) или реакции (сечения за реакции);

Права (фундаментална) задача

На базата на експериментално изследване на ядрени лъчения се определят характеристики на ядрени състояния:

- Ядрени модели – ядрен много-частичен проблем и ядрена структура;
- Параметри за астрофизични и космологични модели;

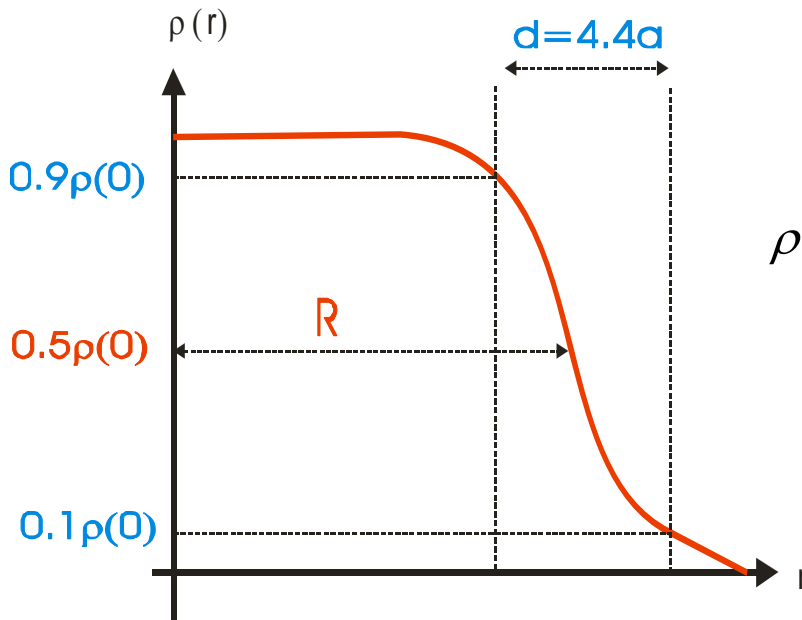
Обратна (приложна) задача

На базата на известни ядрени характеристики да се използват ядрените лъчения и реакции:

- Радиоекология;
- Ядрена енергетика – реактори и батерии;
- Датиране;
- Нуклеарна медицина – диагностика и терапия;
-

Единици в ядрената физика - разстояния

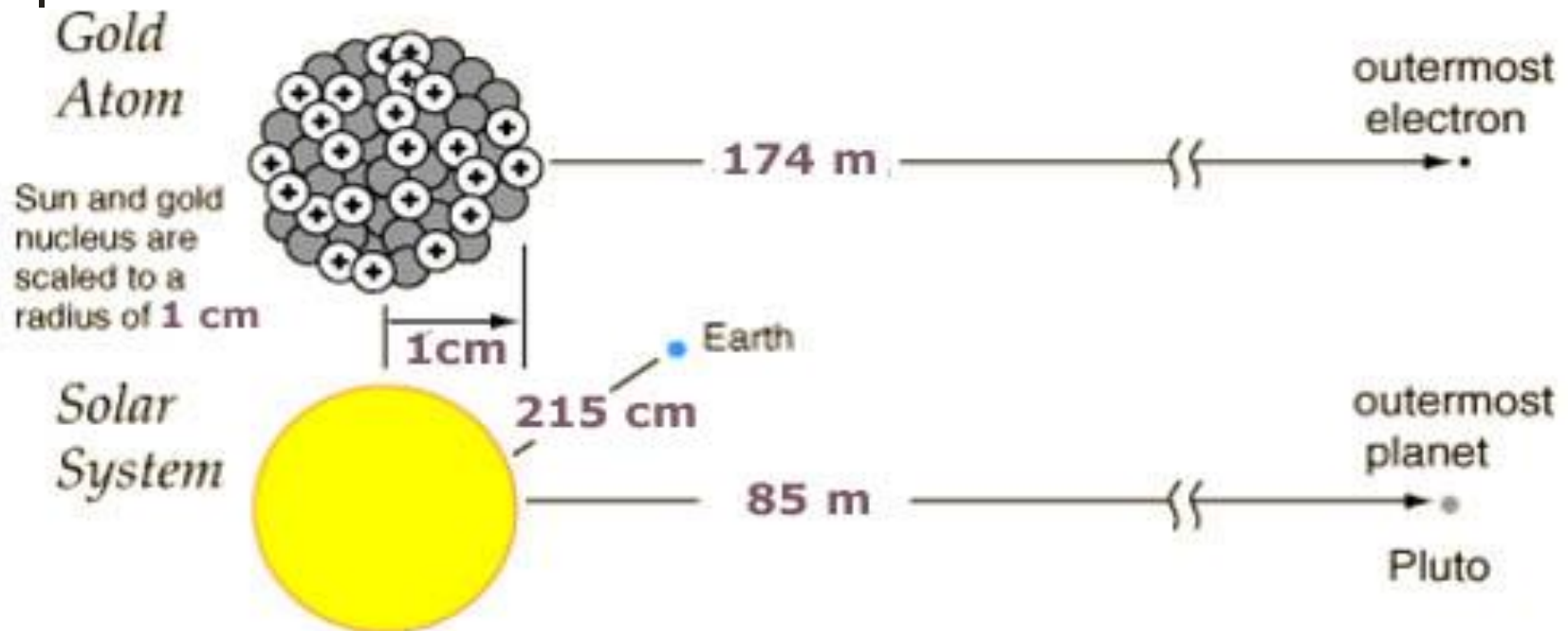
Функция на Ферми



$$\rho(r = R) = 0.5\rho_0 \quad \frac{A}{(4/3)\pi R^3} \sim \text{const} \Rightarrow R = \text{const} \cdot A^{1/3}$$

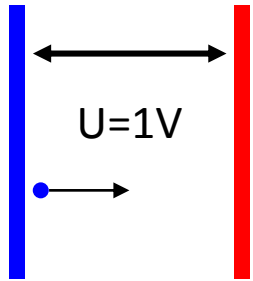
$$R = 1.23(2)A^{1/3} \text{ (fm)}$$

$$1 \text{ fm} = 10^{-15} \text{ m}$$



Единици в ядрената физика - енергия

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



$$E = eU$$

Типичните енергии за γ и β разпади са $\sim 1 \text{ MeV}$, за $\alpha \sim 5-6 \text{ MeV}$

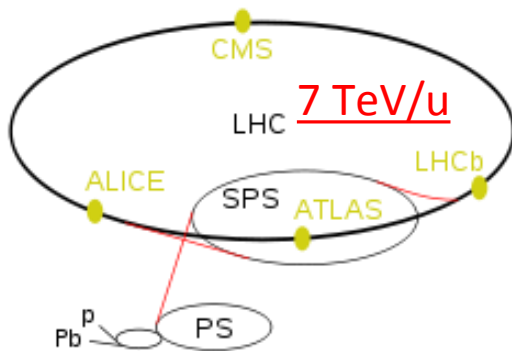
100 W електрическа крушка, за 1 час ще отдели:

$$E = P.t = 100 \text{ W} \cdot 3.6 \times 10^4 \text{ s} = 3.6 \times 10^5 \text{ J} = (3.6 \times 10^5 \text{ J}) / (1.602 \times 10^{-19} \text{ J/eV}) = 2.25 \times 10^{24} \text{ eV} = 2.25 \text{ YeV}$$

- Температурен еквивалент

$$\frac{1 \text{ eV}}{k_B} = \frac{1.60217653(14)10^{-19} \text{ J}}{1.3806505(24)10^{-23} \text{ J/K}} = 11604.505(20) \text{ K} \propto 10^4 \text{ K}$$

Large Hadron Collider
протони до 7 TeV



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

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

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

Колко нуклеона има в една мравка (от C)?

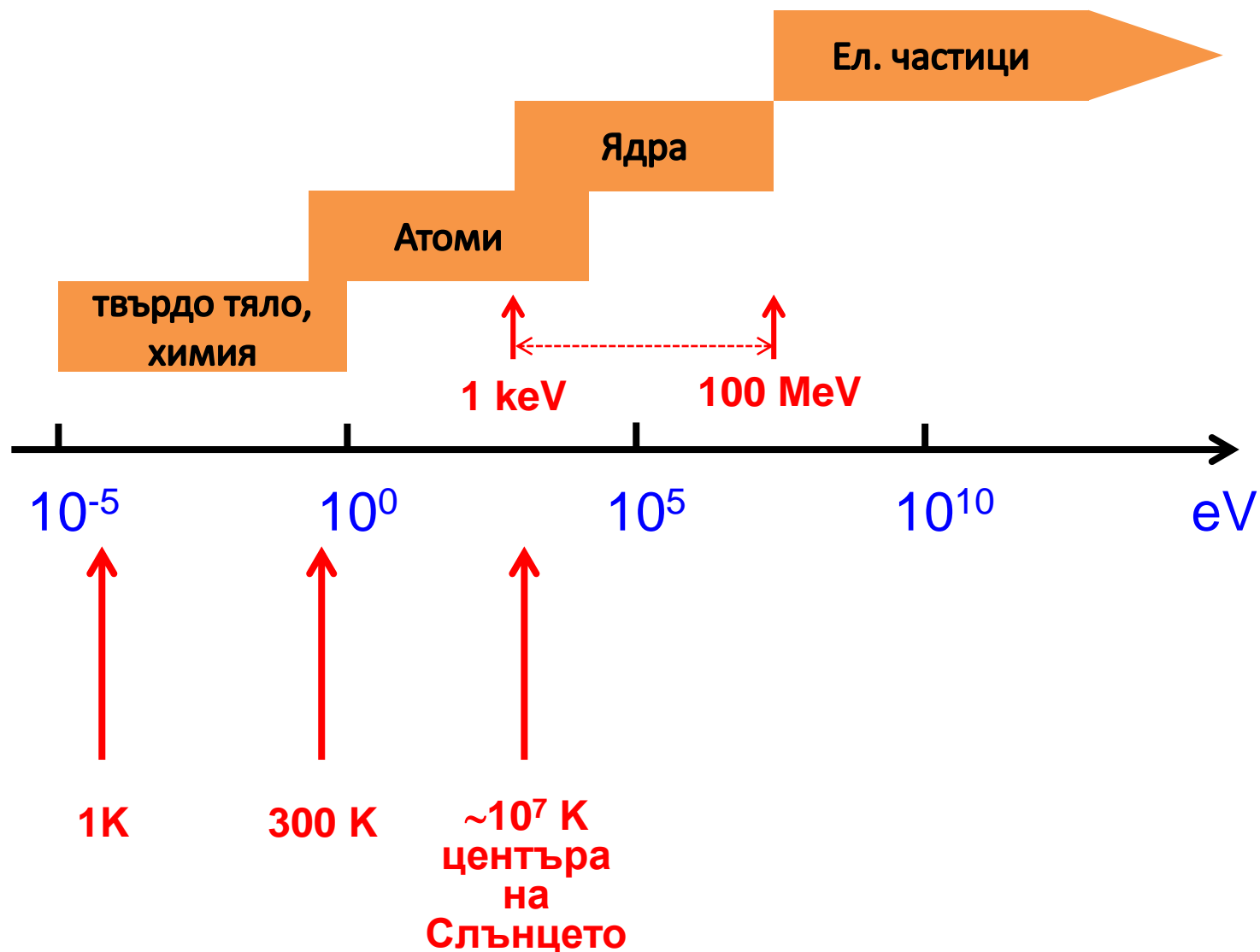
$$N_A = 6.022 \cdot 10^{23} \text{ mol}^{-1}$$

$$\# \text{ C} = \frac{1 \text{ g}}{12} \cdot 6.022 \cdot 10^{23} \text{ mol}^{-1} = 5 \cdot 10^{22}$$

$$E_{\text{нук}} = 1.6 \cdot 10^{19} \text{ eV}$$

$$\# \text{ p} = \# \text{ n} = 6 \cdot 6 \cdot \# \text{ C} = 5 \cdot 10^{23} \text{ u}$$

Физика на микросвета – разделение по енергии



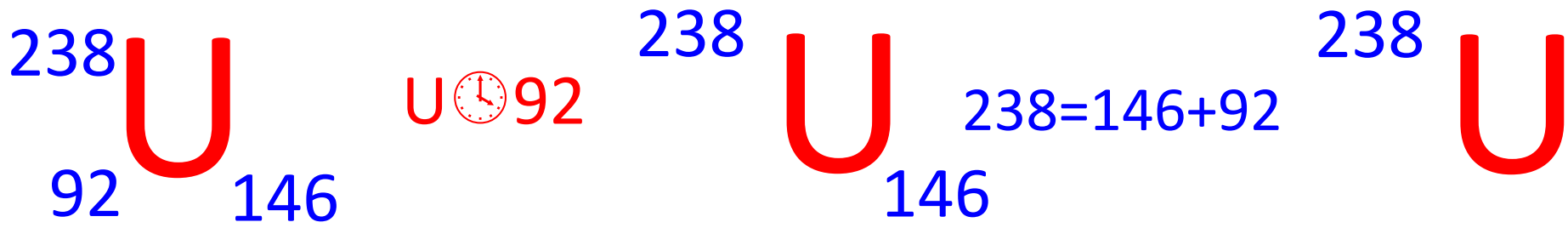
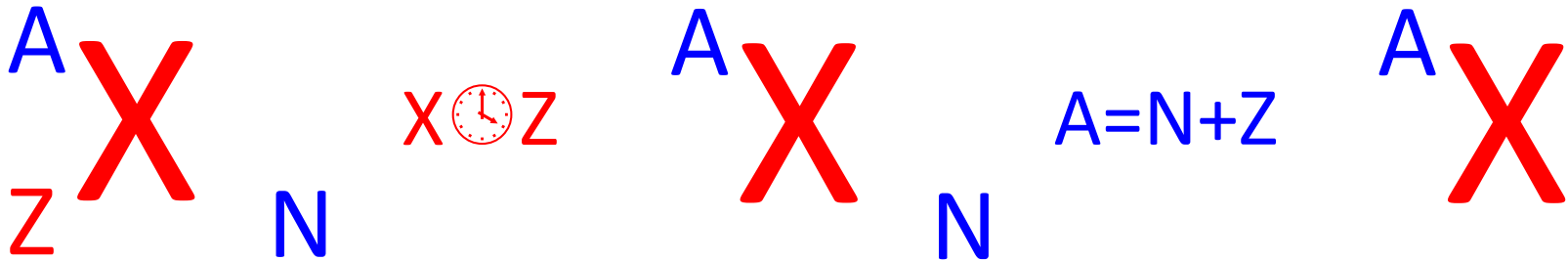
Основни означения

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

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

{**протон, неутрон**} ⌚ **нуклеон**

ЯДРО ⌚ **Z, N, A=N+Z**



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

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

Ядрена маса и енергия на свързване

$$m(N, Z)c^2 = m_{\text{атом}}c^2 - Zm_e c^2 + \sum_{i=1}^Z B_i^e$$

$$B_i^e \approx 10 - 100 \text{ keV}$$
$$m(N, Z) = A \cdot 1000 \text{ MeV}$$

10^{-6}

$$B(N, Z) = (Zm_p + Nm_n - (m_{\text{атом}} - Zm_e))c^2$$

$$B(N, Z) = (Z({}^1\text{H}) + Nm_n - m_{\text{атом}})c^2$$

По дефиниция: $1 \text{ u (amu)} = 1/12 M({}^{12}\text{C})$ или $M({}^{12}\text{C}) = 12 \text{ u}$

$$1 \text{ u} = 1.6605 \cdot 10^{-24} \text{ g}$$
$$c^2 = 931.494 \text{ MeV/u}$$

$$m_p = 1.00782503207(10) \text{ u}$$
$$m_n = 1.0086649157(6) \text{ u}$$

Експериментално определяне на ядрените маси

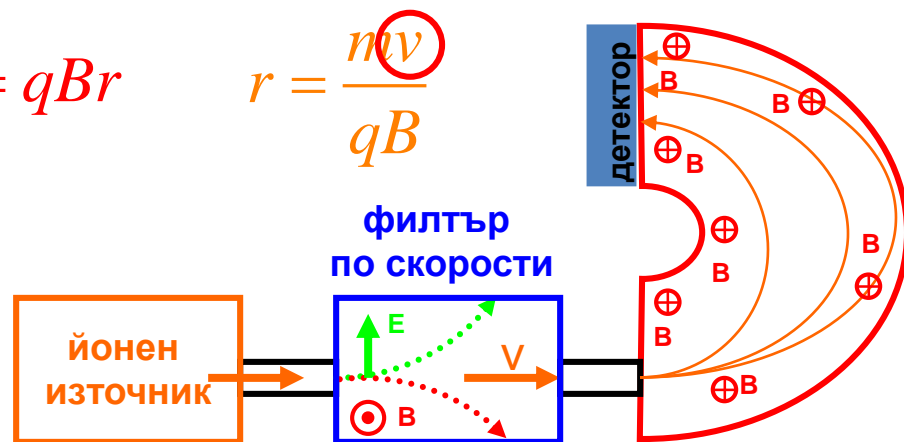
Мас спектроскопия

$$qE = qvB$$

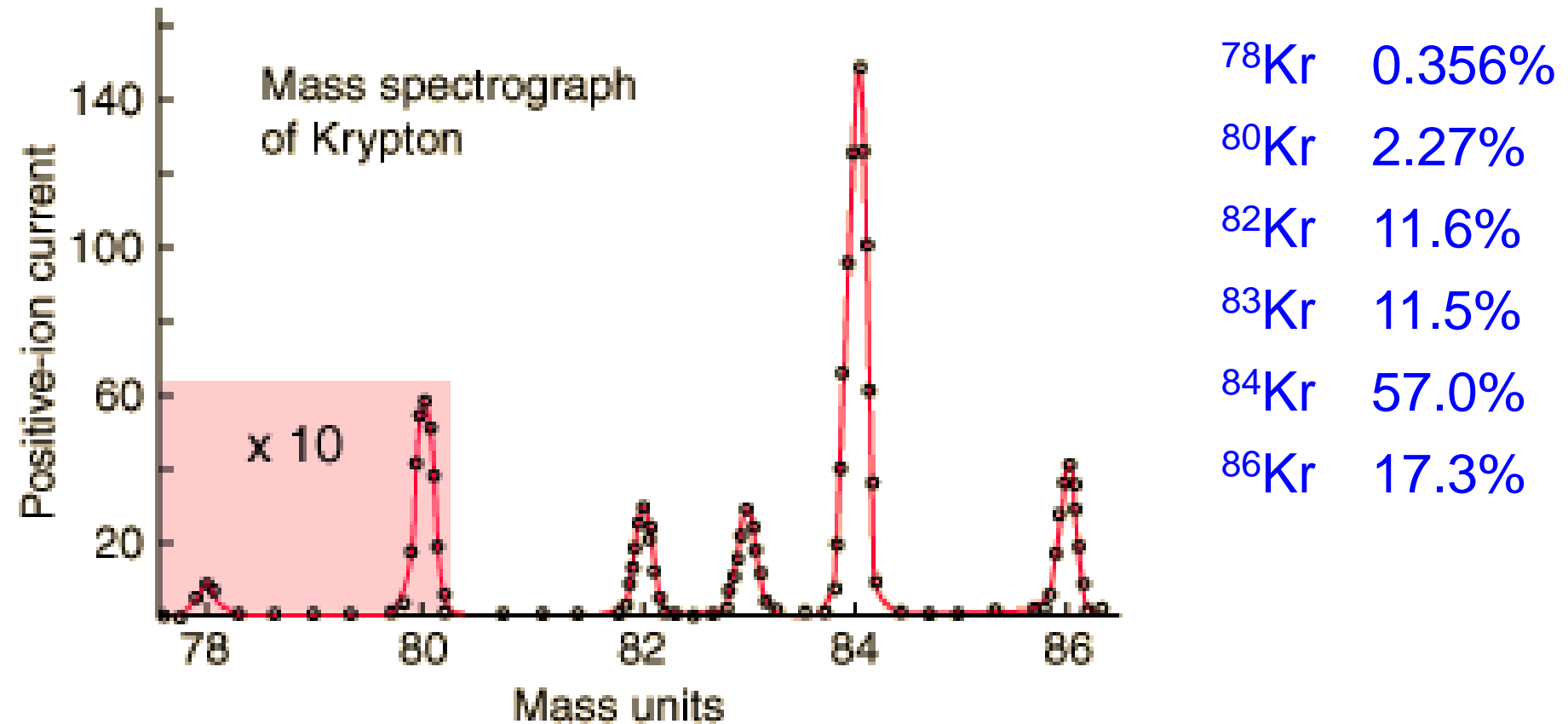
$$v = \frac{E}{B}$$

$$m = \frac{qrB^2}{E}$$

$$mv = qBr \quad r = \frac{mv}{qB}$$



Разпространение на изотопите

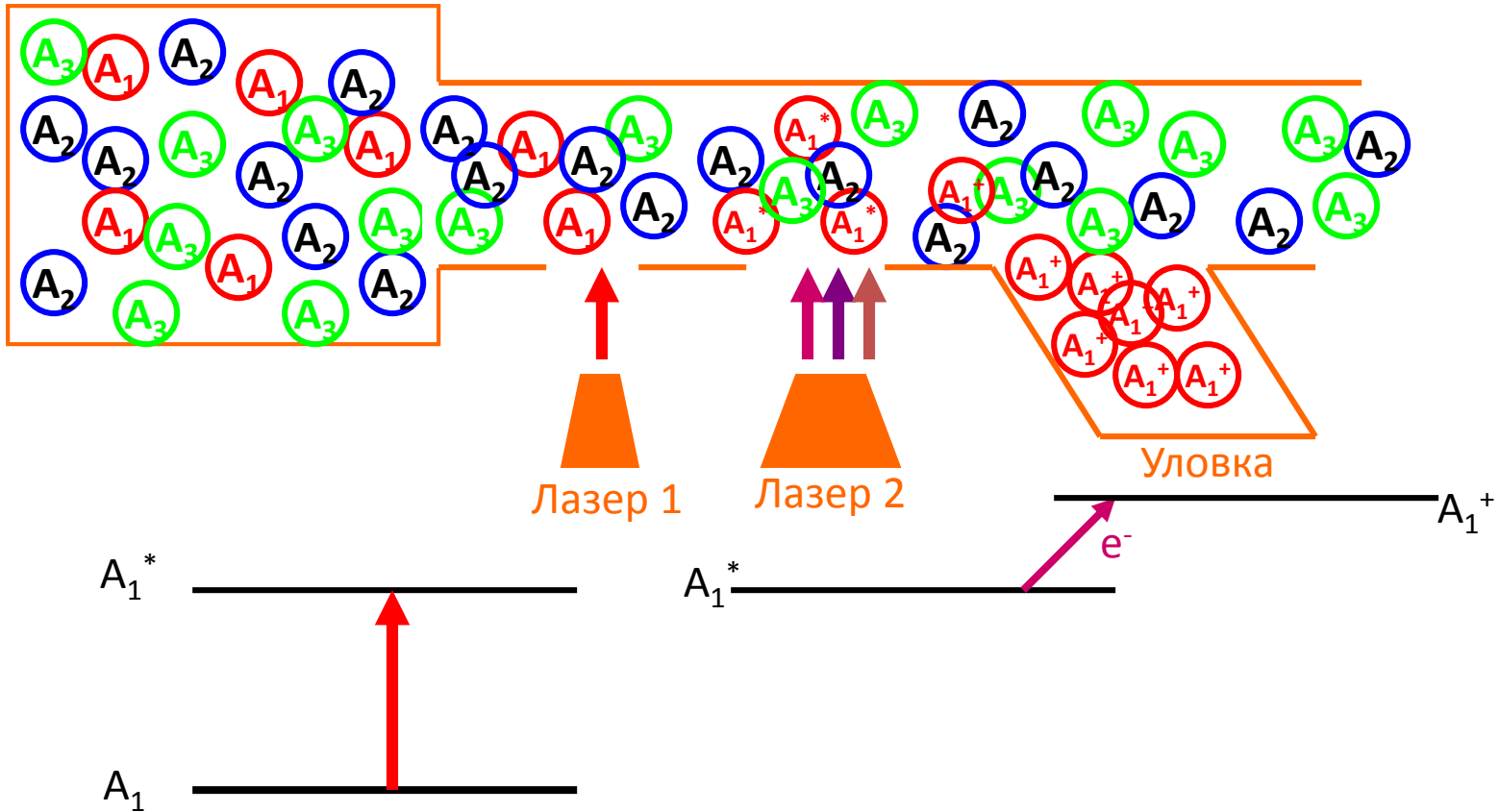


$$m(\text{Kr}) = 0.00365 m(^{78}\text{Kr}) + 0.0227 m(^{80}\text{Kr}) + \dots = 83.8 \text{ u}$$

Лазерен метод за разделяне на изотопи

Източник на
неутрални атоми

$$\Delta E_k(A) = -\frac{2 Z^4 e^2}{5 4\pi\epsilon_0} \frac{(1.2 A^{1/3})^2}{a_0^3}$$

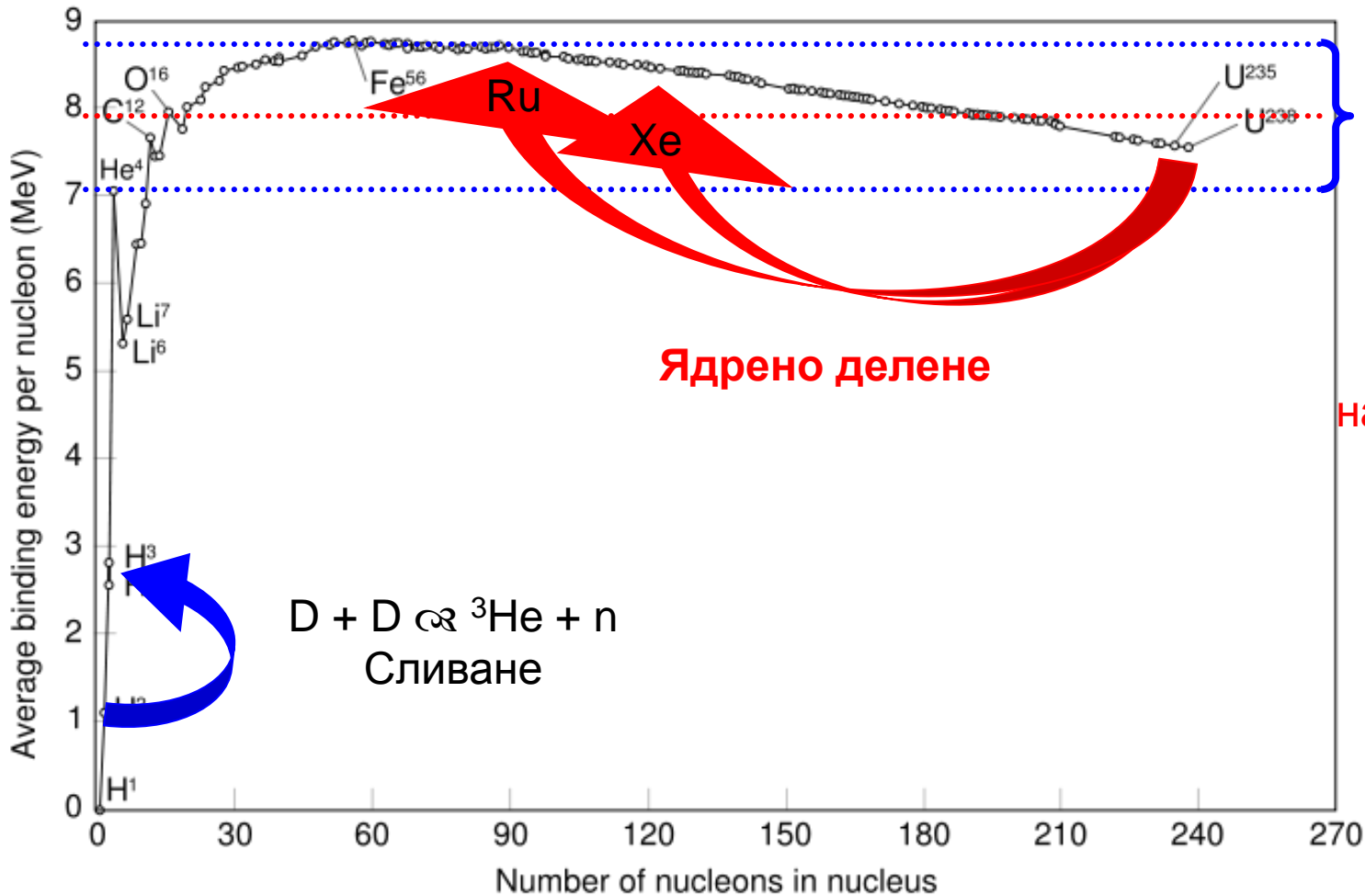


Енергия на свързване

$$m({}_Z^A X_N) = [Zm({}^1\text{H}) + Nm_n - \frac{1}{c^2} B(N, Z)]$$

$$\Delta = (m({}_Z^A X_N) - A)c^2$$

Енергетичния остатък/излишък от образуването на ядрена свързана система



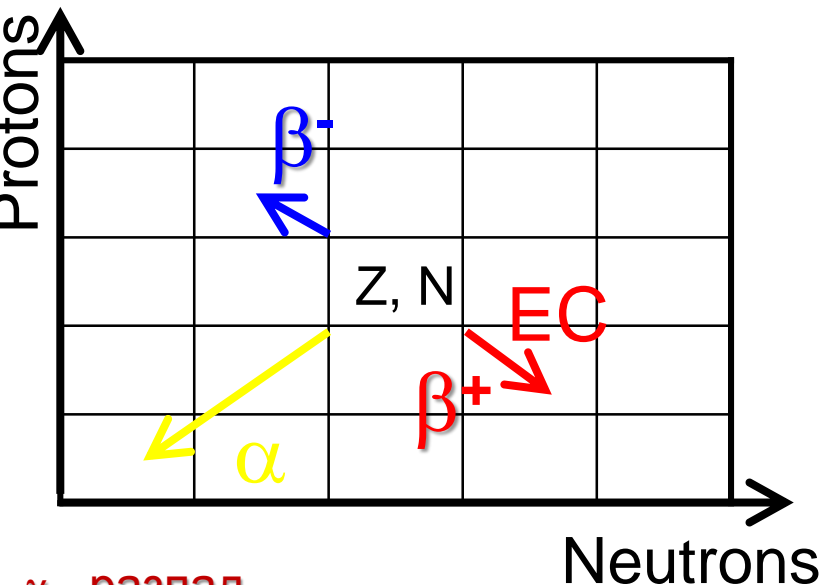
$B/A \approx \text{const} = 8.0(8) \text{ MeV}$

~~$B \approx A(A-1)$~~

$B \approx A$

най-близки съседи

Ядрени разпади



α-разпад:

- излъчване на ${}^4\text{He}$ ядра
- $Z \rightarrow Z-2$ $N \rightarrow N-2$
- $A \rightarrow A-4$

β⁻ - разпад:

- излъчване на e^- и $\bar{\nu}$
- $Z \rightarrow Z+1$ $N \rightarrow N-1$
- $A = \text{const}$

β⁺ - разпад:

- излъчване на e^+ и ν
- $Z \rightarrow Z-1$ $N \rightarrow N+1$
- $A = \text{const}$

γ - разпад

- $Z, N, A = \text{const}$

Редки разпад

- n или p ;
- ${}^8\text{Be}$, ${}^{12}\text{C}$, ${}^{16}\text{O}$

Спонтанно делене

- $A > 230$
- ${}^AX \rightarrow {}^{A1}Y + {}^{A2}Z + \#n$

Електронен захват (EC)

- Поглъщане на e^- и излъчване на ν
- $Z \rightarrow Z-1$ $N \rightarrow N+1$
- $A = \text{const}$

Вероятност за разпад за единица време на ядро

$$\lambda = -\frac{dN / dt}{N}$$



$$\tau = \int_0^{\infty} t \lambda e^{-\lambda t} dt = \frac{1}{\lambda} \quad T_{1/2} = \frac{\ln 2}{\lambda}$$

$$\lambda = \frac{2\pi}{\hbar} \rho(E_n) |V_{nl}|^2$$

$$V_{fi} = \int \psi_f^* \hat{V} \psi_i d\nu$$

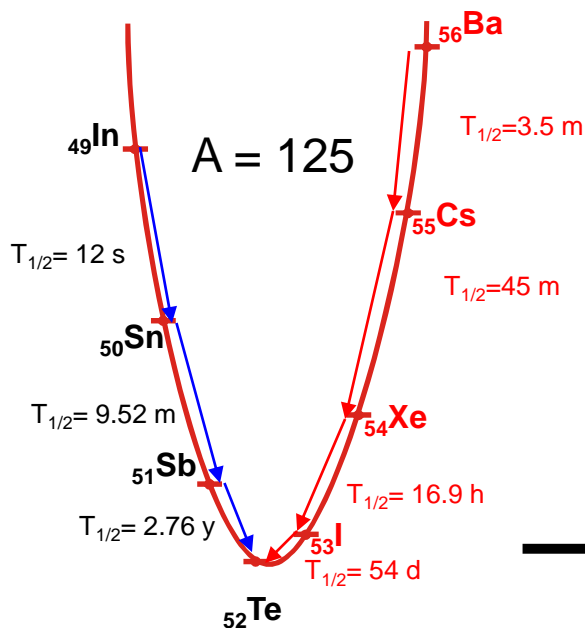
Линия на стабилност

$$m(Z, A) = Zm({}^1\text{H}) + Nm_n - B(Z, A) / c^2$$

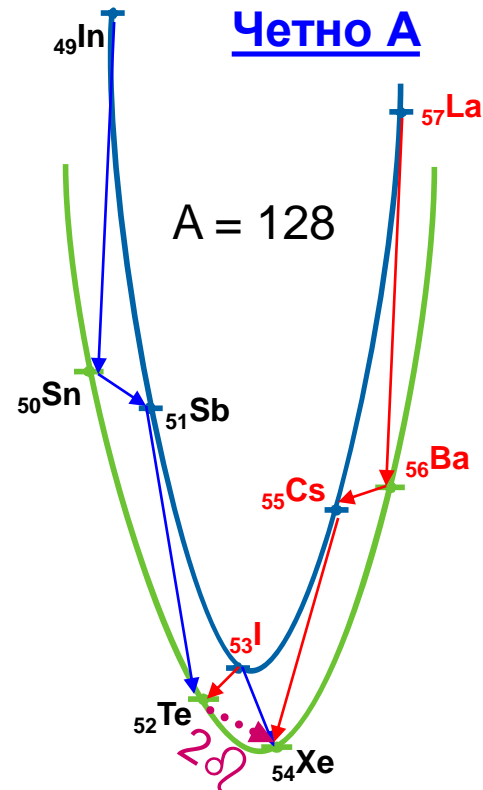
$$\left(\frac{\partial m(Z, A)}{\partial Z} \right)_{A=\text{const}} = 0$$

$$Z_{\min} \xrightarrow{A < 40} \frac{A}{2} \quad Z_{\min} < \frac{A}{2}$$

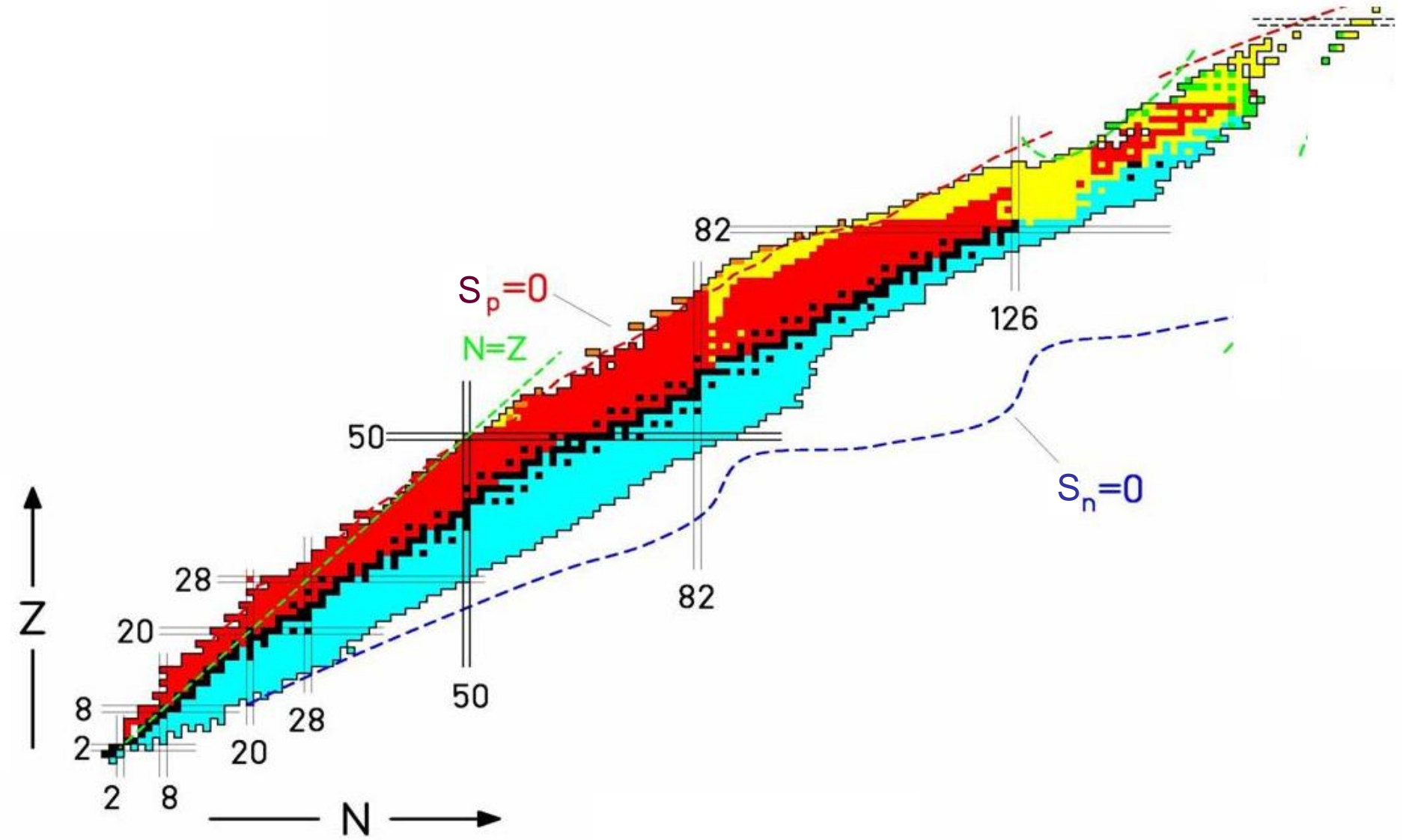
Нечетно A



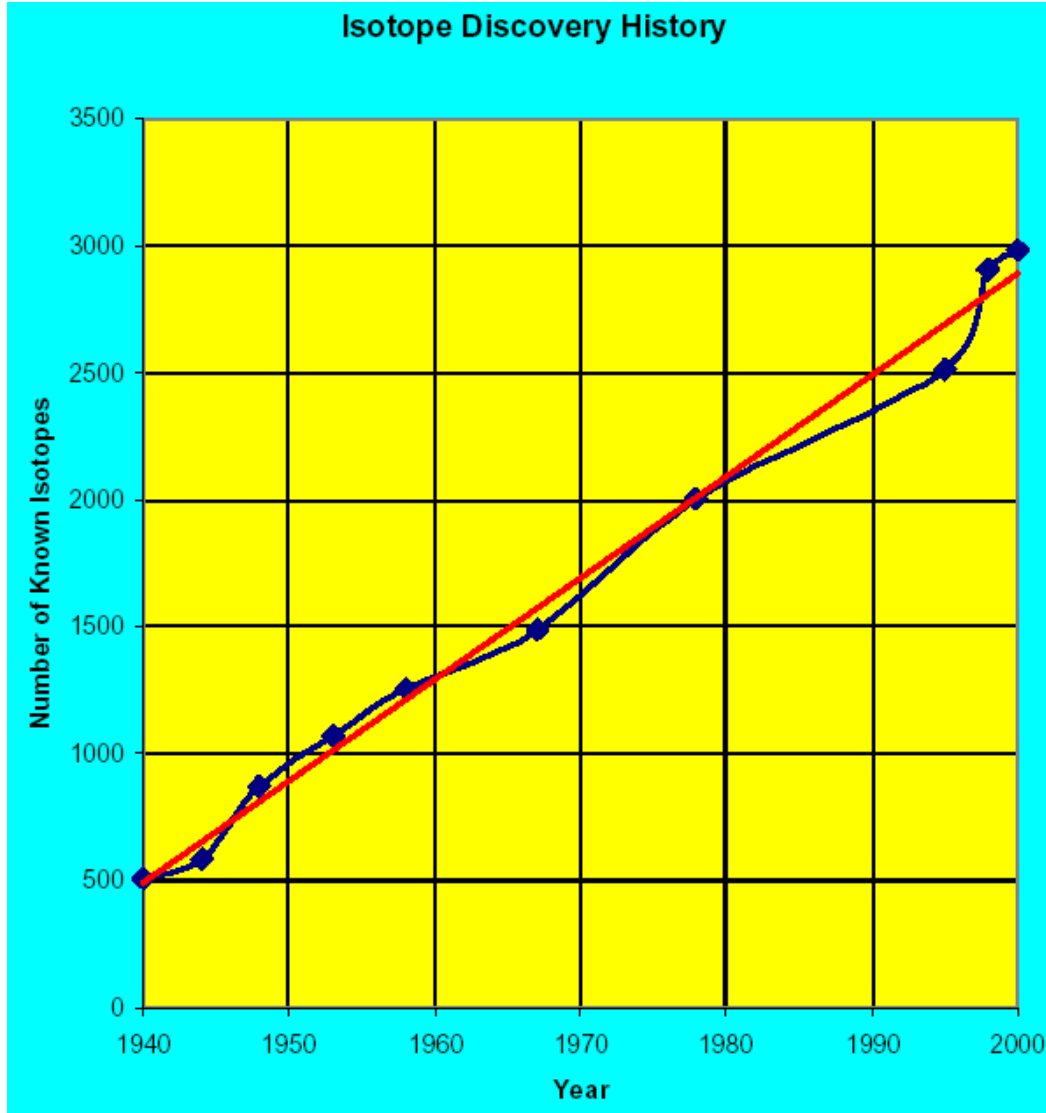
Четно A



Граници на съществуване ядрената материя



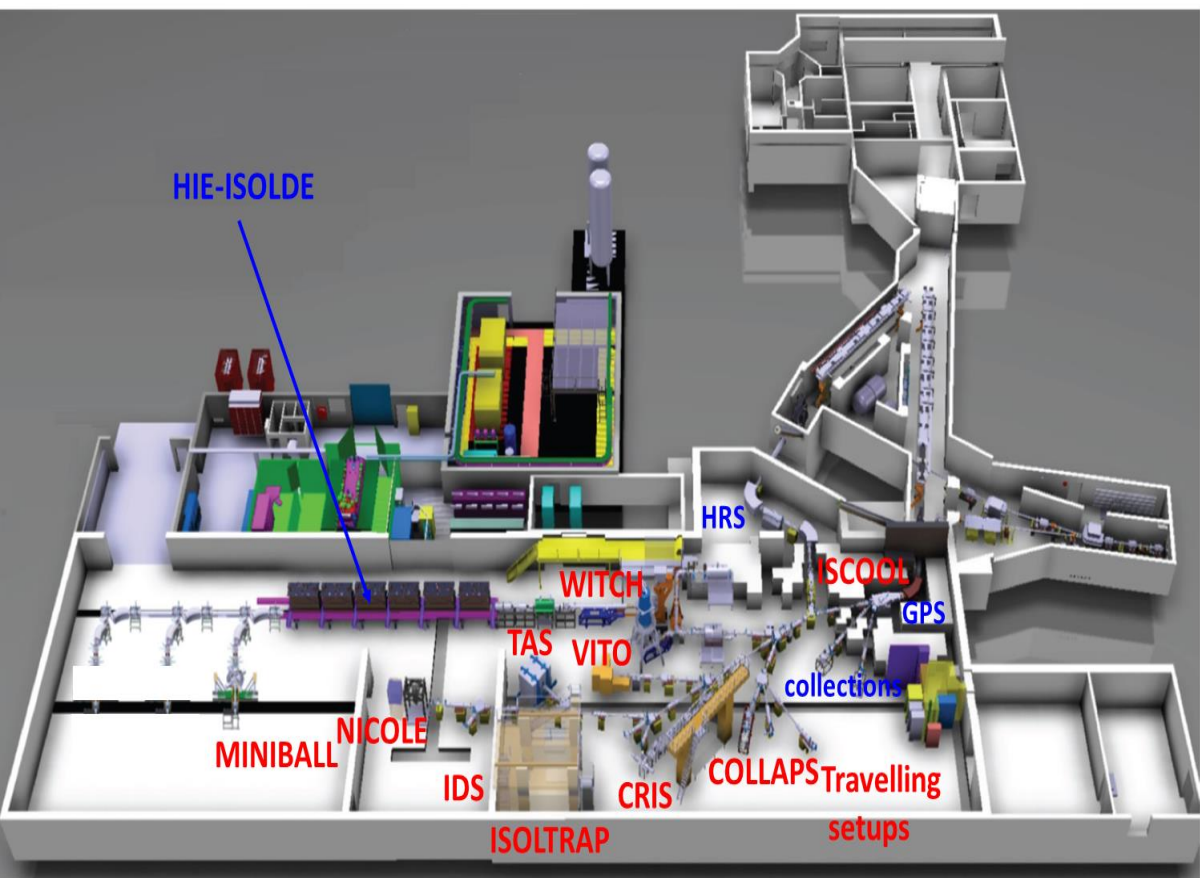
Карта на нуклидите



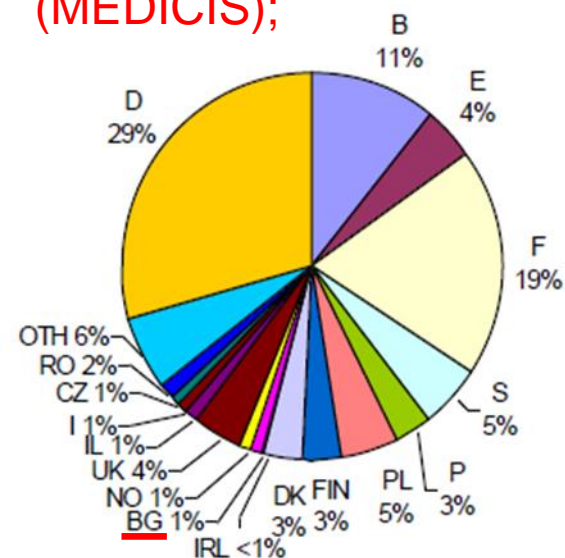
- До днес са идентифицирани над **3000** нуклида;
- От тях само **284** са стабилни;
- Известни са 118 химични елемента (потвърдени до **Z=116** Lv – Livermorium
Z=117 Ts – Tennessine
Z=118 Og – Oganesson);

Ядрена физика в ЦЕРН - ISOLDE

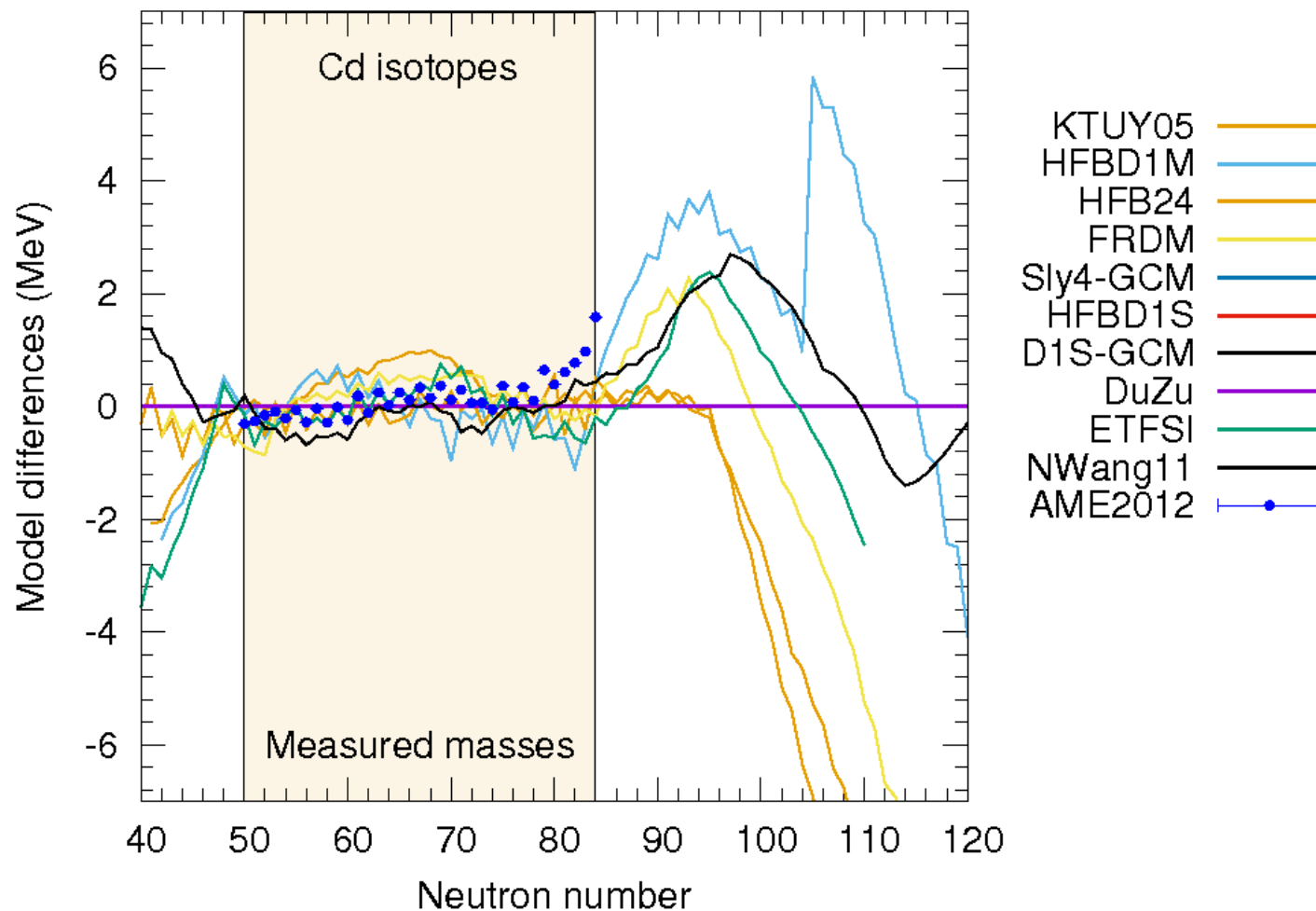
- ISOLDE (Isotope Separator On Line DEvice) е установка в ЦЕРН за производство на радиоактивни снопове;
- Предлага най-богата селекция от ускорени или ниско-енергетични снопове от радиоактивни ядра в света;
- Отворена е за изследователи от целия свят;



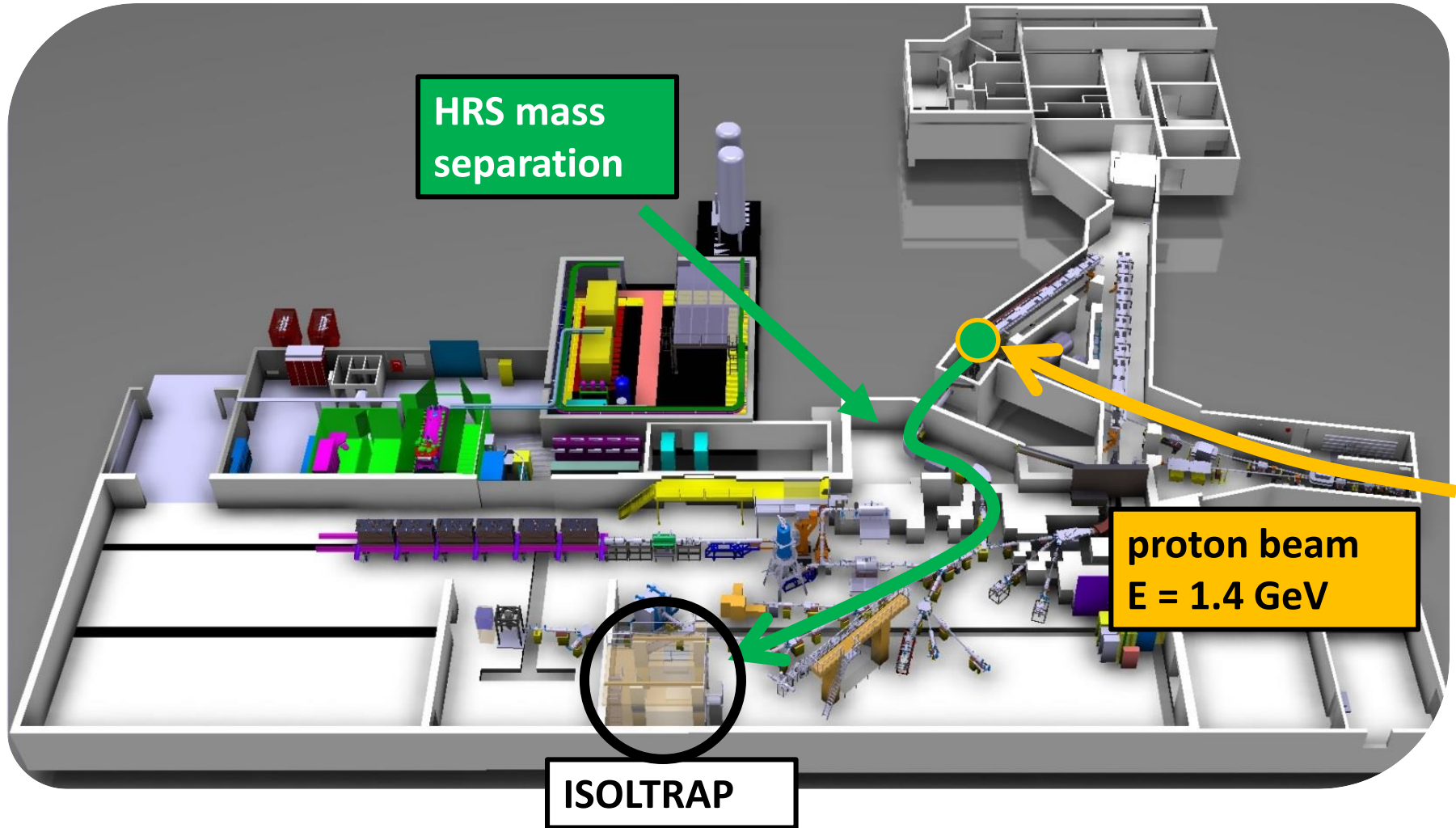
- Ядрена структура;
- Екзотични разпади;
- Лазерна спектроскопия;
- Измерване на маси;
- Радиуси и моменти;
- Ядрени реакции от астрофизичен интерес;
- Физика на твърдо тяло ;
- Медицинска физика (MEDICIS);



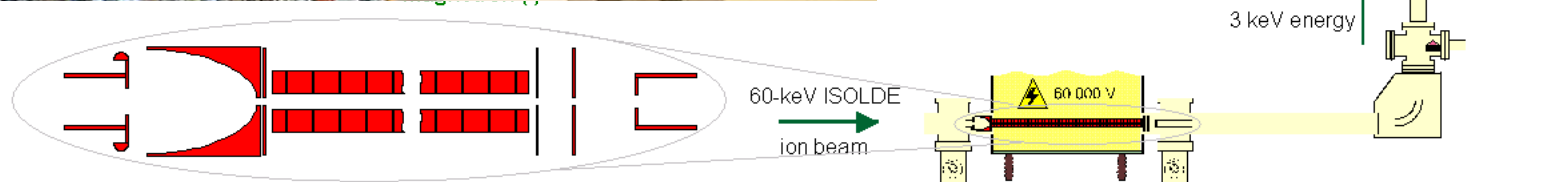
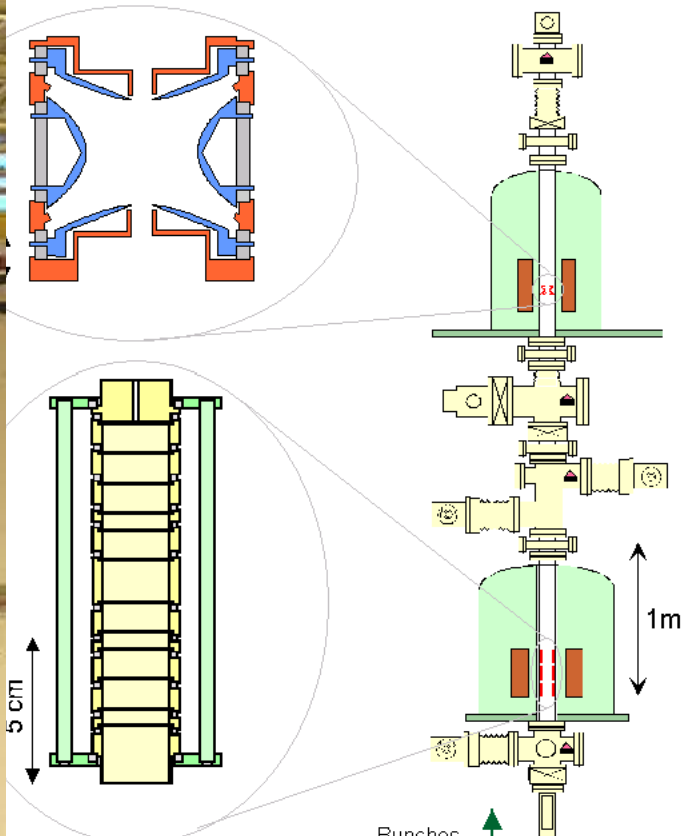
Директно измерване на маси - ISOLTRAP



Директно измерване на маси - ISOLTRAP



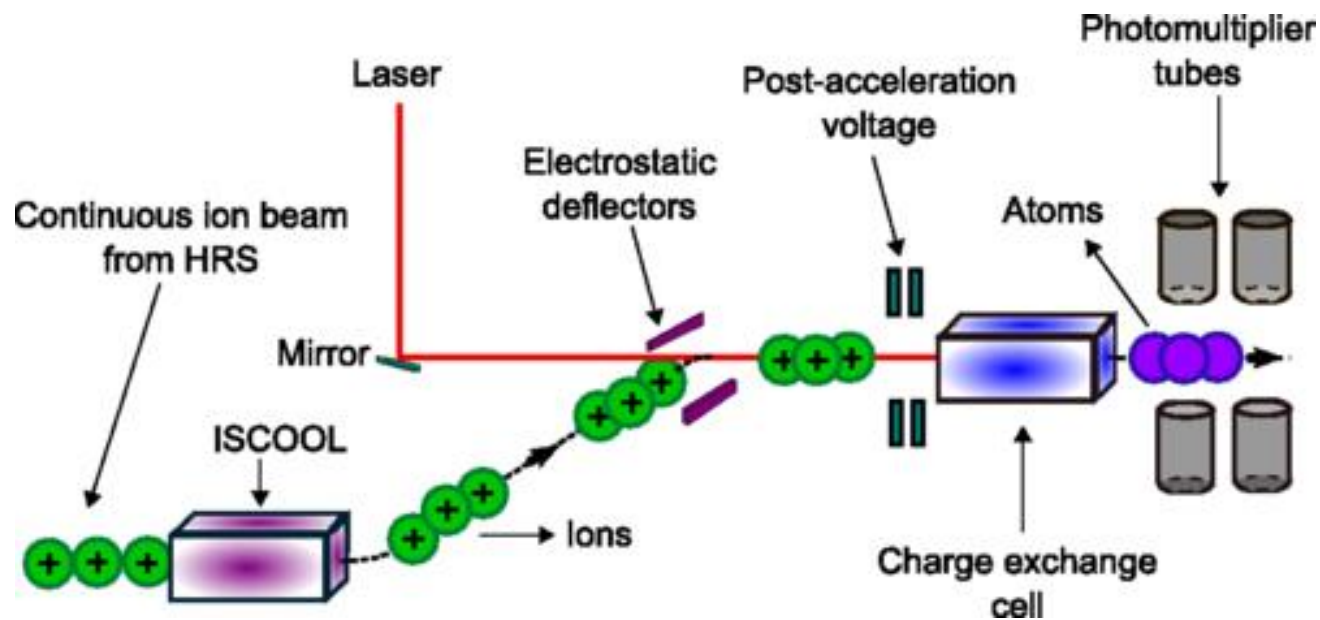
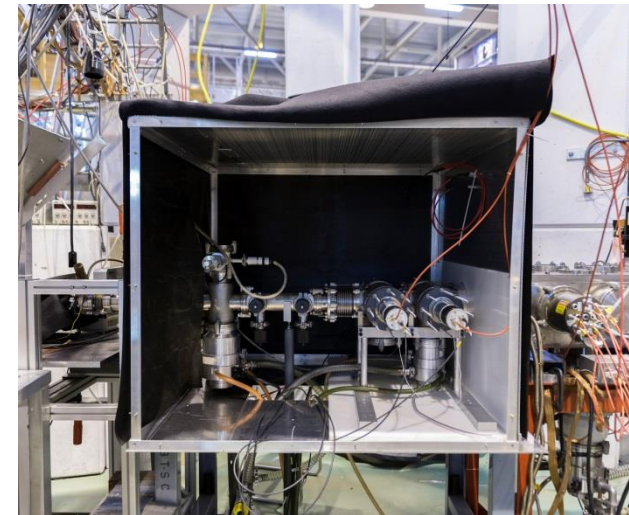
Директно измерване на маси - ISOLTRAP



10^3 pps, с точност 10^{-8}

Измерване на радиуси и моменти - COLLAPS

Колинеарна лазерна спектроскопия на екзотични атоми



Ядрени модели – средно поле

$$\hat{H}\Psi(1, 2, \dots, A) = E\Psi(1, 2, \dots, A) \quad \{i\} = \{\vec{r}_i, \vec{p}_i, \vec{s}_i, \vec{t}_i\}$$

$$\hat{H} = \hat{T} + V(1, 2, \dots, A) = \sum_{i=1}^A -\frac{\hbar^2}{2m} \Delta_i + V(1, 2, \dots, A)$$

$$V(1, 2, \dots, A) \approx \sum_{i < k} V(i, k) = \frac{1}{2} \sum_{i=1}^A \sum_{k \neq i}^A V(i, k) \approx \sum_{i=1}^A V(i)$$

$$\hat{H} = \sum_{i=1}^A -\frac{\hbar^2}{2m} \Delta_i + \sum_{i < k} V(i, k) = \sum_{i=1}^A \left(-\frac{\hbar^2}{2m} \Delta_i + V(i) \right) + \underbrace{\sum_{i < k} V(i, k) - \sum_{i=1}^A V(i)}_{\hat{H}_{res}}$$
$$\hat{H} = \hat{H}_0 + \cancel{\hat{H}_{res}}$$

В ядрото отделните нуклеоните се държат като не взаимодействащи частици движещи се в потенциал генериран от всички тях!

Ядрен слоест модел и магични числа

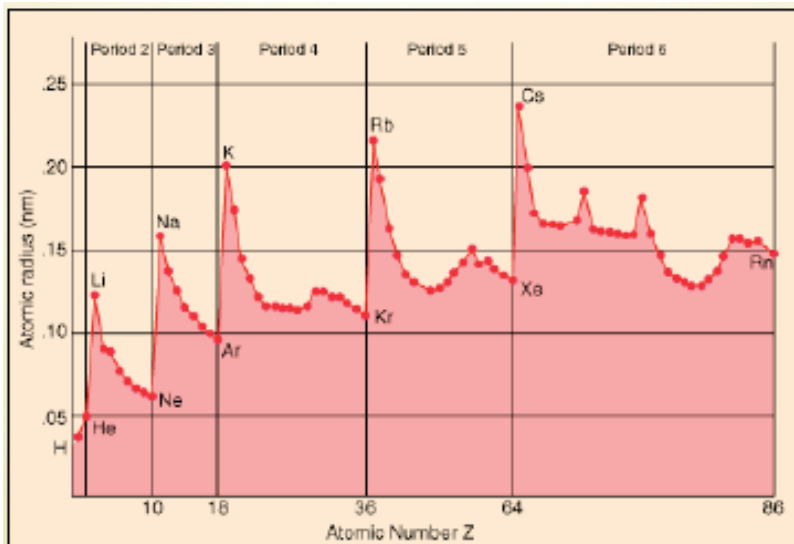
$$\hat{H} = \hat{H}_0 + \cancel{\hat{H}}_{res} \quad \hat{H}_0 = \sum_{i=1}^A \left(-\frac{\hbar^2}{2m} \Delta_i + V(i) \right) = \sum_{i=1}^A h_i \quad h_i \varphi_i \equiv \epsilon_i \varphi_i$$

$$\Psi(1, 2, \dots, A) = \varphi_1 \varphi_2 \dots \varphi_A = \prod_{i=1}^A \varphi_i$$

$$E = \sum_{i=1}^A \epsilon_i$$

$$\Psi(1, 2, \dots, A) = \begin{vmatrix} \varphi_1(1) & \varphi_1(2) & \dots & \varphi_1(A) \\ \varphi_2(1) & \varphi_2(2) & \dots & \varphi_2(A) \\ \dots & \dots & \dots & \dots \\ \varphi_A(1) & \varphi_A(2) & \dots & \varphi_A(A) \end{vmatrix}$$

Нуклеоните последователно запълват енергетични нива в средното поле.



В ядрото съществува слоеста структура, която се асоциира със следните магически числа **2, 8, 20, 28, 50, 82, 126 (Z?)**

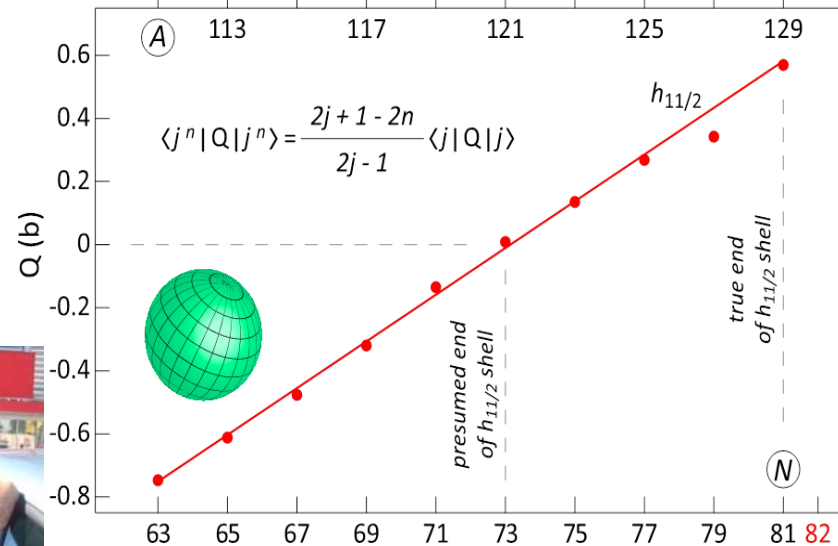
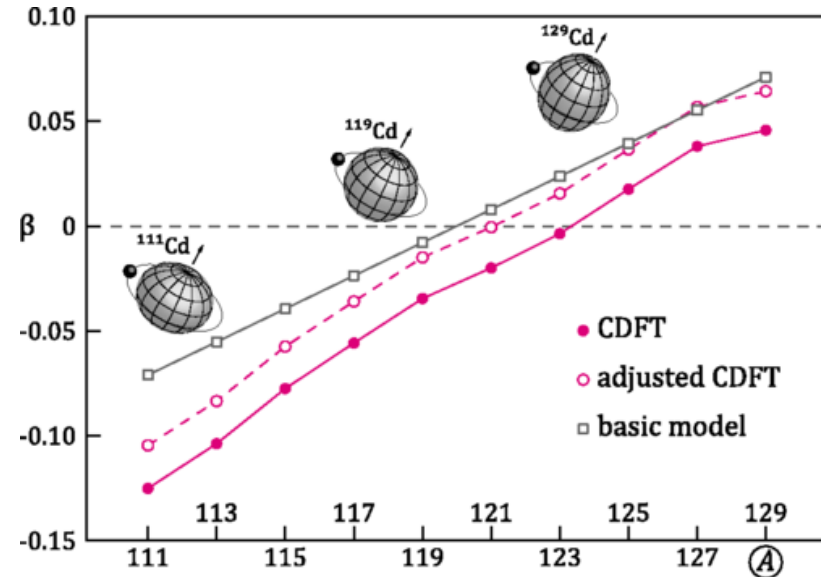
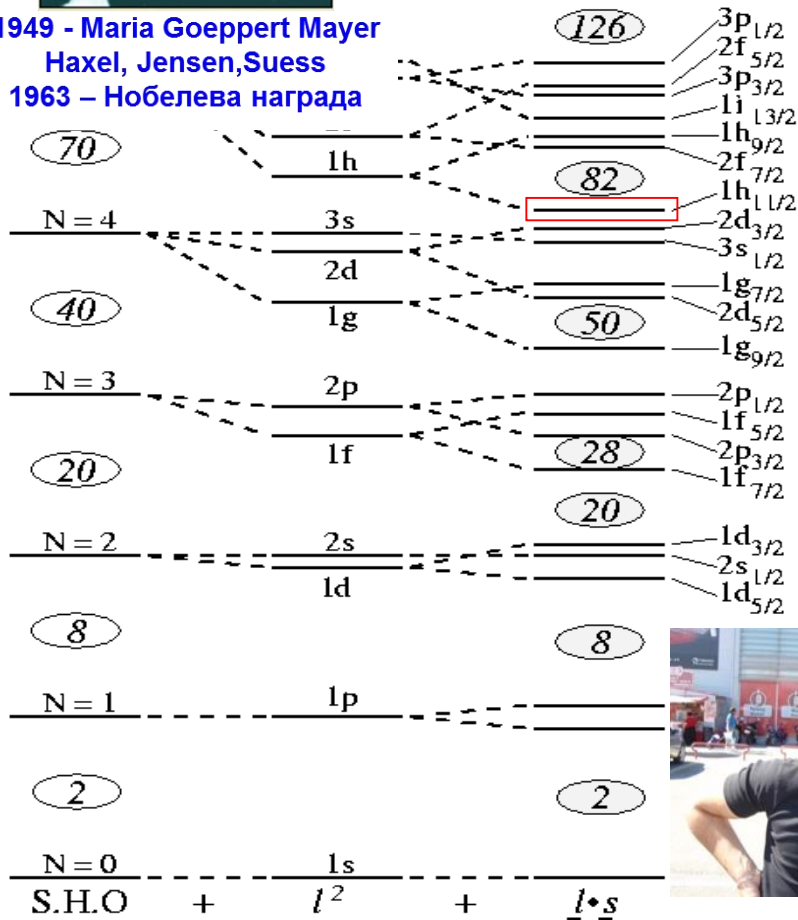
Как да се подбере средното поле, т.ч. да се възпроизведат магическите числа?

Измерване на моменти - COLLAPS



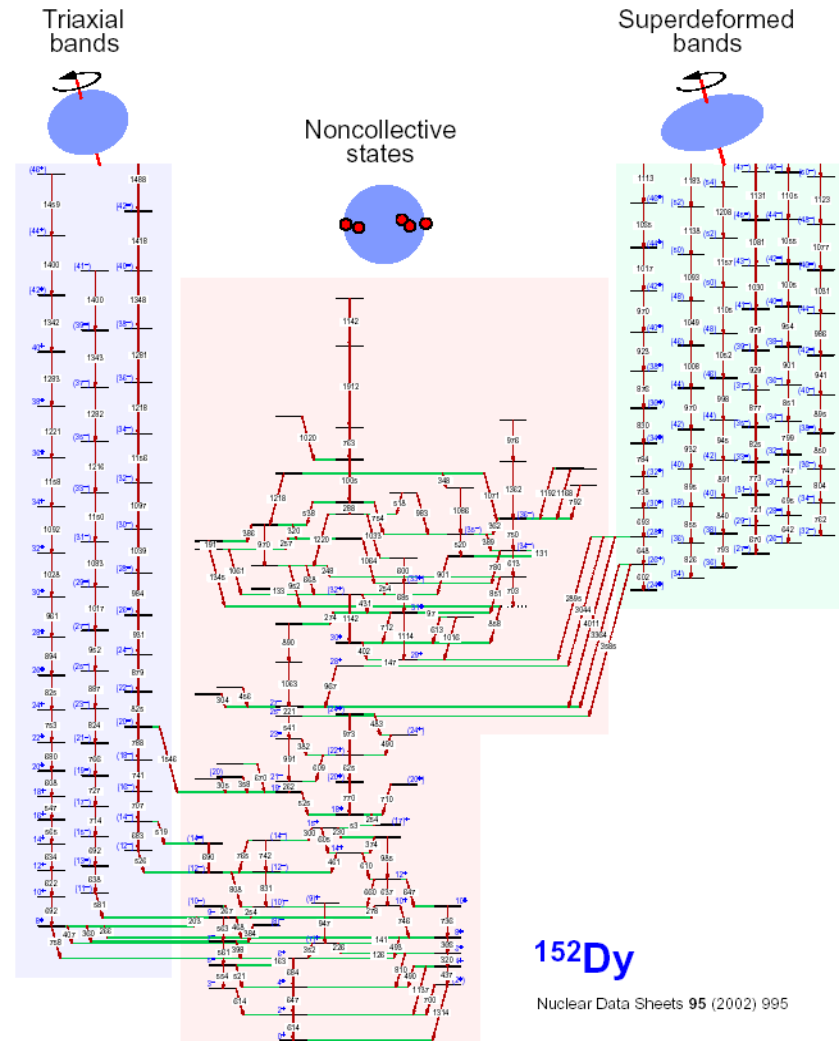
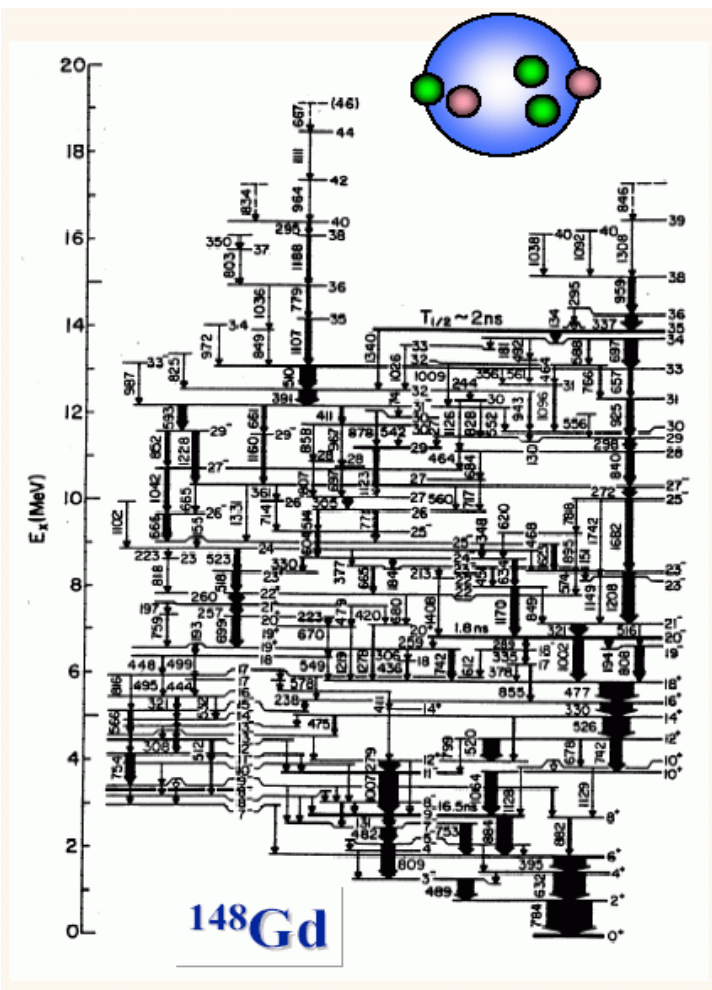
$$V(r) = -V_0 + \frac{1}{2} m \omega_0^2 r^2 - \frac{2\alpha}{\hbar^2} \vec{l} \cdot \vec{s}$$

1949 - Maria Goeppert Mayer
 Haxel, Jensen, Suess
 1963 - Нобелева награда



D. T. Jordanov *et al.*, PRL 110, 192501 (2013)
 D. T. Jordanov *et al.*, PRL 116, 032501 (2016)

Възбудени ядрени състояния



^{152}Dy

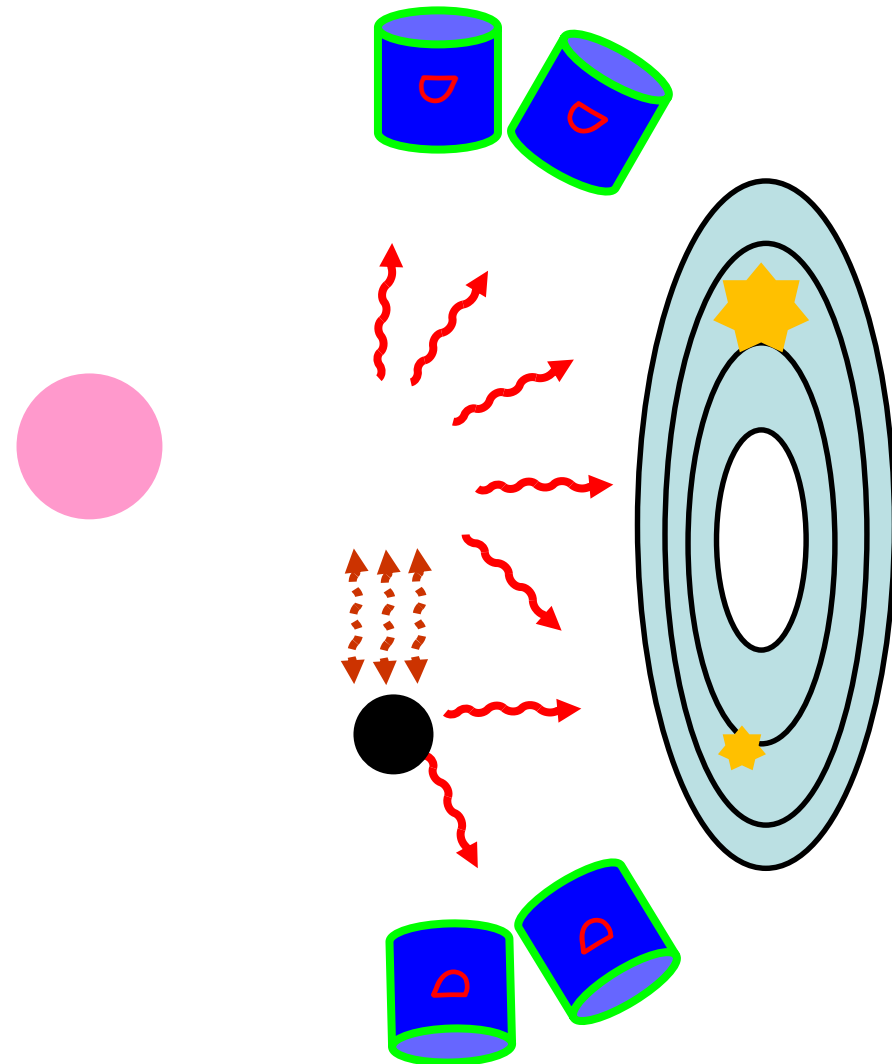
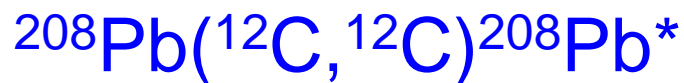
Nuclear Data Sheets 95 (2002) 995

Цел: чрез изучаване характеристиките (енергия на възбудане, спин-четност, е-м моменти, времена на живот, модове и характеристики на разпад) на възбудените ядрени състояния да се изучи динамиката на ядрената ситема

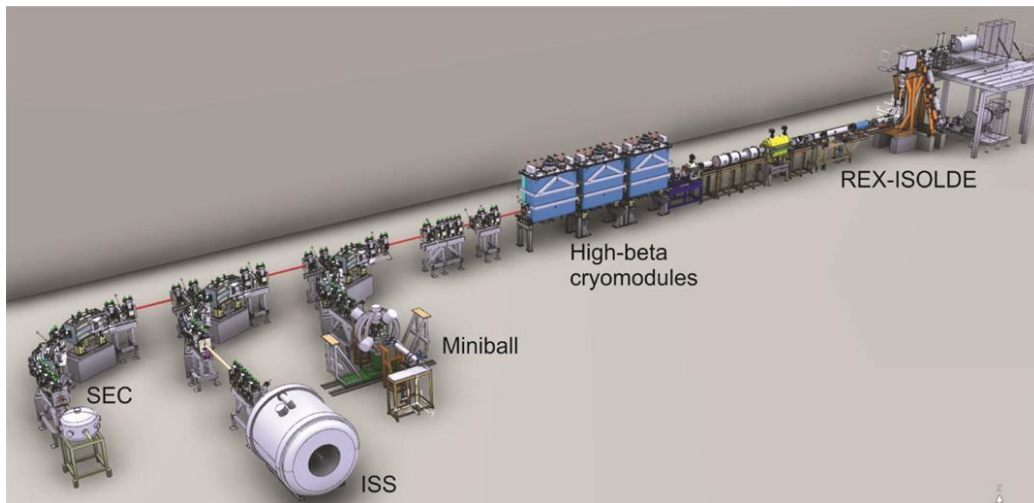
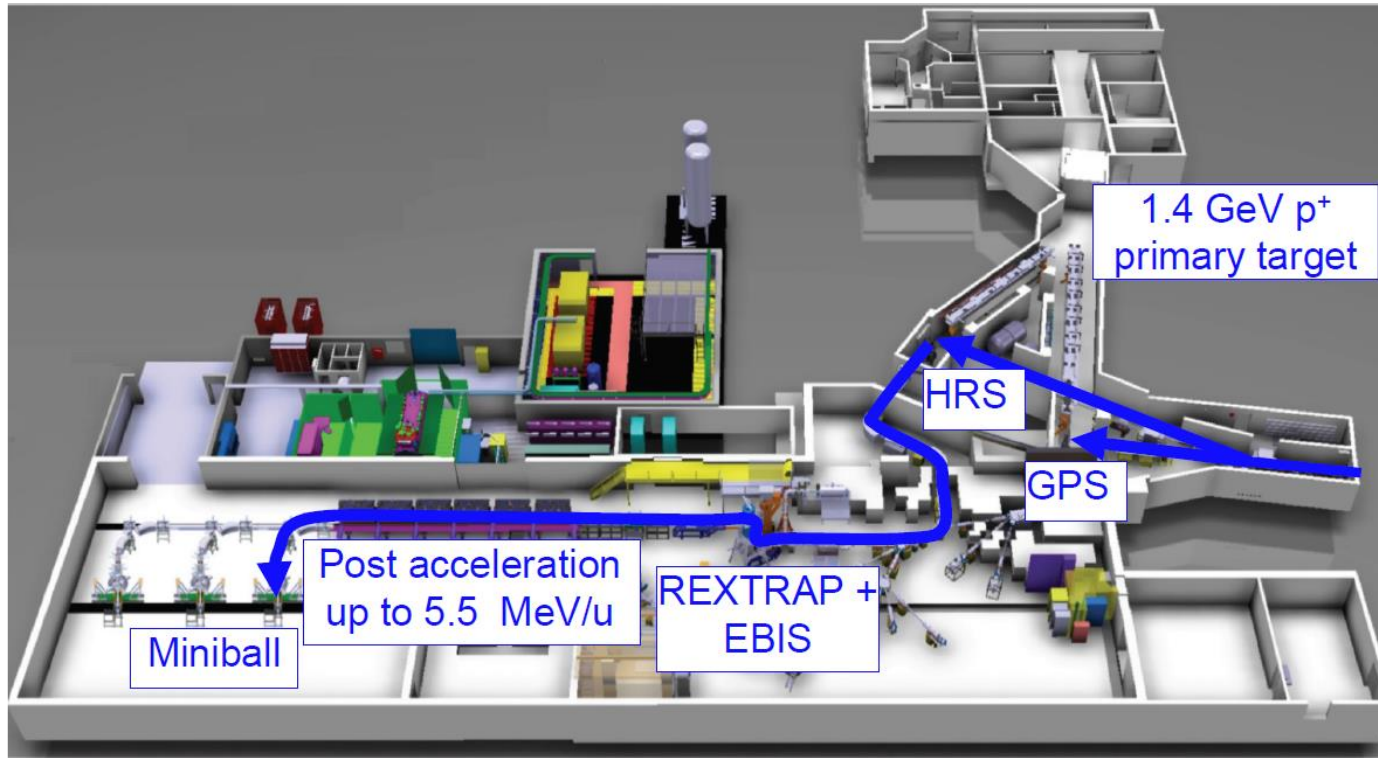
Възбудени ядрени състояния

Ядрени реакции

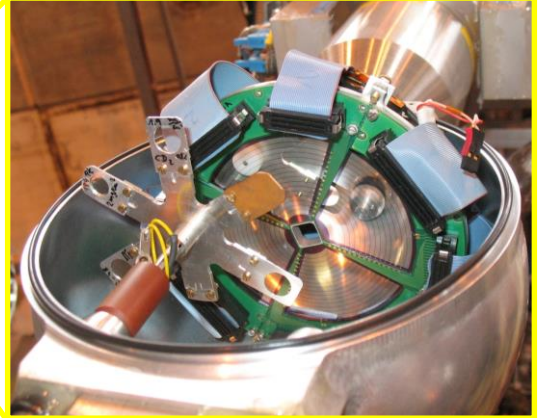
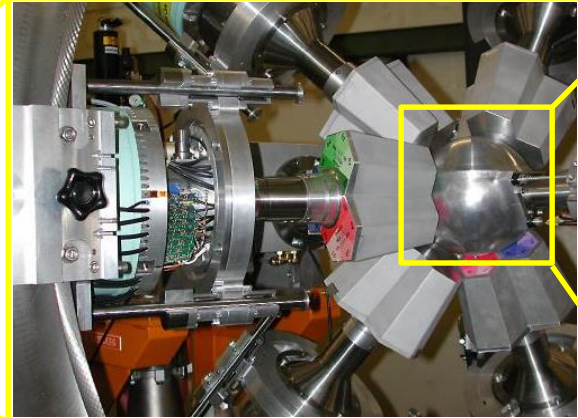
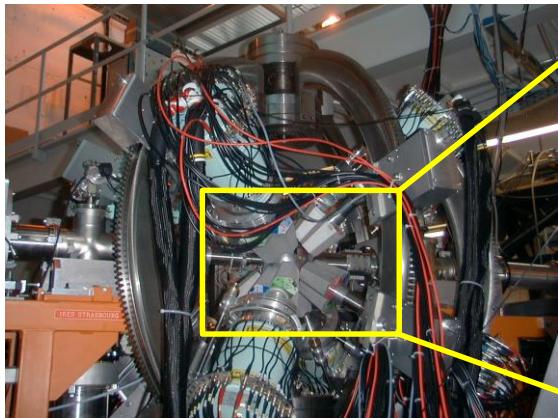
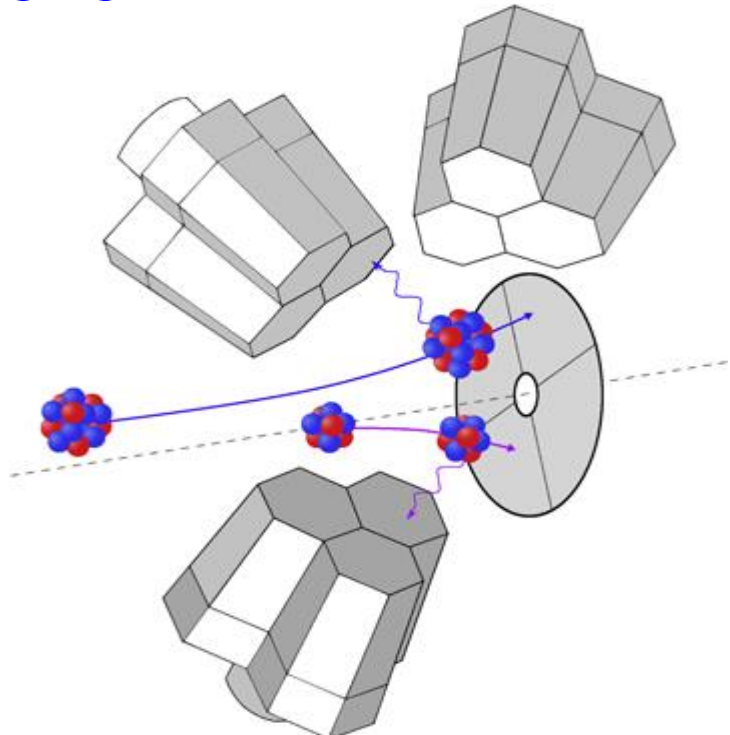
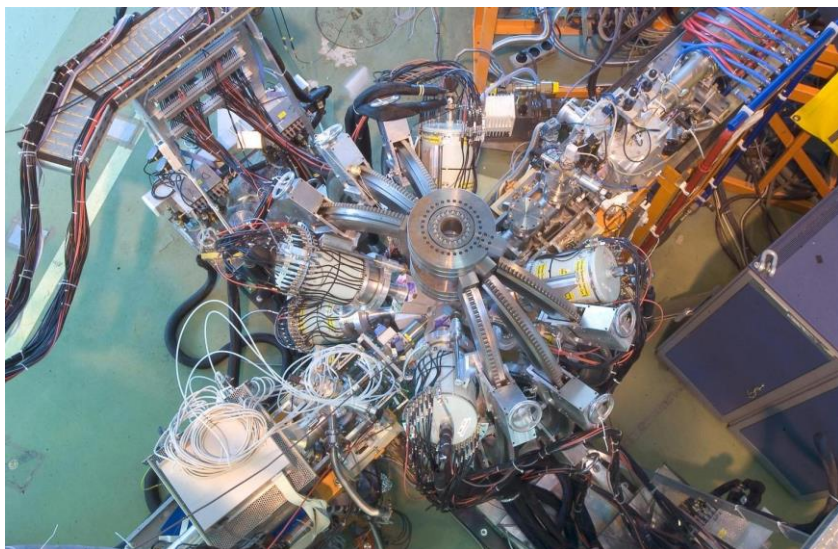
- Ускорени ядра (сноп)
x (@ E_{beam})
- Мишена
X (mg/cm^2 , $\sim \mu\text{m}$)
- Продукти на реакцията
y, Y



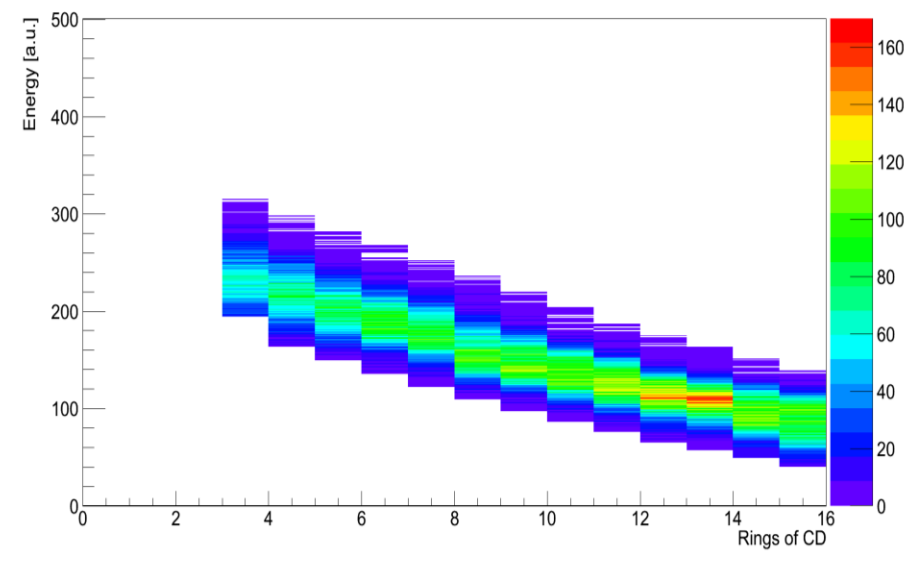
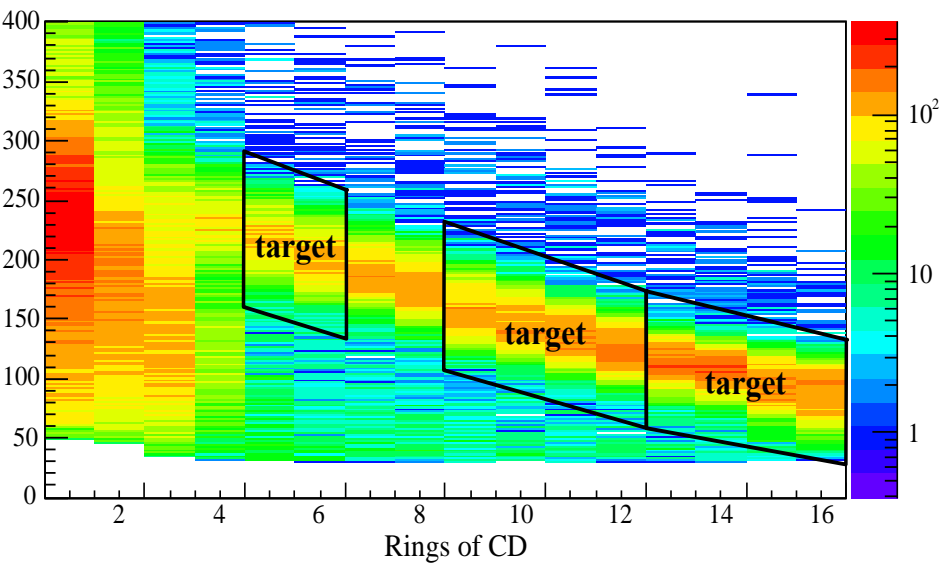
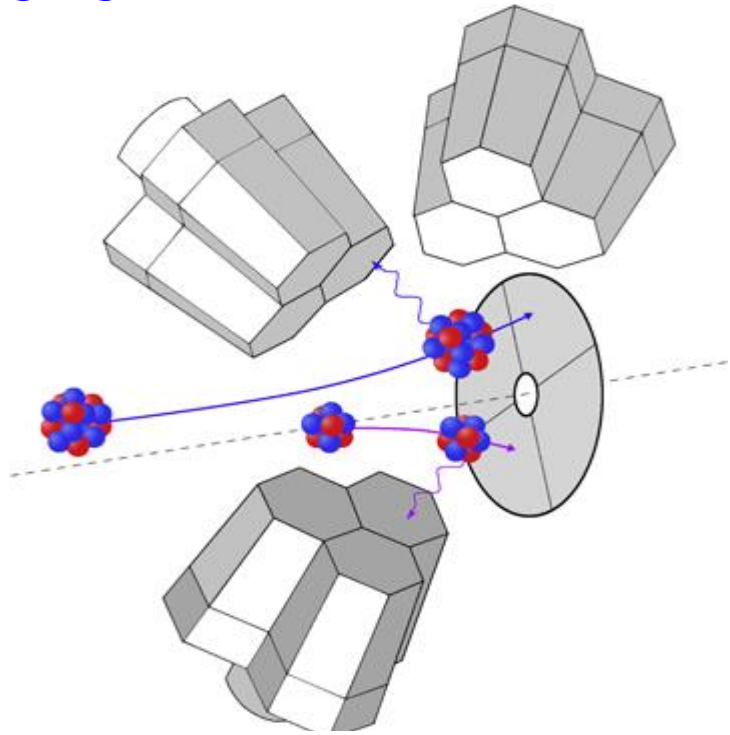
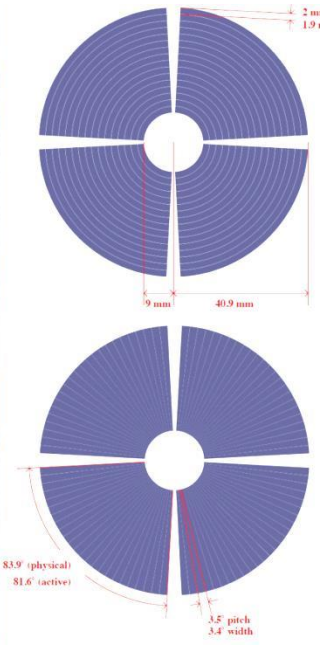
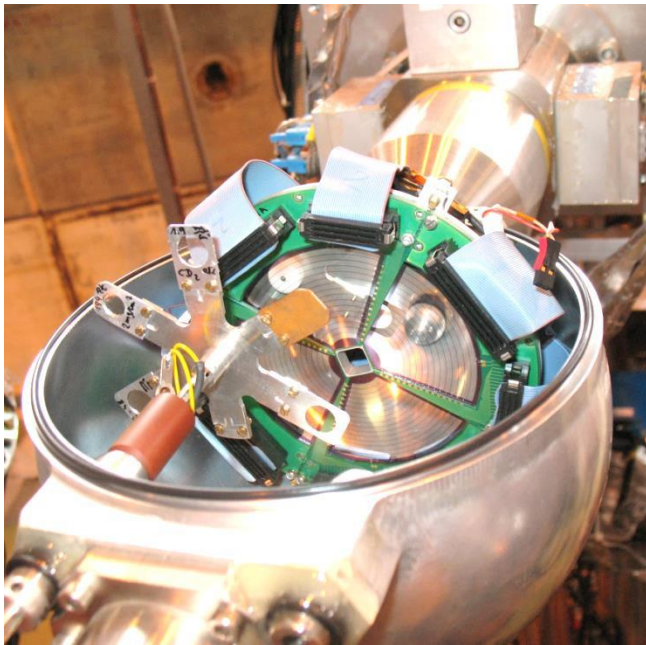
Структура на възбудени състояния – HIE-ISOLDE



Структура на възбудени състояния - MINIBALL

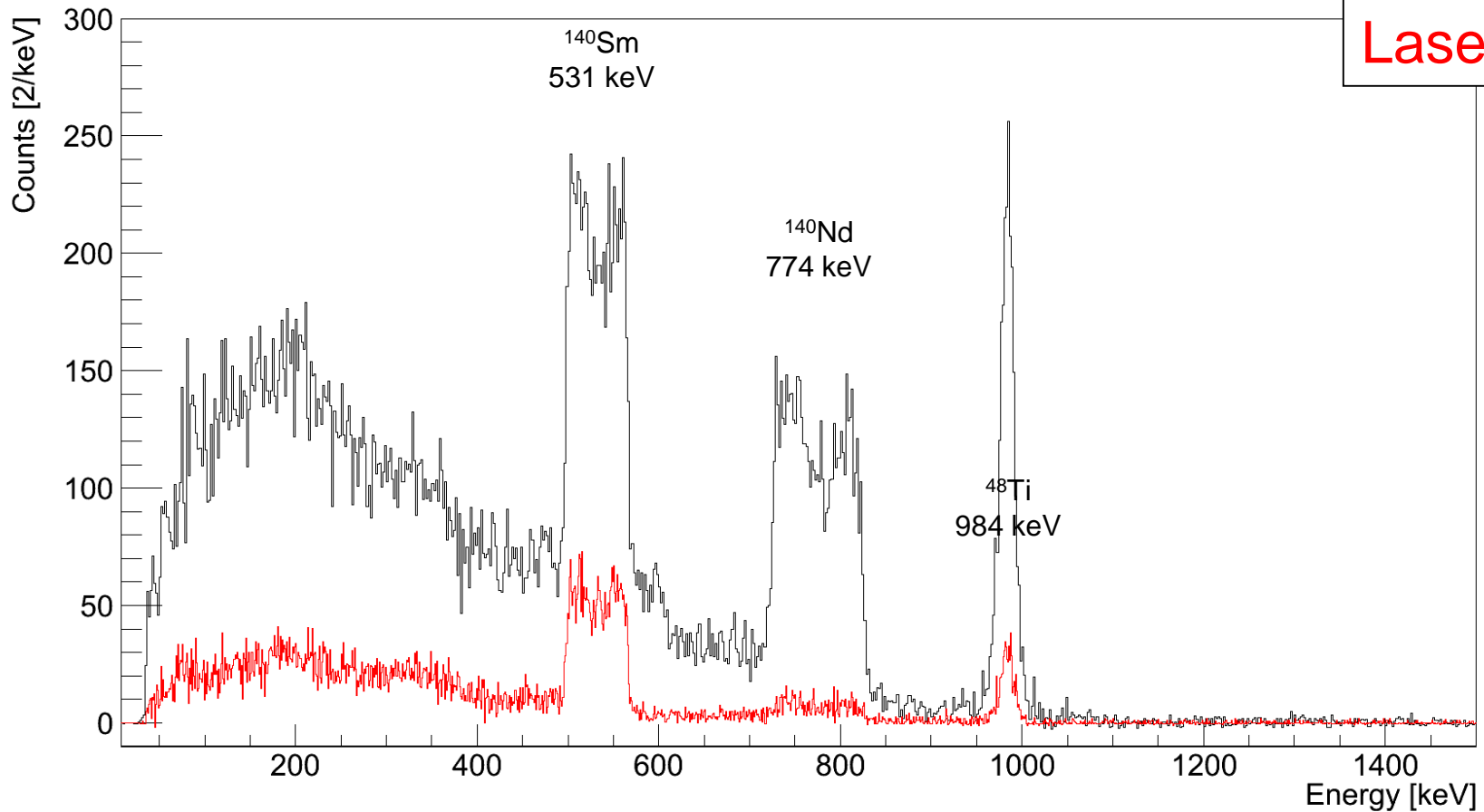


Структура на възбудени състояния - MINIBALL



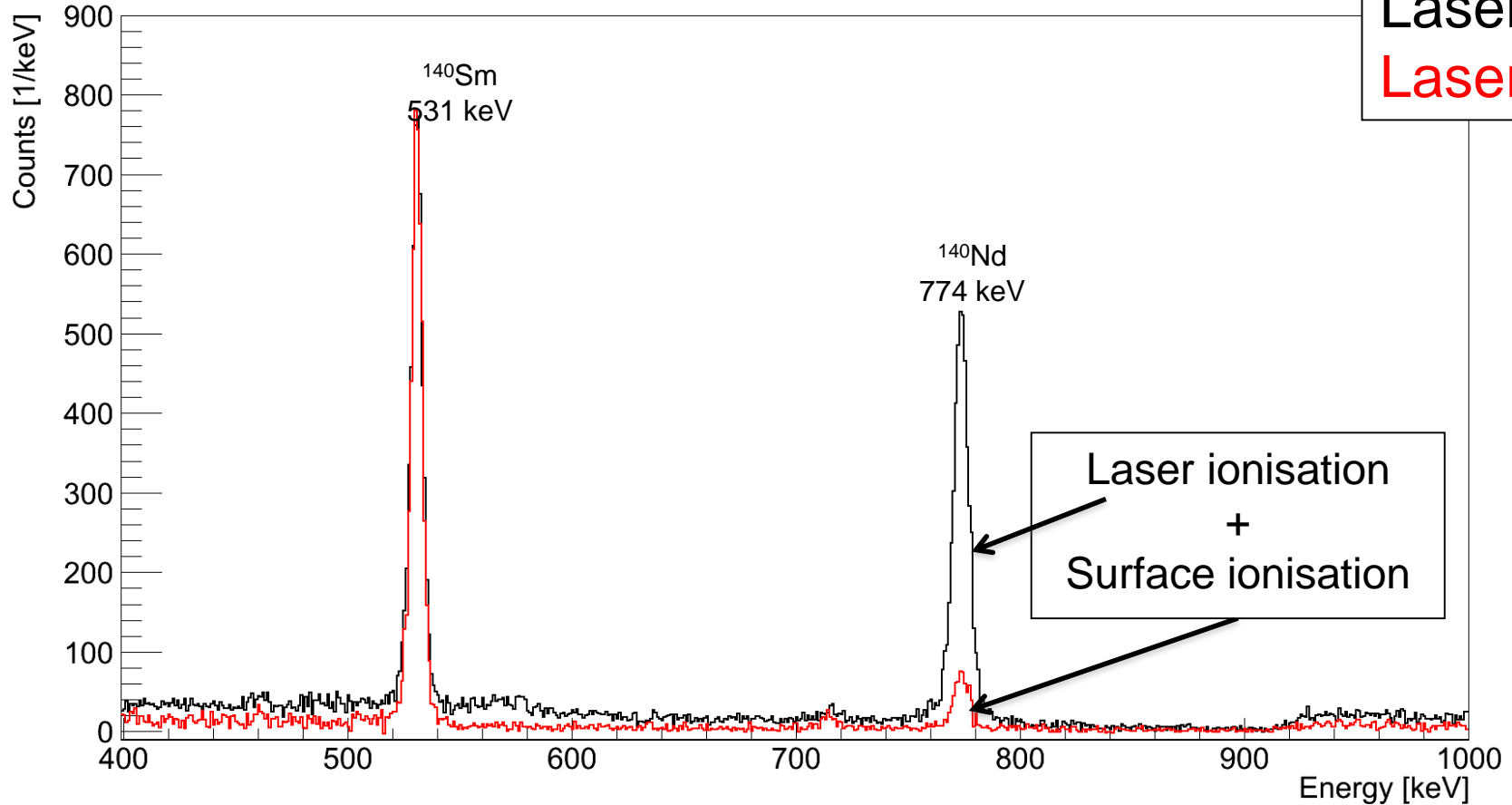
Структура на възбудени състояния - MINIBALL

Coulex, DC (targ.), subtracted, full statistics



Структура на възбудени състояния - MINIBALL

Coulex, DC (proj.), subtracted, full statistics

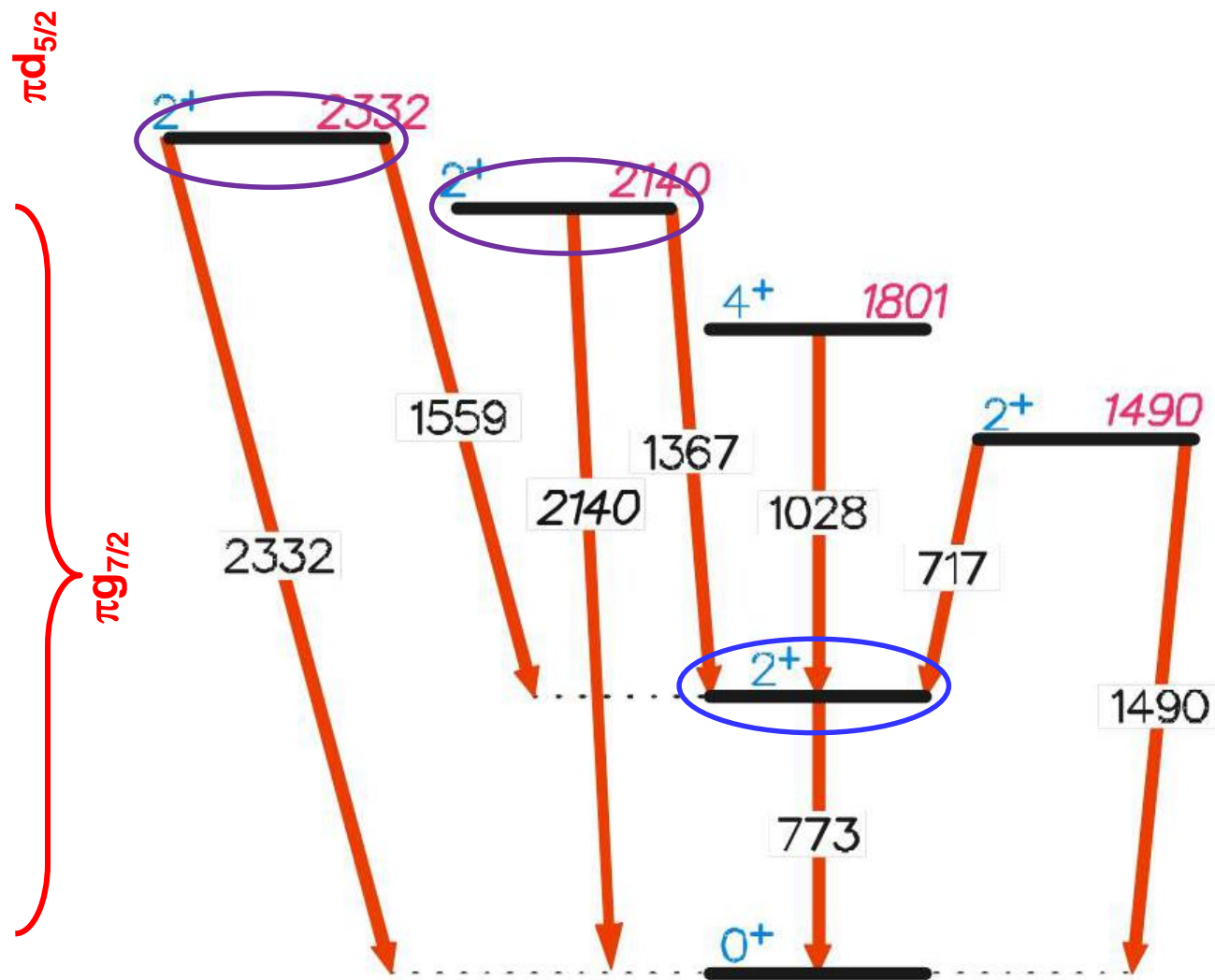
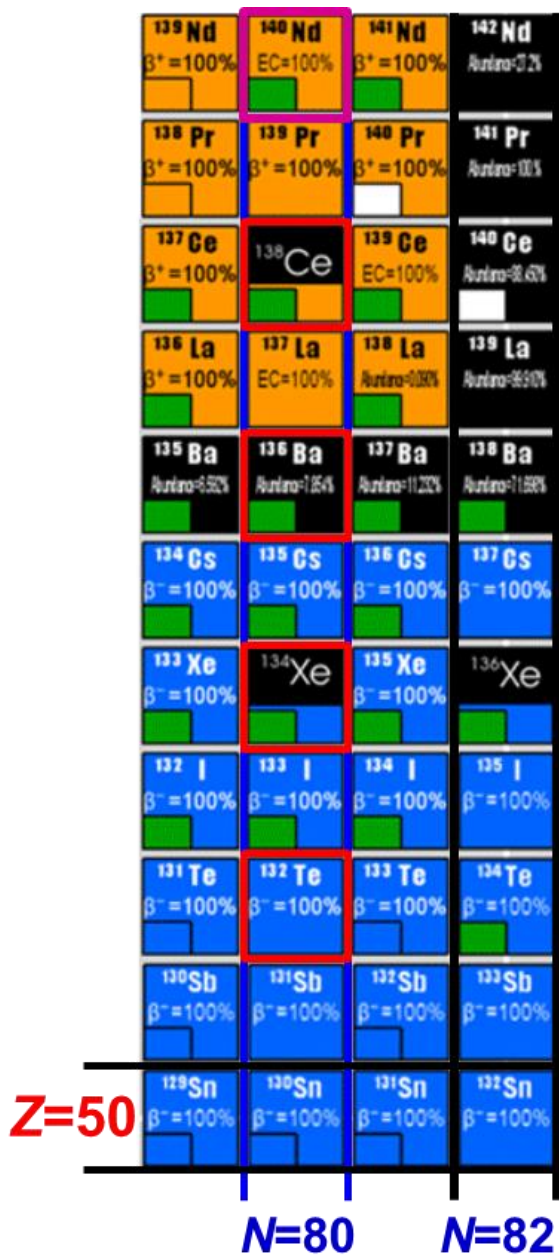


Laser on
Laser off

Laser ionisation
+
Surface ionisation

Кулоново възбуждане на ядрата ^{140}Nd и ^{142}Sm

СУ – ТУ Дармщат



25.09 – 03.10.2017

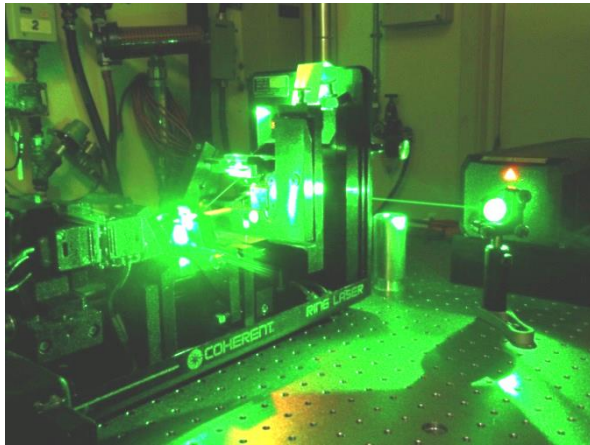
Българско участие в експерименти на ISOLDE

COLLAPS

Prof. Krasimira Marinova (JINR)

Prof. Dimiter Balabanski (ELI-NP)

Dr. Deyan Yordanov (CSNSM Orsay)



ISOLTRAP

Dinko Atanasov
(TU Dresden)



REX(HIE)-ISOLDE, MINIBALL

Prof. Dimiter Balabanski (ELI-NP, Bucharest)

Dr. Georgi Georgiev (CSNSM Orsay)

Dr. Andrej Blazhev (Uni Köln)

Prof. Georgi Rainovski (Uni Sofia)

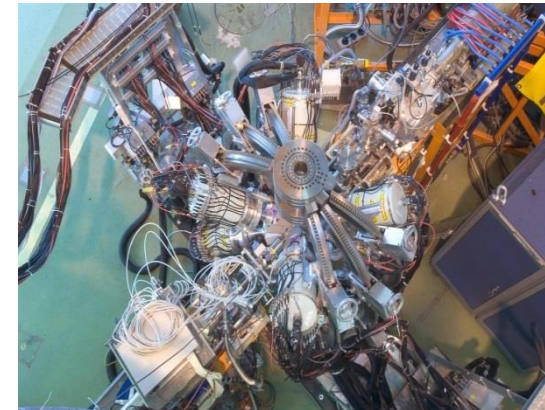
Assoc. Prof. Kalin Gladnishki (Uni Sofia)

Assist. Prof. Martin Djongolov (Uni Sofia)



Mössbauer spectroscopy at ISOLDE:

Dr. Petko Krastev (INRNE Sofia)



Bulgarian summer students at ISOLDE:

Raostina Zidarova (2017)

Bozidar Dimitrov (2015)

Maria Trichkova (2014, PhD student at Uni Sofia)

Vasil Karayonchev (2013, PhD student at Uni Köln)

Antoaneta Damyanova (2011, PhD student at Uni Geneva)

Физически факултет на СУ Св. Кл. Охридски



Физически факултет на СУ Св. Кл. Охридски

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Квантова електроника

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Оптика и спектроскопия

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Теоретична физика

Физика на кондензираната материя

Физика на твърдото тяло и микроелектрониката

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(1946 – проф. Елисавета Карамихайлова)



Благодаря за вниманието!