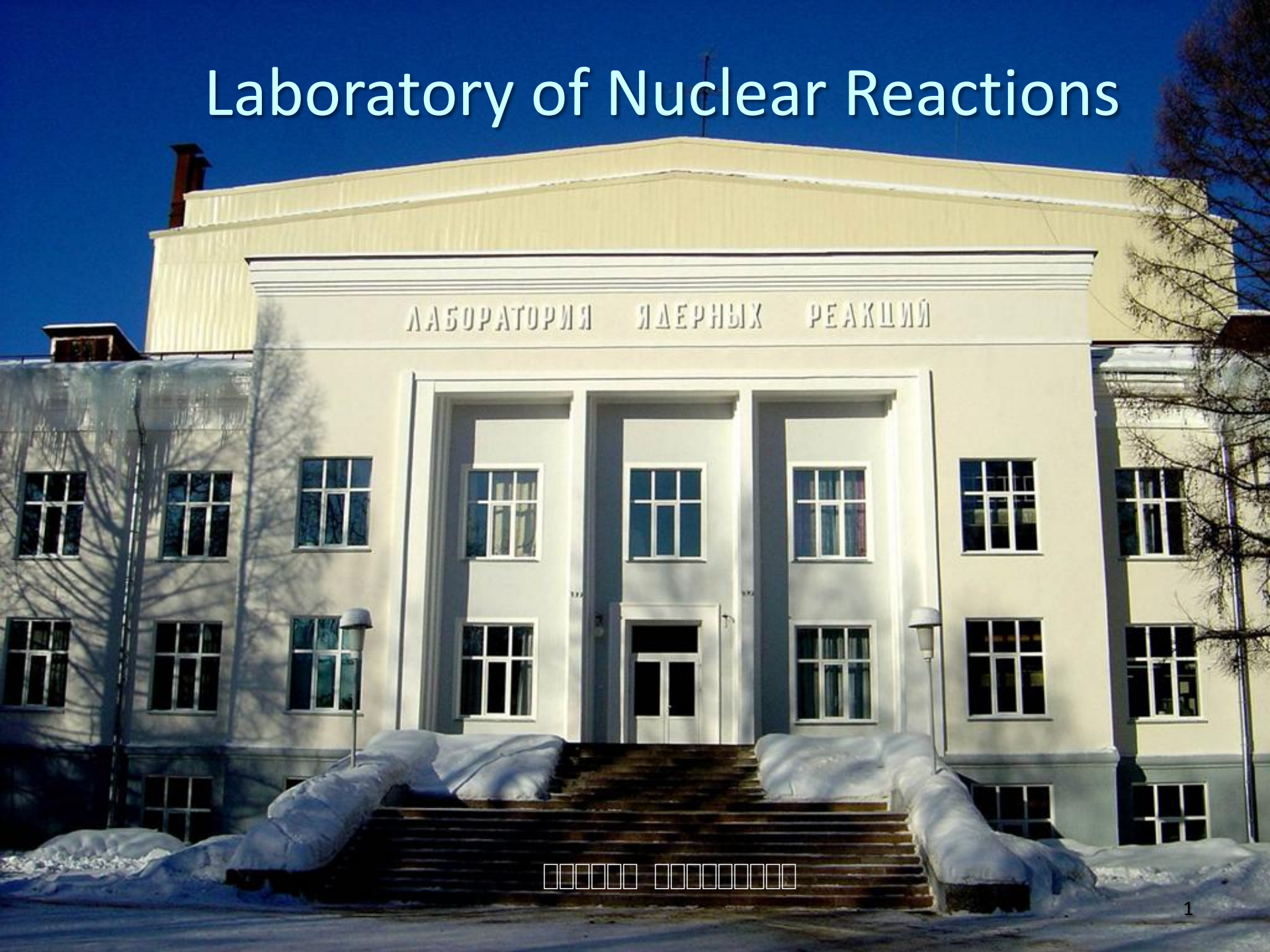
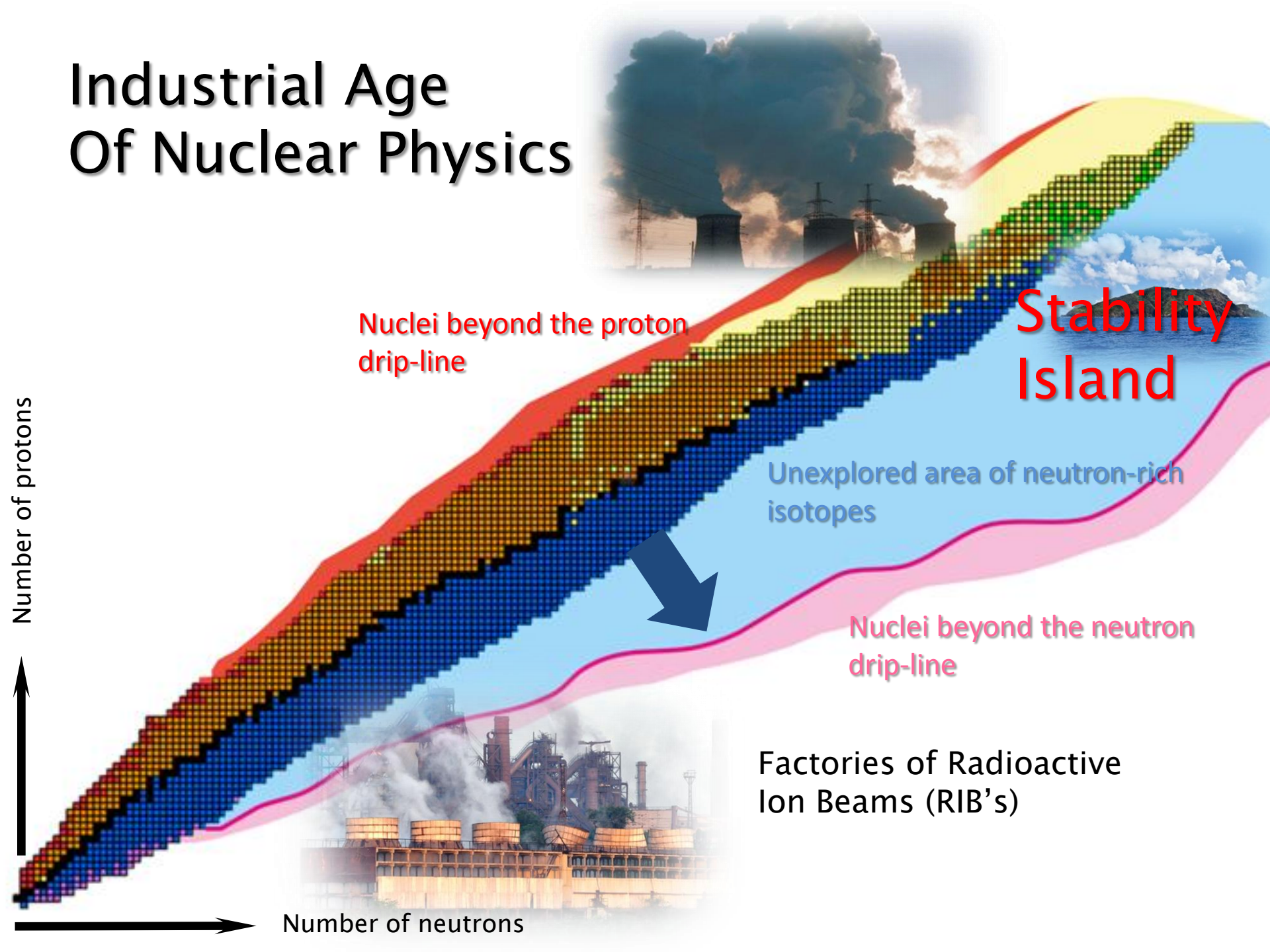
Laboratory of Nuclear Reactions

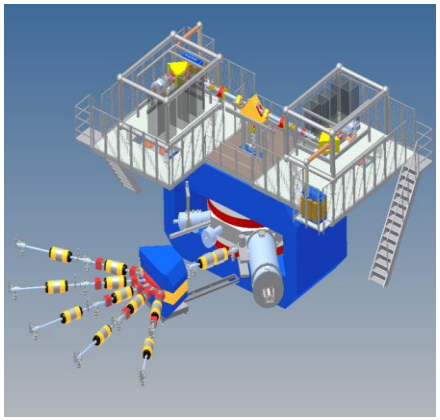


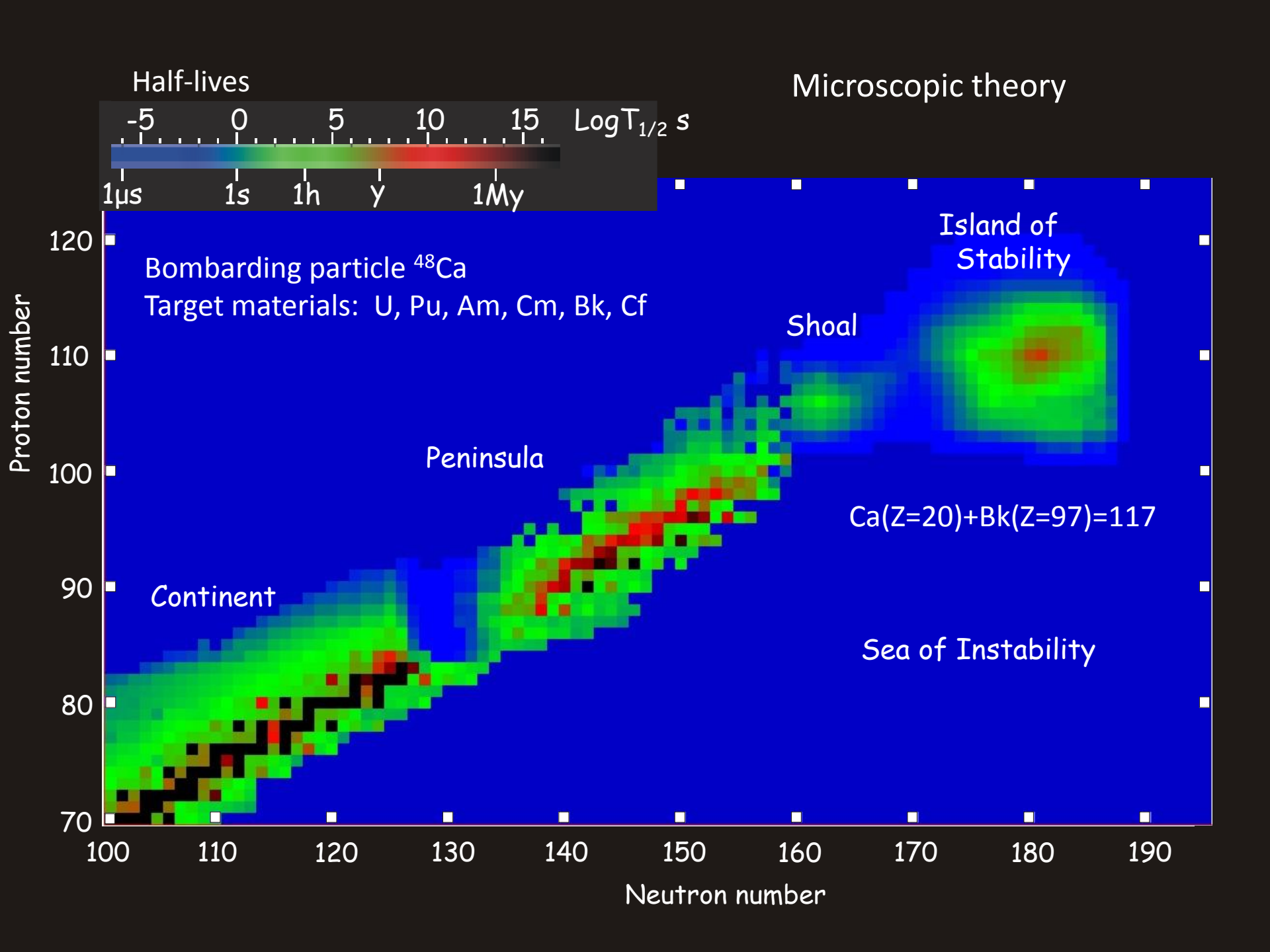
Industrial Age Of Nuclear Physics



Factories of Radioactive Ion Beams (RIB's)


DC-280
SHE factory
U-400
Heavy and superheavy nuclei
U-400M
Light exotic nuclei
IC-100
Applied research
DRIBs gallery
NanoLab
MT-25
Microtron

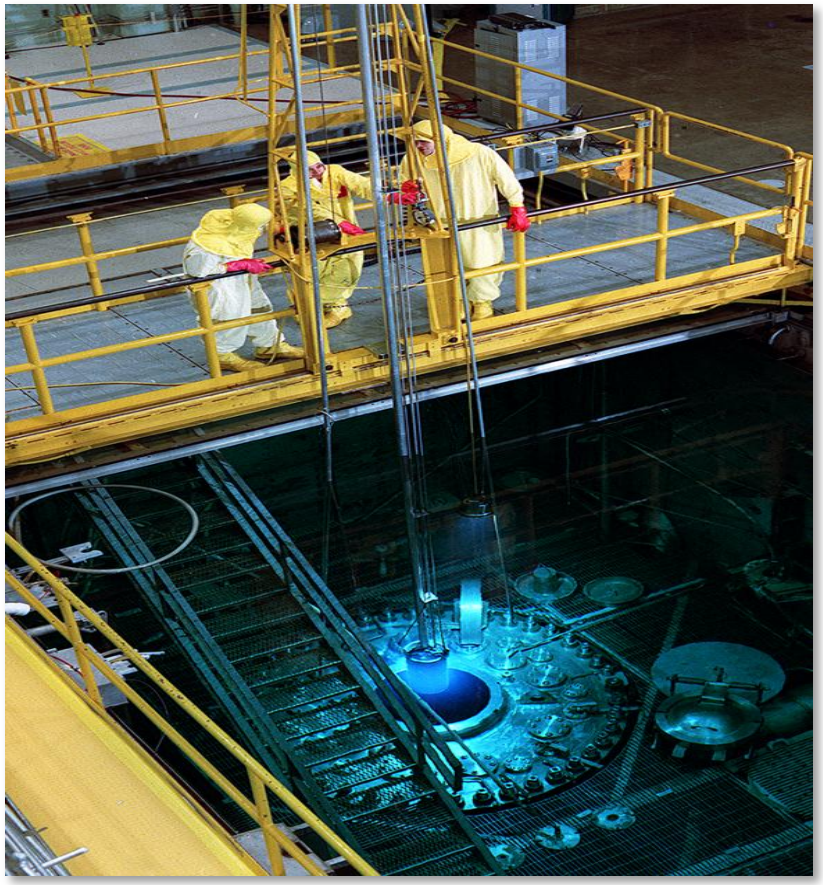



Half-lives
-5
0
5
10
15
Log$T_{1/2}$ s
1μs
1s
1h
y
1My
Microscopic theory
Bombarding particle ^{48}Ca
Target materials: U, Pu, Am, Cm, Bk, Cf
Island of Stability
Shoal
Peninsula
Continent
Ca(Z=20)+Bk(Z=97)=117
Sea of Instability
Proton number
Neutron number
120
110
100
90
80
70
100
110
120
130
140
150
160
170
180
190

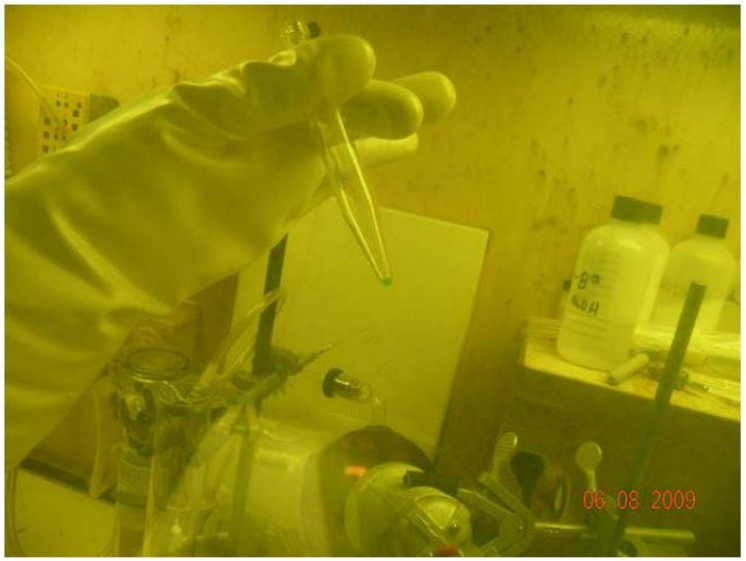
$$^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{239}_{92}\mathrm{U} \xrightarrow[23.5\ \mathrm{min}]{\beta^-} {}^{239}_{93}\mathrm{Np} \xrightarrow[2.3565\ \mathrm{d}]{\beta^-} {}^{239}_{94}\mathrm{Pu}$$

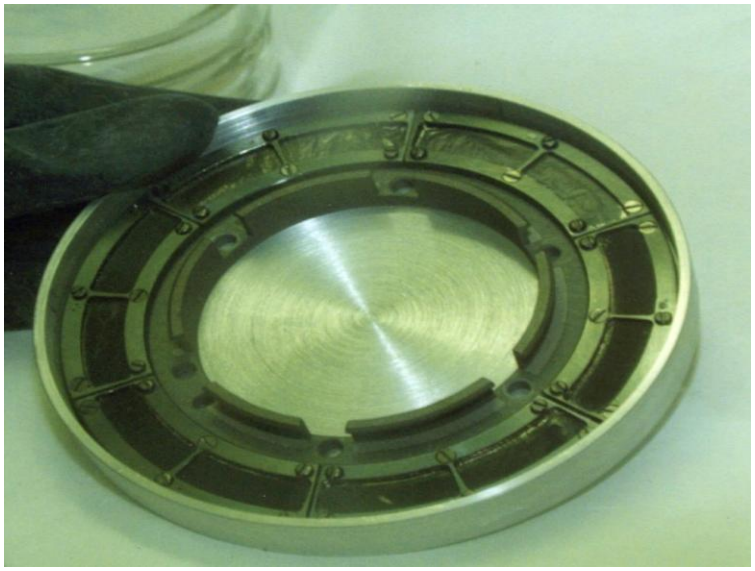
$$^{239}_{94}\mathrm{Pu} \xrightarrow{(\mathrm{n},\gamma)} {}^{240}_{94}\mathrm{Pu} \xrightarrow{(\mathrm{n},\gamma)} {}^{241}_{94}\mathrm{Pu} \xrightarrow[14{,}35\ \mathrm{a}]{\beta^-} {}^{241}_{95}\mathrm{Am} \left(\xrightarrow[432{,}2\ \mathrm{a}]{\alpha} {}^{237}_{93}\mathrm{Np} \right)$$

- **Irradiation in the HFIR flux trap**
  - **Thermal-neutron flux of 2.5 × 10^{15} neutrons/cm²·s**
  - **31 target positions (10–13 targets typically irradiated)**
  - **Produces ~35 mg ^{252}Cf per target (smaller quantities of Bk, Es, Fm)**

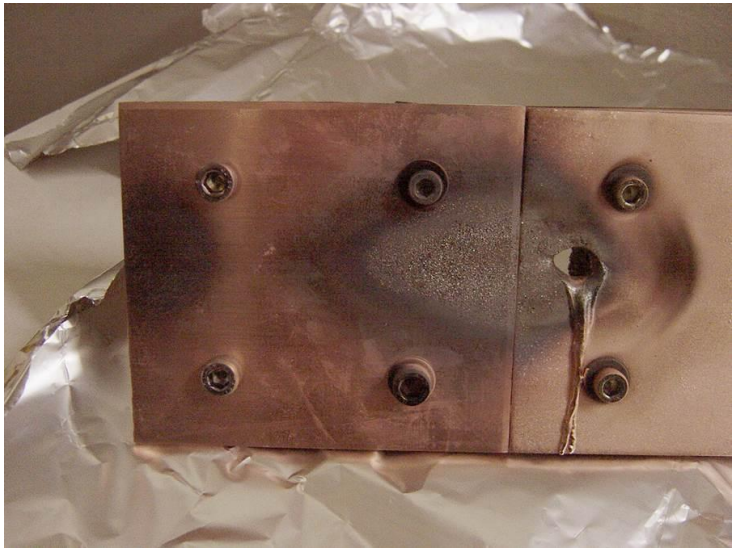


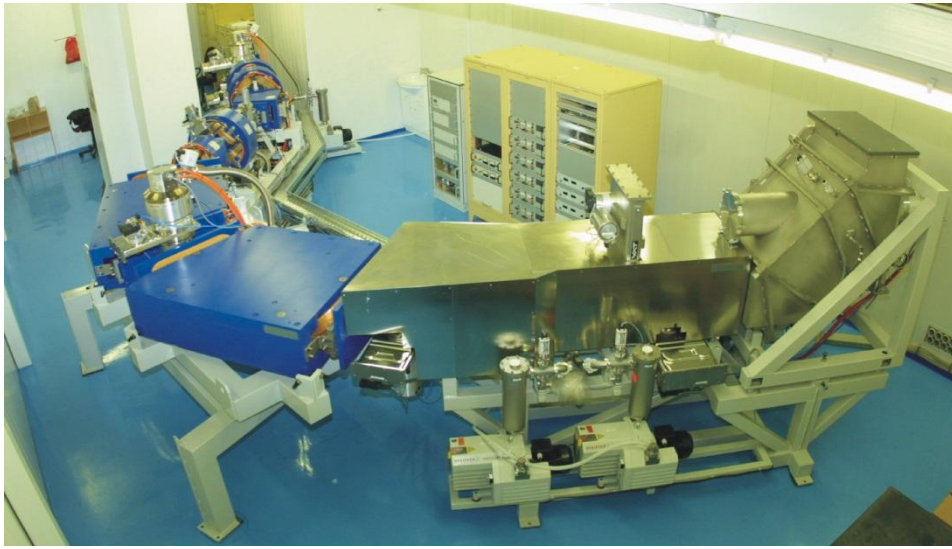
Experimental setup



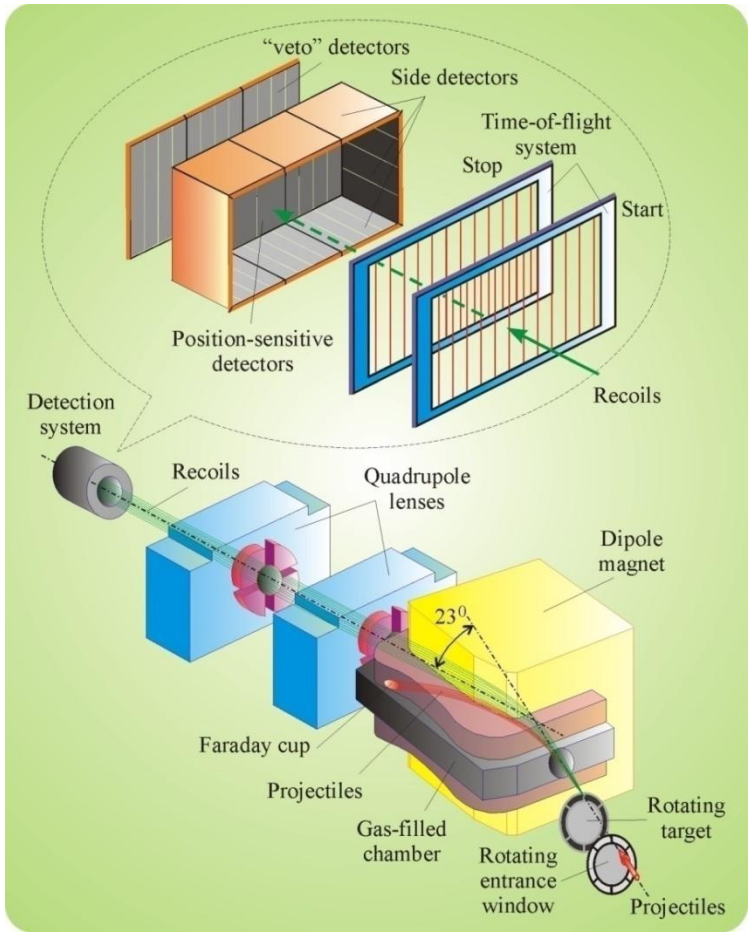


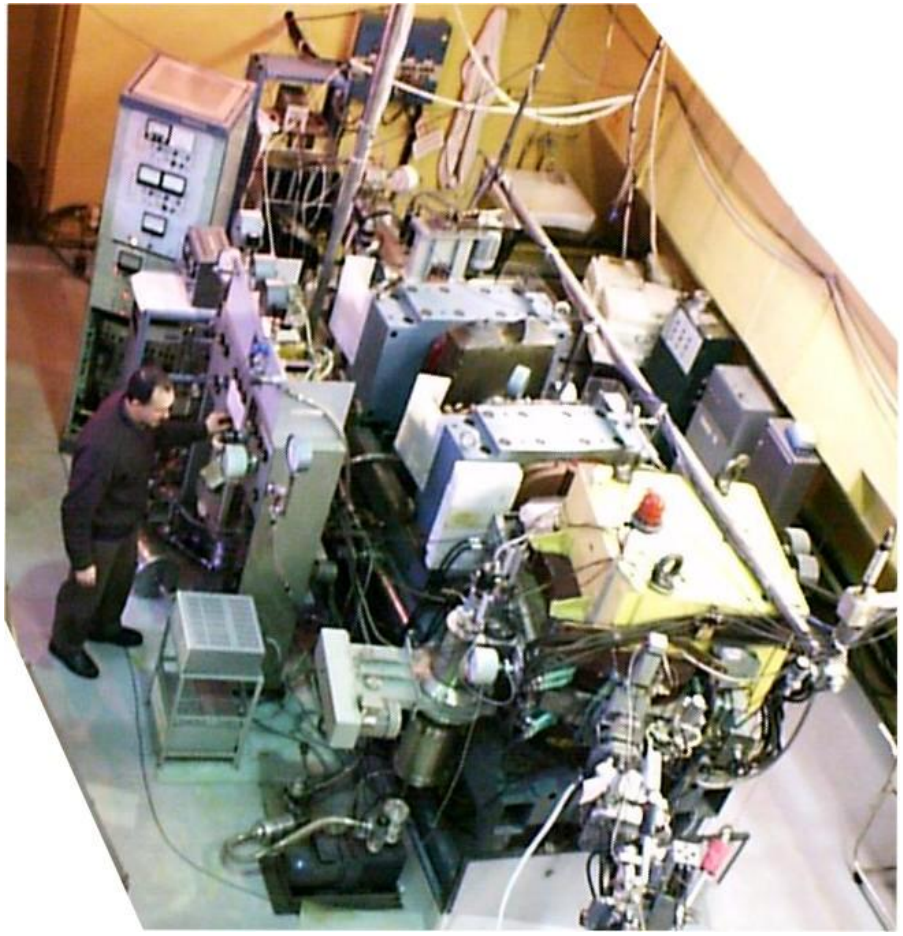
$Bk(NO_3)_3$Product





Dubna gas-filled separator



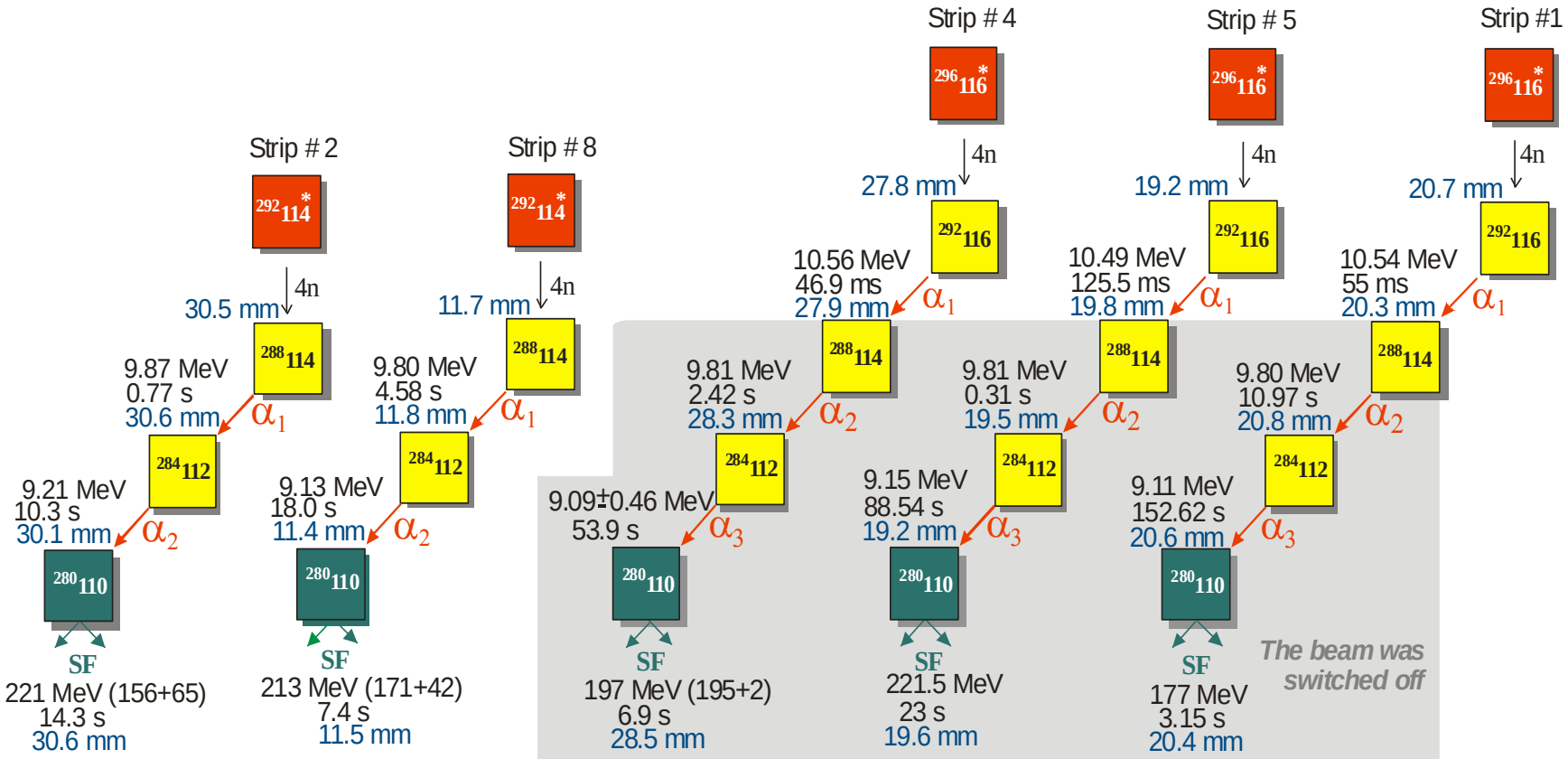


$^{244}_{Pu} + ^{48}_{Ca} \rightarrow ^{292}_{114}*$

Total beam dose: $1.5 \cdot 10^{19}$

$^{248}_{Cm} + ^{48}_{Ca} \rightarrow ^{296}_{116}*$

Total beam dose: $2.3 \cdot 10^{19}$



June 25, 1999 05:39 *Oct. 28, 1999 22:24* *July 19, 2000 01:21* *May 02, 2001 06:21* *May 08, 2001 16:54*

$$N_{SHN} = I_0 \cdot t \cdot N_{target} \cdot \sigma$$

I_0 – number of incoming particles	10^{12} s^{-1}
N_{target} – thickness of the target	10^{18} atoms/cm^2
	(or 0.4 mg/cm^2, or < 0.5 μ)
σ– cross section.	1 pb (or 10^{-36} cm^2)

$$N_{SHN} = 10^{12} s^{-1} \cdot 10^{18} cm^{-2} \cdot 10^{-36} cm^2 \sim 10^{-6}\ events/s$$

1 event/10 days

International Union of Pure and Applied Chemistry

May 2011:
Approval of the discovery of new elements *114* and *116*

May 2012:
Official approval of the name *Flerovium* for element *114*
and the name *Livermorium* for element *116*

30th December 2015:
Approval of the discovery of new elements *113, 115, 117, and 118*

- Priority for elements *115* and *117* is assigned to: JINR (Dubna) - LLNL (USA) – ORNL (USA) collaboration
- Priority for element *118* is assigned to JINR (Dubna) – LLNL collaboration.

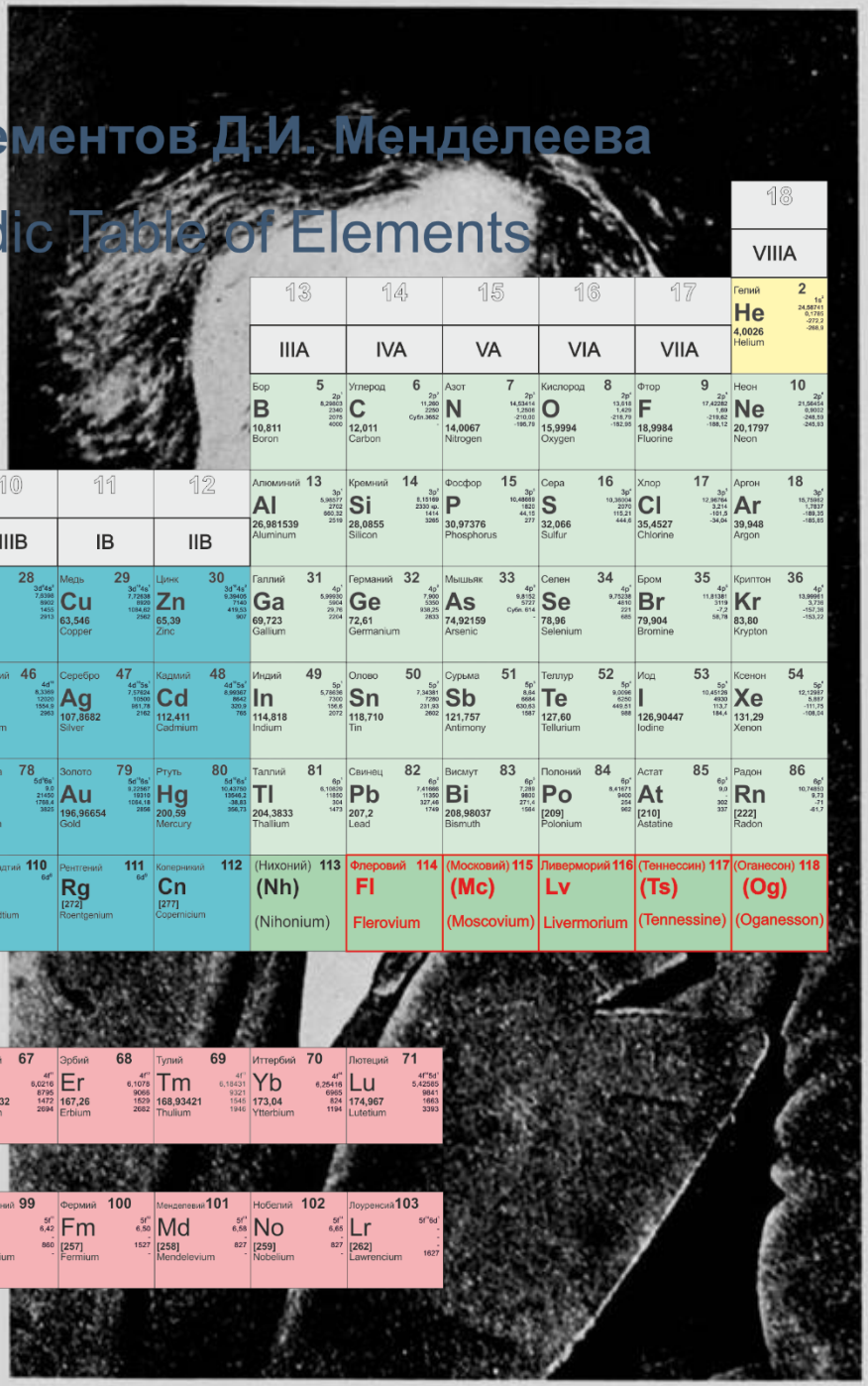
8th June 2016:
Provisional recommendations for naming elements *113, 115, 117, 118*

The 7th period of the periodic table of elements is now complete

All these elements were synthesized for the first time at the U400 accelerator complex of the Flerov Laboratory of Nuclear Reactions of JINR.

Периодическая таблица элементов Д.И. Менделеева

D.I. Mendeleev's Periodic Table of Elements



1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
Водород 1 **H** 1,00794 Hydrogen																	Гелий 2 **He** 4,0026 Helium
Литий 3 **Li** 6,941 Lithium	Бериллий 4 **Be** 9,01218 Beryllium											Бор 5 **B** 10,811 Boron	Углерод 6 **C** 12,011 Carbon	Азот 7 **N** 14,0067 Nitrogen	Кислород 8 **O** 15,9994 Oxygen	Фтор 9 **F** 18,9984 Fluorine	Неон 10 **Ne** 20,1797 Neon
Натрий 11 **Na** 22,989768 Sodium	Магний 12 **Mg** 24,3050 Magnesium											Алюминий 13 **Al** 26,981539 Aluminum	Кремний 14 **Si** 28,0855 Silicon	Фосфор 15 **P** 30,97376 Phosphorus	Сера 16 **S** 32,066 Sulfur	Хлор 17 **Cl** 35,4527 Chlorine	Аргон 18 **Ar** 39,948 Argon
Калий 19 **K** 39,0983 Potassium	Кальций 20 **Ca** 40,078 Calcium	Скандий 21 **Sc** 44,95591 Scandium	Титан 22 **Ti** 47,88 Titanium	Ванадий 23 **V** 50,9415 Vanadium	Хром 24 **Cr** 51,9961 Chromium	Марганец 25 **Mn** 54,93805 Manganese	Железо 26 **Fe** 55,847 Iron	Кобальт 27 **Co** 58,93320 Cobalt	Никель 28 **Ni** 58,6934 Nickel	Медь 29 **Cu** 63,546 Copper	Цинк 30 **Zn** 65,39 Zinc	Галлий 31 **Ga** 69,723 Gallium	Германий 32 **Ge** 72,61 Germanium	Мышьяк 33 **As** 74,92159 Arsenic	Селен 34 **Se** 78,96 Selenium	Бром 35 **Br** 79,904 Bromine	Криптон 36 **Kr** 83,80 Krypton
Рубидий 37 **Rb** 85,4678 Rubidium	Стронций 38 **Sr** 87,62 Strontium	Иттрий 39 **Y** 88,90585 Yttrium	Цирконий 40 **Zr** 91,224 Zirkonium	Ниобий 41 **Nb** 92,90638 Niobium	Молибден 42 **Mo** 95,94 Molybdenum	Технеций 43 **Tc** [98] Technetium	Рутений 44 **Ru** 101,07 Ruthenium	Родий 45 **Rh** 102,90550 Rhodium	Палладий 46 **Pd** 106,42 Palladium	Серебро 47 **Ag** 107,8682 Silver	Кадмий 48 **Cd** 112,411 Cadmium	Индий 49 **In** 114,818 Indium	Олово 50 **Sn** 118,710 Tin	Сурьма 51 **Sb** 121,757 Antimony	Теллур 52 **Te** 127,60 Tellurium	Иод 53 **I** 126,90447 Iodine	Ксенон 54 **Xe** 131,29 Xenon
Цезий 55 **Cs** 132,90543 Cesium	Барий 56 **Ba** 137,327 Barium	Лантан 57 **La** 138,9055 Lanthanum	Гафний 72 **Hf** 178,49 Hafnium	Тантал 73 **Ta** 180,9479 Tantalum	Вольфрам 74 **W** 183,84 Tungsten	Рений 75 **Re** 186,207 Rhenium	Осмий 76 **Os** 190,23 Osmium	Иридий 77 **Ir** 192,22 Iridium	Платина 78 **Pt** 195,08 Platinum	Золото 79 **Au** 196,96654 Gold	Ртуть 80 **Hg** 200,59 Mercury	Таллий 81 **Tl** 204,3833 Thallium	Свинец 82 **Pb** 207,2 Lead	Висмут 83 **Bi** 208,98037 Bismuth	Полоний 84 **Po** [209] Polonium	Астат 85 **At** [210] Astatine	Радон 86 **Rn** [222] Radon
Франций 87 **Fr** [223] Francium	Радий 88 **Ra** 226,025 Radium	Актиний 89 **Ac** [227] Actinium	Резерфордий 104 **Rf** [261] Rutherfordium	Дубний 105 **Db** [262] Dubnium	Сиборгий 106 **Sg** [266] Seaborgium	Борий 107 **Bh** [262] Bohrium	Хассий 108 **Hs** [269] Hassium	Мейтнерий 109 **Mt** [268] Meitnerium	Дармштадтий 110 **Ds** [269] Darmstadtium	Рентгений 111 **Rg** [272] Roentgenium	Коперниций 112 **Cn** [277] Copernicium	(Нихоний) 113 **(Nh)** (Nihonium)	Флеровий 114 **Fl** Flerovium	(Московий) 115 **(Mc)** (Moscovium)	Ливерморий 116 **Lv** Livermorium	(Теннессин) 117 **(Ts)** (Tennessine)	(Оганесон) 118 **(Og)** (Oganesson)

Лантаноиды Lanthanides

Церий 58 **Ce** 140,115 Cerium	Празеодим 59 **Pr** 140,90765 Praseodymium	Неодим 60 **Nd** 144,24 Neodymium	Прометий 61 **Pm** [145] Promethium	Самарий 62 **Sm** 150,36 Samarium	Европий 63 **Eu** 151,965 Europium	Гадолиний 64 **Gd** 157,25 Gadolinium	Тербий 65 **Tb** 158,92534 Terbium	Диспрозий 66 **Dy** 162,50 Dysprosium	Гольмий 67 **Ho** 164,93032 Holmium	Эрбий 68 **Er** 167,26 Erbium	Тулий 69 **Tm** 168,93421 Thulium	Иттербий 70 **Yb** 173,04 Ytterbium	Лютеций 71 **Lu** 174,967 Lutetium

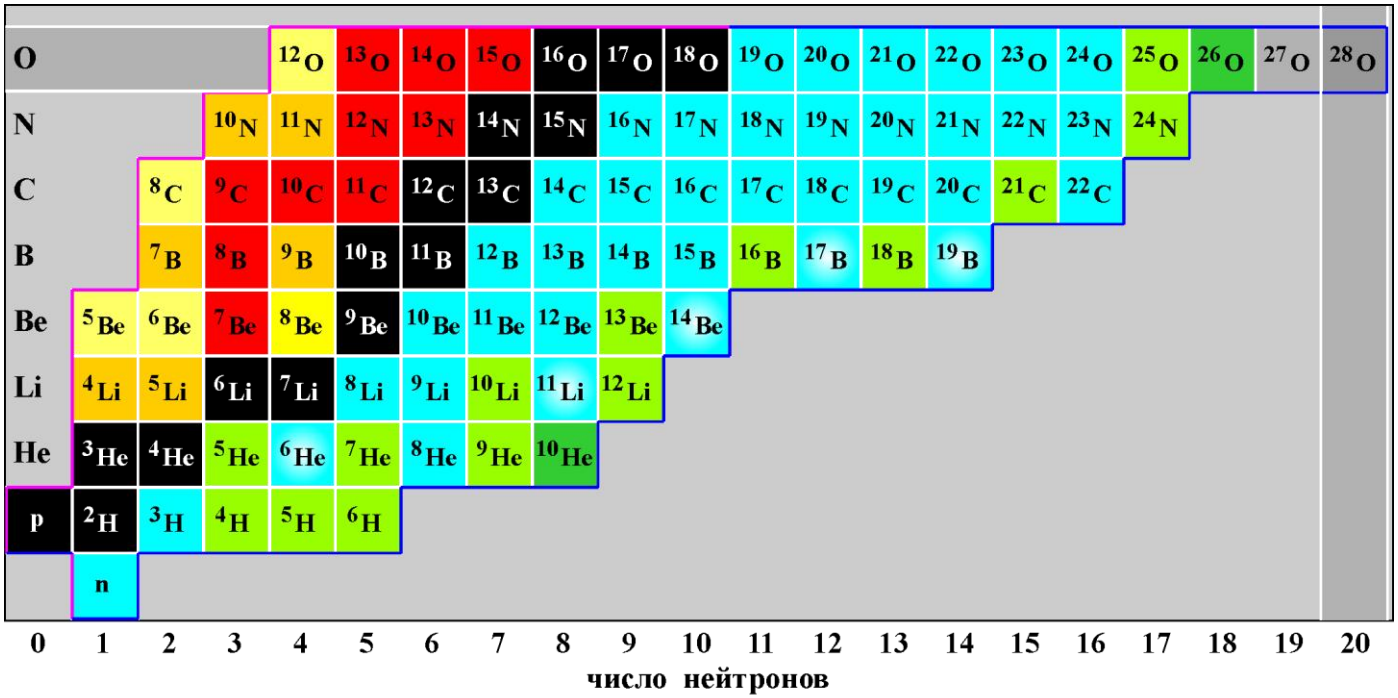
Актиноиды Actinides

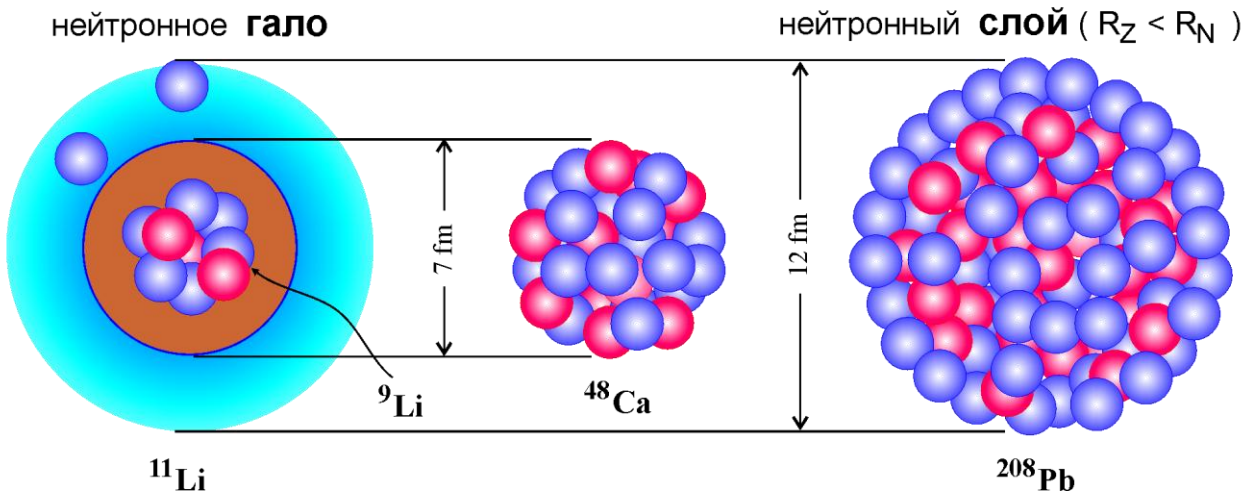
Торий 90 **Th** 232,0381 Thorium	Протактиний 91 **Pa** 231,03588 Protactinium	Уран 92 **U** 238,0289 Uranium	Нептуний 93 **Np** [237] Neptunium	Плутоний 94 **Pu** [244] Plutonium	Америций 95 **Am** [243] Americium	Кюрий 96 **Cm** [247] Curium	Берклий 97 **Bk** [247] Berkelium	Калифорний 98 **Cf** [251] Californium	Эйнштейний 99 **Es** [252] Einsteinium	Фермий 100 **Fm** [257] Fermium	Менделевий 101 **Md** [258] Mendelevium	Нобелий 102 **No** [259] Nobelium	Лоуренсий 103 **Lr** [262] Lawrencium

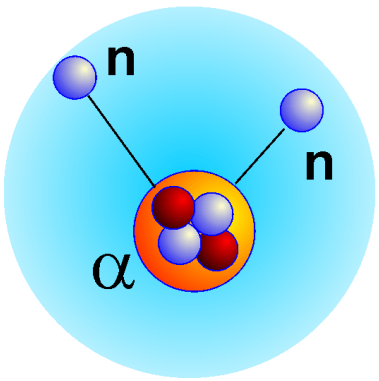
SHE-factory

- Synthesis and study of properties of SHE.
- Search for new reactions for SHE-synthesis.
- Chemistry of new elements.

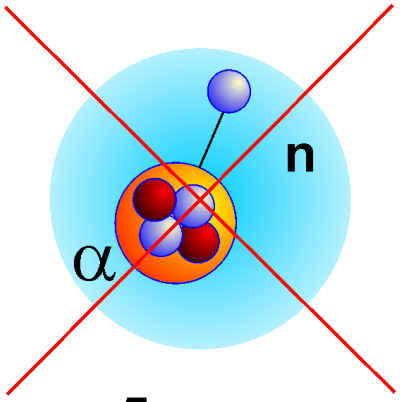
Halo nuclei


O 12O 13O 14O 15O 16O 17O 18O 19O 20O 21O 22O 23O 24O 25O 26O 27O 28O
N 10N 11N 12N 13N 14N 15N 16N 17N 18N 19N 20N 21N 22N 23N 24N
C 8C 9C 10C 11C 12C 13C 14C 15C 16C 17C 18C 19C 20C 21C 22C
B 7B 8B 9B 10B 11B 12B 13B 14B 15B 16B 17B 18B 19B
Be 5Be 6Be 7Be 8Be 9Be 10Be 11Be 12Be 13Be 14Be
Li 4Li 5Li 6Li 7Li 8Li 9Li 10Li 11Li 12Li
He 3He 4He 5He 6He 7He 8He 9He 10He
p 2H 3H 4H 5H 6H
n
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
число нейтронов

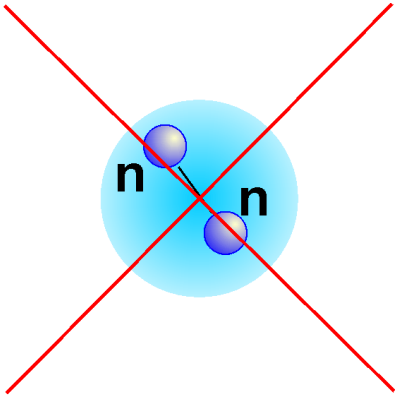

нейтронное гало
нейтронный слой ($R_Z < R_N$)
7 fm
12 fm
9Li
48Ca
11Li
208Pb



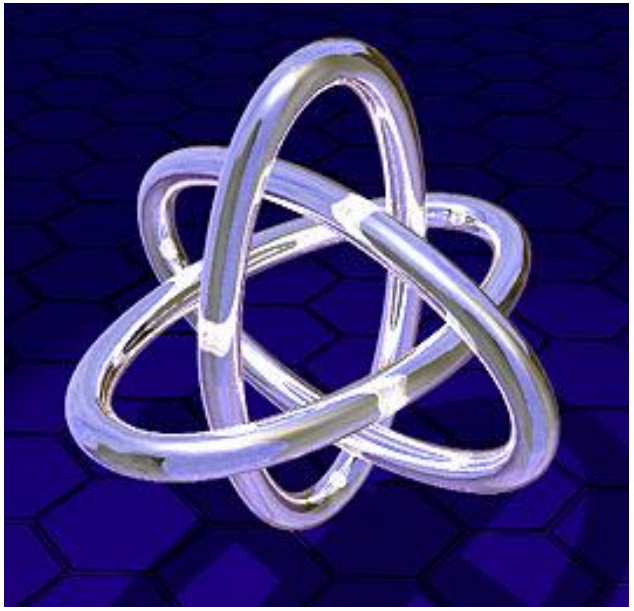
^{6}He

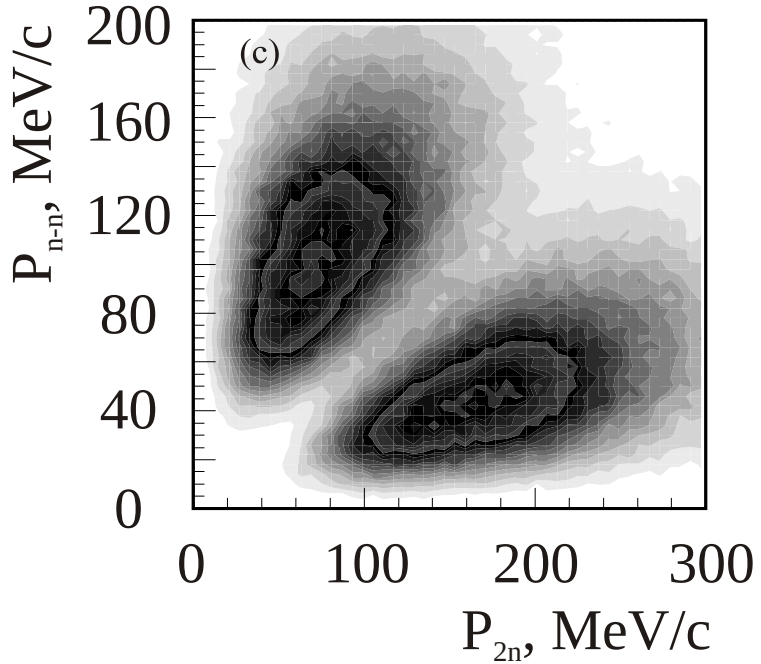


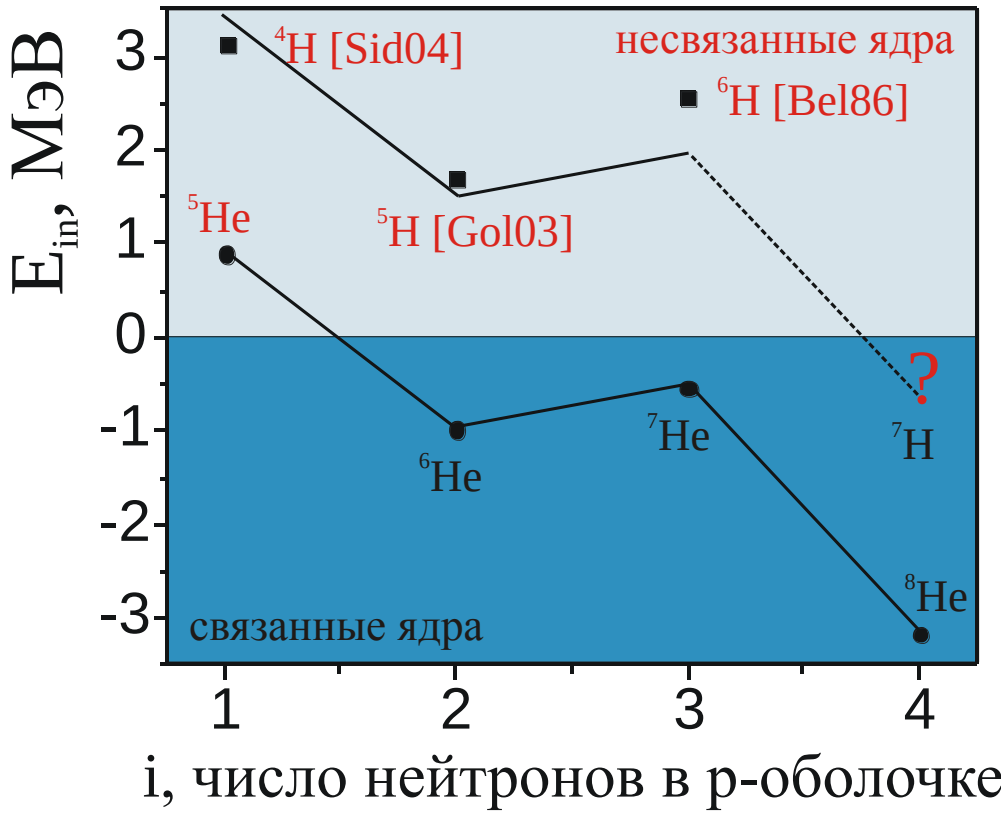
^{5}He

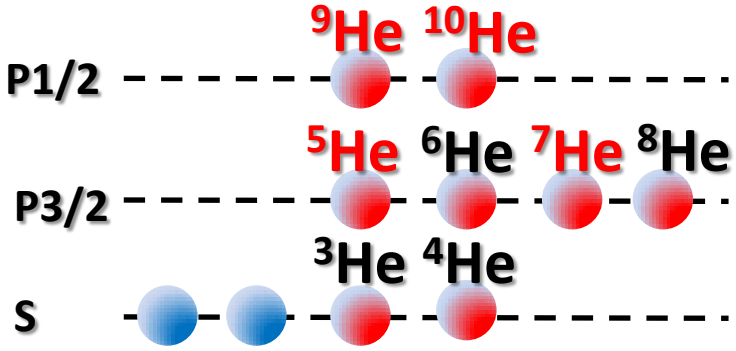


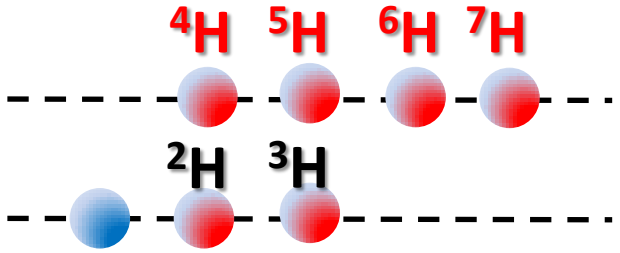
^{2}n



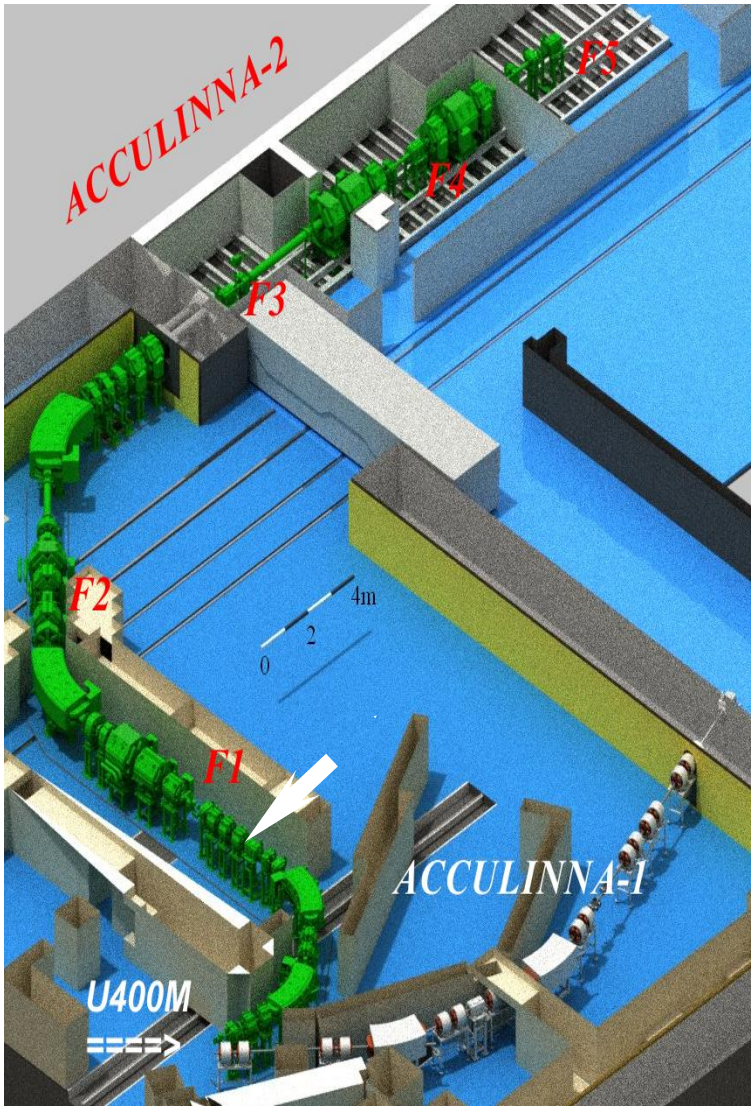


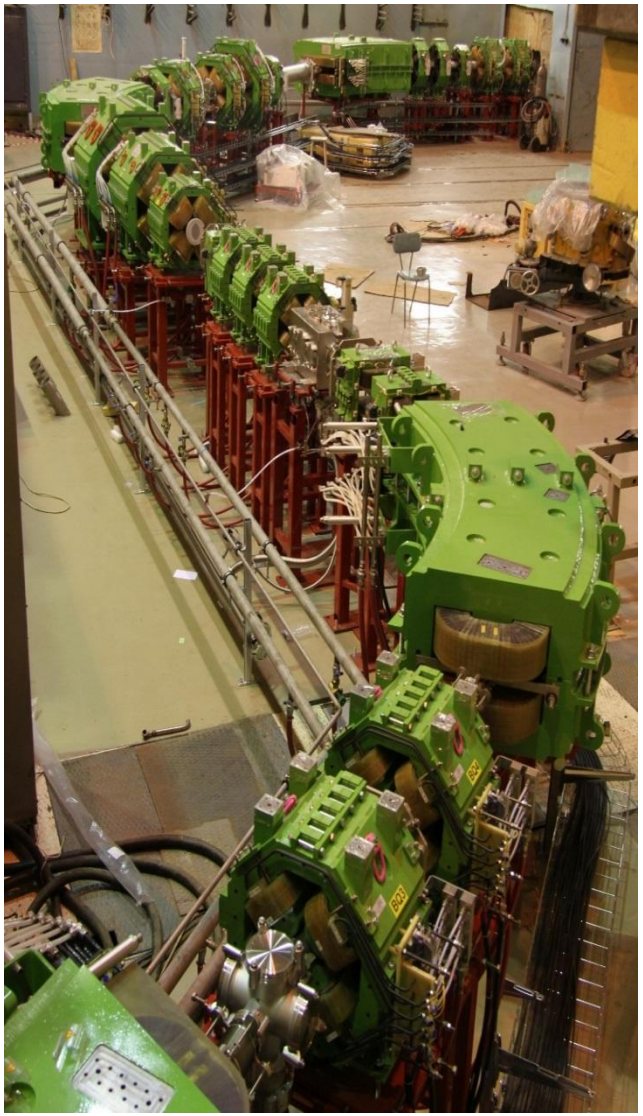

E_{in}, МэВ
3
2
1
0
-1
-2
-3
1
2
3
4
^{4}H [Sid04]
несвязанные ядра
^{6}H [Bel86]
^{5}He
^{5}H [Gol03]
?
^{7}He
^{7}H
^{6}He
^{8}He
связанные ядра
i, число нейтронов в p-оболочке


^{9}He ^{10}He
P1/2
^{5}He ^{6}He ^{7}He ^{8}He
P3/2
^{3}He ^{4}He
S
protons
neutrons


^{4}H ^{5}H ^{6}H ^{7}H
^{2}H ^{3}H
protons
neutrons

Fragment-separator ACCULINNA-2





APPLIED RESEARCH (Nanotechnology Centre)

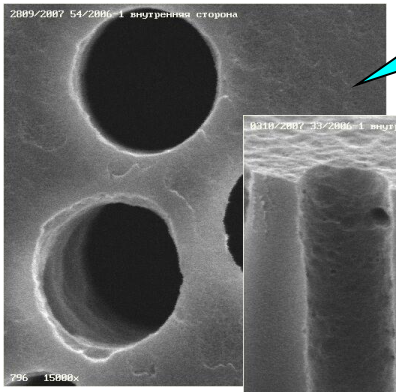
- Study of effects arising under irradiation by heavy ions;
- Controlled modification of properties of material with the use of heavy ion beams;
- Development of technologies of track membranes.

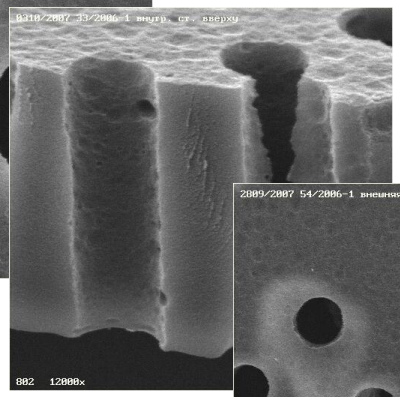
General view of the new laboratory building (Centre of Nanotechnology)

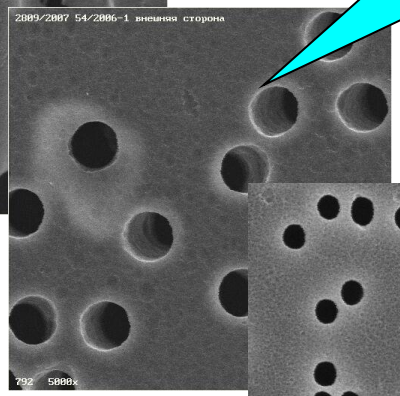
Cyclotron IC-100

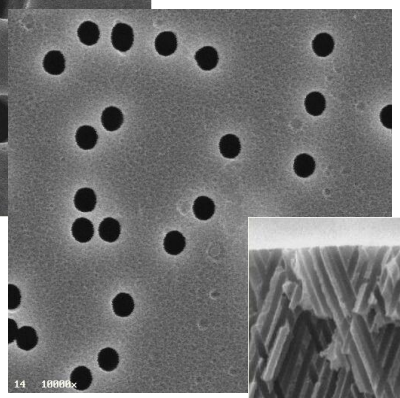
Micrometers

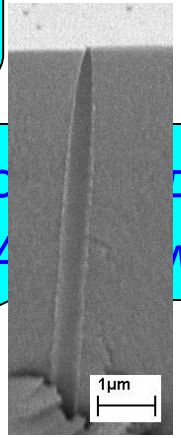
Early cancer diagnostics, 4-7 мсм

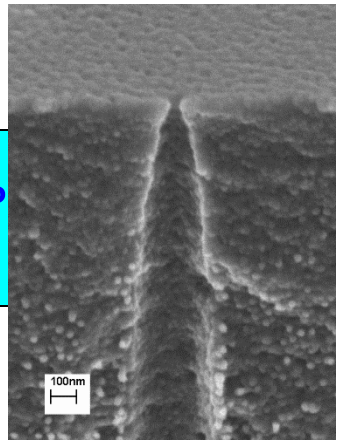


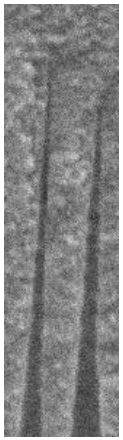




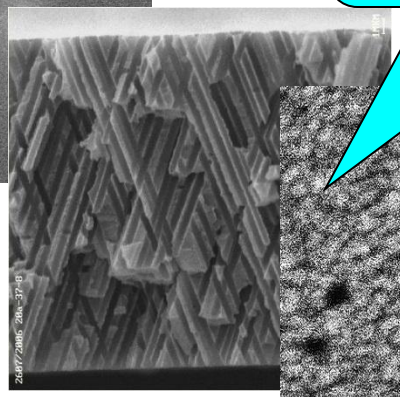


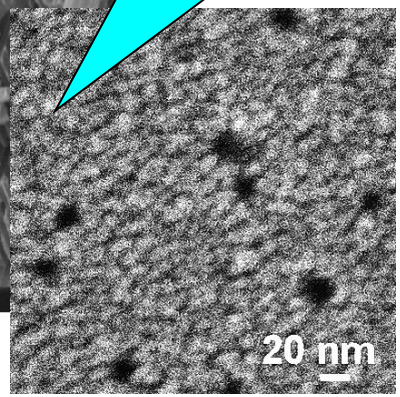






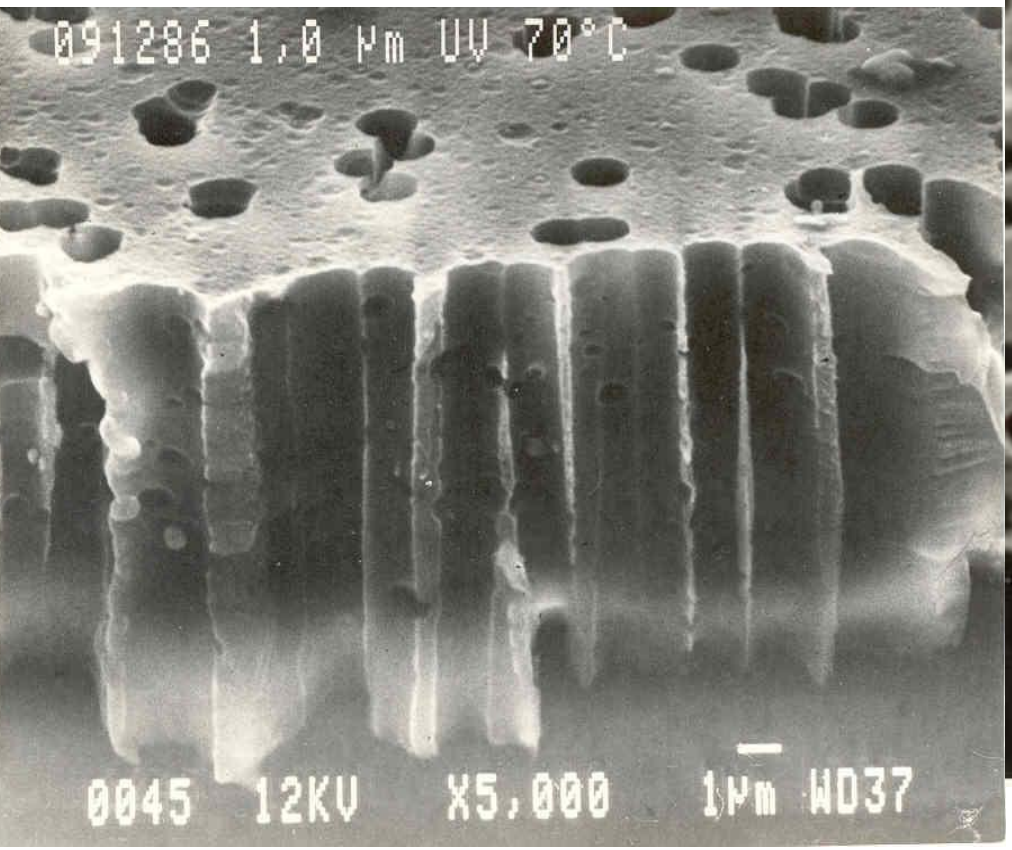
Molecular sensors, < 20 нм

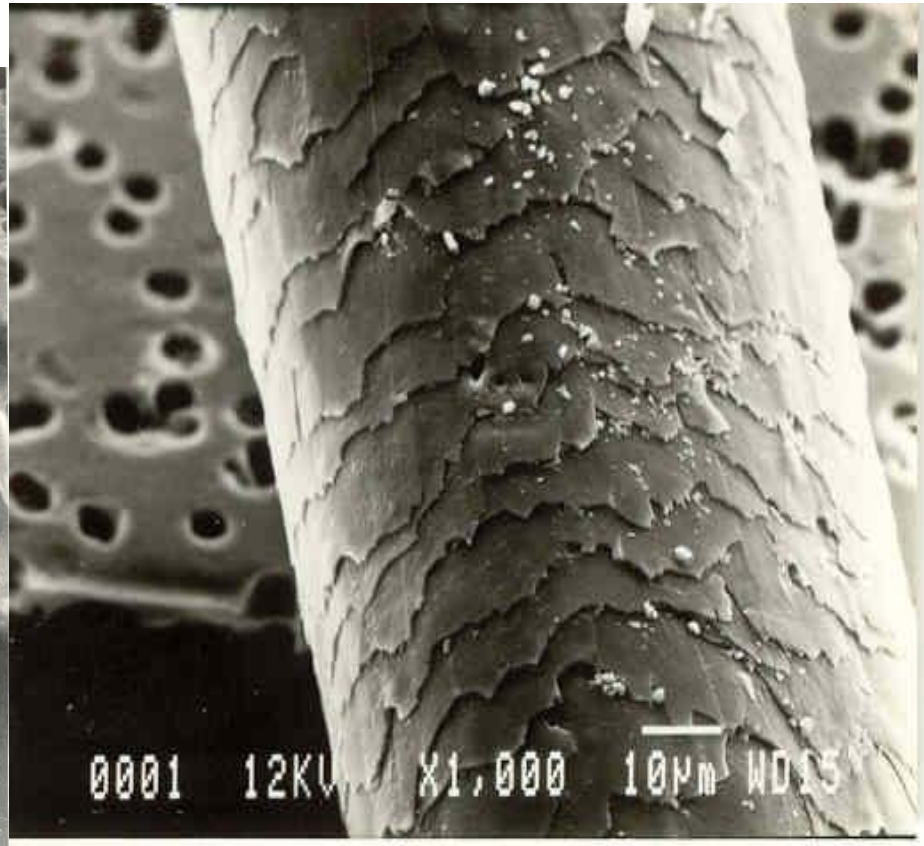




Track membranes

Nanometers





Снимок ядерного фильтра под электронным микроскопом.

а) Срез ядерного фильтра. В правом нижнем углу белой линией показан масштаб снимка.

б) Снимок ядерного фильтра под электронным микроскопом на фоне человеческого волоса.

Single-Event Effects (SEE) testing at the FLNR cyclotrons

Main user:
The Russian Space Agency (Roscosmos)

- ✓ Dedicated beam-line (3 60 MeV/nucleon) ions (usually Ne, Ar, Kr, Xe, Fe or Bi)
- ✓ Irradiation area – 200 200 mm^2.
- ✓ Beam uniformity better than 30%
- ✓ Beam flux 1 10^5 $cm^{-2}s^{-1}$