CURRENT STATUS AND PROSPECTS OF NUCLEAR PHYSICS RESEARCH

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PHYSICS OF ATOMIC NUCLEI. SHORT HISTORICAL SURVEY

I. 1896 – 1939. Fundamental studies, great expectations of application. 11 Nobel prices.

II. 1940 – 1963. Applied and fundamental studies. Great results. 13 Nobel prices.

III. 1964 – the present day. Fundamental studies with a limited application areas. 4 Nobel prices motivated for bygone results.

PHYSICS OF ATOMIC NUCLEI. MODERN WELL-ACCEPTED AREAS

1. Nuclear astrophysics.

2. Radioactive-beam studies.

3. Nucleus-nucleus collisions. Superheavy elements.

4. High-spin states including high-spin isomers.

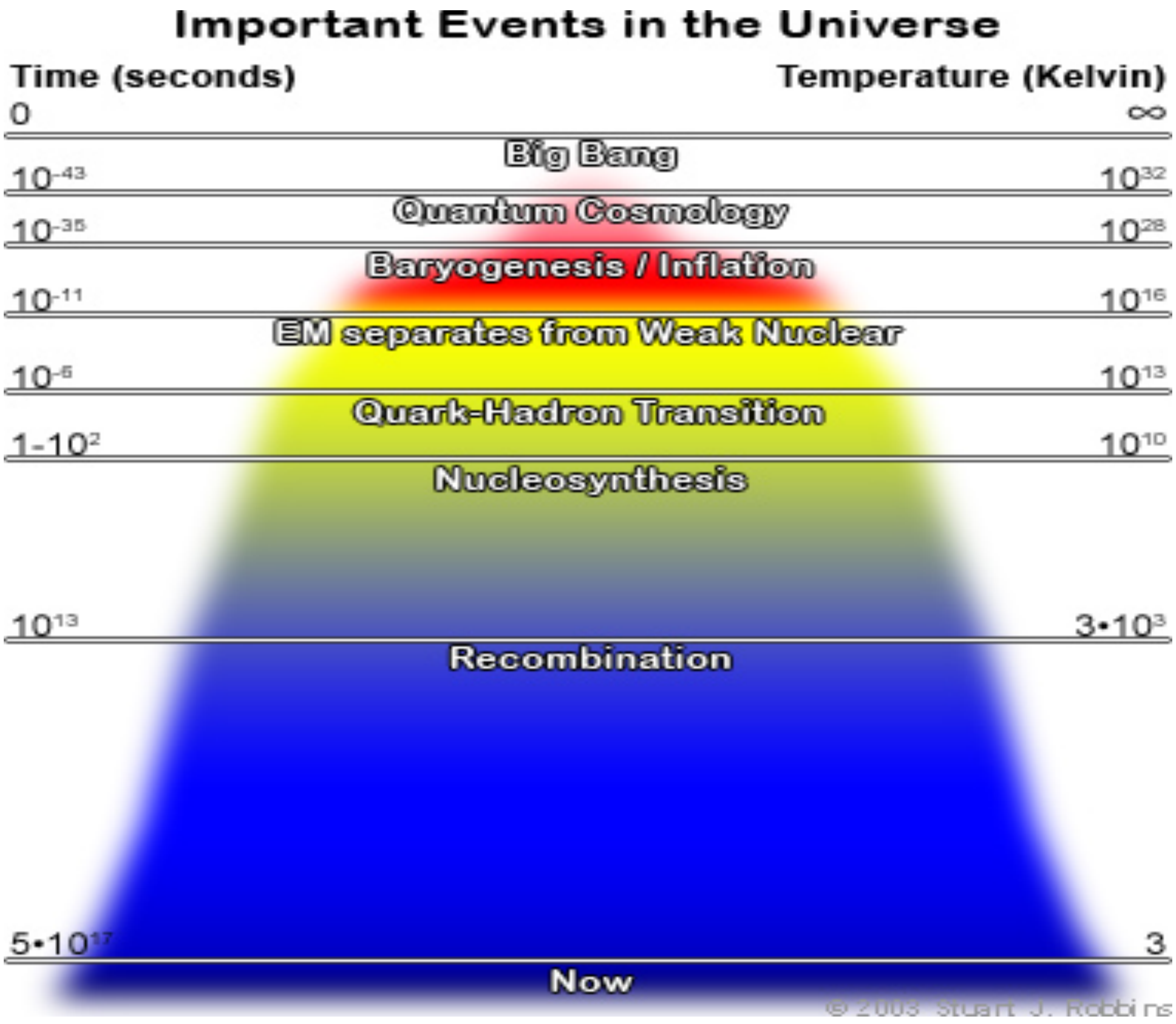
5. New gamma-ray sources.

6. Few-body investigations.

7.Exotics.

8. Clustering.

NUCLEAR ASTROPHYSICS



BIG BANG NUCLEOSYNTHESIS. BASIC REACTIONS

d(p,γ)h	d(d,n)h	d(d,p)t	t(d,n)α
t(α,γ)7Li	h(α,γ)7Be	7Li(p,α)α	p(n,γ)d
h(d,p)α	7Be(n,p)7Li	h(n,p)t	

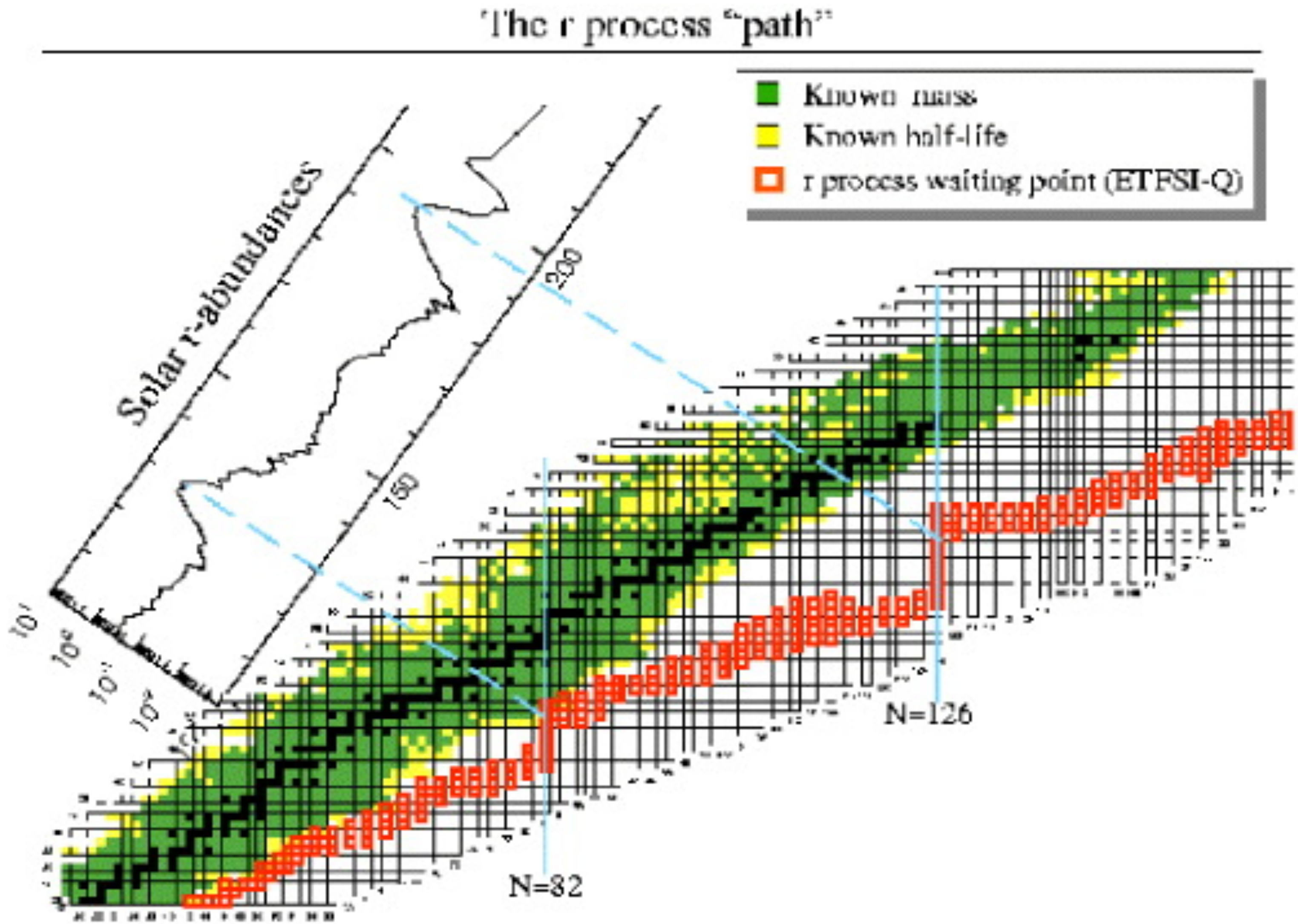
The basis quantity to be calculated – so-called astrophysical S-factor:

$$S = e^{2\pi\eta} E\sigma$$

STELLAR NUCLEOSINTHESIS

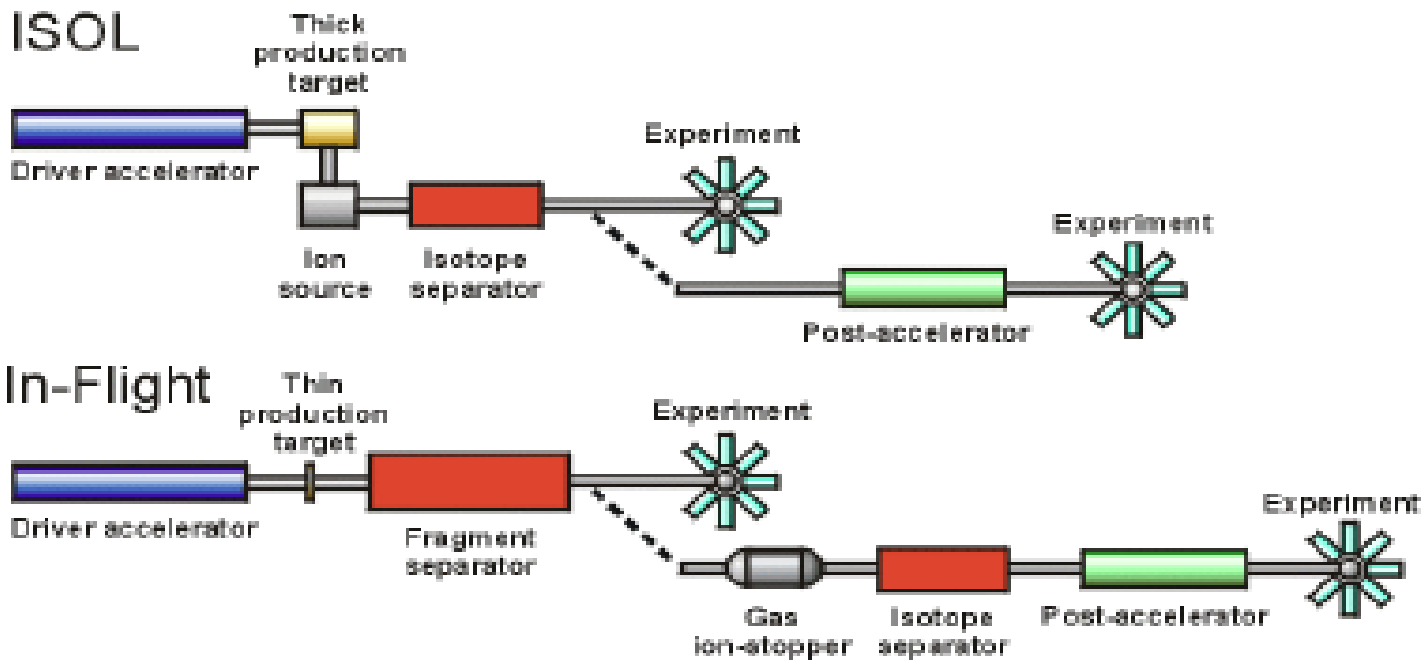
Stellar nucleosynthesis involves all reactions of nuclei A≤70 with light particles: p, d, t, h, α; the reactions 12C +12C, 12C+16O, 16O+16O; neutron capture reactions on all stable and long-lived isotopes at moderate neutron density (s-process).

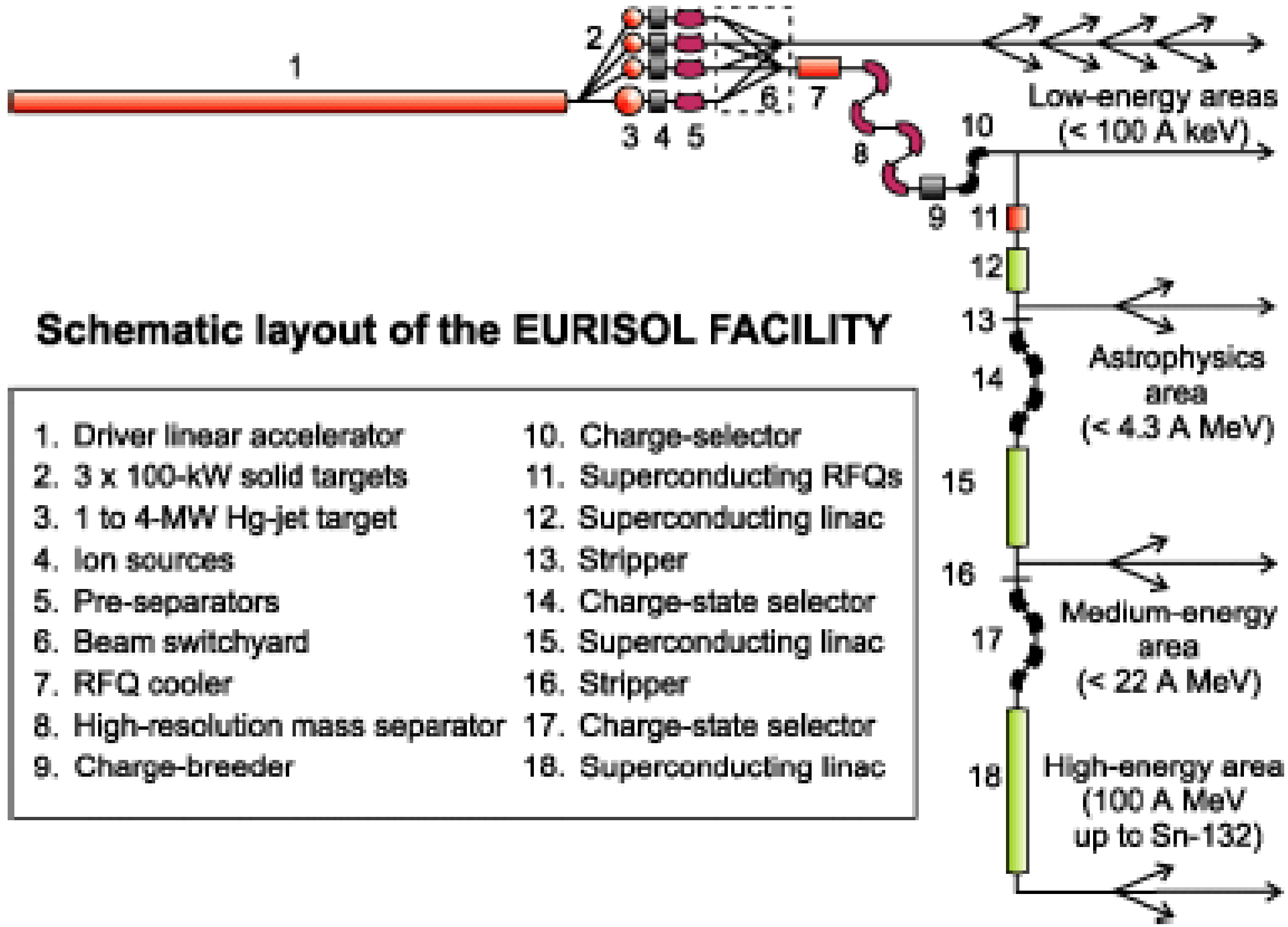
EXPLOSIVE NUCLEOSINTHESIS

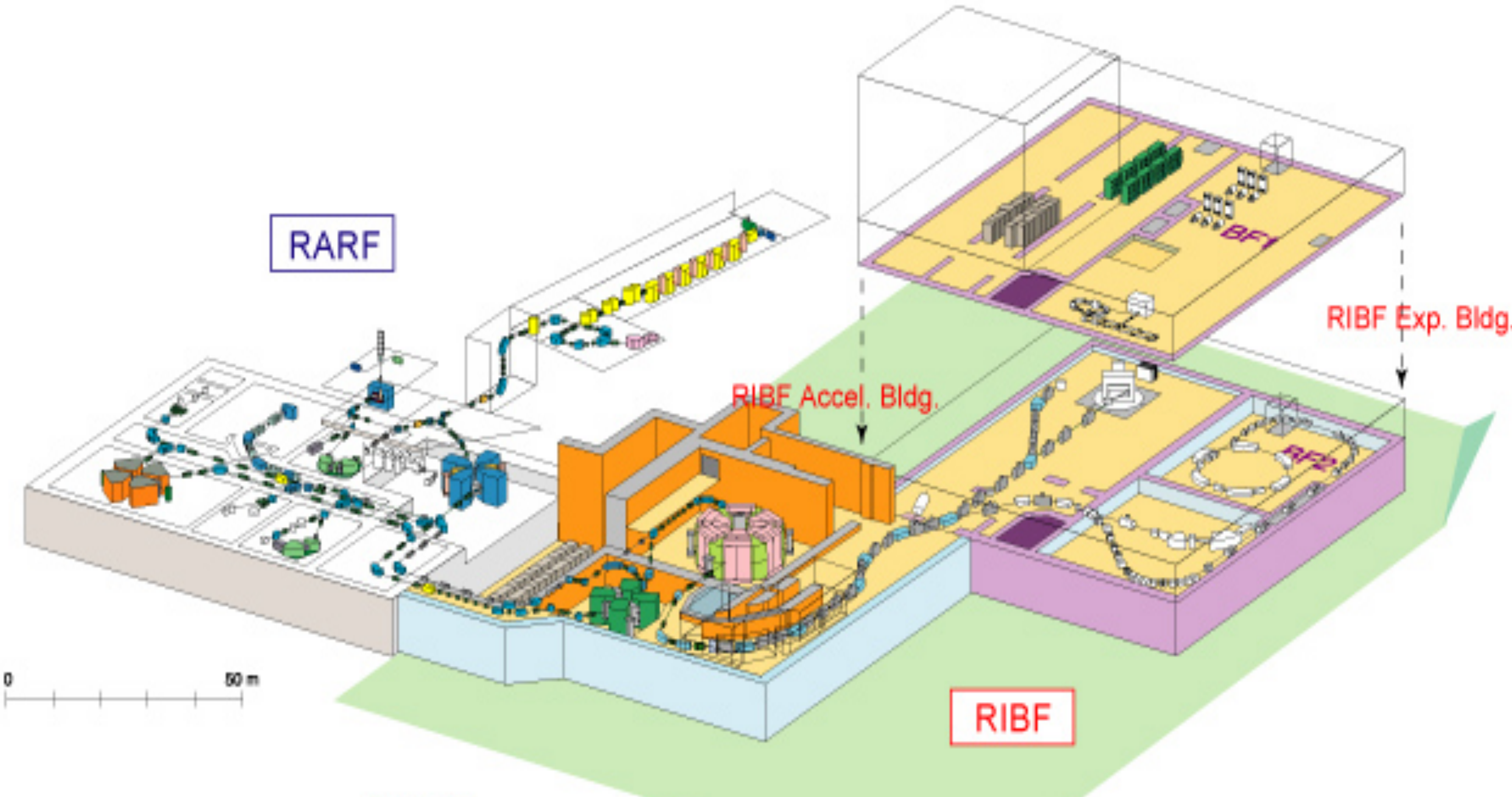


Proton, neutron, photon, neutrino reactions.

RADIOACTIVE-BEAM STUDIES




Schematic layout of the EURISOL FACILITY
1. Driver linear accelerator
2. 3 x 100-kW solid targets
3. 1 to 4-MW Hg-jet target
4. Ion sources
5. Pre-separators
6. Beam switchyard
7. RFQ cooler
8. High-resolution mass separator
9. Charge-breeder
10. Charge-selector
11. Superconducting RFQs
12. Superconducting linac
13. Stripper
14. Charge-state selector
15. Superconducting linac
16. Stripper
17. Charge-state selector
18. Superconducting linac
Low-energy areas
(< 100 A keV)
Astrophysics
area
(< 4.3 A MeV)
Medium-energy
area
(< 22 A MeV)
High-energy area
(100 A MeV
up to Sn-132)

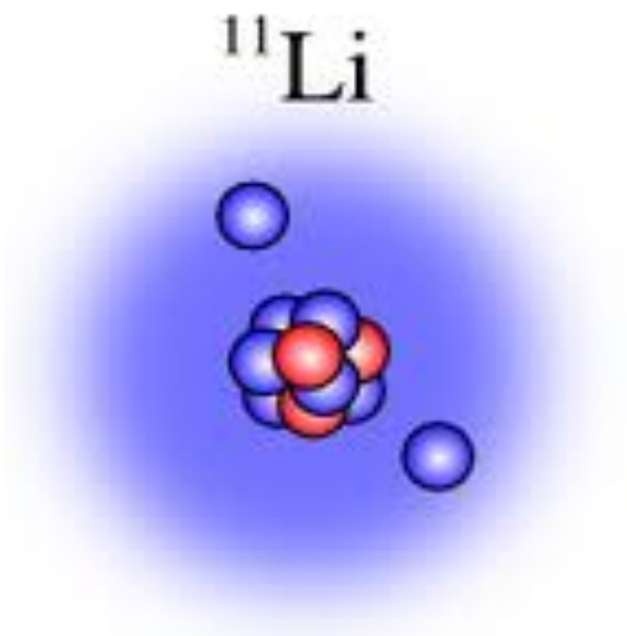


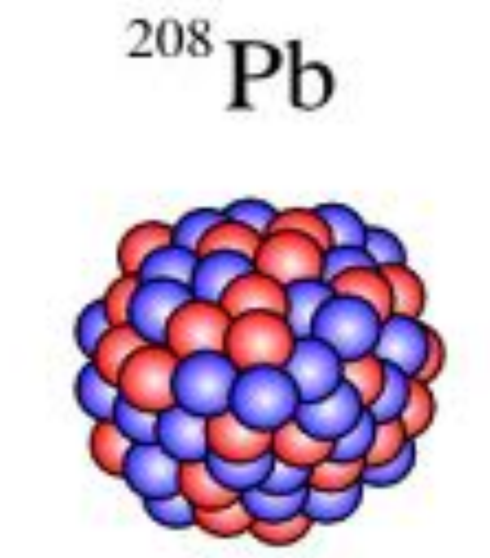
RIBF RI beam generator
featuring superconducting ring cyclotron (SRC)
and projectile fragment separator (BigRIPS)
will be commissioned late in 2006.

RIBF RI beam experiments
will be started in 2007,
with colored experimental installations.

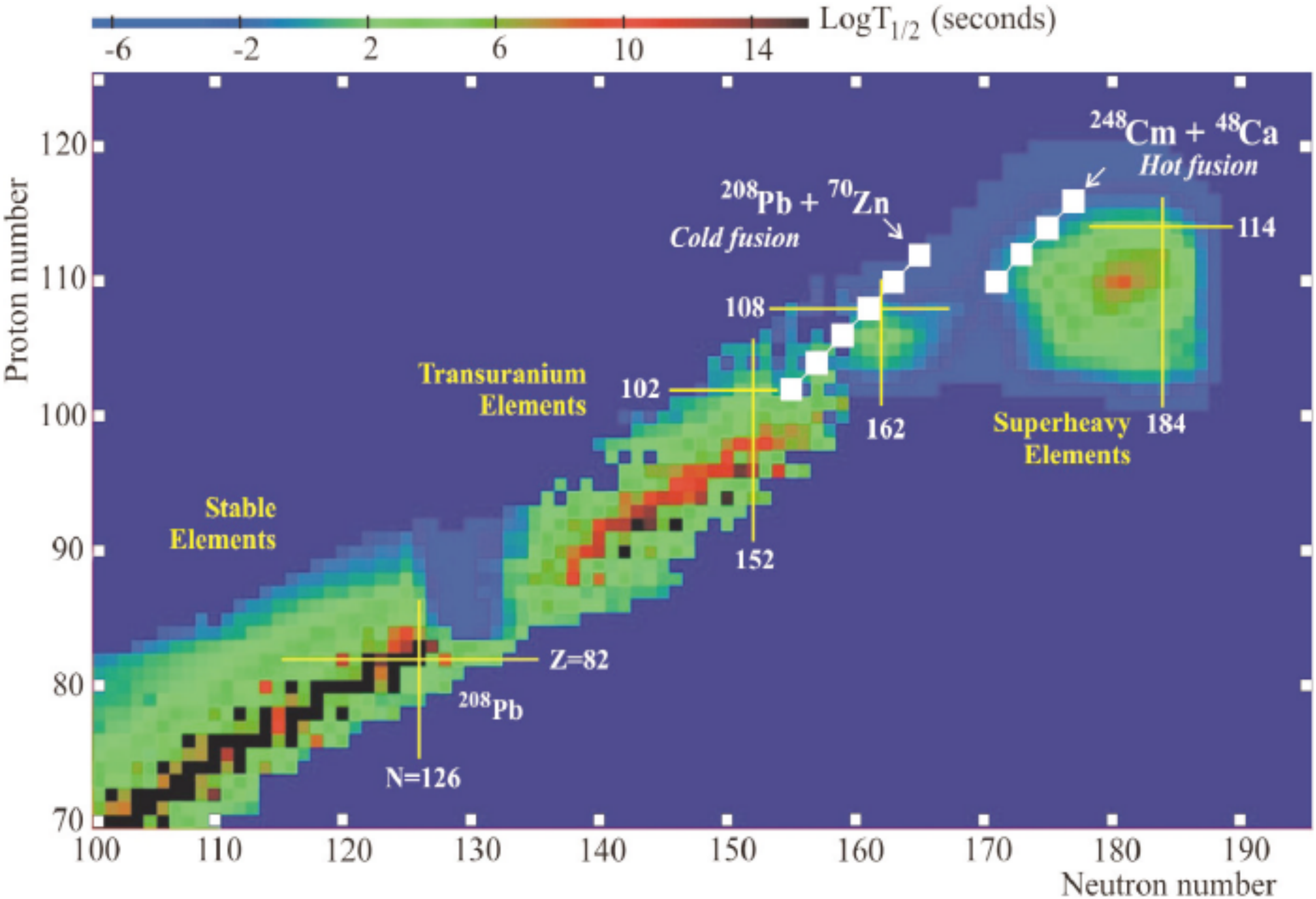
Goals:

1. Borders of stability.
2. New magic numbers.
3. Deformation.
4. Form-factors.
5. New decay properties.
6. Proton and neutron distributions.
7. Equation of state.





NUCLEUS-NUCLEUS COLLISIONS. SUPERHEAVY ELEMENTS



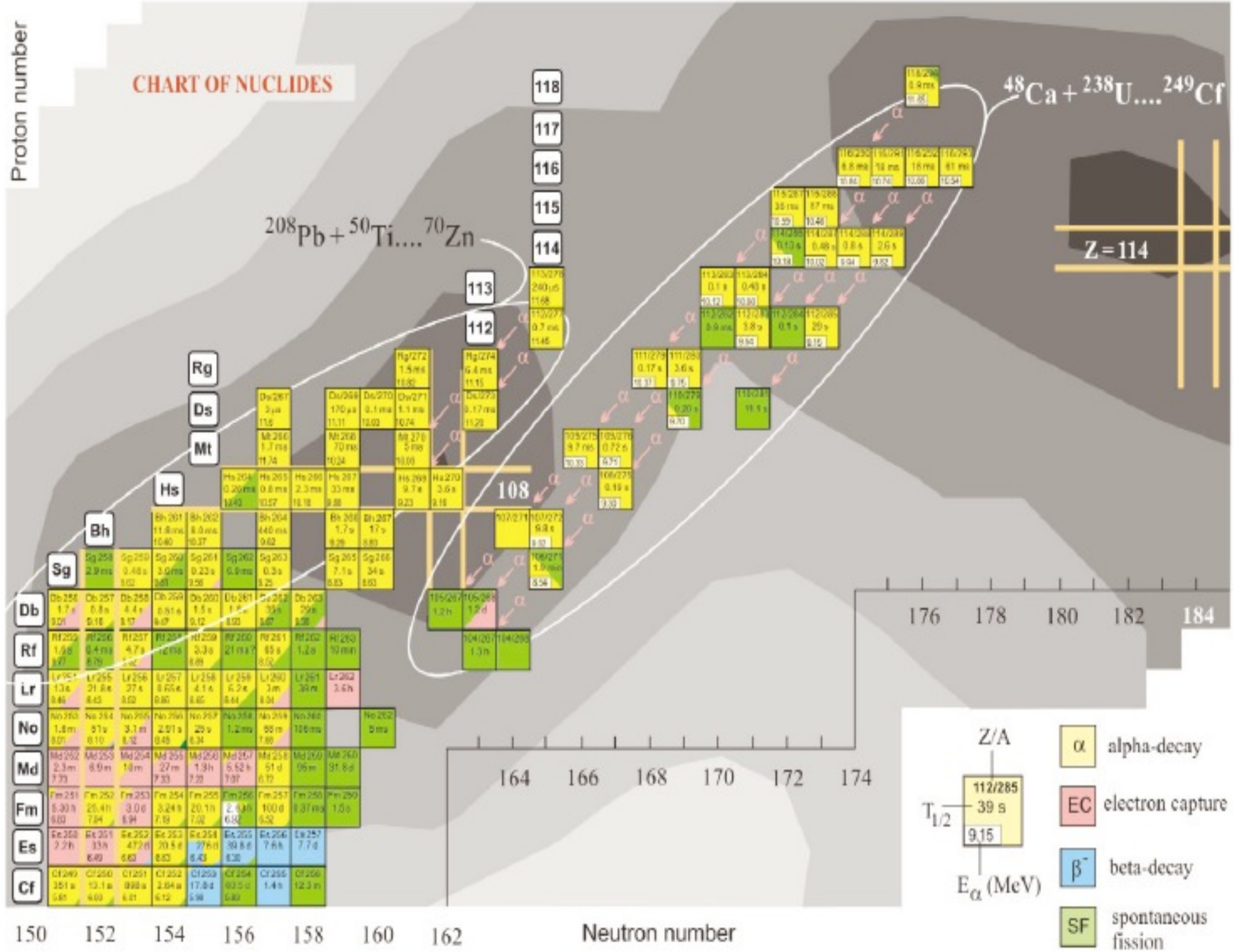
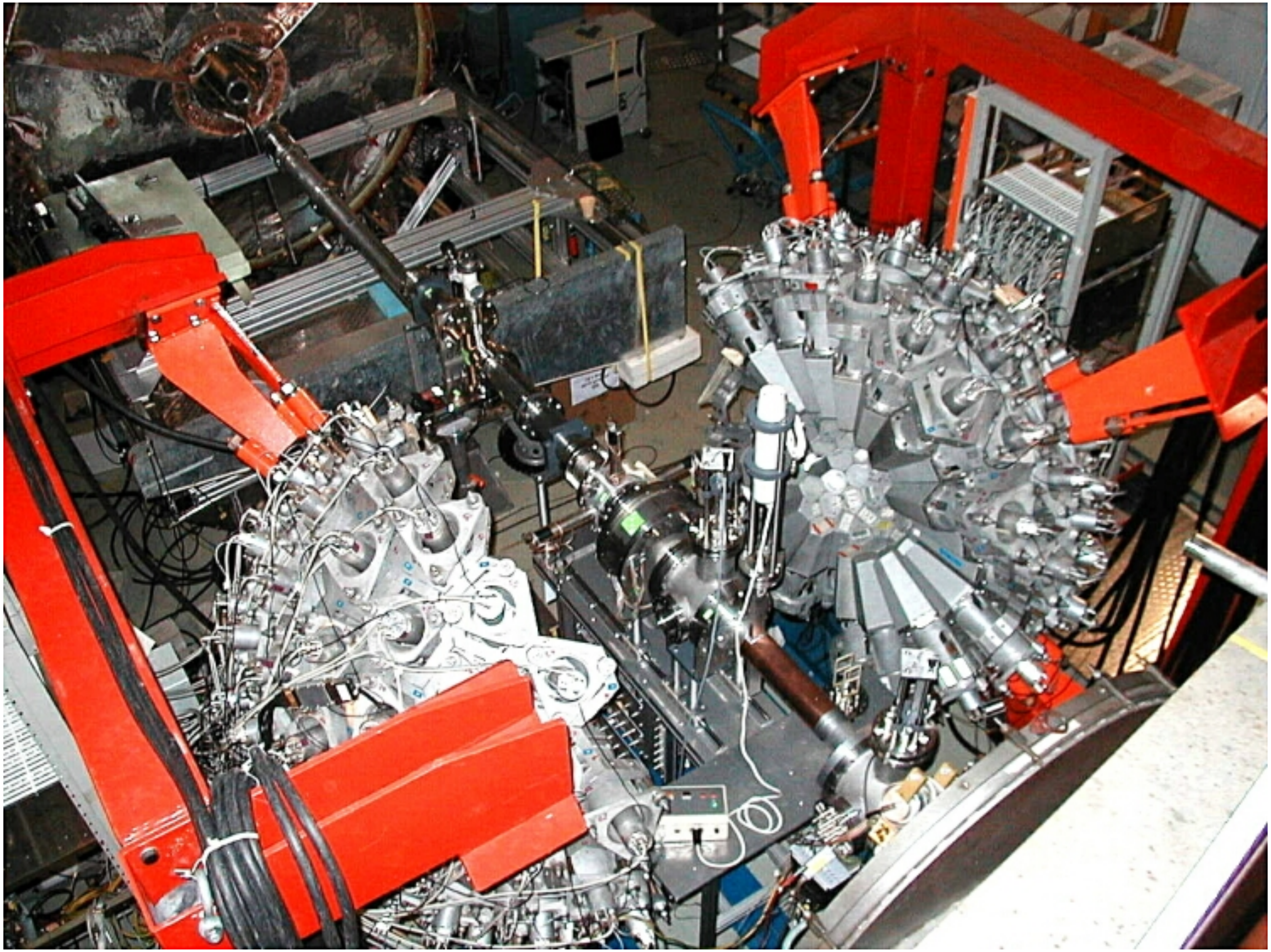
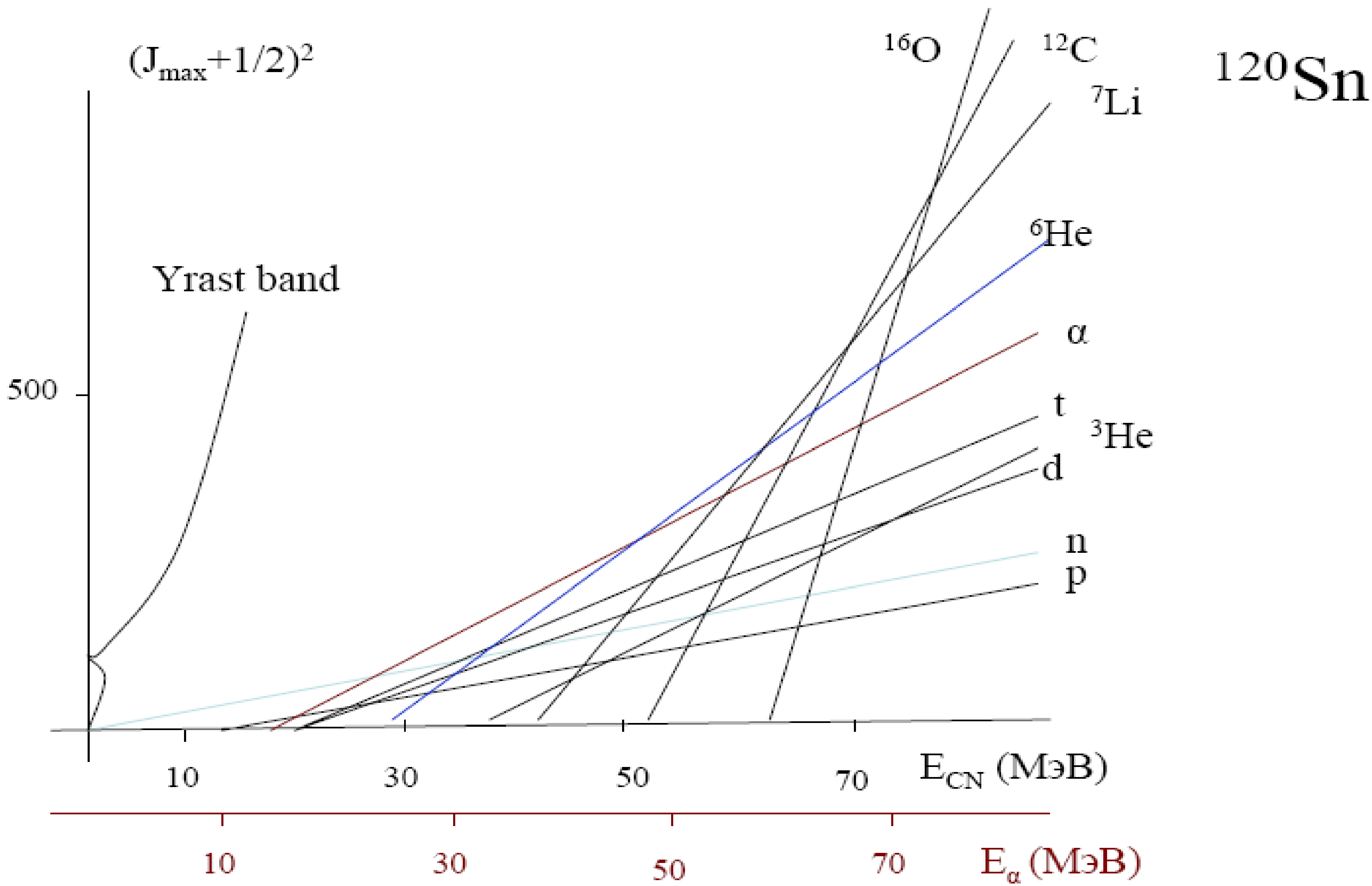


CHART OF NUCLIDES
Proton number
Neutron number
$^{208}Pb + ^{50}Ti....^{70}Zn$
$^{48}Ca + ^{238}U....^{249}Cf$
Z = 114
108
118
117
116
115
114
113
112
Rg
Ds
Mt
Hs
Bh
Sg
Db
Rf
Lr
No
Md
Fm
Es
Cf
150
152
154
156
158
160
162
164
166
168
170
172
174
176
178
180
182
184
Z/A
112/285
39 s
9.15
$T_{1/2}$
E_{α} (MeV)
α alpha-decay
EC electron capture
β^- beta-decay
SF spontaneous fission

HIGH-SPIN STATES INCLUDING HIGH-SPIN ISOMERS

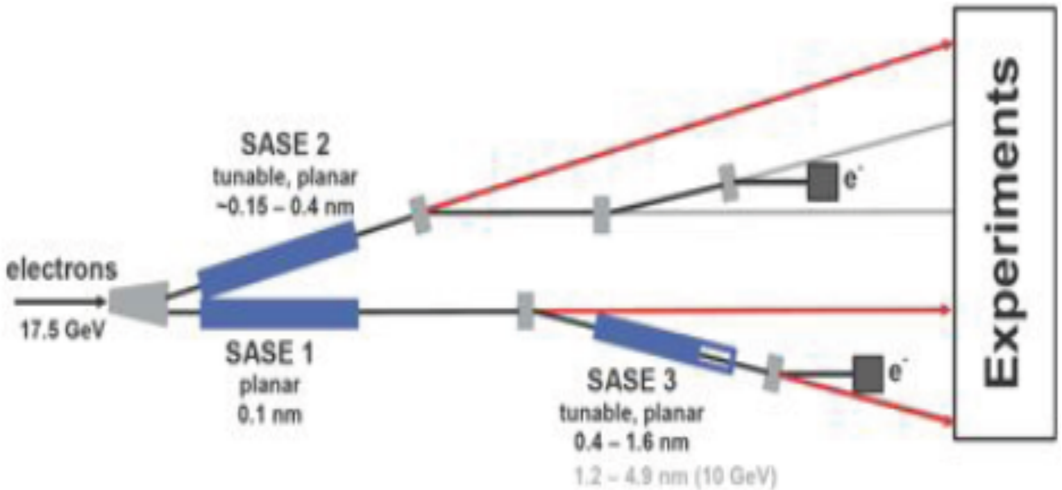


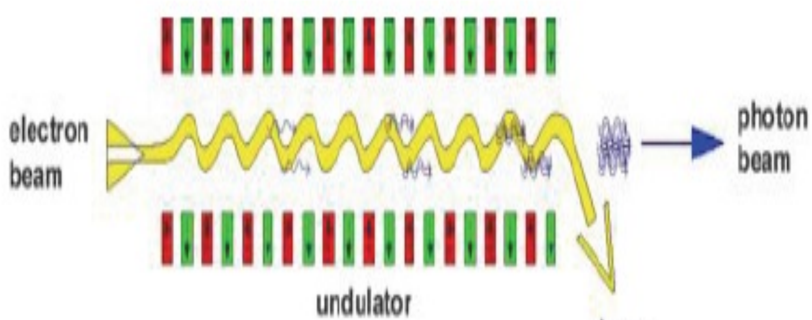


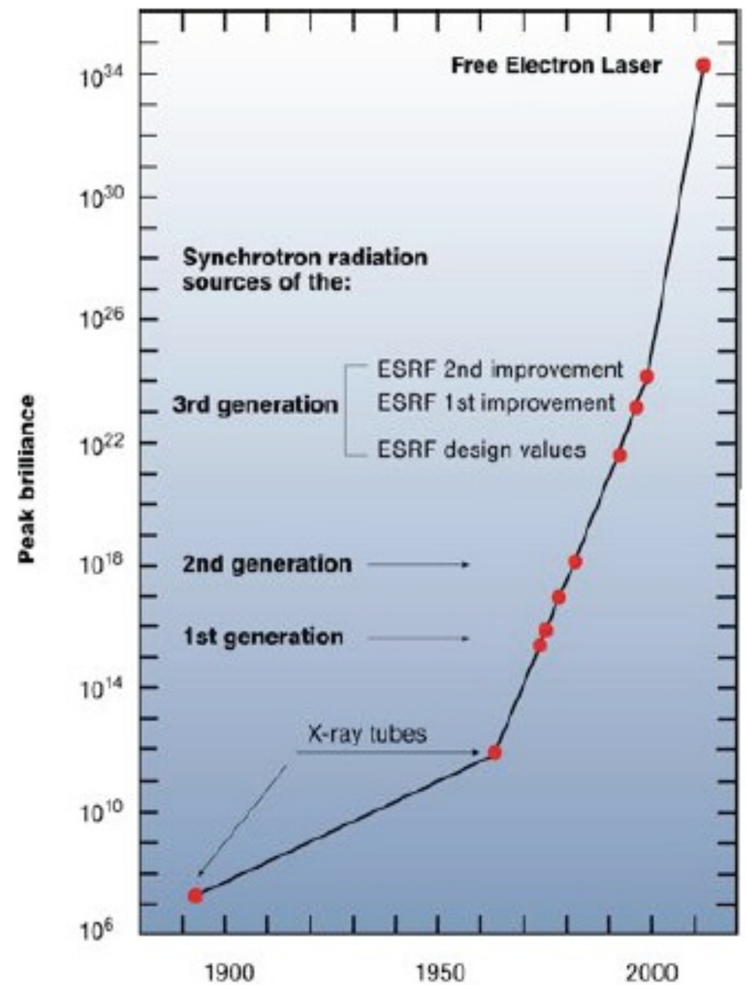
(J$_{max}$+1/2)^2
^{120}Sn
^{16}O
^{12}C
^{7}Li
^{6}He
α
t
^{3}He
d
n
p
Yrast band
500
10
30
50
70
E$_{CN}$ (МэВ)
10
30
50
70
E$_α$ (МэВ)

NEW X- AND GAMMA-RAY SOURCES – FREE ELECTRON LASERS

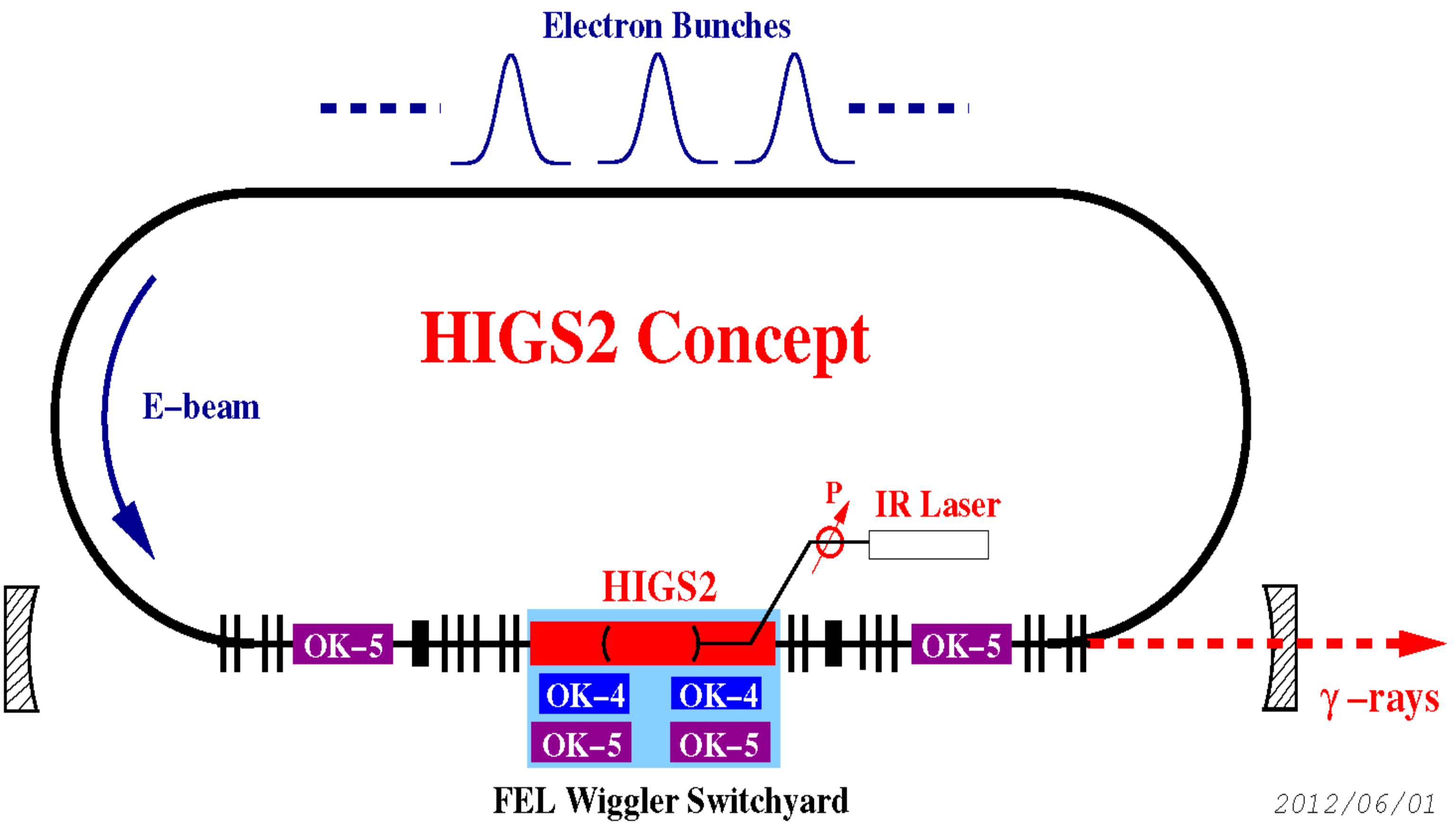
European XFEL







	LCLS (USA)	SCSS (JAPAN)	EUROPEAN XFEL (SASE1)
Max. Electron Energy (GeV)	14.3	8.0	17.5
Minimum Wavelength(nm)	0.15	0.13	0.10
Peak Brilliance	1.5 10^33	1. 10^33	5. 10^33
Average Brilliance	4.5 10^22	1.5 10^23	1.6 10^25
Pulses/s	120	60 (X 50?)	30 000
Photons/pulse	10^12	2 10^11	10^12
First Beam	2009	2011	2014


Electron Bunches
HIGS2 Concept
E−beam
P
IR Laser
HIGS2
OK−5
OK−5
OK−4
OK−4
OK−5
OK−5
γ −rays
FEL Wiggler Switchyard
2012/06/01

Expected Range of HIGS2 Machine Specifications

Parameters	Value Range
Gamma-ray Beam Energy (With an external laser of wavelength = 2 microns, Subject to change based upon scientific programs)	2 - 12 MeV
Gamma-ray Beam Pulse Rate	89.3 MHz
Polarization (Rapid Switch) (Degree of polarization depends on collimation, laser beam polarization, electron beam energy, etc)	Linear and Circular (90% - 99%)
Total Gamma-ray Flux Collimated flux = 0.015 x (total flux) x (FWHM energy resolution in %)	10^{11} - 10^{12} photons/second
Best Energy Resolution (Tight collimation and at a low flux)	FWHM < 0.5 %
Gamma-ray Beam Angular Spread (full opening) (=D/L, D is the collimator diameter, L=53 m)	Typical D/L = 0.19 - 0.60 mrad Dmin = 10 mm, Dmax = 32 mm
Full Beam "Without" Collimation	D ~ 32 mm (effective collimation)
Gamma-ray beam angular spread	D/L ~ 0.6 mrad
Gamma-ray beam energy spread	7% (2 MeV) to 30% (12 MeV)

EXOTICS

A. New experimentally-observed effects: proton, two-proton, neutron, two-neutron, cluster radioactivity.
B. Reactor neutrino physics, beta-decay and double-beta-decay.
C. Quarks in nuclei.
D. Investigation of fundamental symmetry break-up: parity violation, nonconservation of time-reversal invariance by nuclear methods.
E. Exotic properties of nuclear fission.
F. Nuclear and atomic degrees of freedom interplay.
G. ……………………………………………………..

CLUSTER RADIOACTIVITY

The discovery and the history

1984, H. Rose, J. Jones   223Ra→ 209Pb + 14C

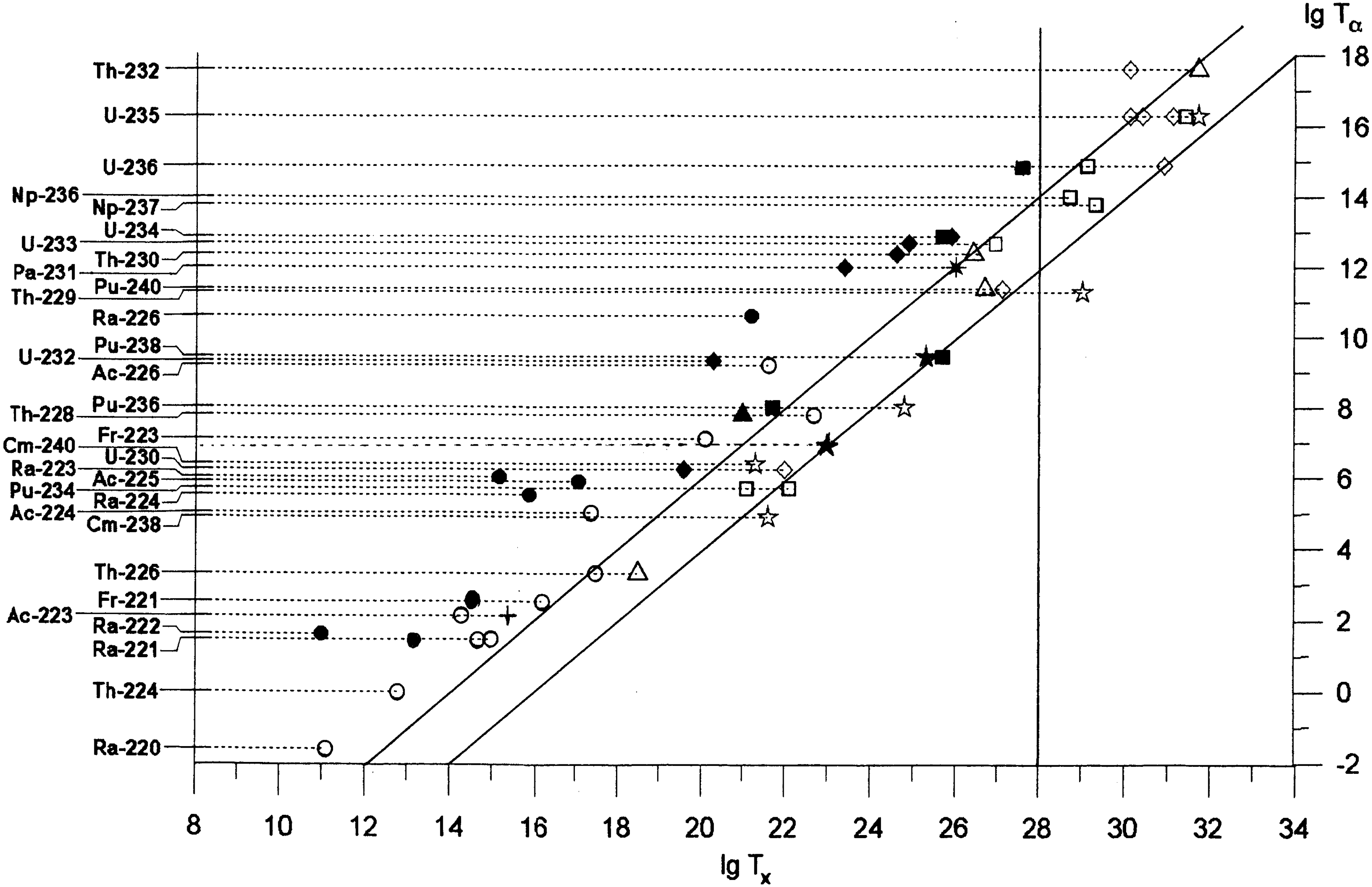
1914, E Rutherford – No other heavy particles besides alpas at the level 10^{-4}

50th – 60th Geochemists – too much Ar in uranium ores.

End of 70th – A. Sandulescu demonstrated that the penetrability of the cluster potential barrier is of the same order as the alpha-particle one.

End of 70th – beginning of 80th – the group under the guide of B. Novatsky (Kurchatov Center) searced for the effect and confirmed the discovery in May 1985.

Known and promising examples



FUNDAMENTAL SYMMETRY BREAK-UP

Parity violation

2008, V. Vesna, Yu. Gledenov et al. Azimutal asymmetry of the 6Li(n_{pol},α)3H reaction:

$$a_{pv} = (-8.8 \pm 2.1) \times 10^{-8}$$

Nonconservation of time-reversal invariance

2007 V.Tsinoev (Kurchatov Center). T-noninvariant correlation

$$(\vec{k}_\gamma \cdot [\vec{\varepsilon} \times \vec{J}])(\vec{k}_\gamma \cdot \vec{J}(\vec{\varepsilon} \times \vec{J}).$$

$$a_t = (\pm 1.1) \times 10^{-4}$$

EXOTIC PROPERTIES OF NUCLEAR FISSION

1. Properties of the ternary and four-fragment fission.

2. Heavy tripartition.

3. Hard gamma (E>30 MeV) and pion (!?) emission.

4. Pseudo T-noninvariant correlations:

$$(\vec{k}_{ff} \cdot [\vec{\sigma} \times \vec{k}])$$

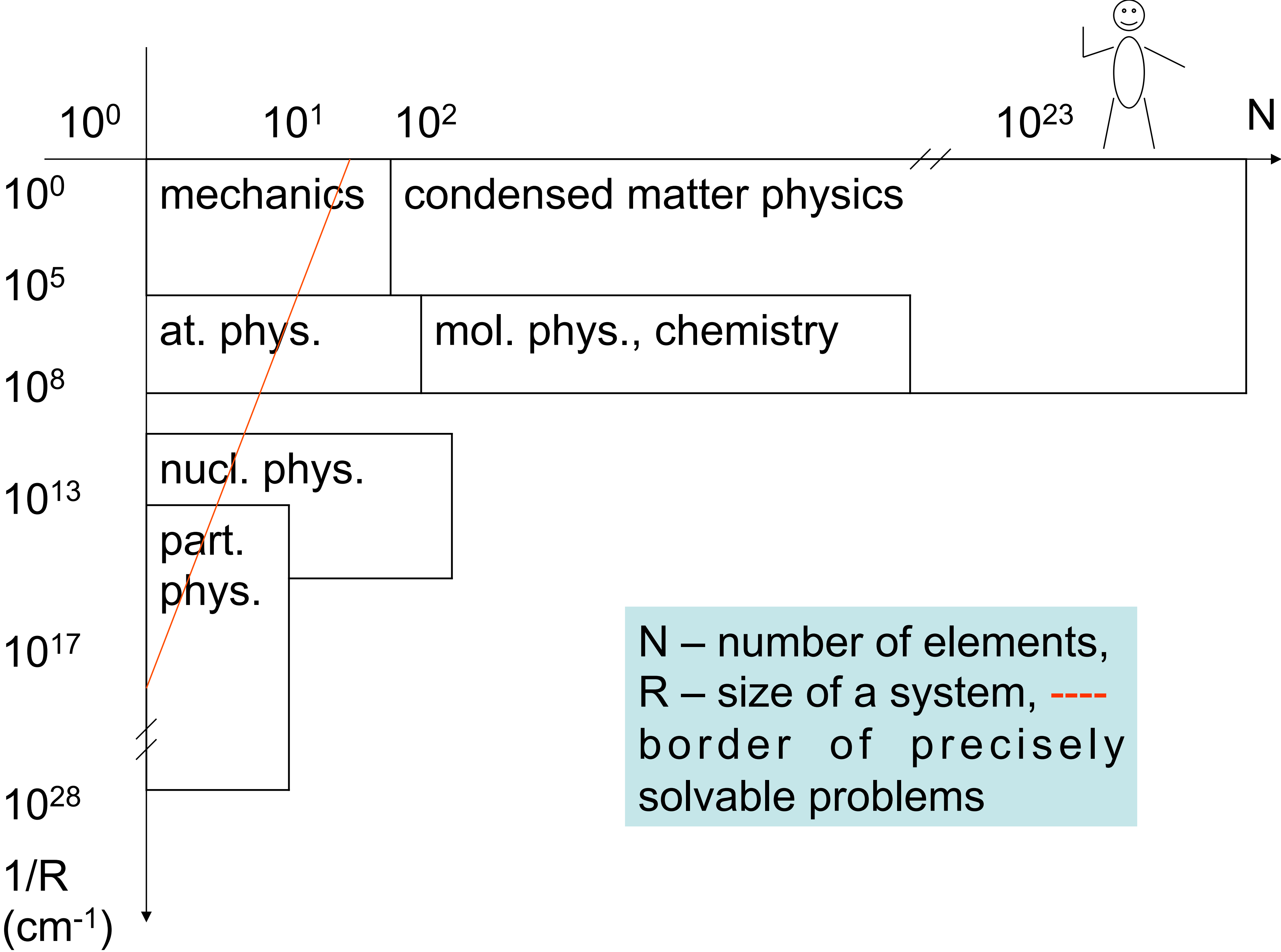
$$(\vec{k}_{ff} \cdot [\vec{\sigma} \times \vec{k}])(\vec{k}_{ff} \cdot \vec{k})$$

NUCLEAR AND ATOMIC DEGREES OF FREEDOM INTERPLAY

Parity violation in the nucleus-electron interaction

1978, M. Barkov, M. Zolotarev. Measurement of the circular polarization (or the angle of linear polarization rotation) of M1-optical transitions in Bi atom – parity violation effect based totally on the neutral currents (Z-boson exchange):

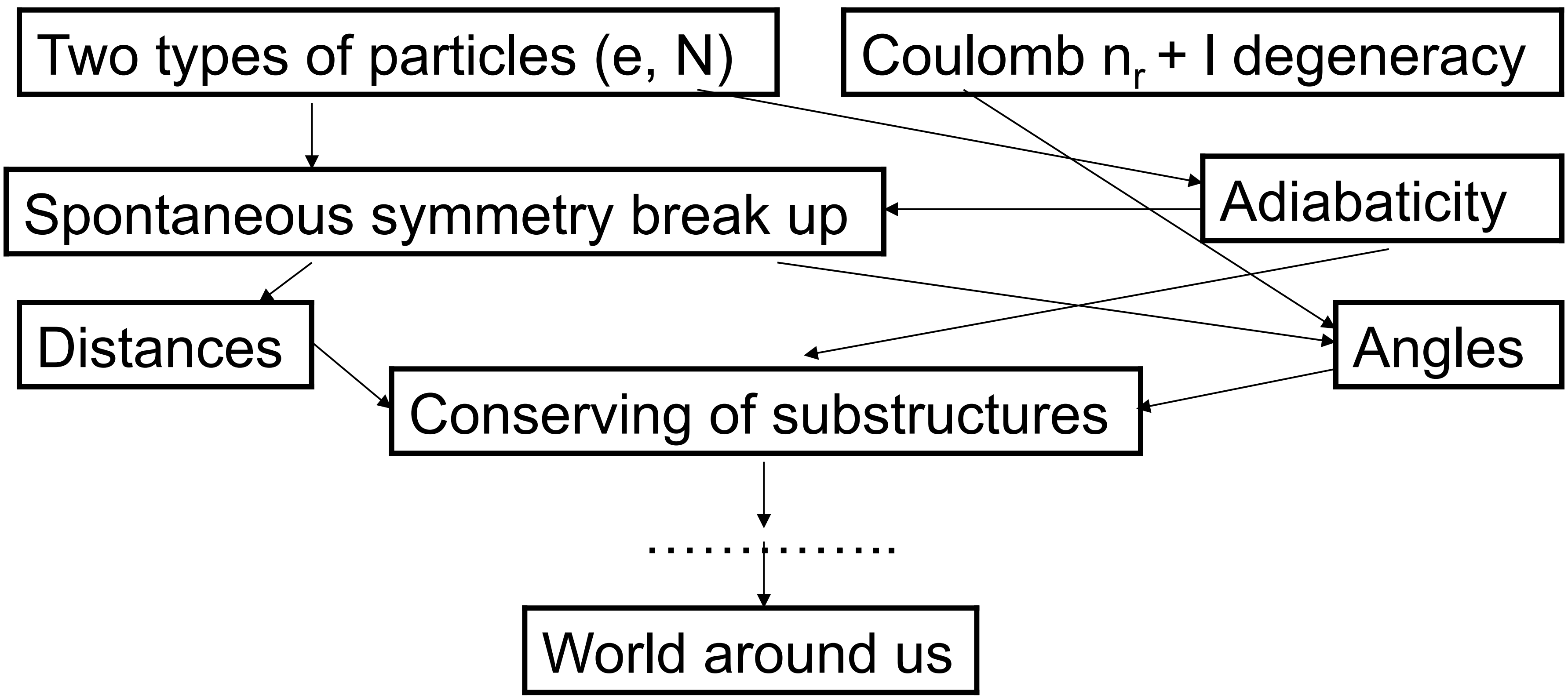
$$c_{pv} = (4.04 \pm 0.54) \times 10^{-7}$$


10^0
10^1
10^2
10^{23}
N
10^0
10^5
10^8
10^{13}
10^{17}
10^{28}
1/R (cm^{-1})
mechanics
condensed matter physics
at. phys.
mol. phys., chemistry
nucl. phys.
part. phys.
N – number of elements,
R – size of a system, ---- border of precisely solvable problems

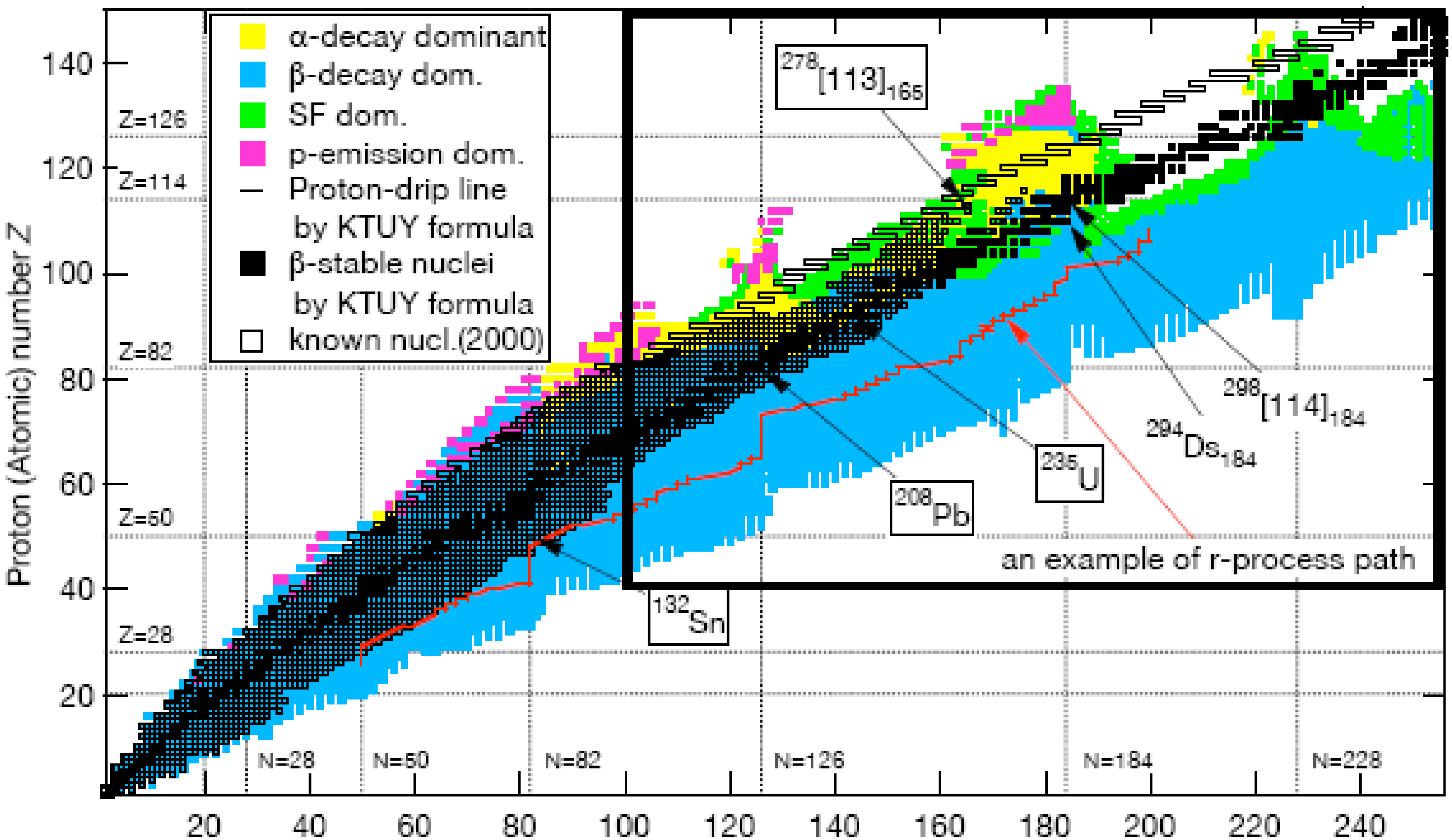
PROBLEM OF STRUCTURING

How to state the problem of substructures (clusters) in two- (or few-) cluster system taking into account indistingvishibility of identical fermions and the strong nuclear interaction?

STRUCTURING OF MOLECULES



THANK YOU FOR ATTENTION!


α-decay dominant
β-decay dom.
SF dom.
p-emission dom.
Proton-drip line
by KTUY formula
β-stable nuclei
by KTUY formula
known nucl.(2000)
Proton (Atomic) number Z
Z=126
Z=114
Z=82
Z=50
Z=28
N=28
N=50
N=82
N=126
N=184
N=228
278[113]165
298[114]184
294Ds184
235U
208Pb
132Sn
an example of r-process path
20
40
60
80
100
120
140
160
180
200
220
240

t(α,γ)7Li reaction in the multi-channel resonating group model (RGM) approach

RGM is a microscopic model of nuclear reactions based on the A-nucleon Hamiltonian:

$$\hat{H}\Psi_{A_1+A_2} = E\Psi_{A_1+A_2}, \quad \hat{H} = \hat{T} + \hat{V},$$

$$\hat{T} = \sum_{i=1}^{A_1+A_2} \frac{\vec{p}_i^{\,2}}{2m_i}, \quad \hat{V} = \sum_{i<j=1}^{A_1+A_2} V(\vec{r}_i - \vec{r}_j)$$

Channels: 1) T + α; 2) 6Li +n;3) 6He + p are described by the wave functions:

$$\Psi_C = \hat{A}\{\Psi_{A_1}\Psi_{A_2}\varphi(\vec{\rho})\},$$

h(α,γ)7Be is a mirror reaction.