Flerov Laboratory of Nuclear Reactions
Joint Institute for Nuclear research

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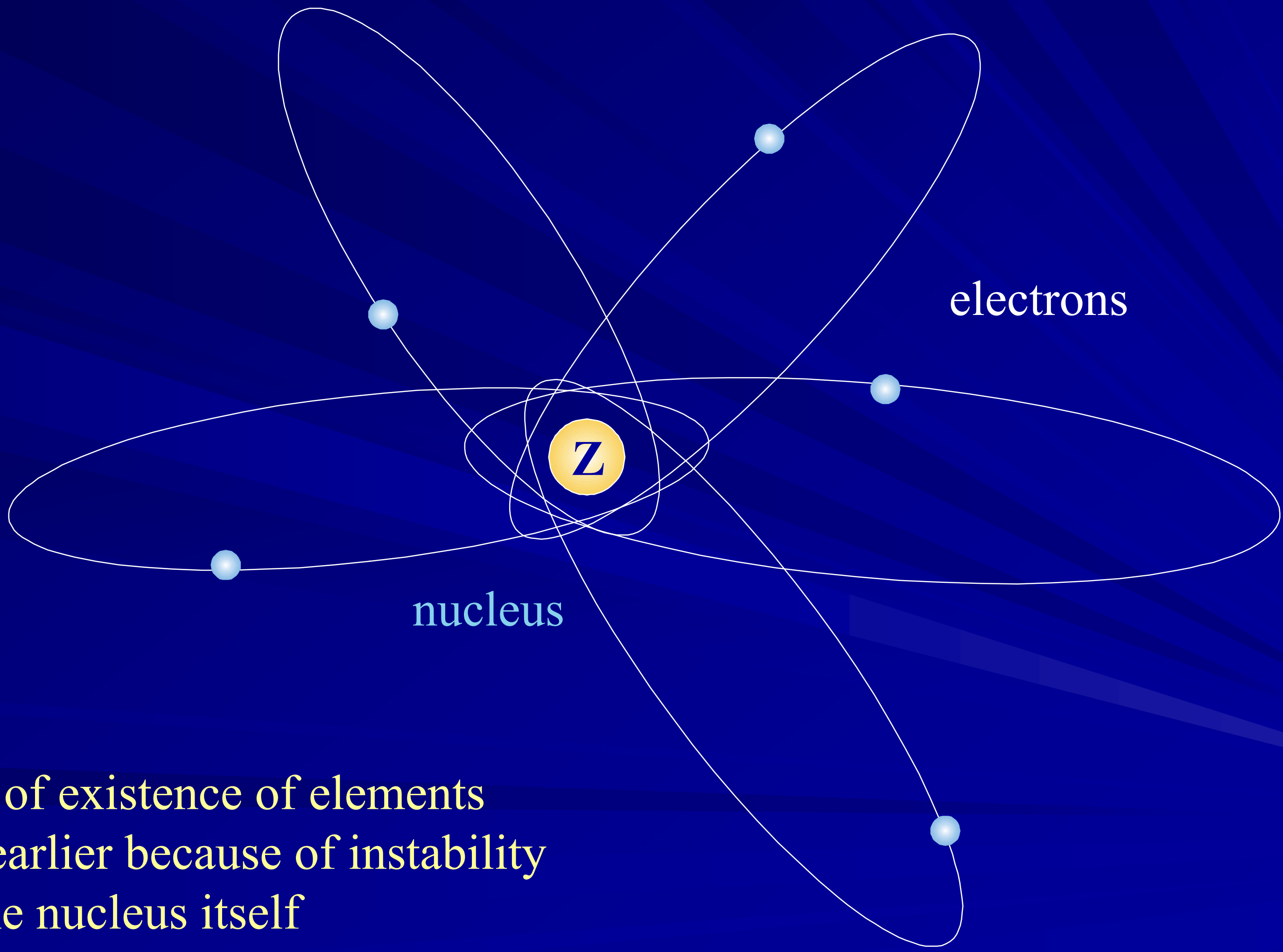
Superheavy Elements

current status and future trends

Frontiers in the Physics of Nucleus, Peterhof 2005

E. Rutherford (1932)

According to QED such an atomic structure is valid for very heavy atoms with Z~170 or even more



…but the limit of existence of elements is reached much earlier because of instability of the nucleus itself

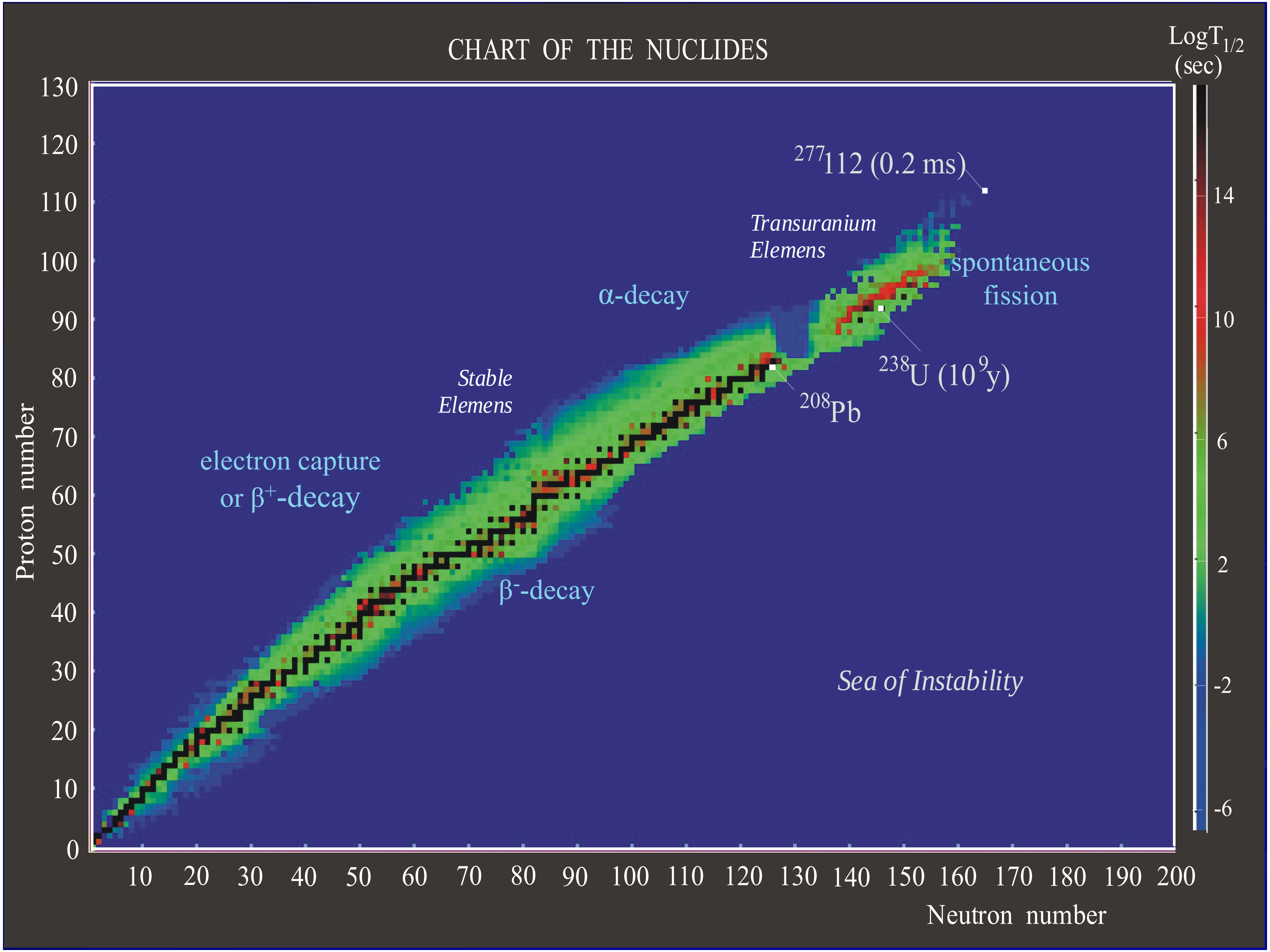
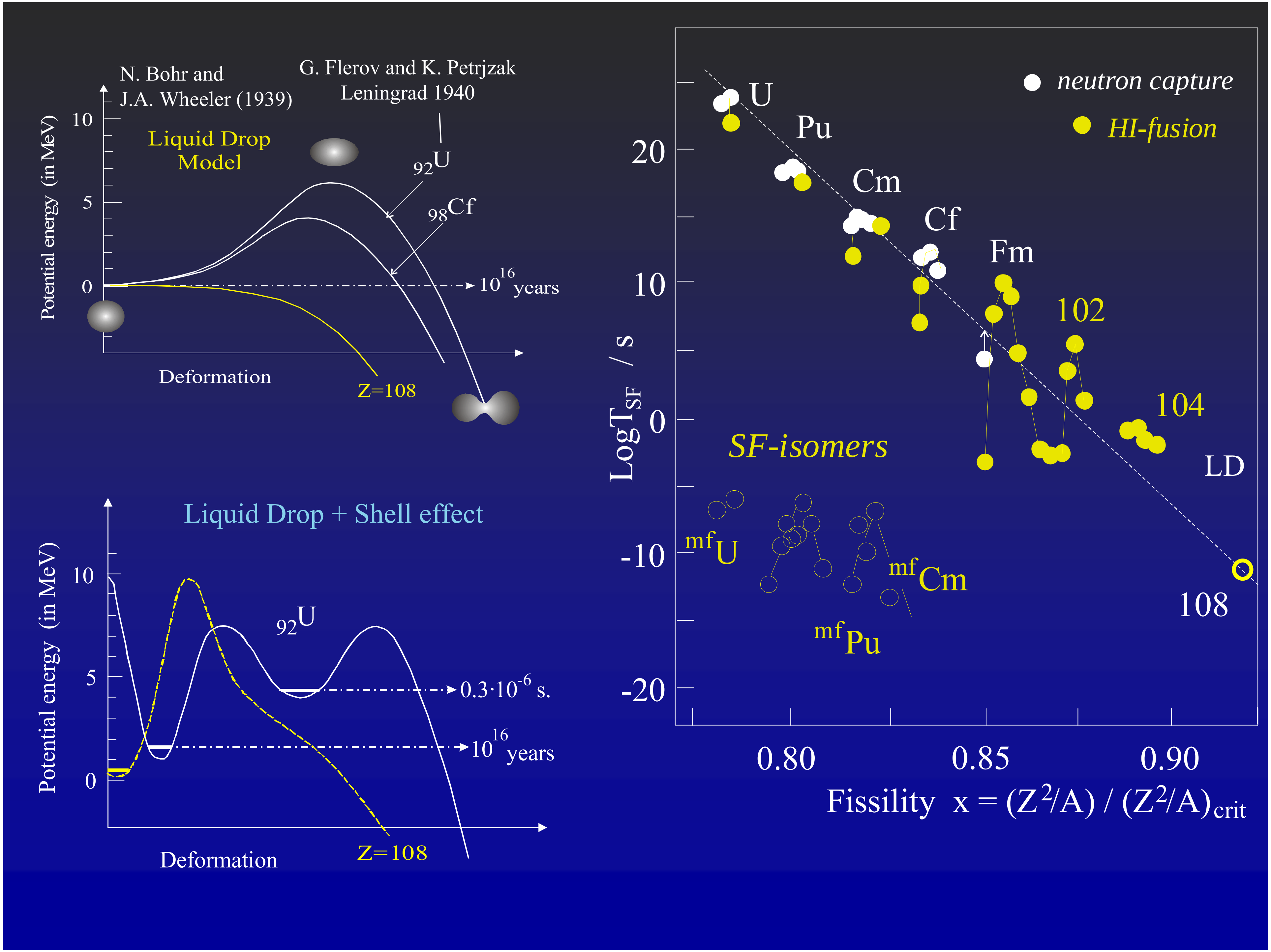


CHART OF THE NUCLIDES
LogT1/2 (sec)
14
10
6
2
-2
-6
Proton number
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Neutron number
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
277112 (0.2 ms)
Transuranium Elemens
spontaneous fission
α-decay
238U (109y)
208Pb
Stable Elemens
electron capture or β+-decay
β--decay
Sea of Instability



N. Bohr and
J.A. Wheeler (1939)
G. Flerov and K. Petrjzak
Leningrad 1940
Liquid Drop
Model
Potential energy (in MeV)
10
5
0
$_{92}$U
$_{98}$Cf
10^{16} years
Deformation
Z=108
Liquid Drop + Shell effect
Potential energy (in MeV)
10
5
0
$_{92}$U
$0.3 \cdot 10^{-6}$ s.
10^{16} years
Deformation
Z=108
neutron capture
HI-fusion
U
Pu
Cm
Cf
Fm
102
104
LD
108
SF-isomers
^{mf}U
^{mf}Pu
^{mf}Cm
$\log T_{SF}$ / s
20
10
0
-10
-20
0.80
0.85
0.90
Fissility $x = (Z^2/A) / (Z^2/A)_{crit}$

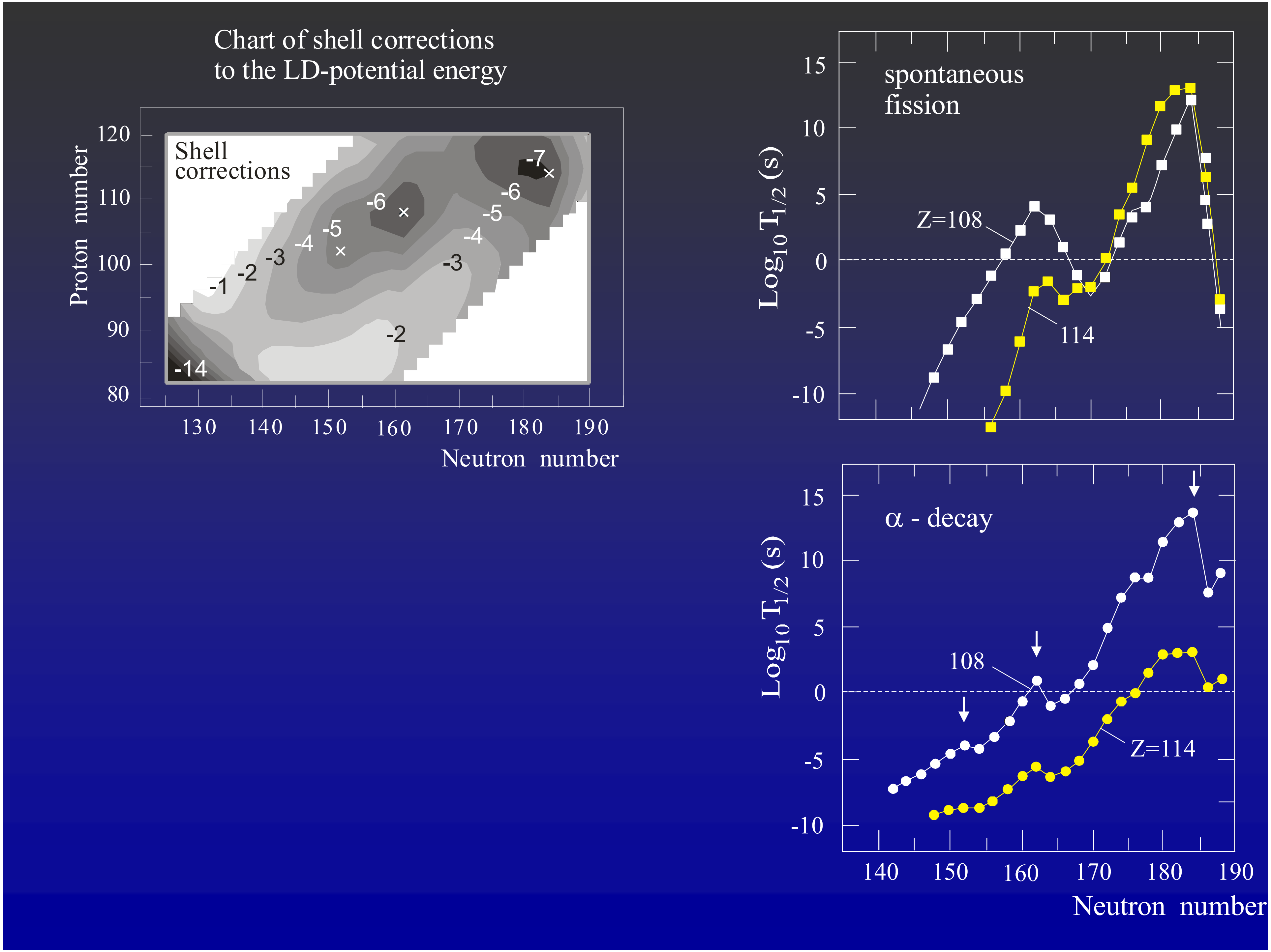


Chart of shell corrections
to the LD-potential energy
Shell
corrections
Proton number
Neutron number
120
110
100
90
80
130
140
150
160
170
180
190
-1
-2
-3
-4
-5
-6
-7
-6
-5
-4
-3
-2
-14
spontaneous
fission
Log10 T1/2 (s)
15
10
5
0
-5
-10
Z=108
114
α - decay
108
Z=114
140
150
160
170
180
190
Neutron number

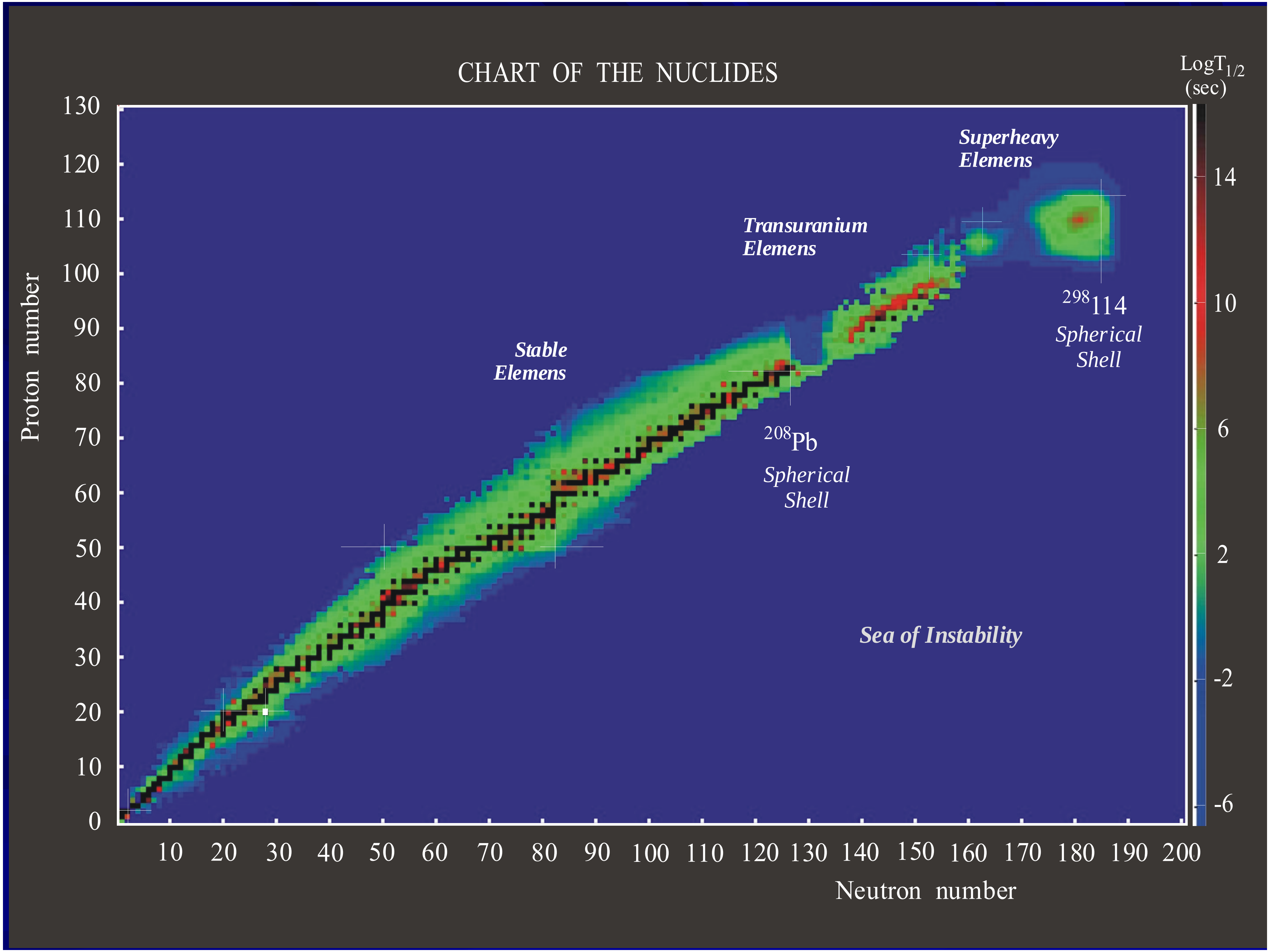


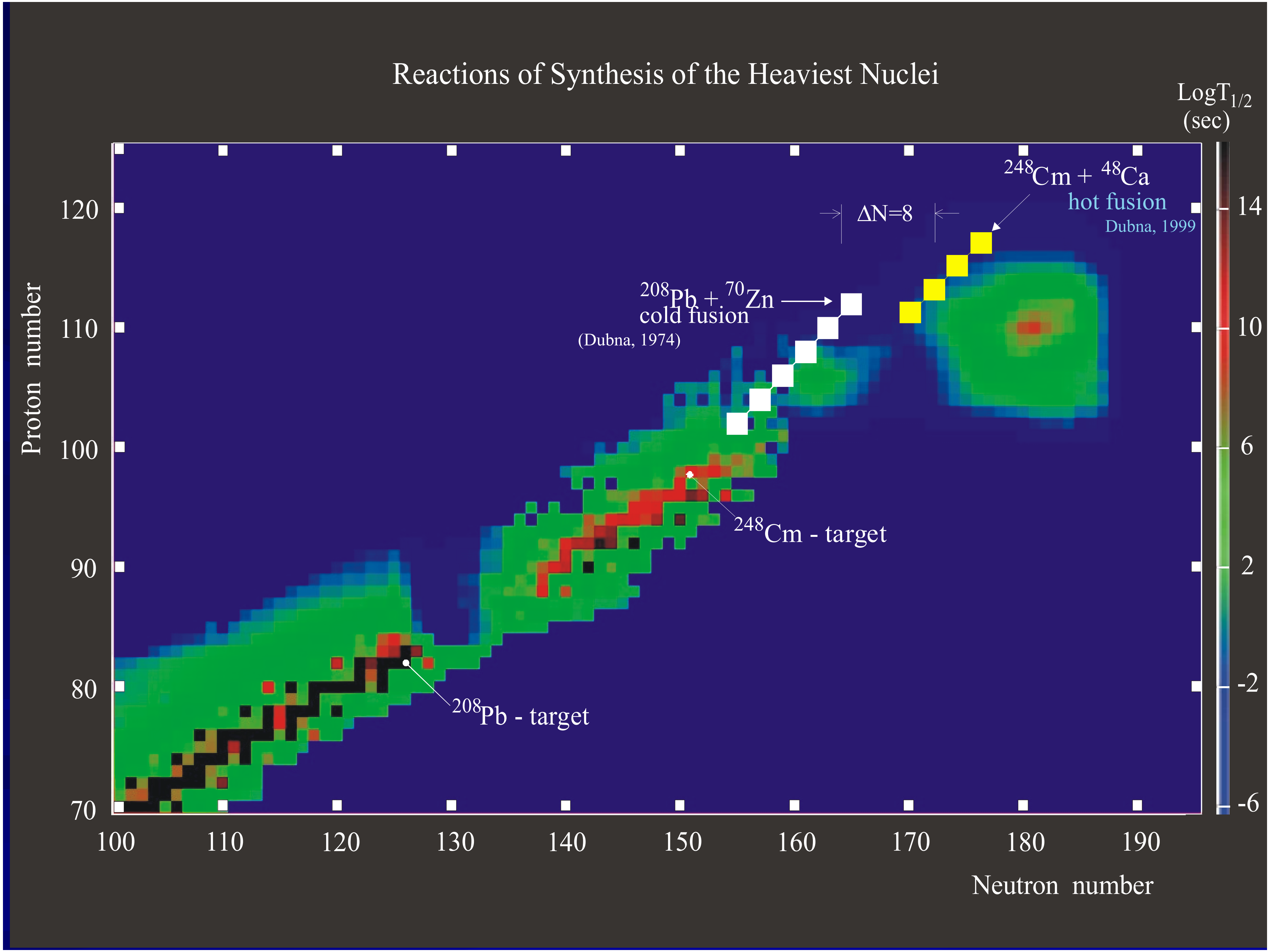
CHART OF THE NUCLIDES
LogT1/2 (sec)
14
10
6
2
-2
-6
Proton number
130
120
110
100
90
80
70
60
50
40
30
20
10
0
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
Neutron number
Superheavy Elemens
Transuranium Elemens
Stable Elemens
298114
Spherical Shell
208Pb
Spherical Shell
Sea of Instability

How to check the idea about the existence of hypothetical "Islands of Stability" in the region of yet unknown super heavy elements?

- reactions of the SHE synthesis — ***key problem***
- what are we expecting to see in the experiment — ***unusual properties of SHE***
- what we have already observed — ***decay modes of SHE***
- setting the experiments — ***synthesis of elements 113,115 and 118***

-Chemistry of SHE — ***identification of atomic numbers of SHE***

- overall picture of SHE — ***nuclear shells and stability of the SHE***
- the search for surviving SHE. Prospects



Reactions of Synthesis of the Heaviest Nuclei
LogT1/2 (sec)
248Cm + 48Ca
hot fusion
Dubna, 1999
ΔN=8
208Pb + 70Zn
cold fusion
(Dubna, 1974)
248Cm - target
208Pb - target
Proton number
Neutron number
120
110
100
90
80
70
100
110
120
130
140
150
160
170
180
190
14
10
6
2
-2
-6

Here there are two questions:

What is the fusion probability for ^{48}Ca and actinide nuclei?

What is the survival probability of the compound nucleus with Z=114-118 at the excitation energy $E^* \geq 30$ MeV?

Fusion probability

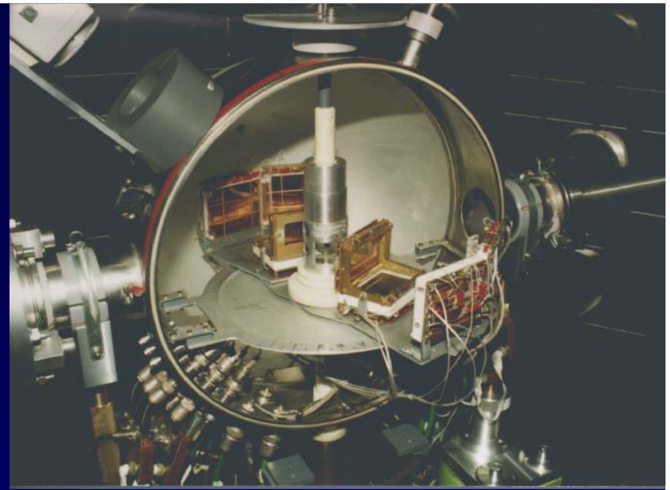
Let us consider the fusion of the ^{48}Ca and ^{248}Cm occurred and resulted in the formation of the compound nucleus ^{296}116 with an excitation energy of about 40 MeV

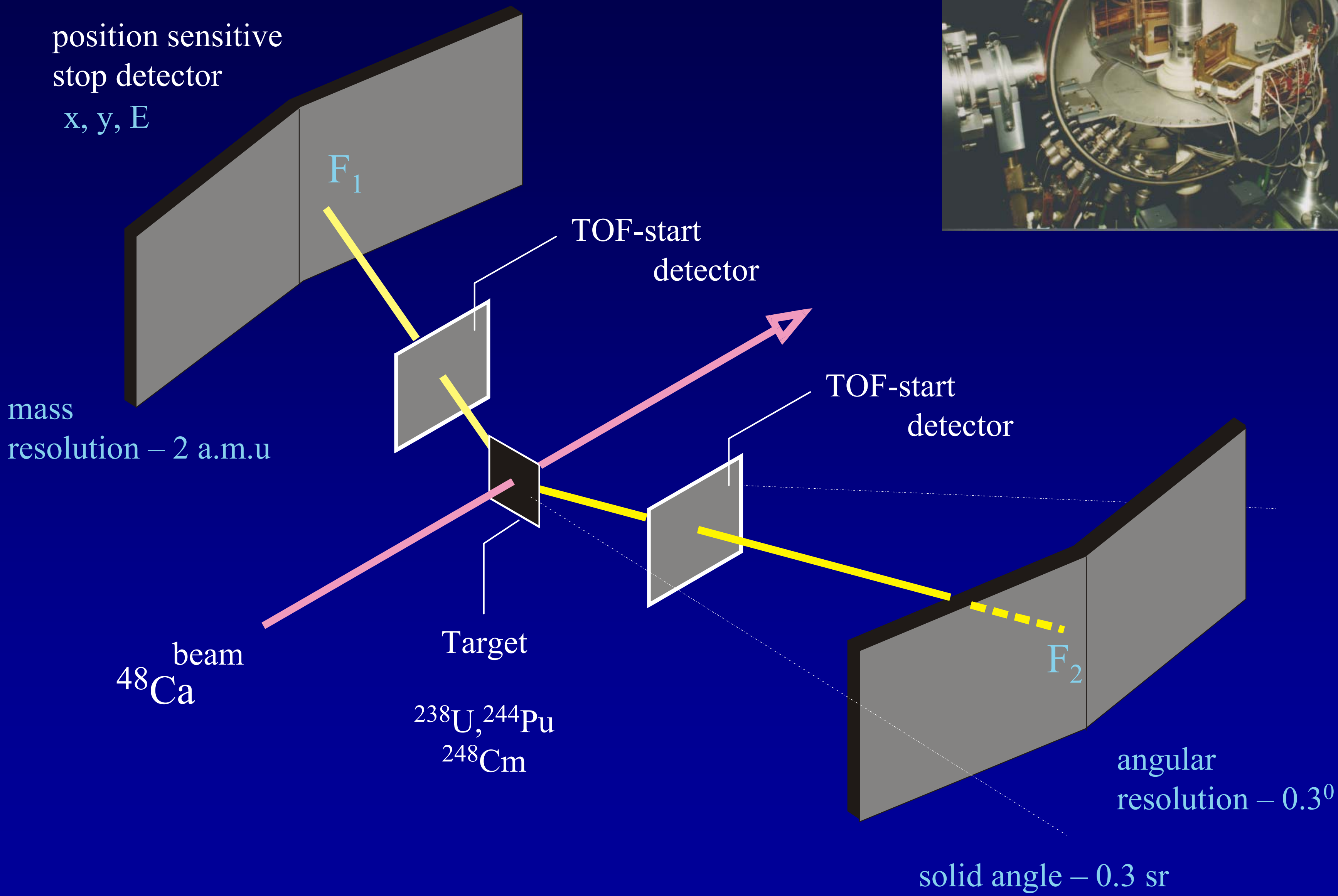
Evidently, the dominant decay mode of such a nucleus would be fission into two fragments

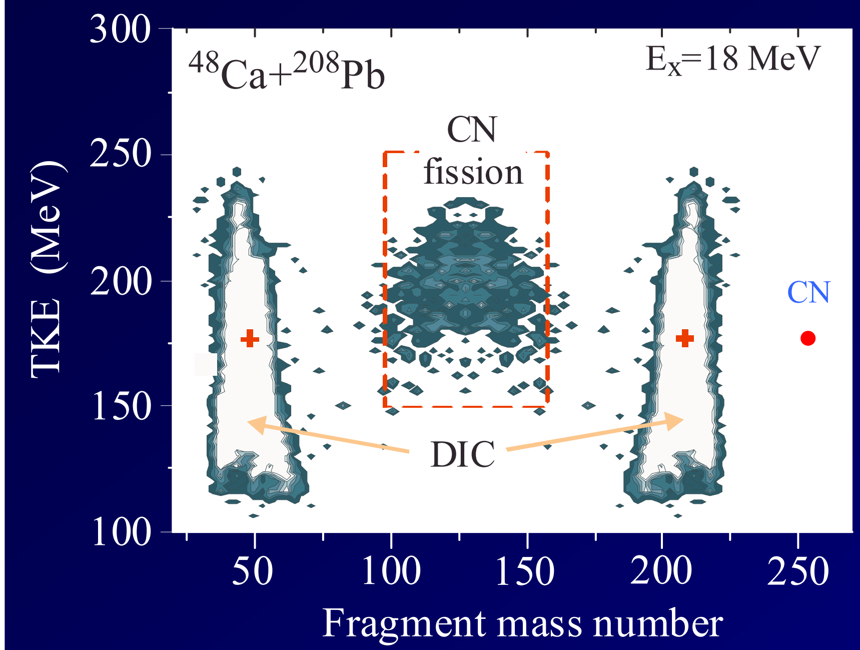
Accordingly, one could attempt investigating the probability of formation of the compound nucleus by measuring its fission characteristics.

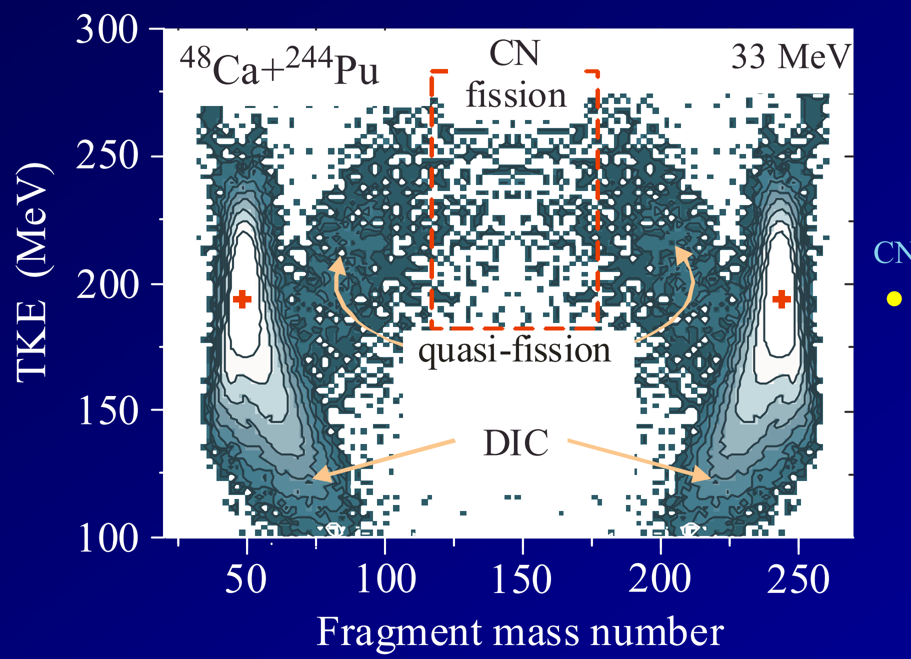
In other words, one should measure mass and energy distributions of the fission fragments in the kinematics that corresponds to the full momentum transfer from the ^{48}Ca-projectile to the composite system with A=296

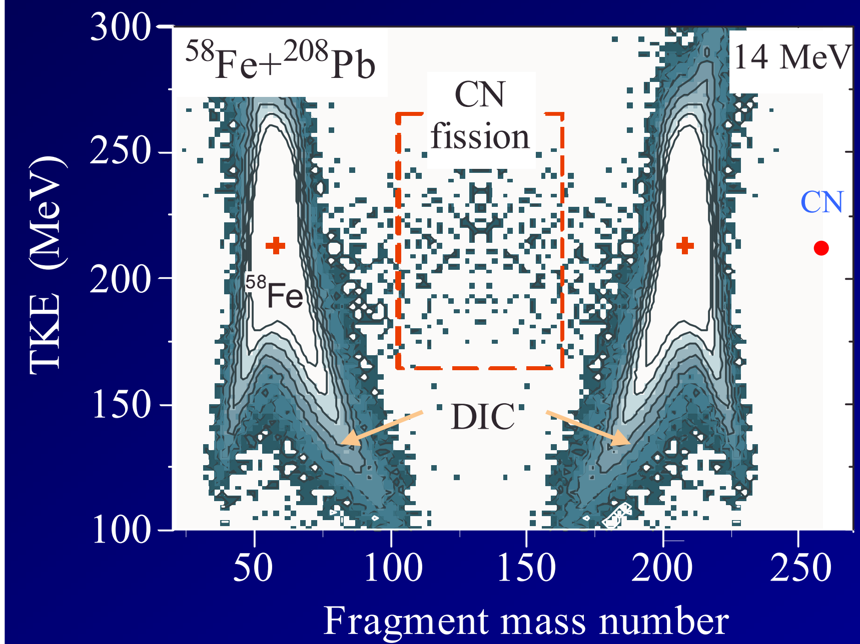
CORSET setup







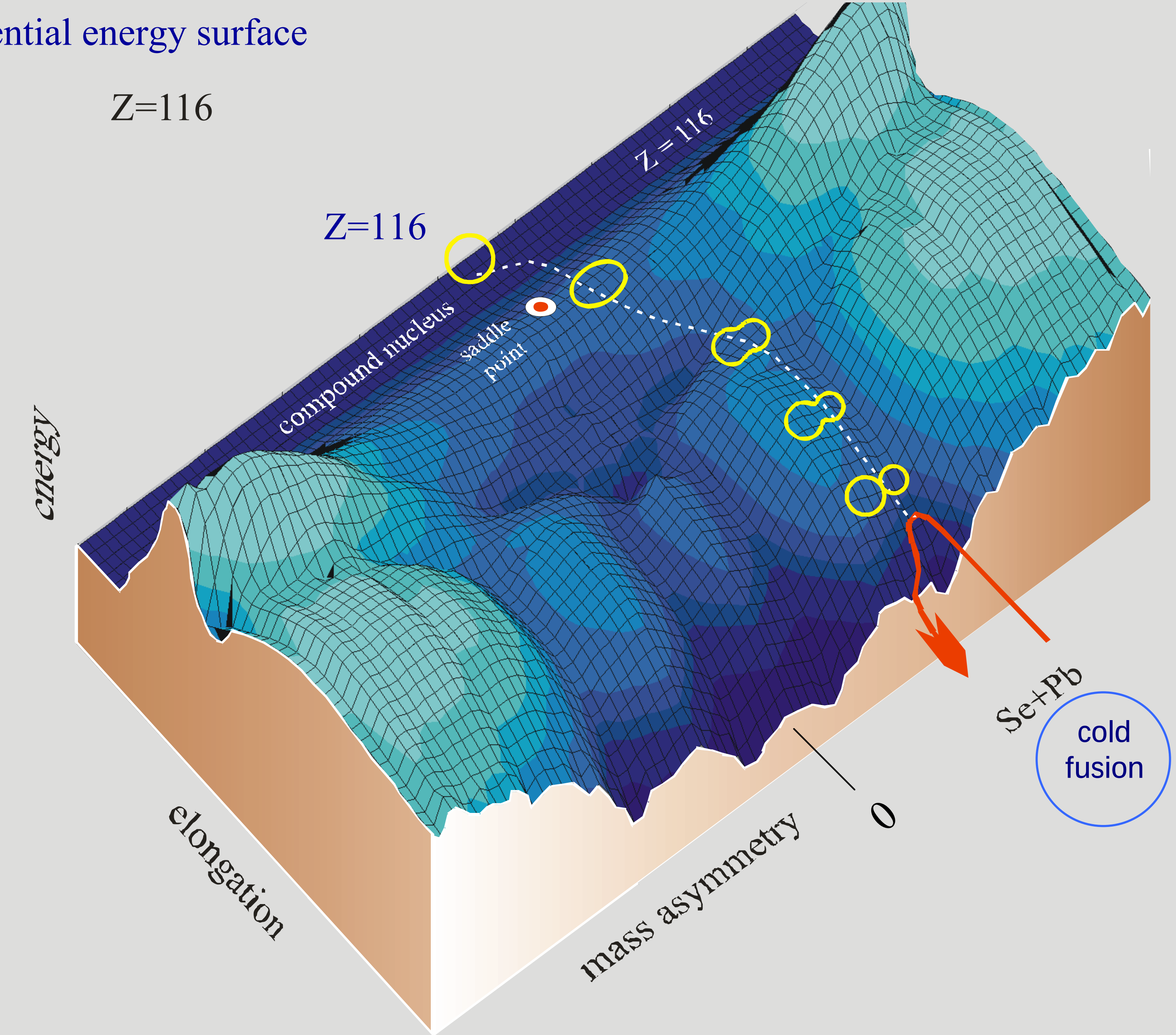




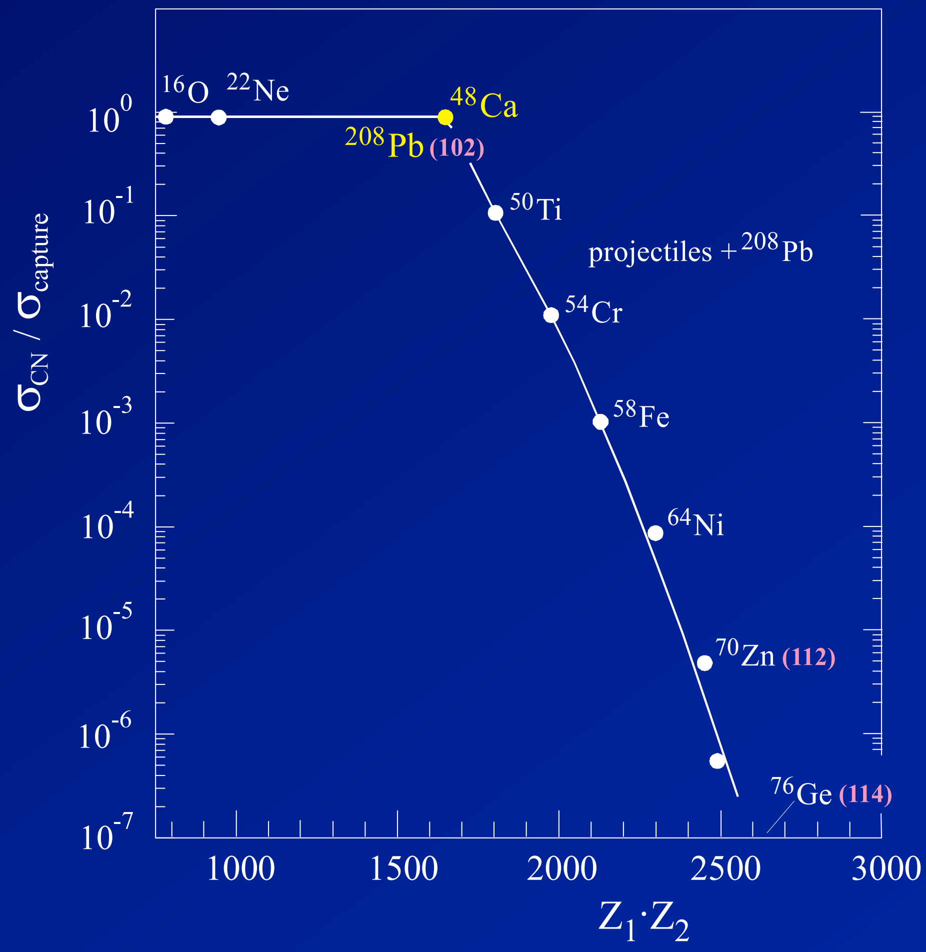
M. Itkis et al., (2002)
Fragment Energy and Mass Distributions in Cold and Hot Fusion Reactions

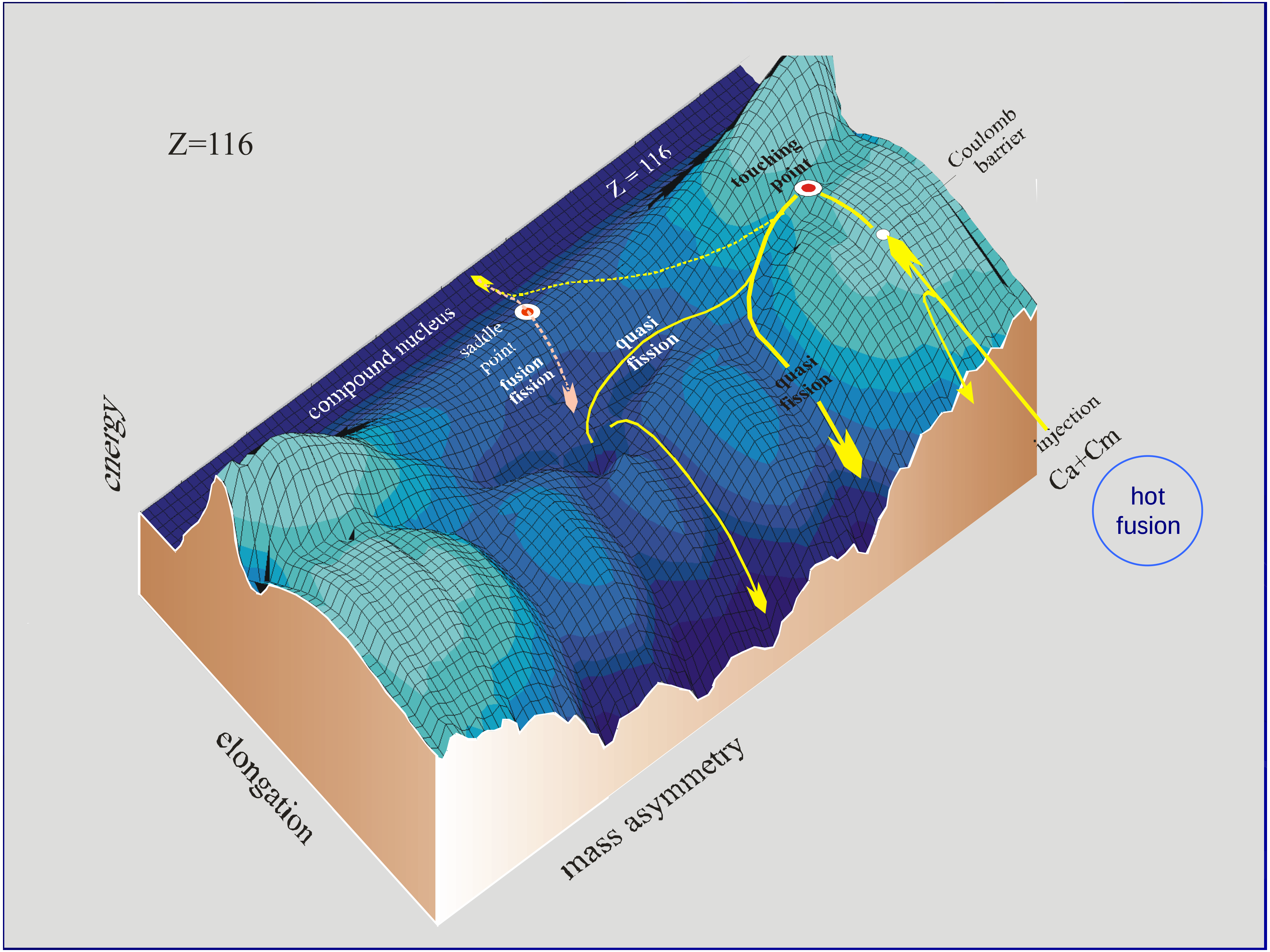
Potential energy surface

Z=116

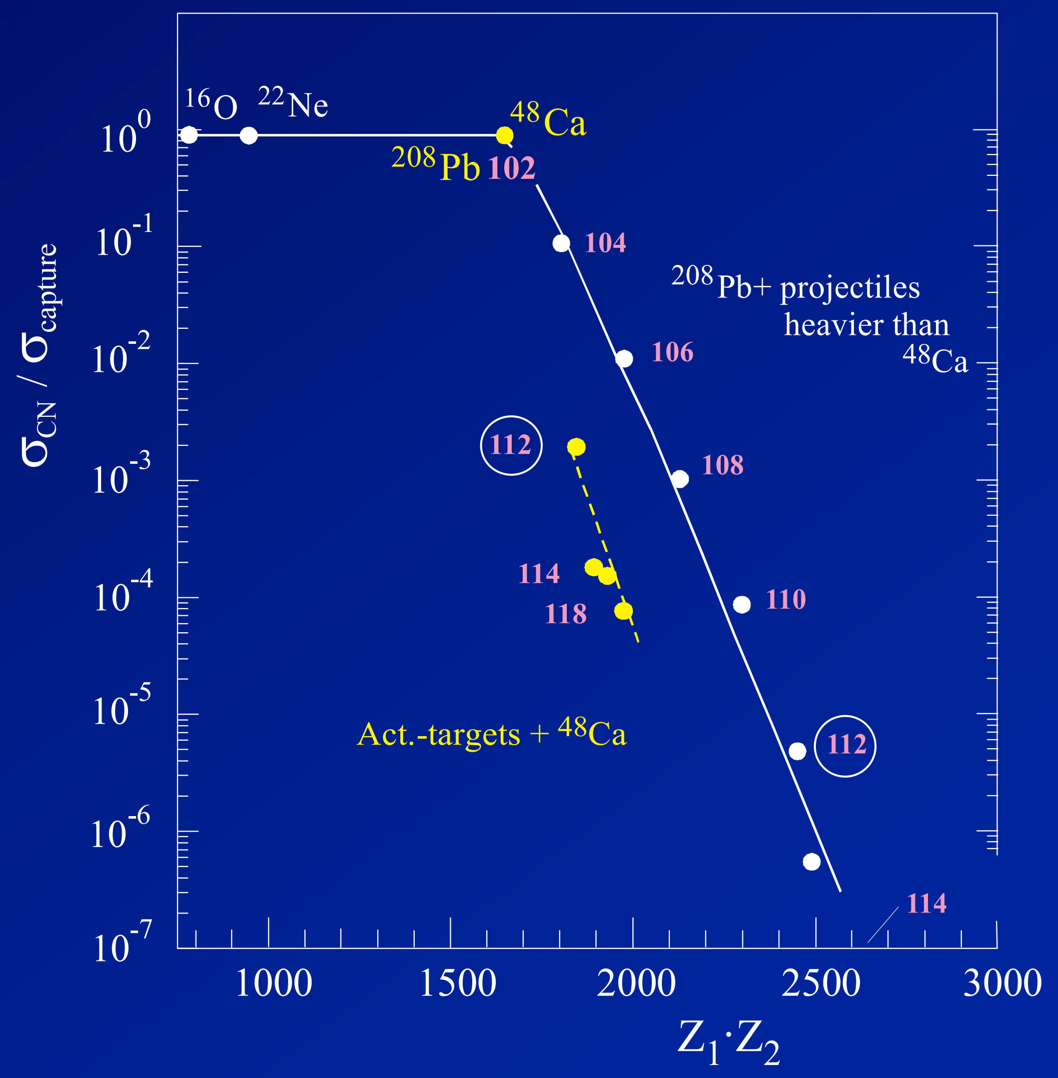


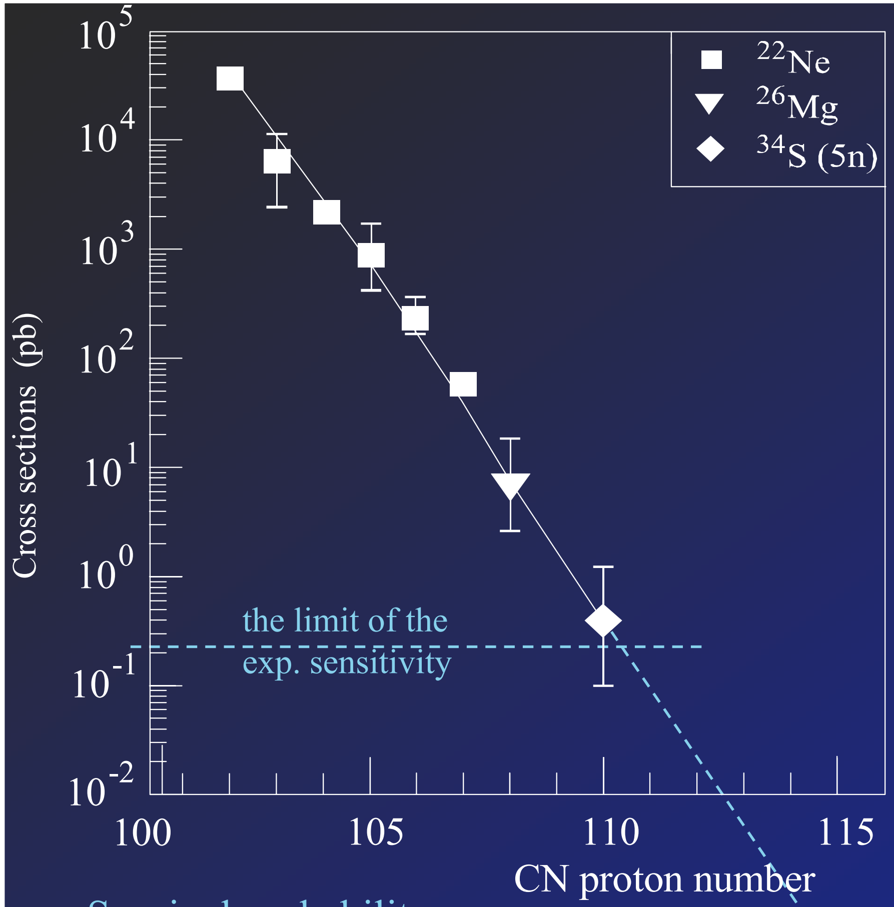
Fusion probability

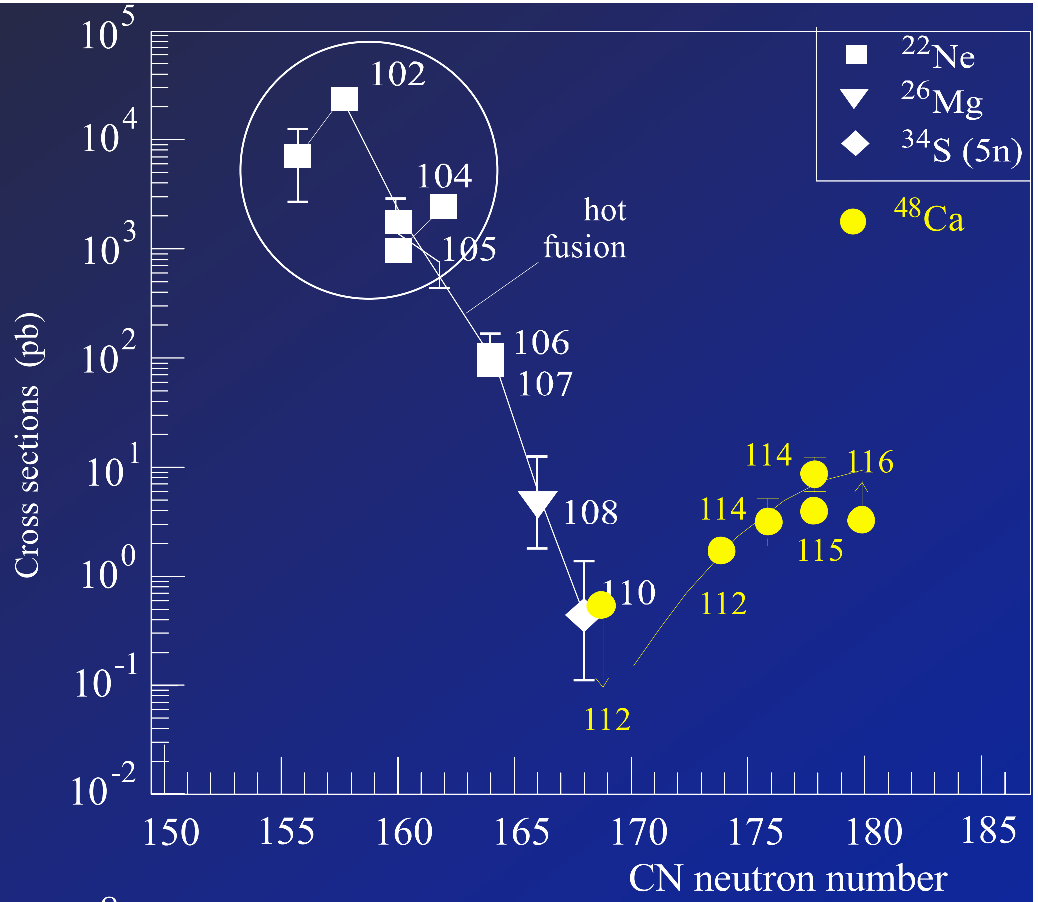



Z=116
Z = 116
touching point
Coulomb barrier
compound nucleus
saddle point
fusion fission
quasi fission
quasi fission
injection
Ca+Cm
hot fusion
energy
elongation
mass asymmetry

Fusion probability







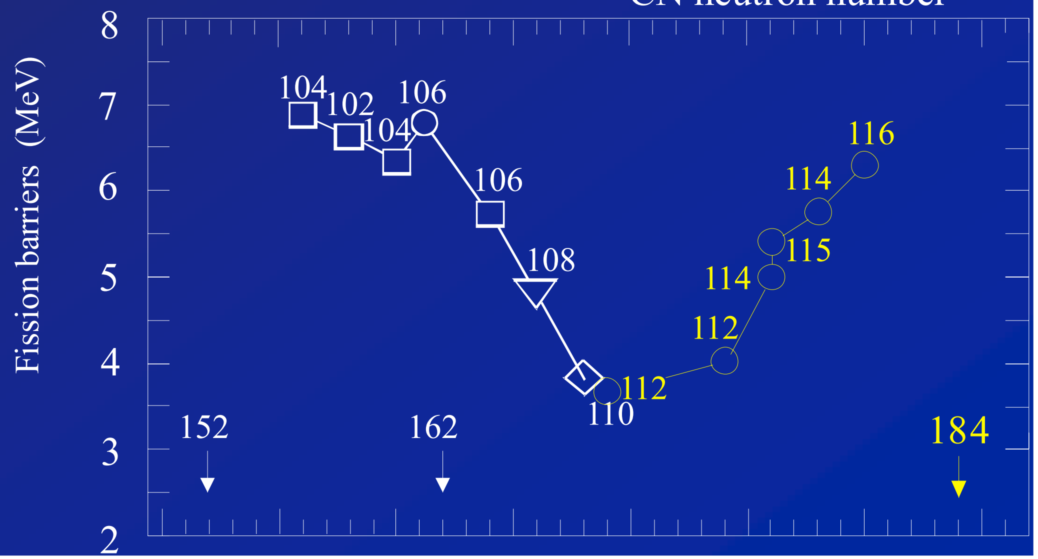
Survival probability

$$\sigma_{xn} = P_{xn} \cdot \prod_{i=1}^{i=x} (\Gamma_n / \Gamma_f)_I \sim (\Gamma_n / \Gamma_f)^x$$

$$(\Gamma_n / \Gamma_f)_I \sim \exp\left[(B_f - B_n) / T\right]$$

where $B_f = B_f^{LD} + \Delta E^{Shell}$

B_f^{LD}: 0



Higher neutron number in the compound nucleus increases its survivability considerably

The survivability of the compound nucleus, i.e., the $\sigma_{EVR}(N)$ is an independent evidence for the stabilizing effect of the N=184 shell in the domain of SHE

Natural occurrence of Ca isotopes (in %):

^{40}Ca – 96.94
^{42}Ca – 0.647
^{43}Ca – 0.135
^{44}Ca – 2.086
^{46}Ca – 0.004

^{48}Ca – 0.187

x 400

Consumption of ^{48}Ca (68%) - 0.5 mg/h

→ Ca^{5+}

beam intensity - $4 - 8 \cdot 10^{12}$/s

beam time - 4000 h/y

Isotopes:
U[233, 238], Pu[242, 244], Am[243], Cm[245, 247], Cf[249] + ^{48}Ca → Z = 112 - 118

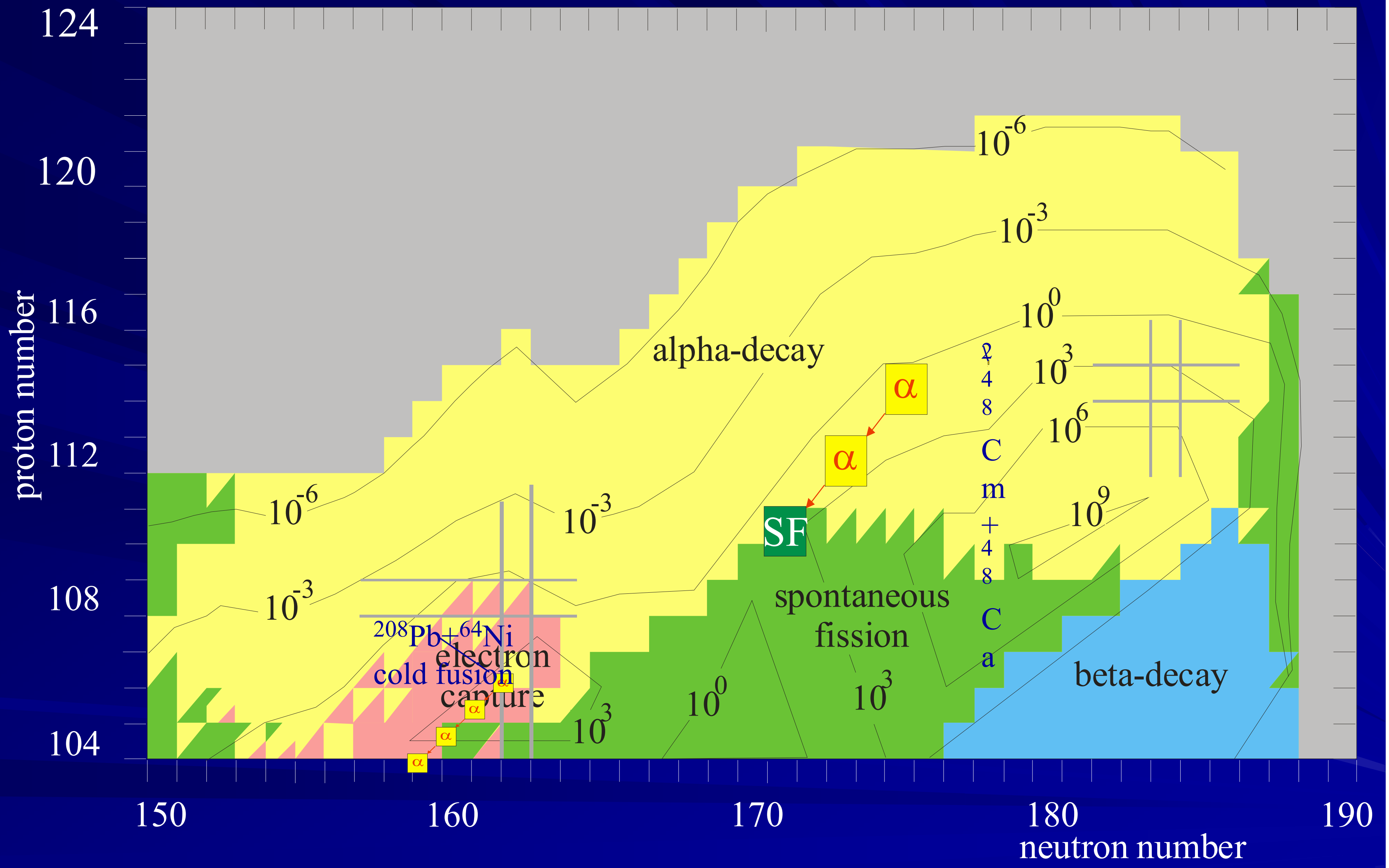
technology of the target preparation – 0.3 mg/cm^2

Separation of super heavy nuclei and detection of their radioactive decays

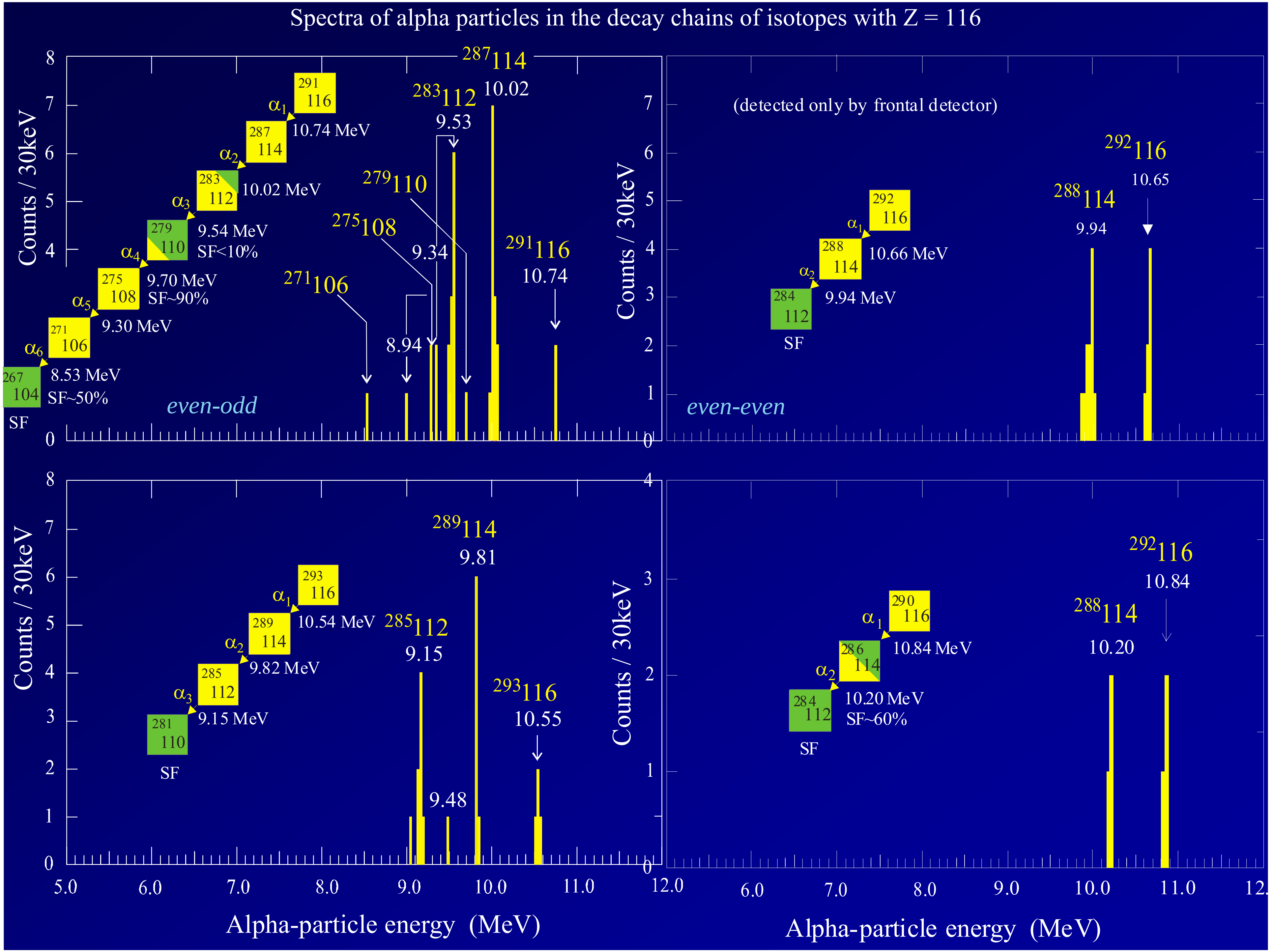
now: DGFRS

isotope enrichment 98-99%
S-2 separator
(Sarov)

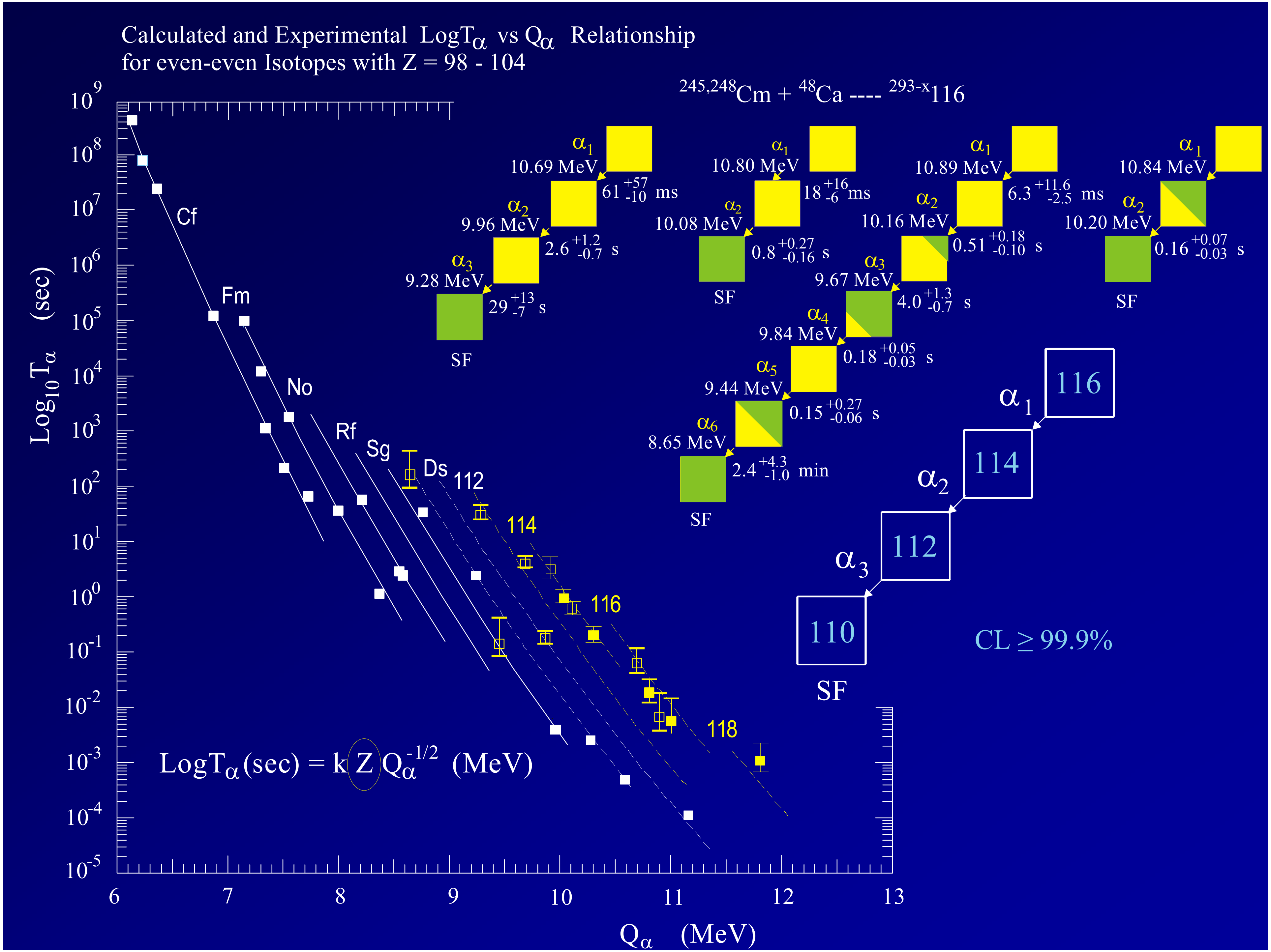
isotope production
high flux reactors
(Oak Ridge, Dimitrovgrad)



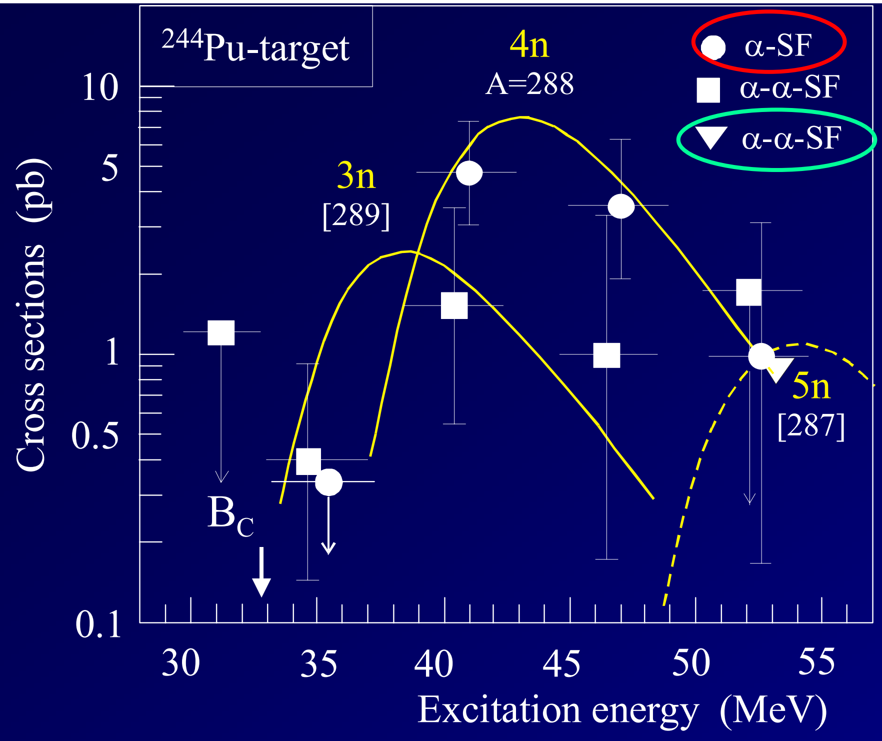
proton number
124
120
116
112
108
104
150
160
170
180
190
neutron number
alpha-decay
spontaneous
fission
beta-decay
electron
capture
208Pb+64Ni
cold fusion
SF
α
248Cm+48Ca
10-6
10-3
100
103
106
109

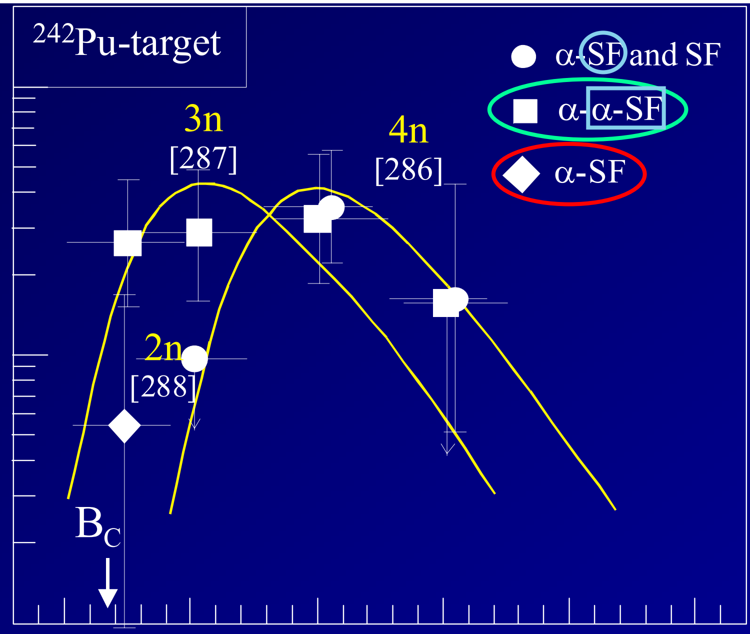


Spectra of alpha particles in the decay chains of isotopes with Z = 116
Counts / 30keV
291 116
α1
10.74 MeV
287 114
α2
10.02 MeV
283 112
α3
9.54 MeV
279 110
SF<10%
α4
9.70 MeV
275 108
SF~90%
α5
9.30 MeV
271 106
α6
8.53 MeV
267 104
SF~50%
SF
even-odd
287 114
10.02
283 112
9.53
279 110
275 108
9.34
291 116
10.74
271 106
8.94
(detected only by frontal detector)
292 116
10.65
288 114
9.94
292 116
α1
10.66 MeV
288 114
α2
9.94 MeV
284 112
SF
even-even
293 116
α1
10.54 MeV
289 114
α2
9.82 MeV
285 112
α3
9.15 MeV
281 110
SF
289 114
9.81
285 112
9.15
9.48
293 116
10.55
292 116
10.84
288 114
10.20
290 116
α1
10.84 MeV
286 114
α2
10.20 MeV
SF~60%
284 112
SF
Alpha-particle energy (MeV)
Alpha-particle energy (MeV)

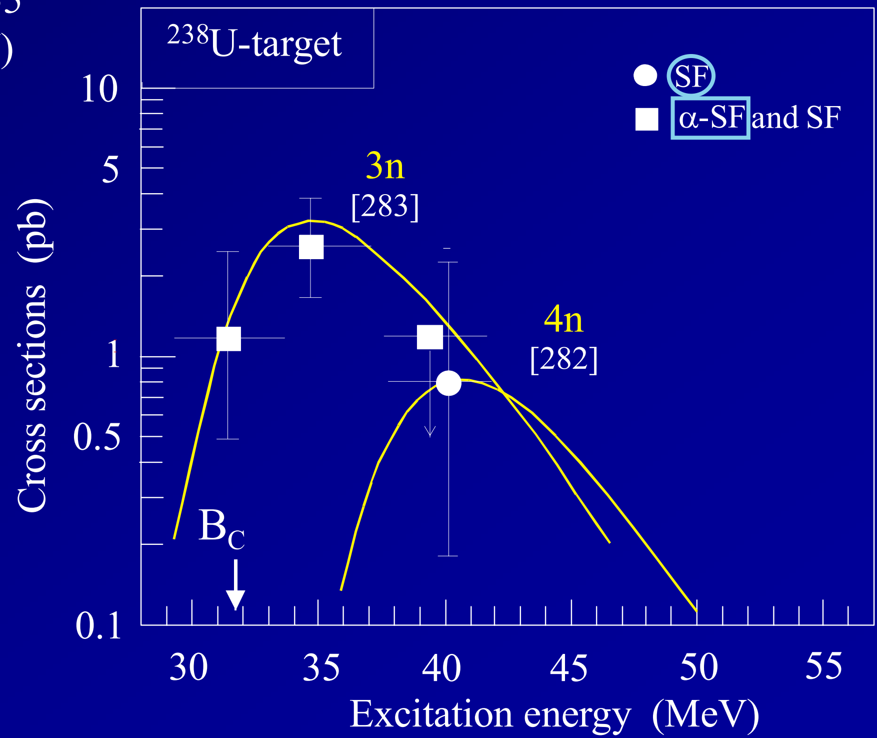


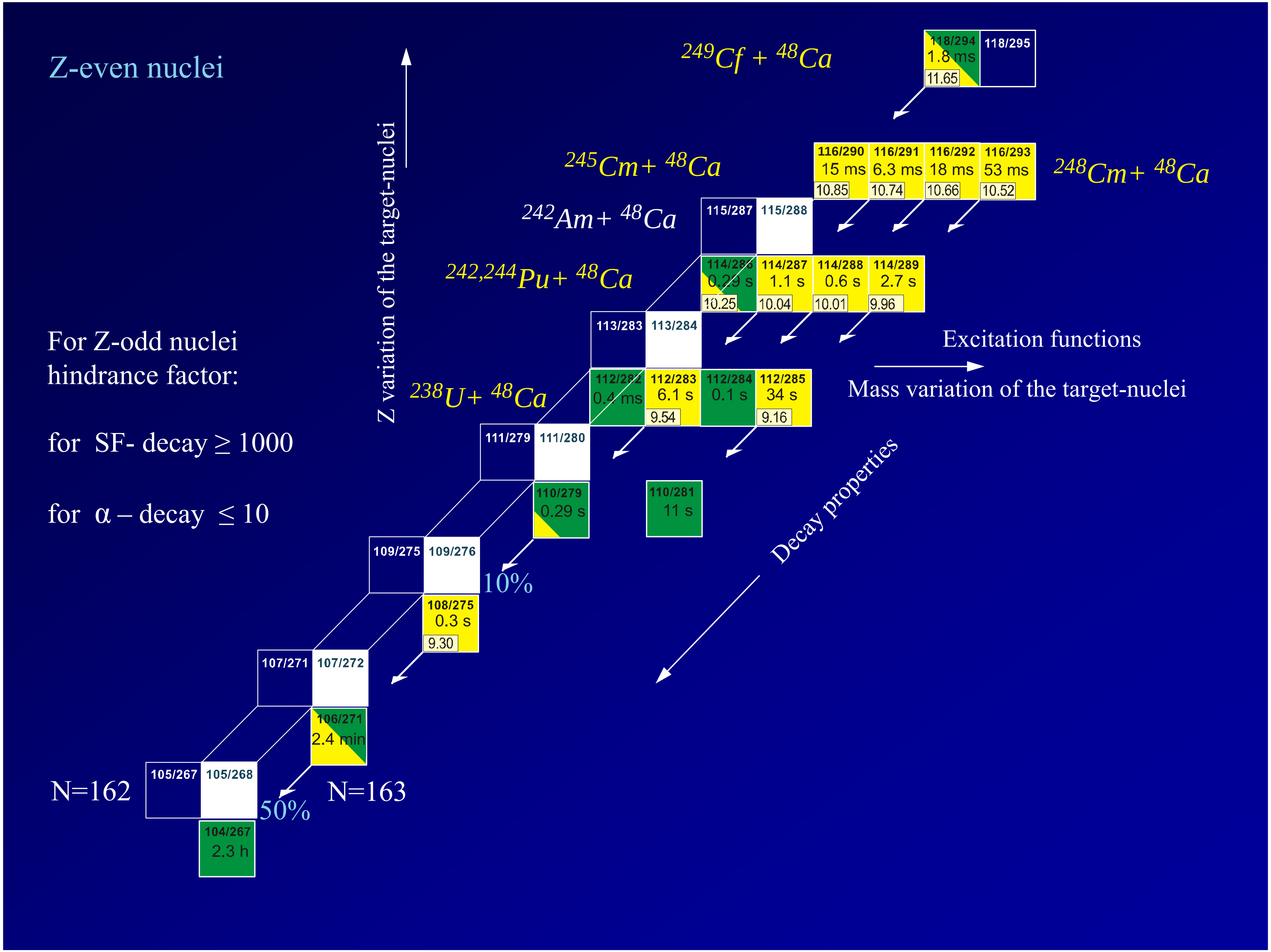
Calculated and Experimental $LogT_\alpha$ vs Q_α Relationship
for even-even Isotopes with Z = 98 - 104
$^{245,248}Cm + ^{48}Ca$ ---- $^{293-x}116$
$Log_{10} T_\alpha$ (sec)
Q_α (MeV)
Cf
Fm
No
Rf
Sg
Ds
112
114
116
118
$LogT_\alpha(sec) = k Z Q_\alpha^{-1/2}$ (MeV)
α_1 10.69 MeV
61^{+57}_{-10} ms
α_2 9.96 MeV
$2.6^{+1.2}_{-0.7}$ s
α_3 9.28 MeV
29^{+13}_{-7} s
SF
α_1 10.80 MeV
18^{+16}_{-6} ms
α_2 10.08 MeV
$0.8^{+0.27}_{-0.16}$ s
SF
α_1 10.89 MeV
$6.3^{+11.6}_{-2.5}$ ms
α_2 10.16 MeV
$0.51^{+0.18}_{-0.10}$ s
α_3 9.67 MeV
$4.0^{+1.3}_{-0.7}$ s
α_4 9.84 MeV
$0.18^{+0.05}_{-0.03}$ s
α_5 9.44 MeV
$0.15^{+0.27}_{-0.06}$ s
α_6 8.65 MeV
$2.4^{+4.3}_{-1.0}$ min
SF
α_1 10.84 MeV
α_2 10.20 MeV
$0.16^{+0.07}_{-0.03}$ s
SF
116
α_1
114
α_2
112
α_3
110
SF
CL ≥ 99.9%





Isotope charge (Z) and mass (A) identifications obtained by the measurements of neutron evaporation cross sections vs. excitation energy of compound nucleus

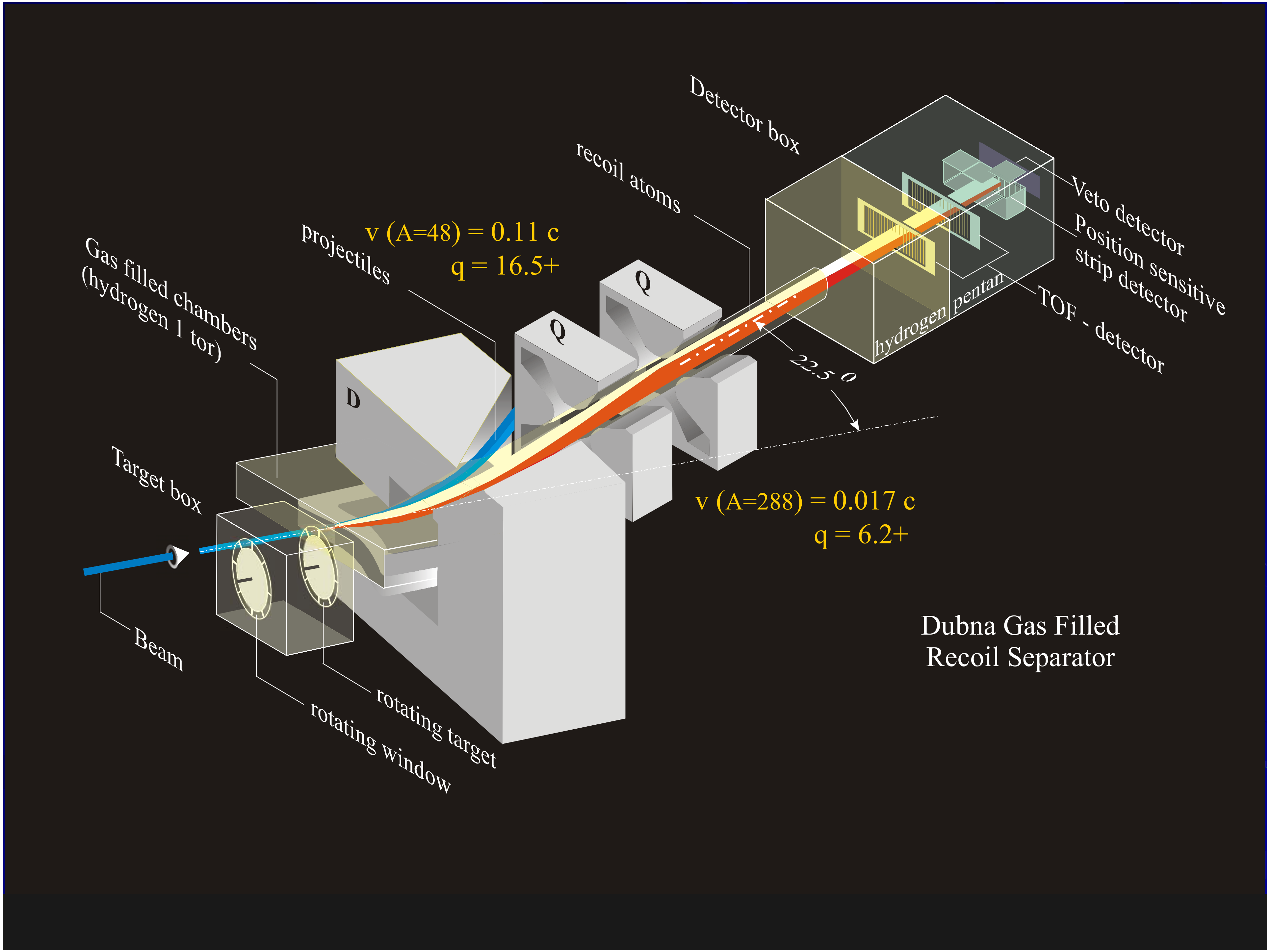


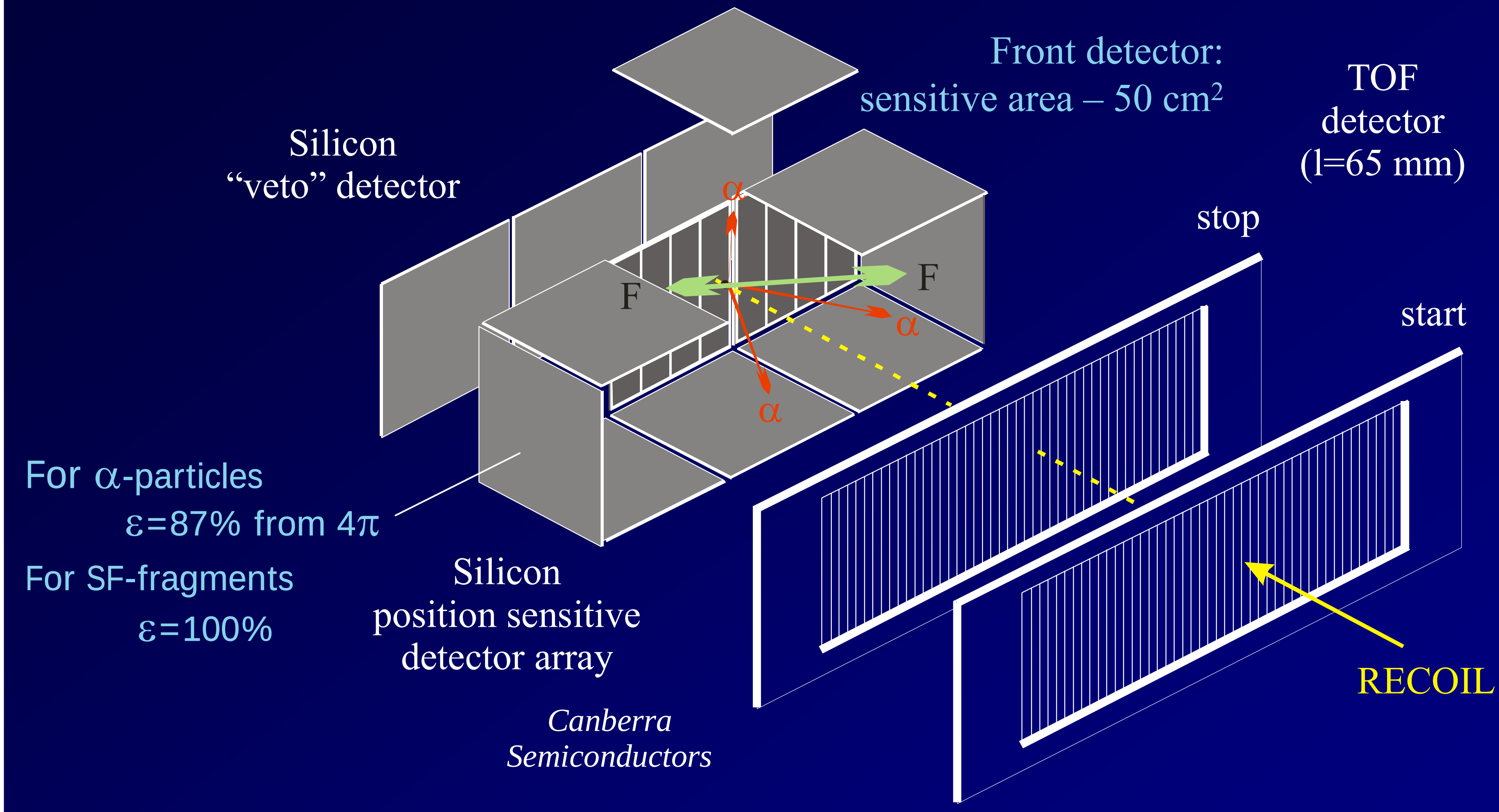

Z-even nuclei
For Z-odd nuclei hindrance factor:
for SF- decay ≥ 1000
for α – decay ≤ 10
Z variation of the target-nuclei
249Cf + 48Ca
245Cm+ 48Ca
248Cm+ 48Ca
242Am+ 48Ca
242,244Pu+ 48Ca
238U+ 48Ca
118/294 1.8 ms 11.65
118/295
116/290 15 ms 10.85
116/291 6.3 ms 10.74
116/292 18 ms 10.66
116/293 53 ms 10.52
115/287
115/288
114/286 0.29 s 10.25
114/287 1.1 s 10.04
114/288 0.6 s 10.01
114/289 2.7 s 9.96
113/283
113/284
112/282 0.4 ms
112/283 6.1 s 9.54
112/284 0.1 s
112/285 34 s 9.16
111/279
111/280
110/279 0.29 s
110/281 11 s
109/275
109/276
108/275 0.3 s 9.30
107/271
107/272
106/271 2.4 min
105/267
105/268
104/267 2.3 h
10%
50%
N=162
N=163
Excitation functions
Mass variation of the target-nuclei
Decay properties

Synthesis of Element 115

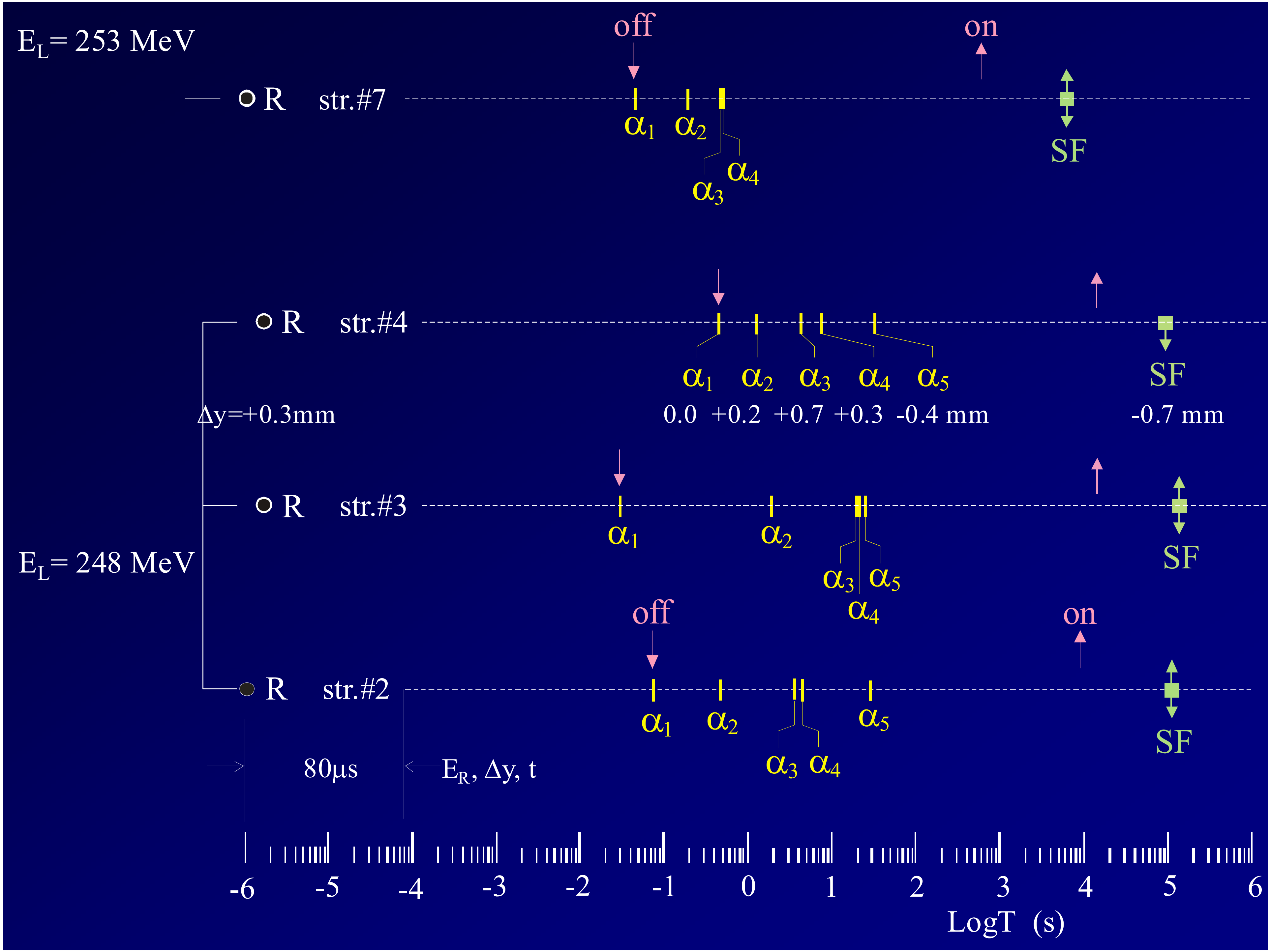
in the Reaction:

$$^{243}Am_{95} + {}^{48}Ca_{20} \rightarrow {}^{291-x}115$$

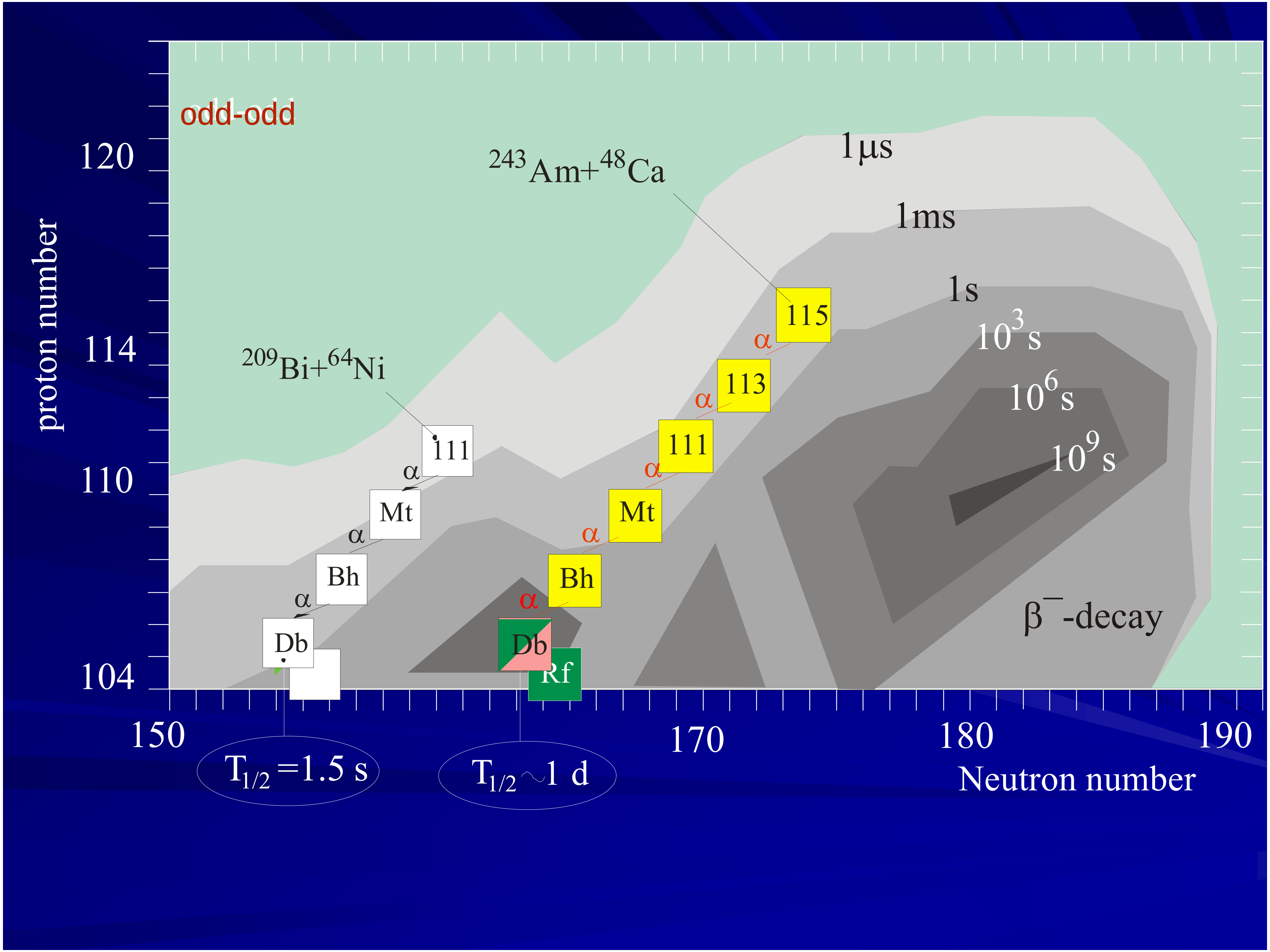

Detector box
recoil atoms
v (A=48) = 0.11 c
q = 16.5+
projectiles
Gas filled chambers
(hydrogen 1 tor)
Veto detector
Position sensitive
strip detector
TOF - detector
hydrogen
pentan
Q
Q
D
22.5 0
Target box
v (A=288) = 0.017 c
q = 6.2+
Beam
rotating target
rotating window
Dubna Gas Filled
Recoil Separator



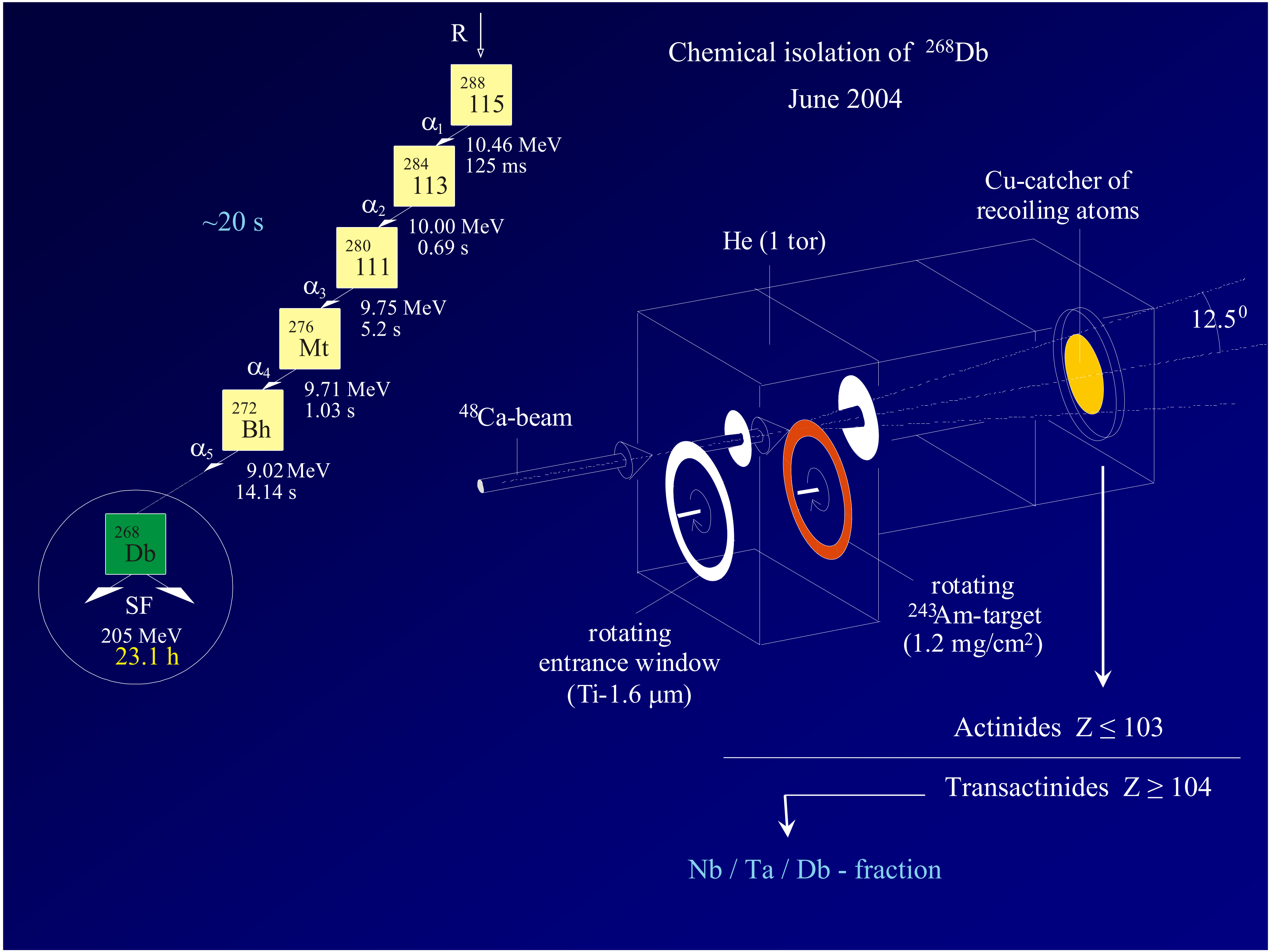
DETECTION SYSTEM
OF THE DUBNA GAS FILLED
RECOIL SEPARATOR



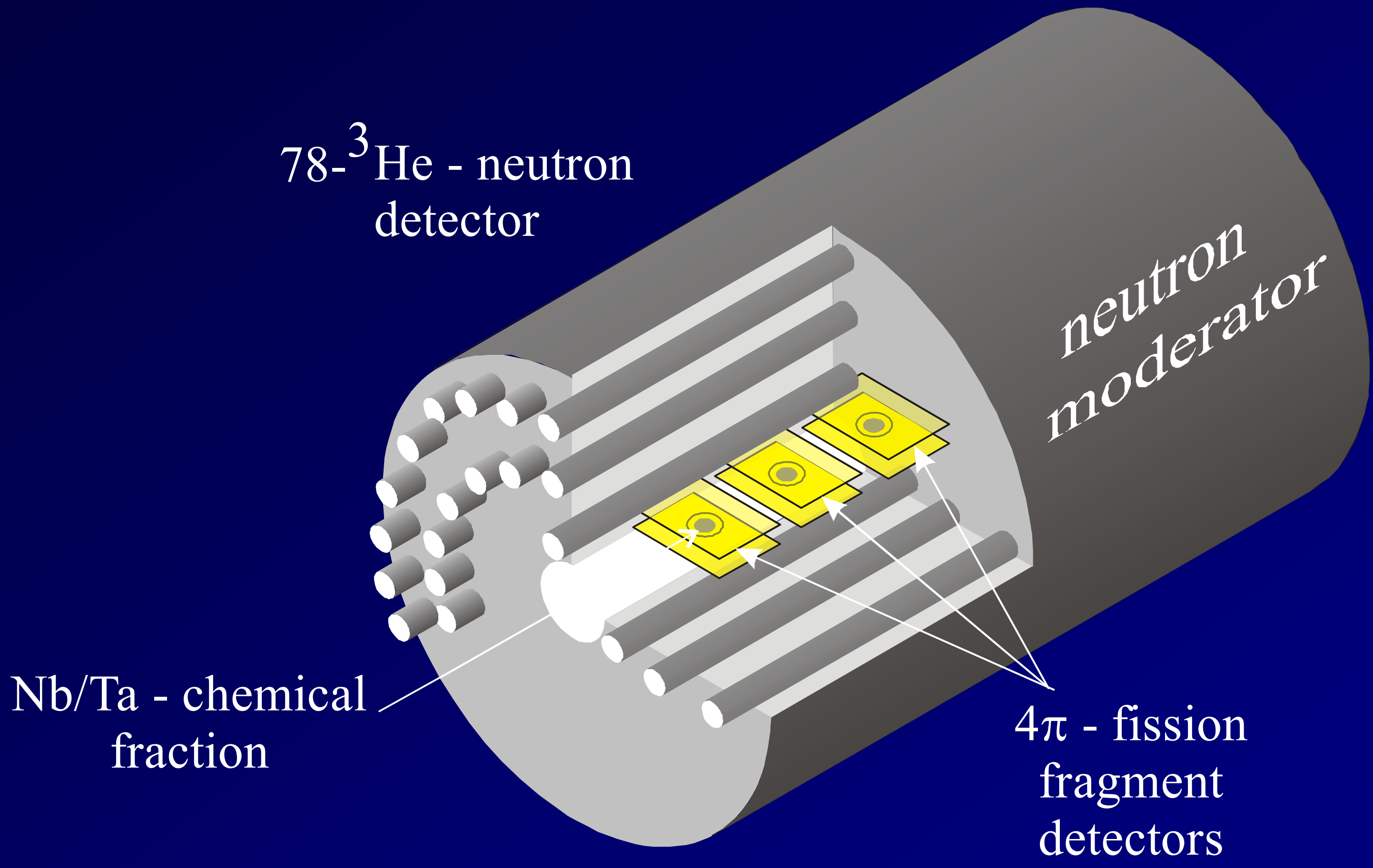
E_L= 253 MeV
off
on
R str.#7
α1 α2 α3 α4
SF
R str.#4
α1 α2 α3 α4 α5
SF
Δy=+0.3mm
0.0 +0.2 +0.7 +0.3 -0.4 mm
-0.7 mm
R str.#3
α1 α2 α3 α4 α5
SF
E_L= 248 MeV
off
on
R str.#2
α1 α2 α3 α4 α5
SF
80μs
E_R, Δy, t
-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6
LogT (s)



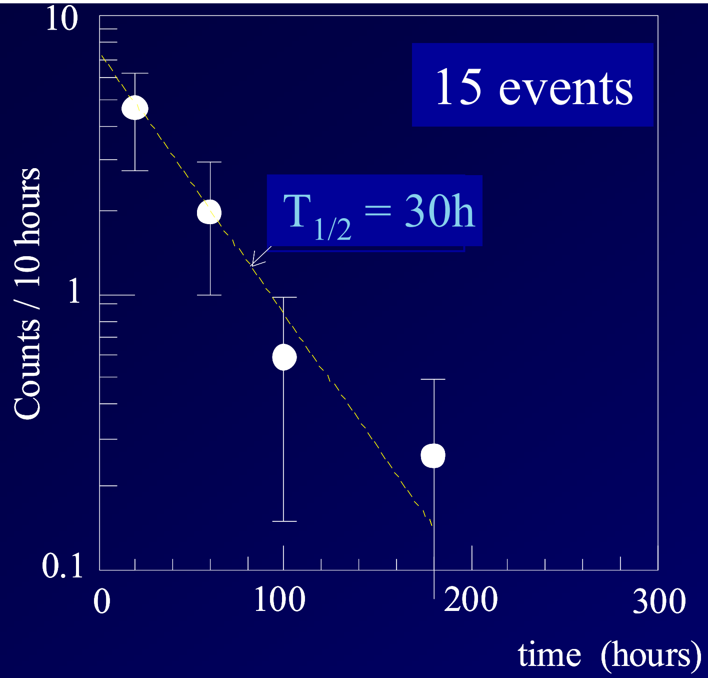
odd-odd
proton number
120
114
110
104
150
170
180
190
Neutron number
$^{243}Am+^{48}Ca$
$^{209}Bi+^{64}Ni$
1 μs
1ms
1s
10^3 s
10^6 s
10^9 s
β⁻-decay
115
113
111
Mt
Bh
Db
Rf
α
$T_{1/2}$ =1.5 s
$T_{1/2}$ ~1 d

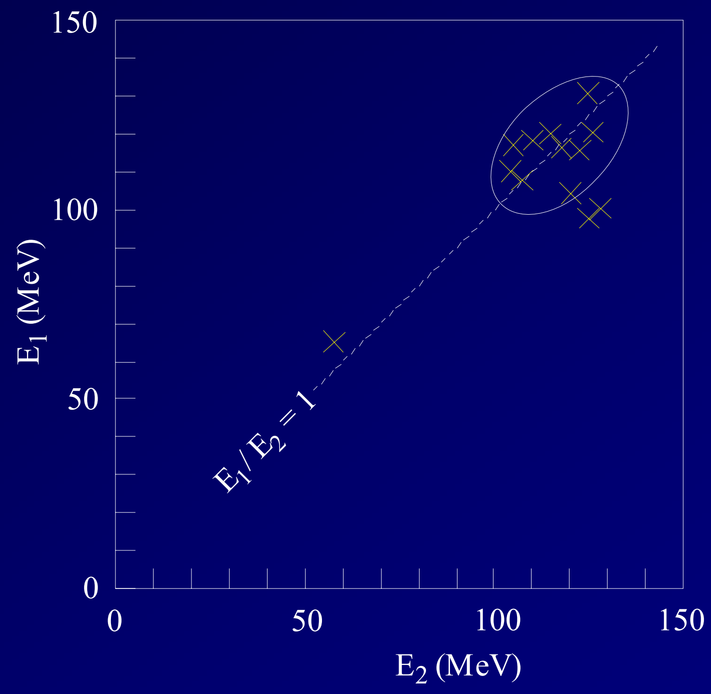

Chemical isolation of ^{268}Db
June 2004
R
288 115
α_1
10.46 MeV
125 ms
284 113
α_2
10.00 MeV
0.69 s
280 111
α_3
9.75 MeV
5.2 s
276 Mt
α_4
9.71 MeV
1.03 s
272 Bh
α_5
9.02 MeV
14.14 s
~20 s
268 Db
SF
205 MeV
23.1 h
Cu-catcher of recoiling atoms
He (1 tor)
12.5^0
^{48}Ca-beam
rotating entrance window (Ti-1.6 μm)
rotating ^{243}Am-target (1.2 mg/cm^2)
Actinides Z ≤ 103
Transactinides Z ≥ 104
Nb / Ta / Db - fraction

SF of Z=105 from the Nb/Ta chemical fraction

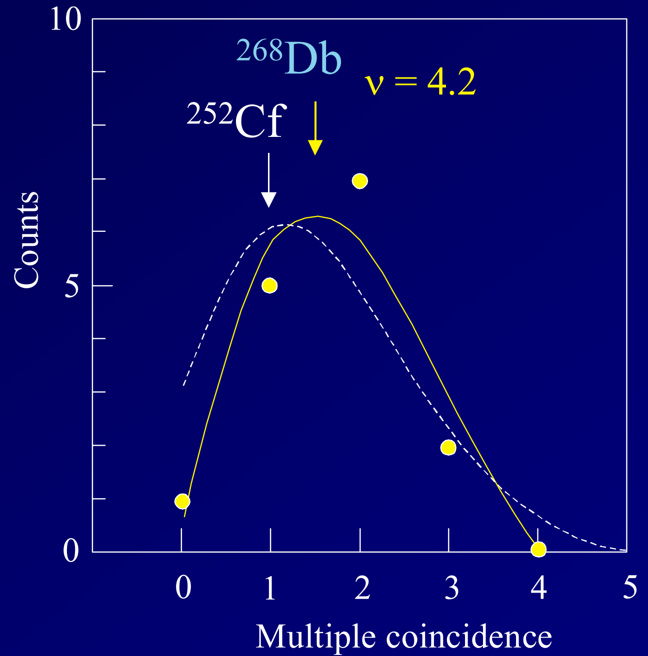


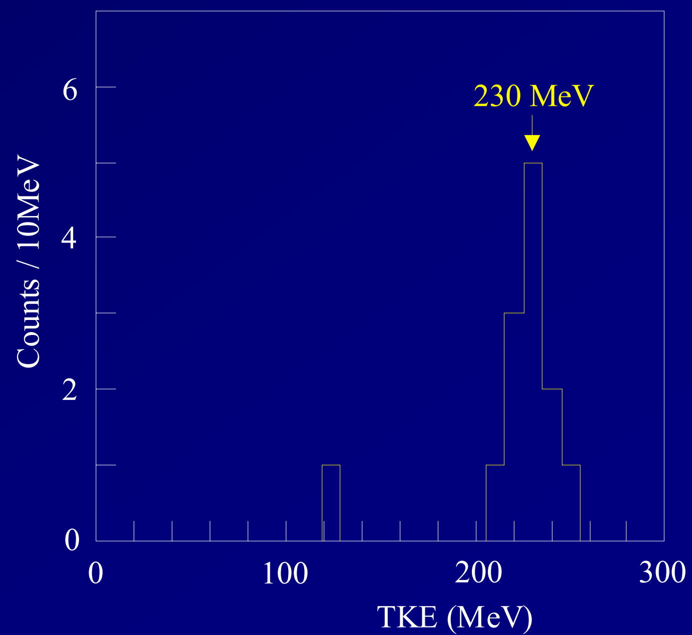
Spontaneous fission half-life of ^{268}Db (N=163)

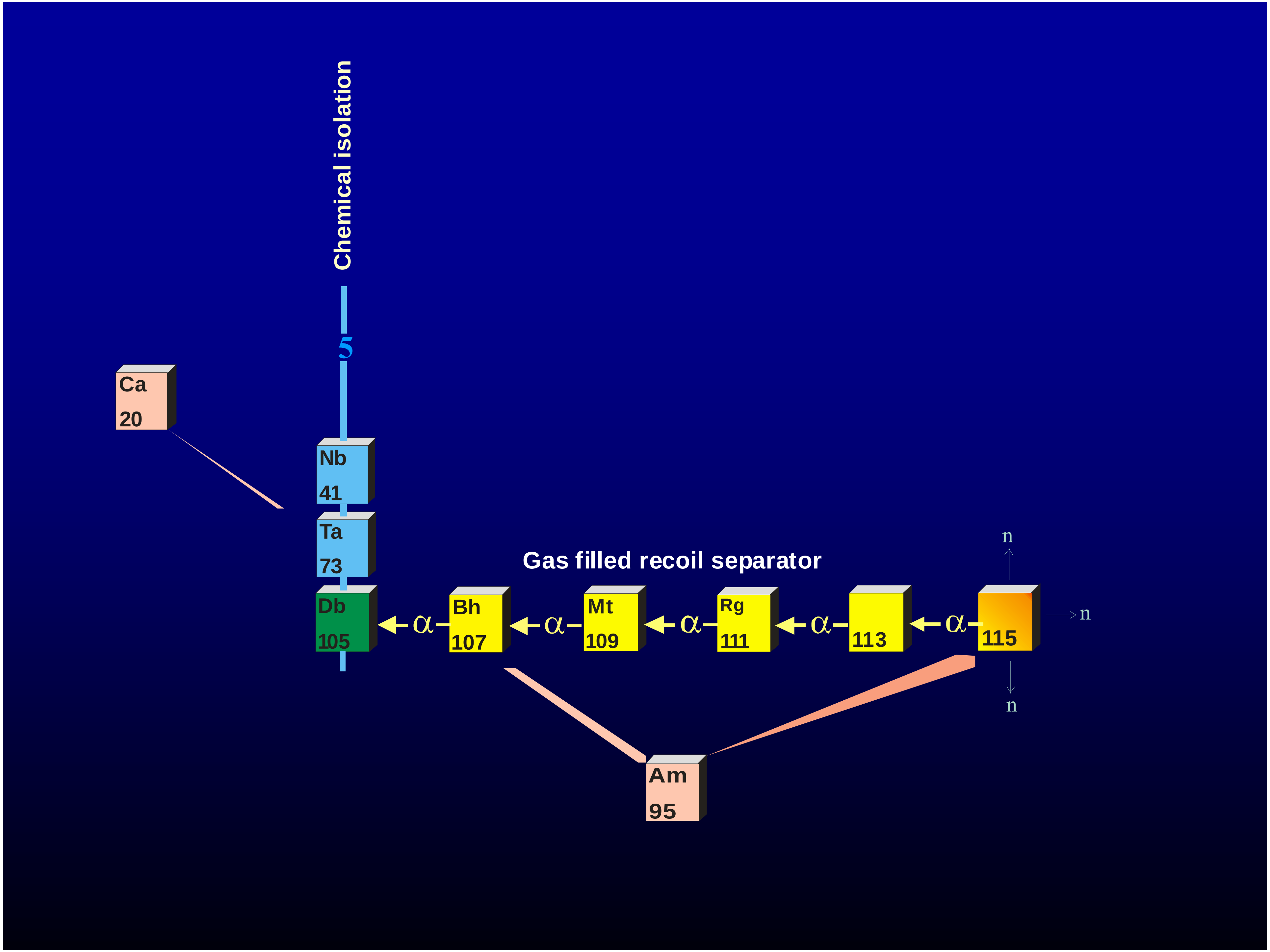




$Q_F \sim$ 280 MeV

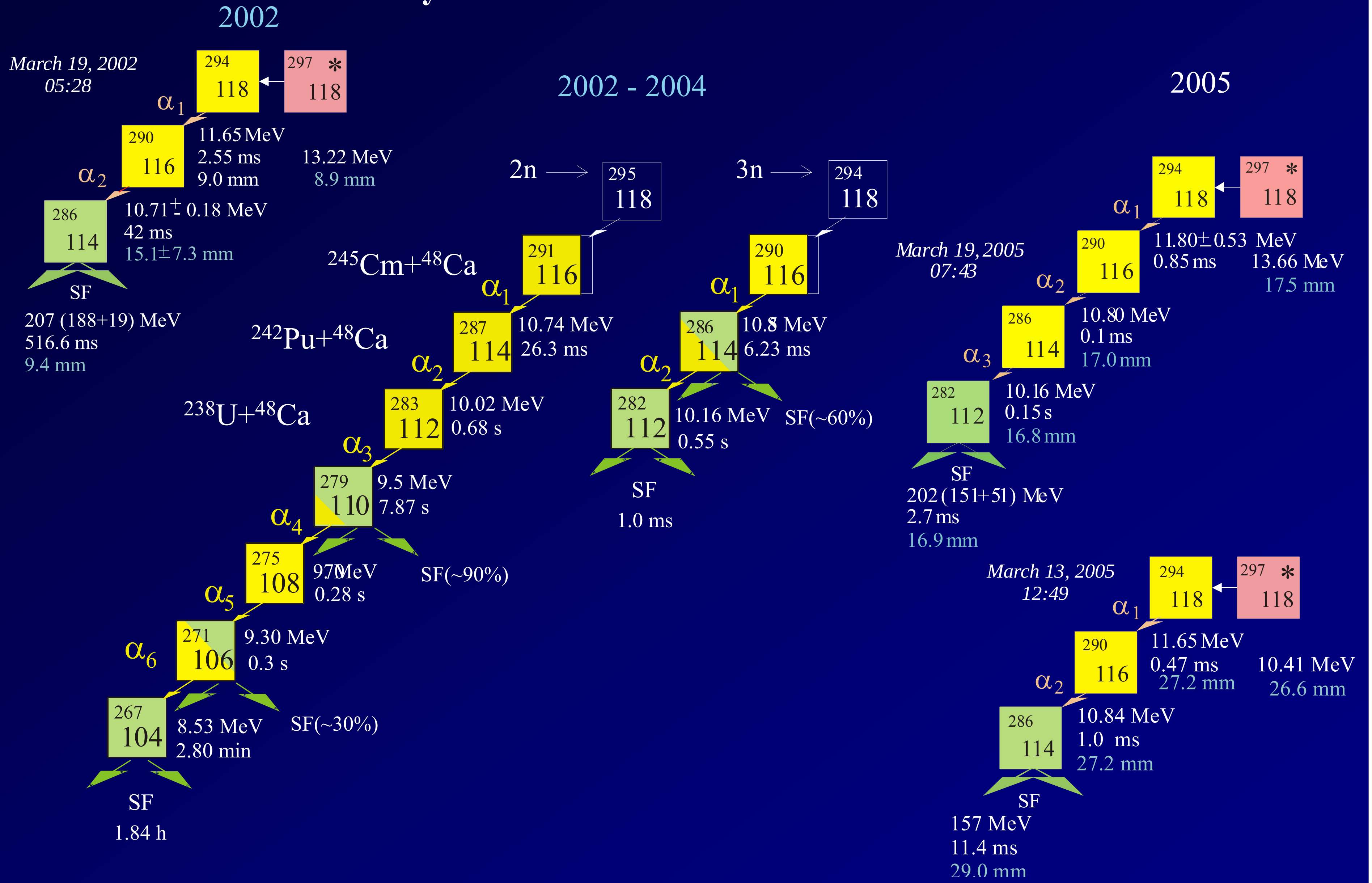






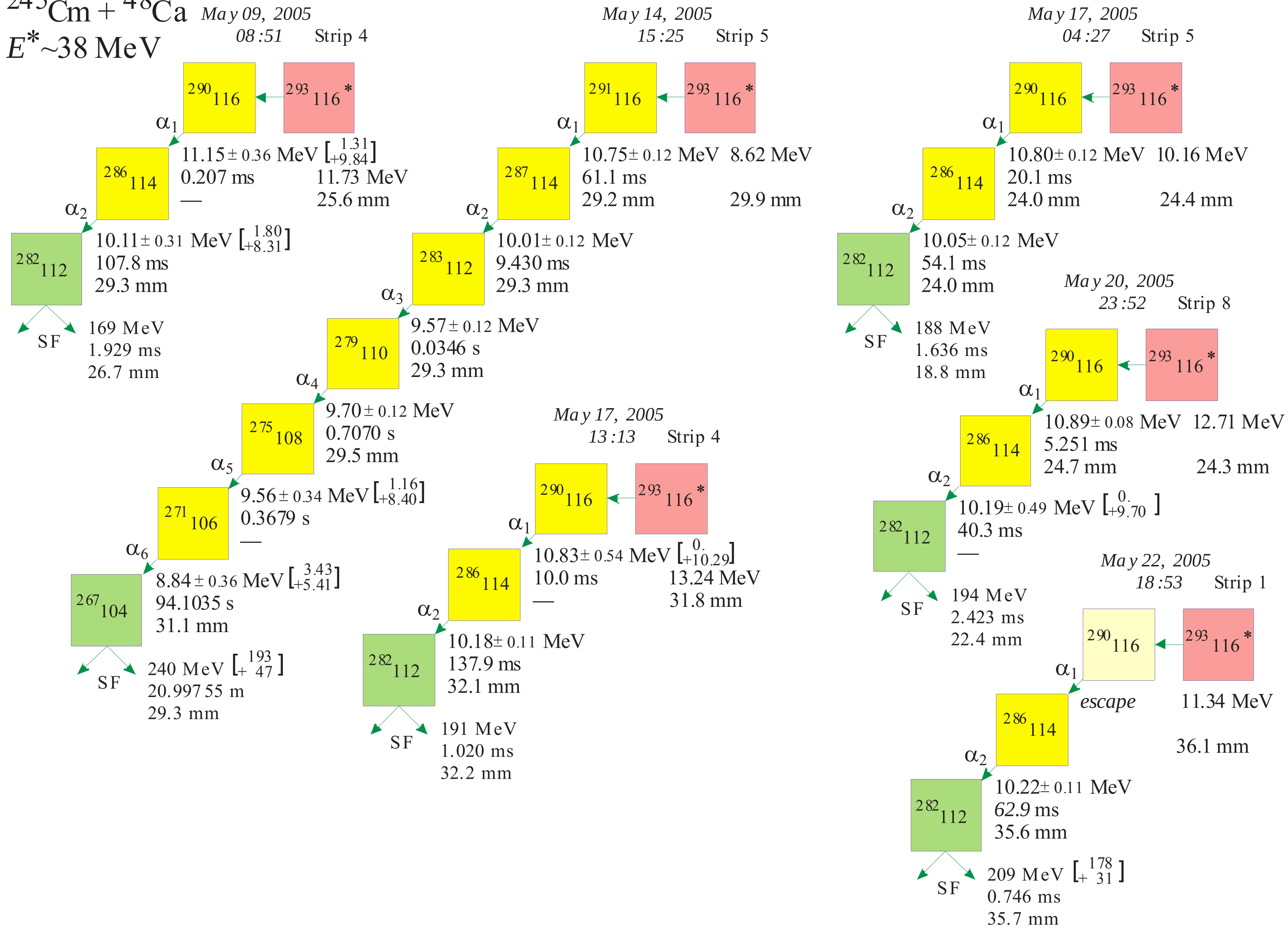
Chemical isolation
5
Ca
20
Nb
41
Ta
73
Db
105
Gas filled recoil separator
Bh
107
Mt
109
Rg
111
113
115
α
n
n
n
Am
95

Synthesis of Element 118 in $^{249}Cf + ^{48}Ca$ Reaction



$^{245}Cm + ^{48}Ca$

$E^* \sim 38$ MeV



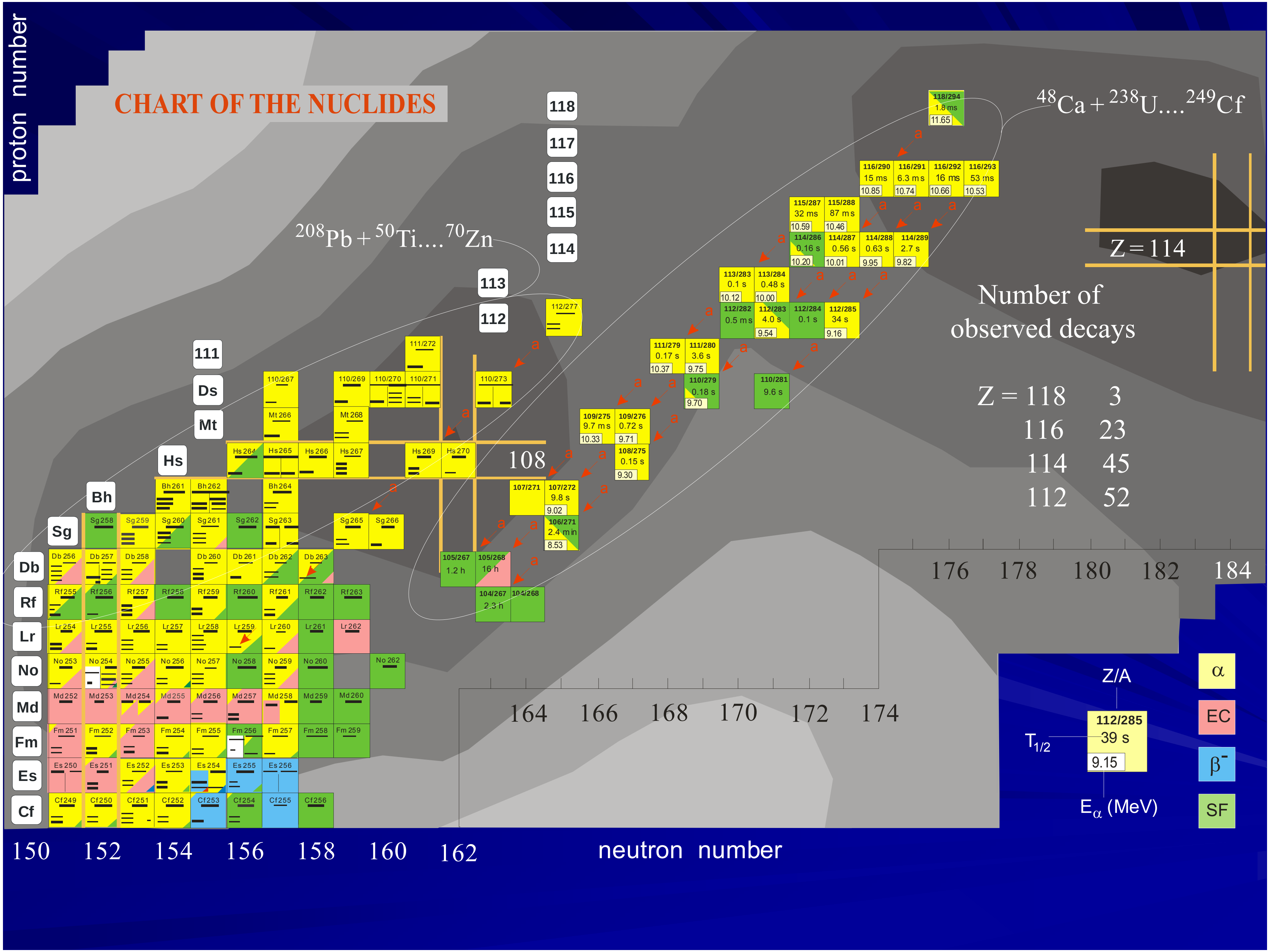
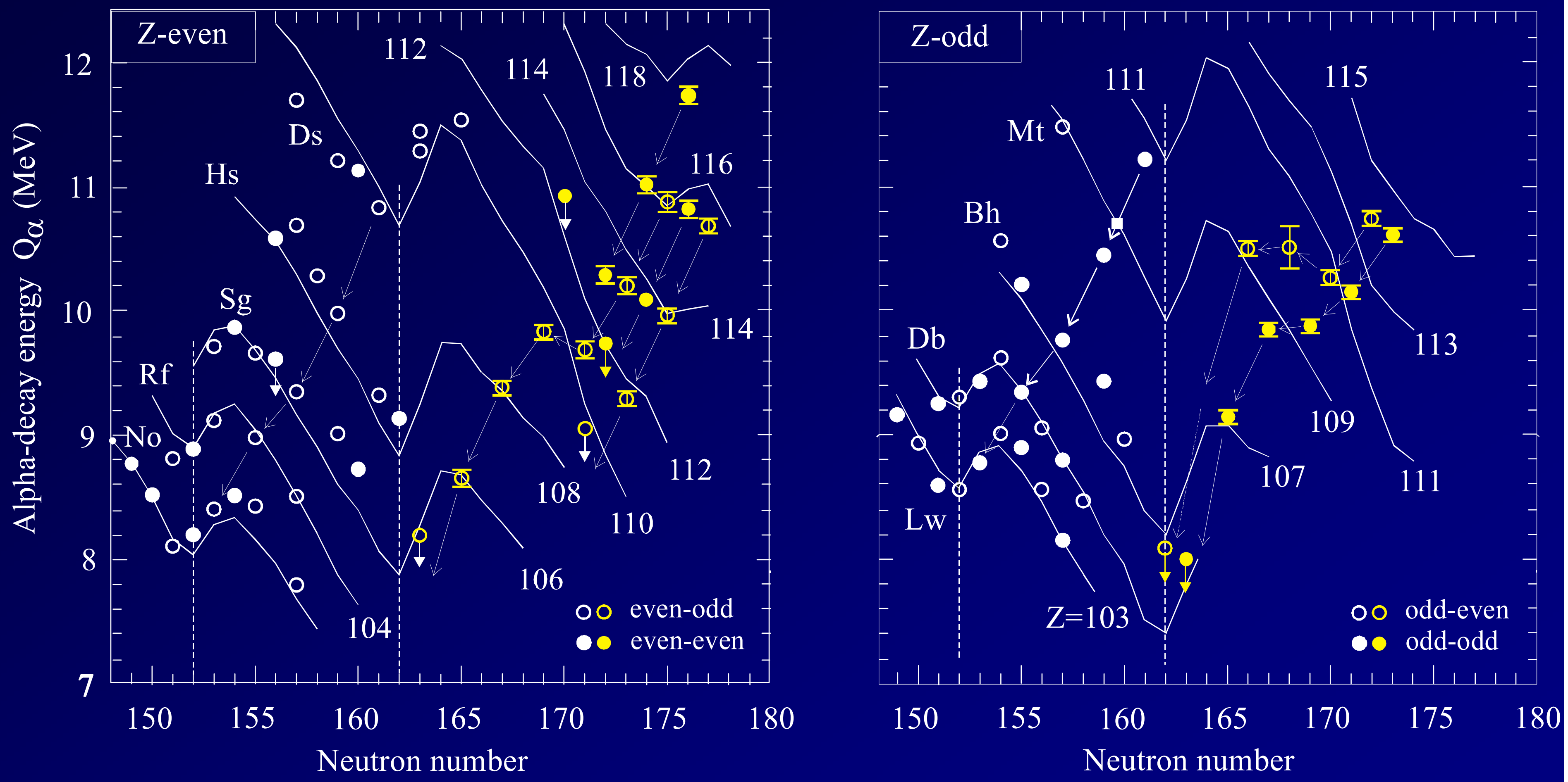
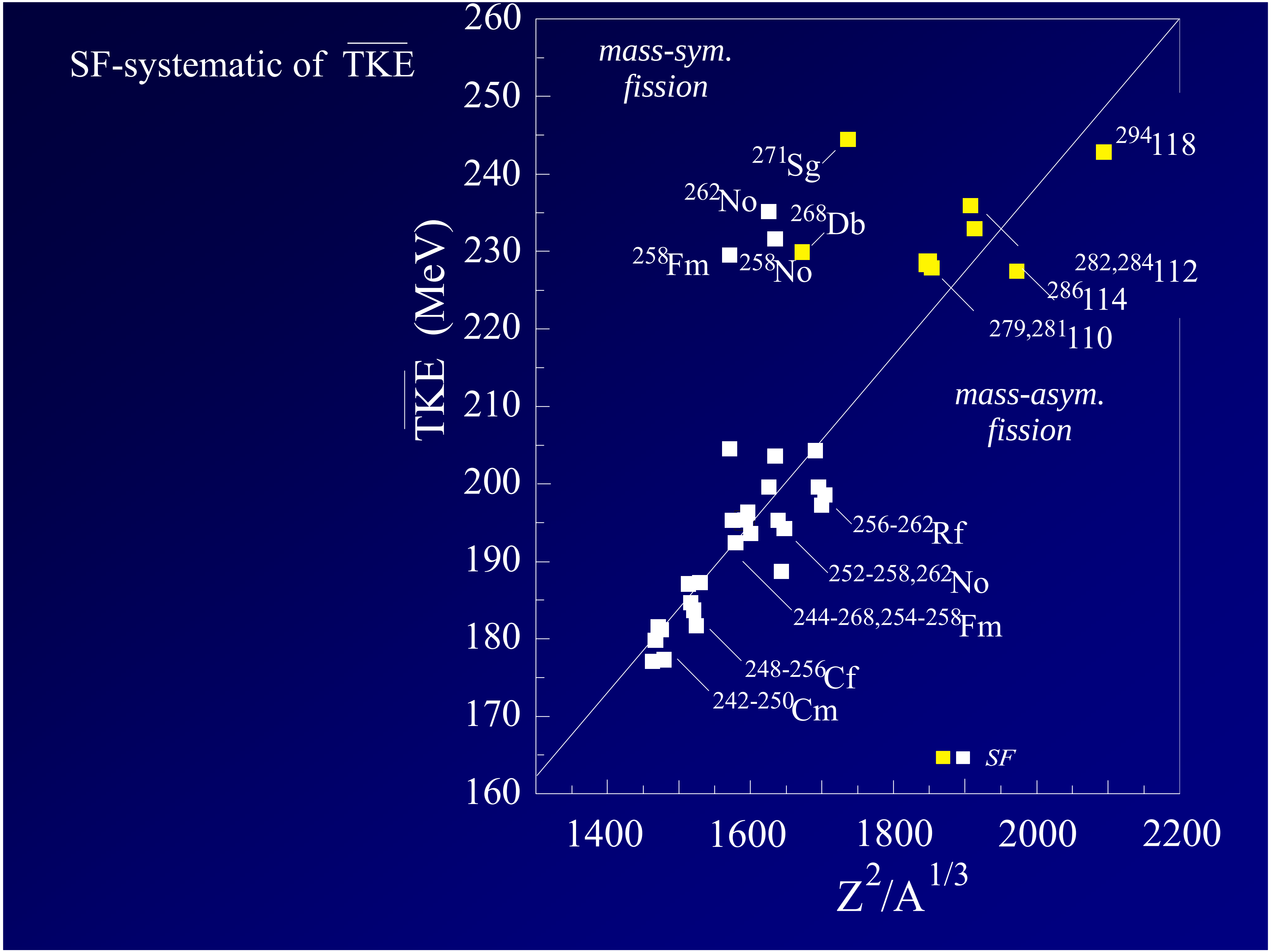


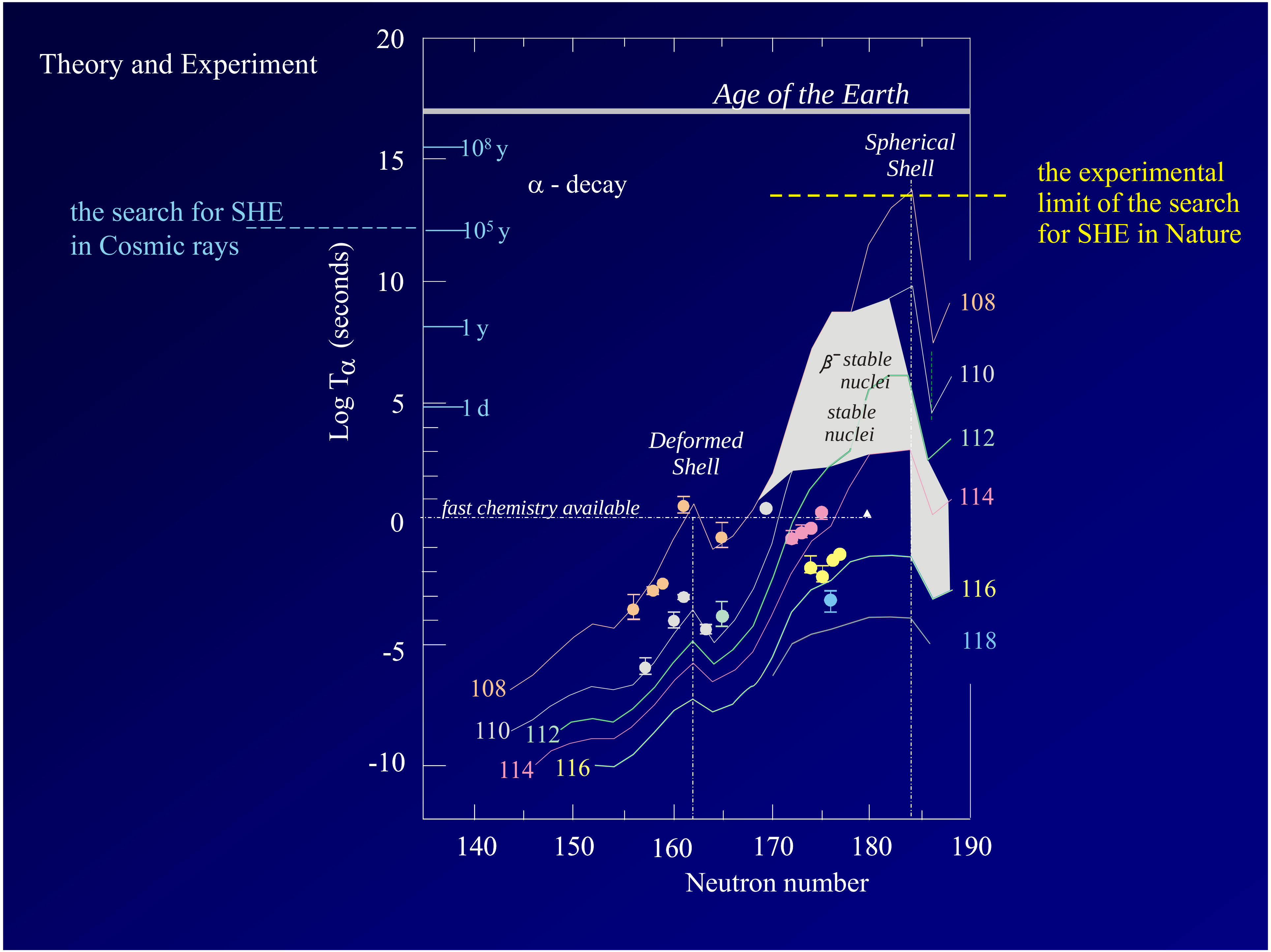
CHART OF THE NUCLIDES
proton number
neutron number
$^{208}Pb + ^{50}Ti....^{70}Zn$
$^{48}Ca + ^{238}U....^{249}Cf$
Z = 114
Number of observed decays
Z = 118 3
116 23
114 45
112 52
118
117
116
115
114
113
112
111
Ds
Mt
Hs
Bh
Sg
Db
Rf
Lr
No
Md
Fm
Es
Cf
108
150
152
154
156
158
160
162
164
166
168
170
172
174
176
178
180
182
184
Z/A
112/285
39 s
9.15
$T_{1/2}$
E_{α} (MeV)
α
EC
β^-
SF

Alpha-decay energy vs. neutron number For the isotopes of elements with Z >102



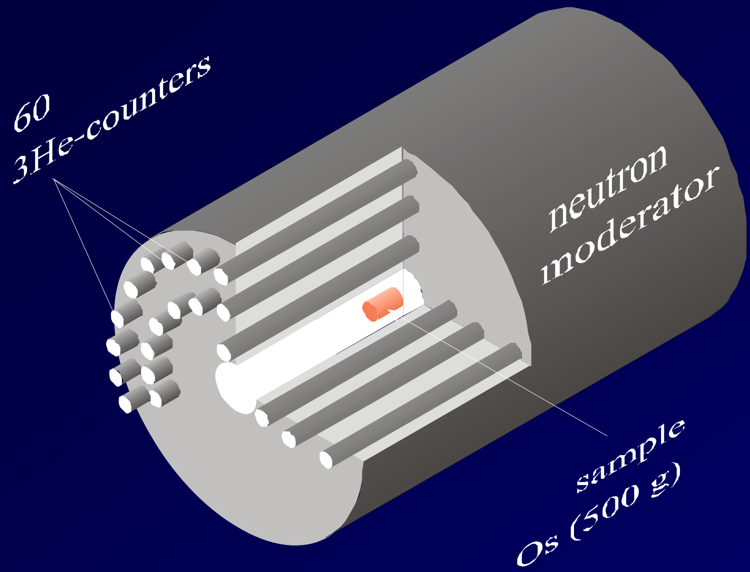


SF-systematic of TKE
mass-sym.
fission
mass-asym.
fission
271Sg
262No
268Db
258Fm
258No
294118
282,284112
286114
279,281110
256-262Rf
252-258,262No
244-268,254-258Fm
248-256Cf
242-250Cm
SF
TKE (MeV)
Z2/A1/3
260
250
240
230
220
210
200
190
180
170
160
1400
1600
1800
2000
2200



Theory and Experiment
Age of the Earth
Spherical Shell
the experimental limit of the search for SHE in Nature
the search for SHE in Cosmic rays
α - decay
10⁸ y
10⁵ y
1 y
1 d
Log Tα (seconds)
20
15
10
5
0
-5
-10
β⁻ stable nuclei
stable nuclei
Deformed Shell
fast chemistry available
108
110
112
114
116
118
140
150
160
170
180
190
Neutron number

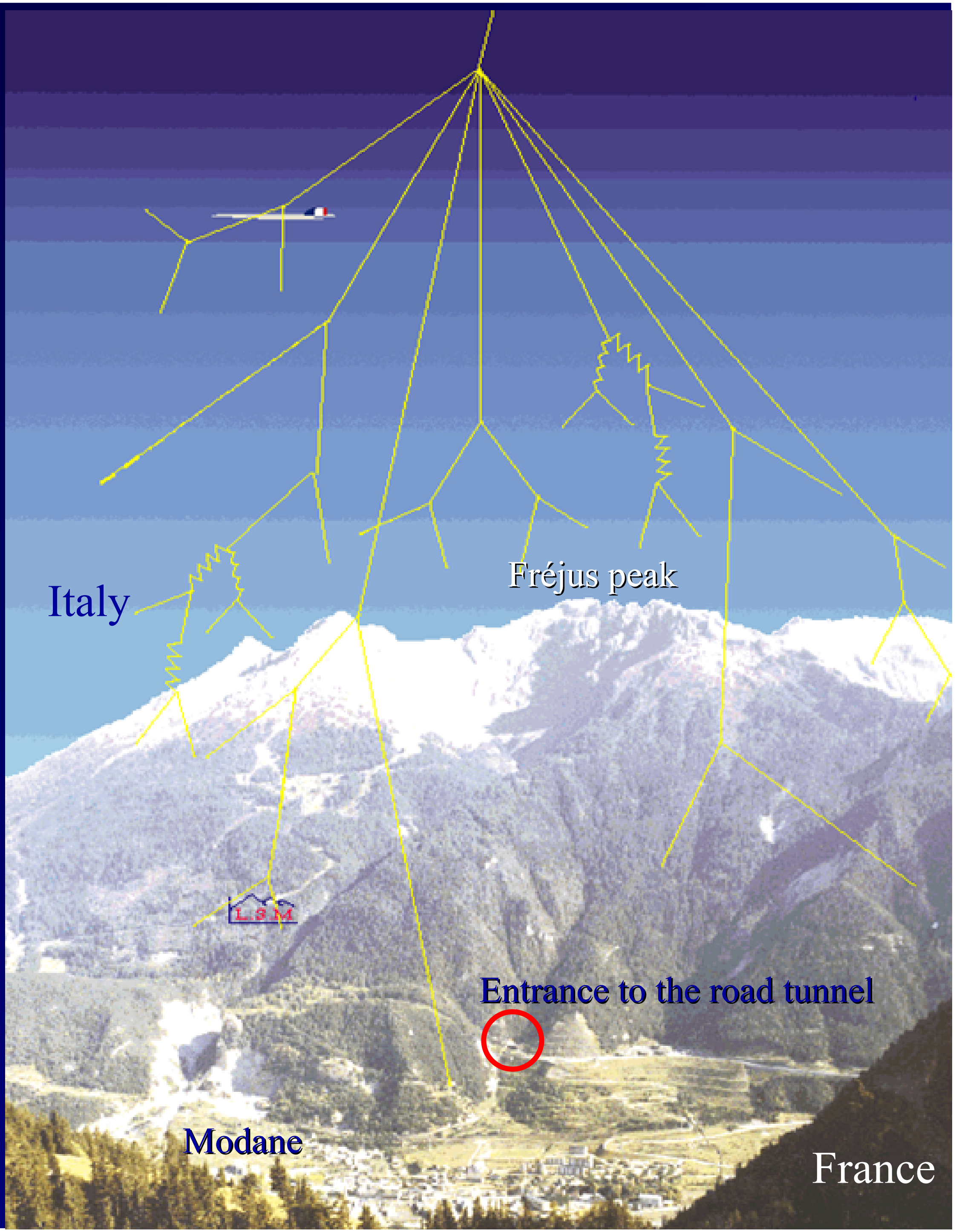
Search for SF of natural Eka Os by detection of fission neutrons

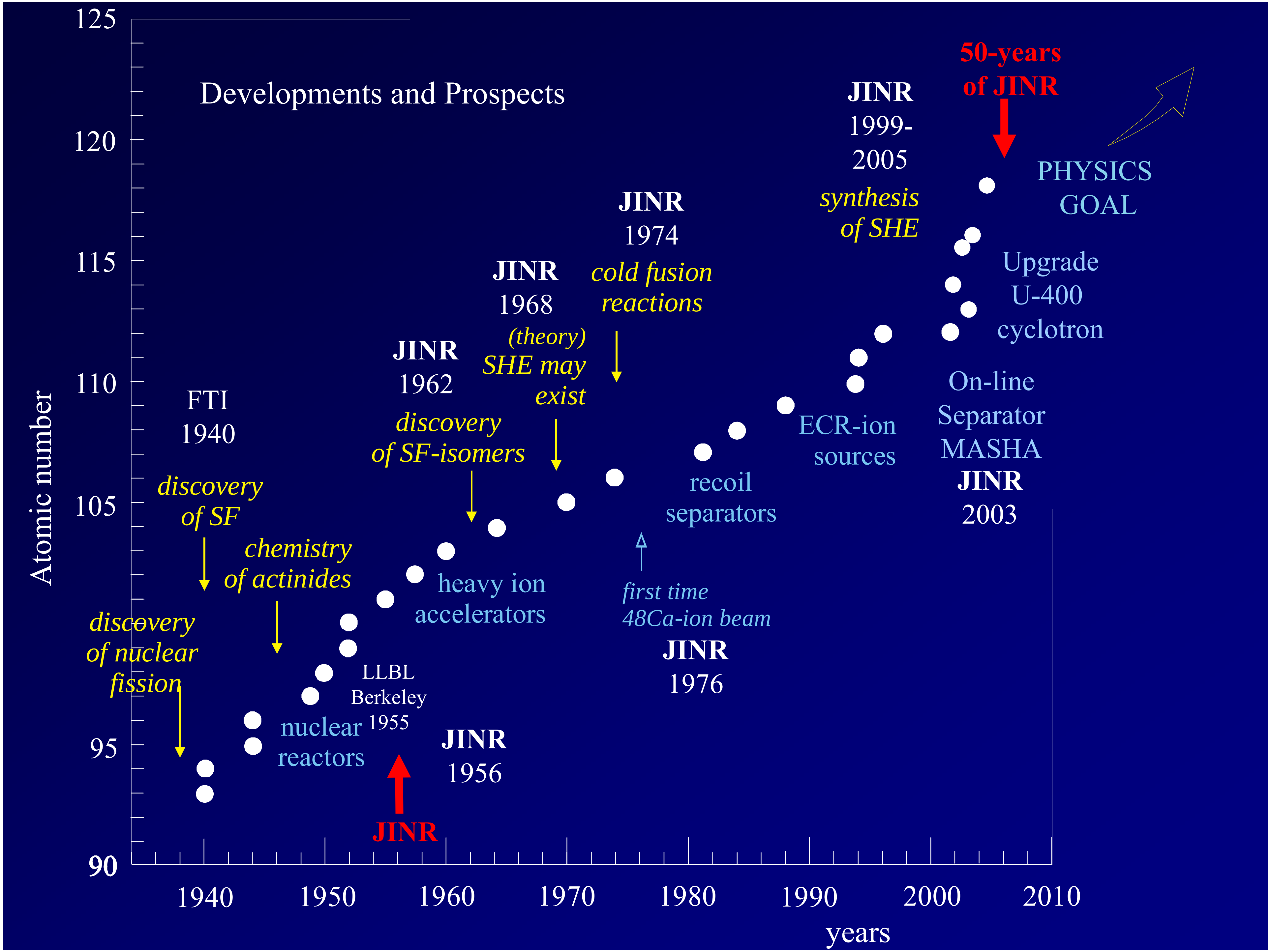


1 SF-event per year ($T_{1/2}=10^9$y) corresponds to the concentration:

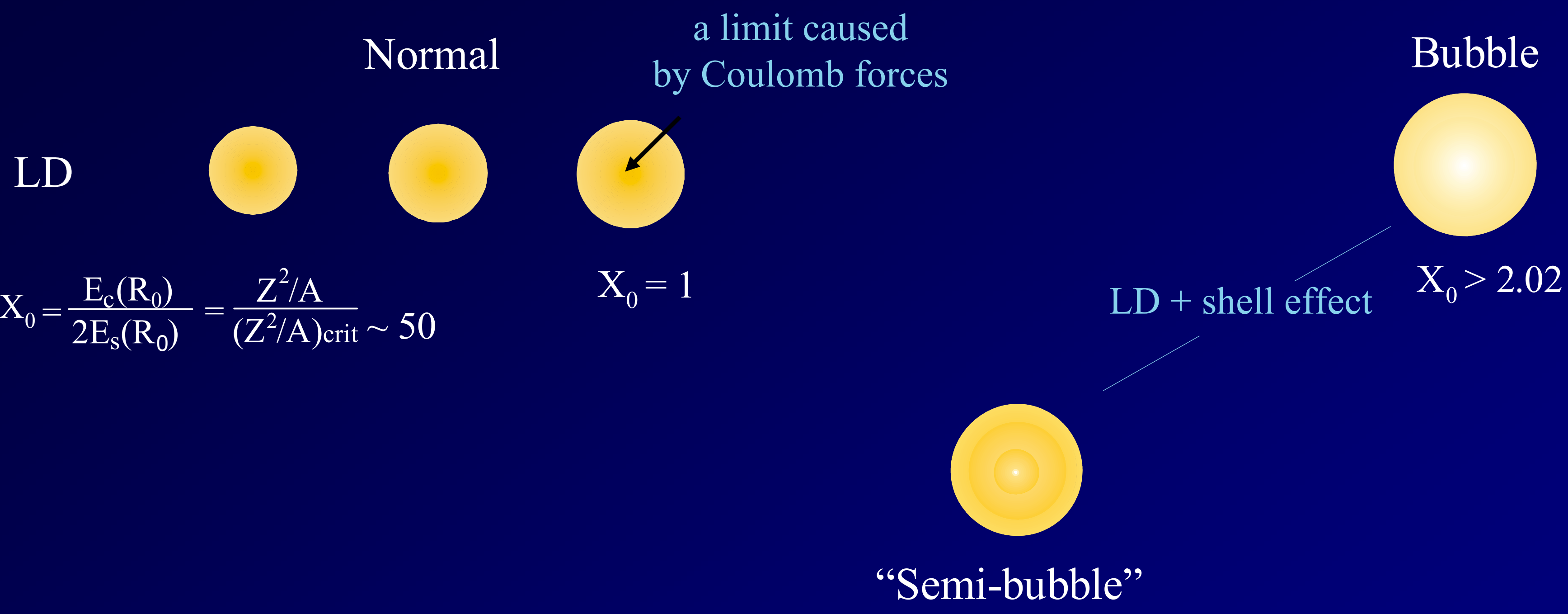
$$EkaOs/Os = 5.10^{-15} g/g$$

(or 10^{-22}g/g in the terrestrial matter, or 10^{-16} of U)

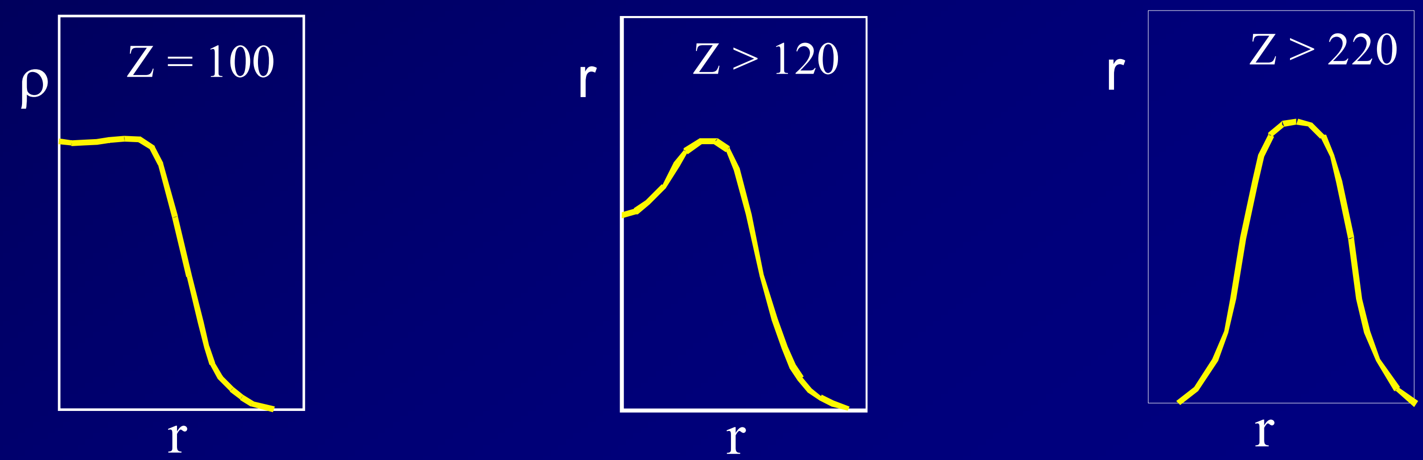


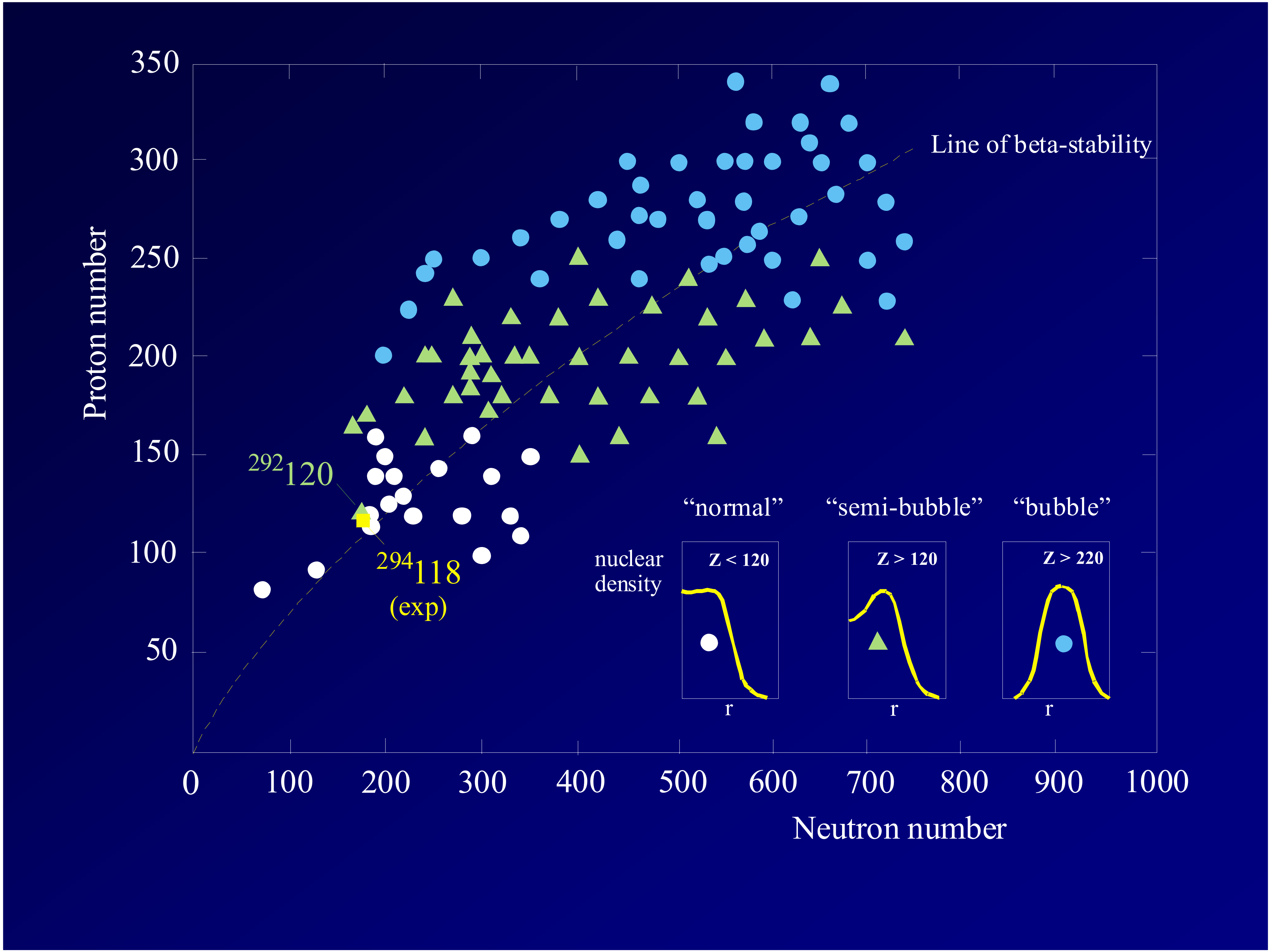

Developments and Prospects
Atomic number
125
120
115
110
105
95
90
1940
1950
1960
1970
1980
1990
2000
2010
years
FTI
1940
discovery
of SF
discovery
of nuclear
fission
chemistry
of actinides
nuclear
reactors
LLBL
Berkeley
1955
JINR
JINR
1956
heavy ion
accelerators
JINR
1962
discovery
of SF-isomers
JINR
1968
(theory)
SHE may
exist
JINR
1974
cold fusion
reactions
first time
48Ca-ion beam
JINR
1976
recoil
separators
ECR-ion
sources
JINR
1999-
2005
synthesis
of SHE
50-years
of JINR
PHYSICS
GOAL
Upgrade
U-400
cyclotron
On-line
Separator
MASHA
JINR
2003

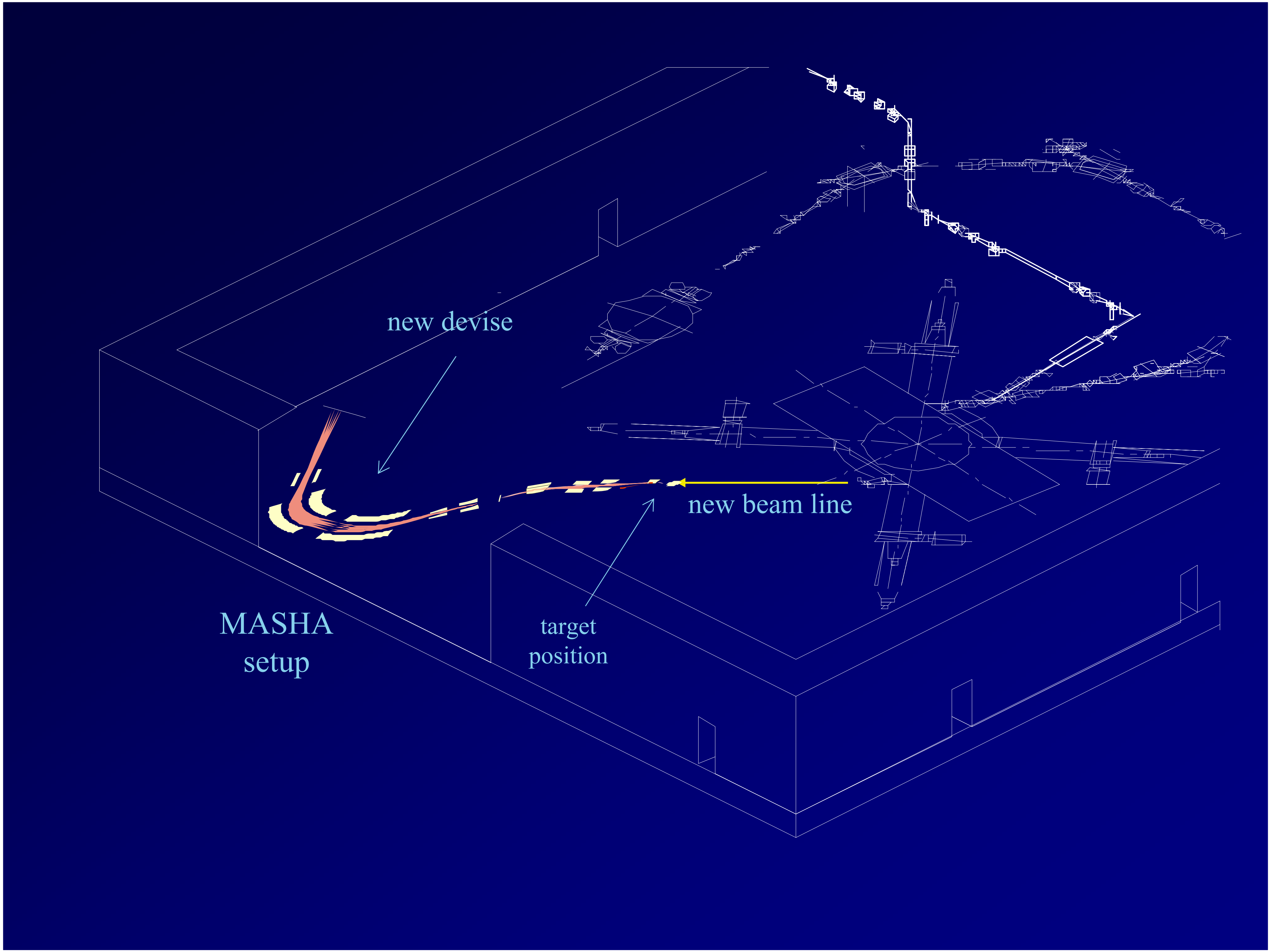
Nuclear Exotica in Superheavy Nuclei



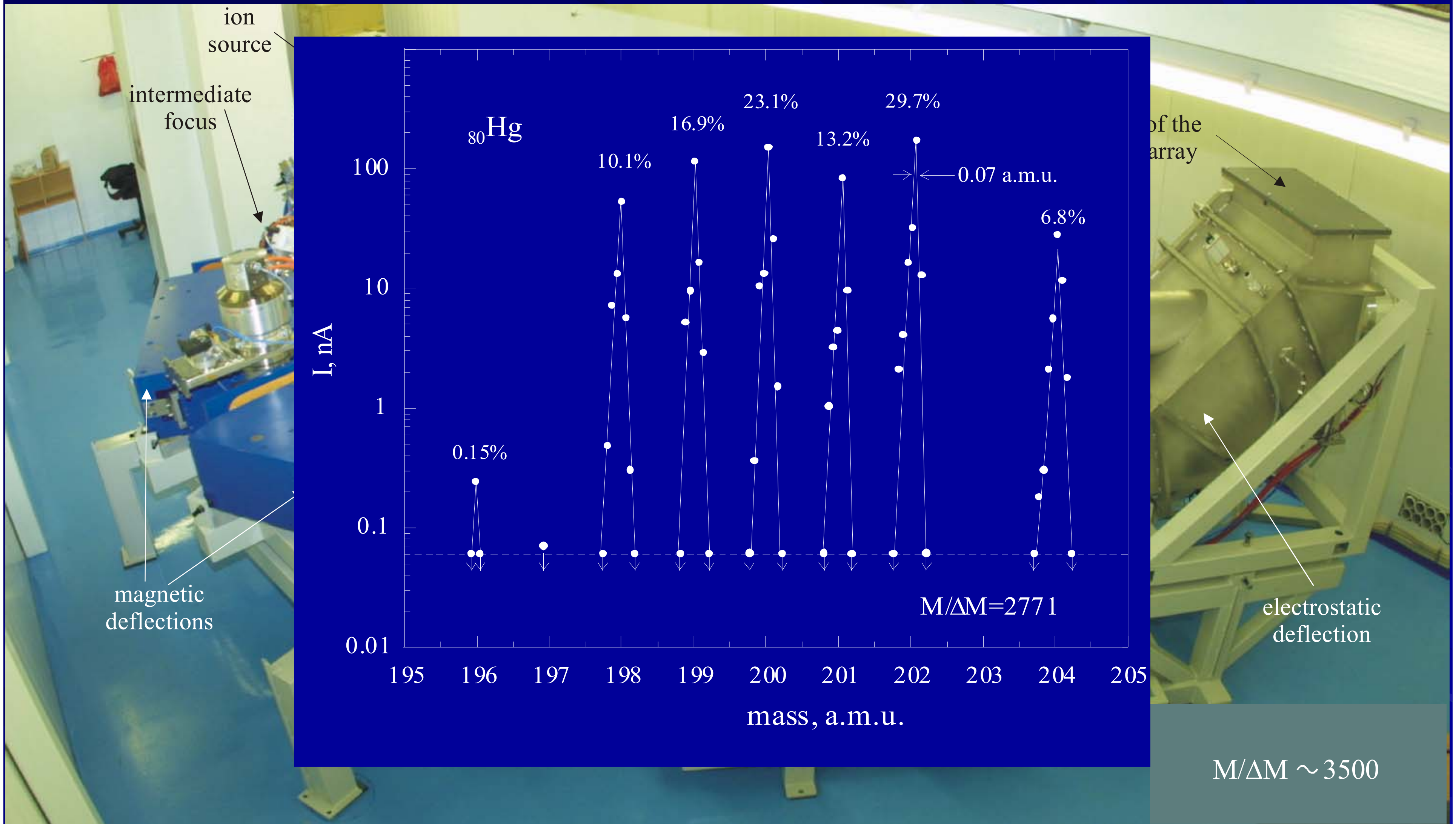
$$X_0 = \frac{E_c(R_0)}{2E_s(R_0)} = \frac{Z^2/A}{(Z^2/A)_{crit} \sim 50}$$

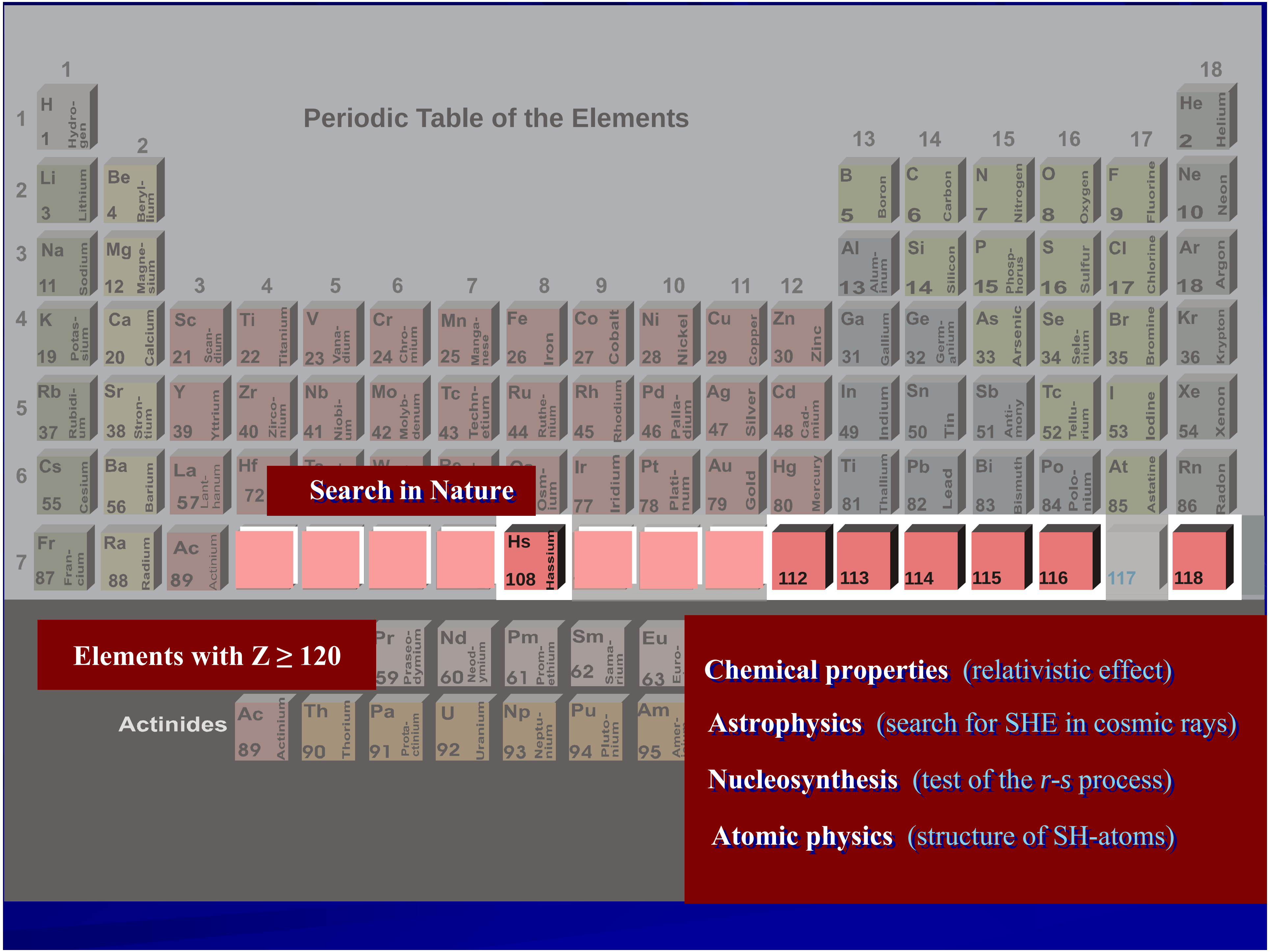



350
300
250
200
150
100
50
Proton number
0
100
200
300
400
500
600
700
800
900
1000
Neutron number
Line of beta-stability
292120
294118
(exp)
"normal"
"semi-bubble"
"bubble"
nuclear
density
Z < 120
Z > 120
Z > 220
r
r
r

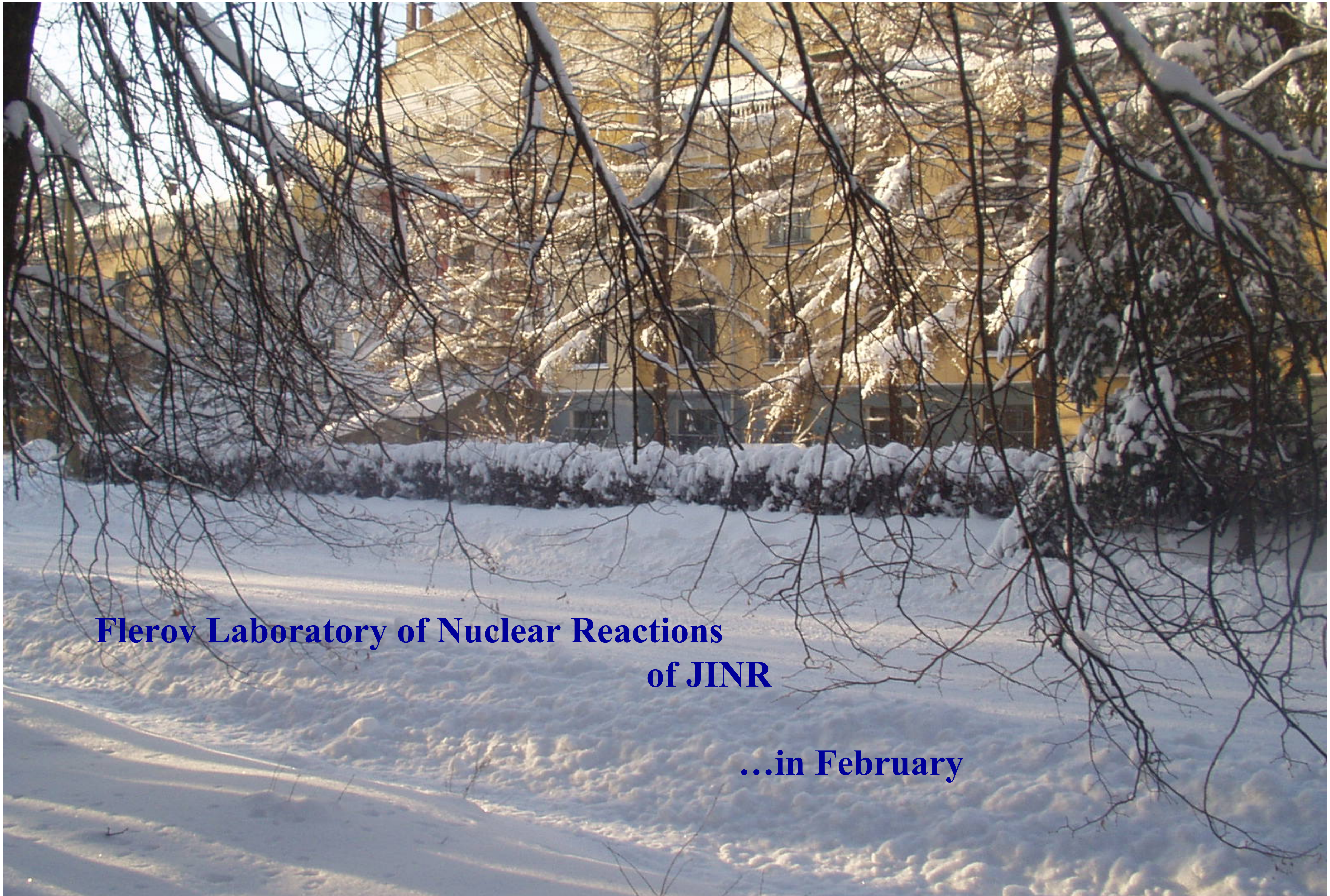

new devise
new beam line
MASHA
setup
target
position

Mass Analyzer of Super Heavy Atoms (MASHA)





Periodic Table of the Elements
Search in Nature
Hs
108
Hassium
112
113
114
115
116
117
118
Elements with Z ≥ 120
Actinides
Chemical properties (relativistic effect)
Astrophysics (search for SHE in cosmic rays)
Nucleosynthesis (test of the r-s process)
Atomic physics (structure of SH-atoms)



Thanks for your attention