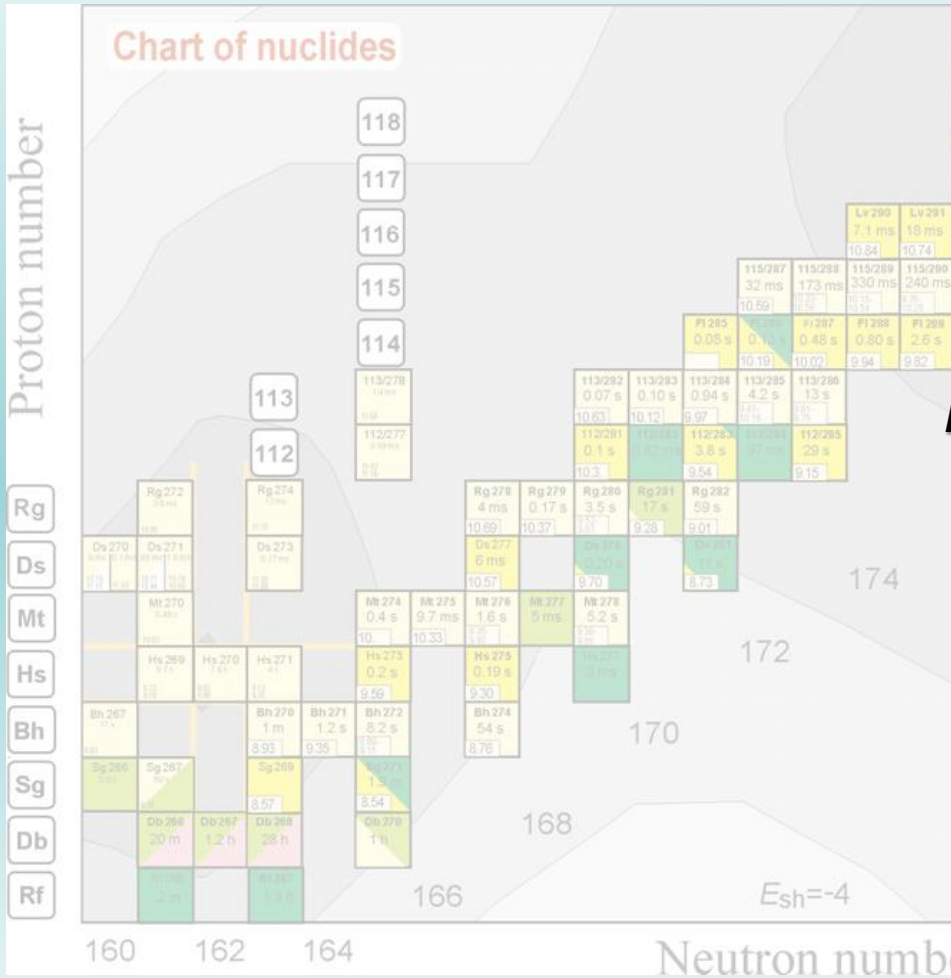


# Synthesis of Superheavy Nuclei with $Z = 112 - 118$



**V.K. Utyonkov**

*for the collaboration of*  
**Joint Institute for Nuclear Research**  
**Oak Ridge National Laboratory**  
**Lawrence Livermore National Laboratory**  
**University of Tennessee**  
**Vanderbilt University**  
**Research Institute of Atomic Reactors**



**BRAZIL-JINR  
FORUM**

Frontiers in Nuclear,  
Elementary Particle, and  
Condensed Matter Physics

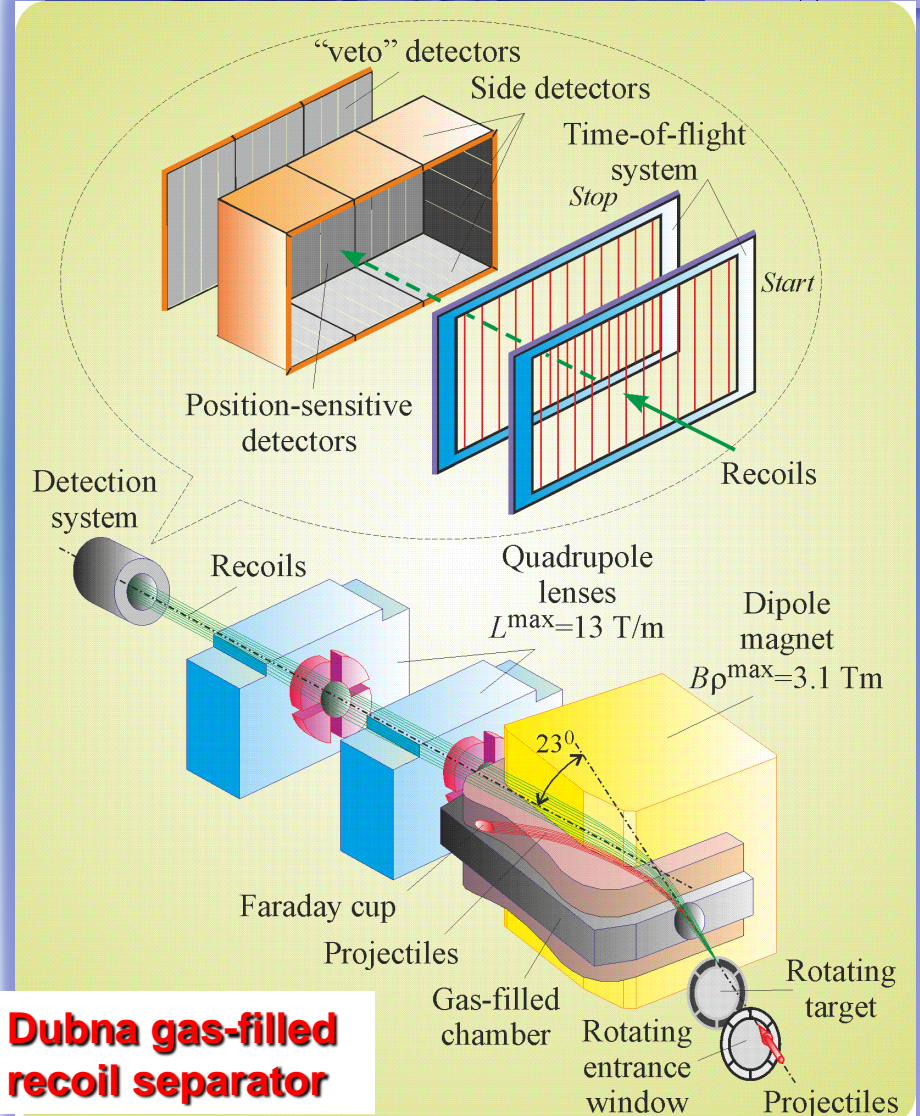
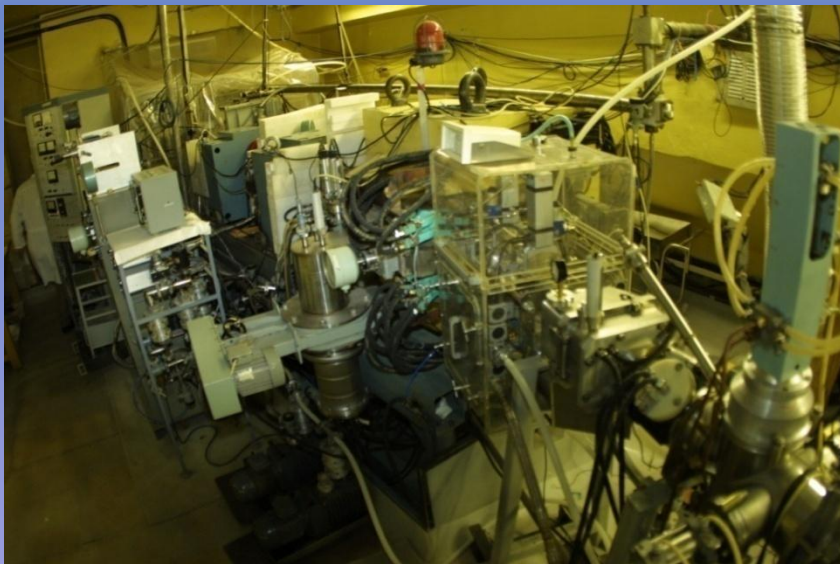
June 15-19, 2015  
Dubna, Russia

# Increase of sensitivity of experiment

## Target materials

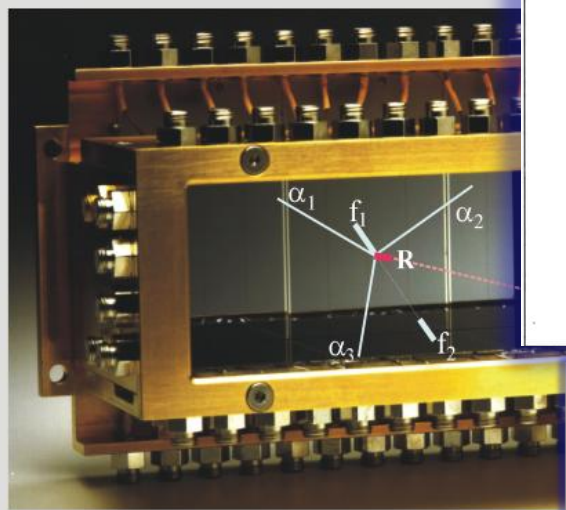
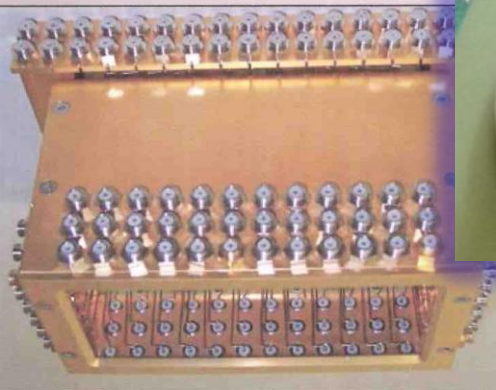


**$^{226}\text{Ra}$ ,  $^{233,238}\text{U}$ ,  $^{237}\text{Np}$ ,  $^{242,244}\text{Pu}$ ,  
 $^{243}\text{Am}$ ,  $^{245,248}\text{Cm}$ ,  $^{249}\text{Bk}$ ,  $^{249}\text{Cf}$**   
**10 - 15 мг**



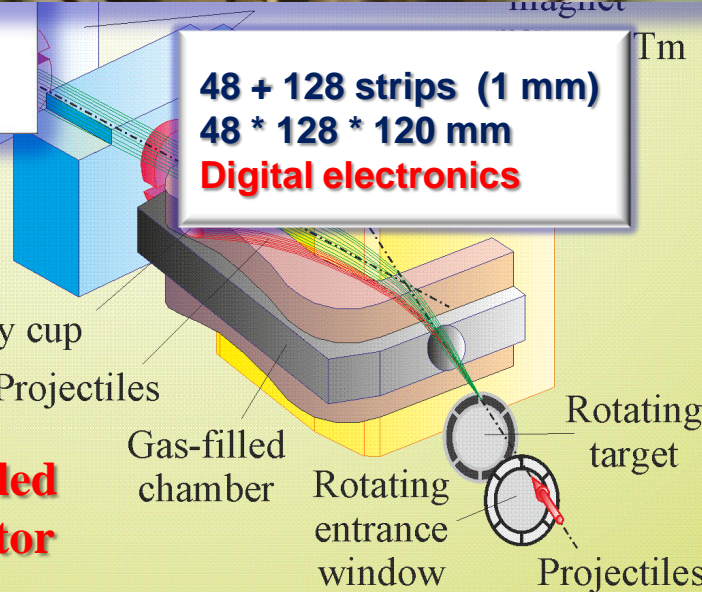
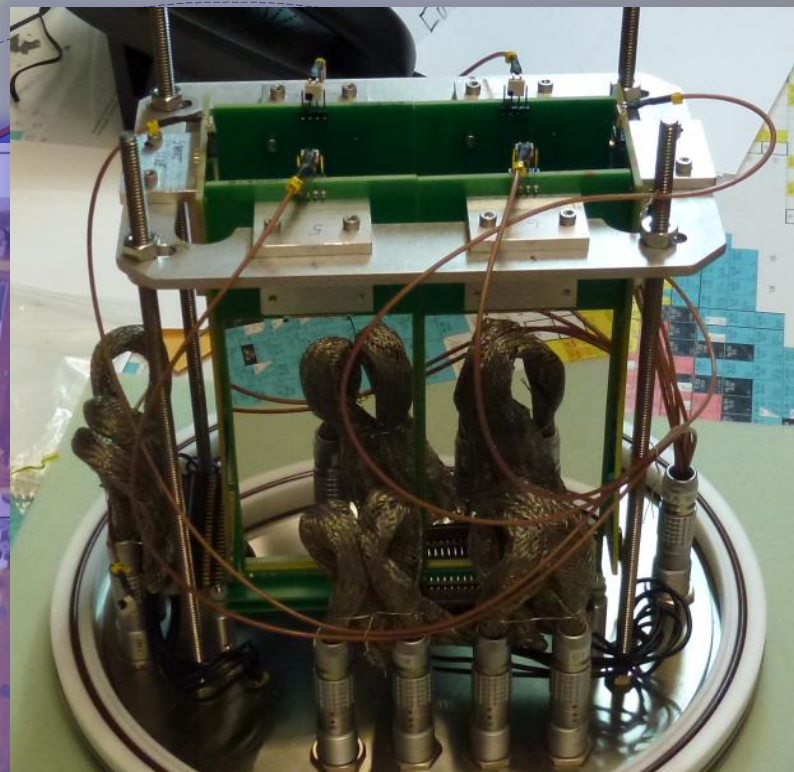
**Dubna gas-filled recoil separator**

# Separator



**32 position-sensitive strips**  
**60 \* 120 \* 60 mm**

**12 position-sensitive strips**  
**40 \* 120 \* 40 mm**

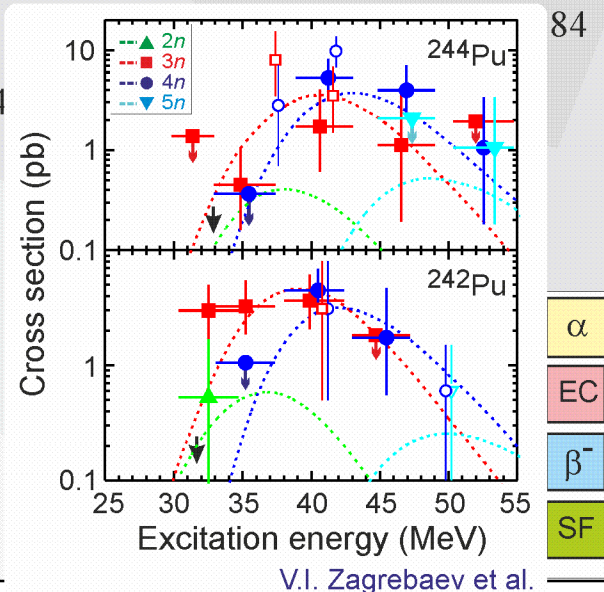
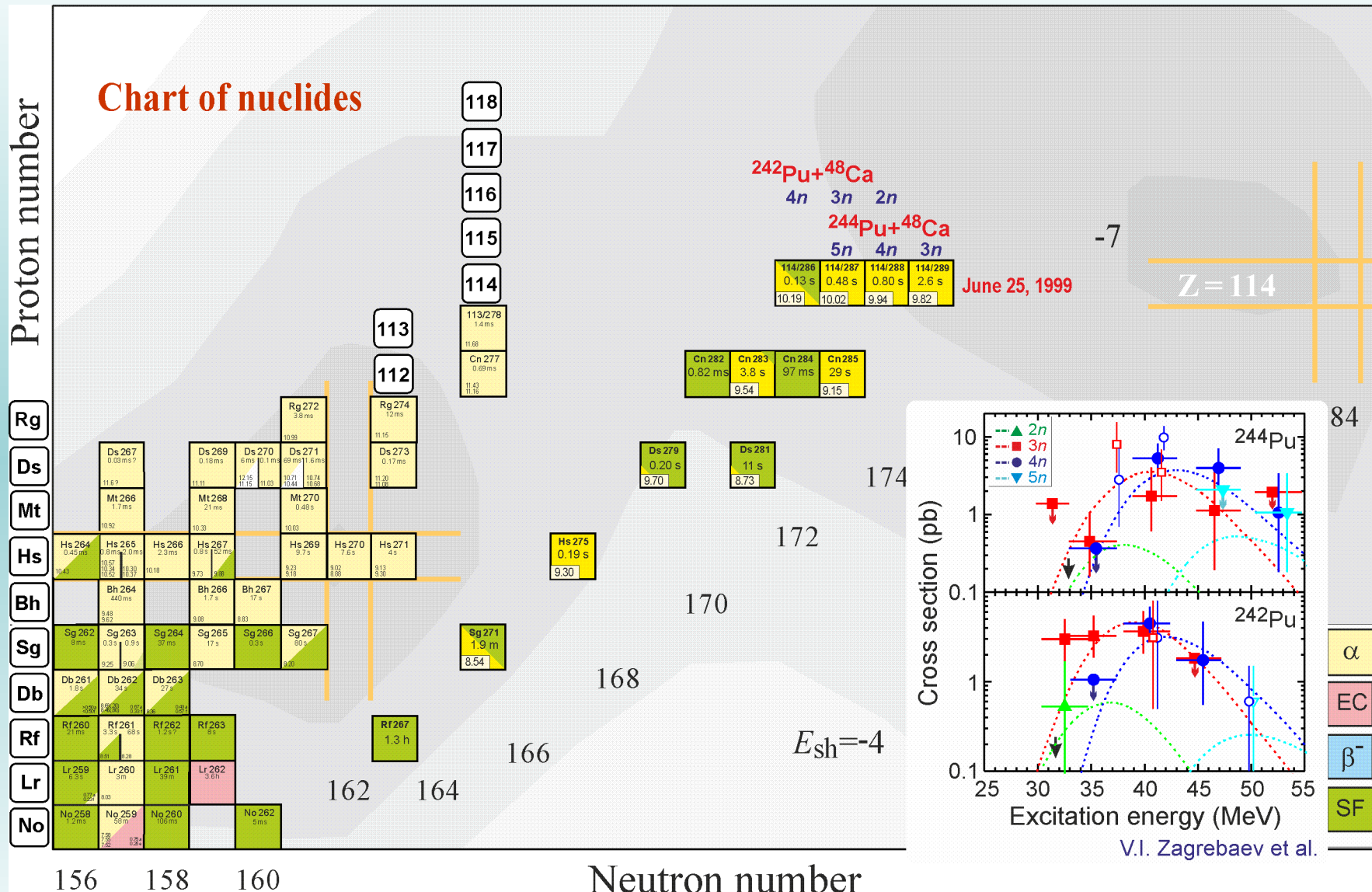


**48 + 128 strips (1 mm)**  
**48 \* 128 \* 120 mm**  
**Digital electronics**

**Dubna Gas-filled  
Recoil Separator**

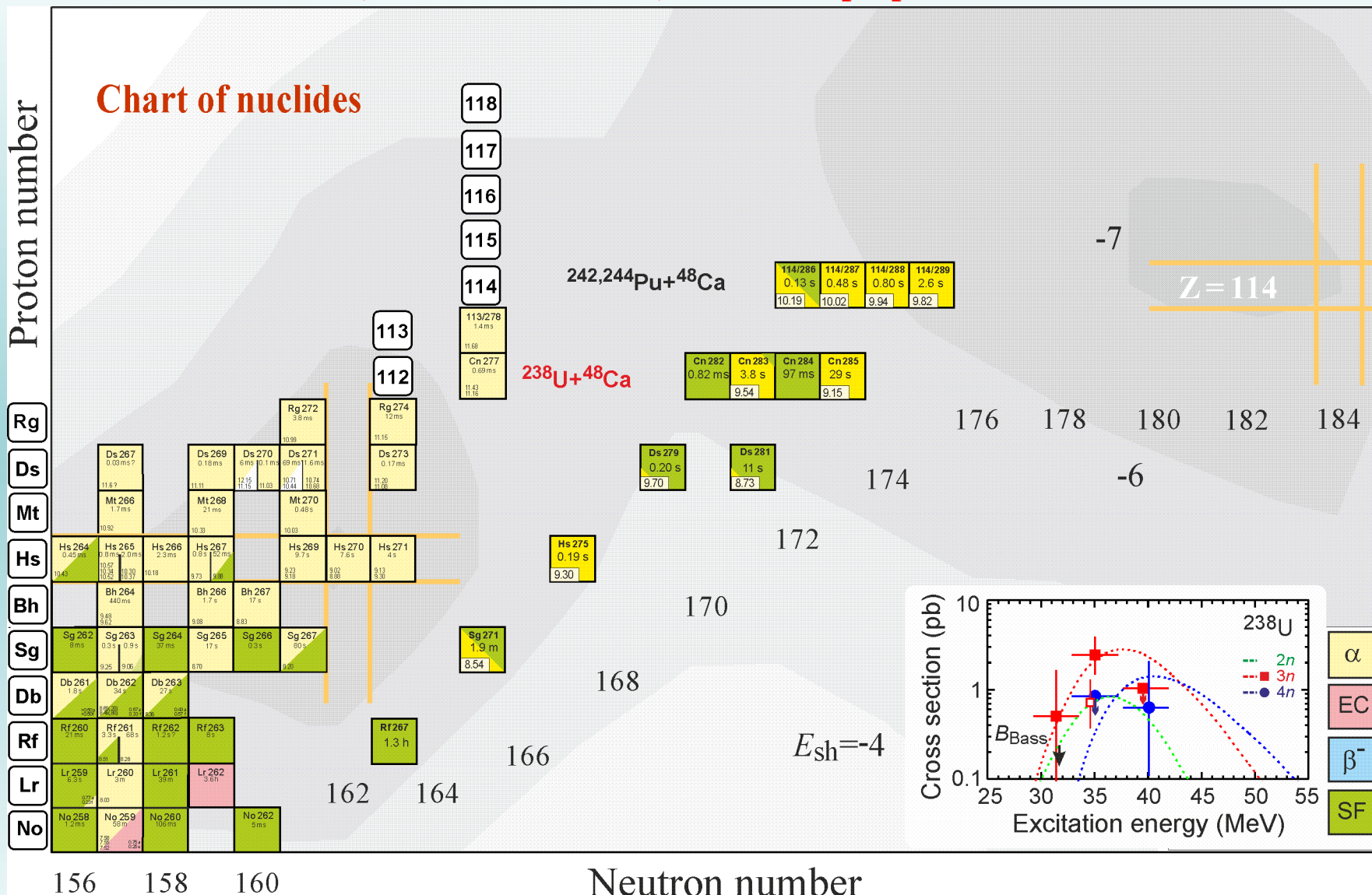
# Synthesis of superheavy nuclei

(cross bombardments, excitation functions, radioactive properties)



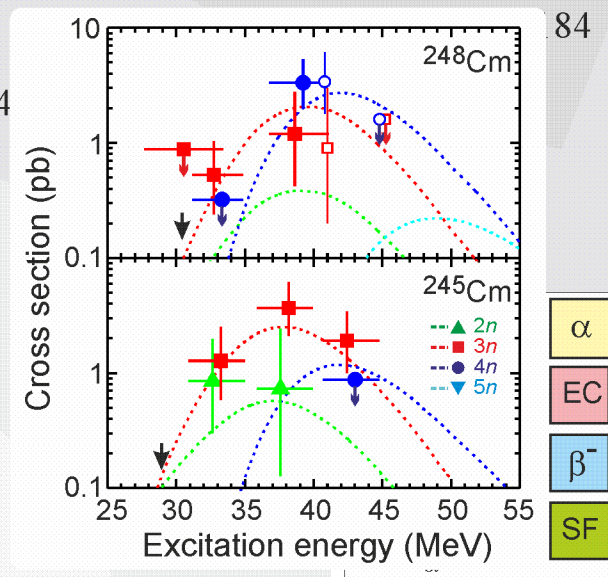
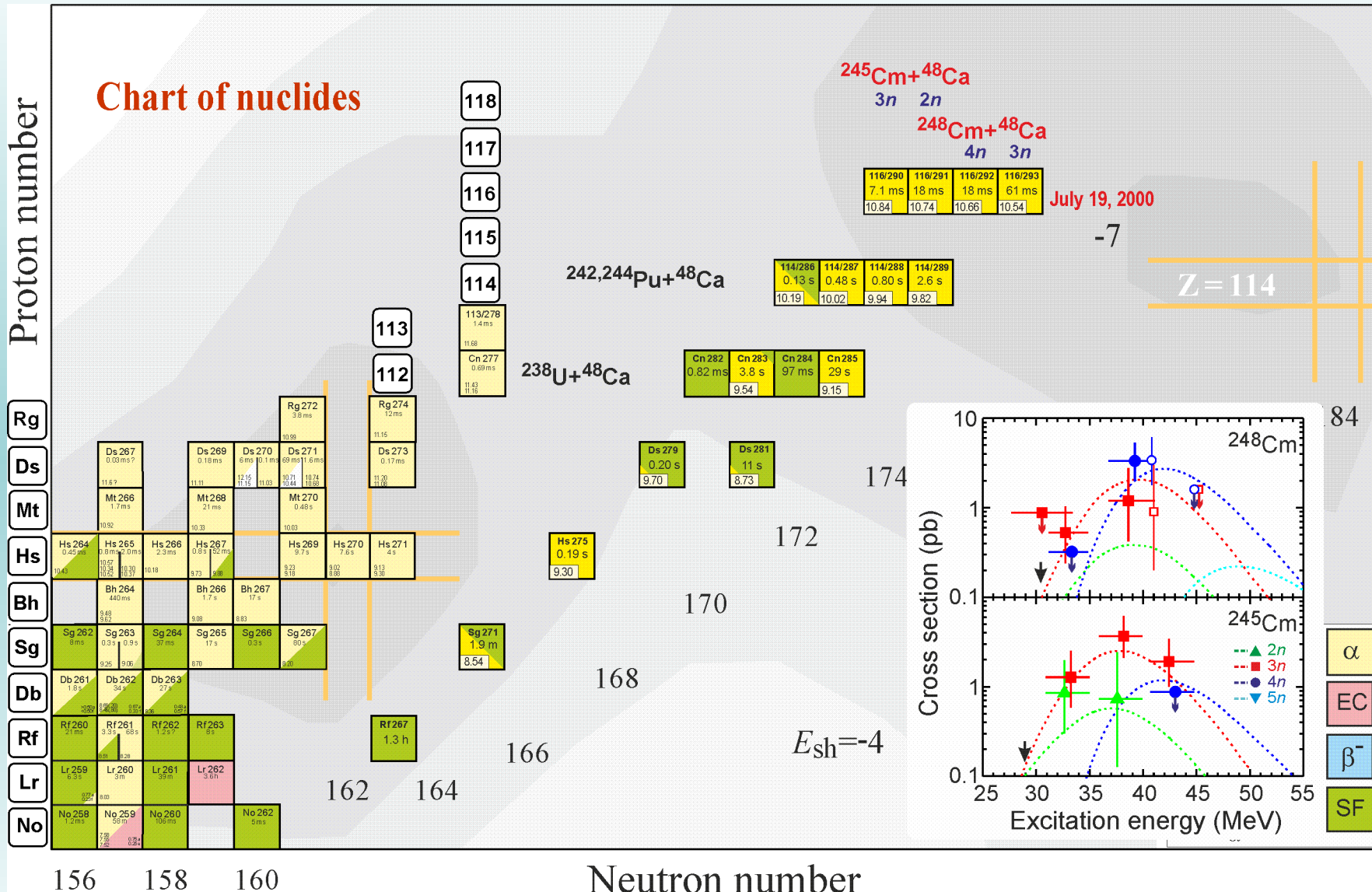
# Synthesis of superheavy nuclei

(cross bombardments, excitation functions, radioactive properties)



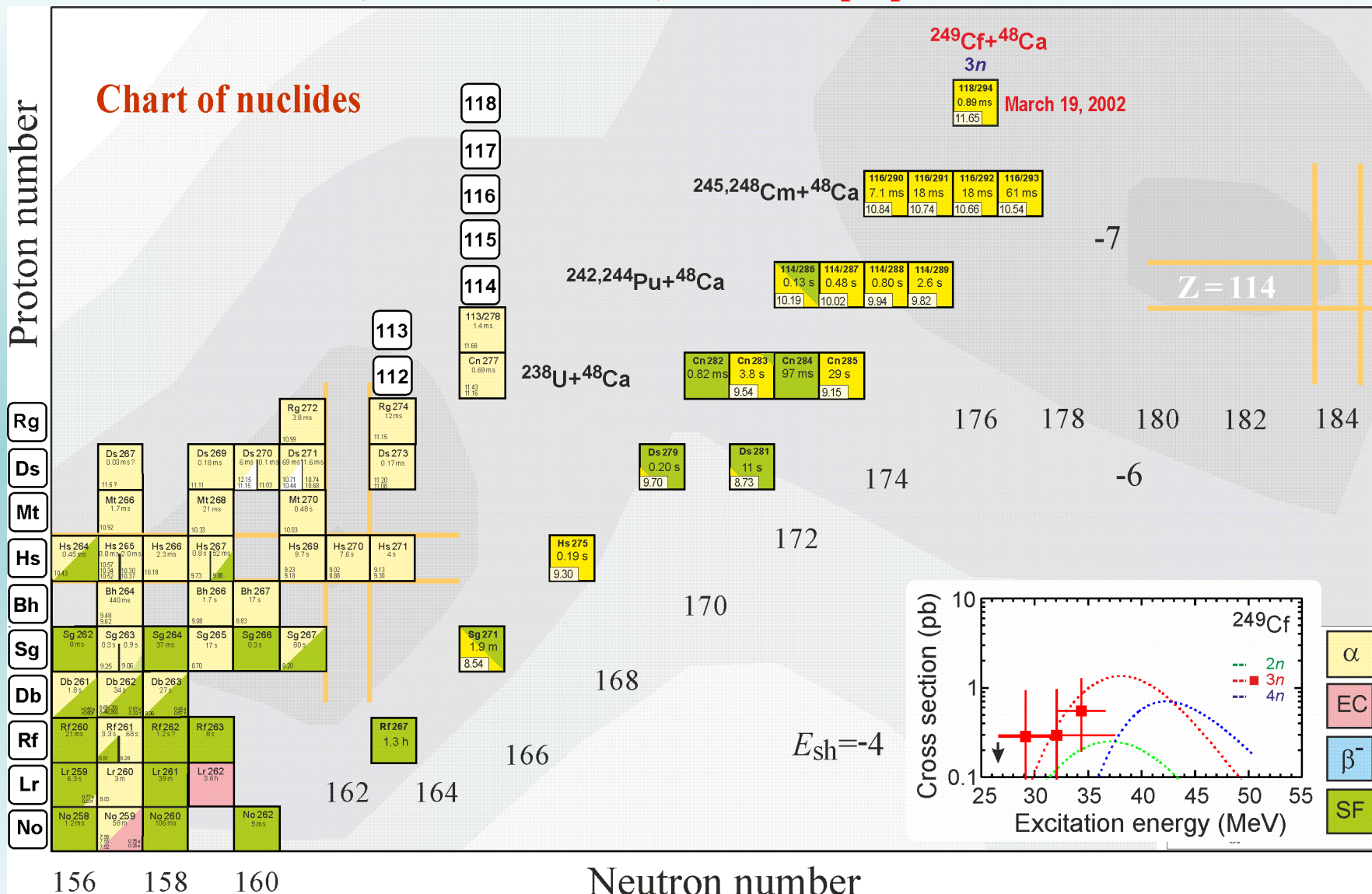
# Synthesis of superheavy nuclei

(cross bombardments, excitation functions, radioactive properties)



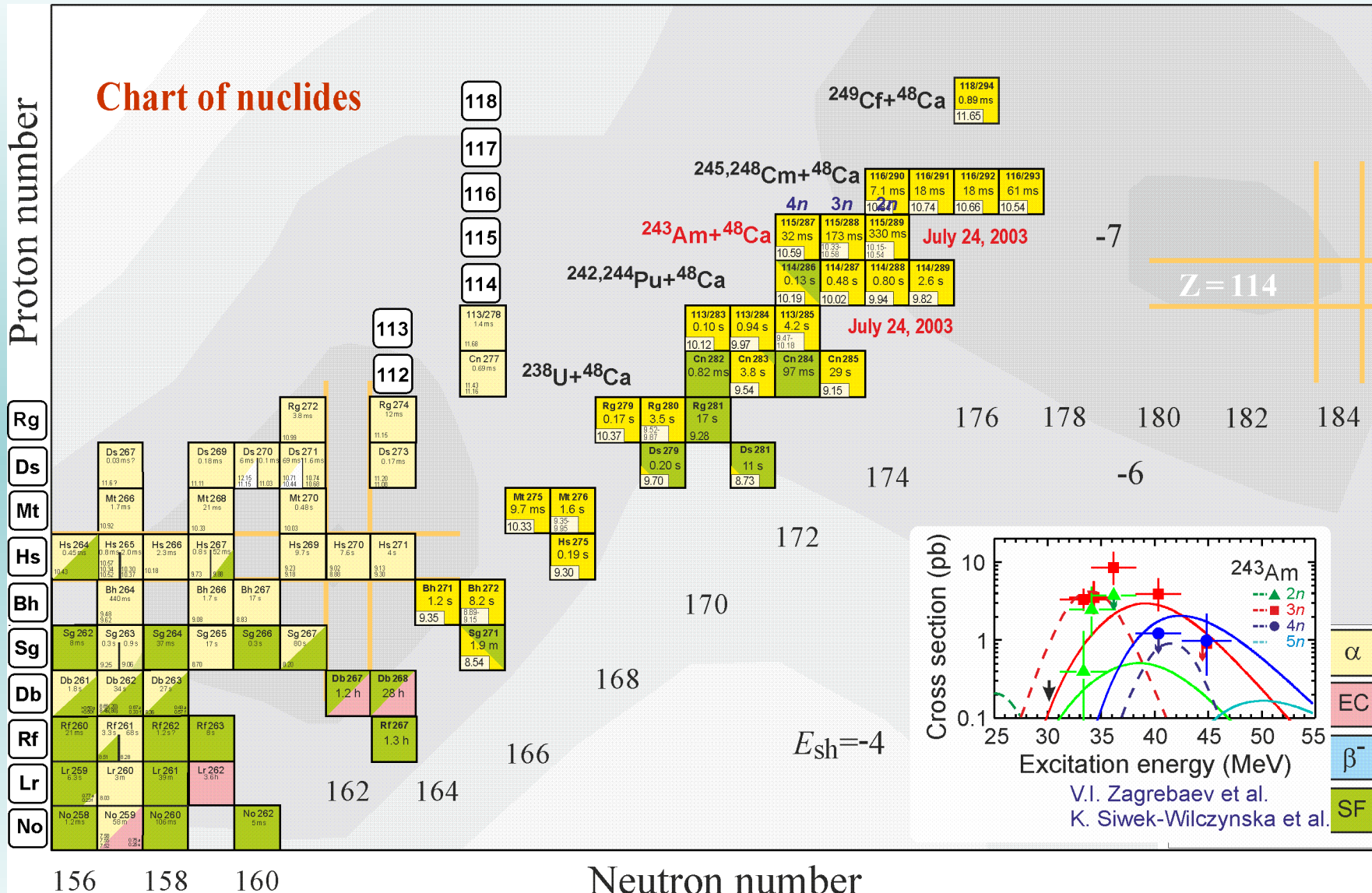
# Synthesis of superheavy nuclei

(cross bombardments, excitation functions, radioactive properties)



# Synthesis of superheavy nuclei

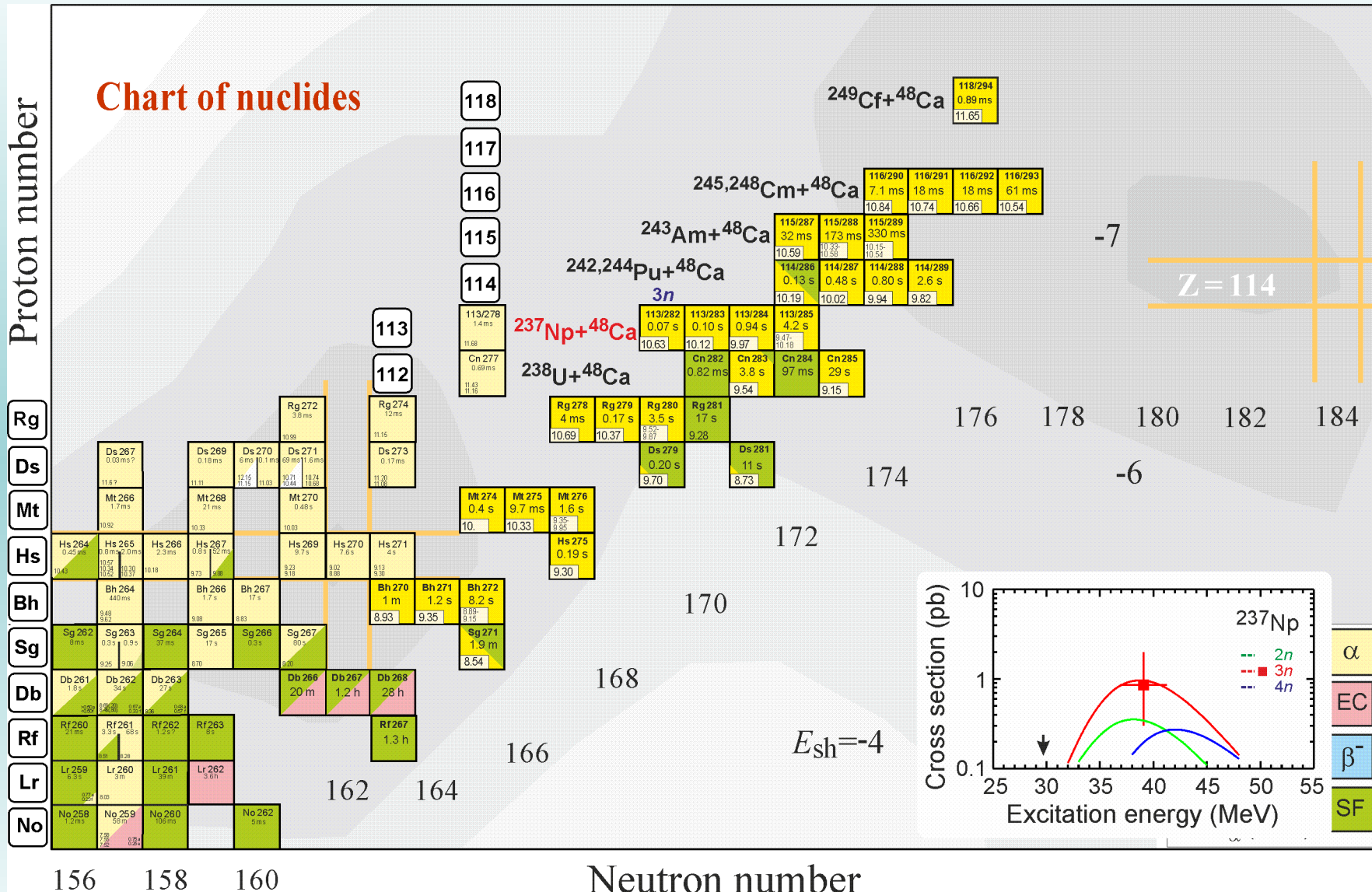
(cross bombardments, excitation functions, radioactive properties, chemistry of  $^{268}\text{Db}$ )





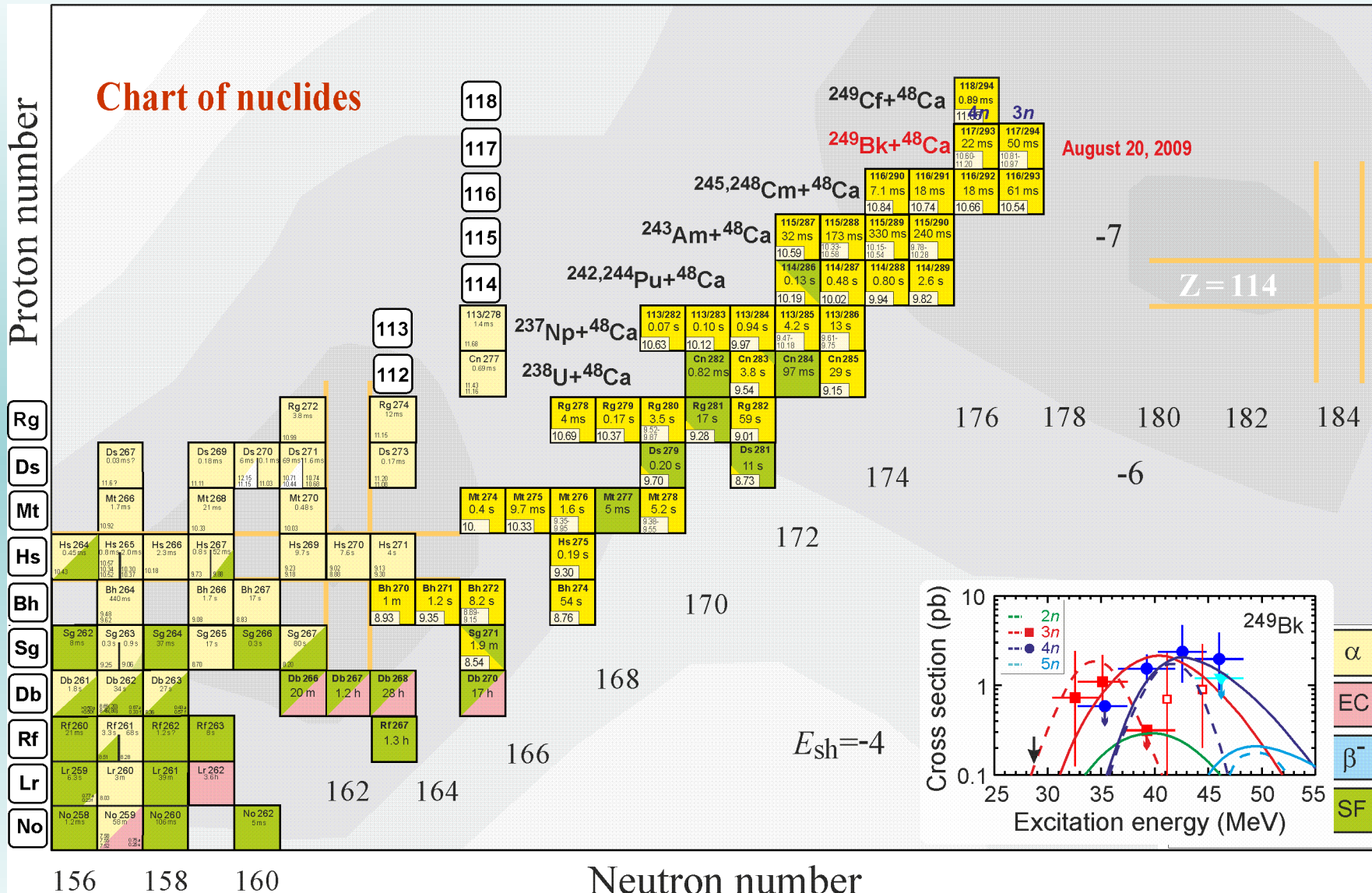
# Synthesis of superheavy nuclei

(cross bombardments, excitation functions, radioactive properties)



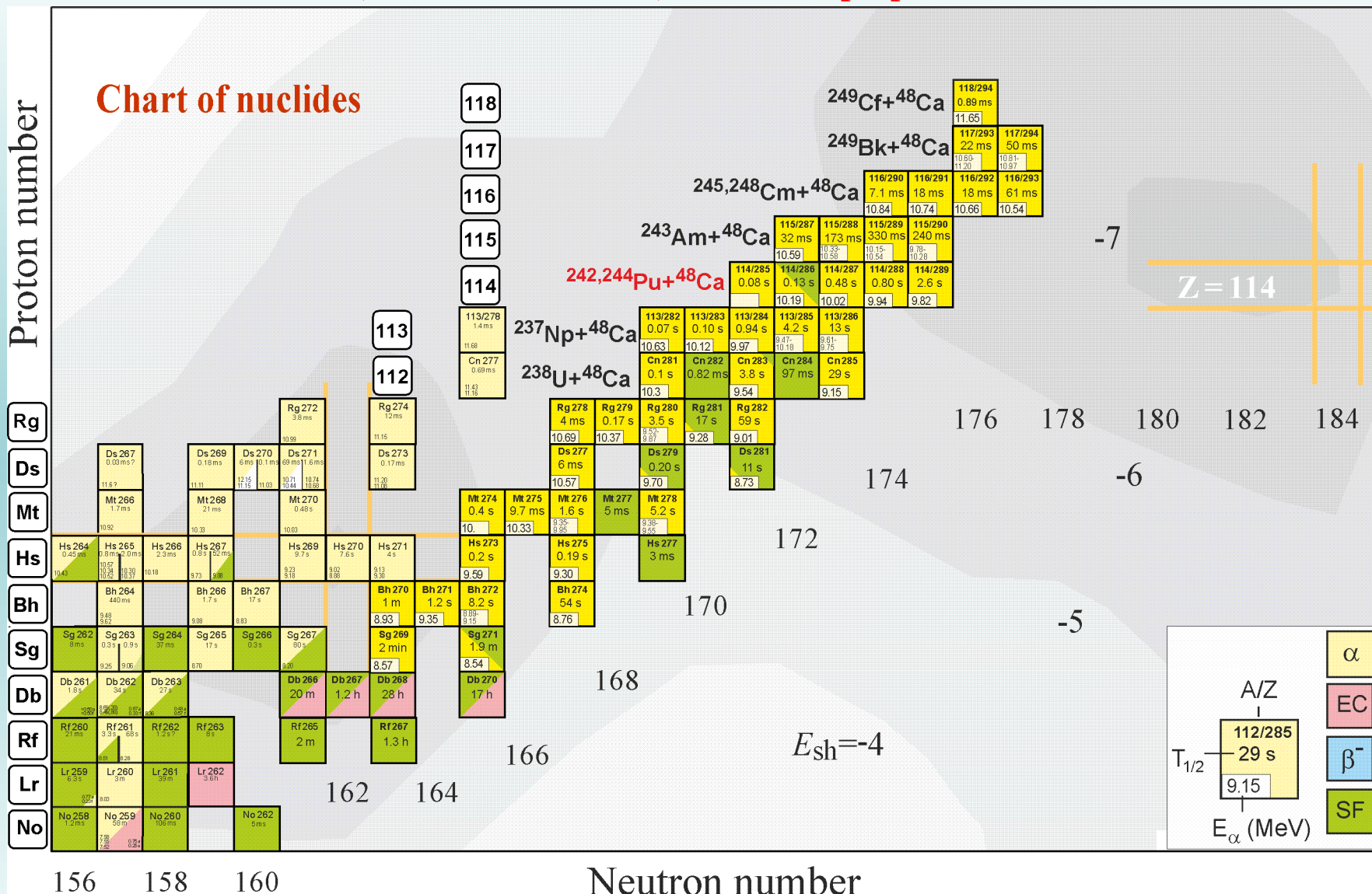
# Synthesis of superheavy nuclei

(cross bombardments, excitation functions, radioactive properties)

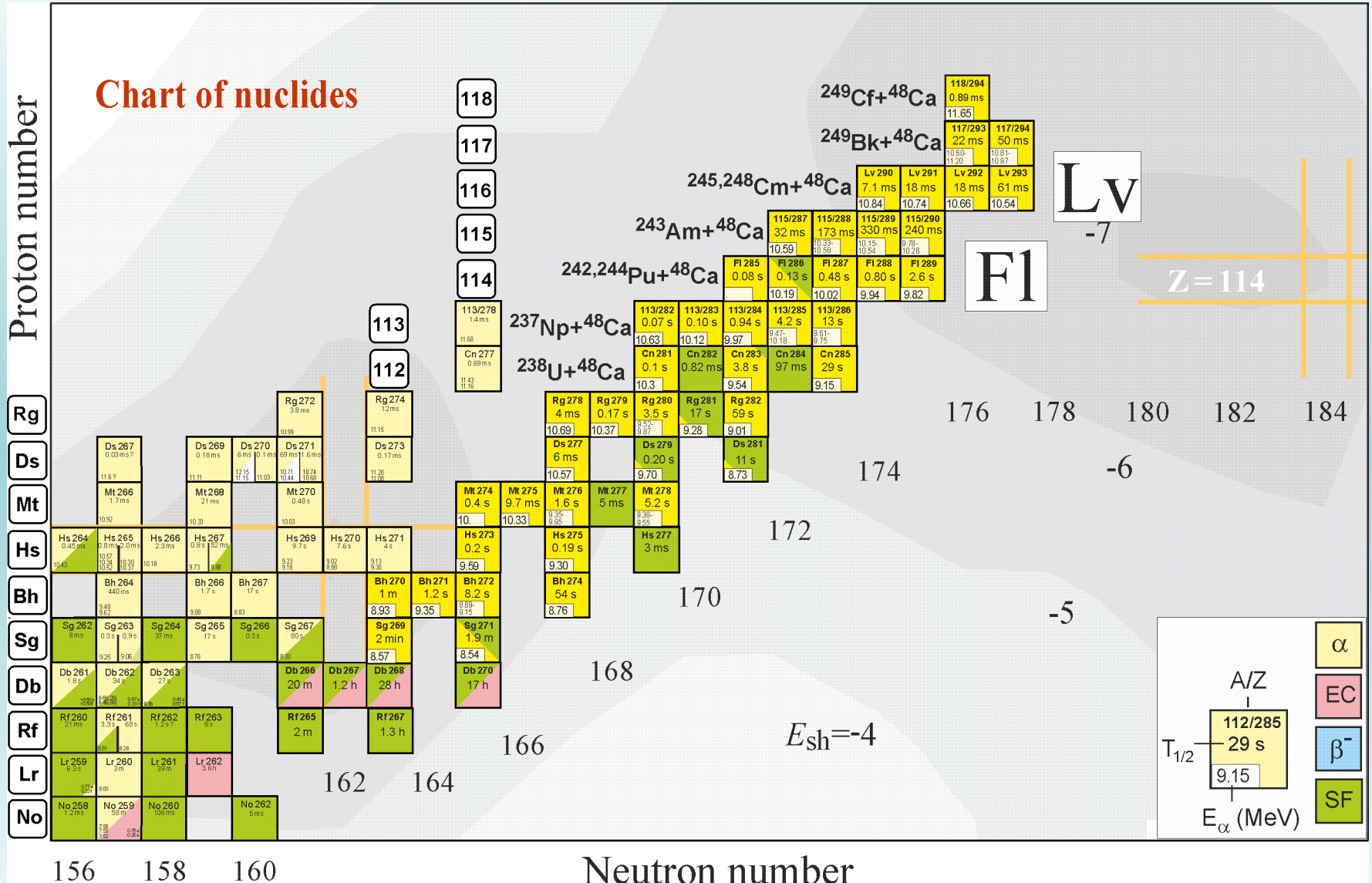


# Synthesis of superheavy nuclei

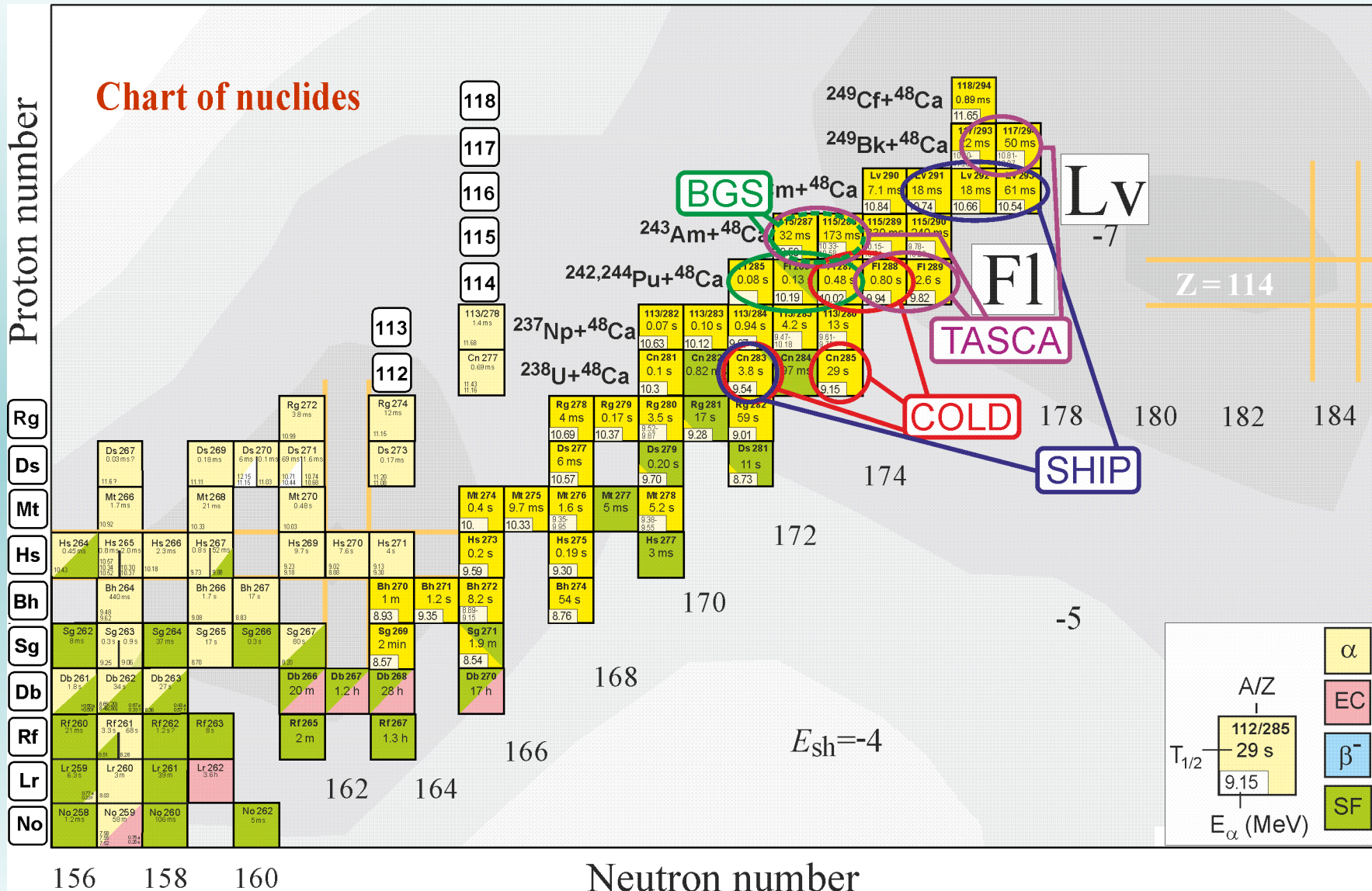
(cross bombardments, excitation functions, radioactive properties)



# The names flerovium and livermorium for elements 114 and 116

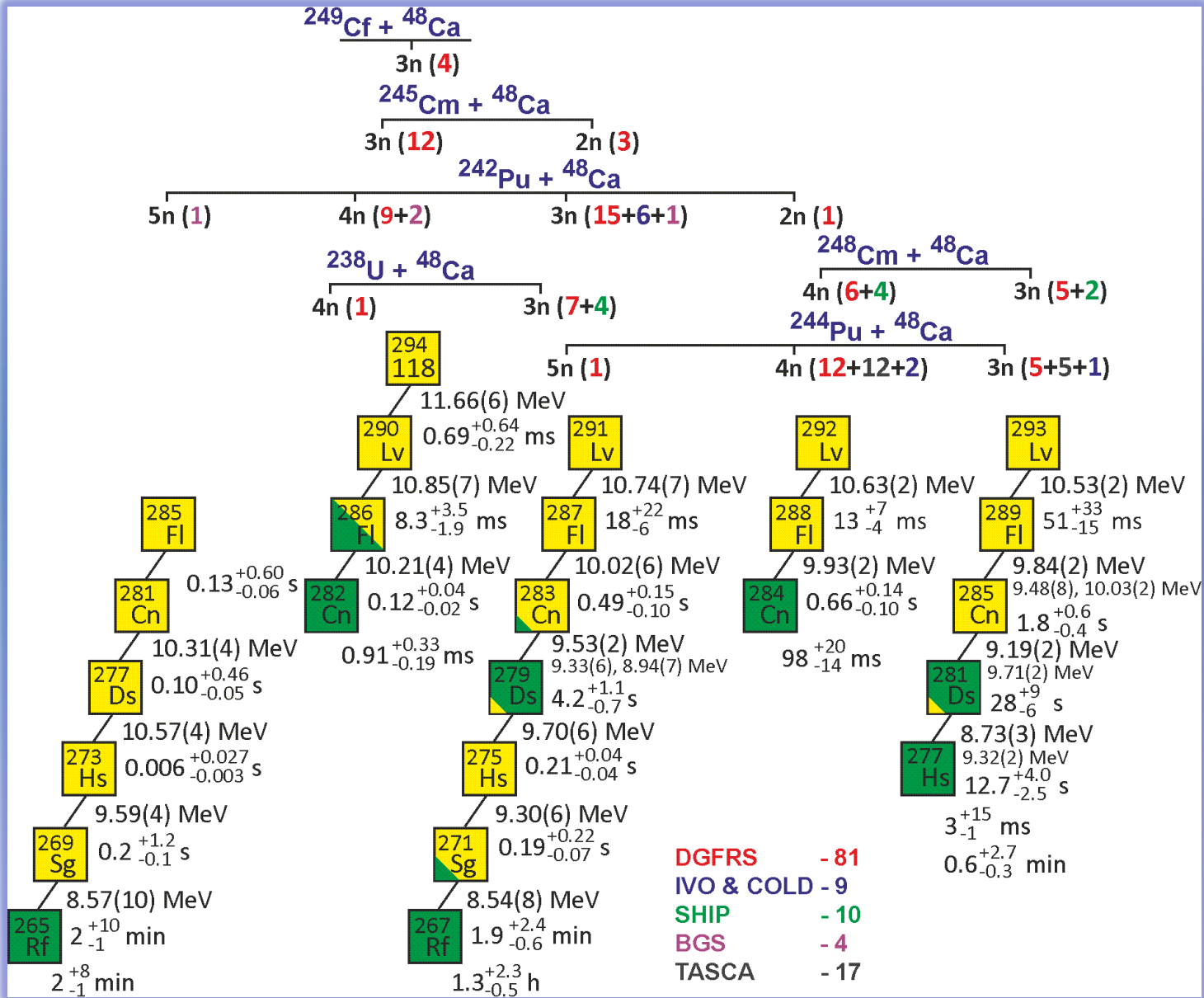


# Confirmation of the DGFRS results



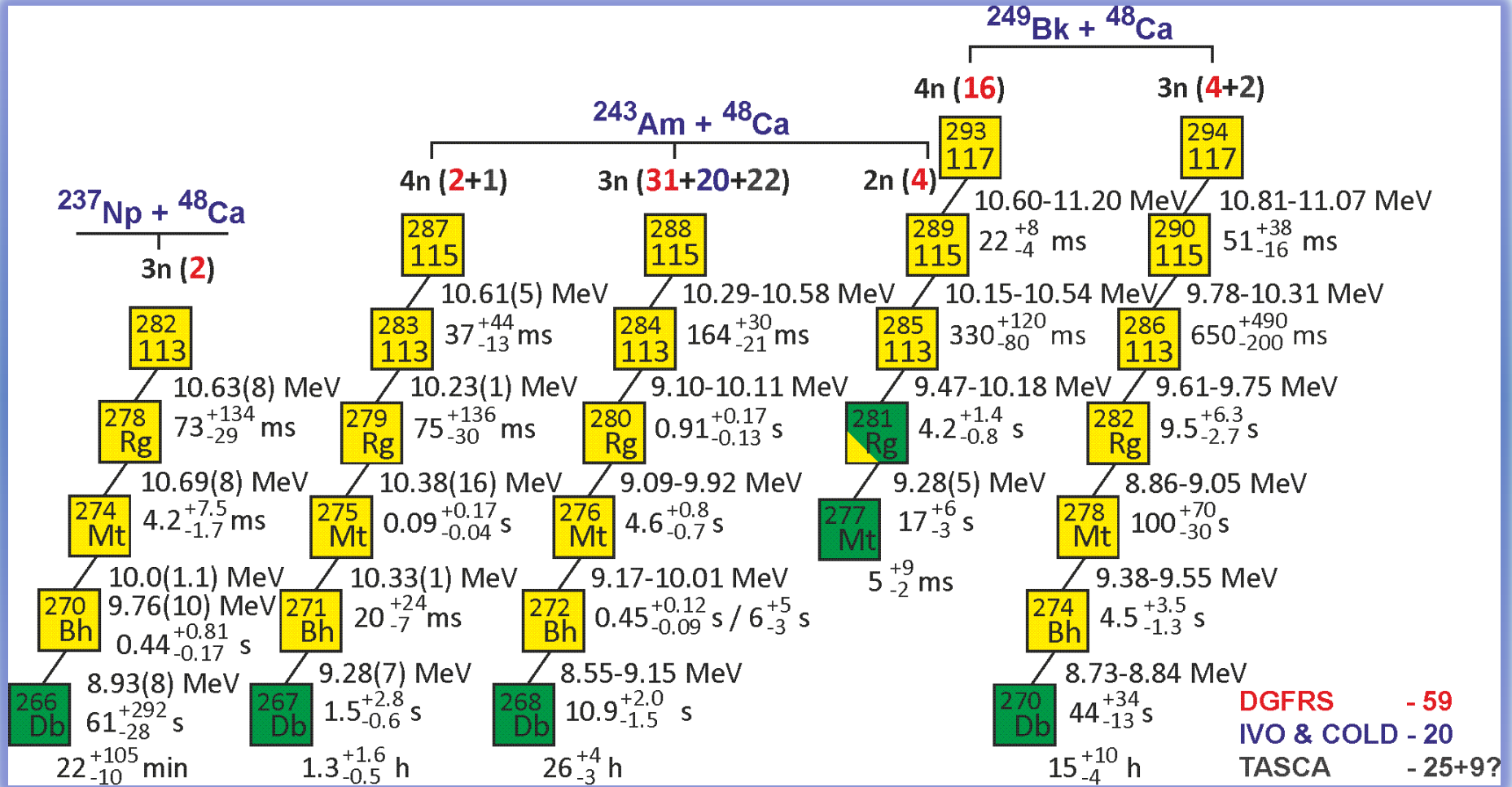
# Decay properties of even-Z nuclei

(6 reactions, 3 elements, 25 isotopes, 121 decay chains)

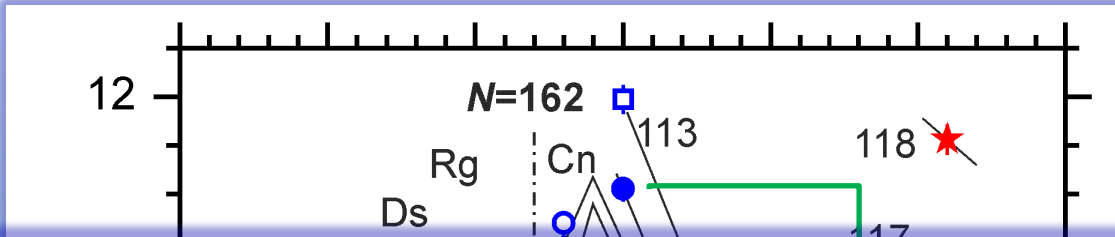


# Decay properties of odd-Z nuclei

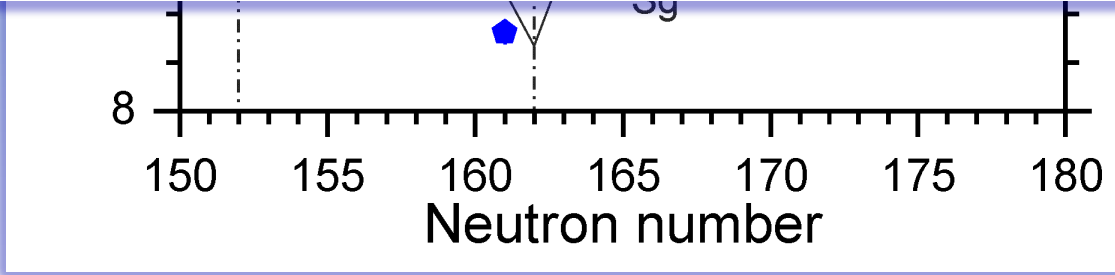
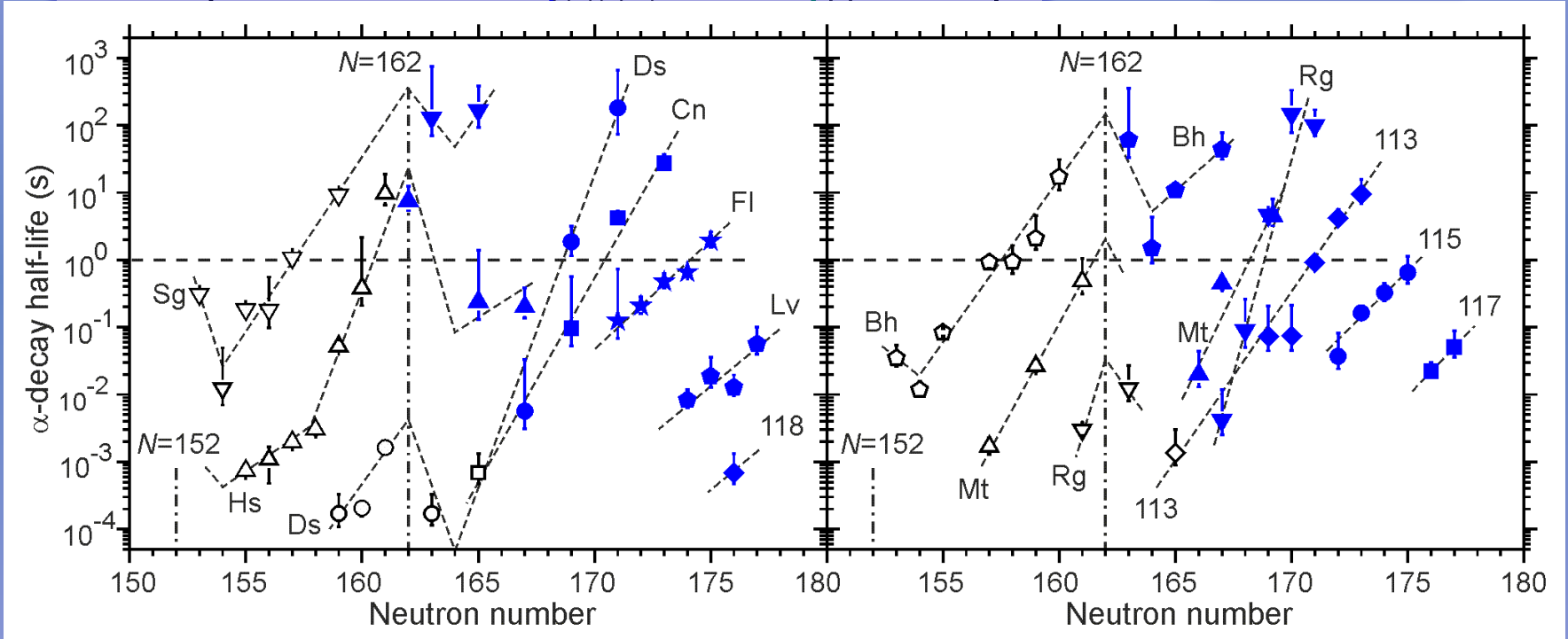
(3 reactions, 3 elements, 29 isotopes, 104+9? decay chains)



# Alpha-decay energy of nuclei (increase of stability for higher $N$ )

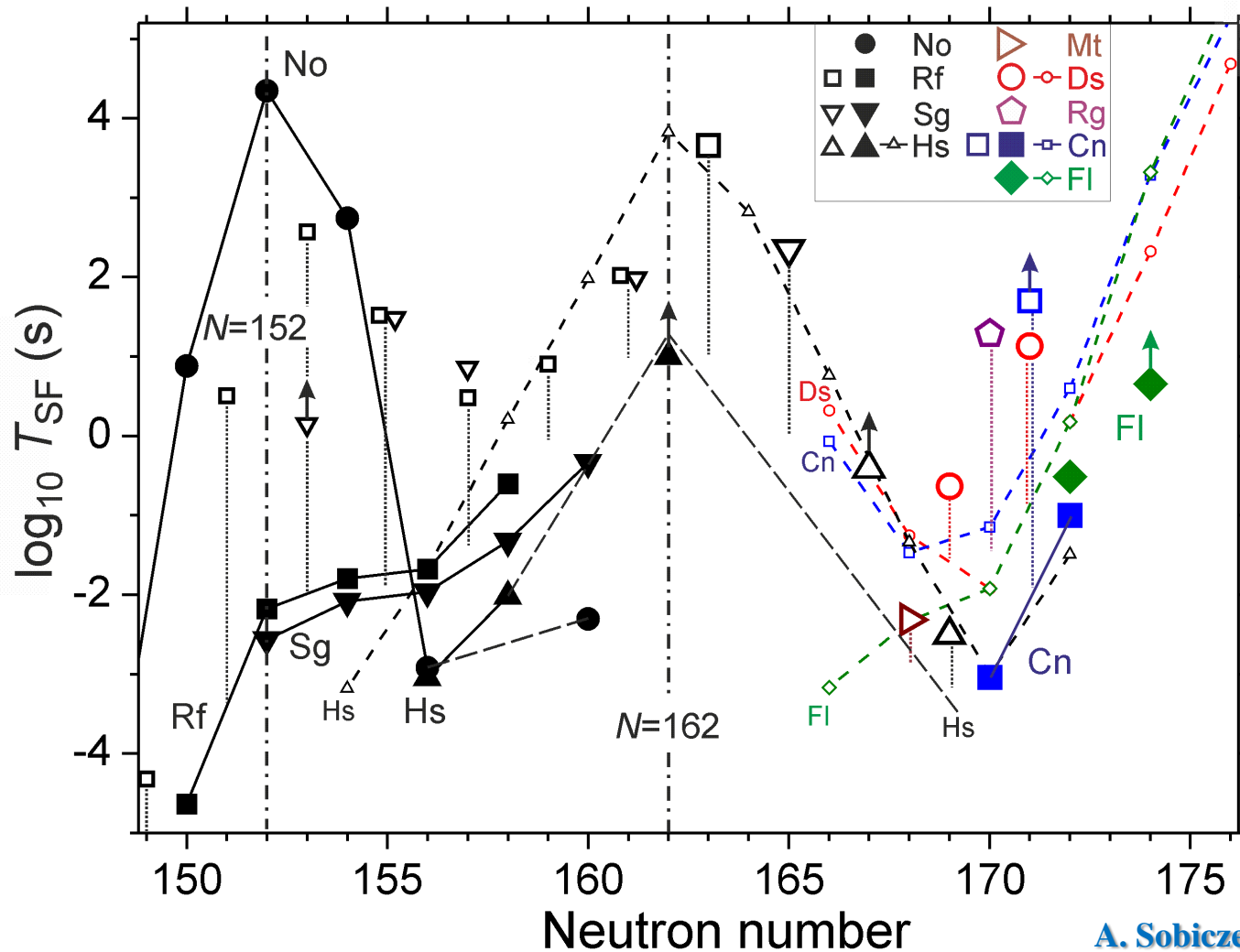


**$Z=111, 113$**   
 **$\Delta N=6$**   
 **$\Delta Lg(T_{\alpha}) \sim 4$**

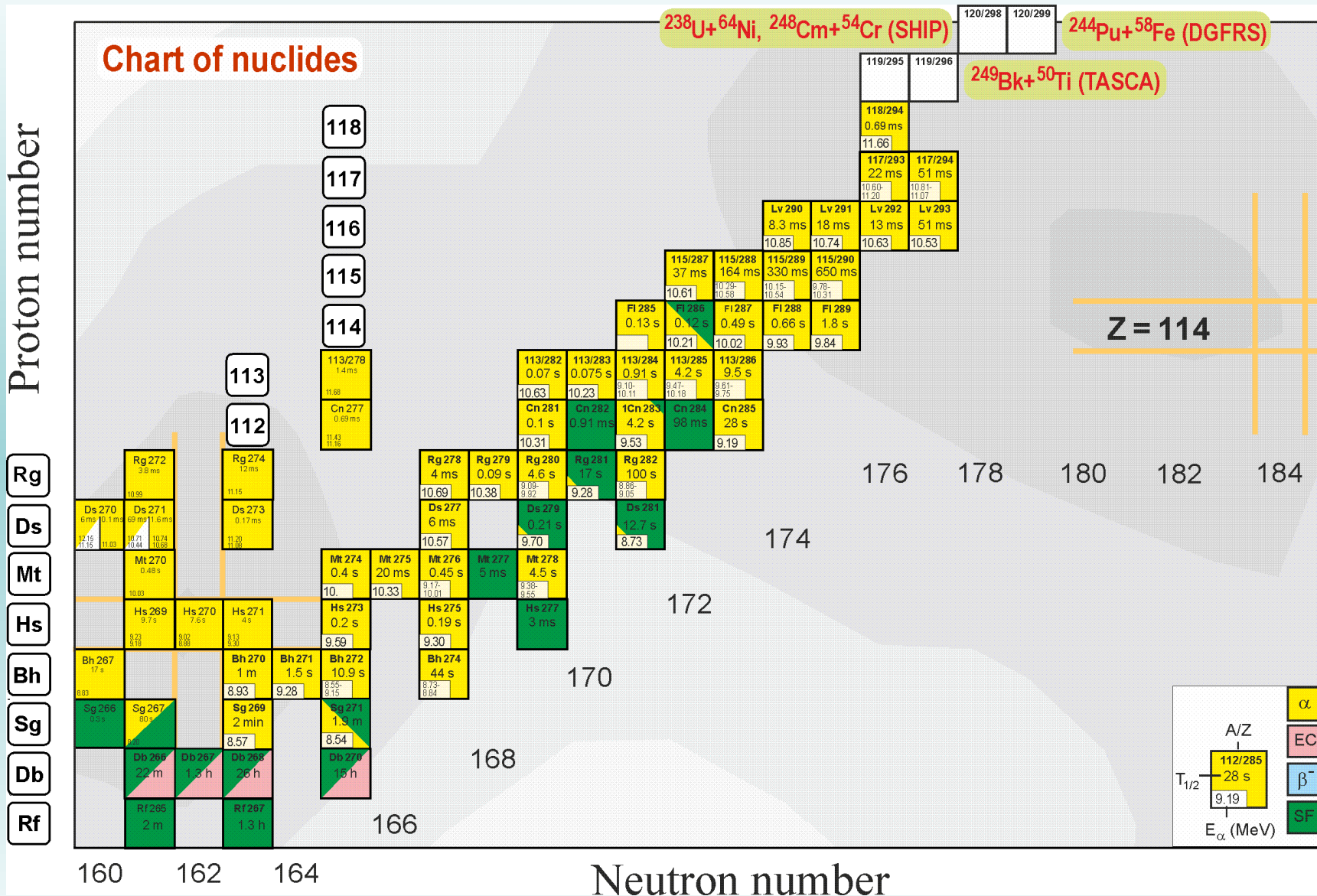




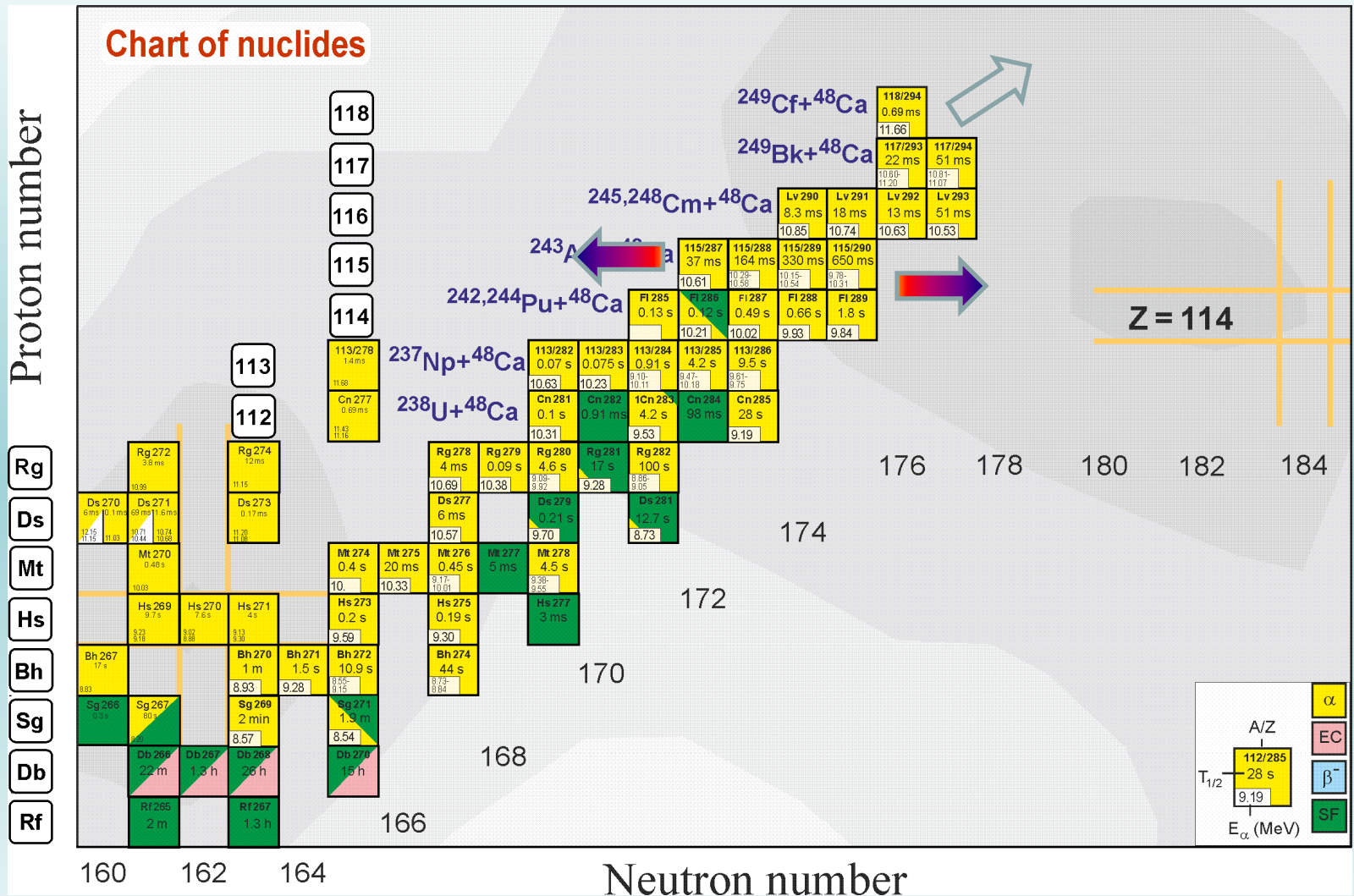
# Spontaneous-fission half-lives for even-even nuclei (increase of stability for higher $N$ )



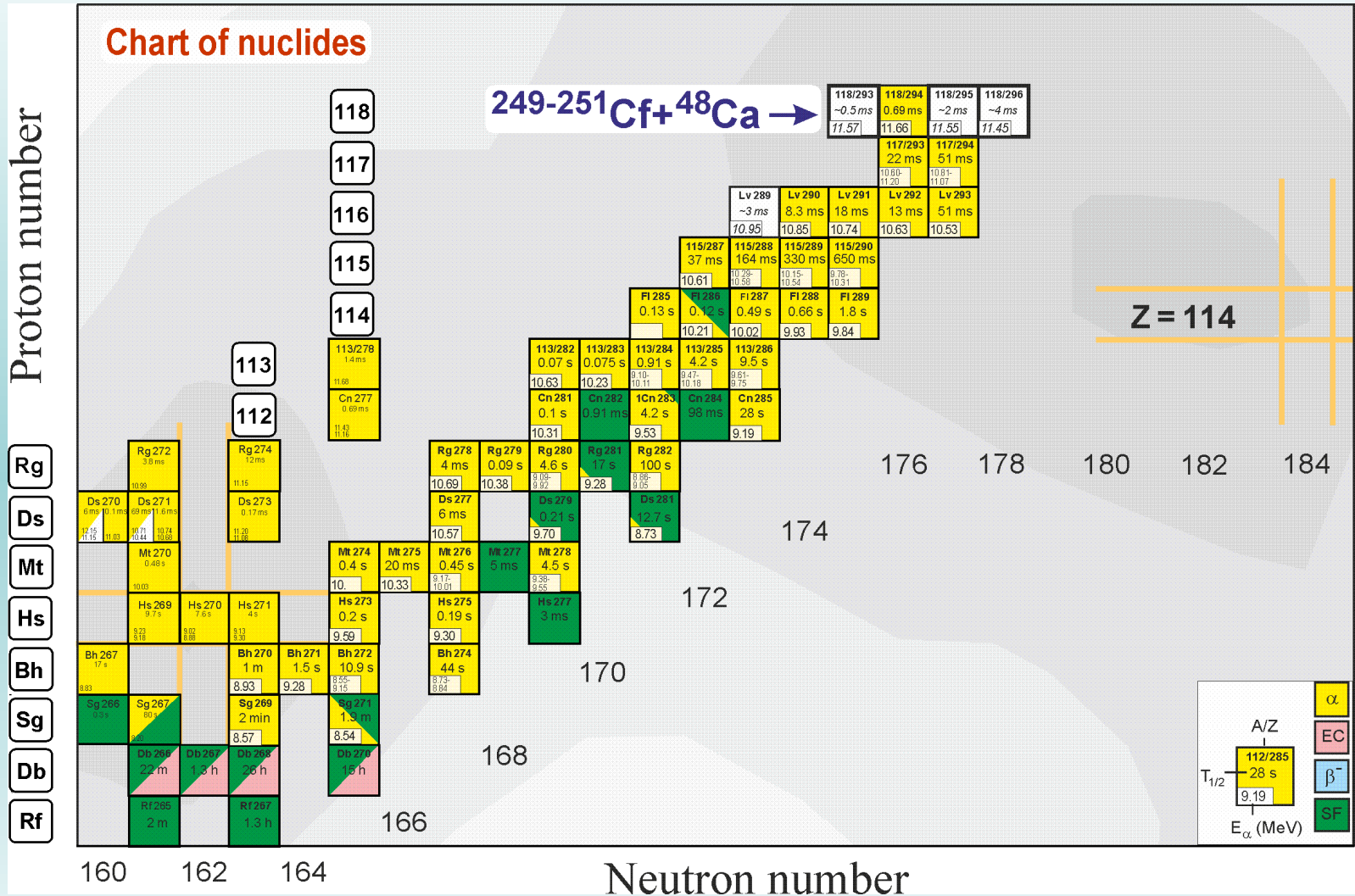
# No events in experiments on the synthesis of elements 119 and 120



# Region of superheavy nuclei



# Synthesis of the heavies isotopes of element 118 in the $^{249-251}\text{Cf} + ^{48}\text{Ca}$ reaction



# Synthesis of the heavies isotopes of element 118 in the $^{249-251}\text{Cf} + ^{48}\text{Ca}$ reaction

$^{249}\text{Cf}$  (351 y)  
5.61 mg  
50.7%

$^{250}\text{Cf}$  (13 y)  
1.43 mg  
12.9%

$^{251}\text{Cf}$  (898 y)  
4.03 mg  
36.4%

$^{252}\text{Cf}$  (2.65 y)  
0.002 mg  
0.02%

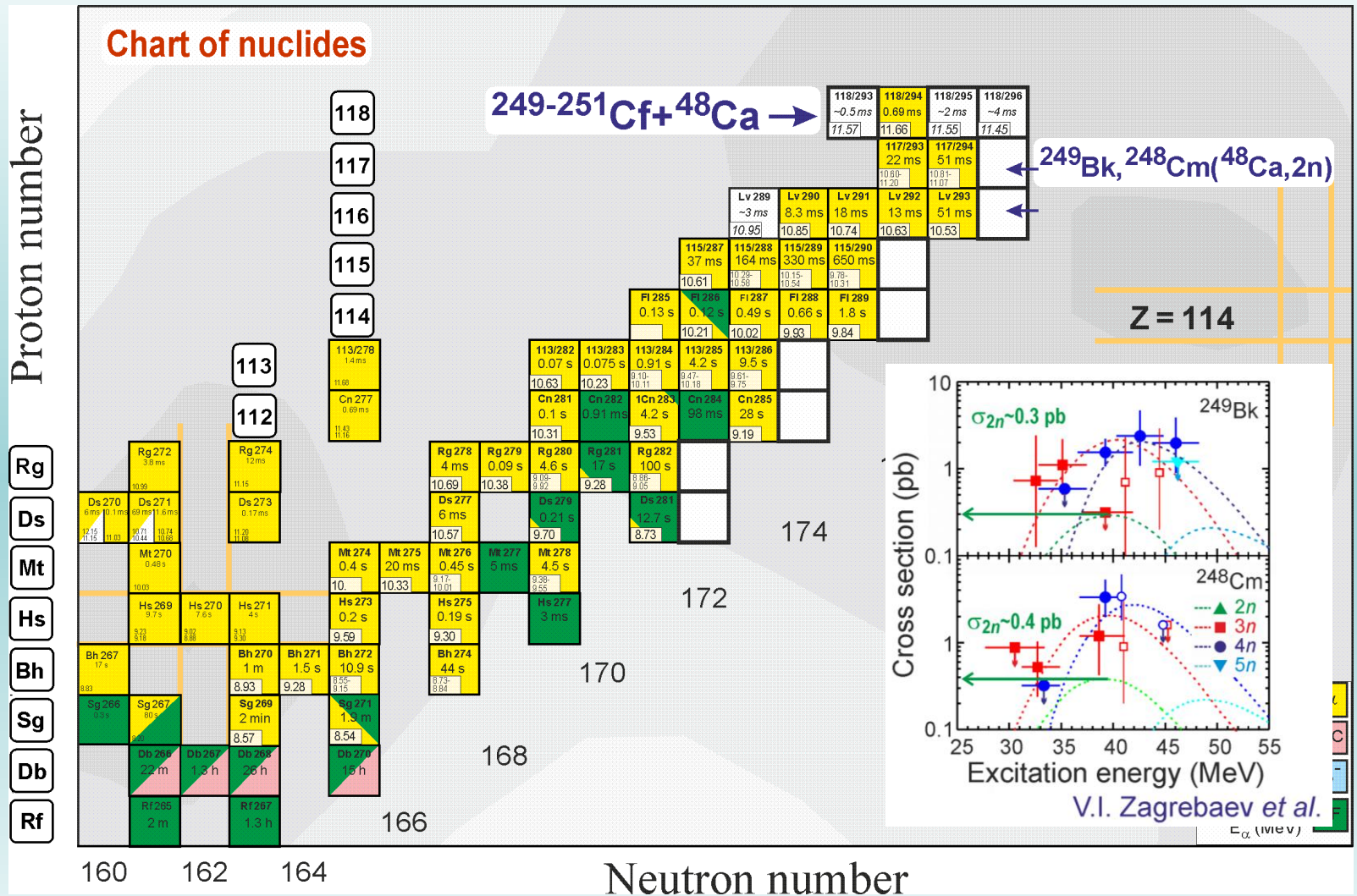


work on mixed Cf  
at REDC

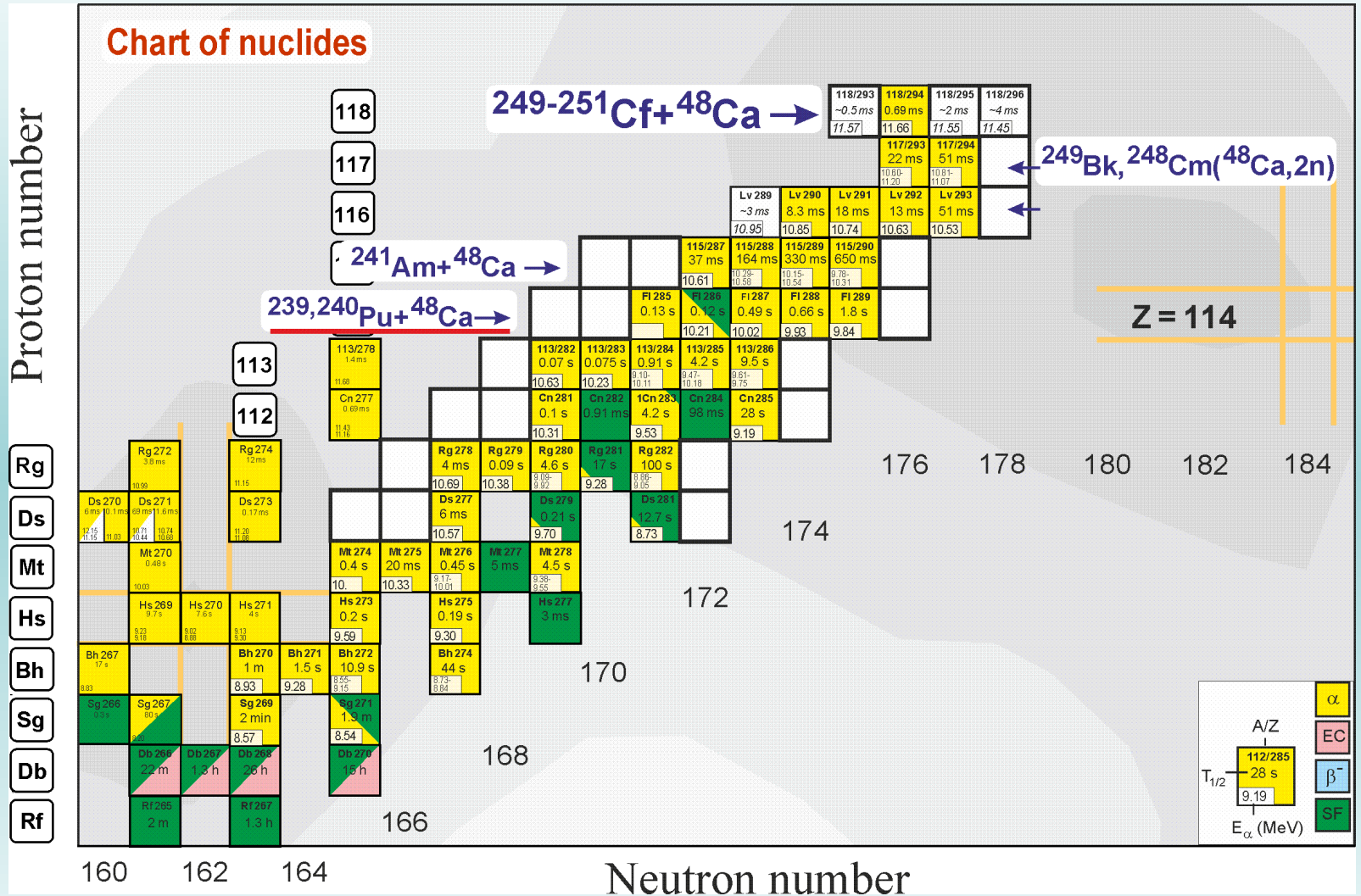


12 target sectors are in Dubna  
Average thickness  $0.35 \text{ mg/cm}^2$

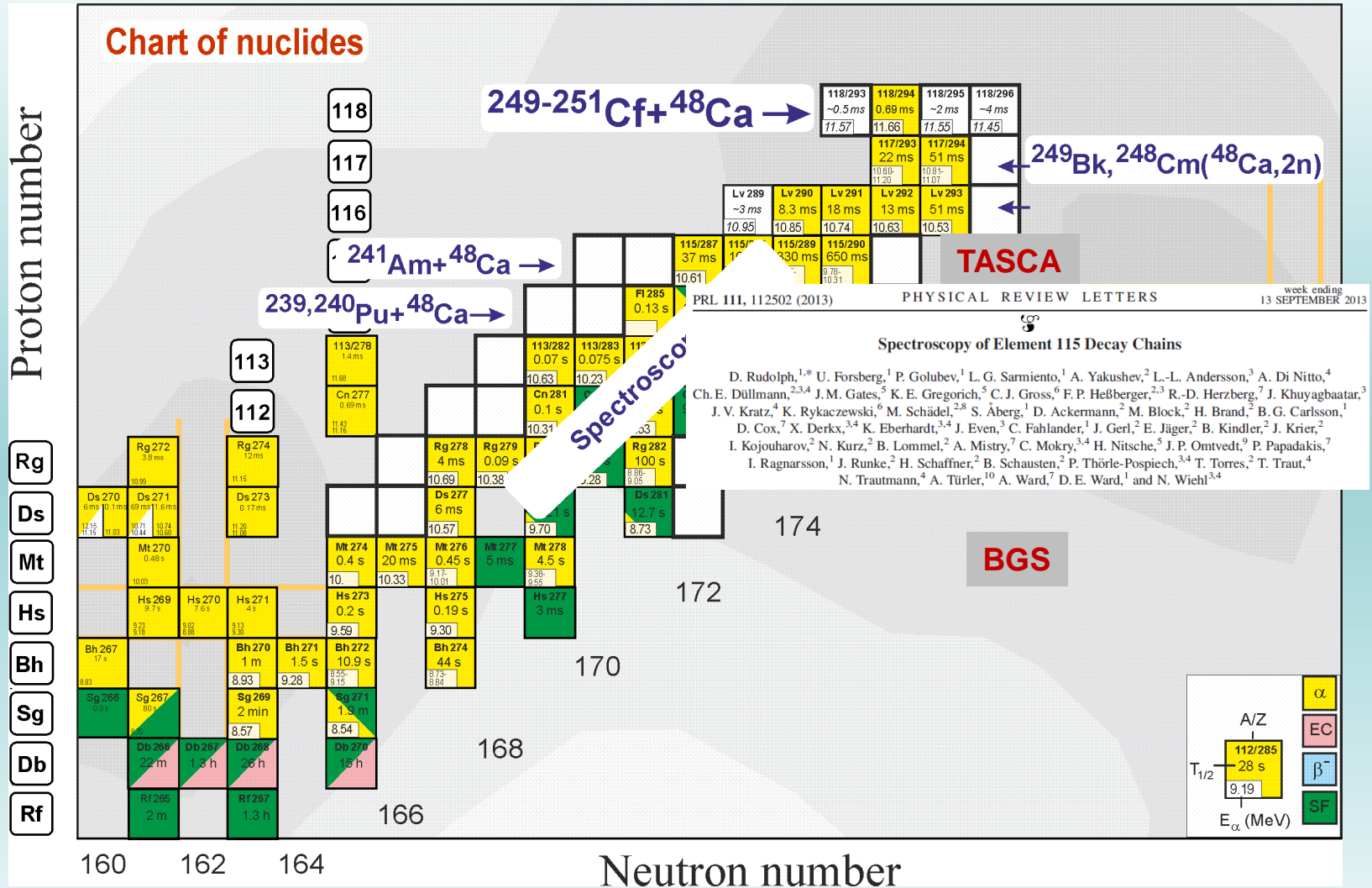
# Synthesis of the heavies isotopes in the 2n-evaporation channel



# Synthesis of neutron-deficient isotopes



# Investigation of structure of nuclei



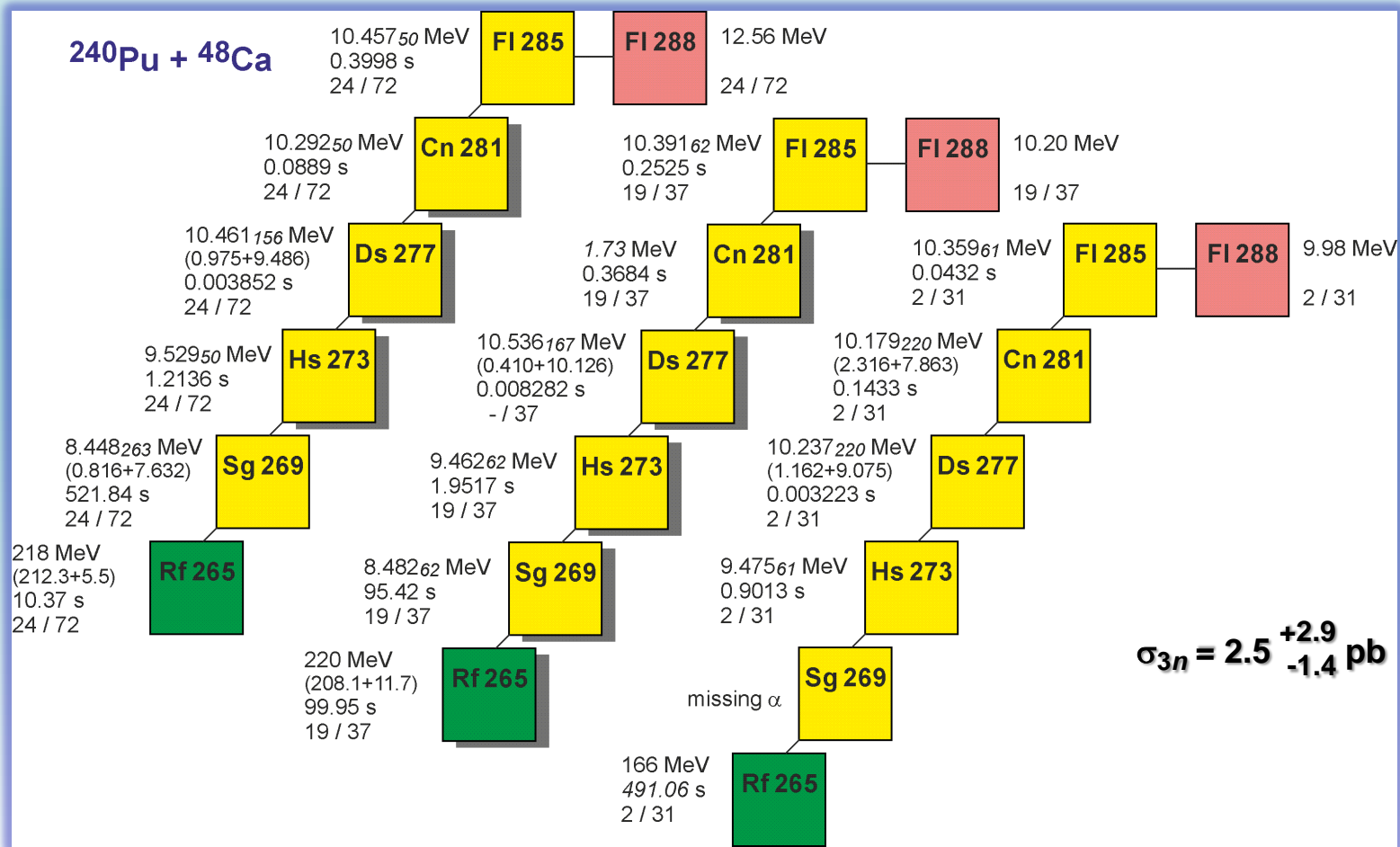


# Synthesis of neutron-deficient isotopes

## $^{240}\text{Pu} + ^{48}\text{Ca}$ reaction

**Target**  
**Energy of  $^{48}\text{Ca}$**   
**Excitation energy**  
**Beam dose**

**0.49 mg/cm<sup>2</sup>**  
**245 MeV**  
**36.5 – 41.1 MeV**  
 **$4.0 \cdot 10^{18}$**



# Synthesis of neutron-deficient isotopes

## $^{240}\text{Pu} + ^{48}\text{Ca}$ reaction

**Target** 0.49 mg/cm<sup>2</sup>  
**Energy of  $^{48}\text{Ca}$**  250 MeV  
**Excitation energy** 40.9 – 45.4 MeV  
**Beam dose**  $4.7 \cdot 10^{18}$

### $^{240}\text{Pu} + ^{48}\text{Ca}$

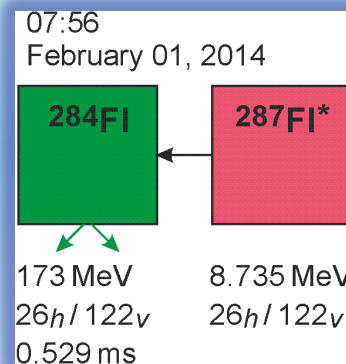
168 MeV 0.555 ms 17 / 118	FI 284	FI 288	14.43 MeV 17 / 118	190 MeV (173+17) 0.857 ms 35 / 19,20	FI 284	FI 288	13.18 MeV 35 / 19,20
140 MeV 8.588 ms 15 / 59	FI 284	FI 288	10.24 MeV 15 / 59	234 MeV (179+55) 7.246 ms 27 / 46	FI 284	FI 288	10.66 MeV 27 / 46

$$\sigma_{4n} = 2.6^{+3.3}_{-1.7} \text{ pb}$$

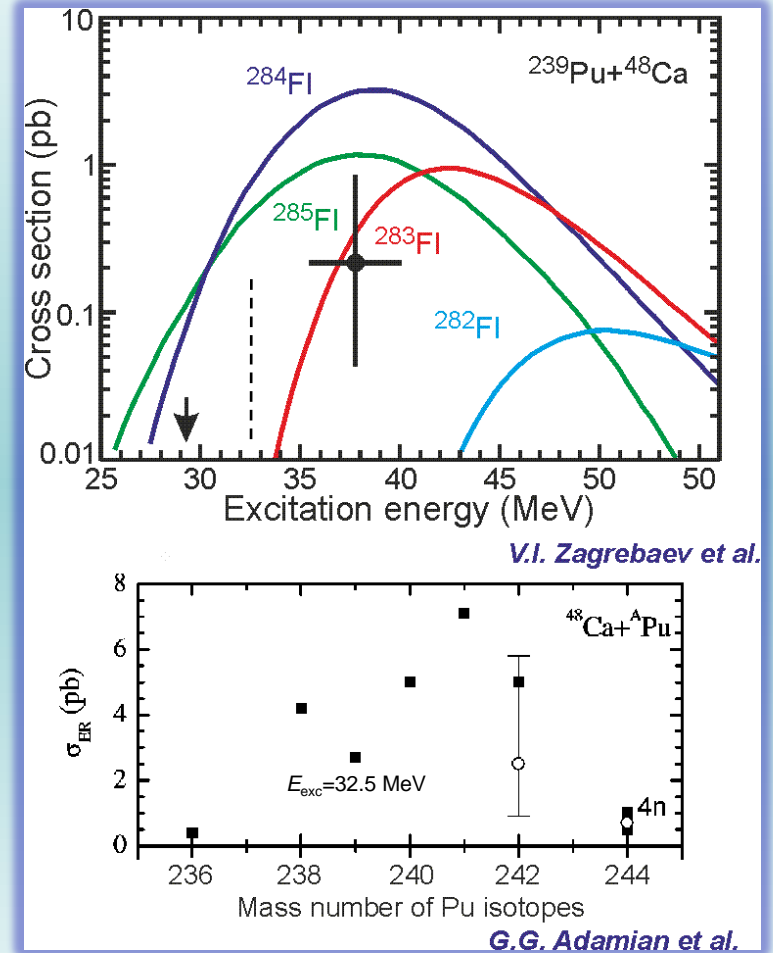
# Synthesis of neutron-deficient isotopes

## $^{239}\text{Pu} + ^{48}\text{Ca}$ reaction

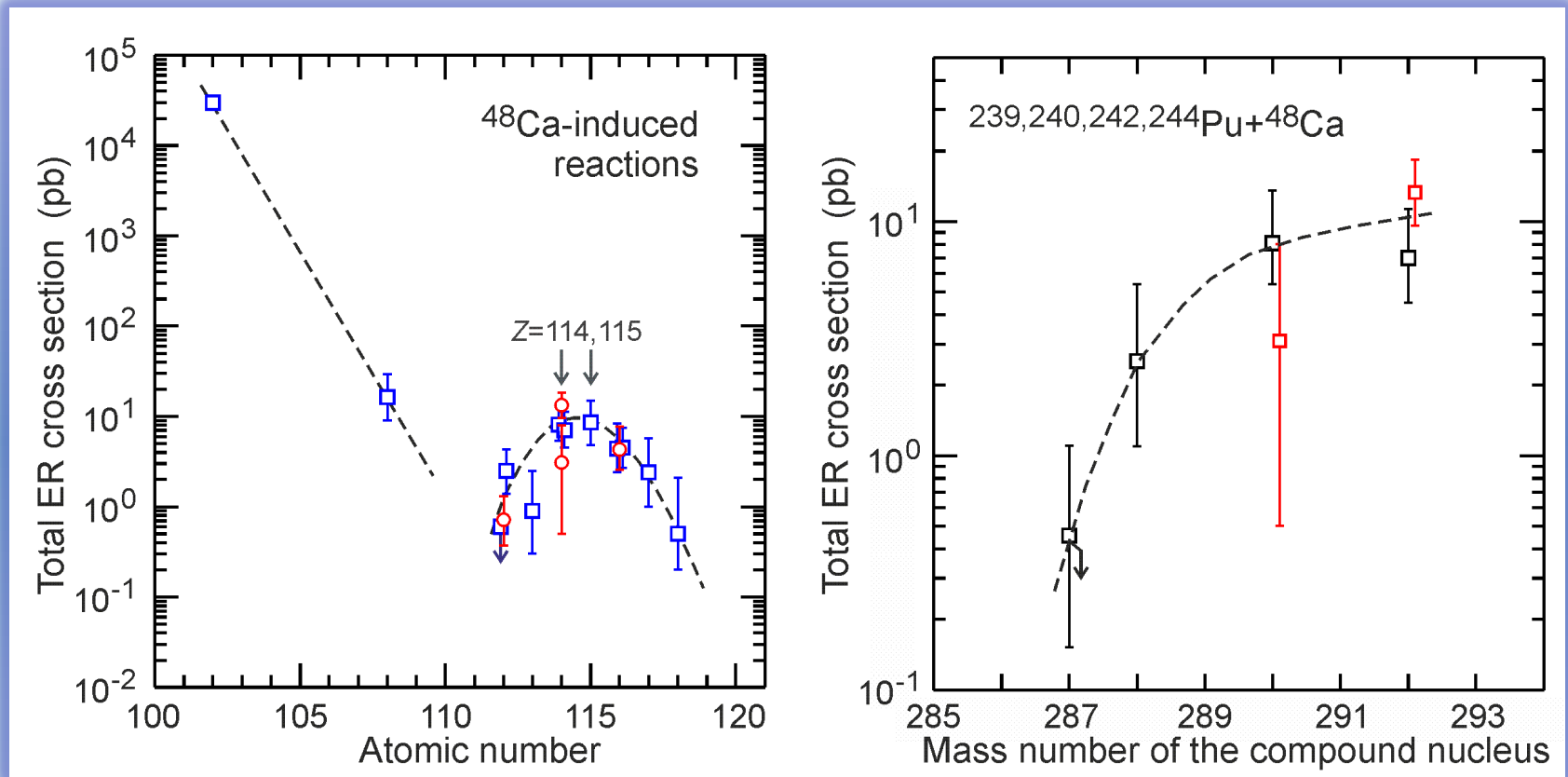
**Target** 0.51 mg/cm<sup>2</sup>  
**Energy of  $^{48}\text{Ca}$**  245 MeV  
**Excitation energy** 35.4 – 40.0 MeV  
**Beam dose**  $1.4 \cdot 10^{19}$



$$\sigma_{3n} = 0.23^{+0.59}_{-0.20} \text{ pb}$$



## Drop of production cross section with increase of $Z$ and decrease of $N$

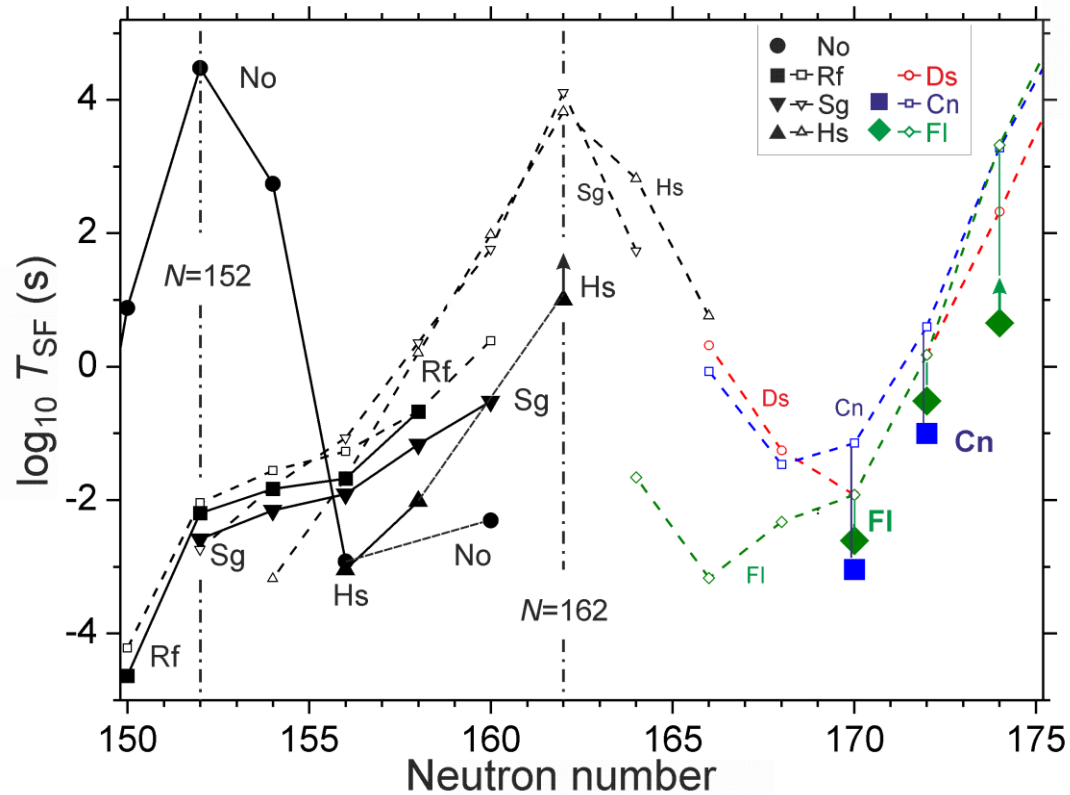


Approaching the border of region of SHN

Measured cross section is lower by factor of 20 than theoretical predictions and by factor of 50 than values measured in the reaction with  $^{244}\text{Pu}$ .  
Decrease of stability (fission barriers) of neutron-deficient FI isotopes.

**SHE Factory**

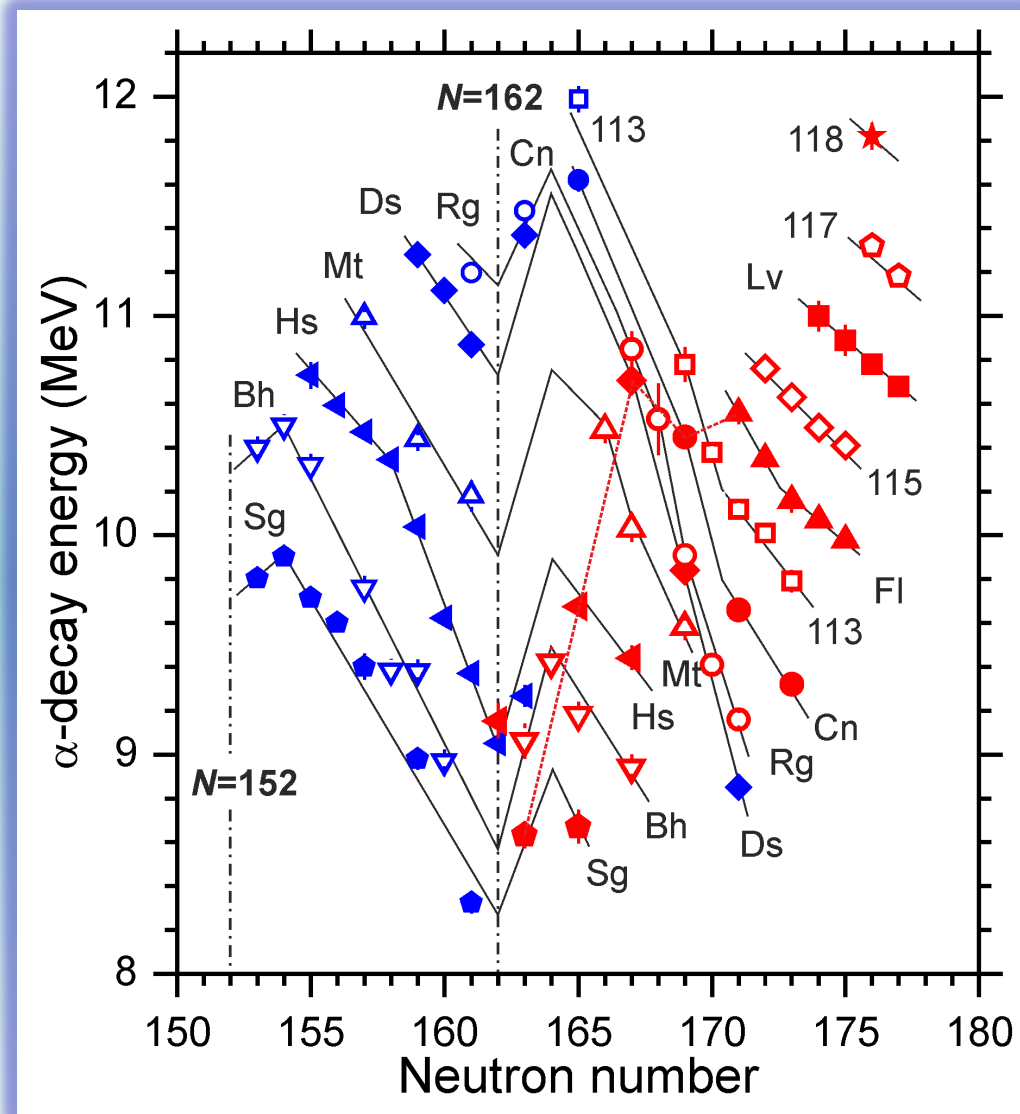
# Decrease of SF half-lives of even-even isotopes of Cn and Fl with receding magic number $N=184$



A. Sobiczewski

Approaching the border of region of SHN

# Increase of $Q_\alpha$ values for isotopes with $Z=112-114$



Approaching the border  
of region of SHN

Yu.Ts. Oganessian<sup>1</sup>, F.Sh. Abdullin<sup>1</sup>, C. Alexander<sup>2</sup>, P.D. Bailey<sup>3</sup>, D.E. Benker<sup>3</sup>, M.E. Bennett<sup>4</sup>, J. Binder<sup>2</sup>, S.L. Bogomolov<sup>1</sup>, R.A. Boll<sup>2</sup>, G.V. Buklanov<sup>1</sup>, S.N. Dmitriev<sup>1</sup>, J. Ezold<sup>2</sup>, K. Felker<sup>2</sup>, B.N. Gikal<sup>1</sup>, J.M. Gostic<sup>3</sup>, R.K. Grzywacz<sup>2,5</sup>, G.G. Gulbekian<sup>1</sup>, J.H. Hamilton<sup>6</sup>, R.A. Henderson<sup>3</sup>, S. Iliev<sup>1</sup>, R.I. Il'kaev<sup>7</sup>, M.G. Itkis<sup>1</sup>, O.V. Ivanov<sup>1</sup>, Ye.A. Karelin<sup>8</sup>, J.M. Kenneally<sup>3</sup>, J.H. Landrum<sup>3</sup>, C.A. Laue<sup>3</sup>, Yu.V. Lobanov<sup>1</sup>, R.W. Lougheed<sup>3</sup>, A.N. Mezentsev<sup>1</sup>, K. Miernik<sup>2</sup>, D. Miller<sup>5</sup>, K.J. Moody<sup>3</sup>, S.L. Nelson<sup>3</sup>, J.B. Patin<sup>3</sup>, A.N. Polyakov<sup>1</sup>, C.E. Porter<sup>2</sup>, A.V. Ramayya<sup>6</sup>, F.D. Riley<sup>2</sup>, J.B. Roberto<sup>2</sup>, M.A. Ryabinin<sup>8</sup>, K.P. Rykaczewski<sup>2</sup>, R.N. Sagaidak<sup>1</sup>, D.A. Shaughnessy<sup>3</sup>, I.V. Shirokovsky<sup>1</sup>, M.V. Shumeiko<sup>1</sup>, M.A. Stoyer<sup>3</sup>, N.J. Stoyer<sup>3</sup>, V.G. Subbotin<sup>1</sup>, K. Subotic<sup>1</sup>, R. Sudowe<sup>4</sup>, A.M. Sukhov<sup>1</sup>, A.N. Tatarinov<sup>9</sup>, R. Taylor<sup>2</sup>, Yu.S. Tsyganov<sup>1</sup>, V.K. Utyonkov<sup>1</sup>, S.P. Vesnovskii<sup>7</sup>, A.A. Voinov<sup>1</sup>, G.K. Vostokin<sup>1</sup>, J.F. Wild<sup>3</sup>, P.A. Wilk<sup>3</sup>, V.I. Zagrebaev<sup>1</sup>

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<sup>3</sup> Lawrence Livermore National Laboratory, Livermore, California 94551, USA

<sup>4</sup> University of Nevada Las Vegas, Las Vegas, Nevada 89154, USA

<sup>5</sup> Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA

<sup>6</sup> Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235, USA

<sup>7</sup> Russian Federal Nuclear Center, All-Russian Research Institute of Experimental Physics, 607190 Sarov, Russian Federation

<sup>8</sup> Research Institute of Atomic Reactors, RU-433510 Dimitrovgrad, Russian Federation

<sup>9</sup> State Enterprise Electrohimpribor, RU-624200 Lesnoy, Russian Federation

Dubna



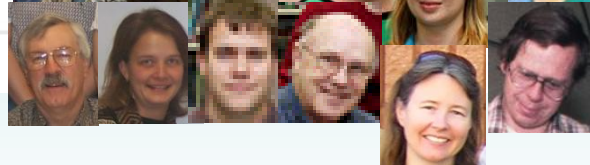
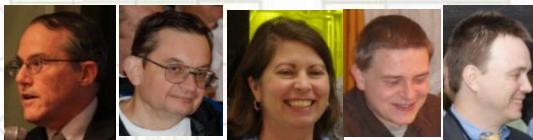
Oak Ridge

Livermore

Nashville

Dimitrovgrad

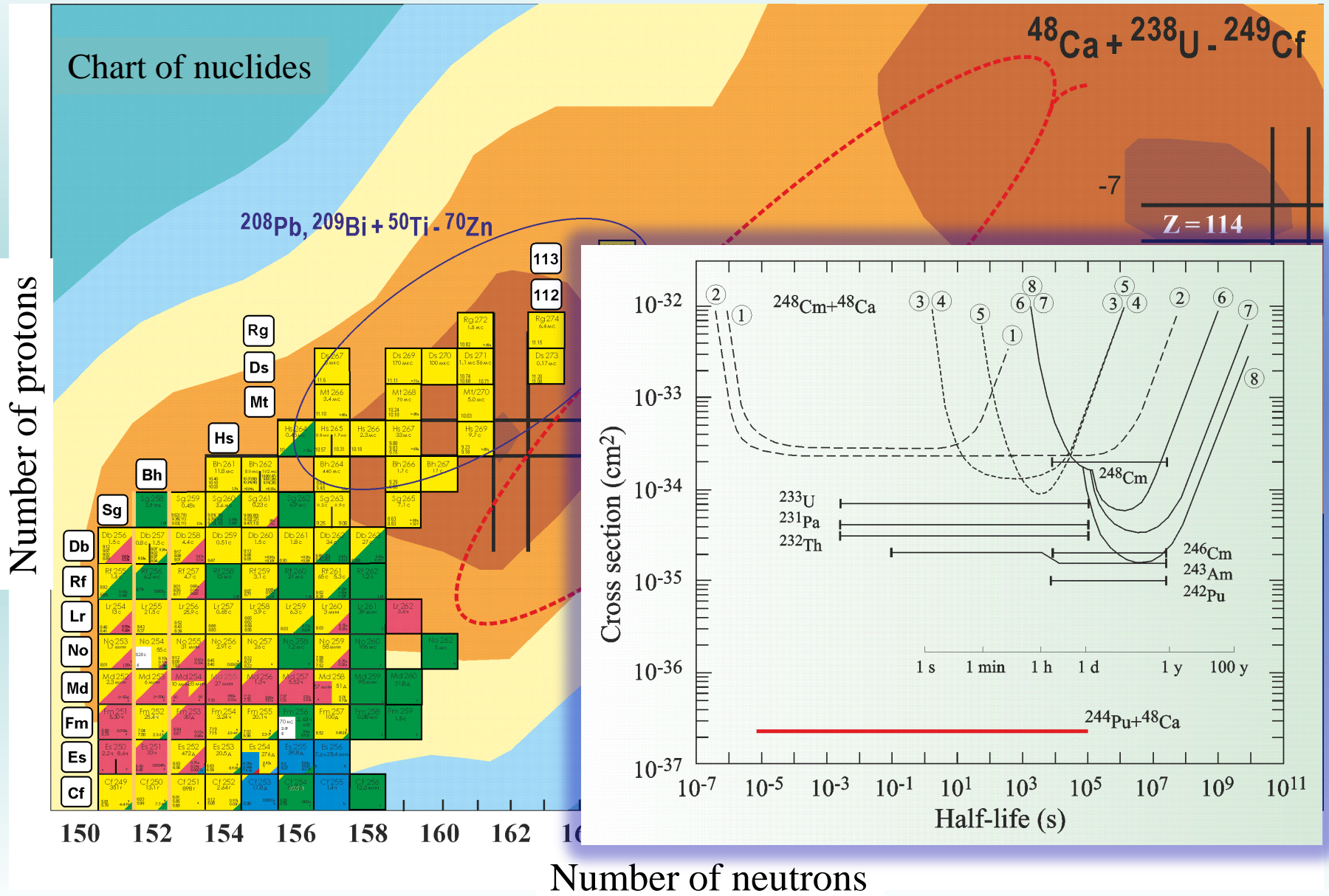
Knoxville



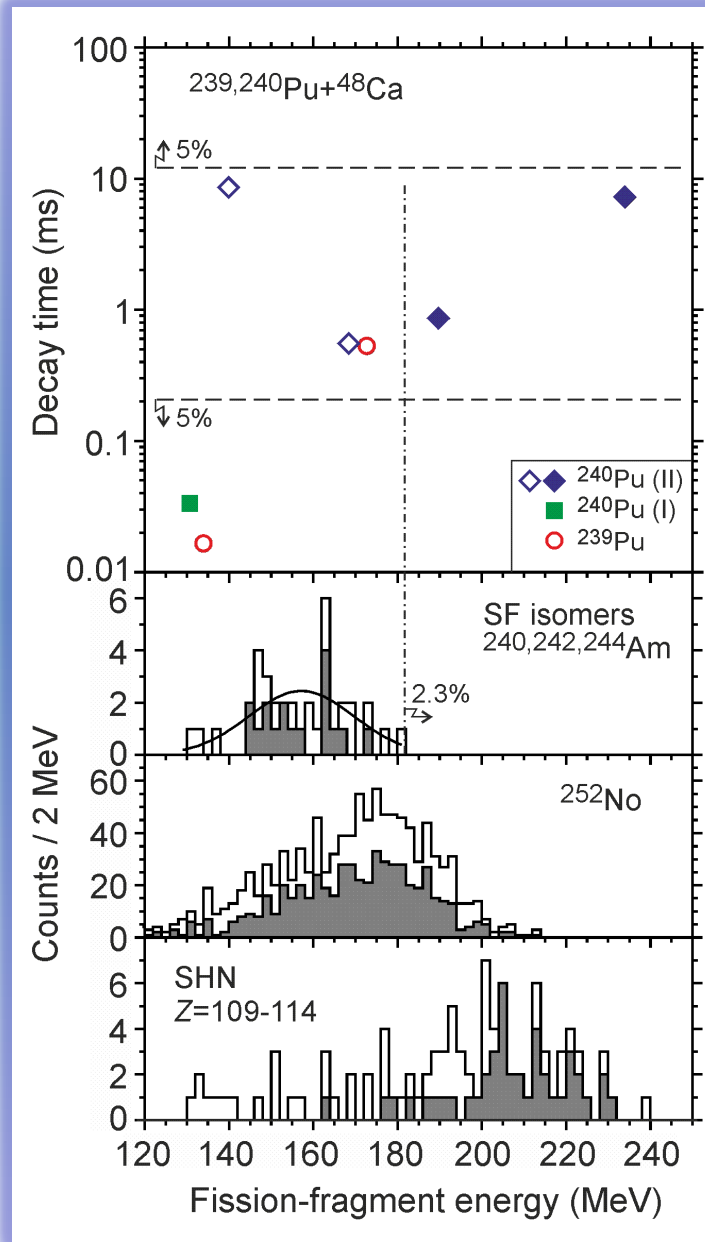




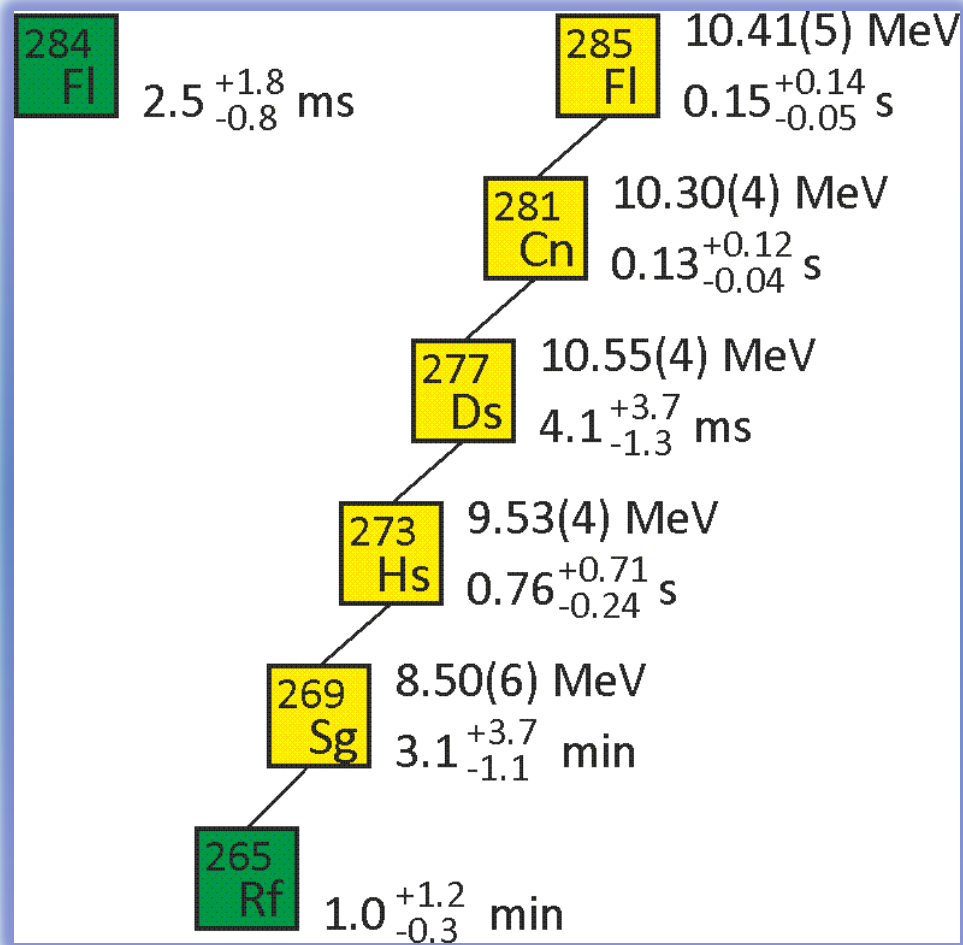
# New region of superheavy nuclei



# Origin of SF activity

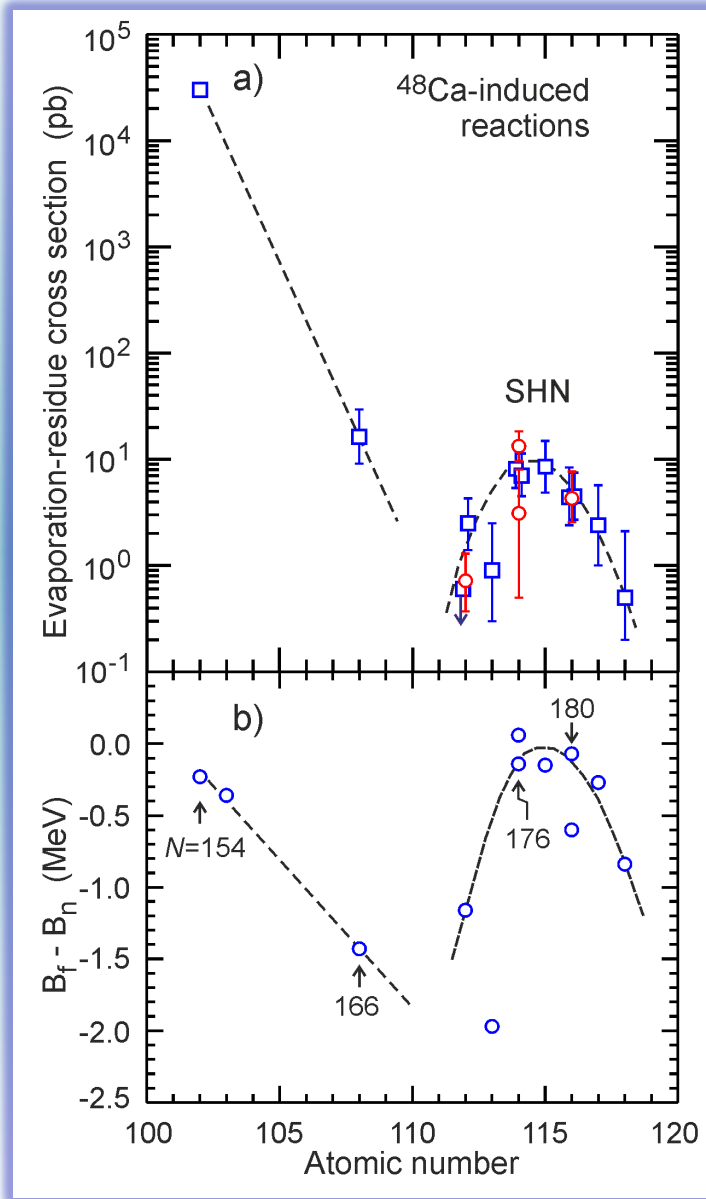


## Decay properties of seven neutron-deficient nuclei



Alpha-particle energy of  $^{285}\text{Fl}$  and SF half-life of  $^{284}\text{Fl}$  were measured for the first time

# Production cross sections



$$\sigma_{ER} = \sigma_{capt} * P_{fus} * P_{surv}$$

$\sigma_{capt}$  are comparable for  $^{48}\text{Ca} + \text{Act}$ .

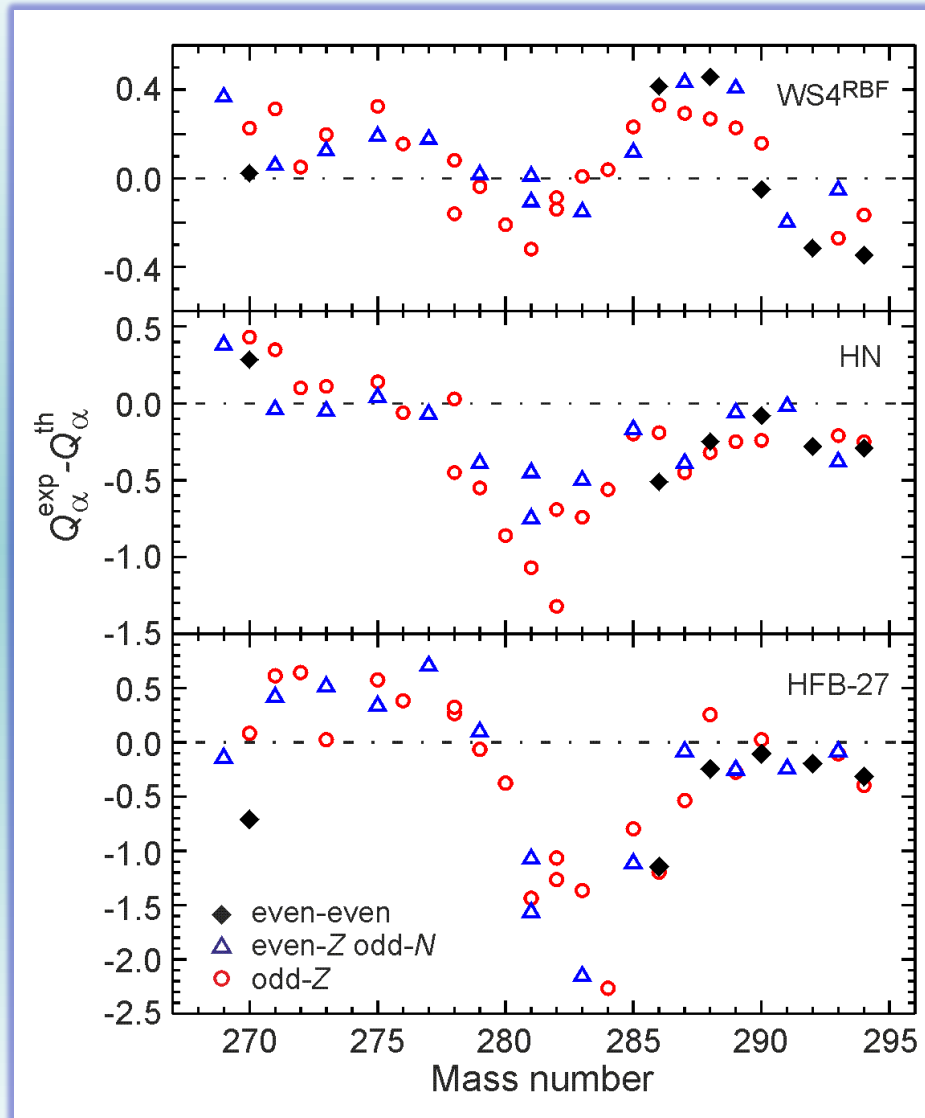
$P_{fus}$  gradually decreases as  $\log_{10}(P_{fus})$

$P_{surv} \sim \prod(\Gamma_r/\Gamma_f)_i \sim \prod \exp[-(B_f - B_r)/T]_i$

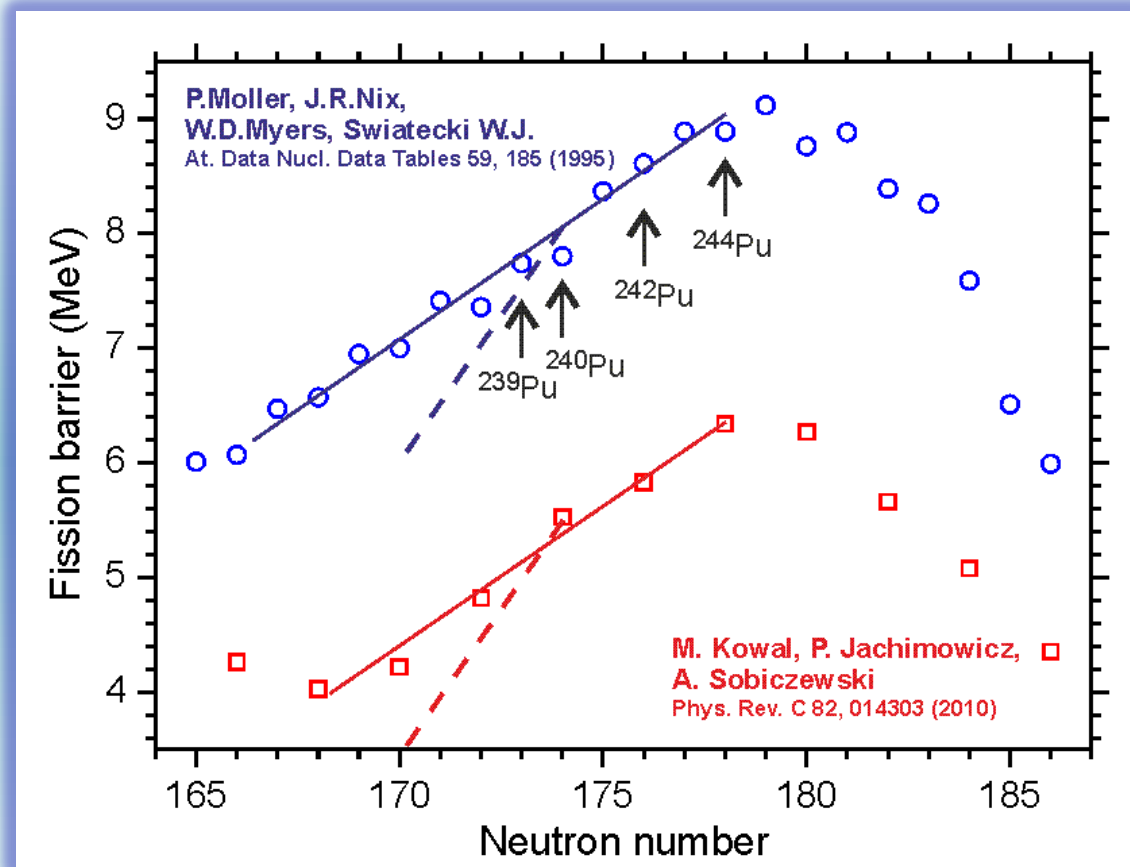
$\log_{10}(\sigma_{ER}) \sim \log_{10}(P_{fus}) + \sum[(B_f - B_r)/T]_i$

# Alpha-decay energy of nuclei

(agreement of experimental and theoretical results)

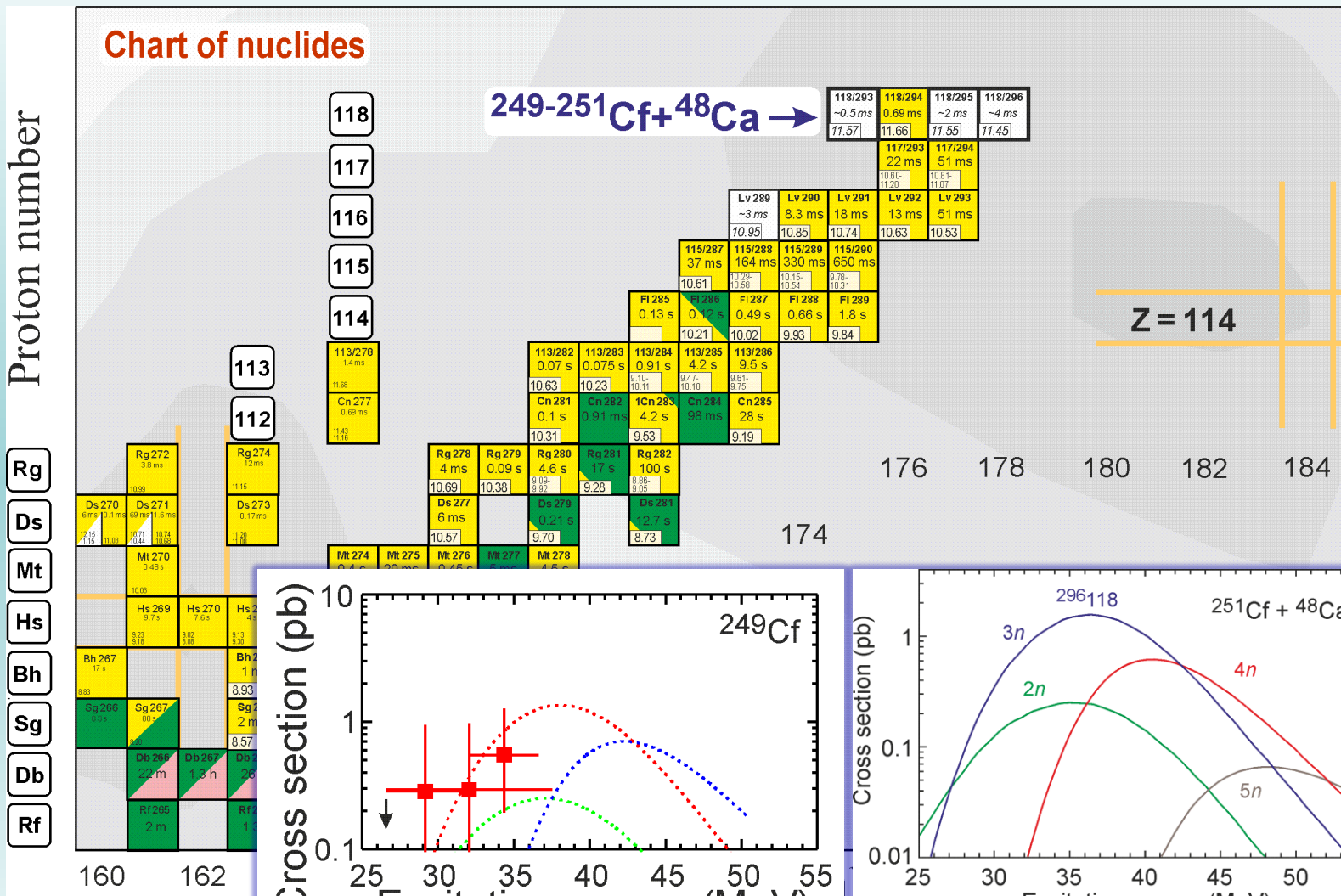


# Decrease of SF half-lives of even-even isotopes of Cn and Fl with receding magic number $N=184$



Approaching the border of region of SHN

# Synthesis of the heaviest isotopes of element 118 in the $^{249-251}\text{Cf} + ^{48}\text{Ca}$ reaction



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