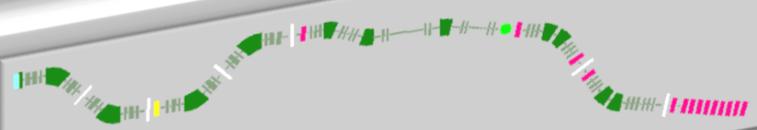
Oleg B. Tarasov
NCSL / MSU, USA

Production of Fast Rare Ion Beams

Euroschool on Exotic Beams 2013, Dubna
Euroschool on Exotic Beams 2013, Dubna

26-31 / 08 / 2013

LISE++



LISE++

1. Introduction to production of Fast Rare Ion Beams
2. Production Area
3. Separation
4. Identification
5. Production of new isotopes
6. LISE++ : Utilities
7. Radioactive beam physicist task

Nuclide discovery project

from Michael Thoennessen

http://www.nscl.msu.edu/~thoennes/isotopes/

- Discovery papers
- Table of top 1000 (co)authors
- Table of top 250 first authors
- Table of top 25 labs
- Table of countries
- Journals and publishers

Discovery of exotic nuclei: past, present and future

GENCO Colloquium

GSI, February 28, 2013

- The limits of nuclear stability provide a key benchmark of nuclear models:
  - *Exploring nuclei with unusual properties*
  - *Exploring changes in shell structure*
  - *Exploring nuclear shapes*
- The context of astrophysics:
  - *What is the origin of the heavy elements?*
  - *Understanding the r-process abundance patterns of elements (see Figure)*
- Production mechanism study to explore Terra Incognita: reaction choice, production cross sections, momentum distributions,
- Secondary beam intensities. Planning new experiments, set-ups (F-RIB, RIBF, FAIR)
- PR

The study of properties (masses, lifetimes, and properties of excited states) of the most exotic isotopes continues to be one of the important tasks in experimental nuclear physics.
The ***first step*** *in the study of a new exotic nucleus is its observation, which for neutron-rich nuclei demonstrates its stability with respect to particle emission.*

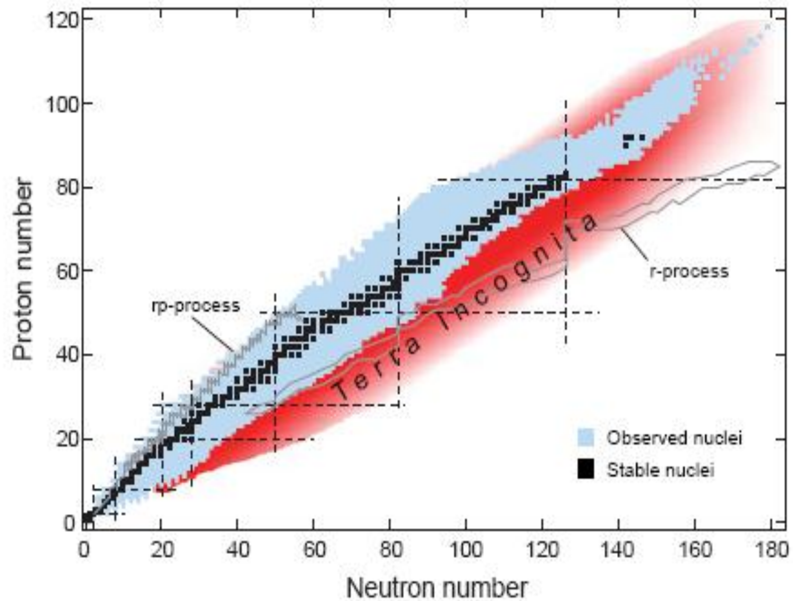
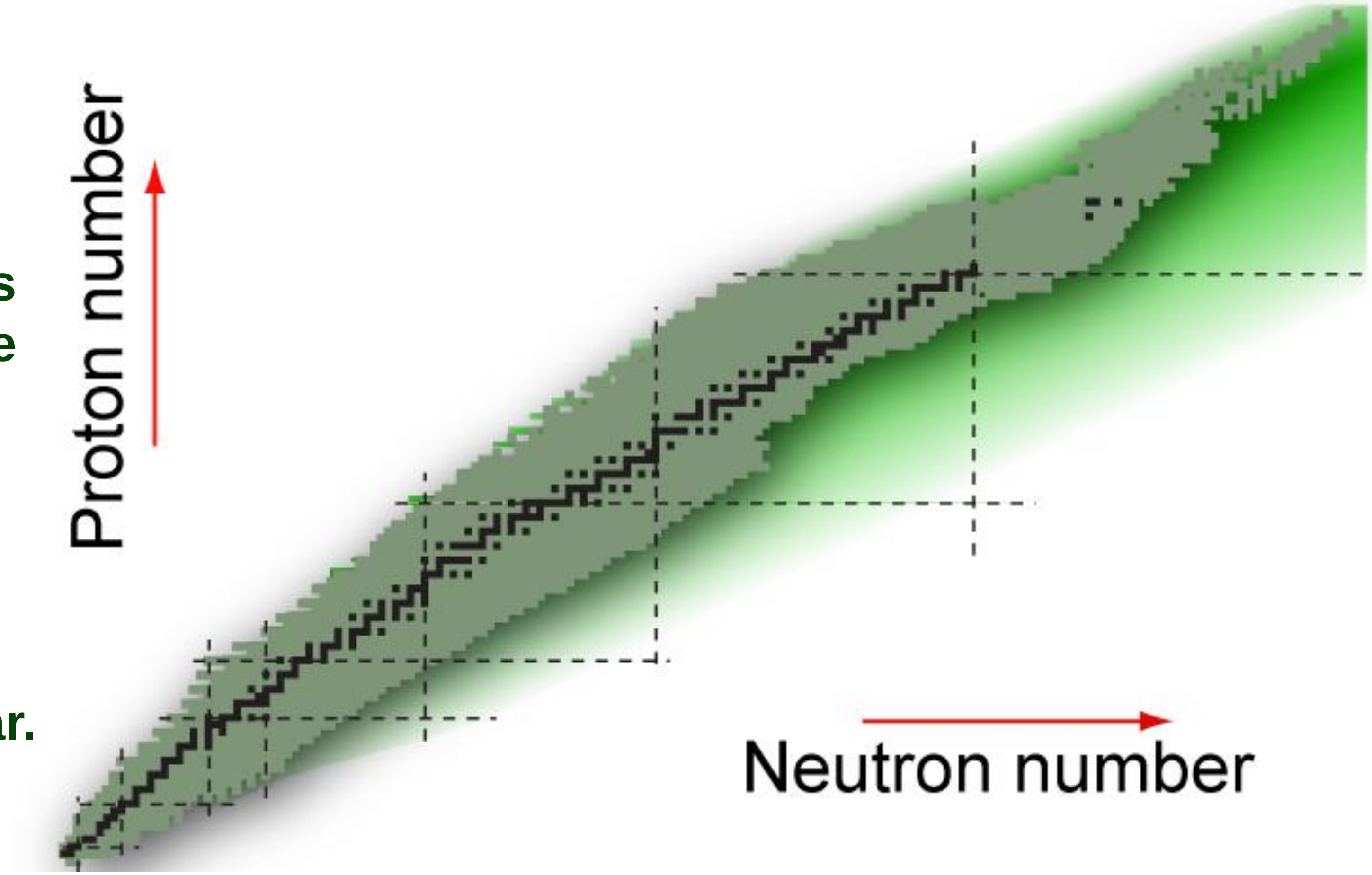


Figure: **Chart of nuclei [1] (element or proton number Z versus neutron number N): stable nuclei along the valley of stability are shown in black, isotopes that have been detected at least once on Earth are shown in blue, and the large terrain of unknown nuclei is shown in red. The estimated paths for the r- and rp-processes for explosive nucleosynthesis in the cosmos are indicated by solid lines.**

[1] "Isotope Science Facility at Michigan State University", MSUCL-1345, November 2006

Nuclear Landscape

- **Chart of the nuclides**
- **Black squares are the 263 stable isotopes found in nature (> 1 Gy)**
- **Dark green closed area is the region of isotopes observed so far.**
- **The limits are not known.**



Open Questions:

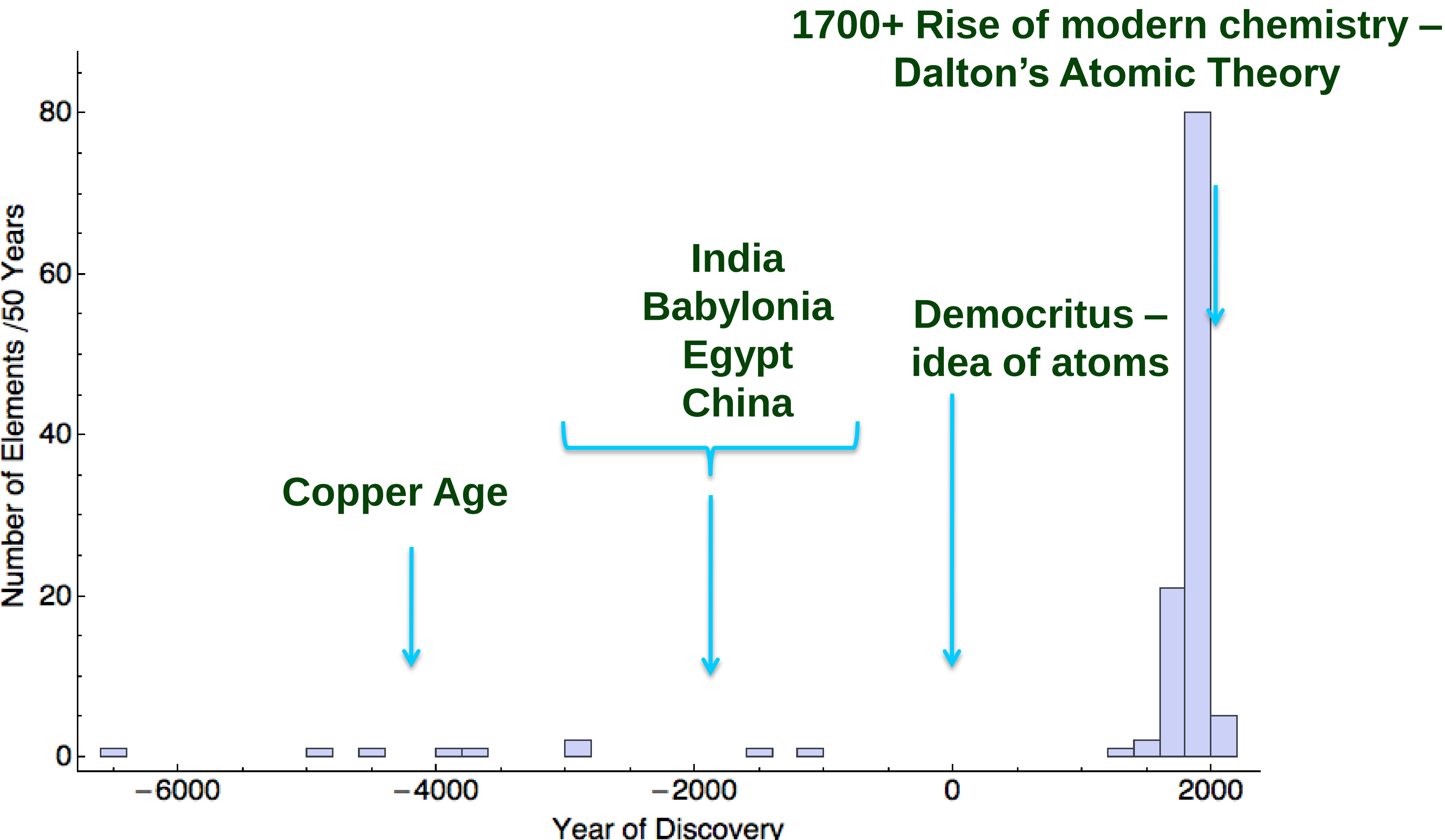
How many elements can exist? We are up to element 118 and counting.

Are there long-lived superheavy elements, with half lives of greater than 1 year?

Where are the atoms of the various elements formed in nature?

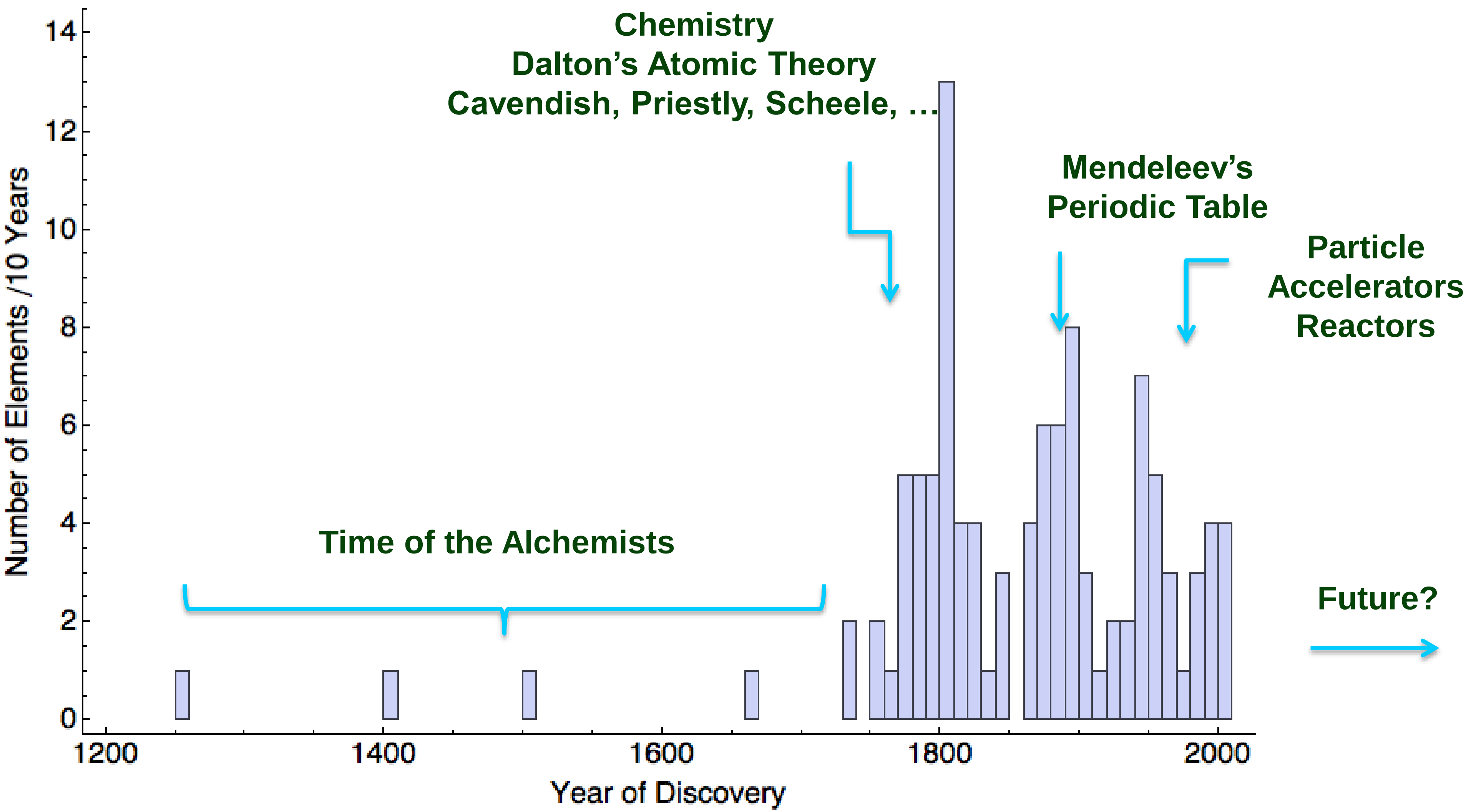
What makes atomic nuclei stable? We know Strong and Electroweak forces are involved, but don’t understand how in detail. The inability to answer this question is reflected in our inability to answer the first three questions.

History of Element Discovery



Source: Mathematica + Wikipedia

The history of element discovery 1200-2010



Discovery of Isotopes

Fredrick Soddy – Credited with discovery of isotopes

- Extremely talented chemist who began his career at McGill as a lecturer in 1900
- Rutherford came to McGill at the same time. Rutherford needed the help of a Chemist to try to understand radioactivity.
- Rutherford won 1908 Nobel prize "for his investigations into the disintegration of the elements, and the chemistry of radioactive substances” (identified α and β radioactivity)

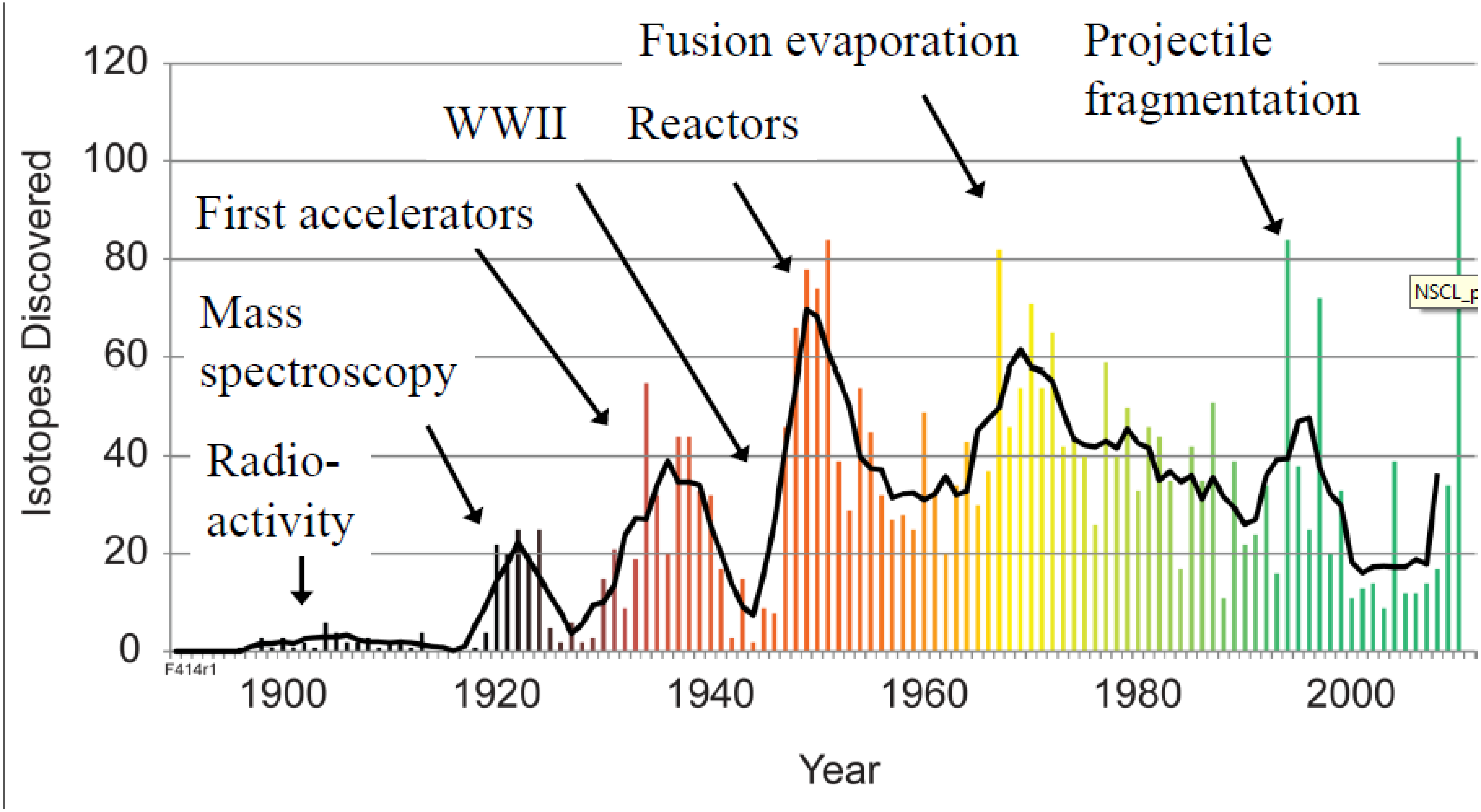
Isotopes

- In 1910 Soddy found that the mass of lead from thorium decay differed from lead from uranium decay
- He realized that atoms of a given elements must come in different forms that he called isotopes (Greek for “at the same place”) JJ Thompson in 1913 showed the first direct evidence – Ne isotopes in cathode ray tube.
- "Put colloquially, their atoms have identical outsides but different insides.” – Soddy Nobel Prize Lecture
- Won Nobel Prize in 1921 for discovery of isotopes

First Synthesis of Radioactive Isotopes

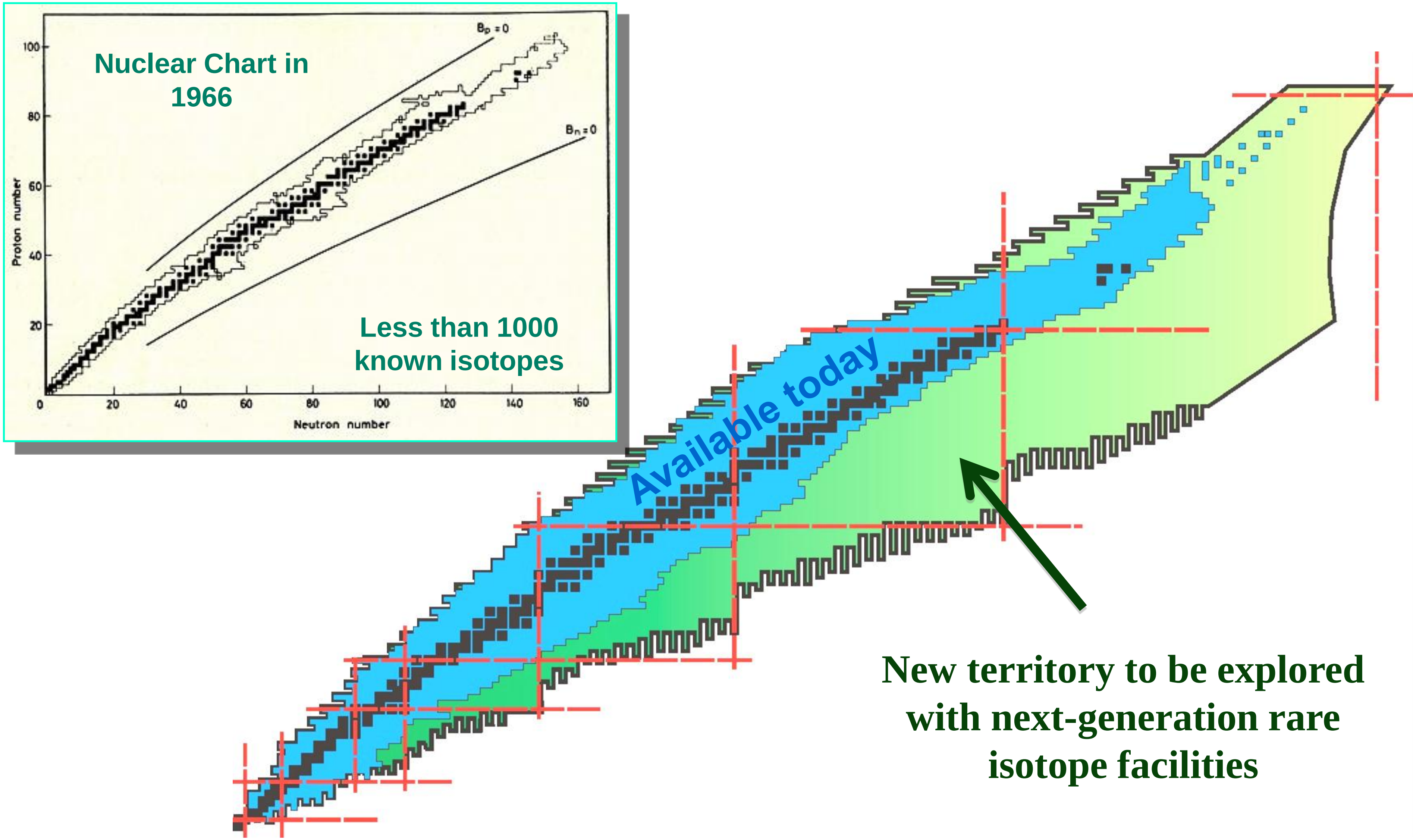
- **The first artificial isotopes were produced by F Joliot and I Curie (*Nature,* 10 Feb 1934) by bombarding B, Al, Mg with alpha particles from Po**
- **"We propose for the new radio-isotopes formed by the transmutation of boron, magnesium and aluminum, the names radionitrogen, radiosilicon, radiophosphorus"**
- **For this discovery, Curie and Joliot won the Nobel Prize in chemistry in 1935**

New isotope discoveries per year



M.Thoennessen and B.Sherrill, Nature 473 (2011) 25

The availability of rare isotopes over time

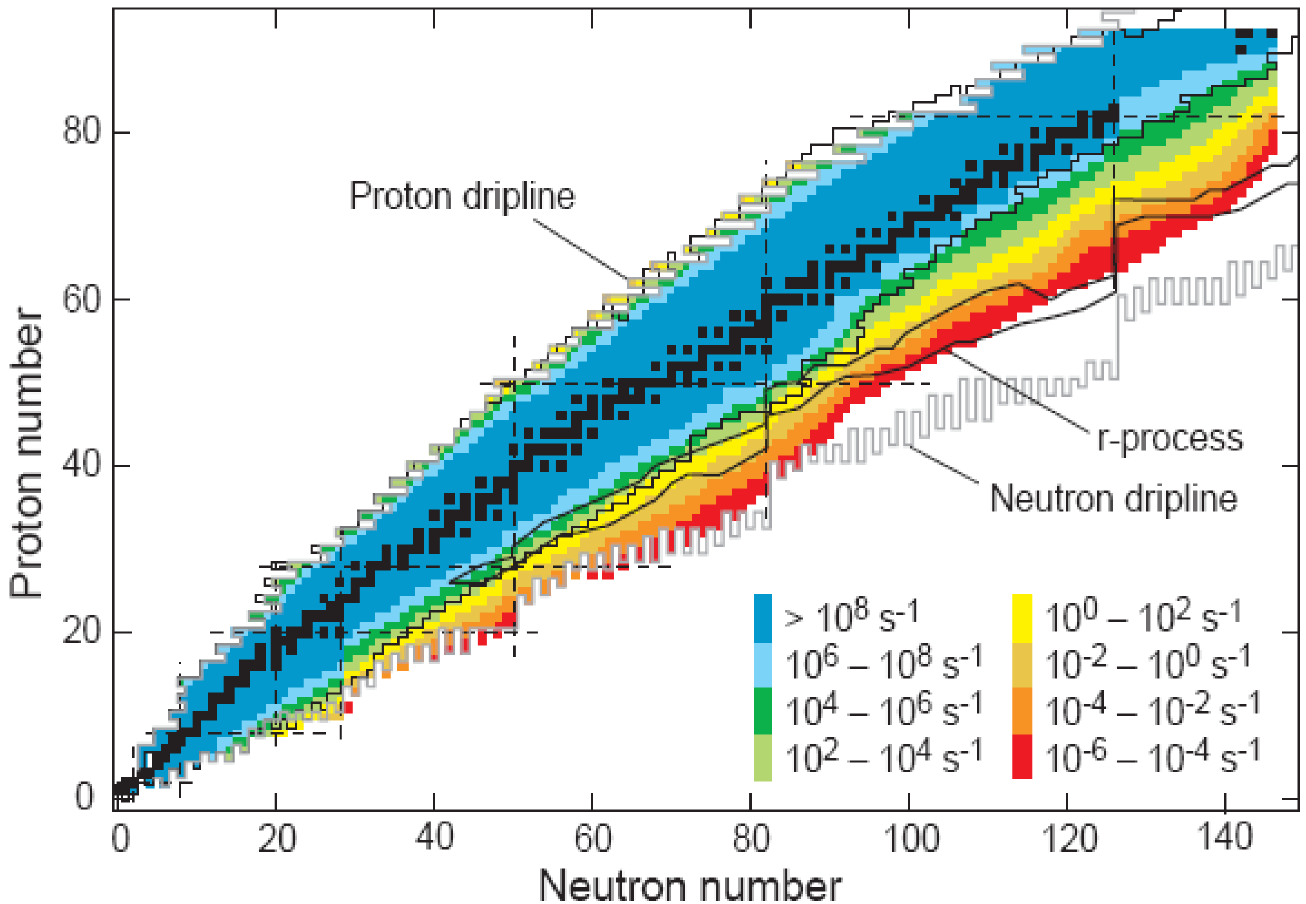


blue – around 3000 known isotopes

Black squares are the around 260 stable isotopes found in nature (> 1 Gy)

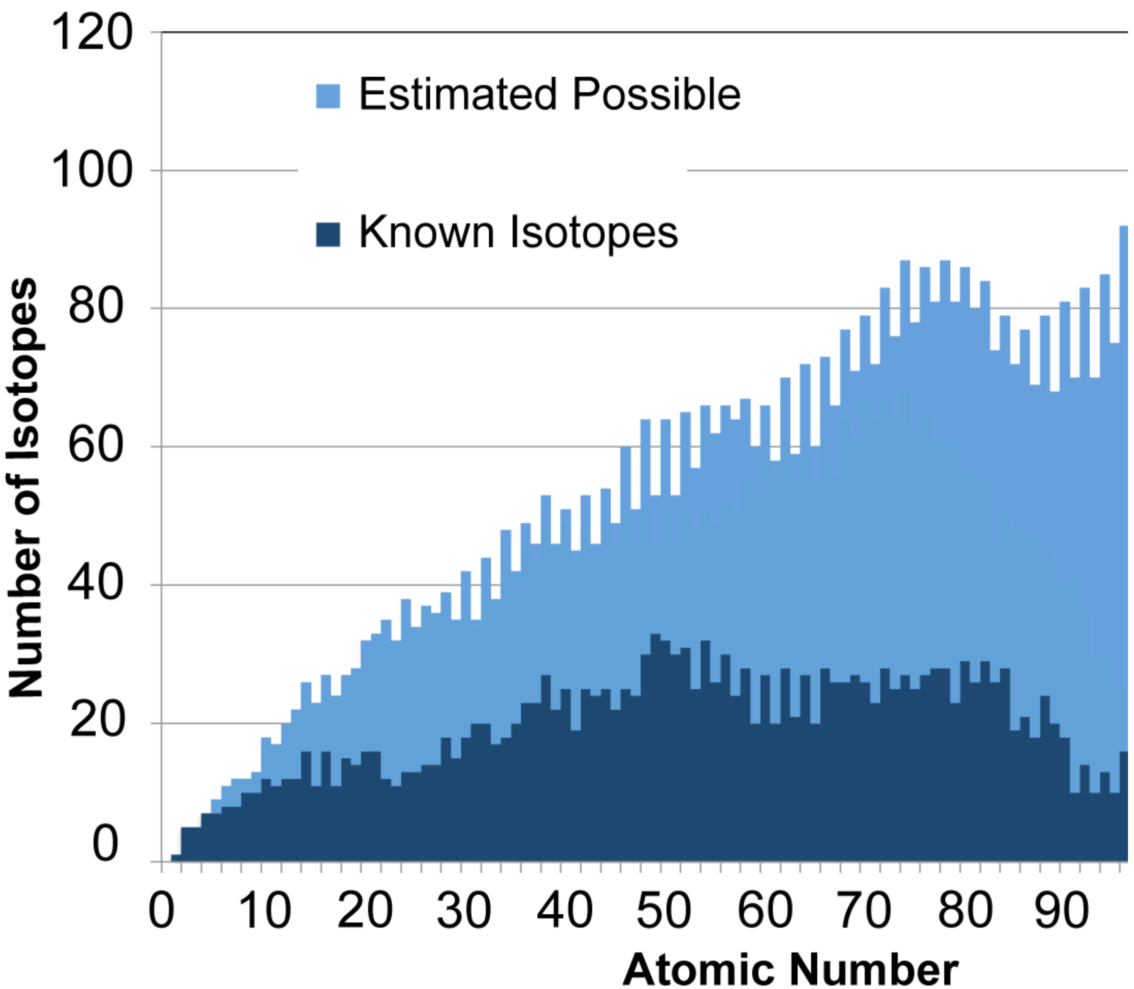
What New Nuclides Will Next Generation Facilities Produce?

- ✓ They will produce more than 1000 NEW isotopes at useful rates (4500 available for study)
- ✓ Theory is key to making the right measurements
- ✓ Exciting prospects for study of nuclei along the drip line to mass 120 (compared to 24)
- ✓ Production of most of the key nuclei for astrophysical modeling
- ✓ Harvesting of unusual isotopes for a wide range of applications



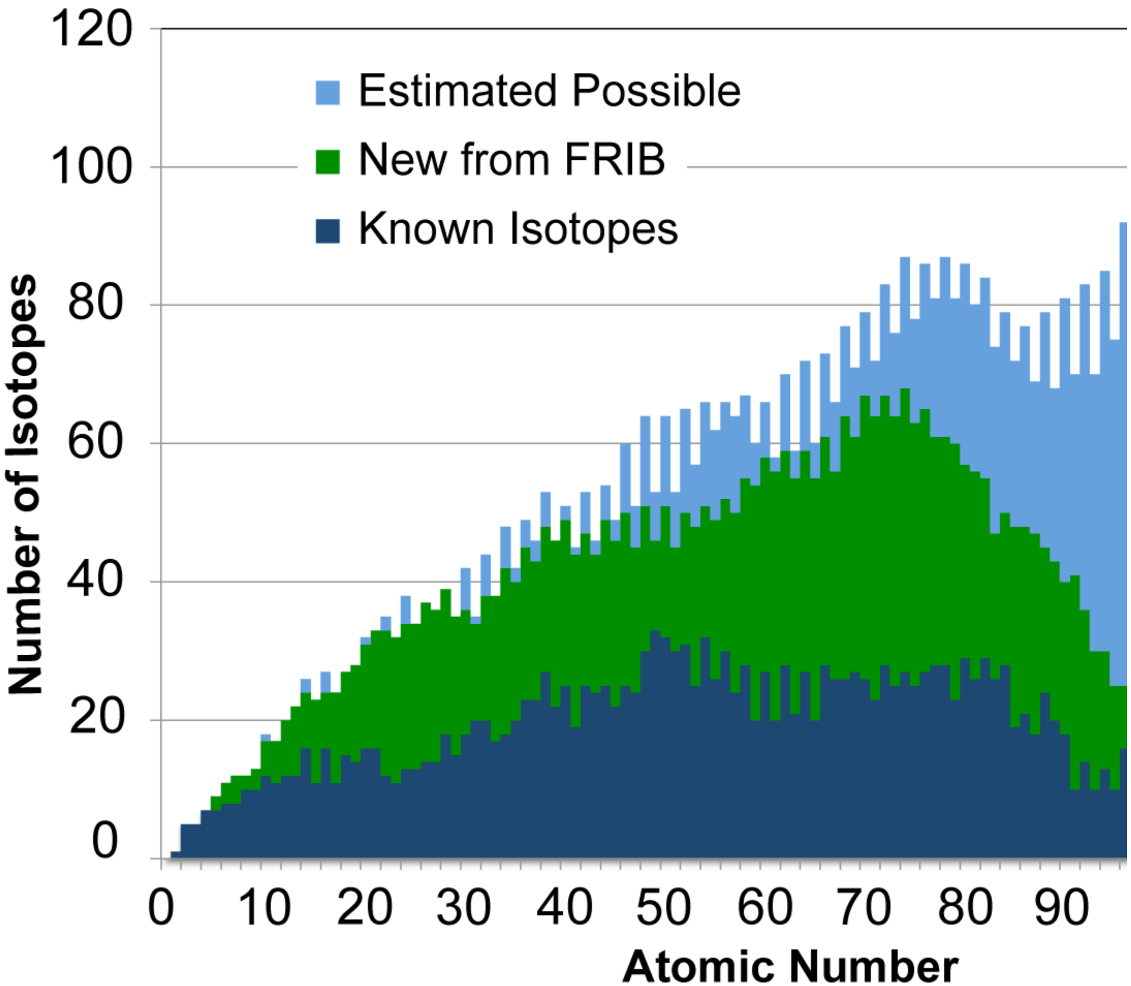
Rates are available at http://groups.nscl.msu.edu/frib/rates/

How many isotopes might exist?



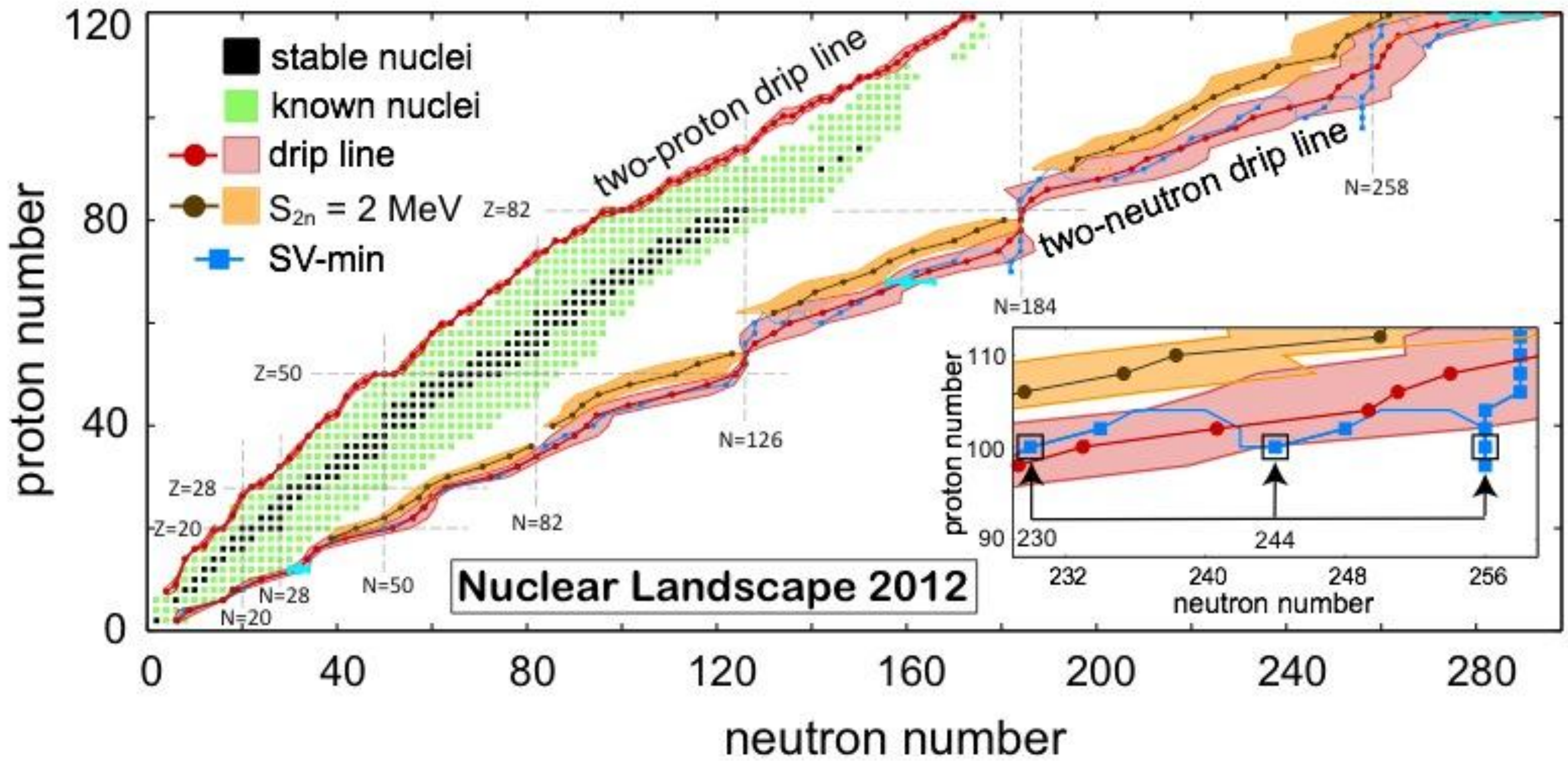
- **Estimated Possible: Erler, Birge, Kortelainen, Nazarewicz, Olsen, Stoitsov, Nature 486, 509–512 (28 June 2012) , based on a study of EDF models**
- **“Known” defined as isotopes with at least one excited state known (1900 isotopes from NNDC database)**
- **Represents what is possible now**

The Number of Isotopes Available for Study at FRIB (next generation facilities)



- **Estimated Possible: Erler, Birge, Kortelainen, Nazarewicz, Olsen, Stoitsov, Nature 486, 509–512 (28 June 2012) , based on a study of EDF models**
- **"Known" defined as isotopes with at least one excited state known (1900 isotopes from NNDC database)**
- **For Z<90 FRIB is predicted to make > 80% of all possible isotopes**

265 stable isotopes, 3100 observed, more like 2000 "known"



J. Erler et al., Nature 486, 509 (2012)

Z=8-14, 1970 - June, 2007

FLNR — 1970: Artukh, A. G. *et al.*, New isotopes ^{21}N, ^{23}O, ^{24}O and ^{25}F, produced in nuclear reactions with heavy ions. *Phys. Lett.* 32B, 43–44 (1970).

GANIL — 1990: Guillemaud-Mueller, D. *et al.*, Particle stability of the isotopes ^{26}O and ^{32}Ne in the reaction 44 MeV/nucleon ^{48}Ca+Ta. *Phys. Rev. C* 41, 937–941 (1990).

GANIL — 1997: Tarasov, O. *et al.*, Search for ^{28}O and study of neutron-rich nuclei near the *N* = 20 shell closure. *Phys. Lett. B* 409, 64–70 (1997).

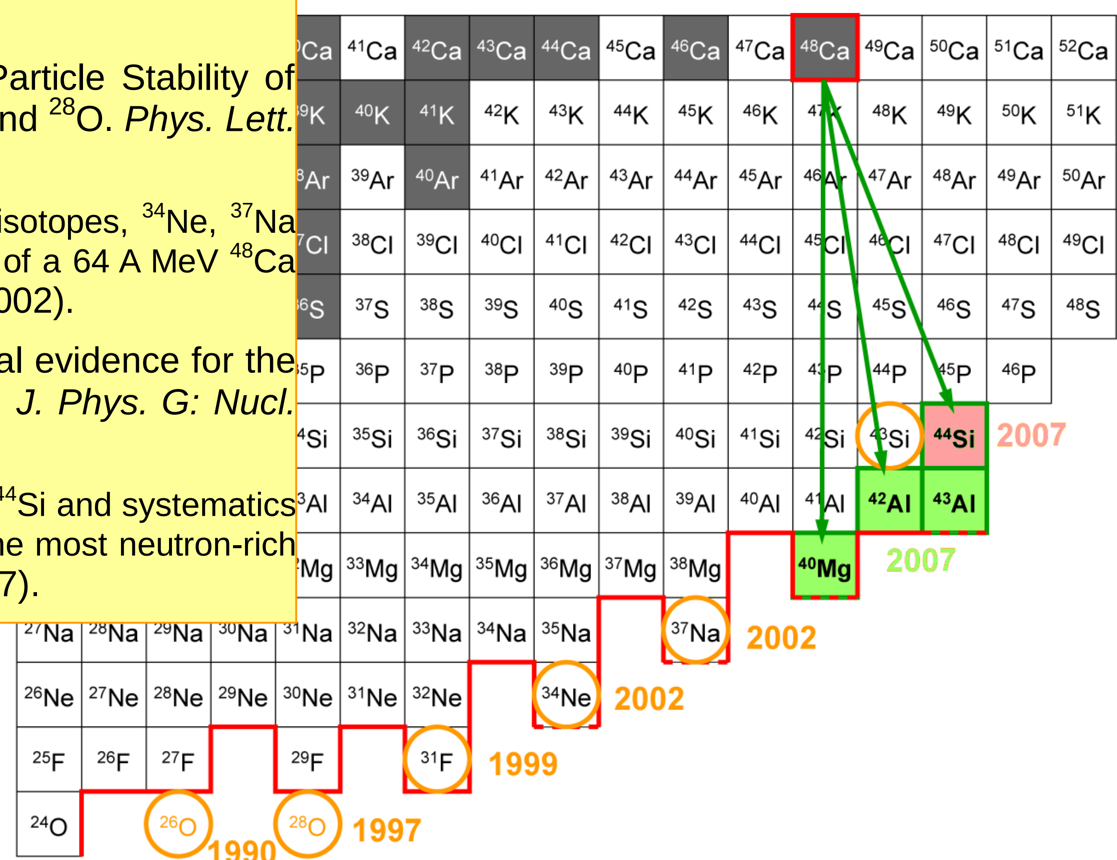
RIKEN — 1999: Sakurai, H. et al., Evidence for Particle Stability of ^{31}F and Particle Instability of ^{25}N and ^{28}O. *Phys. Lett. B* 448 180 (1999).

RIKEN — 2002: Notani, M. *et al.* New neutron-rich isotopes, ^{34}Ne, ^{37}Na and ^{43}Si, produced by fragmentation of a 64 A MeV ^{48}Ca beam. *Phys. Lett. B* 542, 49–54 (2002).

GANIL — 2002: Lukyanov, S. M. *et al.* Experimental evidence for the particle stability of ^{34}Ne and ^{37}Na. *J. Phys. G: Nucl. Part. Phys.* 28, L41–L45 (2002).

MSU — 2007: Tarasov, O. B., *et al.*, New isotope ^{44}Si and systematics of the production cross sections of the most neutron-rich nuclei. *Phys. Rev. C*, in press (2007).

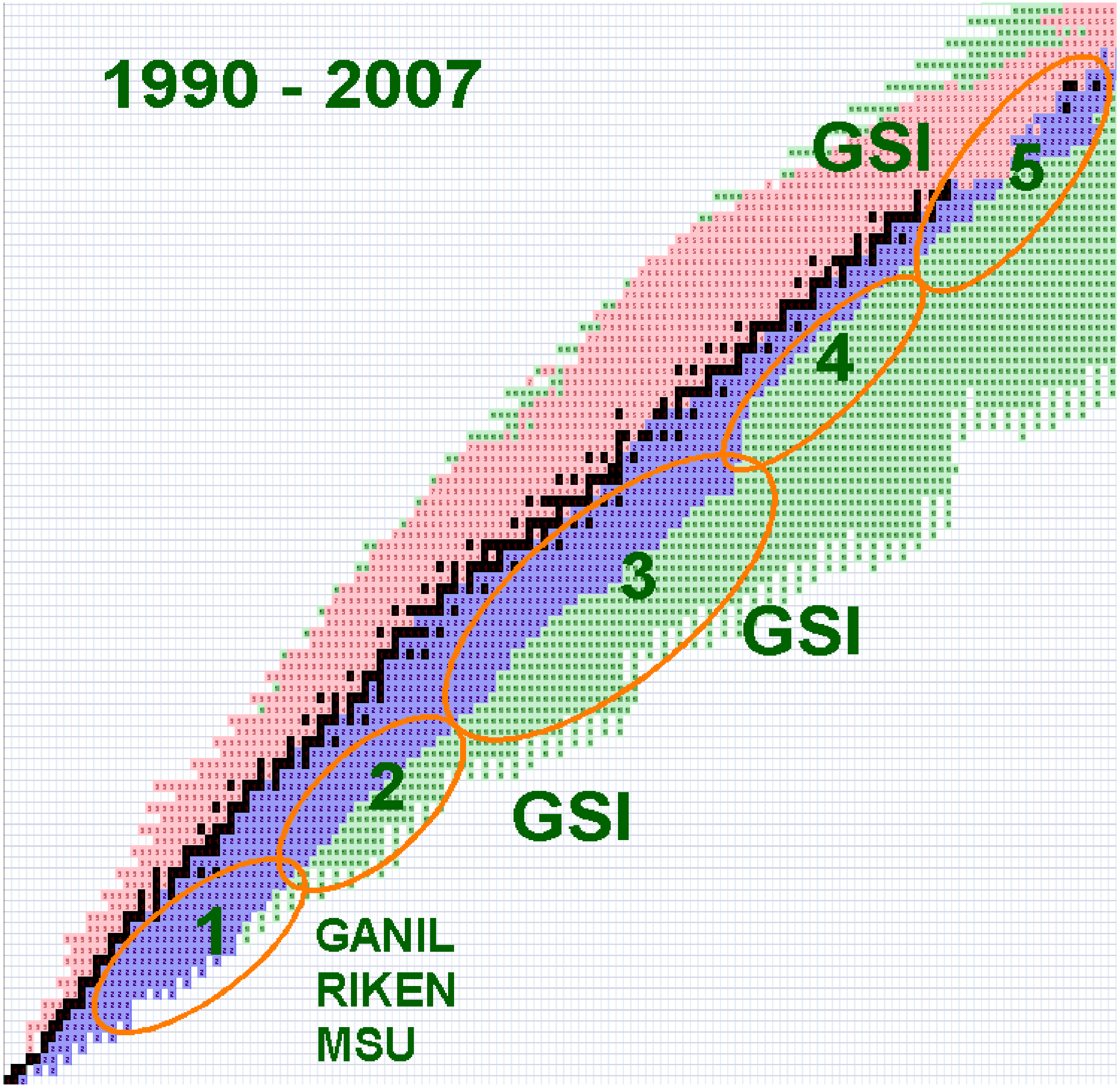
Figure. The region of the chart of nuclides under investigation in this work.



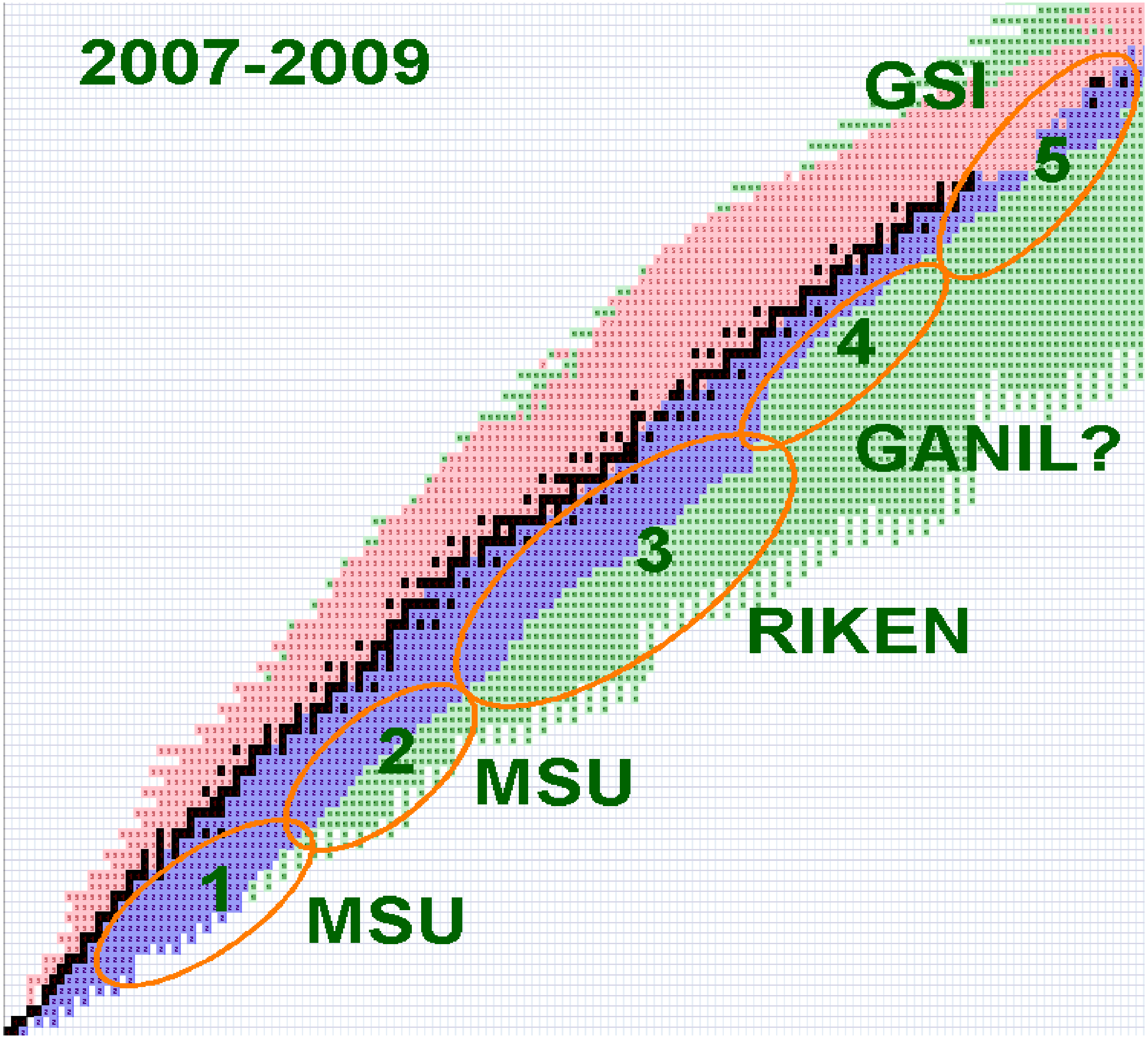
Neutron-rich side

Z< 100

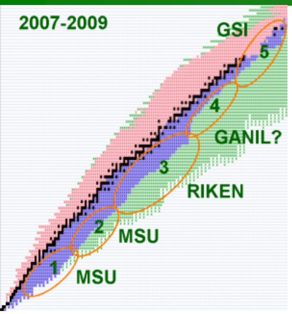
proton-rich side (^{100}Sn, ^{45}Fe, ^{48}Ni, ^{60}Ge etc) omitted:

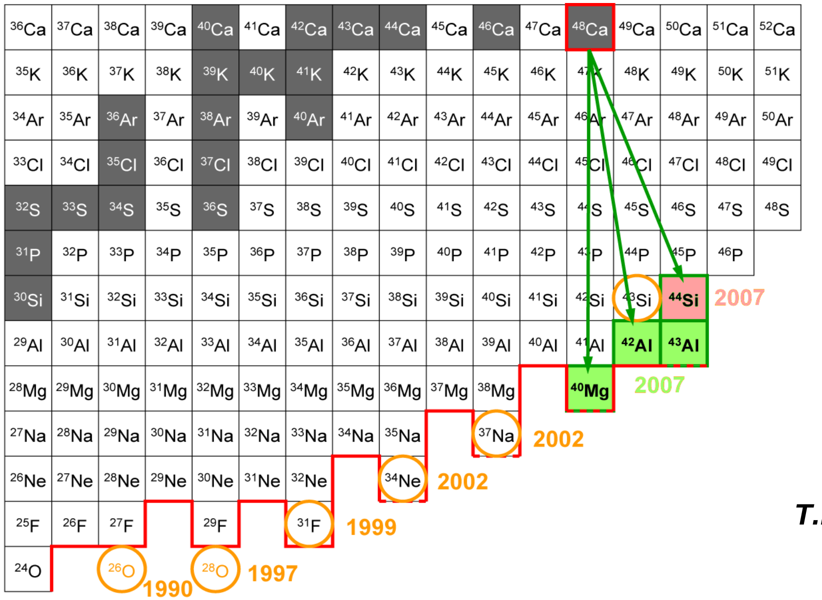


Exploration of unknown neutron-rich region



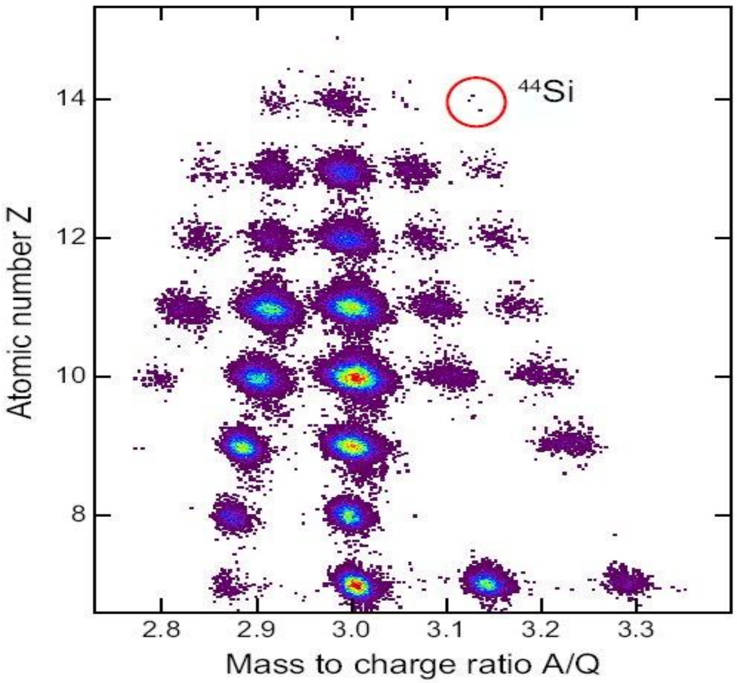
^{48}Ca (140MeV/u) + W (NSCL@MSU)

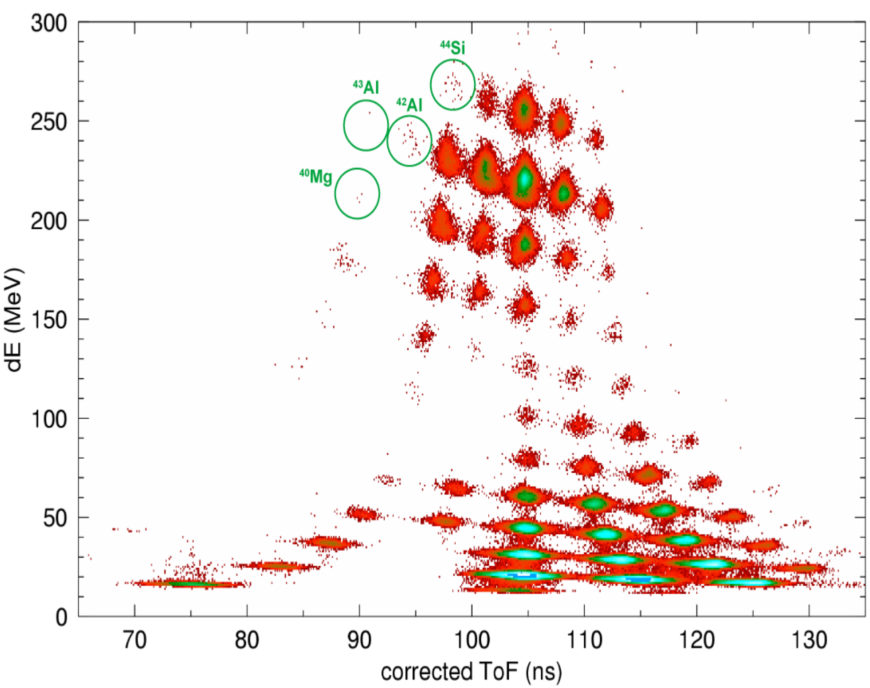




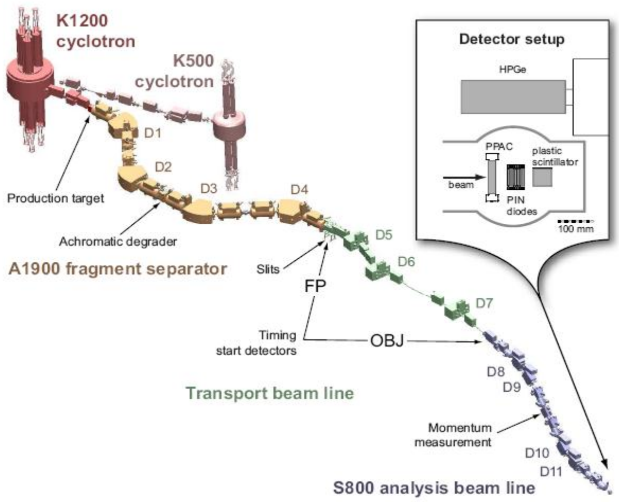
New isotope: ^{44}Si
O.T. et al., Phys.Rev. C 75, 064613 (2007)

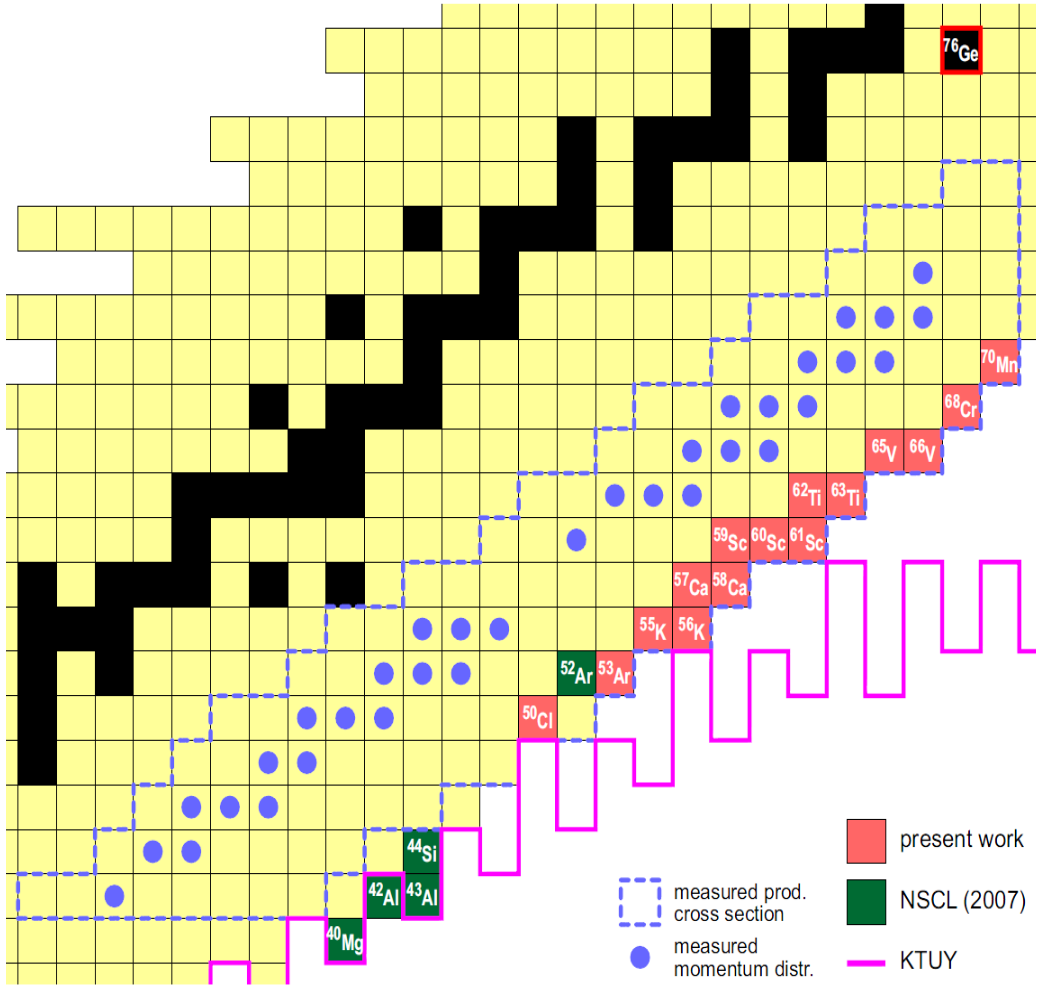
New isotopes ^{40}Mg, ^{42}Al, ^{43}Al
T.Baumann et al.,Nature(London) 449, 1022 (2007)





2009 : ^{76}Ge (130 MeV/u)





^{50}Cl, ^{53}Ar, ^{55,56}K, ^{57,58}Ca, ^{59,60,61}Sc, ^{62,63}Ti, ^{65,66}V, ^{68}Cr, ^{70}Mn

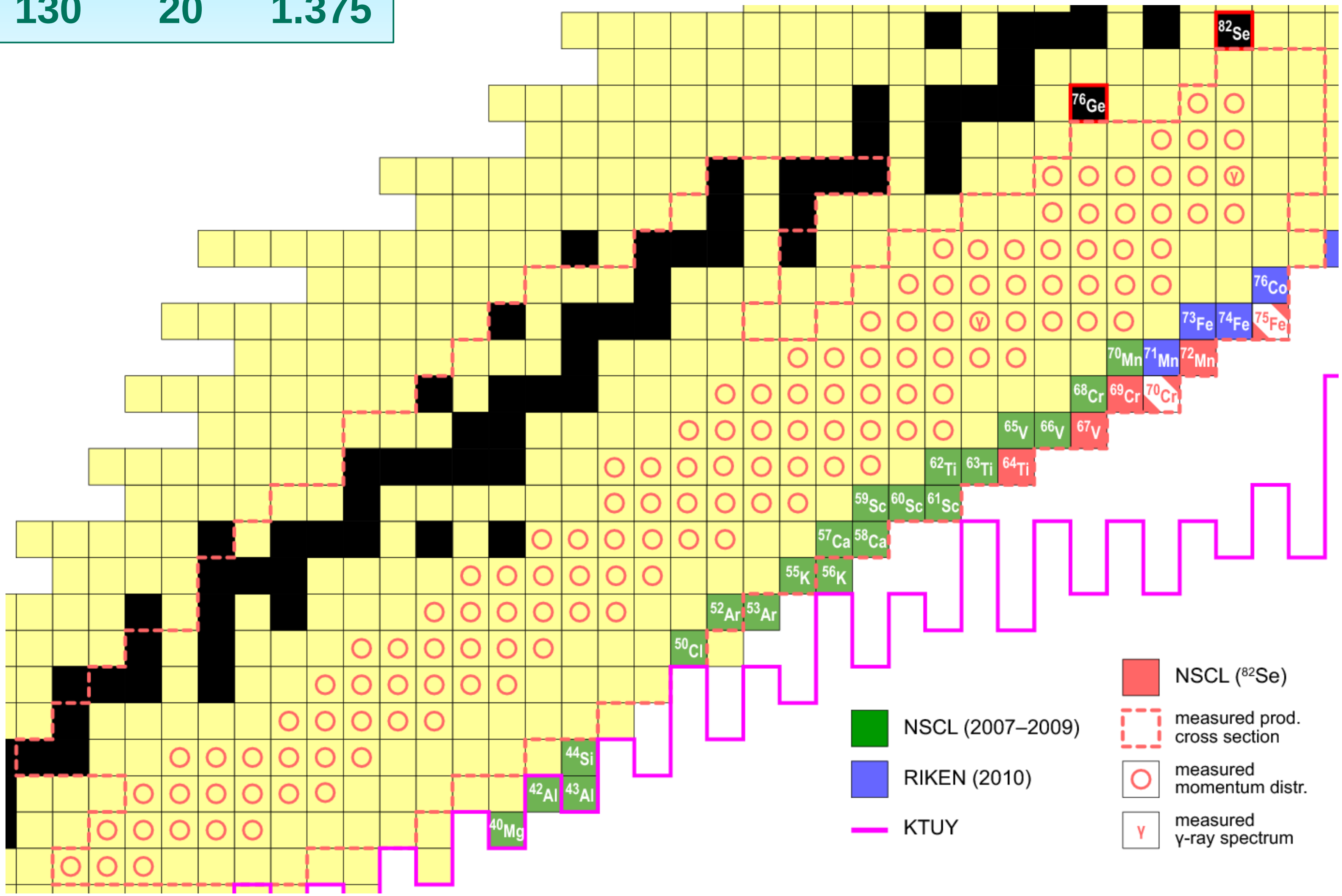
Phys.Rev.Lett.	**102, 142501 (2009) :**	**New isotopes, Evidence for a Change in the Nuclear Mass Surface**
Phys.Rev.C.	**80, 034609 (2009) :**	**Set-up, cross sections, momentum distributions**
NIM A	**620, 578-584 (2010) :**	**A new approach to measure momentum distributions**

Newly-developed ^{82}Se (139 MeV/u)

Beam	E (MeV/u)	I (pna)	N/Z
^{82}Se	139	35	1.412
^{76}Ge	130	20	1.375

^{64}Ti, ^{67}V, ^{69}Cr, ^{72}Mn
^{70}Cr ^{1event} & ^{75}Fe ^{1event}

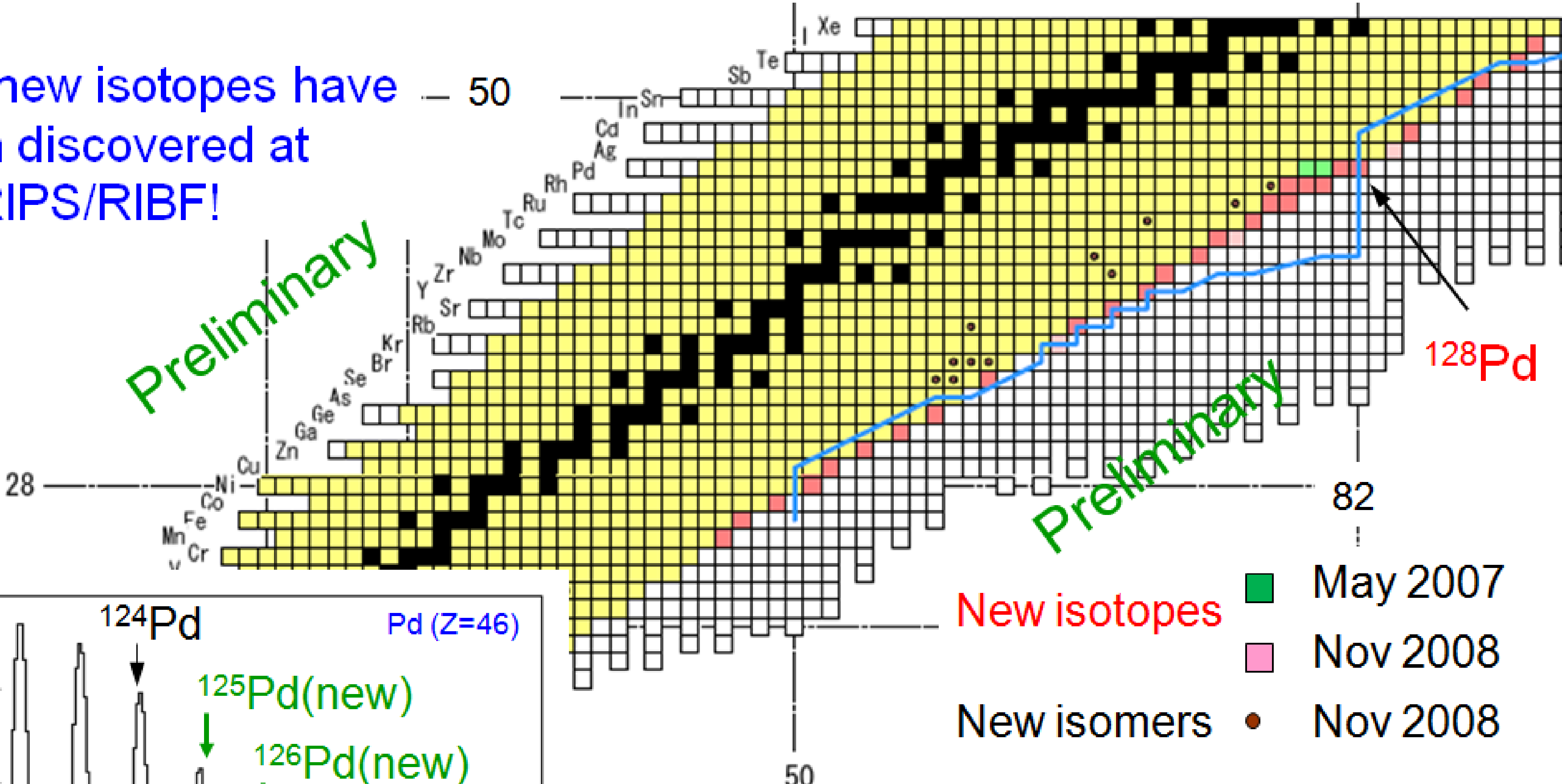
ΔN / ΔZ=2

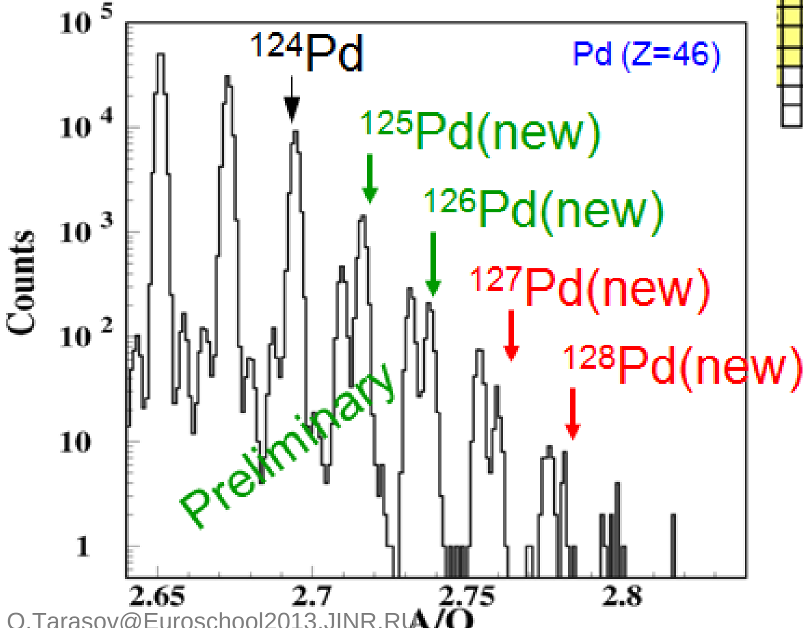


O.T. et al., Phys. Rev. C 87, 054612 (2013)

Search for new isotopes at RIKEN using ^{238}U beam at 345 MeV/u

~30 new isotopes have been discovered at BigRIPS/RIBF!



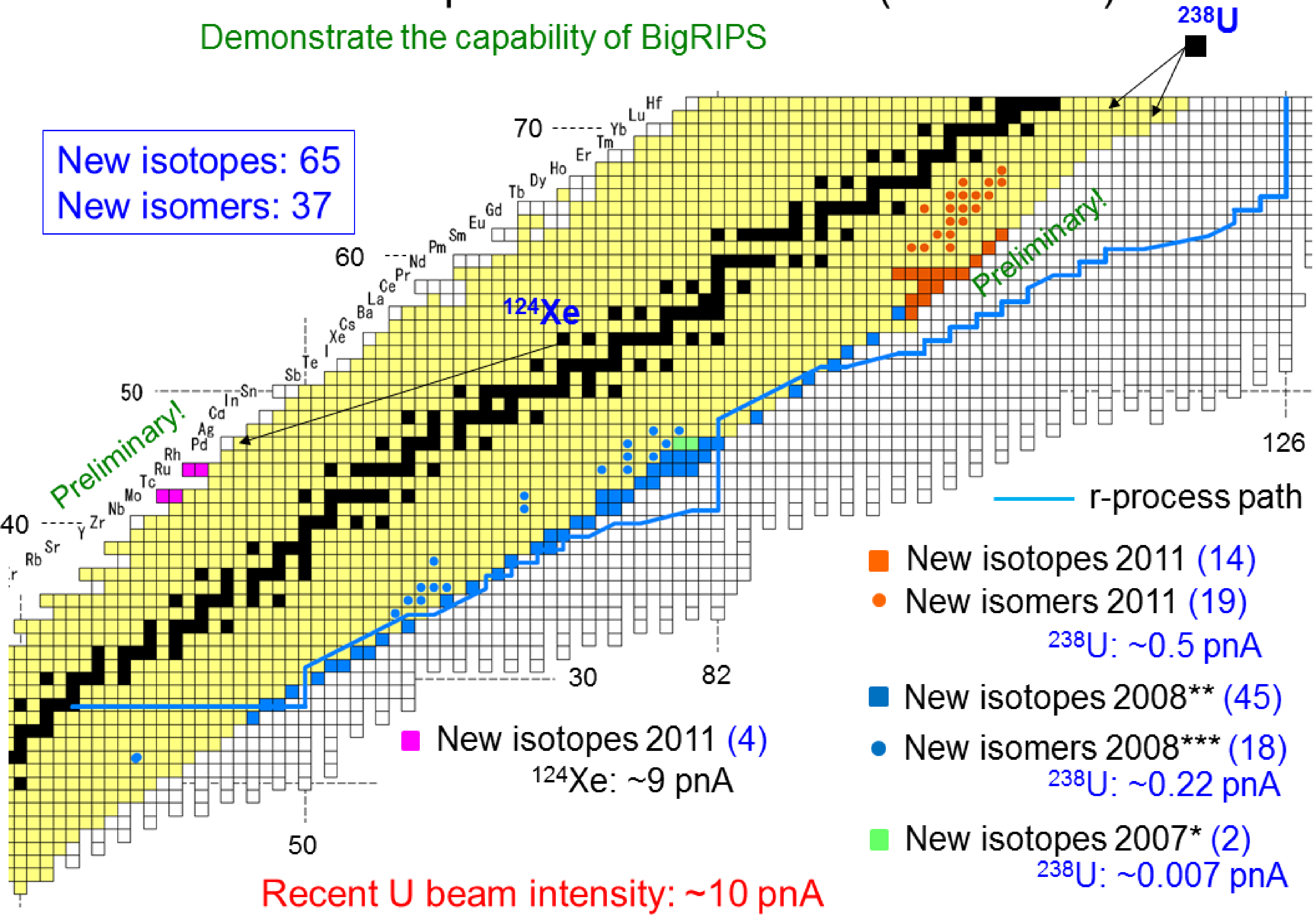


For Pd isotopes, we expanded the known limit by 4 neutrons, and reached N=82 magic number and r-process path.

Courtesy of T. Kubo, RIKEN Oct. 5, 2009

Search for new isotopes and new isomers (2007-2011)

Demonstrate the capability of BigRIPS



GSI : 60 new isotopes in 2012

Physics Letters B 717 (2012) 371–375

ELSEVIER

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Discovery and cross-section measurement of neutron-rich isotopes in the element range from neodymium to platinum with the FRS

J. Kurcewicz [a,*], F. Farinon [a,b,1], H. Geissel [a,b], S. Pietri [a], C. Nociforo [a], A. Prochazka [a,b], H. Weick [a], J.S. Winfield [a], A. Estradé [a,c], P.R.P. Allegro [d], A. Bail [e], G. Bélier [e], J. Benlliure [f], G. Benzoni [g], M. Bunce [h], M. Bowry [h], R. Caballero-Folch [i], I. Dillmann [a,b], A. Evdokimov [a,b], J. Gerl [a], A. Gottardo [j], E. Gregor [a], R. Janik [k], A. Kelić-Heil [a], R. Knöbel [a], T. Kubo [l], Yu.A. Litvinov [a,m], E. Merchan [a,n], I. Mukha [a], F. Naqvi [a,o], M. Pfützner [a,p], M. Pomorski [p], Zs. Podolyák [h], P.H. Regan [h], B. Riese [a,b], M.V. Ricciardi [a], C. Scheidenberger [a,b], B. Sitar [k], P. Spiller [a], J. Stadlmann [a], P. Strmen [k], B. Sun [b,q], I. Szarka [k], J. Taïeb [e], S. Terashima [a,l], J.J. Valiente-Dobón [j], M. Winkler [a], Ph. Woods [r]

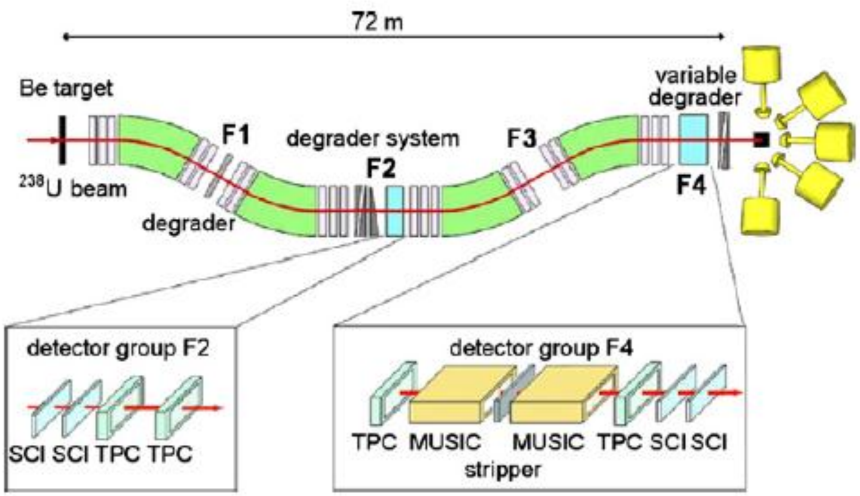


Fig. 1. (Color online.) Schematic view of the four magnetic dipole stages of the FRS with the target area and the detector and degrader systems at the focal planes.

GSI : 60 new isotopes in 2012

Physics Letters B 717 (2012) 371–375

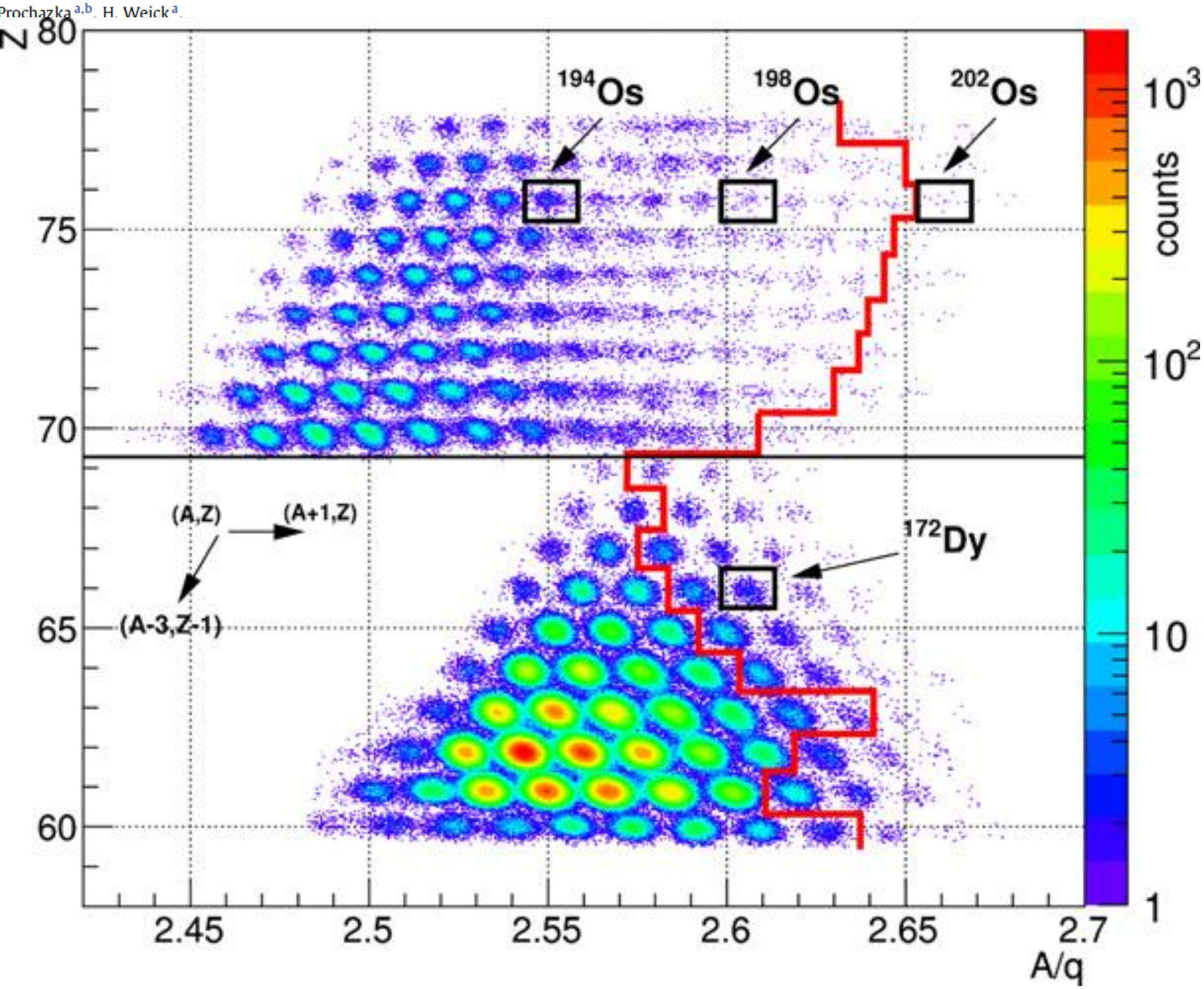
Contents lists available at SciVerse ScienceDirect

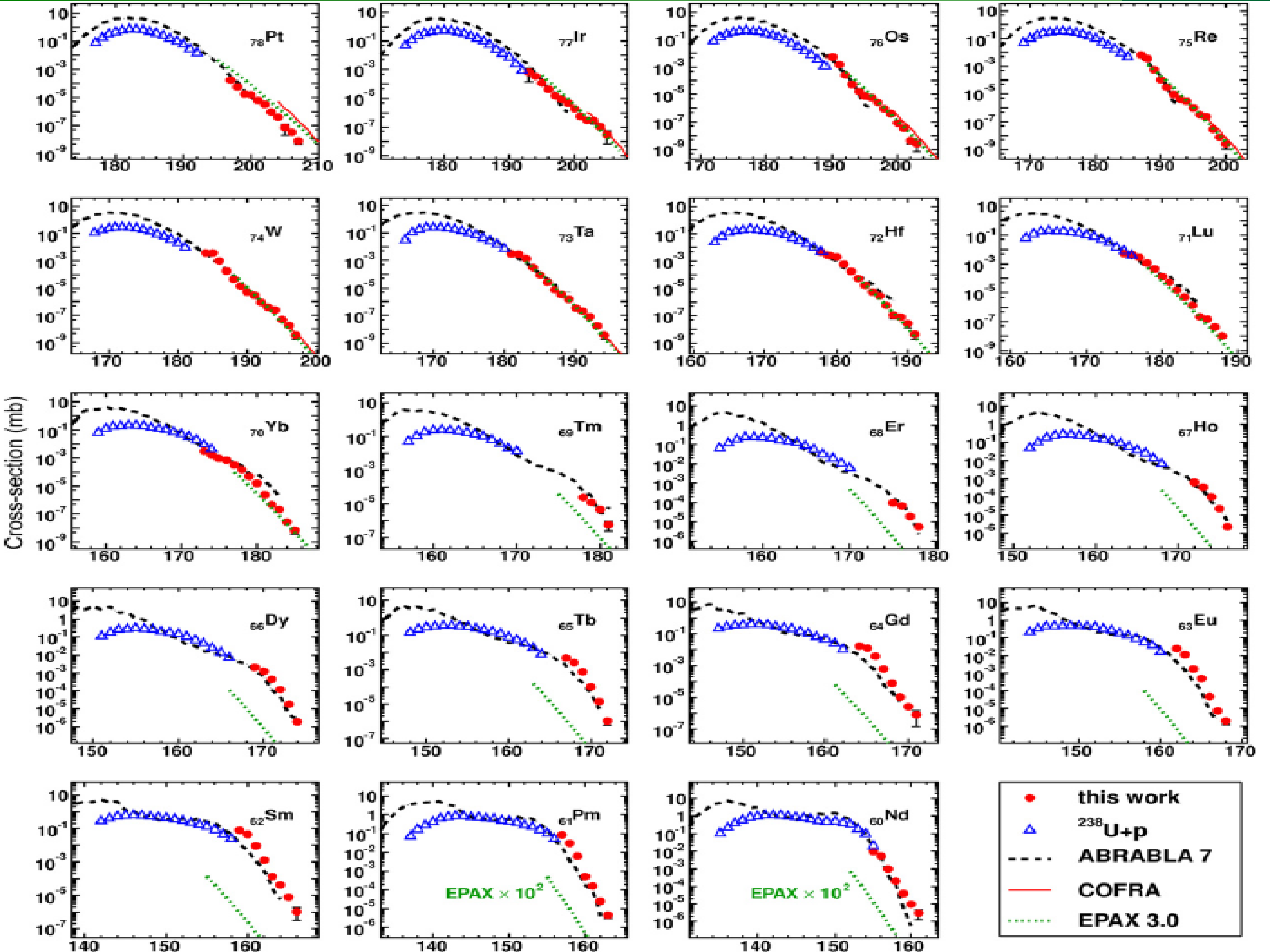
Physics Letters B

www.elsevier.com/locate/physletb

Discovery and cross-section measurement of neutron-rich isotopes in the element range from neodymium to platinum with the FRS

J. Kurcewicz[a,*], F. Farinon[a,b,1], H. Geissel[a,b], S. Pietri[a], C. Nociforo[a], A. Prochazka[a,b], H. Weick[a],
J.S. Winfield[a], A. Estradé[a,c], P.R.P. Allegro[d], A. Bail[e], G. Bélier[e], J. Benlliu
M. Bowry[h], R. Caballero-Folch[i], I. Dillmann[a,b], A. Evdokimov[a,b], J. Gerl
R. Janik[k], A. Kelić-Heil[a], R. Knöbel[a], T. Kubo[l], Yu.A. Litvinov[a,m], E. Merc
M. Pfützner[a,p], M. Pomorski[p], Zs. Podolyák[h], P.H. Regan[h], B. Riese[a,b], M
C. Scheidenberger[a,b], B. Sitar[k], P. Spiller[a], J. Stadlmann[a], P. Strmen[k], B.
S. Terashima[a,l], J.J. Valiente-Dobón[j], M. Winkler[a], Ph. Woods[r]



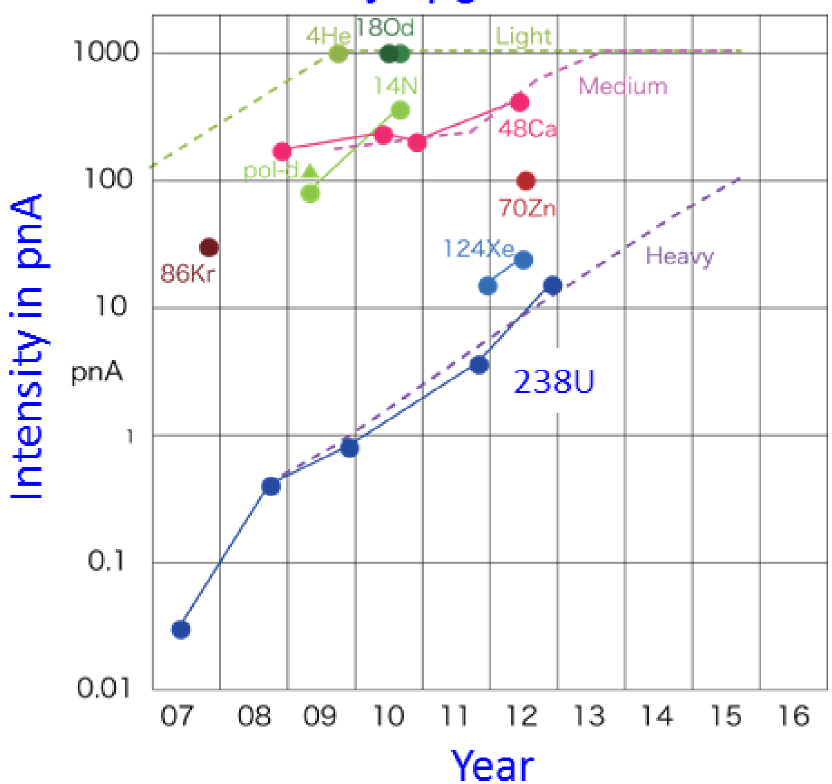


Cross-section (mb)
$_{78}$Pt
$_{77}$Ir
$_{76}$Os
$_{75}$Re
$_{74}$W
$_{73}$Ta
$_{72}$Hf
$_{71}$Lu
$_{70}$Yb
$_{69}$Tm
$_{68}$Er
$_{67}$Ho
$_{66}$Dy
$_{65}$Tb
$_{64}$Gd
$_{63}$Eu
$_{62}$Sm
$_{61}$Pm
$_{60}$Nd
EPAX × 10^2
EPAX × 10^2
this work
^{238}U+p
ABRABLA 7
COFRA
EPAX 3.0

RIKEN : Summary

- Experimental facilities at RIKEN RIBF, such as BigRIPS, ZeroDegree, SAMURAI, SHARAQ, SLOWRI/PALIS, Rare RI Ring, SCRIT, have been reviewed.
- Outlook of primary beam intensity

Planned schedule of intensity upgrade at RIBF



(From RIKEN accelerator group)

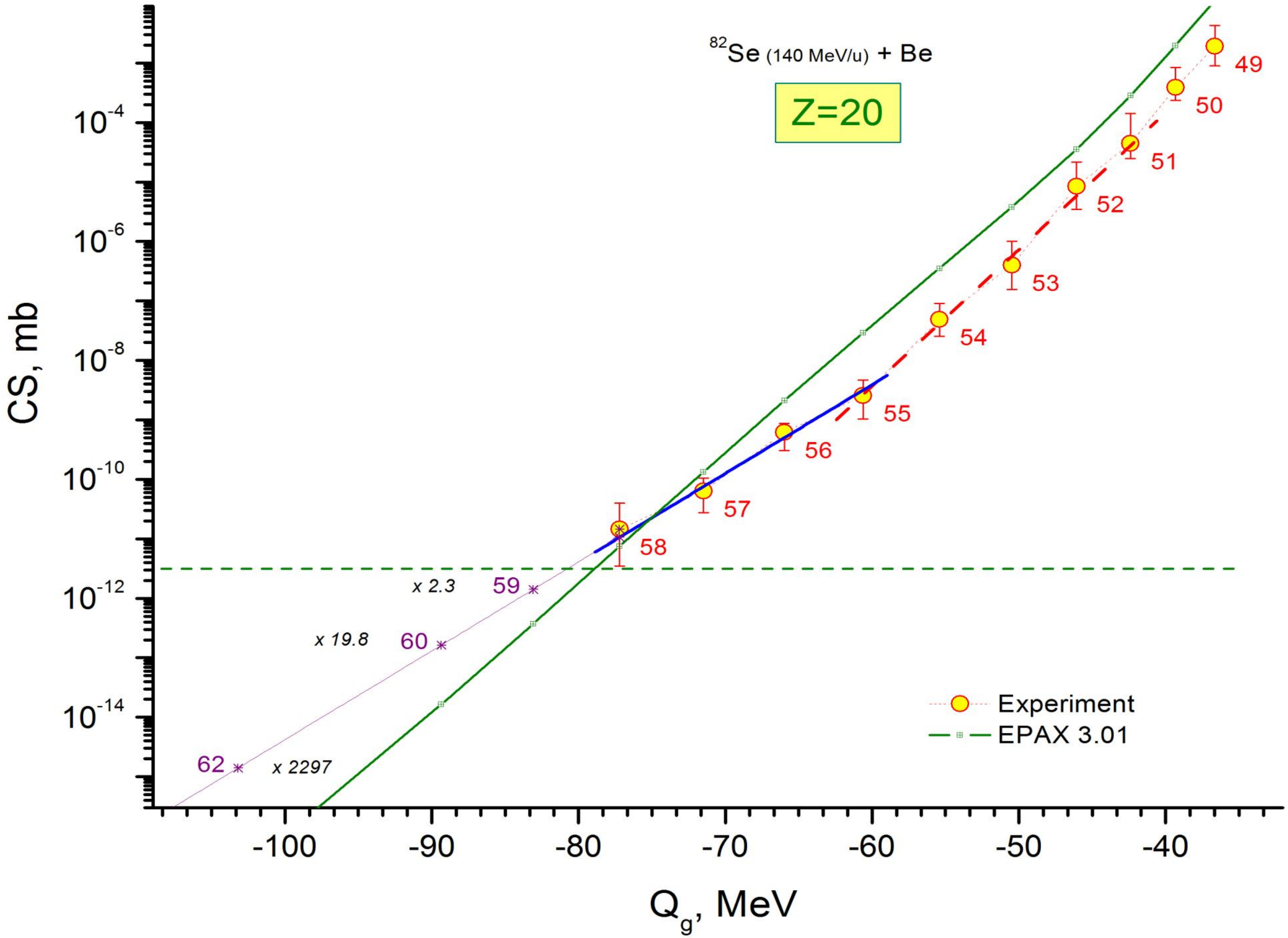
Present status of primary beams

Beam particle	E/A(MeV)	Beam current (pnA) Maximum record	Expected ¶	Injector
d	250	1000	200	AVF
d(pol.)	250	120	30	AVF
^{4}He	320	1000	1000	AVF
^{14}N	250	400	400	RILAC
^{18}O	345	1000	500	RILAC
^{48}Ca	345	415	150	RILAC
^{70}Zn	345	100	75	RILAC
^{76}Ge	345	not tested	N/A	RILAC
^{78}Kr	345	under development	50	RILAC
^{86}Kr	345	30	50	RILAC
^{136}Xe	345	not tested	20	RILAC2
^{124}Xe	345	27	20	RILAC2
^{238}U	345	15.1	10	RILAC2

¶ Some intensities are limited by shielding requirements

Courtesy of T.Kubo

“Next” Calcium isotopes



Intensity: Factors for production of new isotopes

$$Y = I \quad t \quad N_t \quad \sigma \quad \varepsilon_t \quad \varepsilon_s \quad \varepsilon_i$$

Laboratory	Separator	Energy, Mev/u	target thickness	atoms/cm^2	Intensity, pnA	Experiment time	published measured cross section [barn]		dose, beam particles	reduced* CS, barn
GSI	FRS	500-1000	Be:1-10g	8.00E+22	3.00E-03	1 week	1E-10	M.Bernas et al., PL B 415 (1997) 111	1E+13	1E-12
GANIL	LISE	75	Ta:1g	3.60E+21	10-100	1 week	2E-13	O.Tarasov et al., PL B409 (1997)64	2E+17	1E-15
RIKEN	RIPS	90	Ta:0.7g	2.30E+21	10-100	1 week	2E-14	H.Sakurai et al., PL B448 (1999) 180	2E+17	3E-15
GANIL	LISE	60	Ta:0.3g	8.80E+20	10-100	1 week	6E-14	S.Lukyanov et al., J Phys G 28 (2002) L41	4E+17	3E-15
RIKEN	BigRIPS	340	Be:1g	6.20E+22	0.1-10	1 week	1E-13	T.Ohnishi et al., JPSJ 79 (2010) 073201	9E+14	2E-14
Dubna	GFS	6-10	Bk: 3e-4 g	7.30E+17	1000	half year	1E-13	Yu.Oganessian et al., PRL 104 (2010) 142502	1E+20	1E-14
NSCL	A1900	140	W:1.9g	6.30E+21	8.00E+01	11 days	*9.4E-15*	T.Baumann et al., Nature 449 (2007) 1022	5E+17	3.3E-16
NSCL	A1900	130	Be:0.7g	4.70E+22	2.50E+01	1 week	8E-15	O.Tarasov et al., PRL 102 (2009) 142501	9E+16	2.3E-16
NSCL	A1900	140	Be:0.8g	5.35E+22	3.50E+01	1 week	3E-15	O.T. et al., PRC 87 (2013) 054612	1E+17	1.4E-16
	FUTURE									
GSI	SuperFRS	1.50E+03	Be:15g	1.00E+24	1.60E+02	1 week			6E+17	1.7E-18
FRIB	A2400	200	Be:1g	6.20E+22	1.00E+04	1 week			4E+19	4.3E-19

* ***reduced***, **Y=1 , assuming** ε_t ε_s ε_I **equal to 100%, 100% time just for one production run**

**** RIKEN : ^{48}Ca 345 MeV/u 150 pnA**

Estimated rates

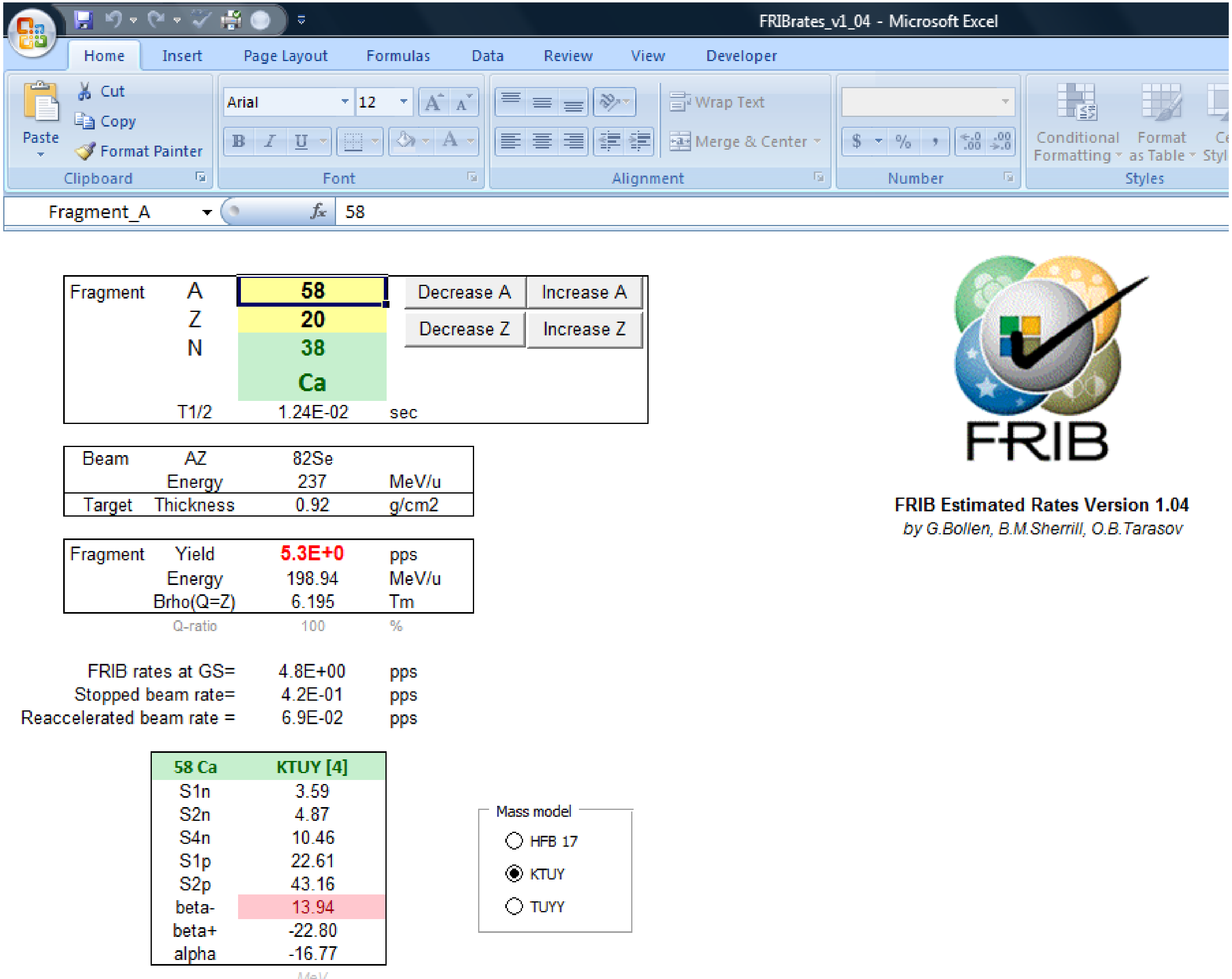
FRIB Estimated Rates

FRIB

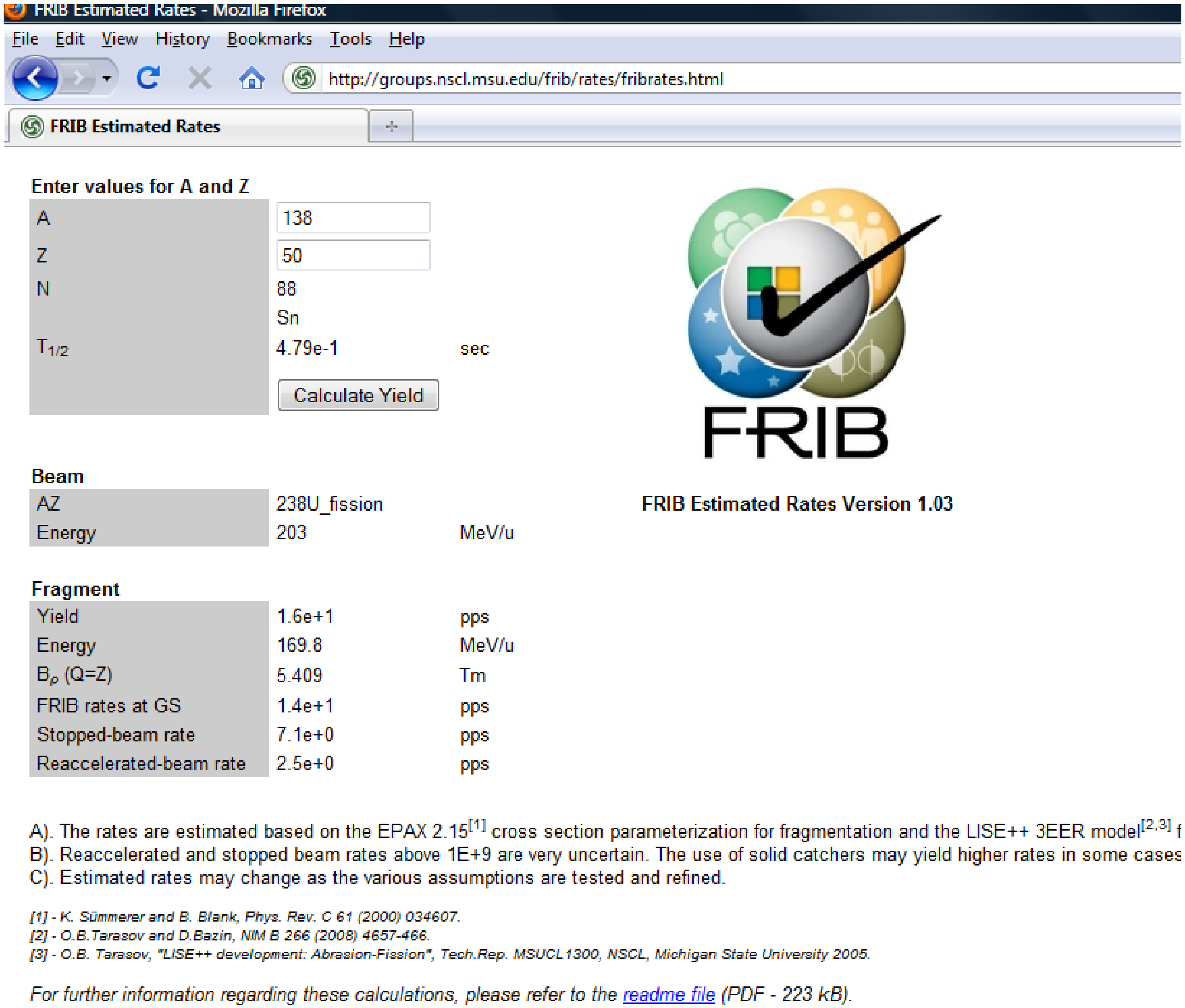
http://groups.nscl.msu.edu/frib/rates/

Readme file : http://groups.nscl.msu.edu/frib/rates/FRIB_rates_readme.pdf

Excel version



Java version



FRIB Estimated Rates - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://groups.nscl.msu.edu/frib/rates/fribrates.html

FRIB Estimated Rates

Enter values for A and Z

A	138	
Z	50	
N	88	
	Sn	
$T_{1/2}$	4.79e-1	sec
	Calculate Yield	

FRIB

FRIB Estimated Rates Version 1.03

Beam

AZ	238U_fission	
Energy	203	MeV/u

Fragment

Yield	1.6e+1	pps
Energy	169.8	MeV/u
B_ρ (Q=Z)	5.409	Tm
FRIB rates at GS	1.4e+1	pps
Stopped-beam rate	7.1e+0	pps
Reaccelerated-beam rate	2.5e+0	pps

A). The rates are estimated based on the EPAX 2.15[1] cross section parameterization for fragmentation and the LISE++ 3EER model[2,3] f
B). Reaccelerated and stopped beam rates above 1E+9 are very uncertain. The use of solid catchers may yield higher rates in some cases
C). Estimated rates may change as the various assumptions are tested and refined.

[1] - K. Sümmerer and B. Blank, Phys. Rev. C 61 (2000) 034607.
[2] - O.B.Tarasov and D.Bazin, NIM B 266 (2008) 4657-466.
[3] - O.B. Tarasov, "LISE++ development: Abrasion-Fission", Tech.Rep. MSUCL1300, NSCL, Michigan State University 2005.

For further information regarding these calculations, please refer to the readme file (PDF - 223 kB).

http://groups.nscl.msu.edu/frib/rates/fribrates.html

Exploration of unknown neutron-rich region. Next

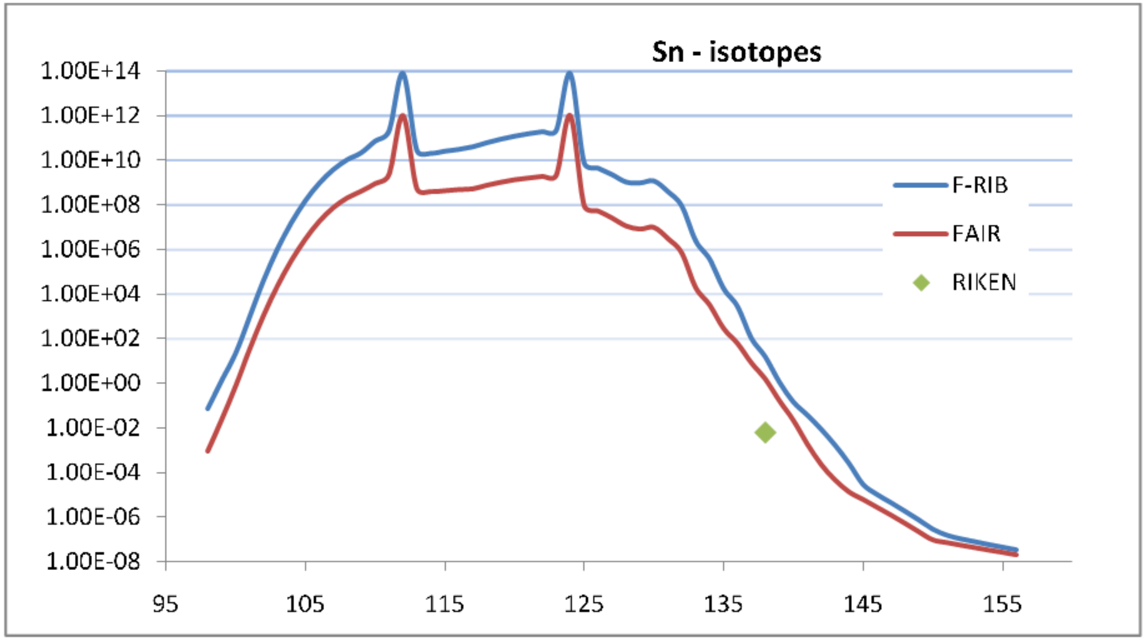
In action: RIBF @ RIKEN
^{238}U 345 MeV/u, 1 pnA

2019 - 2020: GSI – new isotope production
with pre-separator, 1.5 GeV/u, 10^{12} pps

2020-2022: FRIB @ MSU
200-250 MeV/ u , 400 kW

Yields per 1 second

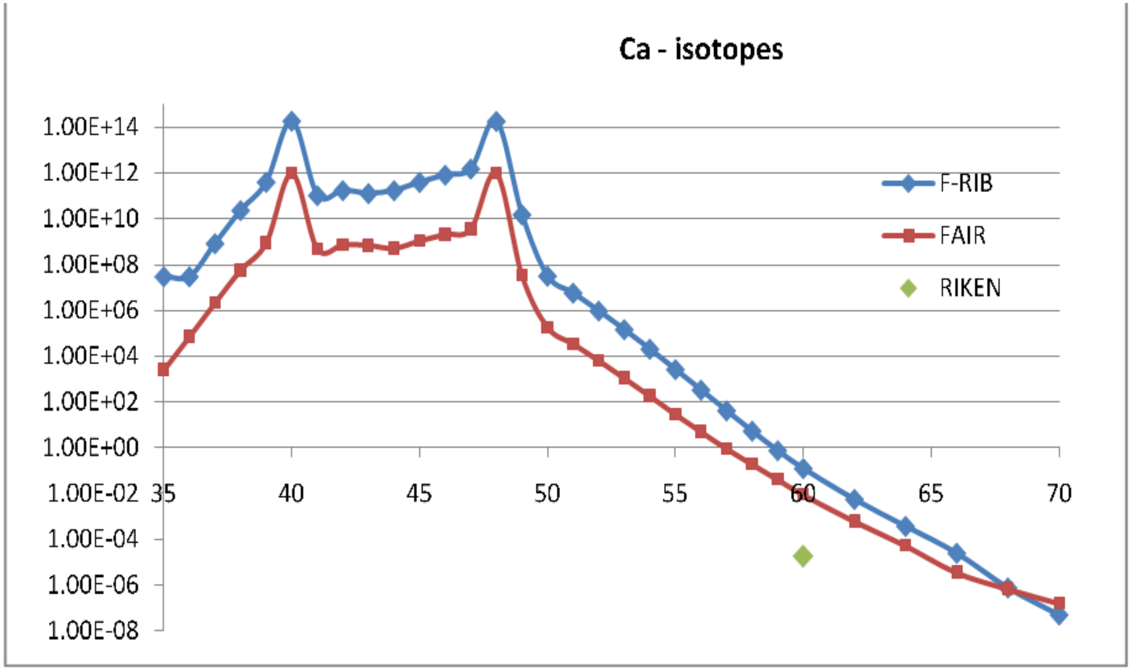
A total of 47 primary beams were used for FRIB yield analysis. These cover nearly 90% of the optimum primary beams for the production of all isotopes.



RIBF @ RIKEN
^{238}U 345 MeV/u, 2pnA

GSI ,1.5 GeV/u, 10^{12} pps

F-RIB @ MSU
200-250 MeV/ u , 400 kW



RIBF beam intensities (2009)

	^{48}Ca	Kr	Xe	^{238}U
FY2008	170 pnA	30 pnA *1	-	0.4 pnA
FY2009 expected	200 pnA	30 pnA *2	10 pnA	5 pnA *3

***1: 1min *2: Limited by e04 CS *3: with SC-ECRIS**

U-beam intensity in future (rumor): ~100 pnA with new injector linac, new 28GHz S.C. ECR ion source and new stripper

Courtesy of T.Kubo

FRIB : new isotopes per 1 second

TimeSec = 0.864 sec

Experiment time =	1.00E-05	days
Mode =	1	

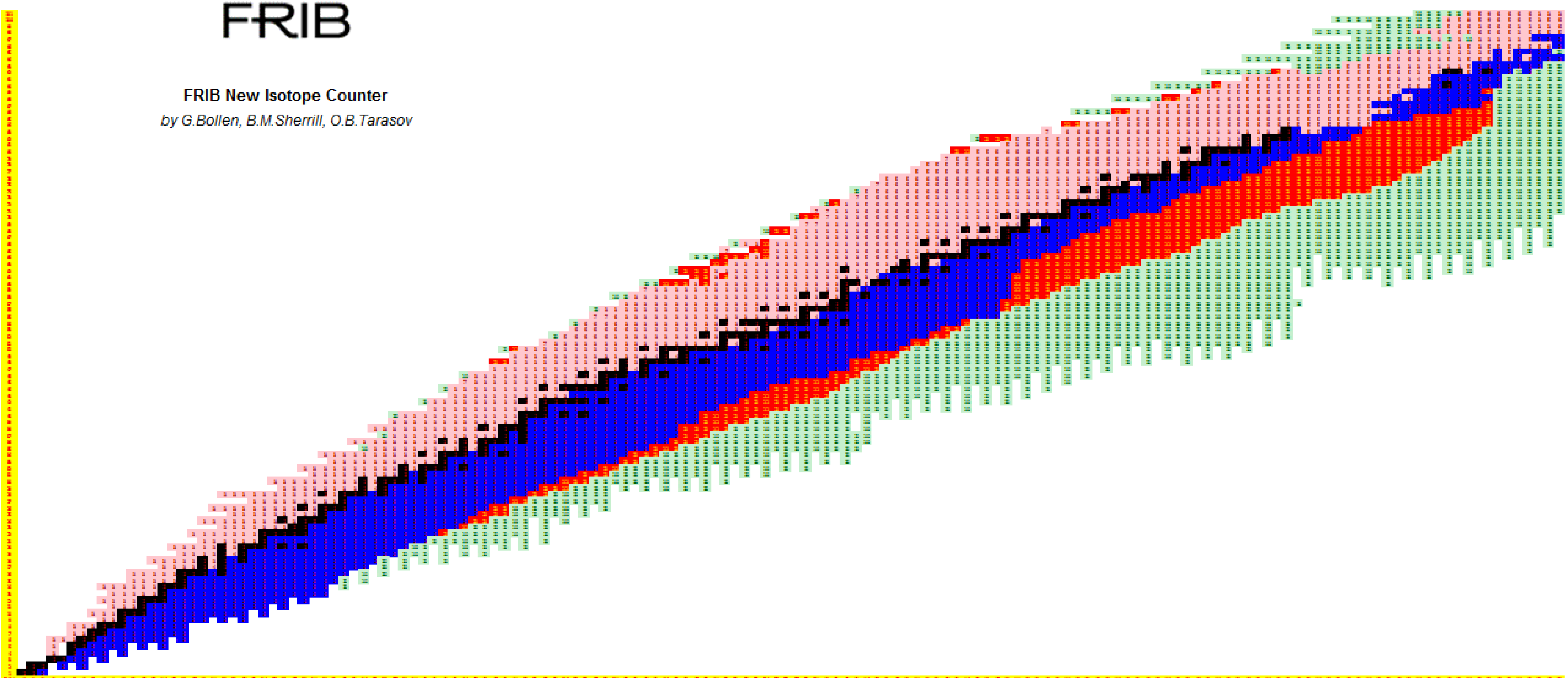
Mode	
0	Yield
1	FRIB rates at GS
2	Stopped-beam rate
3	Reaccelerated beam rate

Symbol	Decay mode / State	Count
-1	unbound	28
0	doesn't exist	
1	stable	278
2	beta- decay	1054
3	beta+ decay	876
4	beta+ & beta-	29
5	alpha decay	218
6	alpha & beta+ decay	249
7	proton decay	15
8	Spontaneous fission	12
9	SF + alpha decay	5
10	KTYU particle bound	3113
11	**new isotopes**	**511**

FRIB

FRIB New Isotope Counter

by G.Bollen, B.M.Sherrill, O.B.Tarasov



FRIB : new isotopes per 1 week

TimeSec = 604800 sec

Experiment time =	7.00E+00	days
Mode =	0	

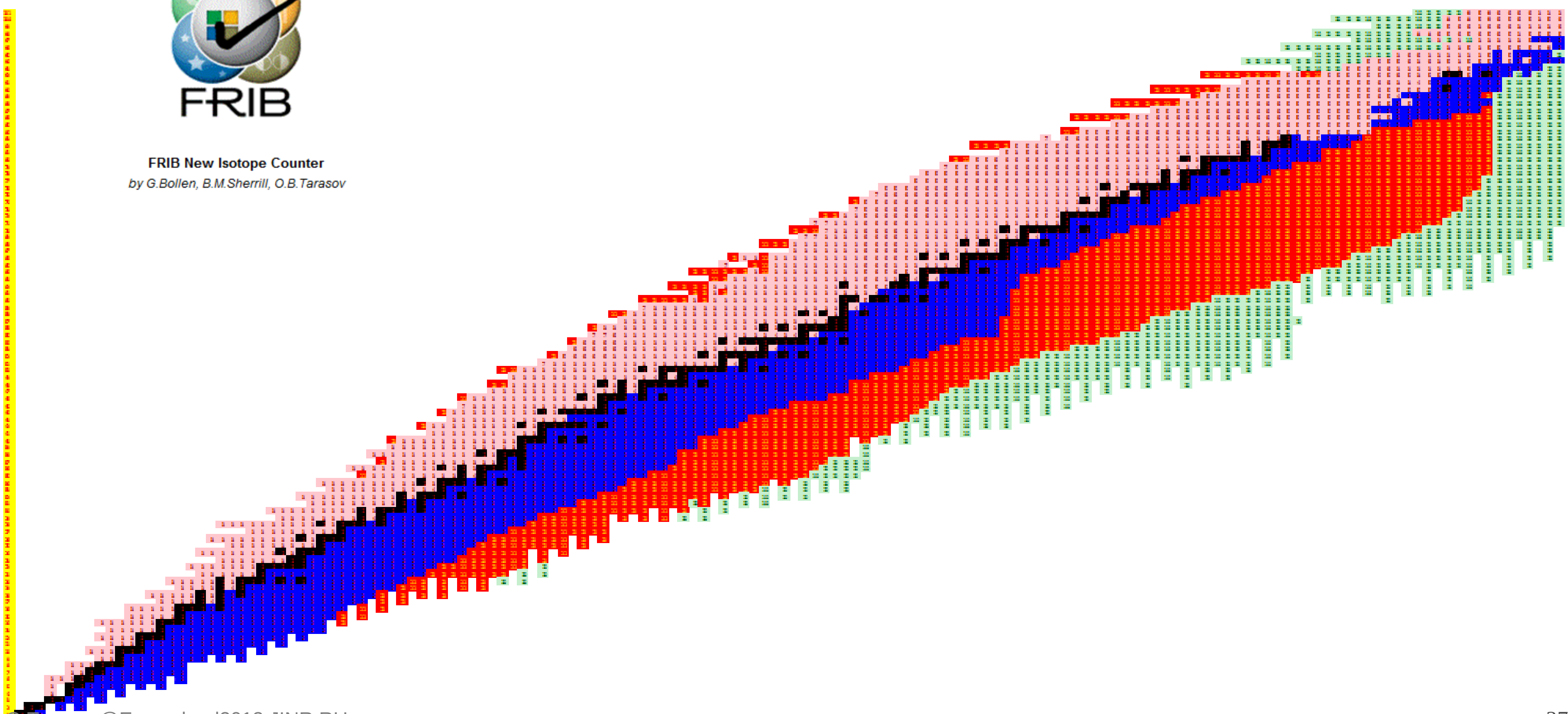
Mode	
0	Yield
1	FRIB rates at GS
2	Stopped-beam rate
3	Reaccelerated beam rate

Symbol	Decay mode / State	Count
-1	unbound	28
0	doesn't exist	
1	stable	278
2	beta- decay	1054
3	beta+ decay	876
4	beta+ & beta-	29
5	alpha decay	218
6	alpha & beta+ decay	249
7	proton decay	15
8	Spontaneous fission	12
9	SF + alpha decay	5
10	KTYU particle bound	3113
11	**new isotopes**	**1213**

FRIB

FRIB New Isotope Counter

by G.Bollen, B.M.Sherrill, O.B.Tarasov



The next decade is expected to be very fruitful in production of new isotopes (> 10^3)

Questions ?

Haben Sie Fragen?

Вопросы ?

有問題嗎？

¿Preguntas?

Demandoj?

質問？

Pytania?

Domande?

Sorular?