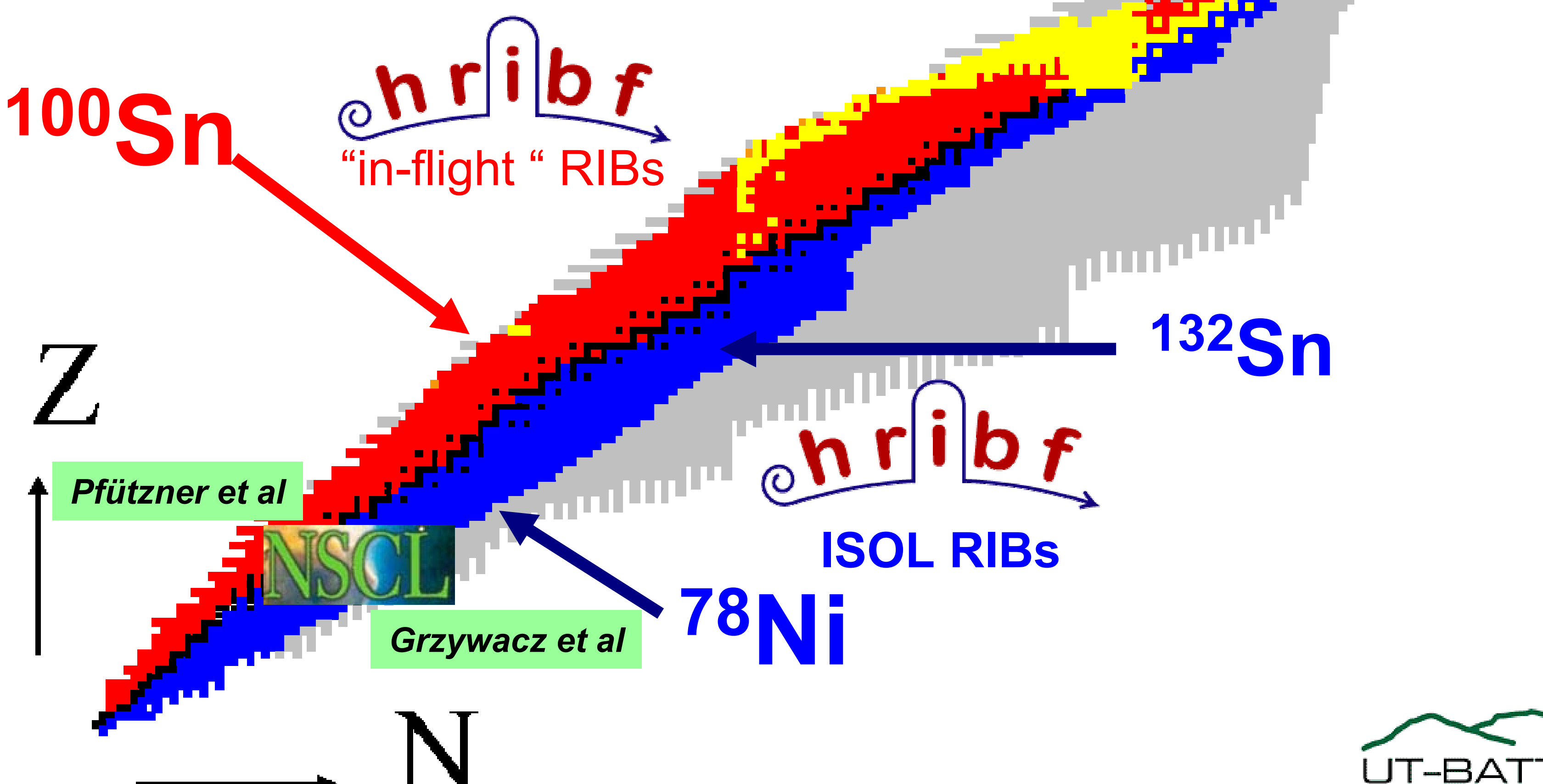
Perspektywy badań rozpadów egzotycznych jąder w laboratorium hribf (Oak Ridge, TN, USA)

K. P. Rykaczewski

perspektywy badań z dalszym udziałem polskich współpracowników
Warszawa, Kraków, Łódź …

hribf = *Holifield Radioactive Ion Beam Facility*



UT-BATTELLE
Oak Ridge National Laboratory

hribf

HRIBF users are getting their decay spectroscopy projects done !

M. Karny (Warszawa) + 26, "proton emiters ^{141m,gs}Ho", submitted to Phys. Lett. B (+ *habilitacja ?*)
A. Korgul (Warszawa) + 14, "Toward ^{100}Sn", Phys. Rev. C77, 034301, 2008
J. Winger (Mississippi) + 17, "Failure of ^{78}Ni core ?", World Scientific, in print
S. Ilyushkin (Mississippi) + 17, "β and βn-decays $^{76-79}$Cu", World Scientific, in print, (+*PhD*)
J. Winger .. A. Korgul, (Mississippi-Warszawa) + 16 coauthors, Acta. Phys. Pol.B39, 525, 2008
S.N.Liddick (UTK) + 22 coauthors, EPJ Special Topics 150, 131, 2007
C. Mazzocchi (UTK-Milano) + 16 coauthors, Phys. Rev. Lett. 98, 212501, 2007
S.N. Liddick (UNIRIB) + 22 coauthors, Phys. Rev. Lett ., 97, 082501, 2006
M.N.Tantawy (UT) + 23 coauthors, PR C73, 024316, 2006 (+PhD)
J.C. Batchelder (UNIRIB) + 21 coauthors, PR C72, 044306, 2005
R.K.Grzywacz (UTK/ORNL) + 12 coauthors, EPJ A25, s01, 145, 2005
T.N.Ginter (Vanderbilt/MSU) +12 coauthors, PR C68, 034330, 2003 (+PhD)
M.Karny (Warszawa) + 17 coauthors, Phys.Rev.Lett. 90, 012502, 2003
W.Królas (Kraków) + 24 coauthors, PR C65, 031303(R), 2002
J.J. Ressler (Maryland) + 17 coauthors, Phys. Rev. Lett. 84, 2104, 2000 (+PhD)
A.Piechaczek (LSU) + 10 coauthors Phys. Rev. C 61, 047306, 2000

Local decay spectroscopy team : 1.25 FTE (only !)

Oak Ridge, Walentynki 2008 badanie rozpadu ^{112}Cs

Diversity ??
No problem !

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OAK RIDGE NATIONAL LABORATORY

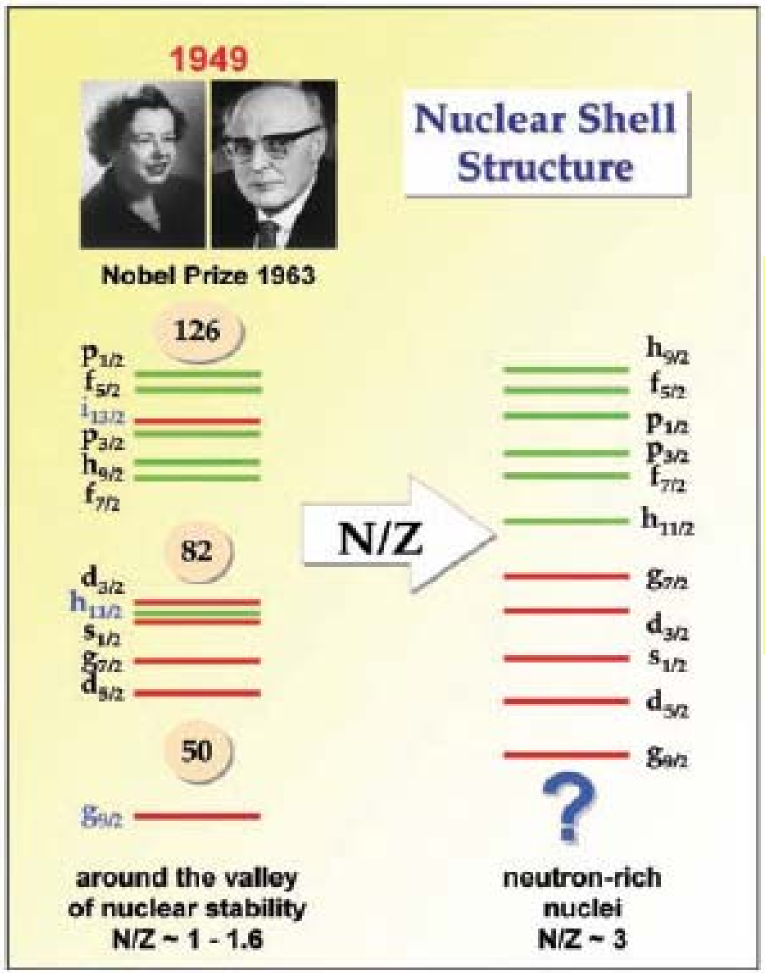
The shell structure description of stable nuclei may not apply as readily to nuclei outside the valley of stability !

"Shell Structure of Exotic Nuclei"
J.Dobaczewski, N.Michel, W.Nazarewicz, M.Płoszajczak, J.Rotureau
Progr. Part.Nucl. Phys. 59, 432, 2007

M. Goeppert-Mayer
J. Hans D. Jensen

M.Goeppert-Mayer
Phys.Rev. 75, 1969, 1949

Haxel, Jensen,Süss
Phys. Rev. 75,1766, 1949



J.Dobaczewski, I.Hamamoto, W.Nazarewicz, J.A.Sheikh
Phys. Rev. Lett. 72, 981, 1994

J.Dobaczewski, W Nazarewicz, *et al.*,
Phys. Rev. C 53, 2809, 1996

"Scientific Opportunities with a Rare-Isotope Facility in the United States"

www.national-academies.org
www.nap.edu
2007

stable Ni — ***N/Z~1.1***

^{78}Ni — ***N/Z=1.8***

" ^{112}Ni , ^{200}Sn "

HRIBF (Oak Ridge) :

staramy się zmierzyć i zrozumieć

strukturę jąder najbardziej odległych od ścieżki stabilności beta

(Lysekil , Szwecja, 1966)

Odkrywamy i badamy nowe nuklidy (2000+):

nowe radioaktywnosci protone (6) i emitery alfa powyżej ^{100}Sn (3),

jak i nowe jądra neutrono-nadmiarowe takie jak ^{79}Cu i ^{85}Ga

(zaakceptowane projekty : rozpady nowych jąder $^{80-82}$Cu, ^{86,87}Ge ,^{86,87}Ga, ^{88}As)

Staramy się znaleźć i zrozumieć :

efekty związane z dużą asymetrią liczb protonów Z i neutronów N,

wpływ asymetrii N/Z na przebieg poziomów jednocząstkowych

neutrony $1g_{7/2}$ vs $2d_{5/2}$ (N=51 ^{101}Sn, N=53 ^{105}Te*),*

protony $1f_{7/2}$ [Z=28] $1f_{5/2}$ vs $2p_{3/2}$,$2p_{1/2}$ (Z=29 Cu)

[N=50] neutrony $2d_{5/2}$ vs $3s_{1/2}$ $\rightarrow$ [N=58]

struktura stanów identyfikowanych jako "jednocząstkowe" (! ?)

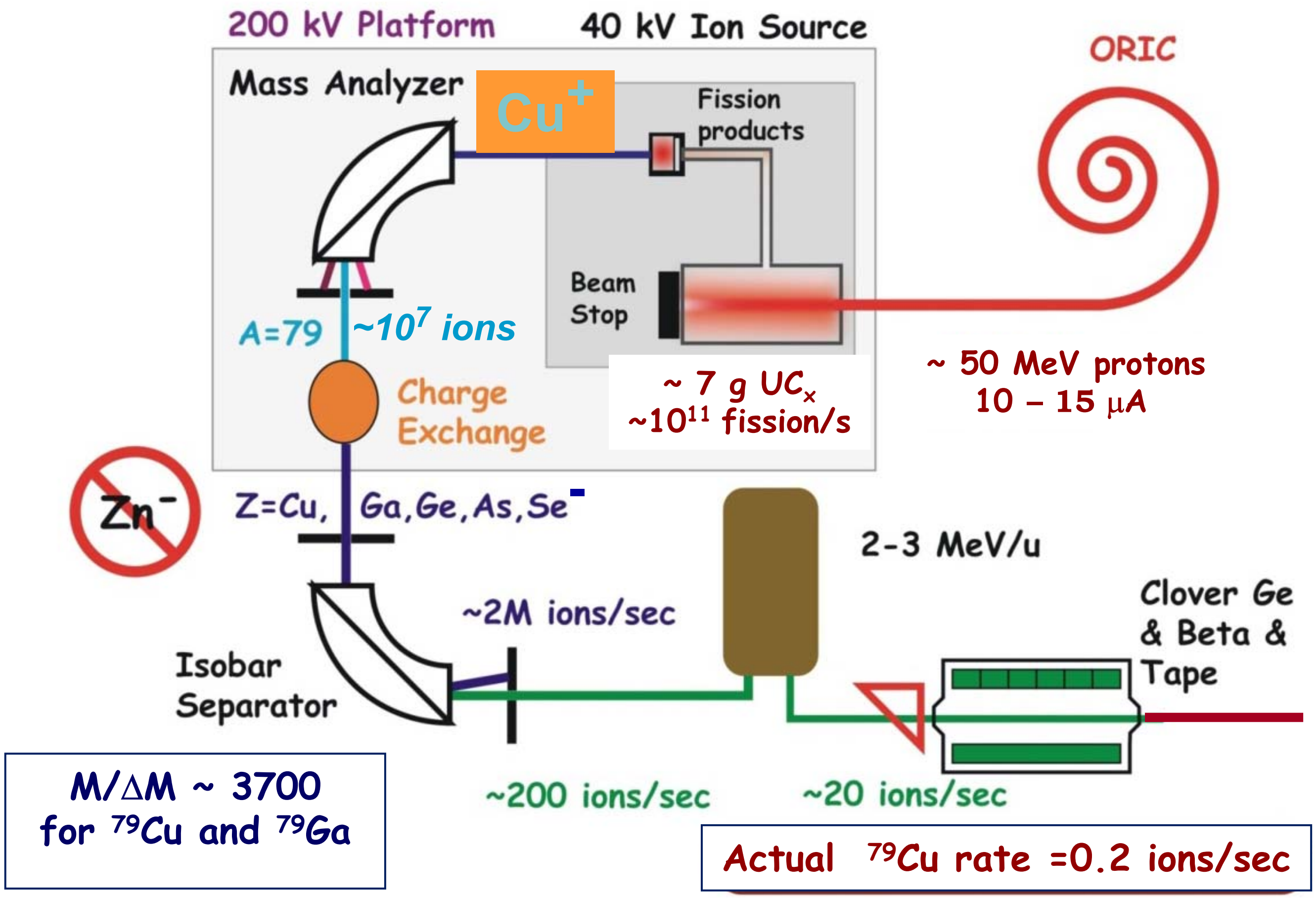
"zastosowania":

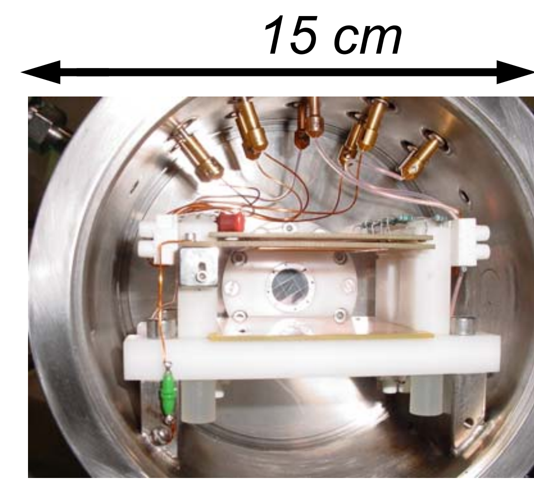
Astrofizyka : r-proces powyżej ^{78}Ni oraz rp-proces powyżej ^{100}Sn

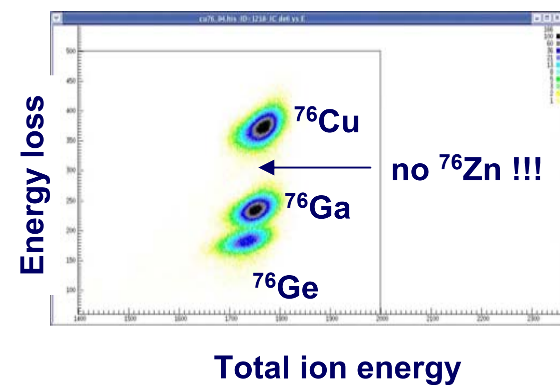
Dane o emisji opóźnionych neutronów i $T_{1/2}(\beta)$ dla nowych generacji reaktorów

Neutron–rich beams at HRIBF (Oak Ridge)

production, mass-separation and „ranging-out”







C.J.Gross et al., Eur.Phys.Jour. A25, s01, 115 (2005)

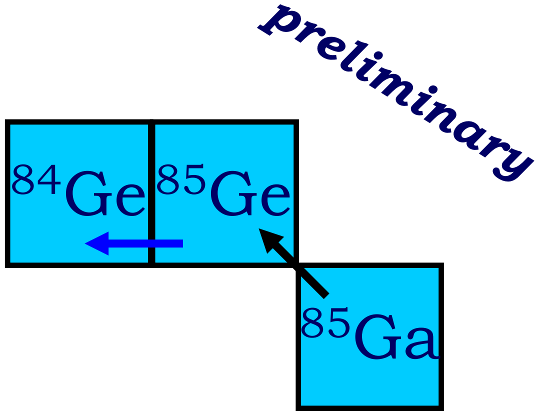
J.A.Winger et al., in contr. to Int. Nucl. Phys. Conf.(INPC) , Japan, June 2007

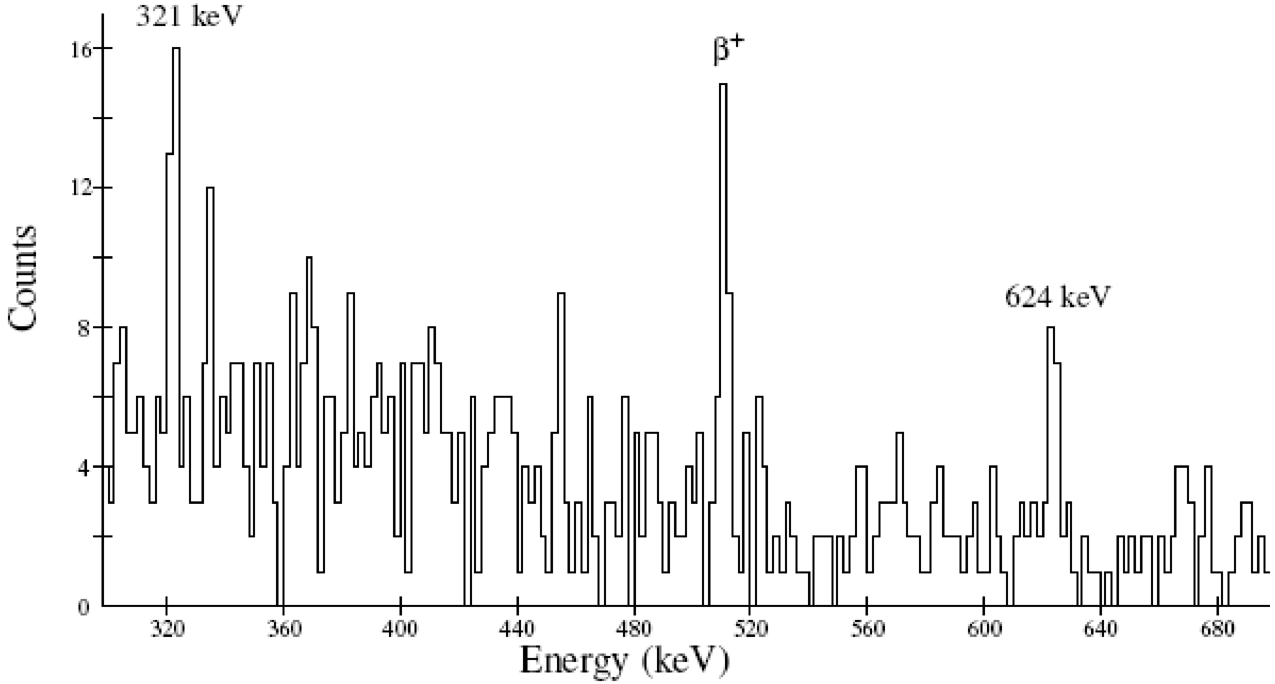
^{85}Ga decay, $T_{1/2}$ = ??? (< 100 ms)

rate ~ 0.1 pps, ~ 6 hours counting

$^{85}Ga \xrightarrow{\beta n} {}^{84}Ge(2^+) \xrightarrow{\gamma} {}^{84}Ge(0^+)$

$^{85}Ga \xrightarrow{\beta} {}^{85}Ge^* \xrightarrow{\gamma} {}^{85}Ge$





Ion-correlated (0-200 ms) β-gated gamma energy spectrum (2 keV/ch)

J.Winger, S.Ilyushkin et al., HRIBF,

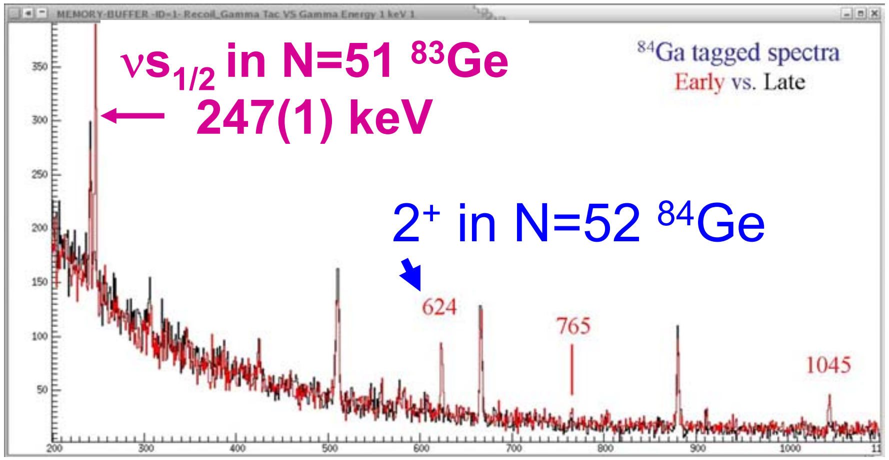
Int. Conf. on Fission and Properties of Neutron-rich nuclei", Nov. '07, Sanibel Island, FL

Nuclear structure beyond the N=50 shell closure

Nov'06 : 23 hours experiment with ~ 2 pps of N=53 ^{84}Ga ($T_{1/2}$=85 ms !!)

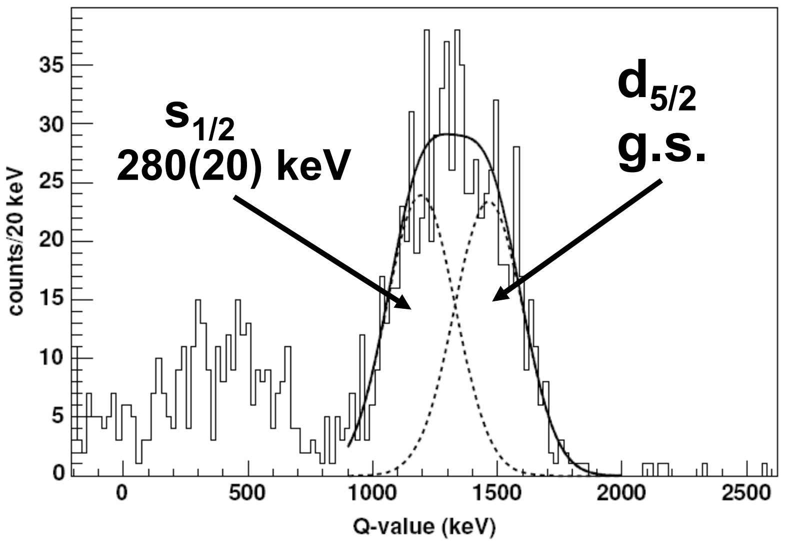
$^{84}Ga \xrightarrow{\beta} {}^{84}Ge^* \xrightarrow{\sim 50\%\ n} {}^{83}Ge^*(\nu s_{1/2}) \xrightarrow{\gamma} {}^{83}Ge(\nu d_{5/2})$

$^{84}Ge^* \xrightarrow{\sim 50\%\ \gamma} {}^{84}Ge$



Ion-correlated βγ-spectrum (1 keV/ch)

$^2H(^{82}Ge,p)^{83}Ge$ *Q-value*

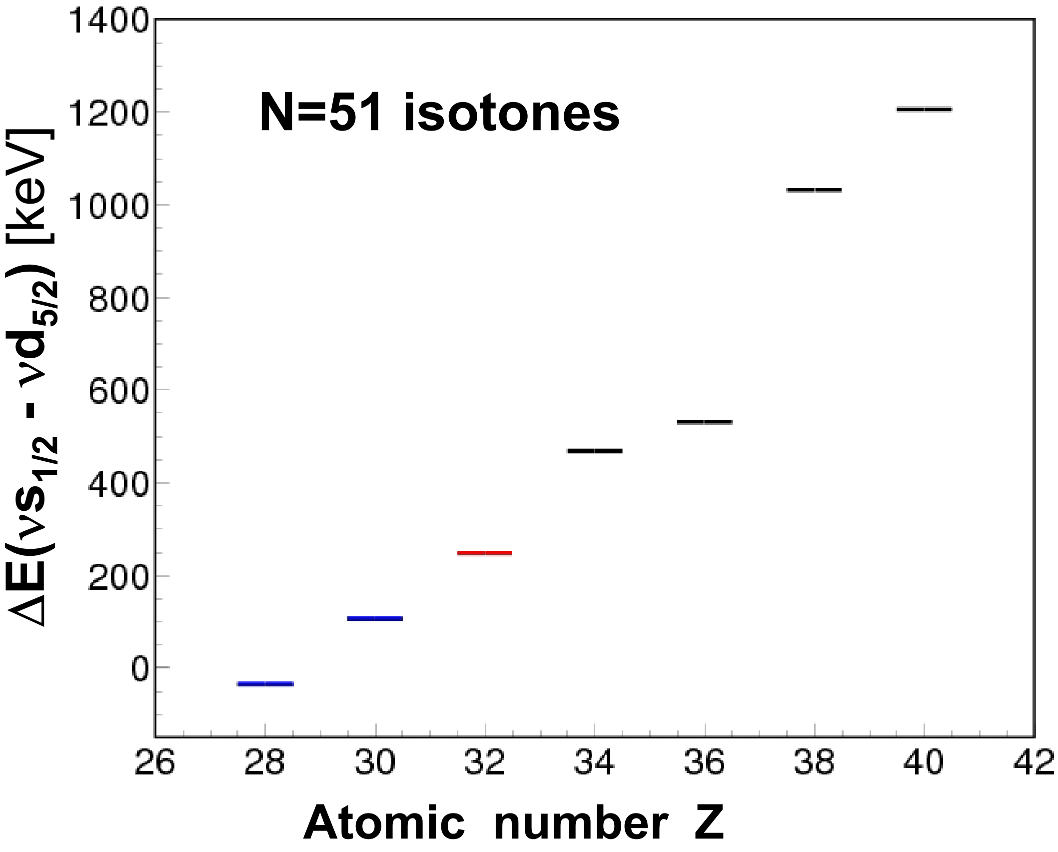


Thomas et al., PR C71, 021302, 2005

$\nu s_{1/2}$ and $\nu d_{5/2}$ orbitals within ~200 keV
new N=58 subshell closure in n-rich nuclei ??

Our result : ***$\nu s_{1/2}$ and $\nu d_{5/2}$ orbitals within 247 keV in Z=32 ^{83}Ge***

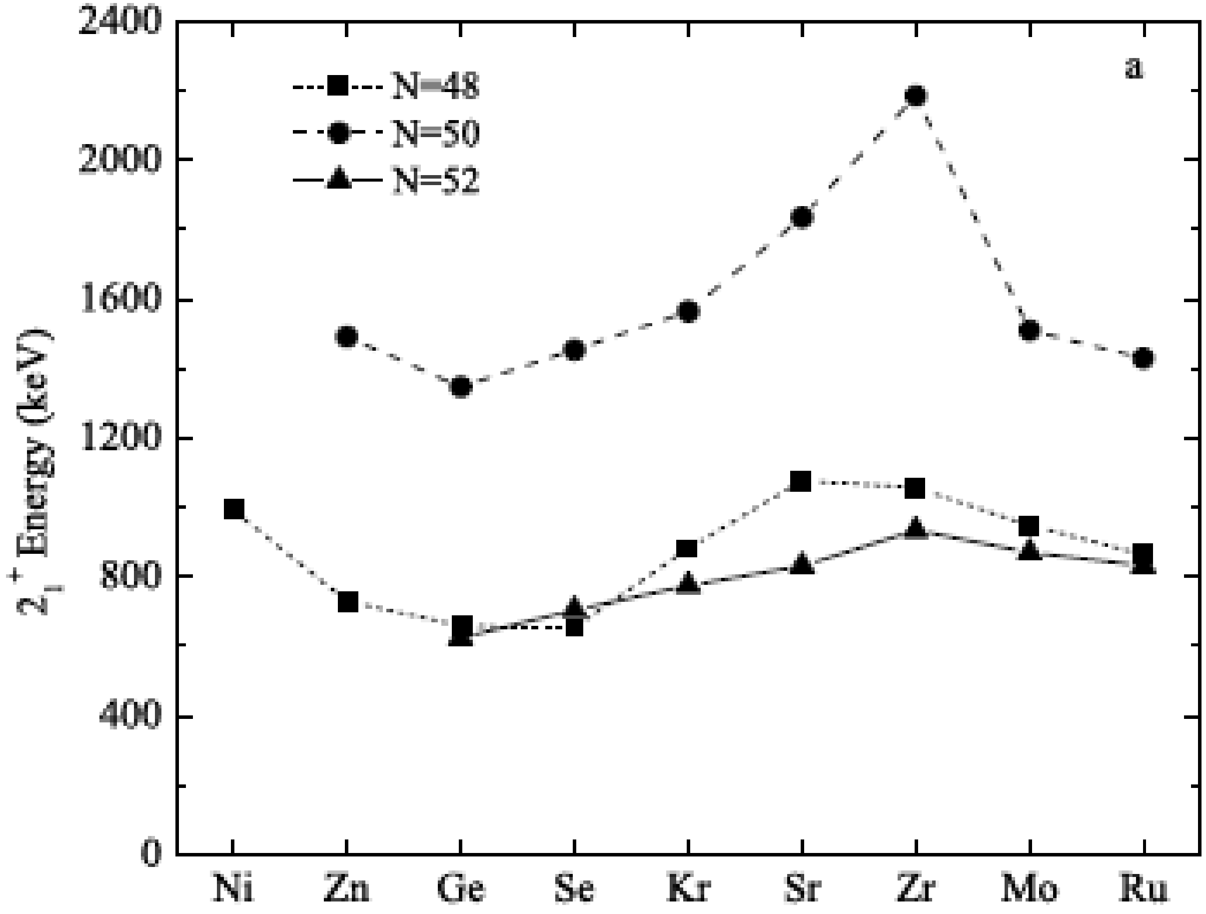
new N=58 subshell closure in n-rich nuclei ??



*extrapolation of the $\nu s_{1/2}$-$\nu d_{5/2}$ energies suggests μs – ms E2 isomers in **^{81}Zn** and **^{79}Ni***

*$\nu s_{1/2}$ isomeric halo in **^{81}Ni** (S_n~ 170 keV) ?*

Zmierzone energie pierwszych stanów 2^+
w parzysto-parzystych izotonach N=48, N=50 oraz N=52

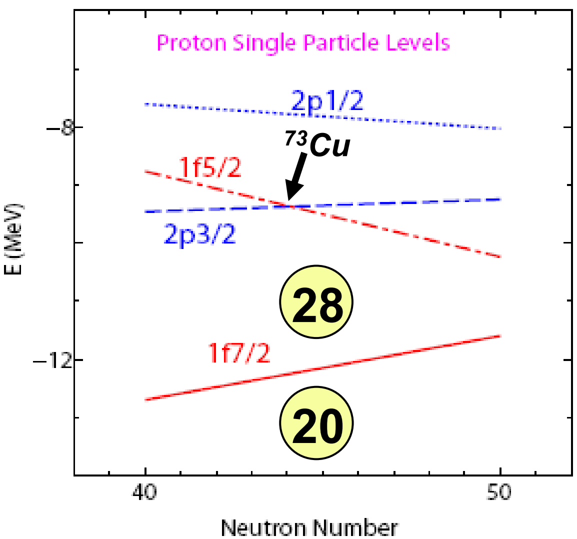


J. Winger et al., Sanibel , Nov 2007

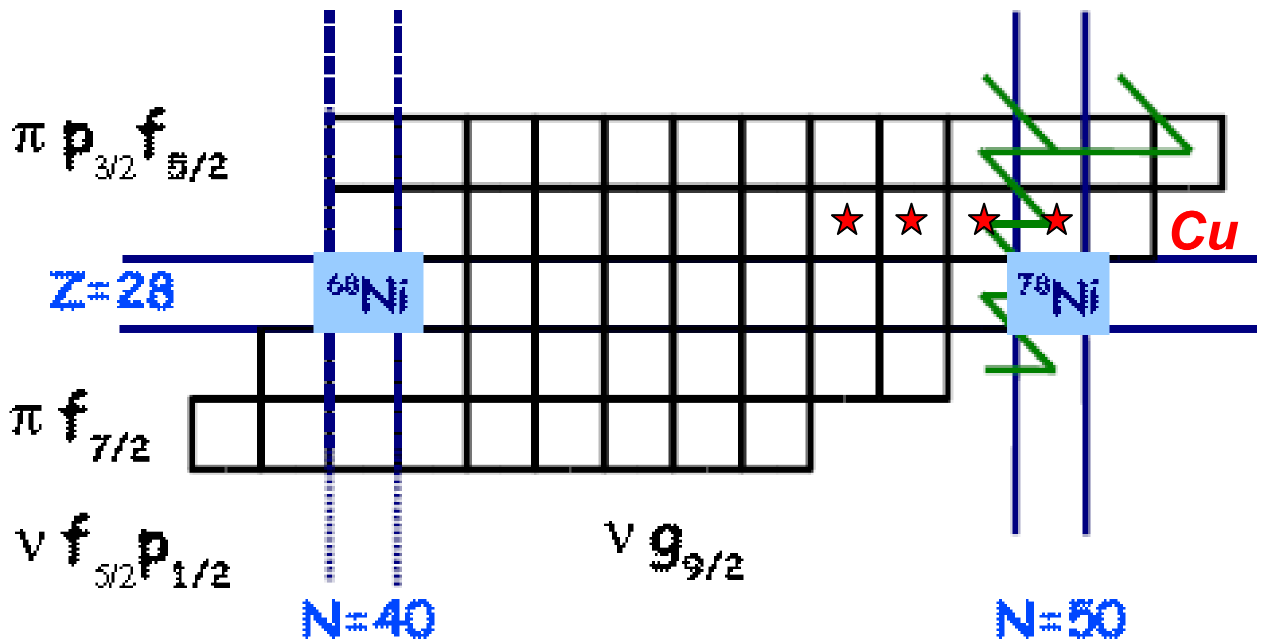
★ *HRIBF studies of ^{76}Cu - ^{79}Cu*

$^{69}_{28+1}Cu_{40}$ ***adding $g_{9/2}$ neutrons*** → $^{79}_{28+1}Cu_{50}$

$\pi p_{3/2}$ $\pi f_{5/2}$



T. Otsuka et al.,
PRL 95, 232502, 2005
linear extrapolation $f_{5/2}$ vs $f_{7/2}$
no Z=28 gap near ^{83}Cu
and Z=34 gap appears !!!



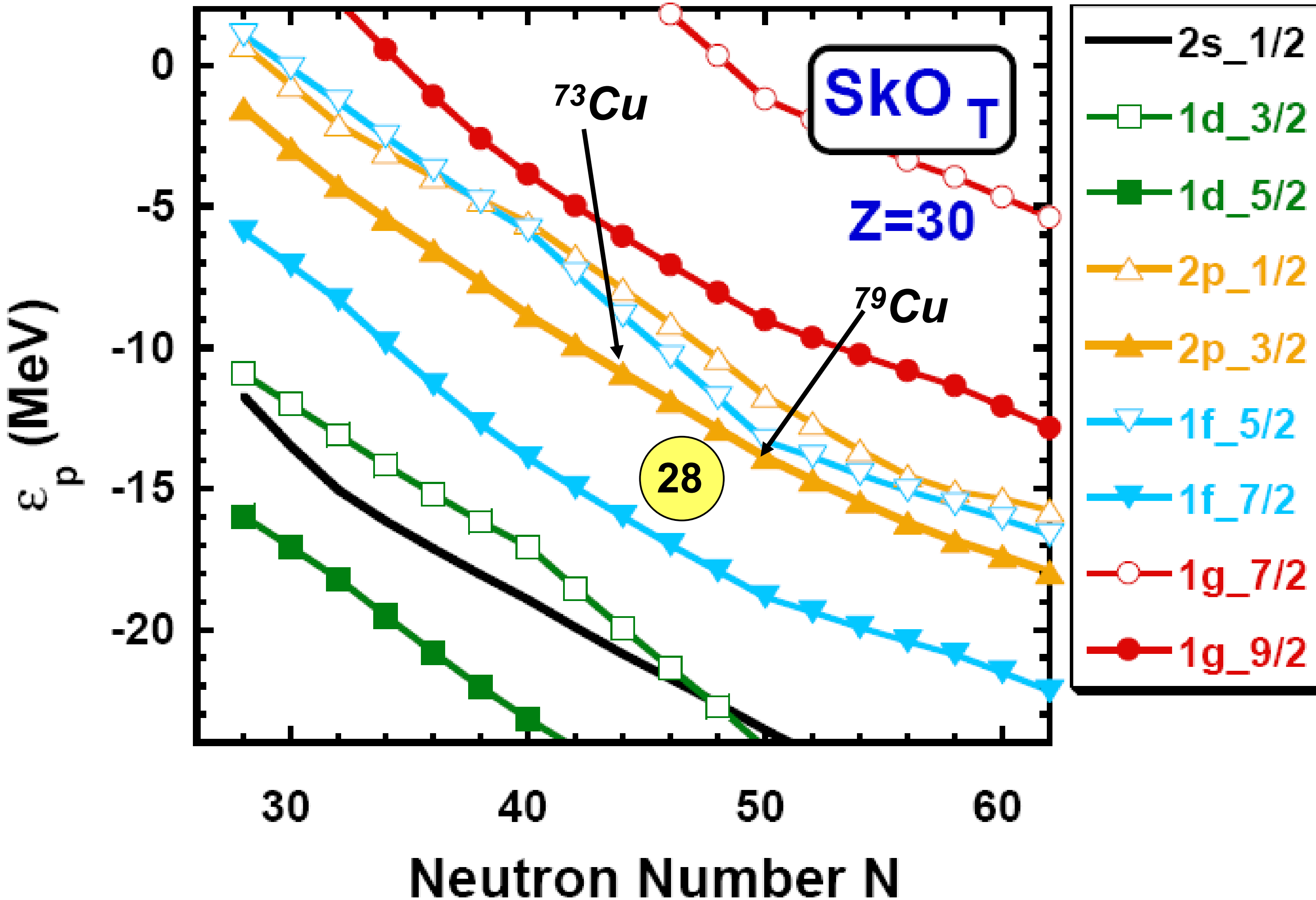
"r-process path"

Jacek Dobaczewski, January 2008

"first attempt" *(to be revisited, refined, retuned, refitted, recalculated)*

Physics : $\pi 2p_{3/2}$ vs $\pi 1f_{5/2}$ crossing (?) and an evolution of Z=28 gap

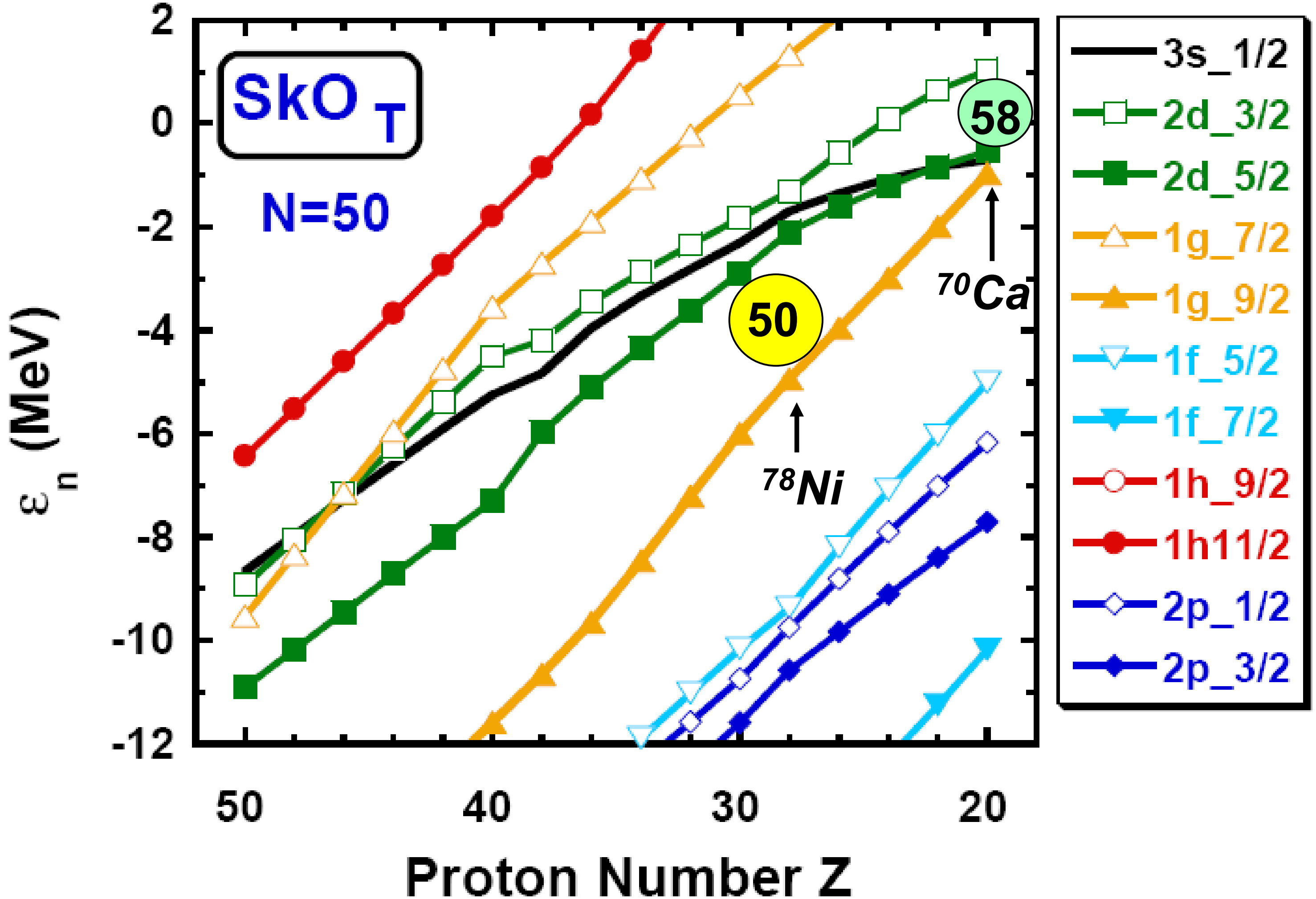
HRIBF contribution : β-decays above Z=28, β-NMR, 2+ energies …



Jeff Winger et al.,

2007 Sanibel conference contr.: "Failure of the ^{78}Ni core for Z>28, N>50 ?"

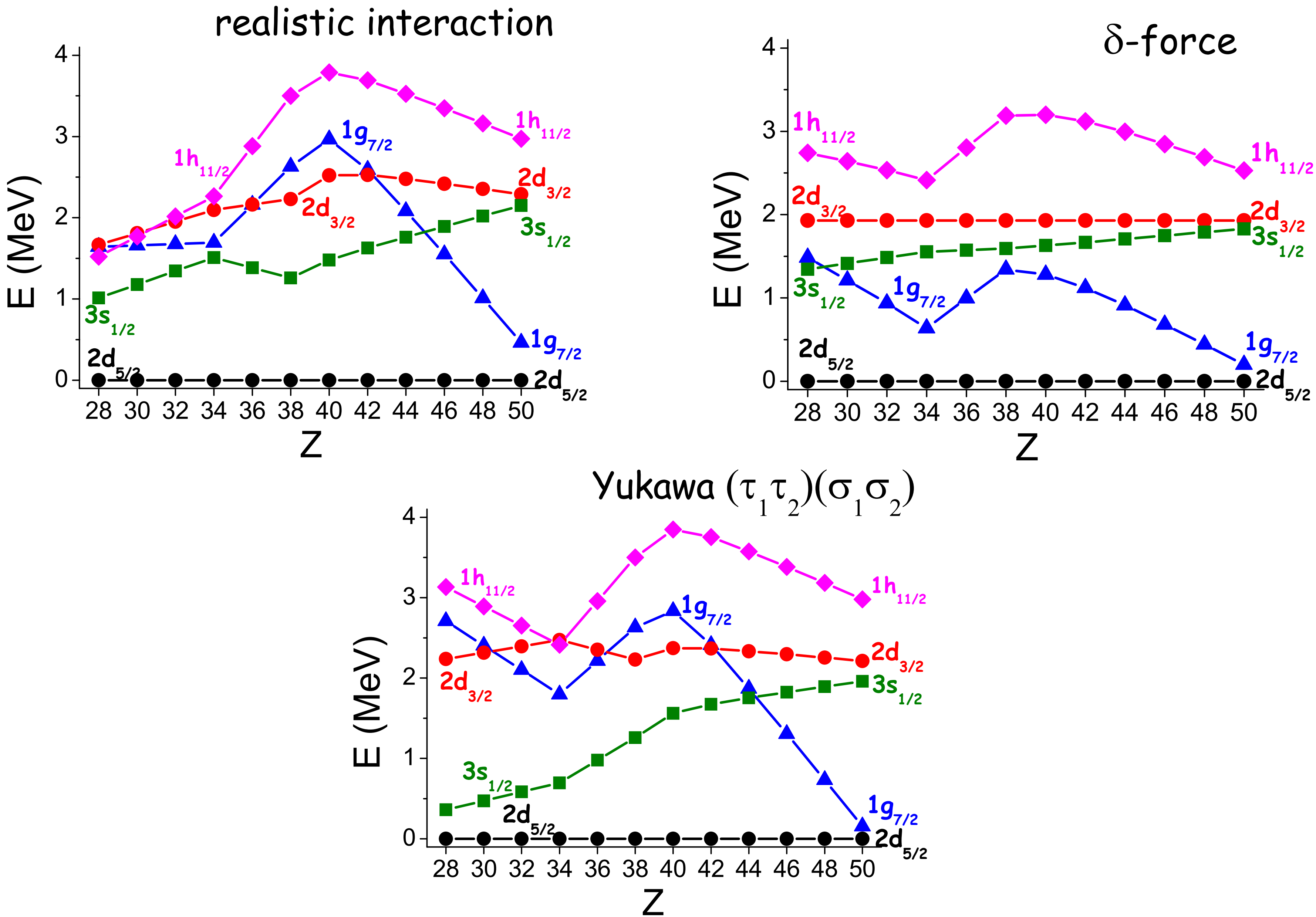
(low 2+ energies like 624 keV in Z=32, N=52 ^{84}Ge)

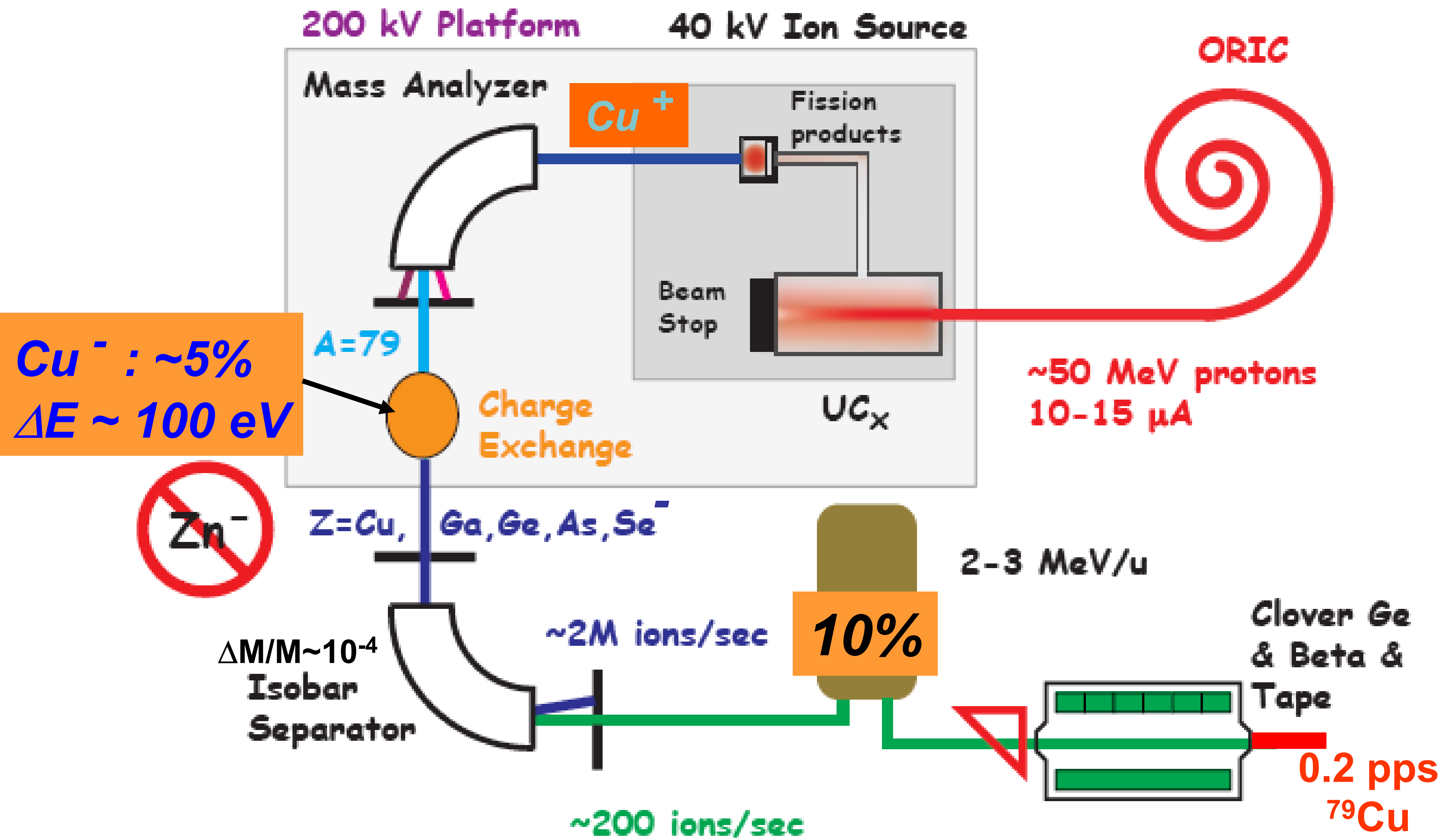


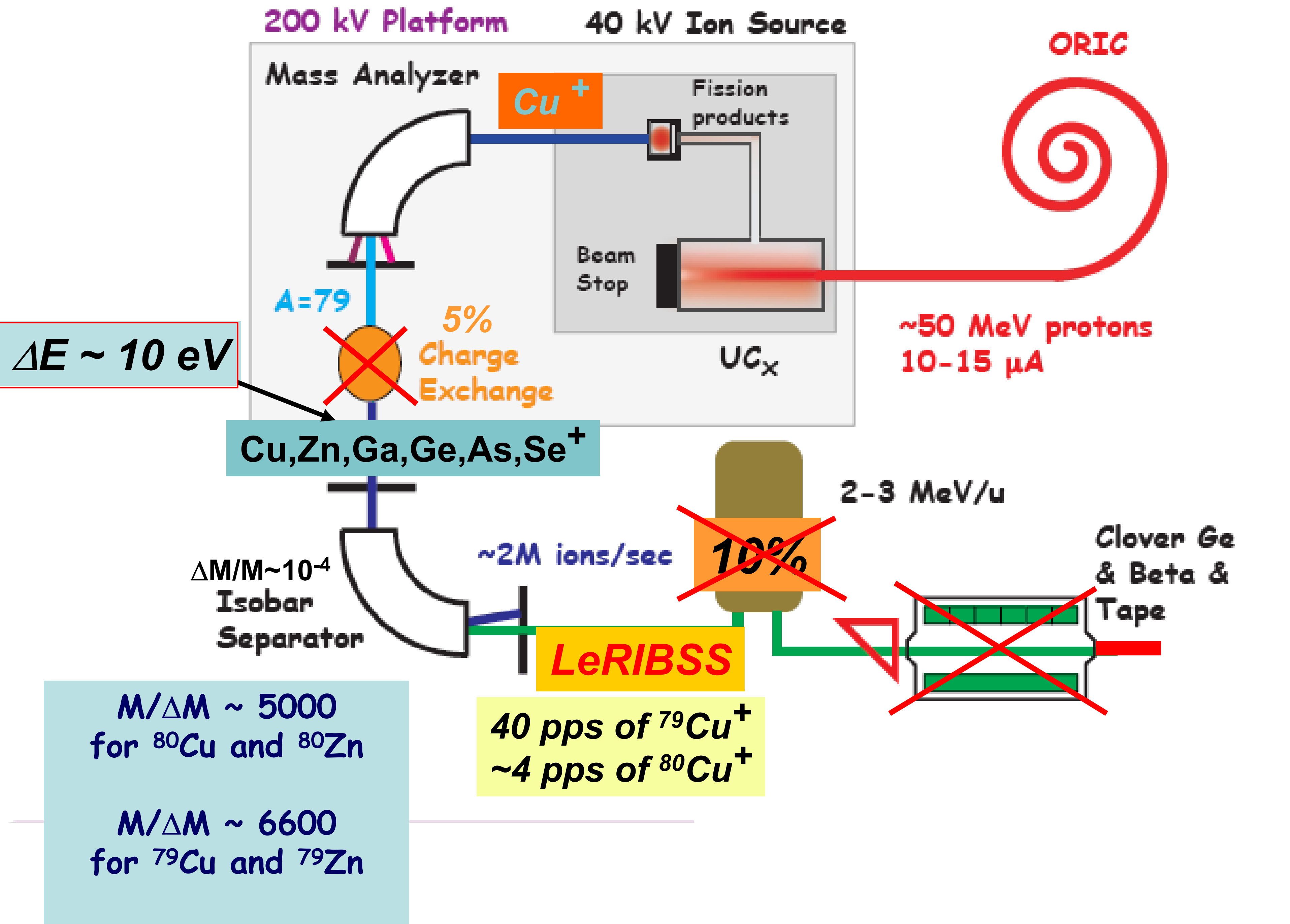
Jacek Dobaczewski, Jan 2008, to be revisited etc. (N=52 – 58 calculations !)

Note : *relative energy of* $\nu s_{1/2}$ *vs* $\nu d_{5/2}$ *state !!*

from Nadia Smirnova, "Nuclear Structure 2006"

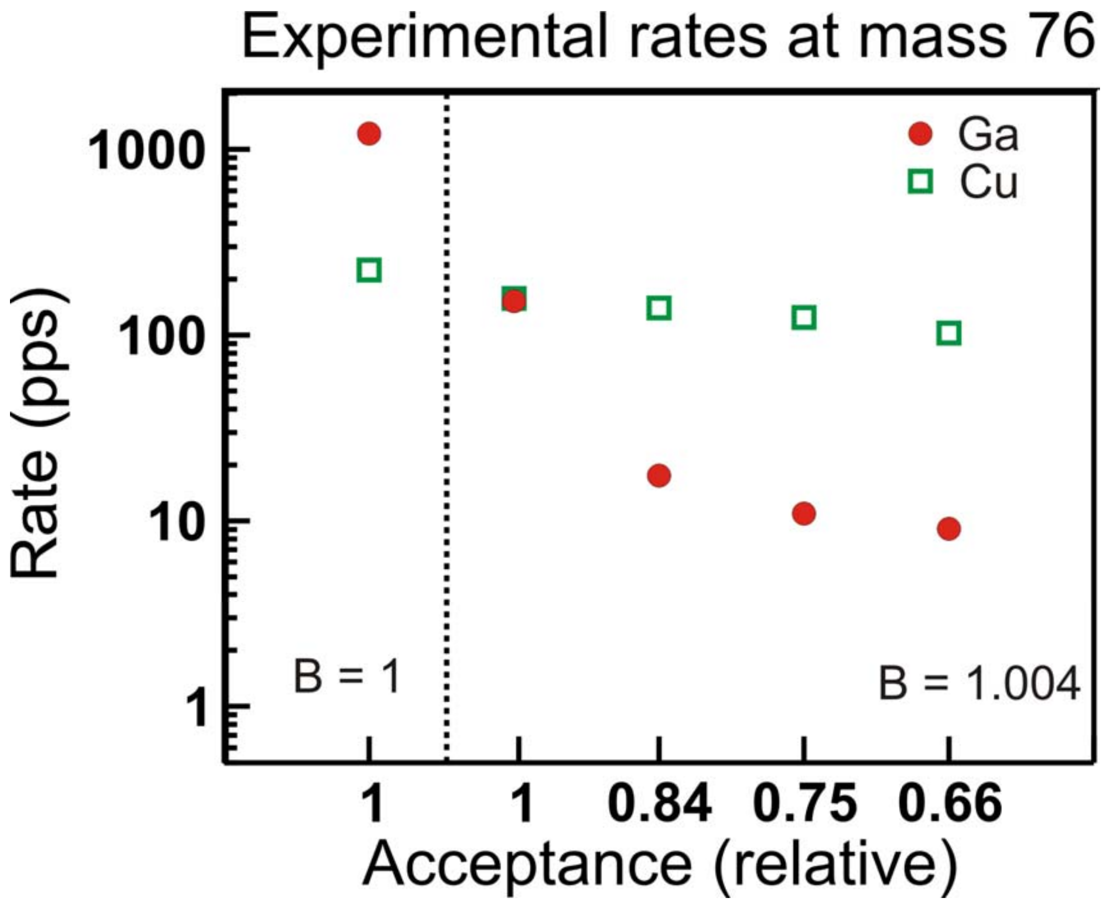



200 kV Platform
40 kV Ion Source
ORIC
Mass Analyzer
Cu +
Fission products
Beam Stop
A=79
Cu - : ~5%
ΔE ~ 100 eV
Charge Exchange
UCx
~50 MeV protons
10-15 μA
Zn-
Z=Cu, Ga,Ge,As,Se-
2-3 MeV/u
ΔM/M~10-4
Isobar Separator
~2M ions/sec
10%
Clover Ge & Beta & Tape
0.2 pps
79Cu
~200 ions/sec


200 kV Platform
40 kV Ion Source
ORIC
Mass Analyzer
Cu +
Fission products
Beam Stop
A=79
5%
Charge Exchange
UCx
~50 MeV protons
10-15 μA
ΔE ~ 10 eV
Cu,Zn,Ga,Ge,As,Se+
2-3 MeV/u
ΔM/M~10-4
Isobar Separator
~2M ions/sec
10%
Clover Ge
& Beta &
Tape
LeRIBSS
40 pps of 79Cu+
~4 pps of 80Cu+
M/ΔM ~ 5000
for 80Cu and 80Zn
M/ΔM ~ 6600
for 79Cu and 79Zn

HRIBF high-resolution RIB injector magnet $\vec{B}$
(designed : $\Delta M/M \sim$ 1 : 20 000)

rate of A=76 isobars ~ 10^5 pps → ***“ $\vec{B}$-optimized“ rate ($^{76}Cu^-$)~220 pps***



for ^{76}Cu - ^{76}Ga $\Delta M/M \sim$ 1 : 4600

Low-energy Radioactive Ion Beam Spectroscopy Station LeRIBSS

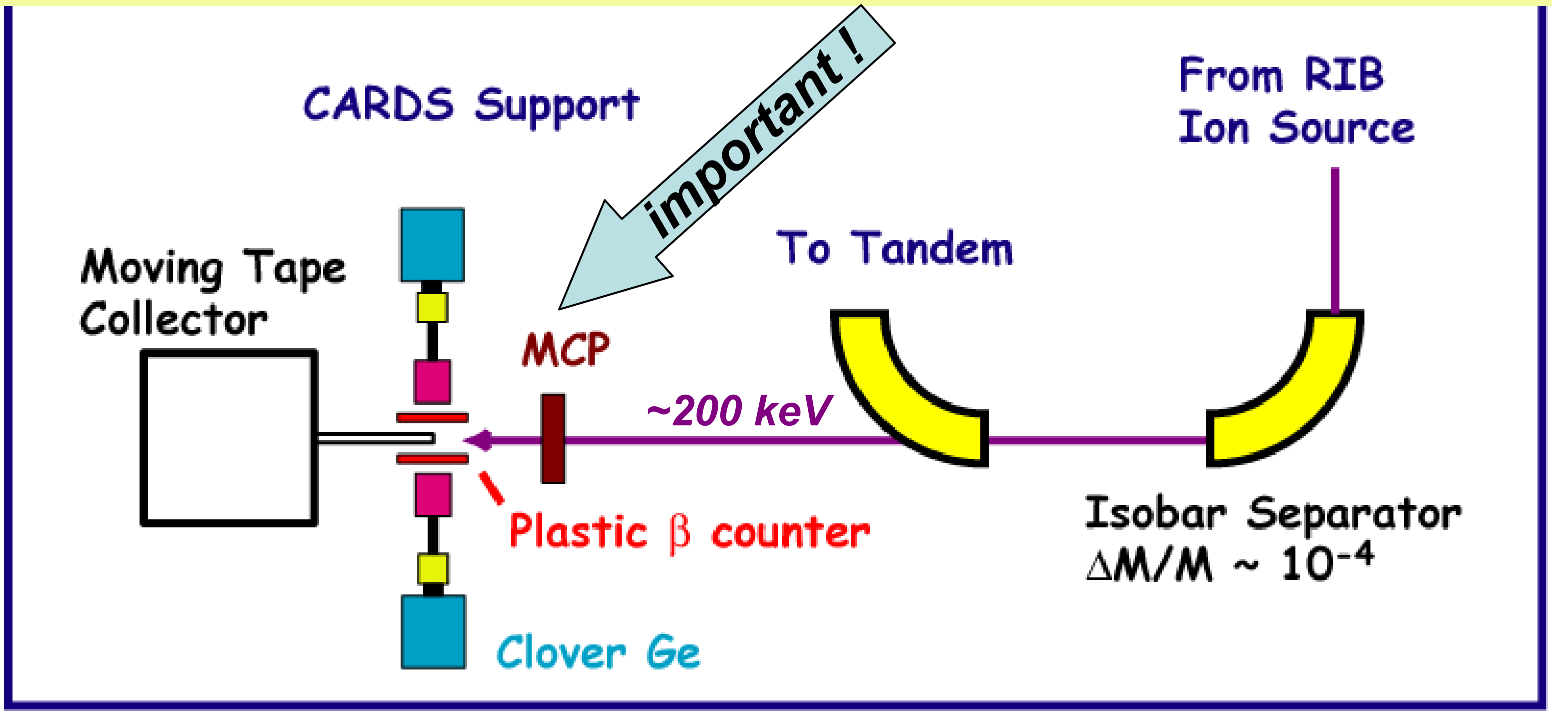
Factor 20 to 1000 improvement in RIBs intensity

no Tandem – 10, no Charge Exchange – 2++ (e.g. Cu,Ga – 10x20=200)

negative AND positive ~ 200 keV ions from IRIS-1 and 250 keV from IRIS-2

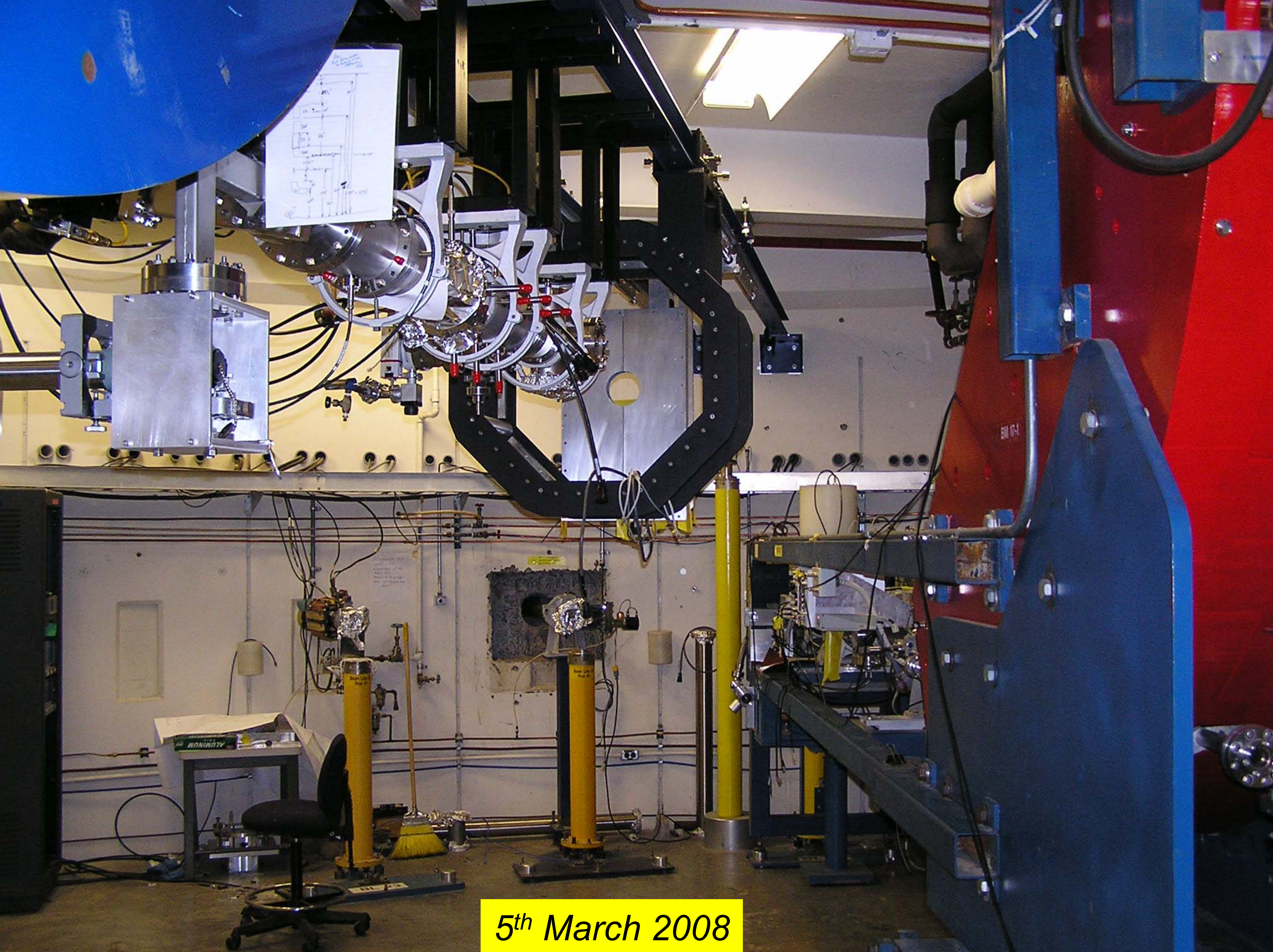
profiting from all HRIBF beam purification methods (except “ranging-out”)

ultra-thin foil MCP : time correlations with implanted ions



LeRIBSS construction should be finished in Spring 2008

New fast Moving Tape Collector and CARDS detector support from LSU !!

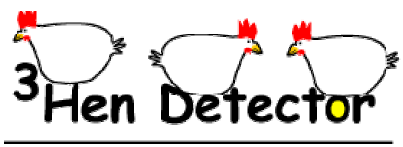


5th March 2008

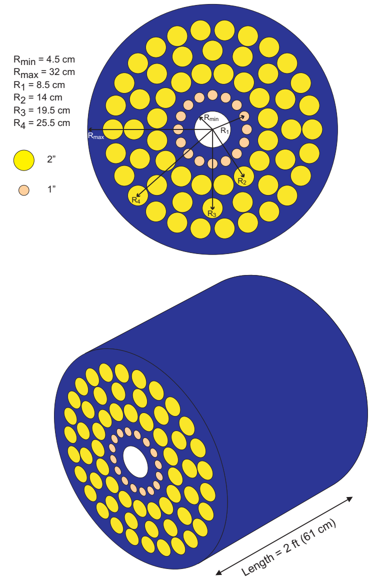
new equipment enhancing LeRIBSS capabilitities

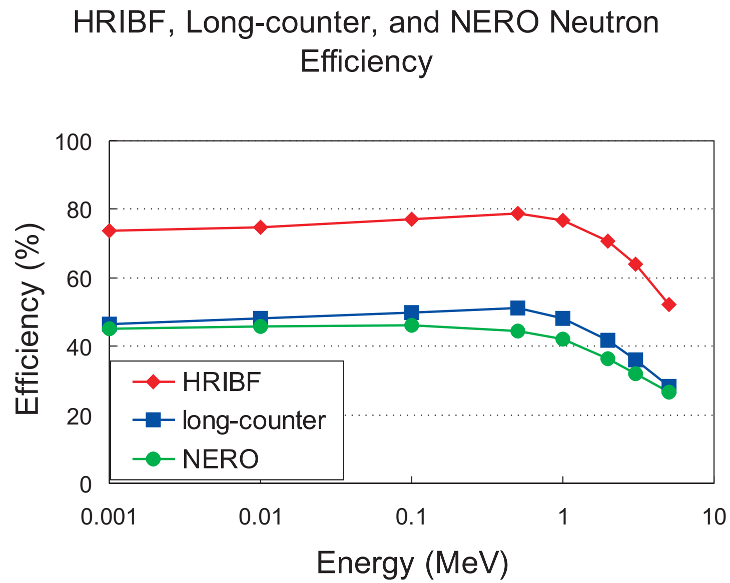
nearly 80% efficient “ ^{3}Hen ” neutron counter

√ purchase orders for all ^{3}He tubes /ORNL/ and MESYTEC preamps /UTK/

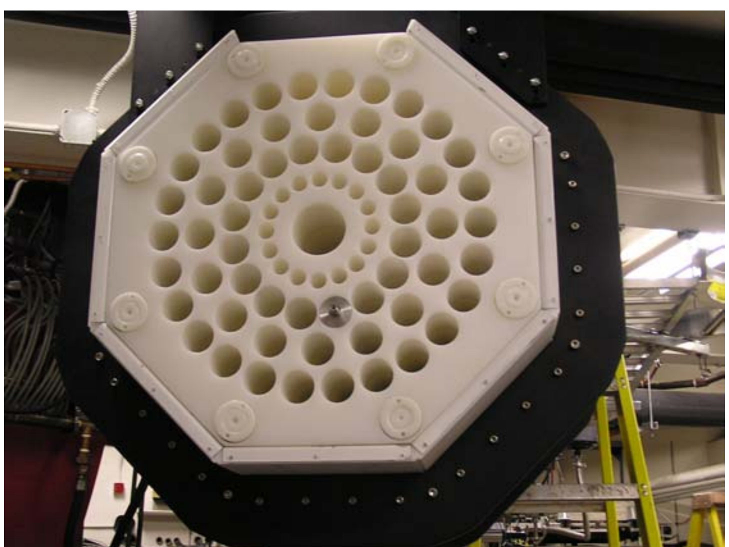


(Art by Carl Gross)

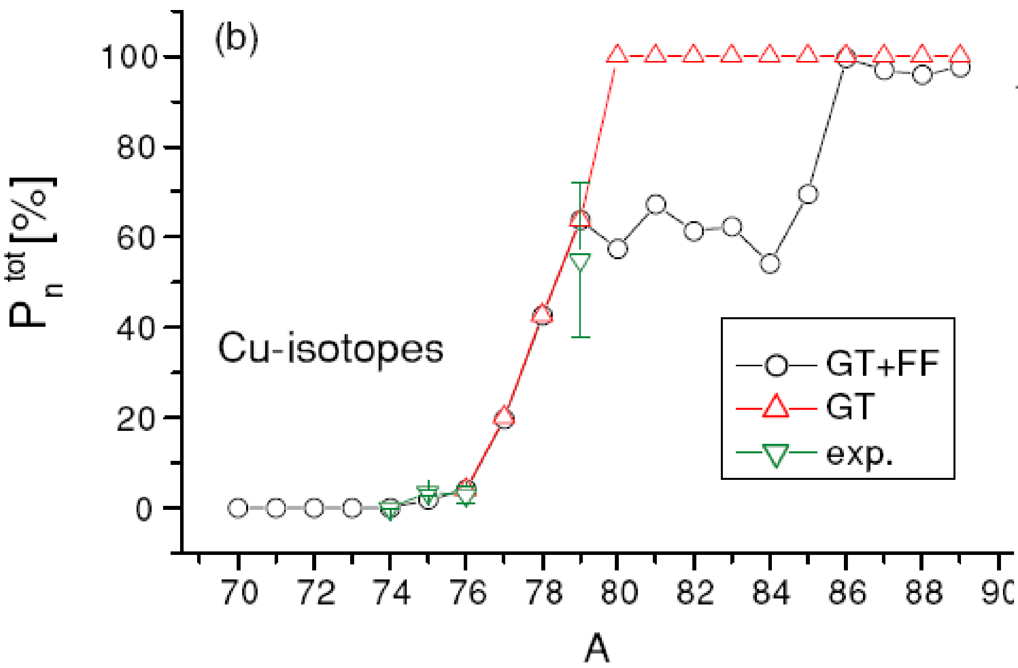


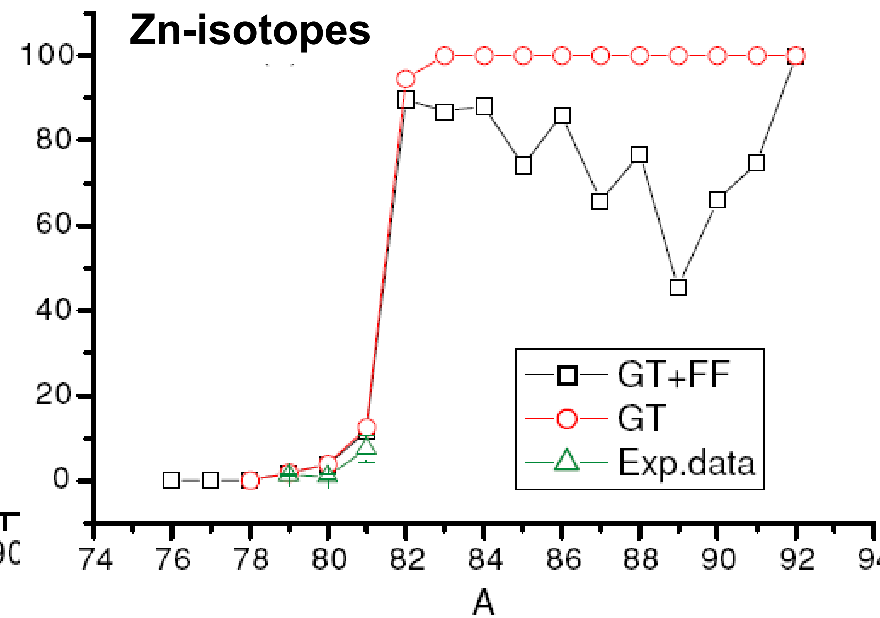


UNIRIB
LSU - Mississippi



Efficient beta-neutron counting is critical for enhancing our "discovery potential" !!!!



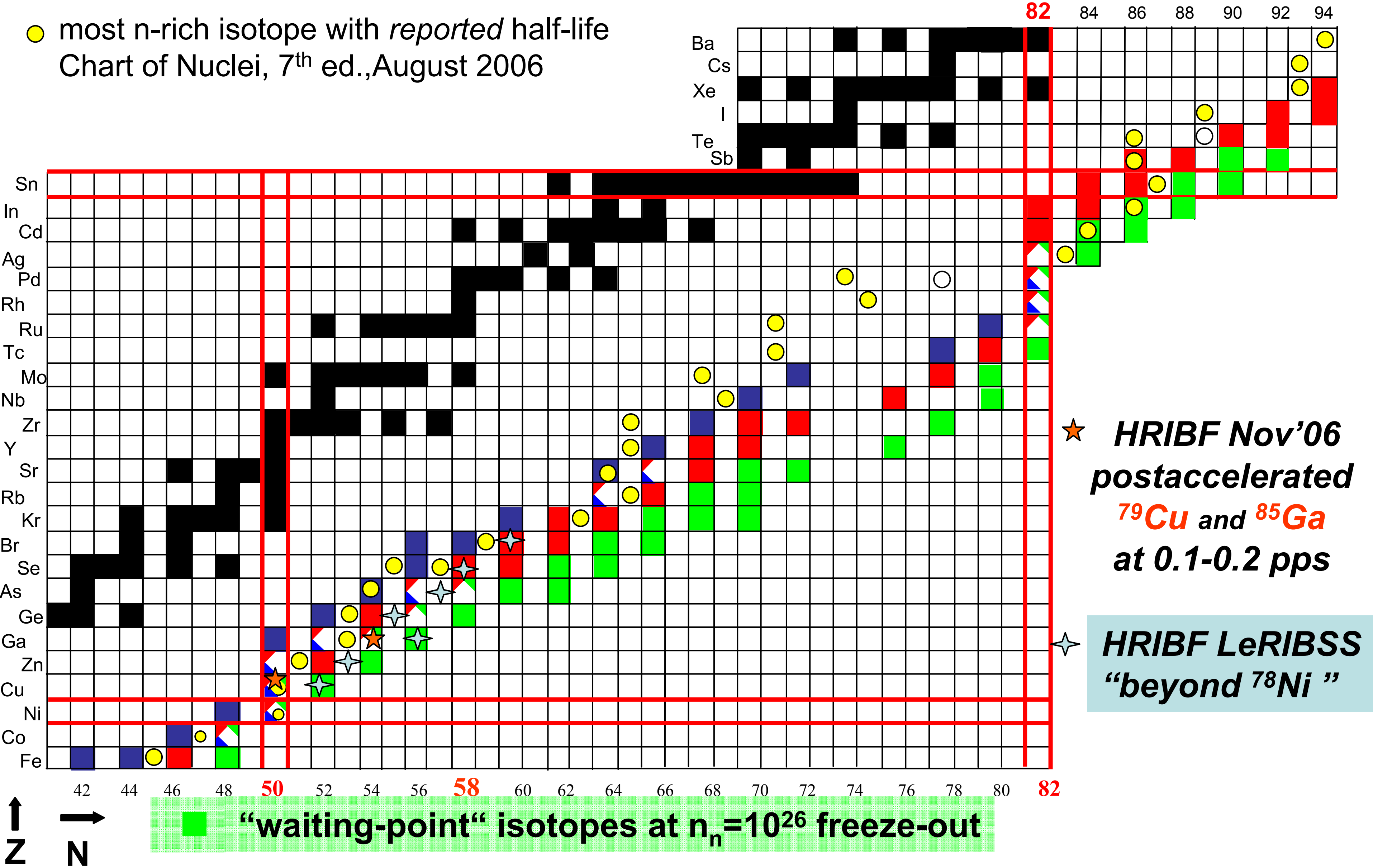


from I.N. Borzov, Phys.Rev. C71, 065801, 2005

Warning : no β–γ, only β-n (γ) measurements ! ????

r-process "FK²L boulevard" for $n_n = 10^{20}$, 10^{23}, 10^{26} neutrons/cm^3

F.-K. Thielemann, K.-L. Kratz, in contr. to Astrophysics Workshop, Oak Ridge 2006



Eksperymenty z pomocą LeRIBSS
(rozpady β produktów rozszczepienia ^{238}U)

Nowe nuklidy procesu r : $T_{1/2}(\beta)$ oraz $I_{\beta n}$

$^{79-82}Cu$, $^{80-83}Zn$, $^{85-87}Ga$, $^{86-87}Ge$, $^{88-90}As$

Stany jednoczastkowe powyzej ^{78}Ni

$\nu s_{1/2}$ w N=51 ^{81}Zn oraz N=53 ^{85}Ge (nowa magiczna liczba N=58 ?),
poziomy 2+ w N=52 ^{82}Zn oraz N=54 ^{88}Se

Funkcja nasilenia β i rola przejsc "first-forbiden"

$^{87-94}Br$ isotopes (chemicznie czyste wiazki i LeRIBSS!)

obszar ^{132}Sn

Czyste wiazki izotopow I, Ag oraz SnS

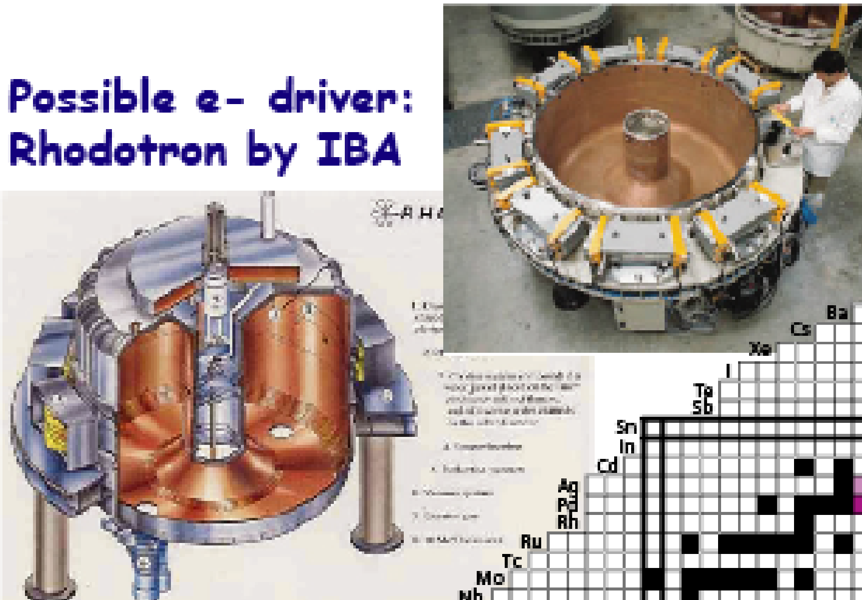
najbardziej egzotyczne (nowe)
isotopy n-nadmiarowe
produkowane w rozszczepieniu ^{238}U przez 50 MeV protony

It's the (pure) beam, stupid!

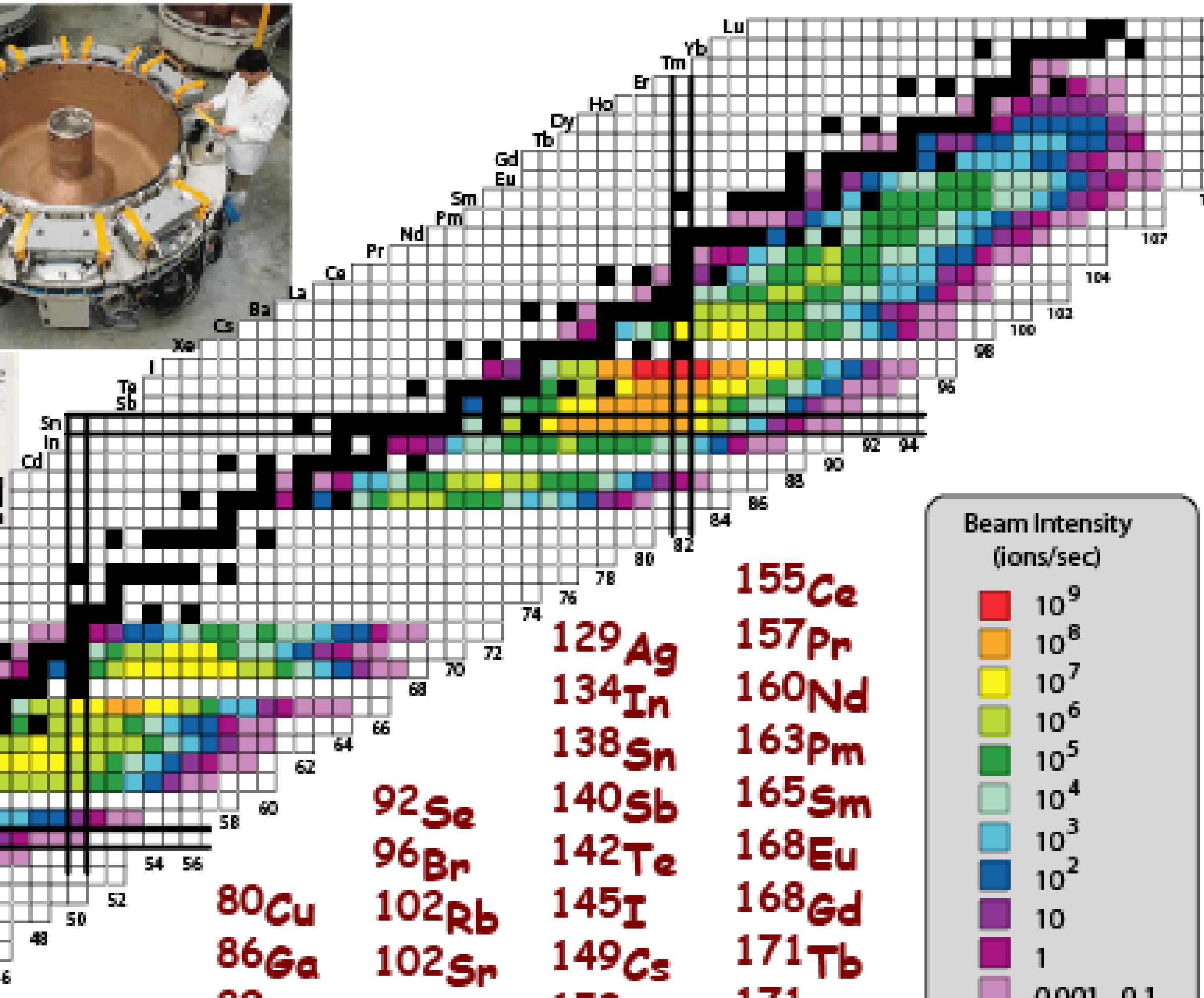
(paraphrase James Carville of the 1992 Clinton campaign)

HRIBF accelerated beam-on-target intensities (produced via photofission of ^{238}U at 10^{13} fissions/sec)

Possible e- driver: Rhodotron by IBA



or a 50 MeV e-LINAC



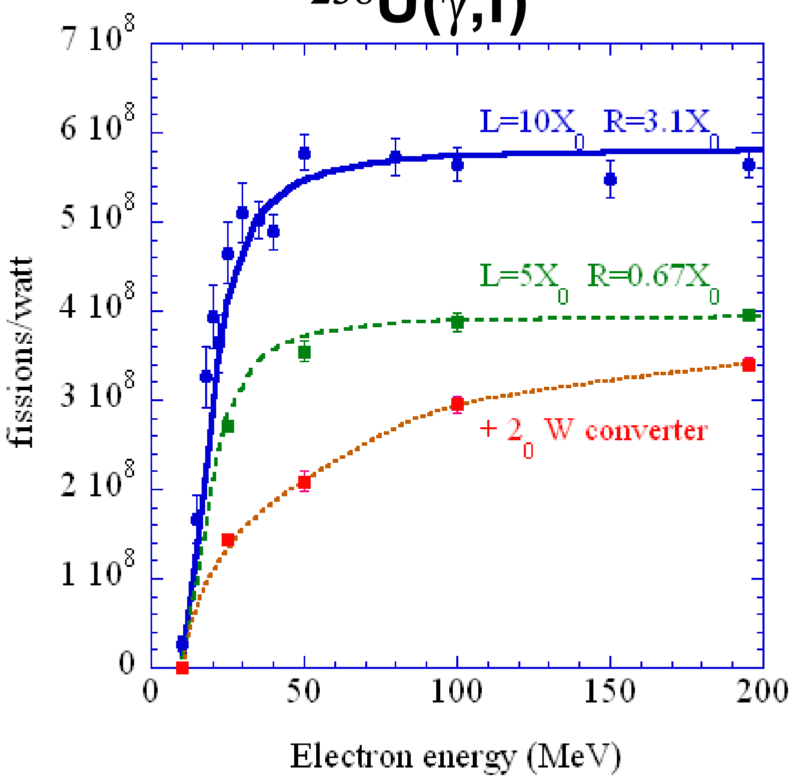
~1 ion/sec

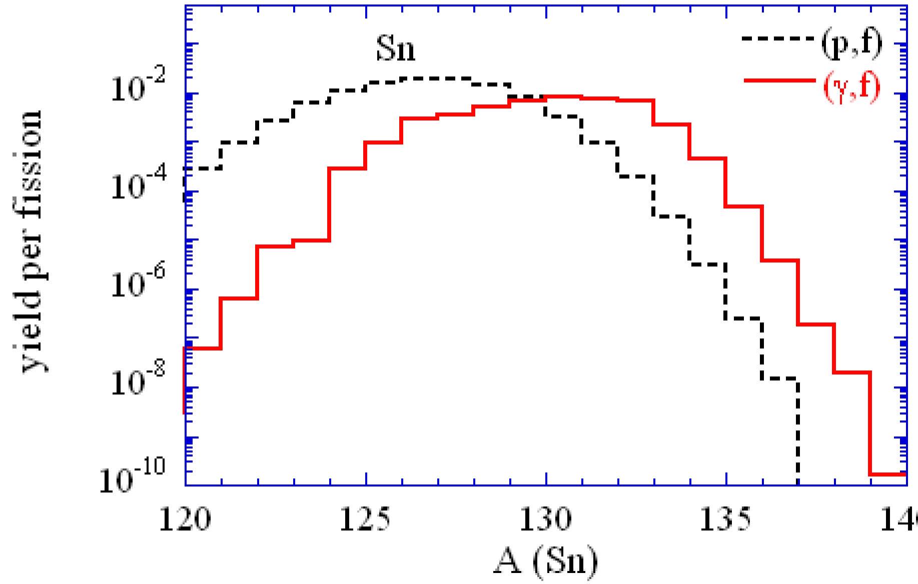
^{80}Cu	^{92}Se	^{129}Ag	^{155}Ce
^{86}Ga	^{96}Br	^{134}In	^{157}Pr
^{89}Ge	^{102}Rb	^{138}Sn	^{160}Nd
^{91}As	^{102}Sr	^{140}Sb	^{163}Pm
	^{105}Y	^{142}Te	^{165}Sm
	^{125}Pd	^{145}I	^{168}Eu
		^{149}Cs	^{168}Gd
		^{150}Ba	^{171}Tb
		^{153}La	^{171}Dy
			^{177}Ho

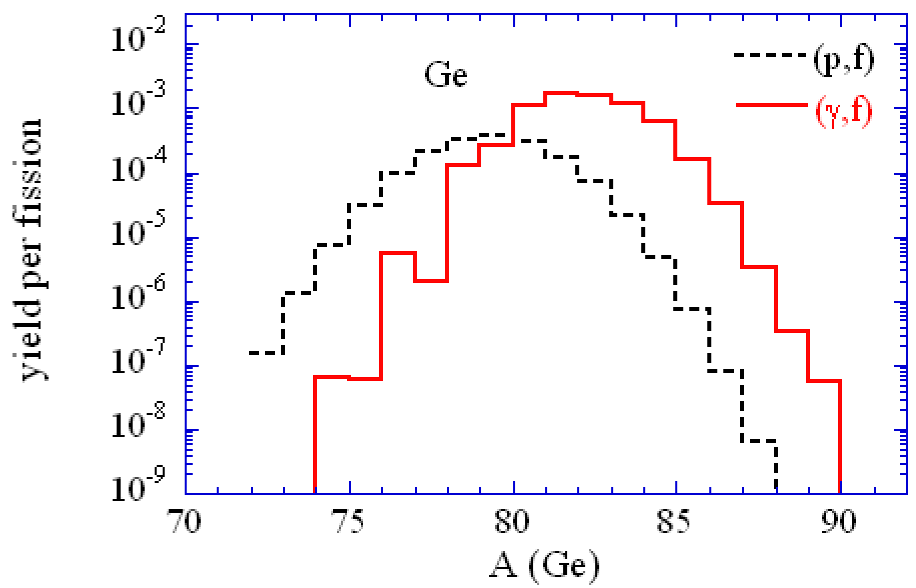
Photofission yields

- 10^{13} f/s "easily" achieved
- About 20x current HRIBF
- But real gain >> 20x

^{238}U(γ,f)



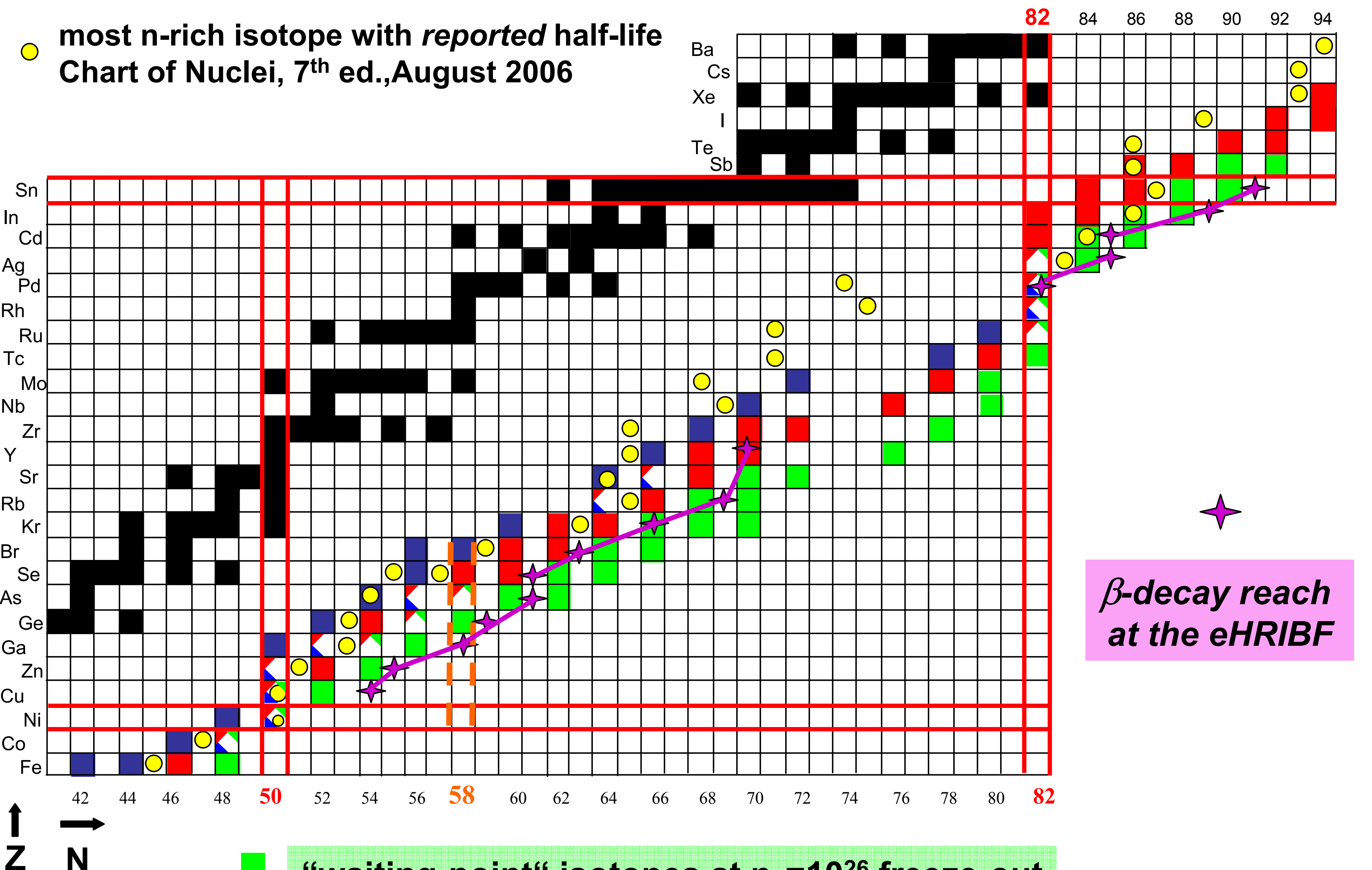




(p,f) systematics from Tsukada
(γ,F) from ORNL systematics + Jyvaskyla model

r-process for $n_n = 10^{20}, 10^{23}, 10^{26}$ neutrons/cm^3

F.-K. Thielemann, K.-L. Kratz, P.Möller, et al., AstroPhys. J. 403,1993; Phys. Rev. C67, 2003

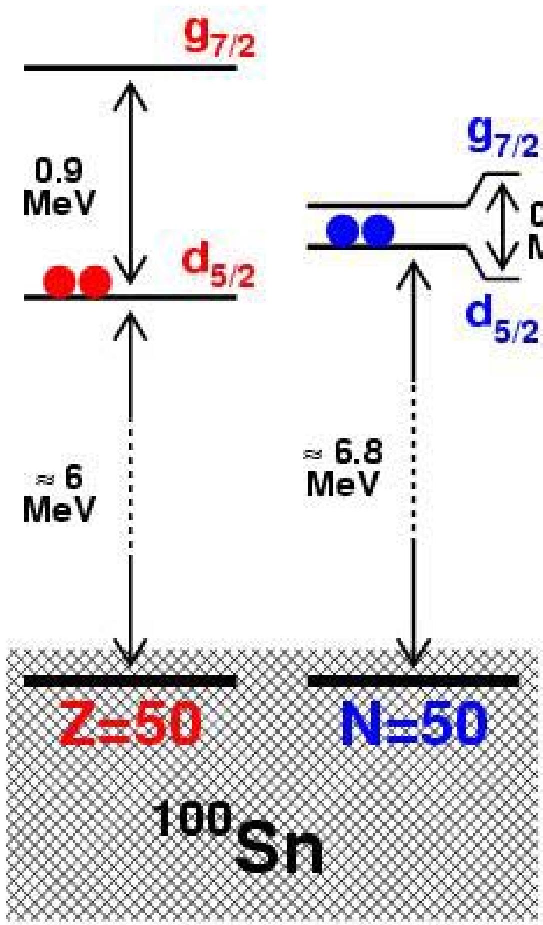


“waiting-point“ isotopes at $n_n=10^{26}$ freeze-out

$^{104}Te = ^{100}Sn + \alpha$

α made out of π and ν
on the same orbitals

enhanced " α-preformation "

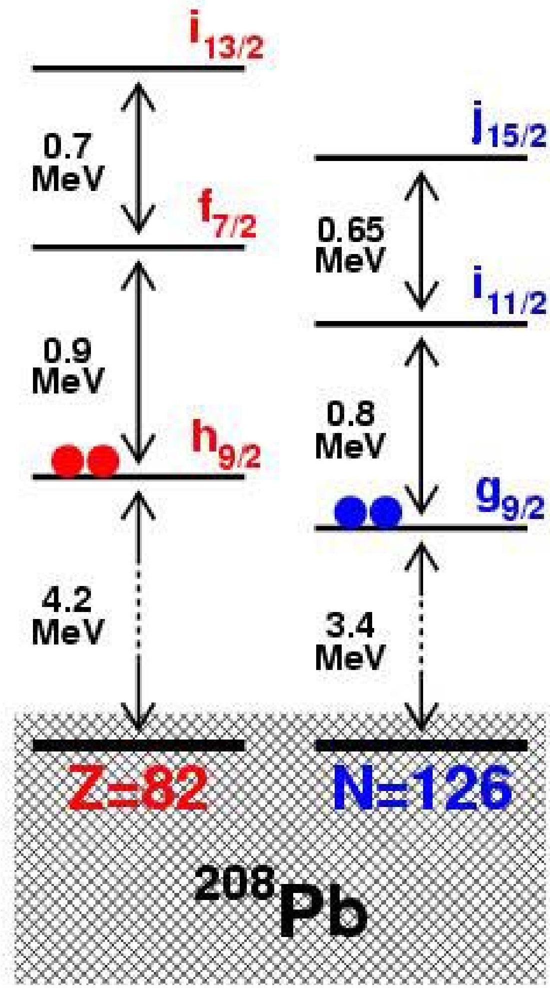


"superallowed" α-decay

Macfarlane and Siivola, PRL 14,114,1965

$^{212}Po = ^{208}Pb + \alpha$

α made out of π and ν
on different orbitals



present reference α-decay

New alpha emitters above ^{100}Sn

Physics :

"superallowed" α-decay ($^{104}Te \rightarrow {}^{100}Sn$ replacing $^{212}Po \rightarrow {}^{208}Pb$ α-reference)

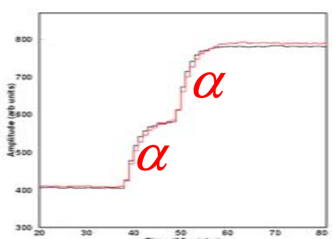
single particle properties near doubly- magic ^{100}Sn

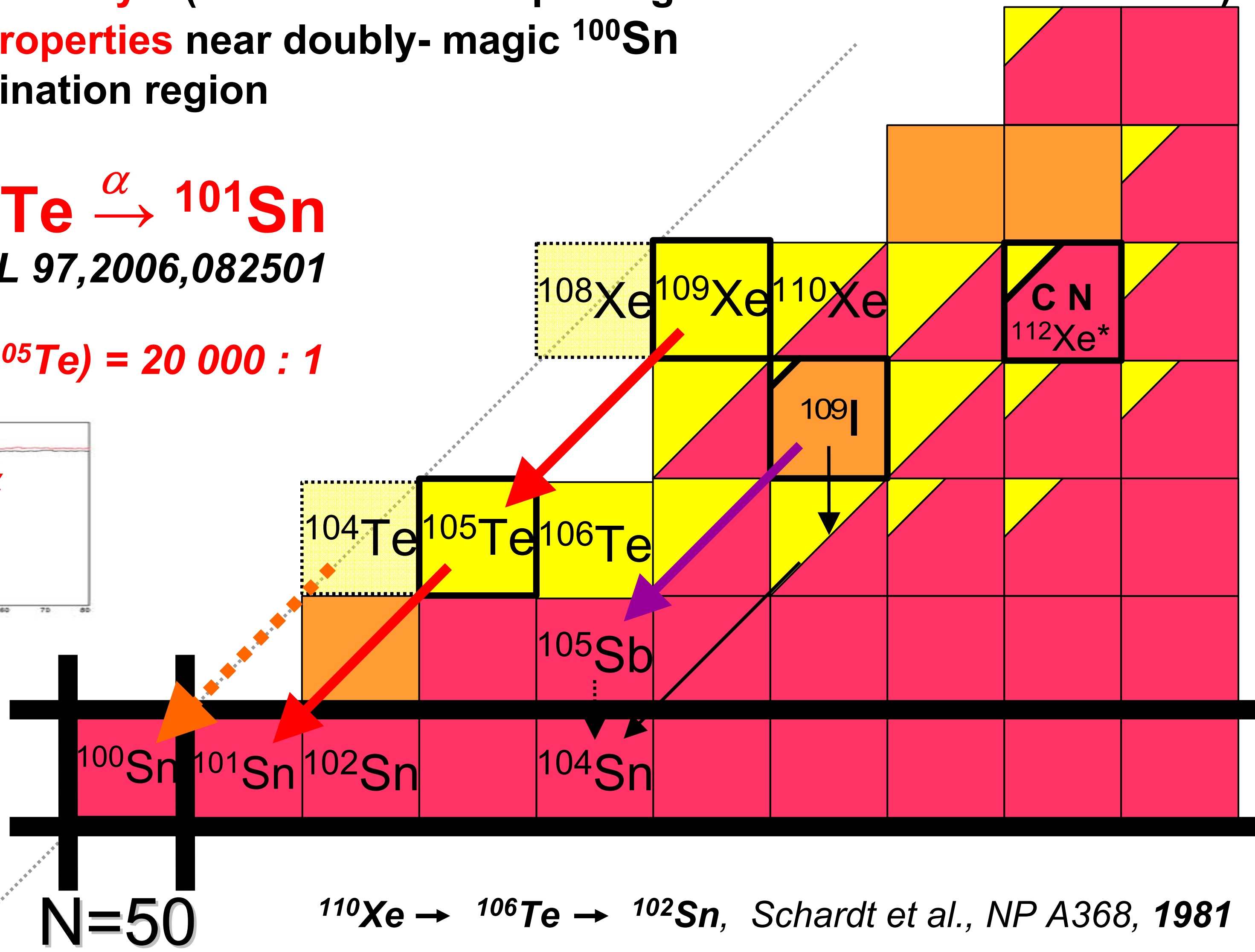
rp-process termination region

$$^{109}Xe \xrightarrow{\alpha} {}^{105}Te \xrightarrow{\alpha} {}^{101}Sn$$

Liddick et al, PRL 97,2006,082501

$$T_{1/2}(^{109}Xe)/T_{1/2}(^{105}Te) = 20\,000 : 1$$



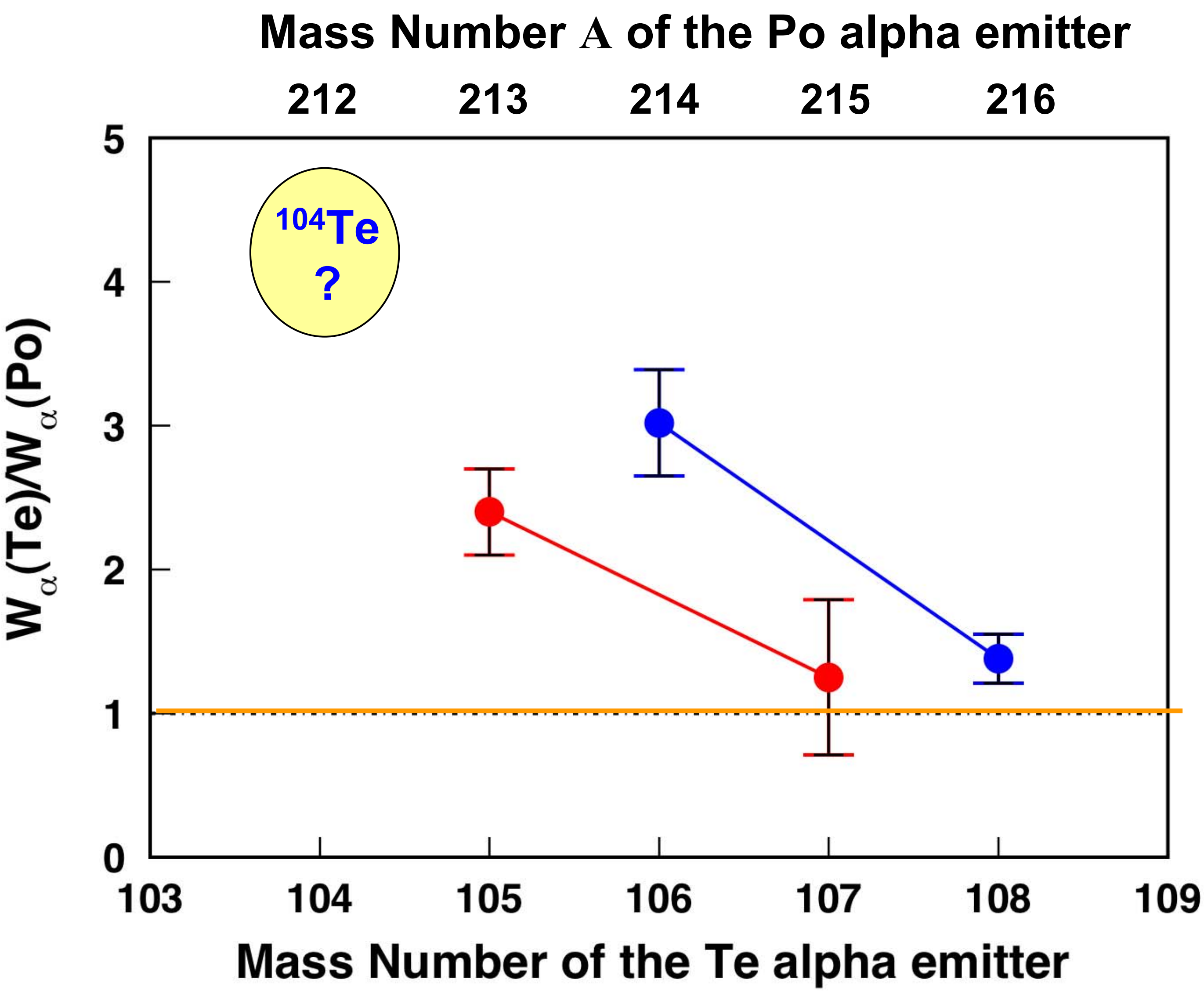


$^{110}Xe \rightarrow {}^{106}Te \rightarrow {}^{102}Sn$, Schardt et al., NP A368, ***1981***

Comparison of the reduced decay width W_α

$^{A}_{84}Po \longrightarrow {}^{(A-4)}_{82}Pb$ and $^{A}_{52}Te \longrightarrow {}^{(A-4)}_{50}Sn$

(see also : Xu,Ren,PR C74,2006, 037302 and P.Mohr, EPJ A31,2007,23)



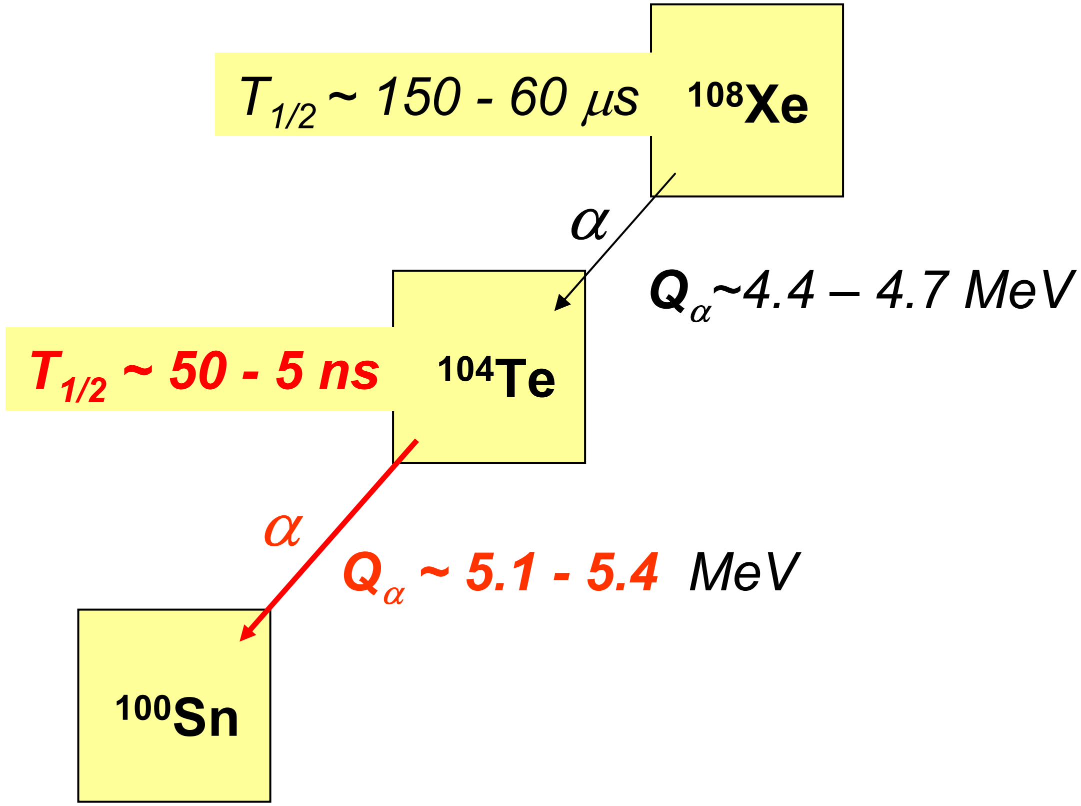
even Z-even N

even Z-odd N

^{106}Te decay :

D.Schardt et al.,
NP A368, 153, 1981
R.Page et al., E_α
PR C49, 3312, 1994
Z.Janas et al.,
EPJ A23, 197, 2005
B.Hadinia et al., $T_{1/2}$
PR C72, 041303R, 2005

Poszukiwanie rozpadów alfa $^{108}Xe \rightarrow ^{104}Te \rightarrow ^{100}Sn$ /R.Grzywacz, R.Page/

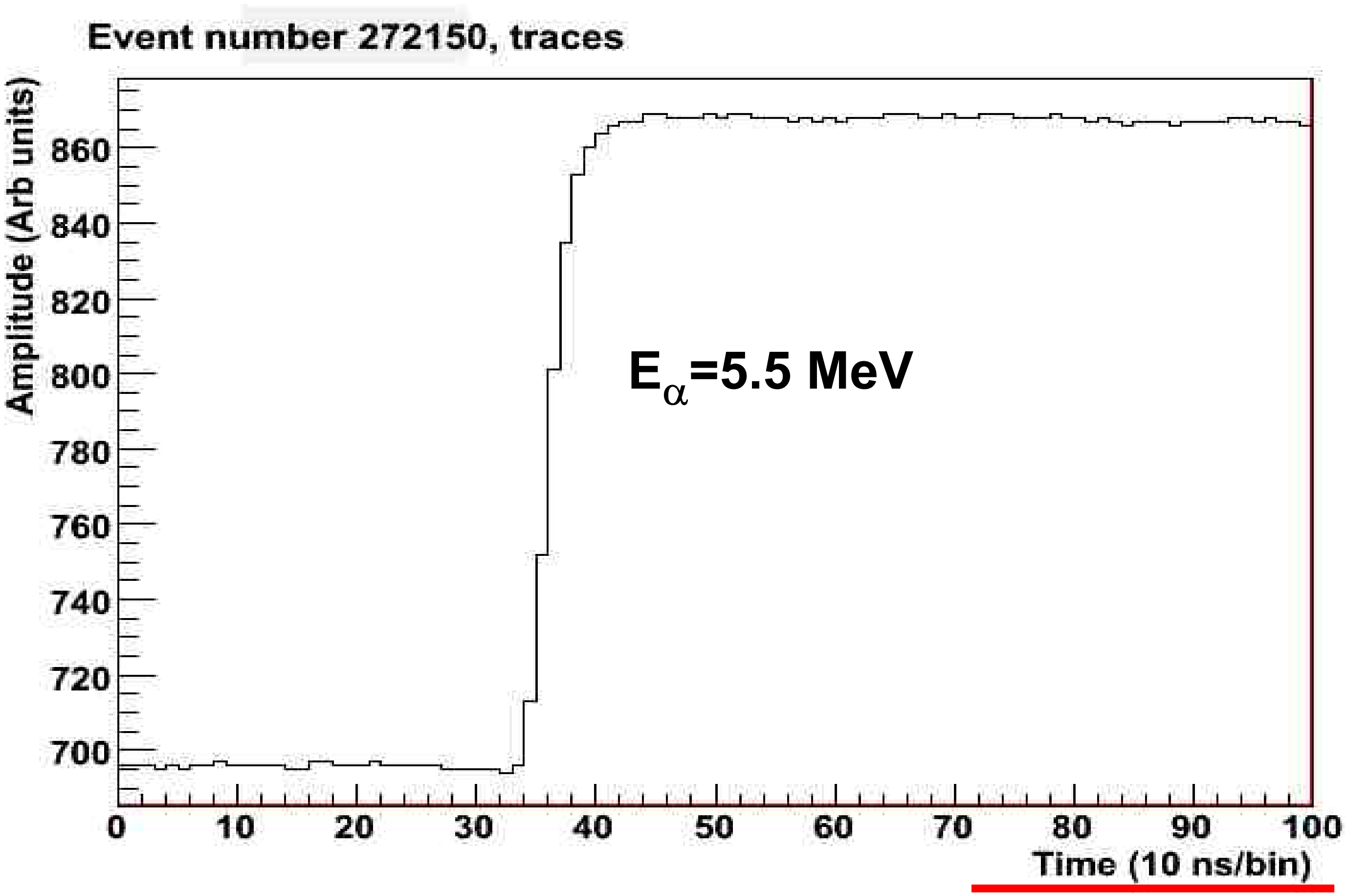


A.Korgul et al., PR C77, 034301, 2008:

100 godzin (HRIBF) → 20 jonów ^{108}Xe (sygnały $E_{\alpha 1} + E_{\alpha 2}$ = 9 - 10 MeV)

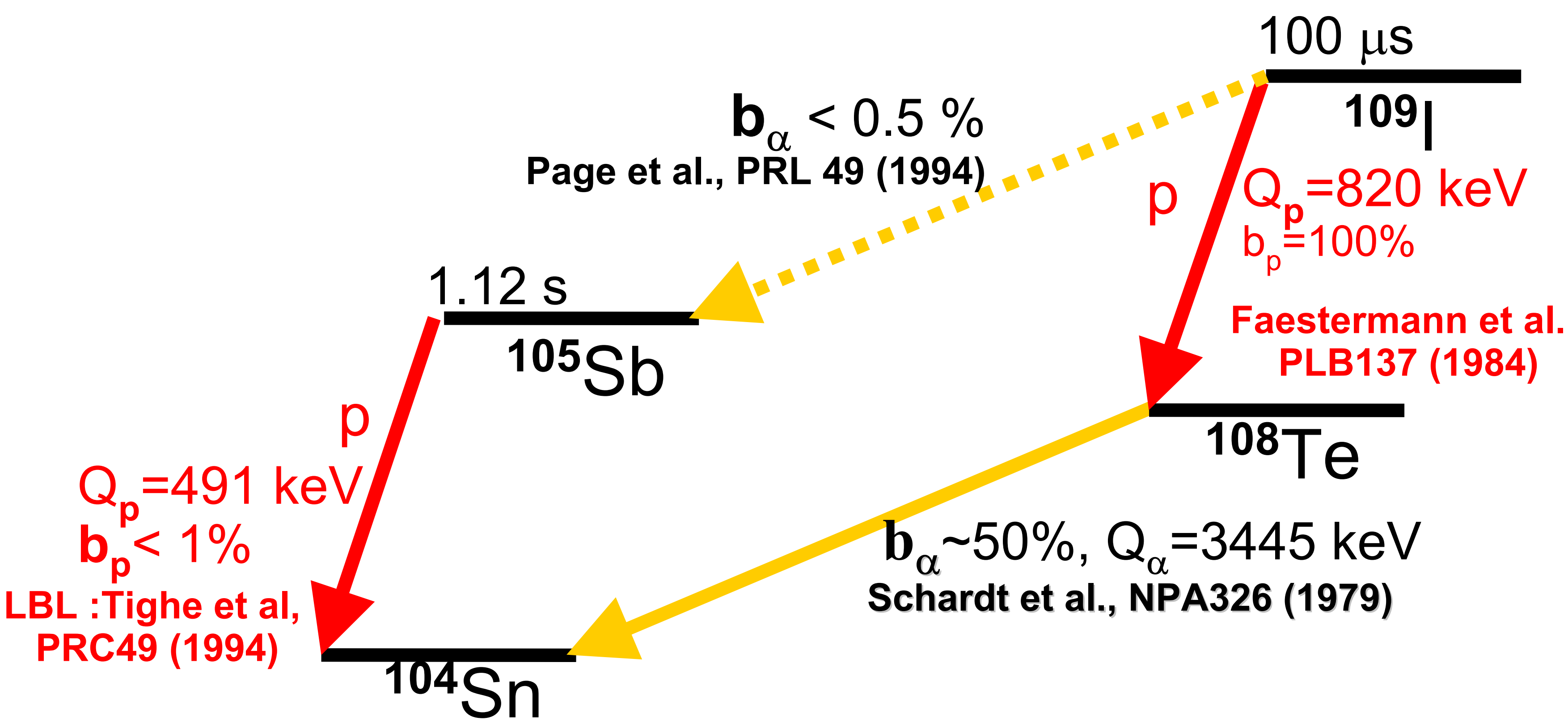
- **wiązka ^{58}Ni, 50 pnA, 240 MeV (ORNL Tandem)** √
- **tarcza ^{54}Fe (J. Szerypo, Monachium, kolaboracja UNIRIB)** √
- **szybkie przedwzmacniacze ~ 20 ns (R.Schneider, MESYTEC, R. Grzywacz)** √
- **elektronika 100 MHz → 10ns/kanał (XIA, R. Grzywacz *et al., ORNL-UTK*)** √

Sean Liddick (UTK), marzec 2008 :
100 MHz Pixie-16 oraz “20 ns” przedwzmacniacze MESYTEC



uruchomienie i sprawdzenie nowego oprogramowanie elektroniki Pixie-16
“decay signal selector” (XIA, R.Grzywacz et al.)

Before hribf experiment:



many attempts were made to detect proton emission from ^{105}Sb (verify LBL result) :

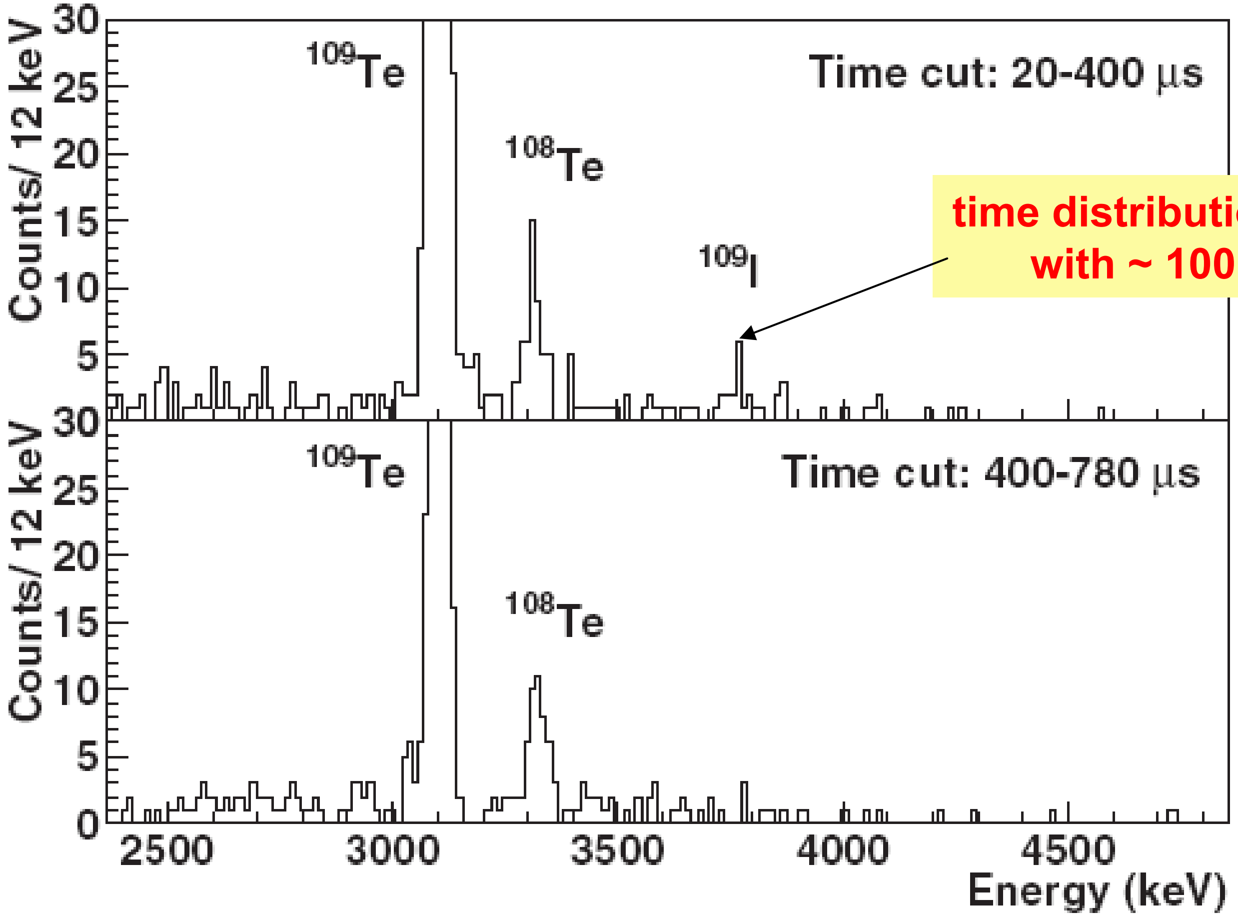
Gillitzer et al., ZPA326 (1987), G. Berthes et al., GSI-87-12 (1987), J.Friese Hirschegg 1996, Liu et al., PRC72 (2005)

over 150 000 of ^{109}I ions implanted into DSSD

directly from ^{109}I protons (113 000) and from a daughter activity ^{108}Te α-decay (70 000)

$T_{1/2}(^{109}I) = 93.5(3)\ \mu s$

$E_\alpha = 3774(20)$ keV, $I_\alpha = 1.4(4)\times10^{-2}$ %



time distribution compatible with ~ 100 μs halflife

C.Mazzocchi et al., PRL 98, 212501, 2007

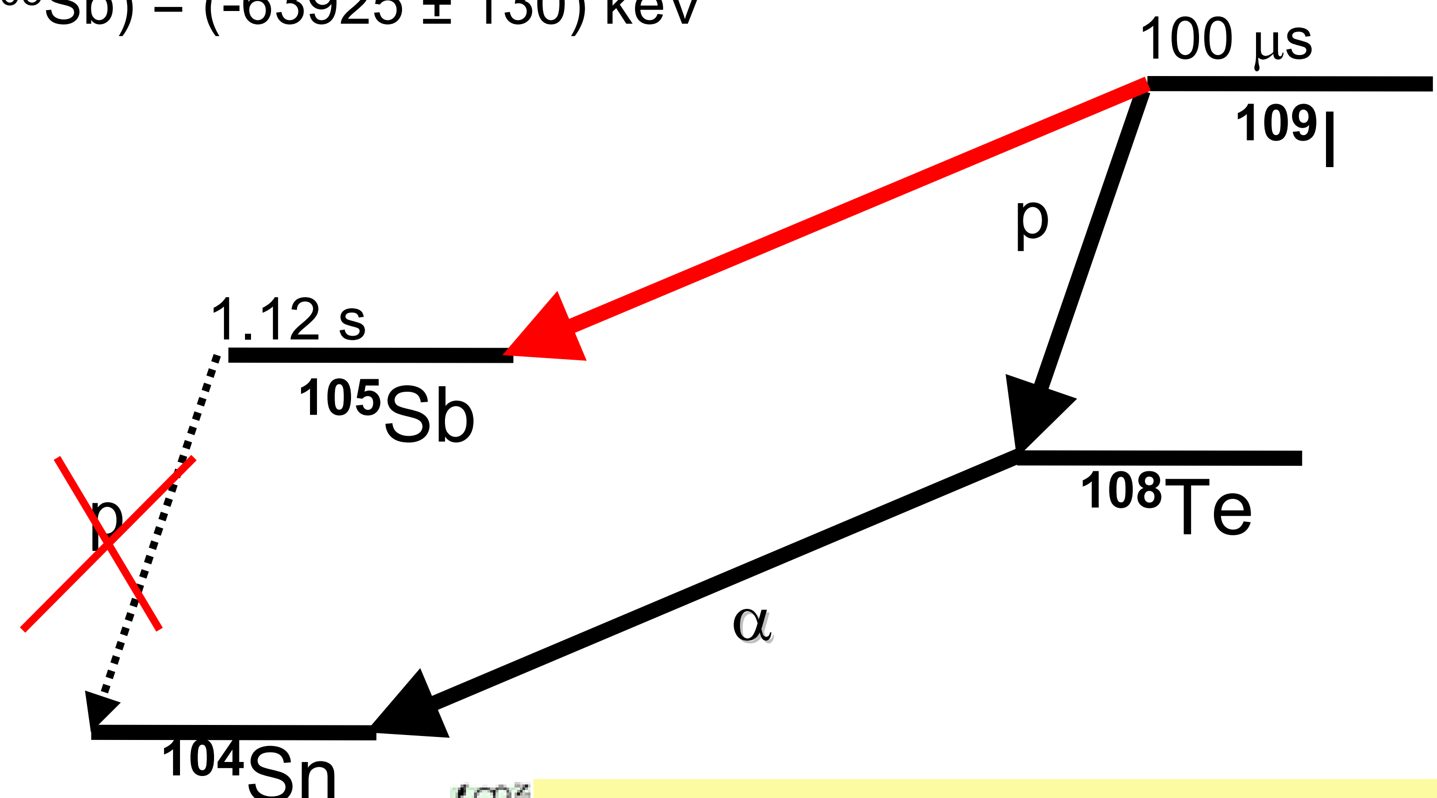
Result : no observable proton emission from ^{105}Sb !

$Q_{\alpha}(^{109}I) = 3918 \pm 21$ keV

$\Rightarrow Q_p(^{105}Sb) = 356 \pm 22$ keV ***(was 491(15) keV, Tighe et al.1994)***

$\Rightarrow T_{1/2}^{p} \sim 10^{7}$ s (=116 days) $\rightarrow b_p \sim 10^{-7}$

$\Delta M\ (^{105}Sb) = (-63925 \pm 130)$ keV

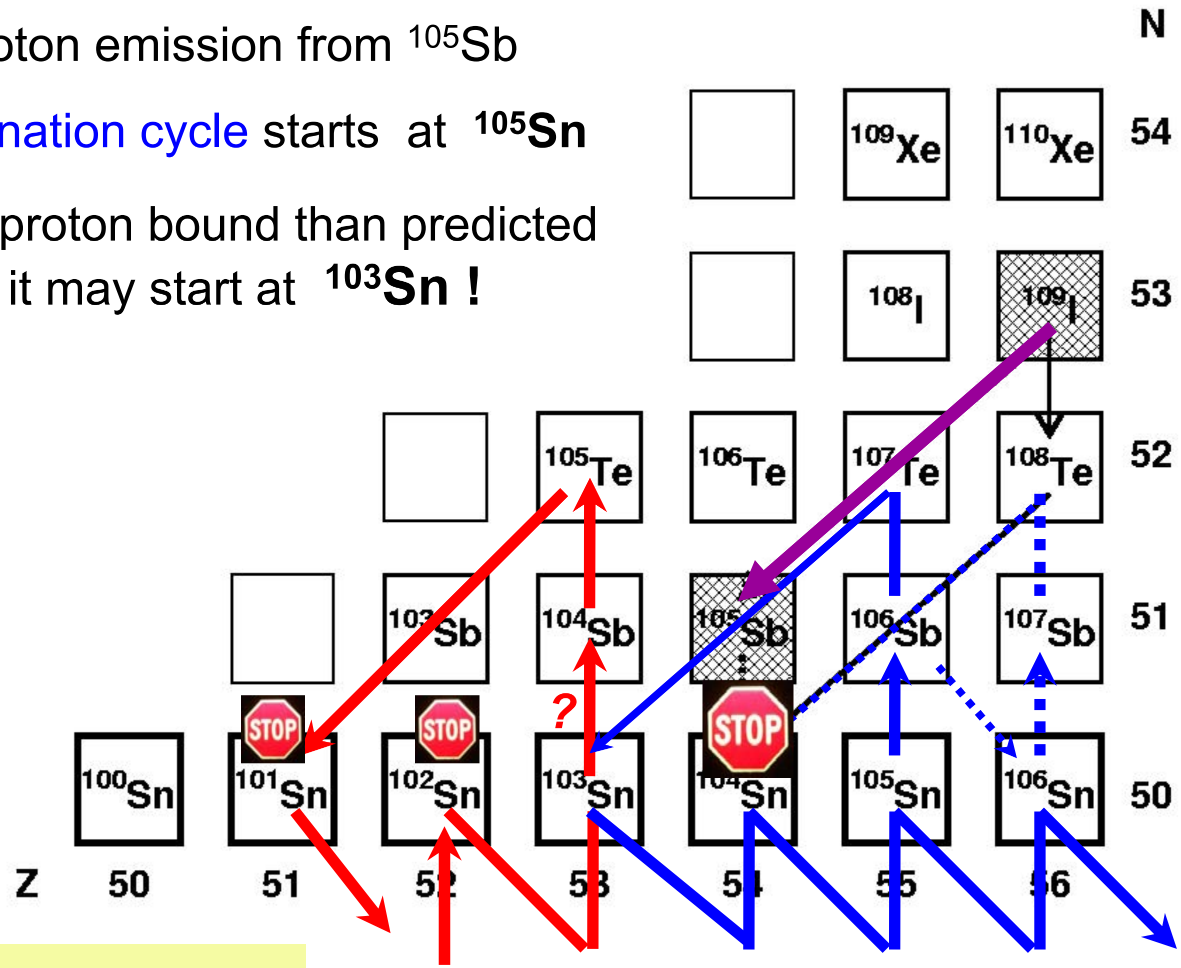


C.Mazzocchi et al., PRL 98, 212501, 2007

Astrophysical relevance :
C.Mazzocchi, …, H.Schatz,…PRL 98,212501, 2007

$$^{109}\mathrm{I} \xrightarrow[\sim 10^{-2}\%]{\alpha} {}^{105}\mathrm{Sb} \not\xrightarrow{p} {}^{104}\mathrm{Sn}$$

- No observable proton emission from ^{105}Sb
- The rp-process termination cycle starts at ^{105}**Sn**
- **If** ^{104}**Sb** is much more proton bound than predicted (strong odd-even effect) it may start at ^{103}**Sn !**



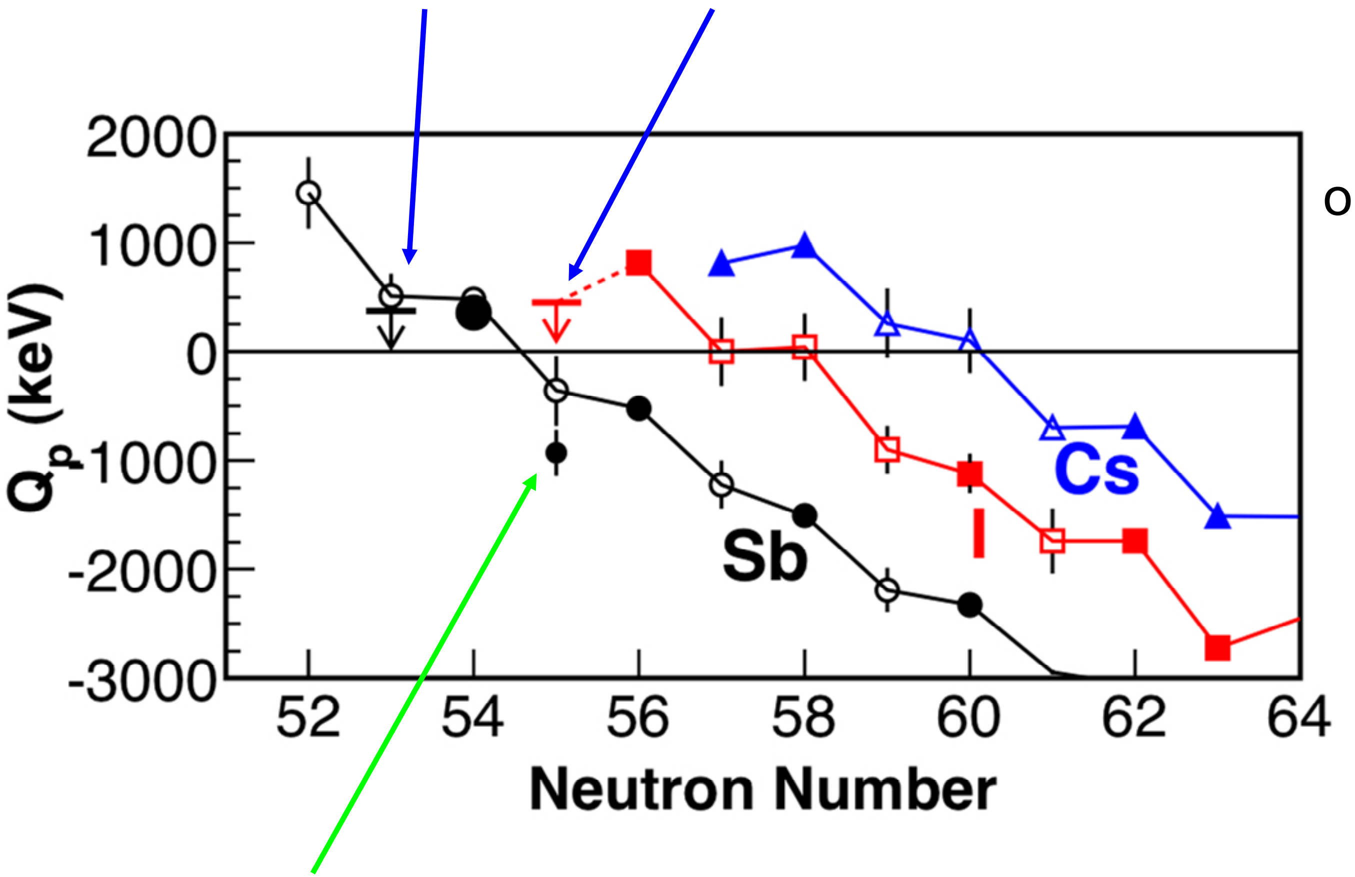
rp-process termination
H.Schatz et al., PRL86 (2001)

search for ^{112}Cs weak α-decay :
*S_P of ^{108}I and ^{104}**Sb***

Odd-even effect in proton decay energies Q_p

Z=55 Cs, Z=53 I, Z=51Sb

^{104}Sb ? ^{108}I ?



open symbols:
Audi 2003

^{106}Sb ???? Płochocki et al., Phys. Lett. 106B, 285 (1981)

^{106}Sb – interesting candidate for trap exp ???

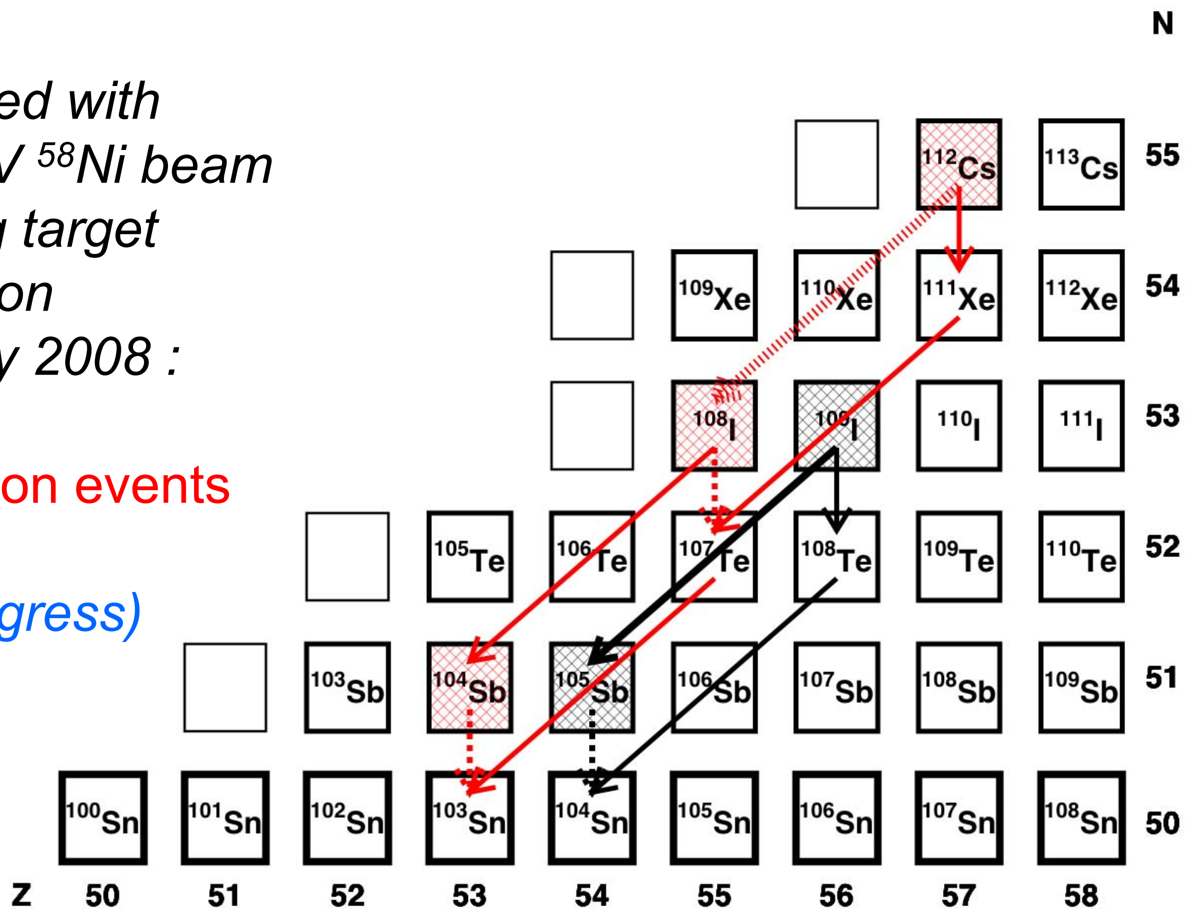
search for ^{112}Cs (very weak) α-decay :
S_P of ^{108}I and ^{104}Sb

statistics achieved with over 50 pnA 250 MeV ^{58}Ni beam and ^{58}Ni rotating target (p3n) reaction

hribf February 2008 :

~ 2000 ^{112}Cs proton events

(analysis in progress)



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