

# The Neutron Long Counter NERO for studies of Beta-delayed Neutron Emission

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# Why do we care about $\beta$ -delayed neutron emission?



**Direct impact in Heavy-Element Nucleosynthesis Models (r-process)**

**...also Nuclear Structure Probes**



## • $\beta$ -delayed neutron-emission probabilities ( $P_n$ ) :

- ✓ *What is the path followed by matter flow after freeze-out (Abundance pattern post freeze-out)*
- ✓ *Additional source of late neutrons*

## • Half-lives of r-process nuclei:

- ✓ *What are the bottle-necks of matter flow? Abundance pattern prior freeze-out*

## • $T_{1/2}$ and $P_n$ (gross $\beta$ -decay properties):

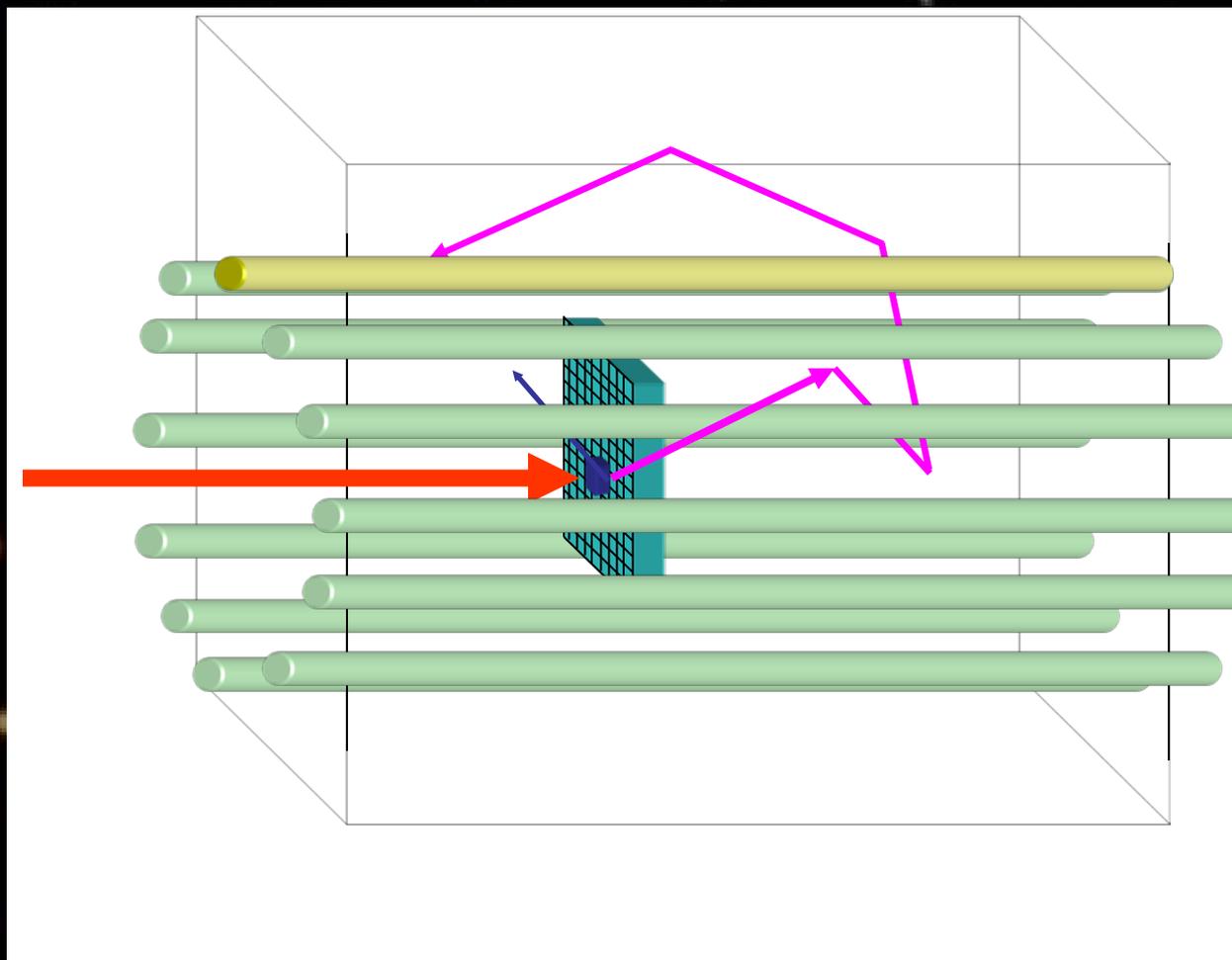
*First insights into shell structure via  $\beta$ -decay strength function (Deformation, nucleon-nucleon interaction, new magic numbers, etc...)*



# Measurements of $\beta$ -delayed neutron-emission probabilities at NSCL



# Measurement of $\beta$ -delayed with a Neutron Long Counter





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# Design of NERO detector: Minimize Background & Maximize Efficiency



# Design of NERO detector: Minimum Background & Maximum Efficiency

## $\beta$ -neutron background:

Spurious coincidences  $\beta$  + neutrons

- $\beta$  background + REAL neutrons
- $\beta$  background + Neutron background
- REAL  $\beta$  decay + Neutron background

## Neutron background origin:

- Electronic noise
- Gamma rays
- Cosmic rays
- Fragmentation reactions

## $\beta$ background origin:

- REAL  $\beta$  decays from implants  $\neq$  mother
- "Light" particles (t, Li, ...)



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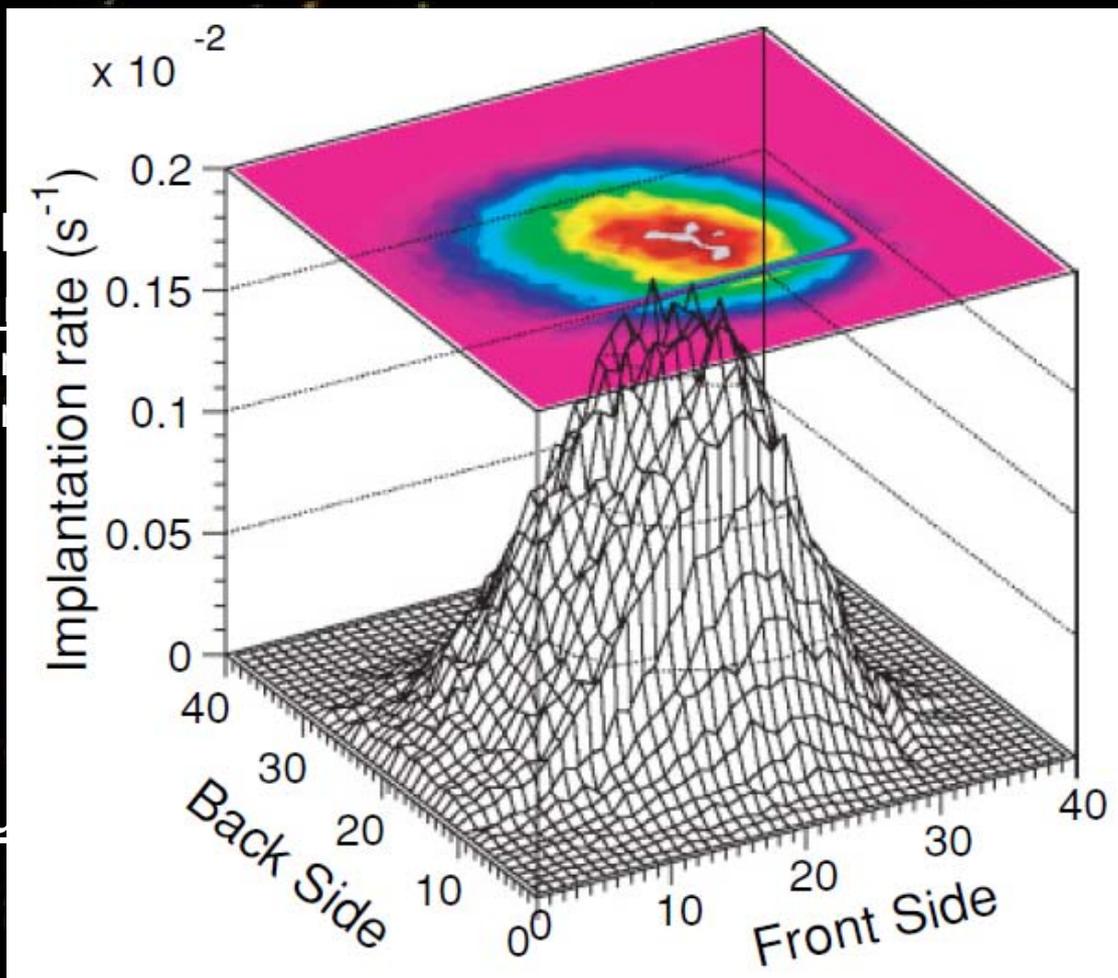
# Design of NERO detector: Minimum Background & Maximum Efficiency

$\beta$ -neutron

Spurious coi

- $\beta$  backg
- $\beta$  backg
- REAL  $\beta$

Redu



nd origin:  
se

n reactions

gin:  
ys from  
ther  
es (t, Li, ...)

nters





# Design of NERO detector: Minimum Background & Maximum Efficiency

Large segmented  
implantation detector



Large NERO cylindrical  
cavity to accommodate  
DSSD



Reduce neutron  
efficiency

MCNP simulations to maximize efficiency

Energy-independent Efficiency

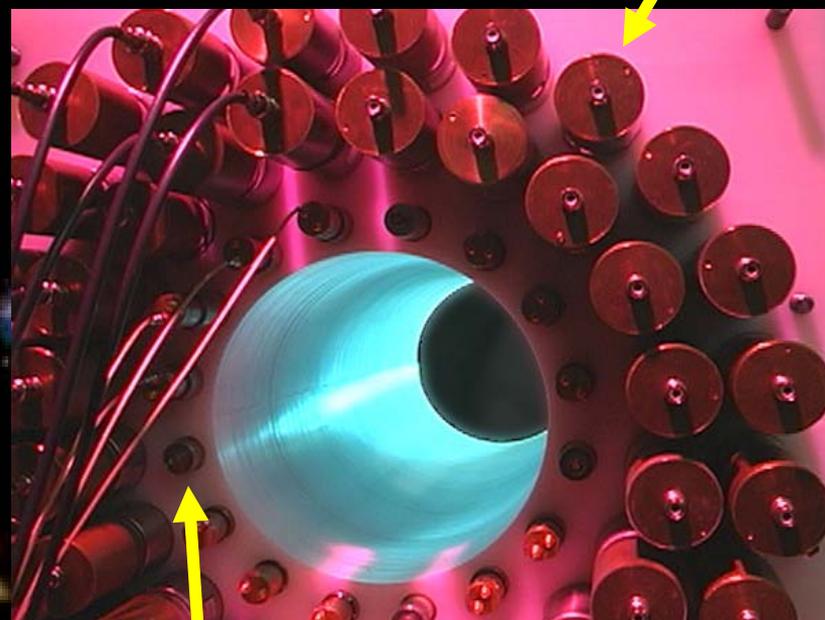


# Final design

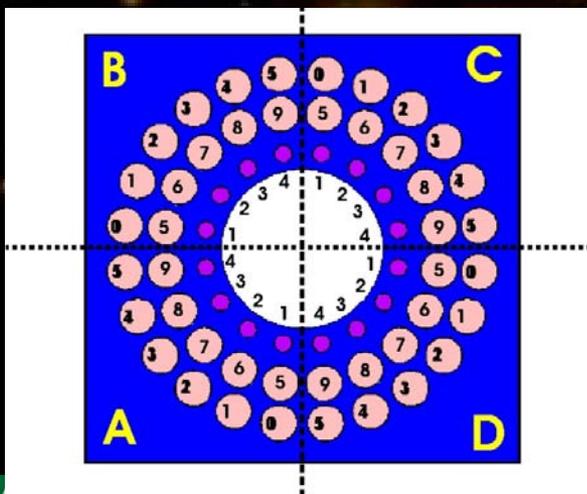
Polyethylene Moderator



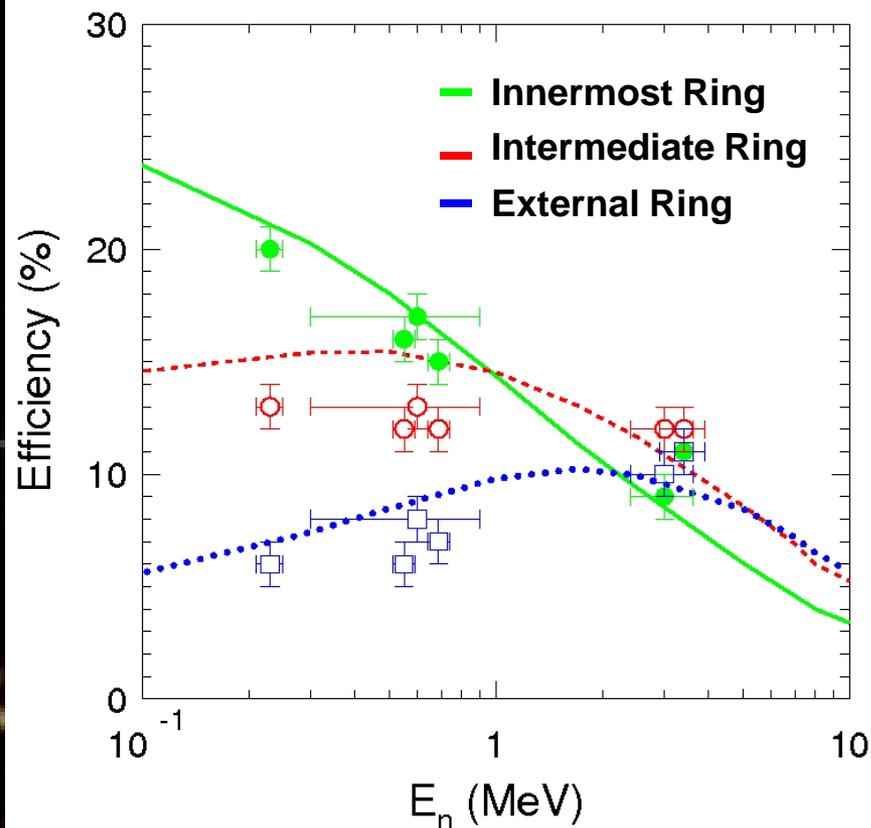
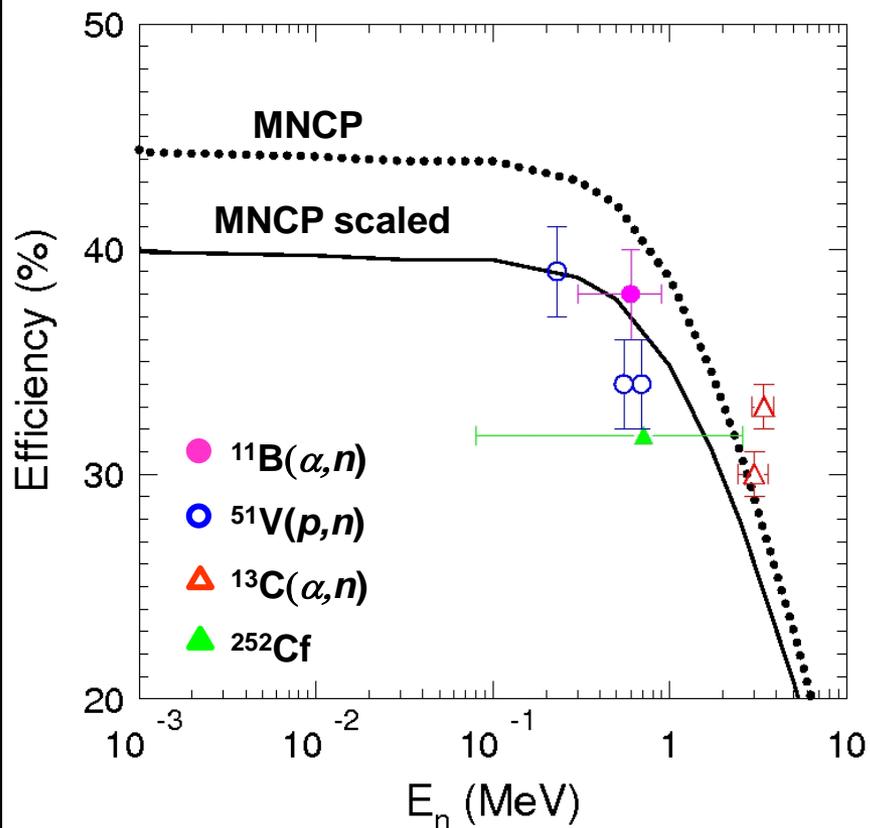
$\text{BF}_3$  Proportional Counters (44)



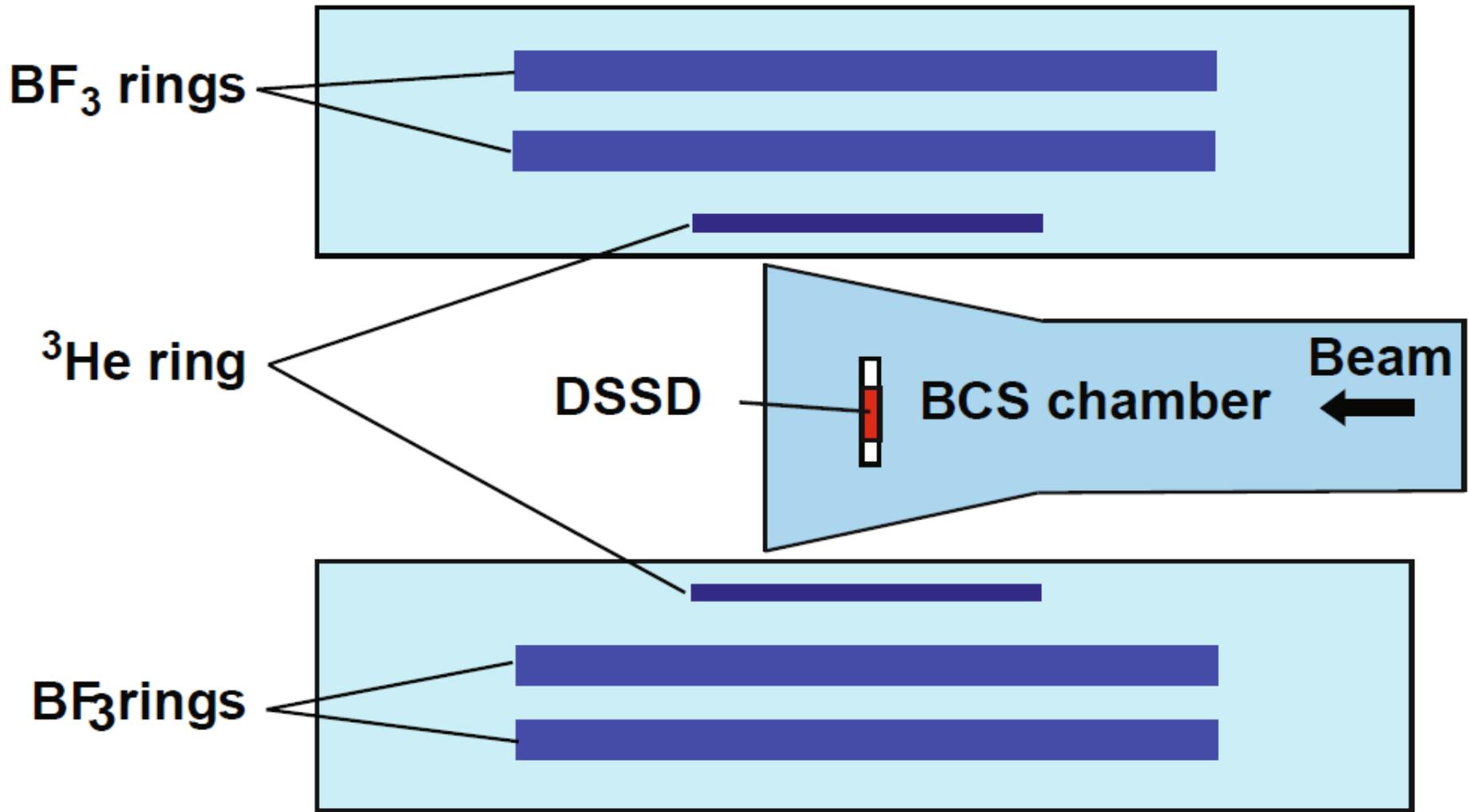
$^3\text{He}$  Proportional Counters (16)



# NERO neutron efficiency



# Beta Counting System + NERO





# Results and discussions



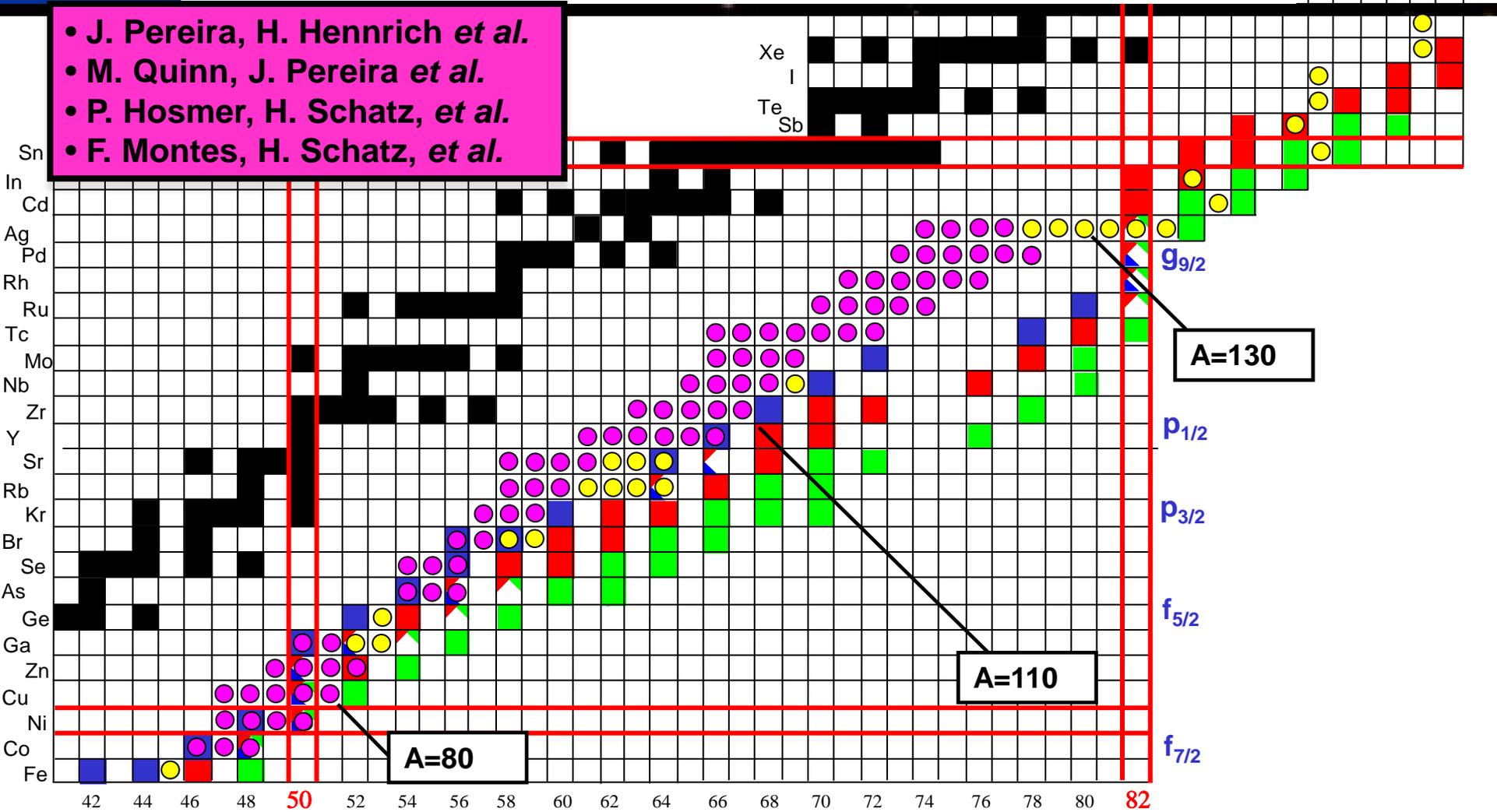


# NSCL $\beta$ -decay r-process campaigns

(NSCL/Mainz/Notre Dame/Maryland)



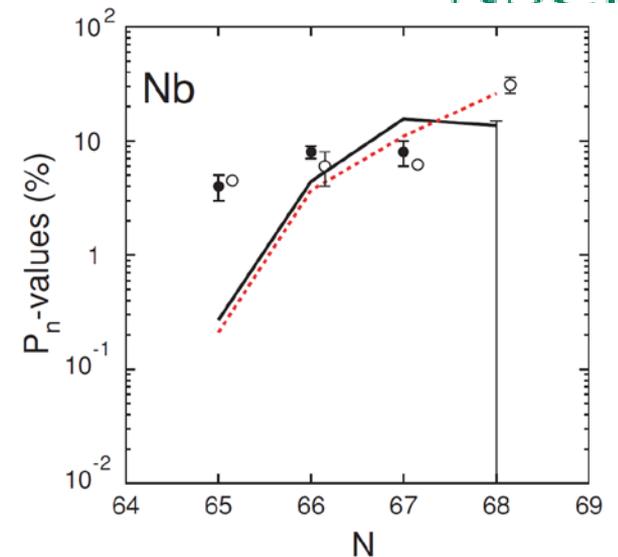
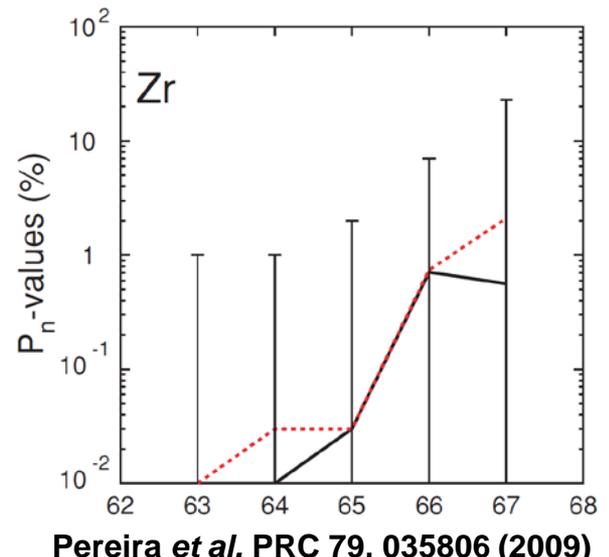
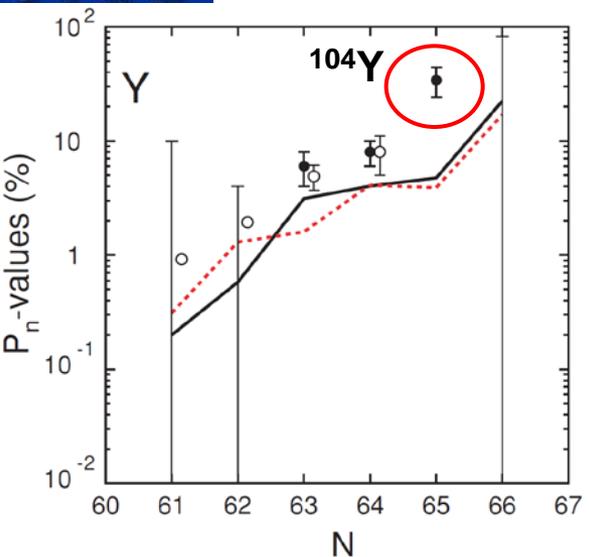
- J. Pereira, H. Henrich *et al.*
- M. Quinn, J. Pereira *et al.*
- P. Hosmer, H. Schatz, *et al.*
- F. Montes, H. Schatz, *et al.*



↑ Z  
 → N  
 K.-L. Kratz (private communication)

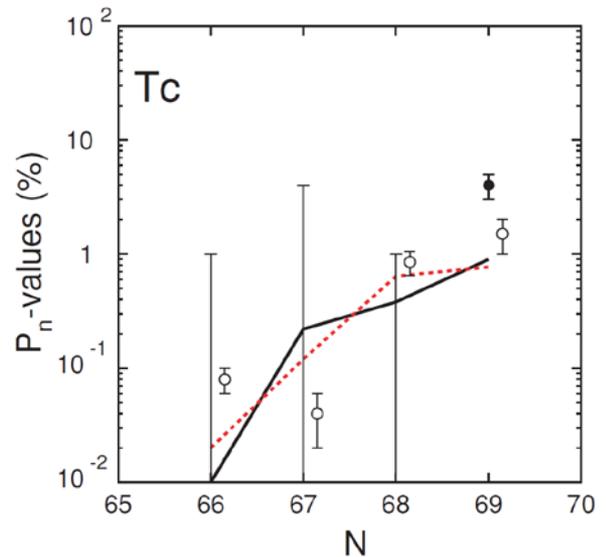
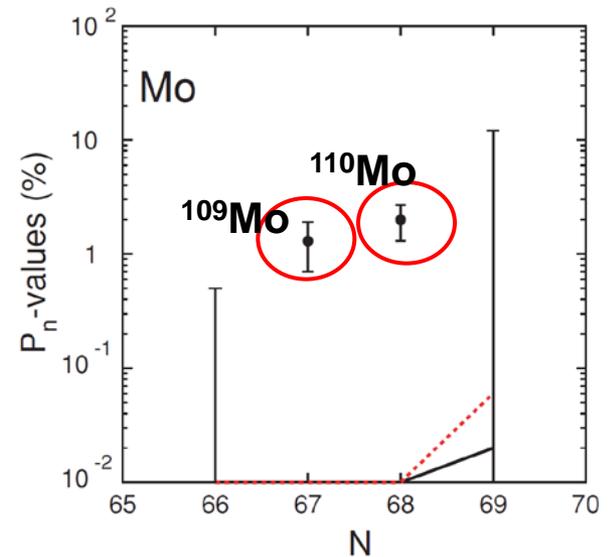
$$n_n = 10^{20} - 10^{26} \text{ cm}^{-3}$$

# $P_n$ values of $A \approx 110$ r-process nuclei



Pereira *et al.* PRC 79, 035806 (2009)  
P. Sarriguren and J. Pereira, PRC 81, 064314 (2010)

FRDM/QRPA  
2003  
—  
FRDM/QRPA  
(triaxiality)  
- - -

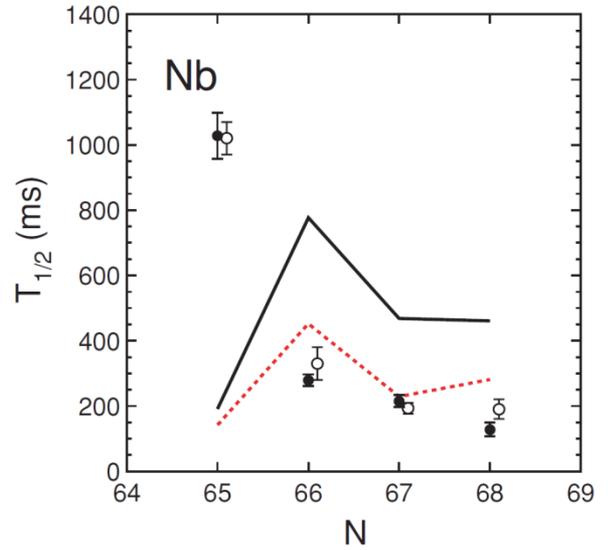
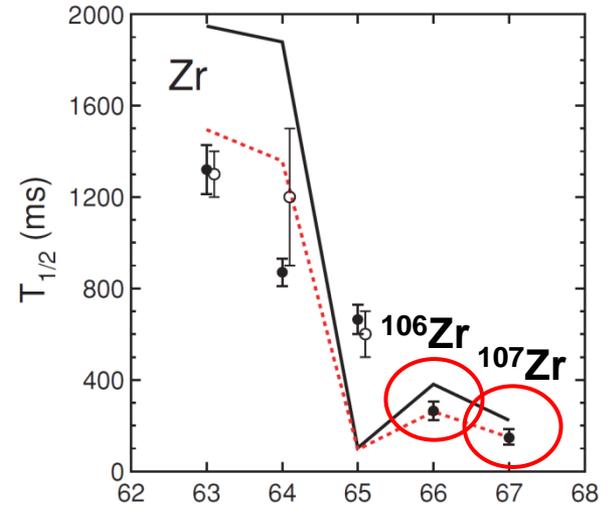
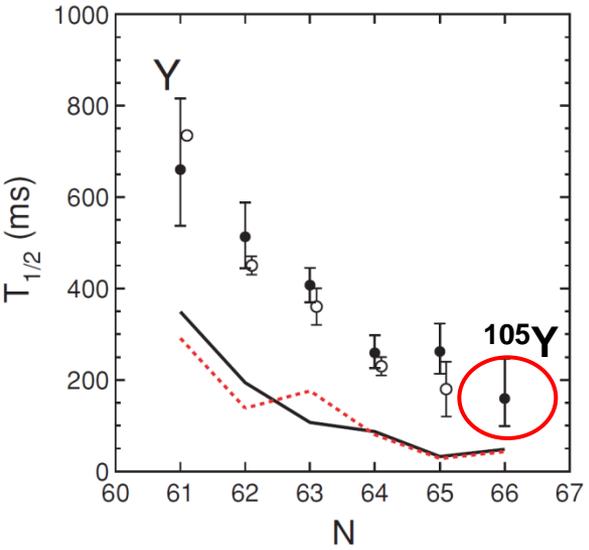




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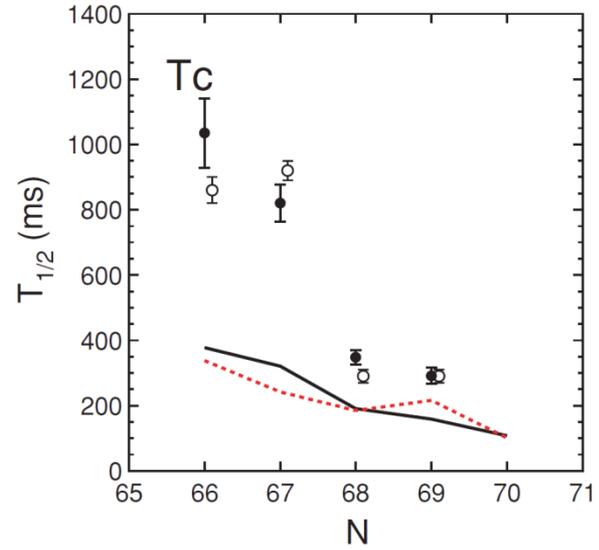
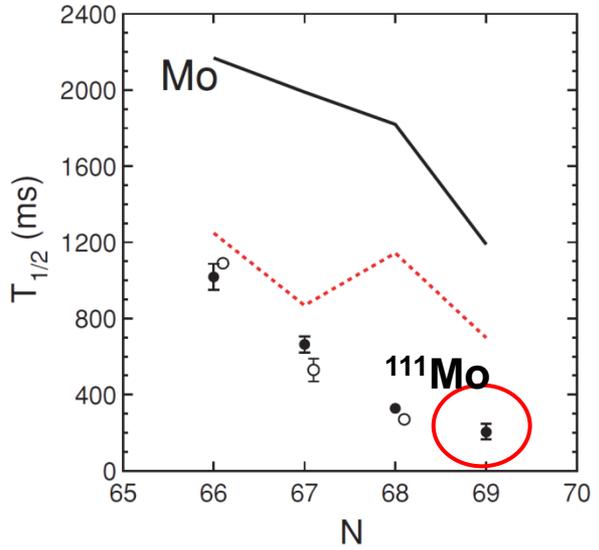
# $T_{1/2}$ of $A \approx 110$ r-process nuclei



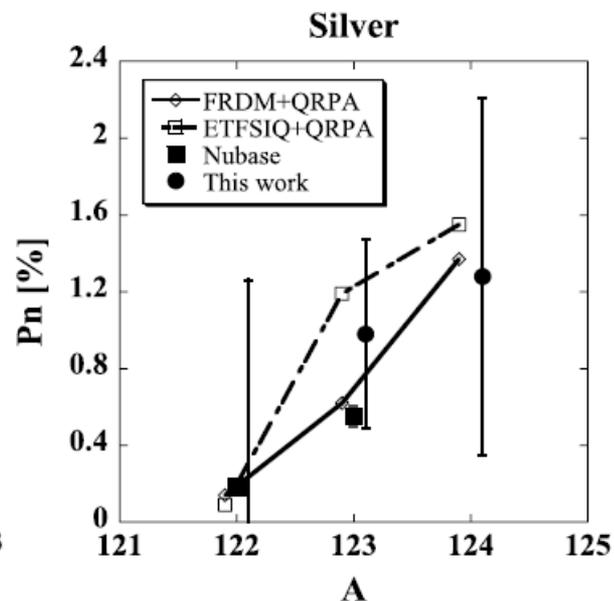
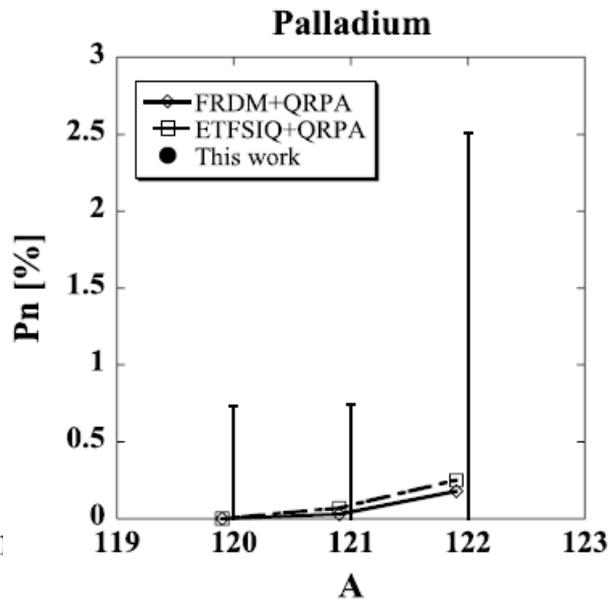
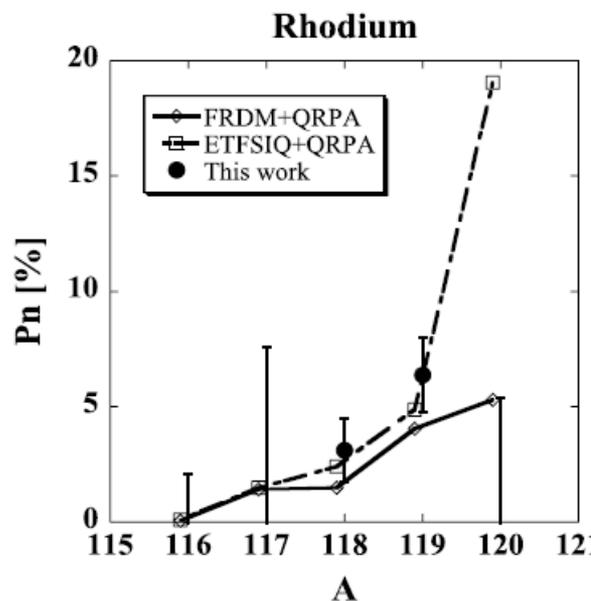
Pereira *et al.* PRC 79, 035806 (2009)  
 P. Sarriguren and J. Pereira, PRC 81, 064314 (2010)

FRDM/QRPA  
 2003  
 —

FRDM/QRPA  
 (triaxiality)  
 - - -

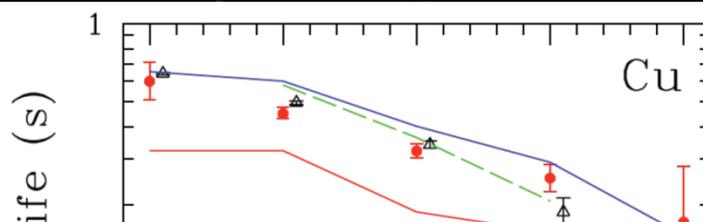
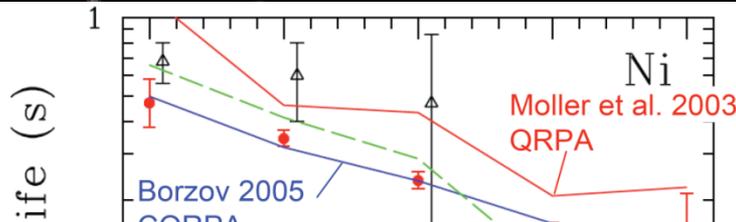


# $T_{1/2}$ and $P_n$ around the $^{120}\text{Rh}$



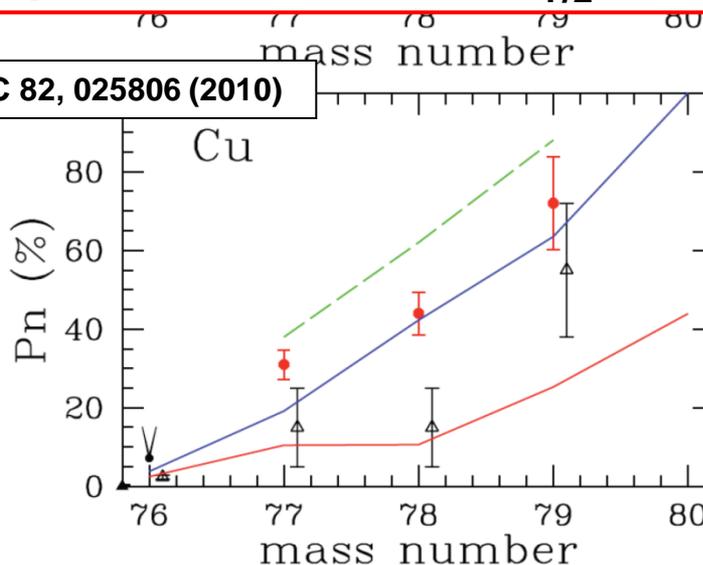
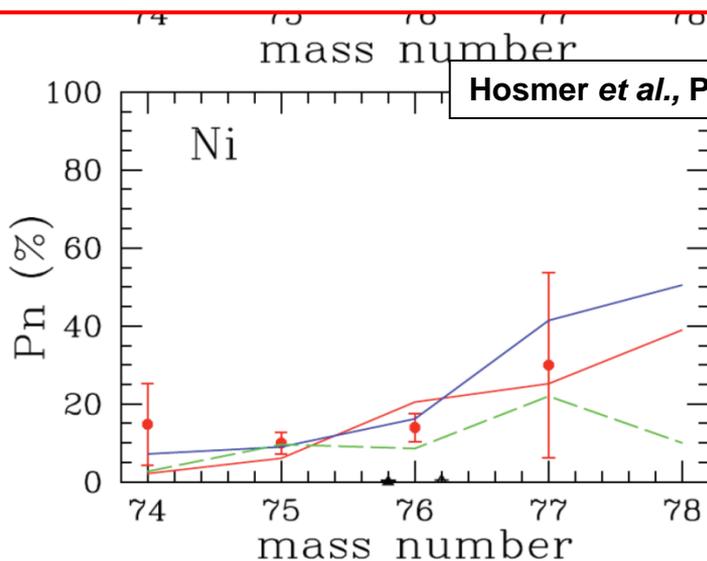
F. Montes *et al.*, PRC73, 35801 (2006)

# $T_{1/2}$ and $P_n$ around the $^{78}\text{Ni}$ waiting-point ( $^{73-75}\text{Co}$ , $^{75-78}\text{Ni}$ , $^{76-80}\text{Cu}$ , $^{79-81}\text{Zn}$ , $^{81-82}\text{Ga}$ )



**Shell-model calculations: GT operator renormalized  
by 0.37 instead of 0.75.**

**Limitation of the model space that excluded  $f_{7/2}$ ?**



# Summary

- $P_n$  values and  $\beta$ -decay half-lives are crucial to model the synthesis of Heavy Elements ; they are also sensitive nuclear structure probes
- The neutron detector NERO was designed for measuring  $P_n$  values. Its performance combines low background rates with high neutron efficiencies  $\sim 40\%$
- Measured  $P_n$  values were used to investigate deformation of nuclei around  $^{106}\text{Zr}$  (triaxiality, weakly-deformed intruder states)
- Measured  $P_n$  values of nuclei around  $^{78}\text{Ni}$  may indicate sensitivity of shell-model calculations to model space (inclusion of  $f_{7/2}$ ). Results for Cu isotopes may indicate the inversion of  $\pi 2p_{3/2}$  and  $\pi 1f_{7/2}$
- MORE INFORMATION @ <http://www.nscl.msu.edu/~nero/>



# Thanks to:



- **NSCL/MSU:** Paul Mantica, Hendrik Schatz, Paul Hosmer, Giuseppe Lorusso, Marcelo Del Santo, Fernando Montes , Linda Schnorrenberger
- **Univ. Notre Dame:** Ani Aprahamian, Joachim Görres, Matt Quinn, Michael Wiescher, Andreas Wöhr
- **Mainz Univ.:** Karl-Ludwig Kratz, Clemens Herlitzius, Bernd Pfeiffer, Florian Schertz
- **Los Alamos NL:** Peter Möller, Peter Santi
- **Univ. Maryland:** Bill Walters
- **Pacific Northwest NL:** Paul Reeder

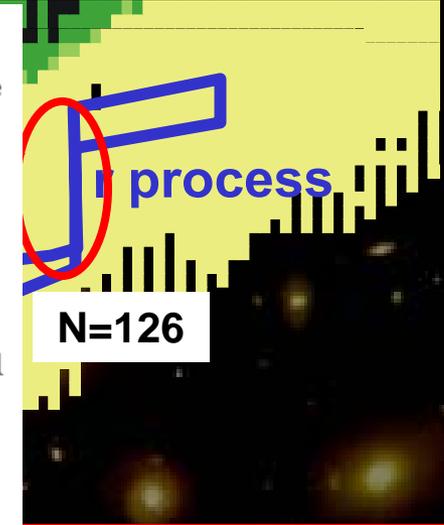
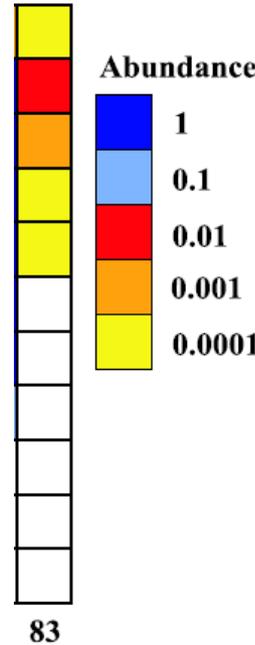
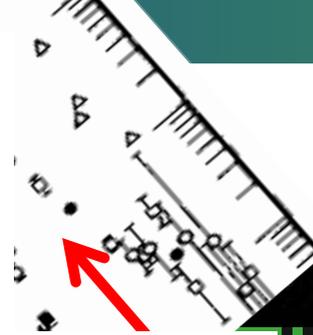
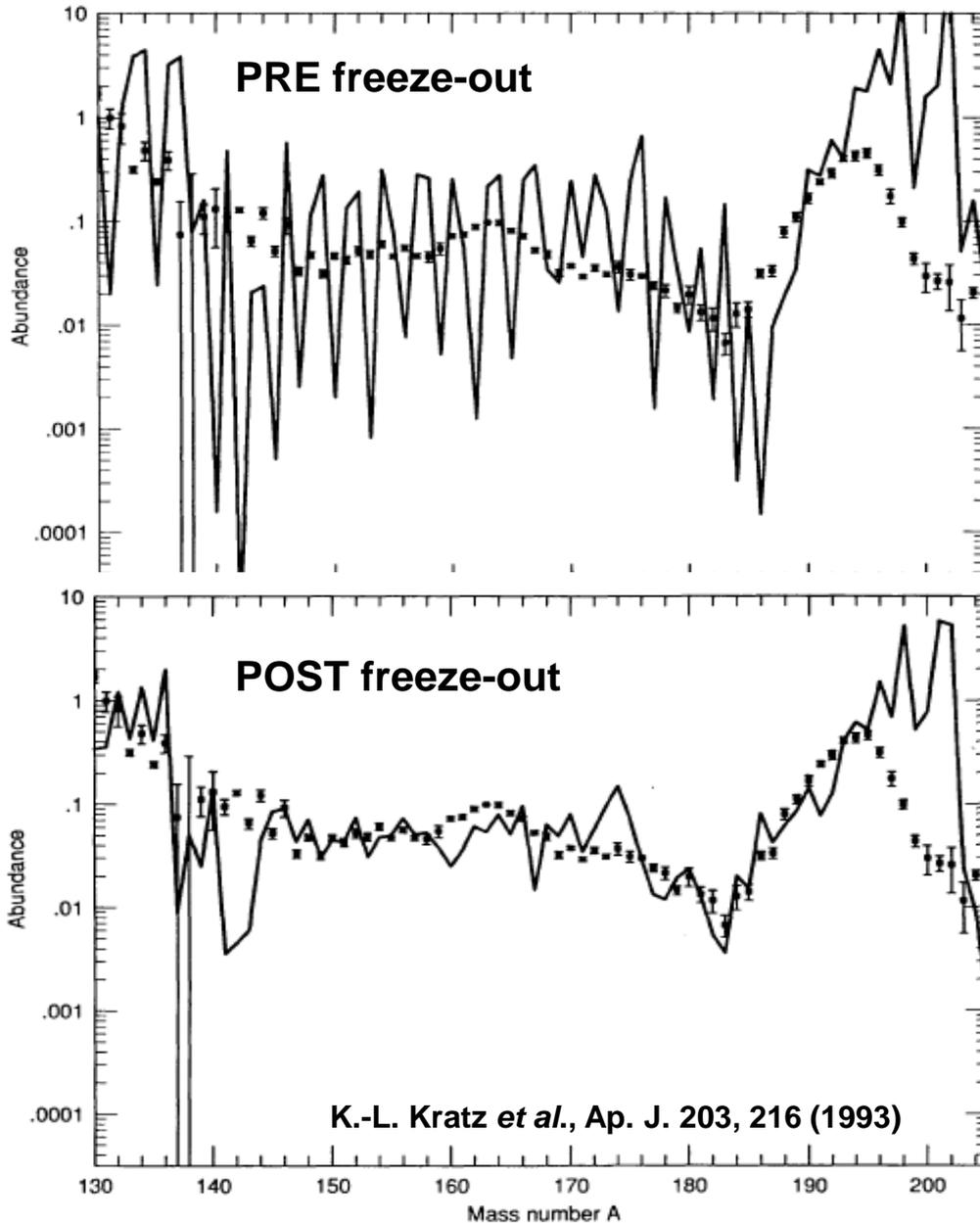




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# Back up slides





in **pre freeze-out**  
(Nuclei involved)  
bottle necks"

Abundance pattern **post freeze-out**  
decay path towards stability

# Nuclear structure probes

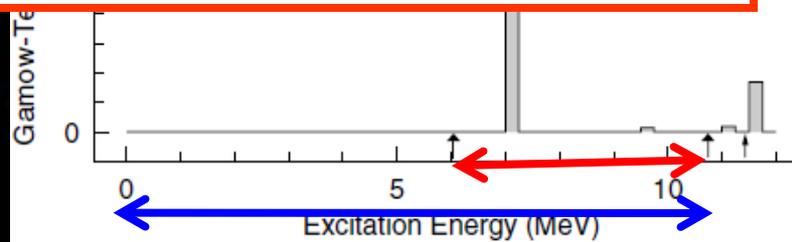
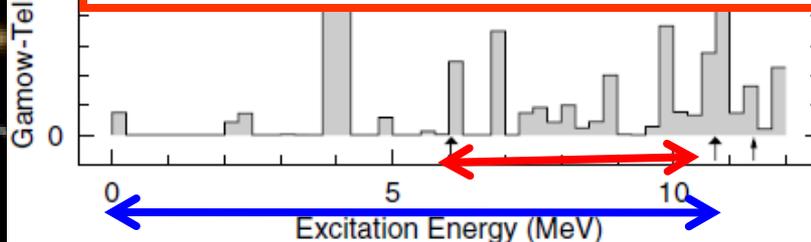
Sensitive to “integral” structure via Strength function  $S_\beta$   
 weighted by Fermi-function  $f \sim (Q_\beta - E)^5$

$$\int_0^{Q_\beta} S_\beta$$

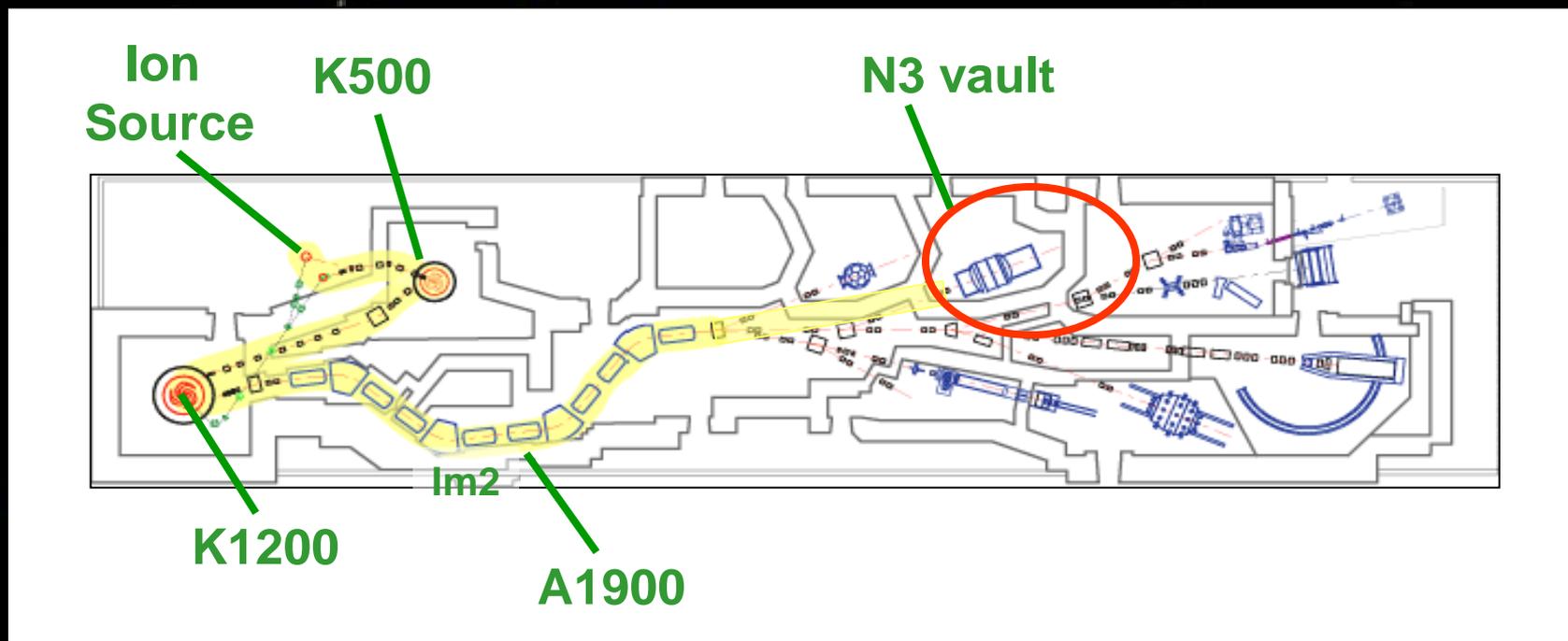
•  $T_{1/2}$  and  $P_n$  – Nuclear-structure probes. “Cheaper” than  $\gamma$ -spectroscopy

• For neutron-rich nuclei,  $Q_\beta$  is large:

- $T_{1/2}$  is mostly sensitive to  $S_\beta$  near the ground-state, only
- $P_n$  is mostly sensitive to  $S_\beta$  at higher energies ( $\sim S_n$ ) (emphasize importance of forbidden transitions)



# Production and separation of nuclei (e.g. A1900 separator at NSCL)



- Production of nuclei by fragmentation (inverse kinematics)
- Separation and identification of exotic beam: A1900
- Exotic beam → Implantation station (in the N3 vault)

# Correlation of implanted nuclei and $\beta$ decays ( $\beta$ -decay end-station)

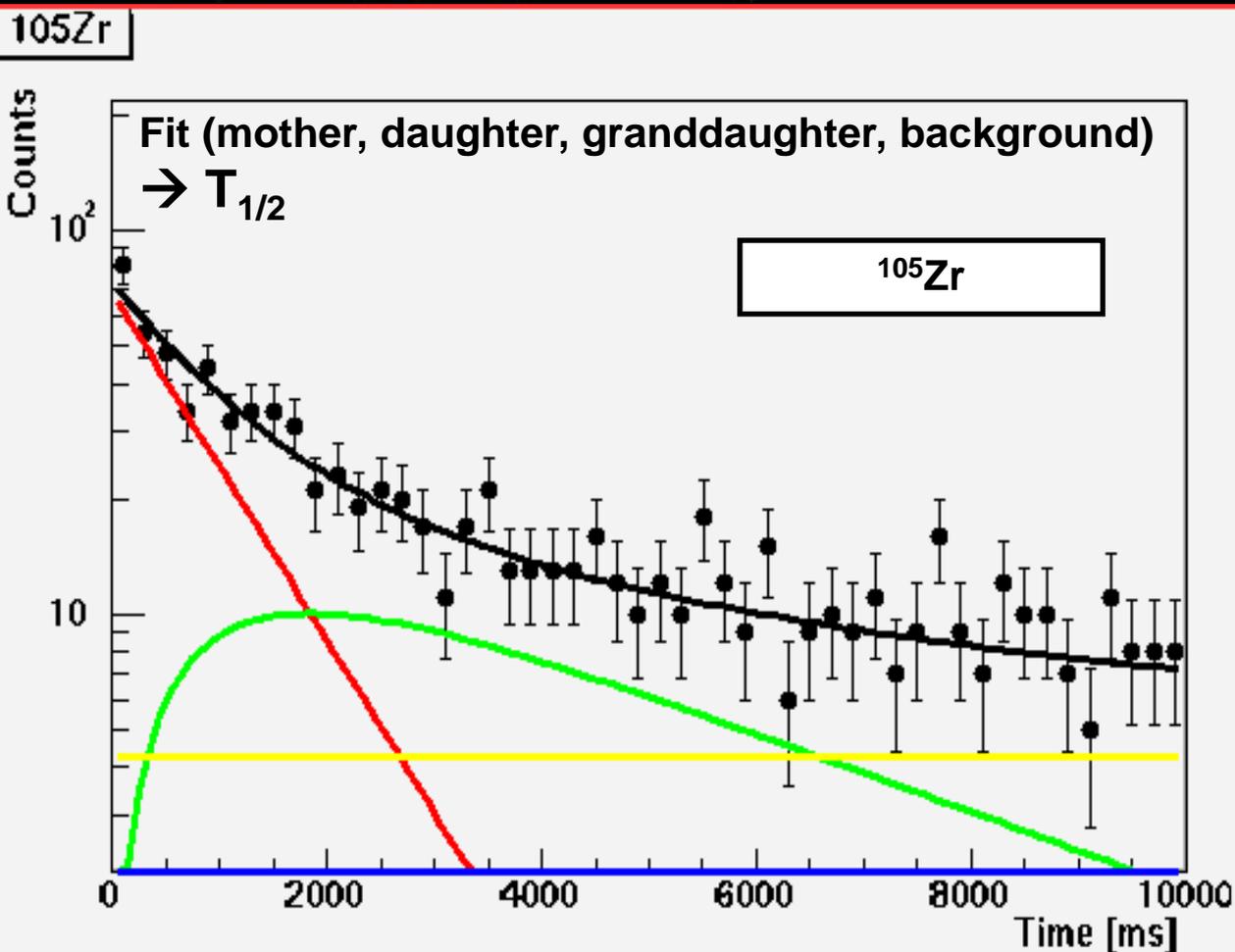
• Implanted

x-y position

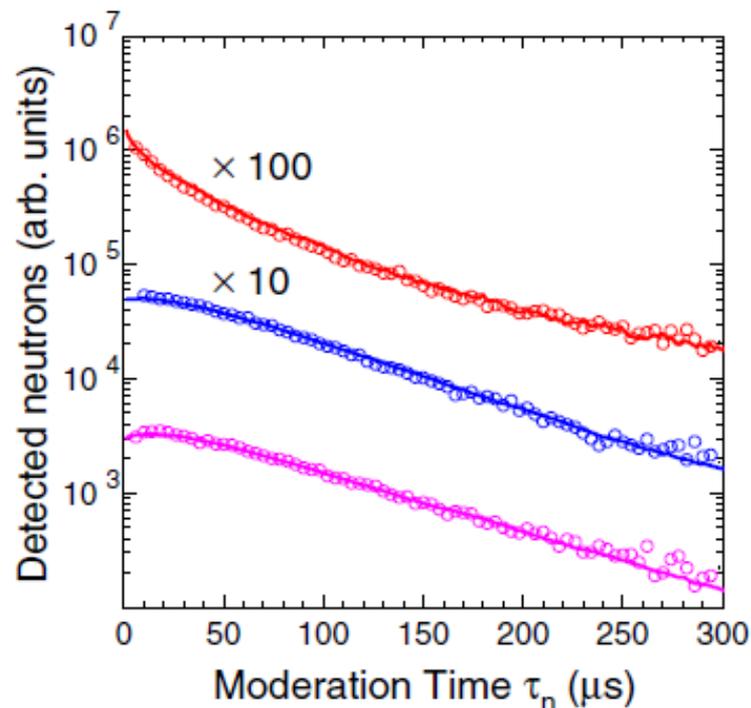
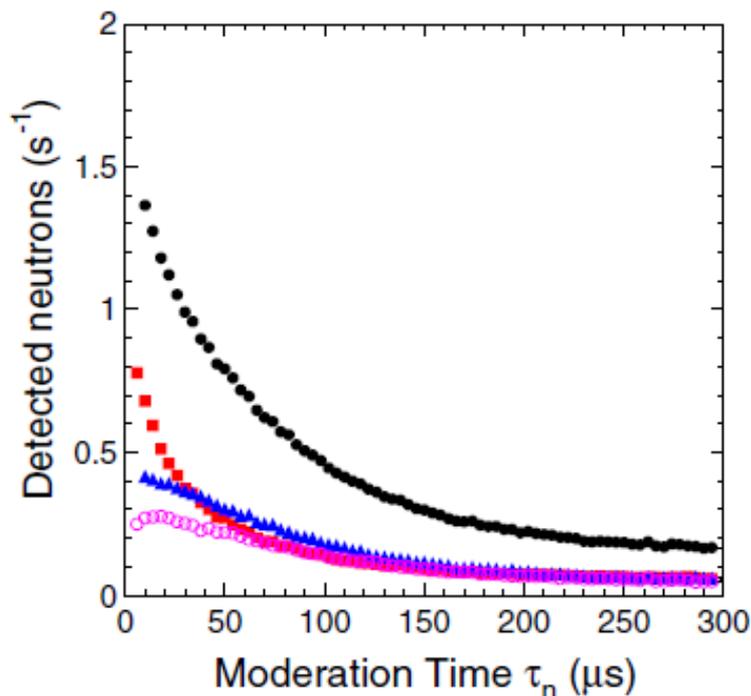
• Veto from A

• Decay

x-y position



# Processing of signals



C  
ode)

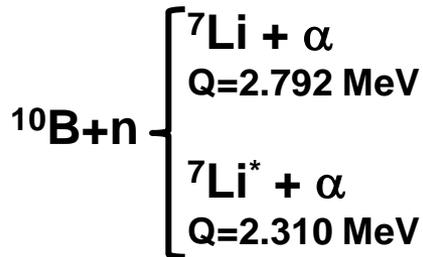
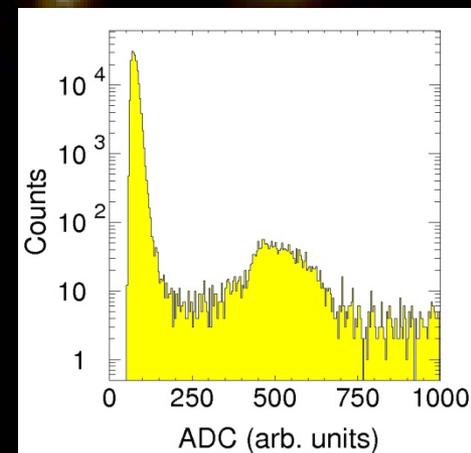
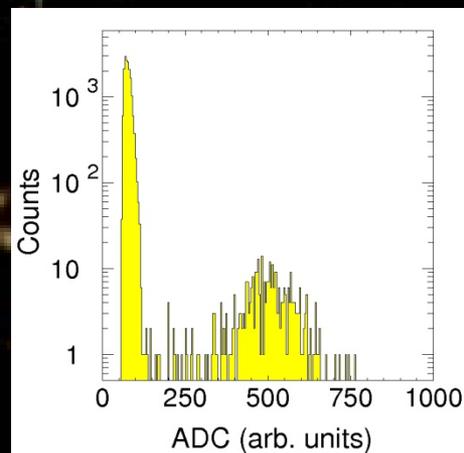
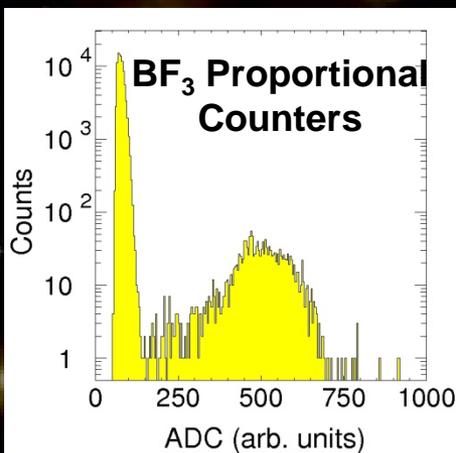
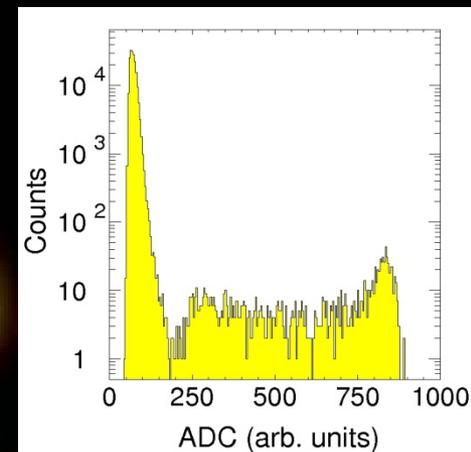
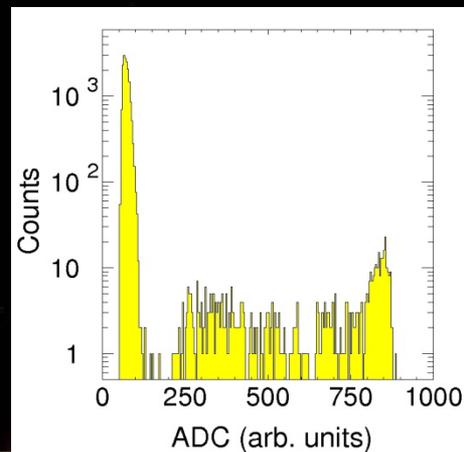
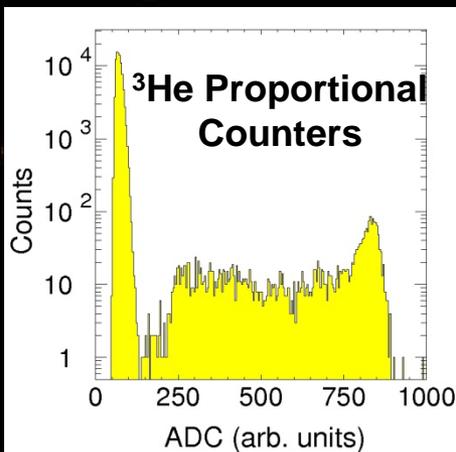
TDC Start

# Processing of signals

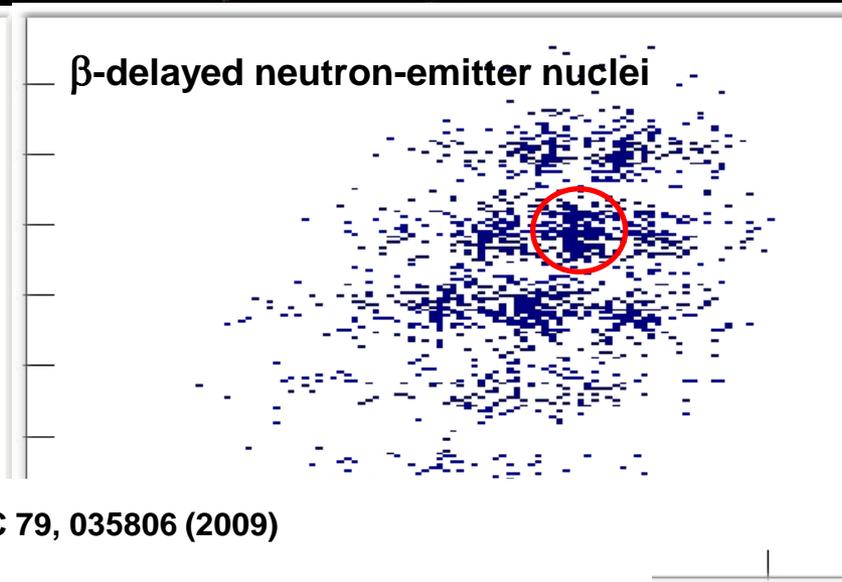
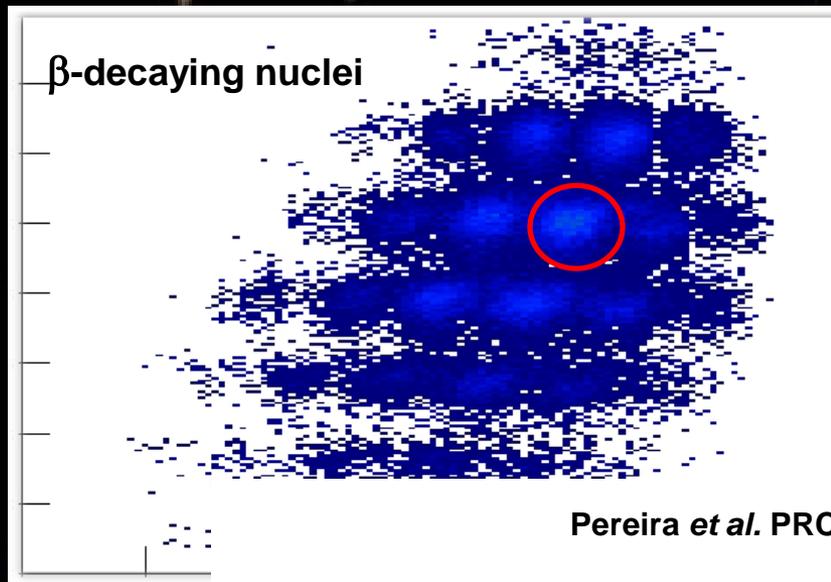
5 min  $^{252}\text{Cf}$  source

1 h experiment data

12 h background



# Determination of $\beta$ -delayed neutrons-emission probabilities ( $P_n$ )

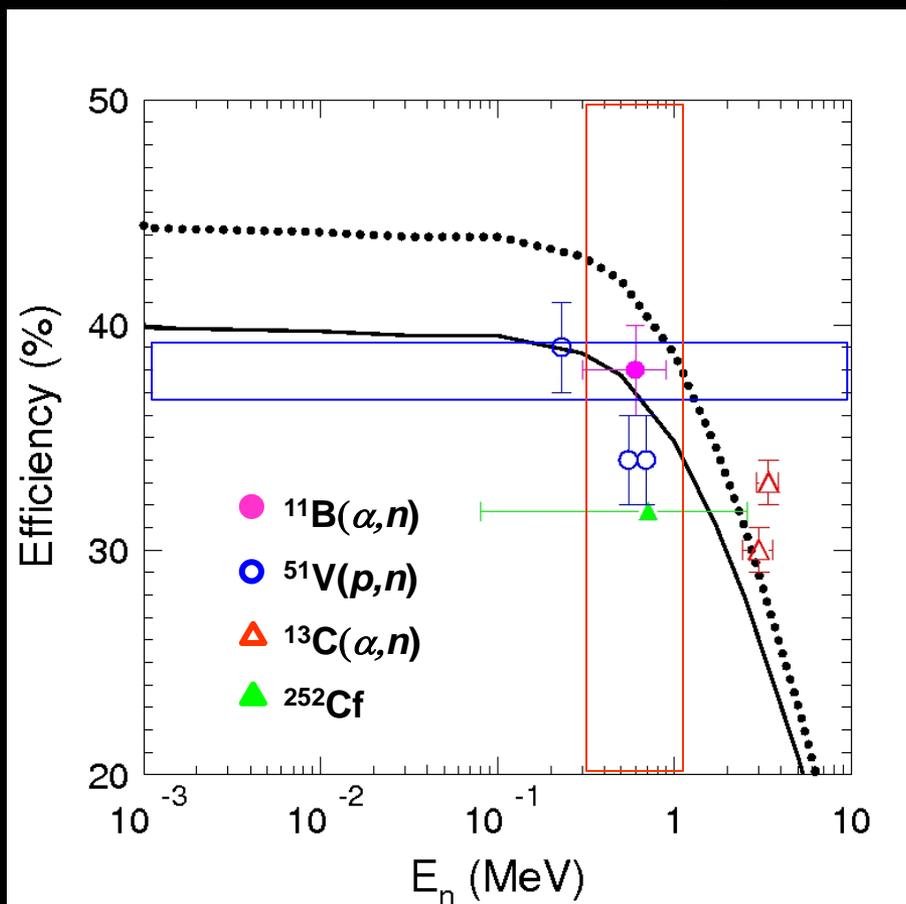


Pereira et al. PRC 79, 035806 (2009)

$$P_n = \frac{N_\beta - B_\beta - N_{\beta\beta}}{N_\beta \omega_{ff}^n} \longrightarrow P_n = \frac{N_\beta - B_\beta - C}{N_\beta \omega_{ff}^n - C}$$

$$C = \frac{\lambda_d \cdot P_{nr} \cdot N_\beta \omega_{ff}^n}{\lambda_d - \lambda_m} \left[ 1 - e^{-\lambda_m \cdot t} - \frac{\lambda_m}{\lambda_d} (1 - e^{-\lambda_d \cdot t}) \right]$$

# Detection of $\beta$ -delayed neutrons: Analysis



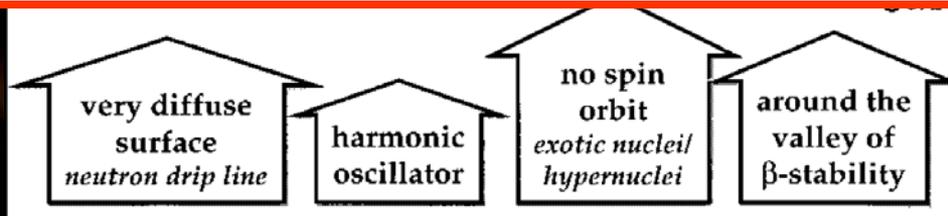
# A=110 r-process nuclei

Epicenter of A=110 r-process nuclei:  $^{110}\text{Zr}_{70}$

Possible existence of a spherical  
double semi-magic  $^{110}\text{Zr}_{70}$

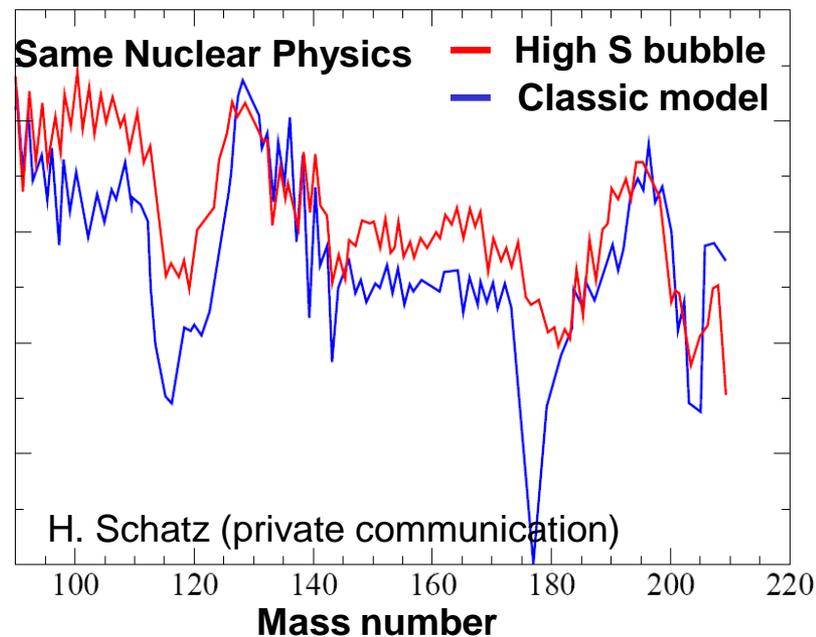
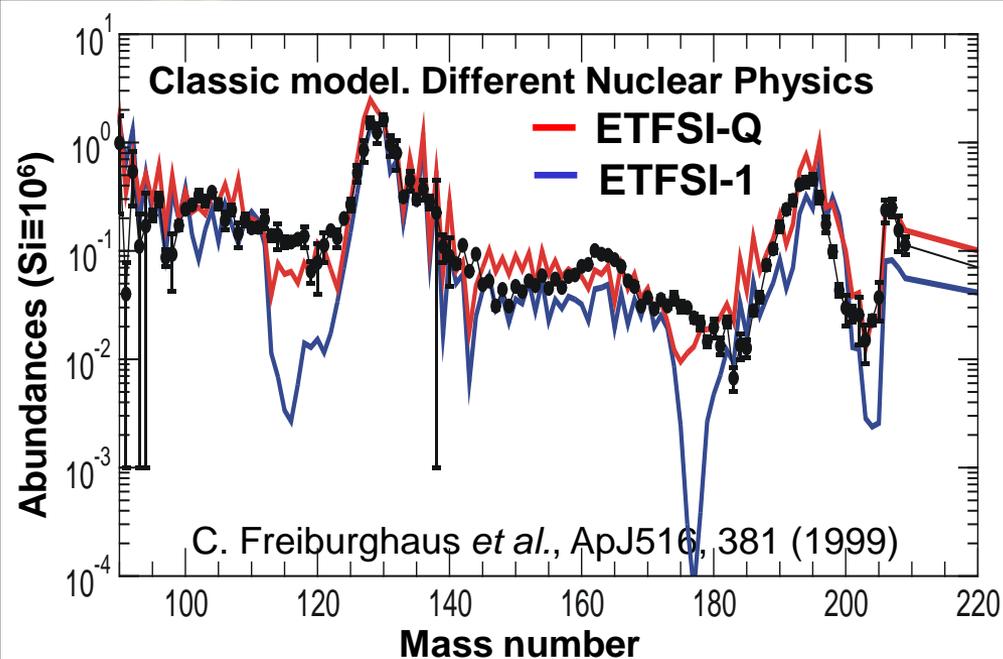
## CONSEQUENCES in the r-process:

- Direct: Change  $S_n \rightarrow$  r-process path (synthesized nuclei)
  - Direct: Reduce  $T_{1/2}$ ,  $P_n$  (factors  $\sim 6$ )
- Indirect: Weakening of N=82 shell (shell quenching)



# A=110 r-process nuclei

A~115 abundance trough predicted in r-process calculations  
“Quenching” of N=82 OR/AND Astrophysical Conditions?



## Macro-Microscopic FRDM/QRPA model

1. Calculation of ground-state masses and deformation parameters  
FRDM + Strutinsky microscopic corrections (Shell + Pairing)
2. Use deformation parameters to determine single-particle levels  $\phi$   
(folded-Yukawa + Lipkin-Nogami)
3. Calculate Gamow-Teller  $\beta$ -strength function using QRPA equations with residual interaction  $V_{GT}=2\chi_{GT}:\beta^{1-} \cdot \beta^1$
4. First-forbidden transitions from statistical gross theory

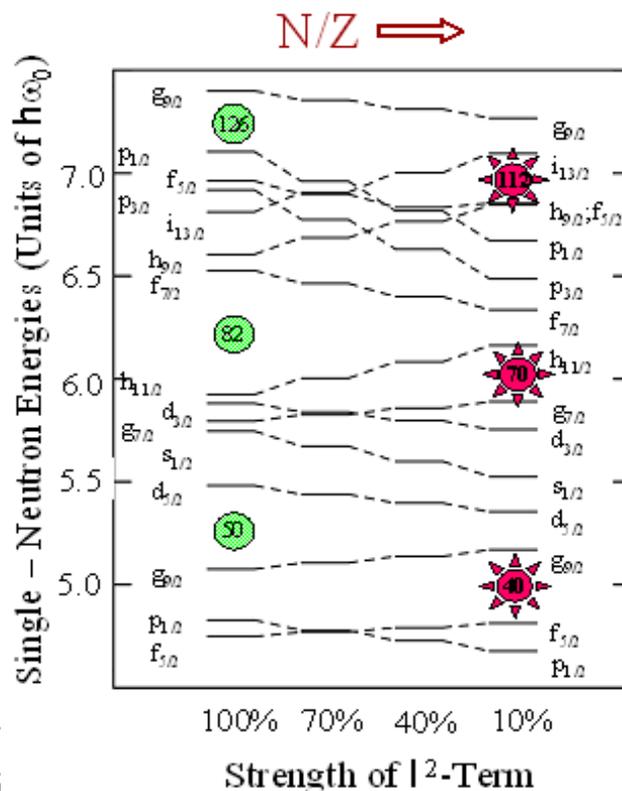
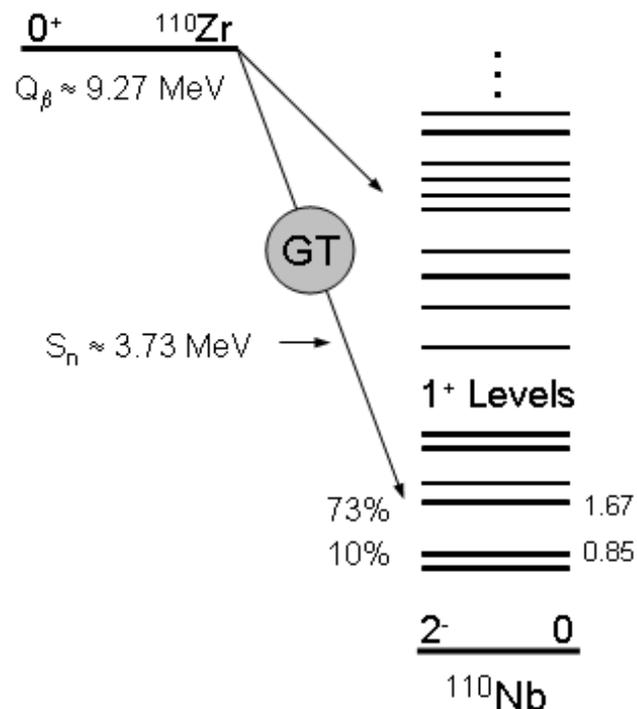
P. Möller et al., NPA 1992; ADNDT 1995, 1997; PRC2003

# Gross $\beta$ -decay properties used as nuclear structure probes

## Beta-decay

Normal shell strength  
strongly deformed ( $\epsilon_2=0.31$ )

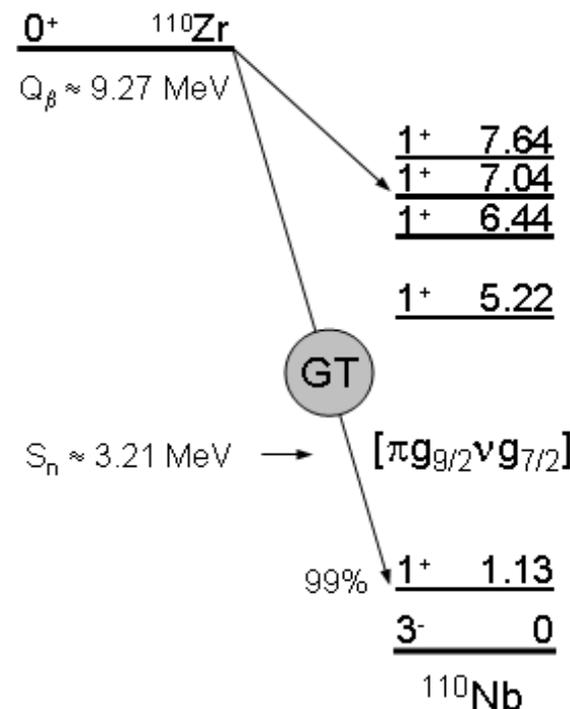
$T_{1/2} = 88$  ms  
 $P_n = 8\%$



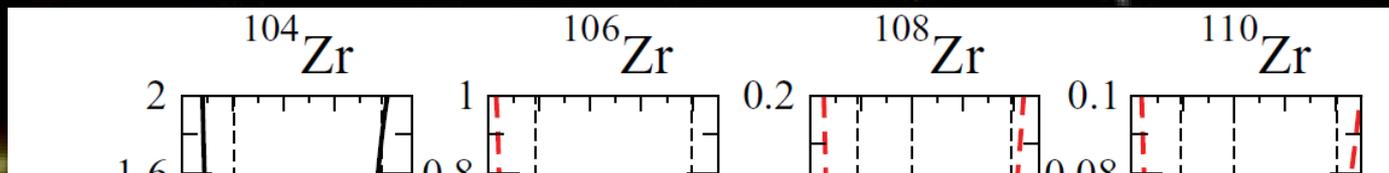
B. Pfeiffer et al.,  
Acta Phys. Polon. **B27** (1996)

Shell strength quenched  
spherical

$T_{1/2} = 14$  ms  
 $P_n = 0.7\%$



# QRPA calculated $T_{1/2}$ and $P_n$ around $^{106}\text{Zr}$

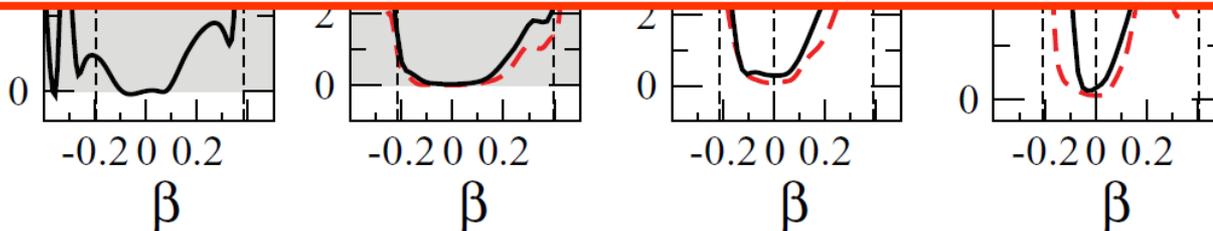


- For  $^{104}\text{Zr}_{64}$ :  $\epsilon_2 \sim 0.25$  inferred from QRPA Calculations

- Lower than  $\epsilon_2 \sim 0.4$  obtained from  $\gamma$ -spectroscopy

[Urban et al., NPA 689, 605 (2001)]

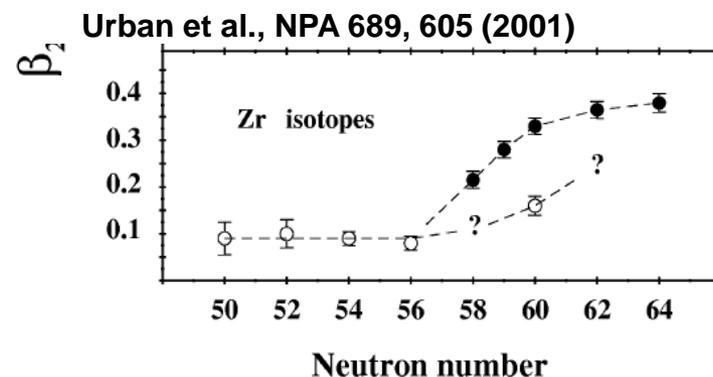
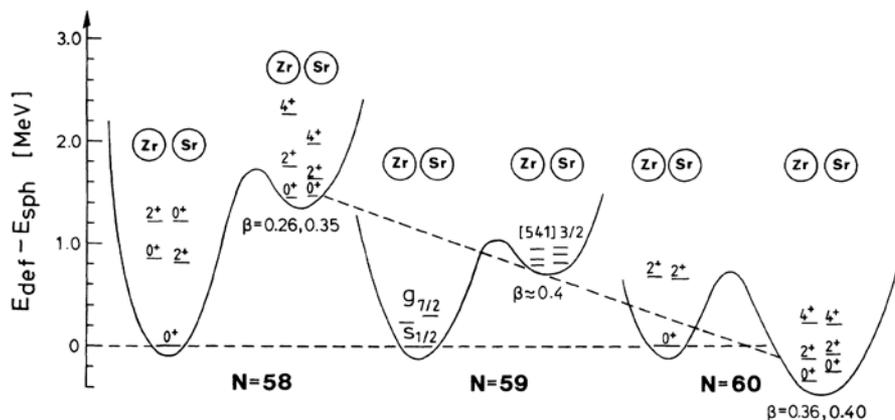
- Presence of weakly-deformed intruder states?



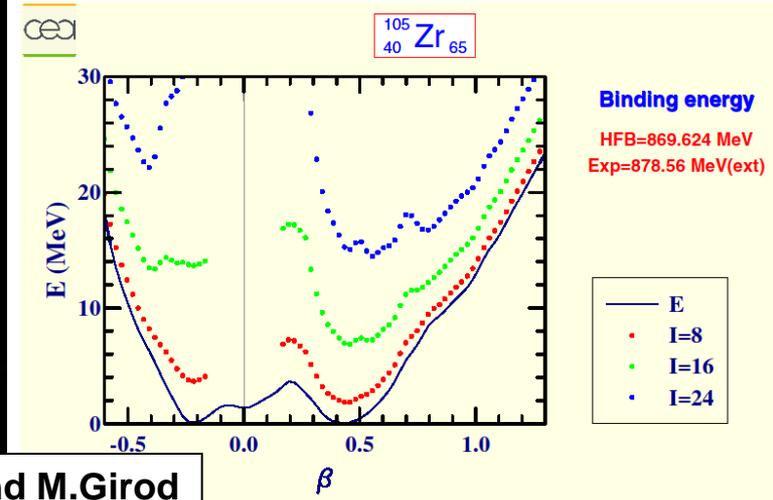
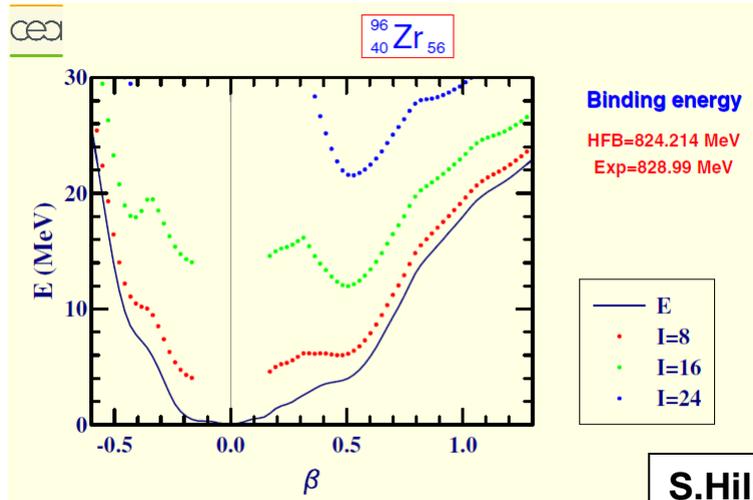
# Intruder “weakly-deformed” configurations → Shape coexistence?

QRPA does not include shape coexistence

Low  $\epsilon_2$  values from QRPA may be really an “average” deformation =  
Coexistence of **prolate ground state + weakly deformed intruder configurations at N=64,65!!!** → **spherical  $^{110}\text{Zr}_{70}$ ?**



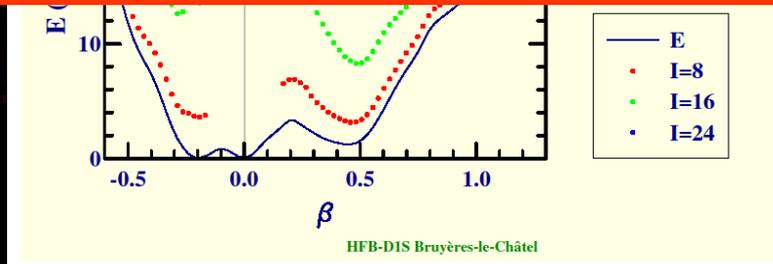
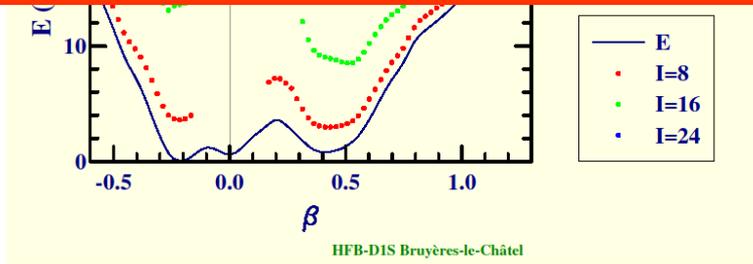
# Predicted intruder spherical configurations with HFB + Goriely effective interaction



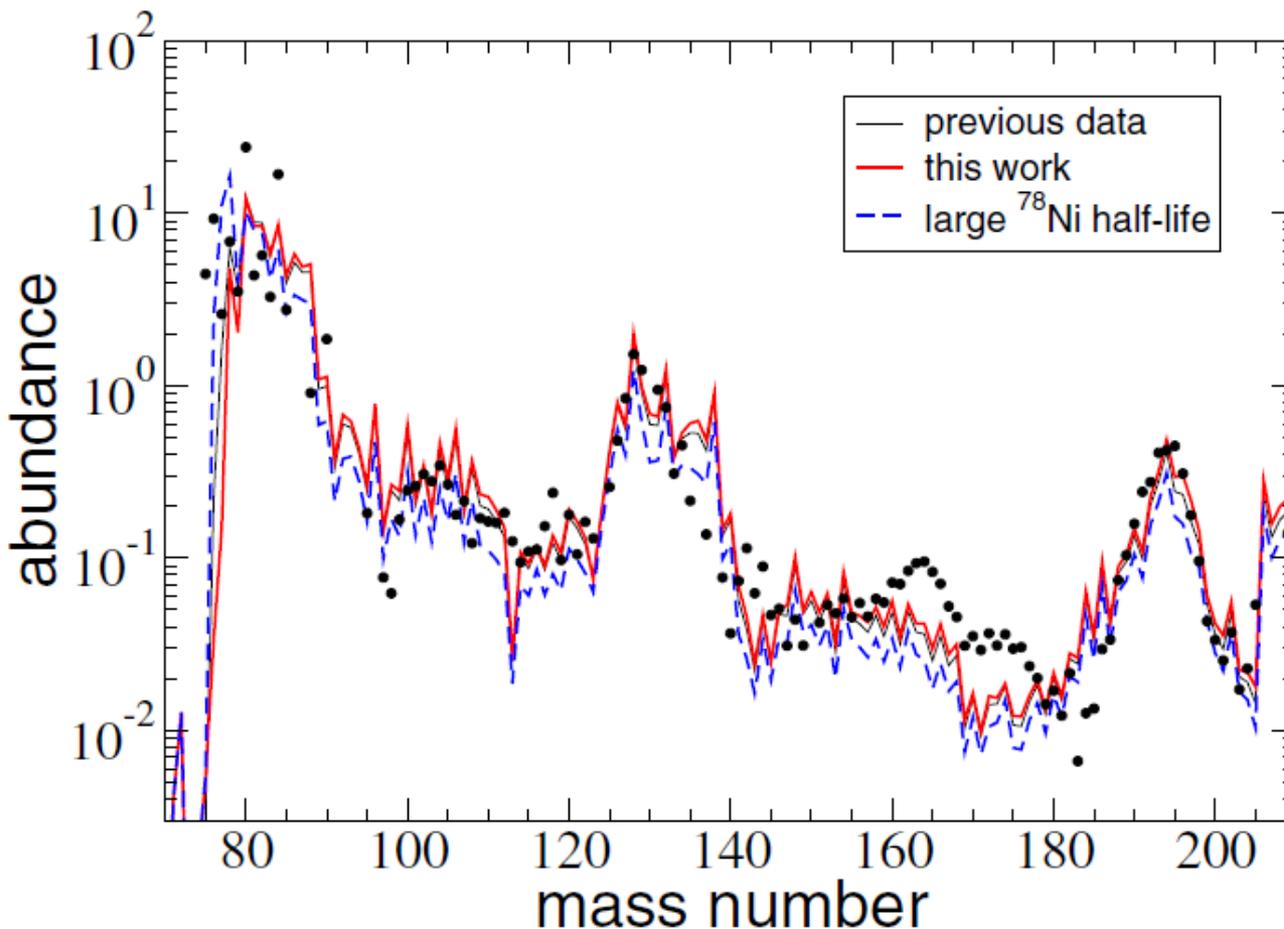
S.Hilaire and M.Girod

[http://www-phynu.cea.fr/science\\_en\\_ligne/carte\\_potentiels\\_microscopiques/carte\\_potentiel\\_nucleaire\\_eng.htm](http://www-phynu.cea.fr/science_en_ligne/carte_potentiels_microscopiques/carte_potentiel_nucleaire_eng.htm)

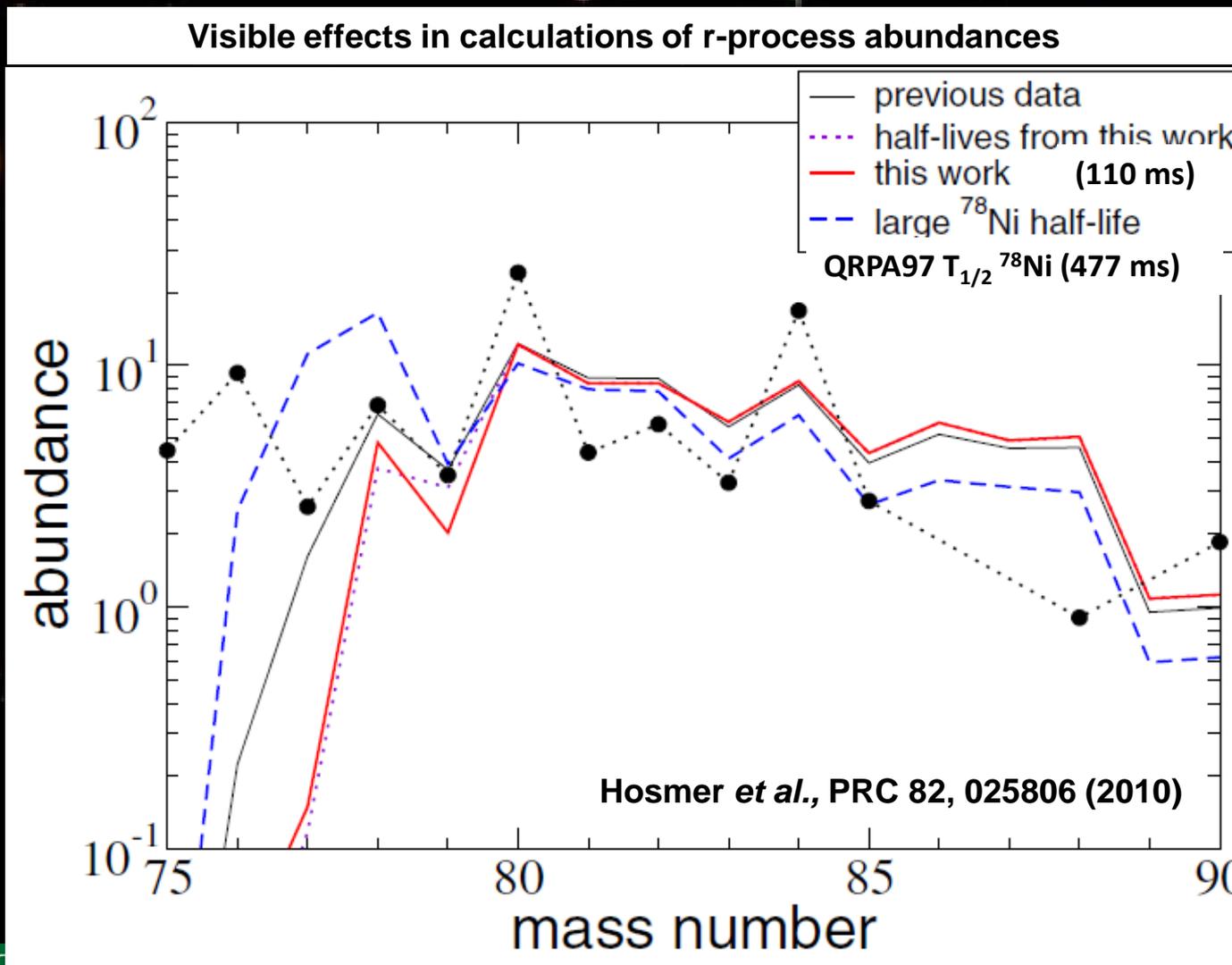
**Could these configurations be investigated with Self-consistent QRPA calculations (P. Sarriguren et al.)?**



# R-process nuclei around the $^{78}\text{Ni}$ waiting-point

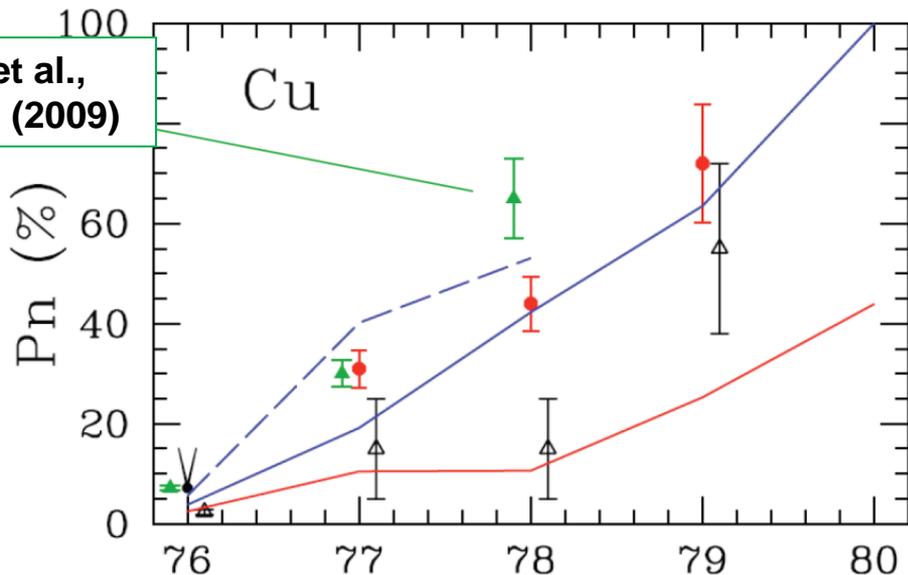


# $T_{1/2}$ and $P_n$ around the $^{78}\text{Ni}$ waiting-point ( $^{73-75}\text{Co}$ , $^{75-78}\text{Ni}$ , $^{76-80}\text{Cu}$ , $^{79-81}\text{Zn}$ , $^{81-82}\text{Ga}$ )



# $T_{1/2}$ and $P_n$ around the $^{78}\text{Ni}$ waiting-point

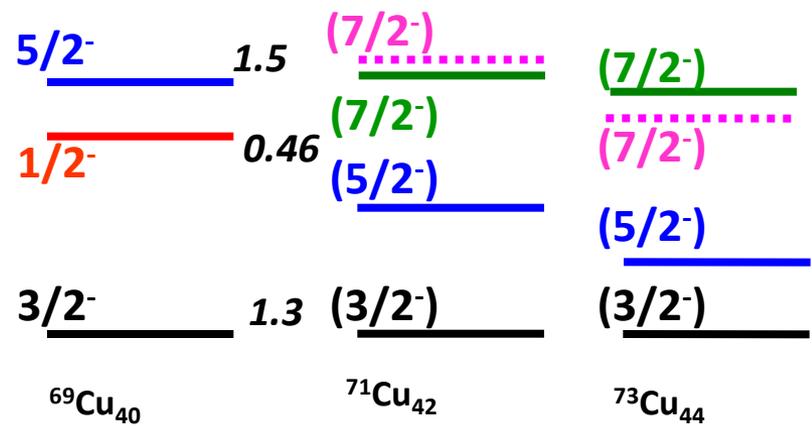
Wigner et al.,  
PRL102, (2009)



- New data
- △ Pfeiffer et al., PNE (2002)
- QRPA-97 Möller et al., PRC (1997)
- CQRPA: I.N. Borsov, PRC (2005)
- - CQRPA:  $\pi f_{5/2} \leftrightarrow \pi p_{3/2}$

Hosmer et al., PRC 82, 025806 (2010)

$\pi p_{1/2}$   
 $\pi f_{5/2}$   
 $\pi p_{3/2}$

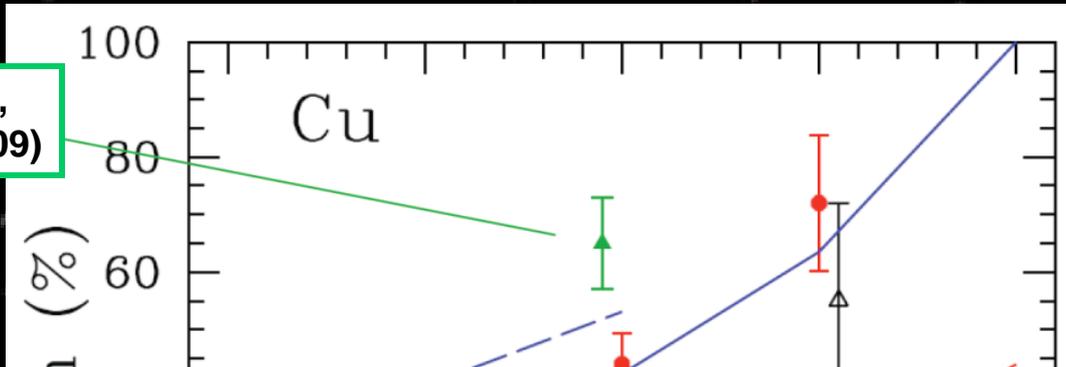


$E_{\text{ex}}$  (MeV)

Evidence for  $5/2^-$  ground state for  $^{75}\text{Cu}$ ,  $^{77}\text{Cu}$  (Walters, Flanagan private communication)

# R-process nuclei around the $^{78}\text{Ni}$ waiting-point

Wigner *et al.*,  
PRL102, (2009)



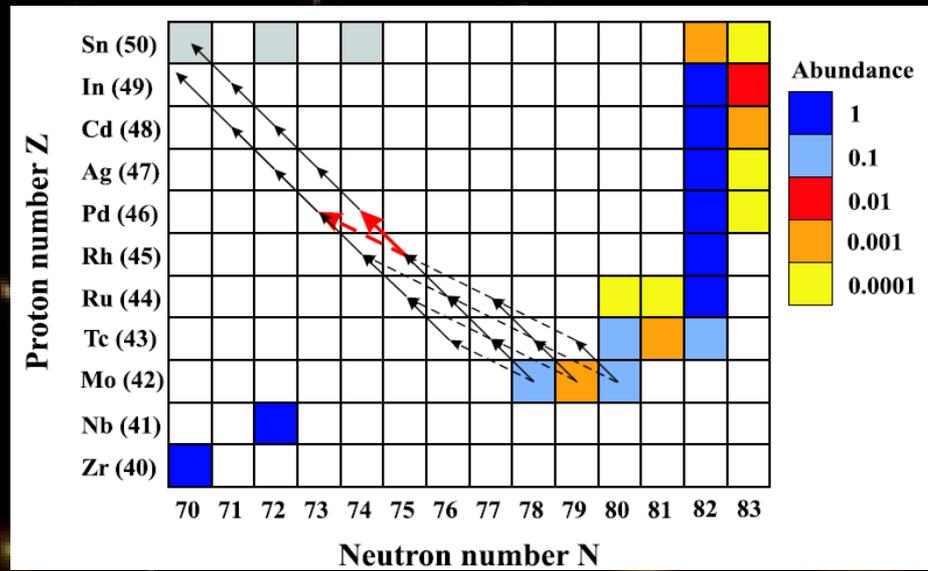
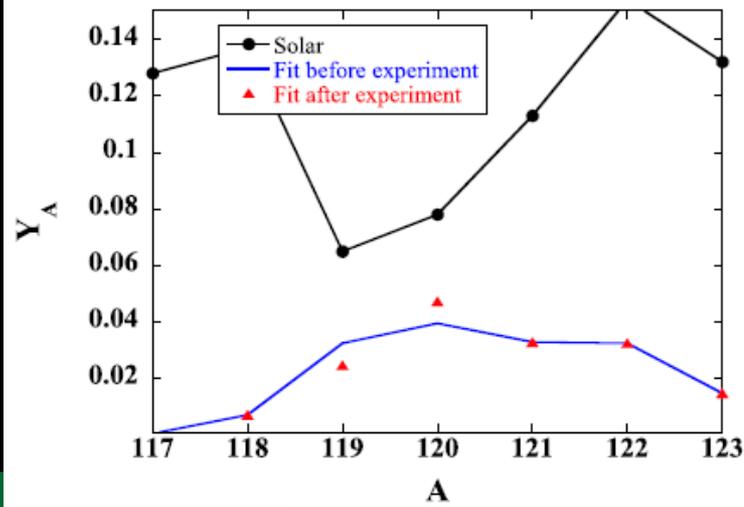
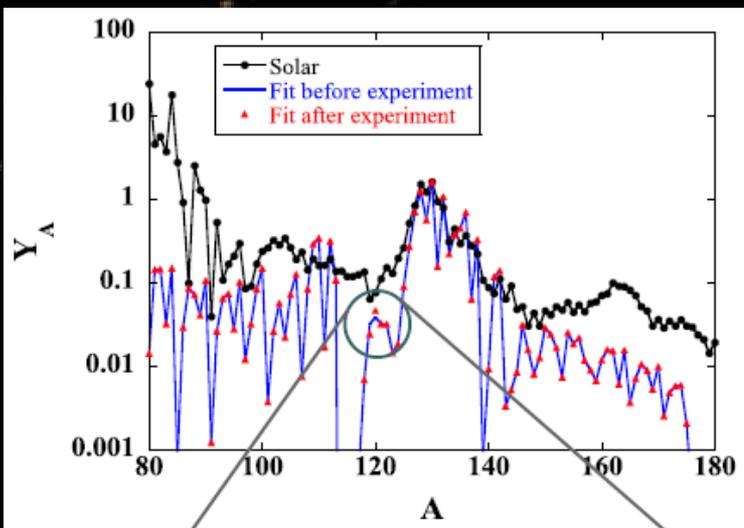
- Underpredicted values (CQRPA and FRDM+QRPA) may be an indication for inversion of the  $\pi 2p_{3/2}$  and  $\pi 1f_{7/2}$  orbitals
- CQRPA + inverted orbitals improves the results (what is the effect in  $T_{1/2}$ ?)
- FRDM+QRPA + inverted orbitals improves  $P_n$  BUT degrades  $T_{1/2}$



J I N A



# R-process nuclei around



- New  $P_n$  value of  $^{120}\text{Rh}$  affects  $^{119}\text{Sn}/^{120}\text{Sn}$  ratio by 20%
- $^{120}\text{Rh}$  is  $\sim 3p$  and  $3n$  away r-process path
- More  $P_n$  values are necessary!

