# Testing the beta strength north-east of $^{78}$Ni

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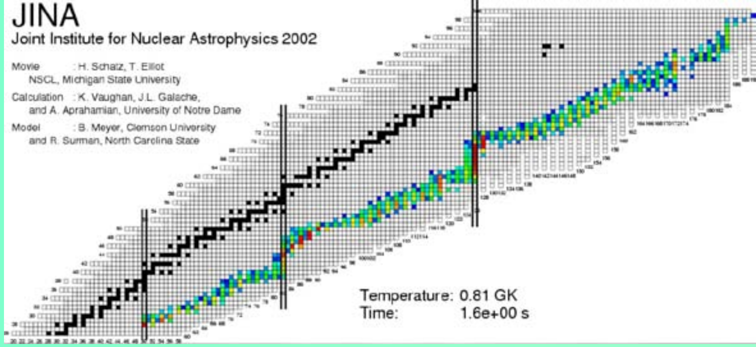
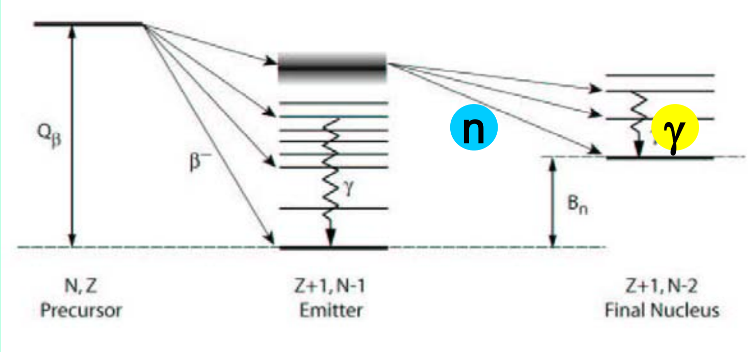
- **The physics: r-process and shell structure**
- **Status of the knowledge in the region**
- **A choice of isotopes**

• **Beta strength calculations are needed in order to obtain $T_{1/2}$ and $P_n$ values for most of the nuclei involved in r-process calculations**




$$S_\beta(E_x) = \frac{1}{D}\frac{4\pi}{g_V^2} B_{i\to f}$$

$$B_{i\to f} = \frac{1}{2J_i+1}\left|\left\langle f \left\| M^{\beta}_{\lambda\pi} \right\| i \right\rangle\right|^2$$




$\lambda\pi$=0+ : Fermi

$\lambda\pi$=1+ : Gamow-Teller

$\lambda\pi$=0-,1- : Non-unique first forbidden

$\lambda\pi$=2- : Unique first forbidden

…

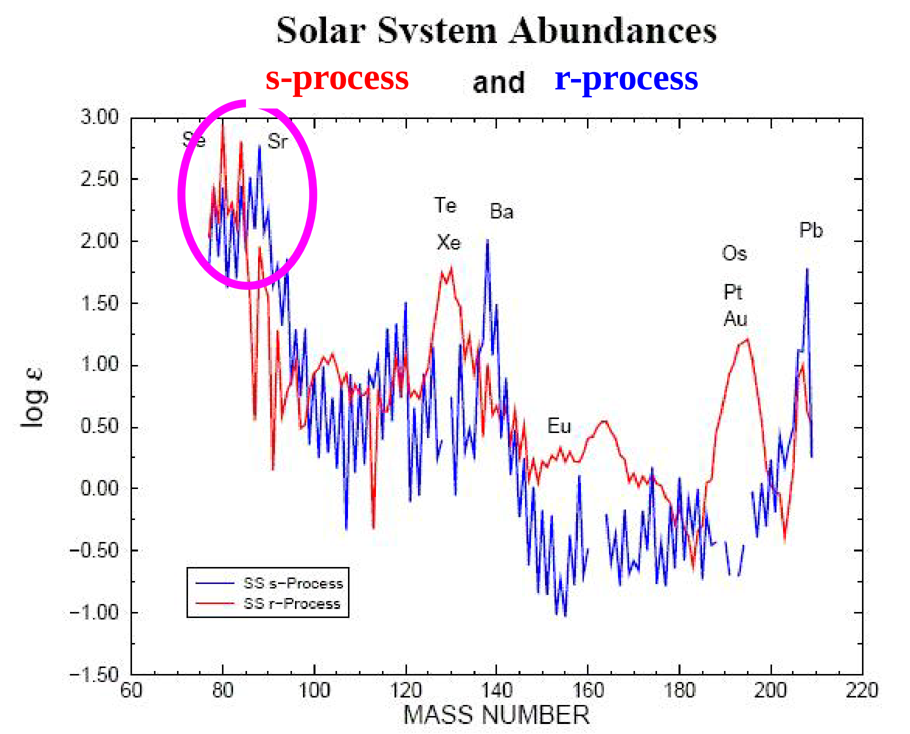
$$S_\beta(E_x) = \frac{I_\beta(E_x)}{f(Q_\beta - E_x)\cdot T_{1/2}}$$

$$\frac{1}{T_{1/2}} = \int_0^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)\,dE_x$$

$$P_n = T_{1/2} \times \int_{S_n}^{Q_\beta} \frac{\Gamma^n}{\Gamma^n + \Gamma^\gamma} S_\beta(E_x)\cdot f(Q_\beta - E_x)\,dE$$

• **The quality of the model calculations is judged by comparison with experimental $T_{1/2}$ and eventually $P_n$ values in particular for the most neutron rich accessible nuclei, which are however integral quantities**

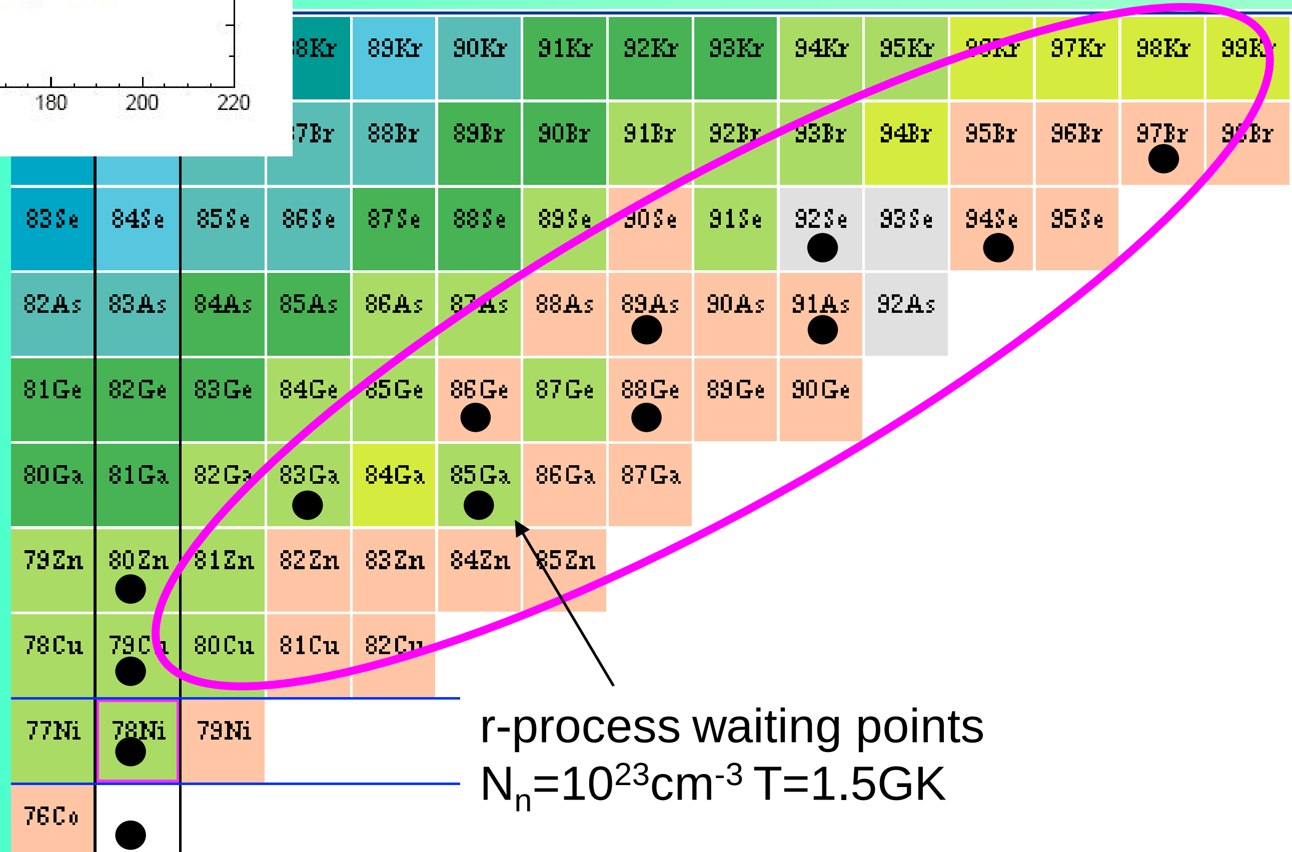
• **Direct comparison of calculated and measured $S_\beta$ provides a more stringent test of the nuclear structure models**




# "North-East" of $^{78}$Ni

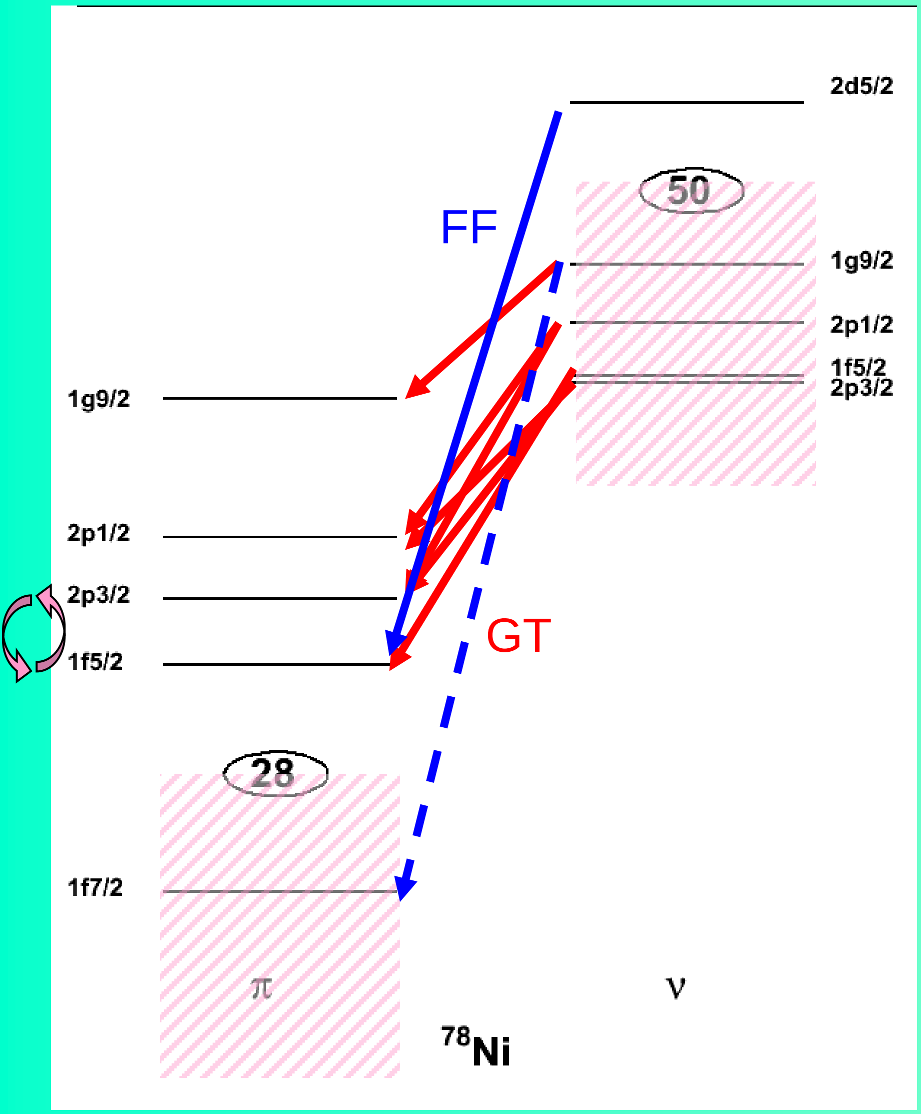
- At (waiting points) or close to the r-process path
- 1st peak in the r-process abundance distribution
- Possibility to access experimentally $T_{1/2}$ and $P_n$

$T_{1/2}$ and $P_n$ along the r-process path shape the abundance distribution




r-process waiting points
$N_n = 10^{23} cm^{-3}$ T=1.5GK

# “North-East” of $^{78}$Ni




- **Competition of First Forbidden respect to Gamow-Teller**
- **Population of ν2d5/2 above N=50 opens the possibility of “fast” transition to π1f5/2 when not filled**
- **Shell reordering of π2p3/2 and π1f5/2 under influence of residual interactions**

All these affect the beta-strength distribution

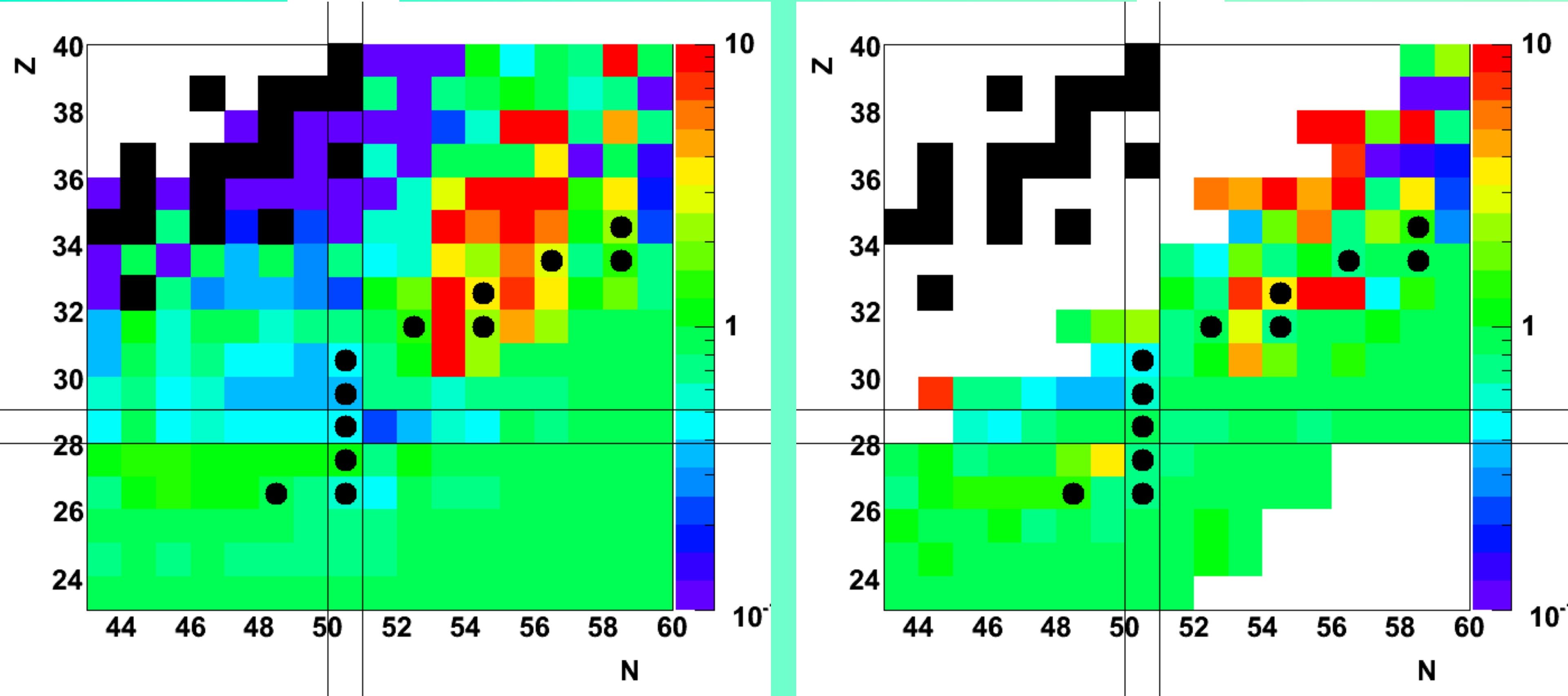
Status of theoretical calculations

**Moeller et al., PRC67(03)55802**:

- FRDM+QRPA
- GT (microscopic)+ FF (Gross Theory)
- Deformation from calculation except when available experimental information
- $Q_\beta$ and $S_n$ experimental or from FRDM calculations
- "Ad hoc" spreading width

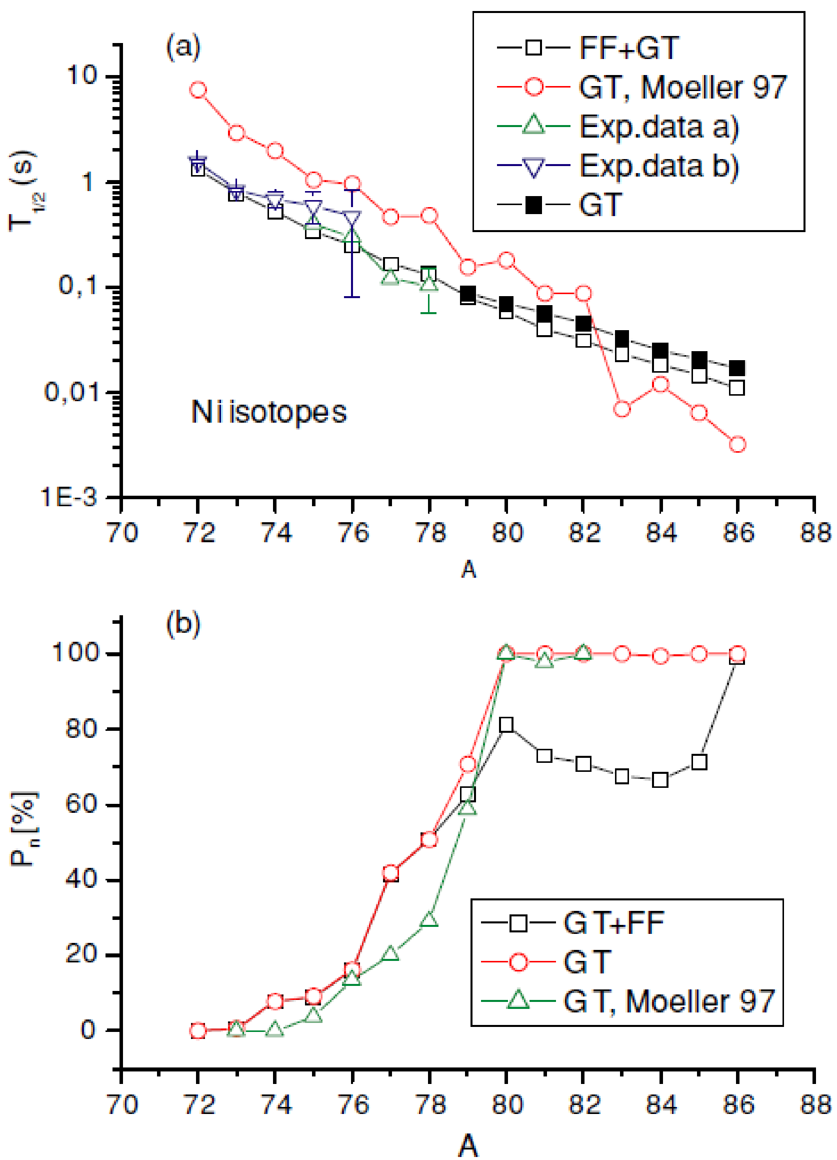
**Ratio: (GT+FF)/GT**

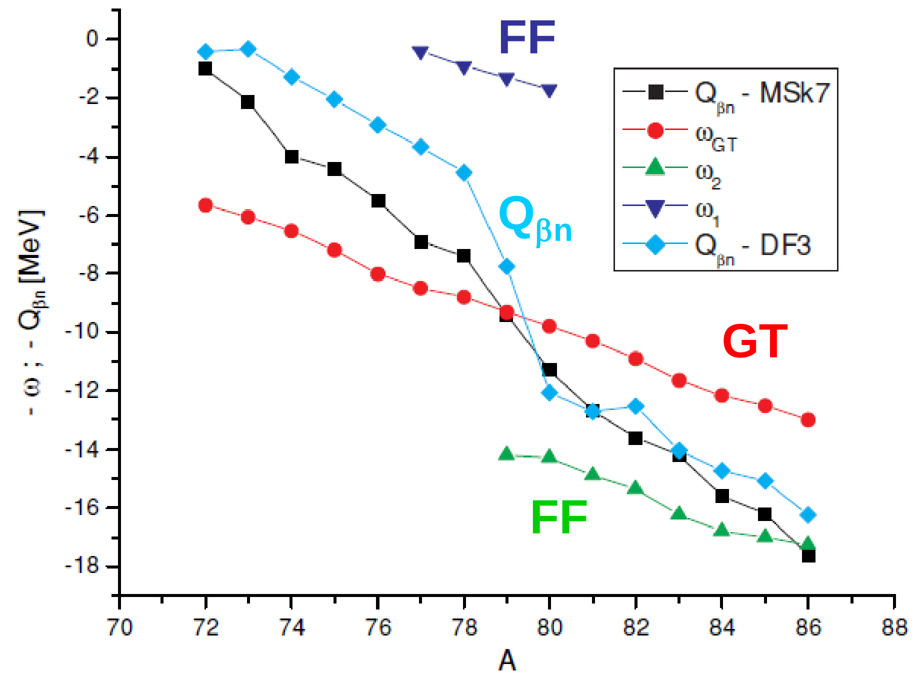
$T_{1/2}$ $P_n$



**Borzov, PRC71(05)65801**:

- DF+CQRPA
- GT+ FF (microscopic)
- No deformation
- $Q_\beta$ and $S_n$ calculated internally



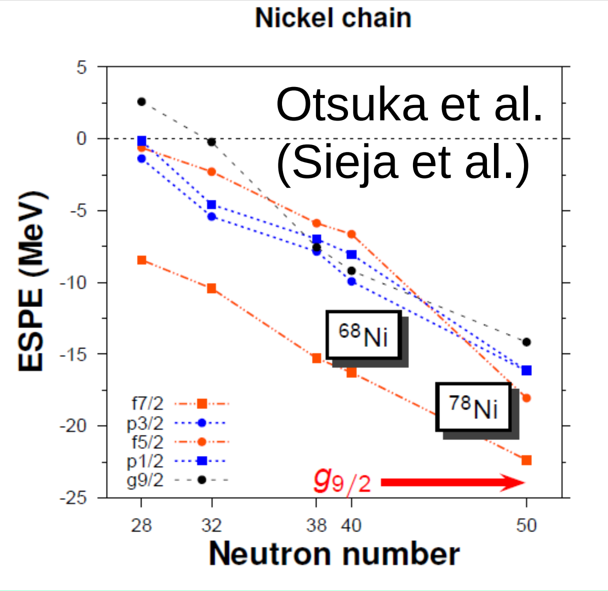

**GT: $\nu$1f5/2,7/2$\rightarrow\pi$1f5/2,7/2**

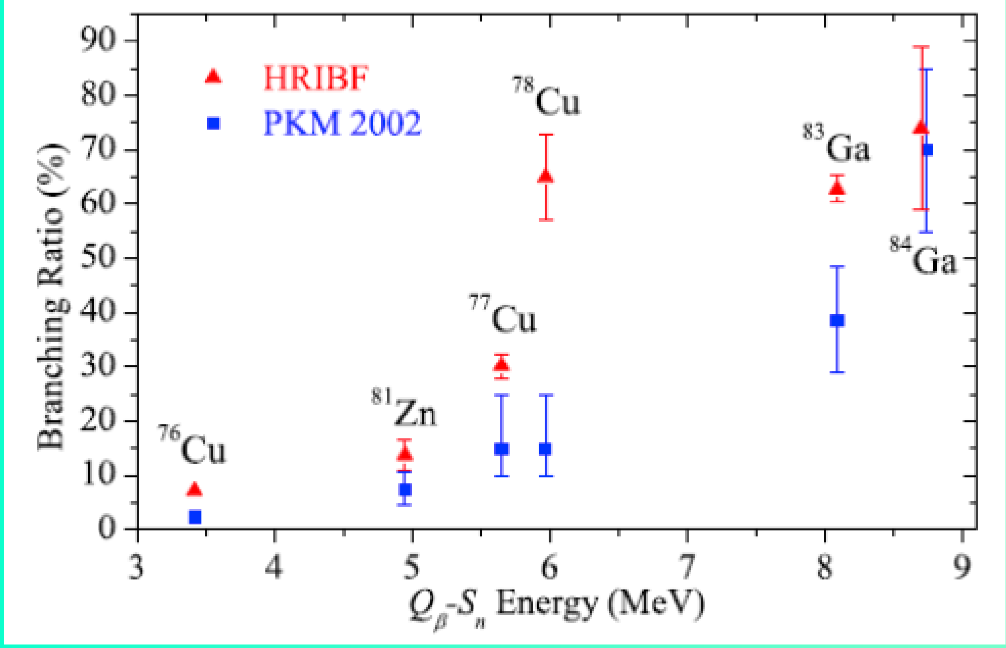
**FF: $\nu$1g9/2$\rightarrow\pi$1f7/2, $\nu$1f5/2$\rightarrow\pi$1d5/2**

**FF: $\nu$2d5/2$\rightarrow\pi$1f5/2**

**Winger et al., PRL102(2009)142502**

- $P_n$ measurement at HRIBF **using γ-intensities**
- New **DF+CQRPA calculations**:
  - Experimental $Q_\beta$ and $S_n$
  - Inversion of proton 2p3/2 and 1f5/2 orbitals and proton shell "weakening"




| | Exp. | Theory | |
|---|---|---|---|
| Nuclide | Adopt | [11] | Current |
| $^{76}$Cu | $7.2_5$ | 4.2 | 5.6 |
| $^{77}$Cu | $30.0_{27}$ | 19.7 | 40.2 |
| $^{78}$Cu | $65_8$ | 42.6 | 53.1 |
| $^{83}$Ga | $62.8_{25}$ | 15.7 | 50.7 |

From K. Rykaczewski

**Hosmer et al., PRC82 (10)025806**

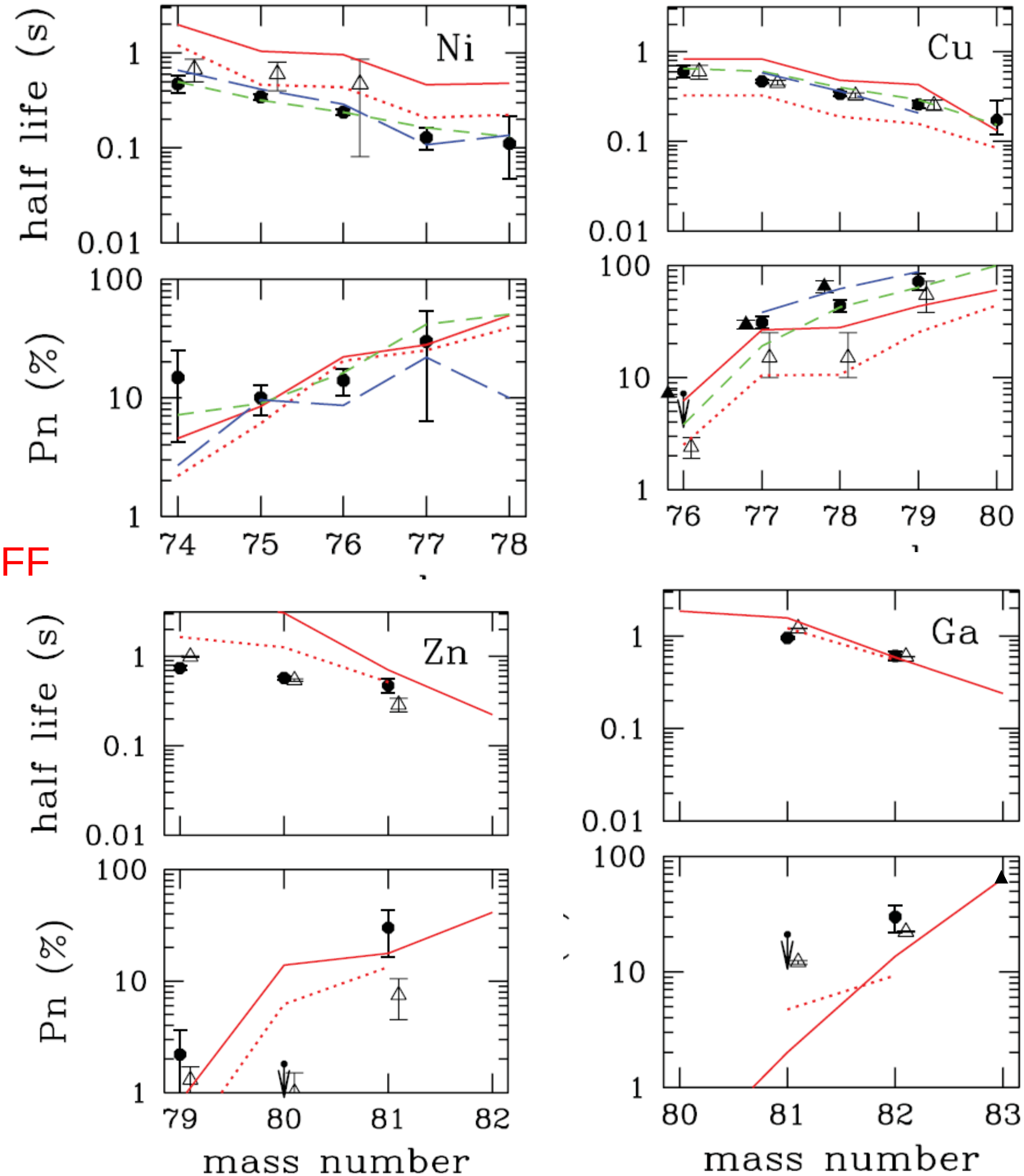
- Measurement at NSCL with NERO neutron counter

— — : OXBASH

——— : Moeller et al. (97) GT

········ : Moeller et al. (03) GT+FF

- - - : Borzov (05) GT+FF

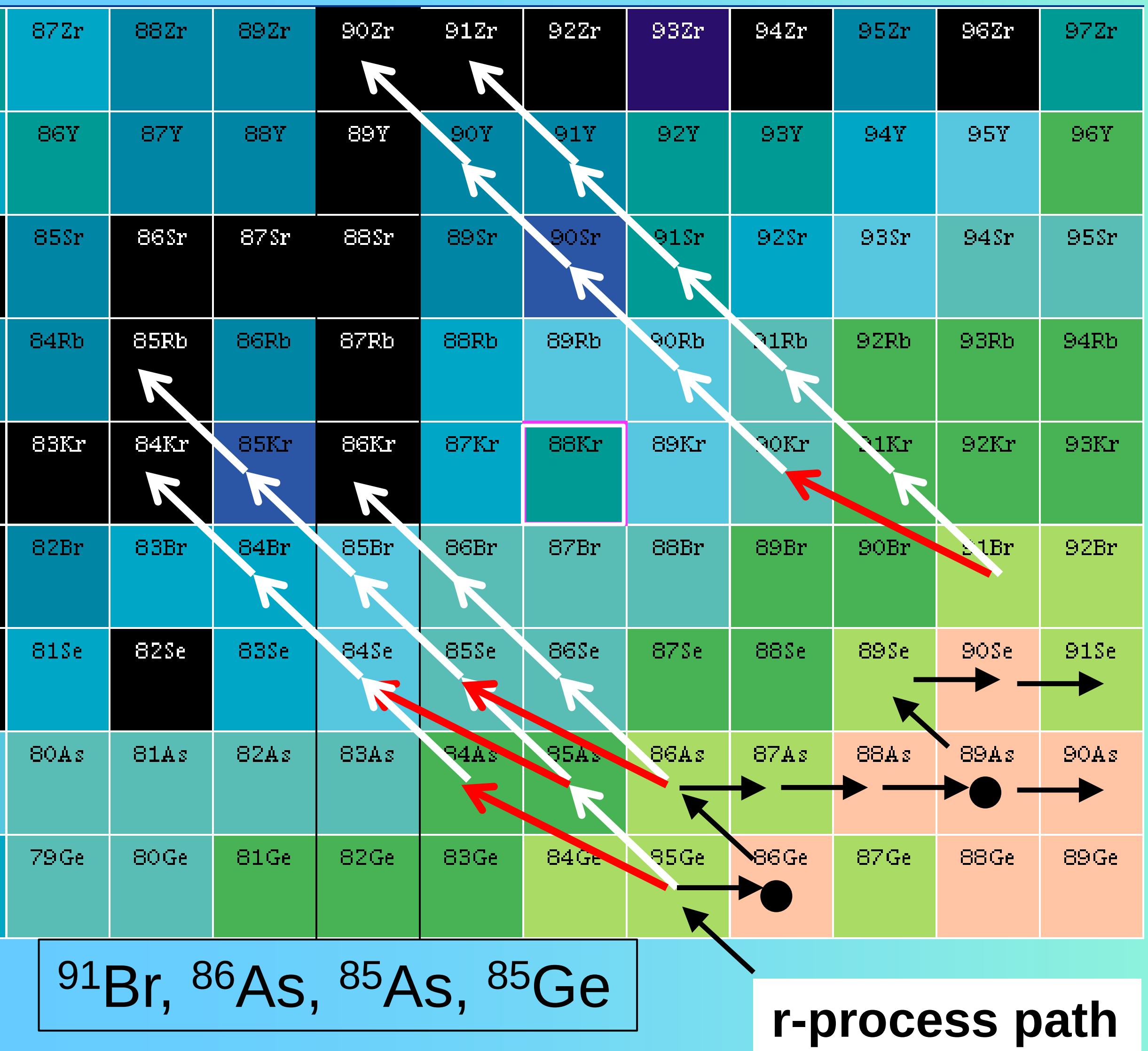



**Shell Model calculations require a renormalization of GT operator of $q_{GT}$=0.37 to adjust experimental $T_{1/2}$!**

# Previous work at JYFL

Presented at ND2013, NY

PhD Thesis:
J. Agramunt & A. Garcia




| Pn (%) | RAS | PKM |
|---|---|---|
| 91Br | 20(3) | 31.3(60) |
| 86As | 33(4) | 26(7) |
| 85As | 59.4(24) | 55(14) |
| 85Ge | - | 14(3) |

**Contribution to $\nu_d$ for thermal fission of $^{235}$U:**

- **$^{91}$Br: ~3%**
- **$^{85,86}$As, $^{85}$Ge: ~7%**

RAS: Rudstam et al. ADNDT53 (93)1
PKM: Pfeiffer et al. PNE41(02)39

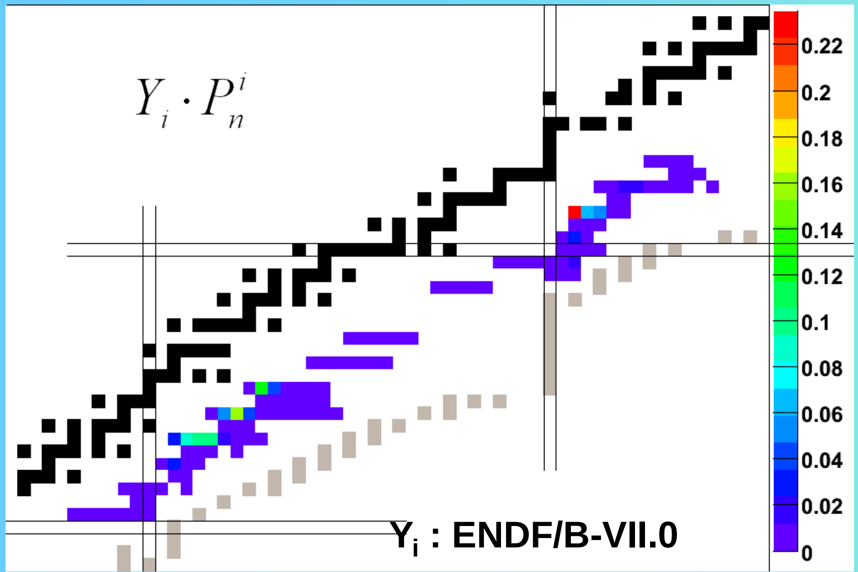
# Motivation: microscopic summation calculations of $\overline{\nu}_d$

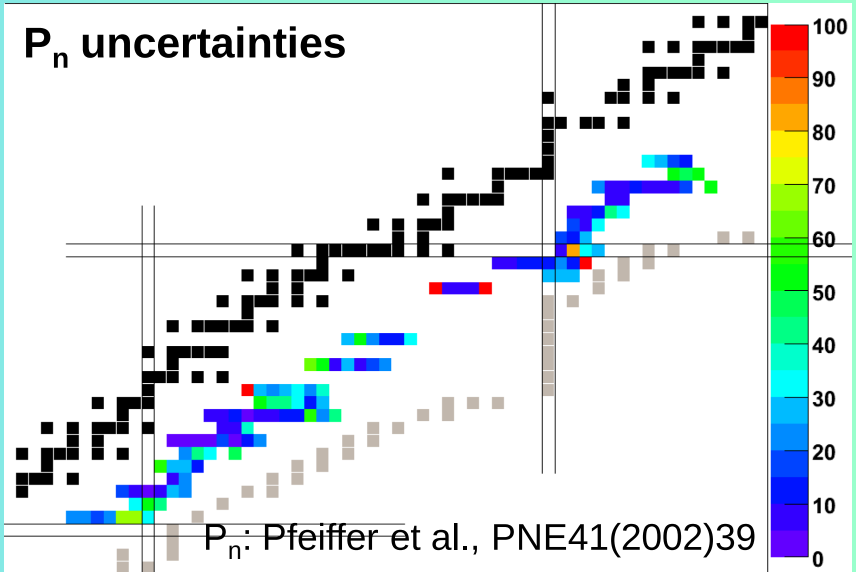
- The delayed neutron fraction $\beta_{eff}$ is a key parameter in the control of reactor power
- Microscopic summation calculations lack still the accuracy of Keepin six-group formula
- Reason: **inaccuracies** in fission yields $Y$ and **delayed neutron emission probabilities** $\boldsymbol{P_n}$

Number of delayed neutrons per fission

$$\overline{\nu}_d = \sum_i Y_i \cdot P_n^i$$

Can be used to identify $P_n$ values that should be revisited



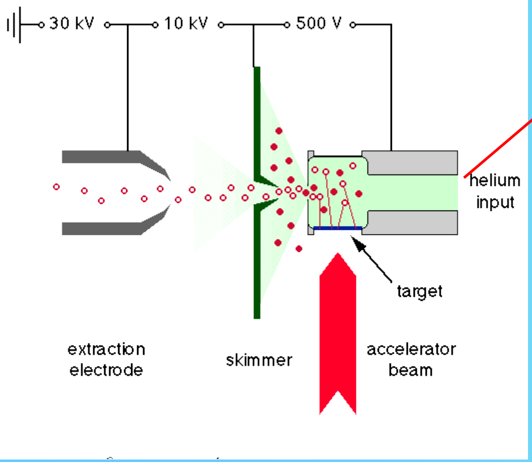
# Experiment: production and selection of isotopes

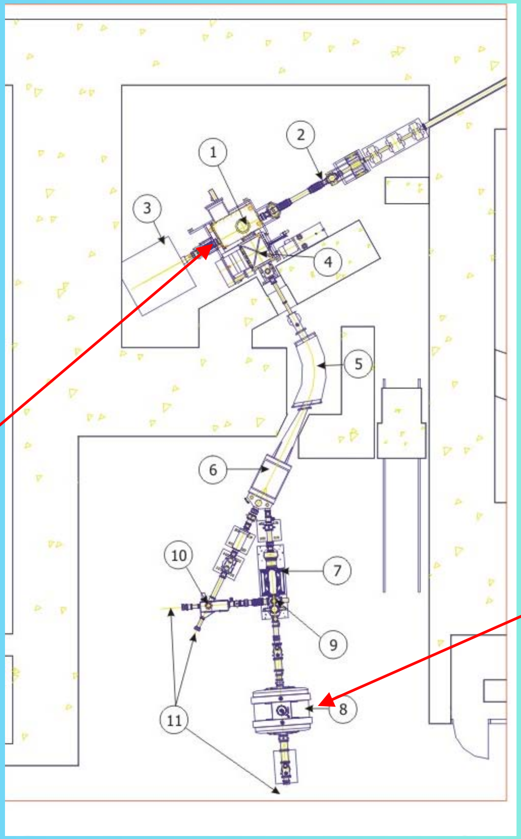
## JYFL Accelerator Laboratory

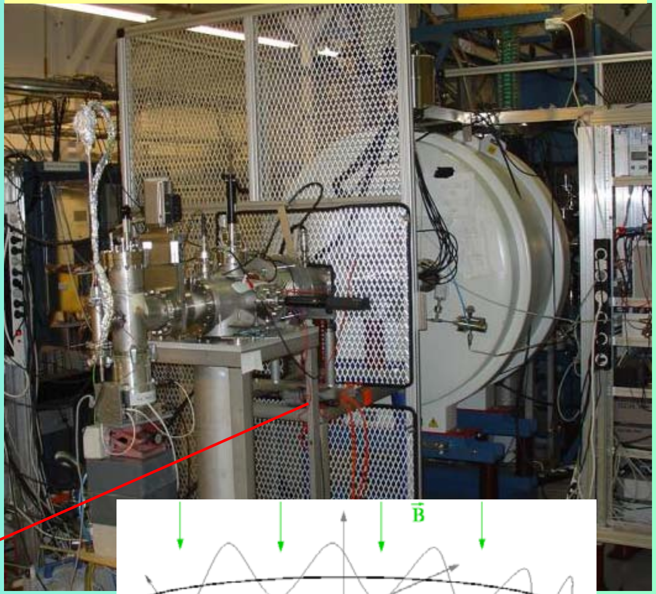
**IGISOL** separator **+ ion guide** source: refractory elements

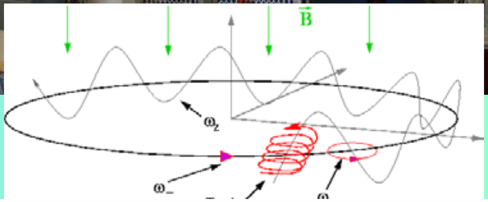
**JYFLTRAP** Penning trap: isotopic purification

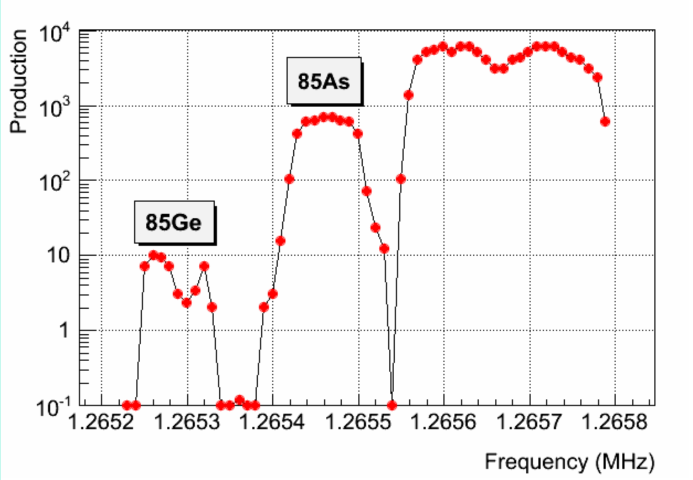
**p(25MeV) + Th => FF**



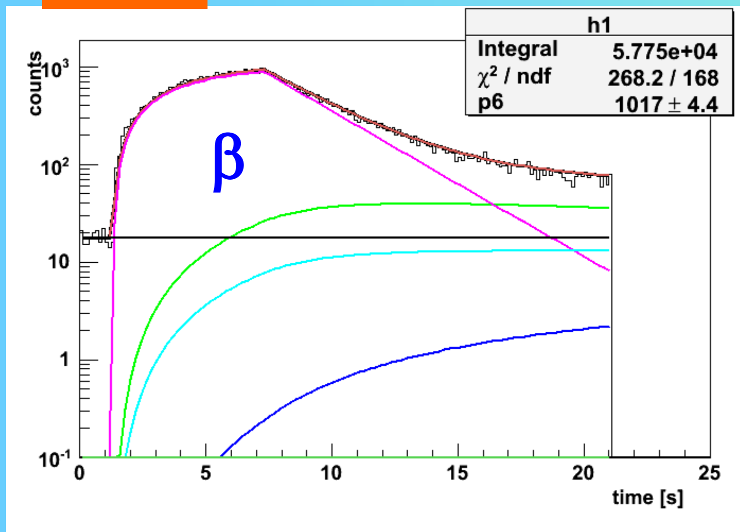



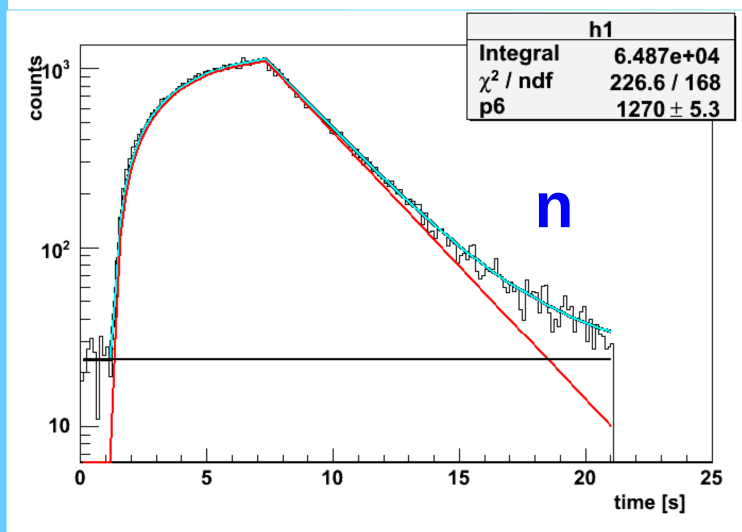



| Isotope | Rate ($s^{-1}$) |
|---|---|
| $^{85}$Ge | 6 |
| $^{85}$As | 175 |
| $^{86}$As | 30 |
| $^{91}$Br | 80 |

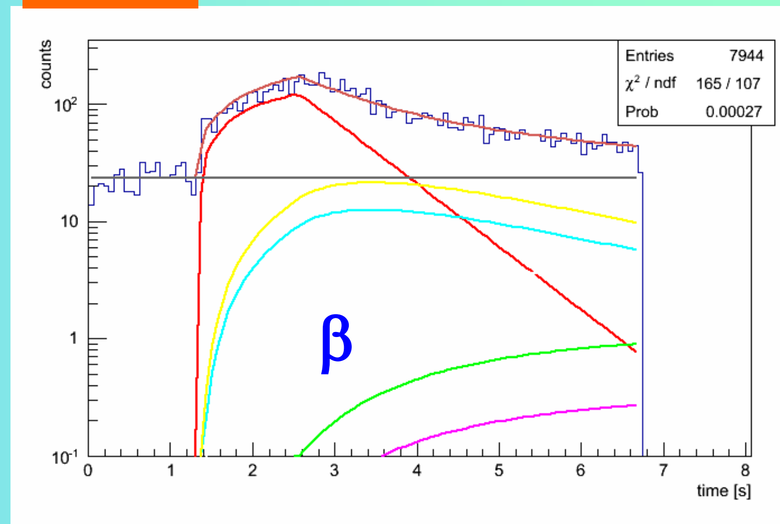
## $^{85}As$

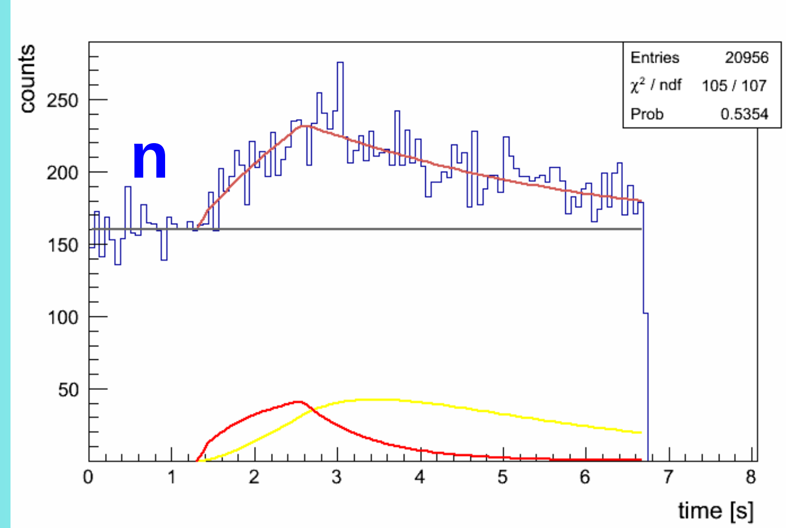



$P_n = 63.1(10)\%$

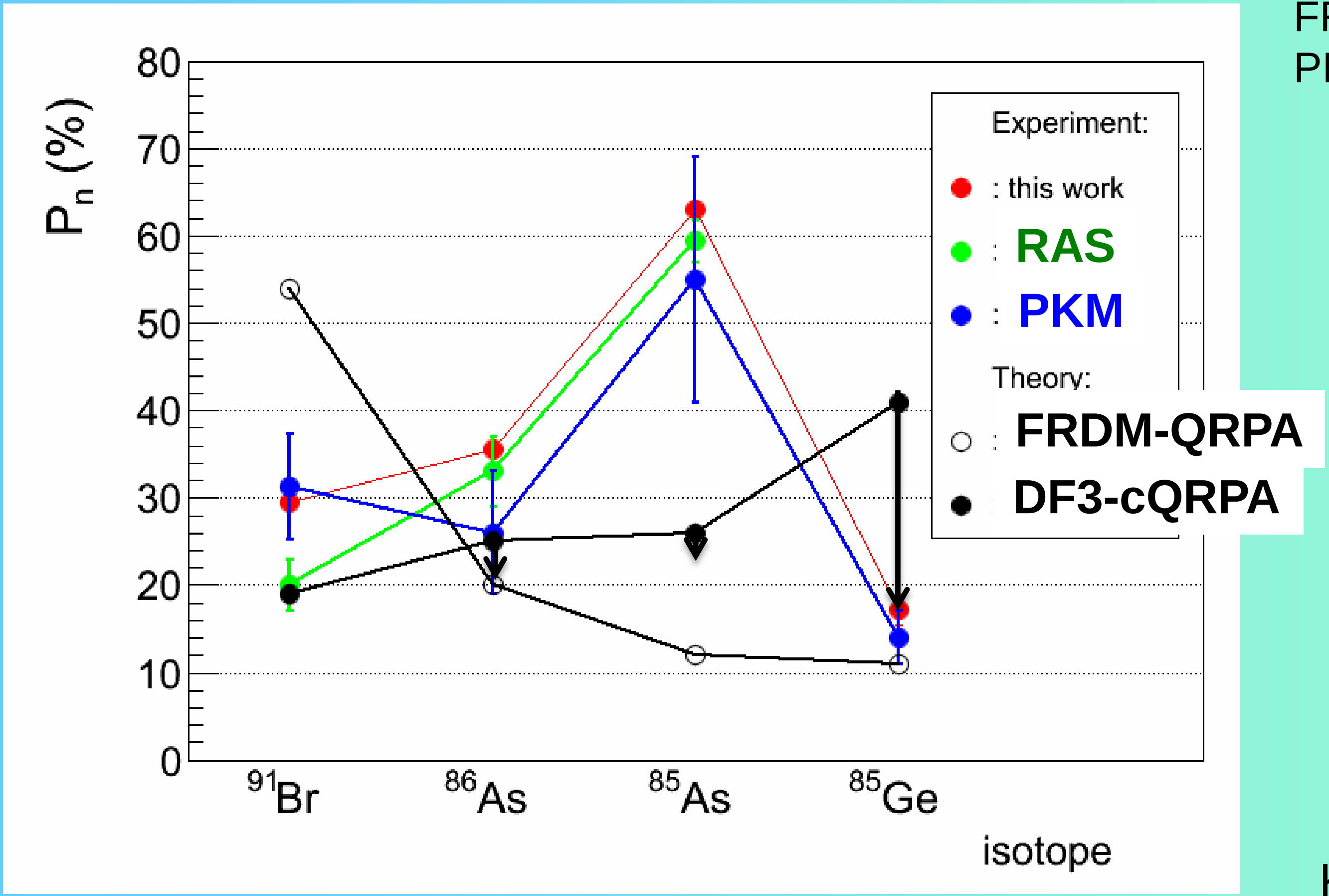
## $^{85}Ge$




$P_n = 17.2(18)\%$

# Results: comparison with theoretical estimates




FRDM-QRPA: Moeller et al., PRC67(03)55802

DF3-cQRPA: Borzov, PRC71(05)65801, NPA777(06)445 and PRC87(13)34315 and priv.com.

Both calculations reproduce $T_{1/2}$ within a factor 2

## …and empirical formulas

| Pn (%) | this work | PKM | MSJABS |
|---|---|---|---|
| 91Br | 29.5(5) | 12.1 | 27.0 |
| 86As | 35.5(6) | 9.3 | 33.2 |
| 85As | 63.1(10) | 7.9 | 36.3 |
| 85Ge | 17.2(18) | 4.3 | 9.8 |

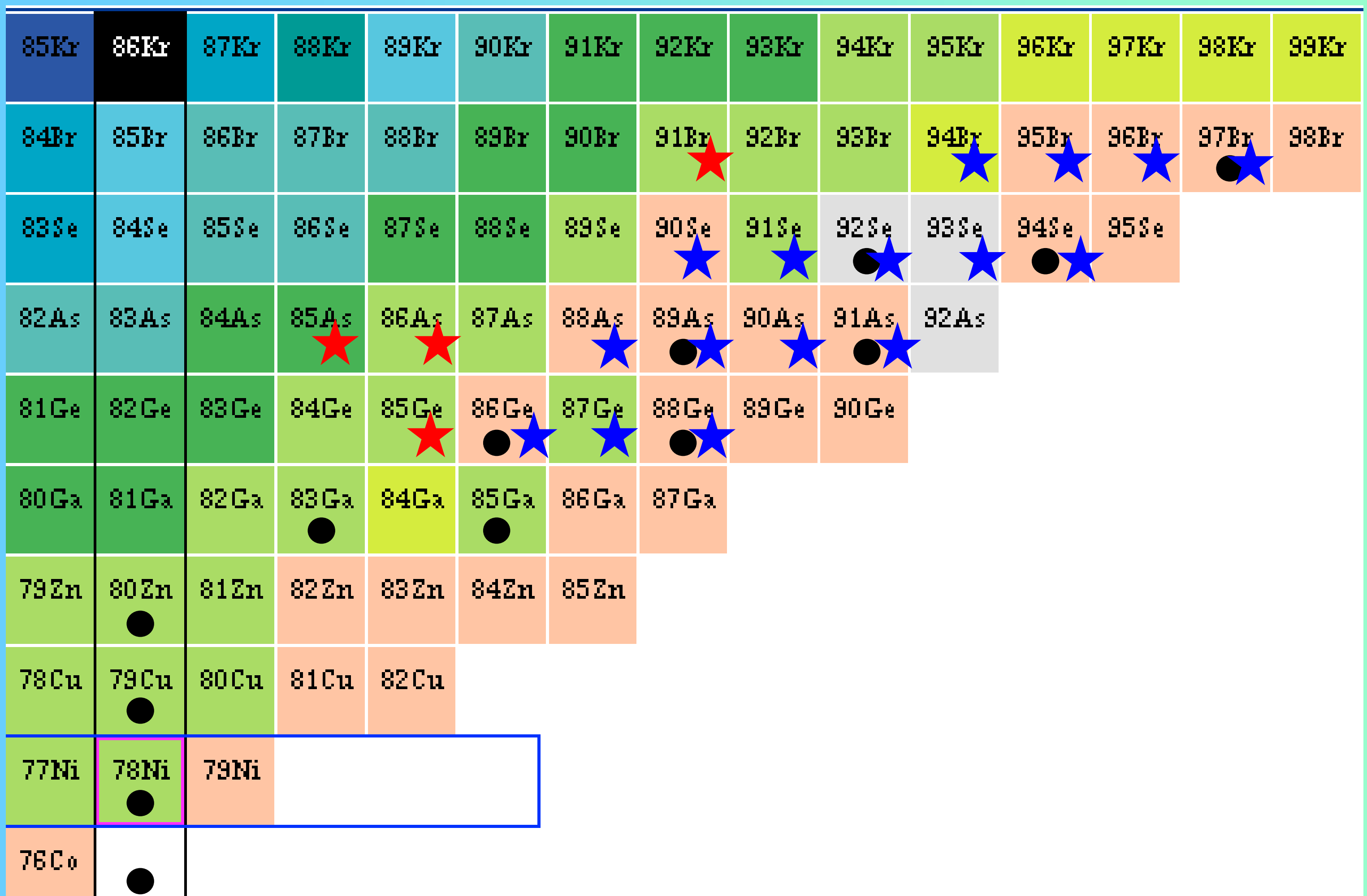
Kratz-Hermann formula:

$$P_n = a\left(\frac{Q_\beta - S_n}{Q_\beta - C}\right)^b$$

McCutchan et al PRC86(12):

$$\frac{P_n}{T_{1/2}} = a\left(Q_\beta - S_n\right)^b$$

# Proposal for measurements at RIKEN

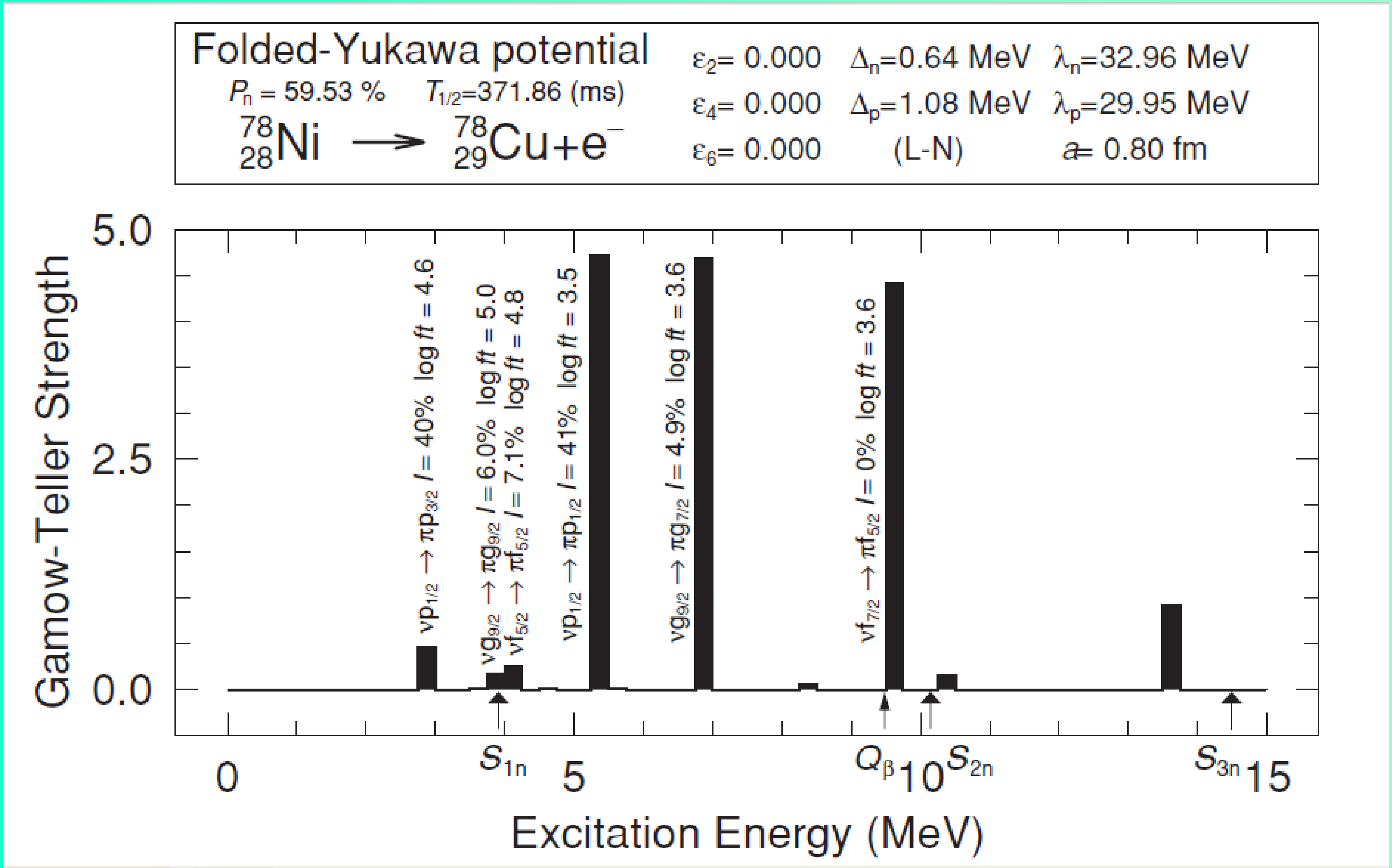


| Isotope | Rate | Q (MeV) | P1n | P2n | PKM | |
|---|---|---|---|---|---|---|
| **86Ge** | 8.2E+01 | 9.2 | 0.2385 | | | |
| **87Ge** | 6.7E+00 | 11.5 | 0.3073 | 0.0458 | | |
| **88Ge** | 6.7E-01 | 10.6 | 0.4907 | 0.0047 | | |
| **88As** | 2.9E+02 | 13.2 | 0.3218 | 0.022 | | |
| **89As** | 3.4E+01 | 12.2 | 0.7635 | 0.0133 | | |
| **90As** | 2.1E+00 | 14.5 | 0.2778 | 0.0261 | | |
| **91As** | 3.2E-01 | 13.4 | 0.8934 | 0.0316 | | |
| **90Se** | 1.4E+03 | 8.2 | 0.0083 | | | |
| **91Se** | 1.1E+02 | 10.8 | 0.0378 | | 21 | 10 |
| **92Se** | 1.2E+01 | 9.5 | 0.0323 | | | |
| **93Se** | 8.2E-01 | 12.3 | 0.0958 | 0.0021 | | |
| **94Se** | 2.0E-01 | 10.8 | 0.0404 | | | |
| **94Br** | 6.7E+01 | 13.7 | 0.146 | 0.0028 | 68 | 16 |
| **95Br** | 7.5E+00 | 12.4 | 0.9389 | 0.0015 | | |
| **96Br** | 5.9E-01 | 14.9 | 0.3218 | 0.0217 | | |
| **97Br** | 7.0E-02 | 13.4 | 0.8699 | 0.0387 | | |

Half-lives unknown or uncertain!

Rate: from U+Be fission file
P1n,P2n: Moeller et al., Phys. Rev. C67 (2003) 55802
PKM: Pfeiffer et al. experimental compilation, Prog. Nucl. Ener. 41 (2002) 39

# GT β-strength calculation (FRDM-QRPA) in 78Ni




Hosmer et al., PRC82 (10)025806