TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

Decay Spectroscopy of Neutron-Rich Cadmium Around the $N = 82$ Shell Closure

Nikita Bernier, UWC and UniZulu

IX Tastes of Nuclear Physics, UniZulu

October 2nd, 2019.

What are atoms made of?

How were the elements made?

What are atoms made of?

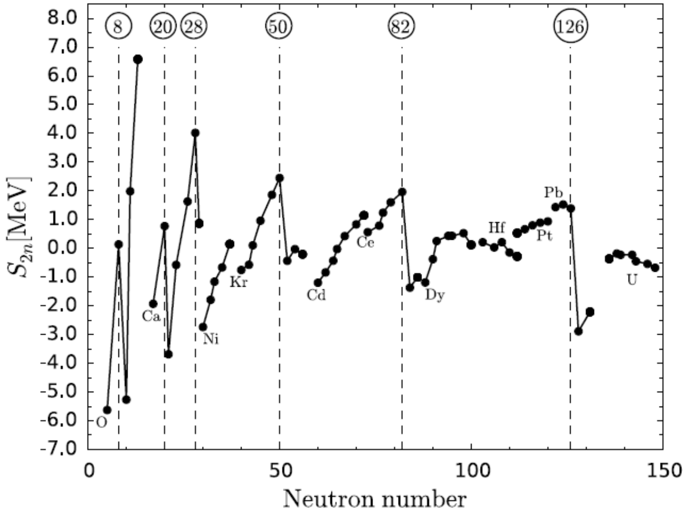
- 1949: Shell model of nuclear structure

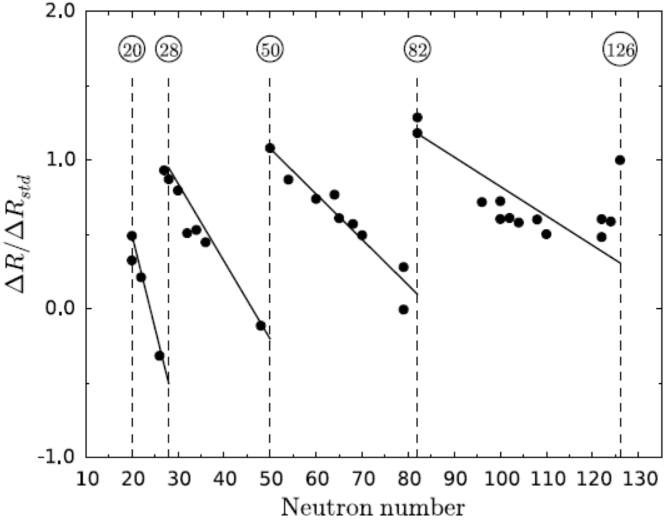
How were the elements made?

- 1939-1948: Big Bang and Stellar nucleosynthesis
- 1957: Heavy element nucleosynthesis

Today: study of exotic radioactive nuclei at accelerator facilities!

- Increased binding energy at particular proton (**Z**) and neutron (**N**) numbers





- Full shell (closures) occur at **magic numbers**
- Closed proton shell and closed neutron shell in **doubly-magic** nucleus

S. Bacca, Eur. Phys. J. Plus (2016)

- Nucleon-nucleon interaction and mean-field potential

$$
\begin{aligned}
H &= \left[\sum_{i=1}^{A} \frac{p_i^2}{2m} + \sum_{i}^{A} v\left(\vec{r}_i\right)\right] + \left[\sum_{i\neq k}^{A} V\left(\vec{r}_{i,k}\right) - \sum_{i}^{A} v\left(\vec{r}_i\right)\right] \\
&= H^0 + W_{RES}
\end{aligned}
$$

- Nucleon-nucleon interaction and mean-field potential

$$H = \left[\sum_{i=1}^{A} \frac{p_i^2}{2m} + \sum_{i}^{A} v\left(\vec{r}_i\right)\right] + \left[\sum_{i\neq k}^{A} V\left(\vec{r}_{i,k}\right) - \sum_{i}^{A} v\left(\vec{r}_i\right)\right]$$
$$= H^0 + W_{RES}$$

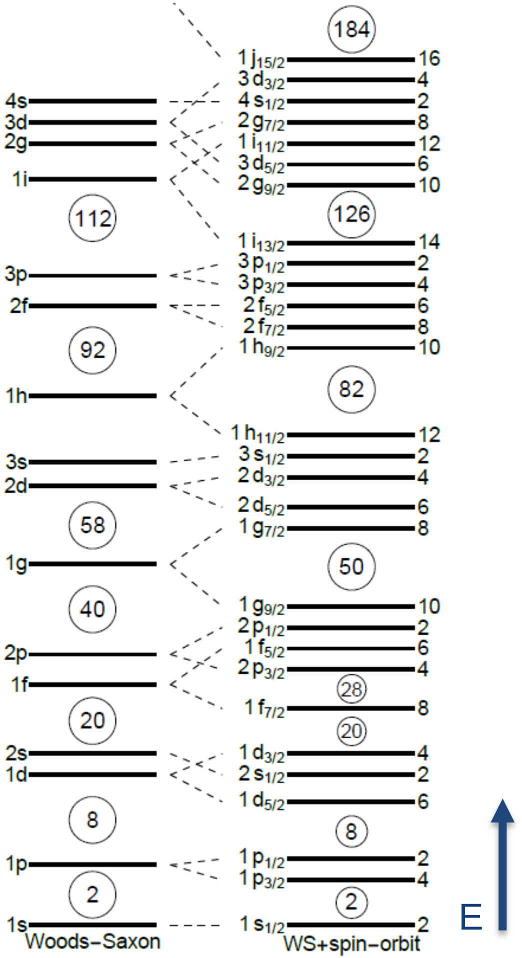
- ***W**$_{RES}$* **= 0**: Non-interacting shell model

$$H^0 = \sum_{i=1}^{A} \frac{p_i^2}{2m} + \sum_{i}^{A} v\left(\vec{r}_i\right)$$

  - Choice of potential gives single-particle energy levels

$$V(r_i) = \frac{-V_0}{1+\exp\left[(r_i - R)/a\right]} + V_{so}(r_i)\, \vec{l}\cdot\vec{s}$$

  - Some ground state properties (J^{π}) are reproduced



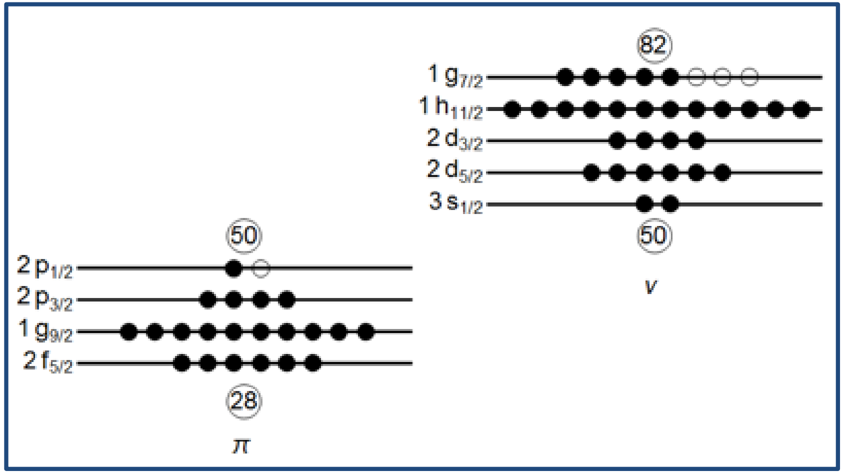
Nuclear shell model

- Nucleon-nucleon interaction and mean-field potential

$$H = \left[\sum_{i=1}^{A} \frac{p_i^2}{2m} + \sum_{i}^{A} v\left(\vec{r}_i\right)\right] + \left[\sum_{i \neq k}^{A} V\left(\vec{r}_{i,k}\right) - \sum_{i}^{A} v\left(\vec{r}_i\right)\right]$$
$$= H^0 + W_{RES}$$

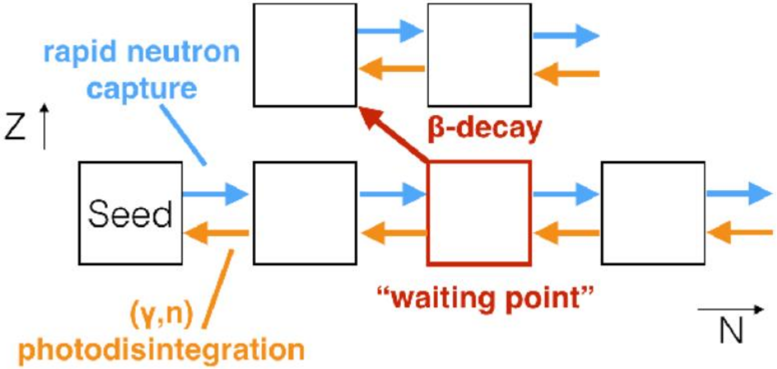
- ***W_{RES}* ≠ 0**: Interacting shell model
  - Configuration mixing
  - Effective two-body (NN) matrix elements

- Recent developments:
  - Chiral effective field theory (3N)
  - Ab initio methods (many-body)

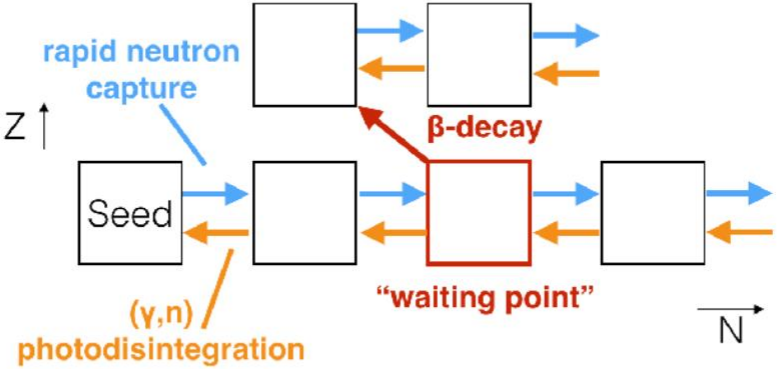


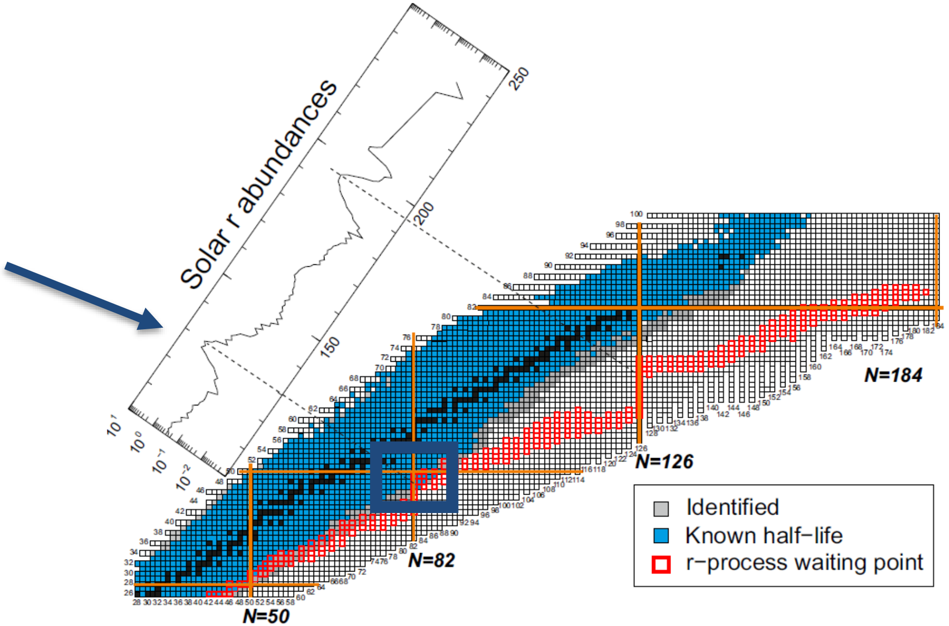
Valence space

- pp-cycle and CNO-cycle up to ^{16}O, advanced burning up to ^{56}Fe
- **Waiting point** nuclei form the rapid neutron capture **(*r*-) process** path, which create half of the nuclei heavier than ^{56}Fe



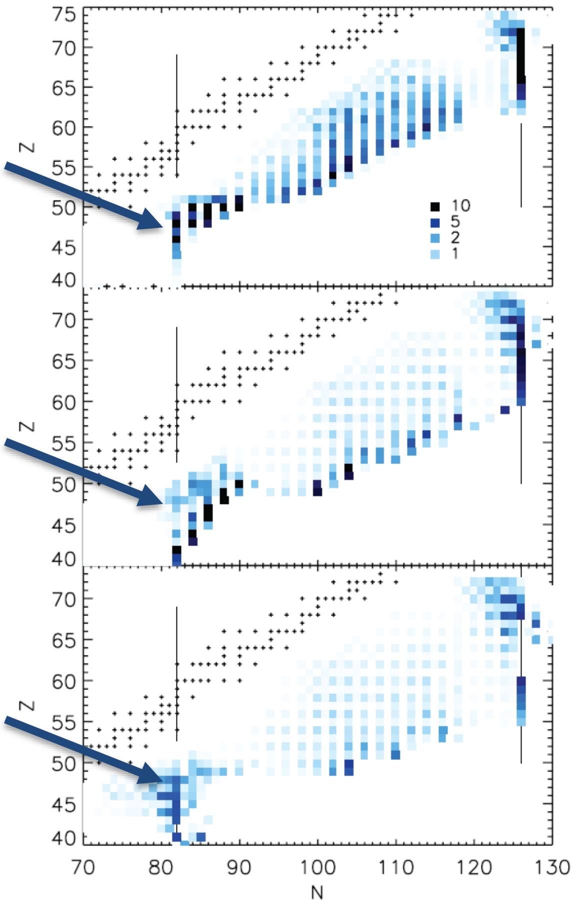
- pp-cycle and CNO-cycle up to ^{16}O, advanced burning up to ^{56}Fe
- **Waiting point** nuclei form the rapid neutron capture **(*r*-) process** path, which create half of the nuclei heavier than ^{56}Fe
- *N* = *82* isotope ^{130}Cd provides critical information on the **abundance peak** at *A* ~ 130.





- Supernova explosion (hot and cold *r*-process winds), and neutron star merger

$$\frac{n(A+1,Z)}{n(A,Z)} = n_n \cdot \sqrt[3]{\frac{A+1}{A} \cdot \frac{2\pi\hbar^2}{k_B T \cdot m_u}} \cdot \exp\left(-\frac{S_n}{k_B T}\right)$$



M. Mumpower et al., AIP ADVANCES (2014)

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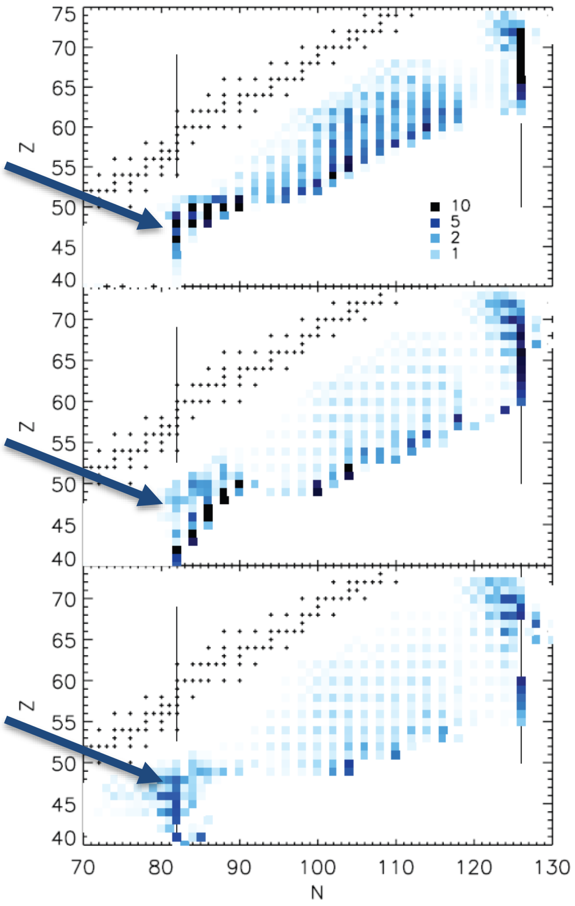
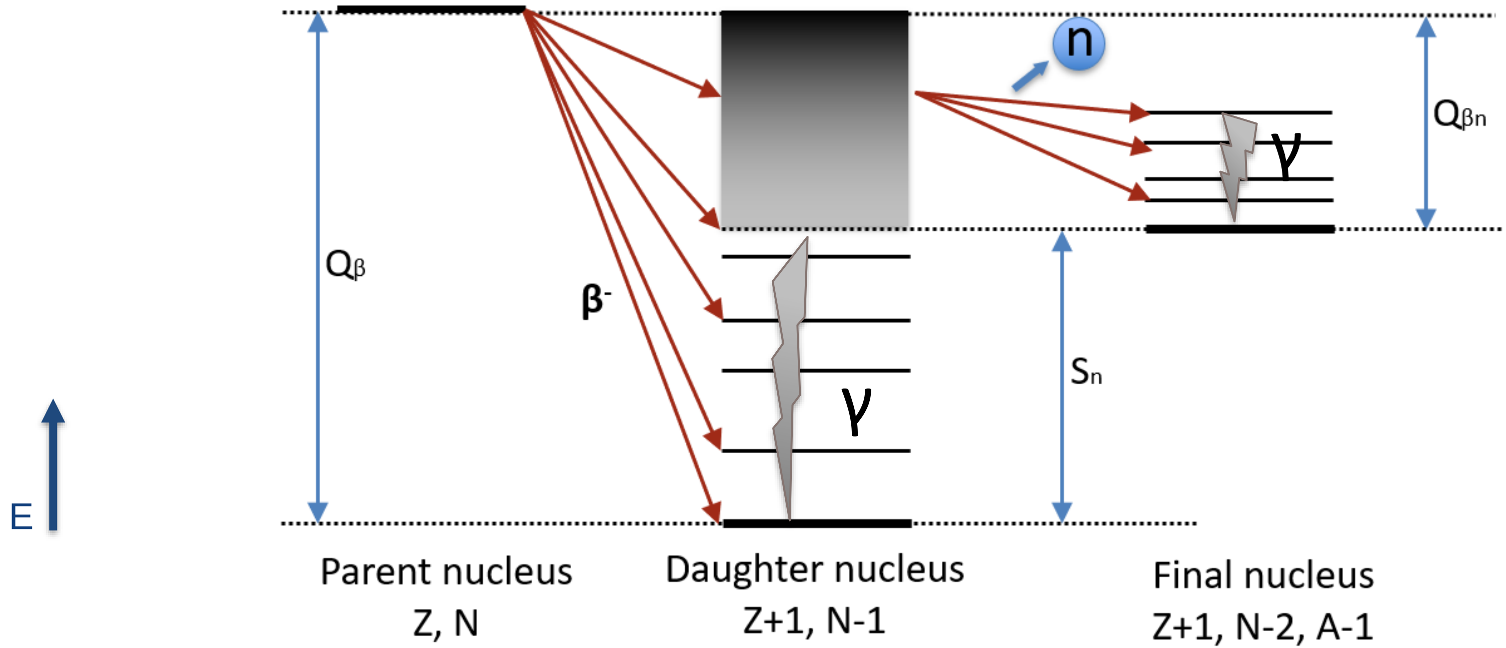
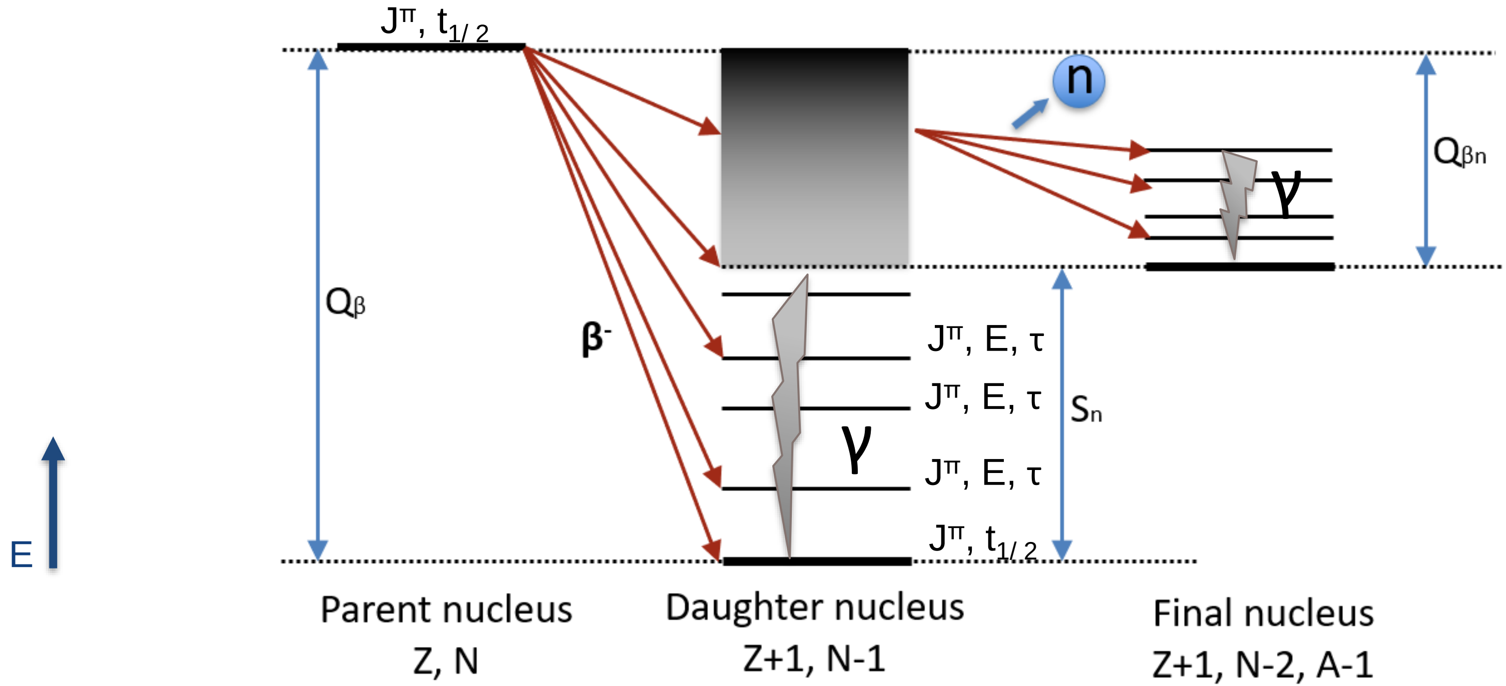
- Defining nuclear physics parameters
  - Masses (S_n, Q_β)
  - β-decay lifetimes
  - β-delayed neutron emission probabilities rates
  - Shell structure far off stability



M. Mumpower et al., AIP ADVANCES (2014)

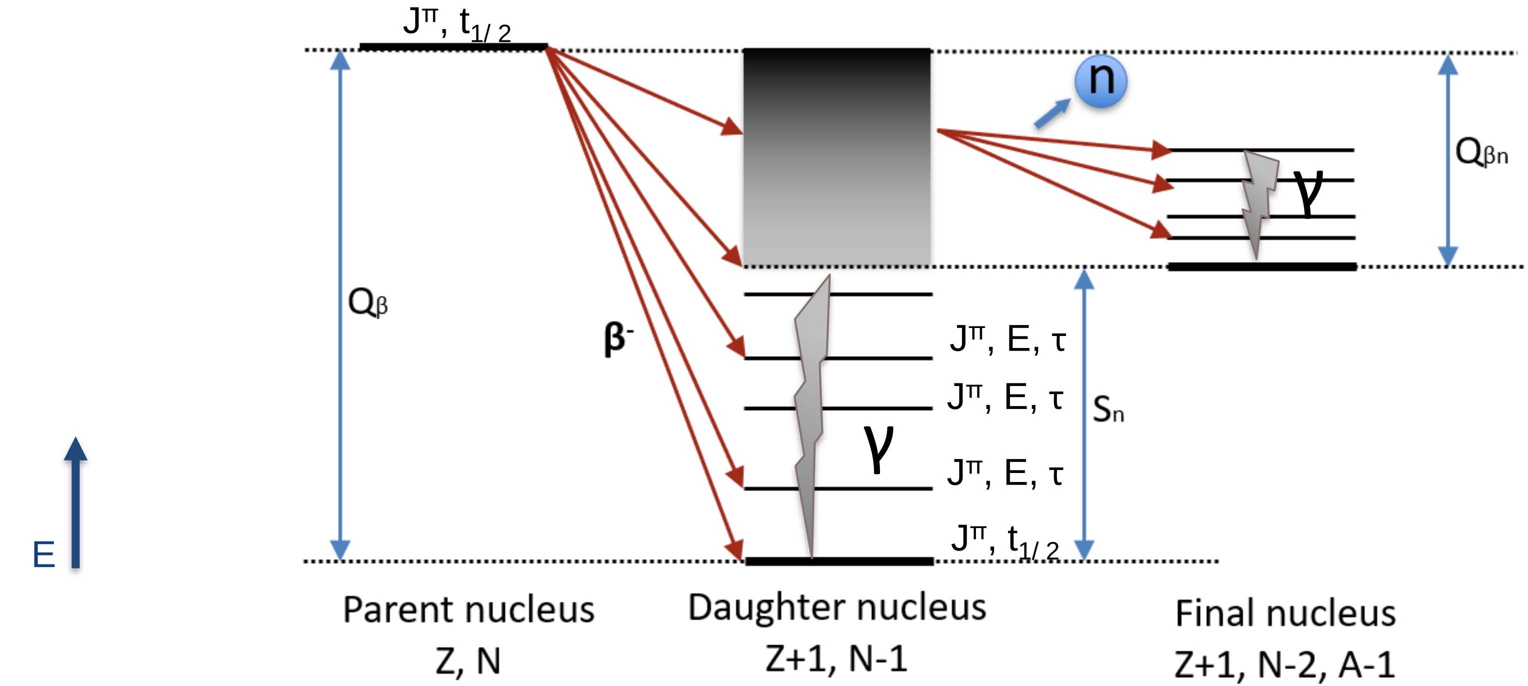

n
Qβn
γ
Qβ
β-
γ
Sn
E
Parent nucleus
Z, N
Daughter nucleus
Z+1, N-1
Final nucleus
Z+1, N-2, A-1



Selection rules of β-decay

Transition Type	L	$\Delta\Pi$	Fermi ΔI	Gamow-Teller ΔI	$\log(ft)$
Allowed	0	No	0	(0),1	~4.0–7.5
First Forbidden	1	Yes	(0),1	0,1,2	~6.0–9.0
Second Forbidden	2	No	(1),2	2,3	~10–13

Neutron-rich nuclear decay



Selection rules of β-decay

Transition Type	L	$\Delta\Pi$	Fermi ΔI	Gamow-Teller ΔI	$\log(ft)$
Allowed	0	No	0	(0),1	$\sim$4.0–7.5
First Forbidden	1	Yes	(0),1	0,1,2	$\sim$6.0–9.0
Second Forbidden	2	No	(1),2	2,3	$\sim$10–13

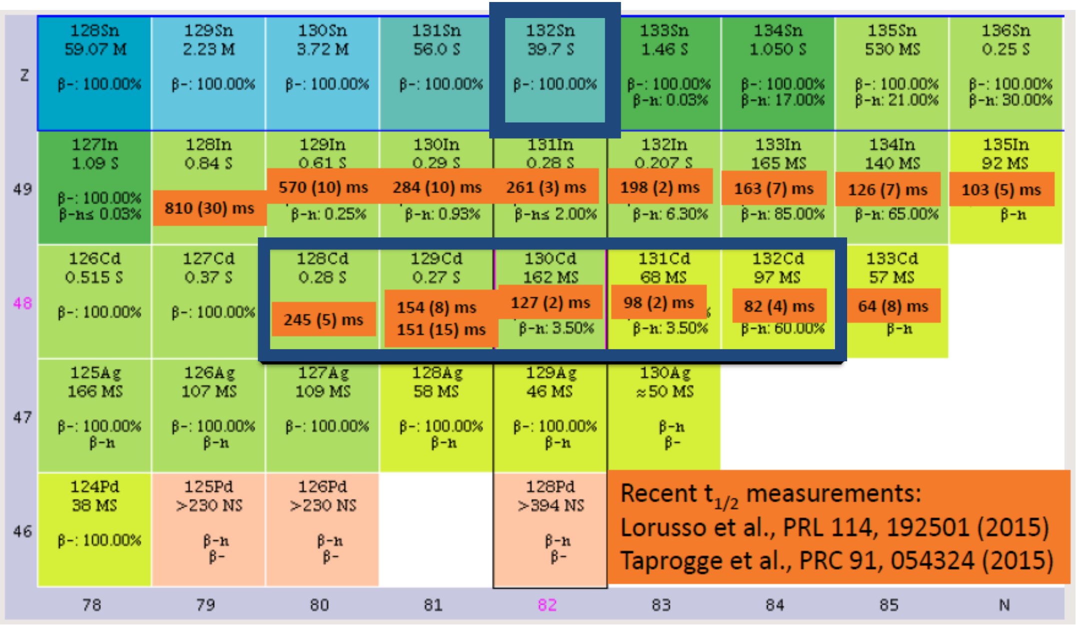
Selection rules of γ-decay

$$|J_i - J_f| \leqslant L \leqslant J_i + J_f$$

$$\Pi(EL) = (-1)^L$$

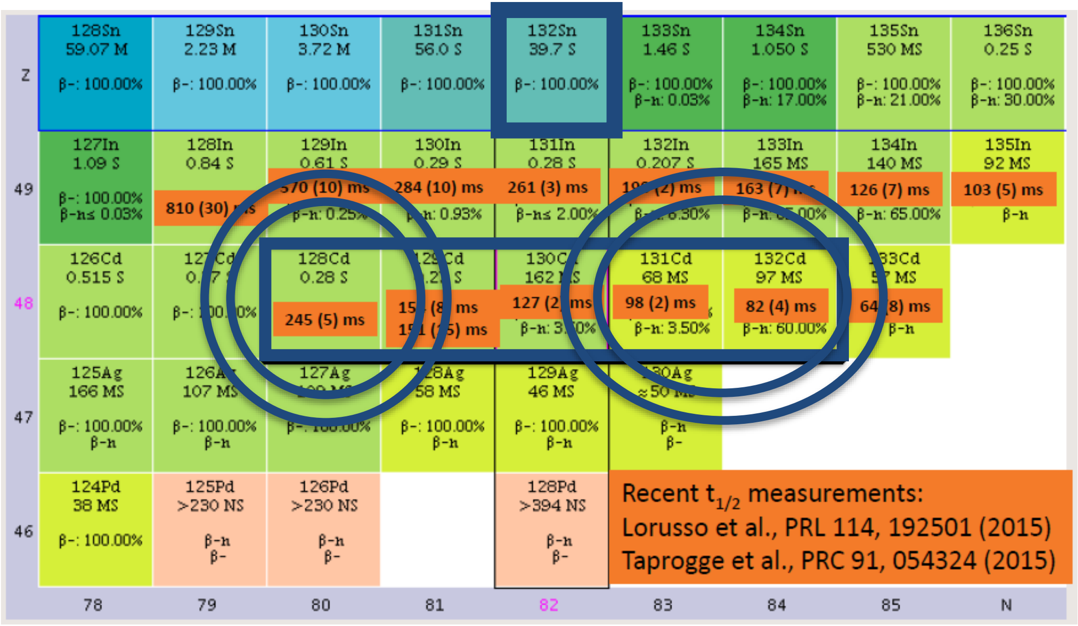
$$\Pi(ML) = (-1)^{(L+1)}$$

- $^{128\text{-}132}$**Cd** are neighboring the **doubly-magic** ^{132}Sn,
  which is central to shell model calculations and *r*-process simulations

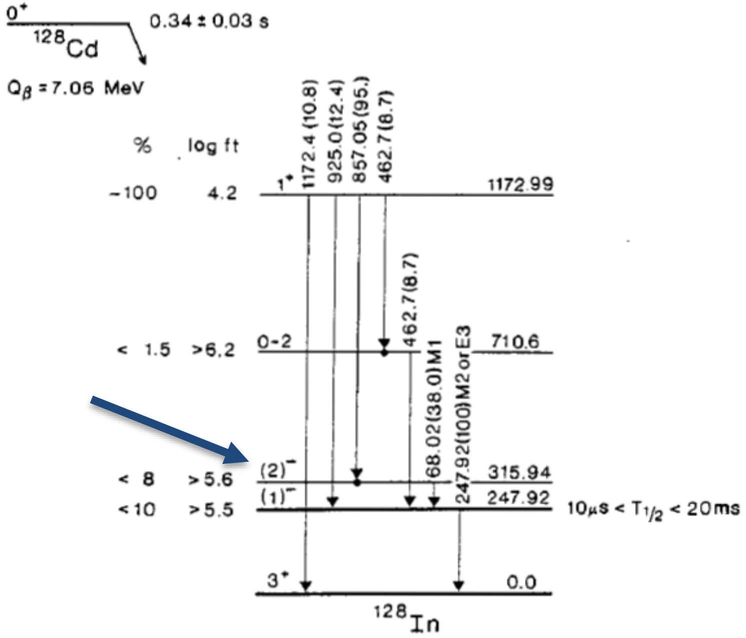


Decay spectroscopy of $^{128-132}$Cd

- $^{128-132}$**Cd** are neighboring the **doubly-magic** ^{132}Sn,
  which is central to shell model calculations and *r*-process simulations

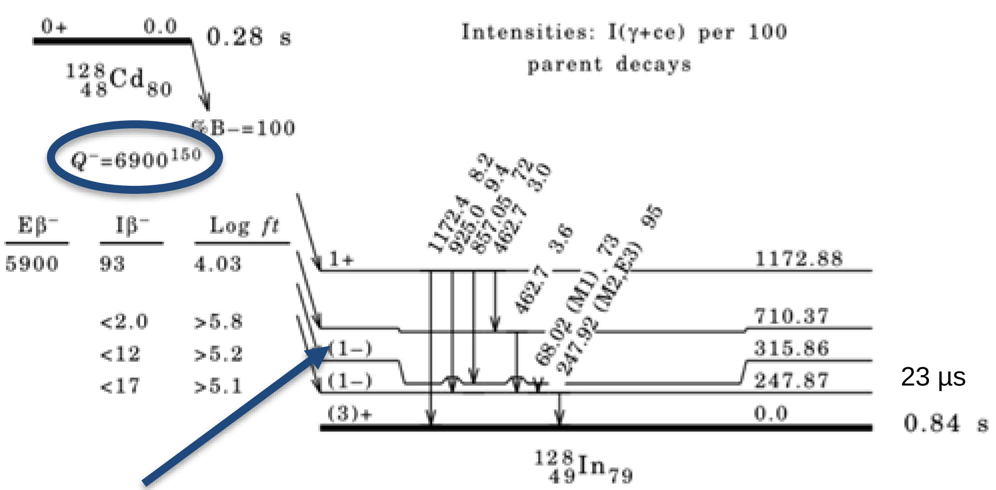


- 1988 experiment in Sweden: 7 transitions and 4 levels (1 isomer)
- Re-evaluated in 2015.



Work by B. Ekstrom quoted in
B. Fogelberg, Nucl. Data for Sc. and Tech., **837** (1988)

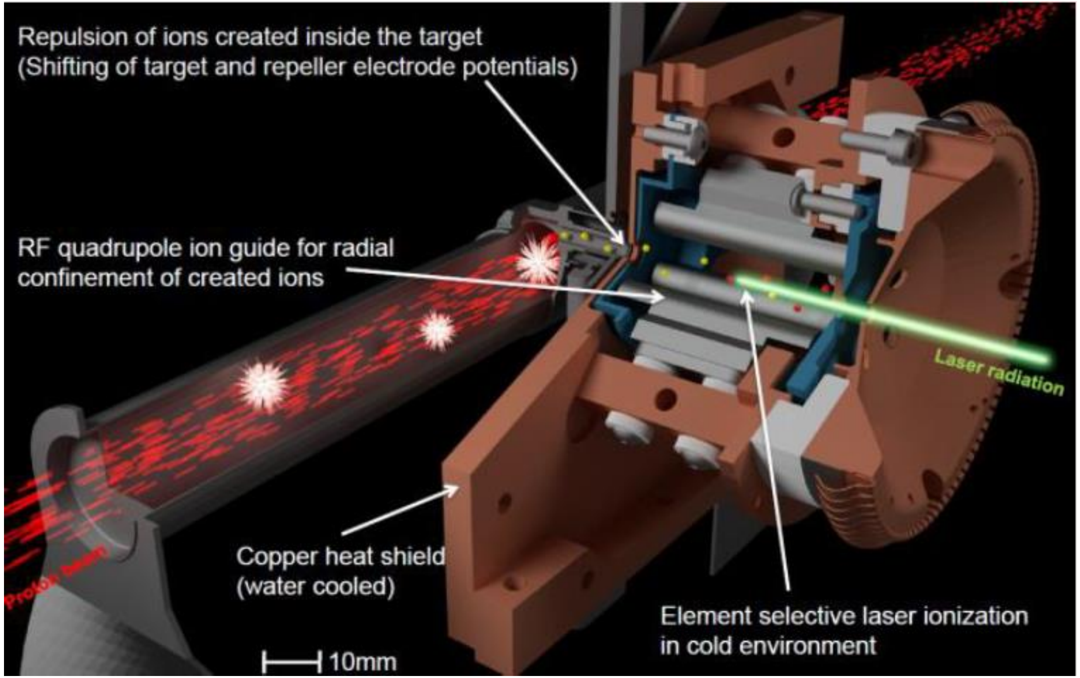
^{128}In S(n) = 5320 (150) keV



Z. Elekes and J. Timar, Nucl. Data Sheets **129**, 191 (2015)

- Selective ionization with the **I**on **G**uide **L**aser **I**on **S**ource [IG-LIS]
    - Background suppression by factors **10^5-10^6**

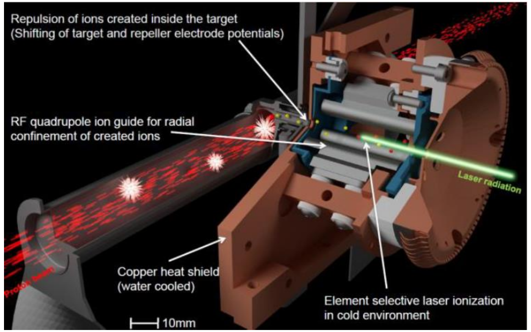
TRIUMF ISAC

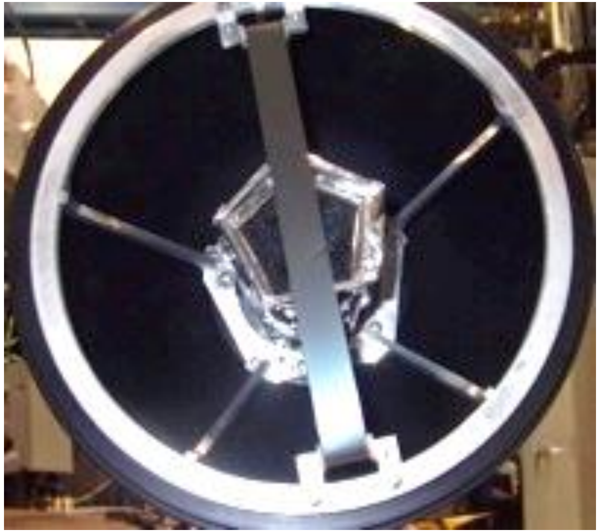


Neutron-rich Cd beams at TRIUMF

- Selective ionization with the **I**on **G**uide **L**aser **I**on **S**ource [IG-LIS]
  - Background suppression by factors **10^5-10^6**
- High statistics β-γ-γ with **SCEPTAR** : SCintillating Electron Positron Tagging Array

TRIUMF ISAC





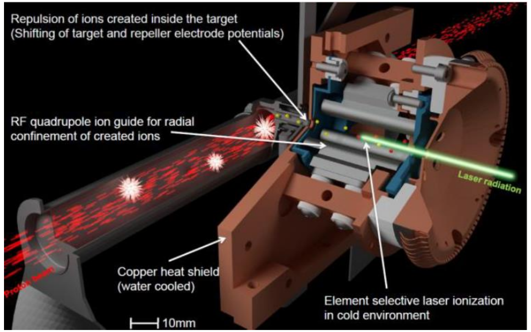
In-vacuum moving tape collector system

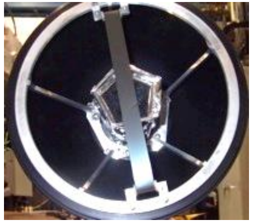
Neutron-rich Cd beams at TRIUMF

- Selective ionization with the **I**on **G**uide **L**aser **I**on **S**ource [IG-LIS]
  - Background suppression by factors **10^5-10^6**
- High statistics β-γ-γ with **SCEPTAR** : SCintillating Electron Positron Tagging Array
- 16 large-volume germanium **GRIFFIN** detectors dedicated to **decay spectroscopy** of the low-energy radioactive ion beams at TRIUMF.

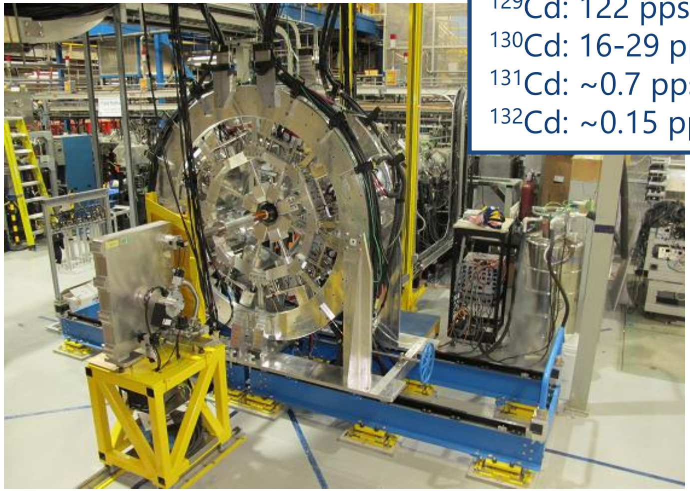
Yields
^{128}Cd: 1067 pps
^{129}Cd: 122 pps
^{130}Cd: 16-29 pps
^{131}Cd: ~0.7 pps
^{132}Cd: ~0.15 pps

TRIUMF ISAC



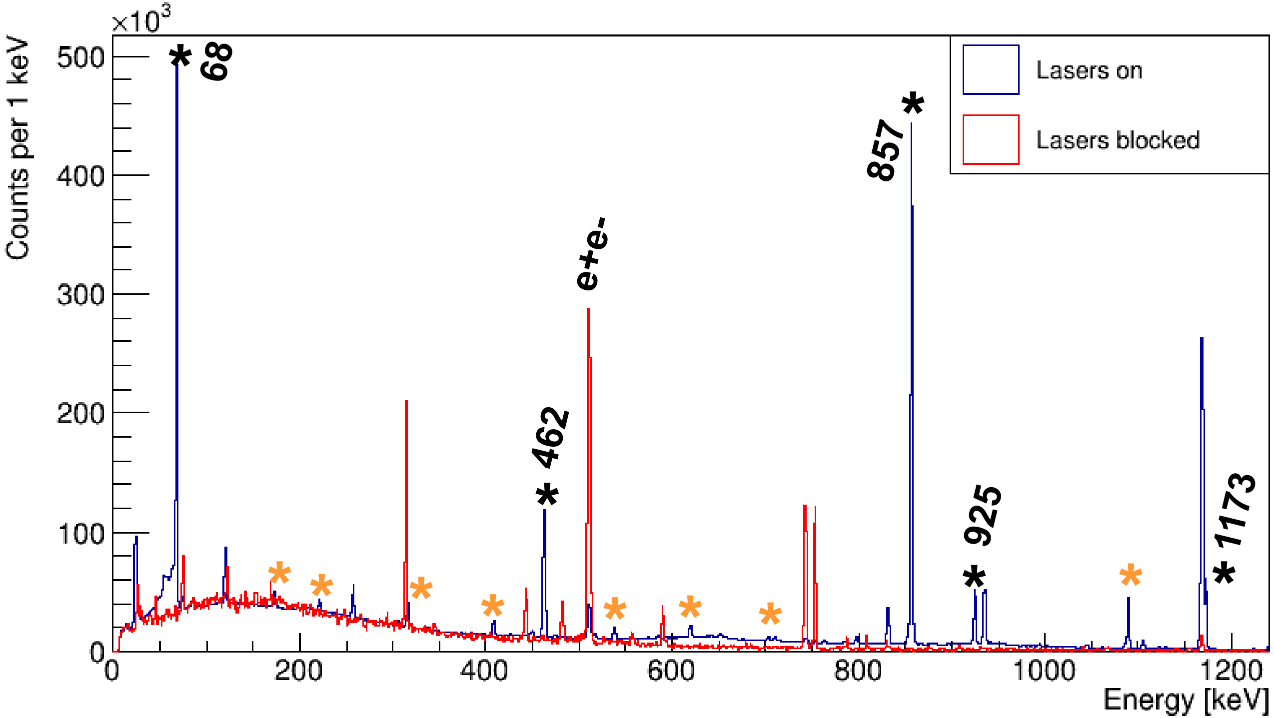


In-vacuum moving tape collector system



Further discrimination of **isobaric background**:

- Identification of transitions by comparing laser **on** (Cd + In) and laser **blocked** (mostly In)

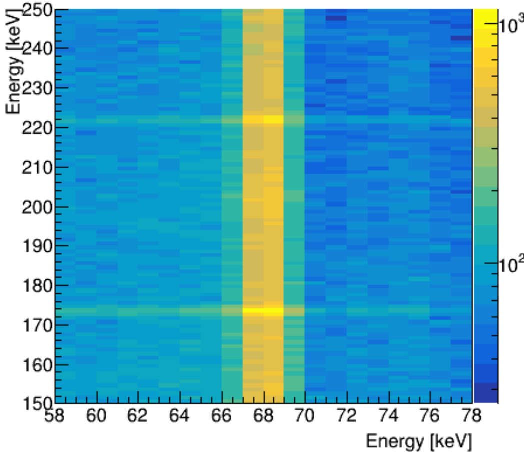


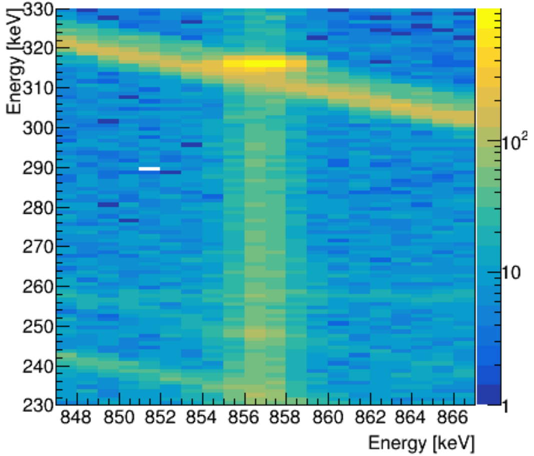
β-gated γ-singles

* *Known* ^{128}Cd→^{128}In

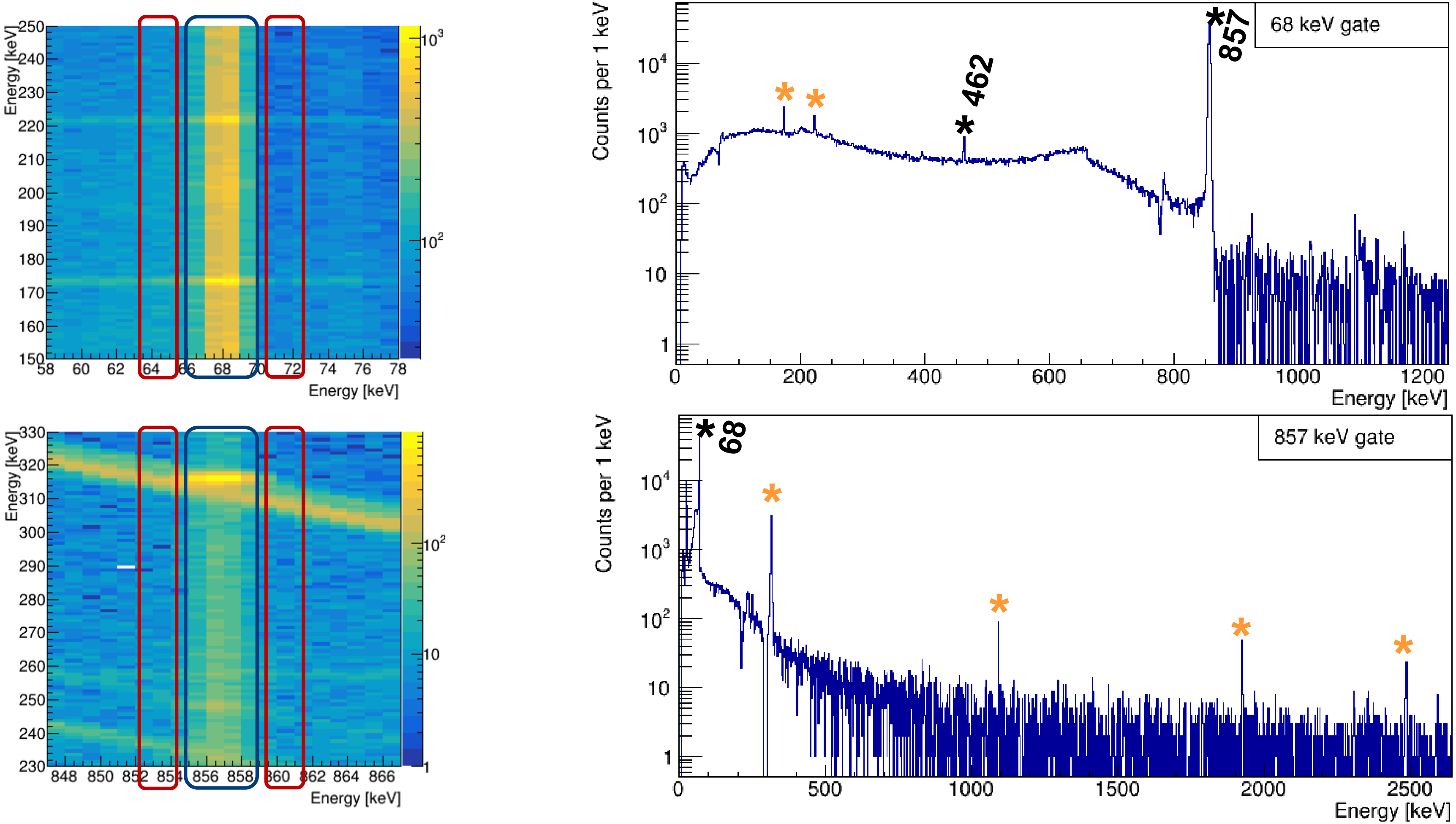
* *New* ^{128}Cd→^{128}In

β-γ-γ coincidence



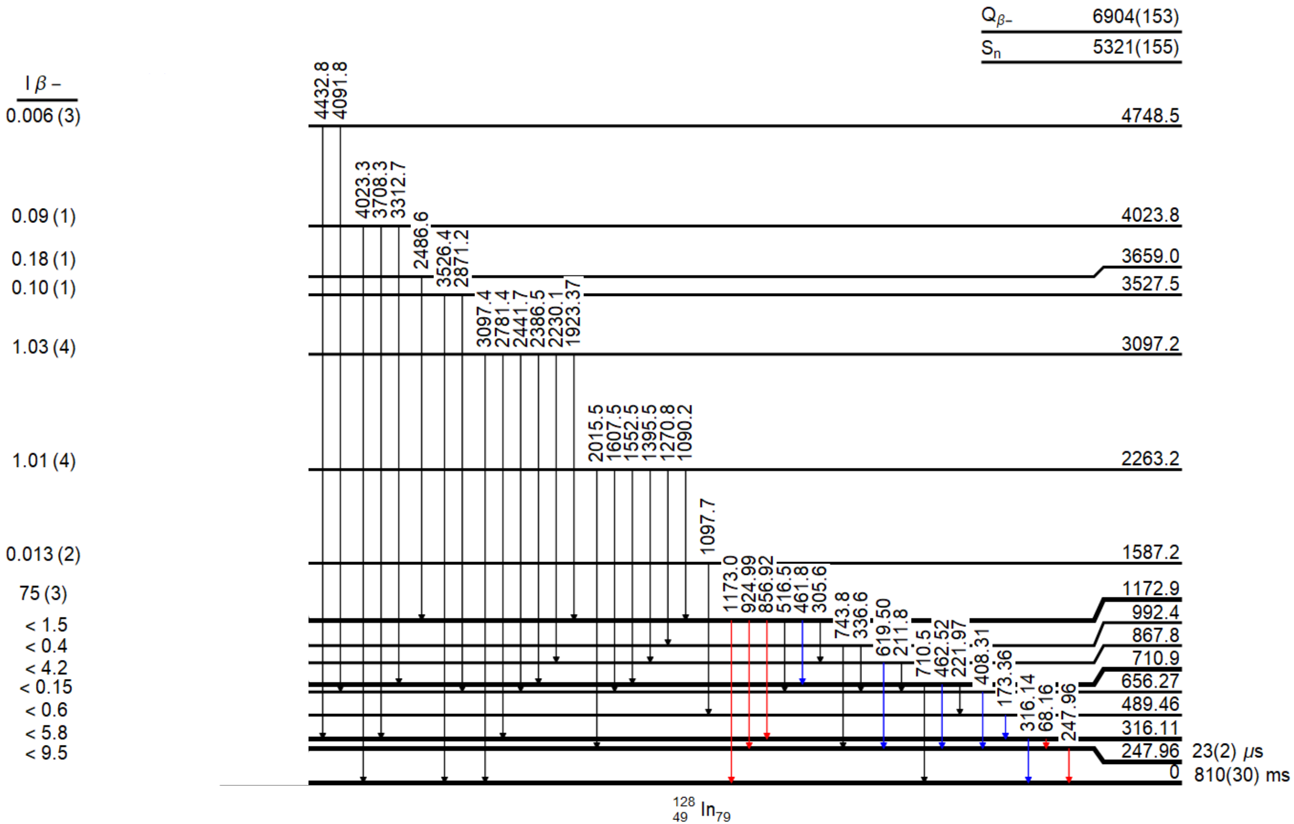


β-γ-γ coincidence



Decay scheme of ^{128}Cd

- 32 **new** transitions and 11 **new** states



Decay scheme of ^{128}Cd

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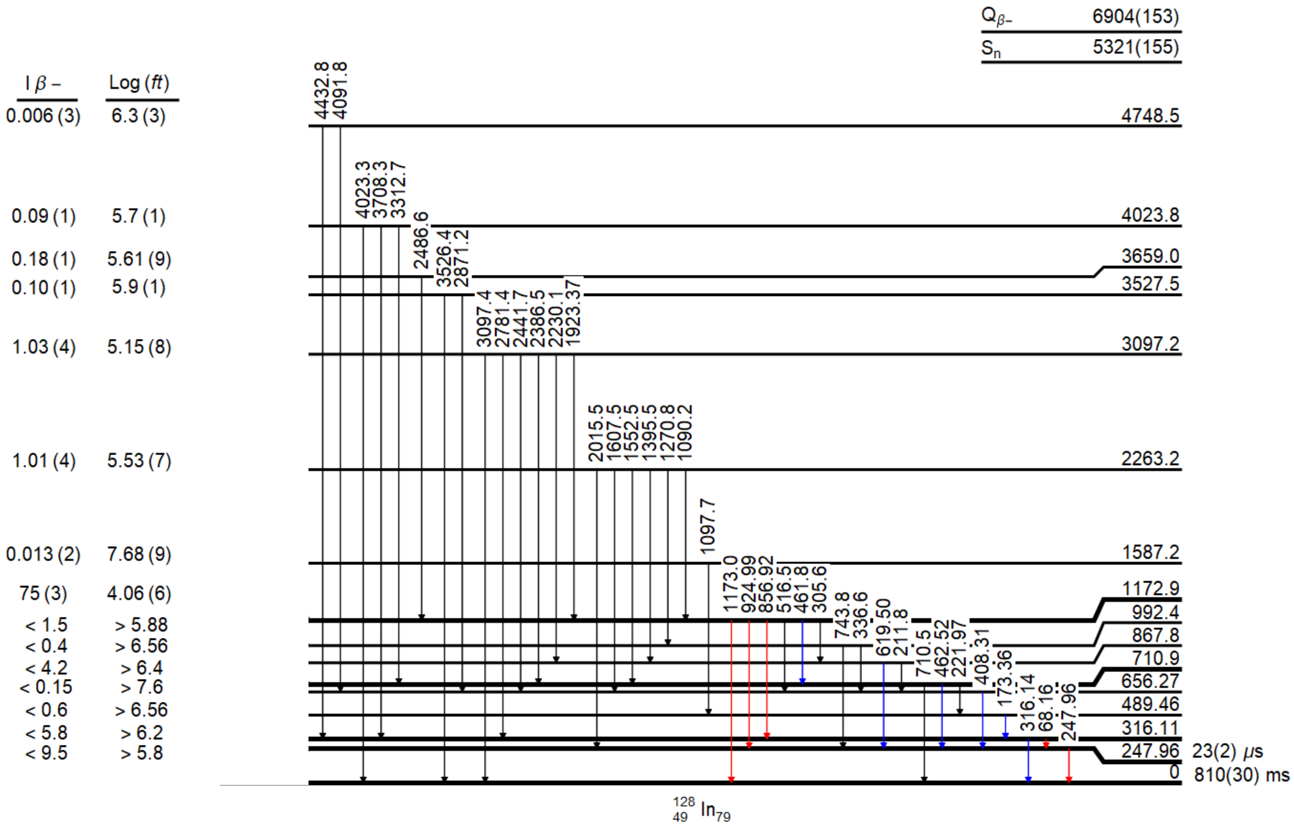
$$ft = \frac{f(Q_\beta - E_f, Z)T_{1/2}}{I_\beta(E_f)} = \frac{k}{g_V^2 B(\mathrm{F}) + g_A^2 B(\mathrm{GT})}$$

$$B(\mathrm{F}) = |\langle \psi_f^* | \tau | \psi_i \rangle|^2$$
$$B(\mathrm{GT}) = |\langle \psi_f^* | \sigma\tau | \psi_i \rangle|^2$$



Decay scheme of ^{128}Cd

- 32 **new** transitions and 11 **new** states
- Structure information from **log(*ft*)** values and angular correlations

$$ft = \frac{f(Q_\beta - E_f, Z)T_{1/2}}{I_\beta(E_f)}$$
$$= \frac{k}{g_V^2 B(\mathrm{F}) + g_A^2 B(\mathrm{GT})}$$

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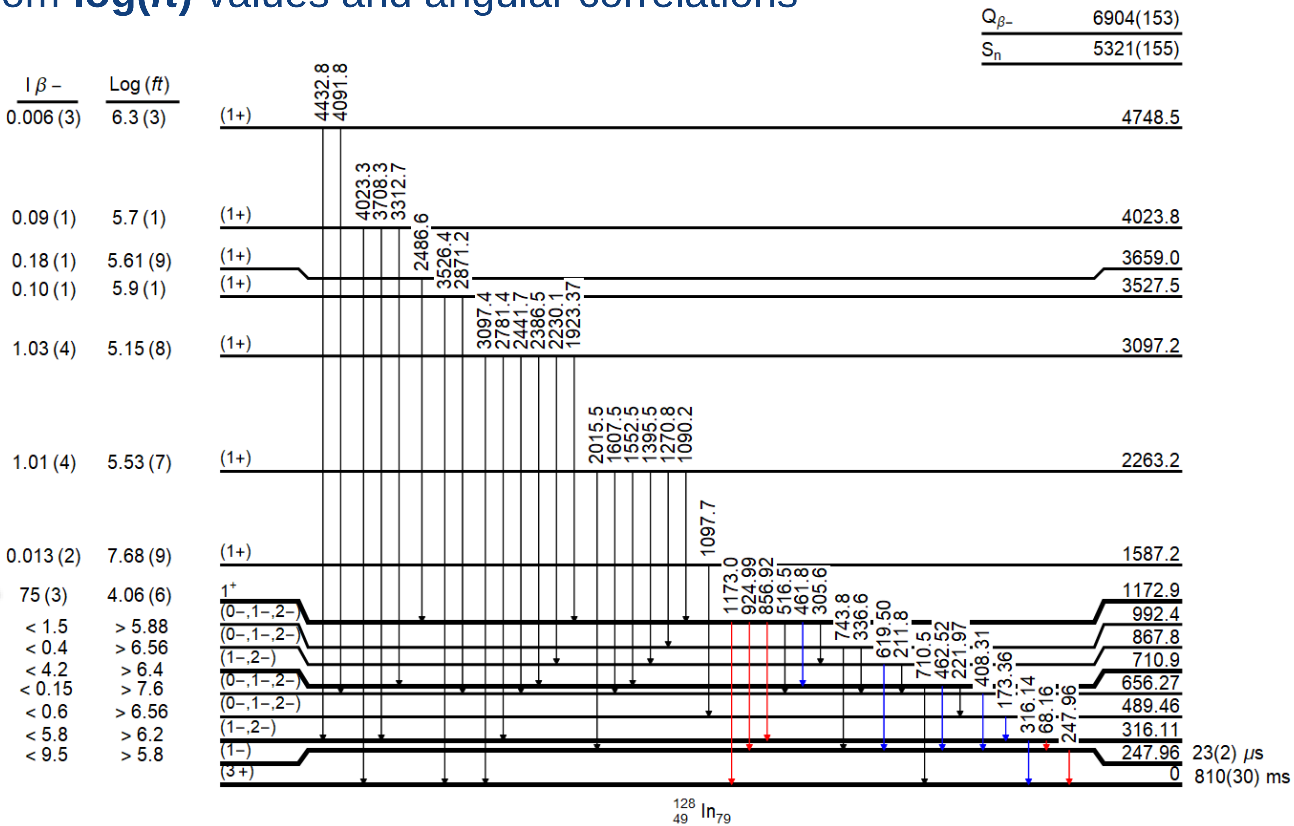
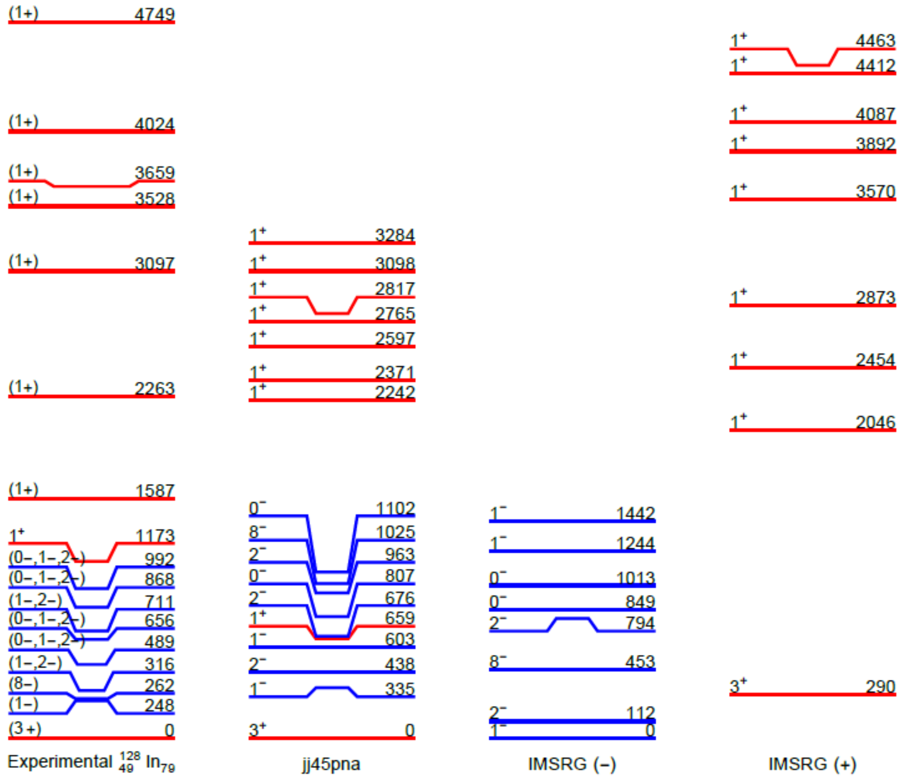
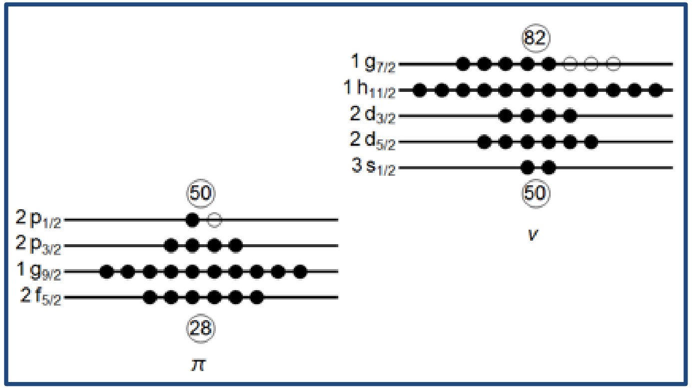


Shell model calculations for ^{128}In

- NuShellX (jj45pna)
- In-Medium Similarity Renormalization Group (IMSRG)





Valence space

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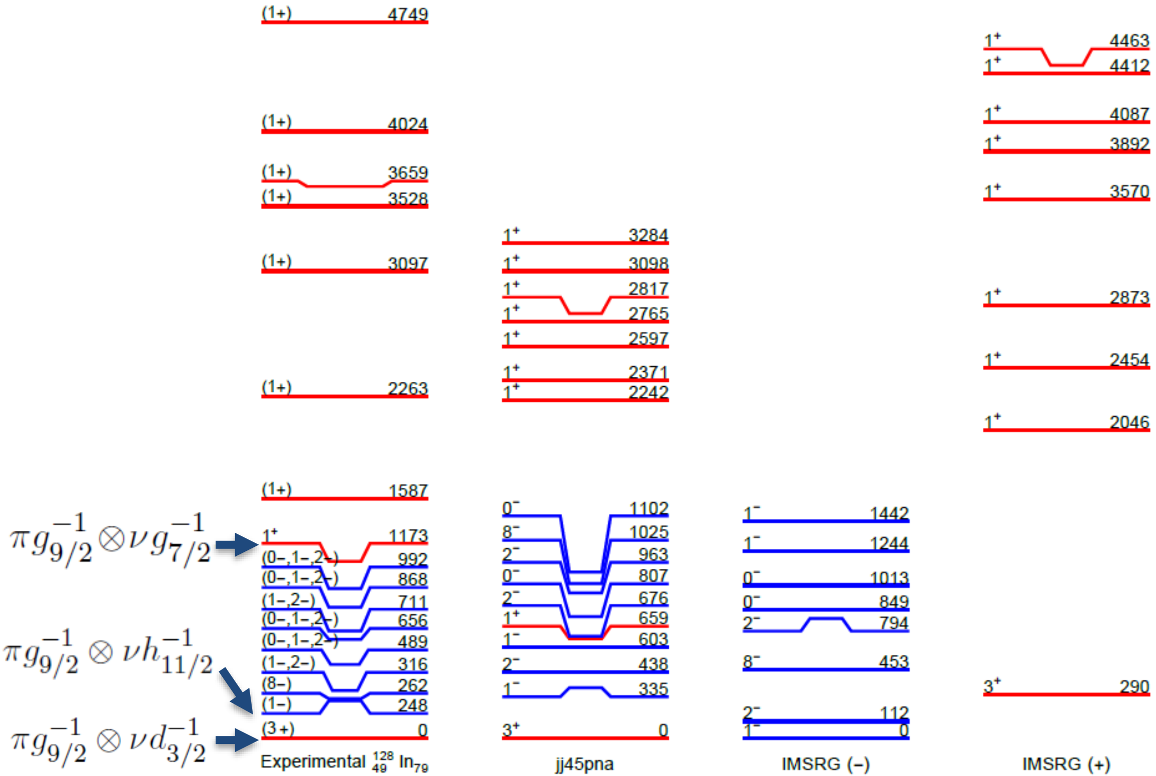
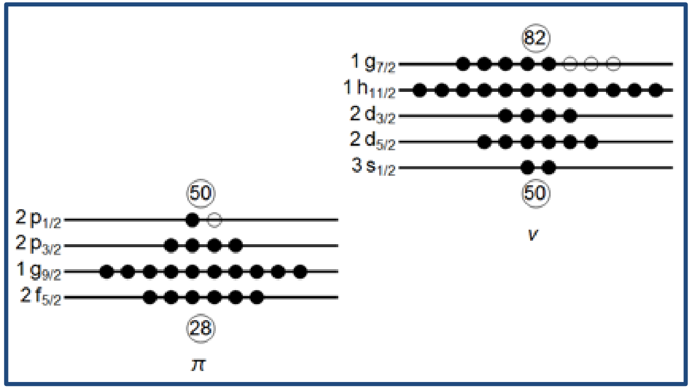


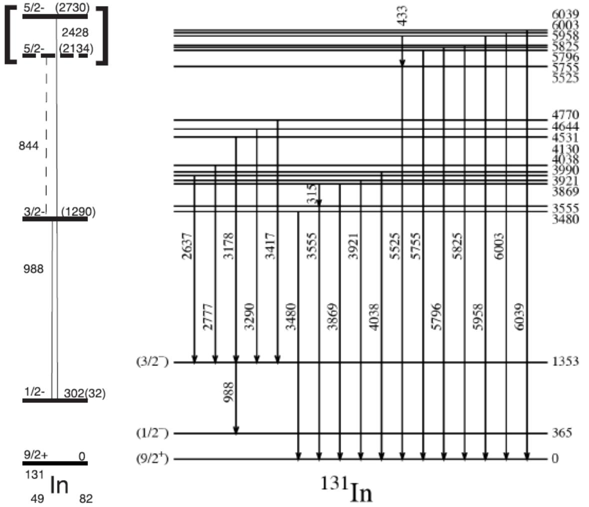


Valence space

Previous work on $^{131\text{-}132}$Cd

- **7** transitions observed in ^{131}In at ISOLDE, **23** at RIKEN: only **4** transitions in common

^{131}Cd Q(β^-) = 12700 (510) keV
^{131}In S(n) = 6210 (40) keV

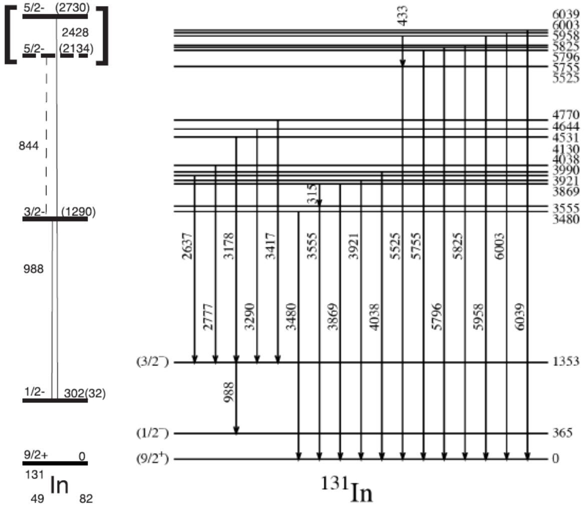


O. Arndt *et al.*, Acta Phys. Pol. B **40**, 437 (2009)
C. Jost, PhD thesis, U of Mainz (2010)

J. Taprogge *et al.*, Eur. Phys. J. A **52**, 347 (2016)

- **7** transitions observed in ^{131}In at ISOLDE, **23** at RIKEN: only **4** transitions in common
- No γ-transitions observed from the β-decay of ^{132}Cd to ^{132}In.

^{131}Cd Q(β^-) = 12700 (510) keV
^{131}In S(n) = 6210 (40) keV



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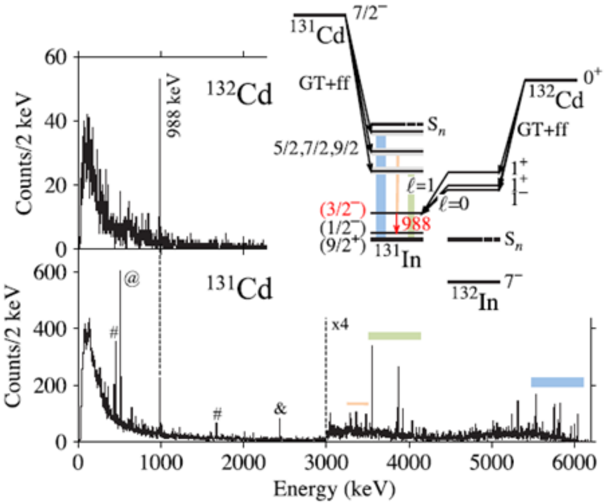
C. Jost, PhD thesis, U of Mainz (2010)

J. Taprogge *et al.*, Eur. Phys. J. A **52**, 347 (2016)

^{132}Cd Q(β^-) = 12150 (510) keV
^{132}In S(n) = 2450 (60) keV

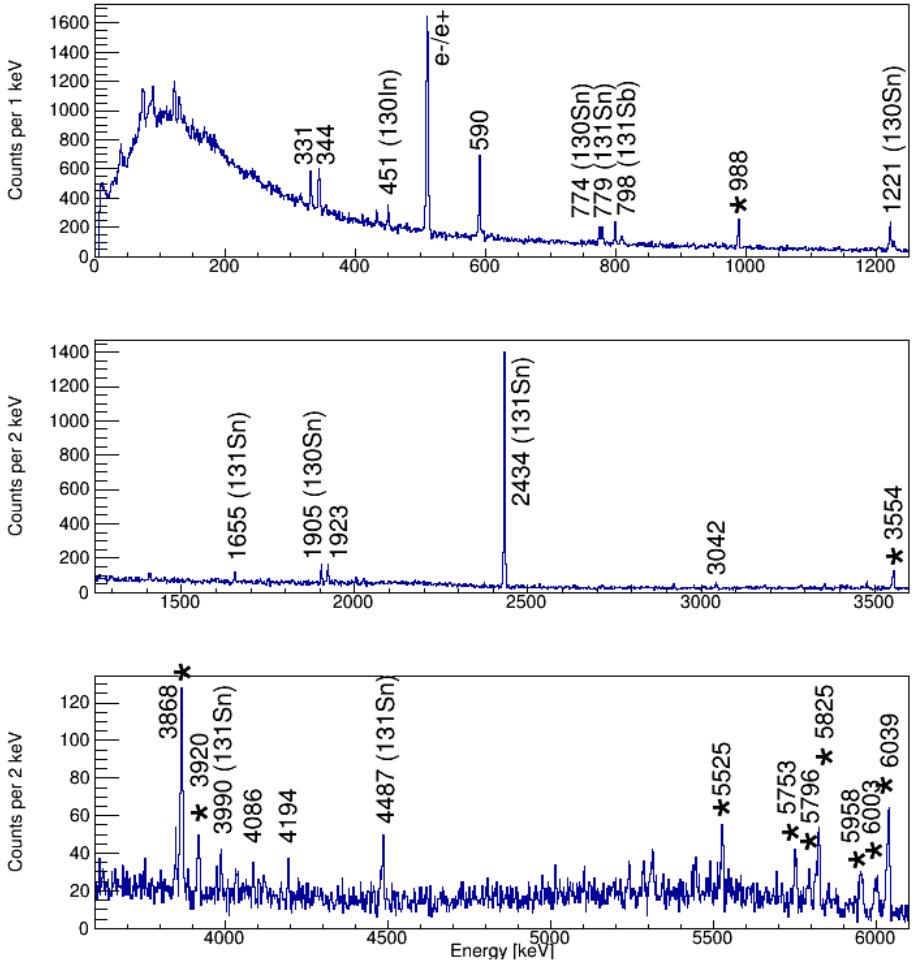


J. Taprogge *et al.*, Phys. Rev. Lett. **112**, 132501 (2014)

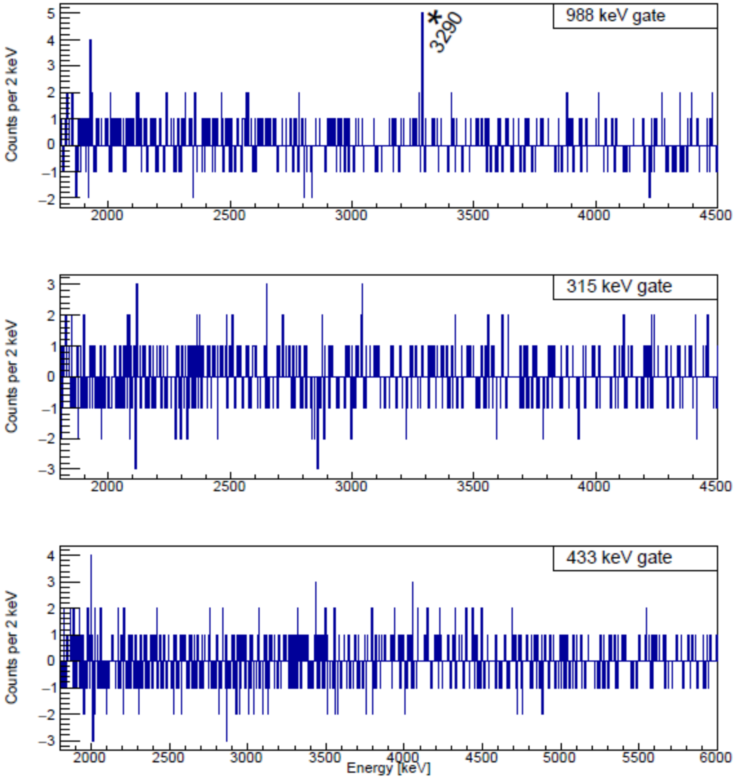
- Delivered at 0.7 pps

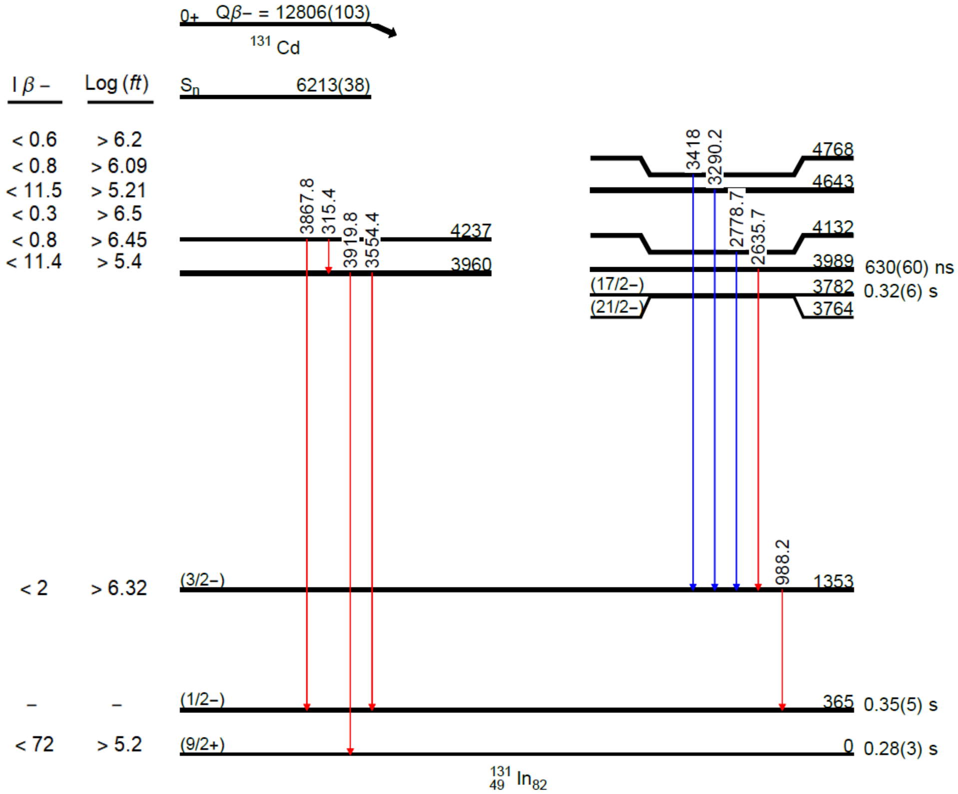
- Many transitions confirmed:
  5/7 (O. Arndt *et al.*, Acta Phys. Pol. B, 2009)
  21/23 (J. Taprogge *et al.*, Eur. Phys. J, 2016)

- One state in ^{130}In strongly populated by βn-decay



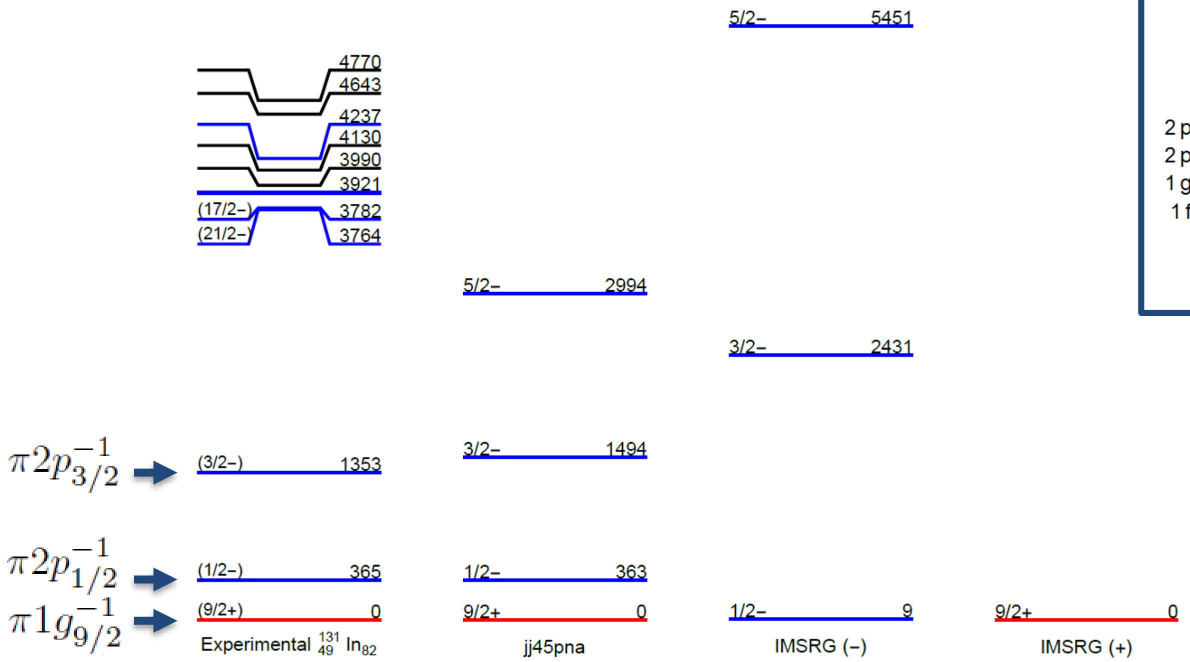
- Only one coincidence relationship observed
- 4 transitions placed based on energy differences

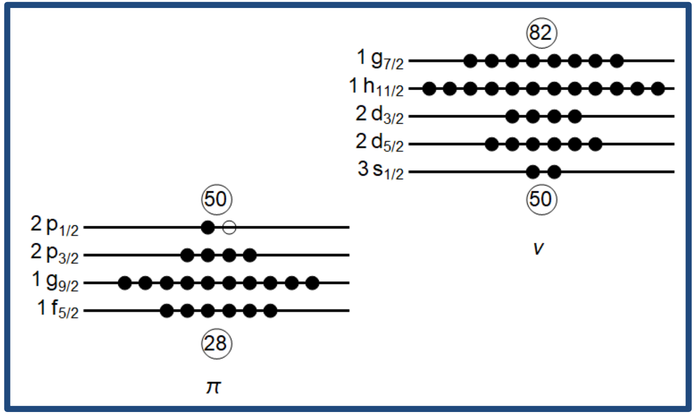




Shell model calculations for ^{131}In

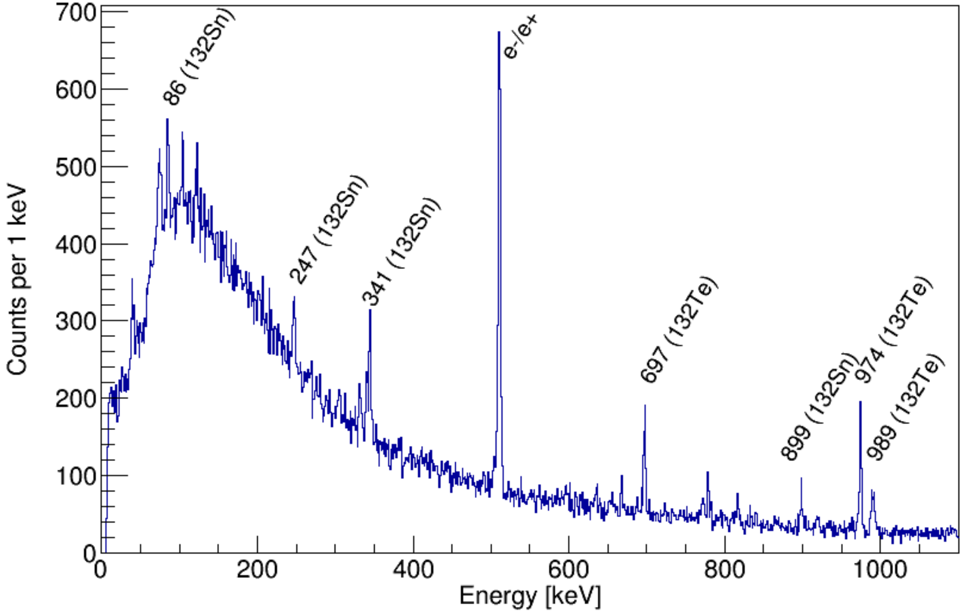
- **1 proton** away from double shell closure
- Only single-particle excited states can be calculated

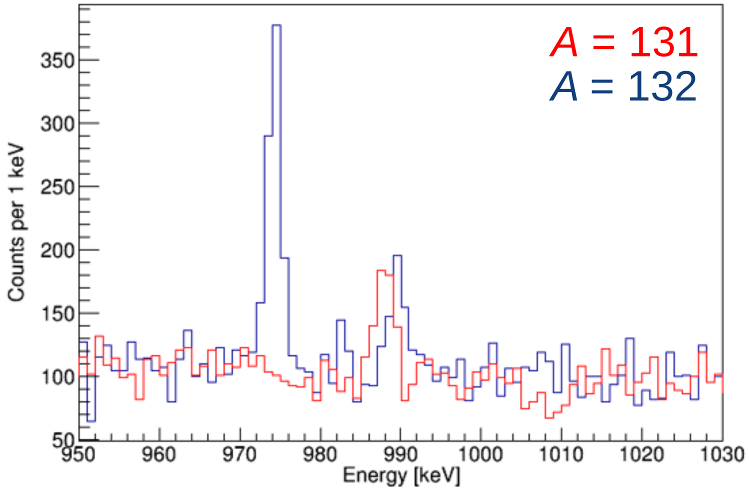




Valence space

- Very low neutron separation energy → large neutron branching ratio
    - **988 keV** transition expected in both $^{131-132}Cd$ datasets





Conclusions

Decay Spectroscopy of Neutron-Rich Cadmium Around the N = 82 Shell Closure

- ^{128}**In:** **32** new transitions and **11** new levels
- ^{131}**In:** **8** transitions placed and **8** levels
- ^{132}**Cd:** Higher yields and cleaner beams required

- Would not have been possible without the discriminating power of **IG-LIS**
- Important inputs for theoretical models of the *r*-process and the nuclear structure of exotic isotopes
- Understanding of nuclear forces and shell evolution in a region which only recently became accessible for more extensive studies!

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and accelerator-based science

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Thank you!

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