TRIUMF

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

Laboratoire national canadien de physique des particules, de physique nucléaire et de science fondée sur les accélérateurs

Nuclear Structure of Neutron-Rich Cadmium Around the *N* = 82 Shell Closure

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Seminarium fizyki jądra atomowego, Uniwersytet Warszawski

10 października 2024 r.

What are atoms made of?

How were the elements made?

What are atoms made of?

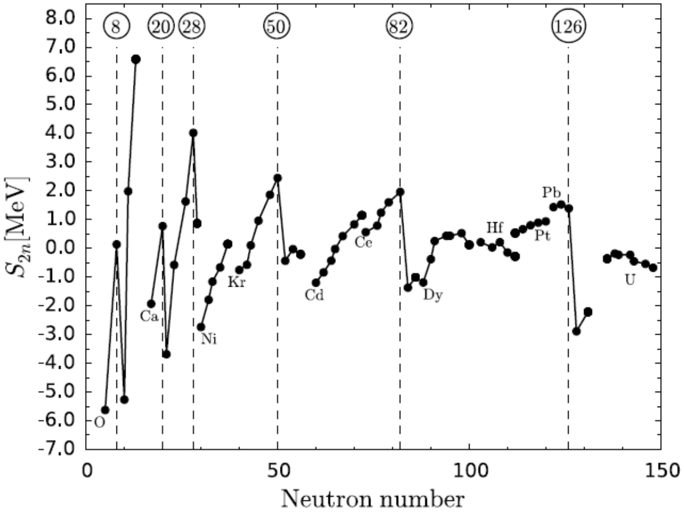
- 1949: Shell model of nuclear structure

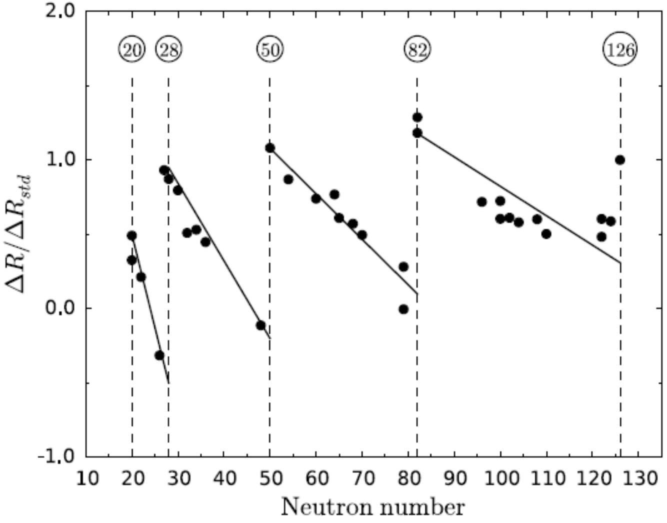
How were the elements made?

- 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

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

$$= H^0 + W_{RES}$$

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$$= H^0 + W_{RES}$$

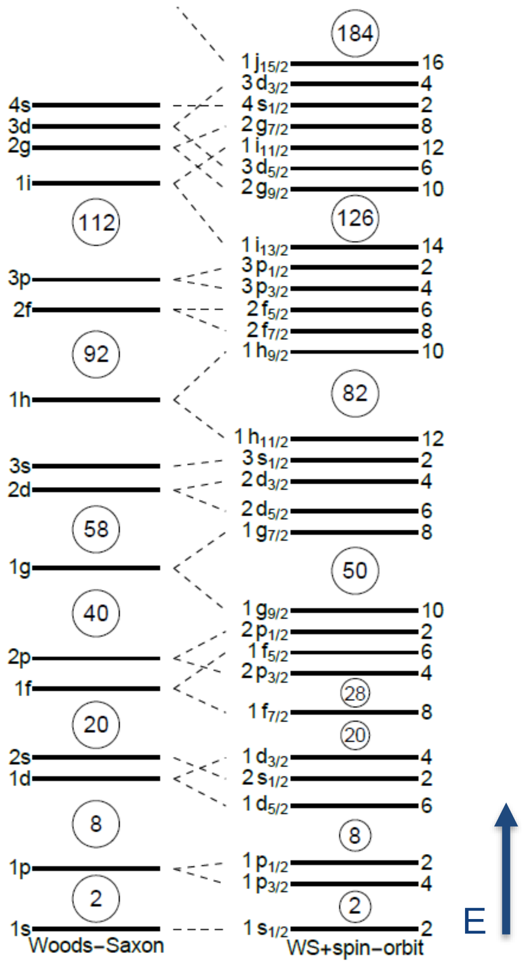
- ***W_{RES}* = 0**: Non-interacting shell model

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

  - 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



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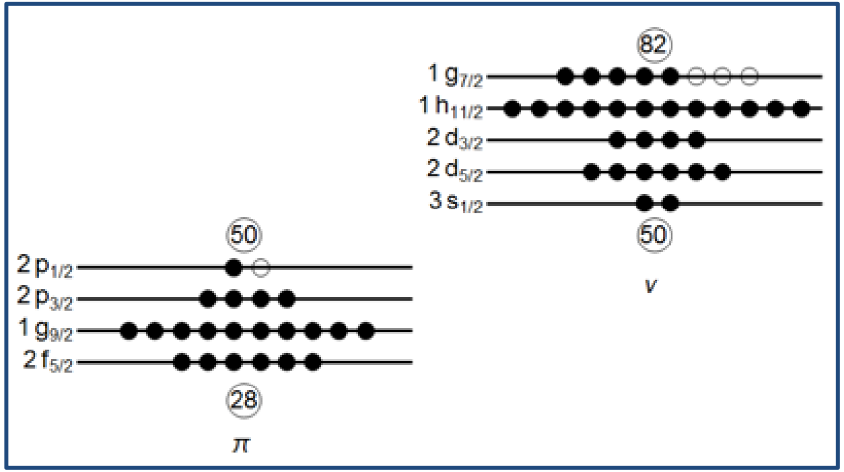
$$= H^0 + W_{RES}$$

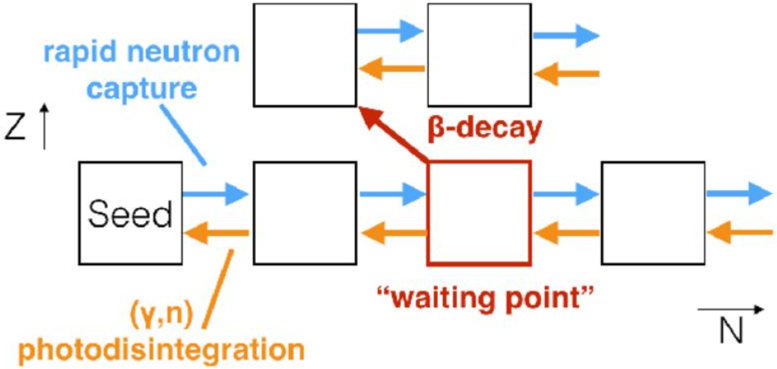
- ***W*** $_{RES}$ **≠ 0**: Interacting shell model
  - Configuration mixing
  - Effective two-body (NN) matrix elements

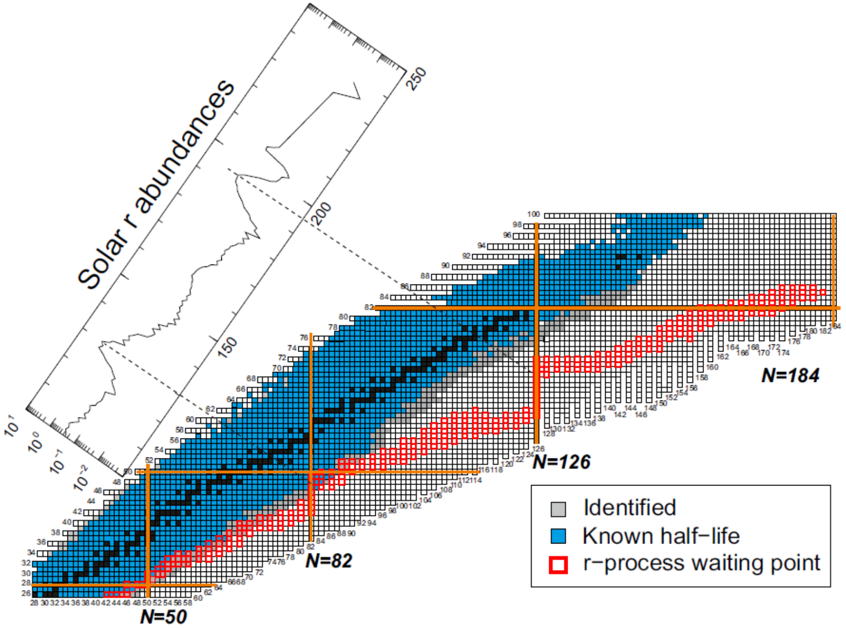
- Recent developments:
  - Chiral effective field theory (3N)
  - Ab initio methods (many-body)



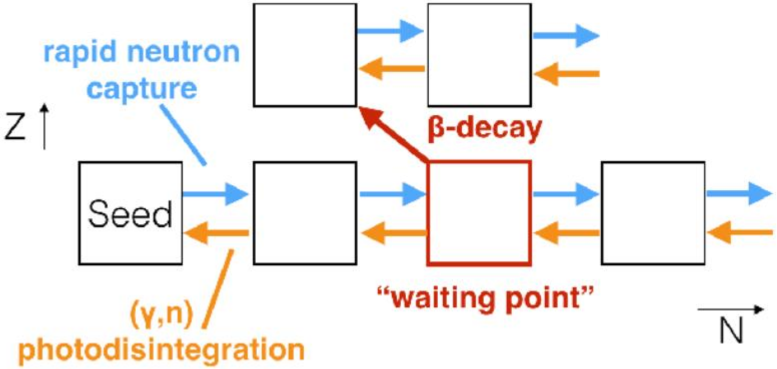
Valence space

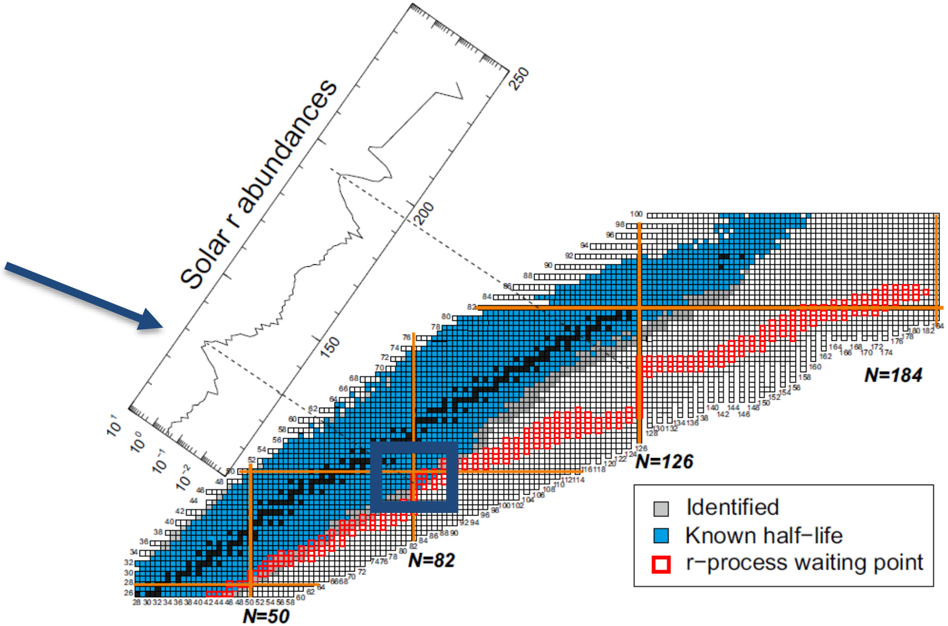
- pp-cycle and CNO-cycle up to ^{16}O, advanced burning up to ^{56}Fe
- Rapid neutron capture **(*r*-) process** path formed by **waiting point** nuclei, which create half of the nuclei heavier than ^{56}Fe





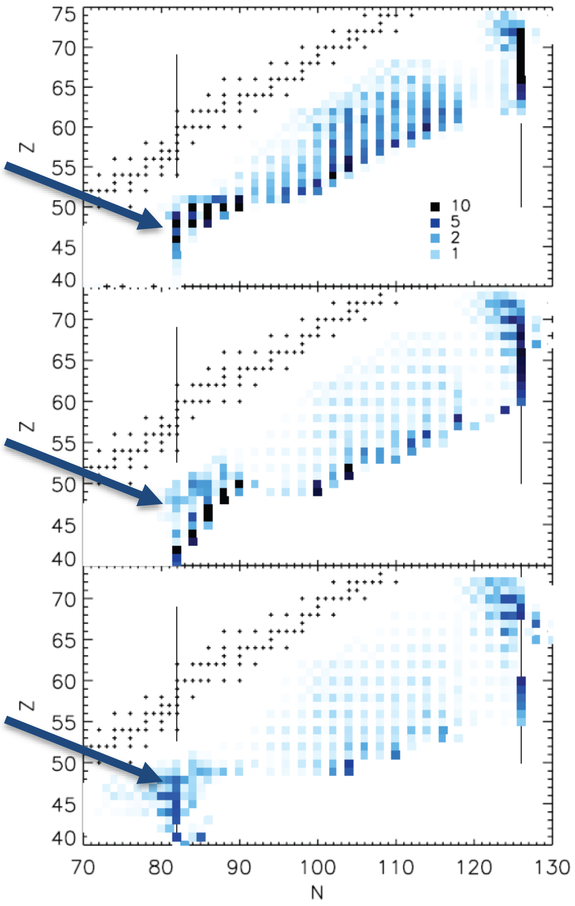
- pp-cycle and CNO-cycle up to ^{16}O, advanced burning up to ^{56}Fe
- Rapid neutron capture **(*r*-) process** path formed by **waiting point** nuclei, which create half of the nuclei heavier than ^{56}Fe
- *N = 82* isotope ^{130}Cd provides critical information on the **abundance peak** at *A* ~ 130.





- Hot and cold *r*-process winds from supernova explosion 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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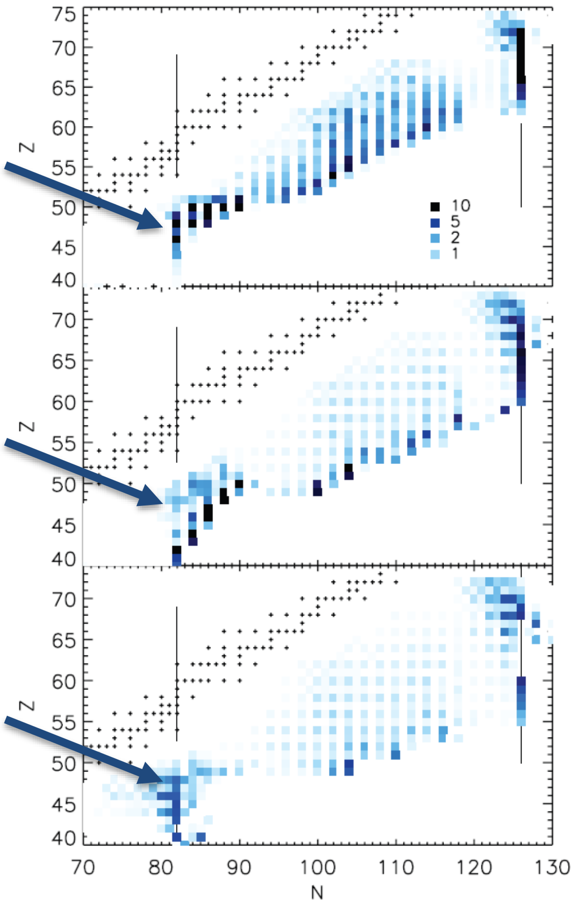
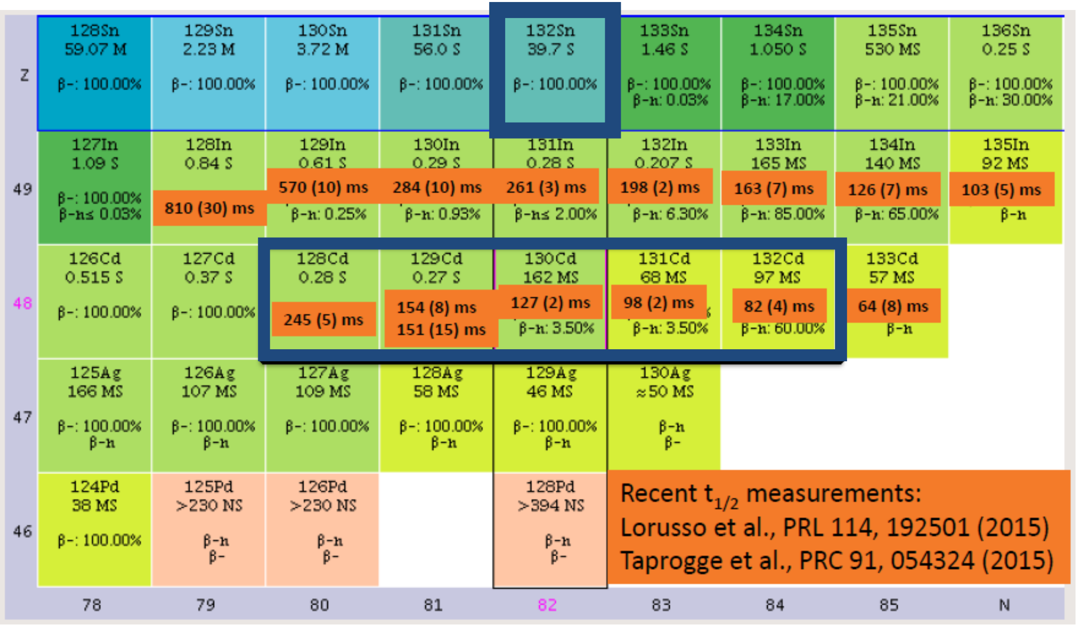
- Defining nuclear physics parameters
  - Masses, S_n, Q_β
  - β-decay lifetimes
  - β-delayed neutron emission probabilities rates
  - Shell structure far off stability



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

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



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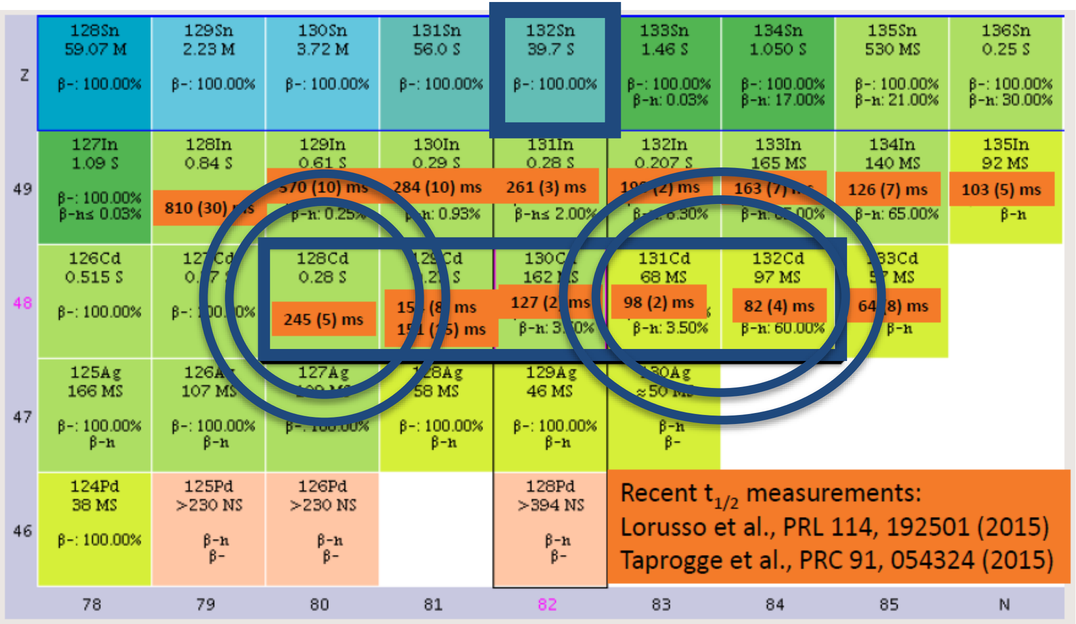
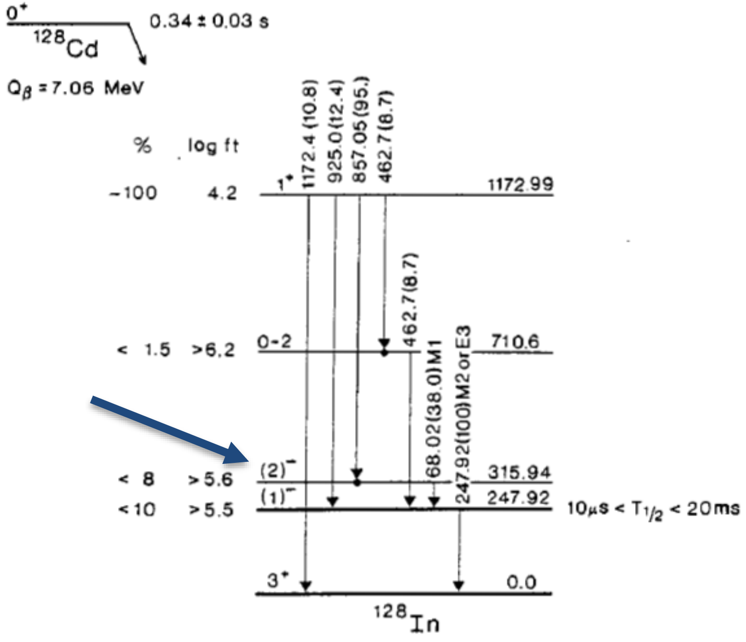


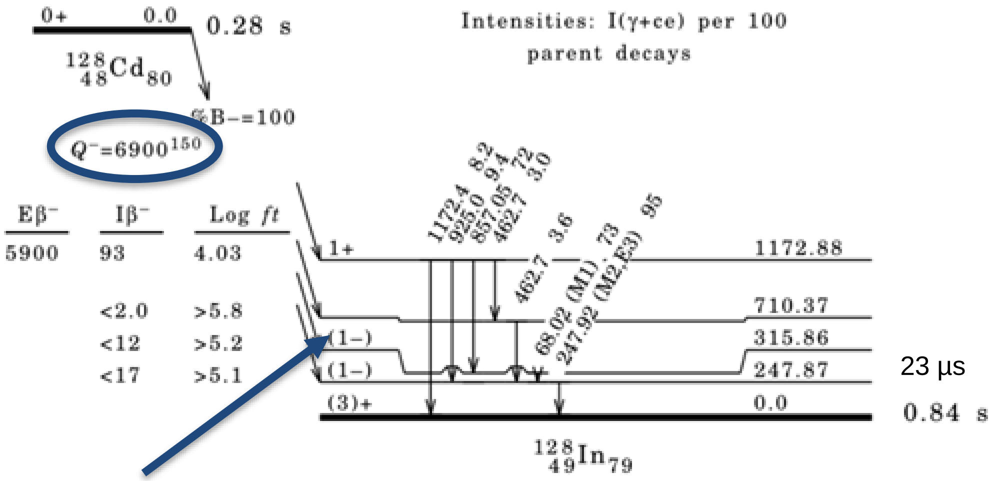
Previous work on ^{128}Cd

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

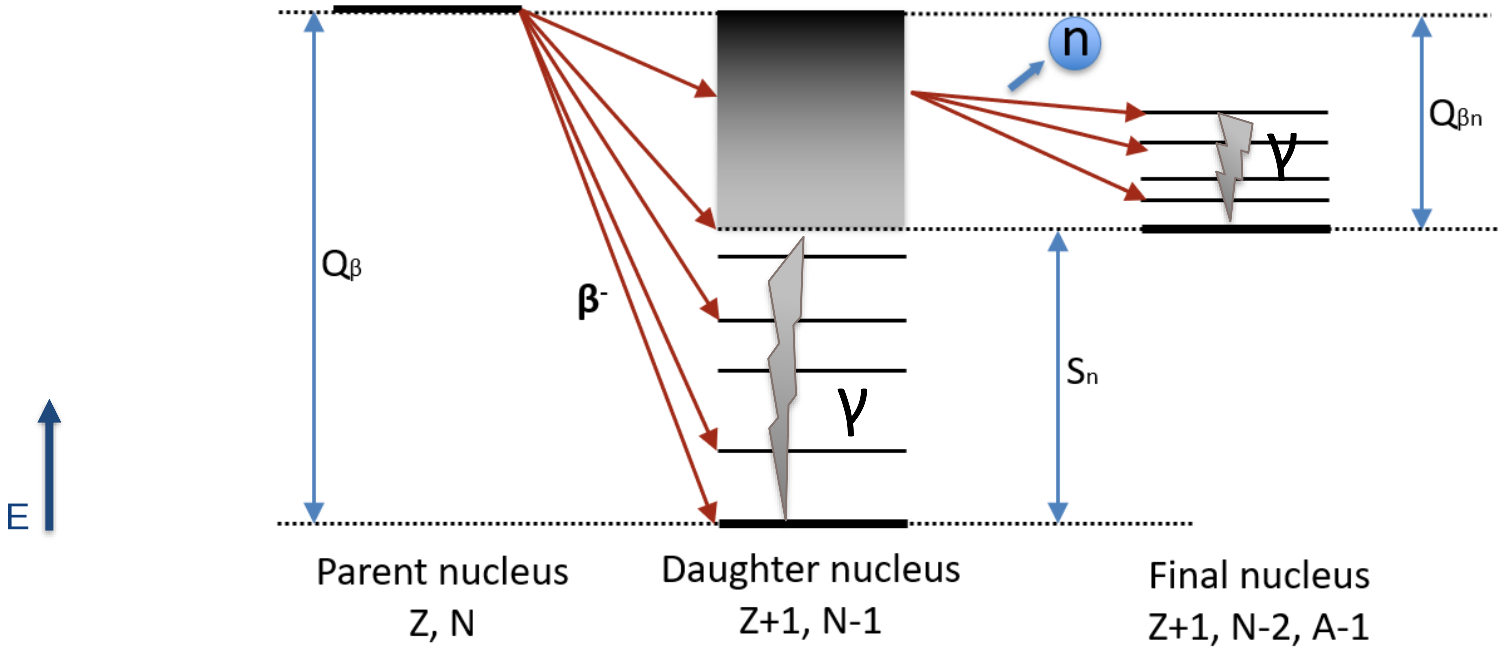


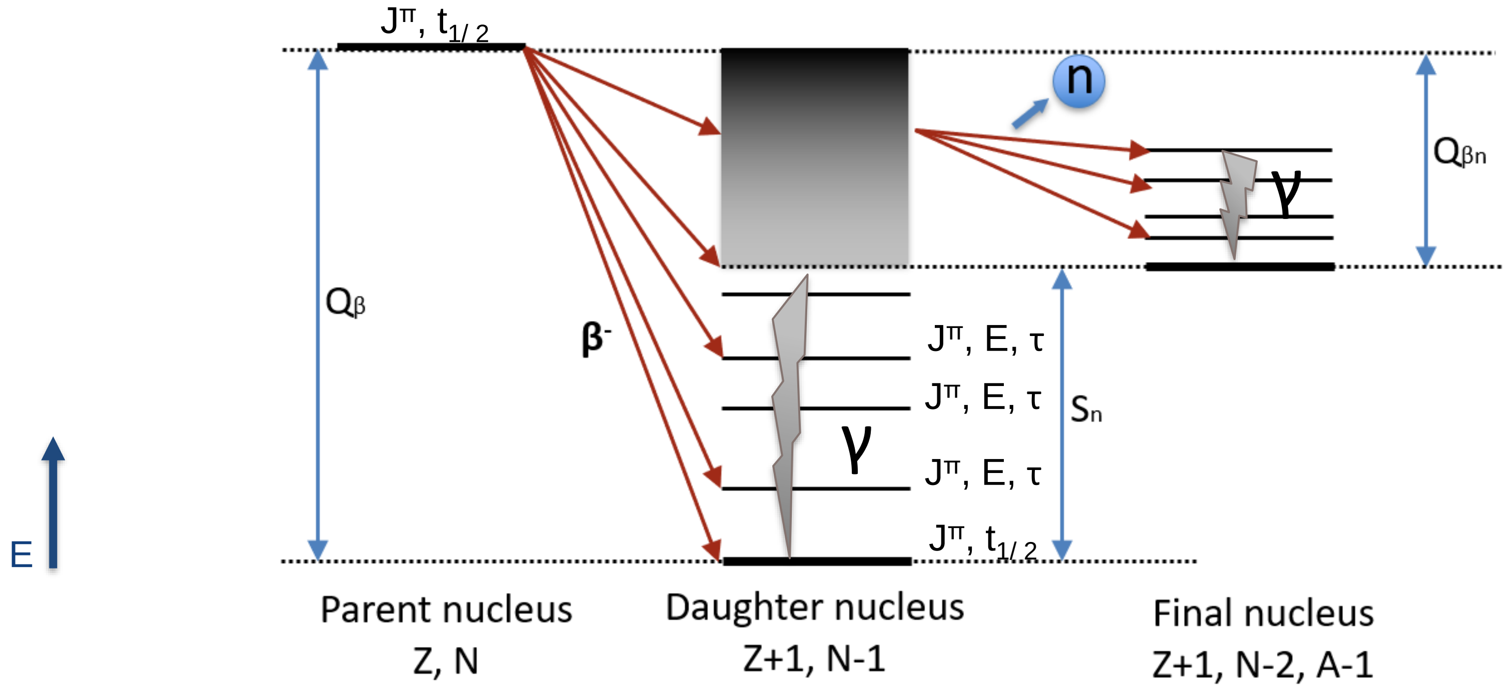
Work by B. Ekstrom quoted in
B. Fogelberg, Nucl. Data for Sc. and Tech., **837** (1988)

^{128}In S_n = 5320 (150) keV



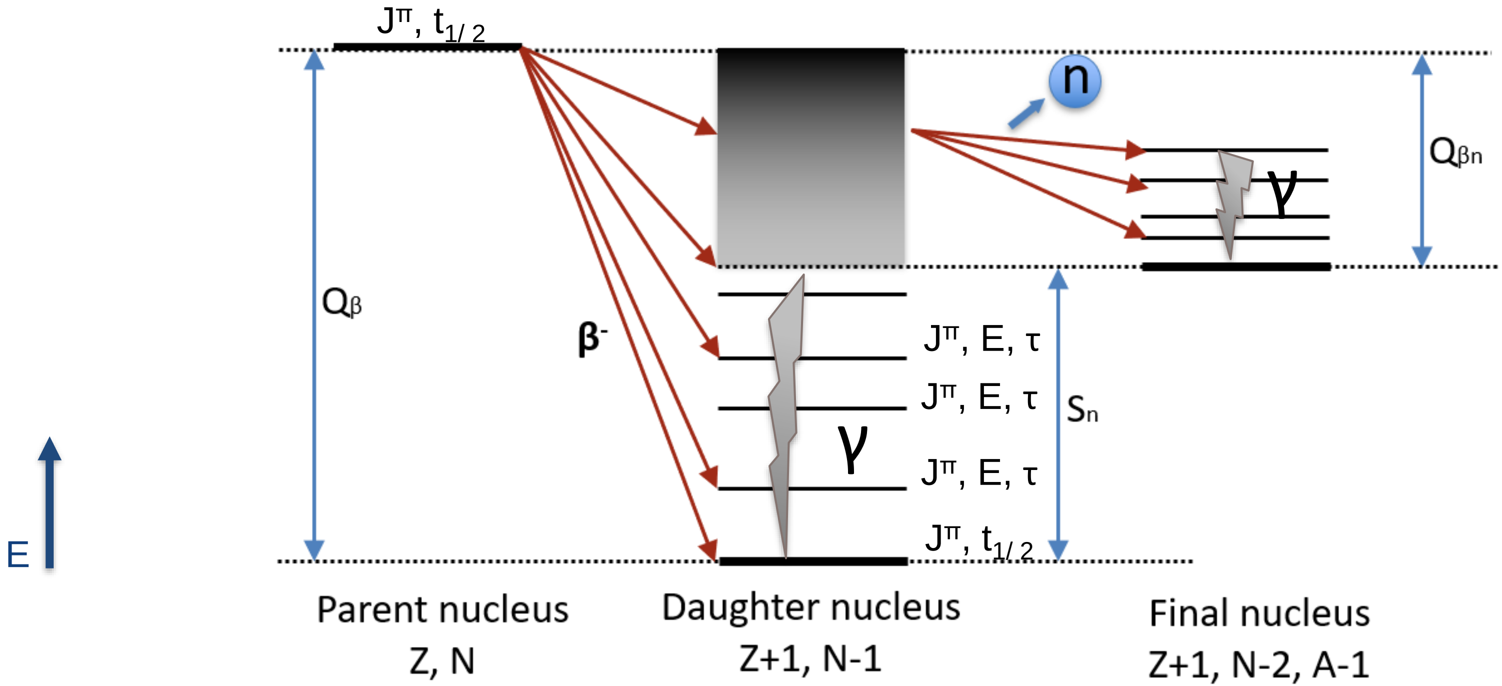
Z. Elekes and J. Timar, Nucl. Data Sheets **129**, 191 (2015)


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



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Selection rules of γ-decay

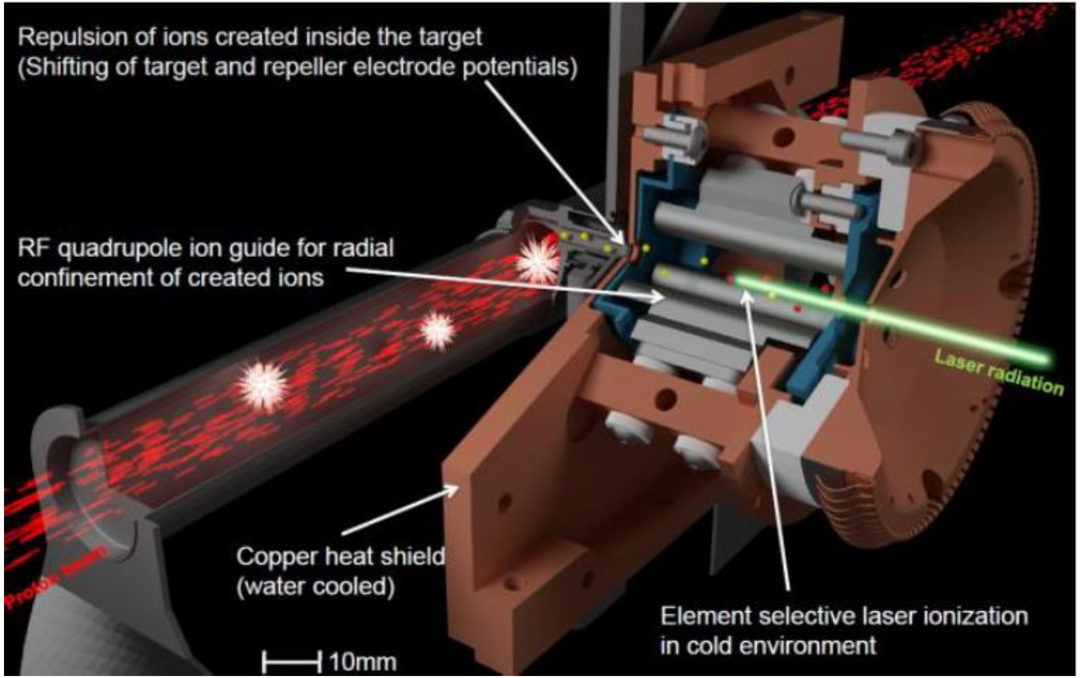
$$|J_i - J_f| \leqslant L \leqslant J_i + J_f$$

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

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

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

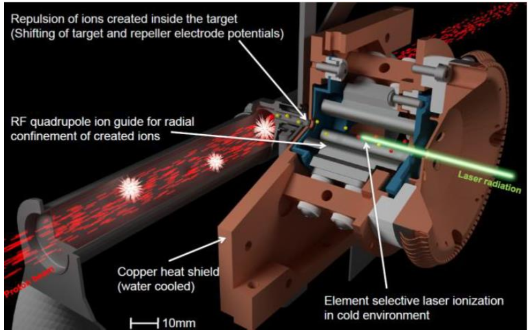
TRIUMF ISAC

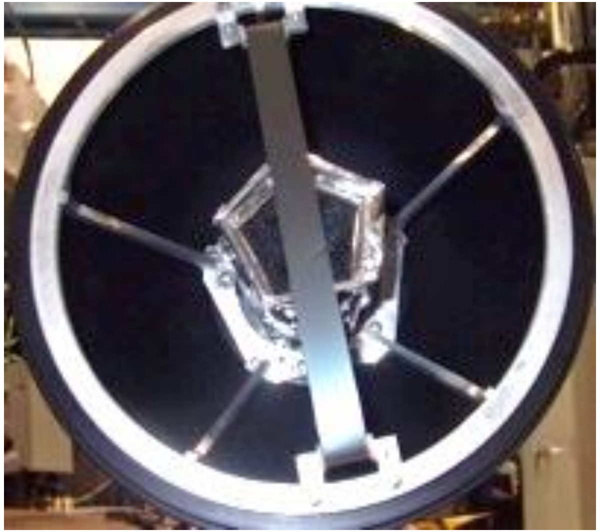


Neutron-rich Cd beams at TRIUMF

- 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





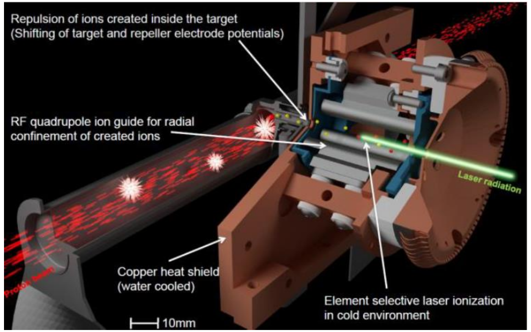
In-vacuum moving tape collector system

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



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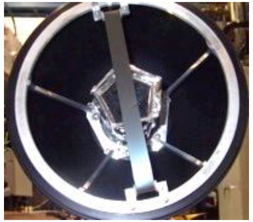

In-vacuum moving tape collector system

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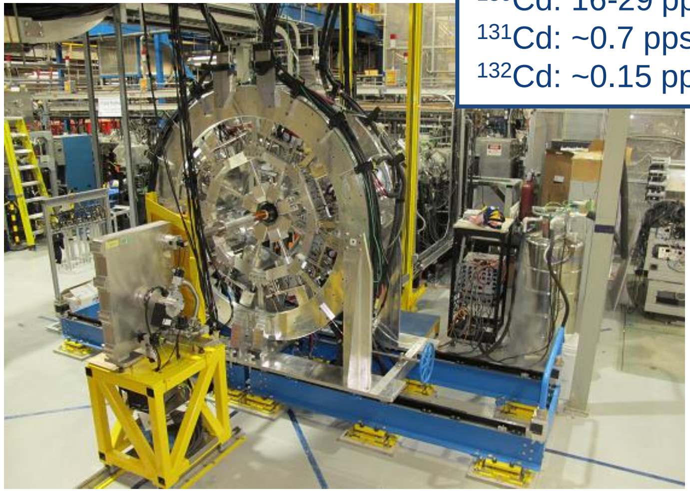
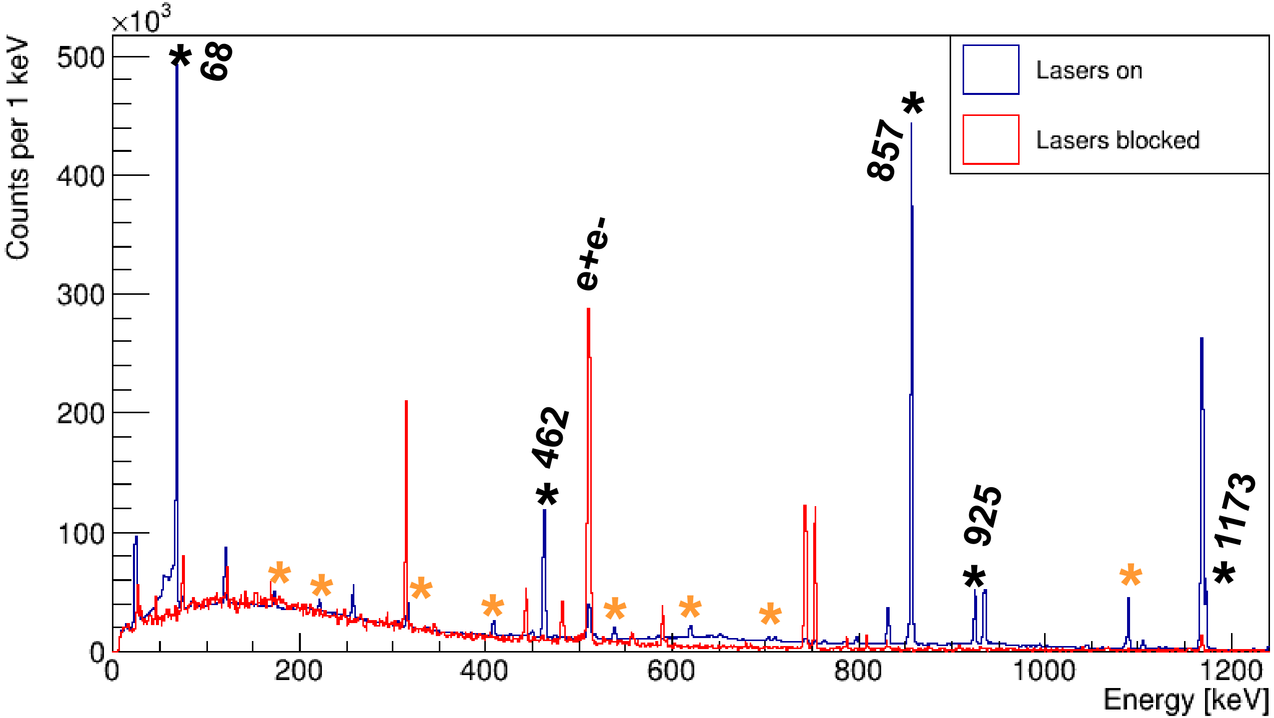


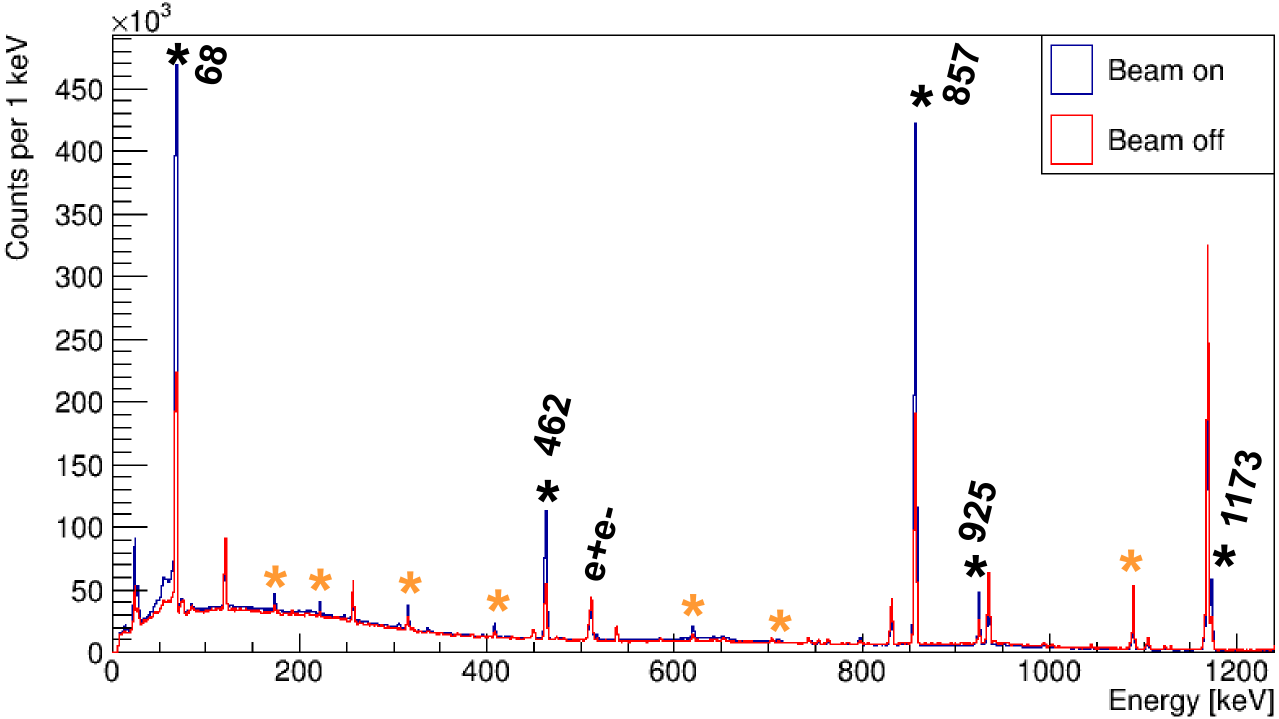
- Discrimination of **isobaric background** by comparing β-gated γ-singles laser **on** (Cd + In) and laser **blocked** (mostly In)



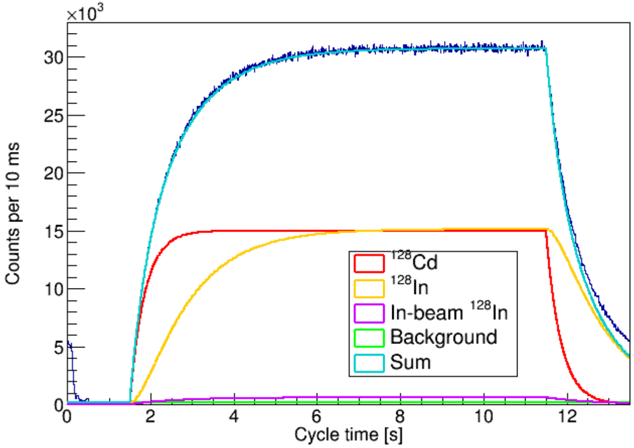
* ***Known*** **^{128}Cd→^{128}In**

* ***New*** **^{128}Cd→^{128}In**

- Discrimination of **decaying daughters** by comparing beam **on** data (Cd + In) and beam **off** data (mostly In)

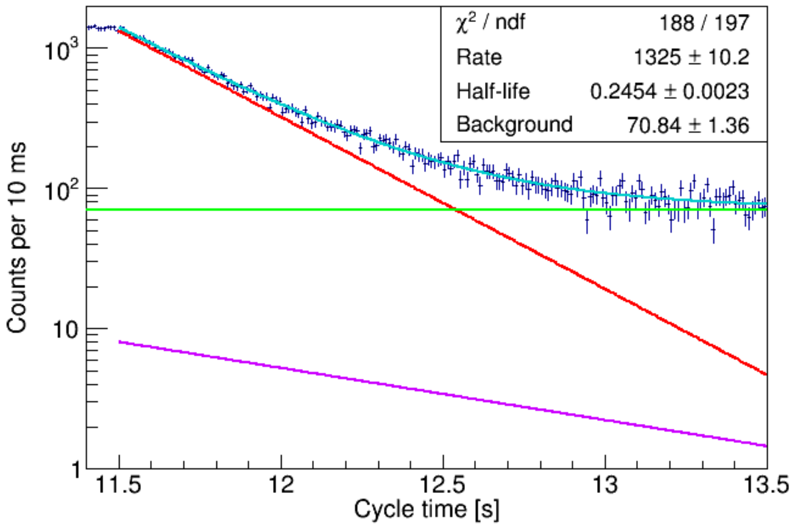


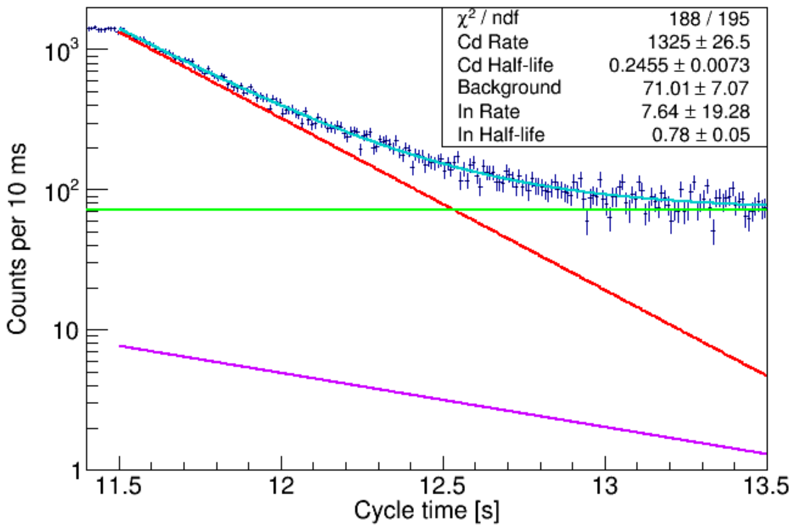
^{128}Cd $t_{1/2}$ = 245 (5) ms
^{128}In $t_{1/2}$ = 810 (30) ms



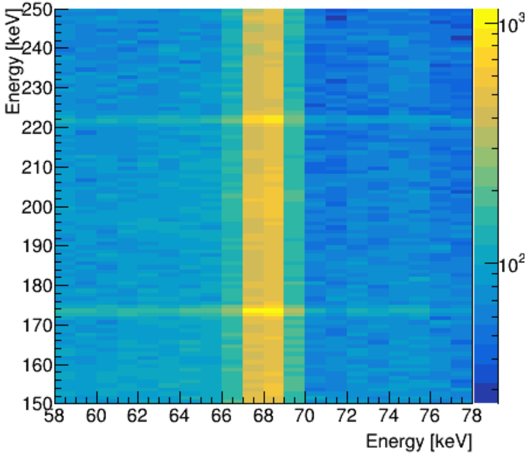
- Sum of 857 and 925-keV transitions
- Agrees with 245(5) ms (G. Lurosso *et al.*, PRL, 2015)
  and 246.2(21) ms (R. Dunlop *et al.*, PRCr, 2016)

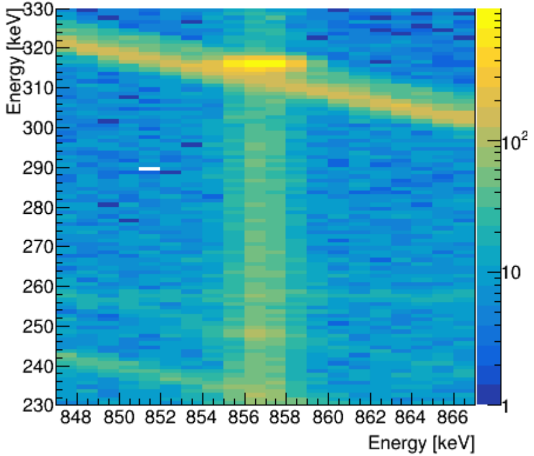
$$A_{total}(t) = Ae^{-\ln 2 \cdot t/t_{1/2,parent}} + Be^{-\ln 2 \cdot t/t_{1/2,daughter}} + C$$





β-γ-γ coincidence





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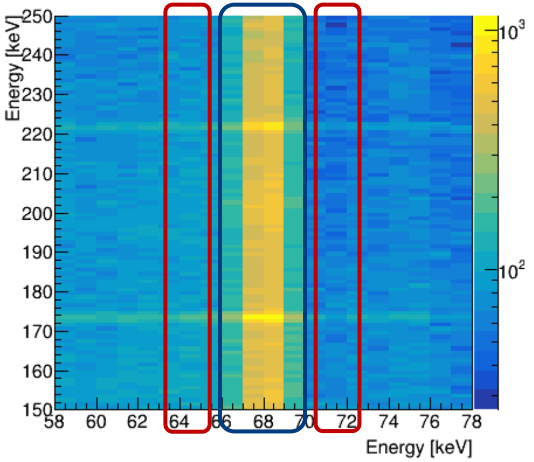
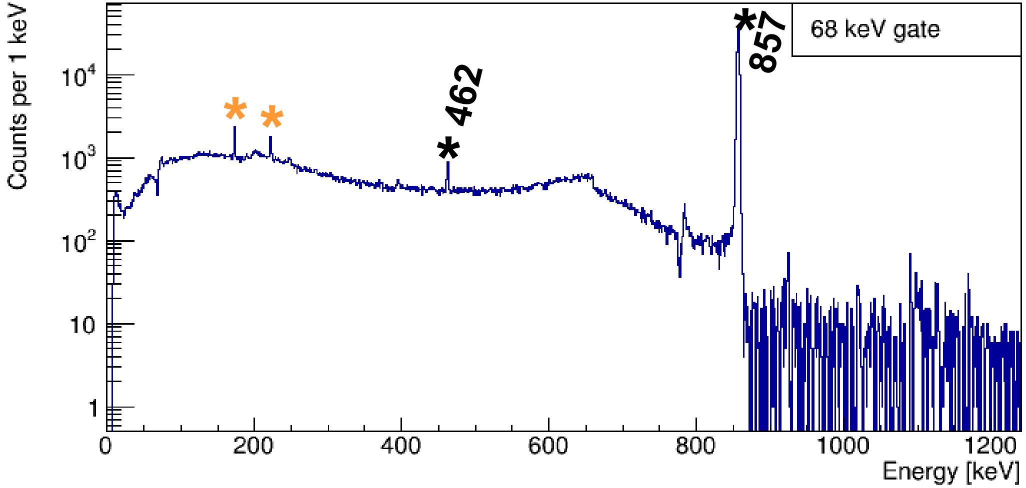
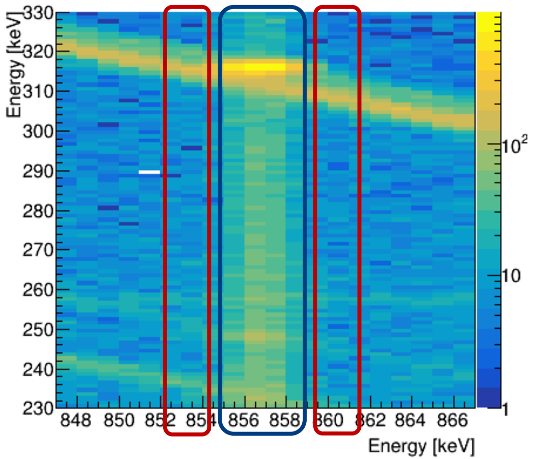
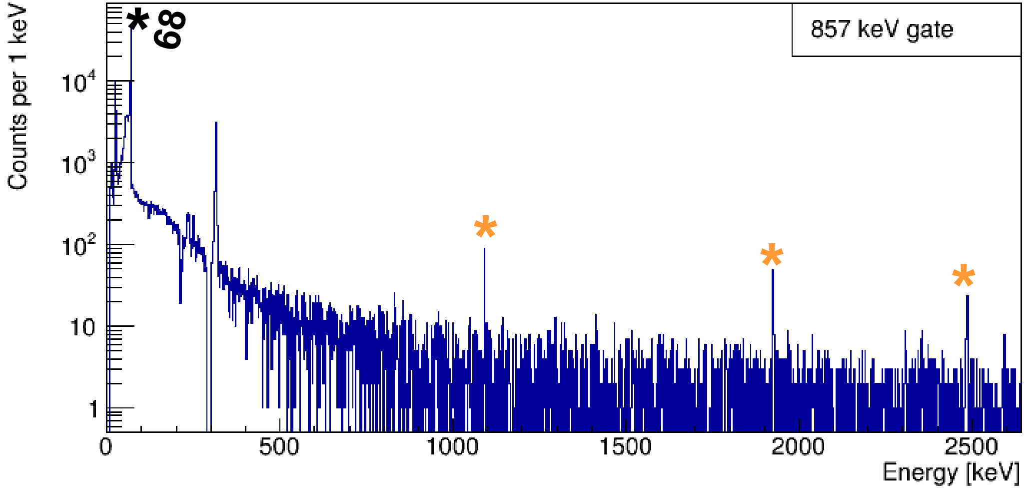


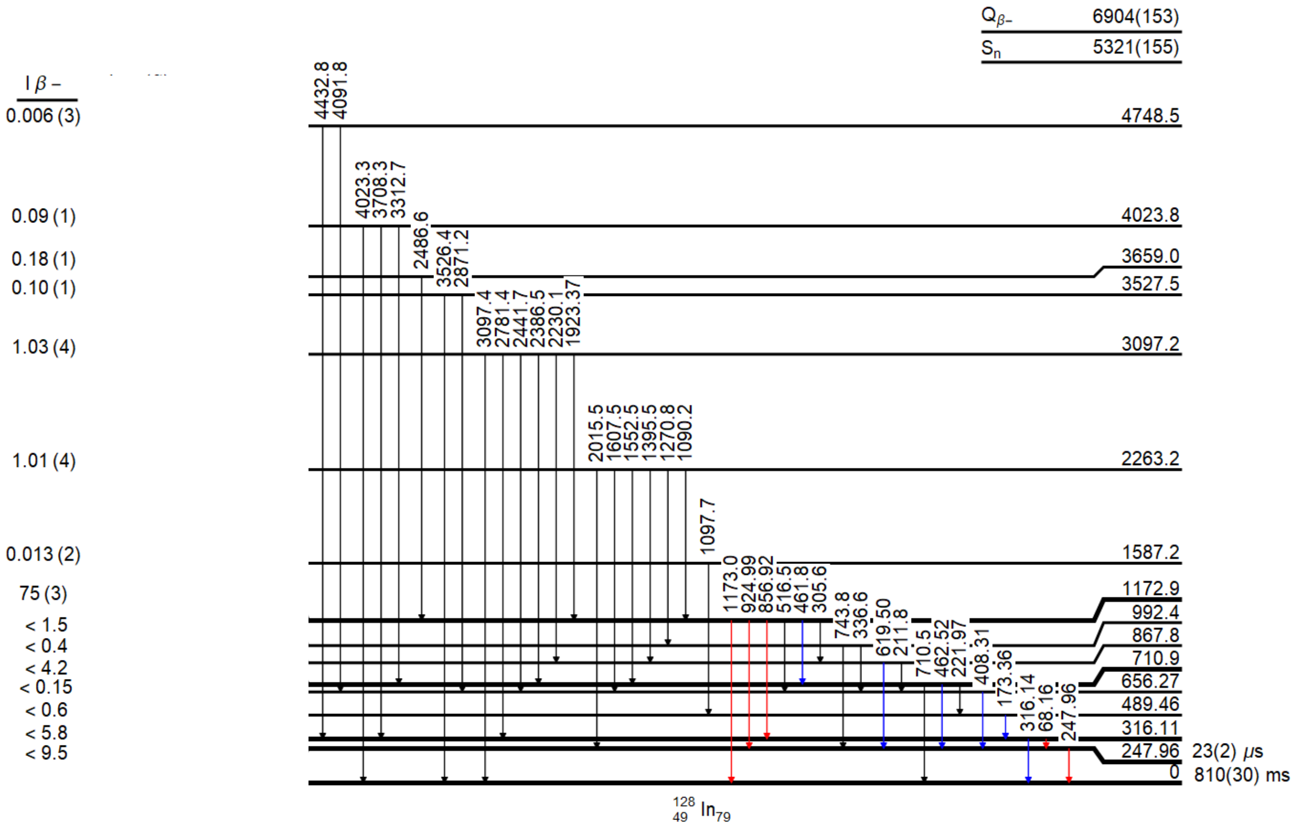






Decay scheme of ^{128}Cd

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



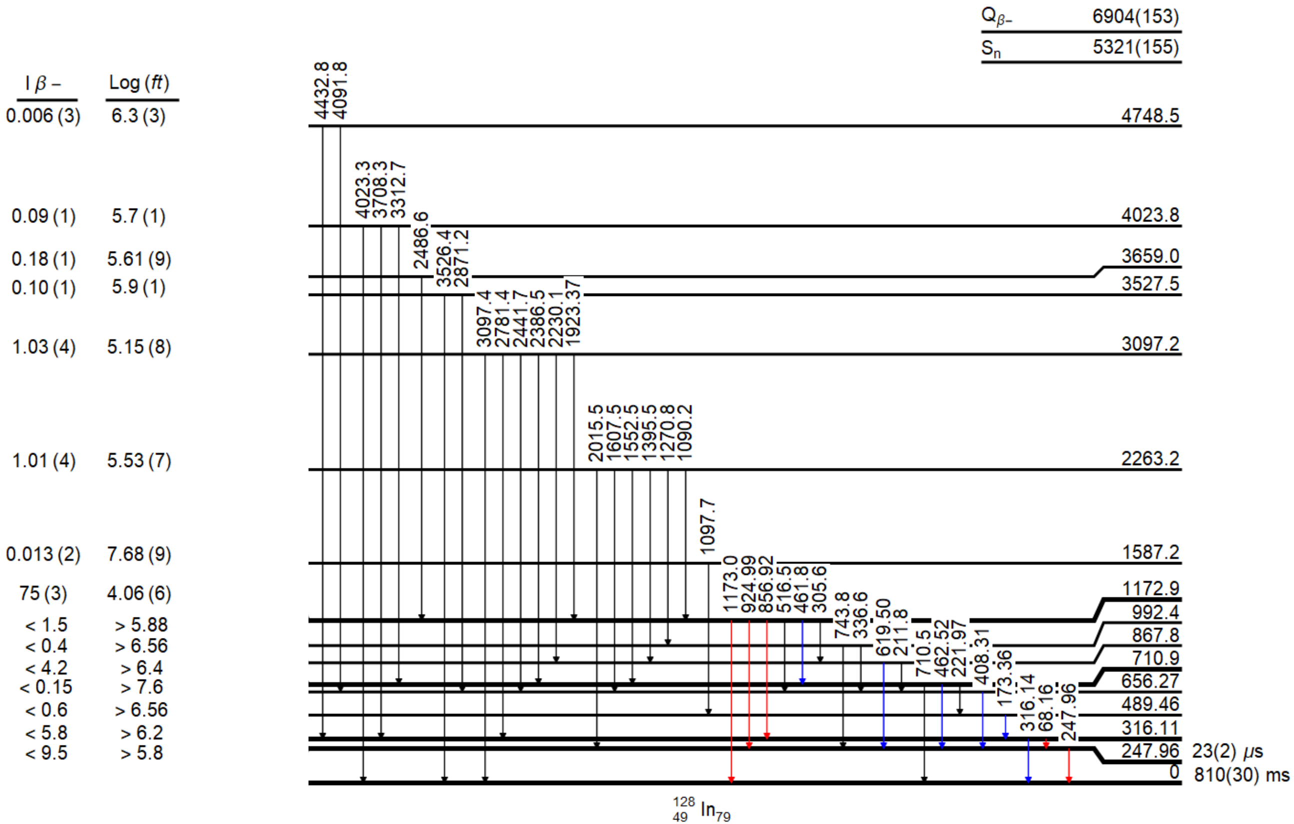
- 32 **new** transitions and 11 **new** states

$$ft = \frac{f(Q_\beta - E_f, Z)T_{1/2}}{I_\beta(E_f)}$$

$$= \frac{k}{g_V^2 B(\mathrm{F}) + g_A^2 B(\mathrm{GT})}$$

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

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



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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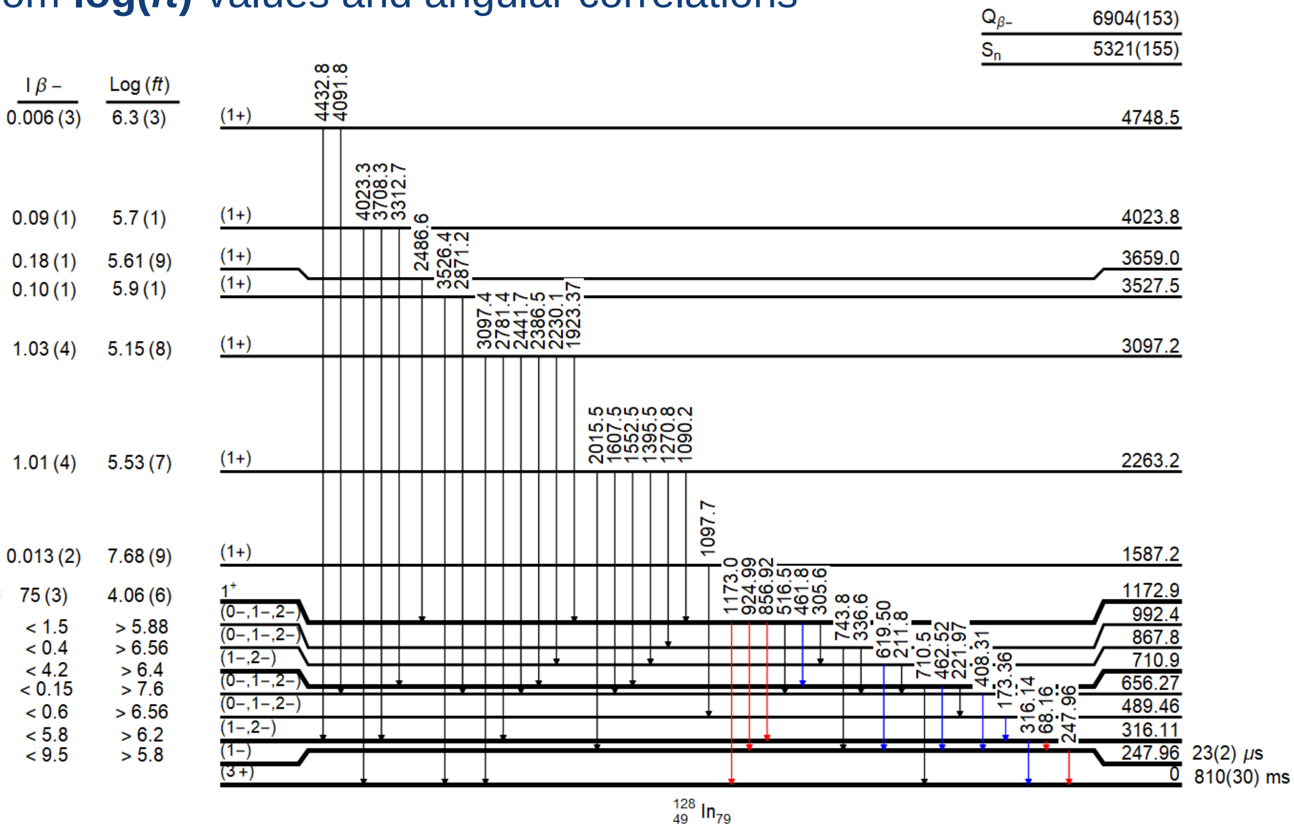
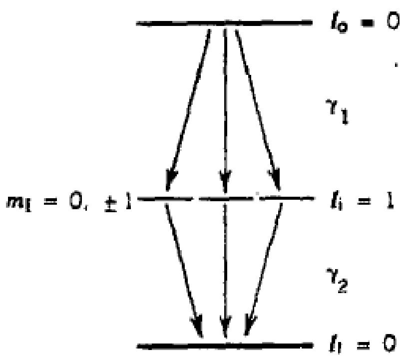
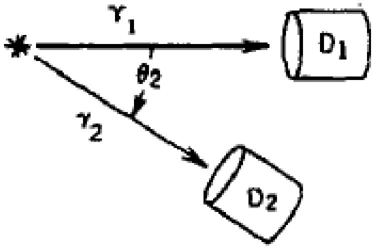


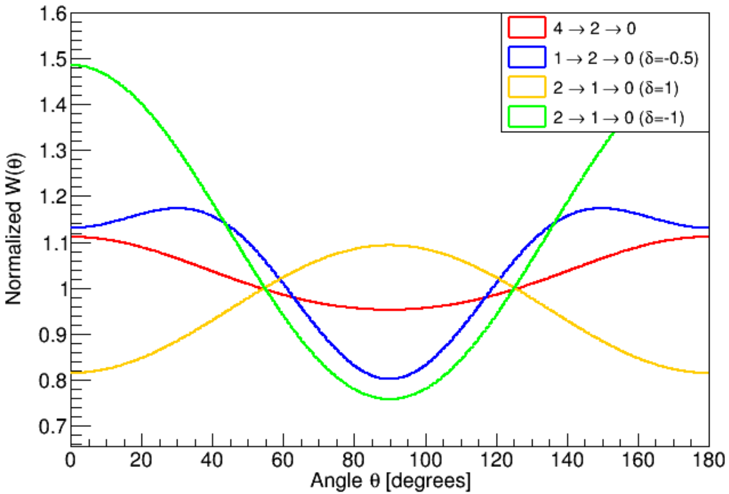
For two γ's in coincidence:

- Uneven population of *m*-substates with respect to the axis of the other γ
- Information on transition **characters** and **mixing ratios** can be extracted by measuring the angular distribution of both γ's as a function of the **angle between the detectors** which detected them:

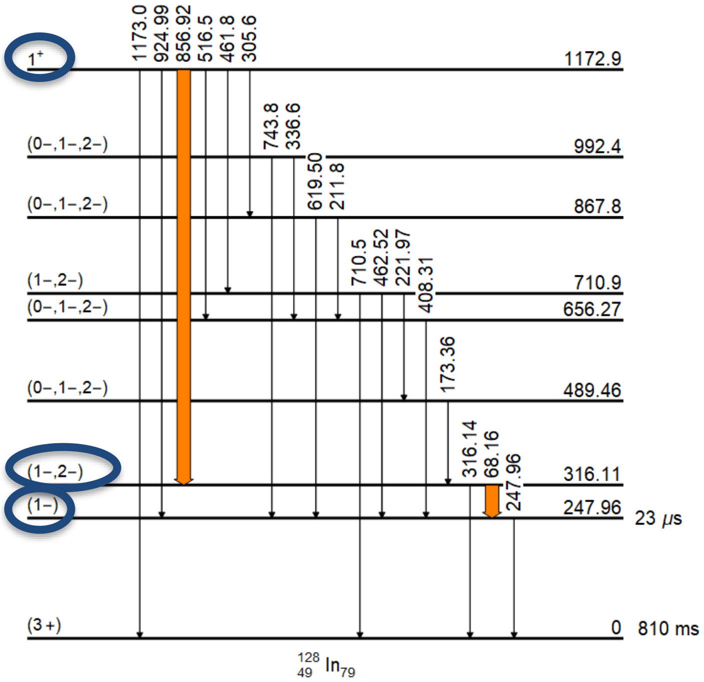
$$W(\theta) = A_0[1 + a_{22}P_2(\cos\theta) + a_{44}P_4(\cos\theta)]$$

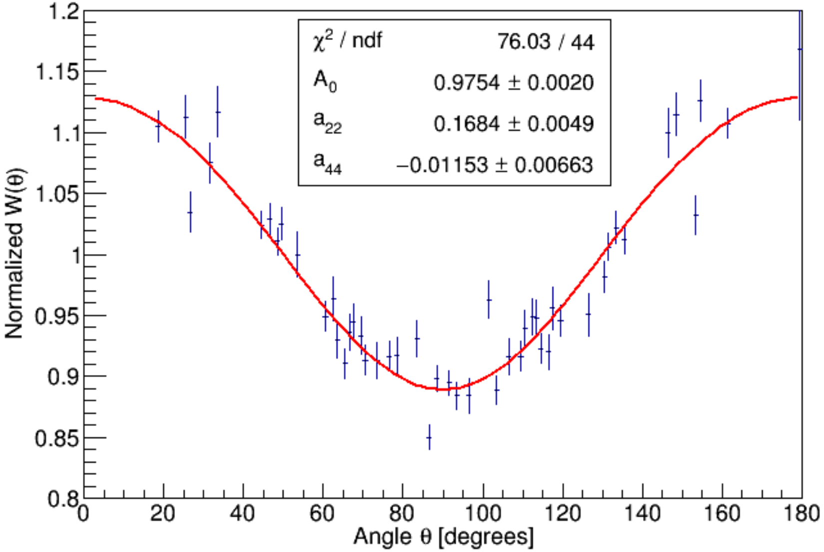






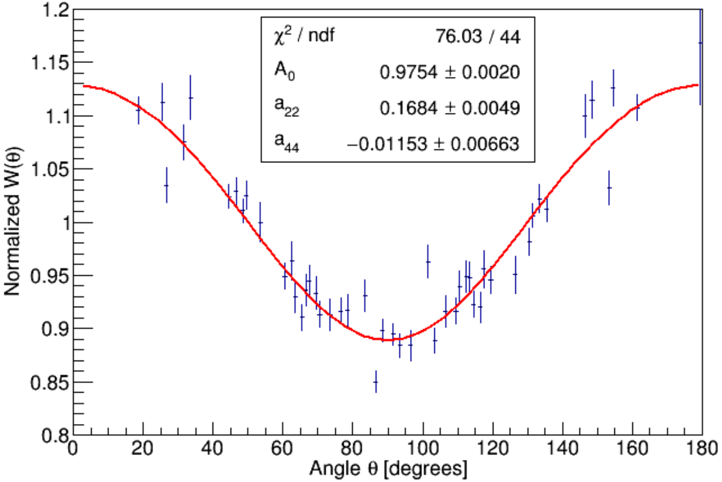
Angular correlations in ^{128}In



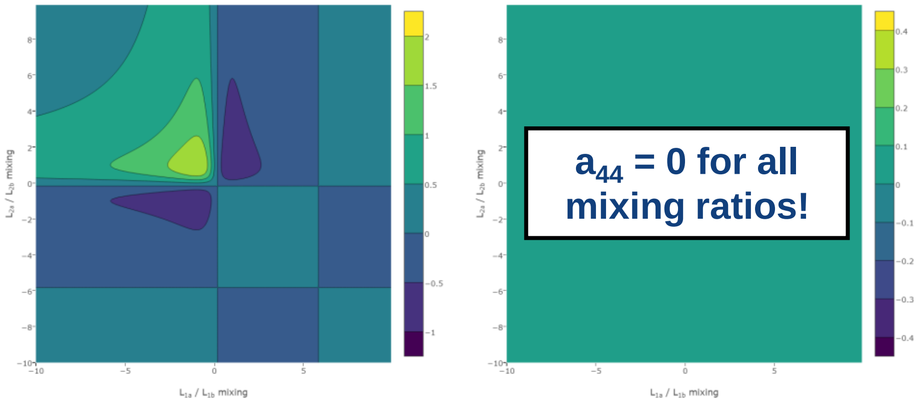


1→1→1 or 1→2→1 ?

- Two mixing ratios mean many a_{22}/a_{44} possibilities
- Solution: Fix one mixing ratio at a time and hope that possibilities do not overlap for different spins
- Here: The cascades could be distinguished for
  $-0.92 > a_{22} > 0.82$ **and** for $a_{44} \neq 0$.

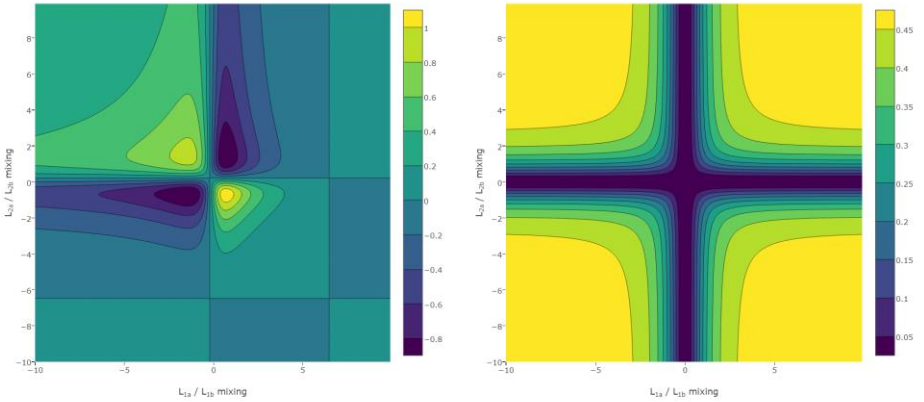


1 → 1 → 1



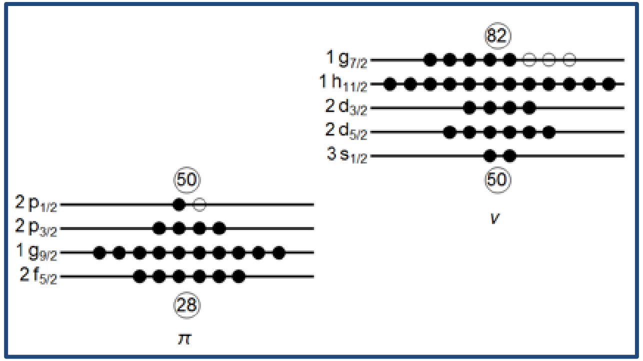
a_{44} = 0 for all mixing ratios!

1 → 2 → 1

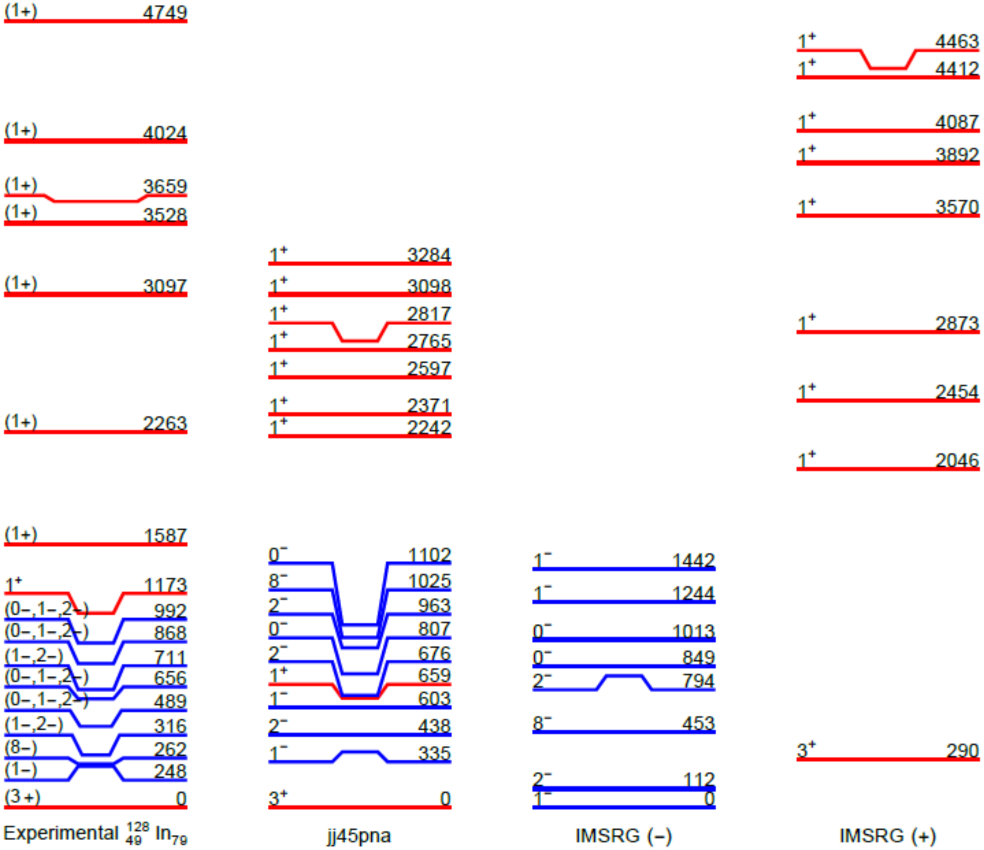


Shell model calculations for ^{128}In

- *jj45pna* interaction: jj-coupling, 4*π*-5*ν* orbitals, proton-neutron coupling
  - B.A. Brown and W.D.M. Rae, Nucl. Data Sheets 120, 115 (2014).
- Ab initio valence-space formulation of In-Medium Similarity Renormalization Group (VS-IMSRG)
  - S.R. Stroberg et al., Annu. Rev. Nucl. Part. Sci. 69, 307 (2019).

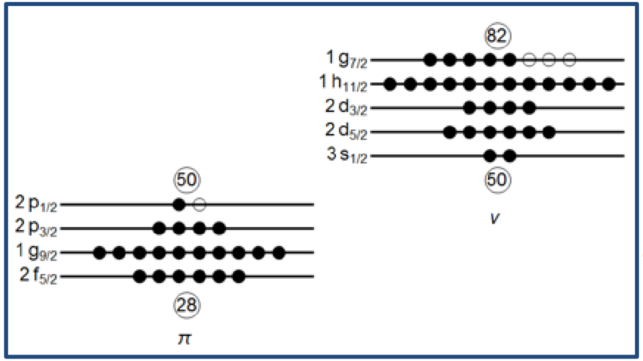


Valence space



Shell model calculations for ^{128}In

- *jj45pna* interaction: jj-coupling, 4*π*-5*ν* orbitals, proton-neutron coupling
  - B.A. Brown and W.D.M. Rae, Nucl. Data Sheets 120, 115 (2014).
- Ab initio valence-space formulation of In-Medium Similarity Renormalization Group (VS-IMSRG)
  - S.R. Stroberg et al., Annu. Rev. Nucl. Part. Sci. 69, 307 (2019).

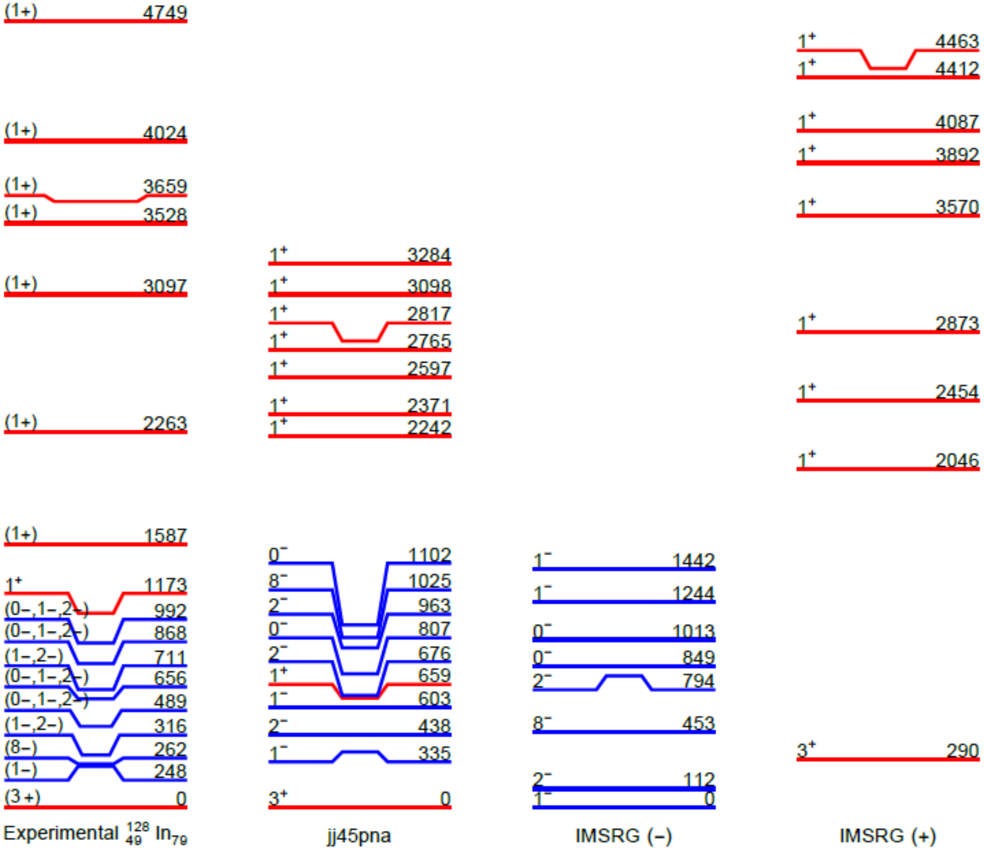


Valence space

$\pi g_{9/2}^{-1} \otimes \nu g_{7/2}^{-1}$

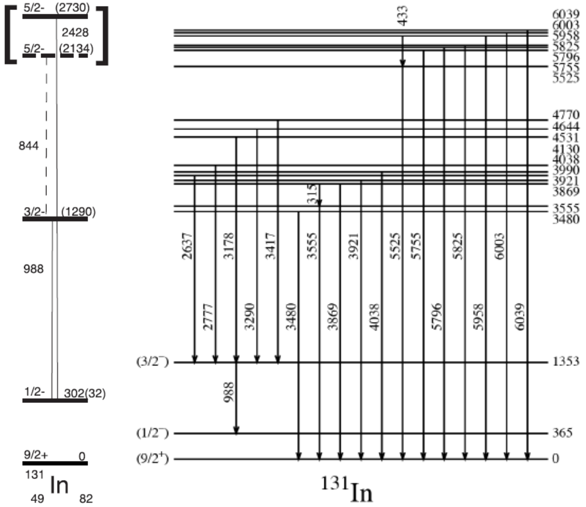
$\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{-1}$

$\pi g_{9/2}^{-1} \otimes \nu d_{3/2}^{-1}$



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

^{131}Cd $Q(\beta^-)$ = 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)

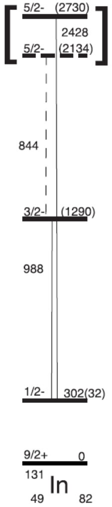
J. Taprogge *et al.*, Eur. Phys. J. A **52**, 347 (2016)

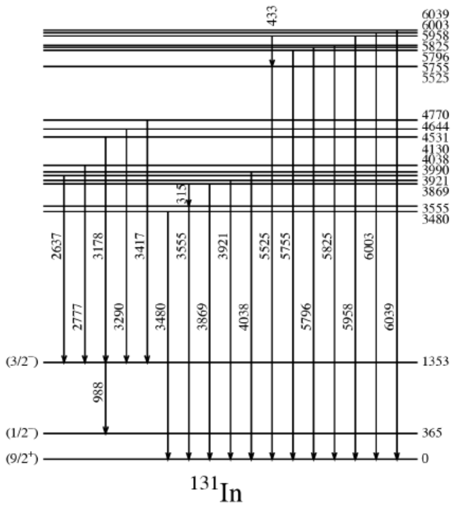
Previous work on $^{131\text{-}132}$Cd

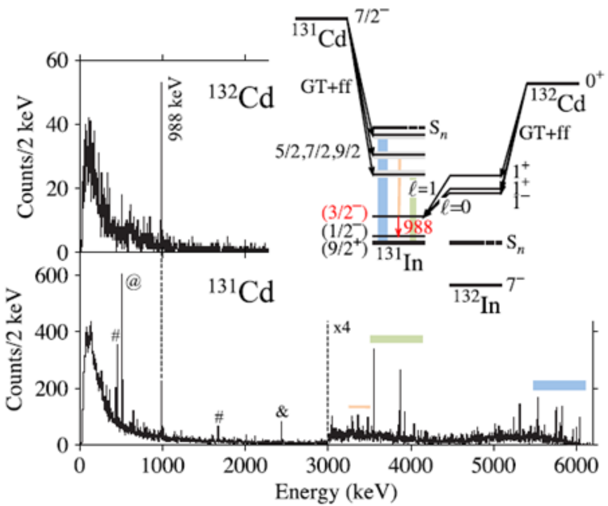
- **7** transitions observed in ^{131}In at ISOLDE, **23** at RIKEN: only **4** transitions in common
- No γ-transitions observed from the β-decay of ^{132}Cd to ^{132}In.

^{131}Cd $Q(\beta^-)$ = 12700 (510) keV
^{131}In S_n = 6210 (40) keV

^{132}Cd $Q(\beta^-)$ = 12150 (510) keV
^{132}In S_n = 2450 (60) keV







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

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

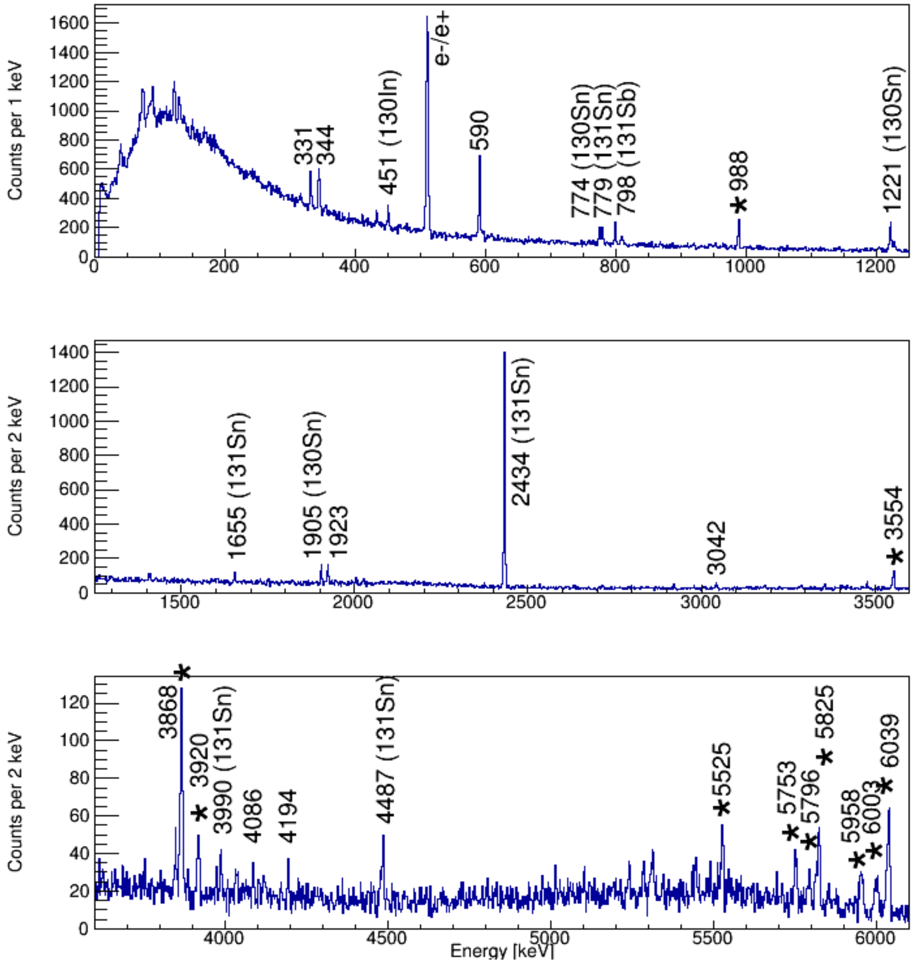
J. Taprogge *et al.*, Eur. Phys. J. A **52**, 347 (2016)

β-decay of ^{131}Cd

- Delivered at 0.7 pps

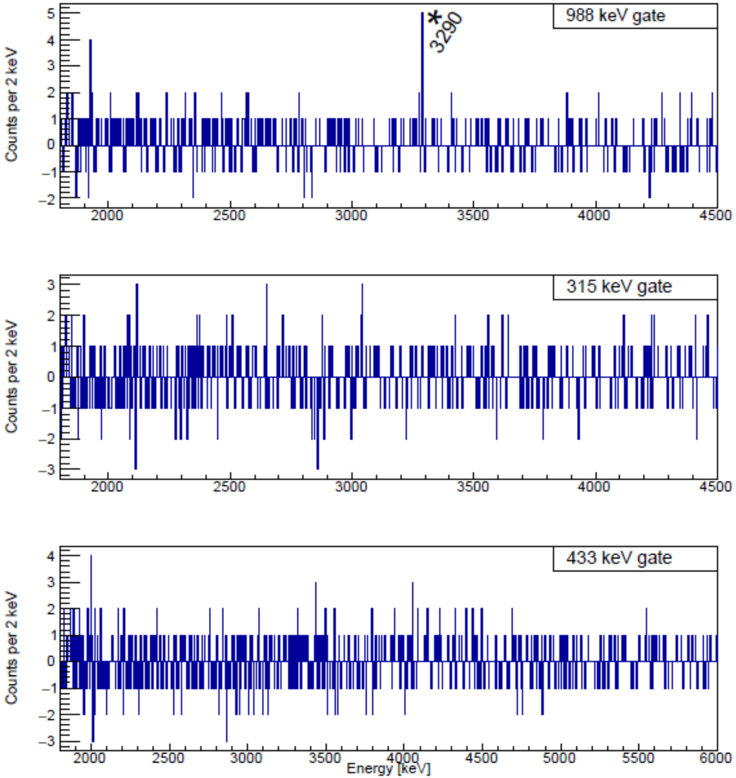
- Many transitions confirmed:
  5/7 (O. Arndt *et al.*, Acta Phys. Pol. B, 2009)
  21/23 (J. Taprogge *et al.*, Eur. Phys. J, 2016)

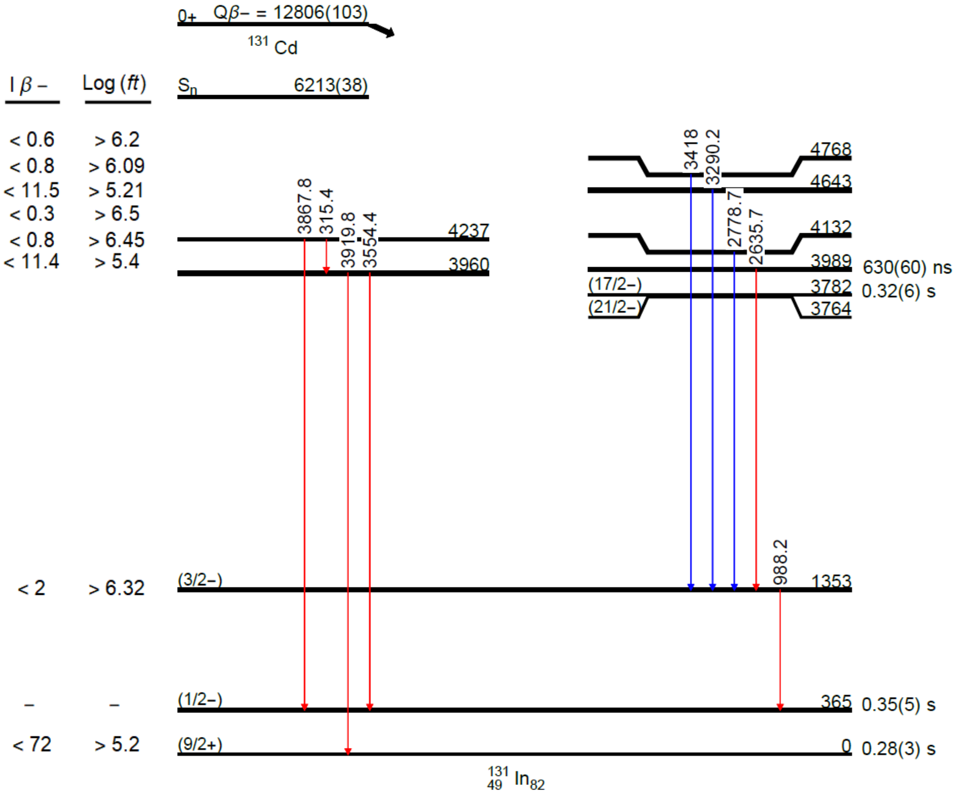
- One state in ^{130}In strongly populated by βn-decay



Decay scheme of ^{131}Cd

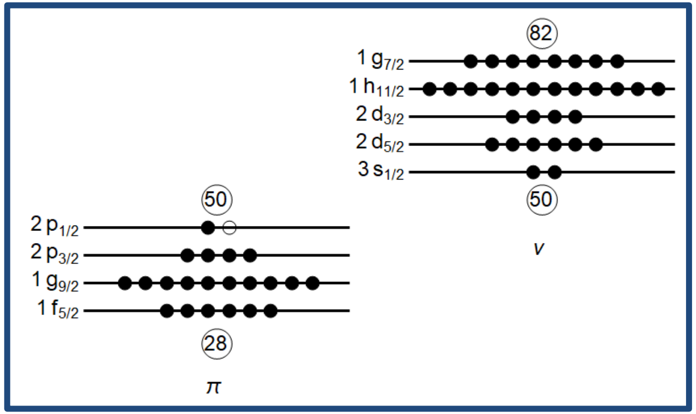
- Only one coincidence relationship observed
- 4 transitions placed based on energy differences



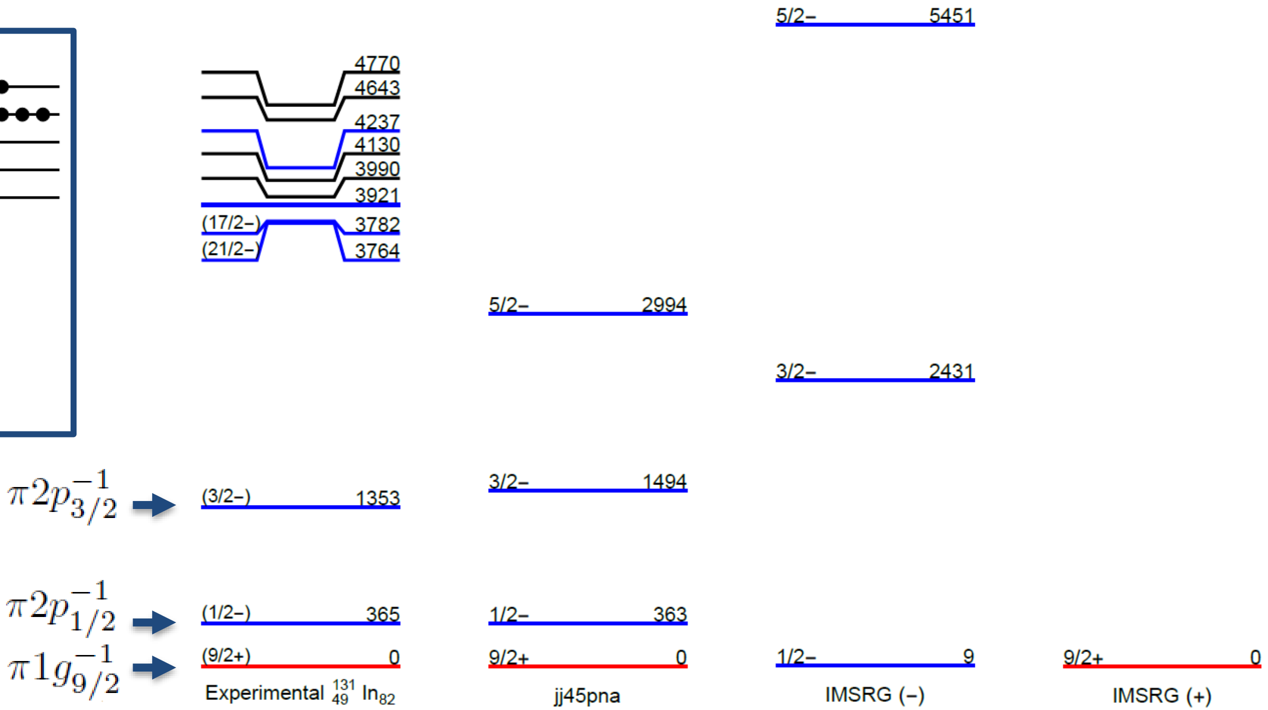


Shell model calculations for ^{131}In

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



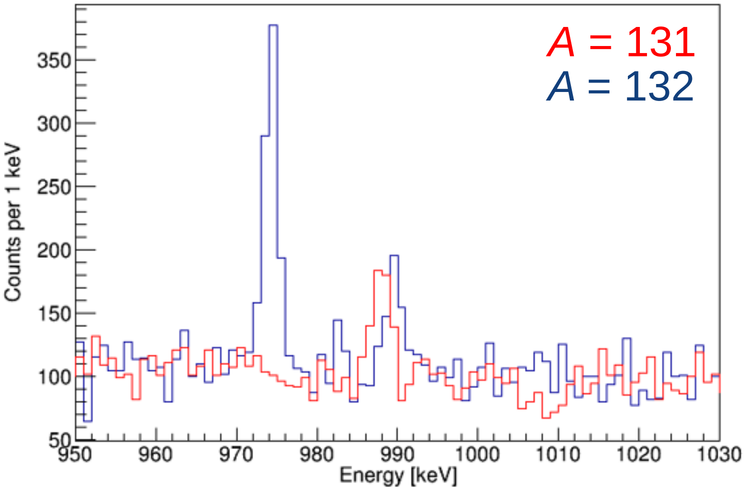
Valence space

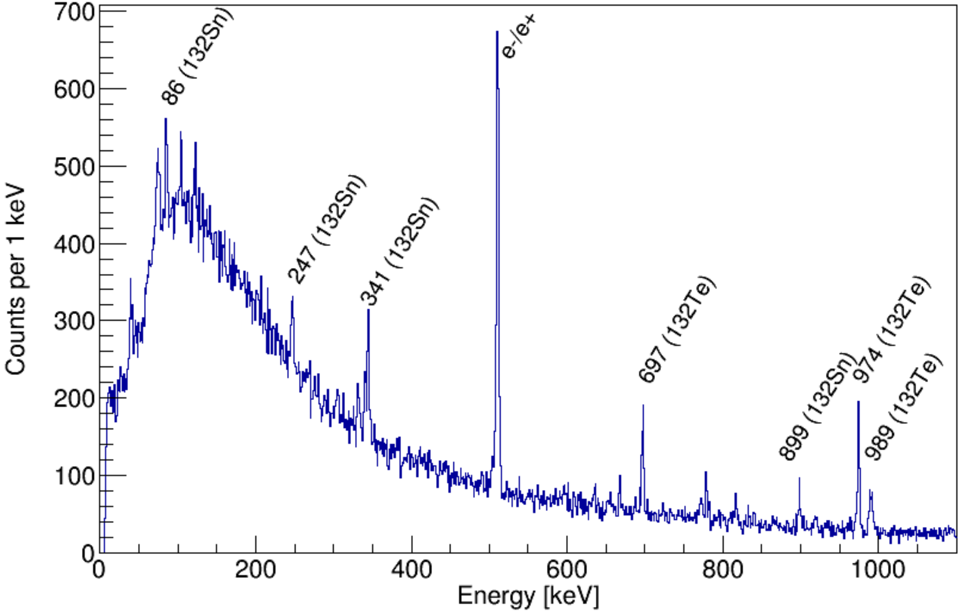


- Very low neutron separation energy → large neutron branching ratio

^{132}Cd $Q(\beta^-)$ = 12150 (510) keV
^{132}In S_n = 2450 (60) keV

- **988 keV** transition expected in both $^{131\text{-}132}$Cd datasets





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

- ^{128}**In:** **32** new transitions and **11** new levels up to ~600 keV from S_n
- ^{131}**In:** **8** transitions placed and **8** levels up to ~1500 keV from S_n
- ^{132}**Cd:** Higher yields and cleaner beams recently obtained with IDS at ISOLDE!

- Would not be 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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Dziękuję!

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