Nuclear Seminar Talk

University of Notre Dame

24th October 2003

Recent nuclear-structure studies at CERN/ ISOLDE for r-process applications

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Overview

(A) Why & How ?

- What is the r-process?
- Production of neutron-rich nuclei at CERN/ ISOLDE
- Improvements of selectivity

(B) What ?

- Nuclear spectroscopy of very neutron-rich Ag and Cd isotopes

(C) Summary, Conclusions & Outlook

The r-process
✪ Solar abundances
✪ r-process „boulevard“
✪ N=82 shell
✪ First r-process nuclides

Neutron-rich beams at ISOLDE

Improvements
✪ Target and converter
✪ Laser Ion Source
✪ Mass separator

Results
✪ Experimental setups
✪ γ-spectroscopy
✪ βdn- spectroscopy
✪ Status Ag and Cd data
✪ ^{126,128,130}Ag: E(2+)/B(E2)
✪ ^{129}Cd: Overview/ Decay Scheme
✪ ^{130}Cd: Overview/ Decay Scheme/ 1+ systematics/ Q_β-value/ Input parameter
✪ ^{131}Cd: Overview
✪ Mass deviation

Summary

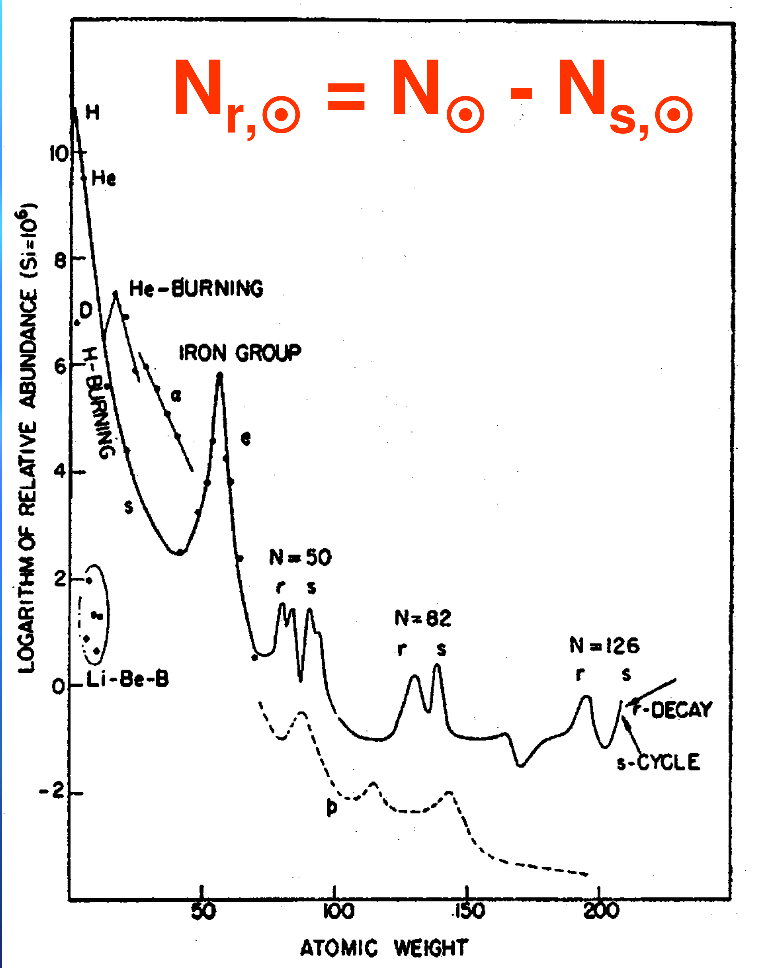
Conclusions

Observation of the relative solar abundances

⇨ Double-peak structure at neutron-magic numbers

⇨ slow and rapid neutron capture processes

$N_{r,\odot} = N_\odot - N_{s,\odot}$



s-process:

- near stability (long $T_{1/2}$)
- low neutron flux (~10^8 cm^{-3})
- elements up to ^{209}Bi
- time scale: ~1000 y´s

r-process:

- far off stability (short $T_{1/2}$)
- high neutron flux (>10^{20} cm^{-3})
- elements up to ^{248}Cm (Z=96), following „fission recycling“
- time scale: <1 s

Urey und Suess, Revs. Mod. Phys. 28 (1956) 53
Burbidge et al., Revs. Mod. Phys. 29 (1957) 547

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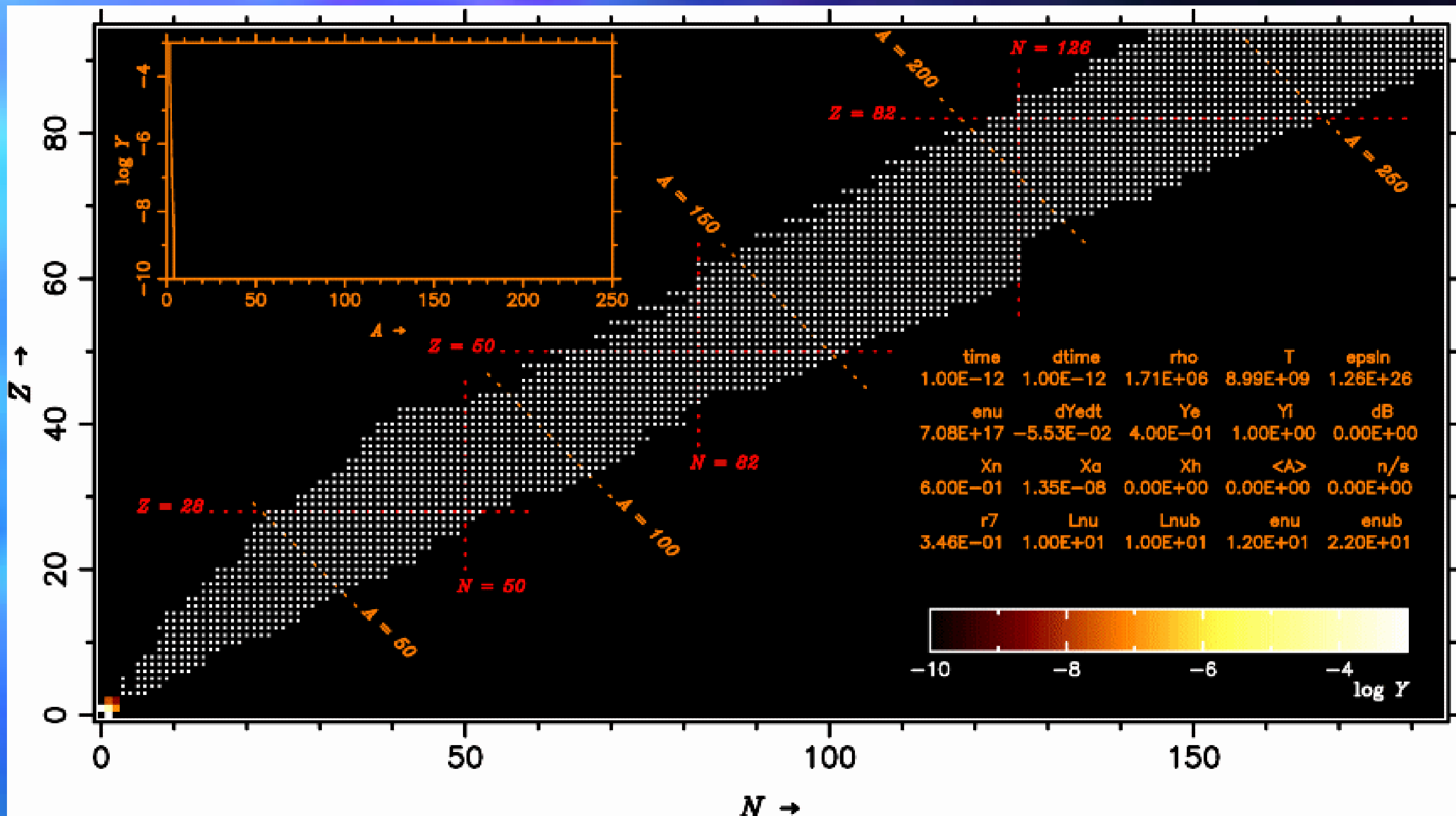
The r-process „boulevard“



• at the neutron magic shells the r-process has to „wait“ for the β-decay („waiting points“)

• not all nuclei can be studied, only a few key nuclides

Movie: S. Wanajo, Sophia University, Japan
www.ph.sophia.ac.jp/~shinya/research/research.html

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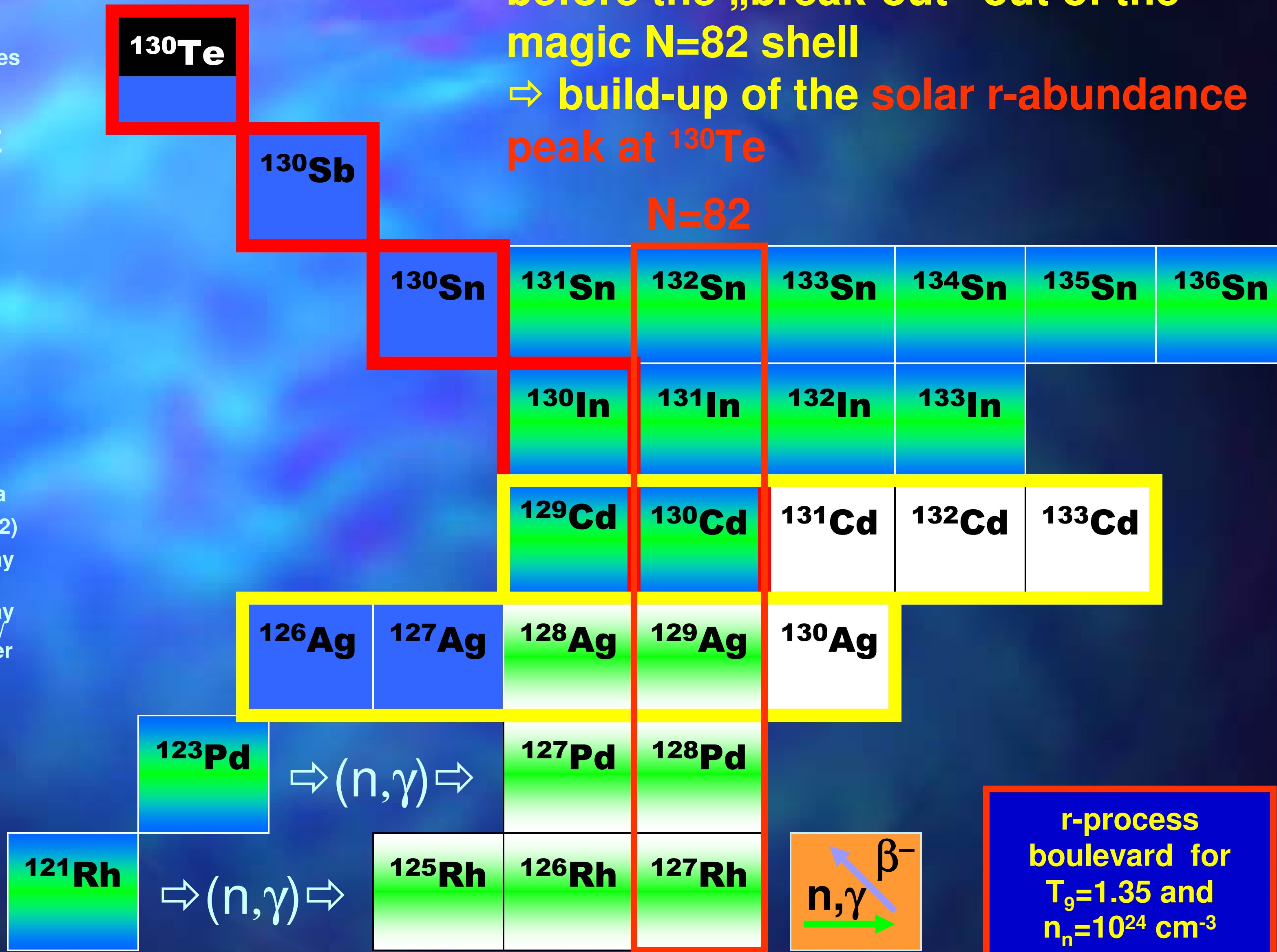
^{130}Cd is the most important nucleus before the „break-out“ out of the magic N=82 shell ⇨ build-up of the solar r-abundance peak at ^{130}Te



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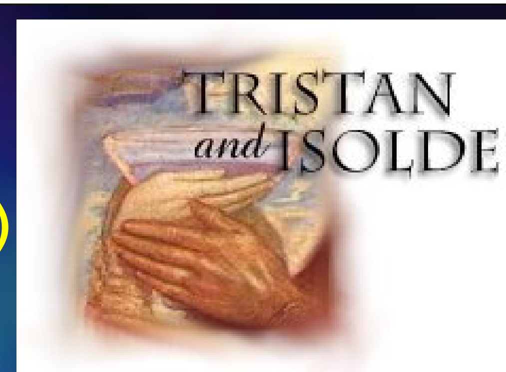
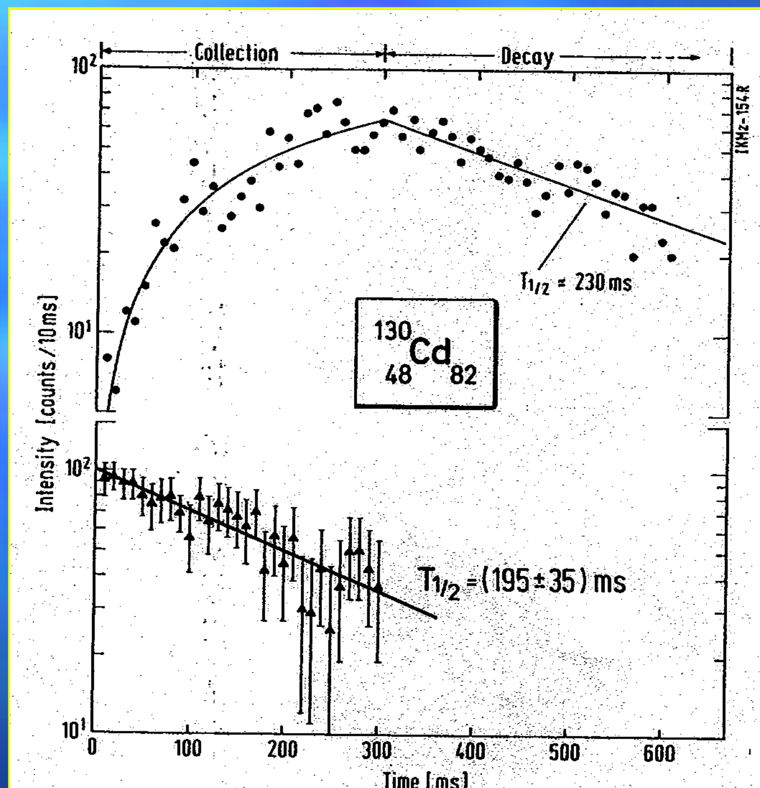
1986: identification of the first two r-process „waiting-points“:

$^{80}Zn_{50}$ (at TRISTAN and OSIRIS)

$^{130}Cd_{82}$ (at the old SC-ISOLDE)





$T_{1/2}$= (195 +/- 35) ms by βdn

P_n-value ~2.5%

Problem: use of a plasma ion-source

High background of
- $[^{40}Ca^{90}Br]^+$ (βdn emitter)
- surface-ionized ^{130}In, ^{130}Cs

➔ No chemical selectivity

Reduction of the isobaric background?

R.L. Gill et al., Phys. Rev. Lett. 56 (1986) 1874
E. Lund et al., Phys. Scr. 34 (1986) 614
K.-L. Kratz et al., Z. Phys. A 325 (1986) 489

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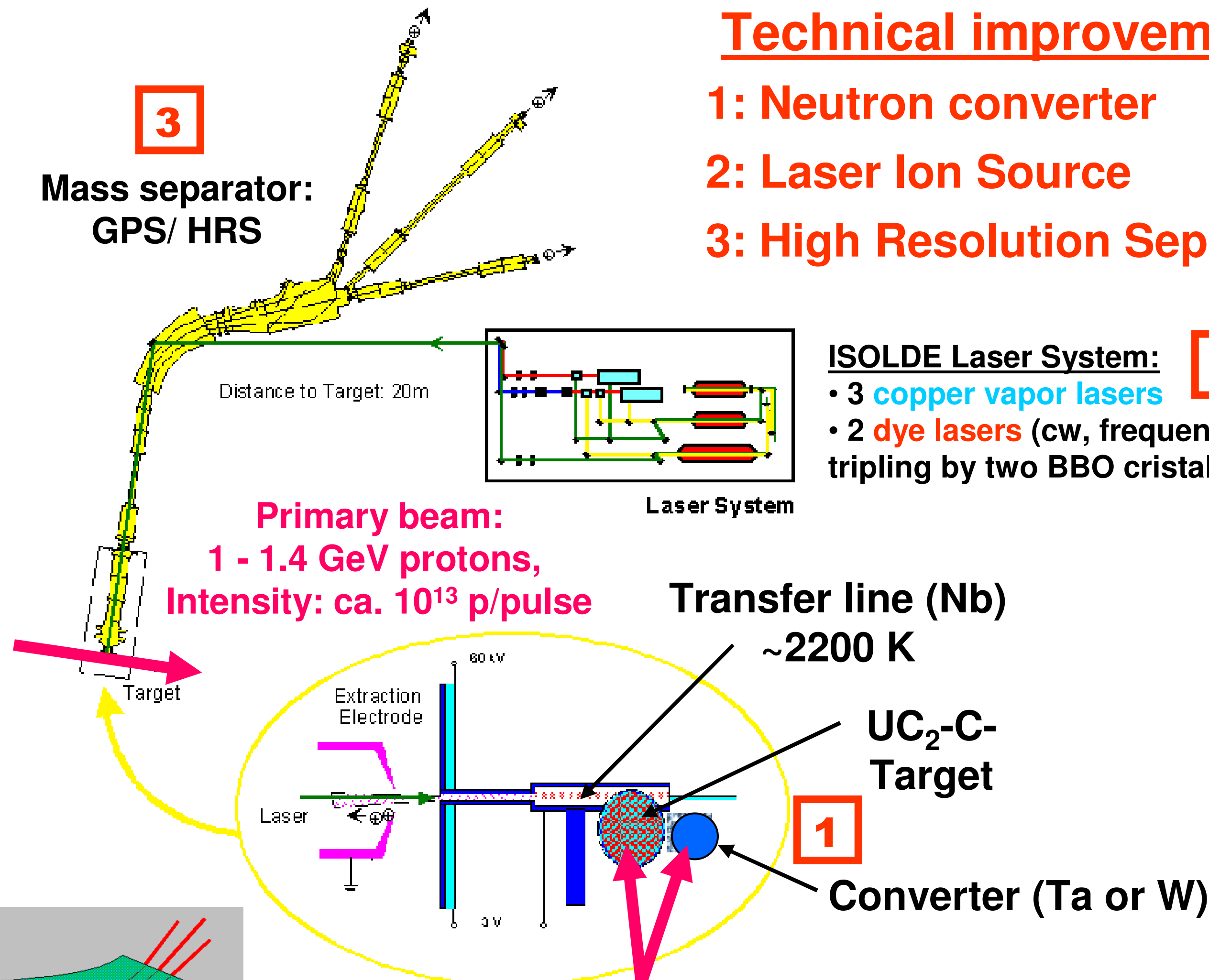
Neutron-rich beams at CERN/ ISOLDE

Technical improvements

1: Neutron converter

2: Laser Ion Source

3: High Resolution Separator



ISOLDE Laser System: 2
- 3 copper vapor lasers
- 2 dye lasers (cw, frequency tripling by two BBO cristals ➔ UV)

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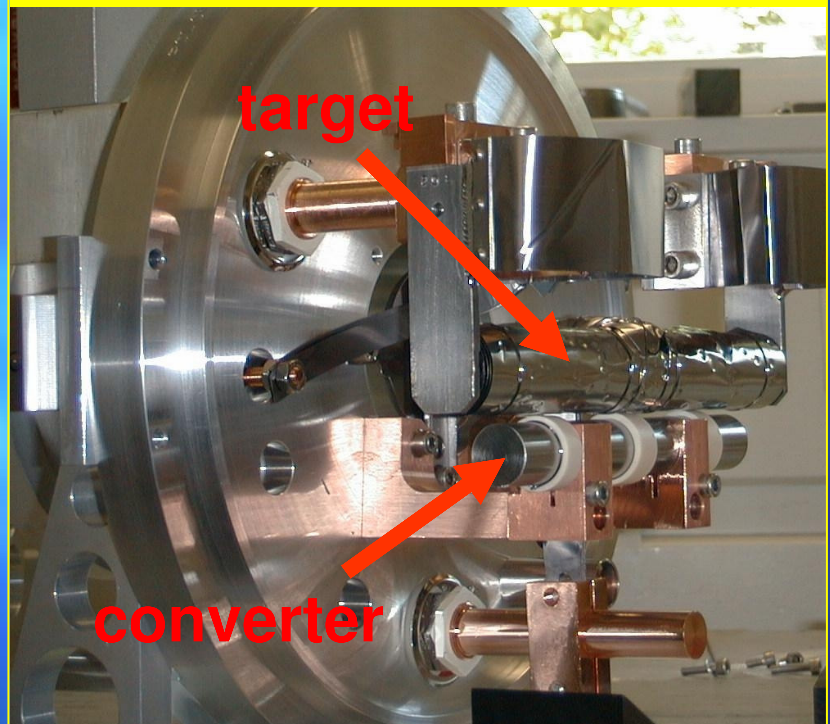
Target and neutron converter
(avoids proton-rich spallation products)

UC_2-C Target #208: W-surface with W-converter



Proton beam hits Ta- or W-rod near the target

⇨ Mini-spallation source: neutrons are emitted

⇨ Neutron induced fission in the target

☺ proton-rich side of isobaric chain is suppressed.

At A=130: surface-ionized ^{130}Cs ($T_{1/2}$= 29 min)

☹ lower yields

J.A. Nolen et al., AIP Conf. Proc. 473 (1998) 477

Picture: R. Catherall (CERN)

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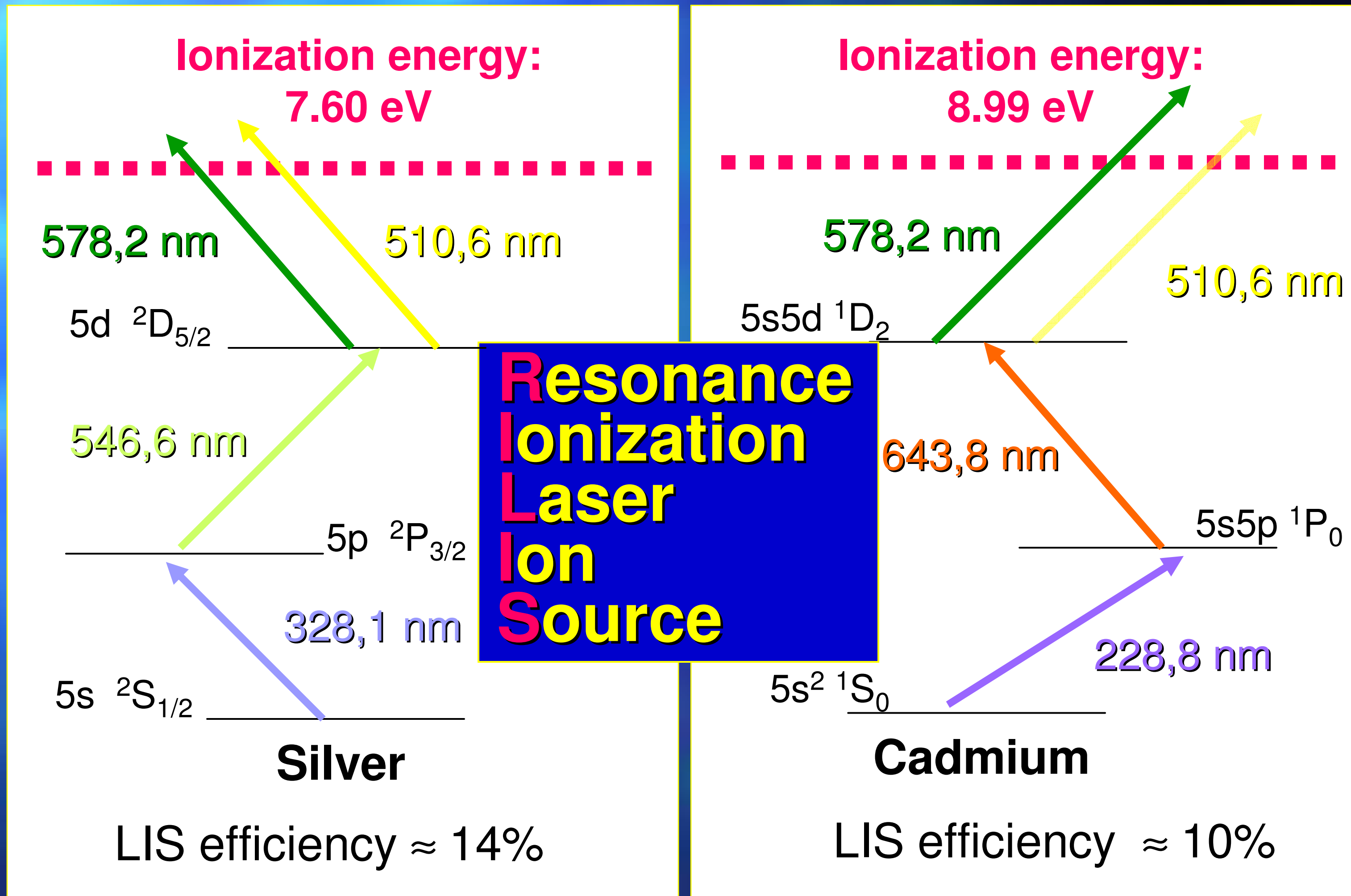
Chemical selectivity

Chemical separation according to Z, e.g. 3-step laser ionization of Silver and Cadmium



N. Erdmann et al., Appl. Phys. B66 (1998) 431

Y. Jading et al., Nucl. Instr. And Meth. B126 (1997) 76

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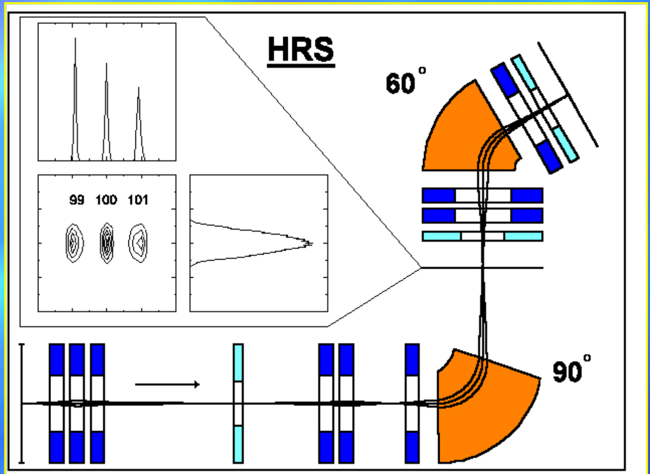
High Resolution Separator

(Mass separation according to A)

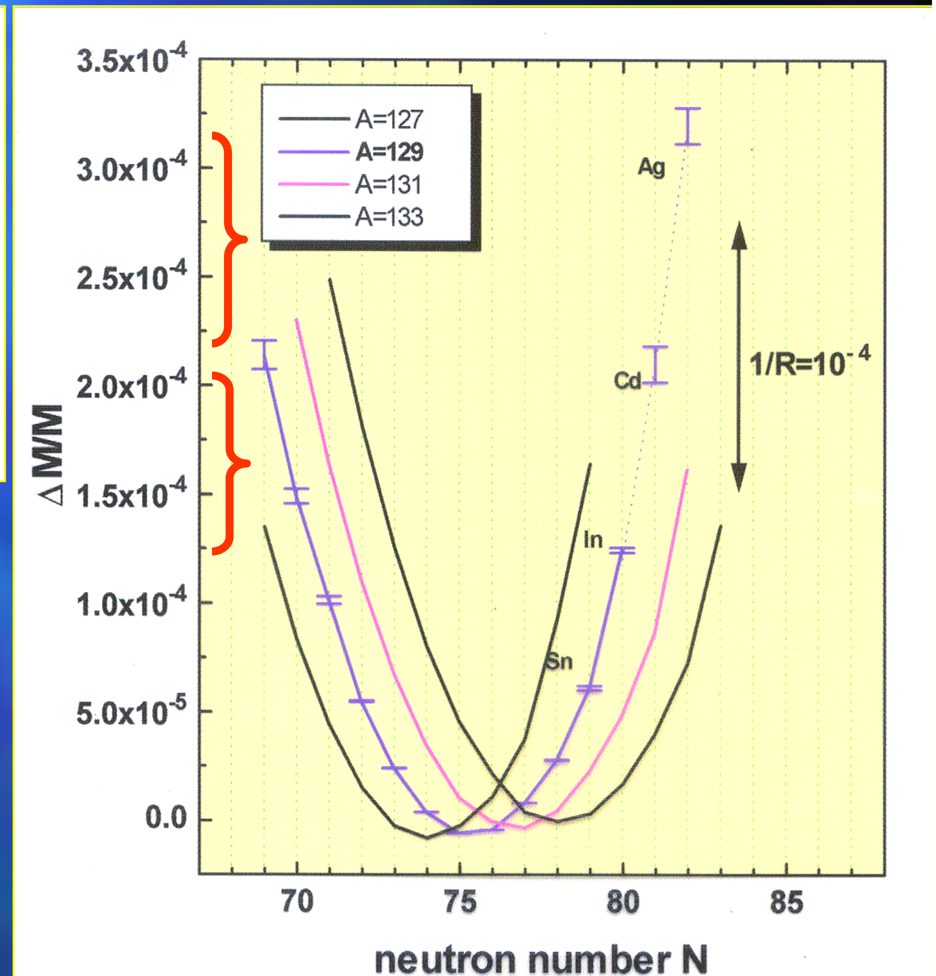


$\Delta M/M$(HRS) up to $1*10^{-4}$

$\Delta M/M$(exp): ~$2.5*10^{-4}$

$\Delta M/M$(Ag-Cd): $1*10^{-4}$

$\Delta M/M$(Cd-In): $7.5*10^{-5}$



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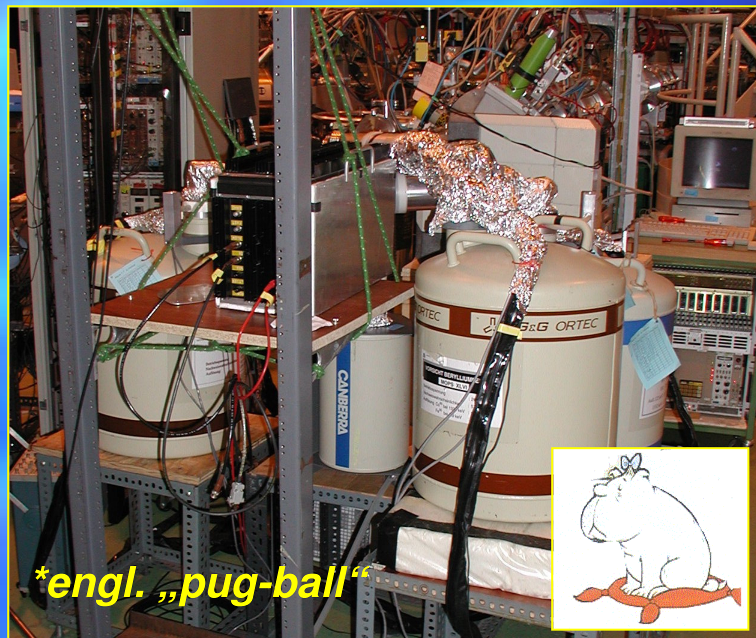
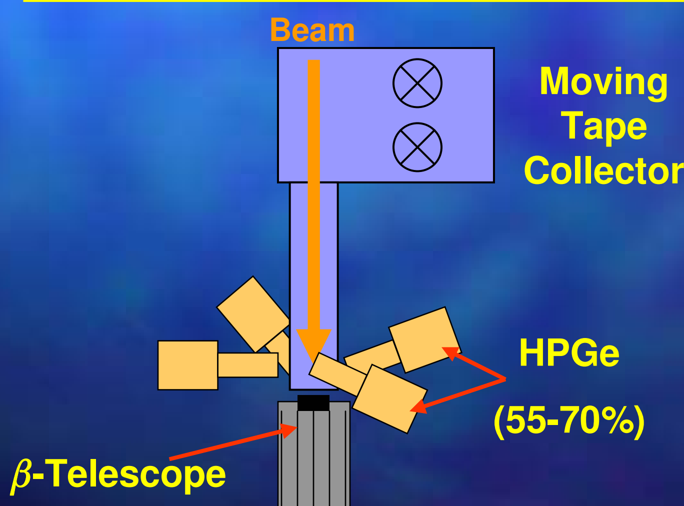
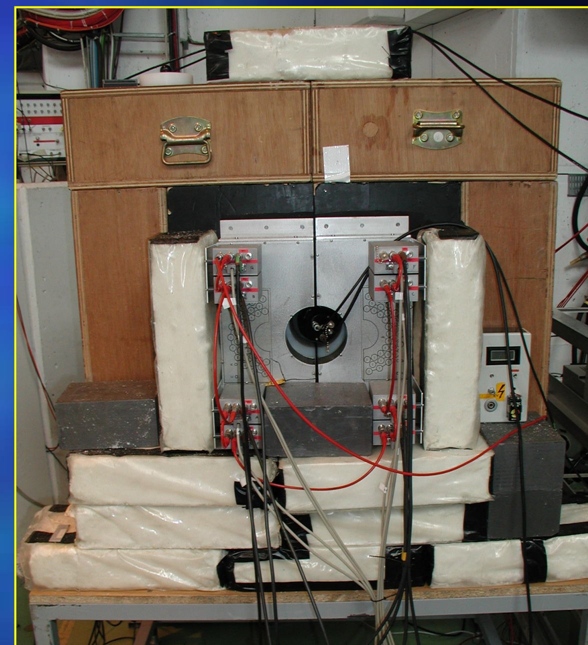
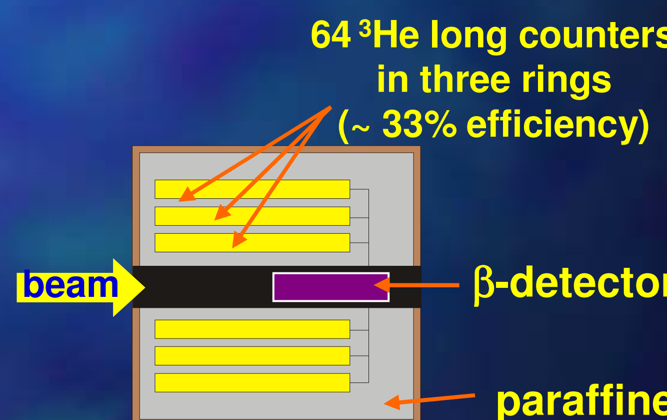
The MOPSBALL* $\beta\gamma\gamma$-detector setup





The Mainz βdn-detector setup





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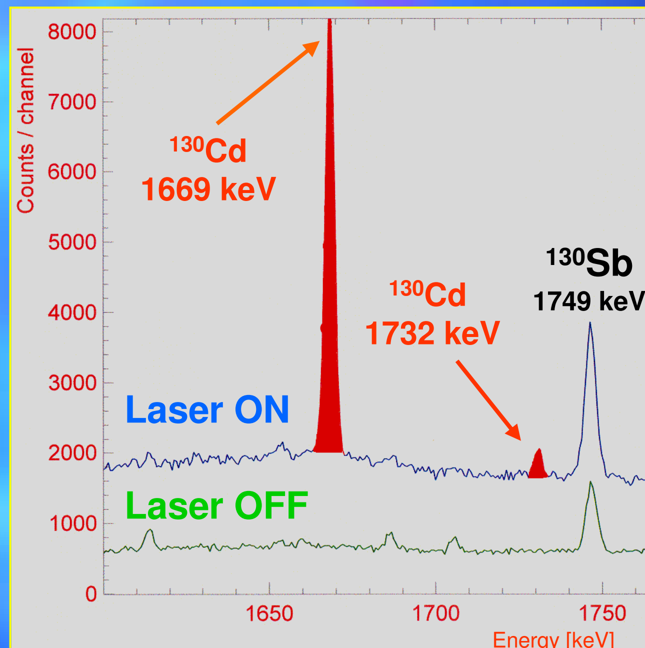
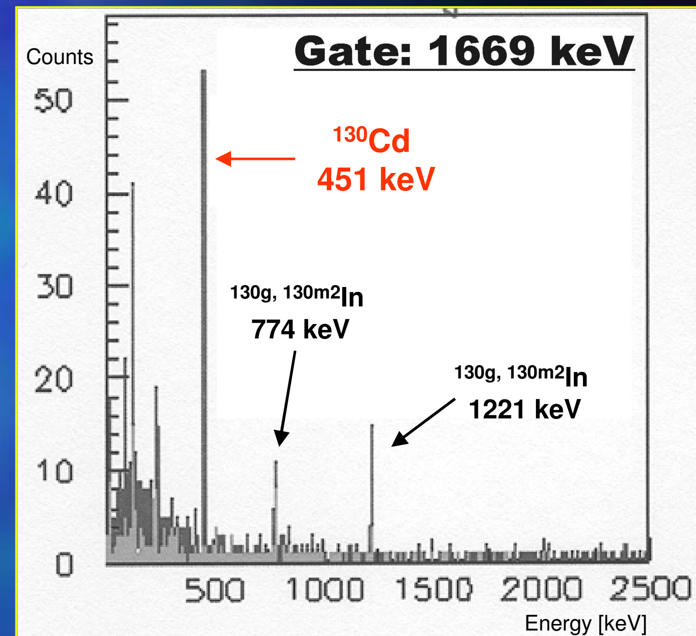
γ-singles spectrum   βγγt-coincidences





Laser OFF: only surface-ionized elements with low ionization potentials (e.g. Cs, In)

Laser ON: surface-ionized elements + laser-ionized Ag & Cd

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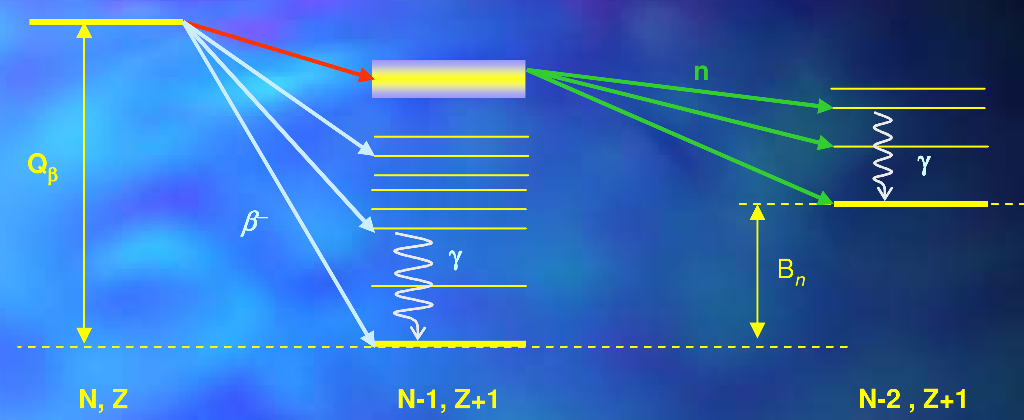
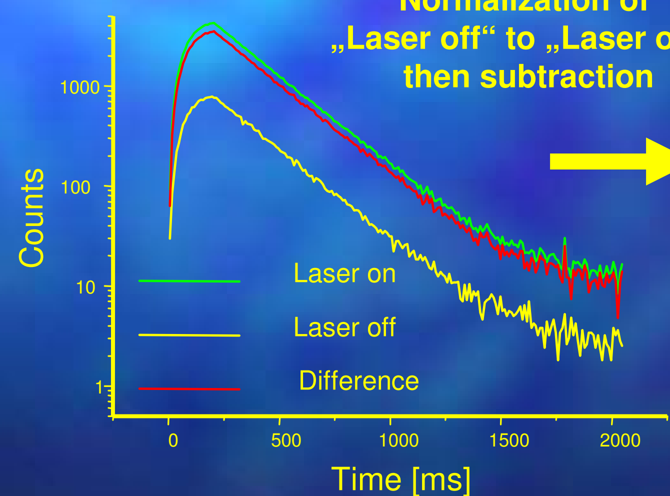
What are β-delayed neutrons (βdn)?

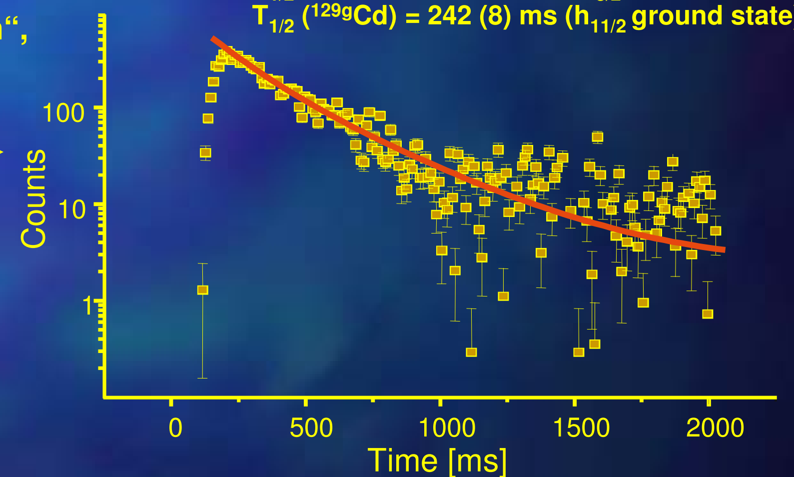


Half-lives by multiscaling of βdn

Normalization of „Laser off“ to „Laser on“, then subtraction



$T_{1/2}$ (^{129m}Cd) = 104 (6) ms ($d_{3/2}$ isomer)
$T_{1/2}$ (^{129g}Cd) = 242 (8) ms ($h_{11/2}$ ground state)



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Status of the Ag and Cd β-decay analysis

Nuclide	Half-life [ms]	Coincidences γ-data	γγ-data	βγ-data	Status
Ag-126	107 (12)	yes	?	?	in progress
Ag-127	79 (3)	yes	?	?	in progress
Ag-128	58 (5)	yes	?	?	in progress
Ag-129	46 (9)	yes	?	?	in progress
Ag-130	*35 (10)**	*(yes)**	no	no	in progress
Cd-129	242 (8)	yes	yes	yes	in progress
Cd-129m	104 (6)	yes	yes	yes	in progress
Cd-130	162 (7)	yes	yes	yes	finished**
Cd-131	68 (3)	*(yes)**	no	no	in progress
Cd-132	97 (10)	no	no	no	finished**
Cd-133	57 (10)	no	no	no	finished**

* low statistics   **Cadmium: addendum submitted

^{126,128,130}Ag: Systematics of the 2^+ states

^{129,130}Cd: (Tentative) decay schemes

^{131}Cd: $T_{1/2}$, P_n-value, first γ-lines

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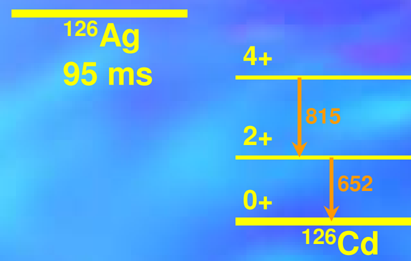
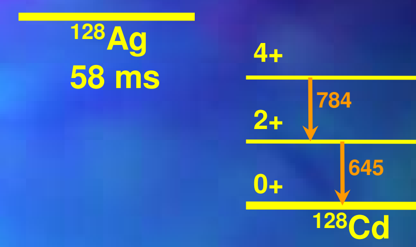
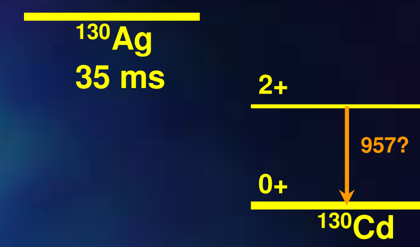
^{126}Ag β-decay

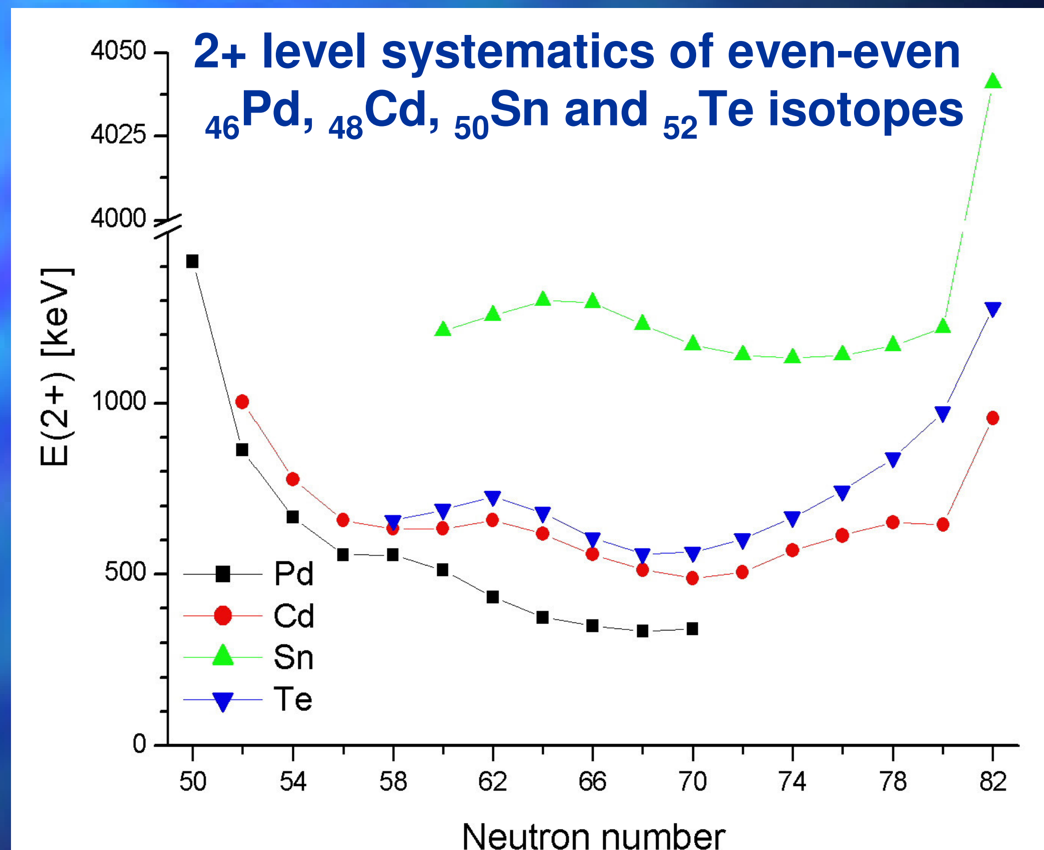


^{128}Ag β-decay



^{130}Ag β-decay





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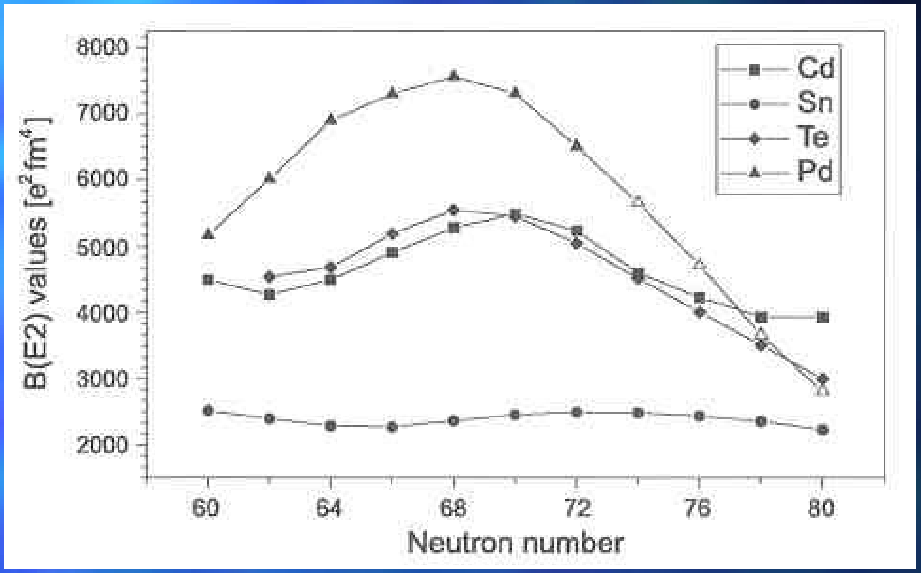
What can be deduced from the E(2+)?

⇨ Reduced transition probability of collective E2-transitions: B(E2) ~ 1/ E(2+)



Pd, Cd and Te:

- higher B(E2)-values = larger collectivity
- maximum around N=68-70
- Cd, Te: different slopes beyond N=74

⇨ Quadrupole deformation β_2 ~ sqrt[B(E2)]

- β_2>0 (prolate deformation): larger quadrupole polarizability for ^{128,130}Cd

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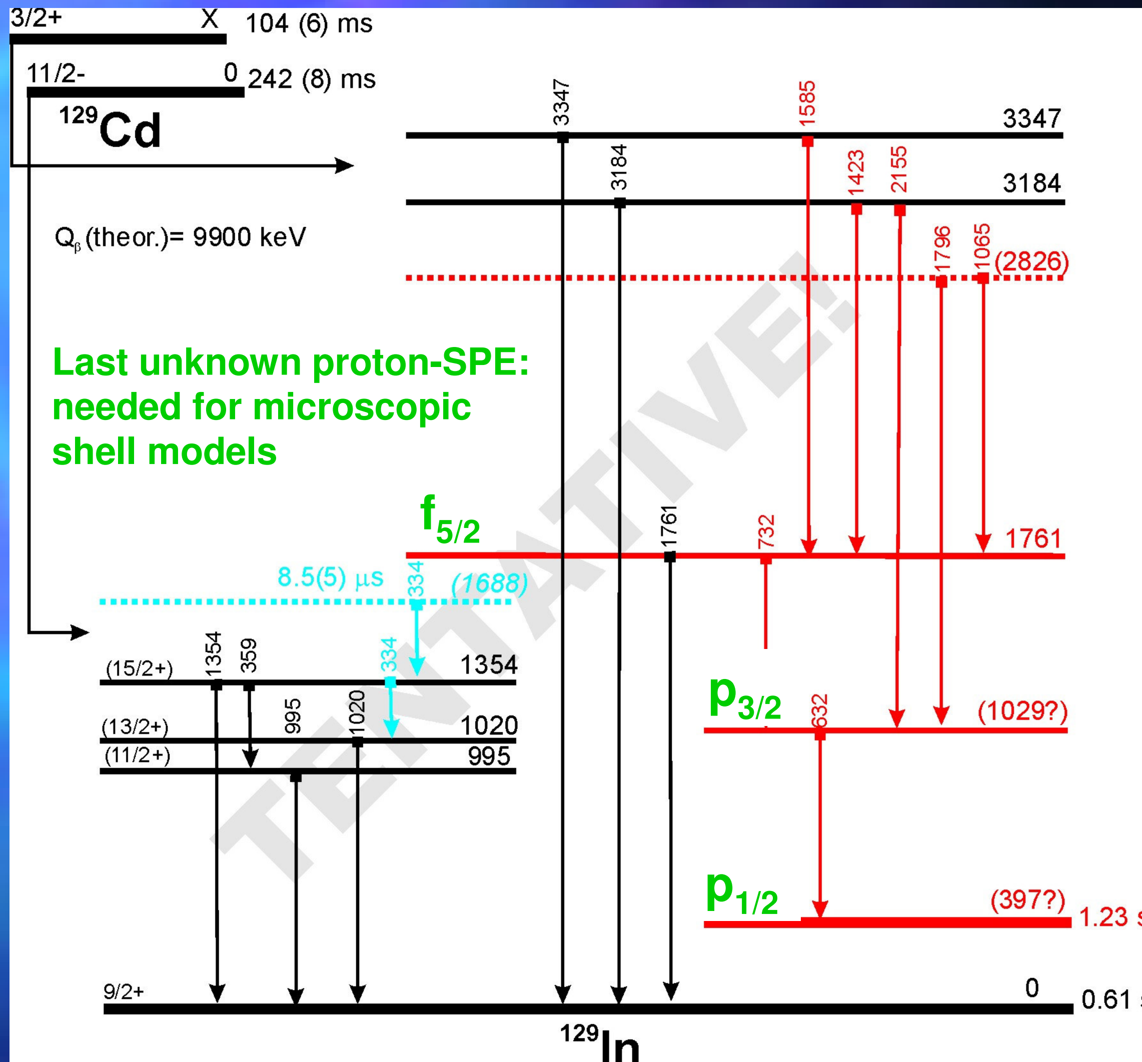
^{129}Cd decay scheme



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✪ ^{130}Cd: Overview/ Decay Scheme/ 1+ systematics/ Q_β-value/ Input parameter
✪ ^{131}Cd: Overview
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^{129}Cd β-decay

- β-decay from $3/2^+$ isomer (104ms, unplaced) and $11/2^-$ g.s. (242ms) in ^{129}Cd *(Arndt, 2002)*
- 4 γ-lines identified incl. 8.5μs 334 keV transition *(Genevey et al., Grenoble)*
⇨ different placement of μs-isomer with our data
- >30 new γ-lines up to 4 MeV
- coincidence data in progress ⇨ $\gamma\gamma$- coincidences, Q_β-value (theor. 9900 keV)
- tentative level scheme

O. Arndt, Diploma Thesis, Universität Mainz (2002)
J. Genevey et al., Phys. Rev. C67 (2003) 054312

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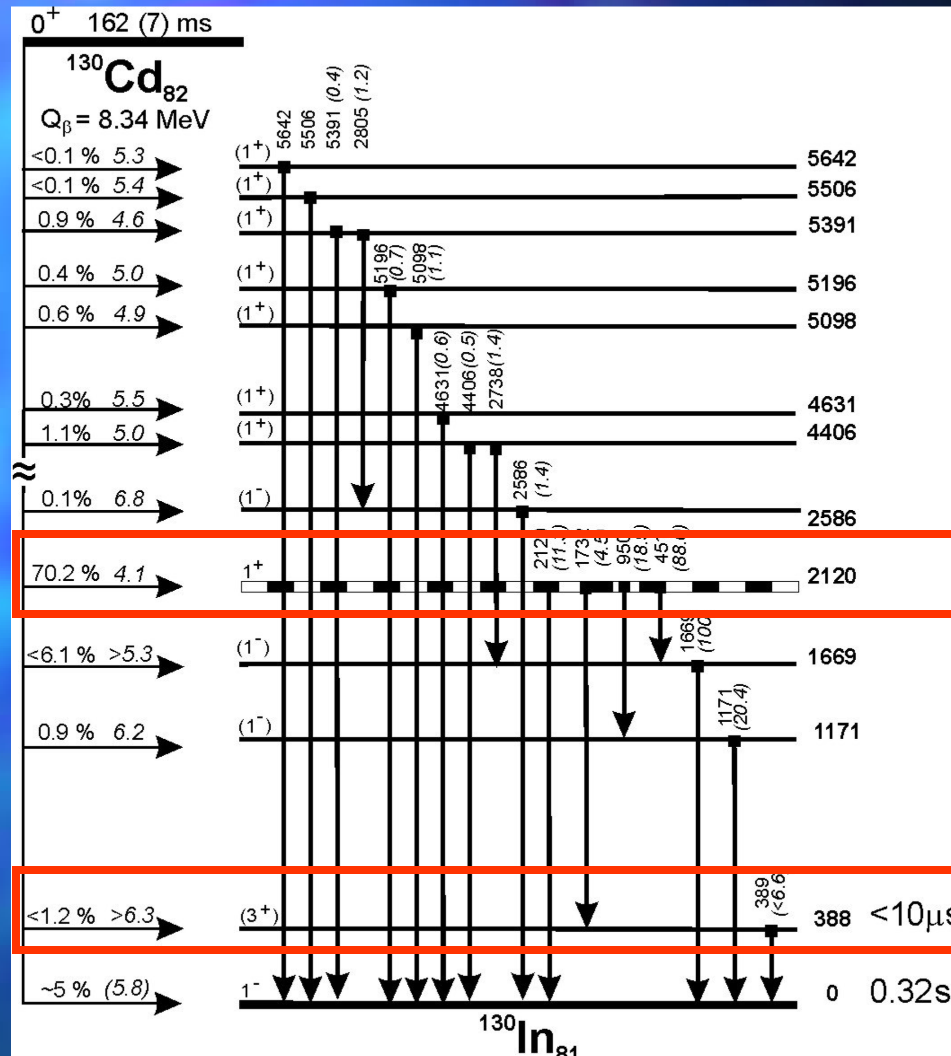
^{130}Cd decay scheme



I. Dillmann, Diploma Thesis (2002) Mainz
I. Dillmann et al., Phys. Rev. Lett. 91, 162503 (2003)

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^{130}Cd β-decay

- 21 new γ-lines up to 6 MeV
- 2 $\gamma\gamma$-coincidences

  ⇨ 451/1669 keV and 950/1171 keV
- γ-line at 389 keV ⇨ 10 μs-isomer (Hellström et al., GSI 2002)
- Q_β-value measured
- decay scheme incl. 17 transitions
- surprisingly high energy of the lowest 1^+ state

Level systematics for the lowest 1^+ state in neutron-rich odd-odd In isotopes

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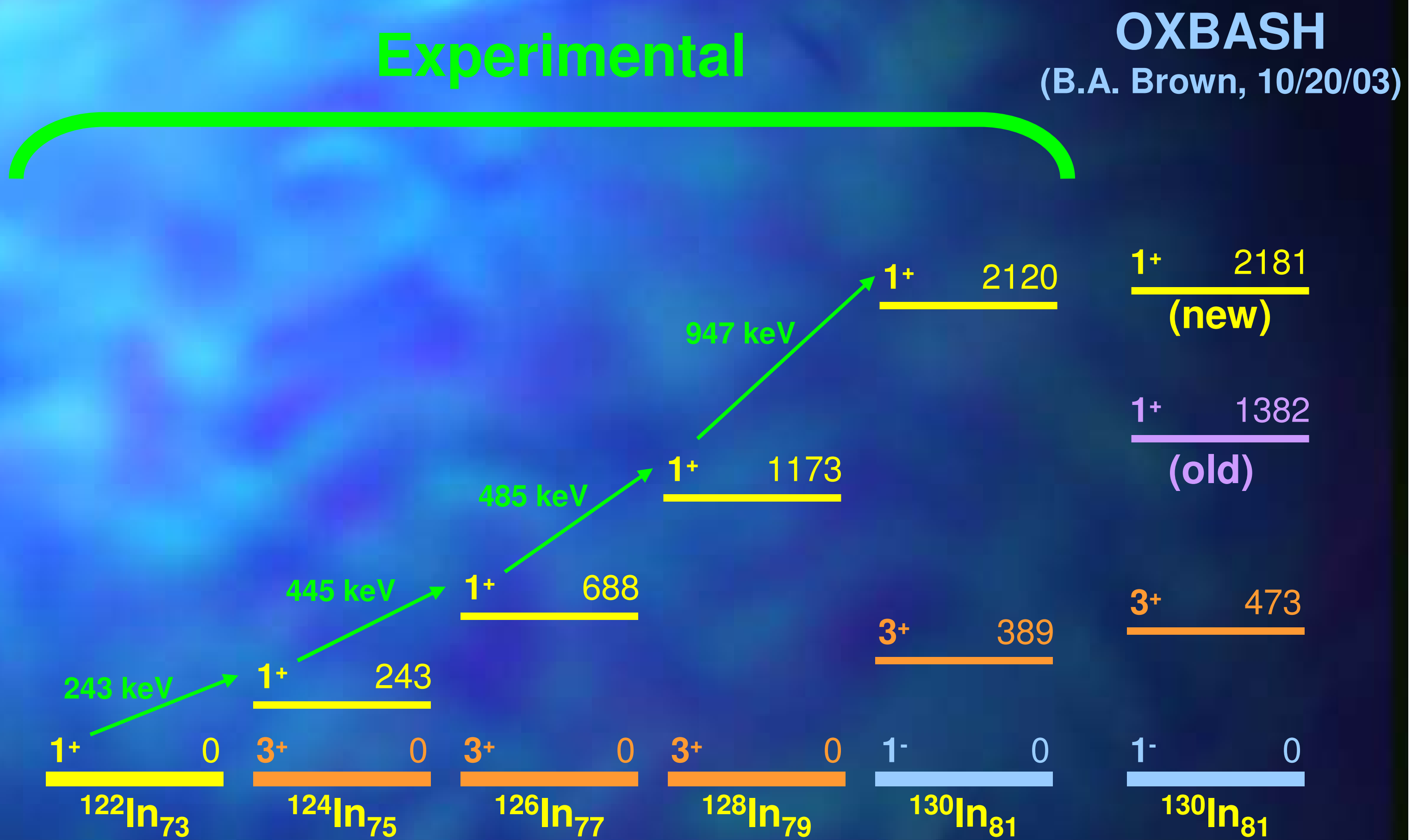

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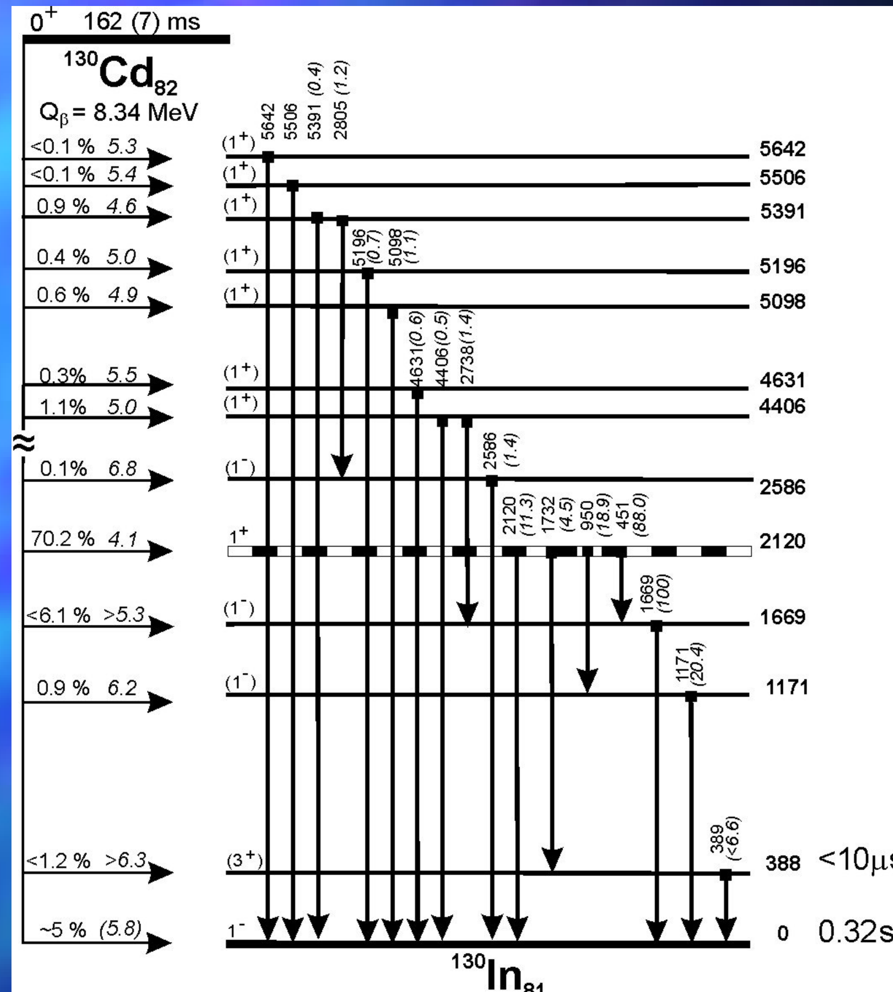
^{130}Cd: Determination of the Q_β-value



$\beta\gamma$-coincidences: summation of 5 transitions depopulation the 1+ level (2120 keV, 950 - 1171 keV, 451 – 1669 keV)

I. Dillmann, Diploma Thesis (2002) Mainz

I. Dillmann et al., Phys. Rev. Lett. 91, 162503 (2003)

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Q_β-value ^{130}Cd and Way-Wood diagram

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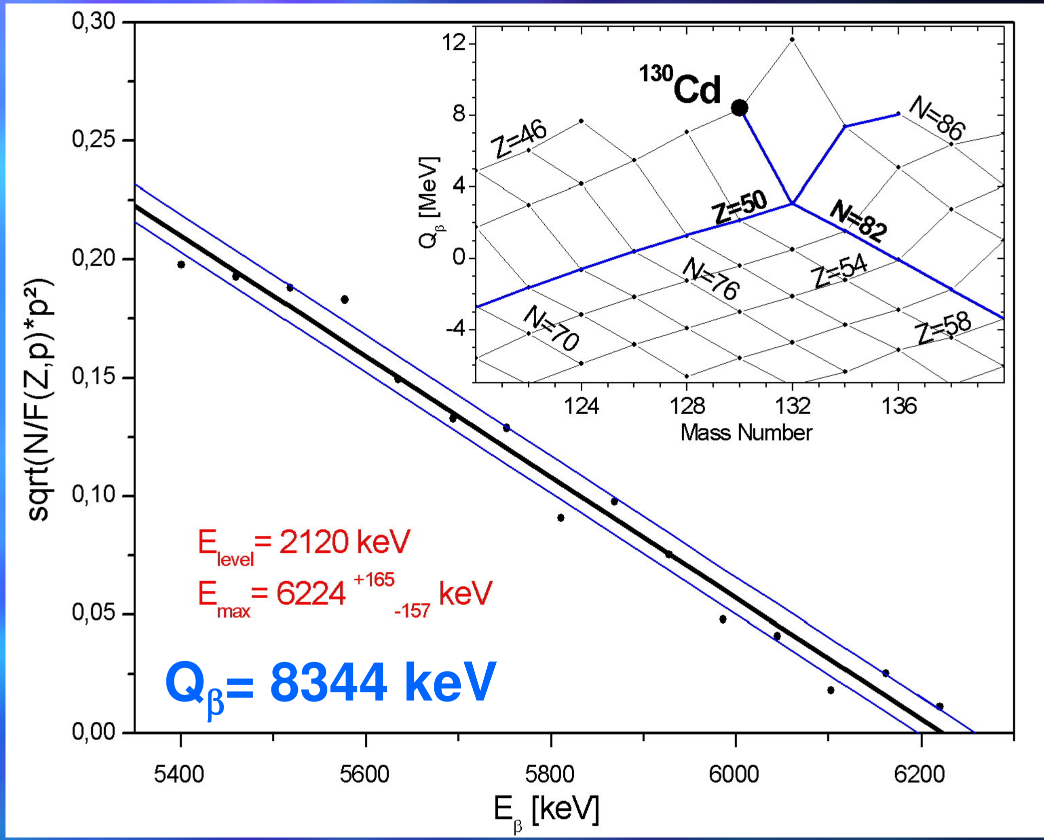

Dobaczewski et al. (*HFB-SkP*, 1996):	8930 keV
Brown et al. (*OXBASH*, 2003):	8753 keV
Audi & Wapstra (*Mass Eval.*, 1997):	8500 keV
Pearson et al. (*ETFSI-Q*, 1996):	8300 keV
Aboussier et al. (*ETFSI-1*, 1995):	7860 keV
Samyn et al. (*HFB-2*, 2002)	7640 keV
Möller et al. (*FRDM*, 1995):	7430 keV
Goriely et al. (*HFBCS*, 2001)	7000 keV

High Q_β-value is another indication for a quenching of the N=82 shell!

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Input parameters for theoretical models to understand the shell-structure

^{130}Cd

	Experimental	OXBASH (10/22/03)
• β-decay $T_{1/2}$	162 ms	233 ms
• Q_β-value	8344 keV	8753 keV

characteristics of the lowest 1^+-level with a $[\nu g_{7/2} \otimes \pi g_{9/2}]$ configuration (main GT-feeding):

	Experimental	OXBASH (10/22/03)
• β-feeding I_β	70%	100%
• log ft-value	4.1	4.2
• E(1+)	2120 keV	2181 keV

Good agreement, BUT only with reduction of the TBME of the 1^+ state by 800 keV (no explanation for this!)

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^{131}Cd β-decay

- Prediction QRPA (pure GT, Folded-Yukawa potential, Lipkin-Nogami pairing, low Q_β from FRDM):

  $T_{1/2}$(GT)= 943 ms, P_n(GT)= 99%

- Experiment *(Hannawald et al.):*

  $T_{1/2}$= 68 ms, P_n= 3.4%

- modified QRPA calculation (GT+ff, Nilsson potential with 0.7*l²-term, Lipkin-Nogami pairing, high Q_β from ETFSI-Q):

  $T_{1/2}$(GT+ff)= 95 ms, P_n(GT+ff)= 3%

- 2-3 possible γ-lines (low statistics):

  1205.3 keV, 4484 keV and 4576 keV

- no coincidence data b/c of low yields

M. Hannawald et al., Phys. Rev. C62, 054301 (2000)
B. Pfeiffer et al., Nucl. Phys. A693, 282 (2001)

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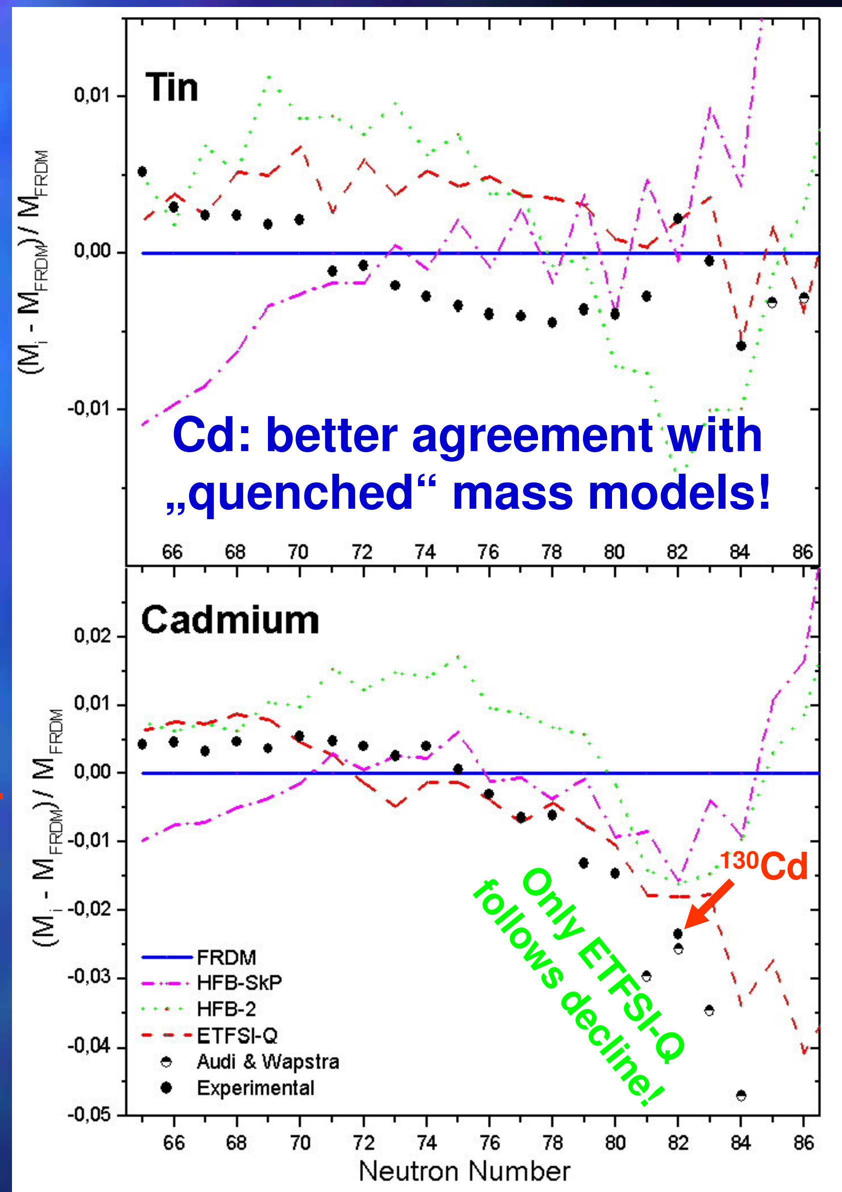
Mass deviation of $_{50}$Sn and $_{48}$Cd isotopes

(normalized to the „unquenched“ FRDM)

Incl. model predictions with „shell-quenching“ (HFB-SkP, HFB-2, ETFSI-Q) and very recent short-range extrapolations* (SRE) for $^{135-137}$Sn and $^{129-132}$Cd

Different behavior of HFB-models and ETFSI-Q/ SRE beyond N=82

⇨ Need for experimental masses



*G. Audi et al., *http://csnwww.in2p3.fr/AMDC/web*

I. Dillmann et al., Phys. Rev. Lett. 91, 162503 (2003)

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- high B(E2) values in Cd isotopes up to N=82
- for the first time $T_{1/2}$ of isomeric 3/2+ state in ^{129}Cd measured
- tentative decay scheme of ^{129}Cd with first indication for placement of 1/2- isomer
- first decay scheme of ^{130}Cd with surprisingly high energy position of the 1^+ state
- trend of high Q_β-values for the decay of neutron-rich Cd´s (as predicted by quenched mass models)
- unexpectedly low $T_{1/2}$ and P_n-value for ^{131}Cd β-decay
- The best agreement with experimental masses is given by quenched models (ETFSI-Q, HFB-SkP)

First experimental evidences for a quenching of the N=82 shell !

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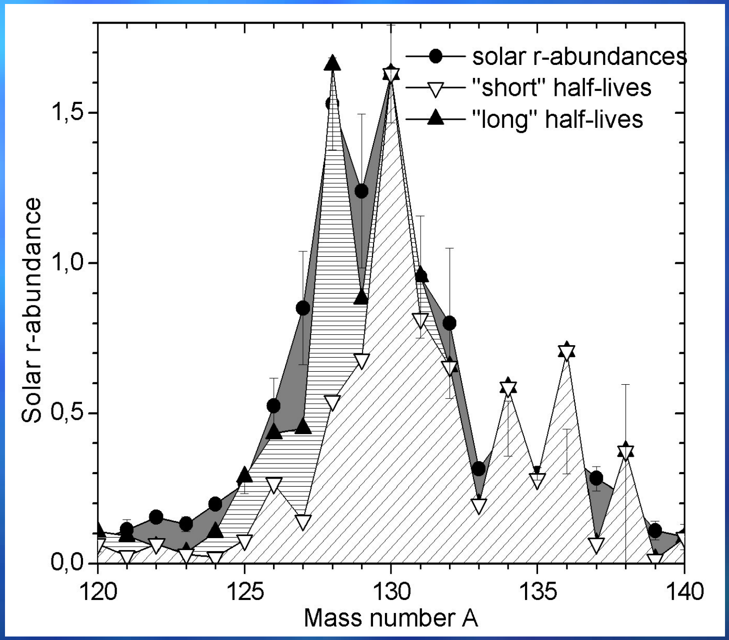
- shell structure around ^{132}Sn is not yet fully understood !
- weakening of the TBME: half-lives of so far unknown N=82 „waiting-point“ nuclei (^{128}Pd, ^{127}Rh, ^{126}Ru and ^{125}Tc) will become *longer* than predicted by recent shell-models



⇨ better under-standing of r-process formation and matter flow through the A≈130 $N_{r,\odot}$-peak

- need for more experimental values: Pd-Tc not possible with ISOL ⇨ Fragment-Separator at MSU

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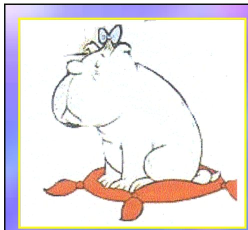
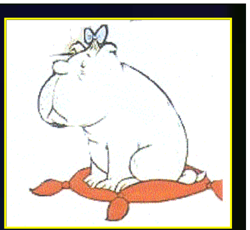


MOPSBALL Productions would like to thank the following persons:



Karl-Ludwig Kratz,
Andreas Wöhr (Notre Dame),
William B. Walters (Maryland),
Oliver Arndt,
Alex Brown (MSU),
Michael Hannawald,
Per Hoff (Oslo),
Thomas Kautzsch,
Ulli Köster (CERN),
Peter Möller (LANL),
Bernd Pfeiffer,
Darek Seweryniak (Argonne),
Jason Shergur (Argonne),
Friedel Thielemann (Basel)
and the CERN/ ISOLDE Collaboration

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