R-Process Experiments at ISOL Facilities

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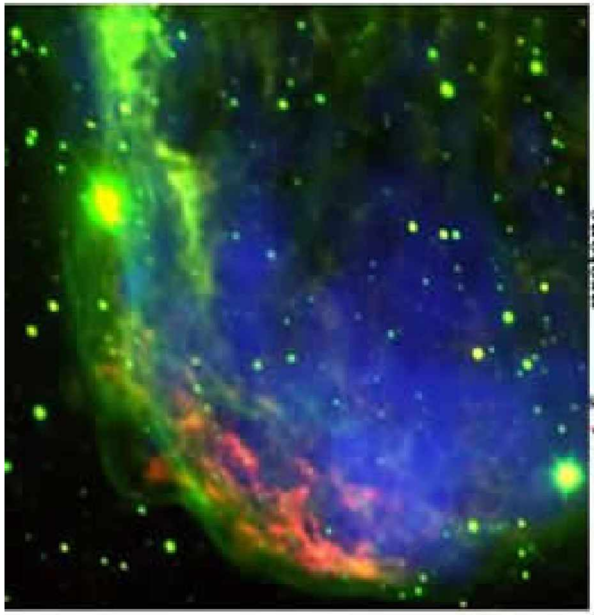
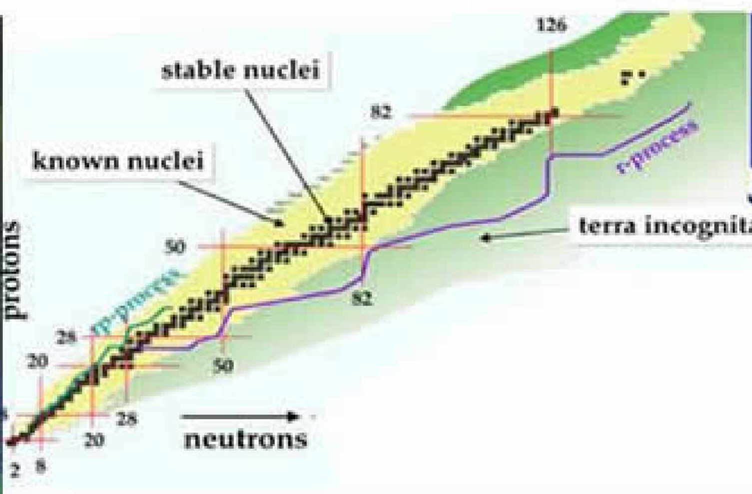




JINA R-Process Discussions

January, 28 – 29 2005   Notre Dame, IN

As the Director of JINA reminded us beforehand,

- “the purpose of this workshop should mainly be to discuss open questions rather than results,
- to stimulate discussion and to trigger new ideas, exchange and collaborations on r – process related topics.“

With respect to

r-process experiments using ISOL techniques

one has to recognize that most of the experiments feasible with standard isotope production, separation and detection methods have already been done.
What has become essential during the past few years, are the continuous technical improvements of the above techniques, in order to obtain background-free, isotopically pure beams of the rare isotopes of astrophysical interest.
Clearly, the catchword request in this context is

“SELECTIVITY“

History and progress in analyzing r-process nuclei

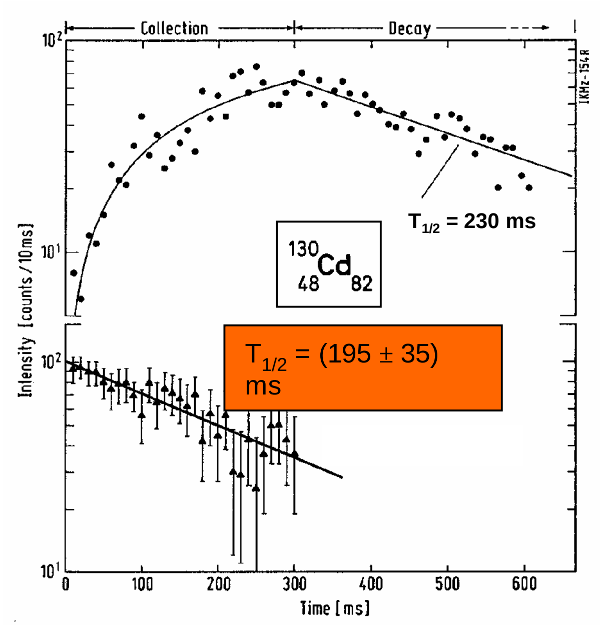
In 1986 – 19 years ago – a new era in experimental nuclear astrophysics started:

- at the ISOL facilities OSIRIS and TRISTAN
  the N=50 r-process “waiting-point“ nucleus
  $^{80}_{30}\mathrm{Zn}_{50}$
  was measured, with a $T_{½} \cong 550$ ms.

- at the ISOL facility ISOLDE
  the N=82 r-process “waiting-point“ isotope
  $^{130}_{48}\mathrm{Cd}_{82}$
  was measured, with a $T_{½} \cong 200$ ms.

Today – in early 2005 – altogether 35 isotopes have been measured (at least) via its $T_{½}$, which lie in the r-process boulevard for moderate neutron densities of $10^{20} < n_n < 10^{25}$ cm^{-3}.
These r-process isotopes range from double-magic $^{78}\mathrm{Ni}_{50}$ to $^{147}\mathrm{Xe}_{93}$.
Out of the 35 r-process nuclei, only ^{78}Ni and ^{139}Te have been measured at fragmentation facilities (MSU, GSI); the large majority was identified at ISOL facilities, in particular at ISOLDE / CERN.

What we knew already in 1986 ...



$T_{1/2}$ = (195 ± 35) ms

K.-L. Kratz et al (Z. Physik A325; 1986)

Exp. at old SC-ISOLDE
with plasma ion-source
and βdn counting

Problems:
high background from
-surface ionized ^{130}In, ^{130}Cs
-molecular ions $[^{40}Ca^{90}Br]^+$

Request: **SELECTIVITY !**

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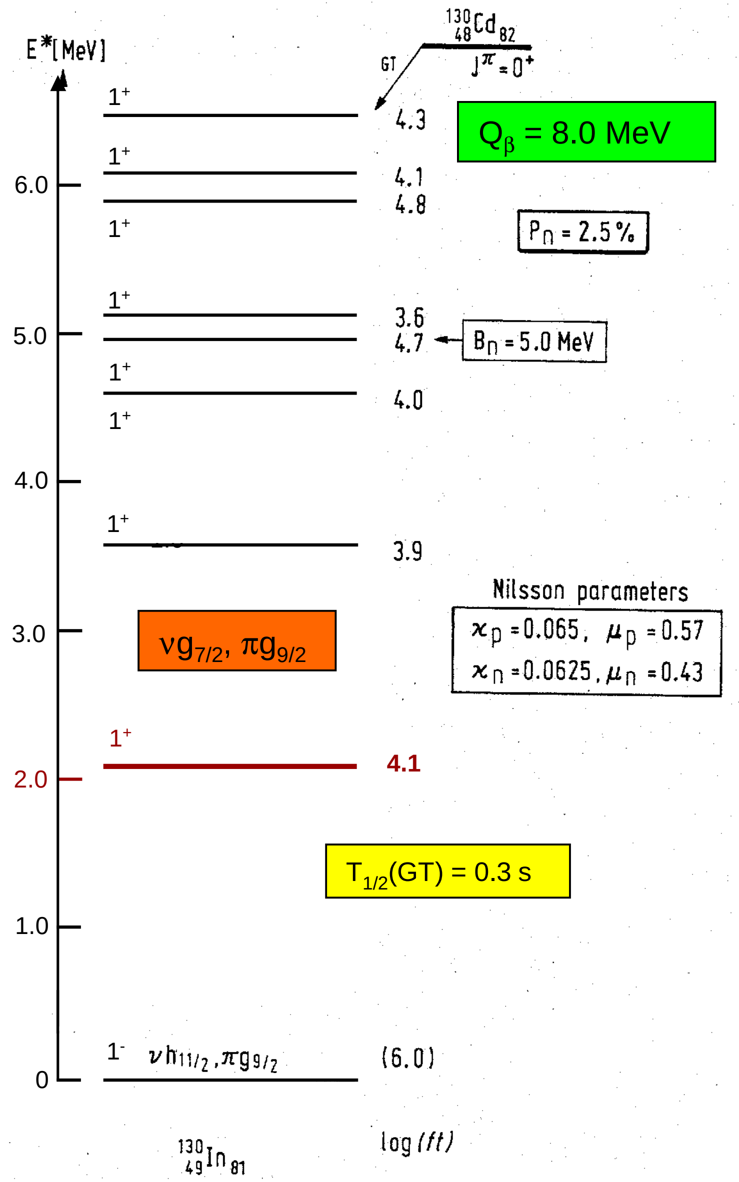
Shell-model (QRPA; Nilsson/BCS) prediction



Q_β = 8.0 MeV

P_n = 2.5 %

B_n = 5.0 MeV

$\nu g_{7/2}, \pi g_{9/2}$

$\varkappa_p = 0.065, \mu_p = 0.57$
$\varkappa_n = 0.0625, \mu_n = 0.43$

$T_{1/2}(GT)$ = 0.3 s

IKMz – 155R(1986)

As shown in this table, the regions
at N=50 and beyond (up to Kr), and
at N=82 and beyond (up to Sn)
are resonably well studied by now.
The majority of these r-process isotopes were identified by, or in close collaboration with the Kernchemie Mainz group.

Experimental information is still missing in the A ≅ 120 region and for A ≥140 (and here in particular for the 3rd $N_{r,\bullet}$ peak and beyond).

	Mass units away from	
Isotope	β-stability	r-process path
$^{70}\mathrm{Fe}_{44}$	12	-6
$^{78}\mathrm{Ni}_{50}$	14	in
$^{79}\mathrm{Cu}_{50}$	14	in
$^{81}\mathrm{Zn}_{51}$	11	in (+1)
$^{84}\mathrm{Ga}_{53}$	13	in (+1)
$^{85}\mathrm{Ge}_{53}$	9	-3
$^{94}\mathrm{Br}_{59}$	13	-3
$^{99}\mathrm{Kr}_{63}$	13	in (+3)
$^{102}\mathrm{Rb}_{65}$	15	-1
$^{105}\mathrm{Zr}_{65}$	9	-7
$^{120}\mathrm{Pd}_{74}$	10	-8
$^{130}\mathrm{Ag}_{83}$	21	in (+1)
$^{133}\mathrm{Cd}_{85}$	17	in (+3)
$^{135}\mathrm{In}_{87}$	21	in (+4)
$^{138}\mathrm{Sn}_{88}$	14	in (+2)
$^{139}\mathrm{Te}_{87}$	9	in (+1)
$^{147}\mathrm{Xe}_{93}$	11	in (+1)
$^{162}\mathrm{Eu}_{99}$	9	-27
$^{177}\mathrm{Tm}_{107}$	8	-18
$^{215}\mathrm{Pb}_{133}$	7	-45

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Usually, study of individual (short-lived) isotopes requires **separation** from bulk radioactivity

- chemical separation acc. to Z à isotopic chain
- mass separation acc. to A à isobaric chain

In particular, for “rare“ isotopes often not sufficient;
additional **selectivity** required

isotopically clean beam

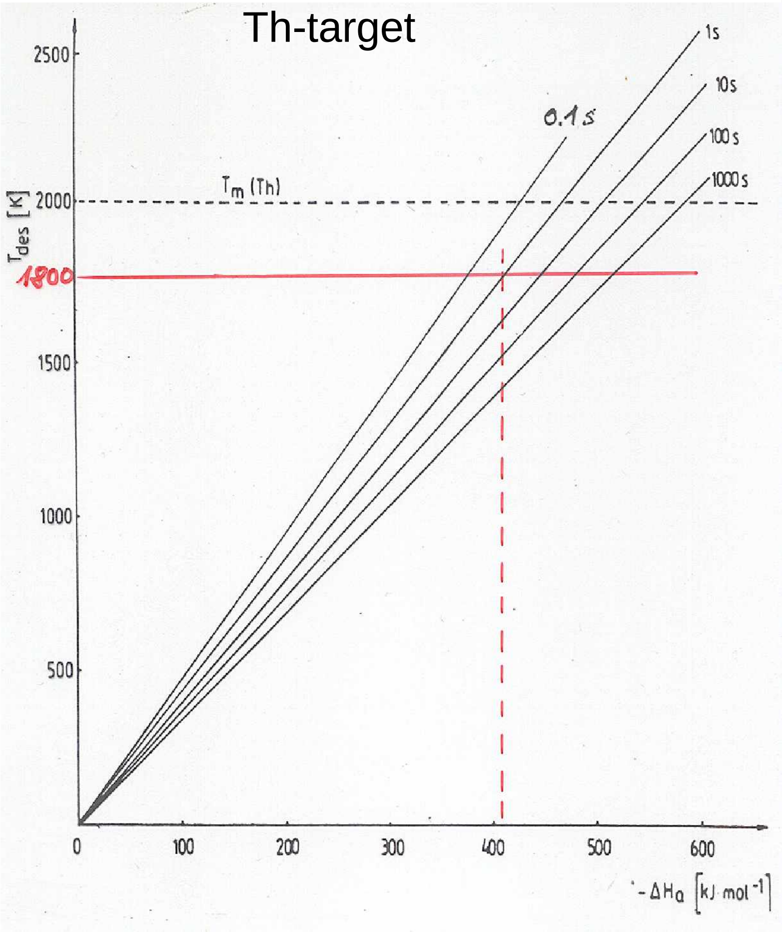
SELECTIVITY

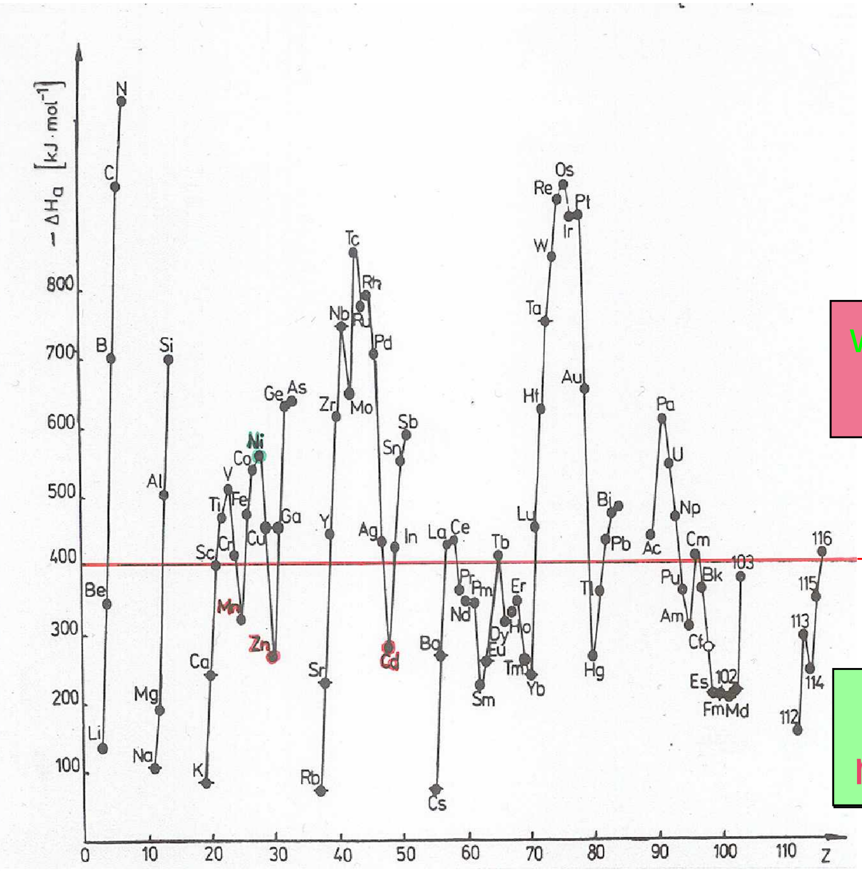
• production	specific reaction A(x,y)B, thermal fission, fast fission/spallation
• target temp.	$\tau_{release} = f(T_{target})$ $T_{target} \approx T_{desorpt.} = f(\Delta H_{adsorpt.}) = f(Z)$
• duty-cycle	optimize acc. to beam structure, $t_{release}$, $T_{½}$, $T_{½}$(isobars)
• ionisation	positive/negative surface ionization; laser ionization
• separation	TOF-DE/E isobaric mass separation (HRS) chemistry before or after mass separation; isomers (HF-splitting)
• detection	shielding against background; specific decay modes, e.g. β–n-γ–t multi-fold coincidences

CERN-ISOLDE

Th-foil target; hot plasma source

Thermal desorption from Th-target





will not be released

will be released

Desorption-Temp. For 50% volatilisation as fct. of Adsorption-Enthalphy

with 1800 K, Th-target too slow !

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Physik Journal

Heft 1 /2005

Kernphysik

Von Schalen, Clustern und Halos – moderne Aspekte der Kernstruktur

Hans Feldmeier und Thomas Neff

Epilog:

Auf dem Weg der Erkenntnis „was unsere Welt im Innersten zusammenhält“, wie es Goethe formulierte, sind die Atomkerne eine reichhaltige Informationsquelle, denn in ihnen sind drei der vier fundamentalen Kräfte (starke, schwache und elektro-magnetische) aktiv, wobei die starke Wechselwirkung der Quantenchromodynamik die größte Rolle spielt. Trotzdem verbrachte die Kernstrukturphysik die letzten Jahrzehnte in einem „Dornröschenschlaf“. Durch neue theoretische ab-initio-Methoden und neue experimentelle Möglichkeiten, insbesondere aber auch durch die großen Fortschritte in der astrophysikalischen Erkundung unseres Universums, konnten die Wissenschaftler die Geldgeber überzeugen, sie wieder aufzuwecken. Davon zeugen z. B. die zur Zeit neu ausgeschriebenen Lehrstühle für nukleare Astrophysik oder auch der SFB „Kernstruktur, nukleare Astrophysik und fundamentale Experimente bei kleinen Impulsüberträgen am supraleitenden S-DALINAC“ an der TU Darmstadt, der in engem Zusammenhang mit den jetzigen und zukünftigen Forschungen der GSI zu sehen ist. Die Erforschung der Kernstruktur wird heute zu einem großen Teil von der Astrophysik angetrieben. Will man verstehen, was in der Weite des Weltalls die Evolution antreibt, muss man auf der Erde das experimentelle und theoretische Studium der exotischen Kerne erweitern. Noch ist man zum Beispiel nicht zu den Isotopen vorgedrungen, die an der Synthese schwerer Elemente durch schnellen Neutroneneinfang (r-Prozess) in explodierenden Sternen beteiligt sind.

Die Autoren

Hans Feldmeier (rechts) studierte und promovierte an der Technischen Hochschule (heute: TU) Darmstadt, wo er sich – nach einem Aufenthalt am Oak Ridge National Laboratory 1981 auch habilitierte. Nach weiteren Stationen als Heisenberg-Stipendiat ist er seit 1986 wissenschaftlicher Mitarbeiter bei der Gesellschaft für Schwerionenforschung GSI. **Thomas Neff** (links) studierte ebenfalls in Darmstadt, wo er an der GSI auch Diplom- und Doktorarbeit (2002) anfertigte. Seither ist er Postdoc an der GSI, mit Auslandsaufenthalten an der Kyoto University, der University of Tokio sowie dem Argonne National Laboratory.

... as an example for long „diffusion time“
from Mainz → GSI (Darmstadt)
from experimentalist → theoretician

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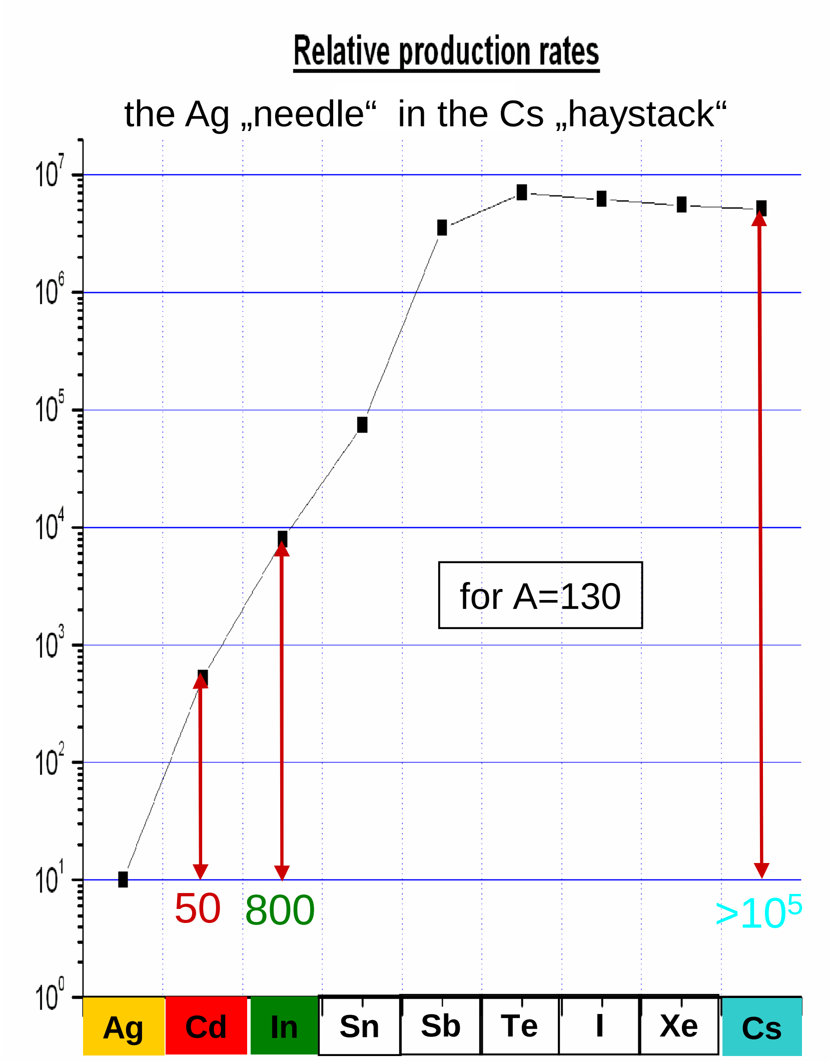
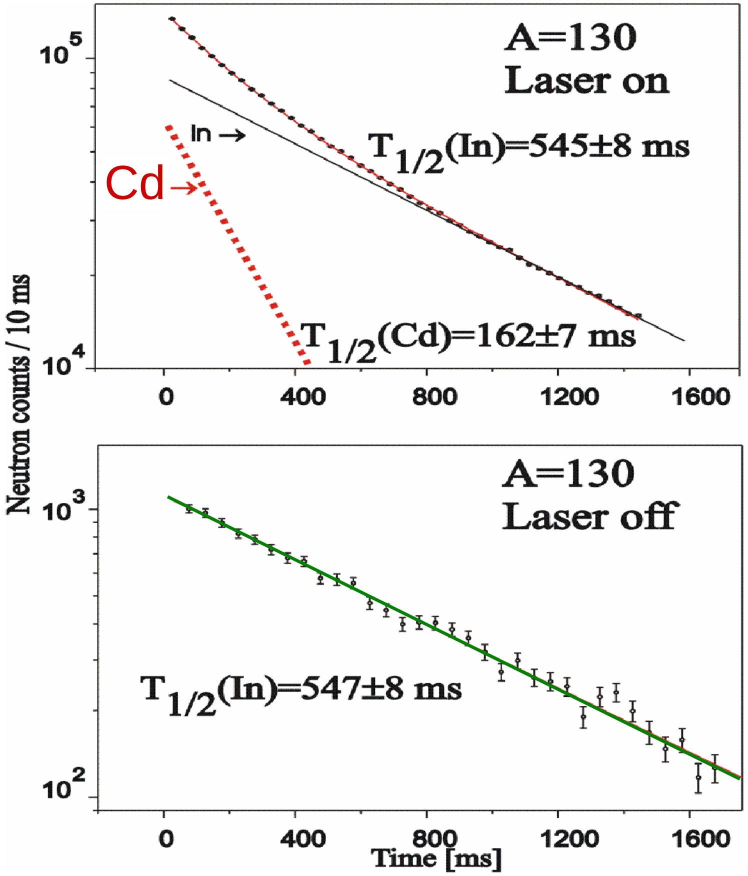
Selectivity at ISOLDE



today, at PSB-ISOLDE

- Fast UC_x target
- Neutron converter
- Laser ion-source (RILIS)
- Hyperfine splitting ($\pi g_{9/2}$)
- Isobar separation (HRS)
- Multi-coincidence setup



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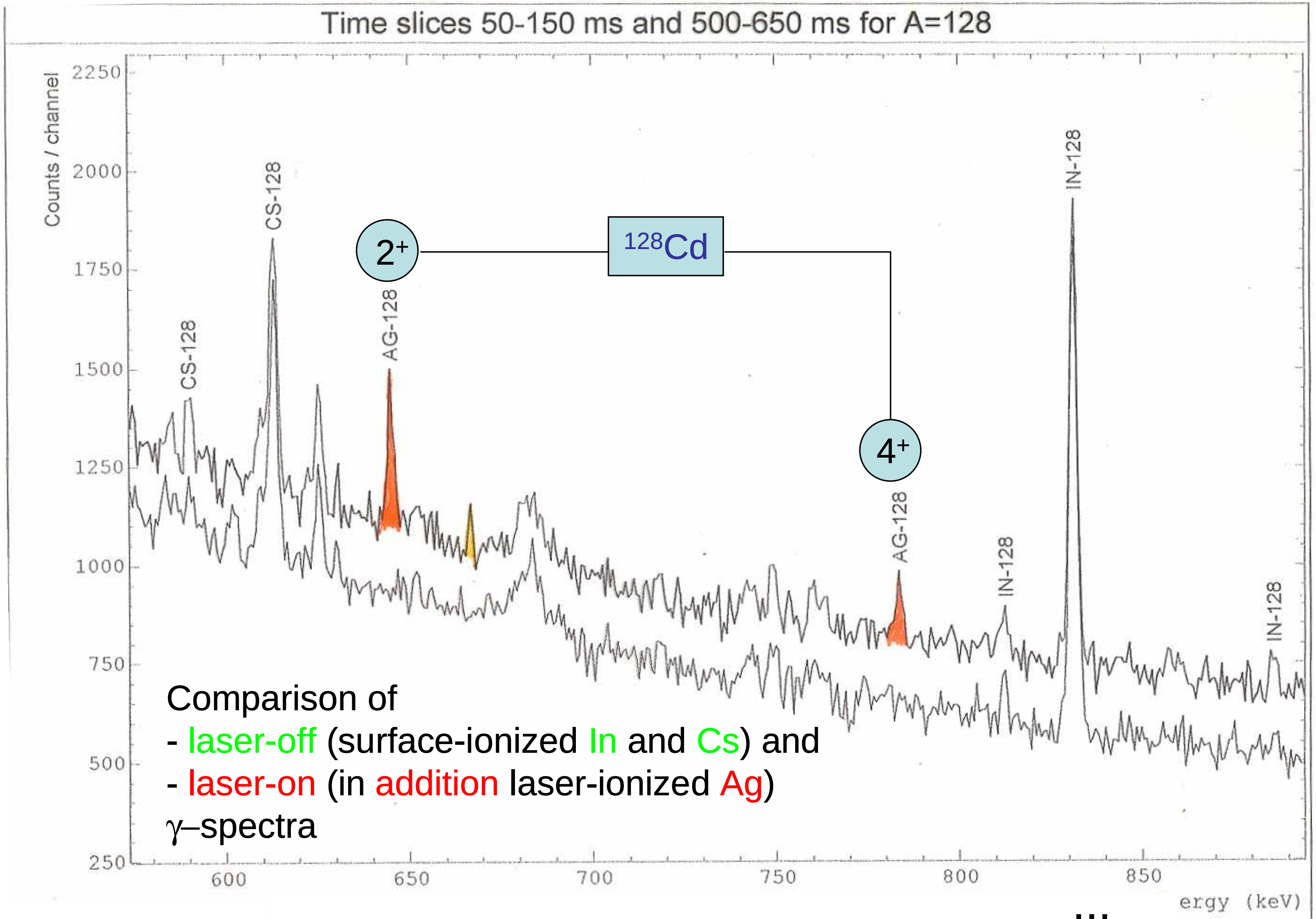


Comparison of
- laser-off (surface-ionized In and Cs) and
- laser-on (in addition laser-ionized Ag)
γ–spectra

Total beam-time at ISOLDE ca. 11 hours !!!

Accessibility of Elements by RILIS

Status 01/2005

🟩 **Elements studied with dye – laser RIS 45**

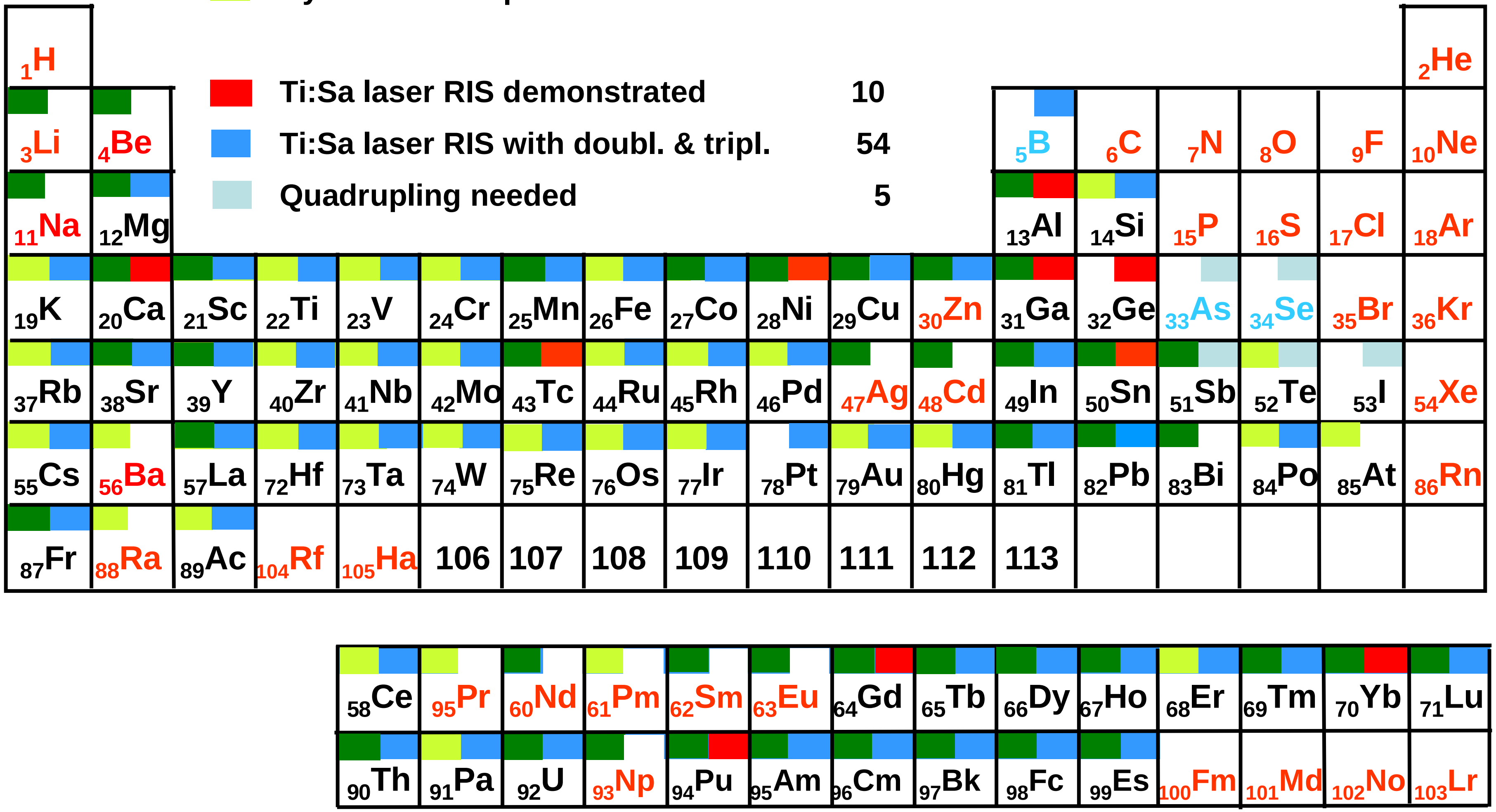
🟨 **Dye - laser RIS possible 33**

🟥 **Ti:Sa laser RIS demonstrated 10**

🟦 **Ti:Sa laser RIS with doubl. & tripl. 54**

⬜ **Quadrupling needed 5**

U. Köster, LAP 2002 & Spec Acta 58B, 2003
B. Federov, LASER 2004 Poznan & Hyp Int to be publ.



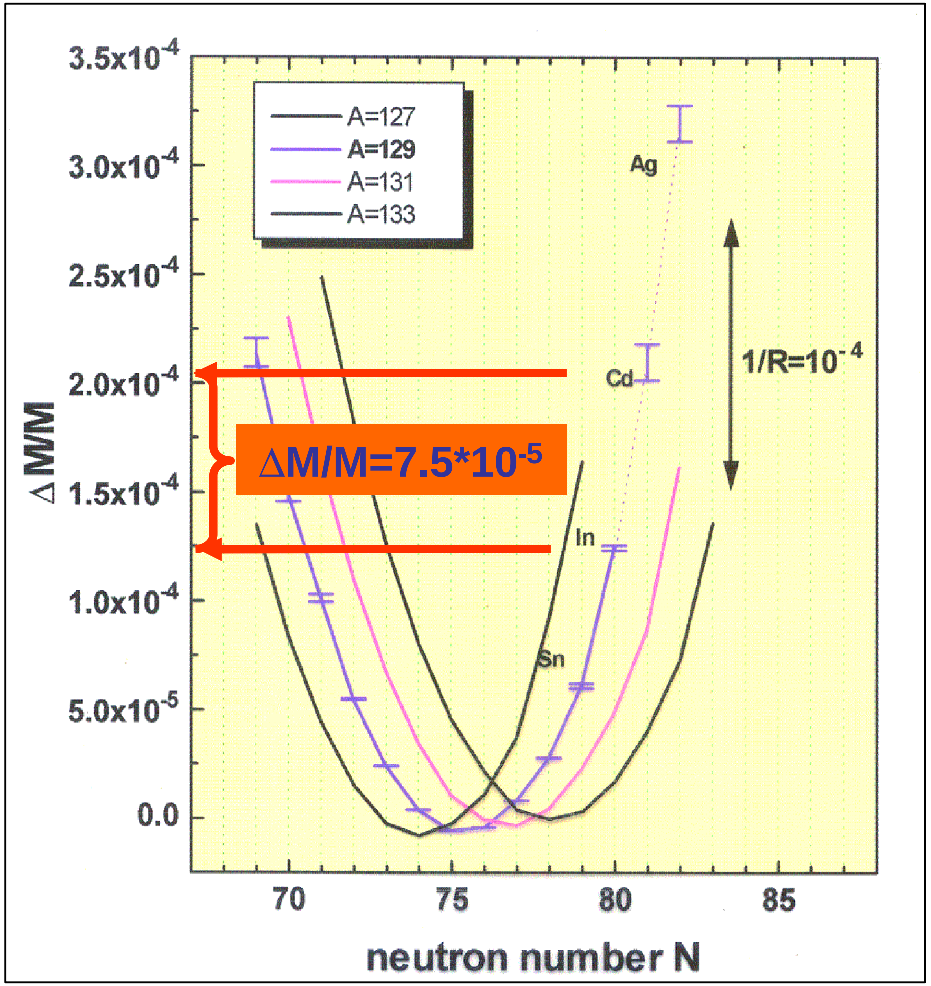
$_1$H																	$_2$He
🟩 $_3$Li	🟩 $_4$Be											🟦 $_5$B	$_6$C	$_7$N	$_8$O	$_9$F	$_{10}$Ne
🟩 $_{11}$Na	🟩🟦 $_{12}$Mg											🟩🟥 $_{13}$Al	🟨🟦 $_{14}$Si	$_{15}$P	$_{16}$S	$_{17}$Cl	$_{18}$Ar
🟨🟦 $_{19}$K	🟩🟥 $_{20}$Ca	🟩🟦 $_{21}$Sc	🟨🟦 $_{22}$Ti	🟨🟦 $_{23}$V	🟨🟦 $_{24}$Cr	🟩🟦 $_{25}$Mn	🟨🟦 $_{26}$Fe	🟩🟦 $_{27}$Co	🟩🟥 $_{28}$Ni	🟩🟦 $_{29}$Cu	🟩🟦 $_{30}$Zn	🟩🟥 $_{31}$Ga	🟥 $_{32}$Ge	⬜ $_{33}$As	⬜ $_{34}$Se	$_{35}$Br	$_{36}$Kr
🟨🟦 $_{37}$Rb	🟩🟦 $_{38}$Sr	🟩🟦 $_{39}$Y	🟨🟦 $_{40}$Zr	🟨🟦 $_{41}$Nb	🟨🟦 $_{42}$Mo	🟩🟥 $_{43}$Tc	🟨🟦 $_{44}$Ru	🟨🟦 $_{45}$Rh	🟨🟦 $_{46}$Pd	🟩 $_{47}$Ag	🟩 $_{48}$Cd	🟩🟦 $_{49}$In	🟩🟥 $_{50}$Sn	🟩⬜ $_{51}$Sb	🟨⬜ $_{52}$Te	⬜ $_{53}$I	$_{54}$Xe
🟨🟦 $_{55}$Cs	🟨 $_{56}$Ba	🟩🟦 $_{57}$La	🟨🟦 $_{72}$Hf	🟨🟦 $_{73}$Ta	🟨🟦 $_{74}$W	🟨🟦 $_{75}$Re	🟨🟦 $_{76}$Os	🟨🟦 $_{77}$Ir	🟦 $_{78}$Pt	🟨🟦 $_{79}$Au	🟨🟦 $_{80}$Hg	🟩🟦 $_{81}$Tl	🟩🟦 $_{82}$Pb	🟩 $_{83}$Bi	🟨🟦 $_{84}$Po	🟨 $_{85}$At	$_{86}$Rn
🟩🟦 $_{87}$Fr	🟨 $_{88}$Ra	🟨🟦 $_{89}$Ac	$_{104}$Rf	$_{105}$Ha	106	107	108	109	110	111	112	113					
			🟨🟦 $_{58}$Ce	🟨 $_{95}$Pr	🟩 $_{60}$Nd	🟨 $_{61}$Pm	🟩 $_{62}$Sm	🟩 $_{63}$Eu	🟩🟥 $_{64}$Gd	🟩🟦 $_{65}$Tb	🟩🟦 $_{66}$Dy	🟩🟦 $_{67}$Ho	🟨🟦 $_{68}$Er	🟩🟦 $_{69}$Tm	🟩🟥 $_{70}$Yb	🟩🟦 $_{71}$Lu	
			🟩🟦 $_{90}$Th	🟨🟦 $_{91}$Pa	🟩🟦 $_{92}$U	🟩 $_{93}$Np	🟩🟥 $_{94}$Pu	🟩🟦 $_{95}$Am	🟩🟦 $_{96}$Cm	🟩🟦 $_{97}$Bk	🟩🟦 $_{98}$Fc	🟩🟦 $_{99}$Es	$_{100}$Fm	$_{101}$Md	$_{102}$No	$_{103}$Lr	

from K. Wendt

K.-L. Kratz ND'05

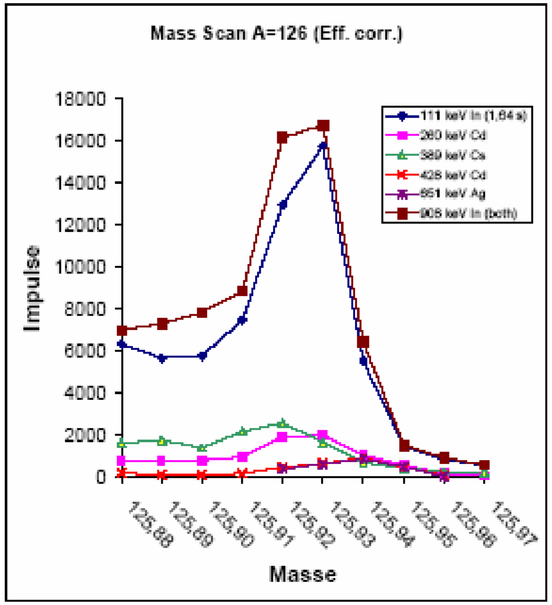
Isobar separation

HRS design $\Delta M/M \geq 1/10^4$

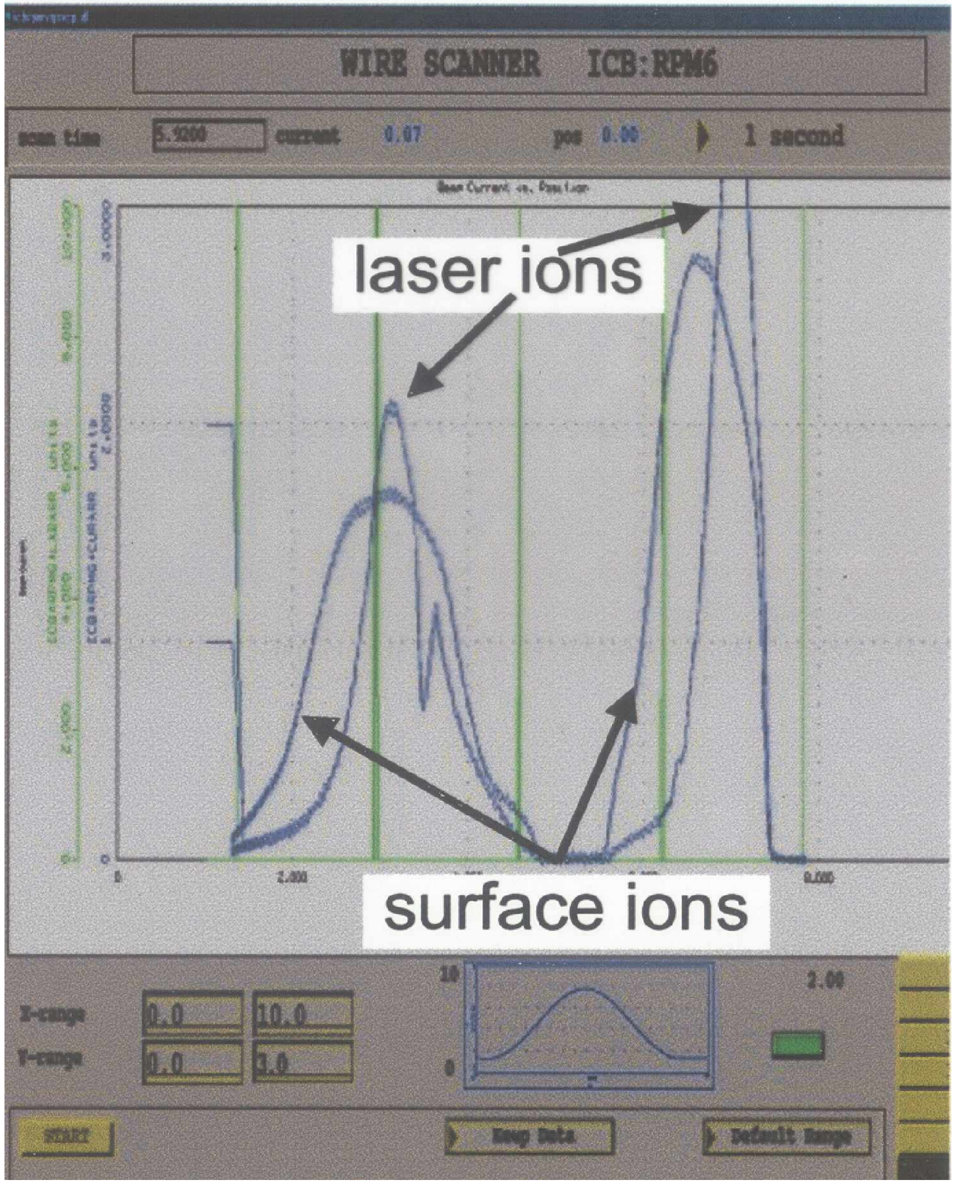


in reality, „on a good day…“

$\Delta M/M \approx 1/4000$



Mass scan at HRS (ISOLDE) in 2002;
efficiency corrected



scan time 5.9200
current 0.07
pos 0.00

X-range 0.0 10.0
Y-range 0.0 3.0

Comparison of spatial beam profiles

28 VOLT repeller:

Selection between

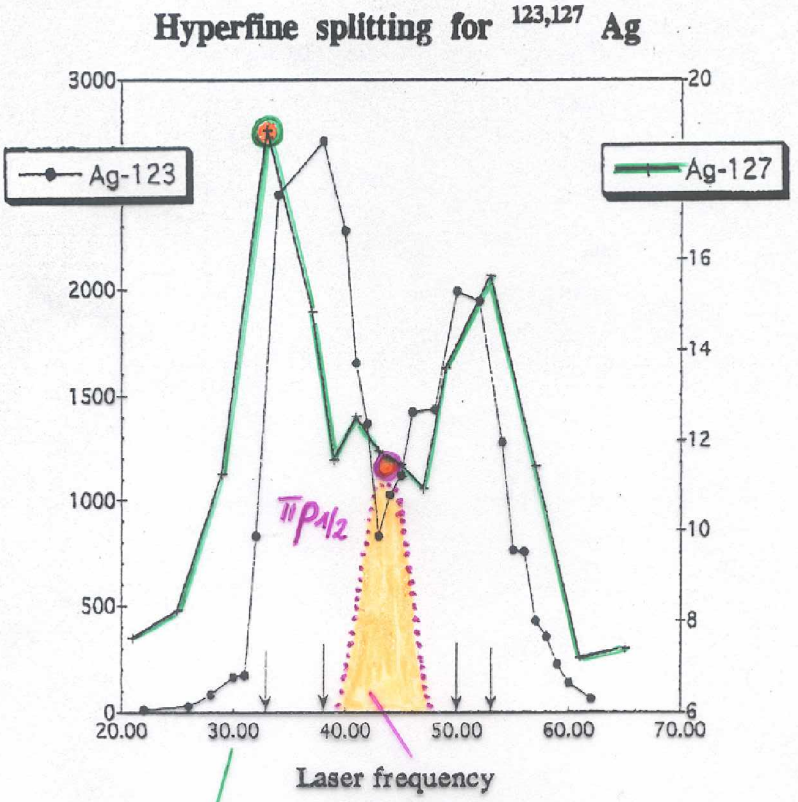
- **laser ions (laser & repeller on)**

and

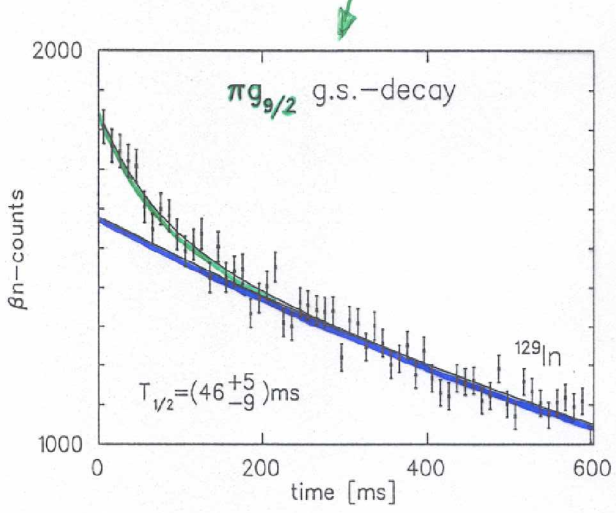
- **surface ions (laser & repeller off)**

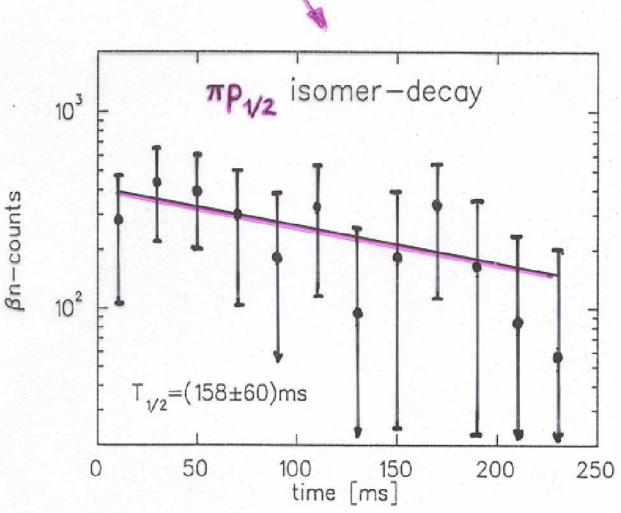
from K. Wendt

K.-L. Kratz ND'05



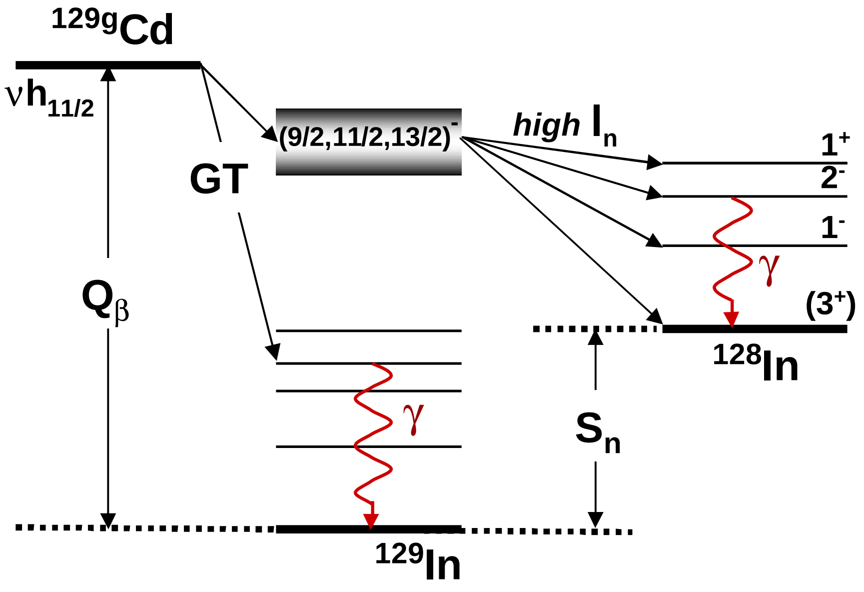
R–Process Waiting–Point $^{129}Ag_{82}$

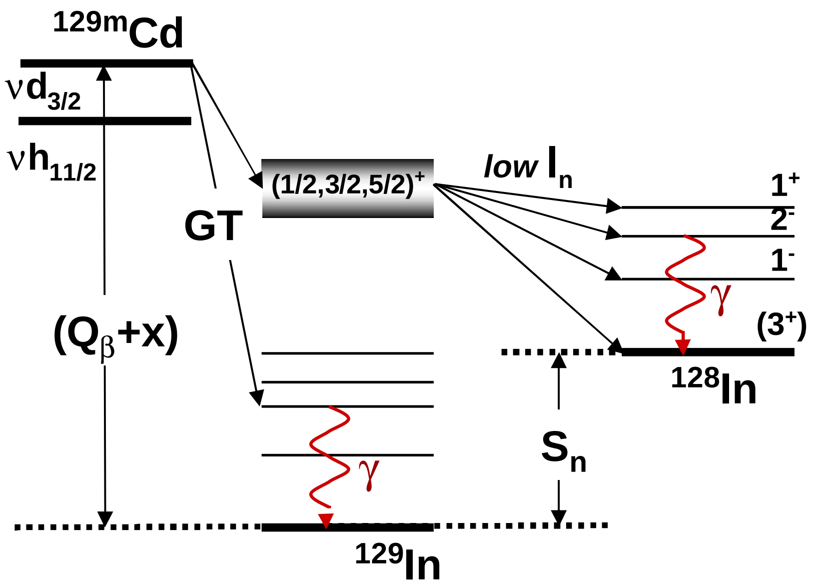




only evidence !

Differences in βdn energy spectra of ^{129}Cd



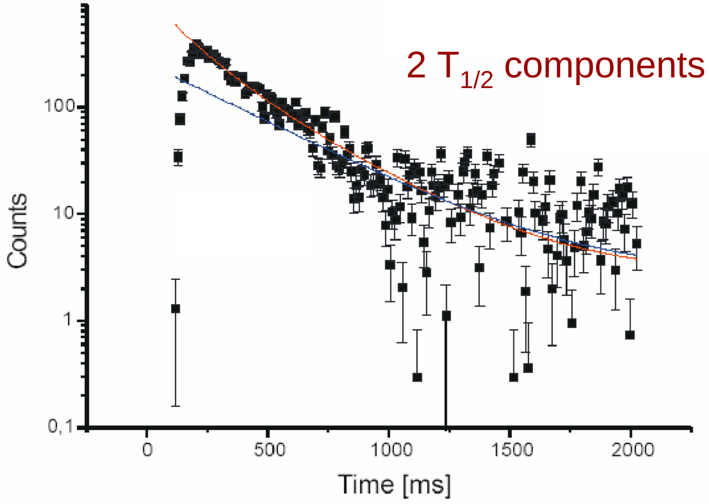


“hard“ βdn-spectrum mainly outer ^{3}He ring

“soft“ βdn-spectrum mainly inner ^{3}He ring

of longcounter

$T_{1/2}(^{129g}\mathrm{Cd}) = 242(8)$ ms

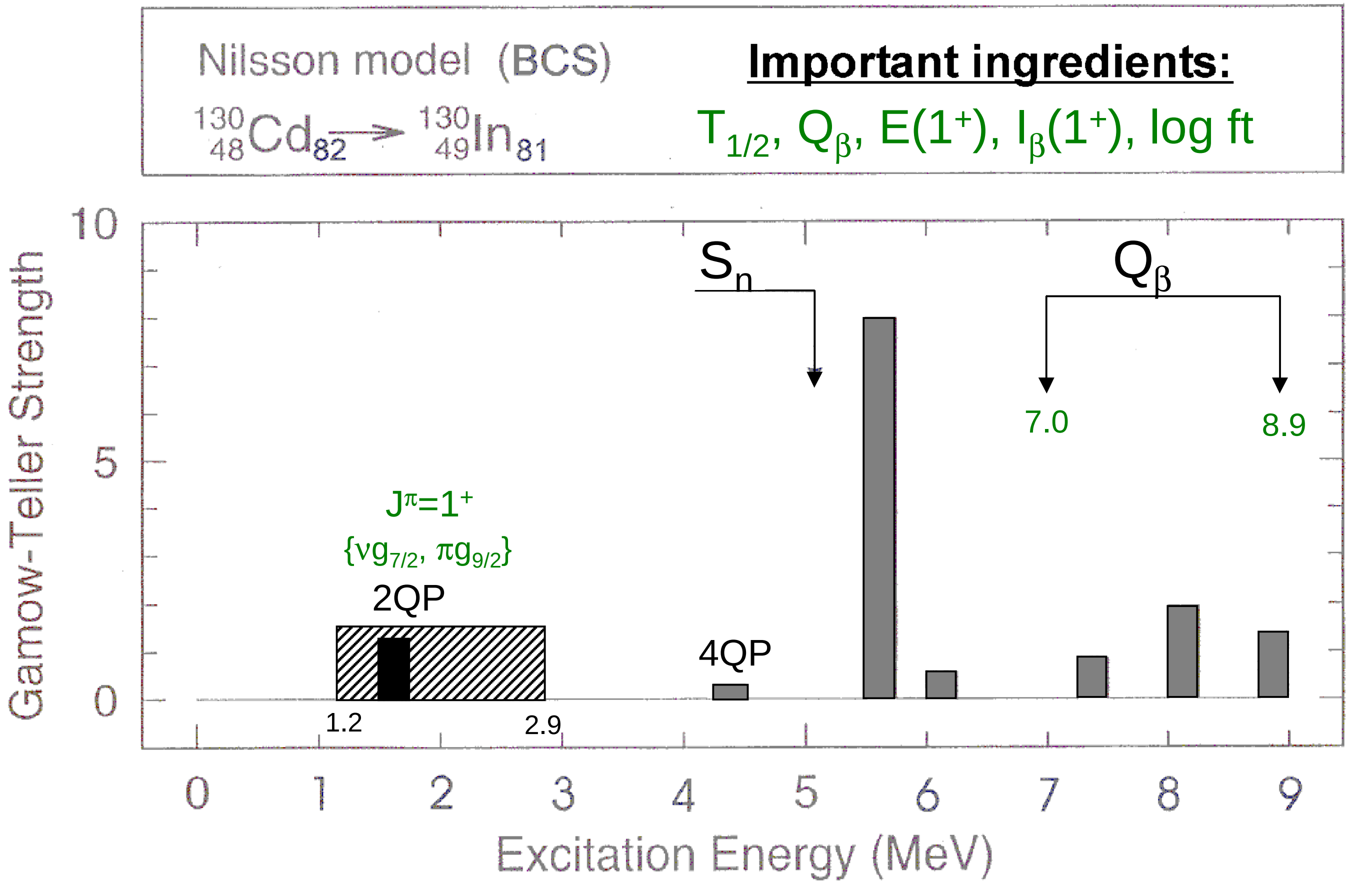


$T_{1/2}(^{129m}\mathrm{Cd}) = 104(6)$ ms

O. Arndt (Diploma Thesis; 2003)

The r-process “waiting-point“ nucleus ^{130}Cd

...obtain a physically consistent picture!



Important ingredients:

$T_{1/2}$, Q_β, $E(1^+)$, $I_\beta(1^+)$, log ft

„free choice“ of combinations:

low $E(1^+)$ with low Q_β
high $E(1^+)$ with low Q_β
low $E(1^+)$ with high Q_β
high $E(1^+)$ with high Q_β

Example:

$^{130}_{48}\mathrm{Cd}_{82}$

…just one proton-pair below double magic ^{132}Sn.

-RPA model prediction in 1986 quite good:

- E(1^+) ≅ 2.1 MeV
- log(ft) ≅ 4.1
- Q_β ≅ 8.0 MeV

$T_{½}$(GT)≅ 300ms

Most recent shell modell calculations are inconsistent:

(i) Martinez-Pinedo & Langanke (ANTOINE)

- E(1^+) ≅ 1.55 MeV
- log(ft) ≅ 3.8 !
- Q_β ≅ 7.56 MeV

$T_{½}$(GT)≅ 146ms

(ii) Brown et al. (OXBASH)

- E(1^+) ≅ 1.38 MeV
- log(ft) ≅ 4.2
- Q_β ≅ 8.75 MeV

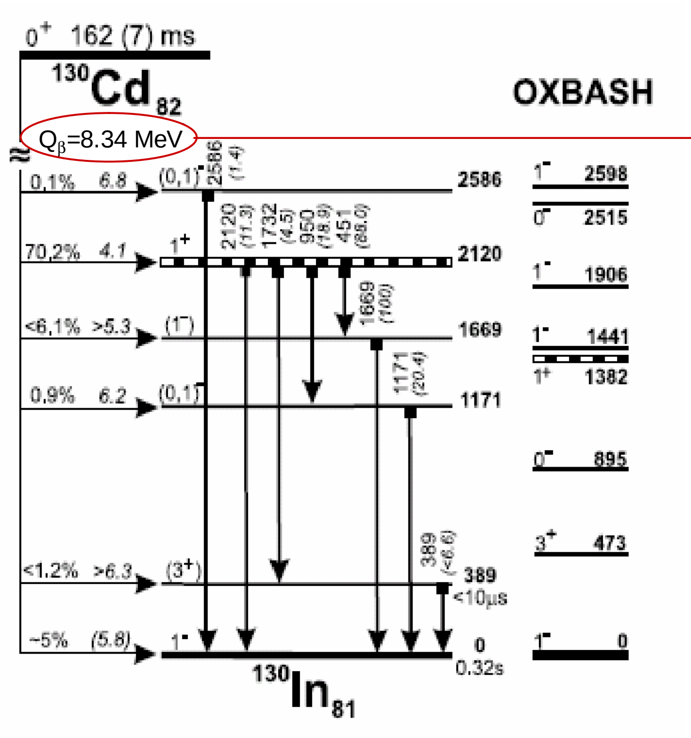
$T_{½}$(GT)≅ 180ms

(iii) Vretenar & Ring (RMF+QRPA)

- no information about E(1^+), log(ft), Q_β, but correct $T_{½}$
  however, ^{132}Sn predicted to be stable !

^{130}Cd decay spectroscopy spectroscopy

ISOLDE experiment – Q_β from measurement of β-spectrum endpoint energy:



Large Q_β value best reproduced by
mass models with N=82
shell quenching

Mass model predictions	Q_β
Hilf et al. (*GTNM*, 1976)	**7.57 MeV**
Möller et al. (*FRDM*, 1995):	**7.43 MeV**
Aboussir et al. (*ETFSI*, 1995):	**7.87 MeV**
Duflo & Zuker (1995)	**7.56 MeV**
Dobaczewski et al. (*HFB/SkP*, 1996):	**8.93 MeV**
Pearson et al. (*ETFSI-Q*, 1996):	**8.30 MeV**
Audi & Wapstra (*Mass Eval.*, 1997):	**8.50 MeV**
Goriely et al. (*HFBCS*, 2001)	**7.00 MeV**
Samyn et al. (*HFB-2*, 2002)	**7.64 MeV**
Brown et al. (*local OXBASH*, 2003):	**8.75 MeV**

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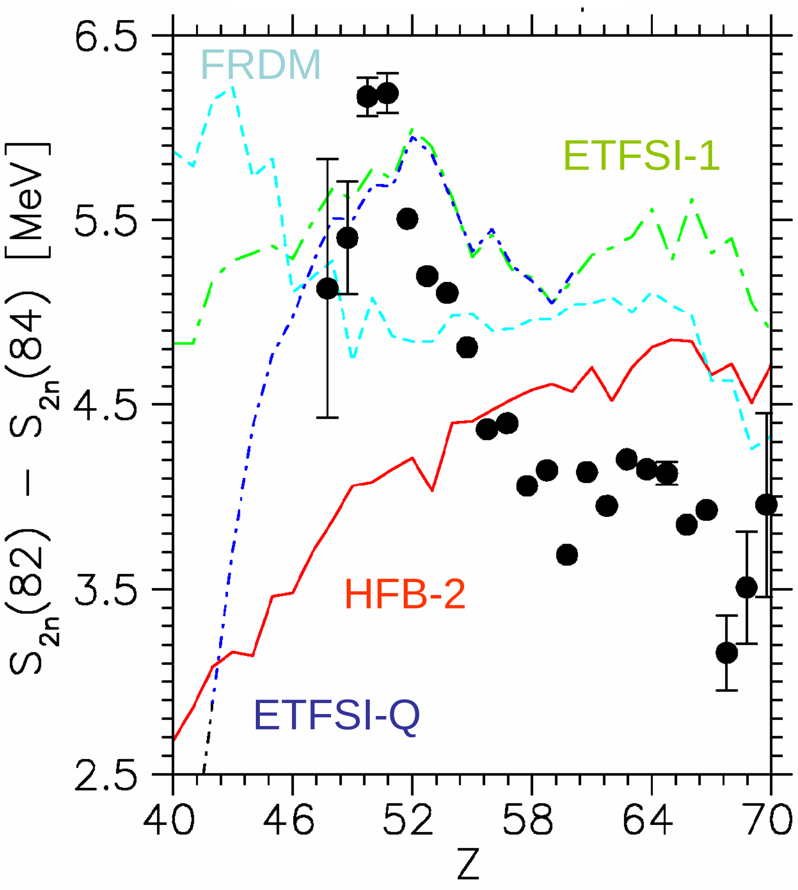
The N=82 shell gap



NONE of the mass models predicts the trend correctly!

Request **mass measurements** south of ^{132}Sn

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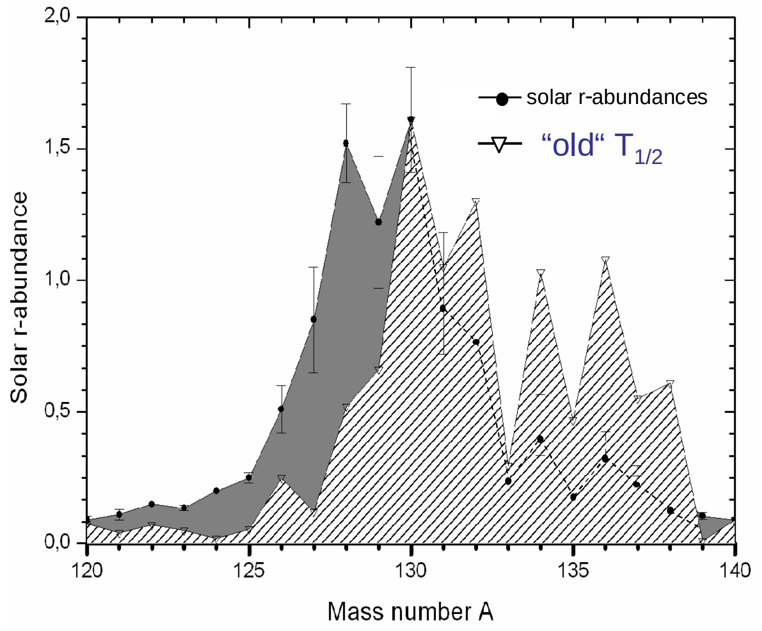
Astrophysical consequences

...mainly resulting from new nuclear-structure information:

- better understanding of formation and shape of as well as r-process matter flow through } the A≈130 $N_{r,¤}$ peak
- no justification to question waiting-point concept (Martinez-Pinedo et al., PRL 83, 1999)
- no need to request sizeable effects from ν-induced reactions (Qian et al., PRC 55, 1997)

ð r-process abundances in the Solar System and in UMP Halo stars...

...are governed by nuclear structure!

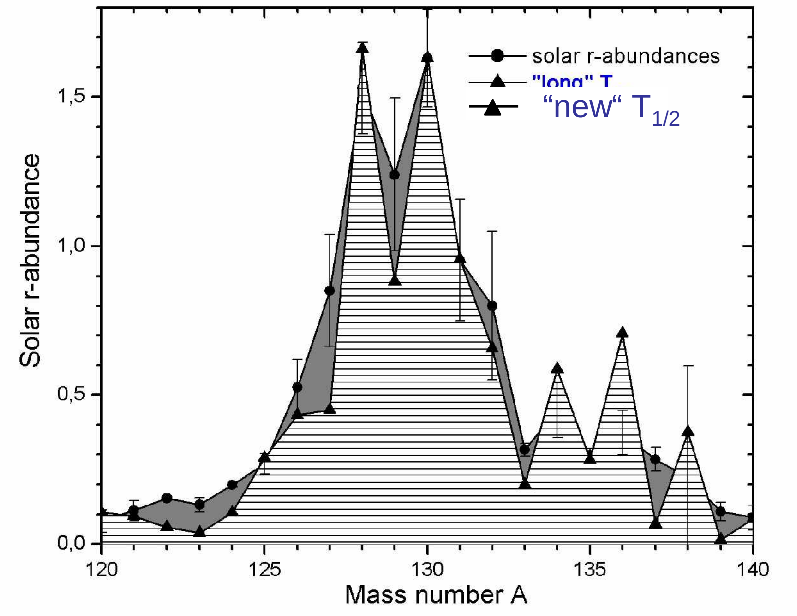


Nuclear masses from AMDC, 2003

&

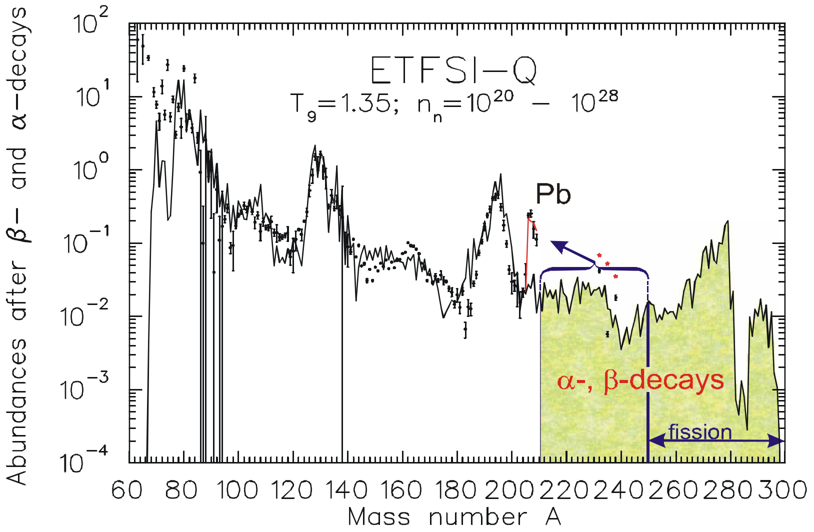
ETFSI-Q

Normalized to $N_{r,¤}$ (^{130}Te)



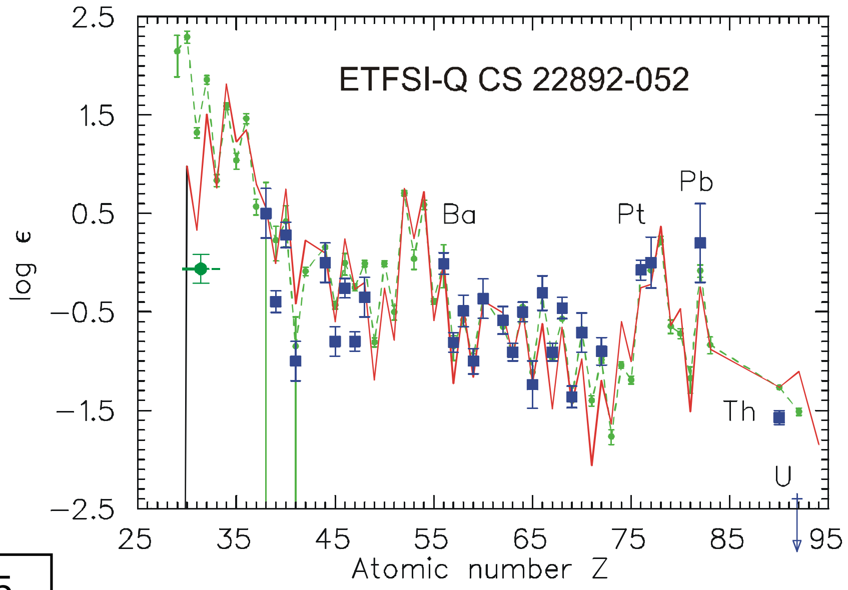
What do we calculate?

Reproduce isotopic $N_{r,\odot}$ distribution using waiting-point approach (lsq-fits; A ⩾ 80, A ⩾ 120)



3rd $N_{r,\odot}$ peak and Pb abundances as reliability criterion for Th,U region!

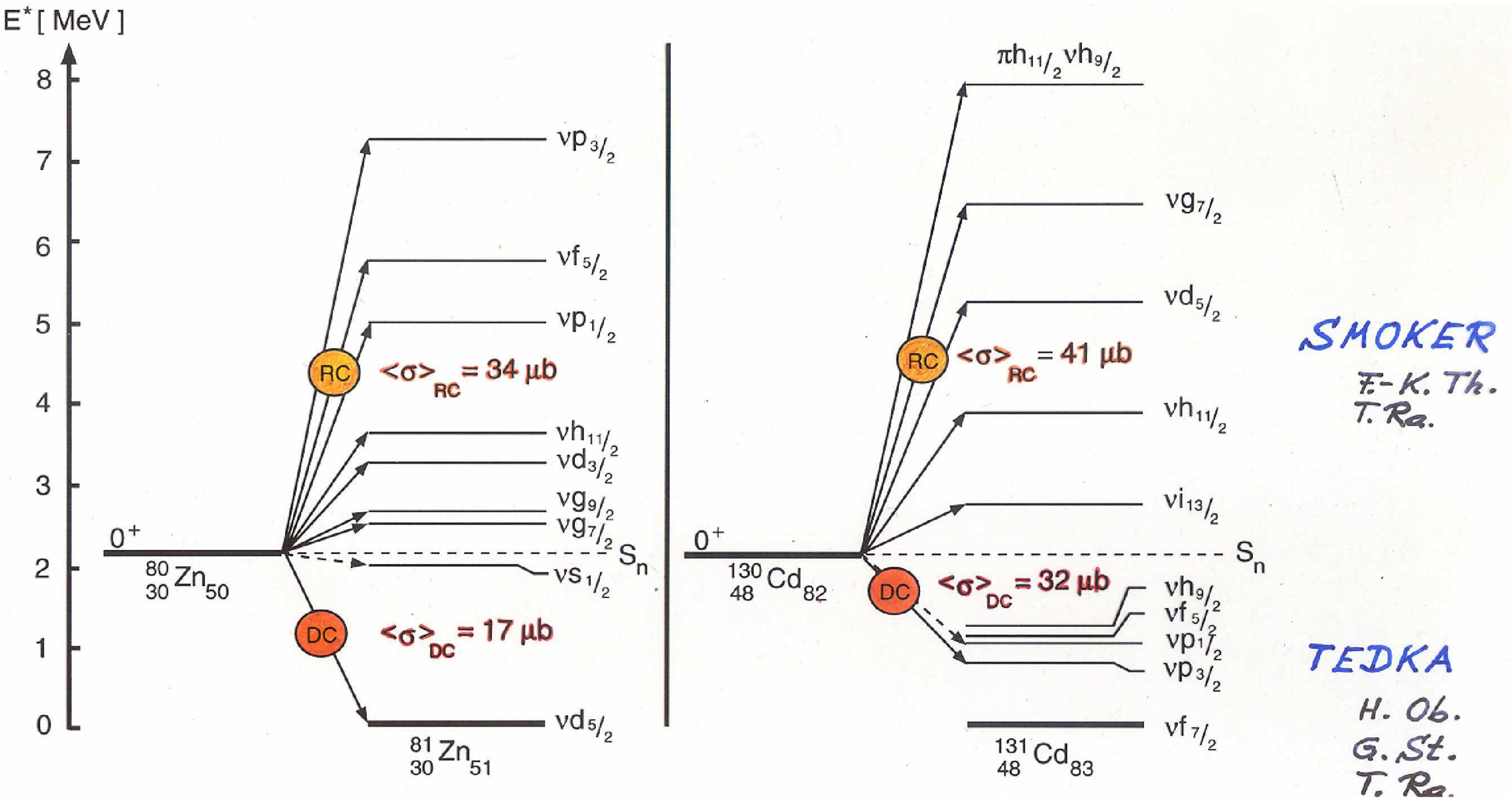
Convert to elemental $N_{r,\odot}$ curve(▬), and scale to halo abundances (■)



comparision to $N_{r,\odot}(Z)$

⇒ excellent agreement above Ba

⇒ Th, U cosmochronometry



old $\langle\sigma\rangle_{HF}$ =35 μb

$\langle\sigma\rangle_{HF}$ = 20 μb

RIB experiment: (d,p) in inverse kinematics → E_L, ln(J^{π}), C^2S

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Near-future perspectives

As shown by selected examples,
the study of r-process isotopes requires
the combination of several optimizations in
isotope production, separation and detection.

However, we nearly have reached the top of the flagpole of present ISOL facilities.

What can still be done ?

1. Detailed decay-spectroscopy of N=50 $^{79}\mathrm{Cu}$ and N=82 $^{129}\mathrm{Ag}$ (similar to $^{80}\mathrm{Zn}$ and $^{130}\mathrm{Cd}$)

2. $^{131}\mathrm{Cd}$ $\beta\gamma$, $^{132}\mathrm{Cd}$ $\beta n\gamma$ à π-hole states in $^{131}_{49}\mathrm{In}_{82}$

3. $^{130}\mathrm{Ag}$ $\beta\gamma$ à E(2^+), E(4^+)/E(2^+) in N=82 $^{130}\mathrm{Cd}$

4. $^{130}\mathrm{Cd}$ (d,p) à “simulate“ n-capture on classical “waiting point“

5. Clever target-ionsource chemistry
   doubly semi-magic $^{110}_{40}\mathrm{Zr}_{70}$ as new “waiting point“ ?