Nuclear Spectroscopy –
helping to understand how heavy elements are made

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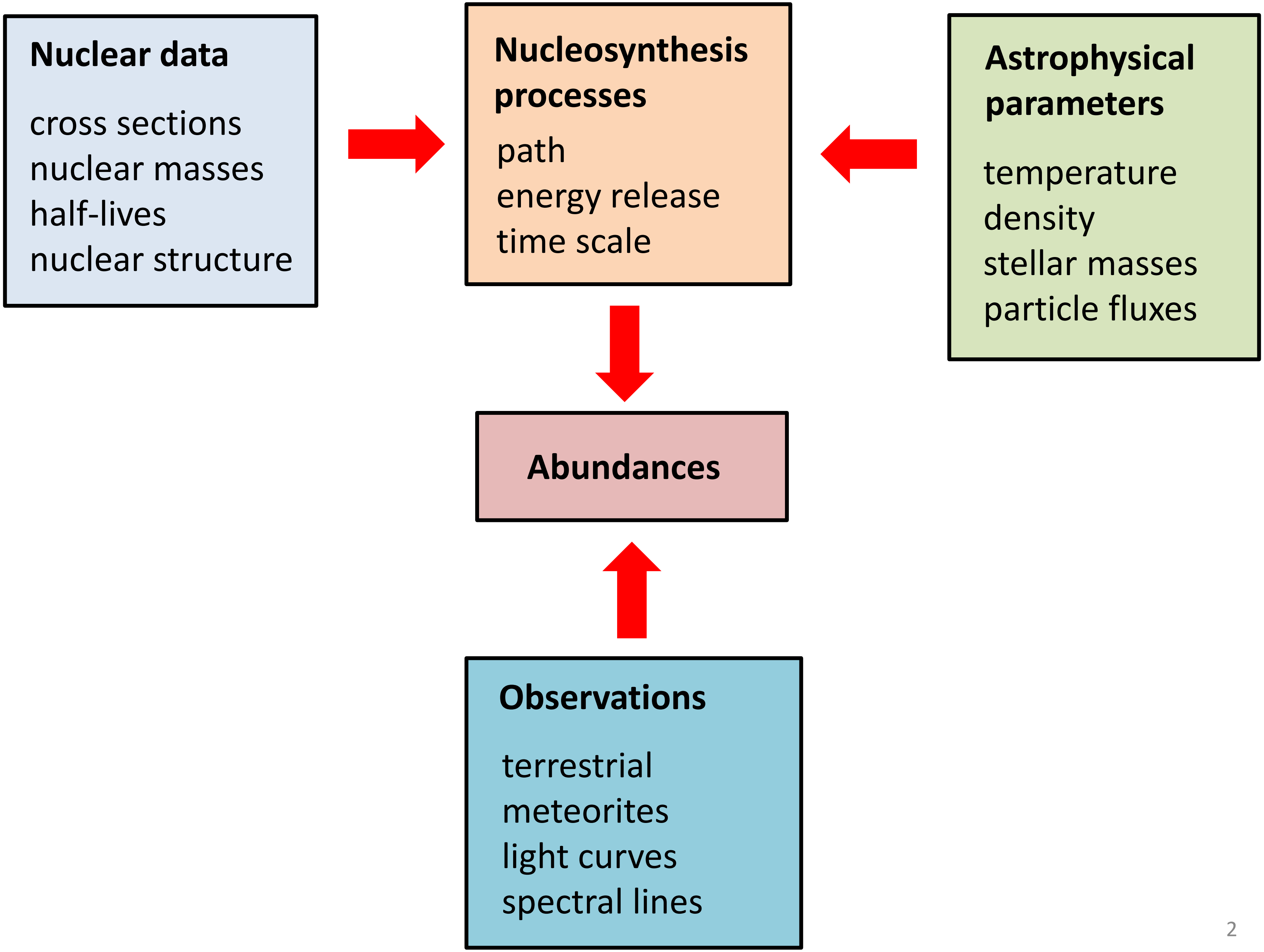


Nuclear data

- cross sections
- nuclear masses
- half-lives
- nuclear structure

Nucleosynthesis processes

- path
- energy release
- time scale

Astrophysical parameters

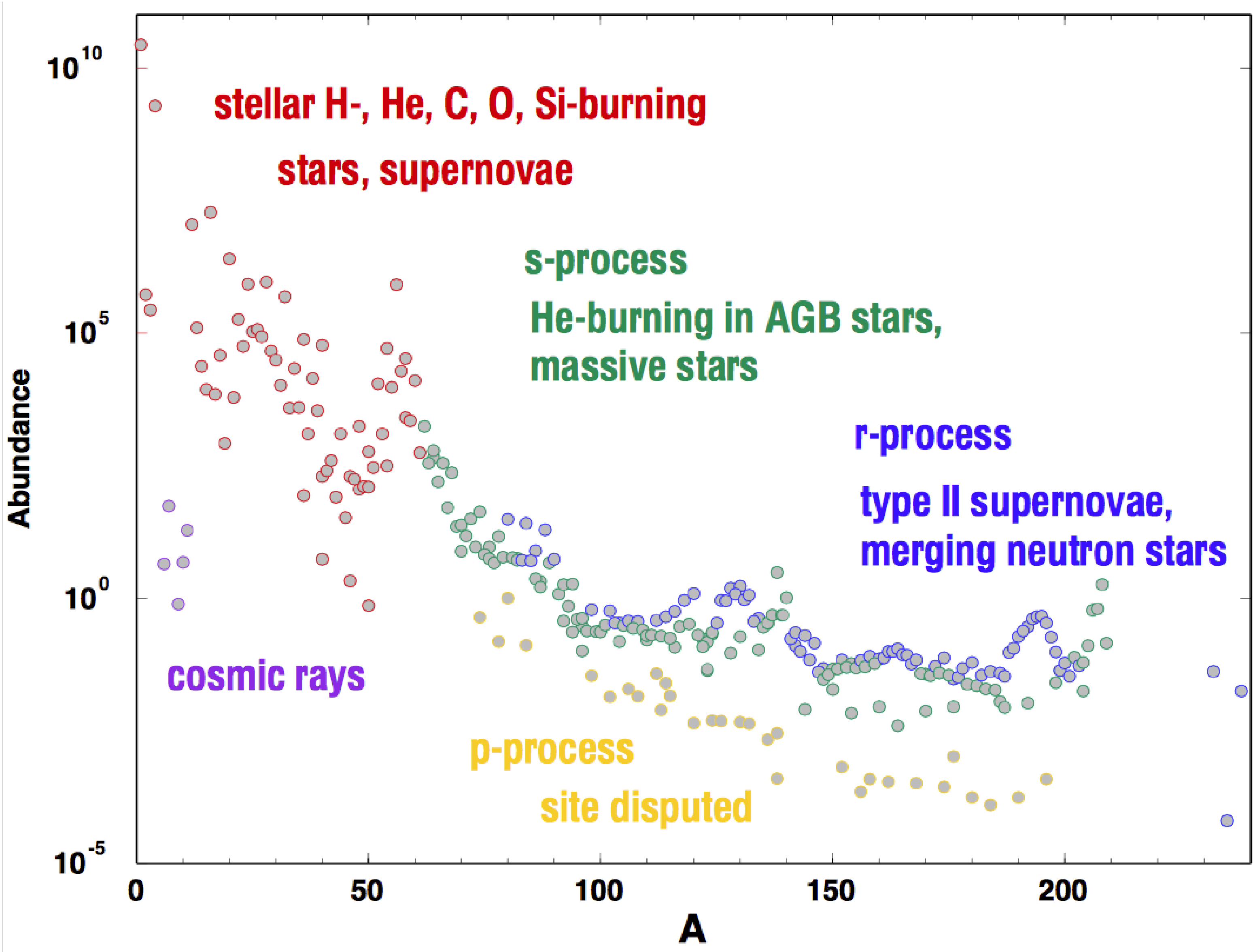
- temperature
- density
- stellar masses
- particle fluxes

Abundances

Observations

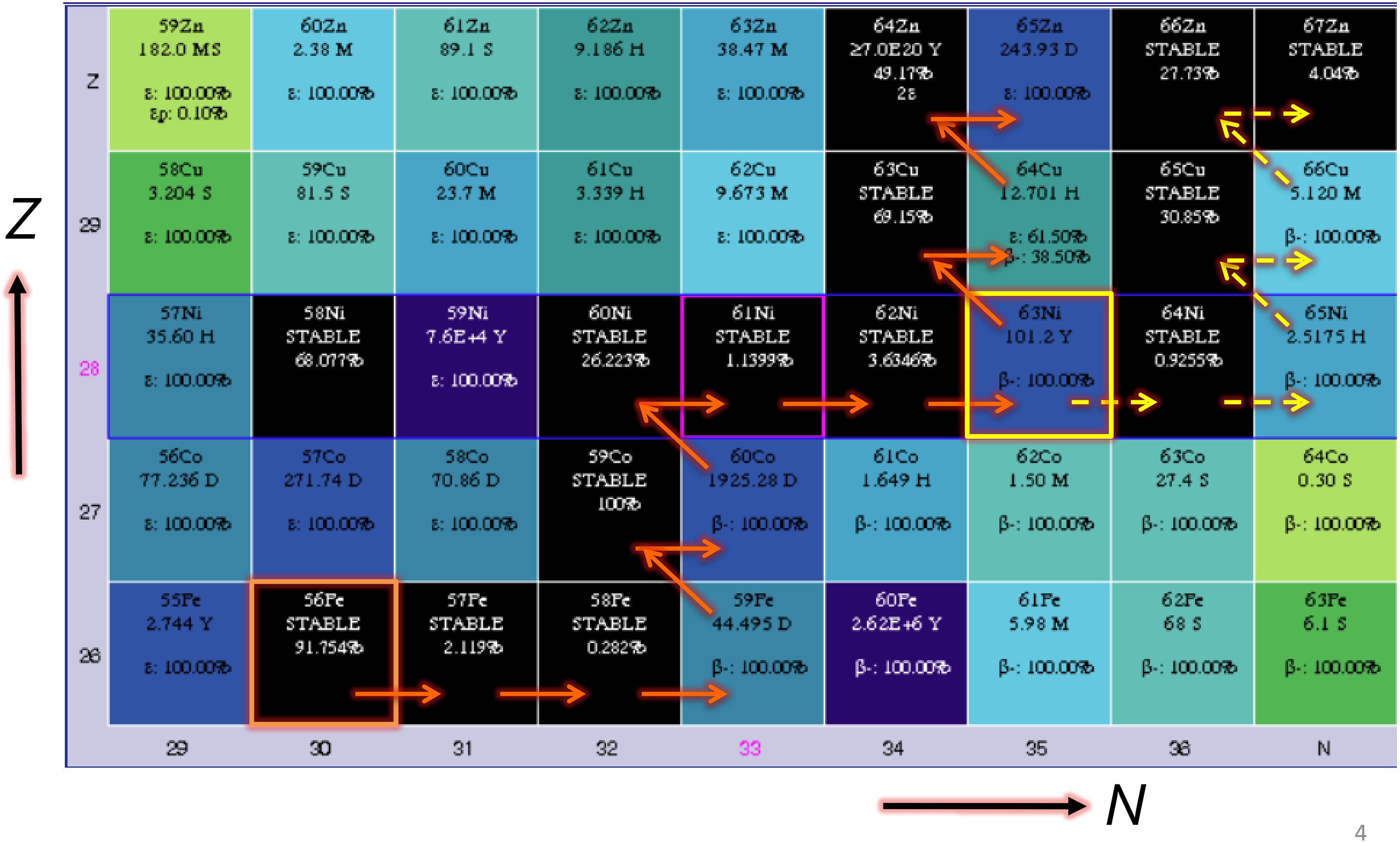
- terrestrial
- meteorites
- light curves
- spectral lines

Nucleosynthesis



from M.Wiescher, JINA lectures Nuclear Astrophysics

s – prosess : slow neutron capture



Z	59Zn 182.0 MS ε: 100.00% εp: 0.10%	60Zn 2.38 M ε: 100.00%	61Zn 89.1 S ε: 100.00%	62Zn 9.186 H ε: 100.00%	63Zn 38.47 M ε: 100.00%	64Zn ≥7.0E20 Y 49.17% 2ε	65Zn 243.93 D ε: 100.00%	66Zn STABLE 27.73%	67Zn STABLE 4.04%
29	58Cu 3.204 S ε: 100.00%	59Cu 81.5 S ε: 100.00%	60Cu 23.7 M ε: 100.00%	61Cu 3.339 H ε: 100.00%	62Cu 9.673 M ε: 100.00%	63Cu STABLE 69.15%	64Cu 12.701 H ε: 61.50% β-: 38.50%	65Cu STABLE 30.85%	66Cu 5.120 M β-: 100.00%
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	29	30	31	32	33	34	35	36	N

r – prosess : rapid neutron capture

Z	74Se STABLE 0.89%	75Se 119.78 D ε: 100.00%	76Se STABLE 9.37%	77Se STABLE 7.63%	78Se STABLE 23.77%	79Se 3.26E+5 Y β-: 100.00%	80Se STABLE 49.61% 2β-	81Se 18.45 M β-: 100.00%	82Se STABLE 8.73%
33	73As 80.30 D ε: 100.00%	74As 17.77 D ε: 66.00% β-: 34.00%	75As STABLE 100%	76As 1.0942 D β-: 100.00%	77As 38.83 H β-: 100.00%	78As 90.7 M β-: 100.00%	79As 9.01 M β-: 100.00%	80As 15.2 S β-: 100.00%	81As 33.3 S β-: 100.00%
32	72Ge STABLE 27.45%	73Ge STABLE 7.75%	74Ge STABLE 36.50%	75Ge 82.78 M β-: 100.00%	76Ge STABLE 7.73%	77Ge 11.30 H β-: 100.00%	78Ge 88.0 M β-: 100.00%	79Ge 18.98 S β-: 100.00%	80Ge 29.5 S β-: 100.00%
31	71Ga STABLE 39.892%	72Ga 14.10 H β-: 100.00%	73Ga 4.86 H β-: 100.00%	74Ga 8.12 M β-: 100.00%	75Ga 126 S β-: 100.00%	76Ga 32.6 S β-: 100.00%	77Ga 13.2 S β-: 100.00%	78Ga 5.09 S β-: 100.00%	79Ga 2.847 S β-: 100.00% β-n: 0.09%
30	70Zn ≥2.3E+17 Y 0.61% 2β-	71Zn 2.45 M β-: 100.00%	72Zn 46.5 H β-: 100.00%	73Zn 23.5 S β-: 100.00%	74Zn 95.6 S β-: 100.00%	75Zn 10.2 S β-: 100.00%	76Zn 5.7 S β-: 100.00%	77Zn 2.08 S β-: 100.00%	78Zn 1.47 S β-: 100.00%
	40	41	42	43	44	45	46	47	N

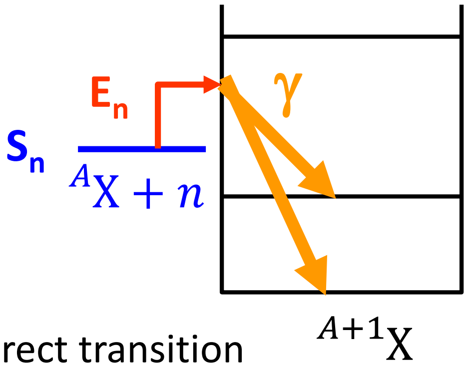
How is ^{76}Ge produced
when $T_{1/2}$ for ^{75}Ge is only 83 min?

or ^{82}Se when $T_{1/2}$ for ^{81}Se is only 18 min?

many neutron ⇒ rapid neutron capture

Neutron capture reactions

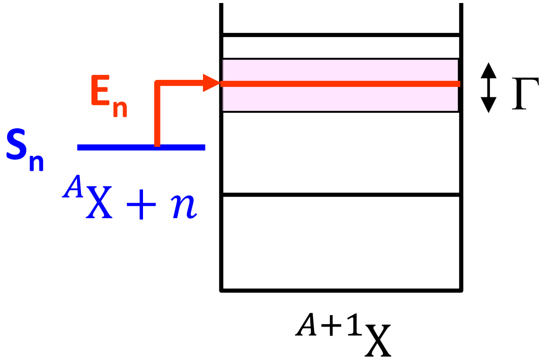
direct capture



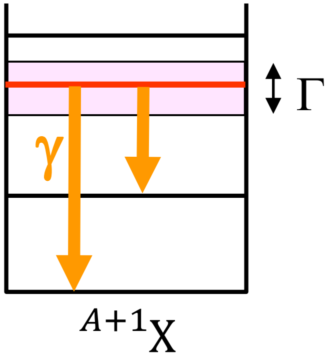
direct transition
into <u>bound states</u>

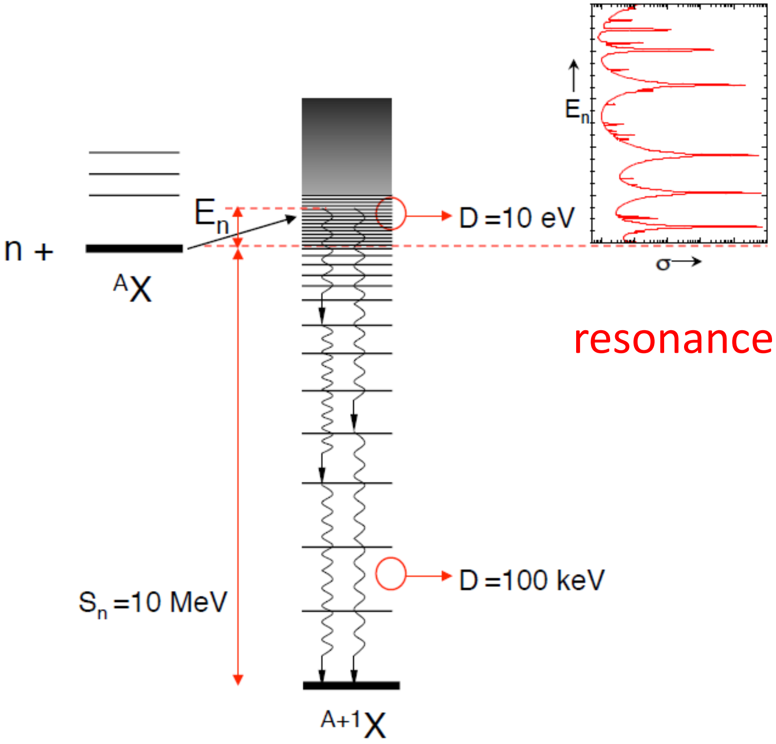
resonant capture

Step 1: Compound nucleus formation
(into an unbound state)



Step 2:
Compound
nucleus decay





resonances

E_n has to "match" an
excited state with width Γ

enhanced cross section for

$$E_n \approx E_x - S_n$$

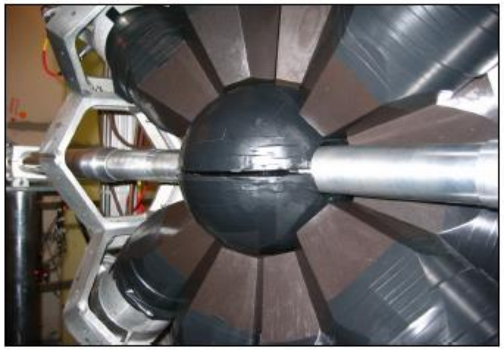
stellar environment:

- Maxwell-Boltzmann distribution
- average cross section over energy
  for given temperature

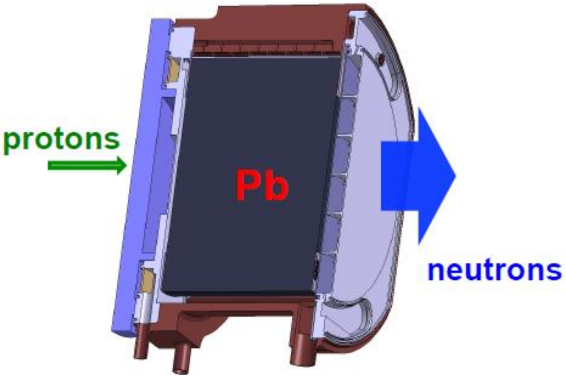
Cross section measurements

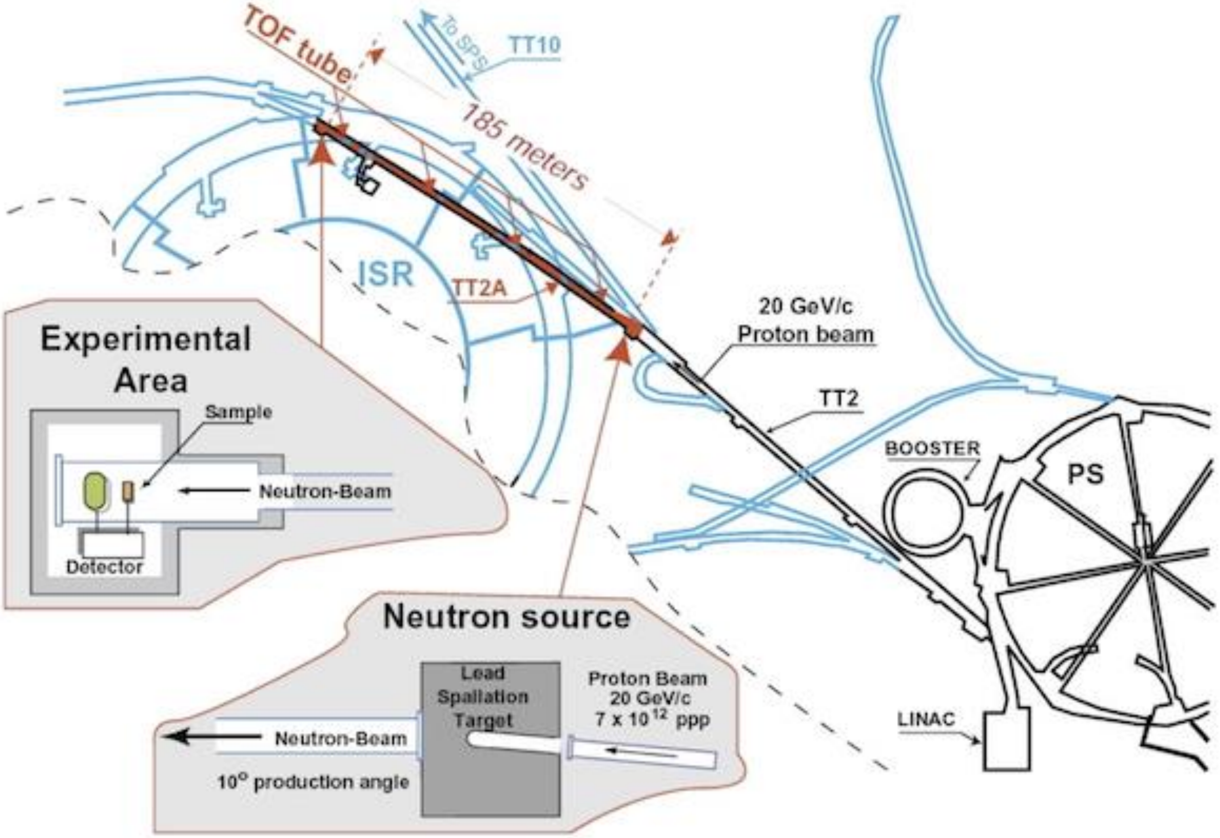
Example: n-ToF at CERN

- 20 GeV protons
- 1 pulse every 2.4 s
- 7×10^{12} protons/pulse
- 2×10^{15} neutrons/pulse
- Flight path: 185 m
- Neutron energy range: 0.1 ev – 250 MeV

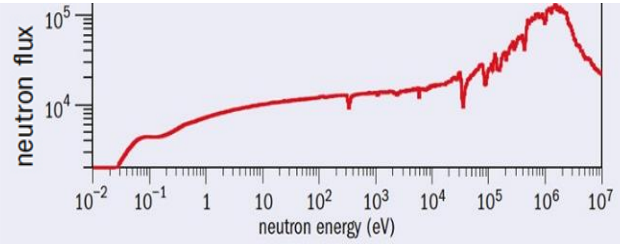


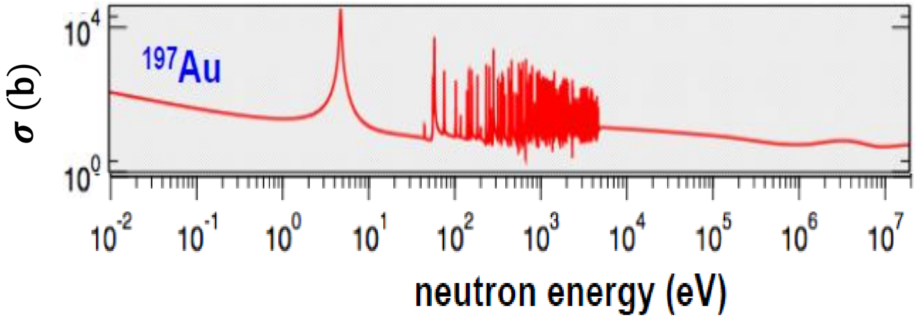
BaF_2 total absorption calorimeter

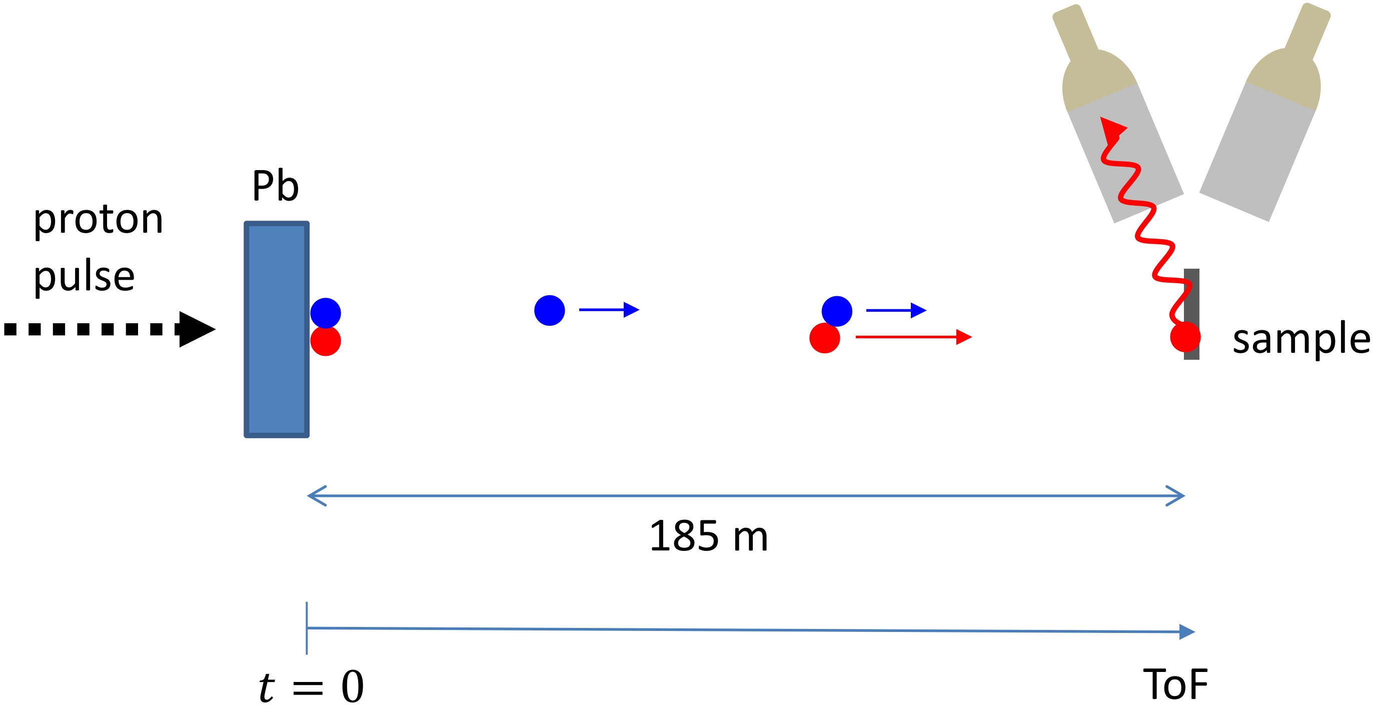




(n,γ) cross sections from neutron time of flight measurements

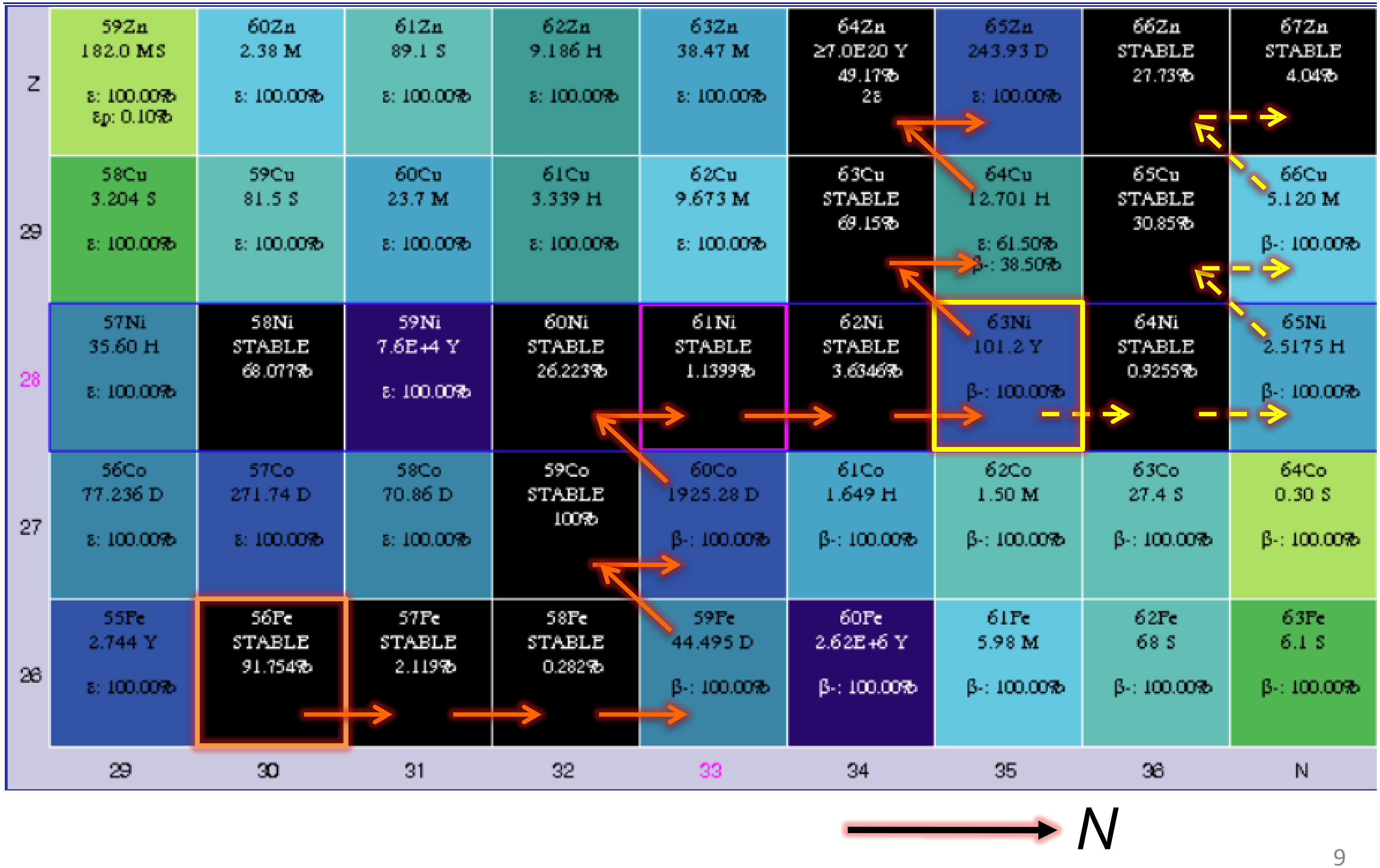






needs samples of stable isotopes
or long-lived radioactive isotopes (e.g. actinides)

s – prosess : slow neutron capture



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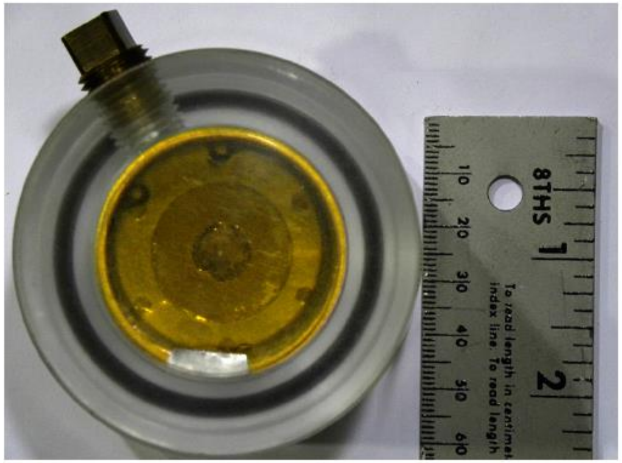
	29	30	31	32	33	34	35	36	N

^{63}Ni(n,γ) cross section

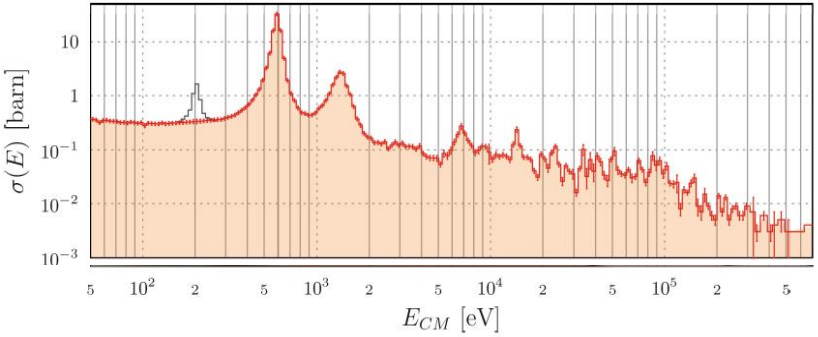
Recipe:

- take 347 mg ^{62}Ni enriched to 98%
- place it in high-flux reactor (ILL Grenoble)
- after 280 days you have 10.77% ^{63}Ni
- do a ToF measurement with ^{62,63}Ni sample
- do a ToF measurement with a pure ^{62}Ni sample
- subtract



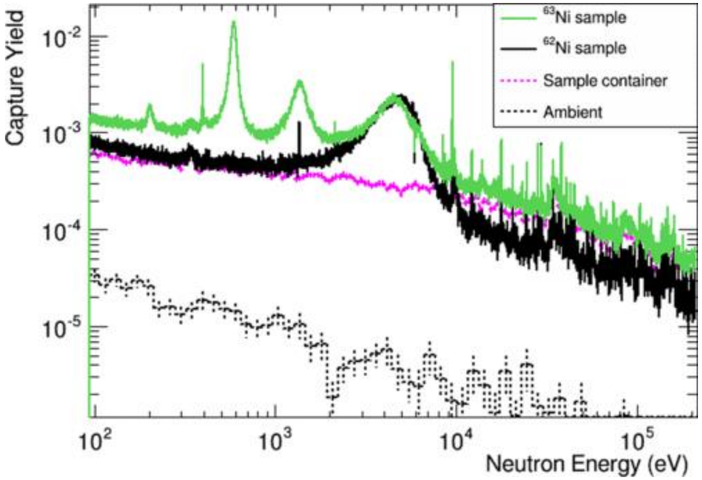
M.Weigand, PhD Univ. Frankfurt (2014)

measurement at DANCE / Los Alamos



M. Weigand et al., PRC 92, 045810 (2015)

measurement at n-ToF / CERN



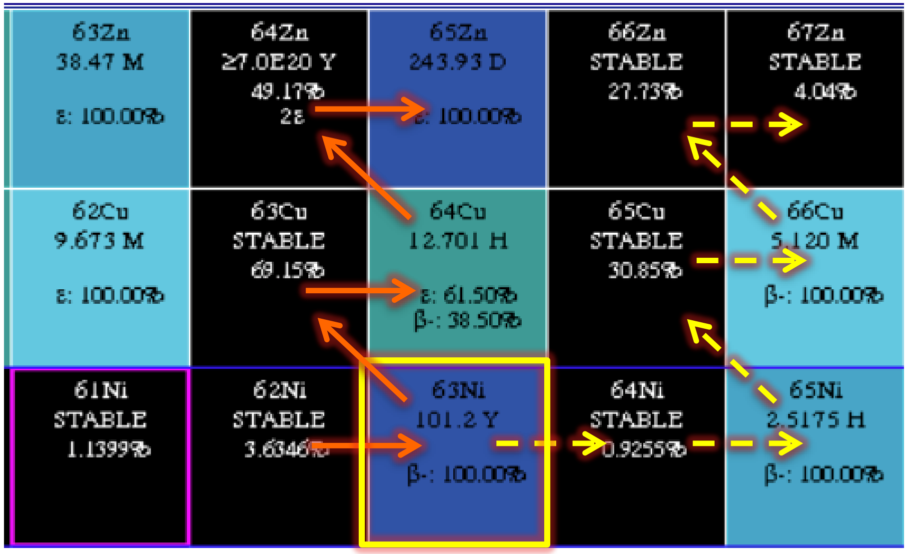
C. Lederer et al., PRC 89, 025810 (2014)

$^{63}\mathrm{Ni}(n,\gamma)$ cross section

- factor 2 higher than previously thought

s-process produces:
- less ^{63}Cu and ^{64}Zn
- more ^{64}Ni, ^{65}Cu and heavy Zn

than previously thought



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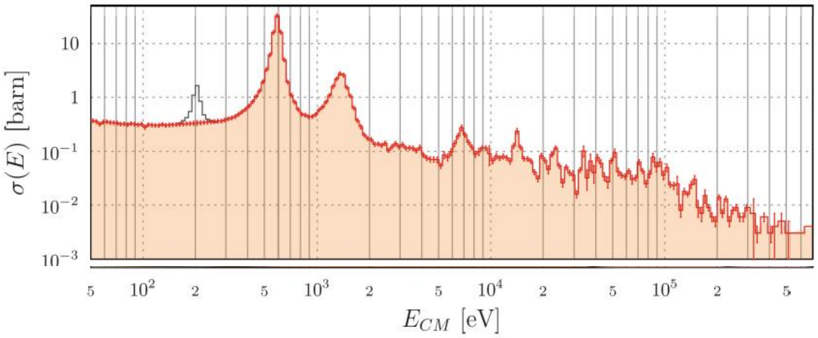
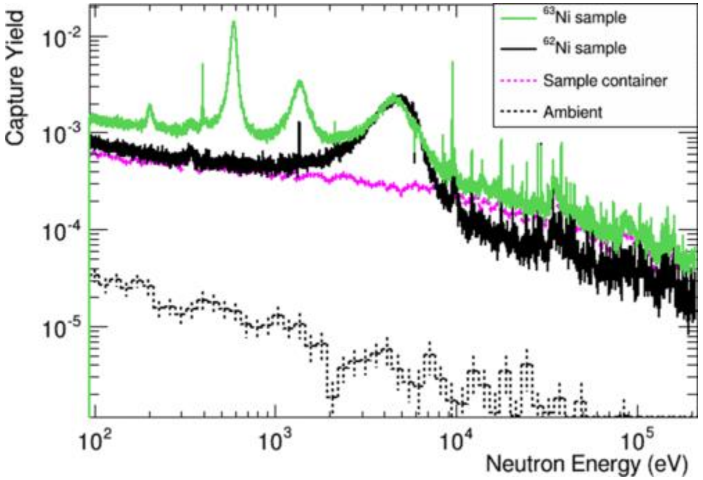
measurement at DANCE / Los Alamos



M. Weigand et al., PRC 92, 045810 (2015)

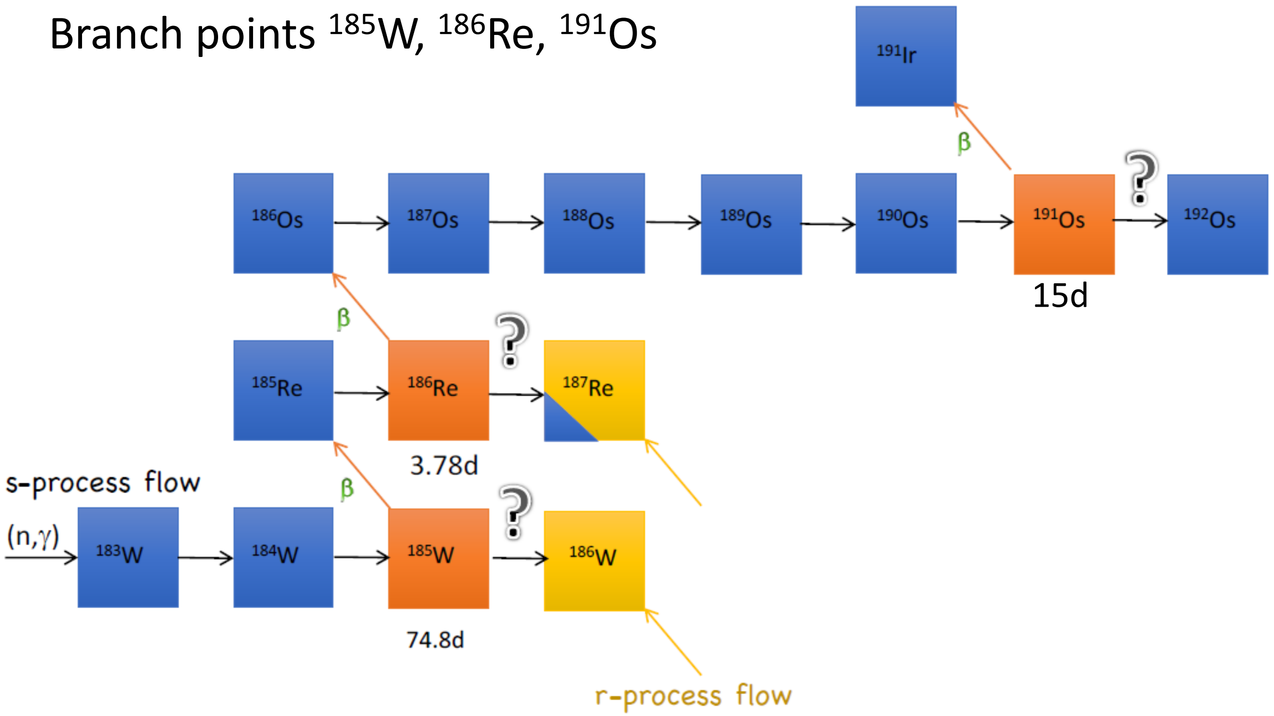
measurement at n-ToF / CERN



C. Lederer et al., PRC 89, 025810 (2014)

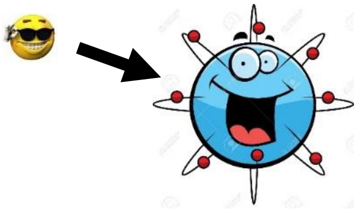
How can we determine (n, γ) cross sections for short-lived branch points?

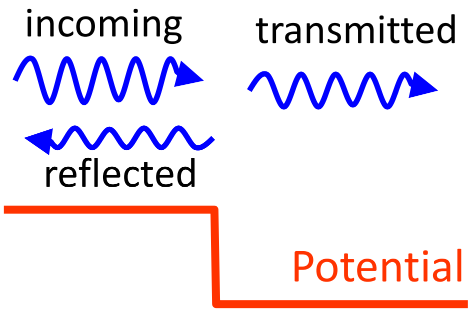
Branch points ^{185}W, ^{186}Re, ^{191}Os



- ➢ Direct measurements impossible due to short lifetime.
- ➢ Rely on theory?
- ➢ Indirect measurements?

What is needed to calculate (n, γ) reaction rates?





Optical model potential

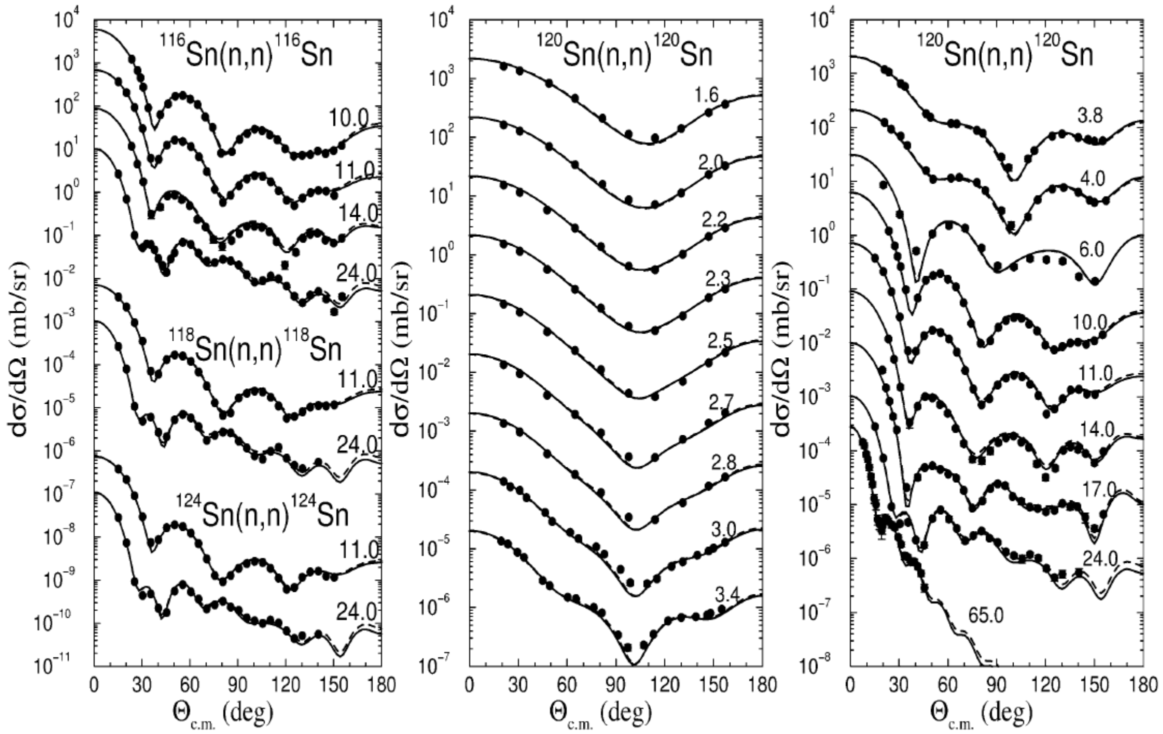
Level density

Gamma strength function

potential important for describing absorption and scattering of the neutron

- ➢ microscopic models
- ➢ phenomenological models

- ✓ good agreement with experimental observables
- ✓ uncertainties under control



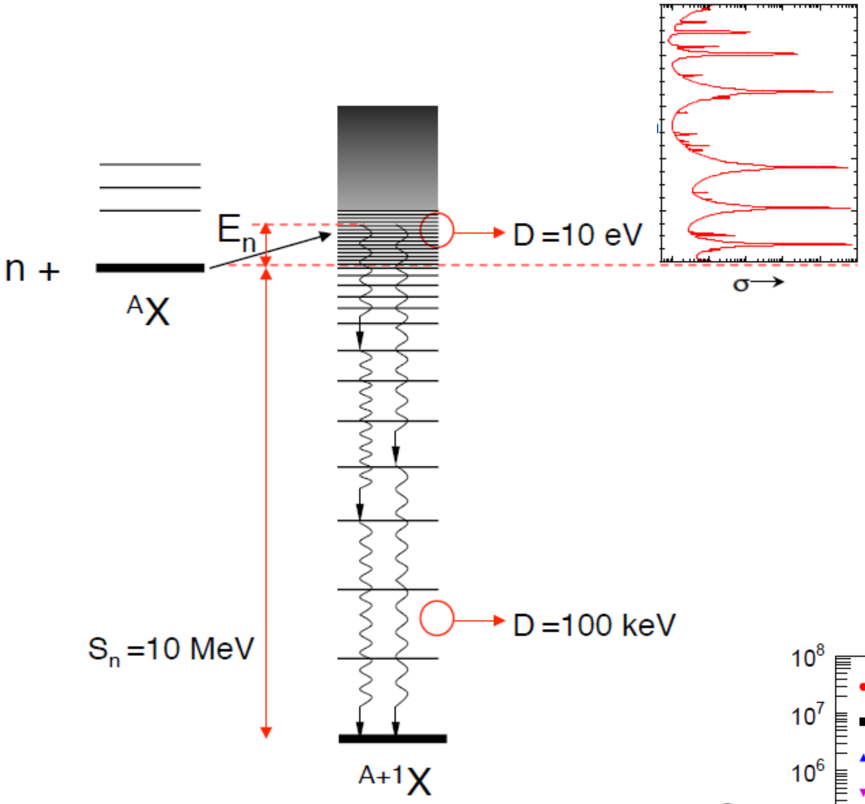
A.J. Koning, J.P. Delaroche
Nucl. Phys. A 713, 231 (2003)

What is needed to calculate (n, γ) reaction rates?

Optical model potential

Level density

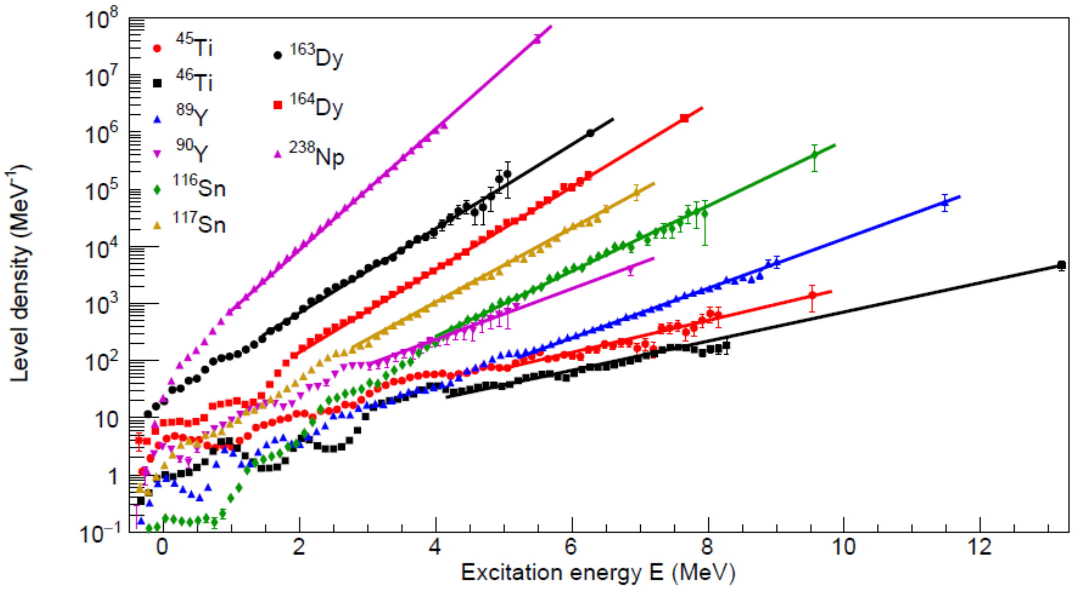
Gamma strength function



- ➢ count low-lying discrete levels
- ➢ count resonances at S_n
- ➢ in between?

- ➢ microscopic models
- ✗ not sufficiently accurate
- ➢ phenomenological models
- ✗ describe general trends, but not details
- ✗ not sufficiently predictive

✓ need experimental data



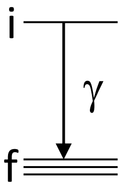
M. Guttormsen et al.
Eur. Phys. J. A 51, 170 (2015)

What is needed to calculate (n,γ) reaction rates?

Optical model potential

Level density

Gamma strength function



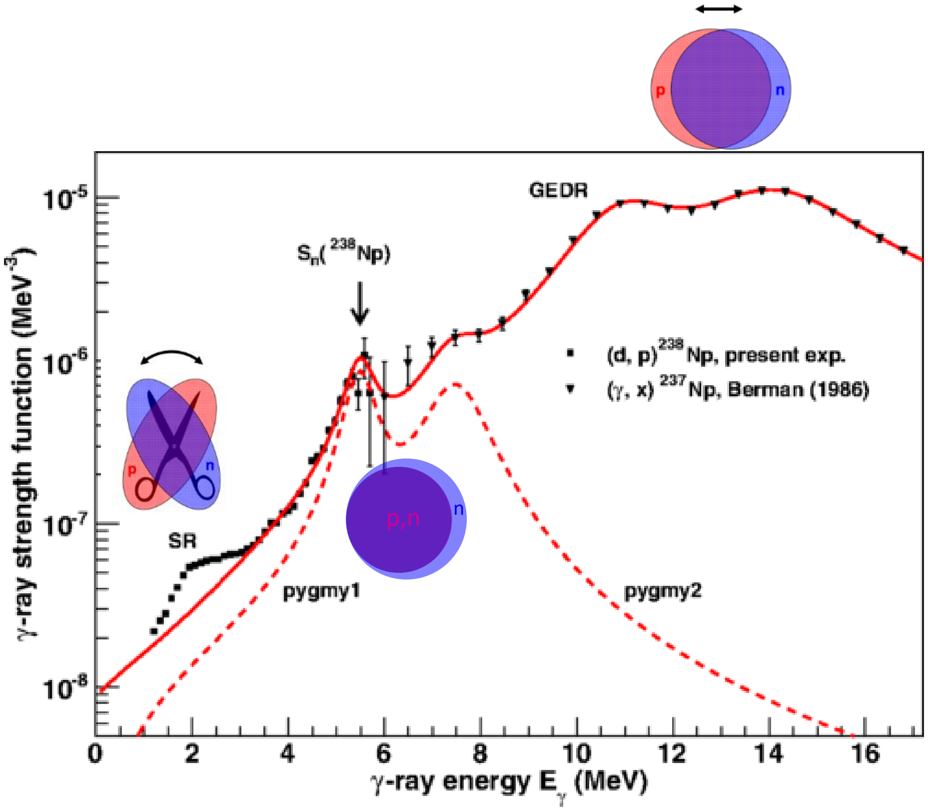
Fermi's golden rule

$$\lambda=\frac{2\pi}{\hbar}\left|\langle f|H_{\rm int}|i\rangle\right|^2\rho(E_f)$$

(quasi-)continuum → average quantity

γSF: average probability to decay with E_γ

- ➢ dominated by Giant Dipole Resonance
- ➢ Pygmy Resonances
- ➢ Scissors Resonance



- ➢ microscopic models
- ✗ not sufficiently accurate
- ➢ phenomenological models
- ✗ describe general trends, but not details
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✓ need experimental data

T.G. Tornyi et al.,
Phys. Rev. C 89, 044323 (2014)

The quasi-continuum

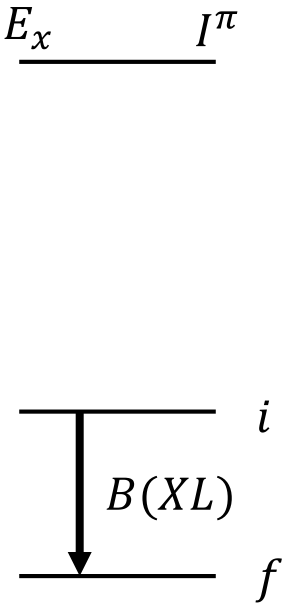
$\Gamma \geq D$
continuum

$\Gamma \leq D$
quasi-
continuum

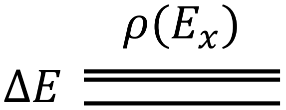
$\Gamma \ll D$
discrete

Γ: width
D: average level spacing

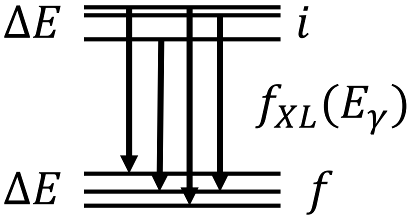
discrete states



quasi-continuum



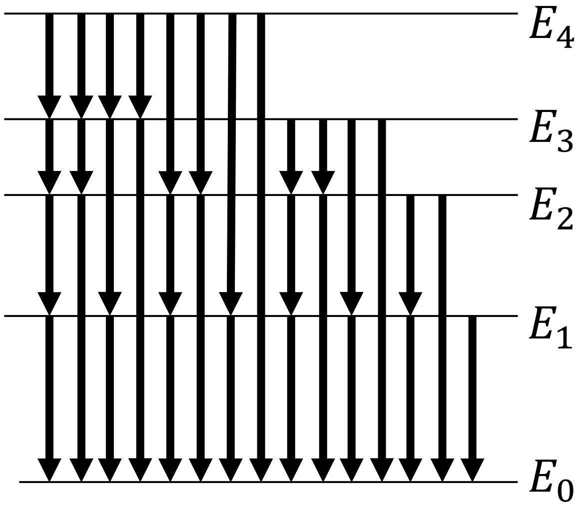
level density:
levels per MeV

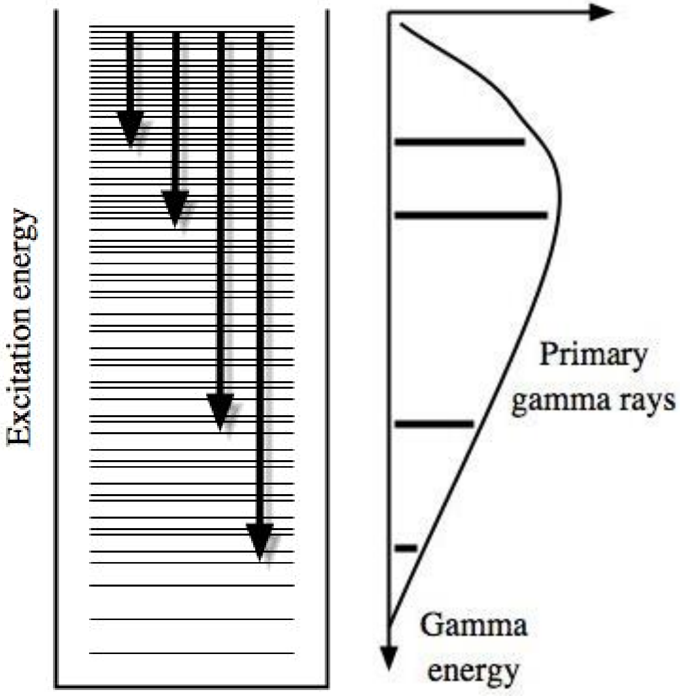


γSF: average nuclear electromagnetic response

$$f_{XL}(E_\gamma) = \frac{\langle \Gamma_{XL}(E_\gamma) \rangle}{D\ E_\gamma^{2L+1}}$$

Primary gamma-ray spectra





weighting function
=
γ strength function

Probability to emit a γ ray of energy E_γ from an initial excitation energy E_i

$$P(E_i, E_\gamma) \propto \rho(E_f)\, T(E_\gamma)$$

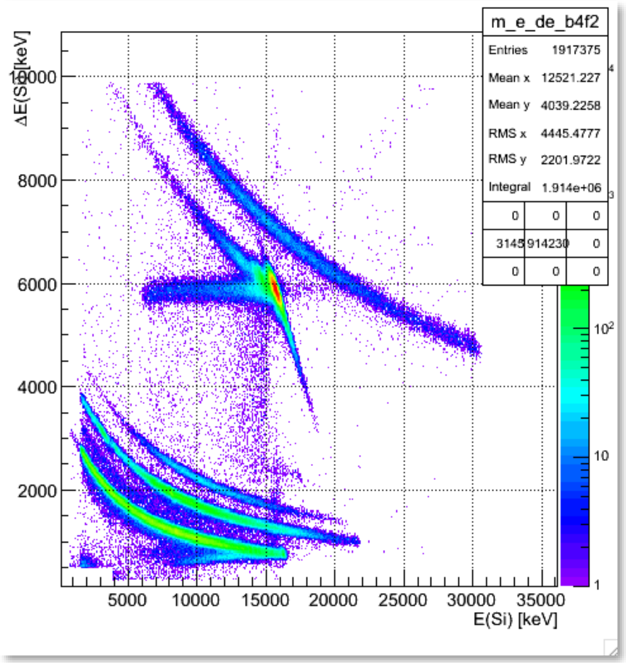
Transmission coefficient:

$$T(E_\gamma) = 2\pi \sum_{XL} E_\gamma^{2L+1}\ f_{XL}(E_\gamma)$$

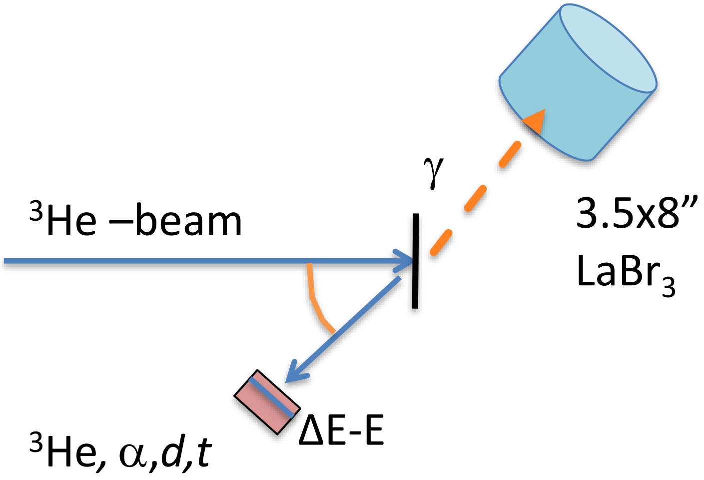
we assume dipole (E1,M1) radiation

measure $P(E_i, E_\gamma)$ → level density and γSF

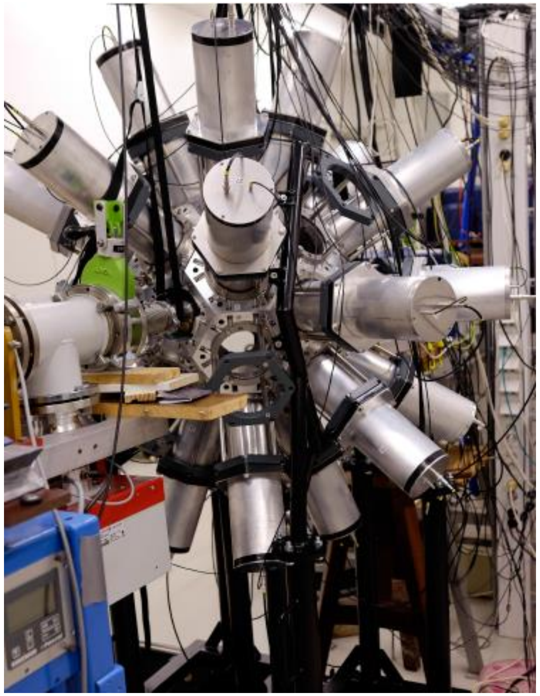
Experiments at the Oslo Cyclotron Laboratory



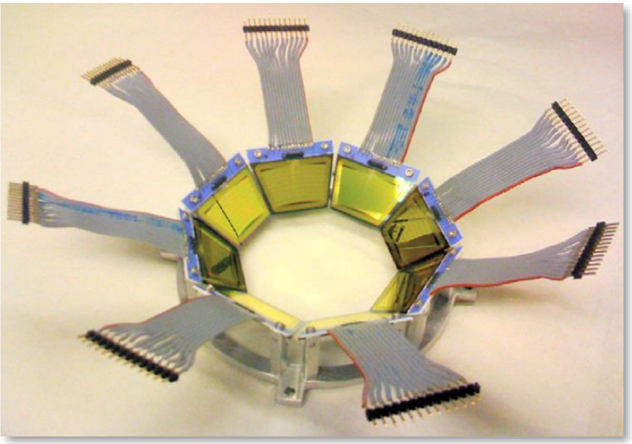
$\Delta E - E$ particle identification
reaction kinematics → excitation energy



Oslo Scintillator Array (OSCAR)

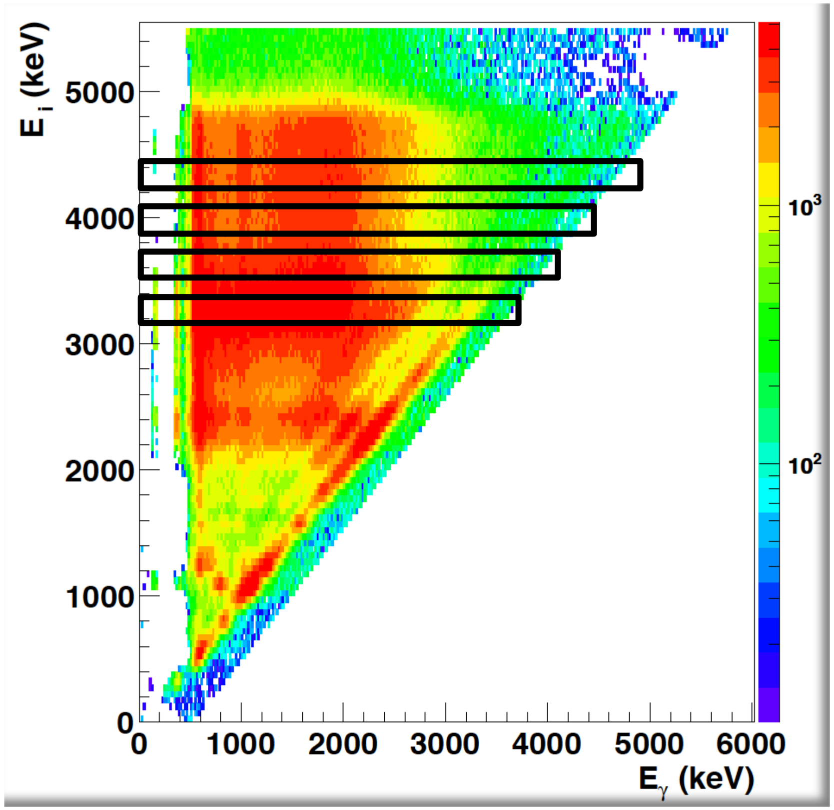


$\Delta E - E$ Si telescopes

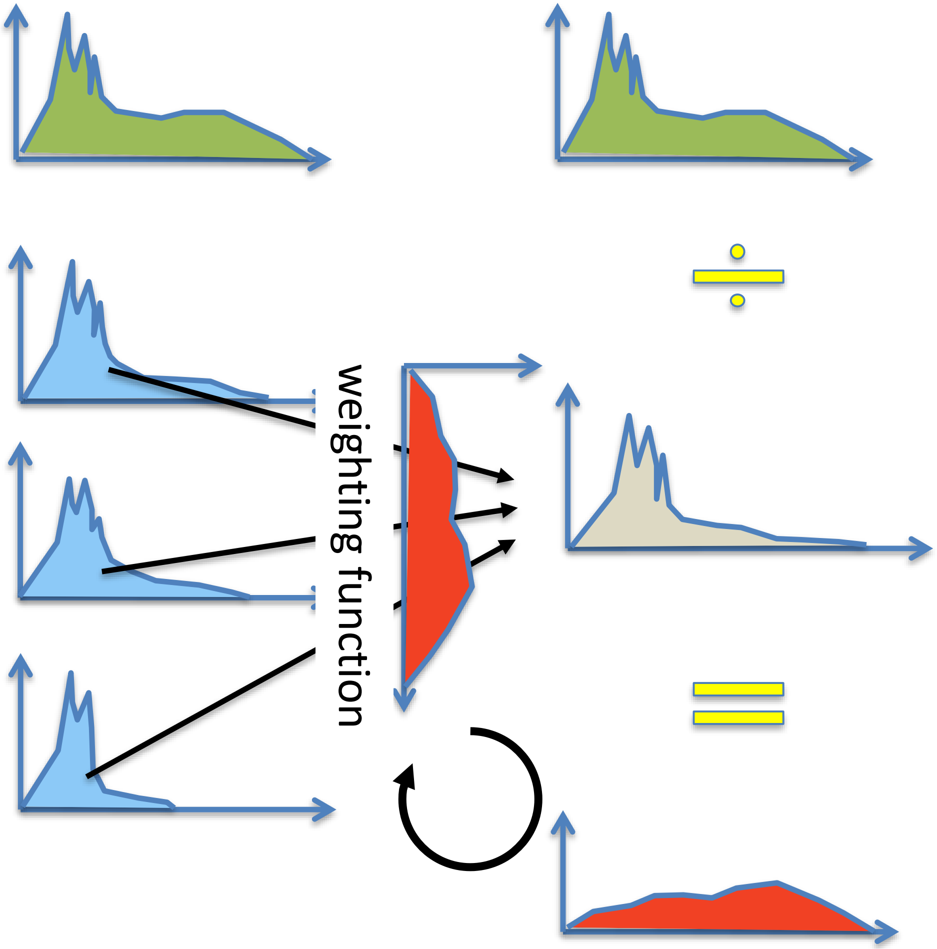


M.Guttormsen et al., NIM A 648, 168 (2011)

The Oslo Method



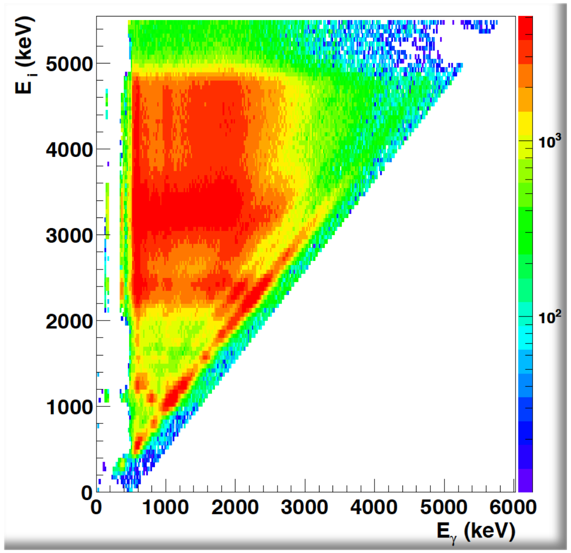
M. Guttormsen et al., NIM A 255, 518 (1987)



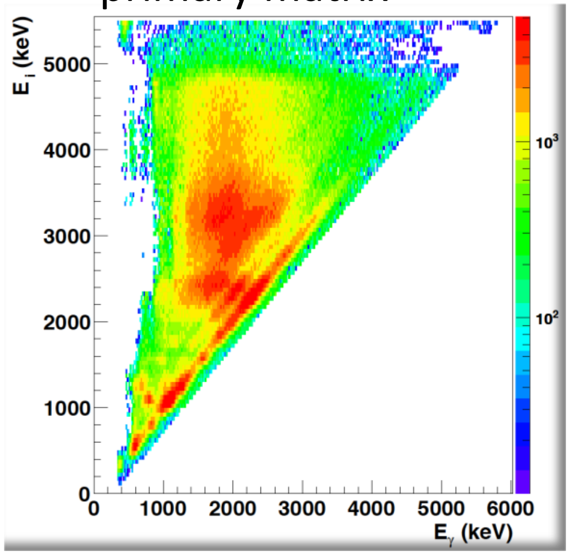
primary spectrum
$P(E_i, E_\gamma)$

The Oslo Method

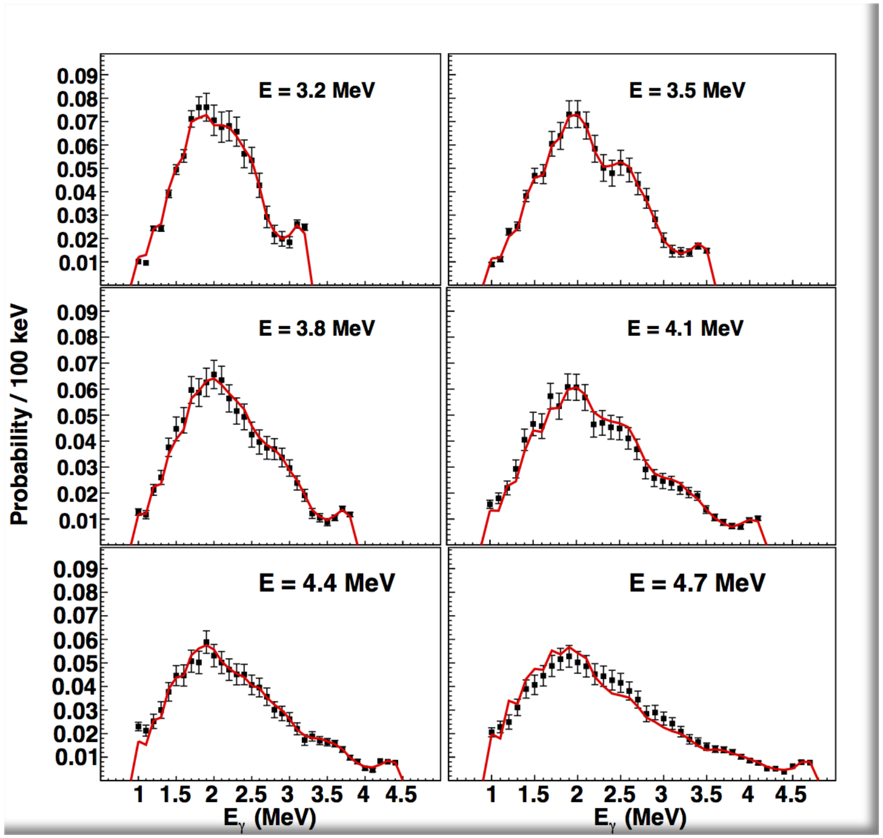
total matrix



primary matrix

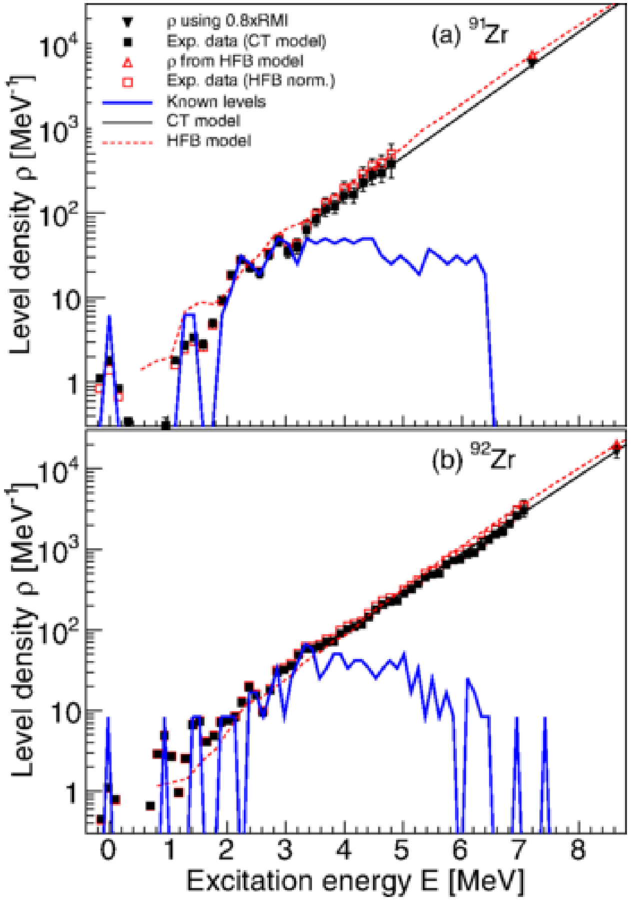


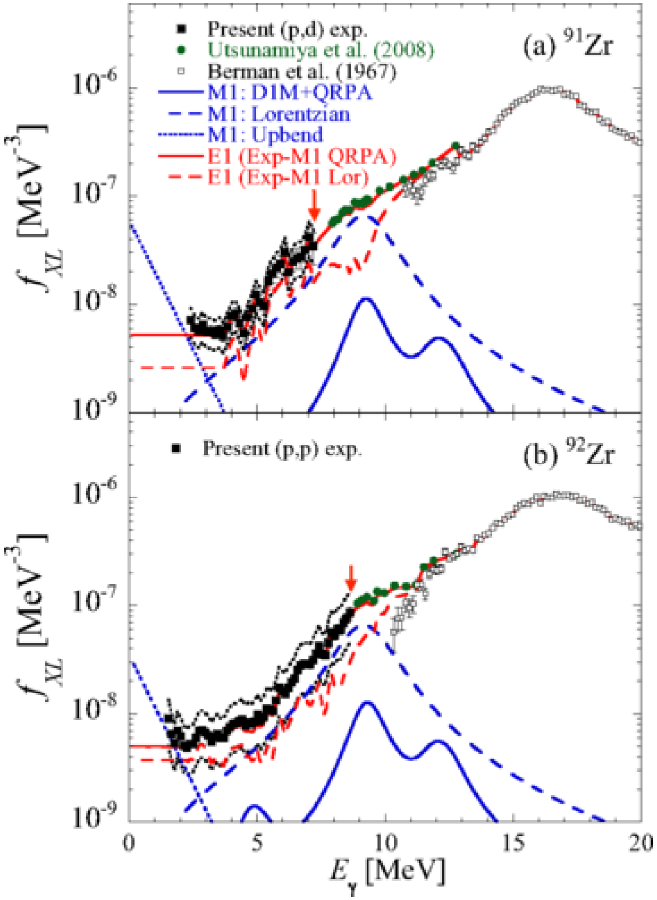
$$P(E_i, E_\gamma) \propto \rho(E_f) T(E_\gamma)$$

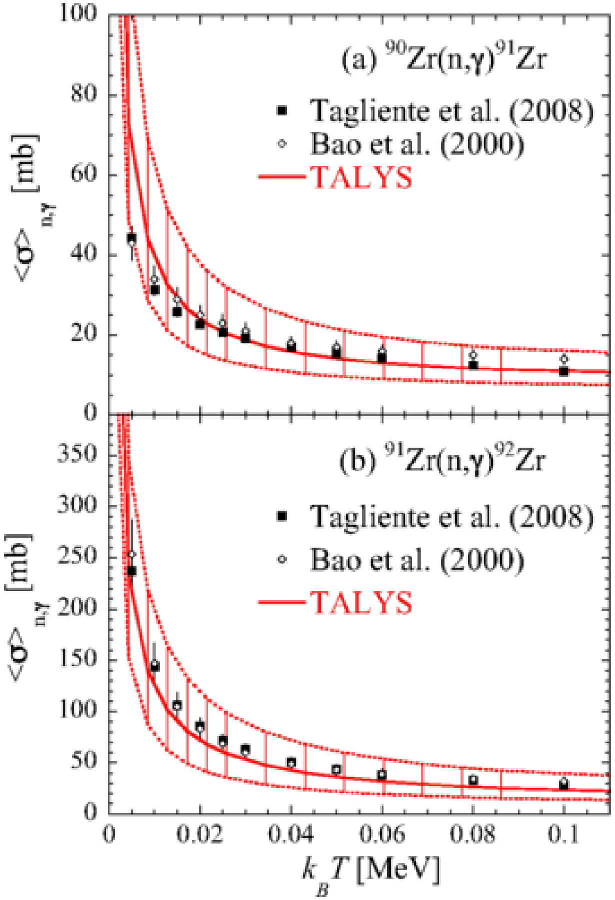


A. Schiller et al., NIM A 447, 498 (2000)
A.C. Larsen et al., PRC 83, 034315 (2011)

NLD and γSF from charged-particle reactions to constrain (n,γ) reactions







^{92}Zr(p,d)^{91}Zr ↔ ^{90}Zr(n,γ)^{91}Zr

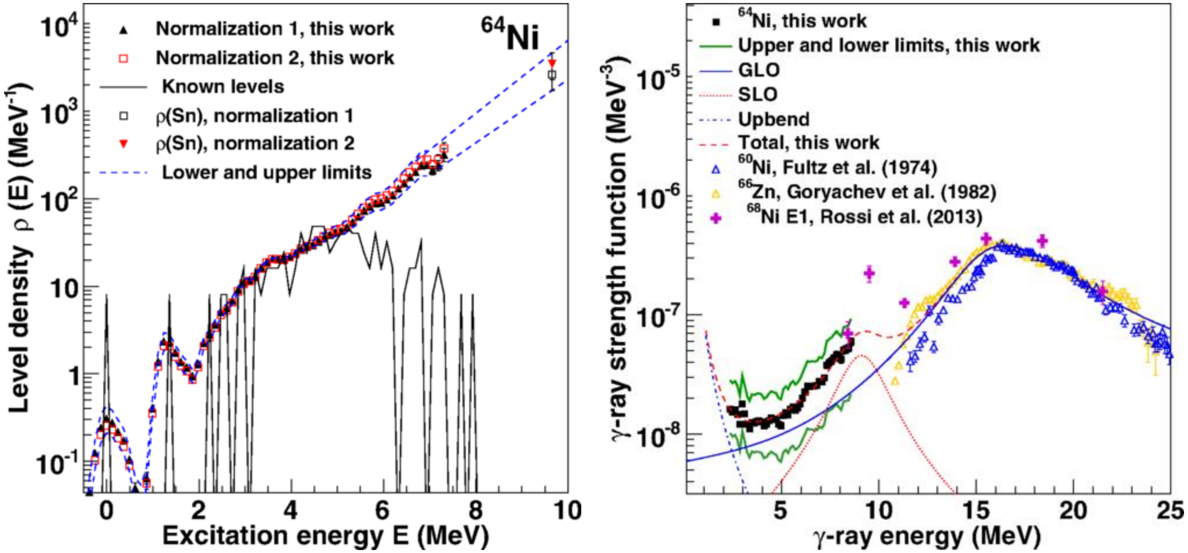
^{92}Zr(p,p’)^{92}Zr ↔ ^{91}Zr(n,γ)^{92}Zr

M. Guttormsen et al.,
Phys. Rev. C 96, 024313 (2017)

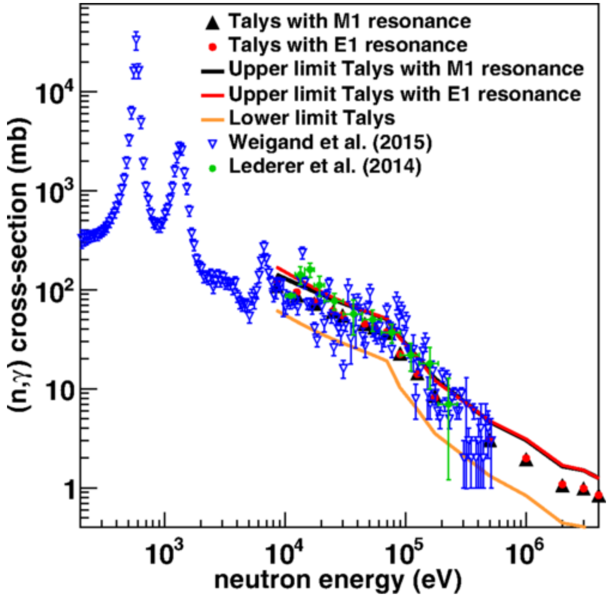
www.talys.eu

^{64}Ni(p,p')^{64}Ni: experiment with stable target

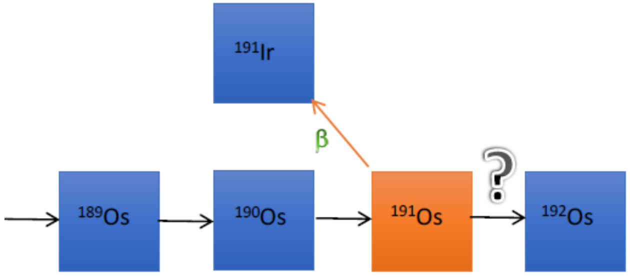
constrain ^{63}Ni(n,γ)^{64}Ni cross section for radioactive ^{63}Ni



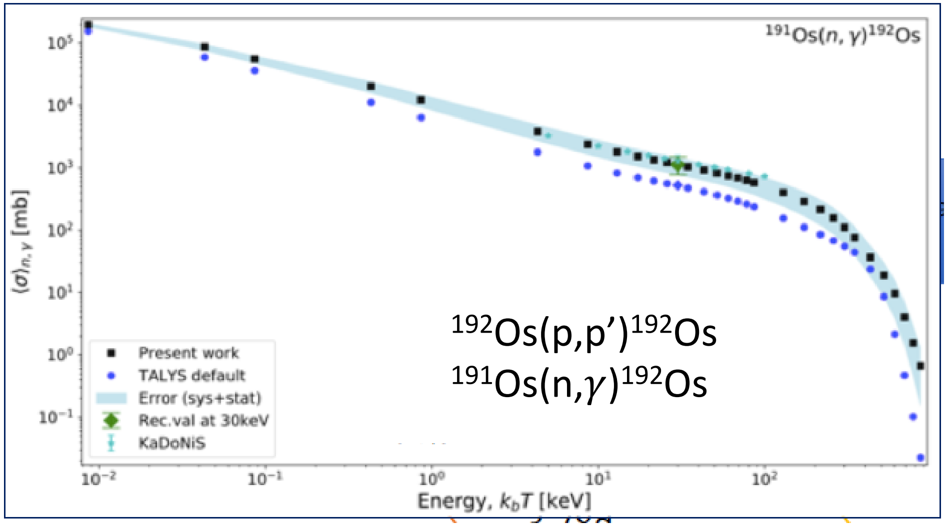
L. Crespo Campo, PRC 94, 044321 (2016)



also for nuclei that are not accessible for direct reactions



15d

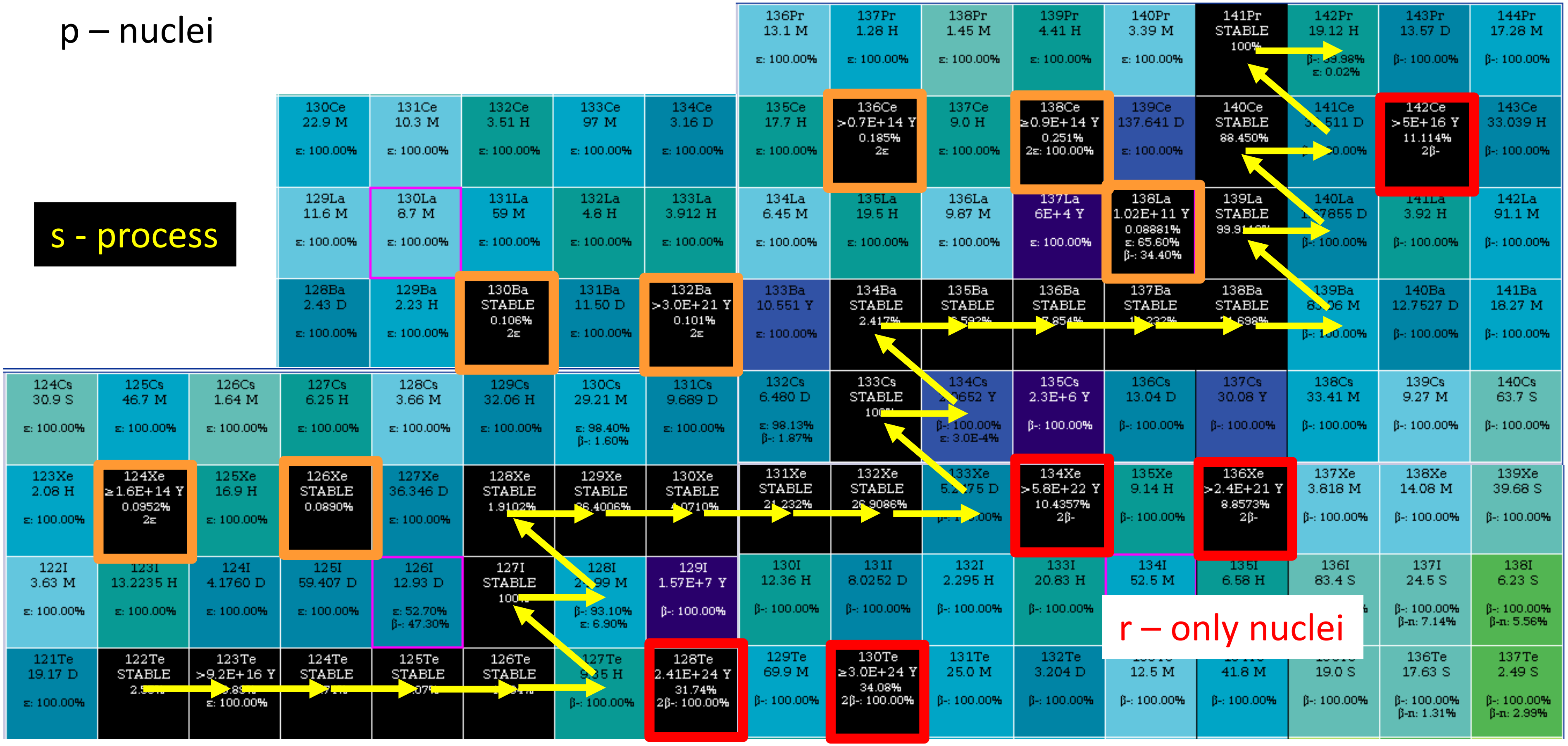


^{192}Os(p,p')^{192}Os

^{191}Os(n,γ)^{192}Os

I. Kullmann, MSc Thesis Univ. Oslo (2018)

p – nuclei

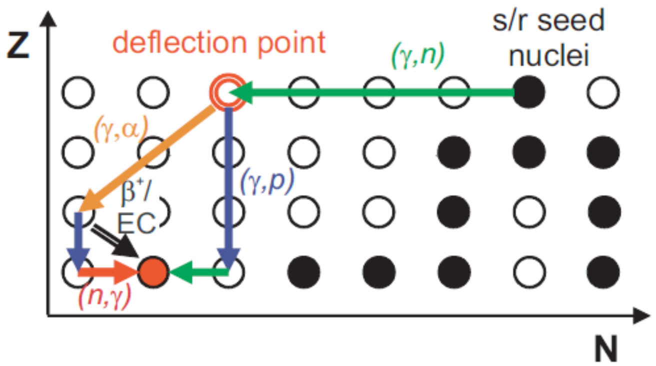


s - process

r – only nuclei

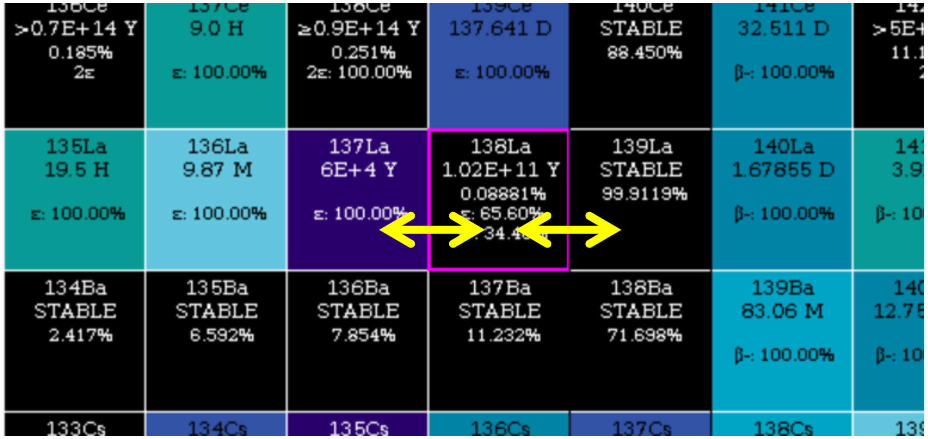
								136Pr 13.1 M ε: 100.00%	137Pr 1.28 H ε: 100.00%	138Pr 1.45 M ε: 100.00%	139Pr 4.41 H ε: 100.00%	140Pr 3.39 M ε: 100.00%	141Pr STABLE 100%	142Pr 19.12 H β-: [illegible].98% ε: 0.02%	143Pr 13.57 D β-: 100.00%	144Pr 17.28 M β-: 100.00%
			130Ce 22.9 M ε: 100.00%	131Ce 10.3 M ε: 100.00%	132Ce 3.51 H ε: 100.00%	133Ce 97 M ε: 100.00%	134Ce 3.16 D ε: 100.00%	135Ce 17.7 H ε: 100.00%	136Ce >0.7E+14 Y 0.185% 2ε	137Ce 9.0 H ε: 100.00%	138Ce ≥0.9E+14 Y 0.251% 2ε: 100.00%	139Ce 137.641 D ε: 100.00%	140Ce STABLE 88.450%	141Ce 3[illegible].511 D [illegible]0.00%	142Ce >5E+16 Y 11.114% 2β-	143Ce 33.039 H β-: 100.00%
			129La 11.6 M ε: 100.00%	130La 8.7 M ε: 100.00%	131La 59 M ε: 100.00%	132La 4.8 H ε: 100.00%	133La 3.912 H ε: 100.00%	134La 6.45 M ε: 100.00%	135La 19.5 H ε: 100.00%	136La 9.87 M ε: 100.00%	137La 6E+4 Y ε: 100.00%	138La 1.02E+11 Y 0.08881% ε: 65.60% β-: 34.40%	139La STABLE 99.9[illegible]	140La 1[illegible]7855 D β-: 100.00%	141La 3.92 H β-: 100.00%	142La 91.1 M β-: 100.00%
			128Ba 2.43 D ε: 100.00%	129Ba 2.23 H ε: 100.00%	130Ba STABLE 0.106% 2ε	131Ba 11.50 D ε: 100.00%	132Ba >3.0E+21 Y 0.101% 2ε	133Ba 10.551 Y ε: 100.00%	134Ba STABLE 2.417%	135Ba STABLE [illegible].592%	136Ba STABLE 7.854%	137Ba STABLE 1[illegible].232%	138Ba STABLE 7[illegible].698%	139Ba 8[illegible]06 M β-: 1[illegible]0.00%	140Ba 12.7527 D β-: 100.00%	141Ba 18.27 M β-: 100.00%
124Cs 30.9 S ε: 100.00%	125Cs 46.7 M ε: 100.00%	126Cs 1.64 M ε: 100.00%	127Cs 6.25 H ε: 100.00%	128Cs 3.66 M ε: 100.00%	129Cs 32.06 H ε: 100.00%	130Cs 29.21 M ε: 98.40% β-: 1.60%	131Cs 9.689 D ε: 100.00%	132Cs 6.480 D ε: 98.13% β-: 1.87%	133Cs STABLE 10[illegible]	134Cs 2[illegible]0652 Y β-: 100.00% ε: 3.0E-4%	135Cs 2.3E+6 Y β-: 100.00%	136Cs 13.04 D β-: 100.00%	137Cs 30.08 Y β-: 100.00%	138Cs 33.41 M β-: 100.00%	139Cs 9.27 M β-: 100.00%	140Cs 63.7 S β-: 100.00%
123Xe 2.08 H ε: 100.00%	124Xe ≥1.6E+14 Y 0.0952% 2ε	125Xe 16.9 H ε: 100.00%	126Xe STABLE 0.0890%	127Xe 36.346 D ε: 100.00%	128Xe STABLE 1.9102%	129Xe STABLE 26.4006%	130Xe STABLE 4.0710%	131Xe STABLE 21.232%	132Xe STABLE 26.9086%	133Xe 5.2[illegible]75 D β-: 1[illegible].00%	134Xe >5.8E+22 Y 10.4357% 2β-	135Xe 9.14 H β-: 100.00%	136Xe >2.4E+21 Y 8.8573% 2β-	137Xe 3.818 M β-: 100.00%	138Xe 14.08 M β-: 100.00%	139Xe 39.68 S β-: 100.00%
122I 3.63 M ε: 100.00%	123I 13.2235 H ε: 100.00%	124I 4.1760 D ε: 100.00%	125I 59.407 D ε: 100.00%	126I 12.93 D ε: 52.70% β-: 47.30%	127I STABLE 100[illegible]	128I 2[illegible]99 M β-: 93.10% ε: 6.90%	129I 1.57E+7 Y β-: 100.00%	130I 12.36 H β-: 100.00%	131I 8.0252 D β-: 100.00%	132I 2.295 H β-: 100.00%	133I 20.83 H β-: 100.00%	134I 52.5 M	135I 6.58 H	136I 83.4 S	137I 24.5 S β-: 100.00% β-n: 7.14%	138I 6.23 S β-: 100.00% β-n: 5.56%
121Te 19.17 D ε: 100.00%	122Te STABLE 2.5[illegible]	123Te >9.2E+16 Y [illegible].89[illegible] ε: 100.00%	124Te STABLE [illegible]	125Te STABLE [illegible].07%	126Te STABLE [illegible]	127Te 9.[illegible]5 H β-: 100.00%	128Te 2.41E+24 Y 31.74% 2β-: 100.00%	129Te 69.9 M β-: 100.00%	130Te ≥3.0E+24 Y 34.08% 2β-: 100.00%	131Te 25.0 M β-: 100.00%	132Te 3.204 D β-: 100.00%	[illegible] 12.5 M β-: 100.00%	[illegible] 41.8 M β-: 100.00%	[illegible] 19.0 S β-: 100.00%	136Te 17.63 S β-: 100.00% β-n: 1.31%	137Te 2.49 S β-: 100.00% β-n: 2.99%

- proton capture (p,γ) ?
  difficult to find suitable environments because of Coulomb barrier
- photodisintegration (γ process)
- neutrino-induced processes (ν process) (core-collapse supernovæ)

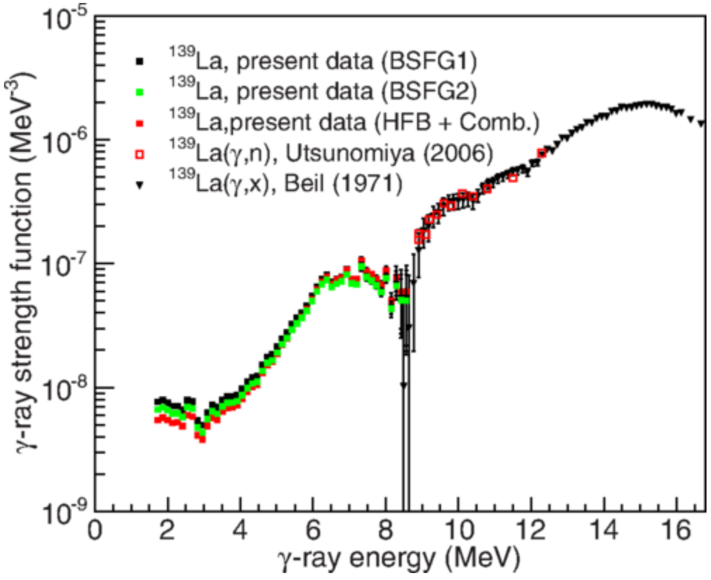


T. Rauscher et al., Rep. Prog. Phys. 76, 066201 (2013)

Galactic production of ^{138}La



136Ce >0.7E+14 Y 0.185% 2ε	137Ce 9.0 H ε: 100.00%	138Ce ≥0.9E+14 Y 0.251% 2ε: 100.00%	139Ce 137.641 D ε: 100.00%	140Ce STABLE 88.450%	141Ce 32.511 D β-: 100.00%	142 >5E+ 11.1 2
135La 19.5 H ε: 100.00%	136La 9.87 M ε: 100.00%	137La 6E+4 Y ε: 100.00%	138La 1.02E+11 Y 0.08881% ε: 65.60% 34.4	139La STABLE 99.9119%	140La 1.67855 D β-: 100.00%	141 3.9 β-: 10
134Ba STABLE 2.417%	135Ba STABLE 6.592%	136Ba STABLE 7.854%	137Ba STABLE 11.232%	138Ba STABLE 71.698%	139Ba 83.06 M β-: 100.00%	140 12.75 β-: 10
133Cs	134Cs	135Cs	136Cs	137Cs	138Cs	13



$^{139}\mathrm{La}(^{3}\mathrm{He},\alpha)^{138}\mathrm{La}$

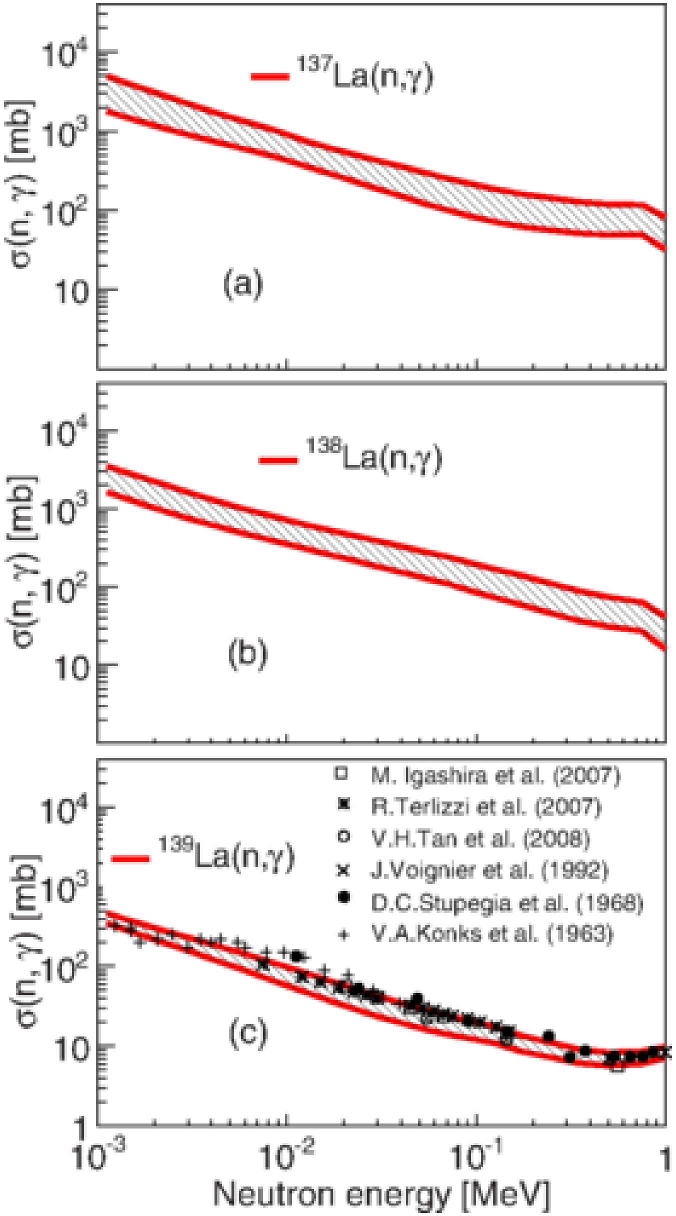
$^{139}\mathrm{La}(^{3}\mathrm{He},\ ^{3}\mathrm{He}')^{139}\mathrm{La}$

$^{139}\mathrm{La}(d,p)^{140}\mathrm{La}$

experiments

→ NLD & γSF

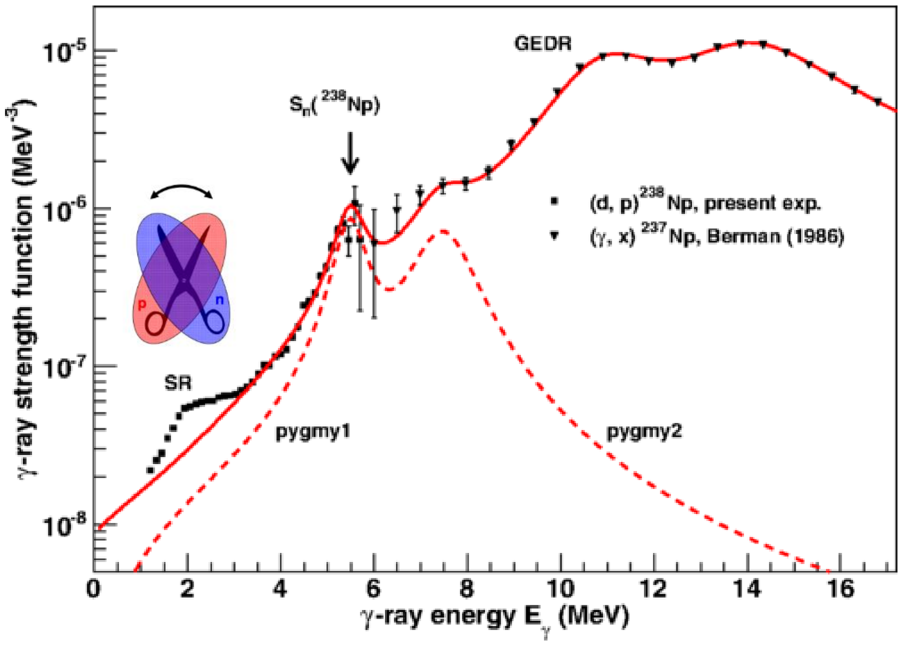
→ $\sigma_{(n,\gamma)}$, $\sigma_{(\gamma,n)}$



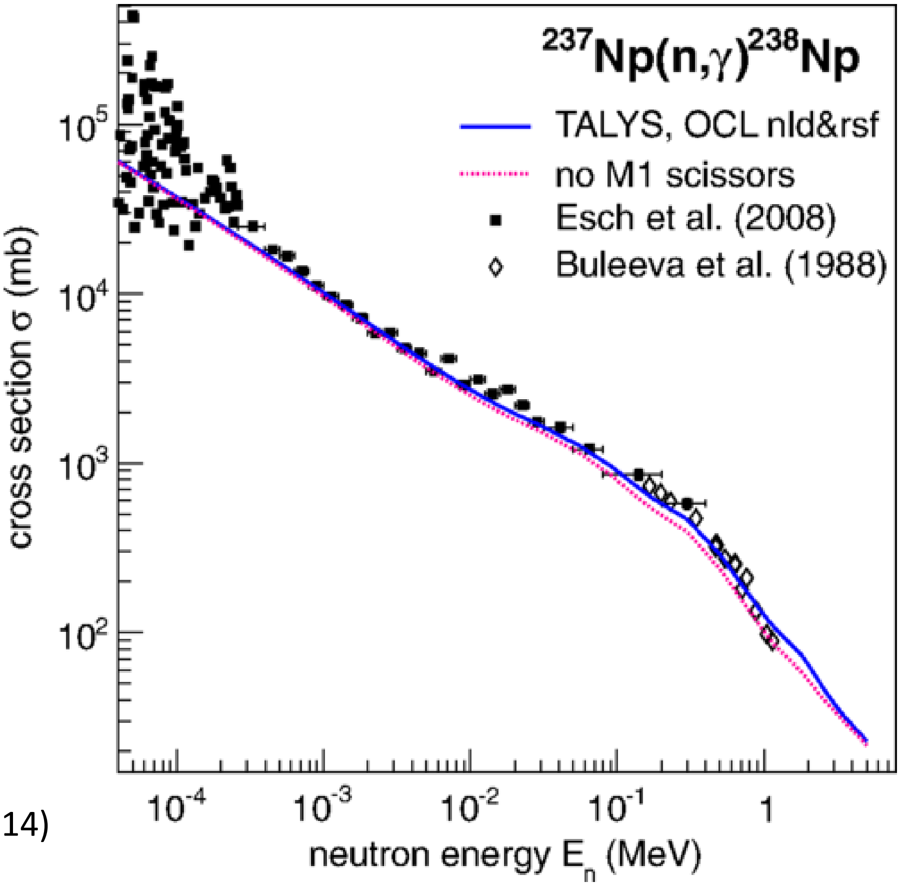
→ need neutrino processes to explain ^{138}La abundance

B.V. Kheswa et al., Phys. Lett. B 744, 268 (2015)
B.V. Kheswa et al., Phys. Rev. C 95, 045805 (2017)

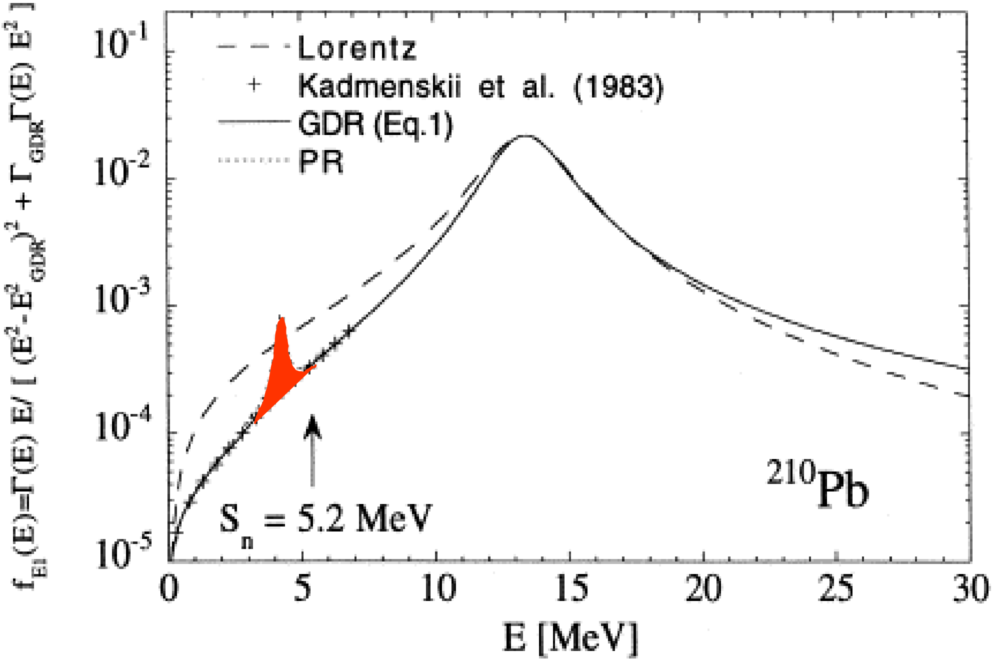
Do small resonances matter?

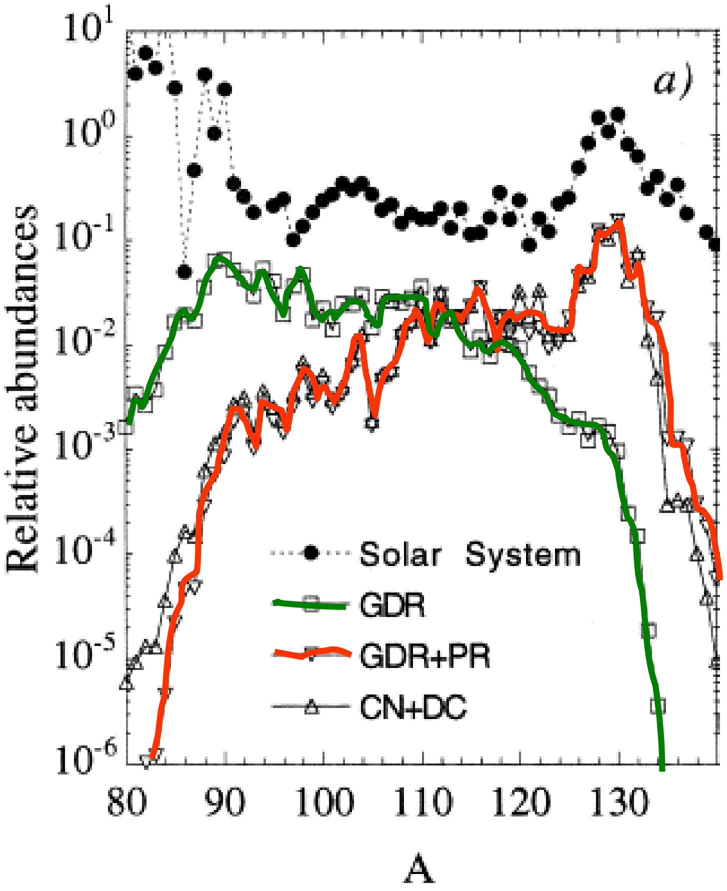


T.G. Tornyi et al., PRC 89, 044323 (2014)



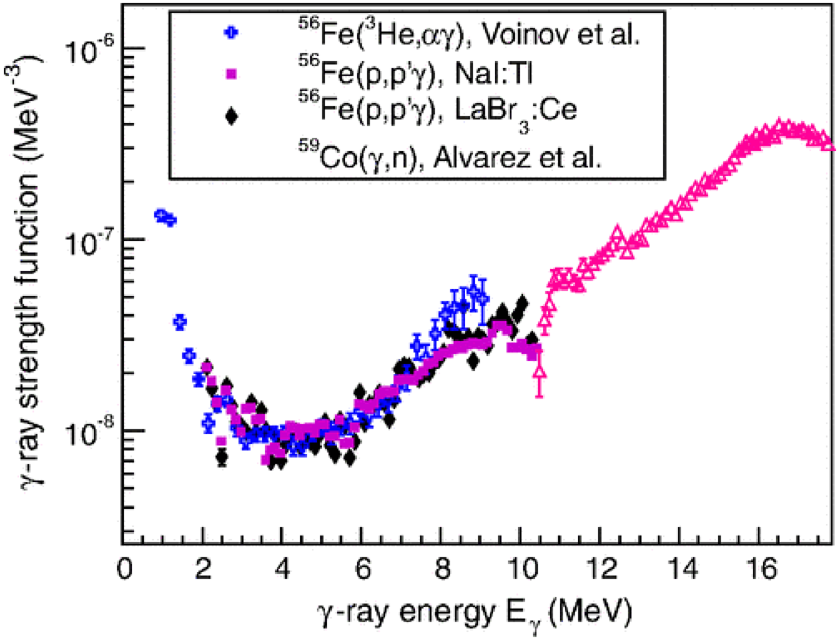
Do small resonances matter?



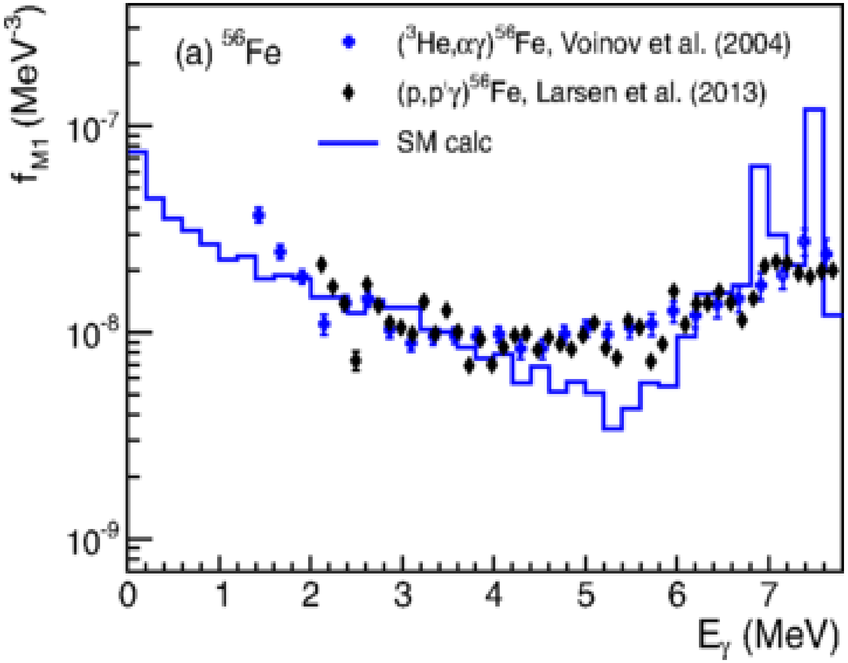


S. Goriely, Phys. Lett. B 436, 10 (1998)

Low-energy enhancement of γSF



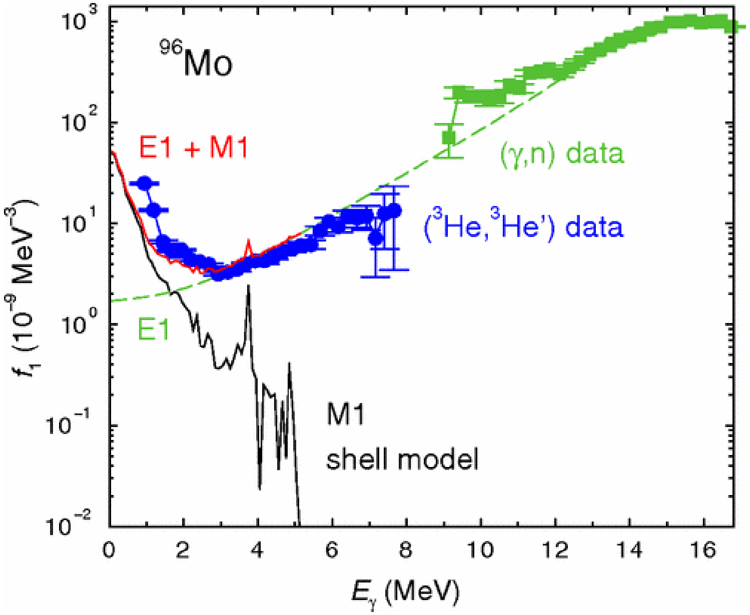
A. Voinov et al, PRL 93, 142504 (2004)
A.C. Larsen et al., PRL 111, 242504 (2013)



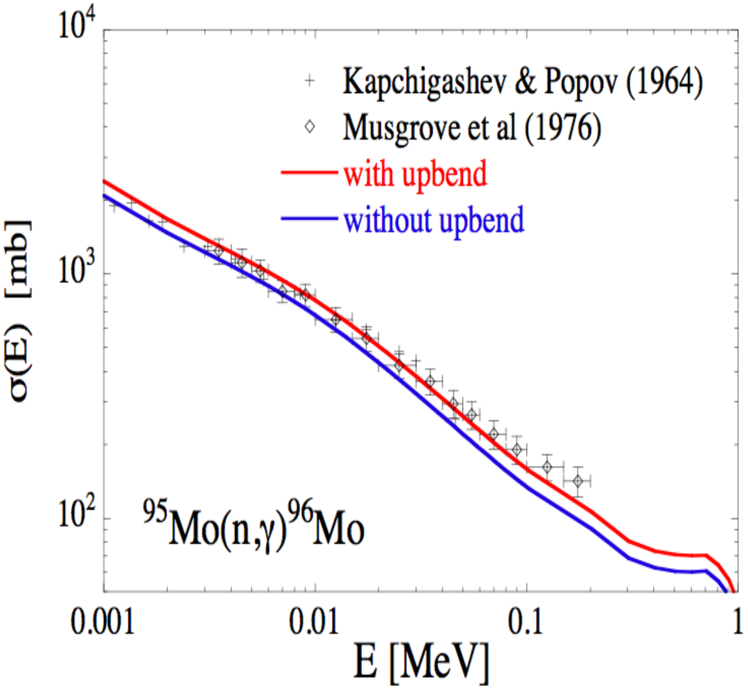
B. Alex Brown and A. C. Larsen
PRL 113, 252502 (2014)

- caused by $0\hbar\omega$ transitions
- reorientation of the spins of high-j proton and neutron orbits

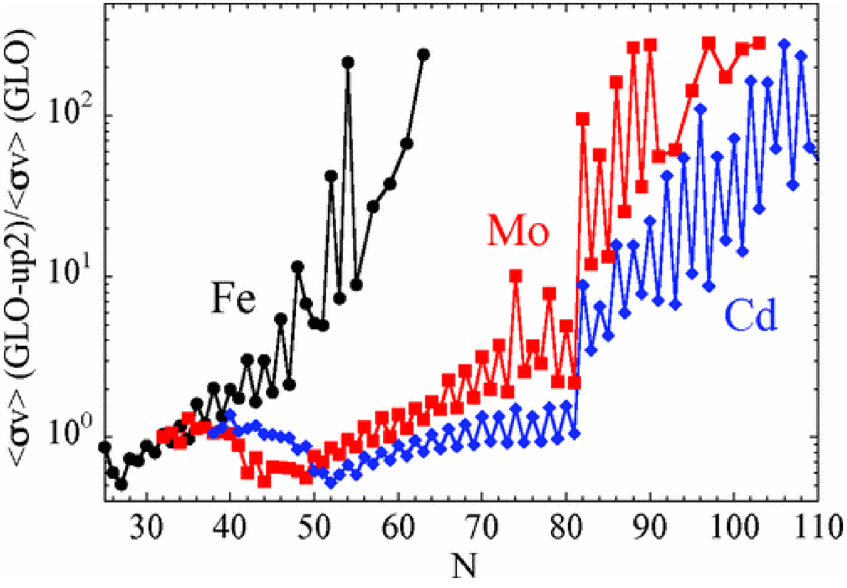
Consequences of low-energy enhancement



M. Guttormsen et al., PRC 71, 044307 (2005)
R. Schwengner et al., PRL 111, 232504 (2013)

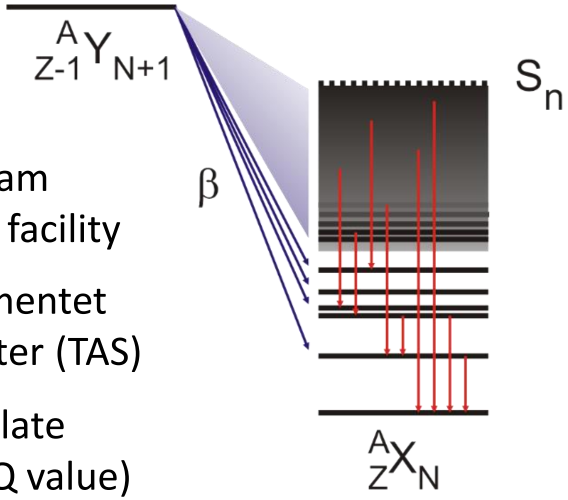


- large increase in (n, γ) cross section for neutron-rich nuclei?
- measure NLD and γSF for neutron-rich nuclei?



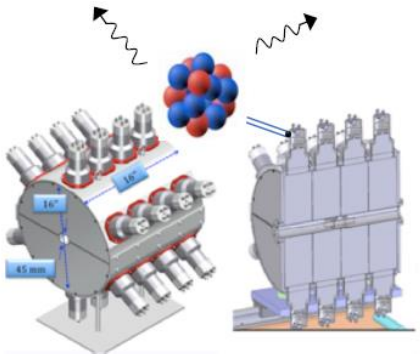
A.C. Larsen and S. Goriely, PRC 82, 014318 (2010)

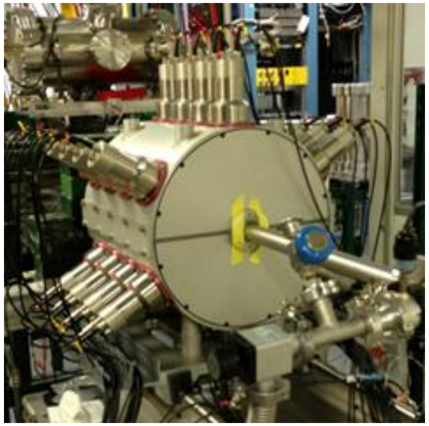
The beta-Oslo method



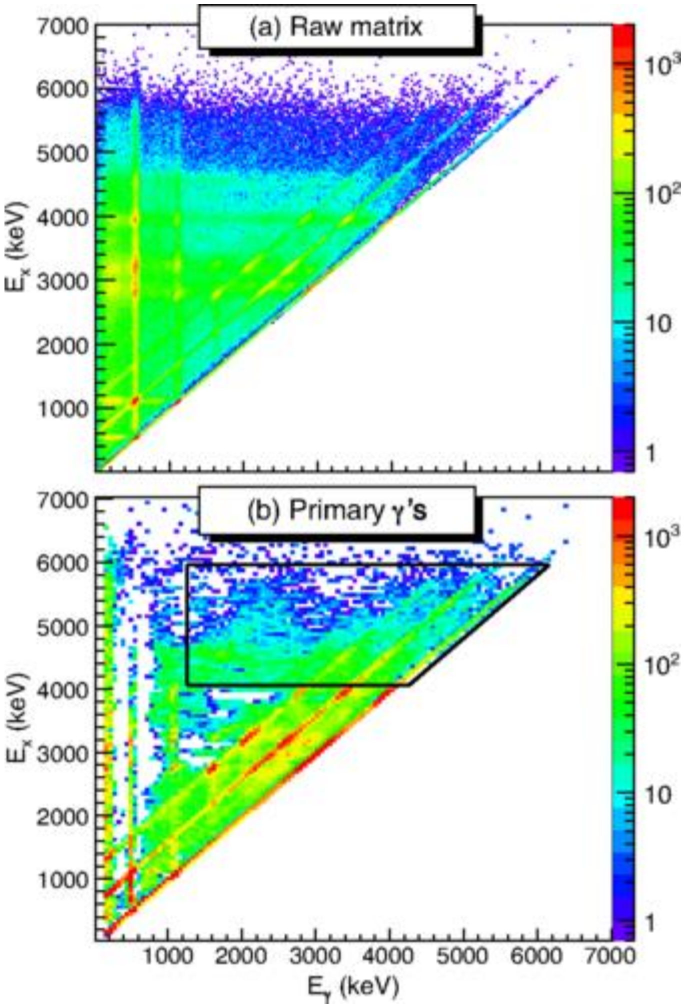
- neutron-rich radioactive beam from fragmentation or ISOL facility
- implant ions in a large, segmentet total absorption spectrometer (TAS)
- wait for beta deacy to populate highly excited states (large Q value)
- get excitation energy from sum spectrum
- get individual cascades from segments
- apply Oslo method to get NLD and γSF
- calculate (n,γ) cross section

SuN at NSCL/MSU



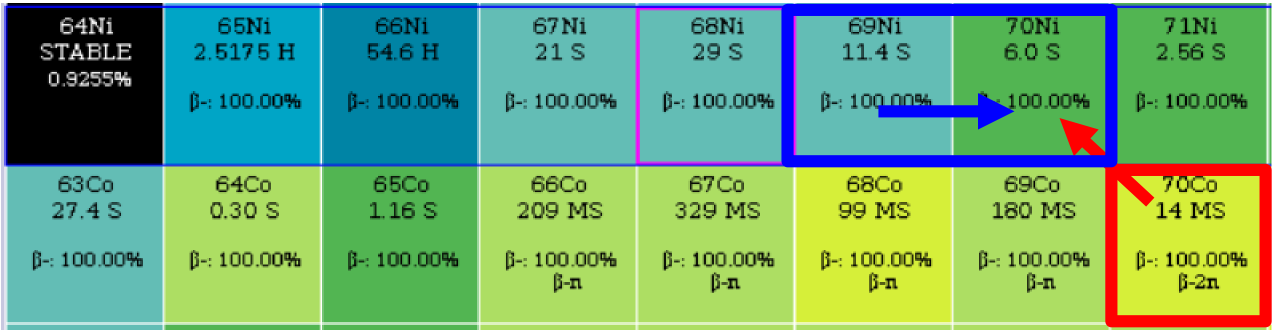


A. Simon et al., NIM A 703, 16 (2013)



A. Spyrou et al.,
Phys. Rev. Lett. 113, 232502 (2014)

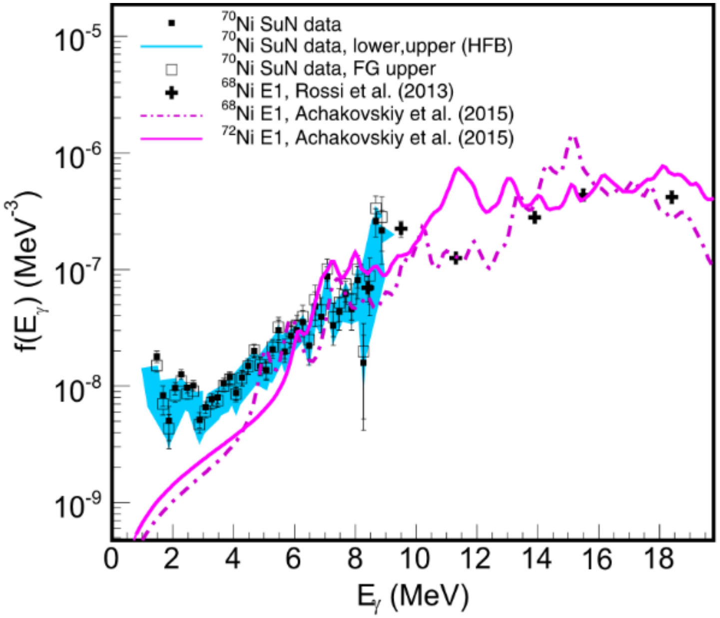
Constraint on (n,γ) cross section far from stability

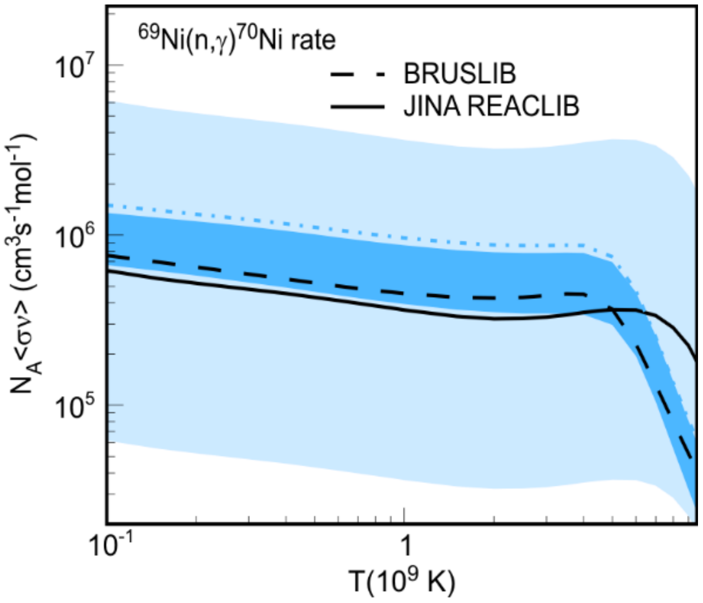


64Ni STABLE 0.9255%	65Ni 2.5175 H β-: 100.00%	66Ni 54.6 H β-: 100.00%	67Ni 21 S β-: 100.00%	68Ni 29 S β-: 100.00%	69Ni 11.4 S β-: 100.00%	70Ni 6.0 S β-: 100.00%	71Ni 2.56 S β-: 100.00%
63Co 27.4 S β-: 100.00%	64Co 0.30 S β-: 100.00%	65Co 1.16 S β-: 100.00%	66Co 209 MS β-: 100.00% β-n	67Co 329 MS β-: 100.00% β-n	68Co 99 MS β-: 100.00% β-n	69Co 180 MS β-: 100.00% β-n	70Co 14 MS β-: 100.00% β-2n

- fragmentation of ^{86}Kr beam at 140 MeV/u on ^{9}Be
- secondary ^{70}Co beam from A1900 fragment separator
- implanted into SuN TAS

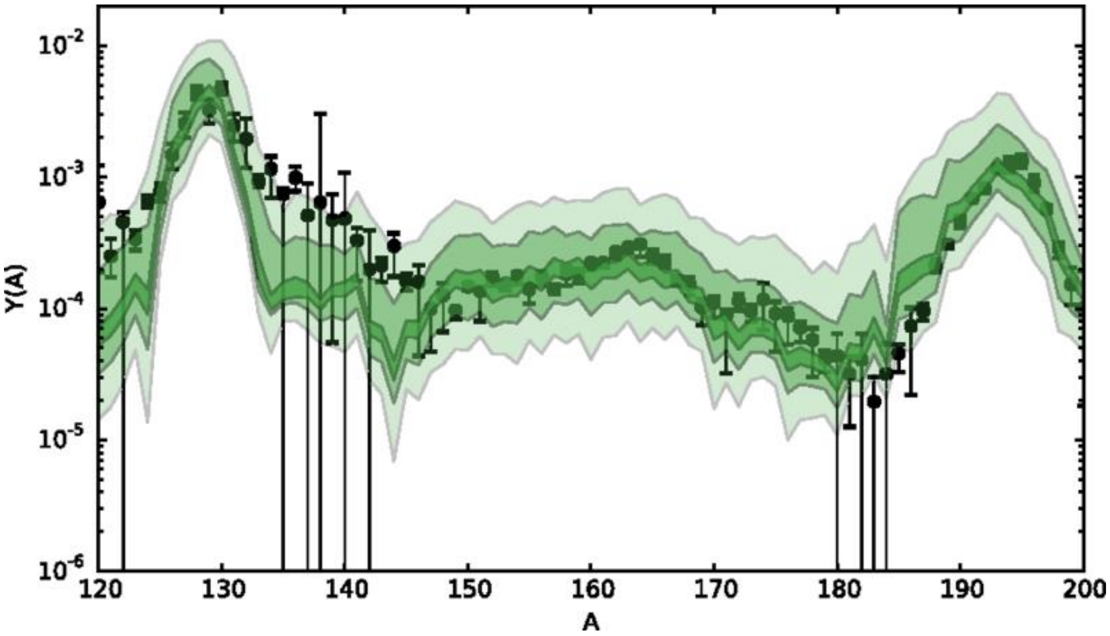
- apply β-Oslo method for ^{70}Ni
- calculate $^{69}\mathrm{Ni}(n,\gamma)^{70}\mathrm{Ni}$ cross section





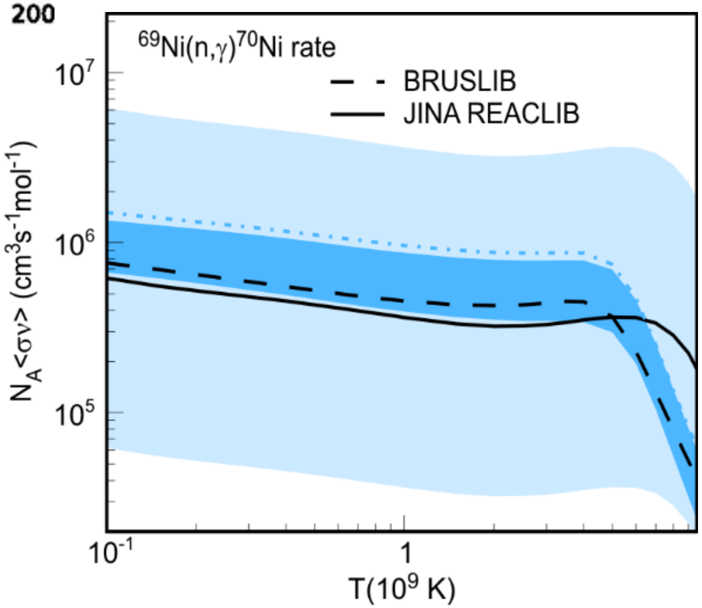
S. N. Liddick et al., PRL 116, 242502 (2016)

Constraint on (n, γ) cross section far from stability



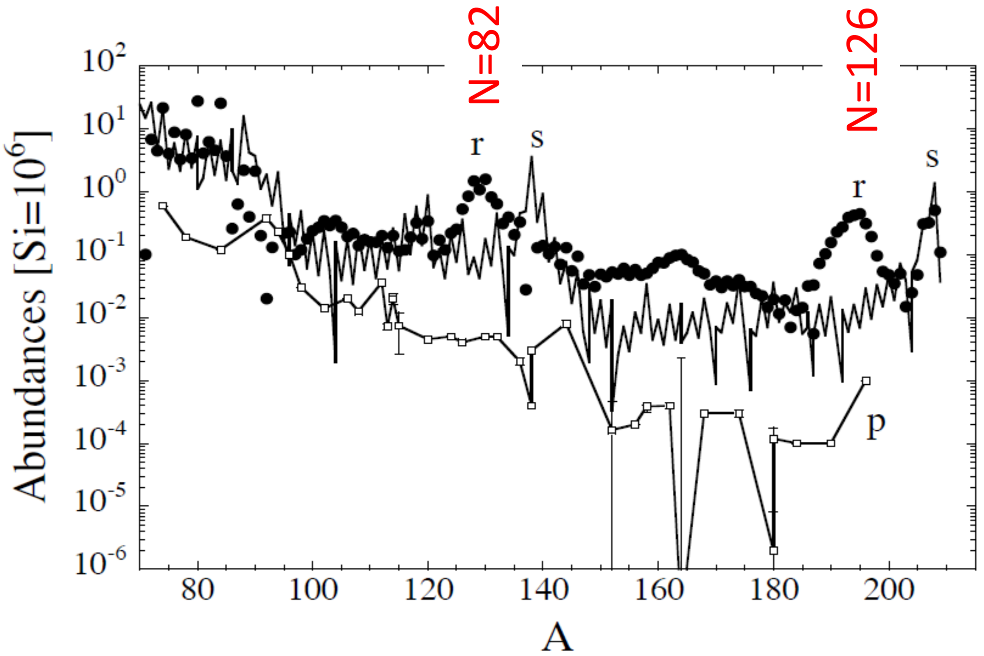
r-process abundances and sensitivity to (n, γ) cross sections (Monte Carlo):

- factor 100
- factor 10
- factor 2

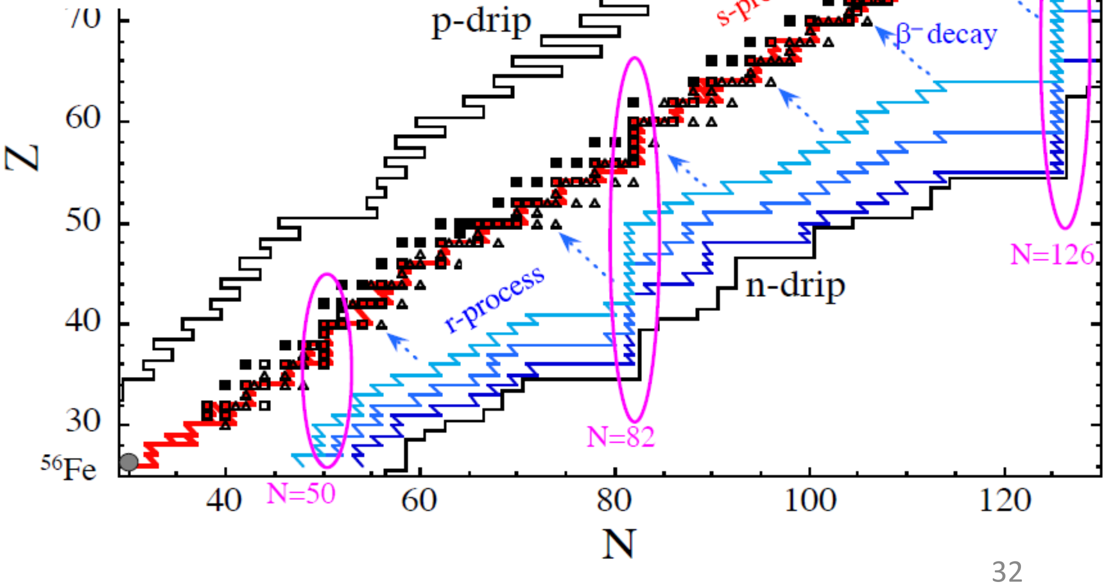


S. N. Liddick et al., PRL 116, 242502 (2016)

Abundance of heavy elements in the universe (solar system)



M. Arnould et al.,
Phys. Rep. 450, 97 (2007)

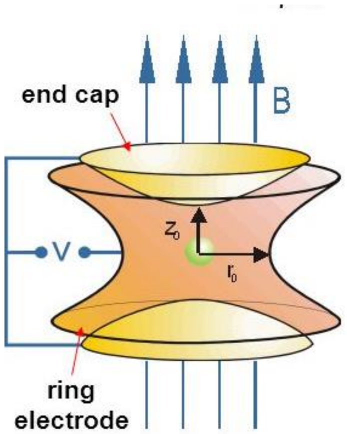


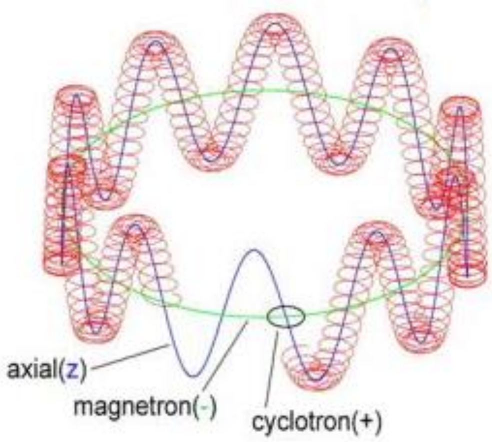
closed shells at $N = 82, 126$

- low cross section for neutron capture
- importance of
  - nuclear structure
  - half-lives
  - masses

Mass measurements

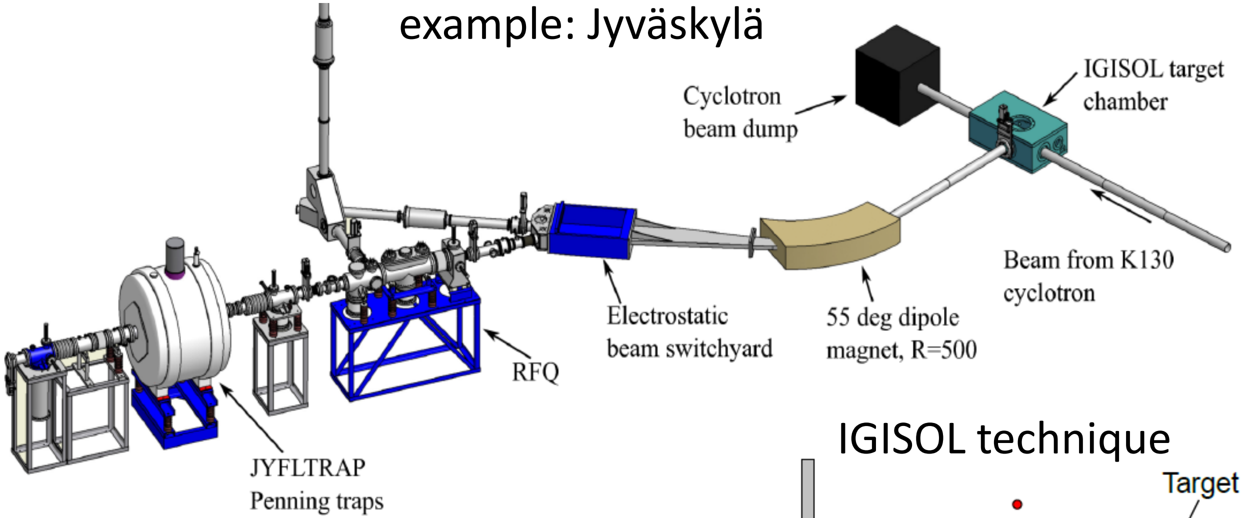
Penning trap





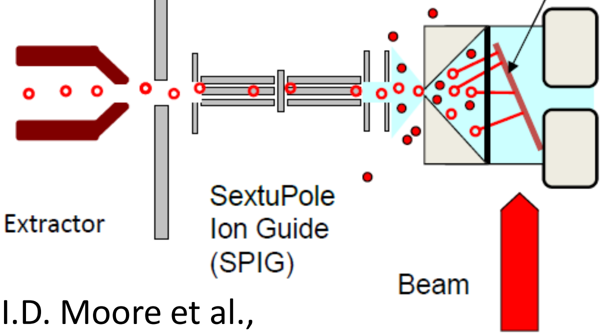
cyclotron frequency: $\omega_c = \frac{qB}{m}$

example: Jyväskylä



T. Eronen et al.,
Eur. Phys. J. A 48, 46 (2012)

IGISOL technique

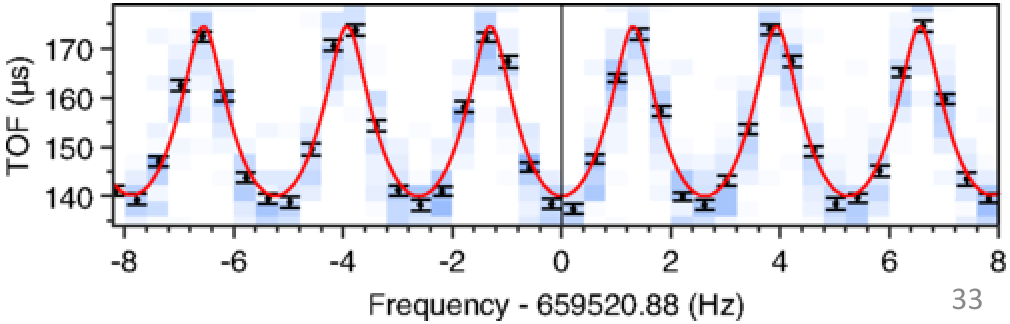


I.D. Moore et al.,
NIM B 317, 2018 (2013)

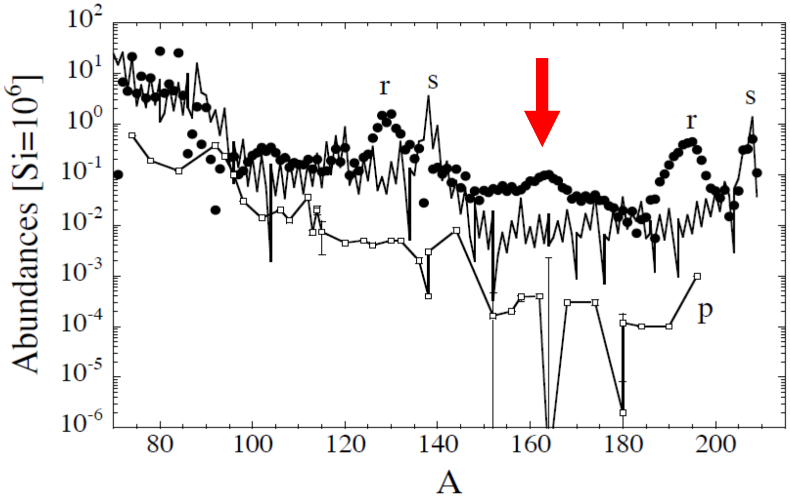
3 eigenmotions:

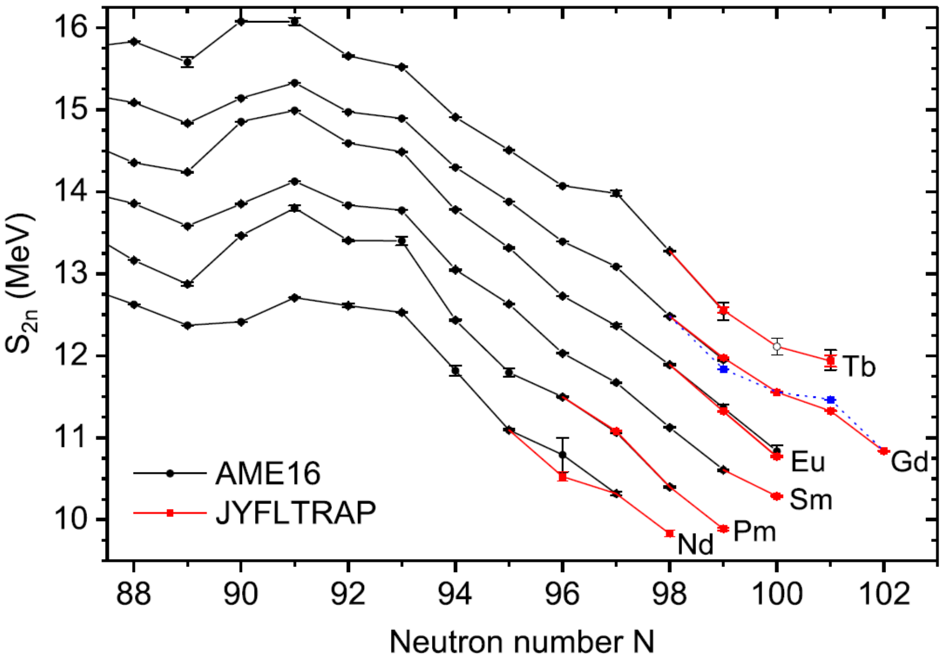
- axial (ω_z)
- magnetron (ω_-)
- modified cyclotron (ω_+)

very high precision: $\Delta m/m \approx 10^{-8}$



Mass measurements in the rare earth peak at JYFL





M. Vilen et al., PRL 120, 262701 (2018)

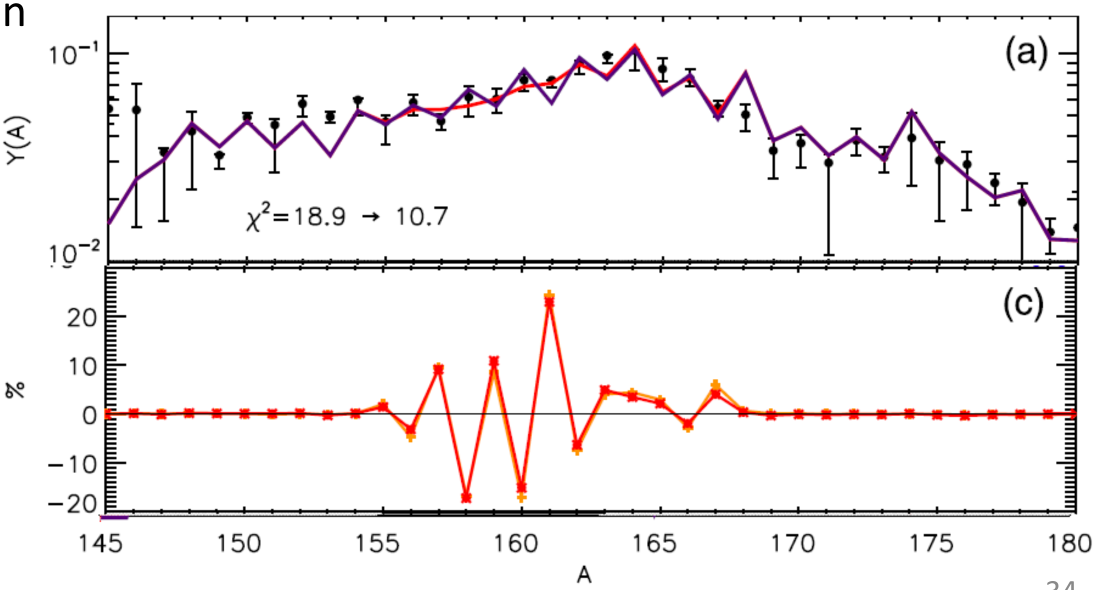
abundance calculations for neutron star merger using masses from:

▬ Vilen et al.

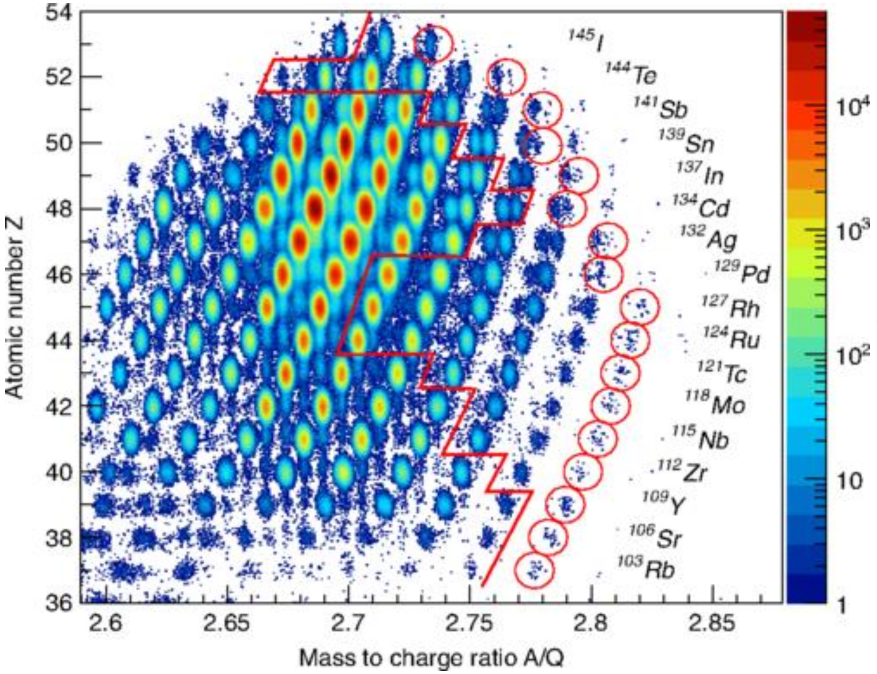
▬ FRDM(2012)

P. Möller et al.,
At. Data Nucl. Data Tab. 109–110, 1 (2016)

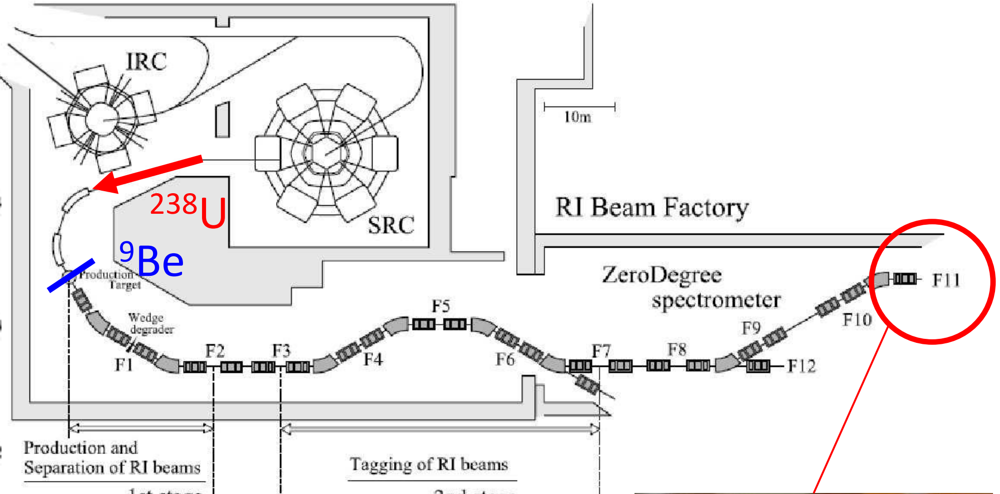
weaker neutron pairing than predicted by theory

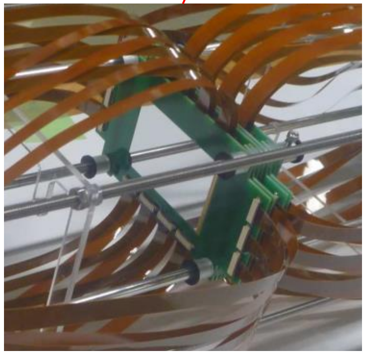


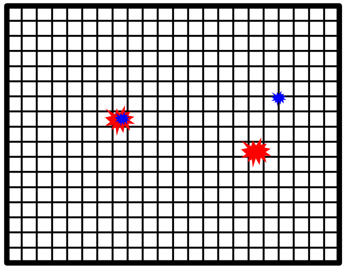
Measurement of half-lives at RIKEN



G. Lorusso et al., Phys. Rev. Lett. 114 (2015)



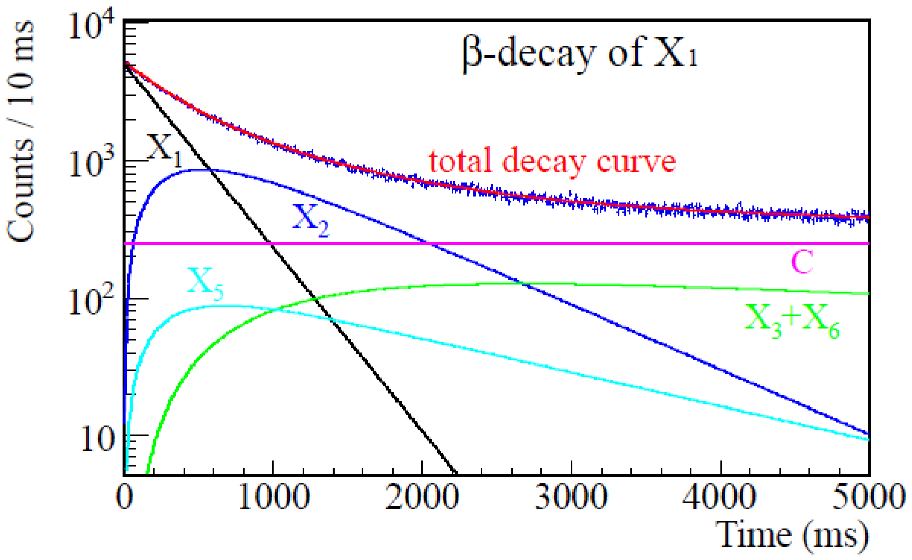


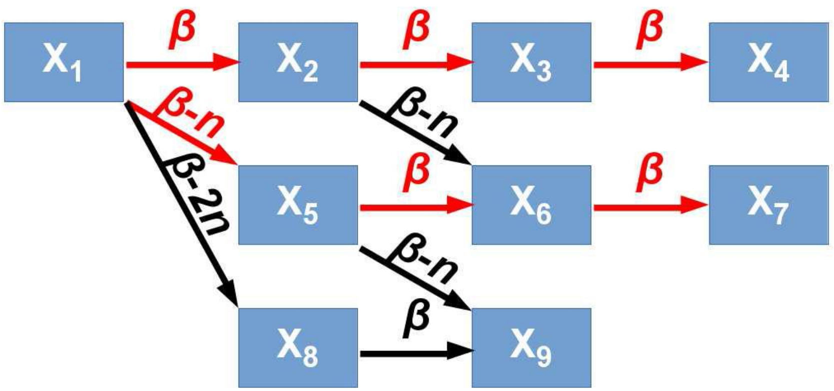


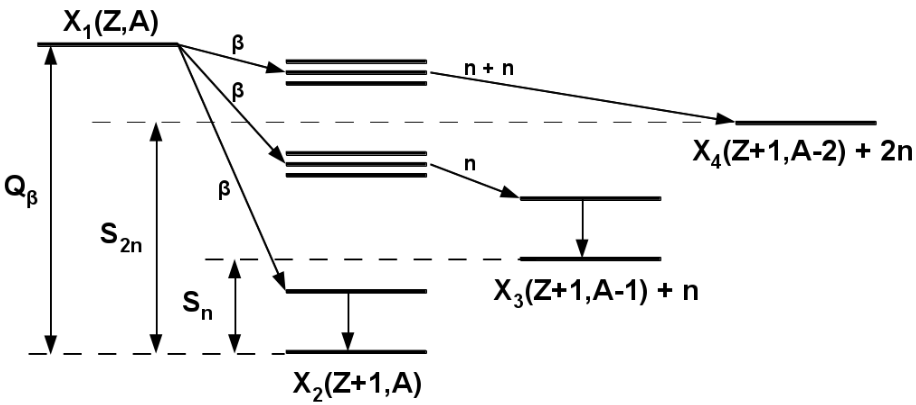
Z: characteristic energy loss ΔE in ionization chamber
A/Q: magnetic rigidity $B\rho$ in dipole
Q: fully stripped

- implant ions in pixelized Si detector
  - start signal (high E)
- β particle in same pixel
  - stop signal (low E)
- ignore if not correlated in space

Decay chains







need to consider

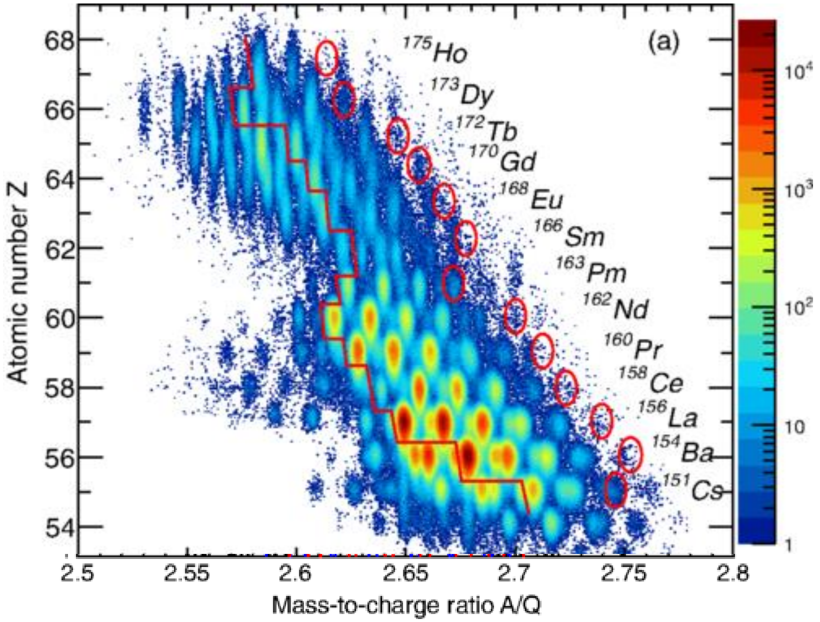
- decay of daughter & granddaughter
- branching for β-delayed neutron emission

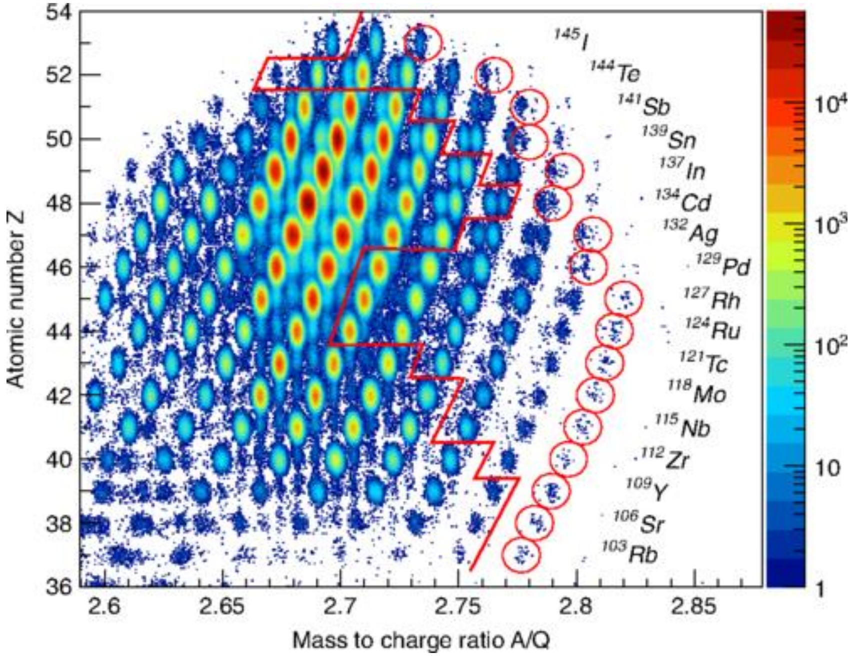
$$\frac{dX_1}{dt} = -\lambda_1 X_1$$

$$\frac{dX_2}{dt} = -\lambda_2 X_2 + \lambda_1 X_1 P_{\beta 1}$$

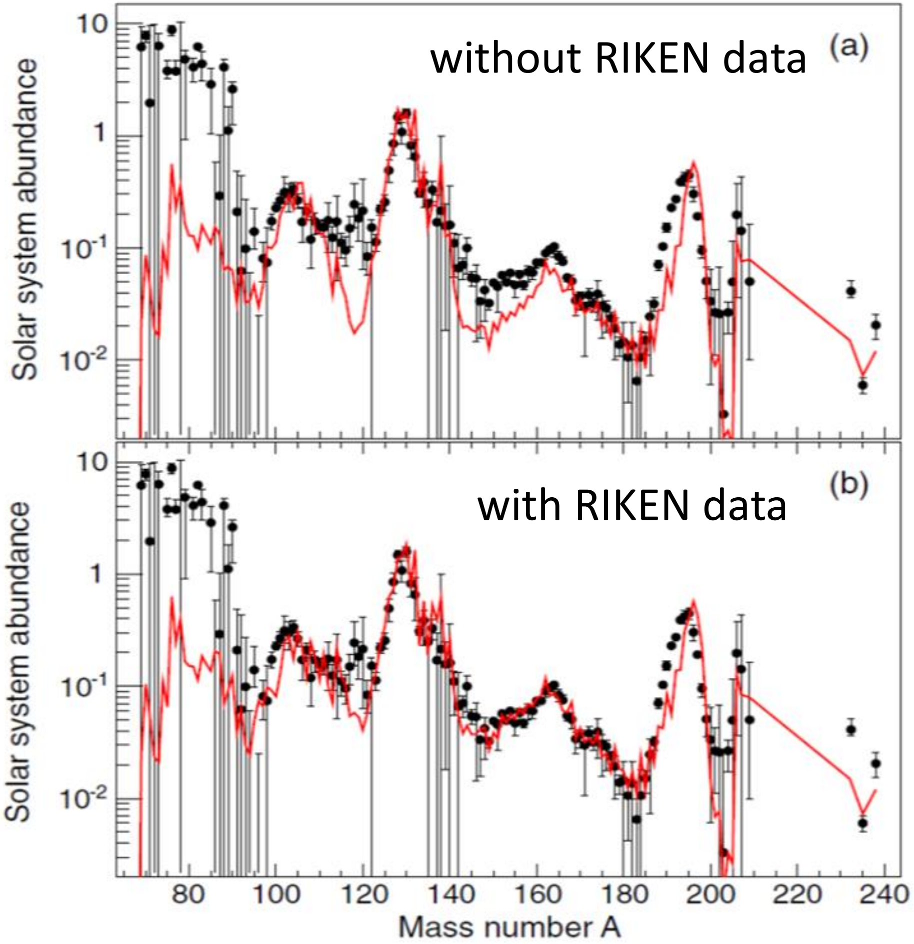
$$\frac{dX_3}{dt} = -\lambda_3 X_3 + \lambda_2 X_2 P_{\beta 2}$$

> 200 new half-lives





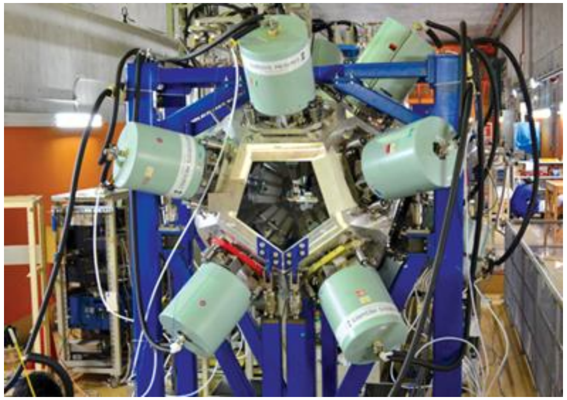
reaction network calculations

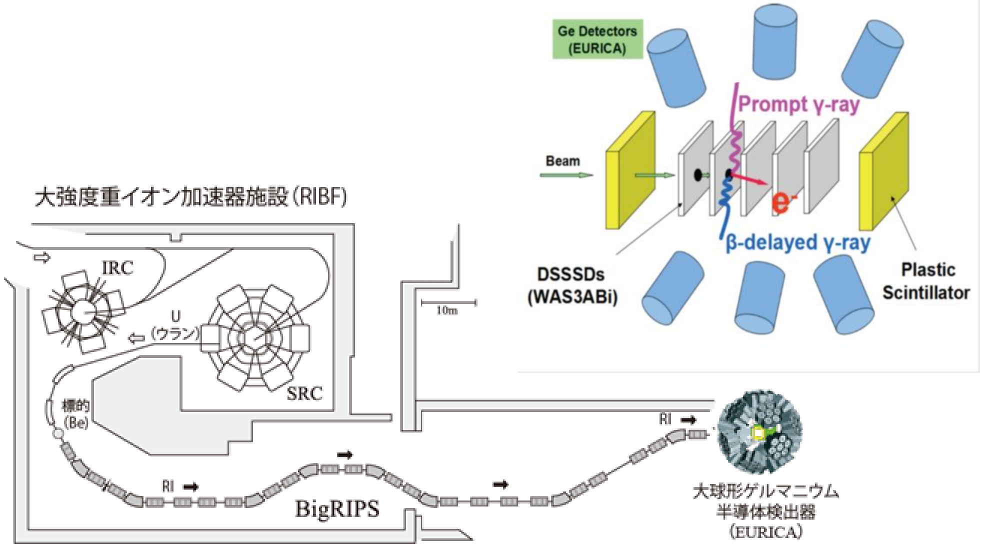


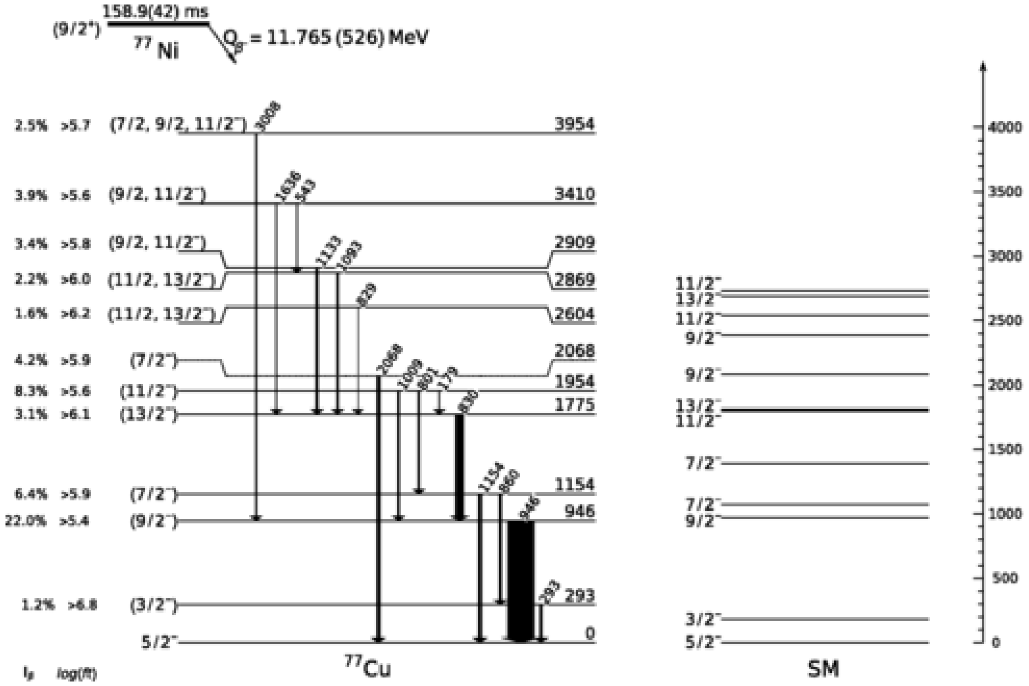
S. Nishimura et al., Phys. Rev. Lett. 106, 052502 (2011)
Z..Y. Xu et al., Phys. Rev. Lett. 113, 032505 (2014)
G. Lorusso et al., Phys. Rev. Lett. 114, 192501 (2015)
J. Wu et al., Phys. Rev. Lett. 118, 072701 (2017)

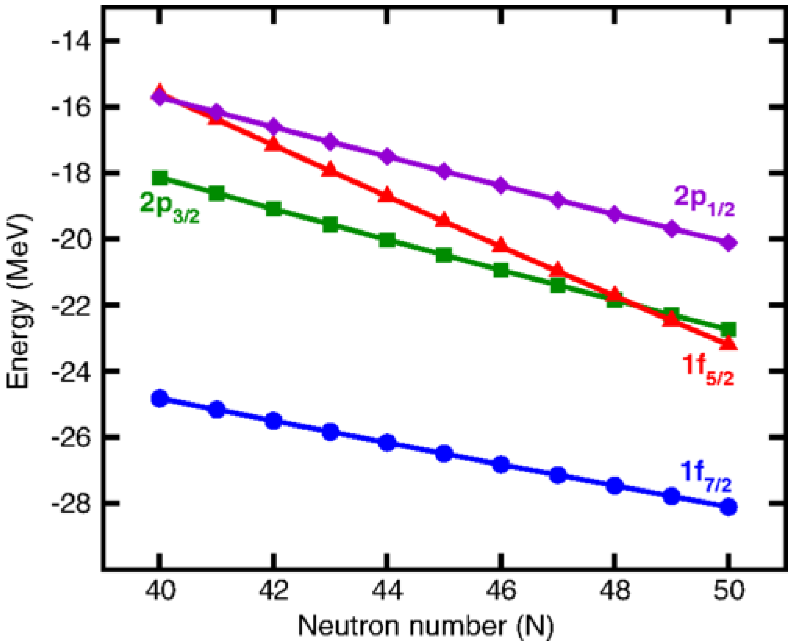
Gamma spectroscopy following β decay

EURICA





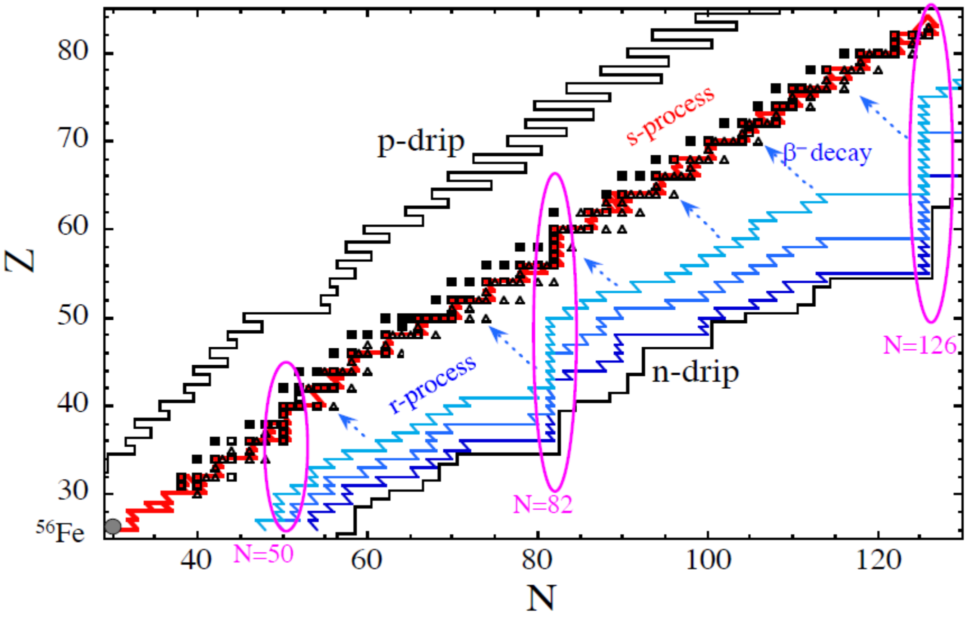


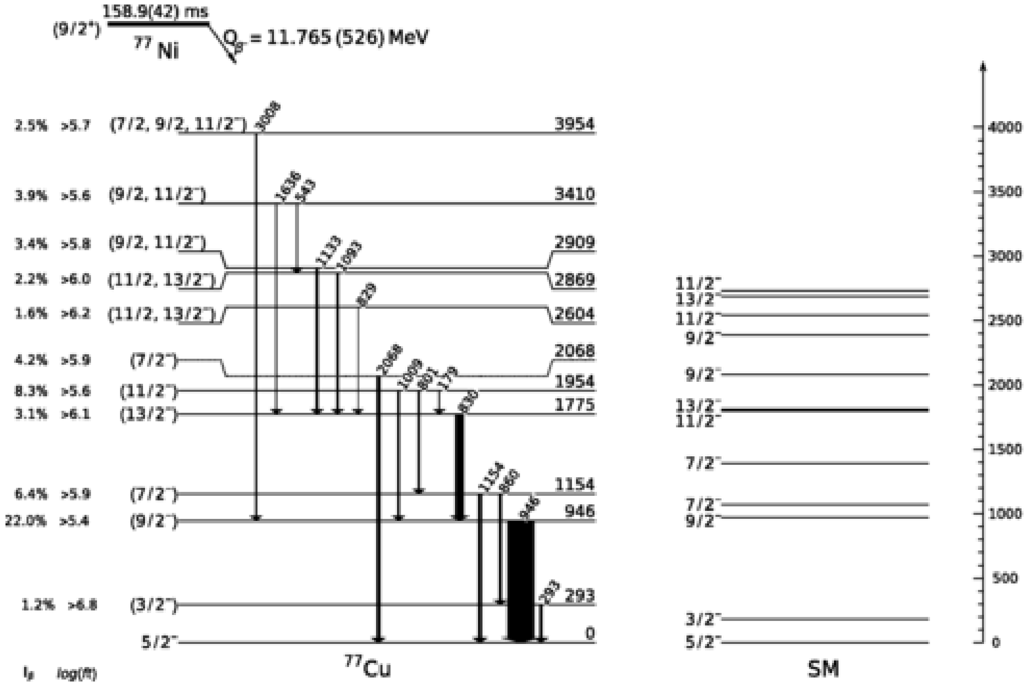


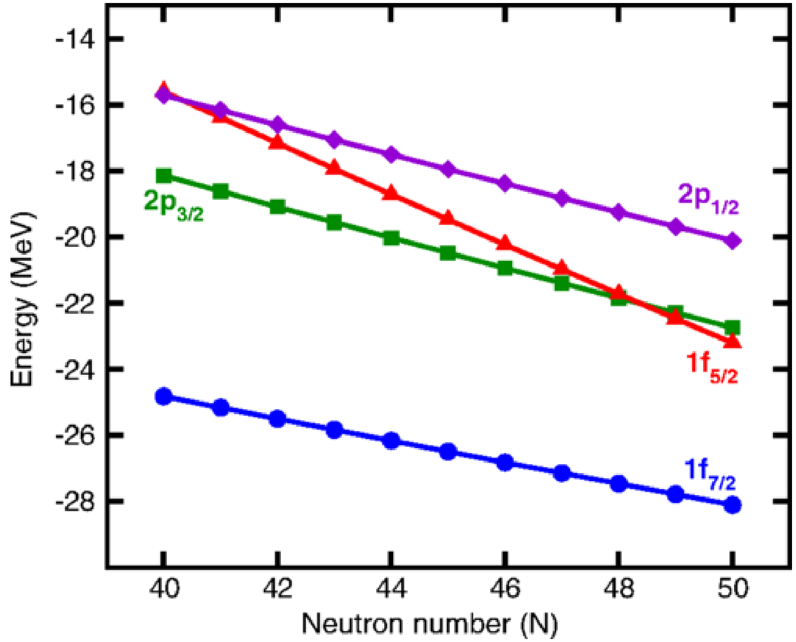
E. Sahin et al., PRL 118, 242502 (2017)

Gamma spectroscopy following β decay

impotance of shell gaps
for r-process path



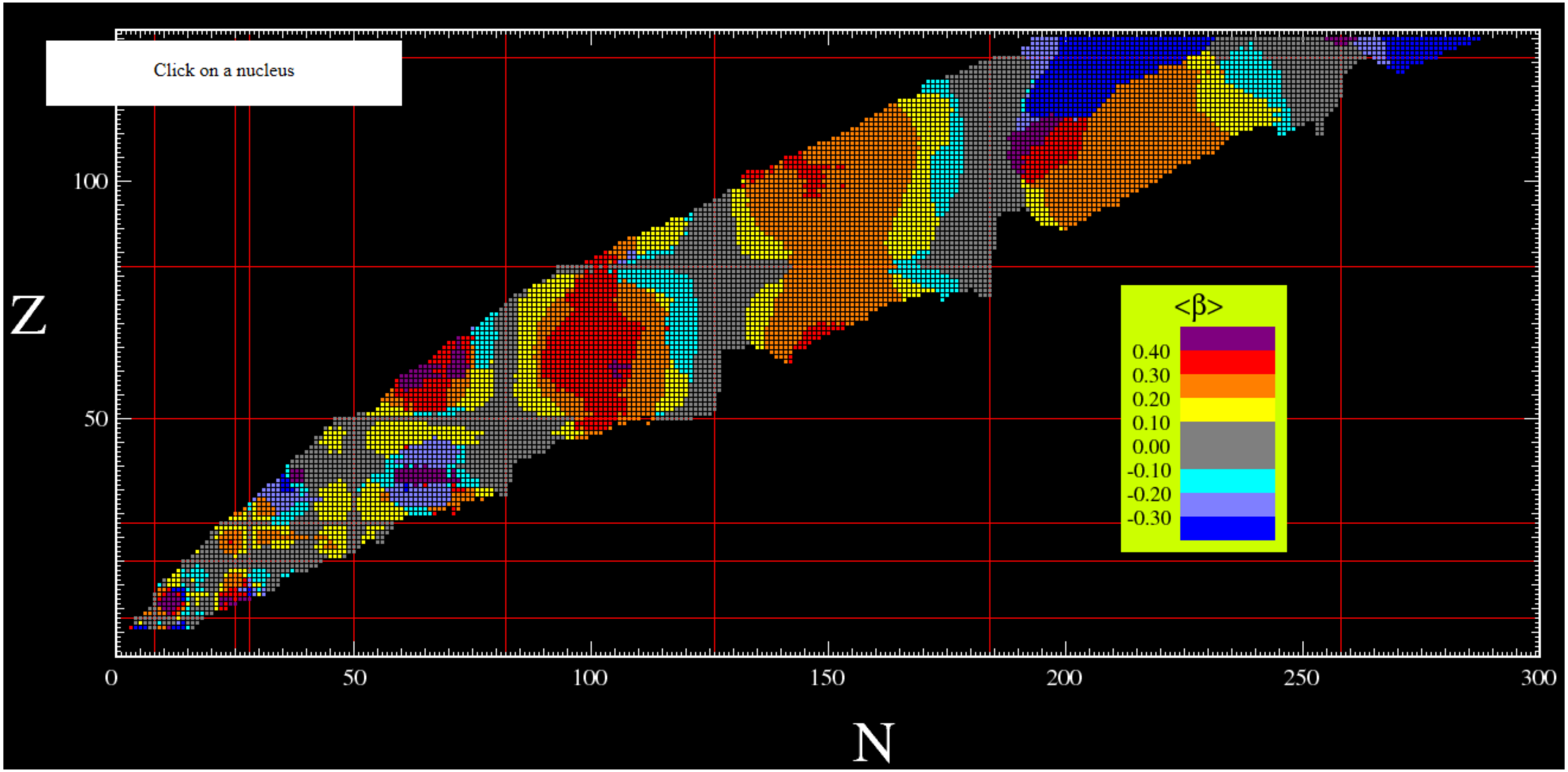




E. Sahin et al., PRL 118, 242502 (2017)

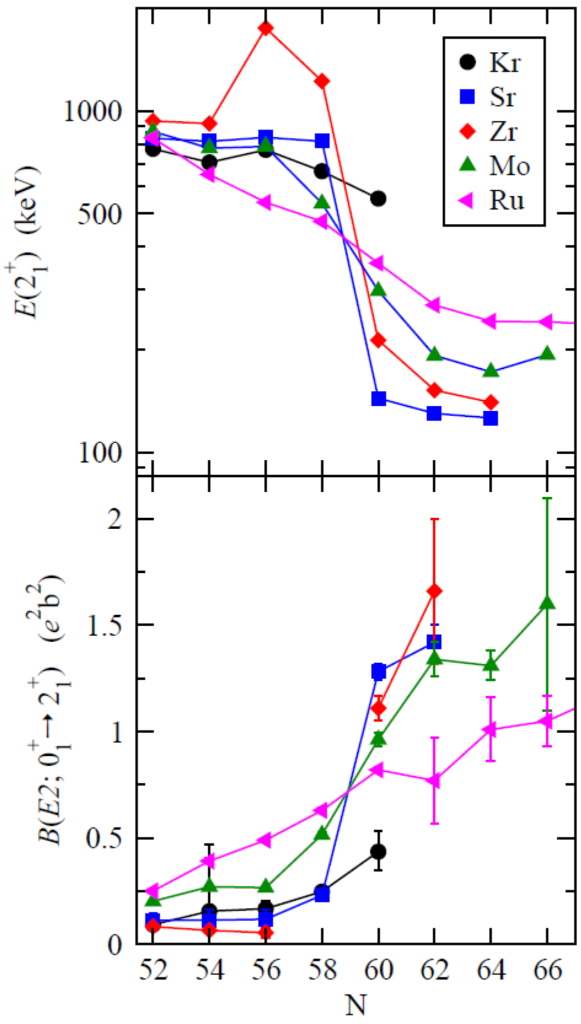
Global nuclear structure models

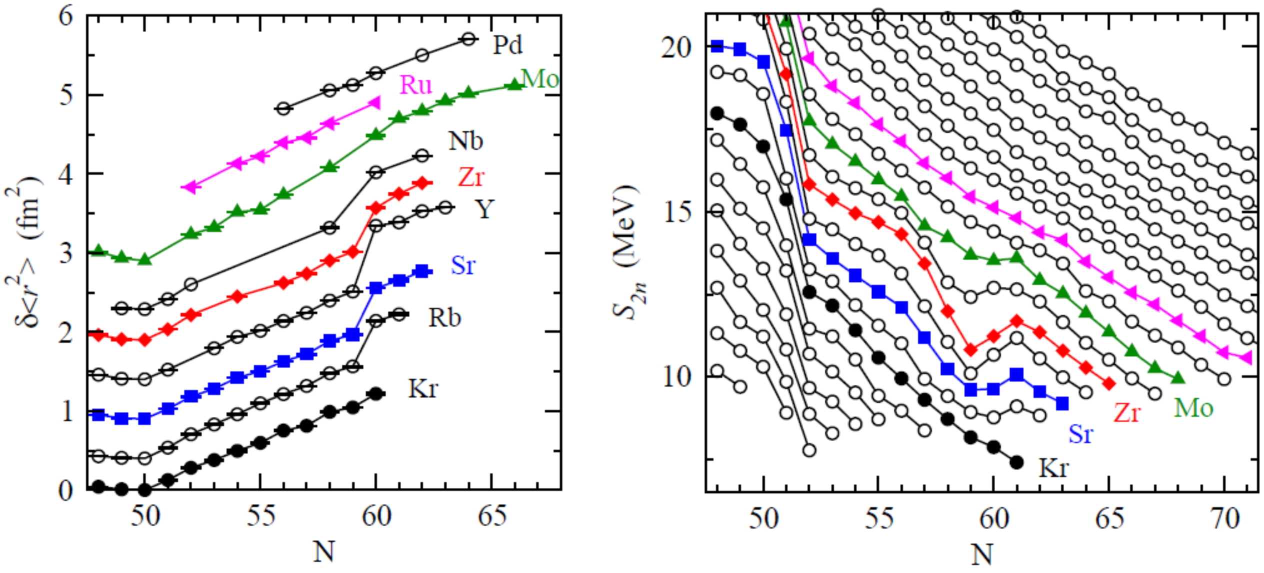
Example: quadrupole deformation across the nuclear chart
HFB extended by GCM with 5DCH and Gogny D1S



http://www-phynu.cea.fr/
S.Hilaire, M.Girod, Eur. Phys. J. A 33, 237 (2007)
J. -P. Delaroche et al., Phys. Rev. C 81, 014303 (2010)

Shape transition at $N = 60$





At $N = 60$:

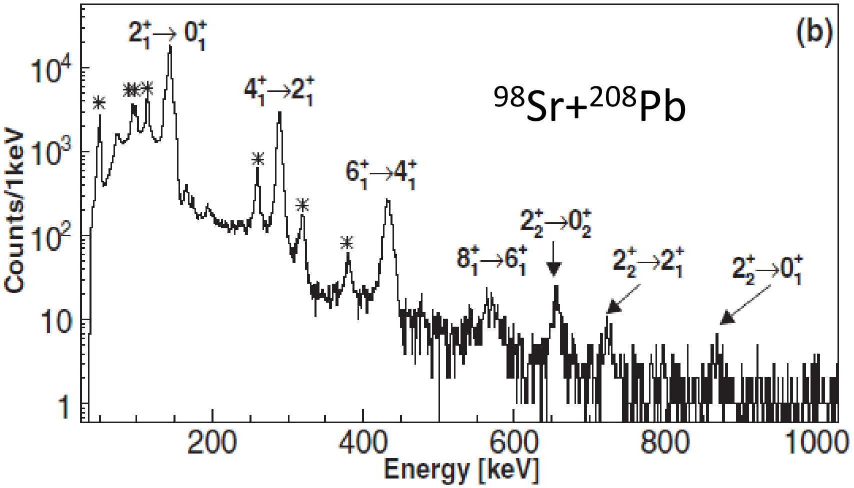
- drop in energy of first 2^+ state
- steep increase of $B(E2;\ 0^+ \rightarrow 2^+)$
- discontinuity in charge radii
- irregularity in two-neutron binding energy

A.Görgen and W.Korten,
J.Phys.G 43, 024002 (2016)

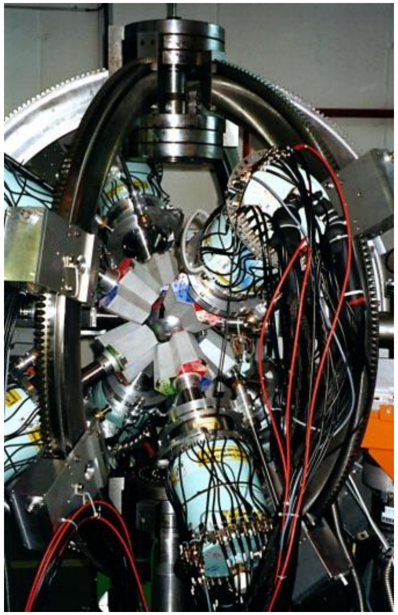
Coulomb excitation at CERN-ISOLDE

Benchmark theoretical models:

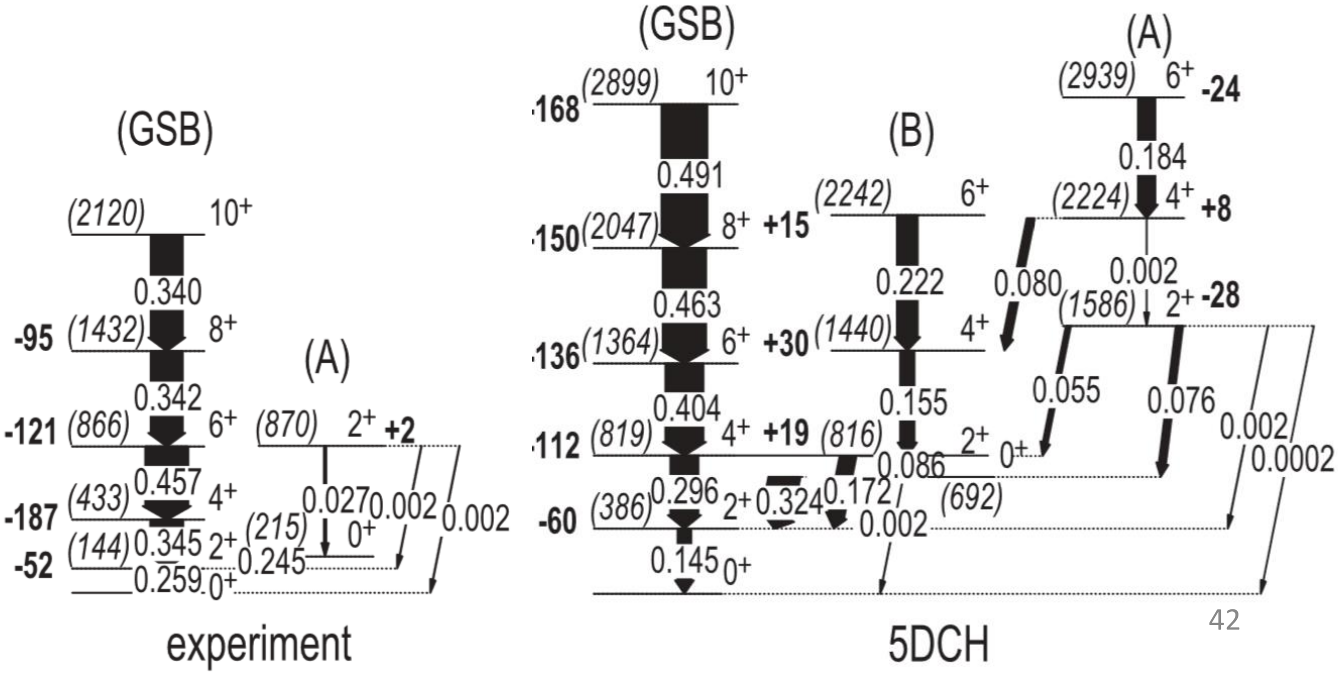
- ➢ $B(E2)$ transition strengths
- ➢ Q_s quadrupole moments



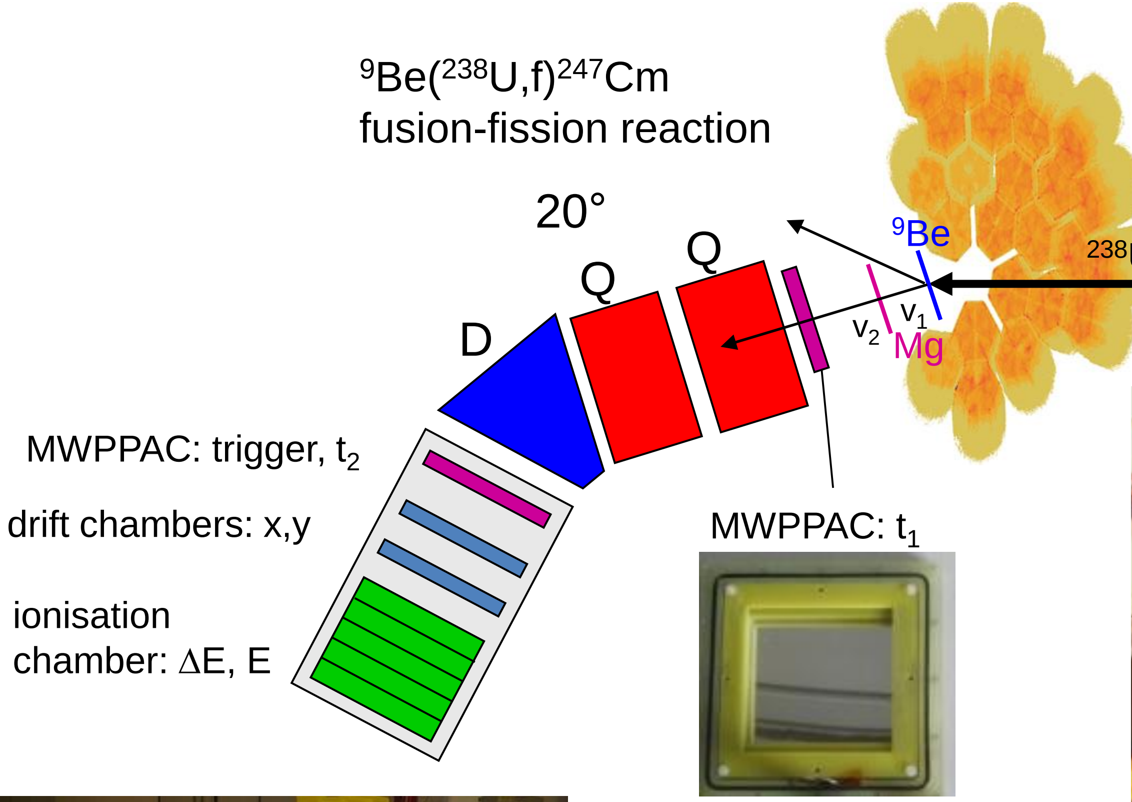
E. Clément et al., PRL 116, 022701 (2016)
E. Clément et al., PRC 94, 054326 (2016)



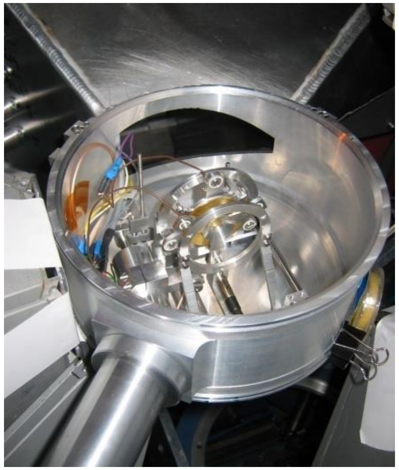
^{98}Sr

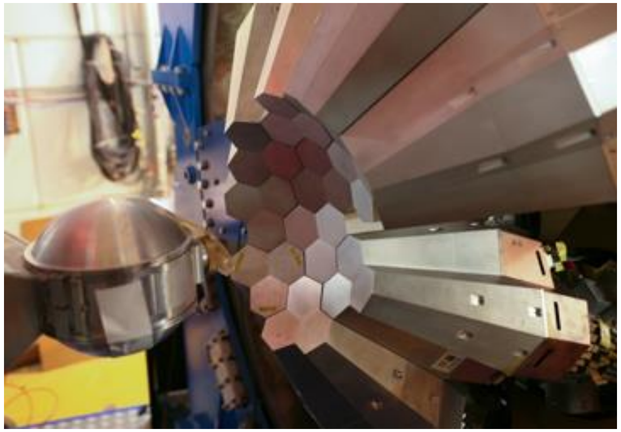


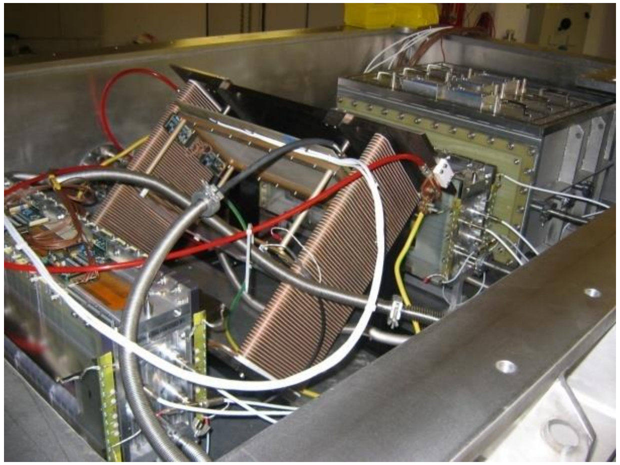
Fission fragment spectroscopy at GANIL



$^{9}Be(^{238}U,f)^{247}Cm$
fusion-fission reaction

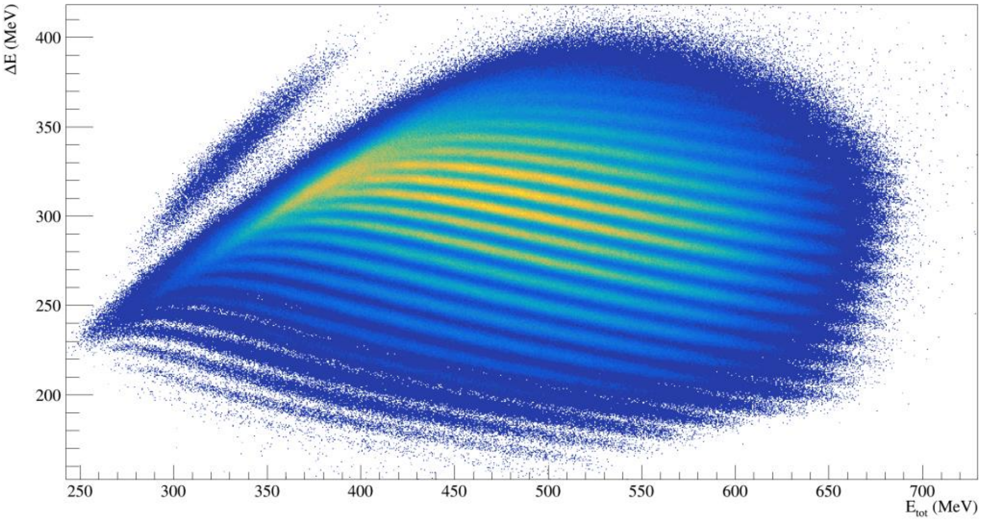




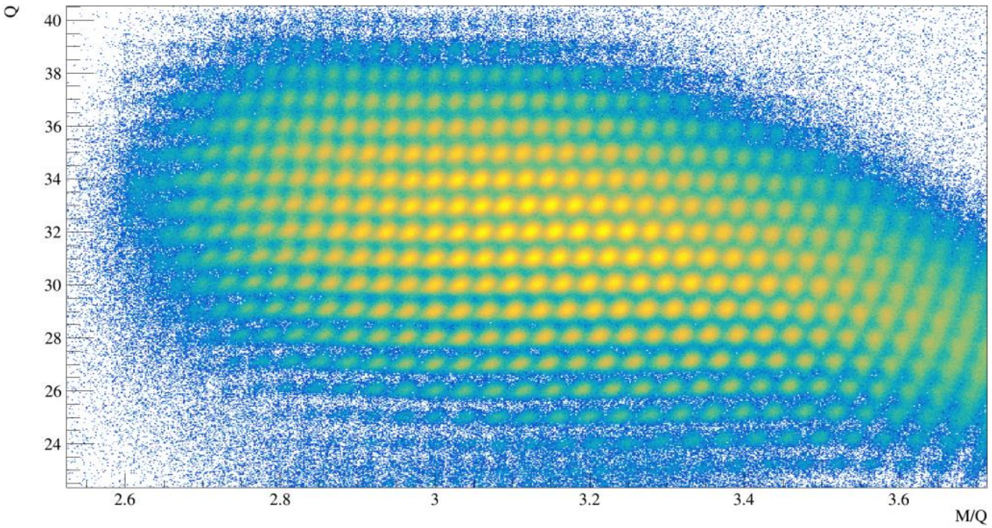


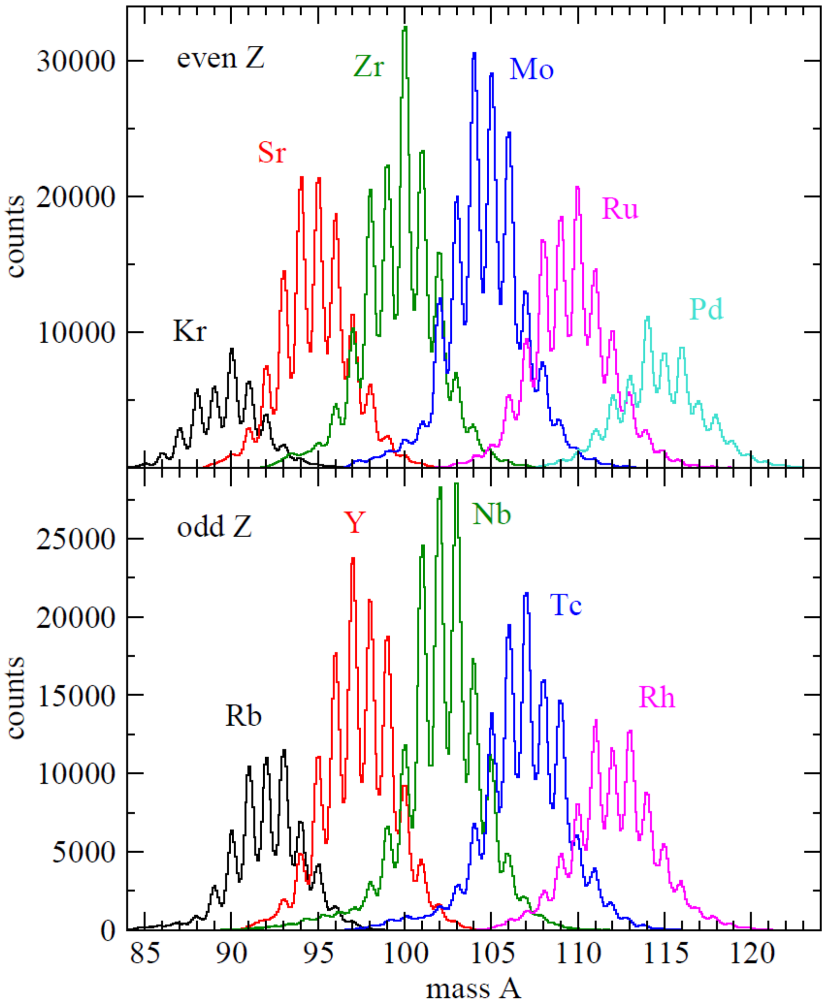
Identification of fission fragments in VAMOS

energy loss and total energy in ionization chamber $\Rightarrow Z$



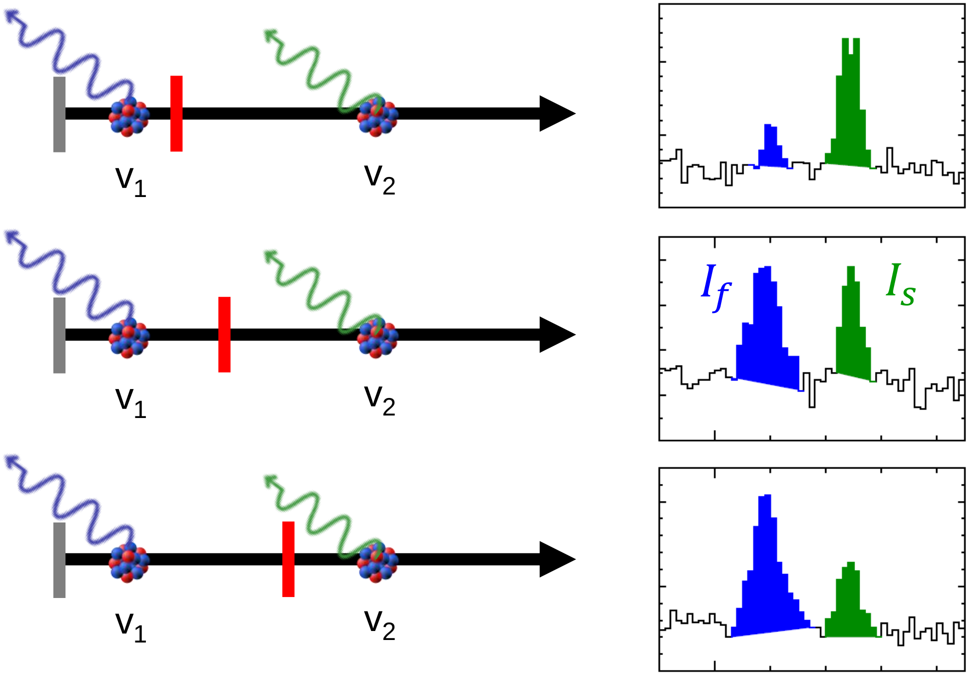
reconstructed trajectory, magnetic rigidity
time of flight, total energy $\Rightarrow$ mass M and M/Q

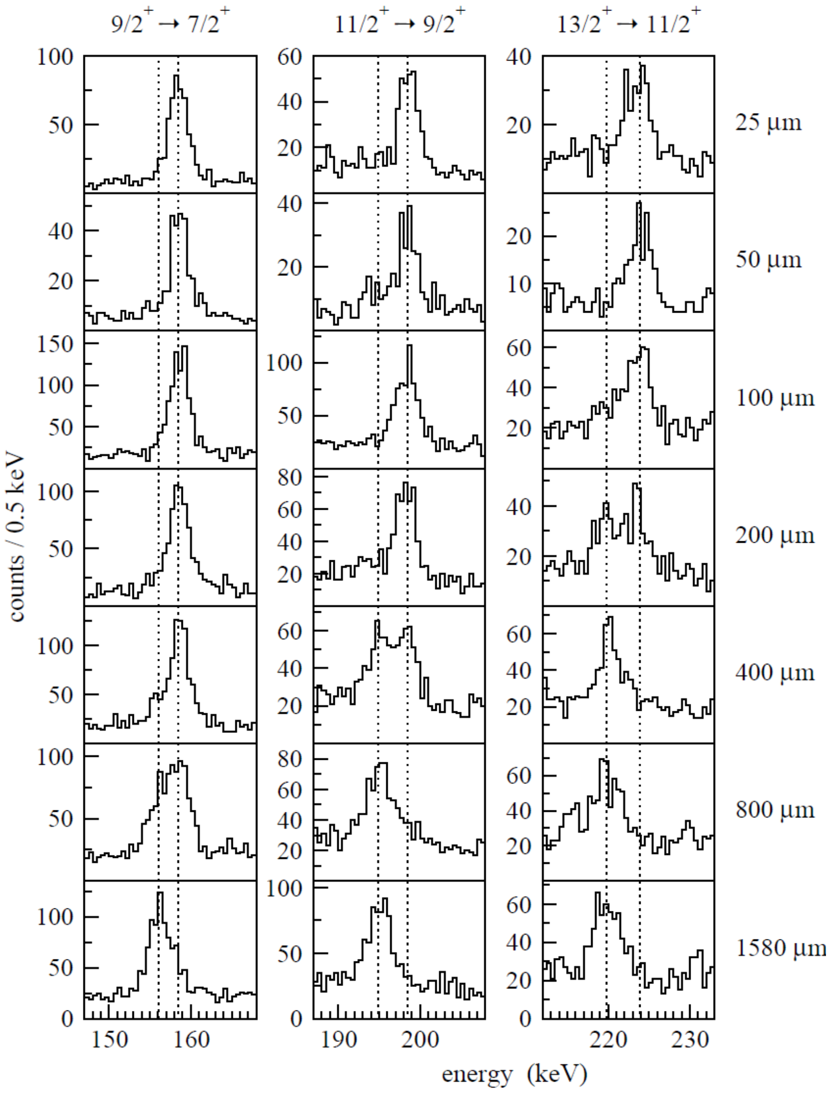




event-by-event identification in Z and A of more than 200 fission fragments

Recoil distance Doppler shift (RDDS) method

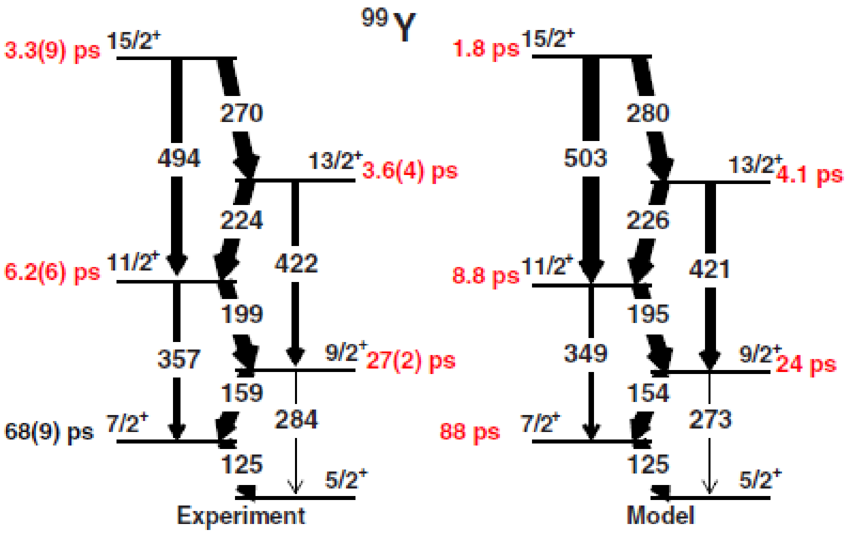




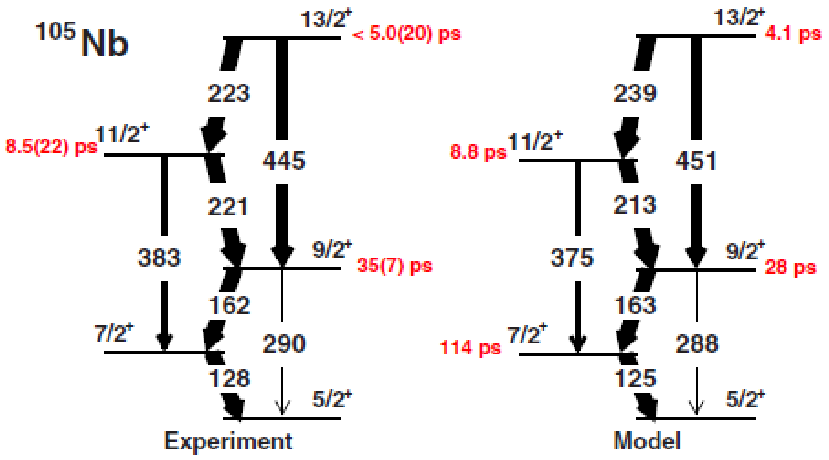
- picosecond lifetimes in n-rich fission fragments
- transition probabilities
- benchmarks for theory
- evolution of deformation across nuclear chart

T.W.Hagen et al.,
PRC 95, 034302 (2017)

Deformed odd-mass nuclei: particle-rotor coupling



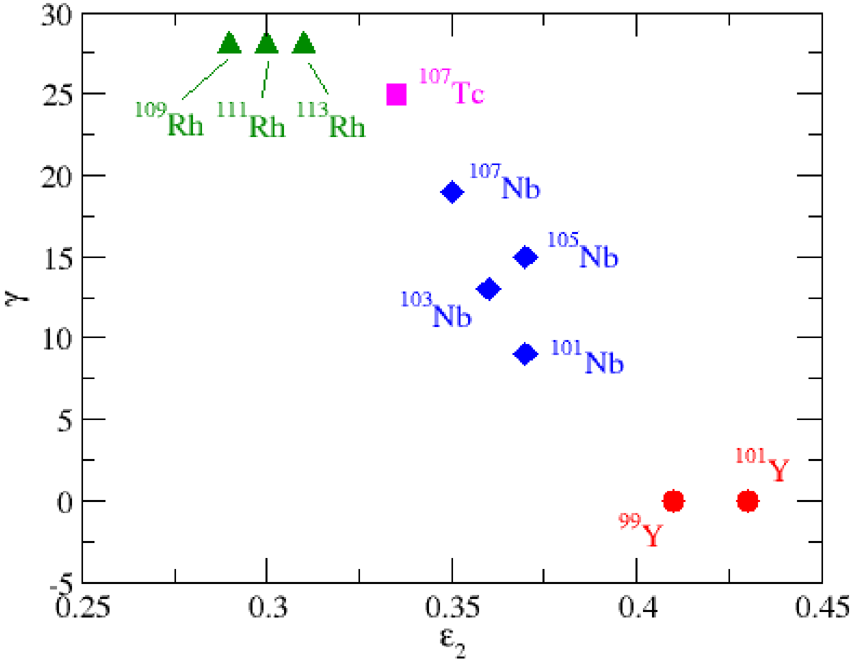
microscopic particle-rotor calculations
with $\varepsilon_2 = 0.41$ and $\gamma = 0°$



$\varepsilon_2 = 0.36, \gamma = 13°$

Results for $_{39}$Y, $_{41}$Nb, $_{43}$Tc, $_{45}$Rh:
with increasing Z:

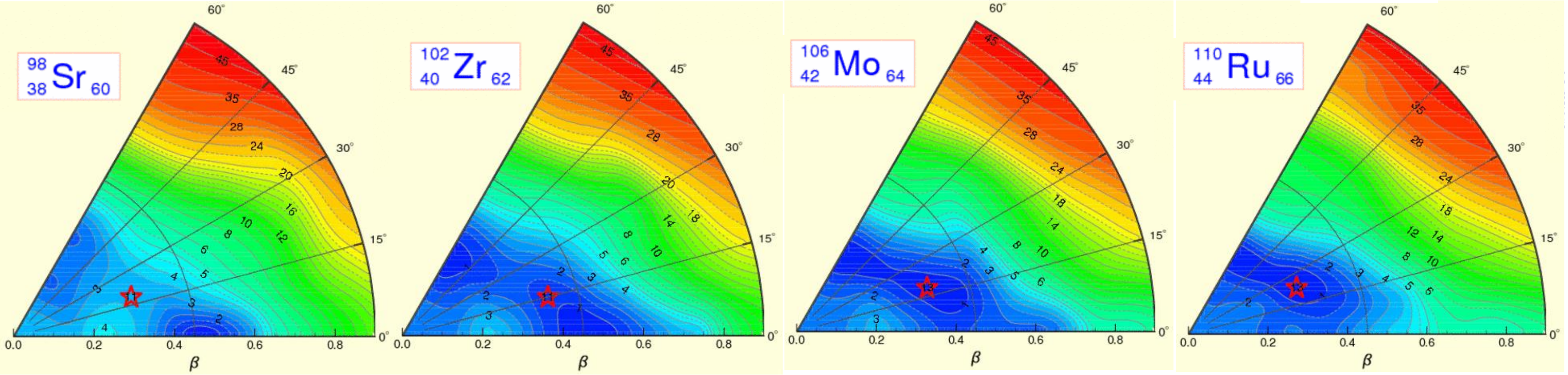
- increase of triaxiality γ
- decrease of deformation ε_2



T.W. Hagen, PhD Univ. Oslo (2016)
T.W. Hagen et al., PRC 95, 034302 (2017)
T.W. Hagen et al., Eur. Phys. J. A 54, 50 (2018)

Many more results from the same experiment

Potential energy surfaces for even-even cores (Gogny D1S)



J. -P. Delaroche et al., Phys. Rev. C 81, 014303 (2010)

Results for ${}_{39}$Y, ${}_{41}$Nb, ${}_{43}$Tc, ${}_{45}$Rh:
with increasing Z:

- ➢ increase of triaxiality γ
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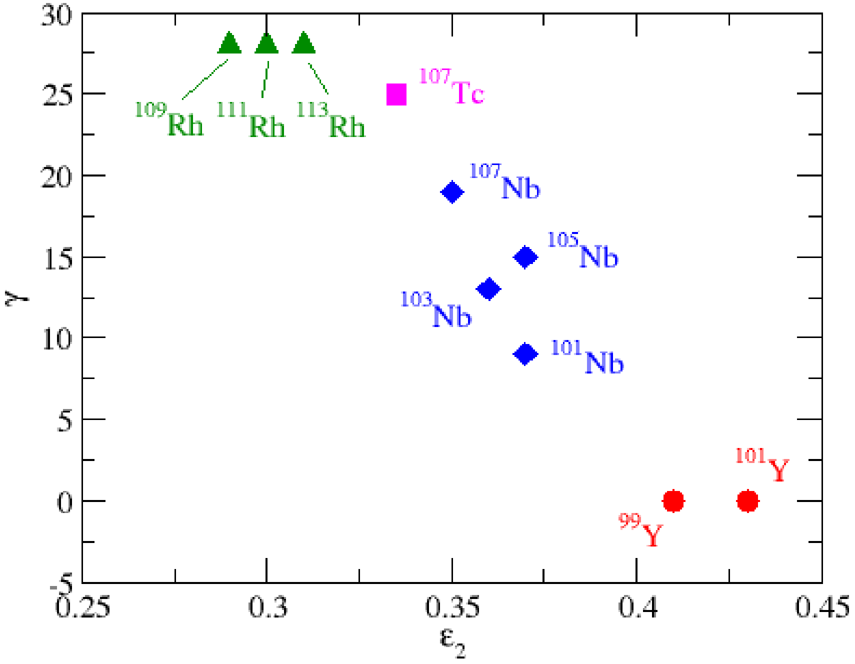

T.W. Hagen, PhD Univ. Oslo (2016)
T.W. Hagen et al., PRC 95, 034302 (2017)
T.W. Hagen et al., Eur. Phys. J. A 54, 50 (2018)

Nuclear data

cross sections
nuclear masses
half-lives
nuclear structure

Nucleosynthesis processes

path
energy release
time scale

Astrophysical parameters

temperature
density
stellar masses
particle fluxes

Abundances

Observations

terrestrial
meteorites
light curves
spectral lines

"If you wish to make an apple pie from scratch, you must first invent the universe."

Carl Sagan