Outline: Experimental Nuclear Astrophysics

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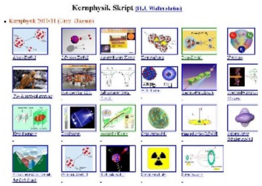
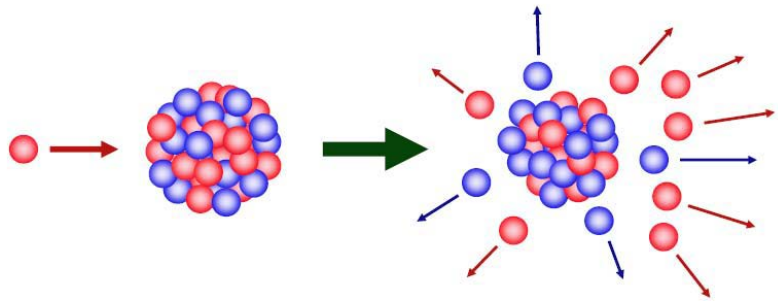
web-page: https://web-docs.gsi.de/~wolle/ and click on

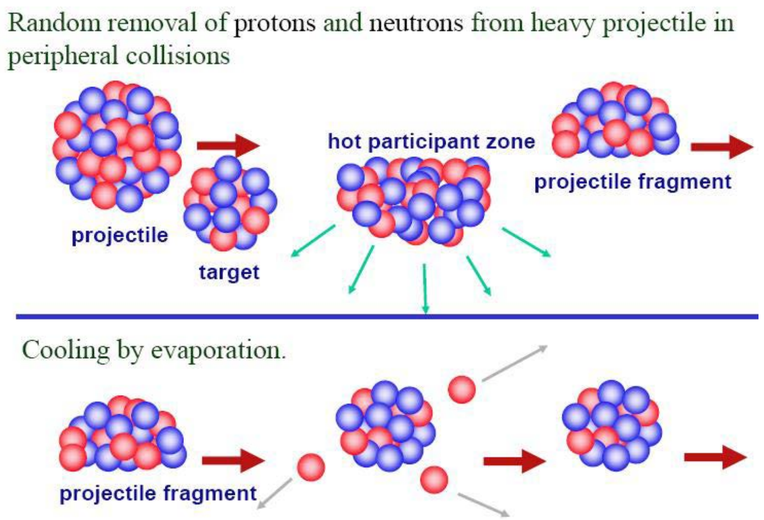


1. Projectile fragmentation
2. Isotope separation on line
3. Waiting point nuclei
4. reactions, masses, radii

Radioactive Ion Beams production methods



Target fragmentation

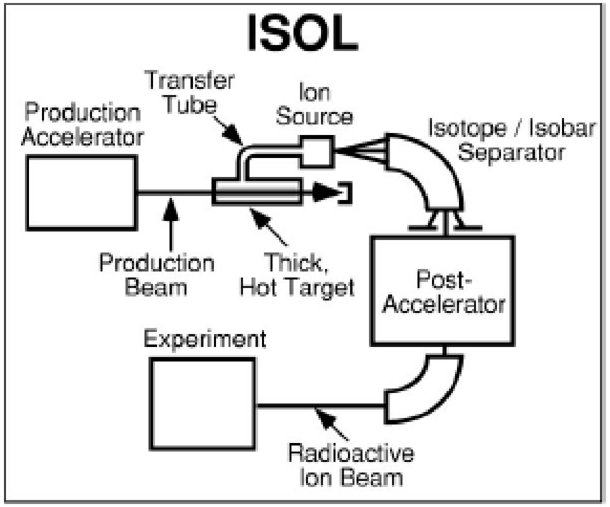


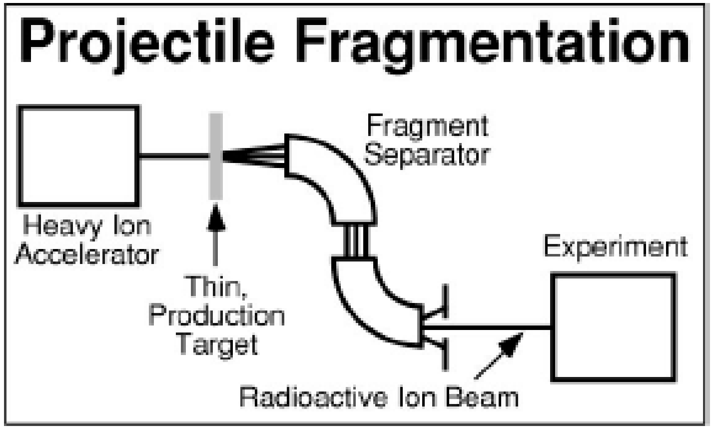
Projectile fragmentation

fragmentation invented at LBNL in the 1980´s

Radioactive Ion Beams production methods

- Isotope Separation on Line (ISOL) (CERN, LLN, ORNL, TRIUMF)
- Projectile Fragmentation (PF) (GANIL, GSI, MSU, RIKEN)
- in-flight production (ANL, Notre Dame, TAMU)
- batch mode production (suitable for long-lived species)
- ...





☺ excellent quality
high purity
high intensities

☹ limited number of species
different production for different species
limited to nuclei with $t_{1/2} \geq 1s$ (allow for diffusion)

☺ independent from chemical properties
no limitations on $t_{1/2}$ (fast separation)

☹ typical beam energies too high for NA
poorer beam quality (energy, size)
possible beam contaminations

M.S. Smith and K.E. Rehm, Ann. Rev. Nucl. Part. Sci, 51 (2001) 91-130

Fast radioactive beams – why?

- Production by the in-flight technique (vs ISOL)
  - Chemical blindness
  - Shortest half-lives
- Experimental issues
  - Doppler boosted
    - Kinematical focusing
    - Resolution
  - Small energy loss
    - Possible to use thick targets
    - Ions, particles are hard to stop
    - Can use many detectors – ion-by-ion tracking

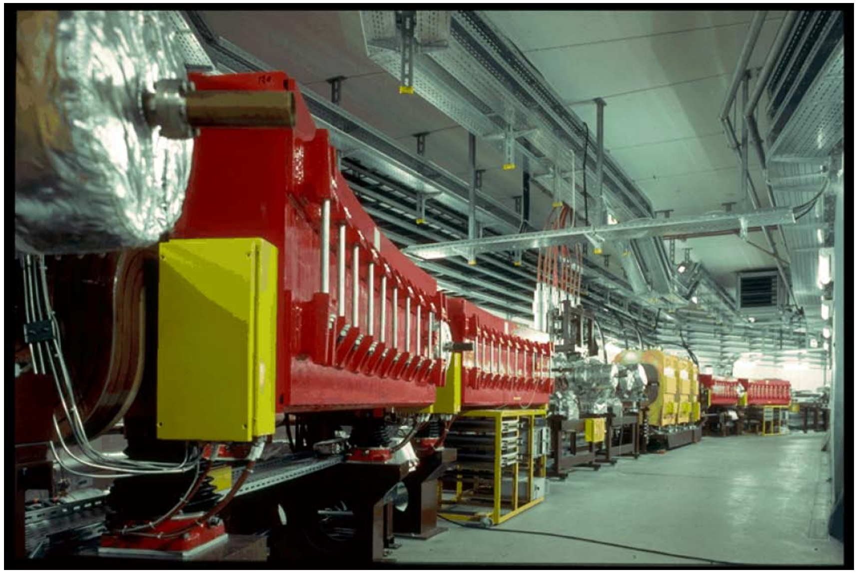
Ranges in silicon	p	^{40}Ar	^{238}U
10 MeV/u (ISOL + post-acc.)	700 μm	127 μm	107 μm
500 MeV/u (Relativistic in-flight)	63 cm	7.6 cm	1.8 cm

Fast radioactive beams – where?

- GSI since SIS (early 90's)

- Intermediate-energy RIBs (tens of MeV/u) since many years at GANIL, MSU, RIKEN

- Future (and current) facilities
  - RIBF@RIKEN
  - FRIB@MSU
  - FAIR-NuSTAR



The future - FAIR

Next generation

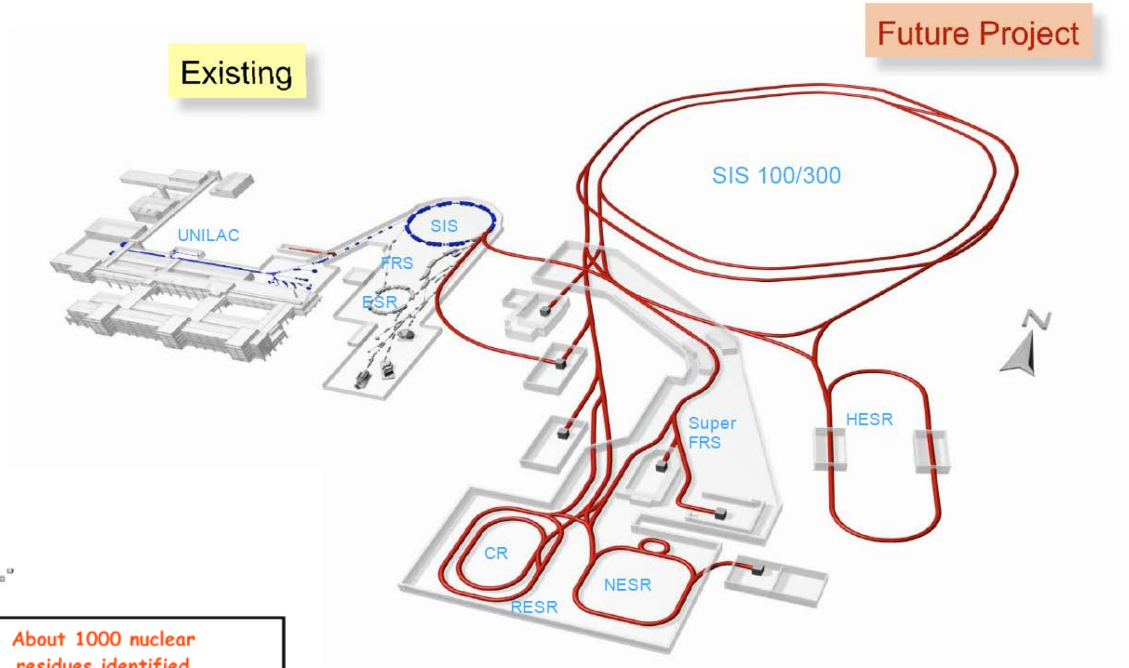
RIBs facilities

1.0-1.5 GeV/u

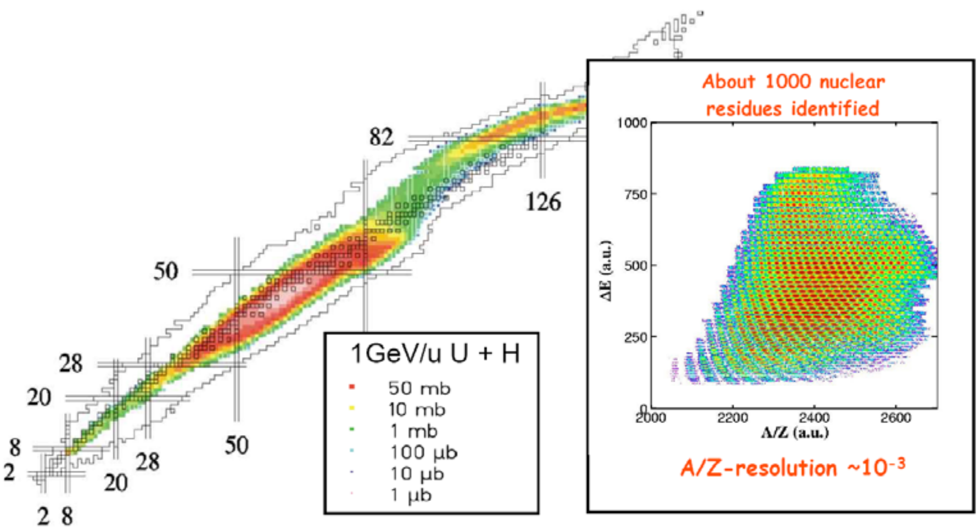
all elements up to uranium

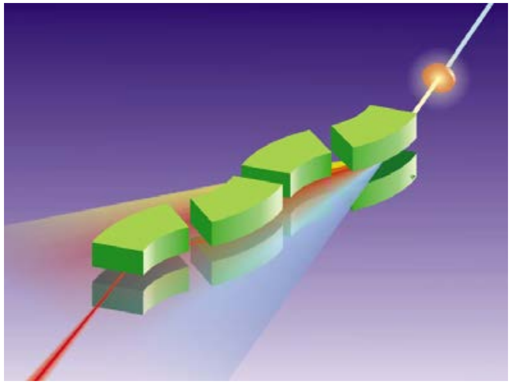
The Future International Facility at GSI:

FAIR – Facility for Antiproton and Ion Research



P. Armbruster et al.; Phys. Rev. Letters, Jan. 05





NuSTAR experiments

Nuclear reactions

- Relativistic energies *R3B*
- Cooled beams *EXL*
- High-res. spectroscopy *HISPEC*

Decay properties

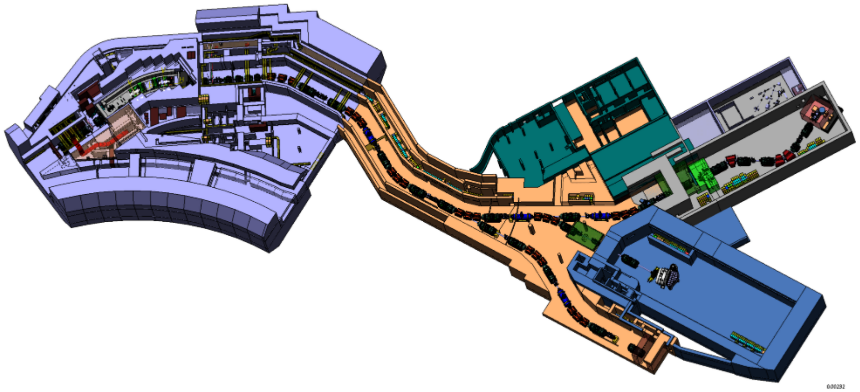
- Stopped beams *DESPEC*

Ground state properties

- Masses *MATS, ILIMA*
- Radii, momenta *LASPEC*

New tools

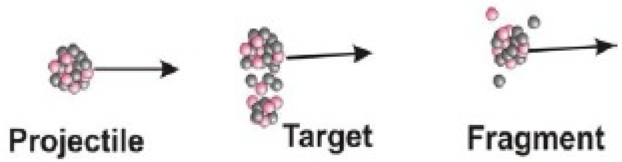
- Electron – RIB scattering *ELISe*
- p-bar – RIB collider *AIC*



super FRagment Separator

Production of exotic nuclei at relativistic energies

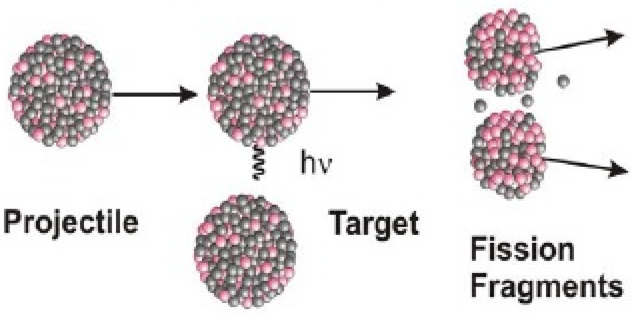
Projectile Fragmentation



Nucleon-nucleon collisions, abrasion, ablation

$$\vec{v}_f \approx \vec{v}_p$$

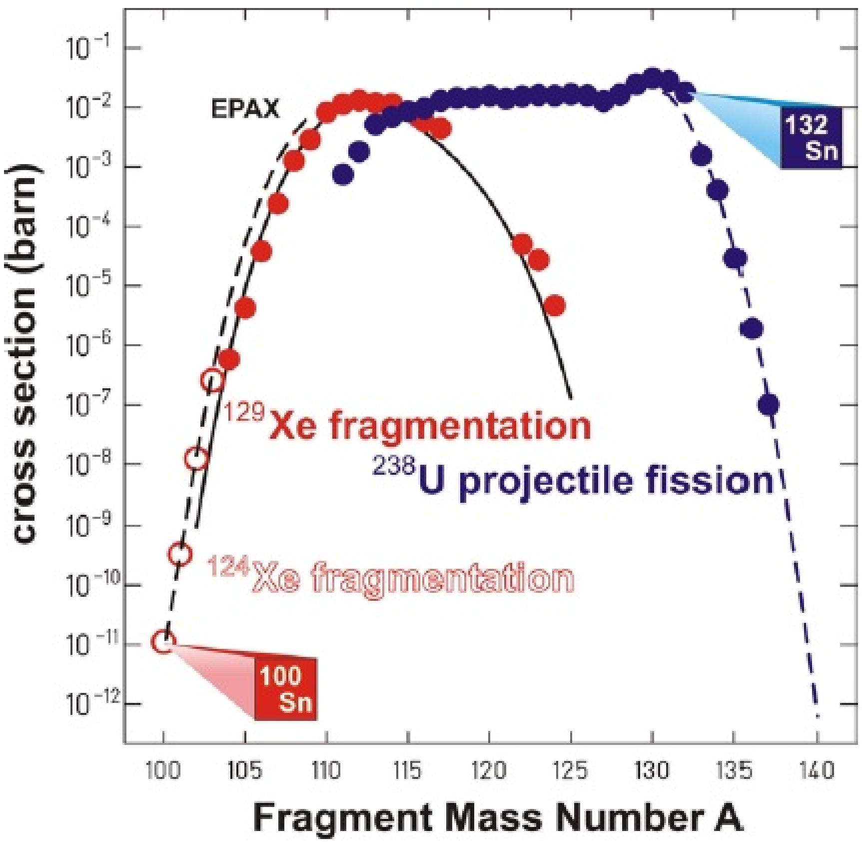
Projectile Fission



Electromagnetic excitation, fission in flight

$$\vec{v}_f \approx \vec{v}_p + \vec{v}_{fission}$$

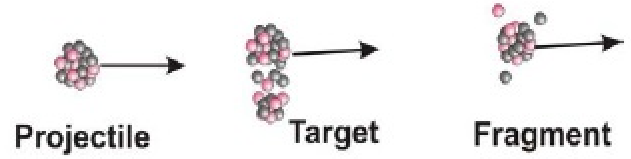
Sn isotope production



K.Sümmerer

Production of exotic nuclei at relativistic energies

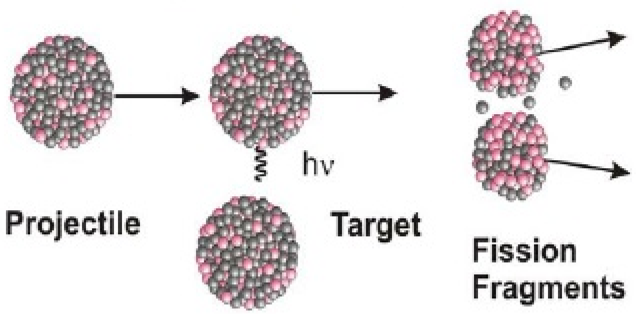
Projectile Fragmentation



Nucleon-nucleon collisions, abrasion, ablation

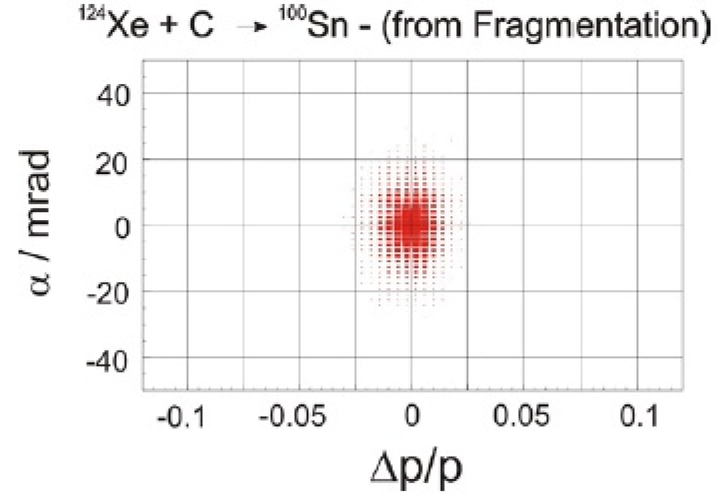
$$\vec{v}_f \approx \vec{v}_p$$

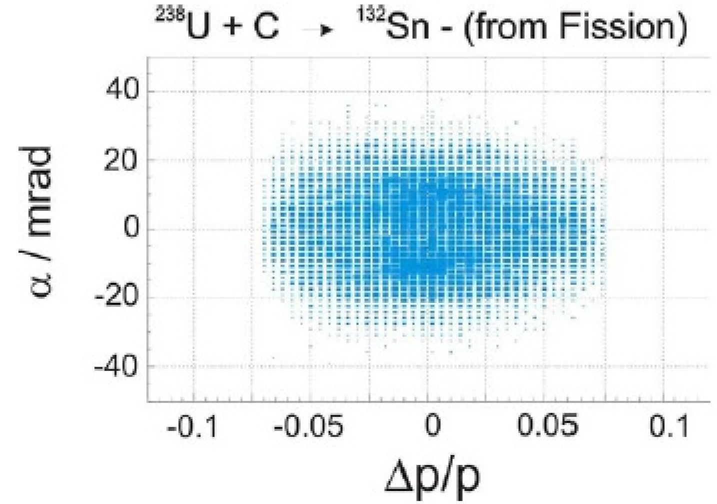
Projectile Fission



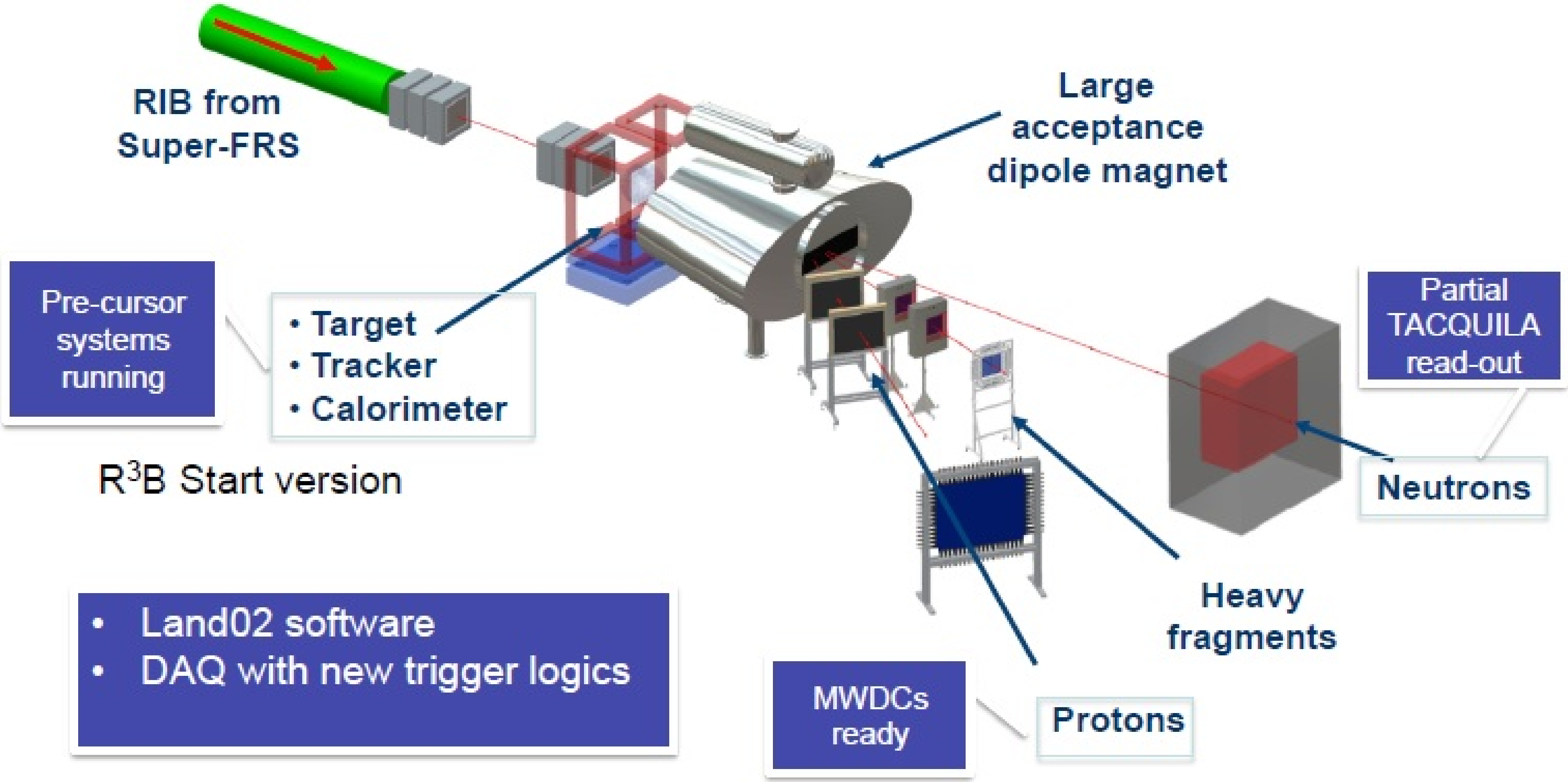
Electromagnetic excitation, fission in flight

$$\vec{v}_f \approx \vec{v}_p + \vec{v}_{fission}$$

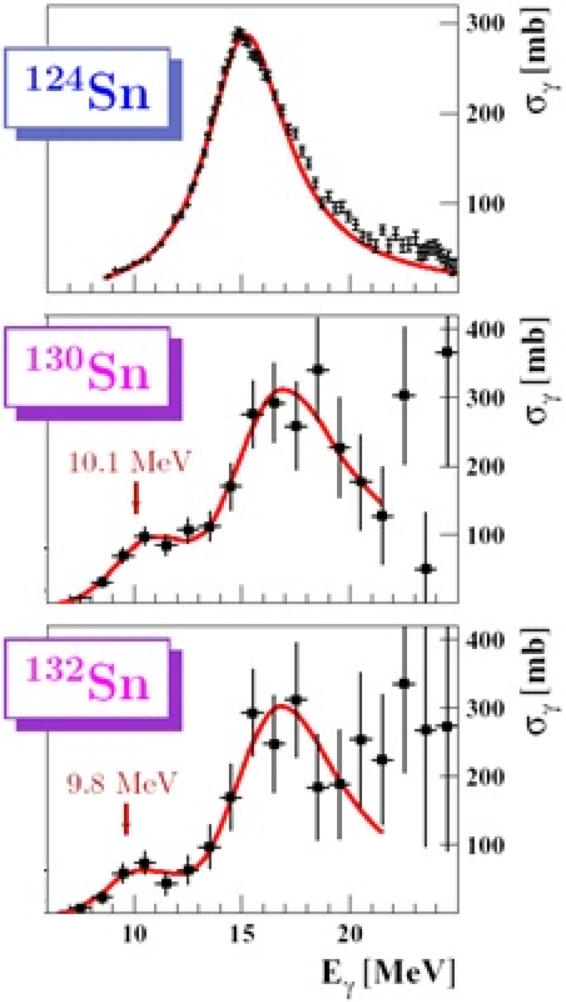


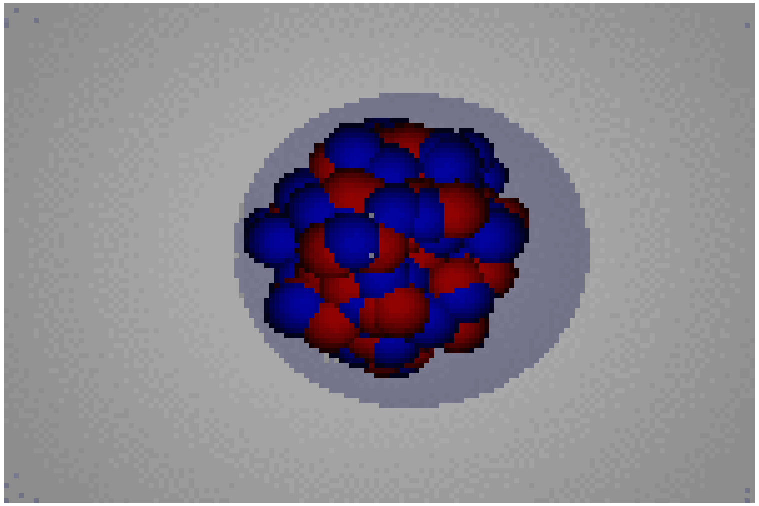


Reactions with Relativistic Radioactive Beams



Pygmy resonances and the neutron skin



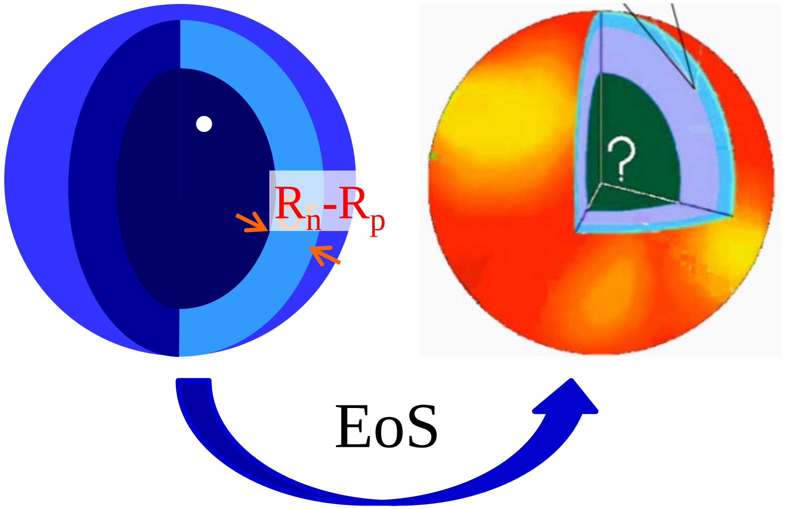


$R_n - R_p$:

^{130}Sn: 0.23 ± 0.04 fm

^{132}Sn: 0.24 ± 0.04 fm

neutron star

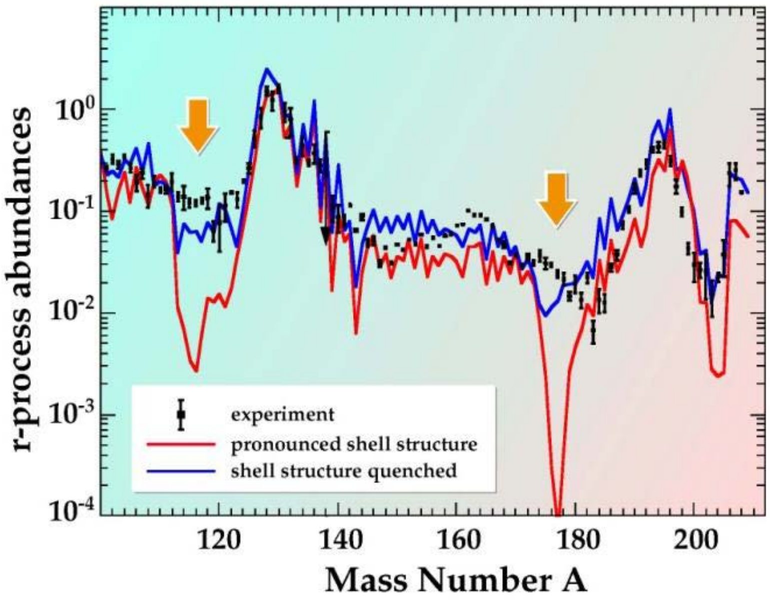


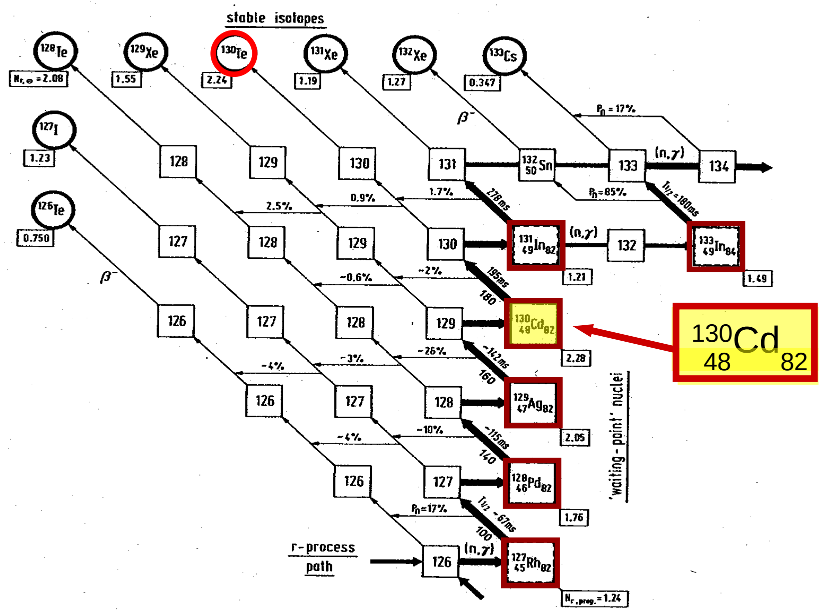
at LAND-GSI: 10^8/s ^{238}U beam (10 d)

at R3B-FAIR: 10^{12} ^{238}U beam (100 s)

P. Adrich et al., PRL 95 (2005) 132501 & A.Klimkiewicz et al., PRC 2008

Waiting point at N=82

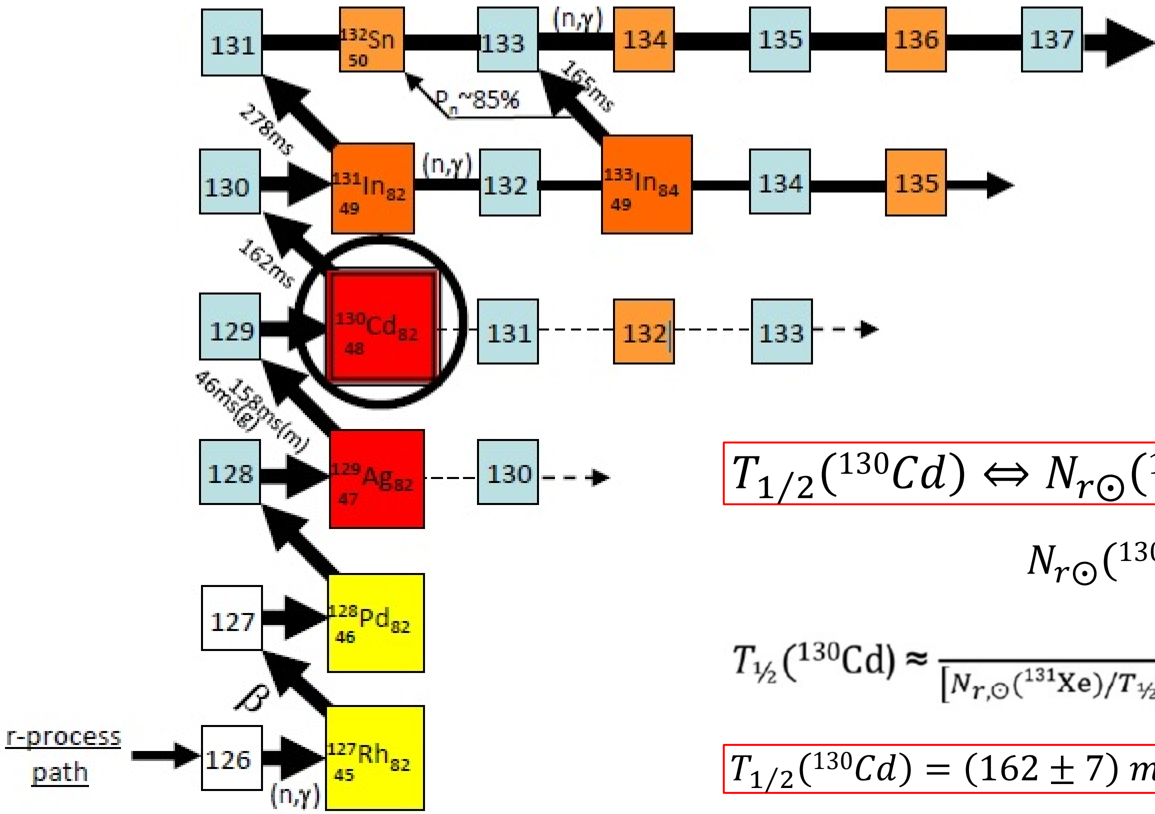




"..the calculated r-abundance 'hole' in the A ≅ 120 region reflects ... the weakening of the shell strength ... below ^{132}Sn " K-L Kratz

bottleneck at N=82 waiting point near stability?

^{130}Cd – the key isotope at the A=130 peak



$$T_{1/2}(^{130}Cd) \Leftrightarrow N_{r\odot}(^{130}Te)$$

$$N_{r\odot}(^{130}Te) \equiv solar\ system\ abundances\ 130Te$$

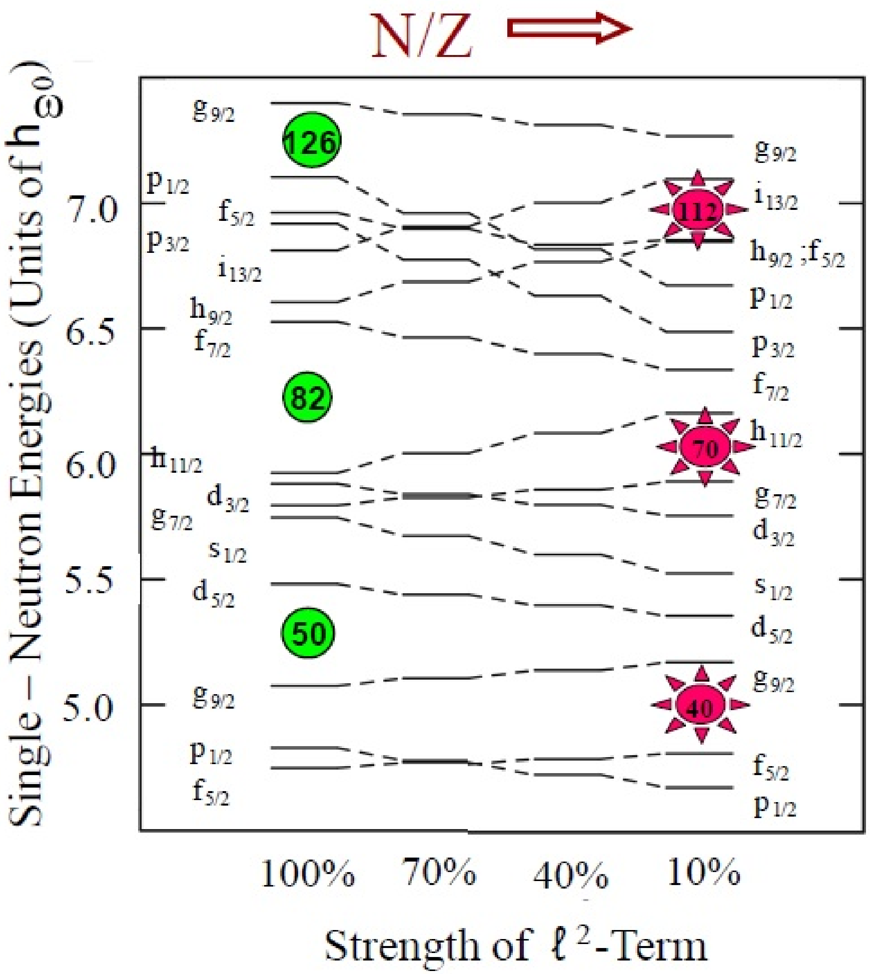
$$T_{1/2}(^{130}\mathrm{Cd}) \approx \frac{N_{r,\odot}(^{130}\mathrm{Te})}{[N_{r,\odot}(^{131}\mathrm{Xe})/T_{1/2}(^{131}\mathrm{In})]+[1.1N_{r,\odot}(^{132}\mathrm{Xe})/T_{1/2}(^{133}\mathrm{In})]} \approx \mathbf{170\ ms}$$

$$T_{1/2}(^{130}Cd) = (162 \pm 7)\ ms$$

climb up the N=82 ladder
A~130 “bottle neck”

K.-L. Kratz, Rev. Mod. Astr. 1 1988

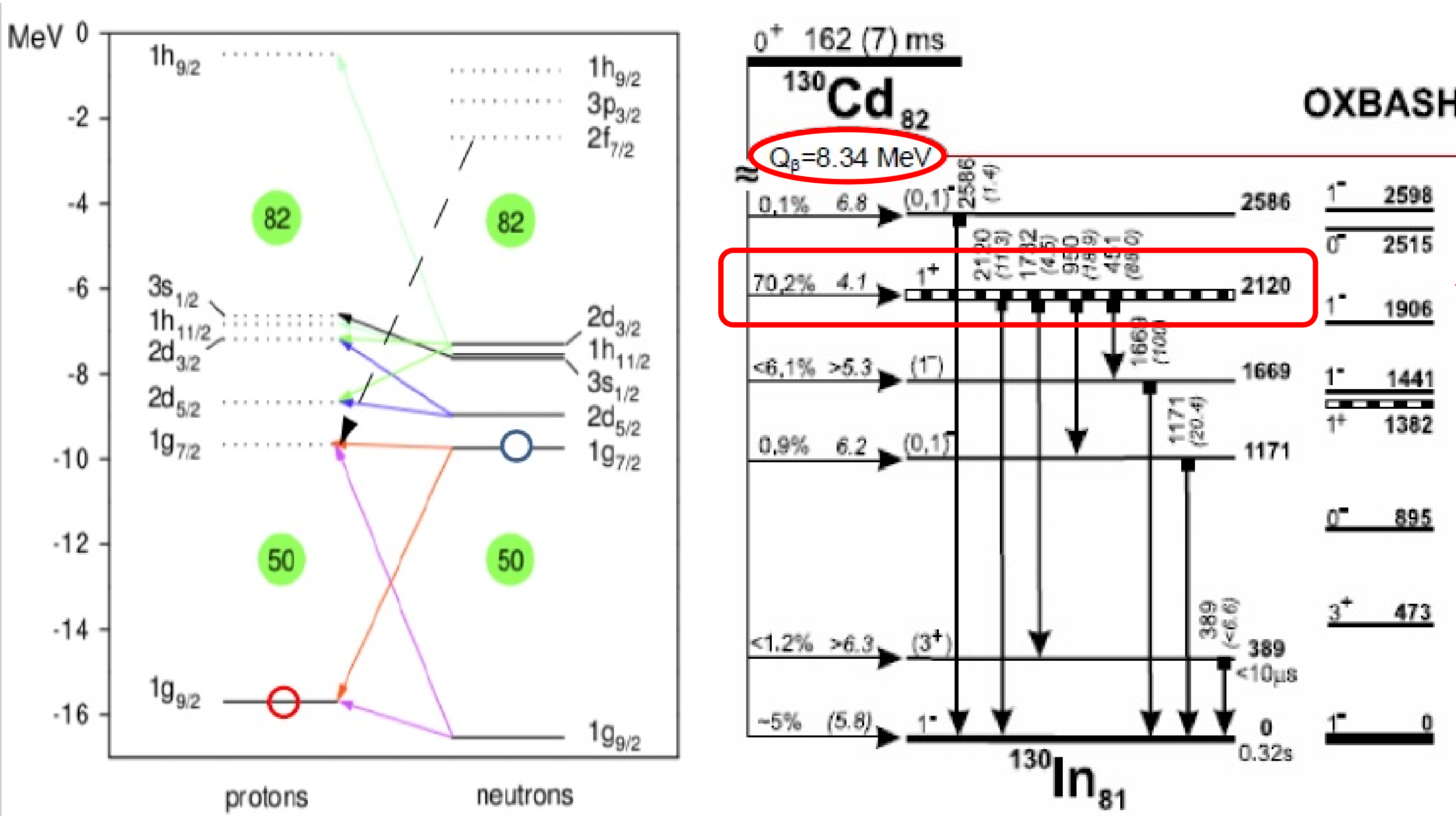
Effects of N=82 "shell quenching"



"Shell quenching"

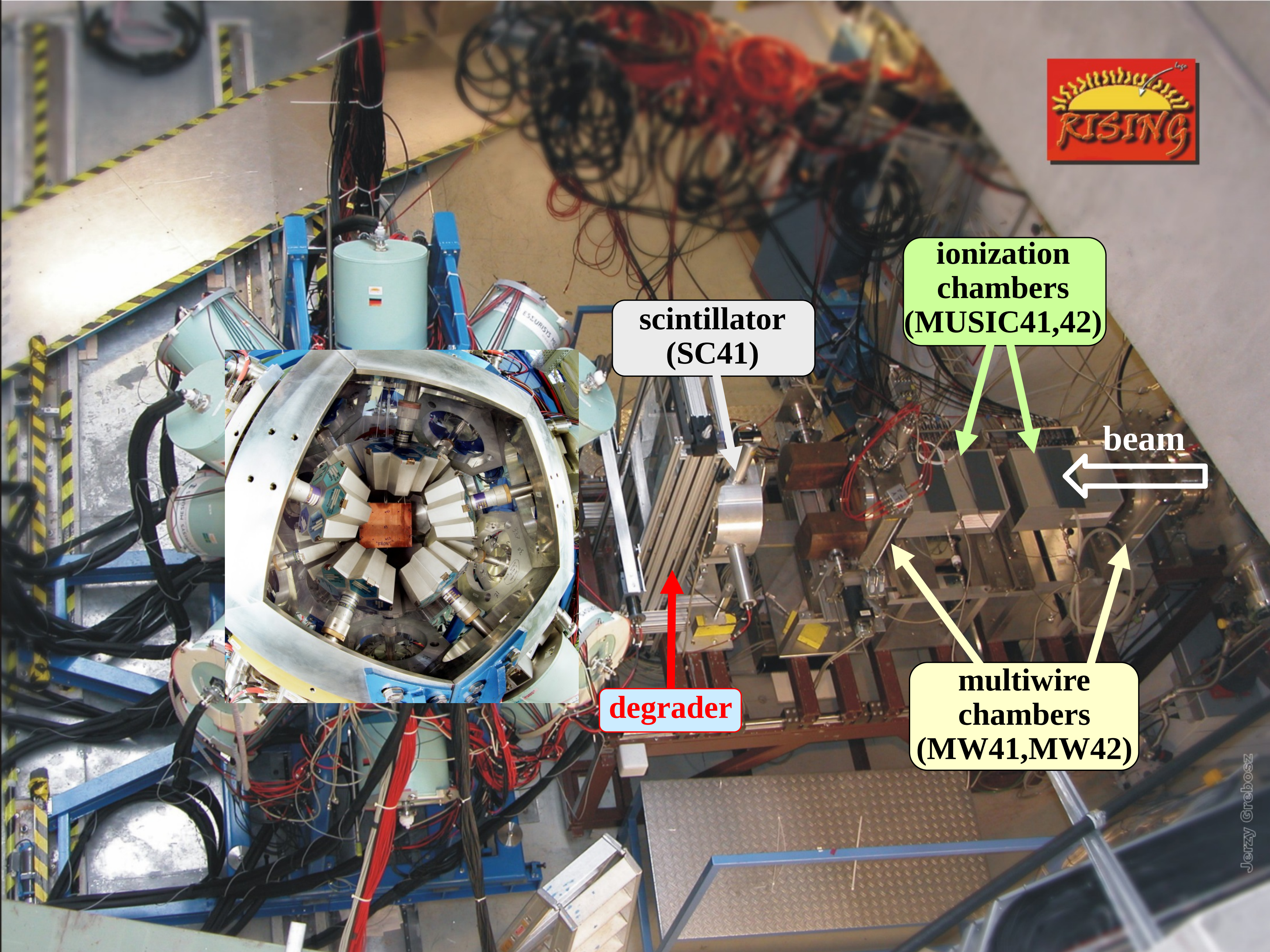
reduction of the spin-orbit coupling strength; caused by strong interaction between bound and continuum states; due to diffuseness of "neutron-skin" and its influence on the central potential

^{130}Cd decay spectroscopy

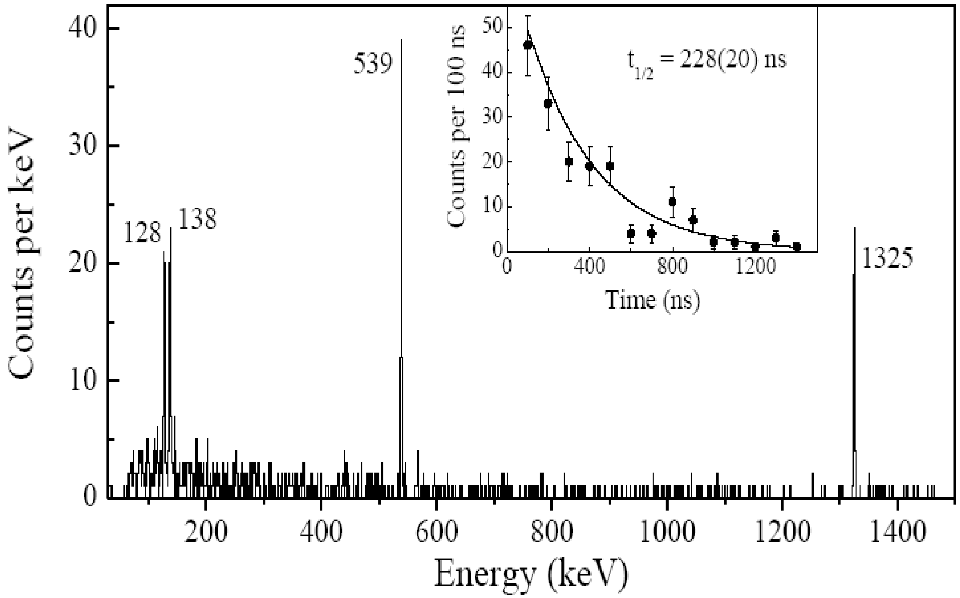


Large Q_β value best reproduced by mass models with N=82 shell quenching

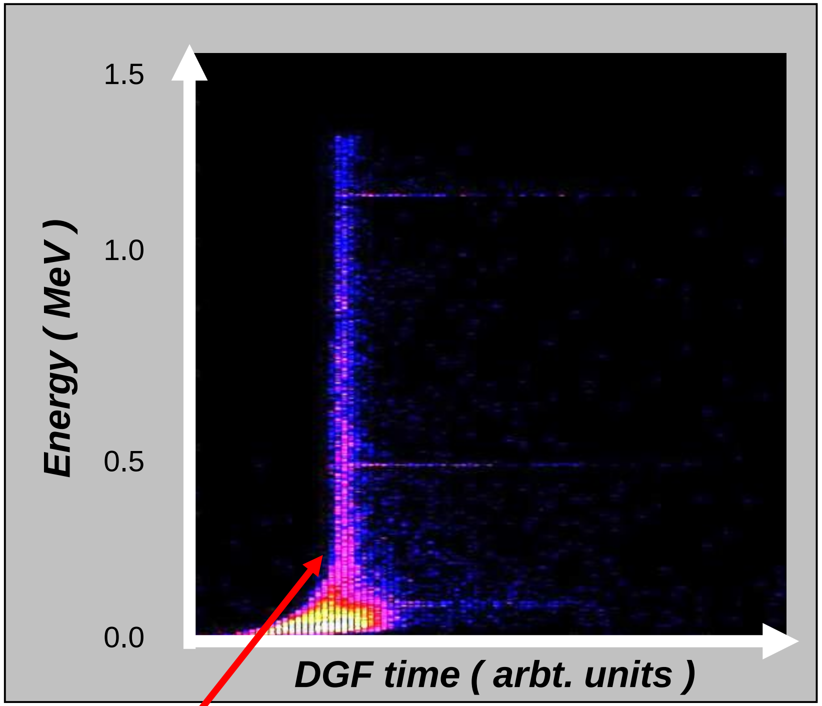
$\pi g_{9/2} \otimes \nu g_{7/2}$


RISING
scintillator
(SC41)
ionization
chambers
(MUSIC41,42)
beam
degrader
multiwire
chambers
(MW41,MW42)
Jerzy Grebosz

Decay spectroscopy probes shell closures



^{130}Cd: DGF-timing

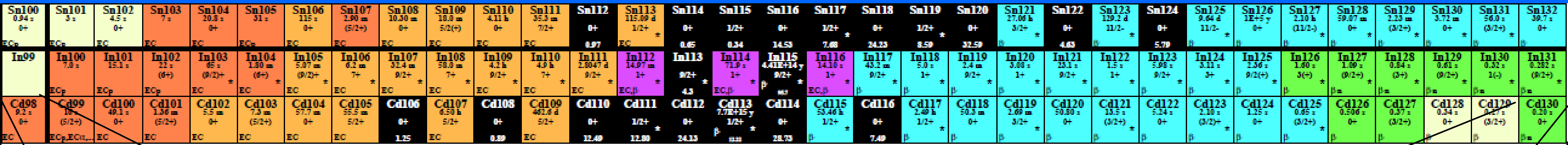


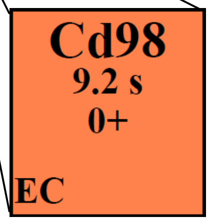
Prompt γ-flash

Decay time range: 20 ns ... 20 μs

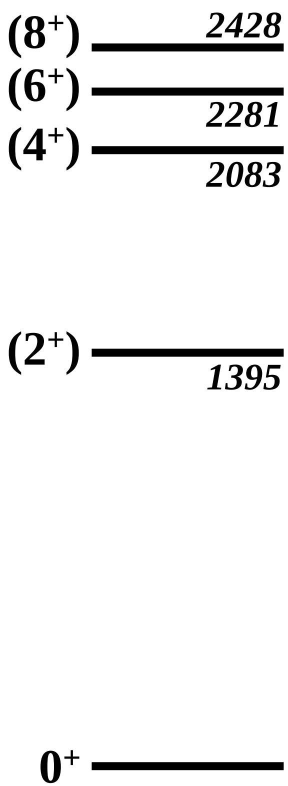
A. Jungclaus et al., Phys. Rev. Lett 99, 132501 (2007)

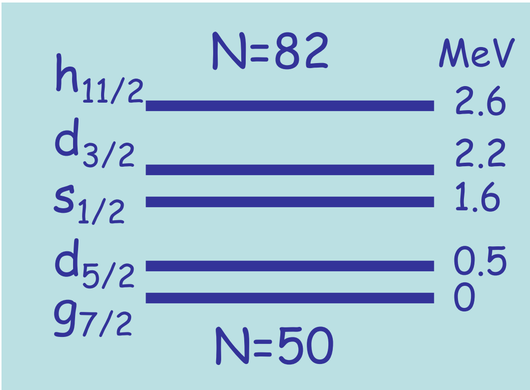
$8^+(g_{9/2})^{-2}$ seniority isomers in ^{98}Cd and ^{130}Cd



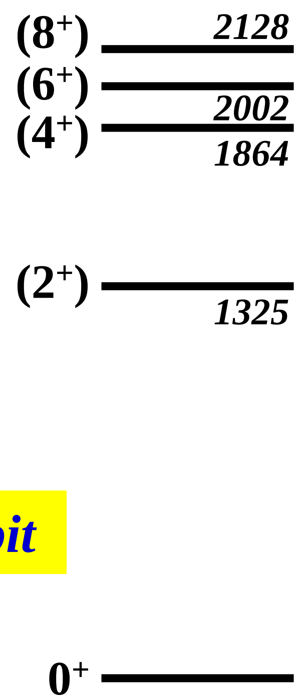


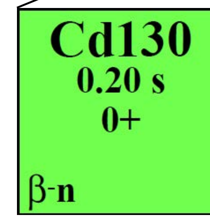
N=50
Z=48





participating neutron-orbitals





N=82
Z=48

two proton holes in the $g_{9/2}$ orbit

No dramatic shell quenching!

A. Blazhev et al., Phys. Rev. C69 (2004) 064304

A. Jungclaus et al., Phys. Rev. Lett. 99 (2007), 132501

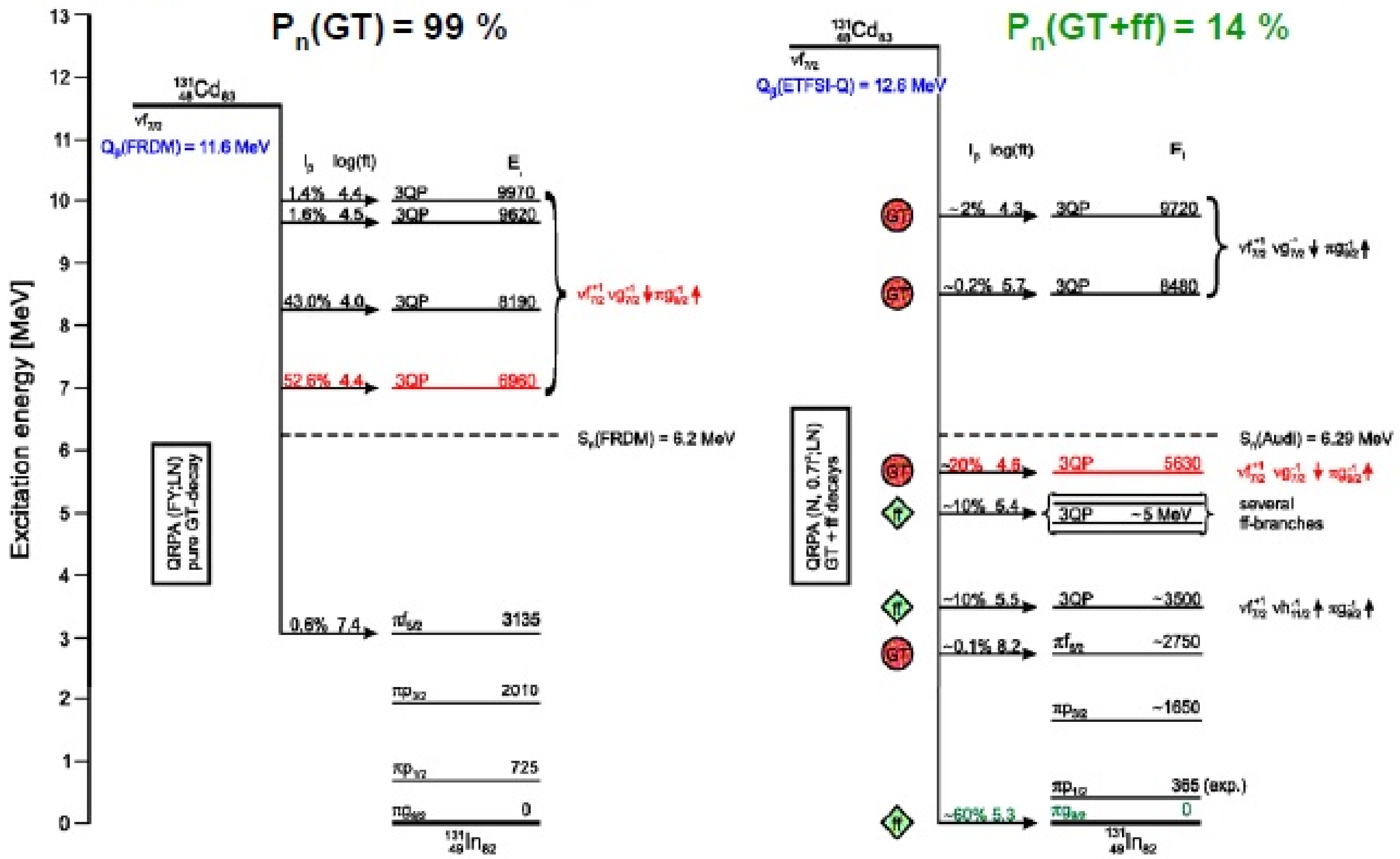
Surprising β–decay properties of ^{131}Cd

…just **ONE** neutron outside N=82 magic shell

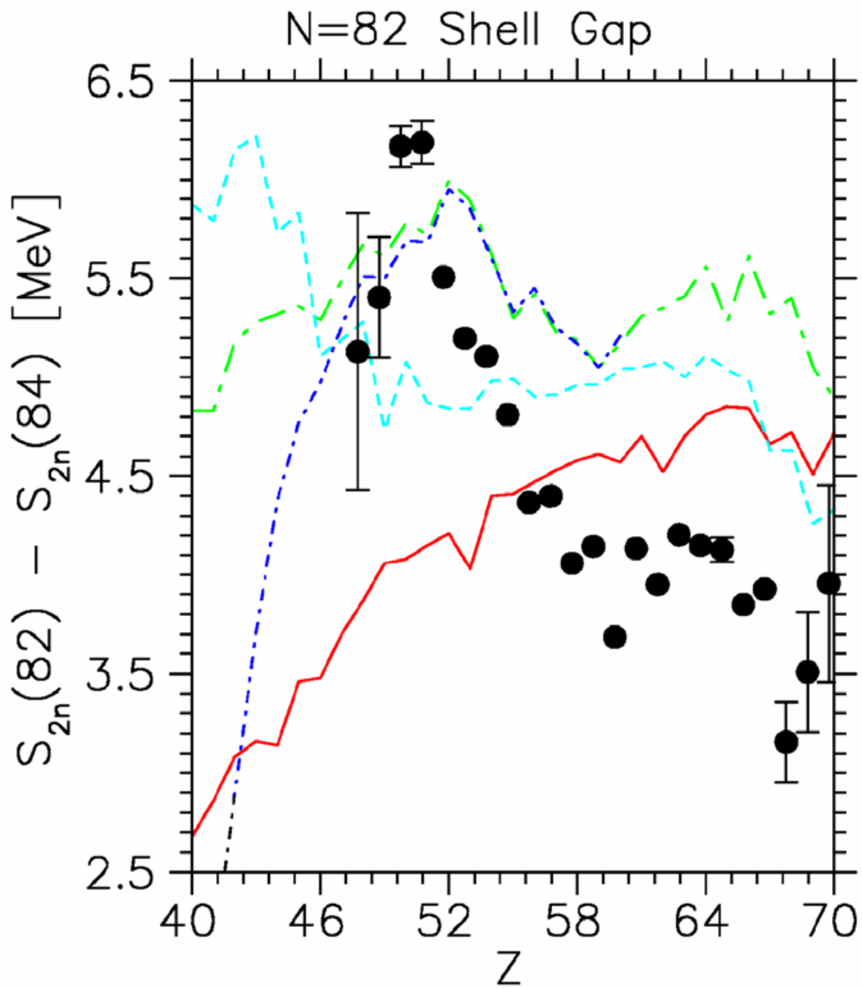
Experiment: $T_{1/2}$ = 68 ms; P_n = 3.4 %

QRPA predictions: **$T_{1/2}$(GT) = 943 ms;** **$T_{1/2}$(GT+ff) = 59 ms;**

P_n(GT) = 99 % **P_n(GT+ff) = 14 %**

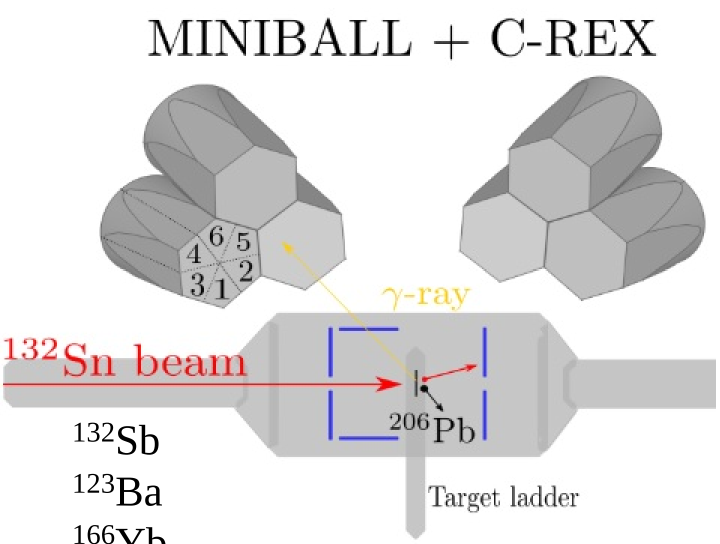


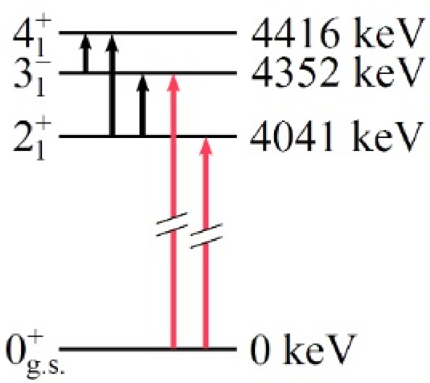
The N=82 shell gap

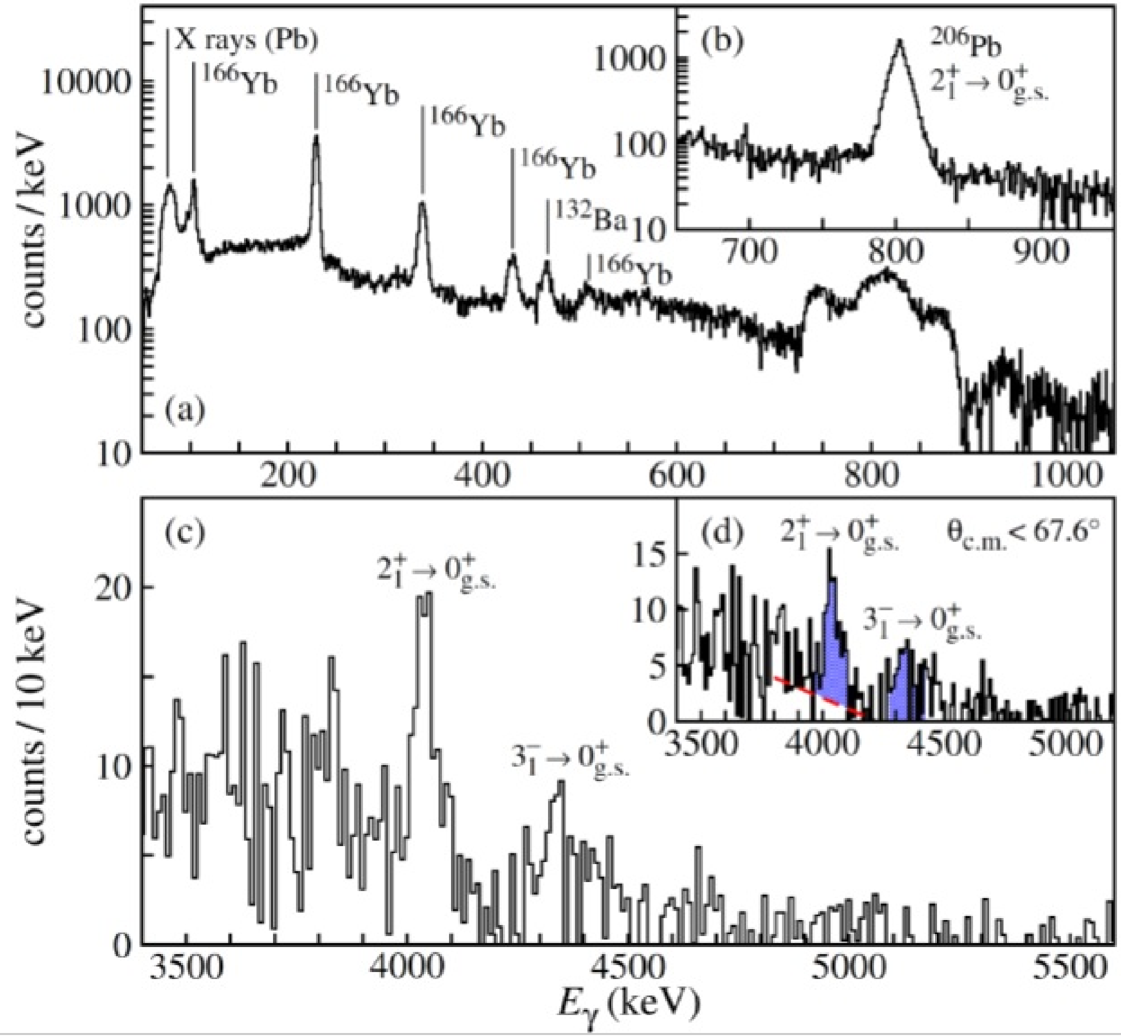


NONE of the mass models predicts the trend correctly!

Enhanced quadrupole and octupole strength in doubly-magic ^{132}Sn







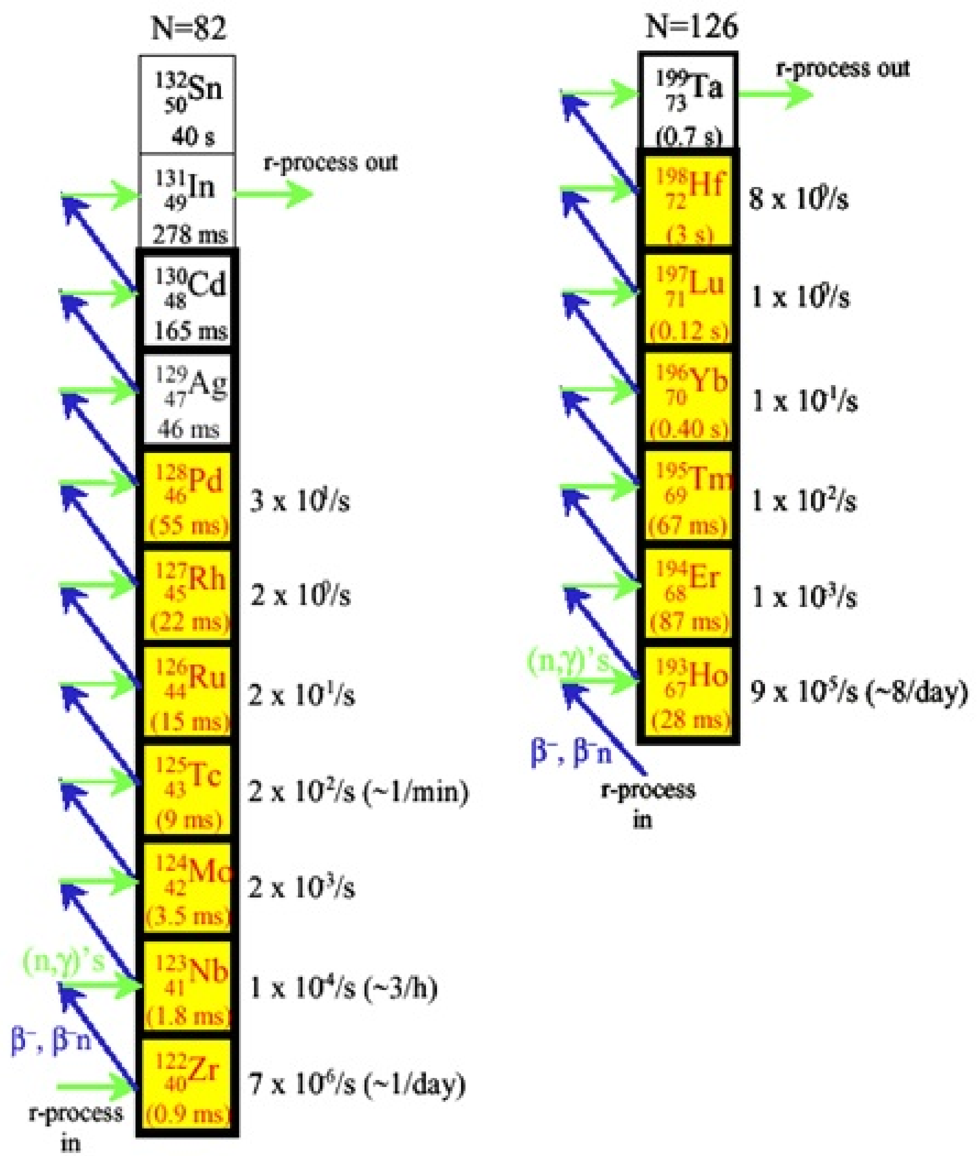
B(E2; $0^+ \rightarrow 2^+$)	0.087(19) e^2b^2
B(E3; $0^+ \rightarrow 3^-$)	0.11(4) e^2b^3
B(E1; $2^+ \rightarrow 3^-$)	9.1(31) x 10^{-6} e^2b

D. Rosiak et al., PRL 121, 252501 (2018)

Waiting point lifetimes with fragmentation facilities

Why fragmentation?

- Lifetime measurements can be done with beams from low energy facilities
- But, fragmentation facilities have advantages:
  - Use beams of mixed nuclides--Identification on event by event basis
  - Greater reach toward dripline
  - FAIR, GSI, RIKEN, NSCL <u>and</u> RIA will cover a large part of r-process path



HISPEC: high resolution in-flight gamma-spectroscopy

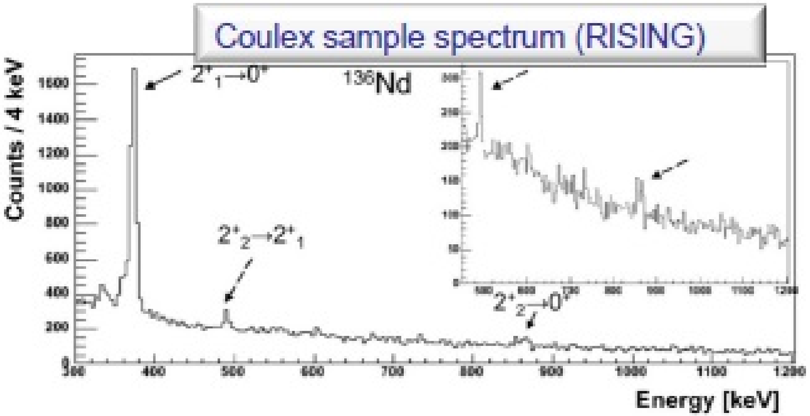
- Excited states in exotic nuclei
  - Inelastic excitation (EM, hadronic), secondary fragmentation, knock-out
- Lifetimes and g-factors of short-lived excited states

  (evolution of shells and collectivity)

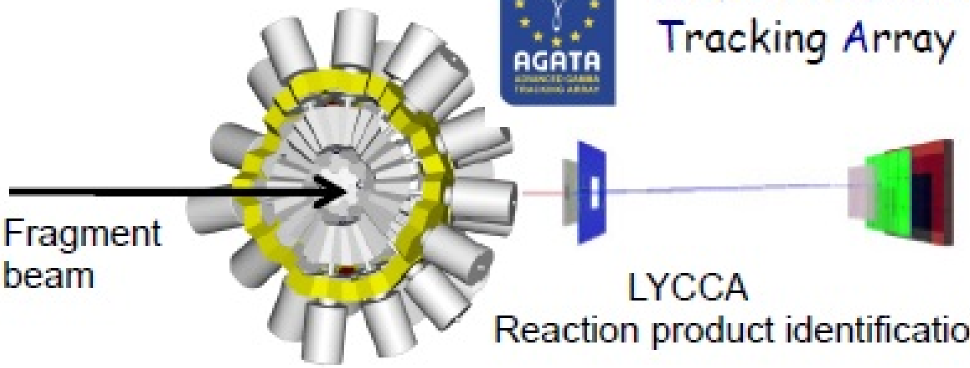
  (phase-/shape-transitions & shape coexistence)

  (isospin symmetry, pn-pairing)

- **Experiments possible with medium-energy beams (50-100 AMeV)**
- **Broad program for nuclei with A up to ~100**

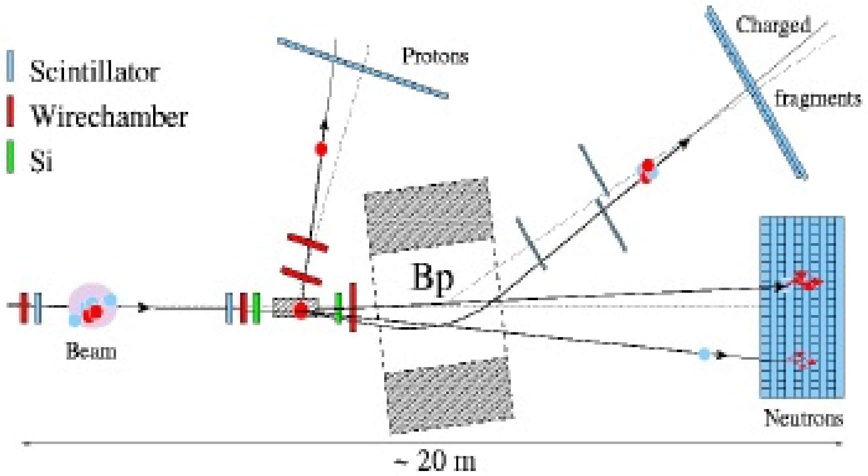


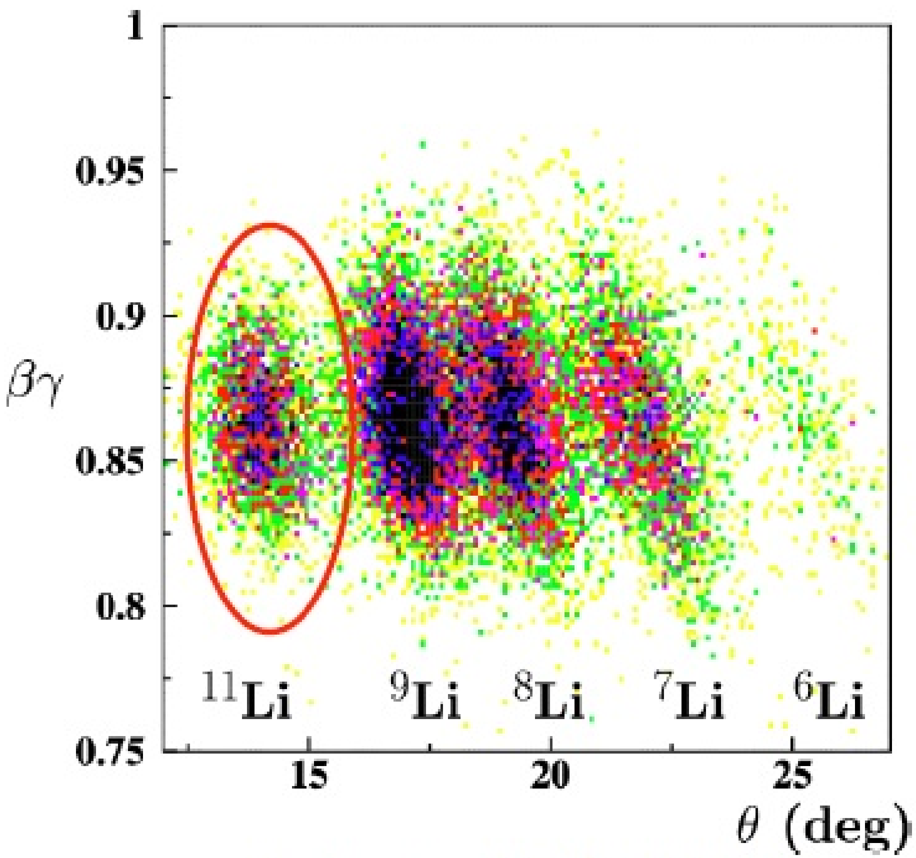
AGATA - Advanced GAmma Tracking Array



Proton knockout from 304 MeV/u ^{14}Be

S245@GSI



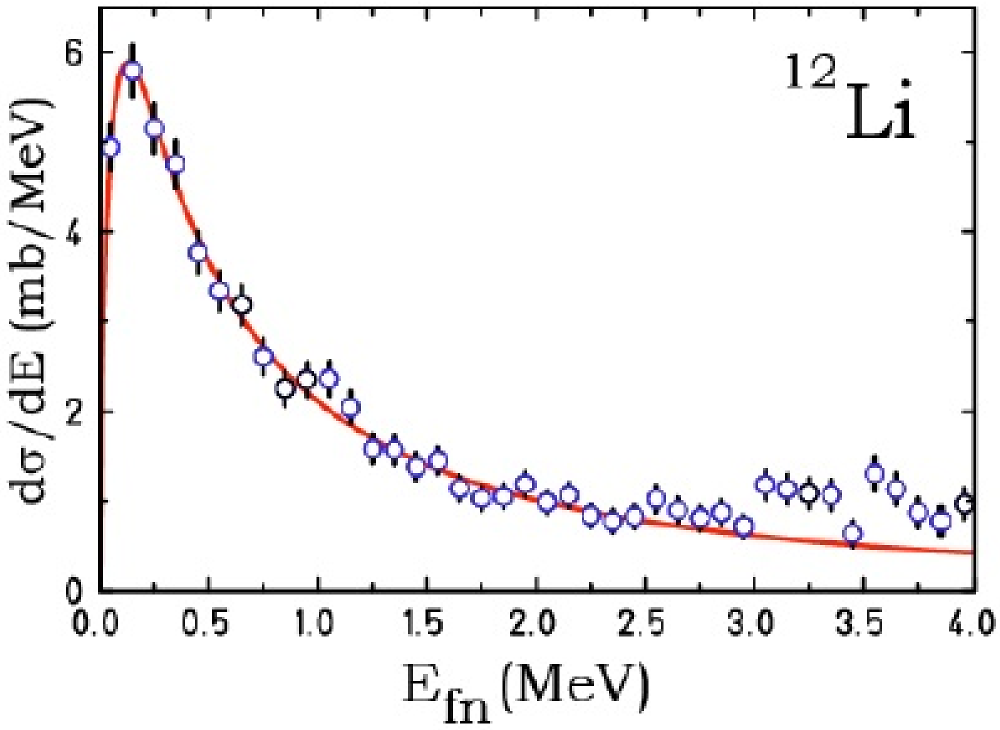


Yu. Aksyutina *et al*. PLB 666(2008)430

$^{1}H(^{14}Be,2pn)^{12}Li$

Going beyond the dripline…

Breit Wigner Resonance



ε =1.47(19)MeV

S_{2n} = 1.26(13) MeV

$$E_{fn} = \left|\vec{P}_f + \vec{P}_n\right| - M_f - m_n$$

$$a_s = -13.7(1.6)\ fm$$

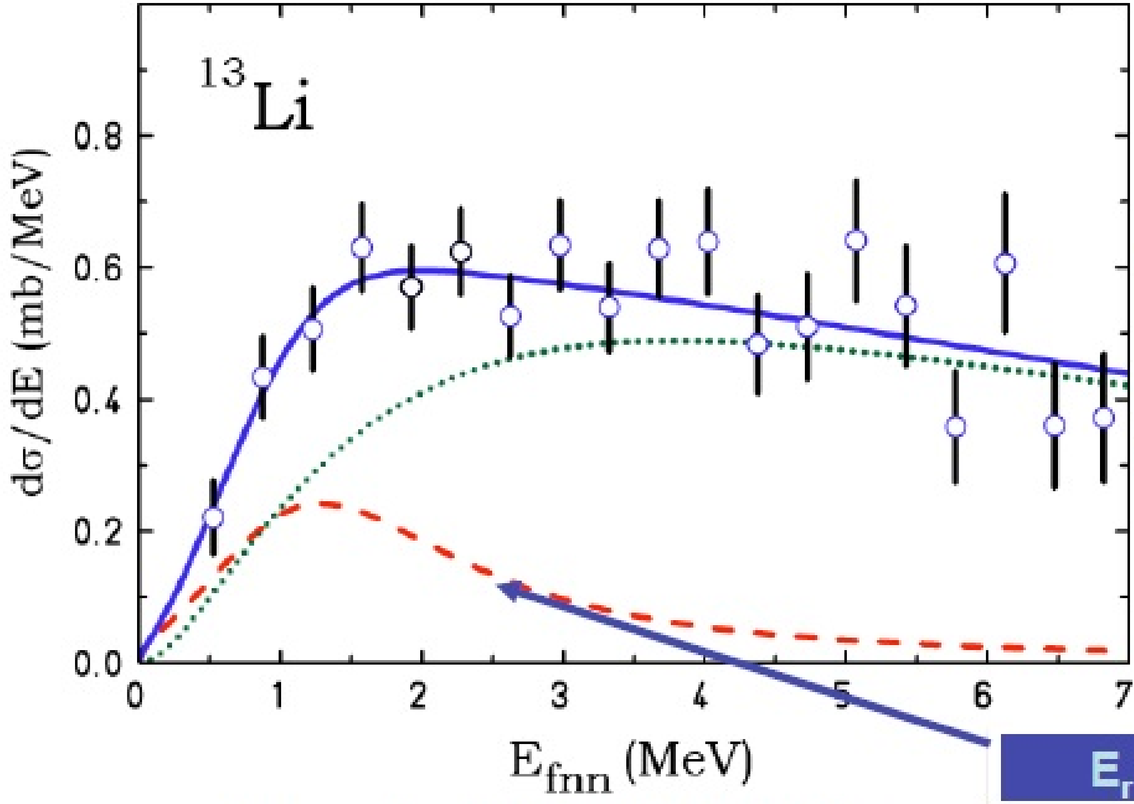
scattering length (virtual s-state)

Yu. Aksyutina *et al.* PLB 666(2008)430

$^{1}H(^{14}Be,2p)^{13}Li$

… and even further

Breit Wigner Resonance



Yu. Aksyutina *et al.* PLB 666(2008)430

$$\frac{d\sigma}{dE_{f2n}} = \frac{E_{f2n}^2}{(2.21S_{2n} + E_{f2n})^{7/2}}$$

C. Forssén *et al.* NPA 673 (2008) 143

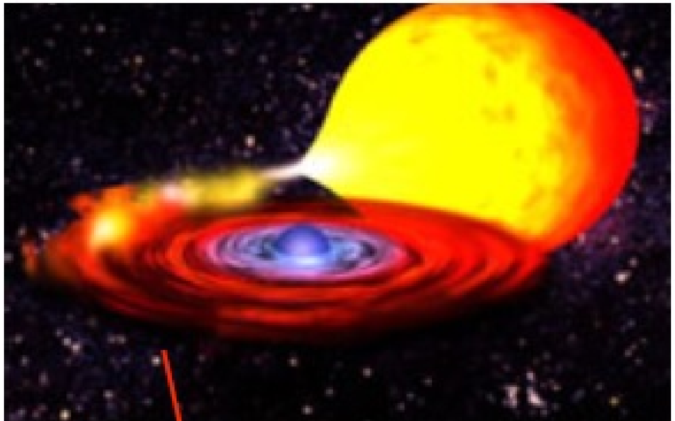
E_r = 1.47(31) MeV

3-body resonance state — — —
correlated background -------
(from nn-correlations in initial
bound-state wave function

$^{15}O(2p,\gamma)^{17}Ne$ in Nuclear Astrophysics: X-ray bursts, rp-process, neutron stars

Cataclysmic binary systems (X-ray bursts):

rp-process *Görres et al., PRC 51 (1995) 392*

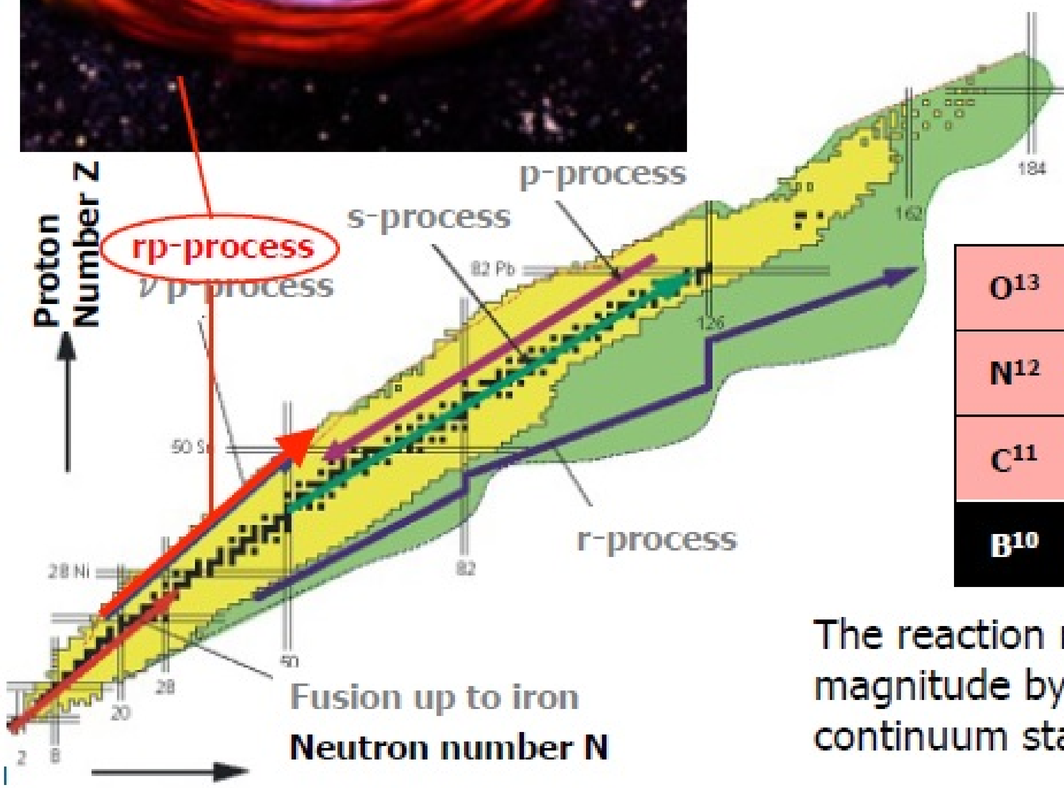


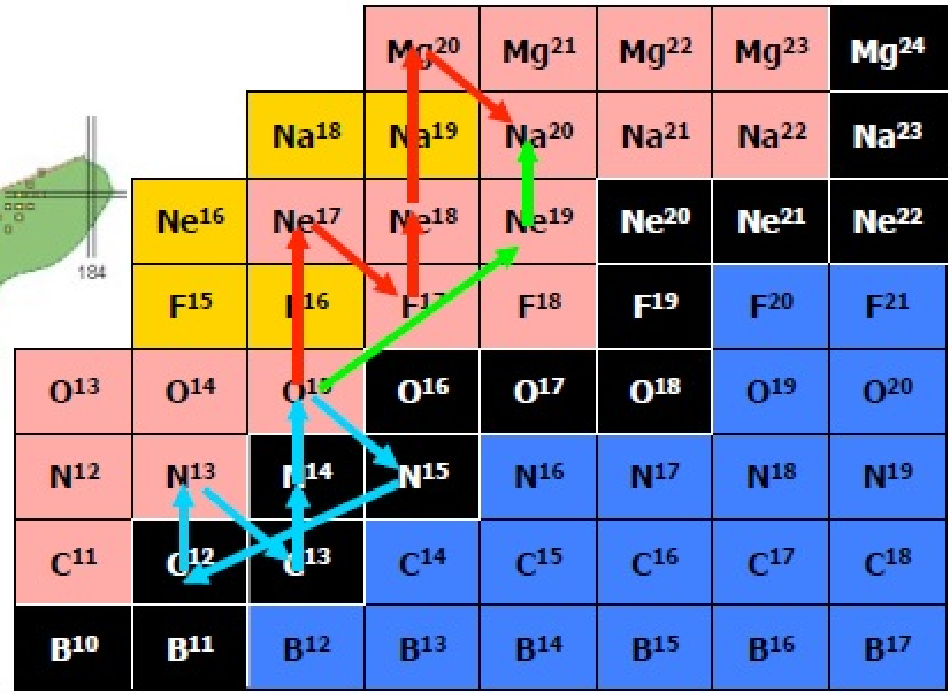
CNO cycle: … $^{14}N(p,\gamma)^{15}$**$O(\beta^-)$**$^{15}N(p,\alpha)$

^{15}O is a waiting point for CNO-cycle breakup:

Heavier elements: … ^{15}**$O(\alpha,\gamma)$**$^{19}Ne(p,\gamma)$ …

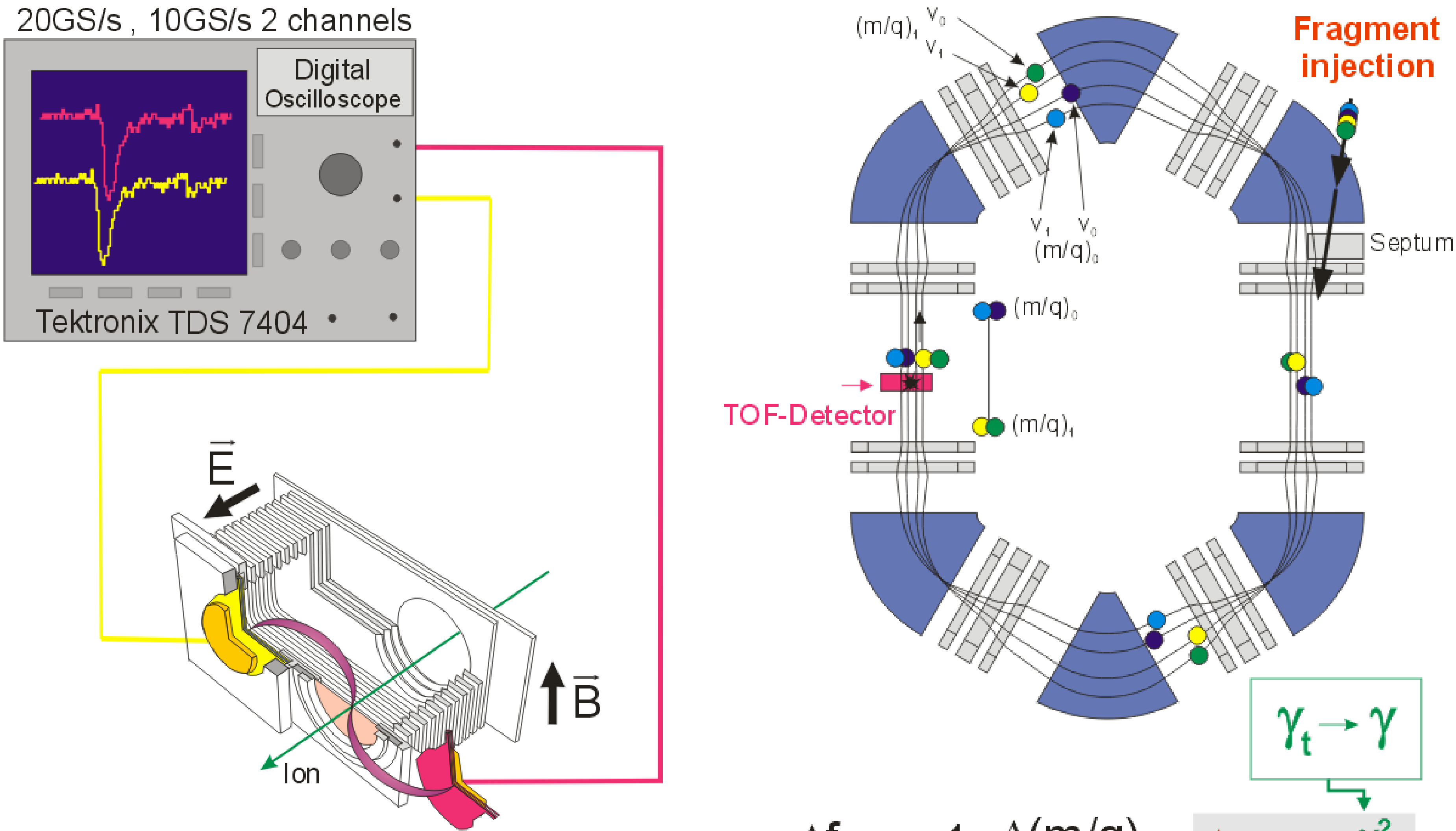
Alternative (rp): … ^{15}**$O(2p,\gamma)$**$^{17}Ne(\beta^+)^{17}F(p,\gamma)$





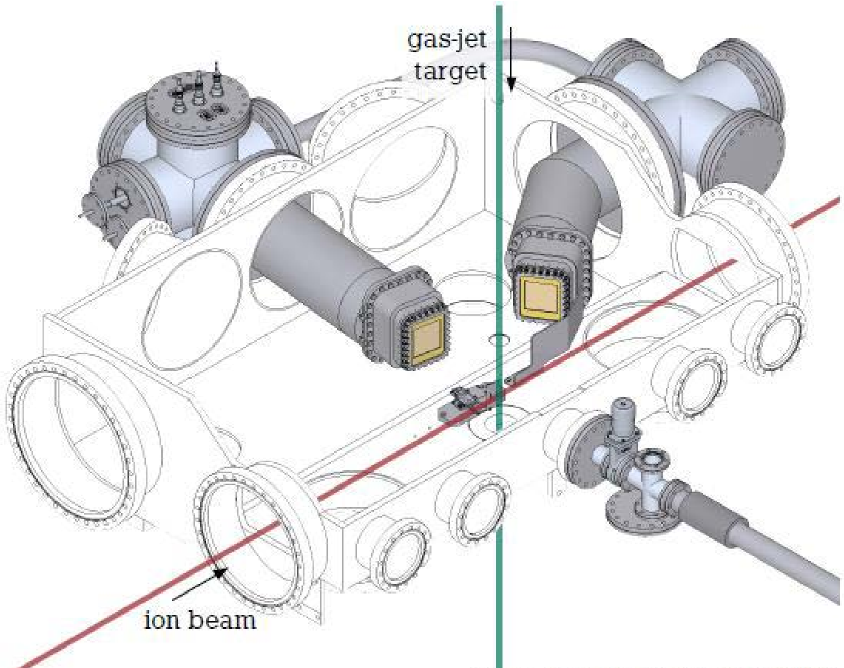
The reaction rate can be enhanced by a few orders of magnitude by taking into account the three-body continuum states. *Grigorenko et al., PLB 641 (2006) 254*

Isochronous mass spectroscopy in the ESR

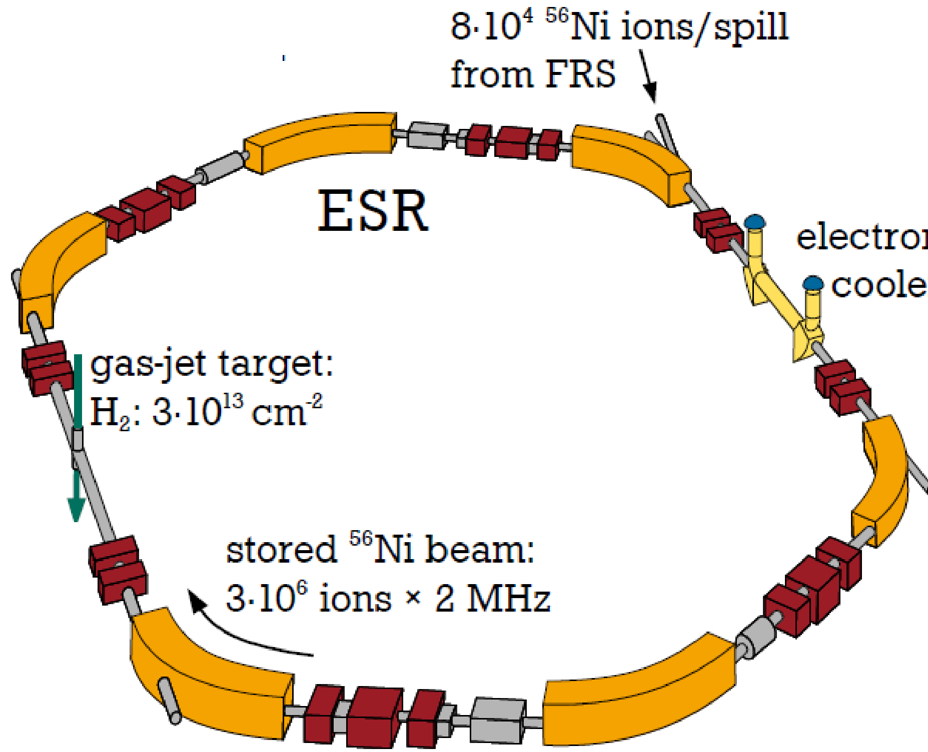


$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1 - \frac{\gamma^2}{\gamma_t^2}\right)$$

Scattering of RIB on hydrogen target



Technical drawings: M. Lindemulder, KVI-CART



Picture: Phys. Scr. T156 (2013) 014016

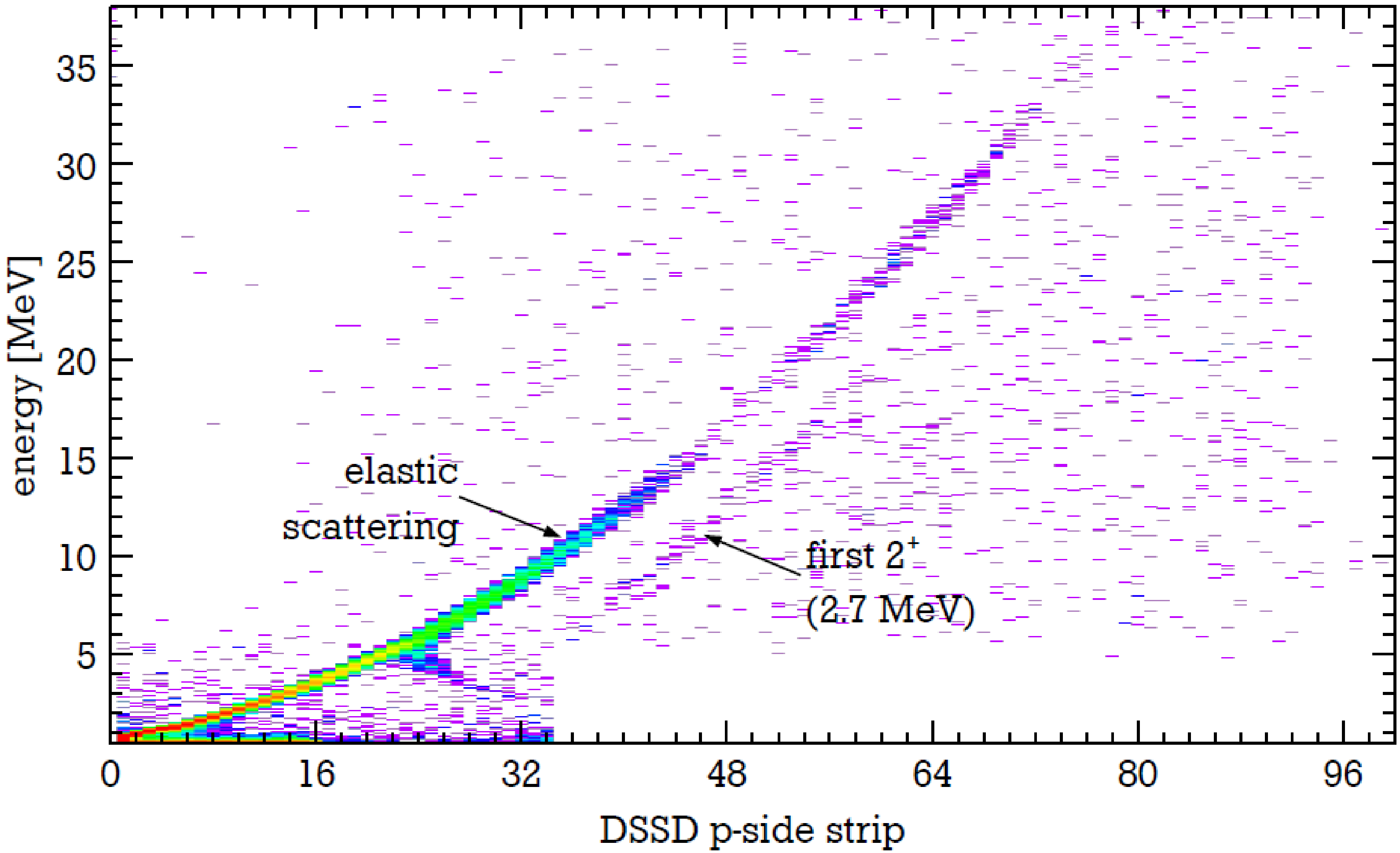
measure position and energy with Si detectors

⇨ RMS radius of ^{56}Ni

luminosity: $2 \cdot 10^{26}\ \frac{particles}{s\ cm^2}$

M. von Schmid, EXL, Phys. Scr. T116 (2015) 014005

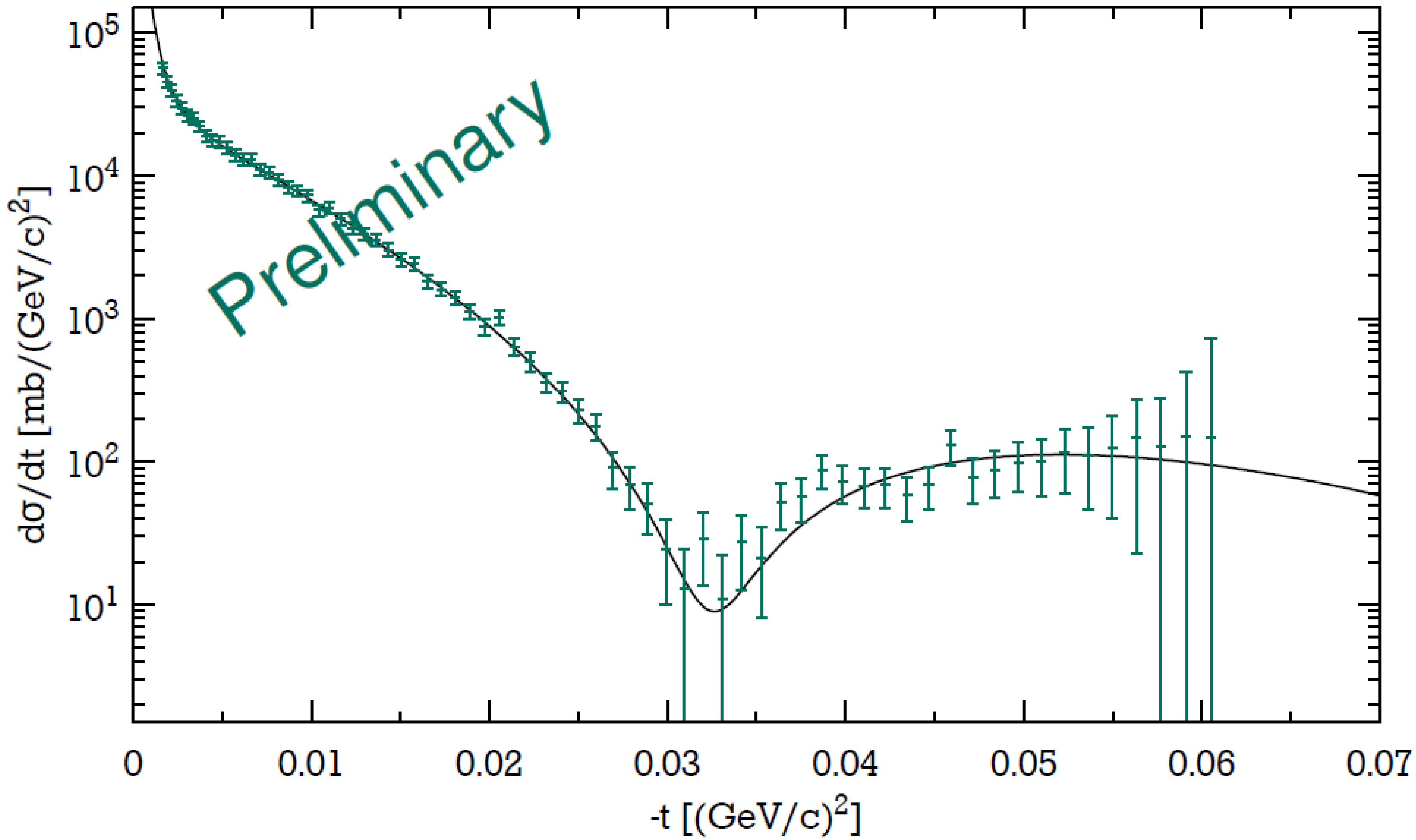
^{56}Ni(p,p) scattering distribution



M. von Schmid, EXL, Phys. Scr. T116 (2015) 014005

^{56}Ni(p,p) scattering distribution

Diffraction pattern (like for a wave after a single slit),
Extract radius of nucleus by fitting theory with parameters.



M. von Schmid, EXL, Phys. Scr. T116 (2015) 014005

Electron capture in hydrogen-like ions

Simple theoretical estimate:

R.B. Firestone, Table of Isotopes, 1996

Gamow-Teller transition $1^+ \rightarrow 0^+$
β^+ to EC branching ratio:

$$\lambda_{\beta+}/\lambda_{EC} \text{ (neutral atom)} \approx 1$$

W. Bambynek et al., Rev. Mod. Phys. 49, 1977

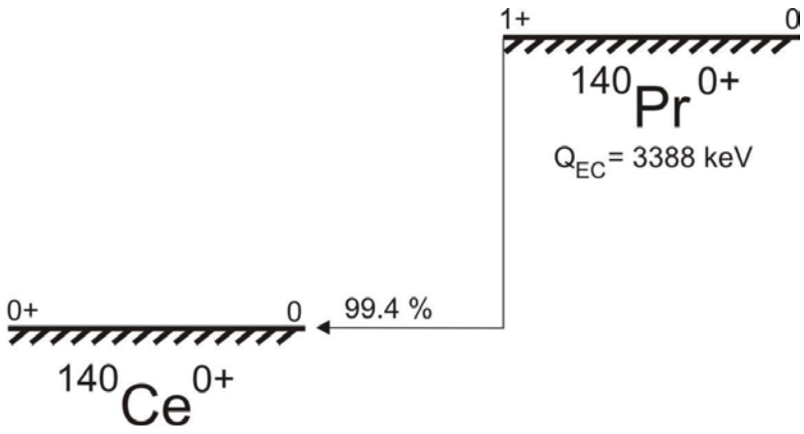
S-electron density at the nucleus:

$$|f_s(0)|^2 \propto 1/n^3$$

$$P_{EC}(neutral\ atom) \propto 2\sum 1/n^3 = 2.4$$

$$P_K(H-like) \propto 1 * 1/1^3 = 1$$

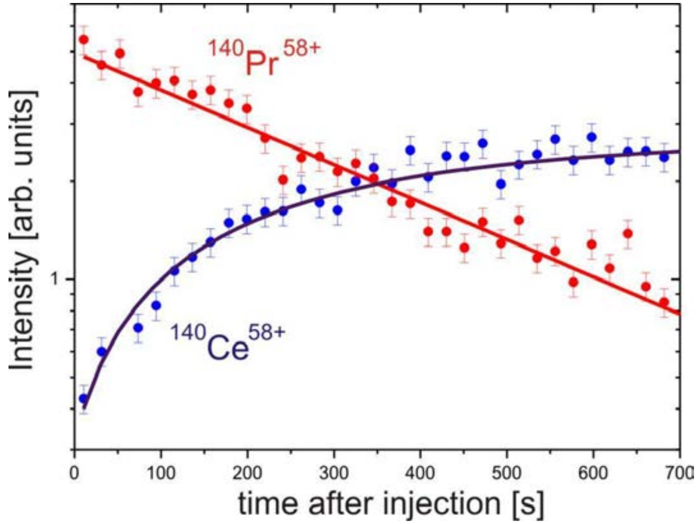
$$\lambda_{\beta+}/\lambda_K \text{ (H-like)} \approx 2.4$$

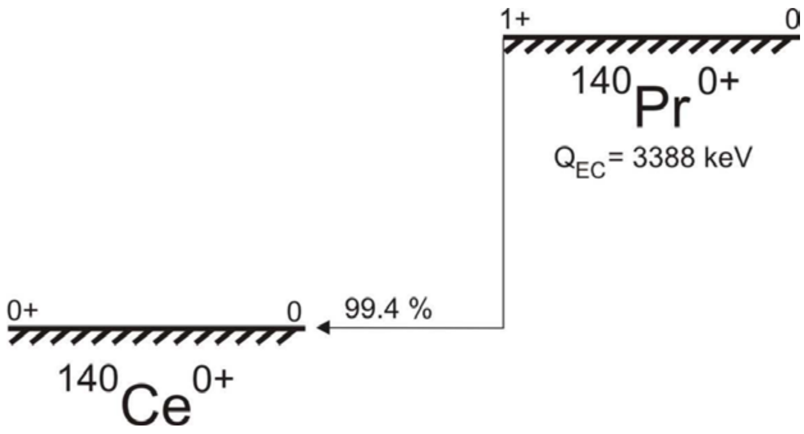


conclusion:

H-like ions should have
41% longer half-life

Electron capture in hydrogen-like ions





G. Audi et al. NPA 729 (2003) 3

$$\lambda(neutral) = 0.0034(1)\ s^{1}$$

Decay of fully-ionized ^{140}Pr:

$$\lambda_{\beta+} = 0.00172(7)\ s^{-1}$$

Decay of H-like ^{140}Pr:

$$\lambda_{K} = 0.00213(19)\ s^{-1}$$

J. Kurcewicz, N. Winckler et al.

Expectation:

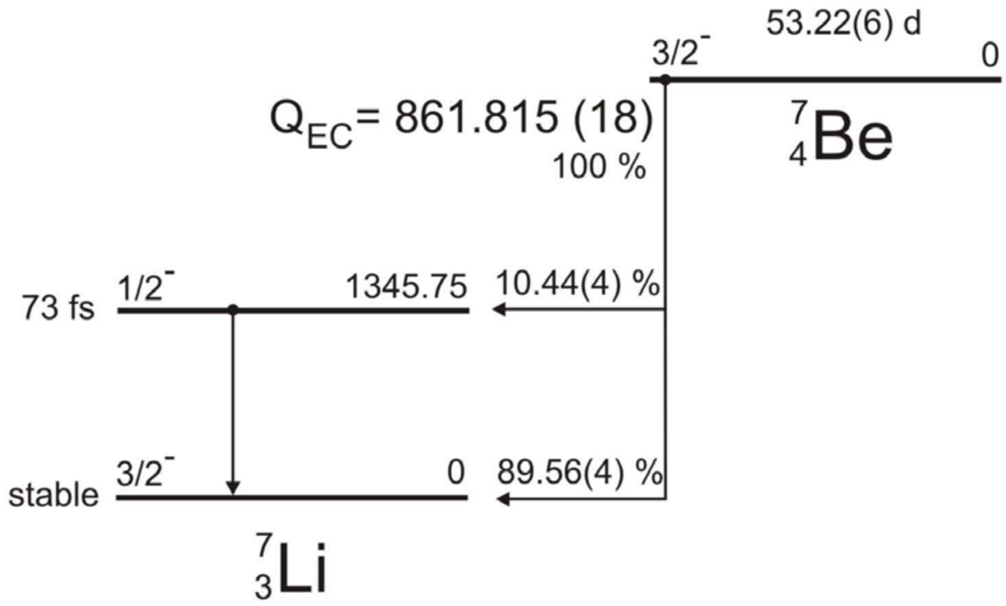
$$\lambda_{\beta+}/\lambda_K \text{ (H-like)} \approx 2.4$$

Experiment:

$$\lambda_{\beta+}/\lambda_K \text{ (H-like)} = 0.81\ (8)$$

H-like ions decay ~20%
faster than neutral atom!!!

Electron capture in hydrogen-like ions



A.V. Gruzinov, J.N. Bahcall, Astroph. J. 490 (1997) 437

Ionization of ^{7}Be in the Sun can be ~20-30%

Nucleosynthesis of heavier elements