Nucleosynthesis studied in the laboratory – recent results from GSI

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GSI und JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Facility overview

Decay spectroscopy

Mass measurements

Reactions

* with (partly unpublished) material kindly provided by M. Heil, W. Plass, P. Woods, et al.

Research opportunities for nuclear astrophysics

production and separation of exotic nuclei

RISING

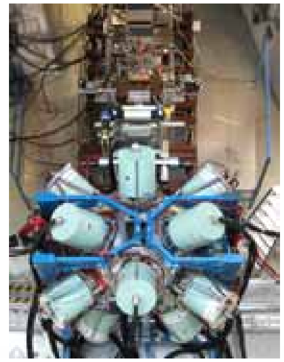
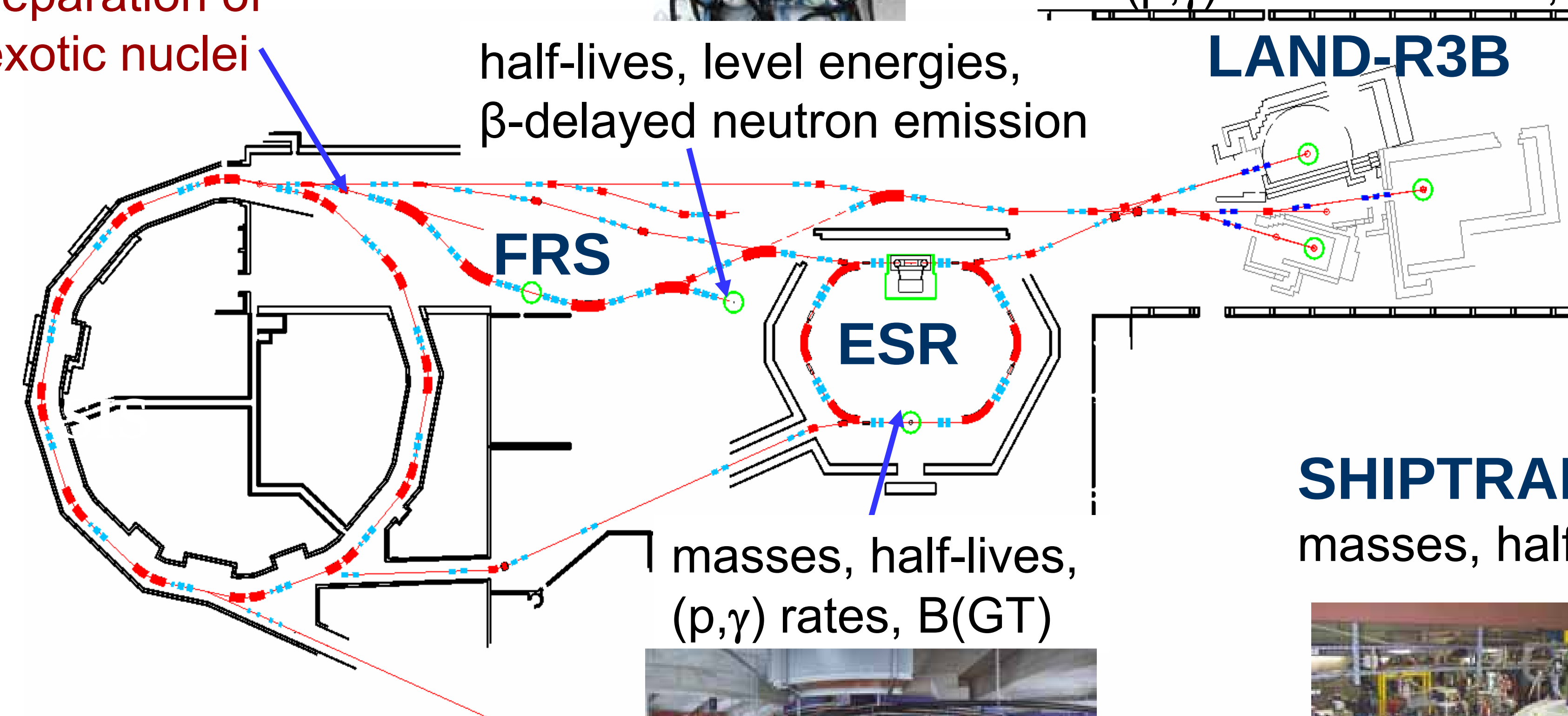


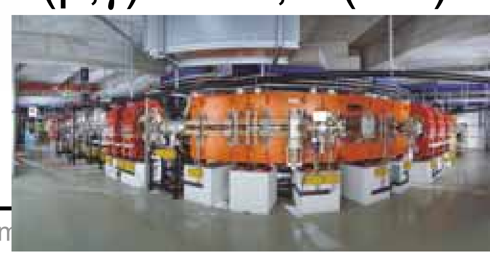
photo-dissociation rates, (n,γ) and (p,γ) cross sections, B(GT)

LAND-R3B

half-lives, level energies, β-delayed neutron emission



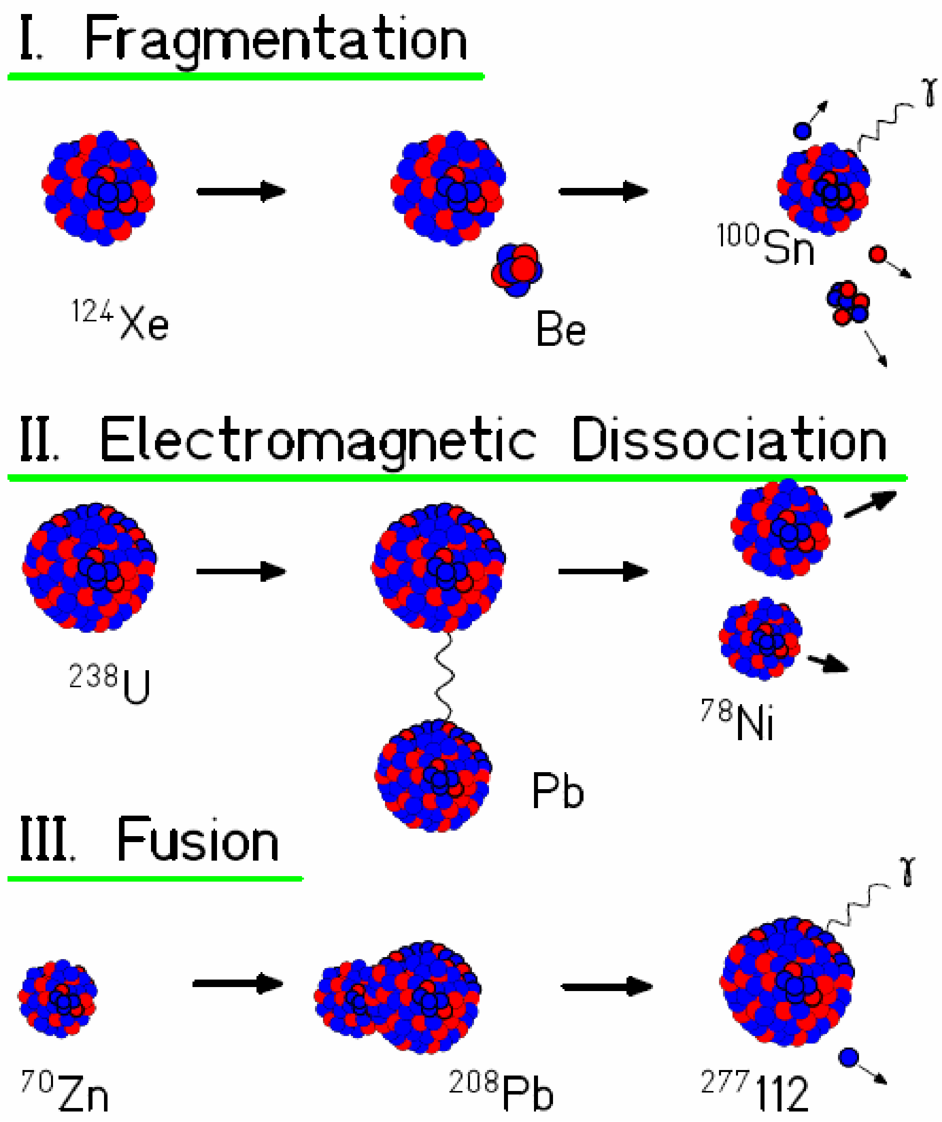
masses, half-lives, (p,γ) rates, B(GT)



SHIPTRAP

masses, half-lives

Production reactions of exotic nuclei



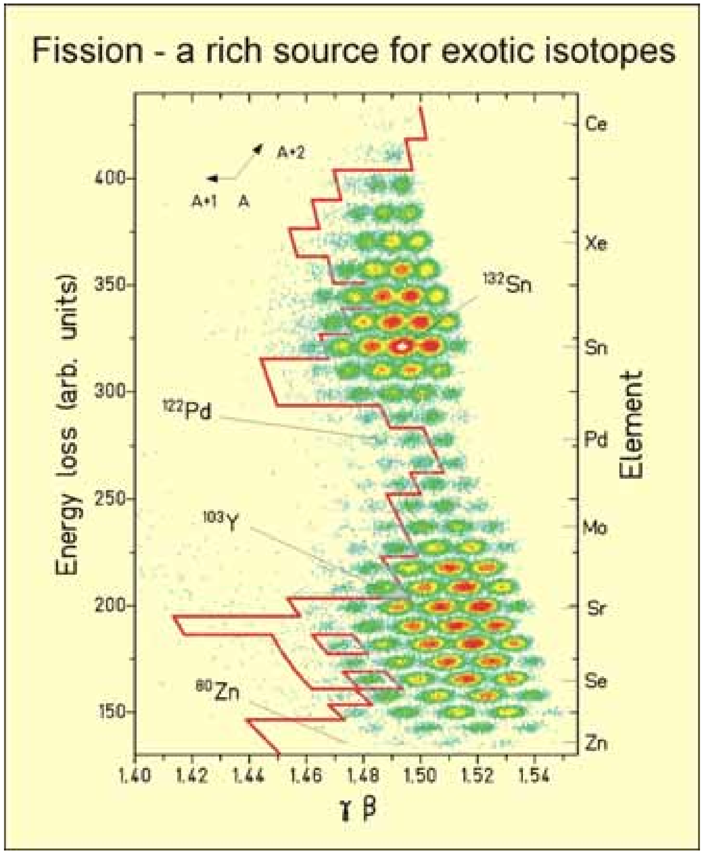
How to produce exotic nuclei at relativistic energies?

- High intensities and thick targets

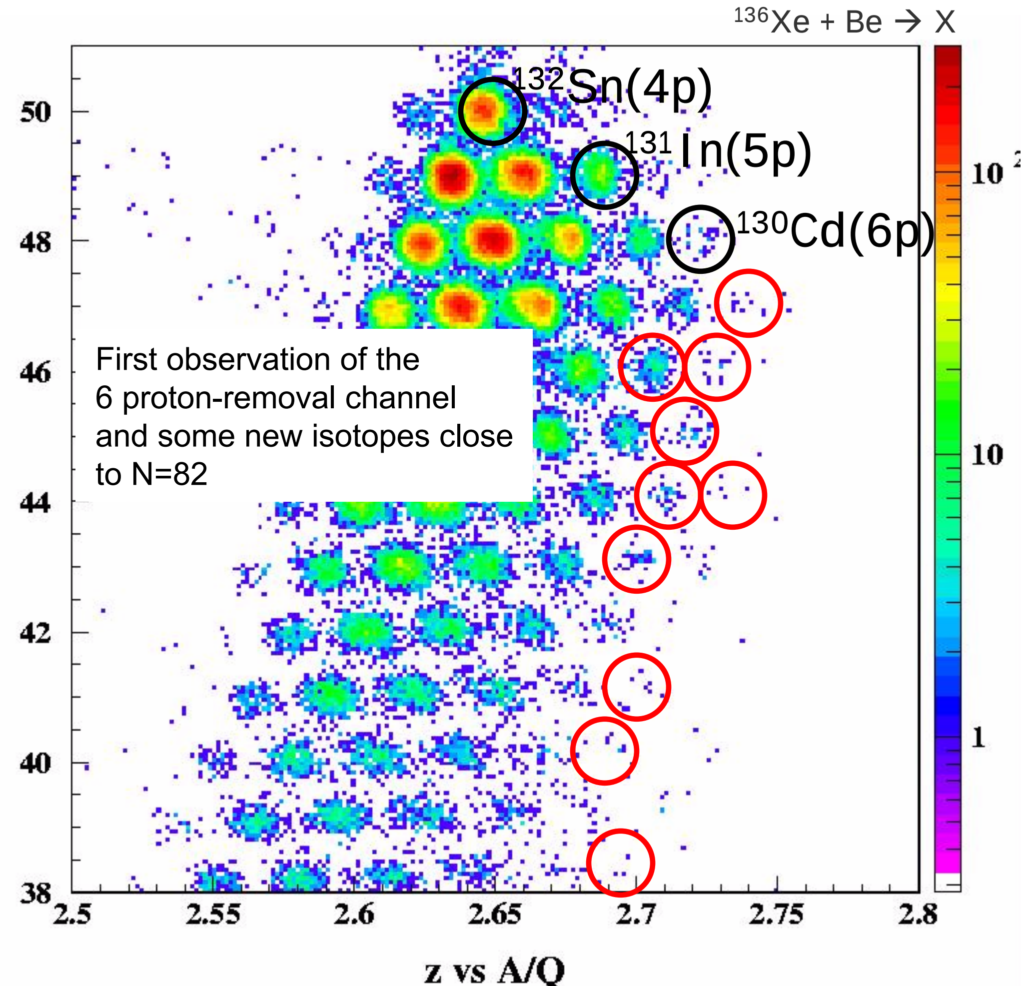
- High cross sections

a) Fission

b) Cold fragmentation



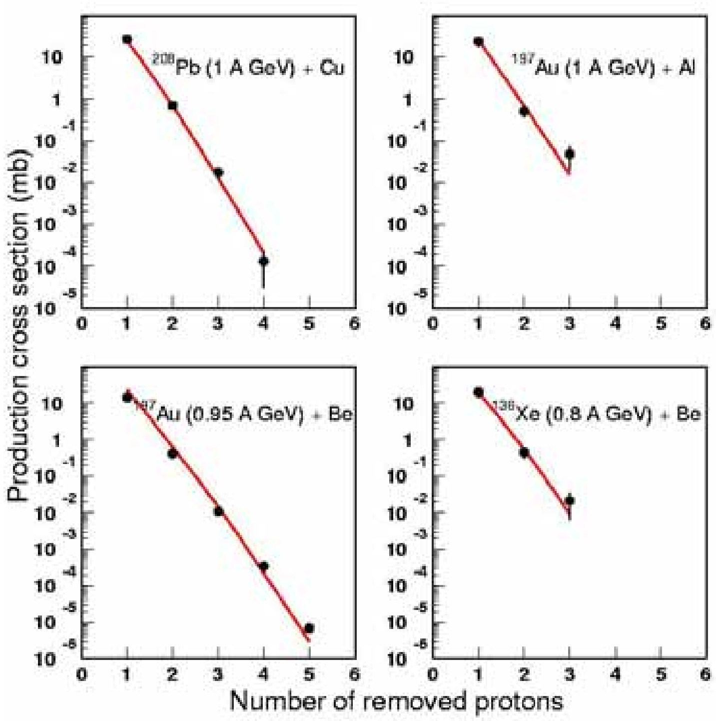
M. Bernas et al., Phys. Lett.



M. Fernandez PhD, U. Santiago de Compostela, Spain

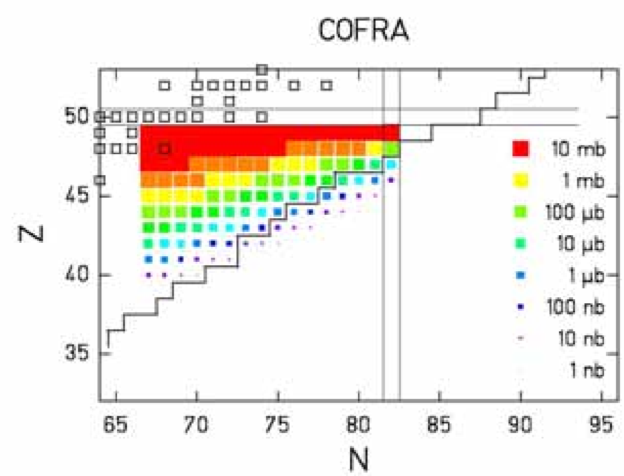
Production of heavy neutron-rich isotopes by proton removal

~1GeV/u Xe,Au,Pb + Be



Mechanism: only protons are abraded, the induced excitation energy remains below the particle emission threshold

Secondary fragmentation may lead to very neutron rich isotopes:



Experimental data

COFRA calculations

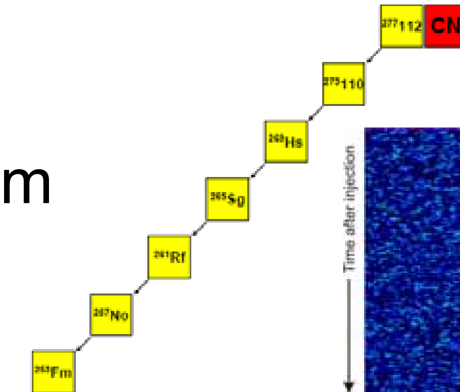
J. Benlliure et al., NPA 660 (1999) 87

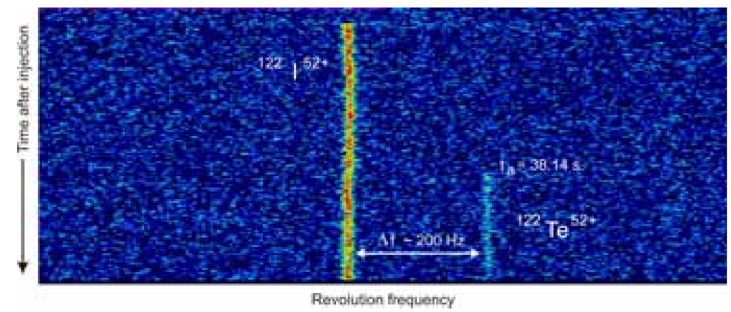
Special features

Ultimate sensitivity

– SHIP, TASCA: 1 single atom

– FRS, ESR: 1 single atom



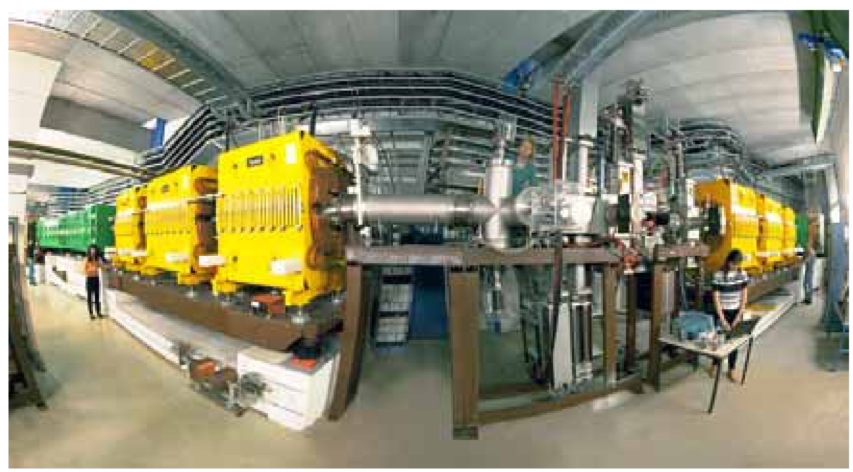


Highest selectivity

– SHIP, TASCA: $1:10^{19}$

– FRS: $1:10^{13}$

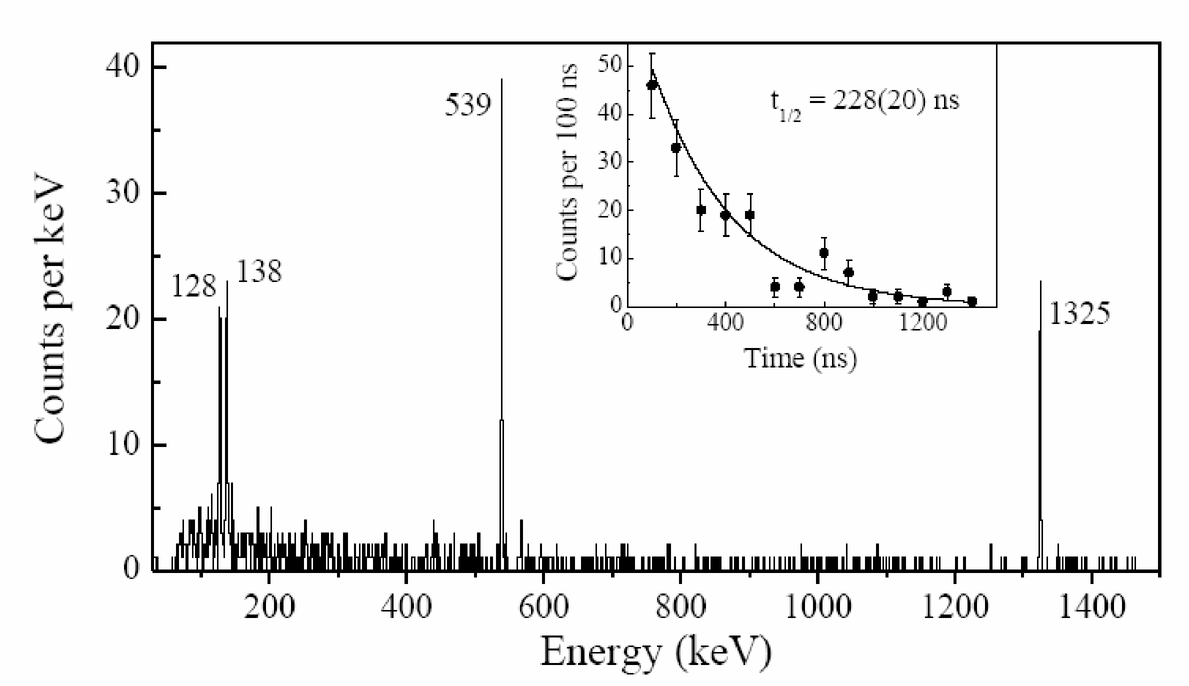
– Chemistry: $< 1:10^{20}$

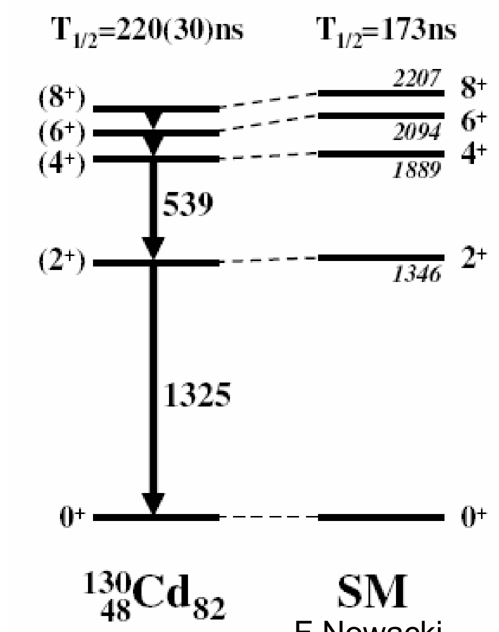


I. Decay spectroscopy

Spectroscopy and ß-decay studies at FRS

8⁺ Isomer in ^{130}Cd





F.Nowacki, H.Grawe, G.Martínez-Pinedo

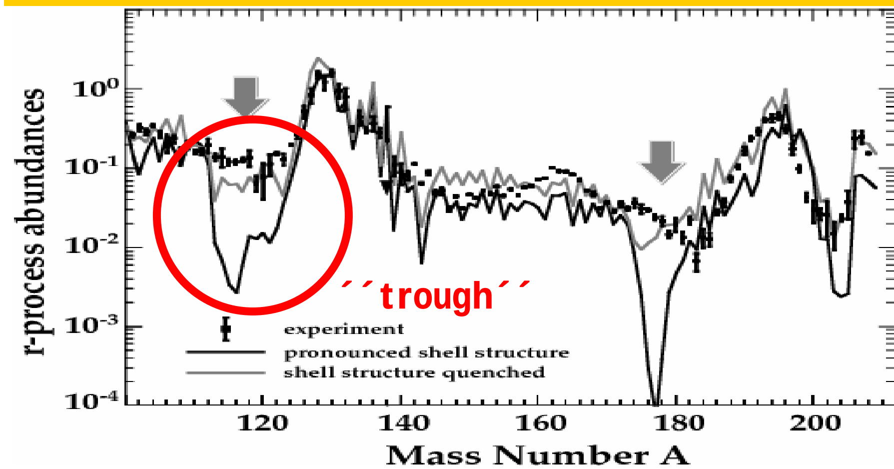
Q_β-measurement (I. Dillmann et al., PRL91, 162503 (2003))
^{130}Cd less bound than expected → "quenching" of N=82 shell closure?

Detailed spectroscopy, unambigous identification, high granularity, high γ-efficiency
no indication of "shell quenching", no weakening of N=82-shell observed
Agreement with SM-calculations:

- level sequence
- energies
- transition rates

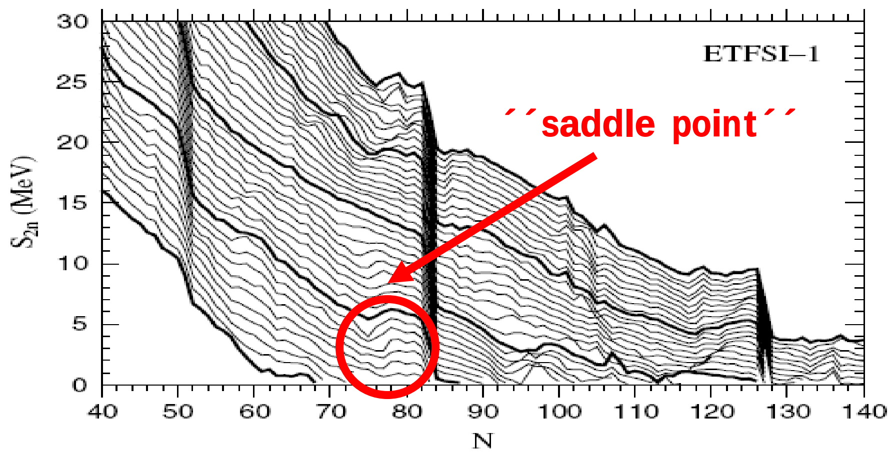
A. Jungclaus et al., PRL 99, 132501 (2007)

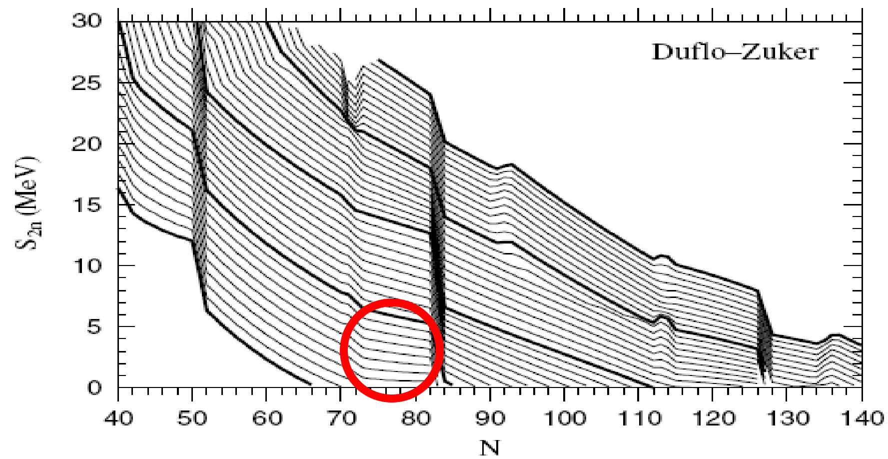
Explaining solar r-abundances

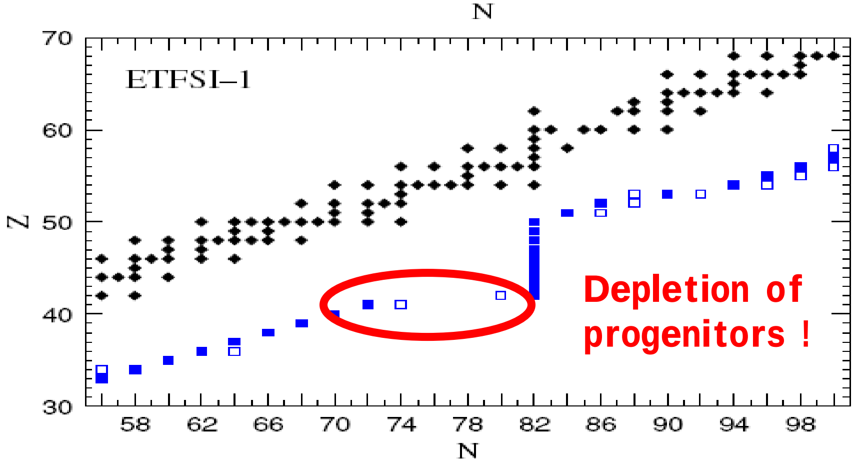


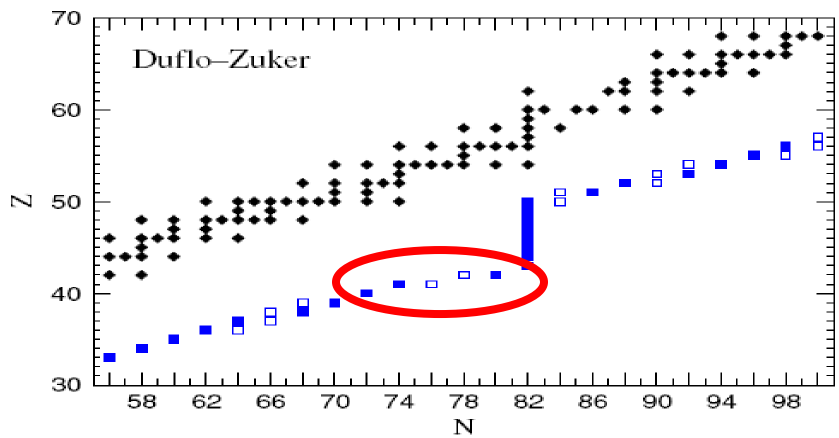
The abundance deficiency ("trough") is due to the changing slope in the neutron separation energy S_{2n} ("saddle point structure") in some mass formulae

From: H. Grawe, K. Langanke, G. Martínez-Pinedo, Rep. Progr. Phys. 70,1525 (2007)





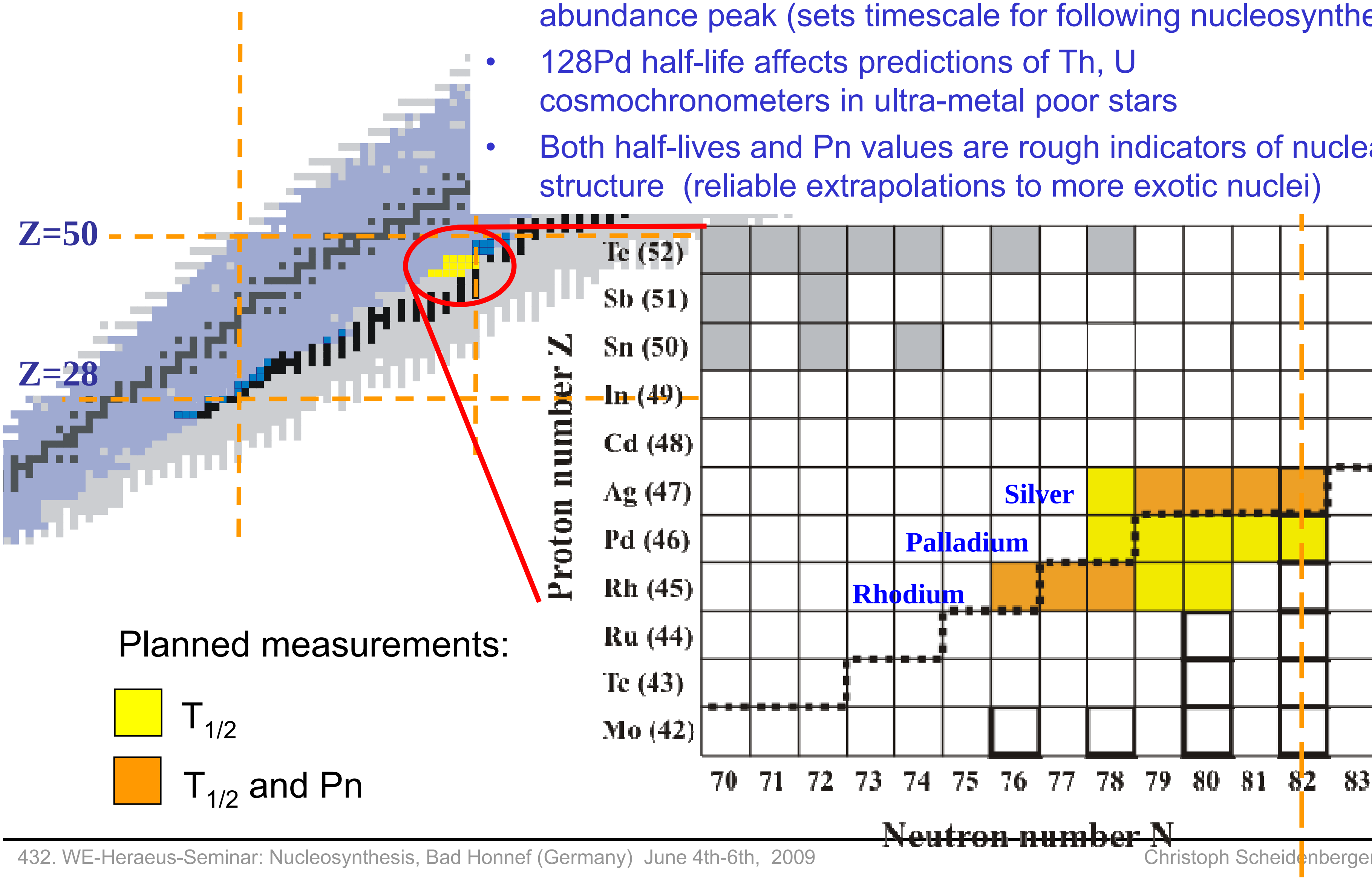




Measurement of P_n-values

Importance:

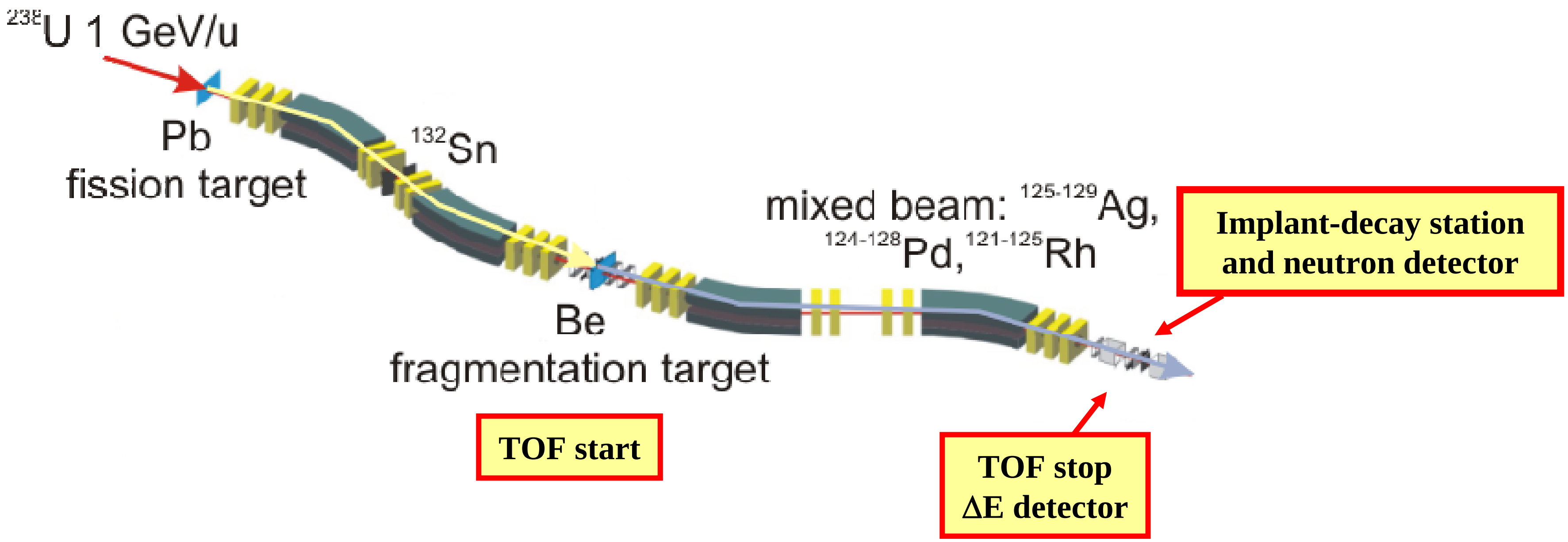
- abundances in the A=115...125 region
- 128Pd is the first bottleneck isotope of the N=82 abundance peak (sets timescale for following nucleosynthesis)
- 128Pd half-life affects predictions of Th, U cosmochronometers in ultra-metal poor stars
- Both half-lives and Pn values are rough indicators of nuclear structure (reliable extrapolations to more exotic nuclei)



Planned measurements:

- $T_{1/2}$ (yellow)
- $T_{1/2}$ and Pn (orange)

Measurement of P_n-values

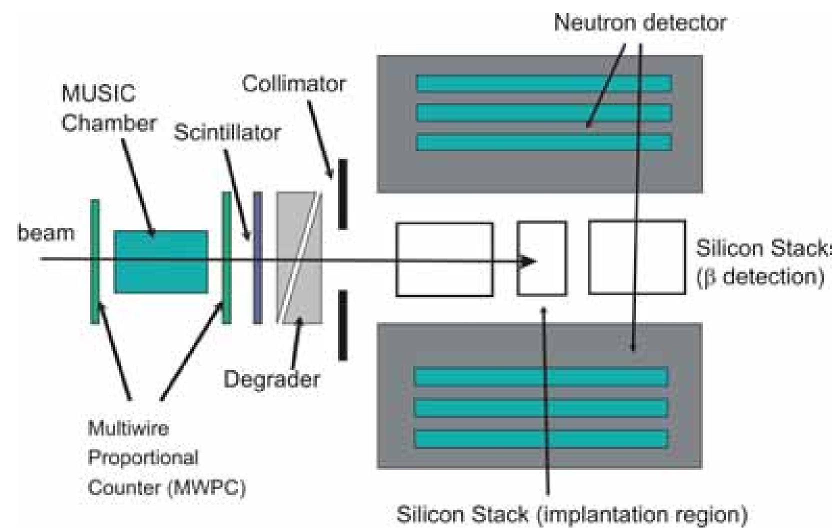


Two-step reaction:

1. U-fission → 10^5 ions/spill ^{132}Sn

2. ^{132}Sn-fragmentation → ~10 /s implantations

→ ^{128}Pd ~1/h

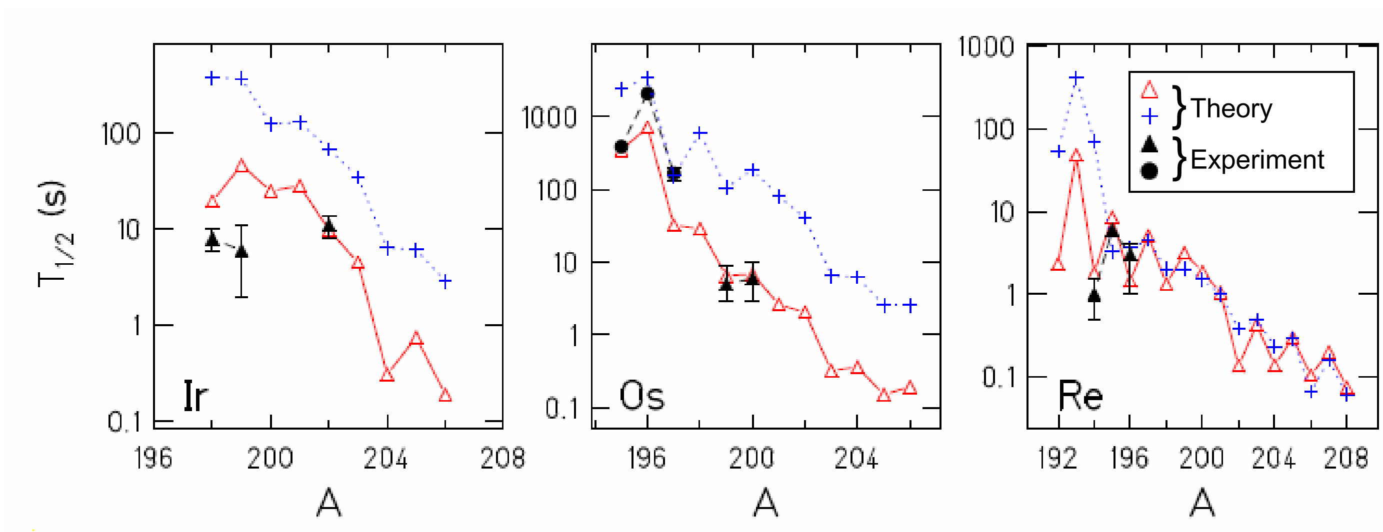


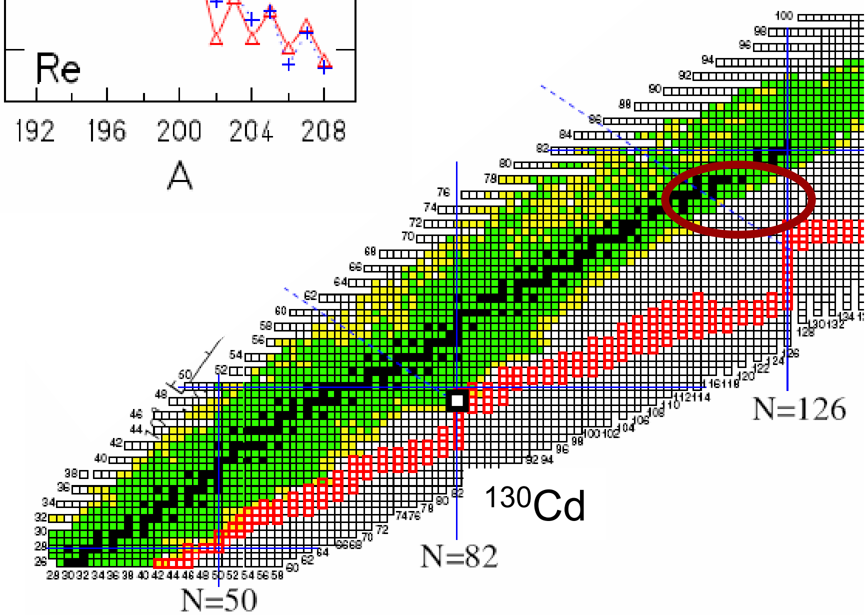
Approved proposal by F. Montes et al.

Spectroscopy and ß-decay studies at FRS

Measured half-lives approaching N=126:

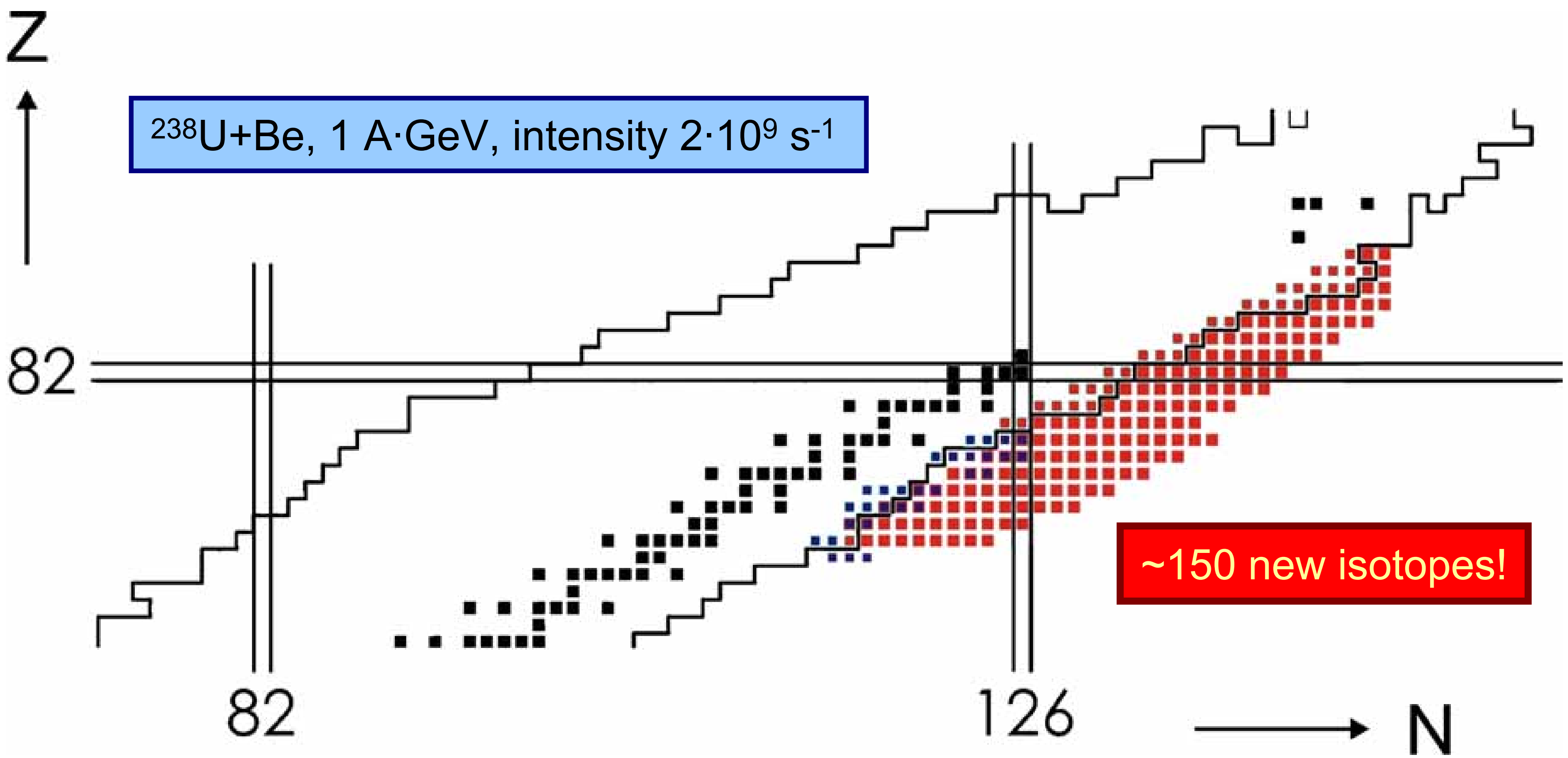
^{198}Ir, ^{199}Ir, ^{200}Ir, ^{199}Os, ^{200}Os, ^{194}Re, ^{195}Re, ^{196}Re





T. Kurtukian-Nieto, J. Benlliure et al.,
arXiv:0711.0101v1, Nov. 2007

New n-rich isotopes along N=126



- Expected production
- Previous FRS experiment, T. Kurtukian-Nieto *et al.*, sub. Phys. Lett. B

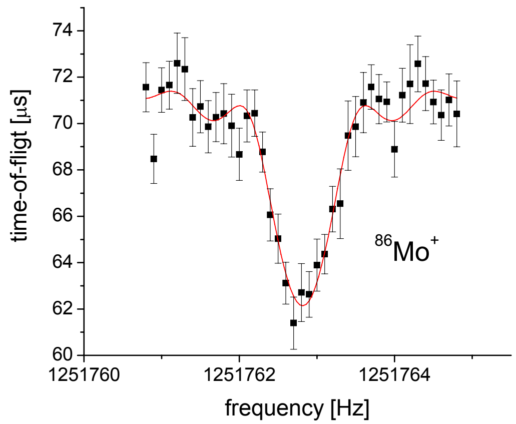
Approved proposal, J. Kurcewicz, S. Pietri, C. Nociforo, et al.

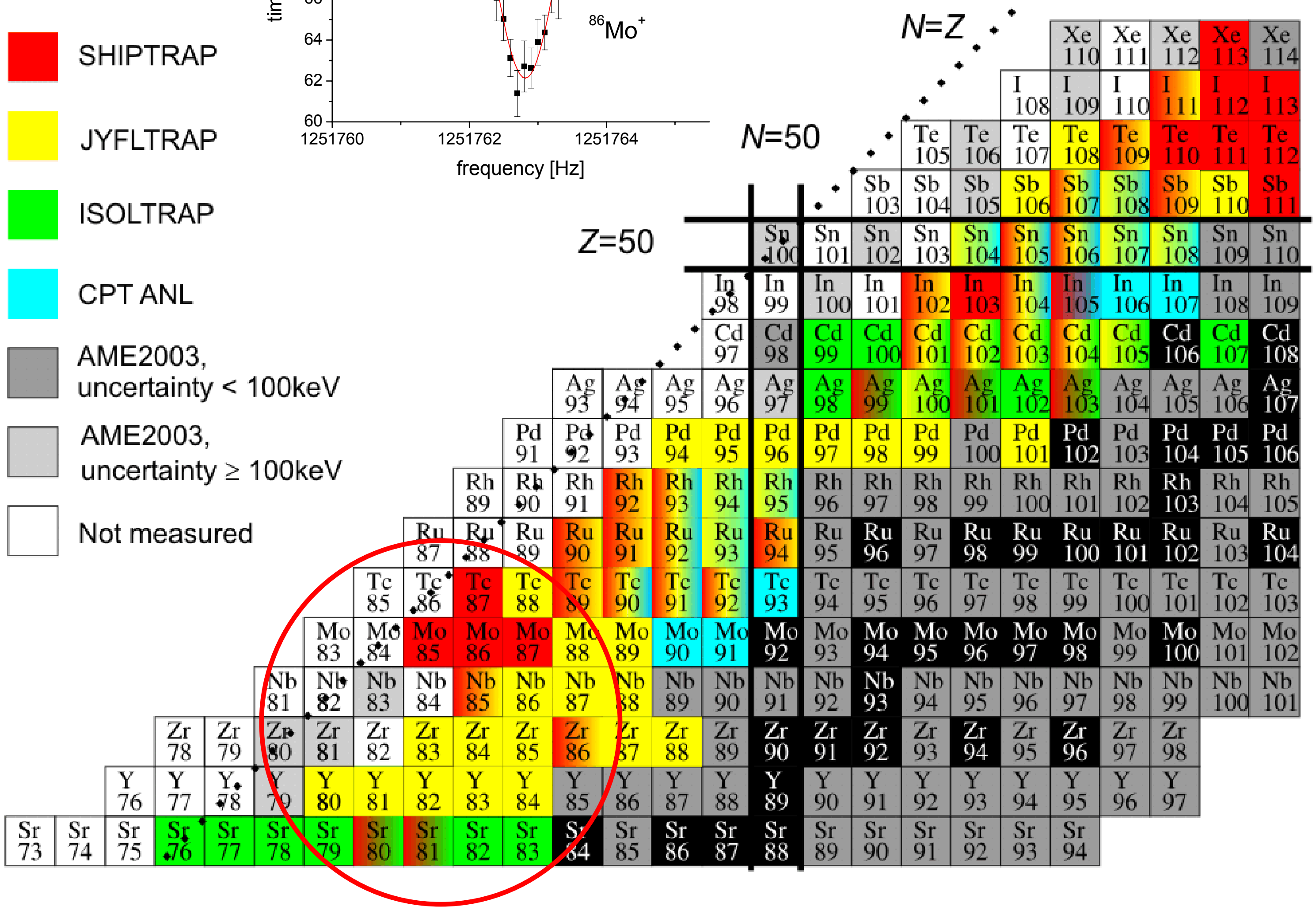
II. Mass measurements

Masses along the rp-process path

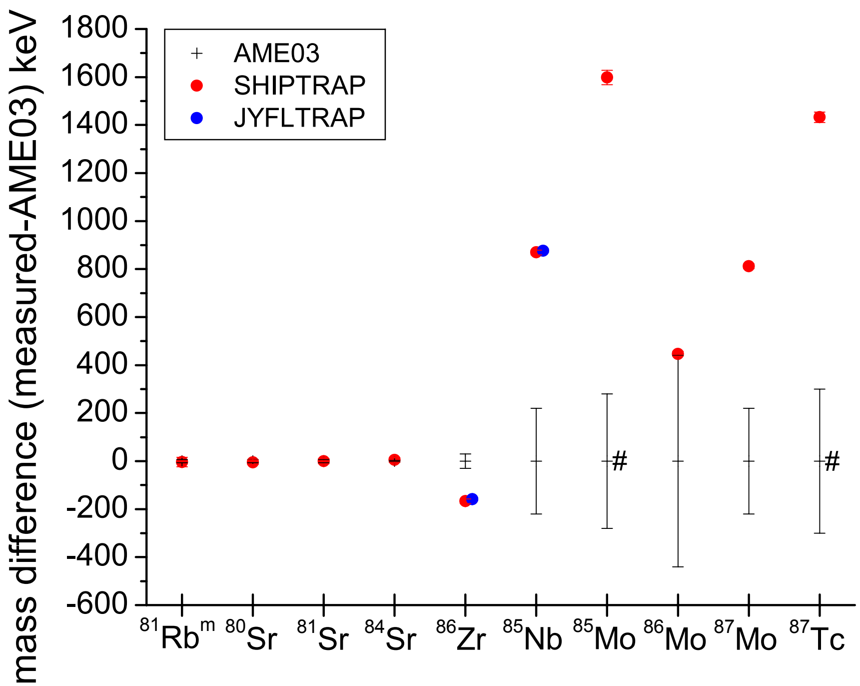
$^{36}Ar + ^{54}Fe \rightarrow ^{90}Ru^*$

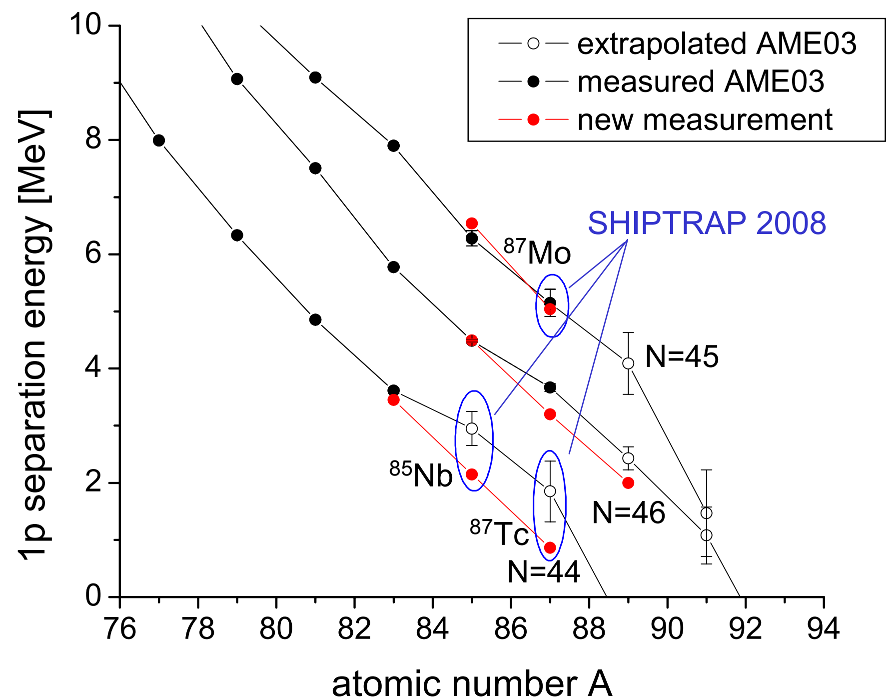
5.0 and 5.9 MeV/u





Results from recent experiment





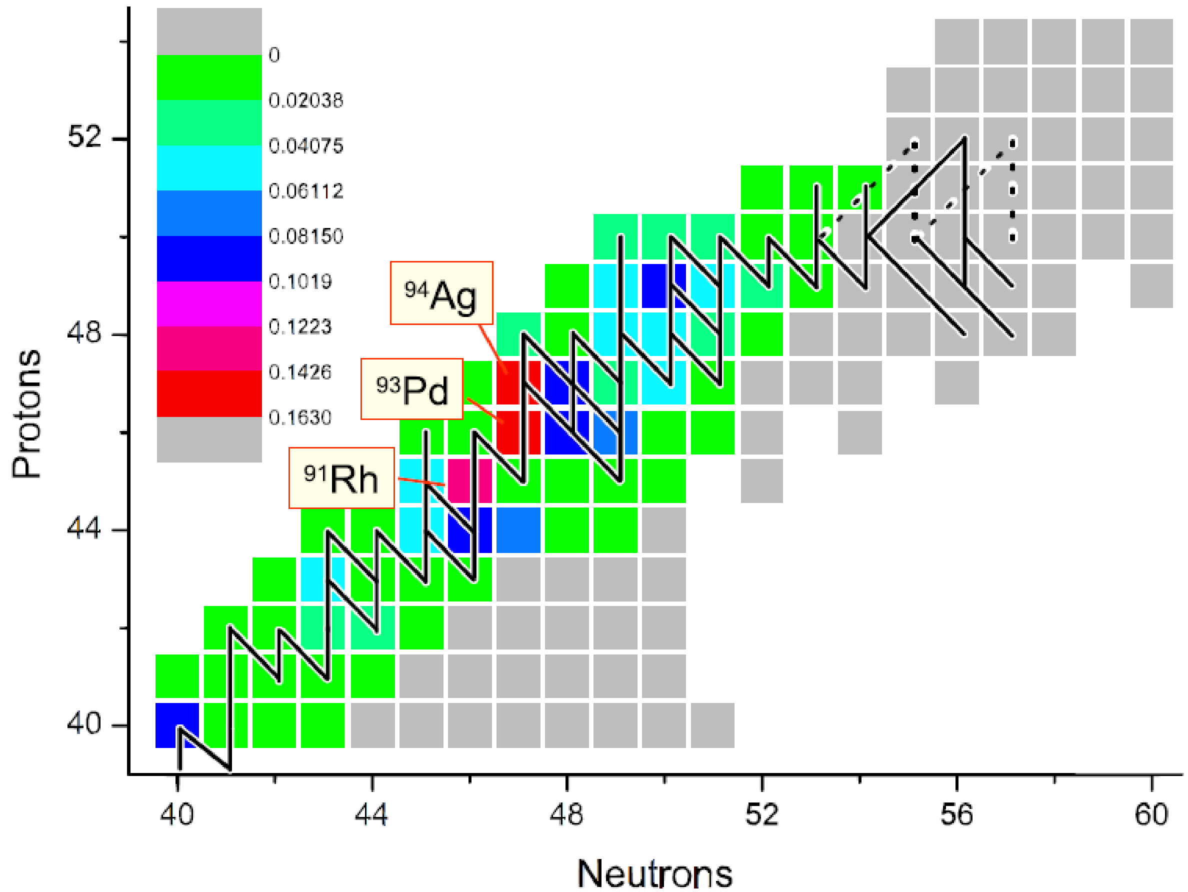
Reduced proton separation energies
→ rp-process shifts towards stability

E. Haettner et al.

Impact of mass variations

X-ray burst parameter study

- ashes
- light curve
- pathway

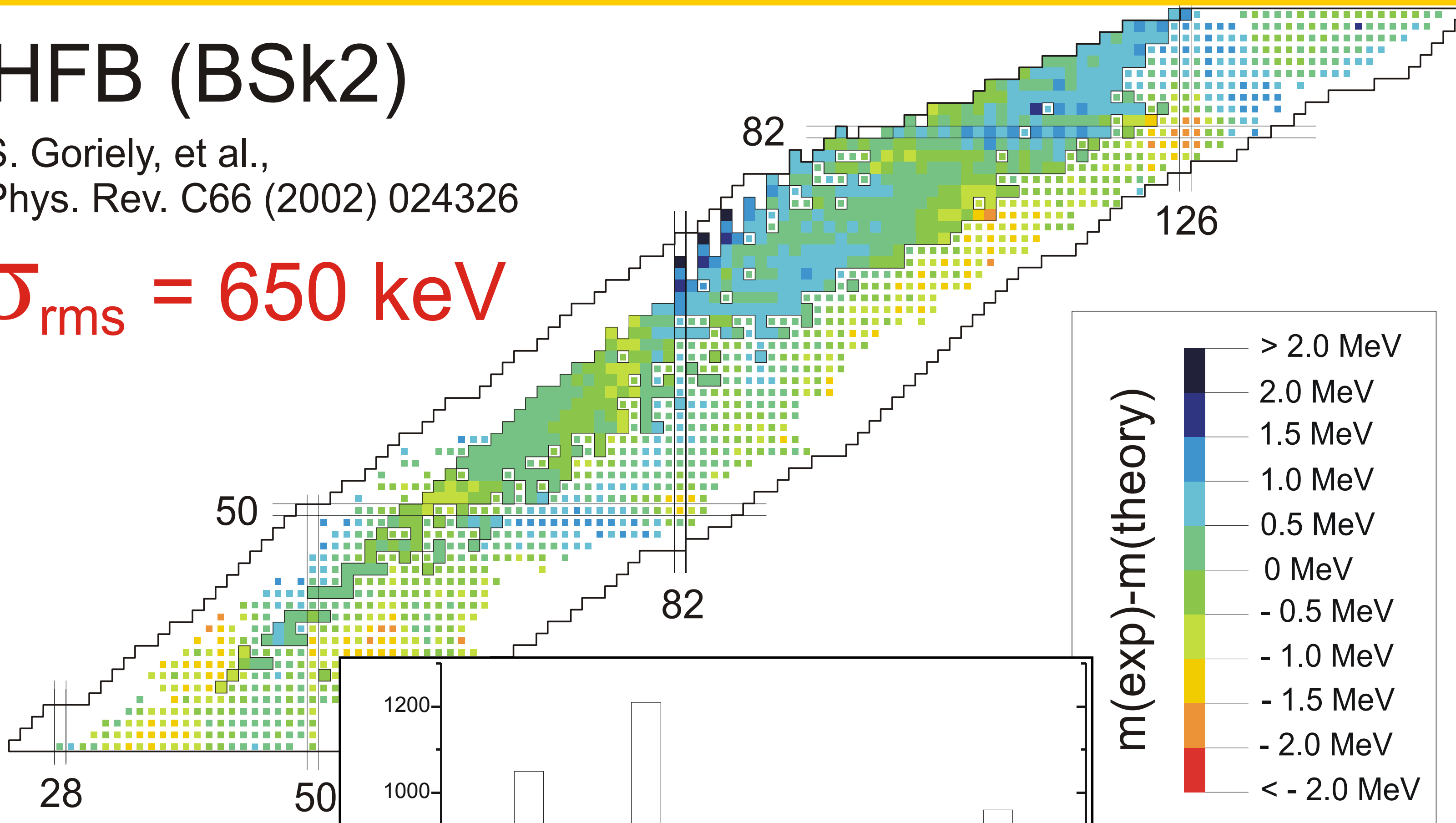


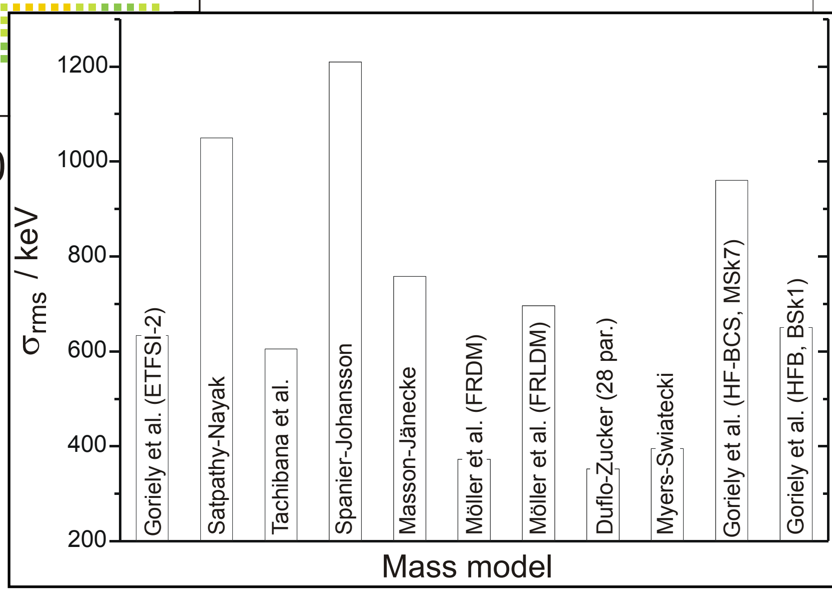
W. Plass, T. Fleckenstein et al.

HFB (BSk2)

S. Goriely, et al.,
Phys. Rev. C66 (2002) 024326

σ_{rms} = 650 keV

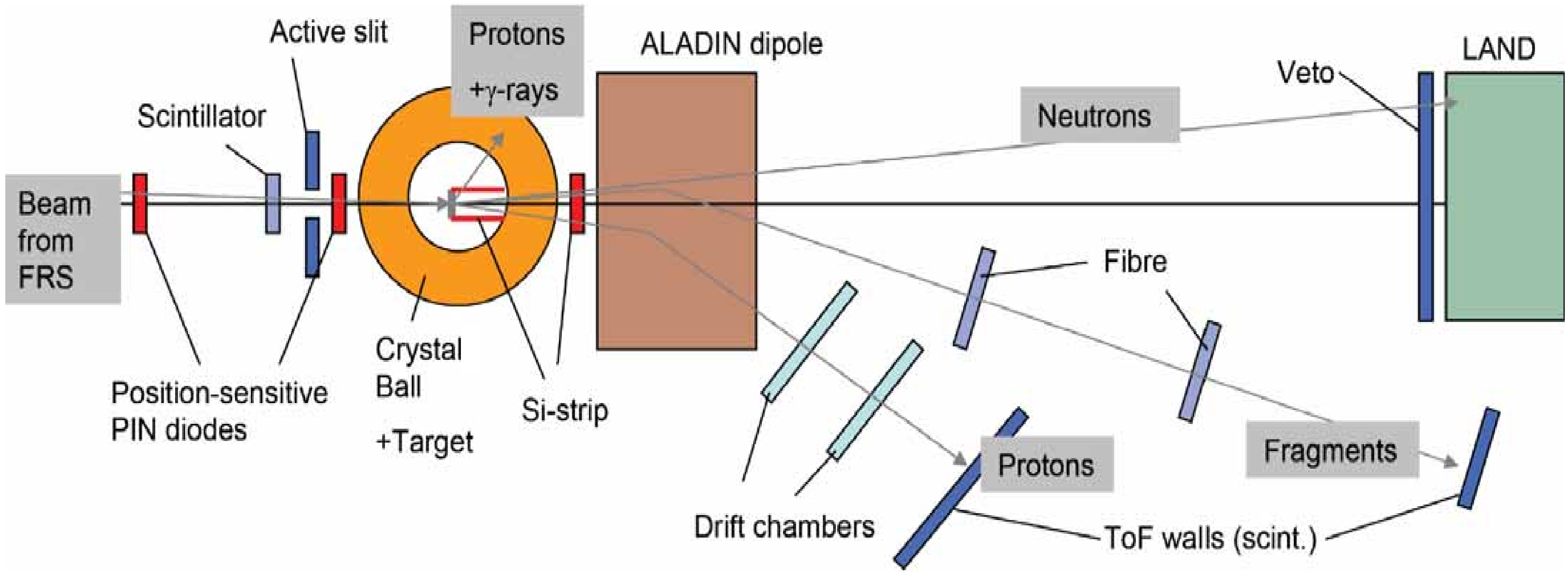




III. Reaction studies

Coulomb dissociation method at ALADIN-LAND

- Indirect methods, such as Coulomb dissociation, are the only way to obtain experimental information about 3-body reactions
- Complete kinematics
- Detection of neutrons, protons, heavy fragments
- New: proton arm with Si-strip detectors and multi-wire drift chambers

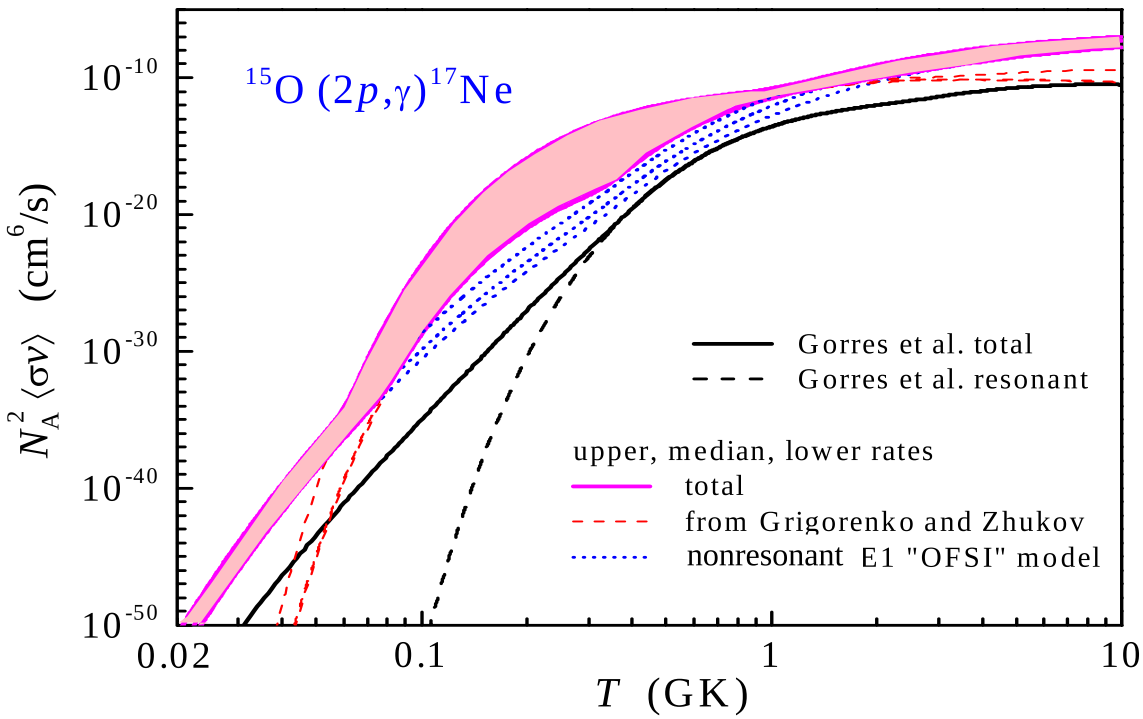


First experiments using the proton arm

$^{15}O(2p,\gamma)^{17}Ne$ reaction

Possible breakout of CNO cycle during rp-process to reach the FeNi region

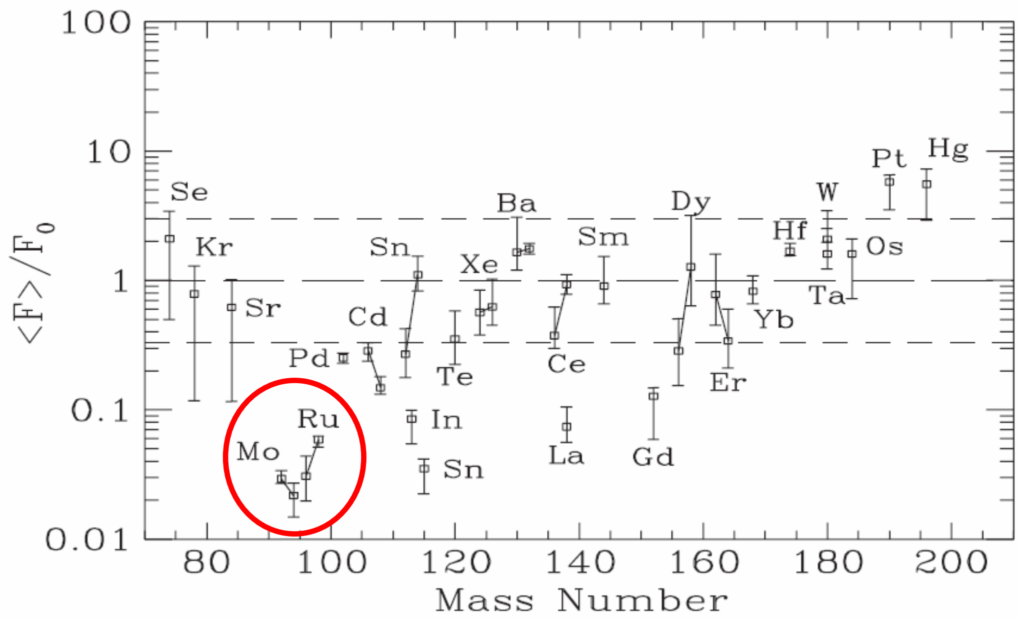
Waiting points (such as ^{15}O,^{18}Ne,^{38}Ca) can be bridged by three-body reactions

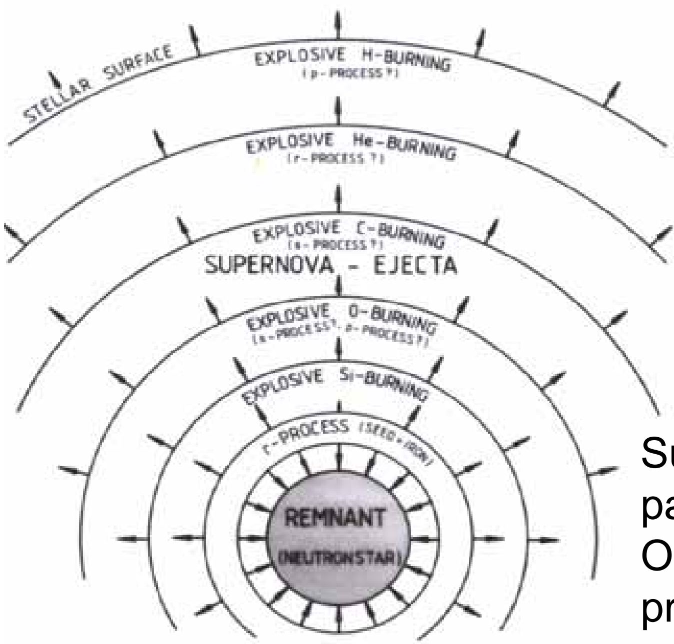


J.Görres, M.Wiescher, and F.-K.Thielemann, Phys. Rev. C 51 (1995) 392

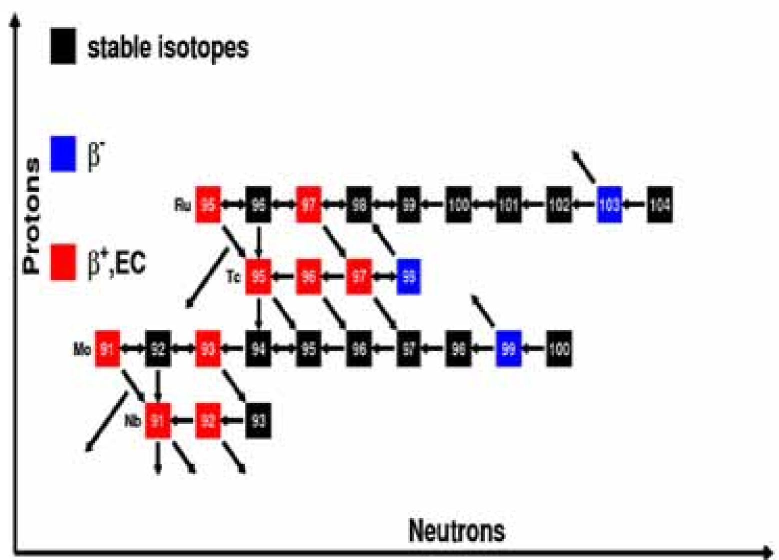
Analysis in progress (M. Heil, J. Marganiec et al.)

Origin of 'p-nuclei' – abundant n-deficient isotopes, e.g. ^{92,94}Mo, ^{96,98}Ru





Supernova shock passing through O-Ne layers of progenitor star

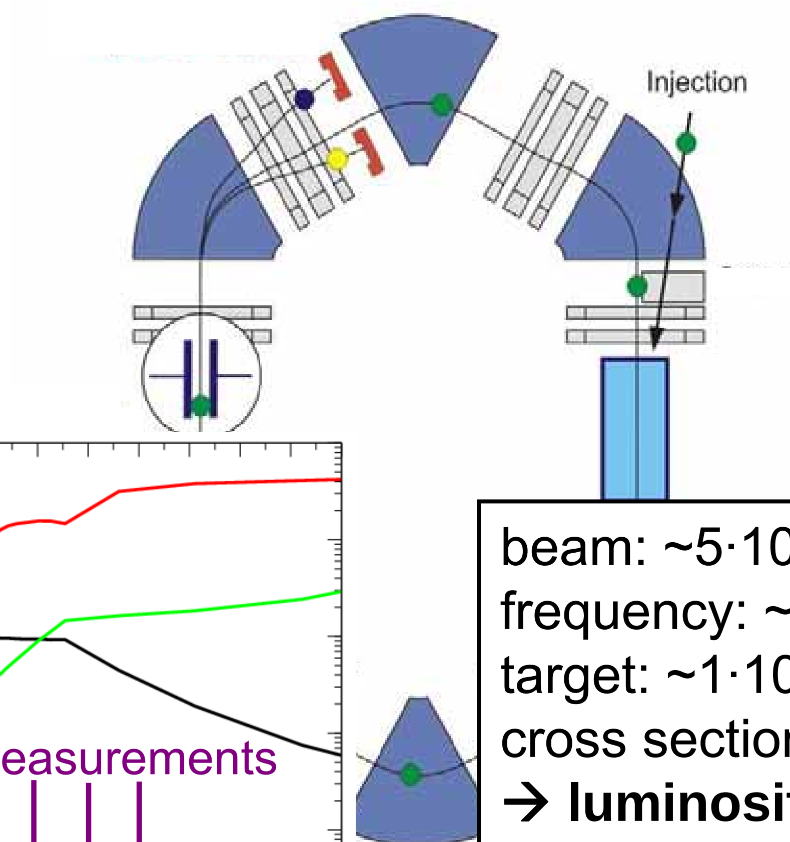


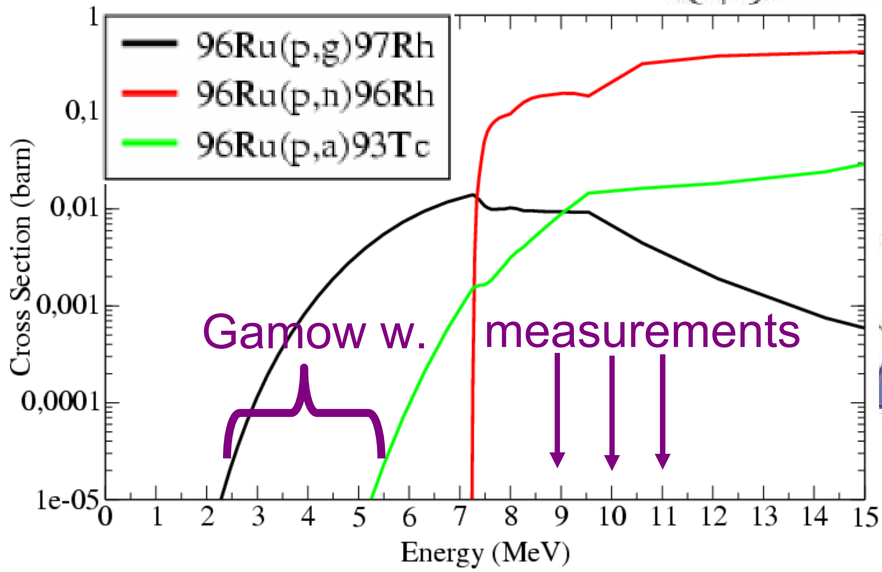
Arnould & Goriely Phys. Rep. 384,1 (2003)

(p,γ) or (α,γ) rates in the Gamow window of the p-process in inverse kinematics

Pilot experiment performed with stable beams:

- direct proton capture of ^{96}Ru in H gas target: ^{96}Ru(p,γ)^{97}Rh
- DSSSD's (Edinburgh) for detection of recoiling reaction products

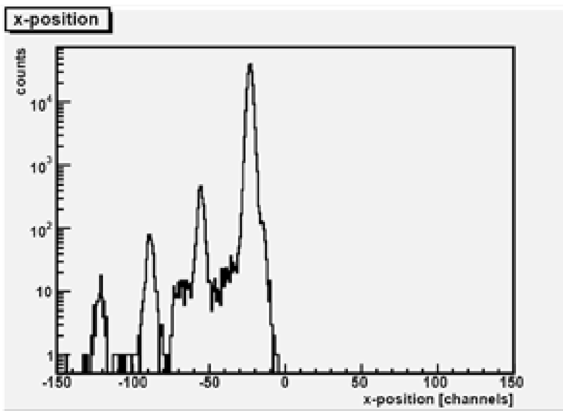




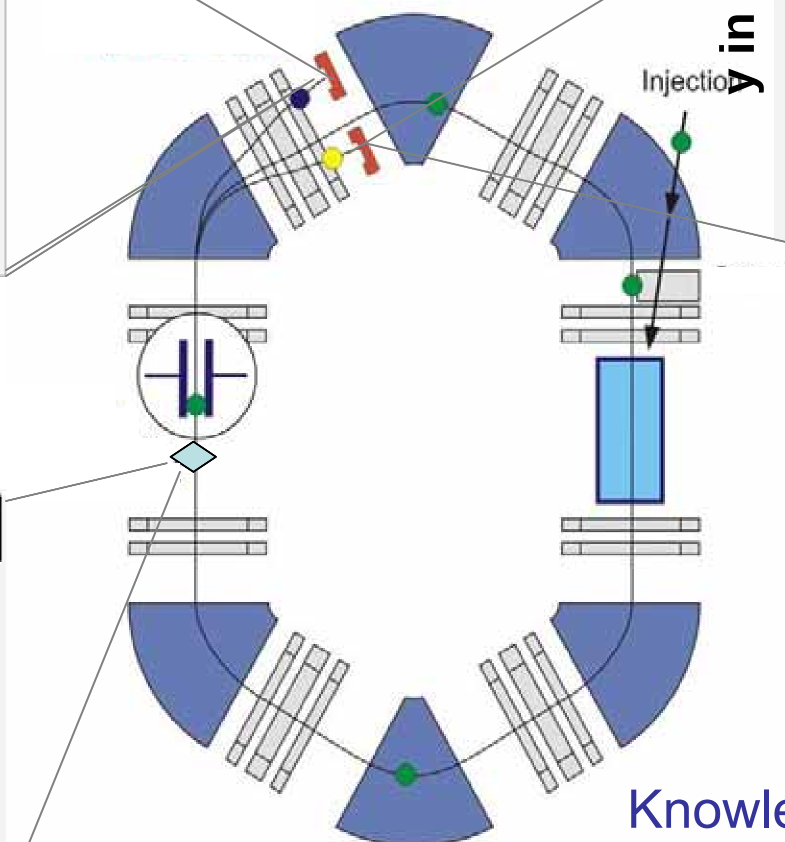
beam: ~5·10^{6} particles per spill
frequency: ~0.5 MHz
target: ~1·10^{13} atoms/cm^{2}
cross section: 2 mbarn
→ **luminosity ~ 2.5·10^{25} cm^{-2} s^{-1}**
→ **count rate ~180 h^{-1}**

(p,γ) or (α,γ) rates in the Gamow window of the p-process in inverse kinematics

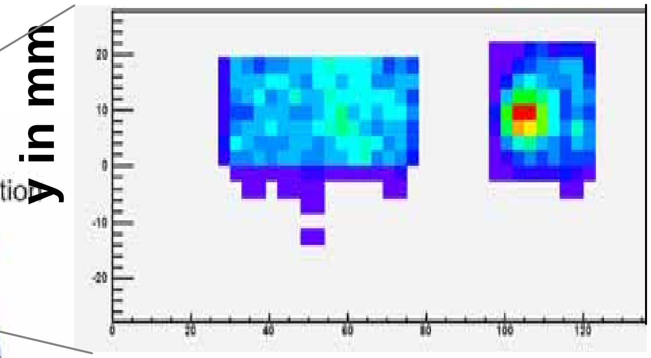
Electron capture



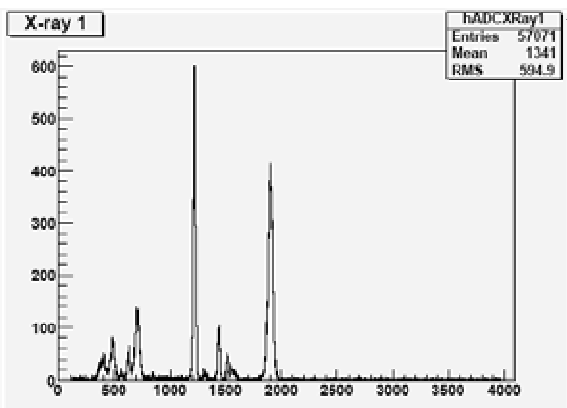
Detection of $^{96}Ru^{43+}$
in MWPC detector
--> normalization



Direct proton capture

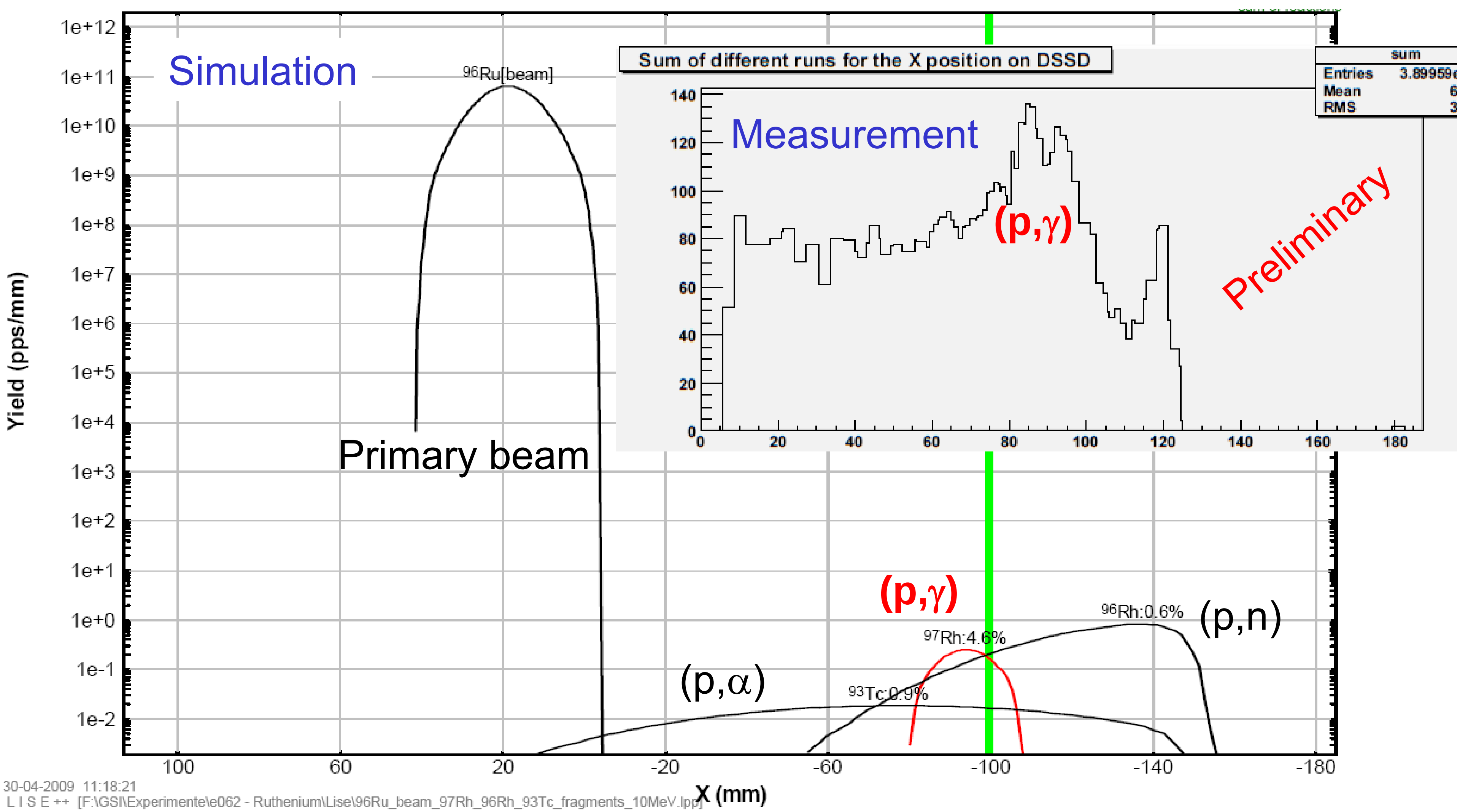


X-rays from radiative electron capture



Knowledge of line intensities of product nucleus not necessary

Preliminary results

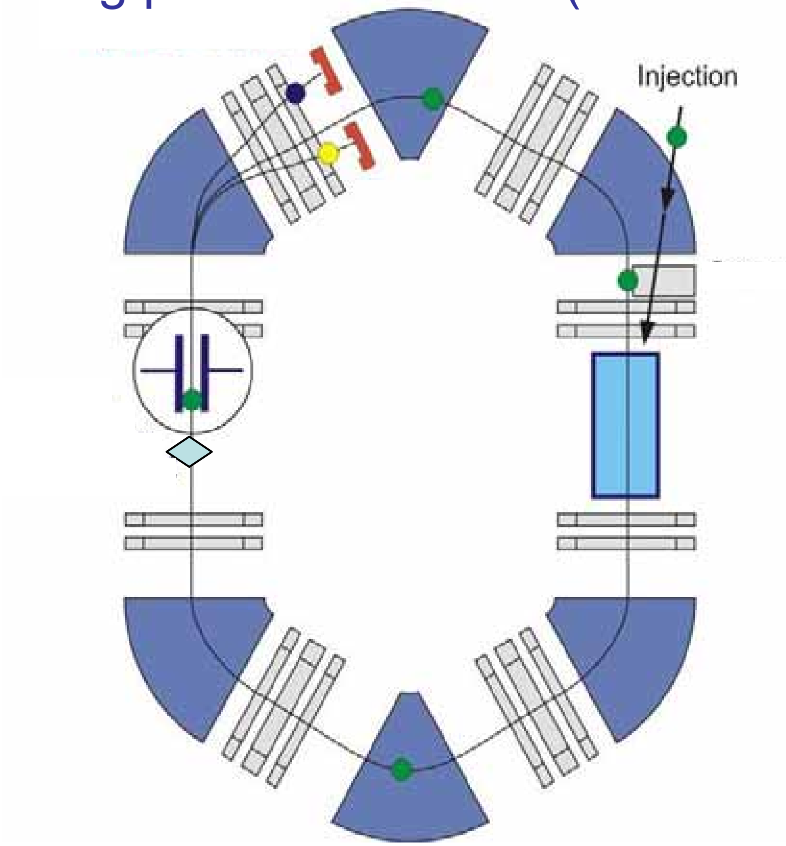


M. Heil, P. Woods, Q. Zhong

(p,γ) or (α,γ) rates in the Gamow window of the p-process in inverse kinematics

Advantages:

- Applicable for radioactive nuclei
- Applicable for gases
- Detection of ions via in-ring particle detectors (low background, high efficiency)



→ $^{13}C(\alpha,n)^{16}O$ planned at TSR (Heidelberg)

→ plans to use technique with RIB on NESR at FAIR for p-process studies

In summary: where does the nuclear physics input come from?

Complementary approaches

- exotic nuclei at low and high energies
- spectroscopy
- reaction studies

....yielding

- masses
- half-lives
- P_n-values
- fission yields
- cross sections
- .....

.....for network calculations in order to confront with observations for an improved understanding of stars and stellar nucleosynthesis