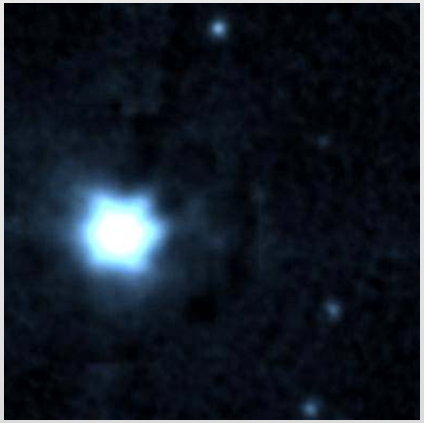
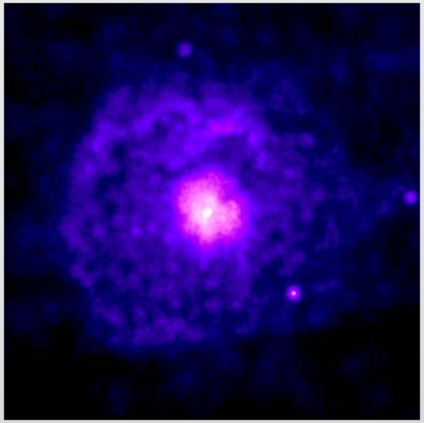
Nuclear Astrophysics at Notre Dame





Michael Wiescher
University of Notre Dame

- Questions in Nuclear Astrophysics
- Experimental Facilities at Notre Dame
- Experiments for CNO hydrogen burning
- Experiments for stellar helium burning
- New techniques for p-process experiments

Goals in experimental Nuclear Astrophysics

Identify nuclear probes (branching, bottleneck or waiting points) for determining site specific stellar conditions

- stellar evolution processes (H-, He-, C- ... burning)
- s-process (AGB & RGB stars)
- rp-process (novae and XRBs)

Determine global nuclear characteristics (masses, decay properties, ...) to identify reaction path, determine & probe site

- p-process (type I or type II SN ...?)
- r-process (type II SN, neutron star mergers, jets ...?)
- ν-process (type II SN ....?)

Current challenges and future facilities

- nucleosynthesis in stellar evolution
  experiments at low energies $\Rightarrow$ LENA, LUNA, NSL, UoW …
  DUSEL
- nucleosynthesis with neutrons
  experiments with high n-flux $\Rightarrow$ FZKarlsruhe, LANSCE
  n-ToF, ORELA, SNS
- nucleosynthesis in stellar explosion
  experiments far of stability $\Rightarrow$ ANL, HRIBF, ISAC, LLN,
  NSCL, RIKEN, REX,
  FAIR-GSI, RIA …

Participants in the experimental program in Nuclear Astrophysics @ Notre Dame

Research Personnel

Manoel Couder
Joachim Görres
Wolfgang Rapp
Ed Stech
Wan Peng Tan
Michael Wiescher

11 Graduate Students

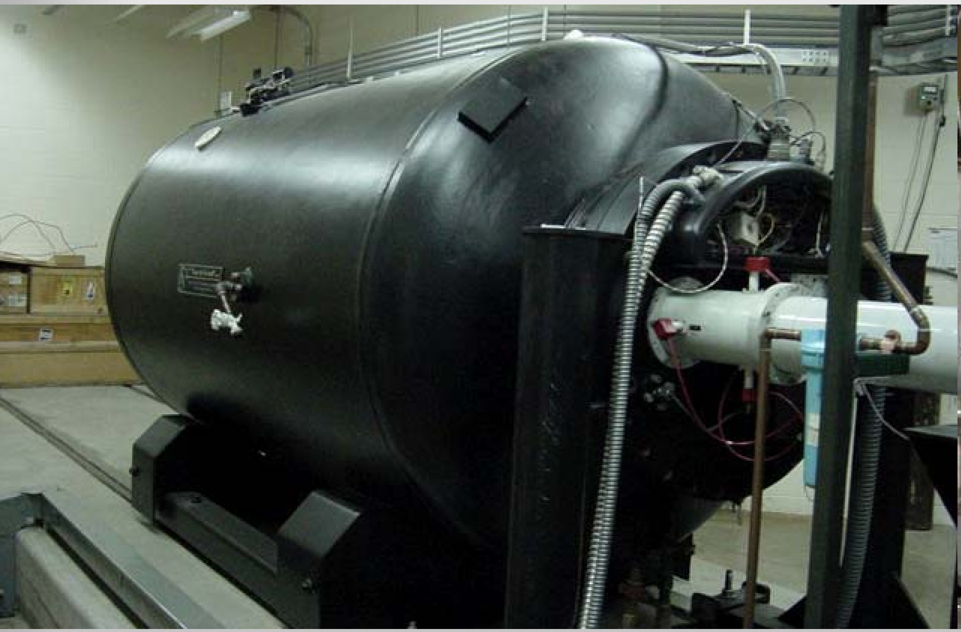
Mary Beard
⇨ Aaron Couture
Jason Daly
Michael Lamey
Paul Le Blanc
Hye-Young Lee
Shawn O’Brien
⇨ Annalia Palumbo
⇨ Elisabeth Strandberg
Barbara Truett
⇨ Claudio Ugalde

4 Undergraduate Students

Nicholas Battafarano
Christoph Bär
James Marquez-Miller
Edward Simpson

Experimental Facilities

Low energy studies at local JN/KN accelerators



Both accelerators have been installed and tested and are being operated by undergraduate and graduate students.

The accelerators are used for low energy nuclear astrophysics measurements with focus on stellar hydrogen and helium burning.

Experimental Facilities

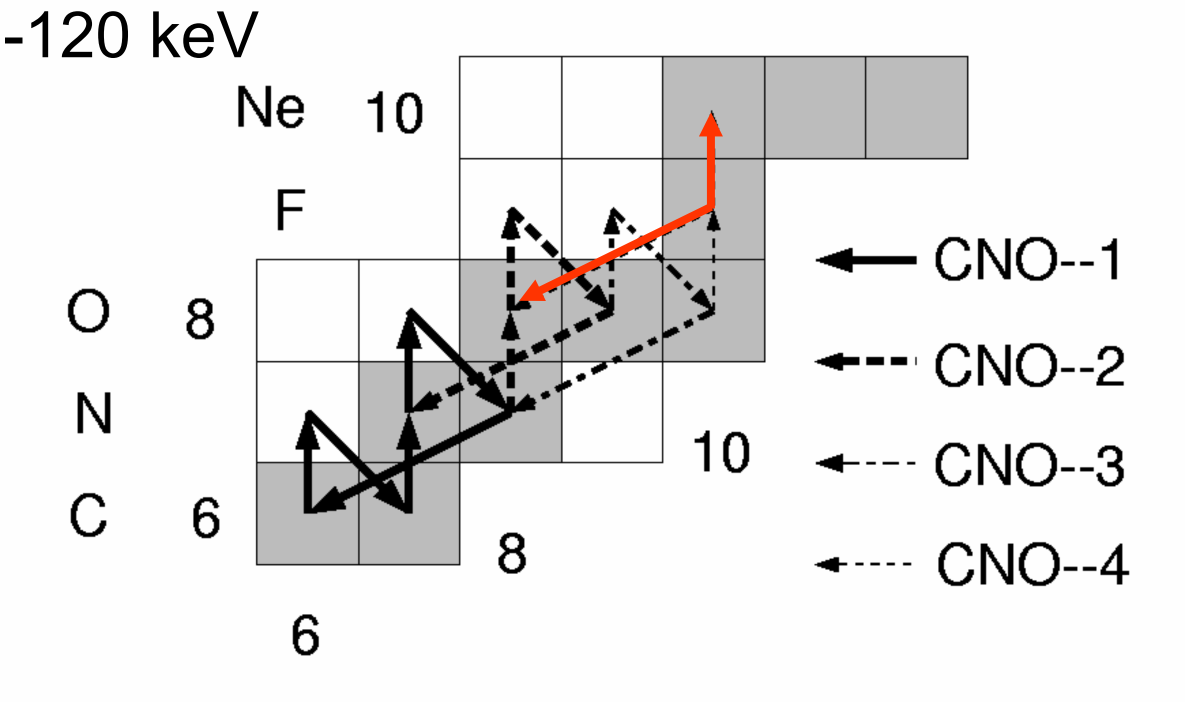
Experiments at the FN tandem accelerator and the TwinSol facility

Transfer, scattering, and reaction studies on nuclear astrophysics related topics

p-process measurements in SN-II shock-front environments
Reaction and structure studies for hot CNO and rp-process

Stellar Hydrogen Burning in Massive Stars
Break-Out from the cold CNO cycles

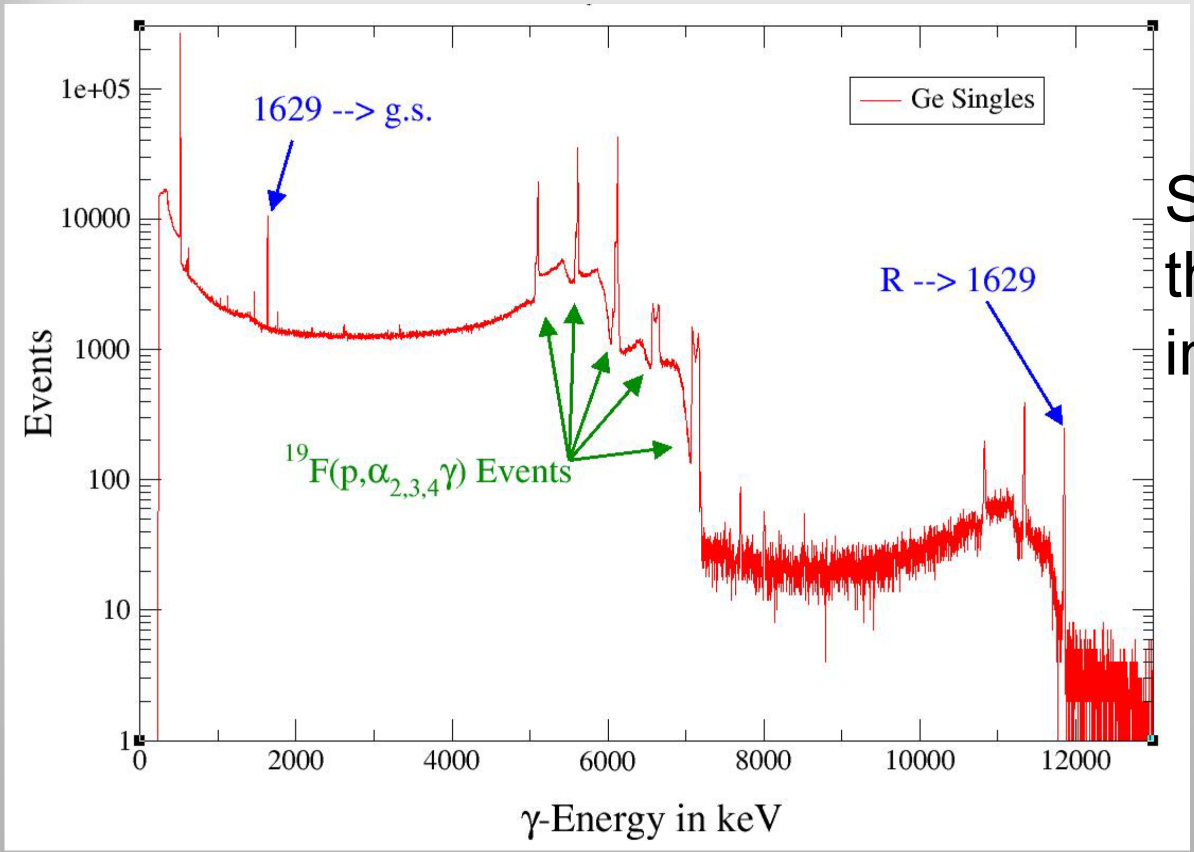
$\Delta E_G = 30$ -120 keV



Small leakage out of CNO cycle could lead to slow CNO fuel depletion in massive main sequence stars!

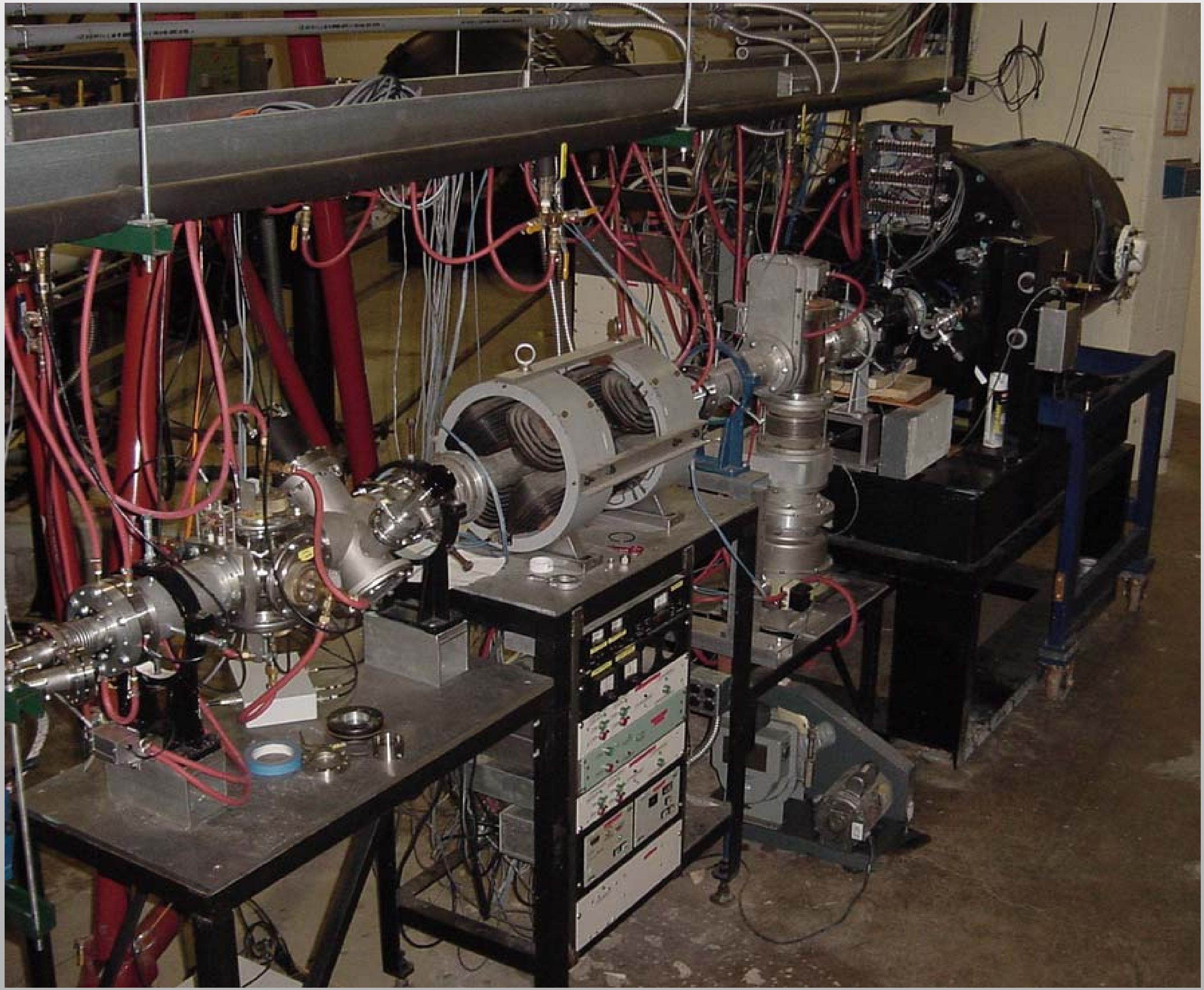
Measurement of $^{19}F(p,\gamma)^{20}Ne$

Handicapped by pile up from strong 19F(p,$\alpha\gamma$) background at 6.125 MeV

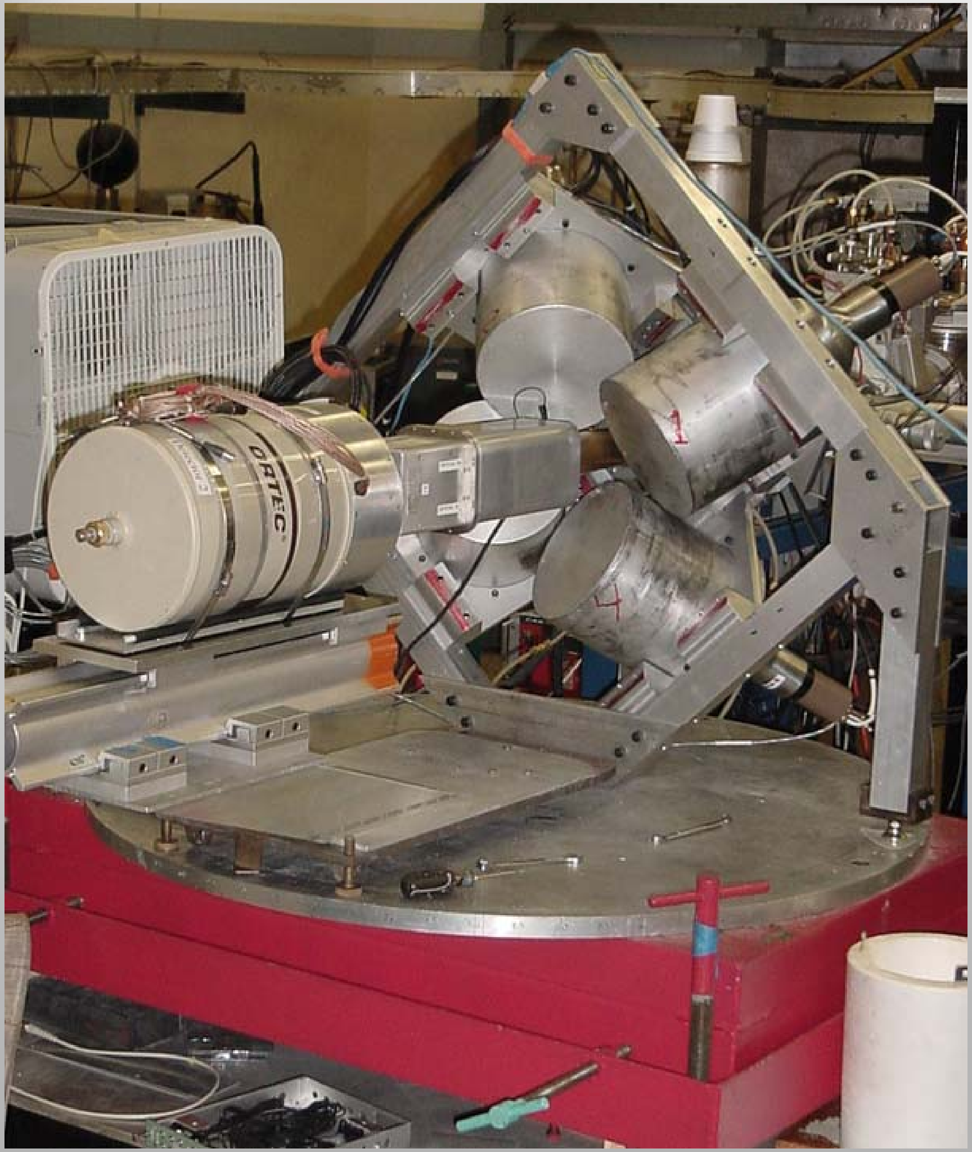


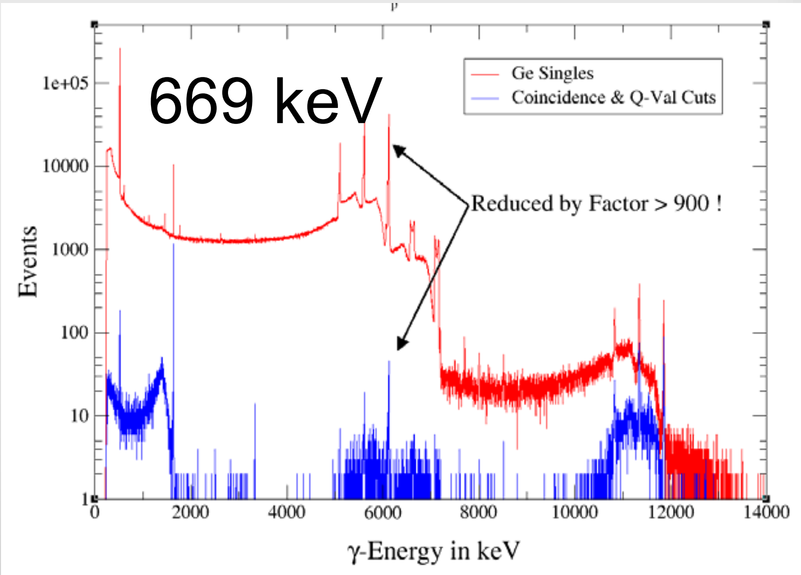
Single γ spectrum of the 669 keV resonance in $^{19}F(p,\gamma)^{20}Ne$

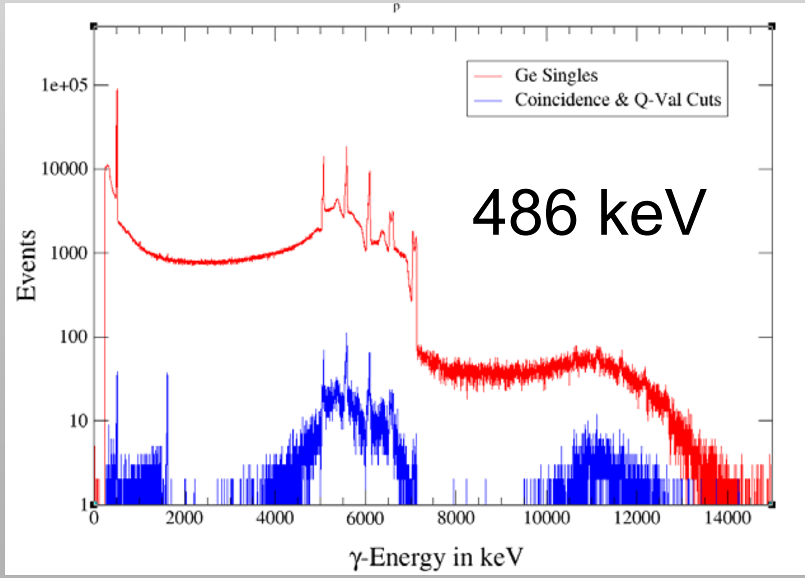
Experimental Sep-Up



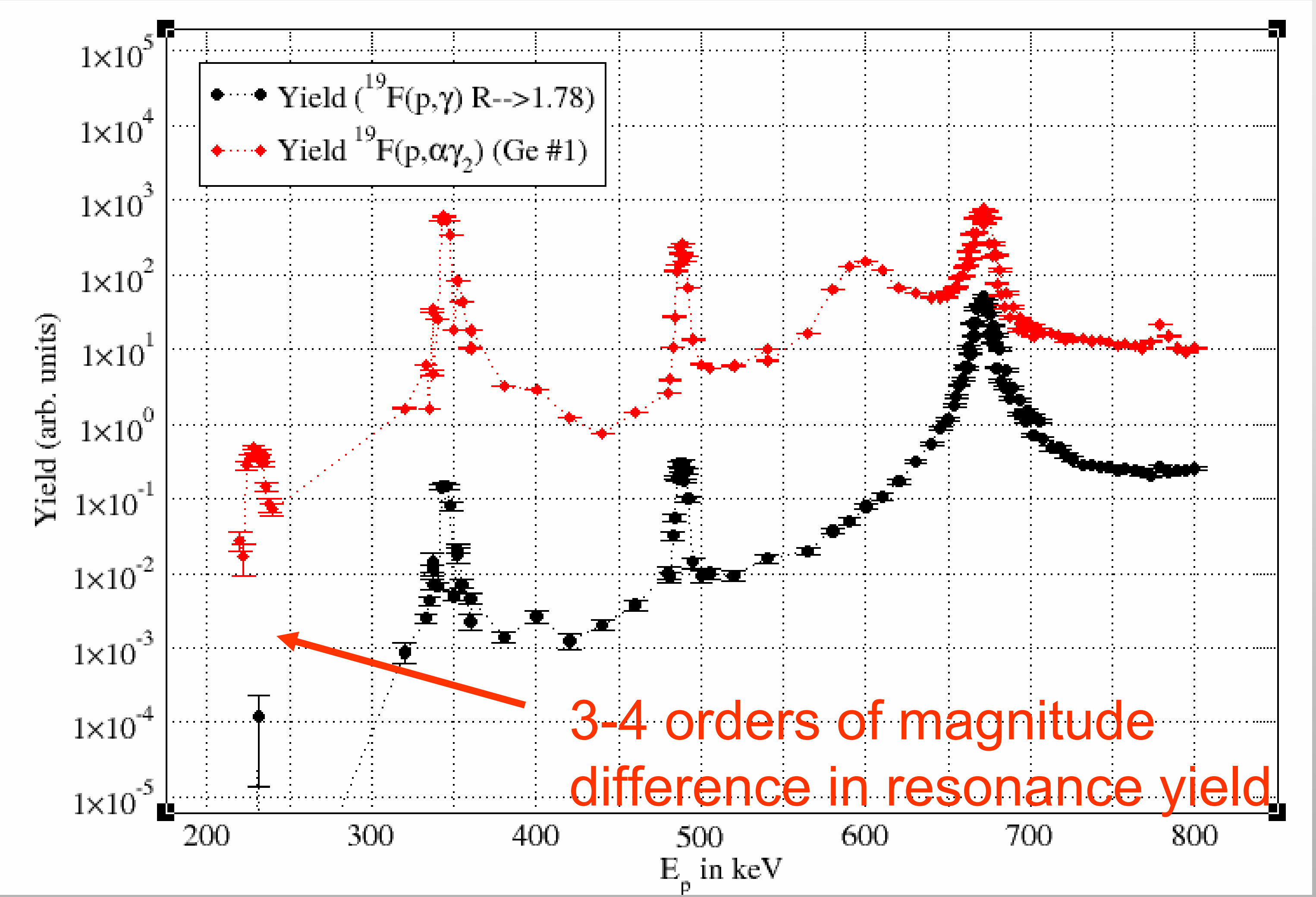
Optimized detector design



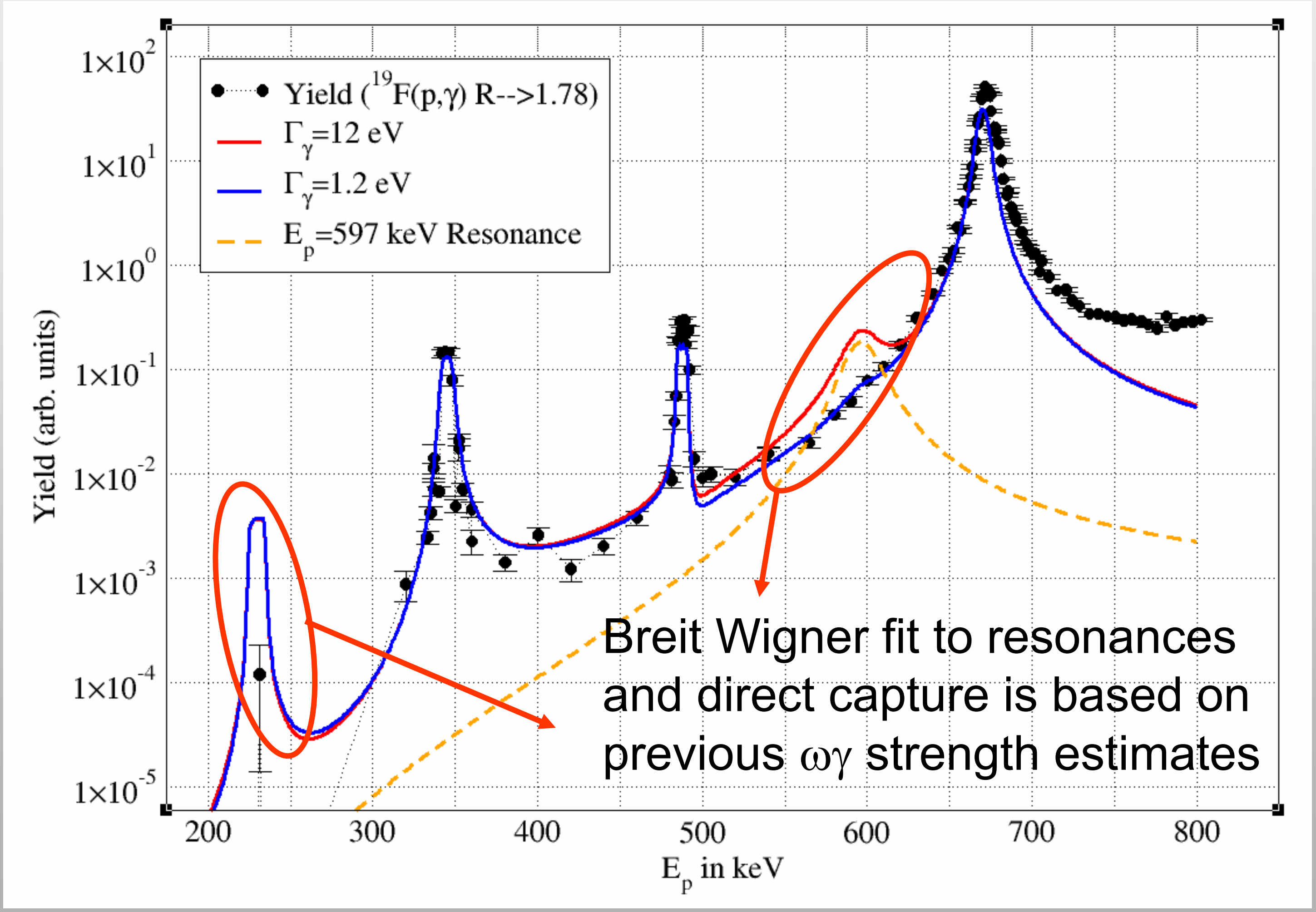




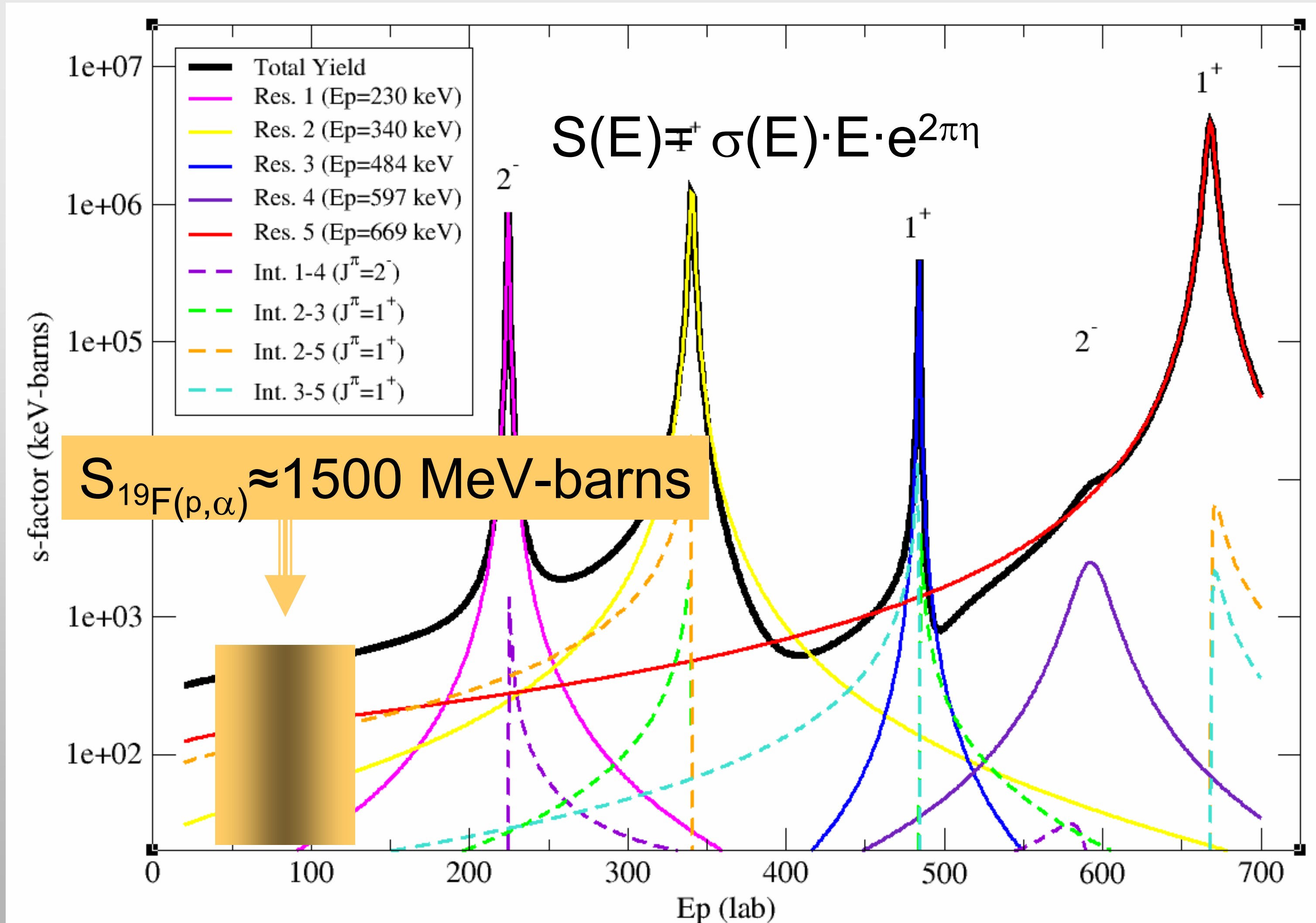
Yield Curve for $^{19}F(p,\alpha\gamma)$ and $^{19}F(p,\gamma)$



$^{19}F(p,\gamma)^{20}Ne$ excitation curve & extrapolation to stellar energies

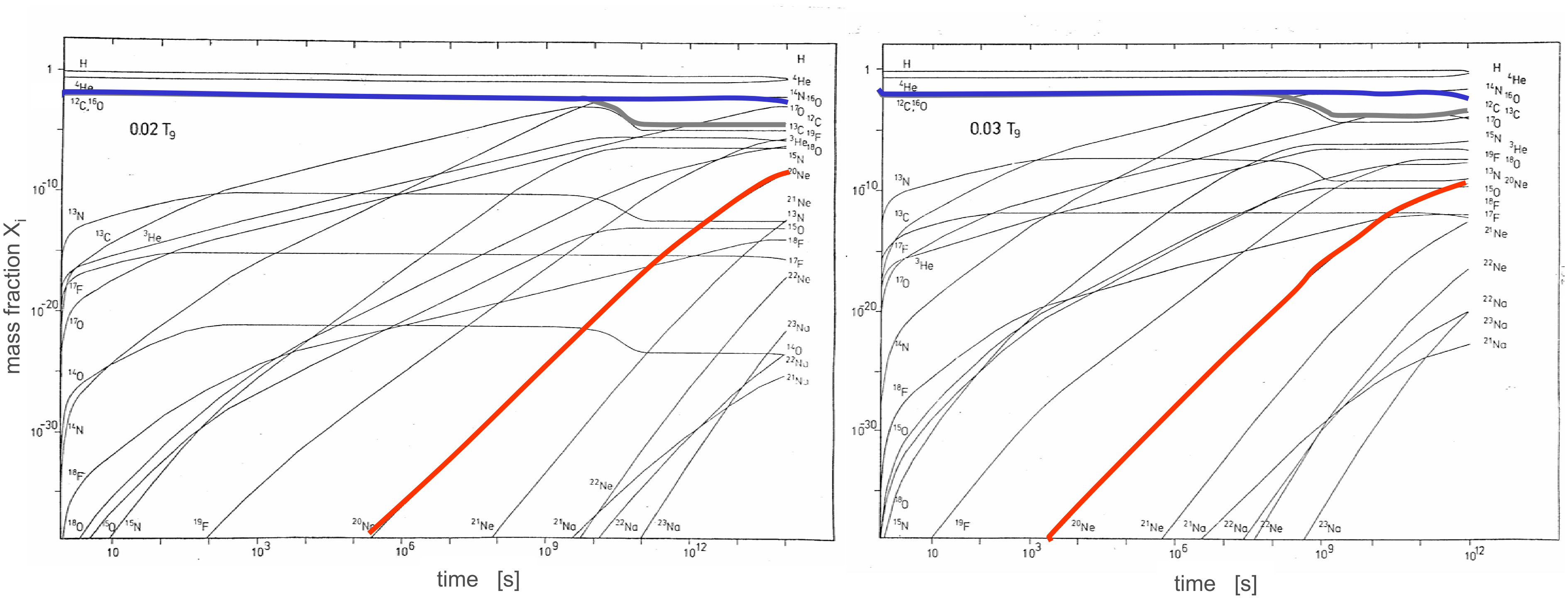


S-factor curve



ΔE_G = 30 -120 keV

Leakage from cold CNO cycles



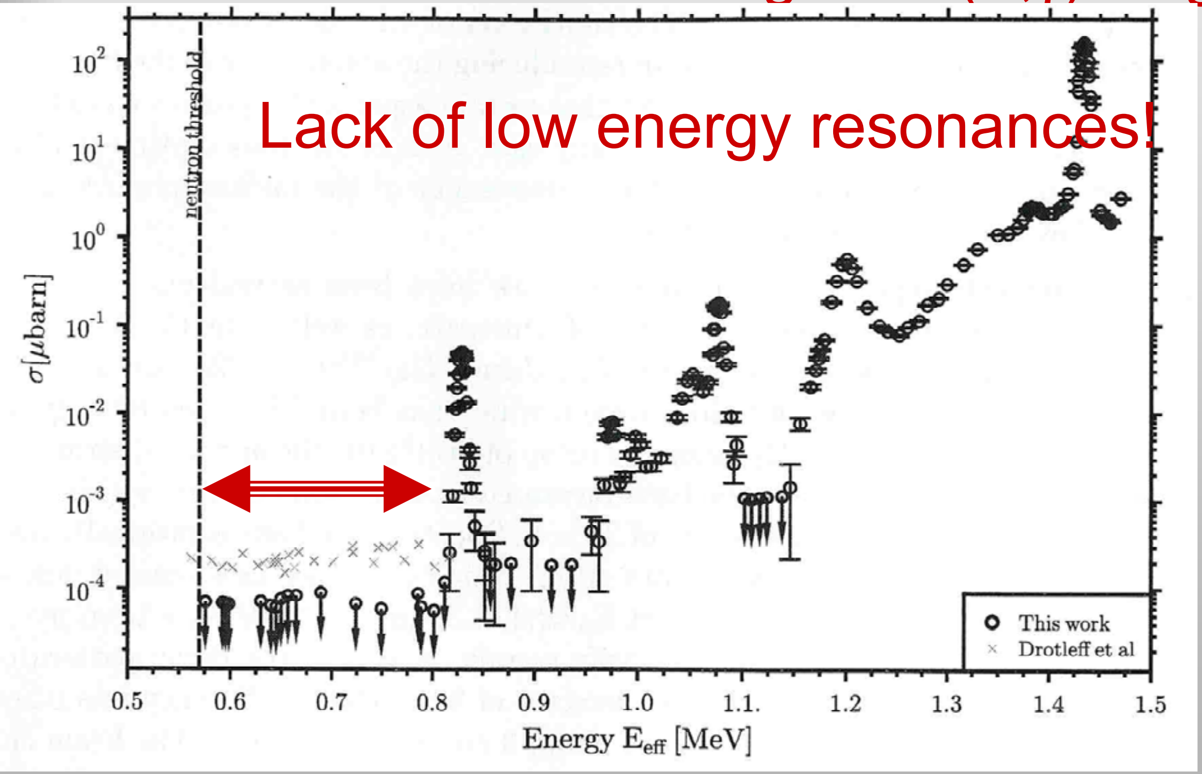
Losses towards Ne-Na mass range are negligible
Over the entire period of stellar hydrogen burning

Challenges in He-burning

$^{12}C(\alpha,\gamma)^{16}O$ – a challenge since 40 years

But also reactions like $^{18}O(\alpha,\gamma)^{22}Ne$ and

e.g. $^{22}Ne(\alpha,\gamma)^{26}Mg$, $^{22}Ne(\alpha,n)^{25}Mg$



The lowest observed resonance is at $E_R \approx 830$keV, but more levels known

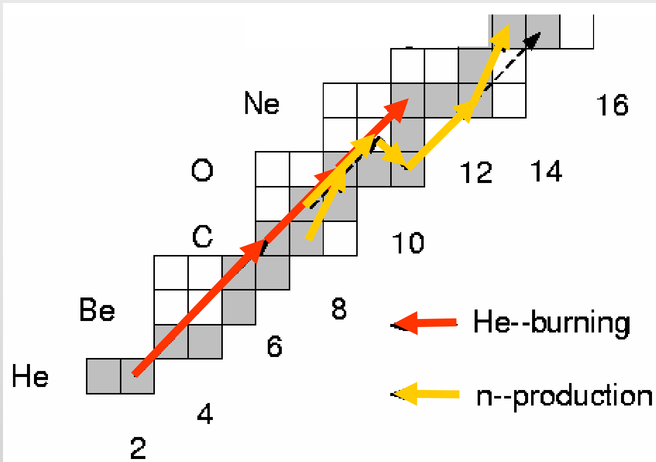
…

alpha cluster states

Low energy study would provide answer for T-dependent n-flux for weak s-process

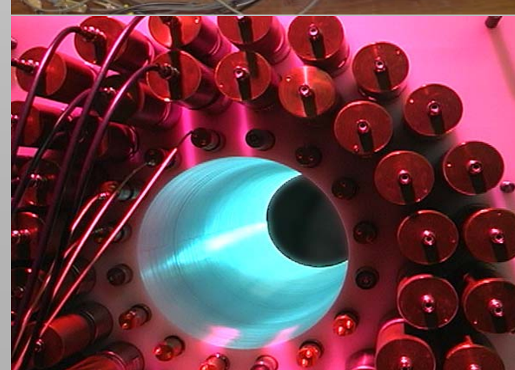
Neutron sources in stellar He burning

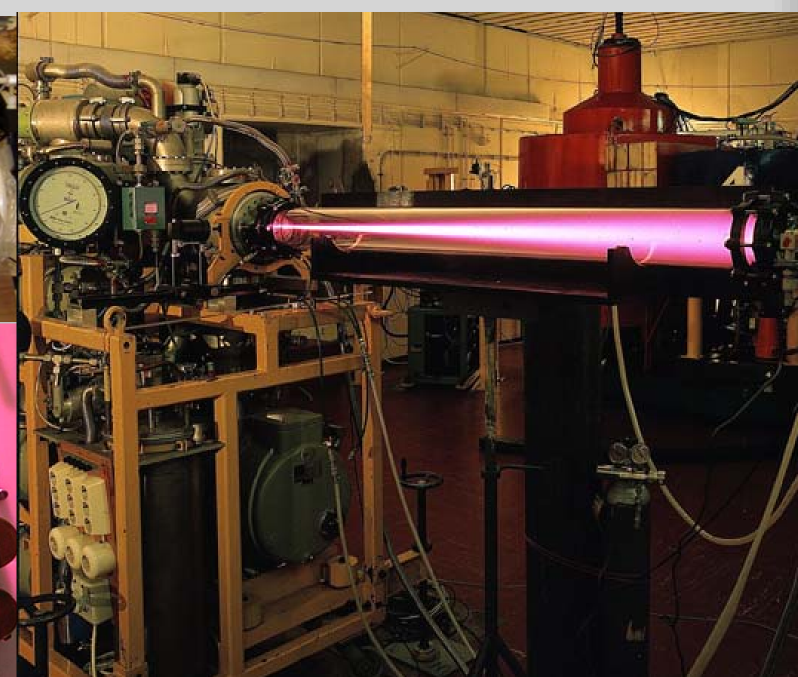
Stellar He-burning, n-sources



$^{13}C(\alpha,n)^{17}O$, $^{13}C(\alpha,\alpha)^{13}C$
Is presently being analyzed
$^{14}N(\alpha,\gamma)^{18}F$ and $^{18}O(\alpha,\gamma)^{22}Ne$
have been completed

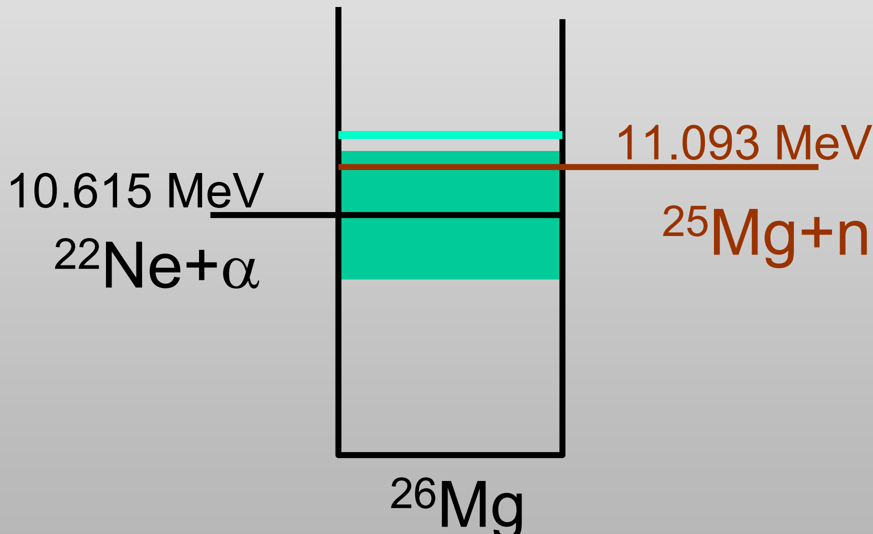
Remaining question:
$^{22}Ne(\alpha,\gamma)^{26}Mg$
$^{22}Ne(\alpha,n)^{25}Mg$
New attempt using the Rhinoceros gas target combined with improved detectors.

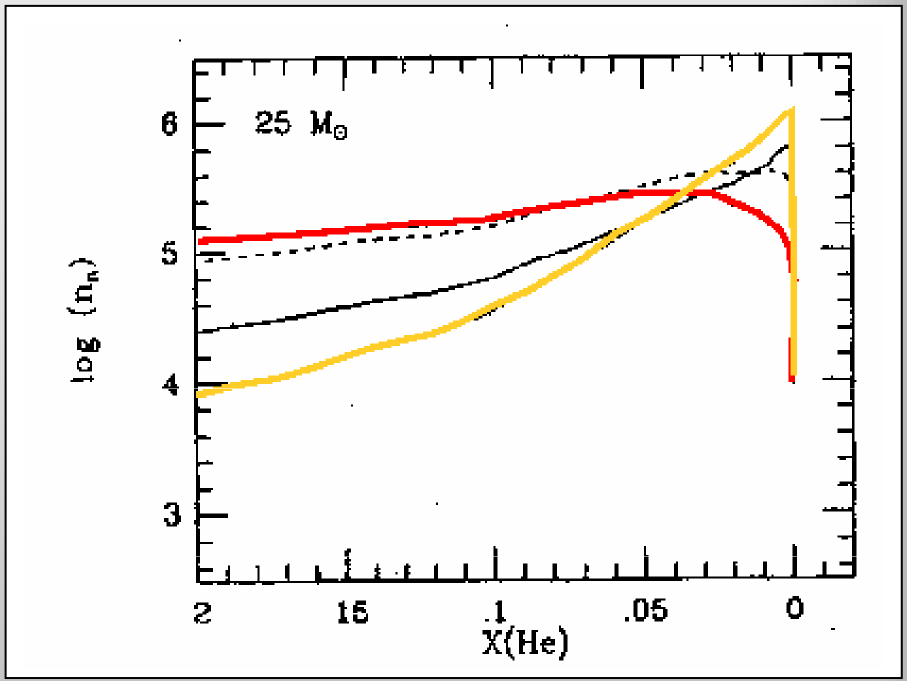




Questions in ^{22}Ne+α

Strong low energy resonances in ^{22}Ne(α,n) but also strong low energy resonances in ^{22}Ne(α,γ)

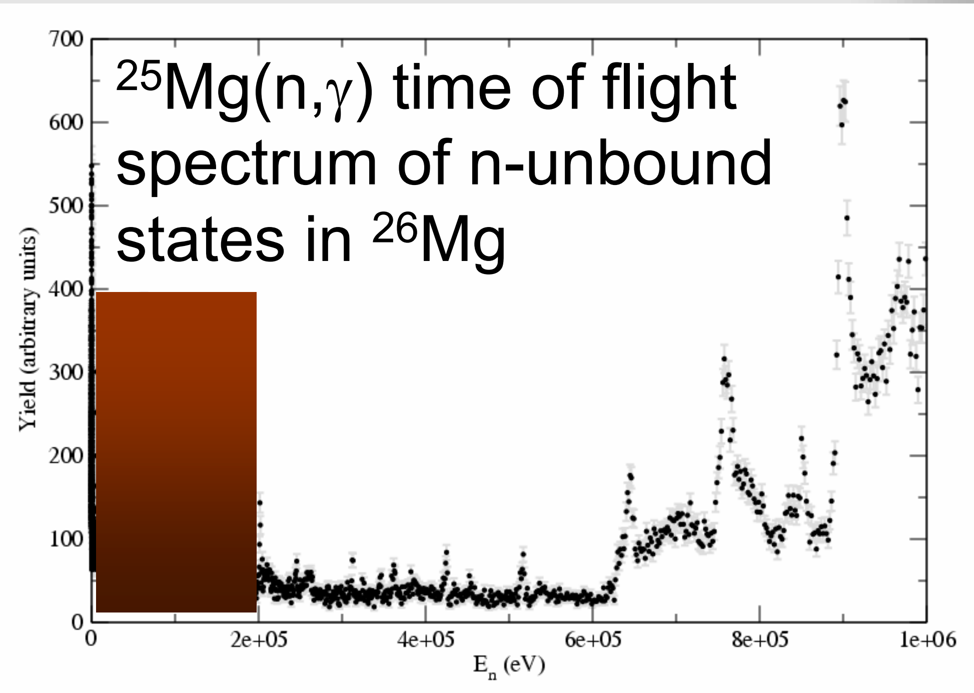




High ^{22}Ne(α,n) rate causes rapid conversion of ^{22}Ne to ^{26}Mg - ^{26}Mg(α,n) as n-source?

n-capture measurements at n-ToF

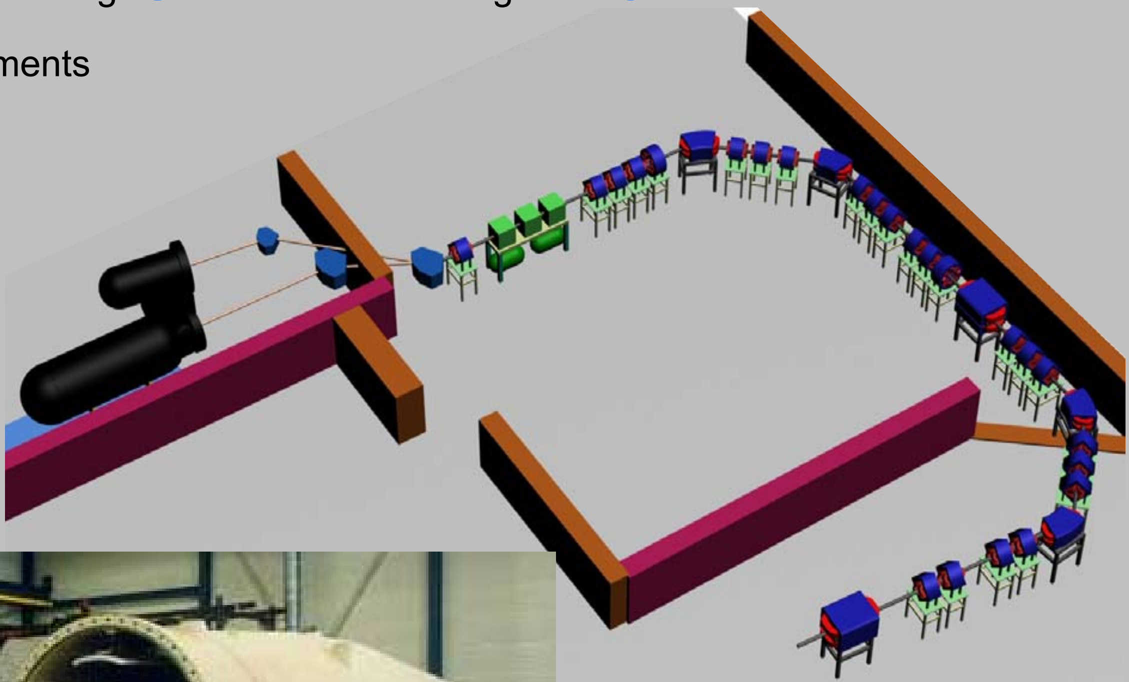
Lead spallation target at CERN ps-booster ring white n-source with ~150 m flight path



Several n-unbound states below the lowest resonance level in ^{22}Ne+α observed, more direct measurements are needed!

Future developments

St. George Separator - STrong Gradient Electromagnetic Online Recoil separator for capture Gamma ray Experiments



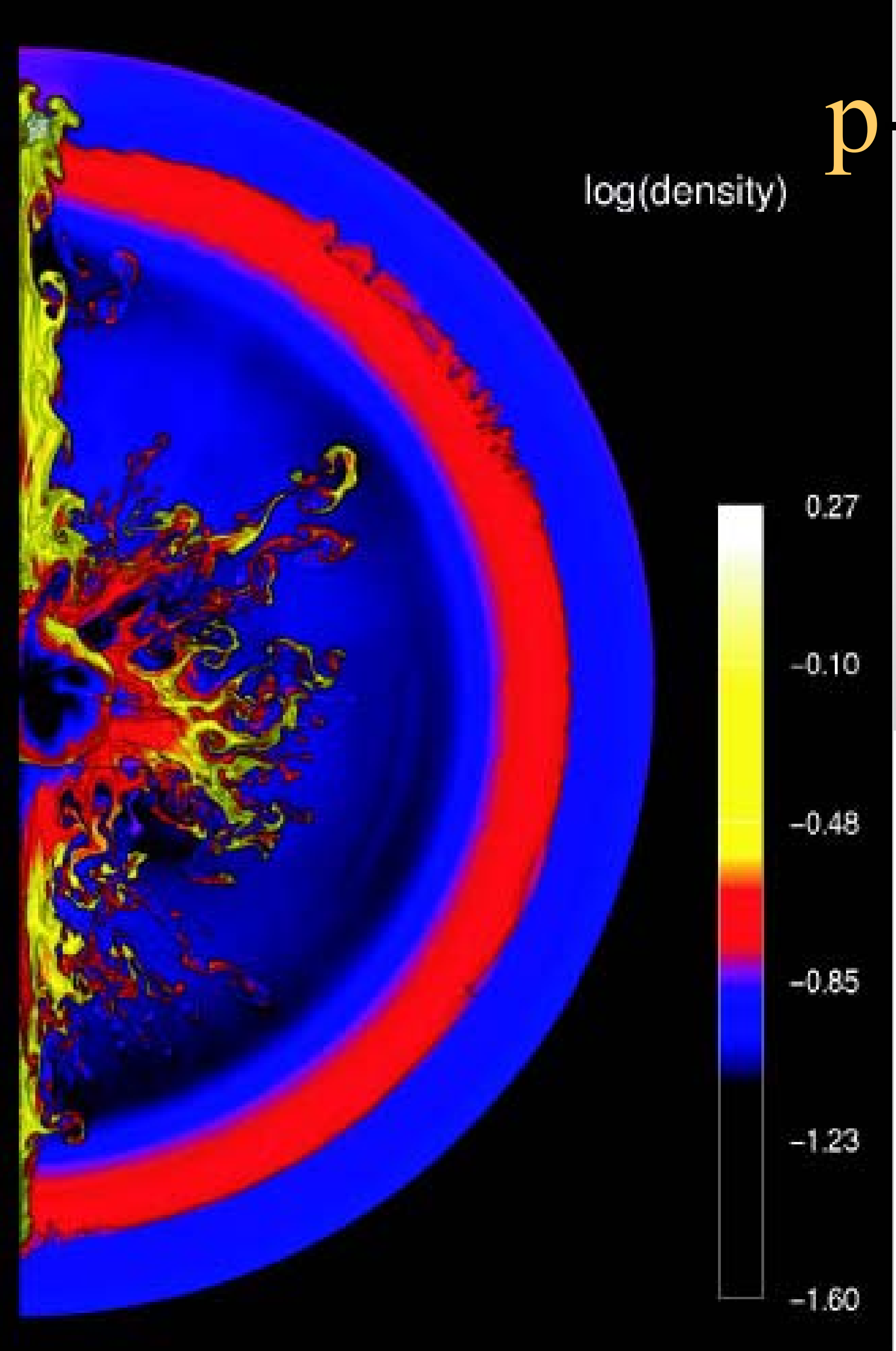
Background Reduction

- Inverse kinematics
- DUSEL underground

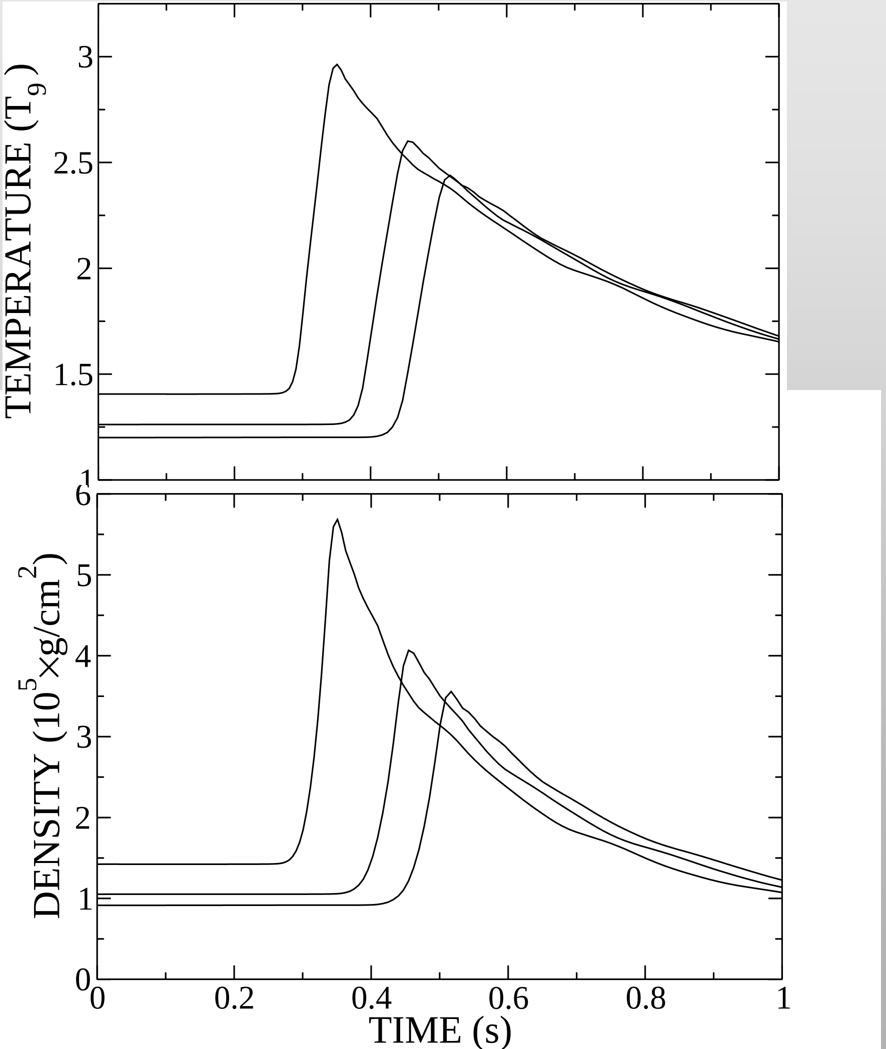
Present accelerators need replacement with 6 MV Singletron

Stable beam Accelerator for Nuclear Astrophysics (St. Ana)

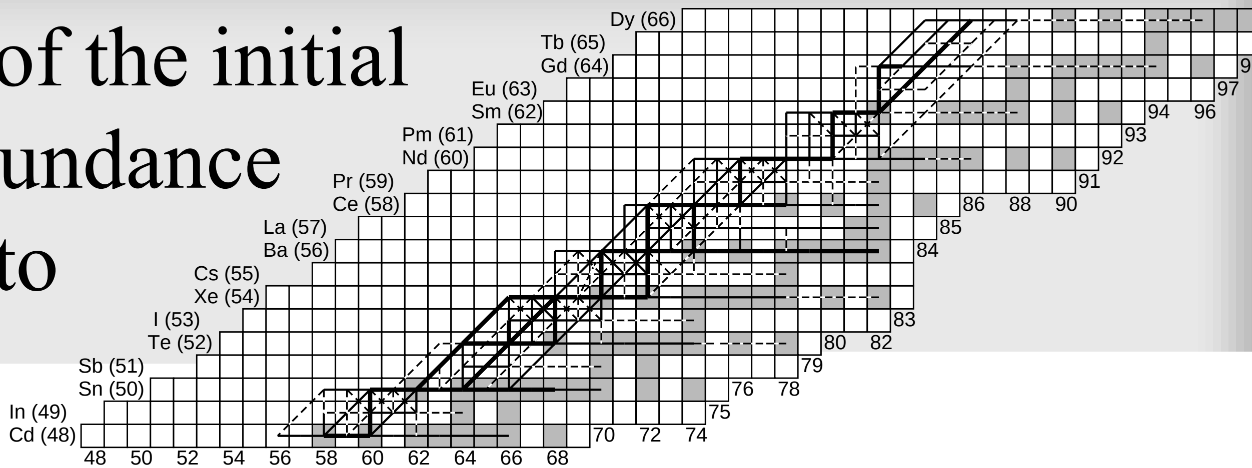
p-process

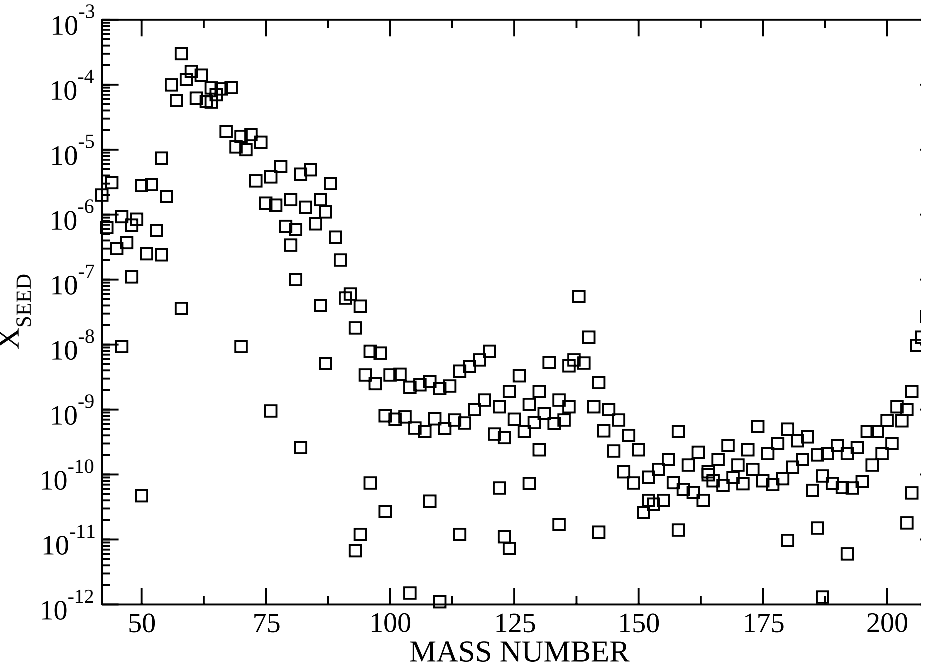


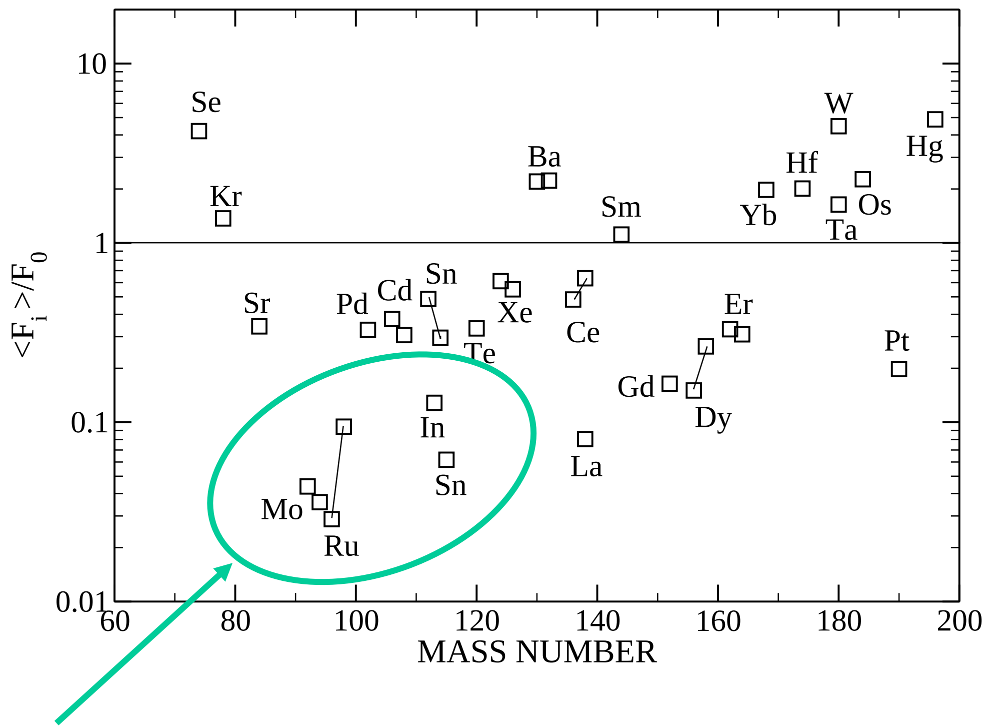
High γ-flux in the O/Ne zone of pre-supernova star



Conversion of the initial s-process abundance distribution to p-nuclei



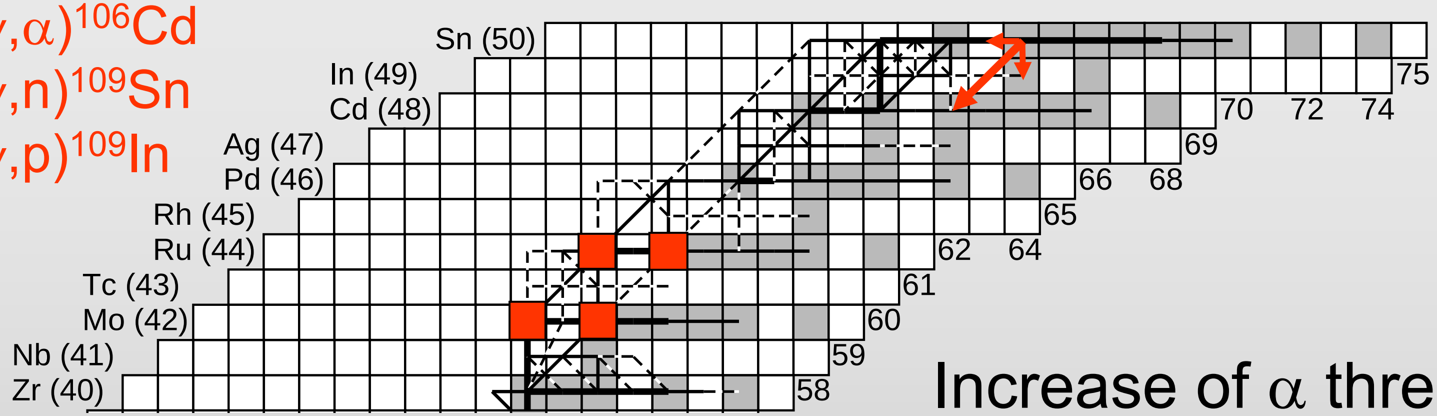




Light p-Nuclei

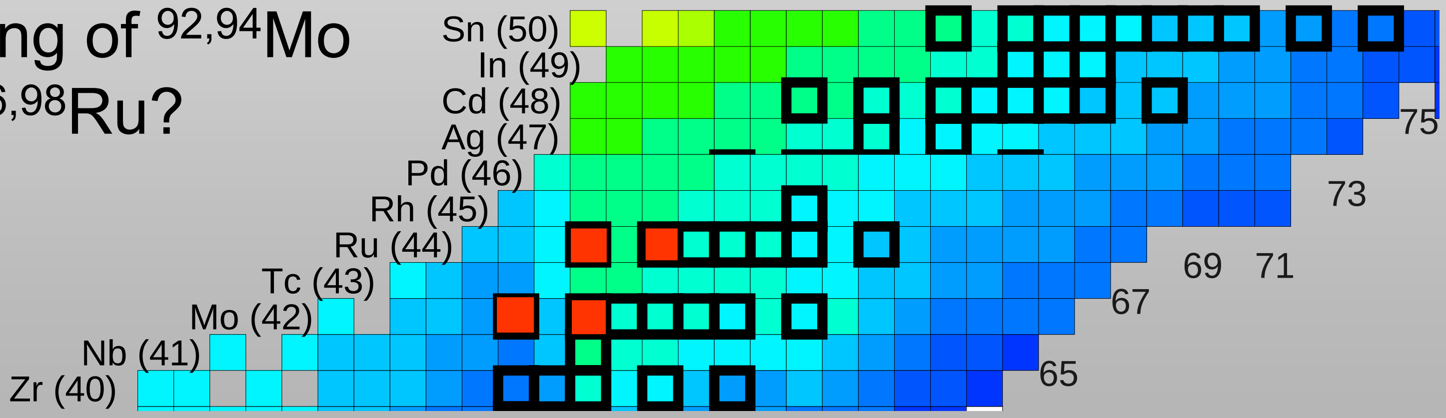
The (γ,α) photodisintegration

$^{110}Sn(\gamma,\alpha)^{106}Cd$
$^{110}Sn(\gamma,n)^{109}Sn$
$^{110}Sn(\gamma,p)^{109}In$



Increase of α threshold near Z,N=50 changes p-process flow pattern

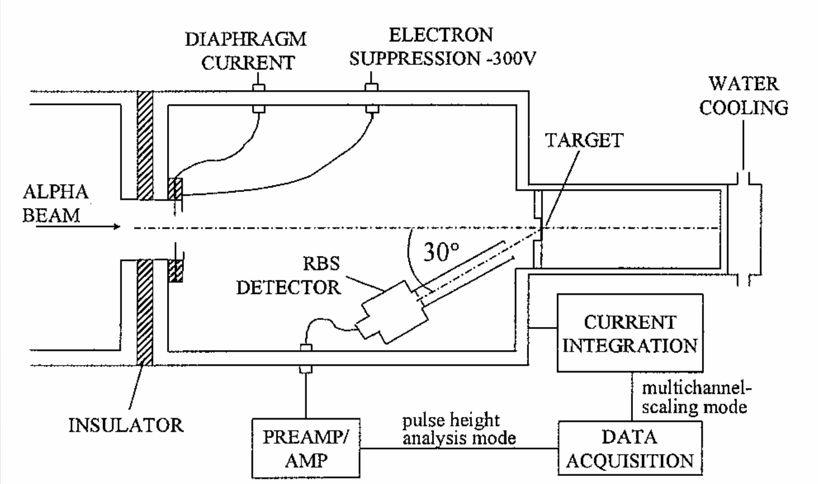
Feeding of ^{92,94}Mo and ^{96,98}Ru?

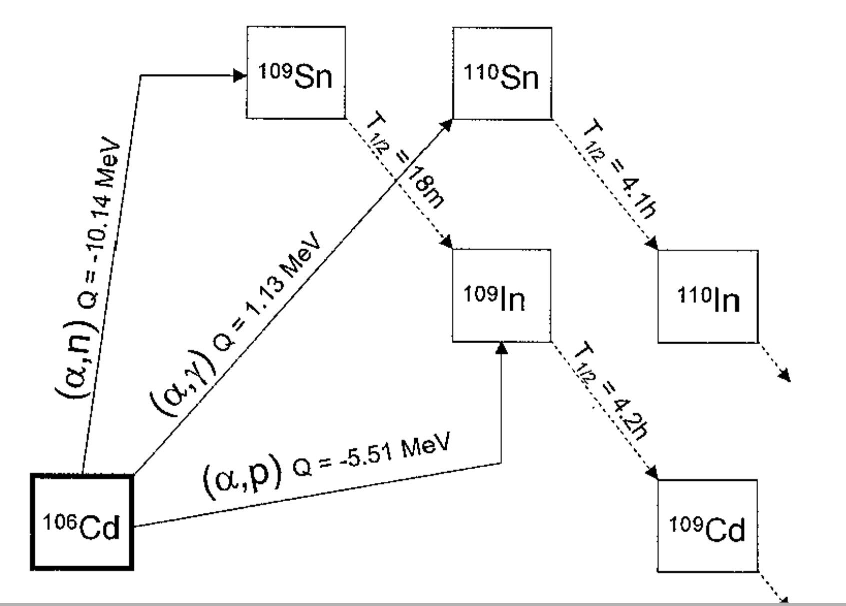


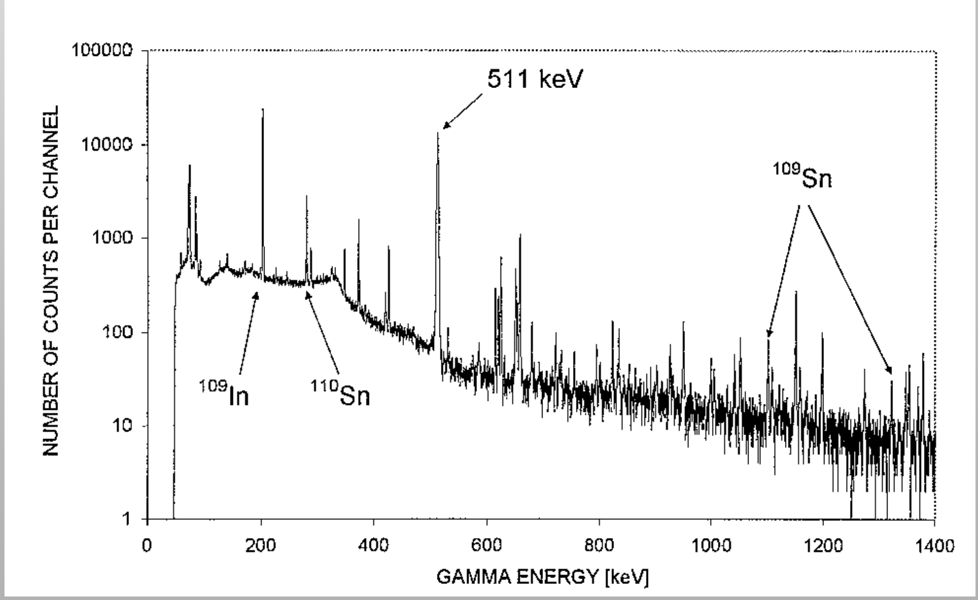
Measurement by Activation Technique

$^{106}Cd(\alpha,\gamma)^{110}Sn$; Q=1.258 MeV
$^{106}Cd(\alpha,n)^{109}Sn$; Q= - 10.144 MeV
$^{106}Cd(\alpha,p)^{109}In$; Q= -5.512 MeV

E_α= 8 -14 MeV

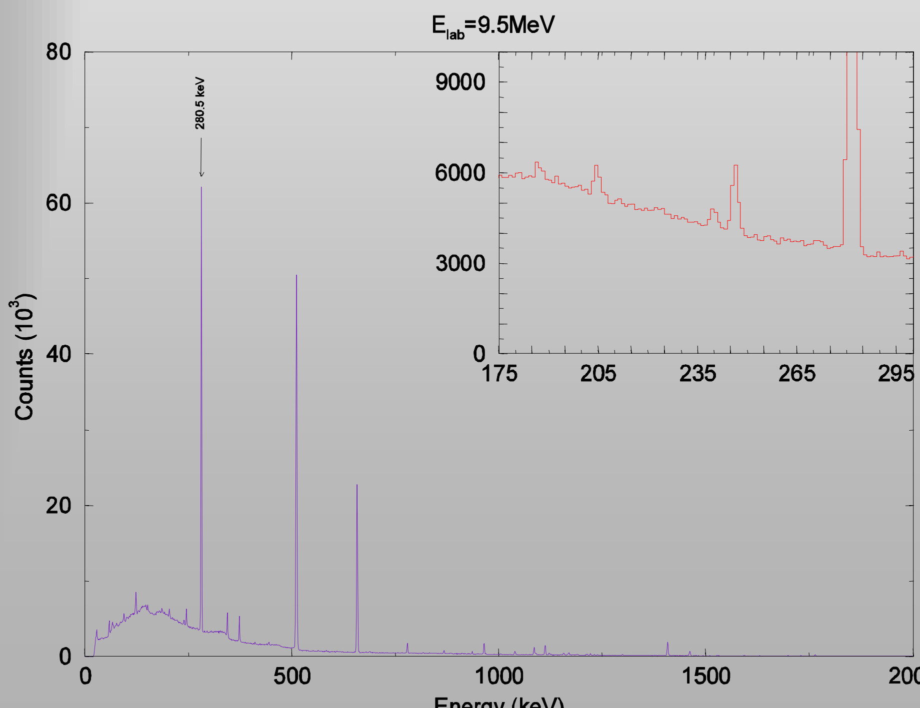


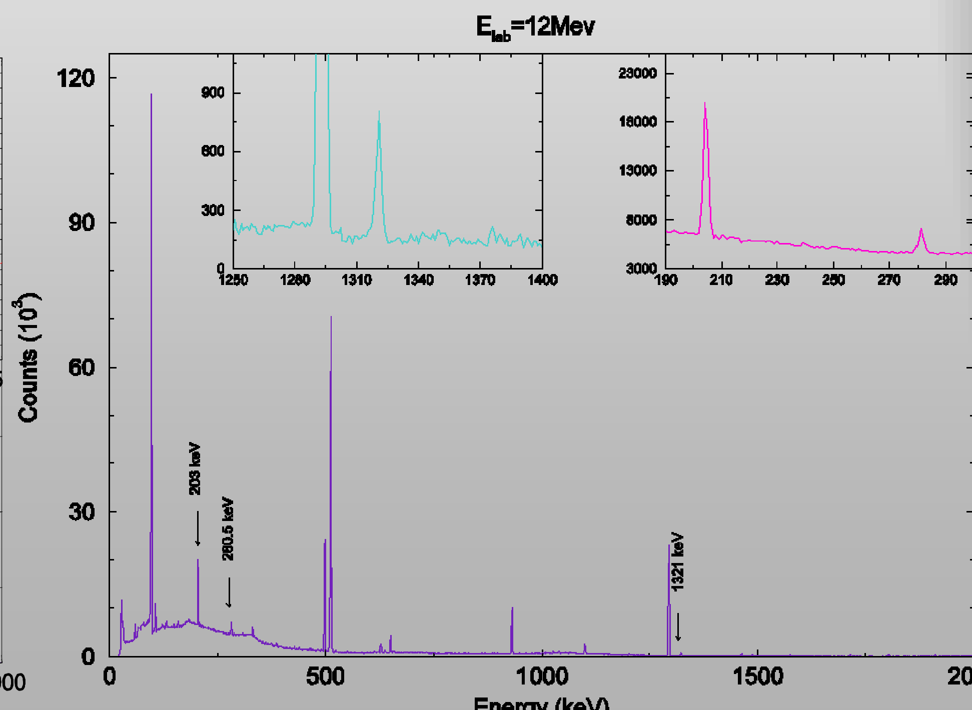




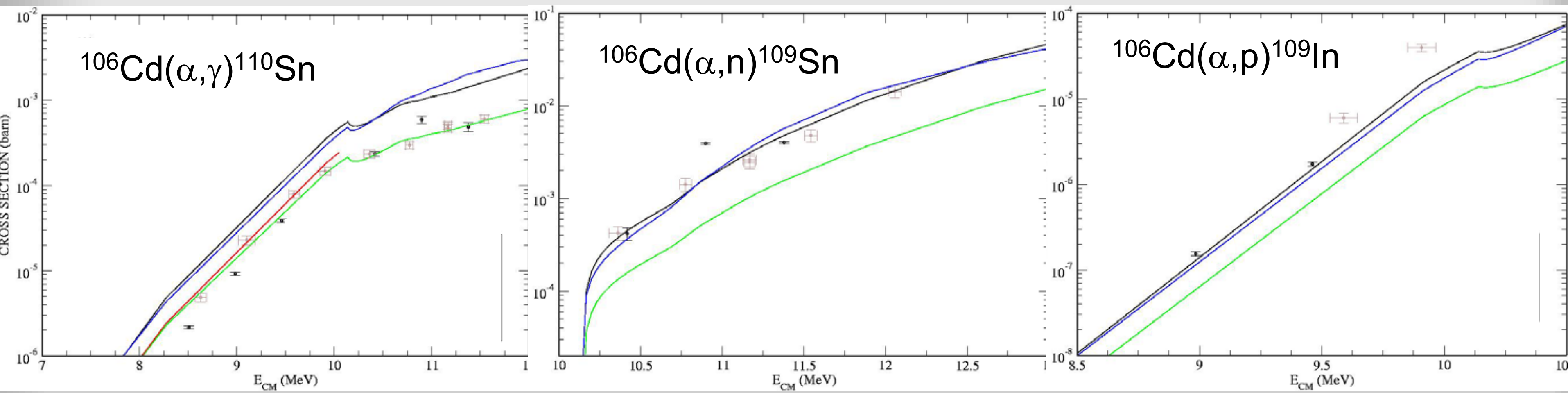
Counting Facility

Two Ge-clover detector array





Excitation curves in comparison with Hauser Feshbach model predictions



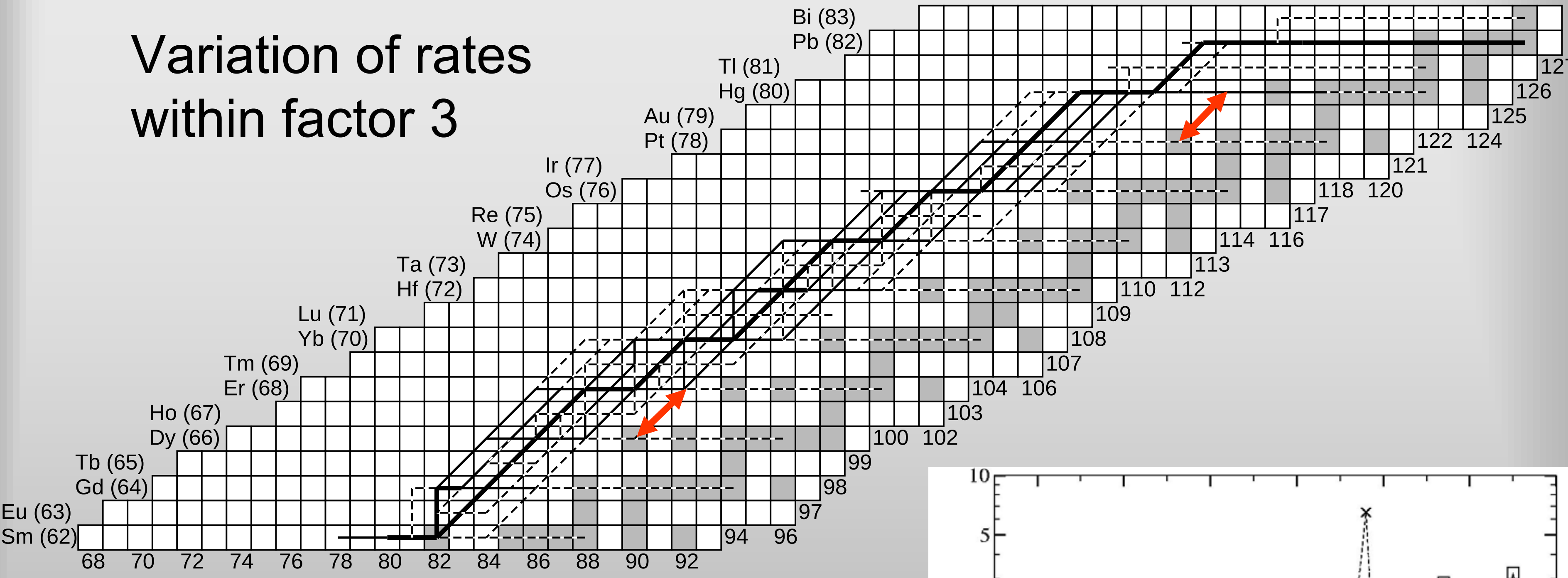
Considerable deviations between different HF models and observed cross sections.

Future activities: p-process simulations defined key reactions

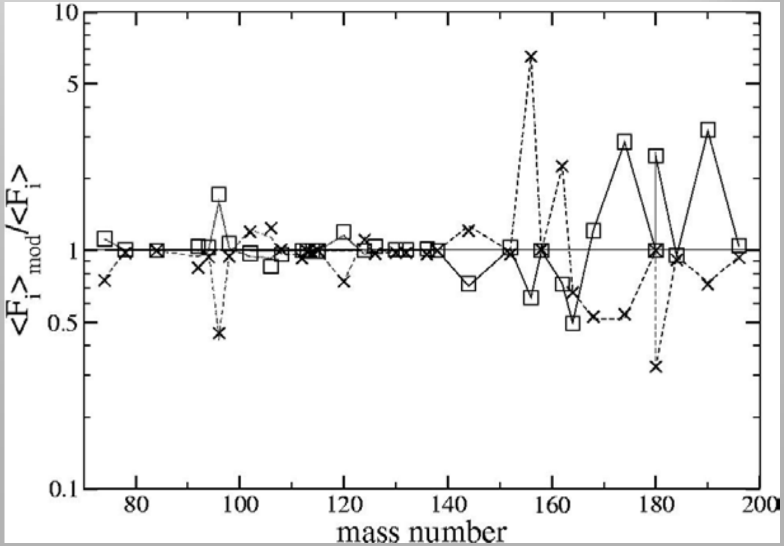
- ❑ Coulomb break-up on RIB p-nuclei
- ❑ (α,γ) on p-nuclei … AMS method

p-process simulations

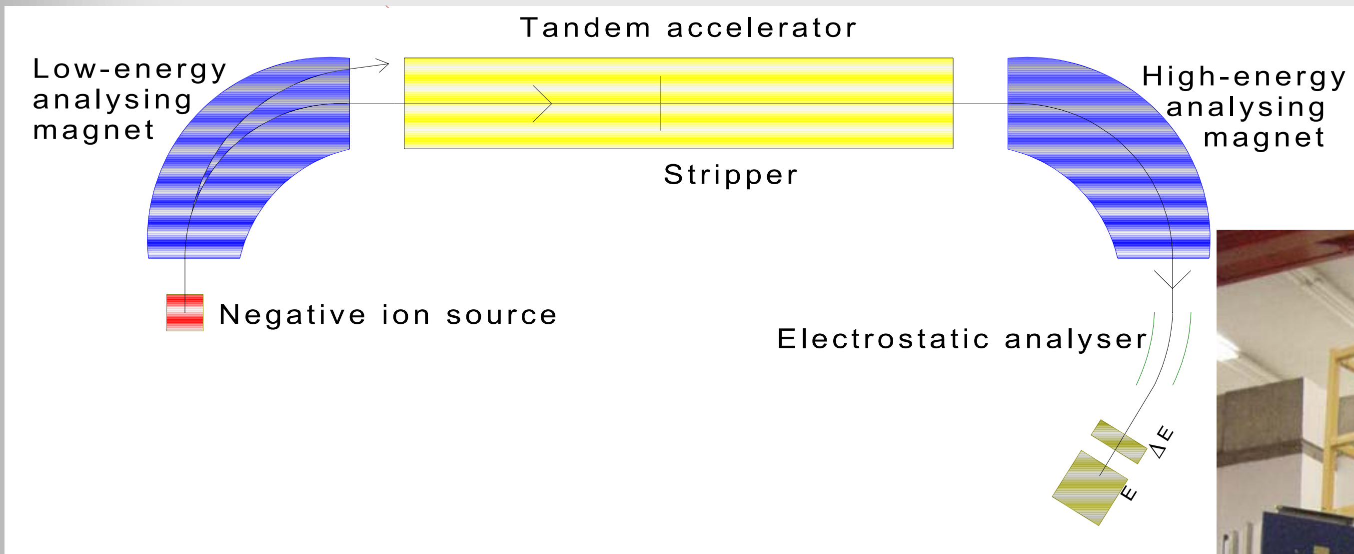
Variation of rates within factor 3



Impact of changes in (γ,α) rates mainly visible in upper mass range activation technique not possible



AMS technique



If reaction products have no or only weak characteristic decay activity, AMS methods can be applied to separate (radioactive reaction products: examples:

$^{156}Dy(\alpha,\gamma)$ ^{160}Er or

^{190}Pt $(\alpha,\gamma)^{160}Hg$ et al.

additional projects

- Spectroscopy of threshold levels with TwinSol $^{15}O(\alpha,\gamma)^{19}Ne$
- Alpha cluster states in He-burning and αp-process
- neutron sources in SN shock-front
- Heavy ion fusion studies at sub-Coulomb energies $^{12}C+^{12}C$
  Collaboration: ND, York (UK), Edinburgh (UK), ININ (Mexico)
- s-process branching points
  n-ToF collaboration
- Development of recoil separator St. George (JINA)
- Development of AMS for p-process (Collon)

Summary

Nuclear Astrophysics projects at ND are focused on nucleosynthesis processes near stability:

- Stellar hydrogen burning in CNO and NeNa range
- Stellar helium burning (neutron sources)
- Novae, hot CNO cycles and αp-process
- p-process nucleosynthesis
- s-process nucleosynthesis (n-ToF)
- rp-process nucleosynthesis (LLN, NSCL)