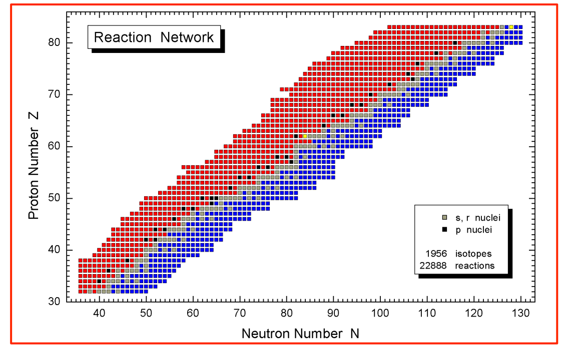
p process: Overview and status of experimental efforts

Artemis Spyrou
National Superconducting Cyclotron Laboratory
Michigan State University

NSCL SuN

Overview

- p-process
- Uncertainties – Sensitivity studies
- Important reactions

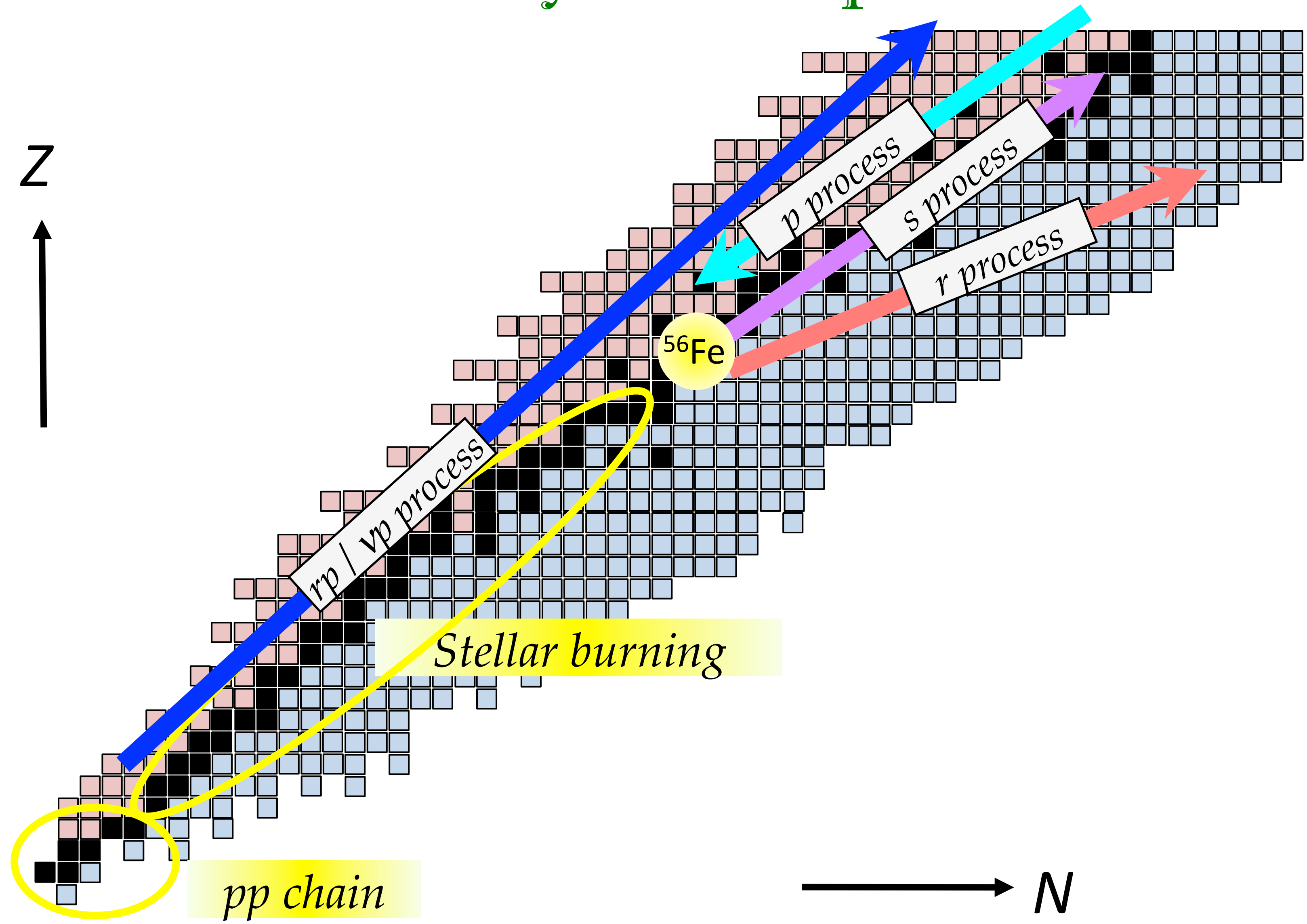


- Experimental methods
- Regular kinematics: Summing technique
- Inverse kinematics efforts
  - DRAGON
  - SuN

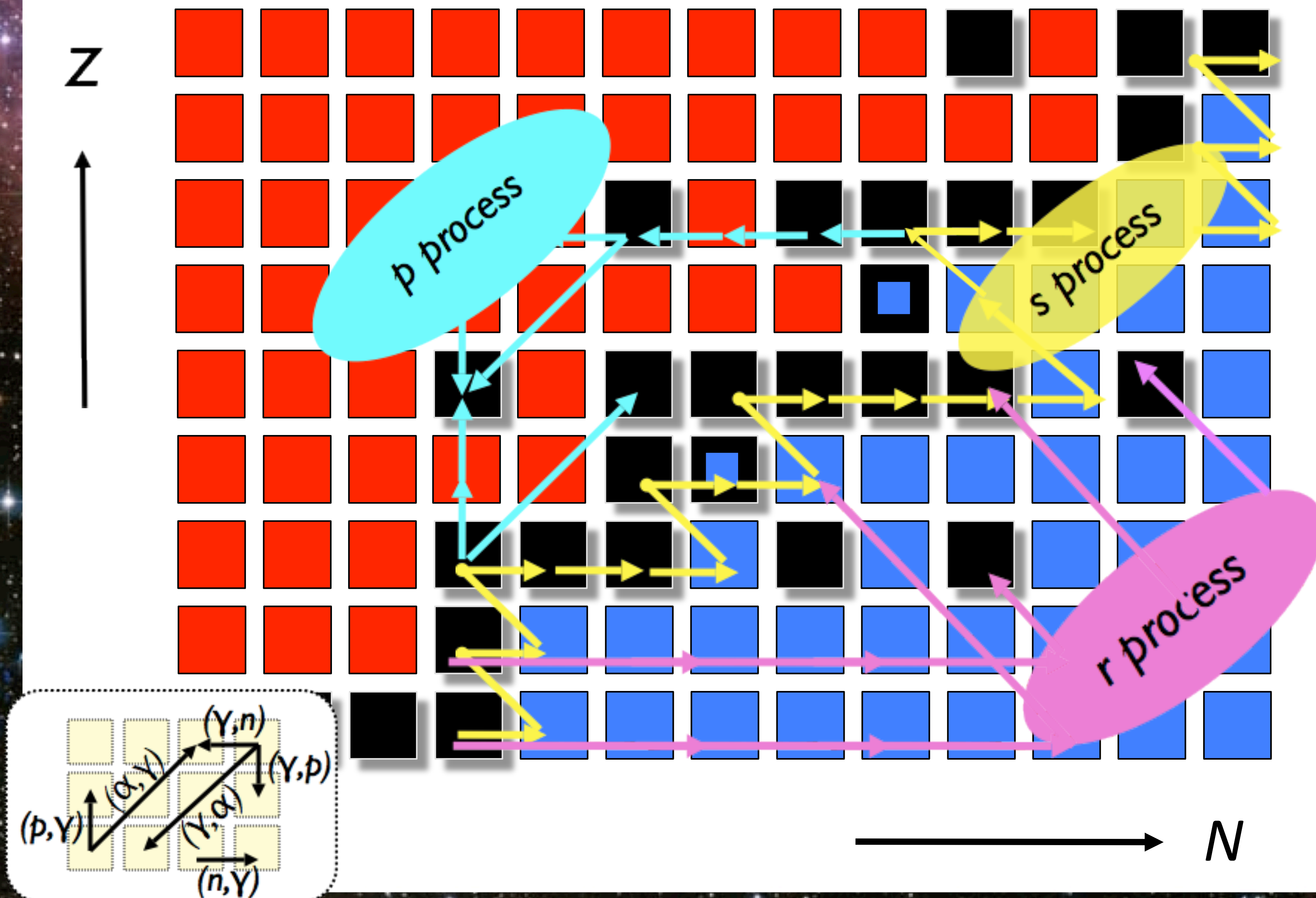
- Towards radioactive beam experiments

Review
Arnould-Goriely, Physics Report 384 (2003) 1
Rauscher et al, Rep. Prog. Phys. 76 (2013) 066201

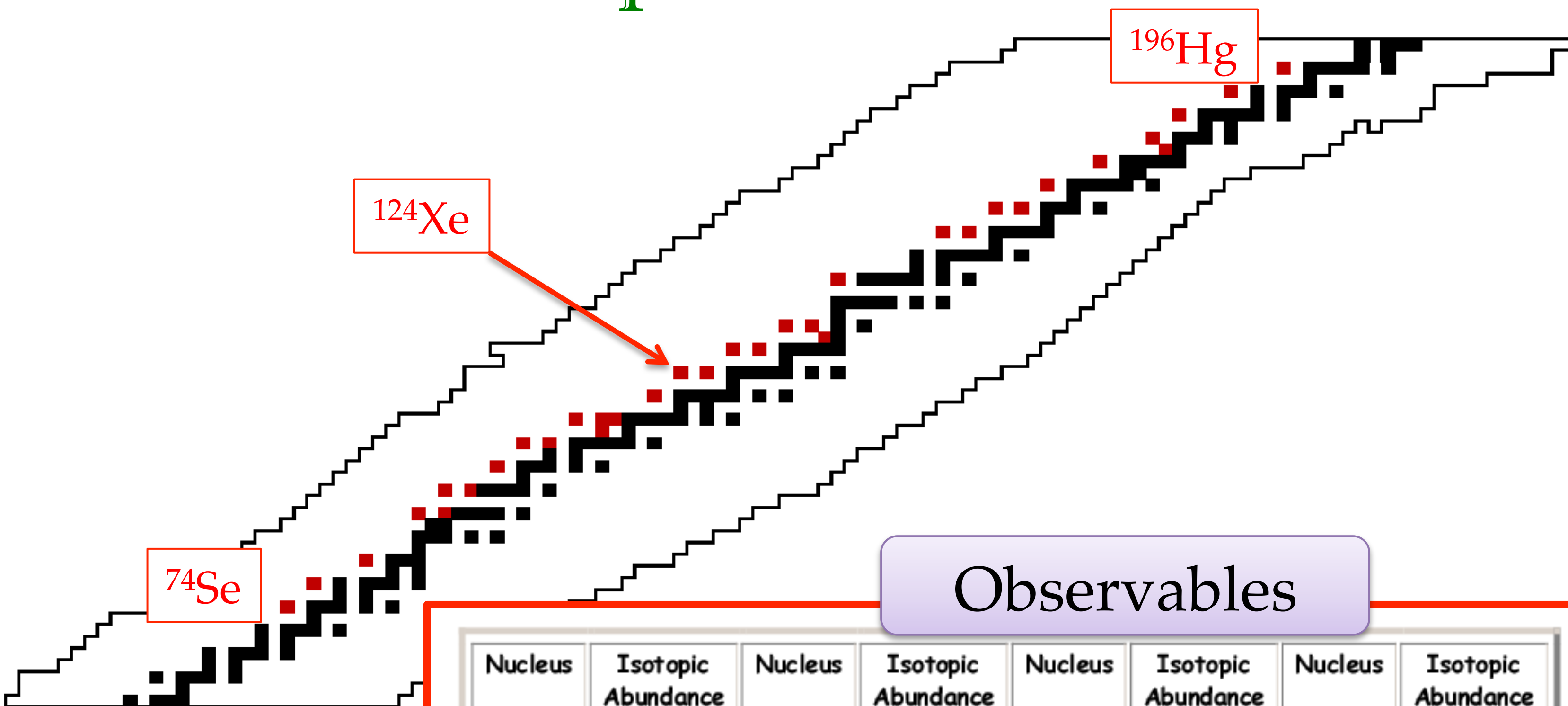
Nucleosynthesis paths



Paths beyond Iron



p nuclei



Observables

Nucleus	Isotopic Abundance (%)	Nucleus	Isotopic Abundance (%)	Nucleus	Isotopic Abundance (%)	Nucleus	Isotopic Abundance (%)
^{74}Se	0.89	^{106}Cd	1.25	^{138}La	0.0902	^{164}Er	1.61
^{76}Kr	0.35	^{112}Sn	0.97	^{136}Ce	0.19	^{168}Yb	0.13
^{84}Sr	0.56	^{115}Sn	0.34	^{138}Ce	0.25	^{174}Hf	0.162
^{92}Mo	14.84	^{120}Te	0.096	^{144}Sm	3.1	^{180}Ta	0.012
^{94}Mo	9.25	^{124}Xe	0.10	^{152}Gd	0.20	^{180}W	0.13
^{96}Ru	5.52	^{126}Xe	0.09	^{156}Dy	0.06	^{184}Os	0.02
^{98}Ru	1.88	^{130}Ba	0.106	^{158}Dy	0.10	^{190}Pt	0.01
^{102}Pd	1.02	^{132}Ba	0.101	^{162}Er	0.14	^{196}Hg	0.15

Proposed Scenarios

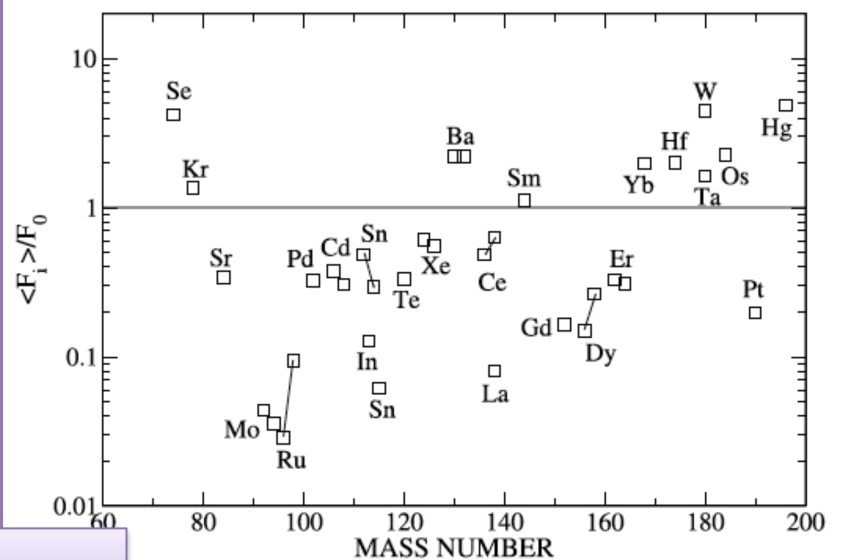
- O/Ne Layers of massive stars during the Type II SN (Most favored scenario) $1.7 \leq T_9 \leq 3.3$

Woosley & Howard 1978

Rayet 1990, 1995

Prantzos 1990

Hayakawa 2004, 2008



Rapp et al. AJ 653 (2006) 474

- Type Ia SN $1.5 \leq T_9 \leq 3.7$

Howard & Meyer 1992, Goriely 2001, Travaglio 2011

- Recently: νp-process, neutrino driven wind $1.0 \leq T_9 \leq 3.0$

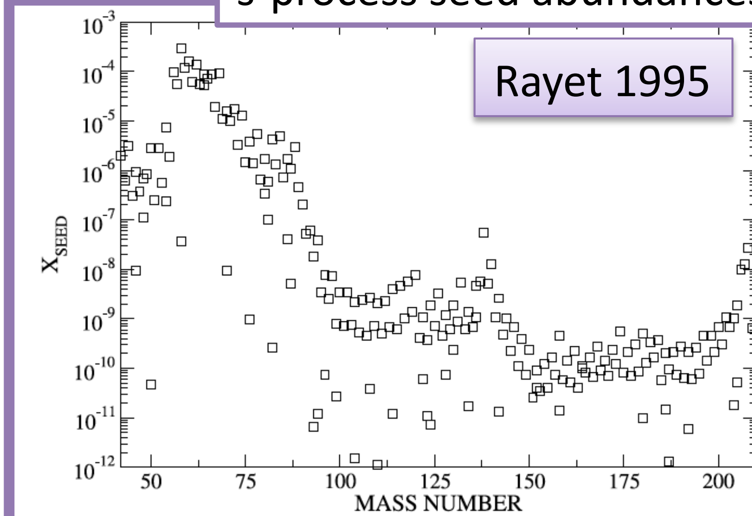
Frochlich 2006, 2012 , Wanajo 2006, 2011

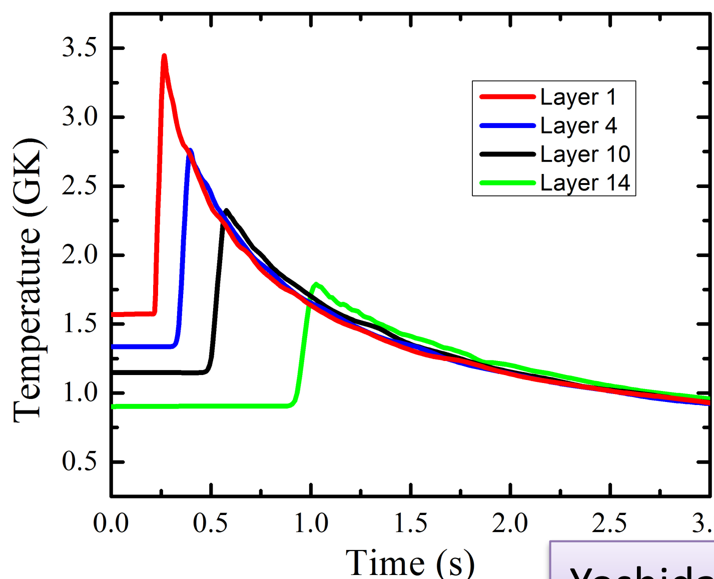
Astrophysical Input

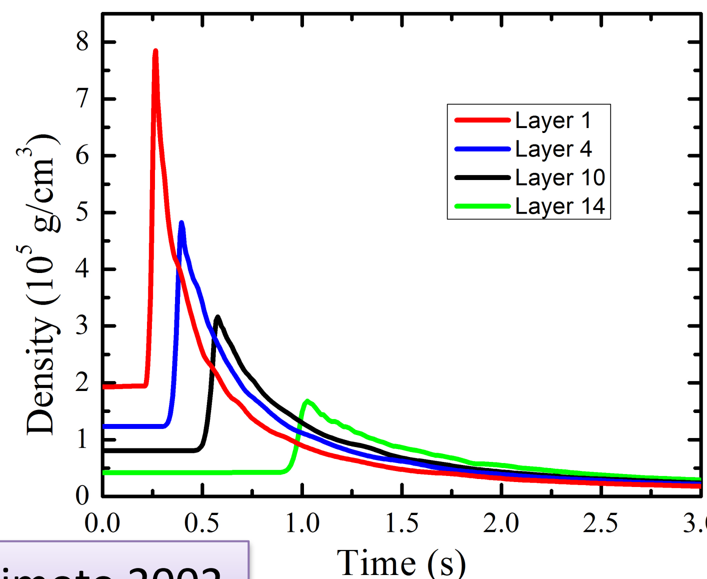
Astrophysical

- *Stellar environment*
- *Initial seed*
- *Density*
- *Temperature*
- *…*

s-process seed abundances







Yoshida & Hashimoto 2002

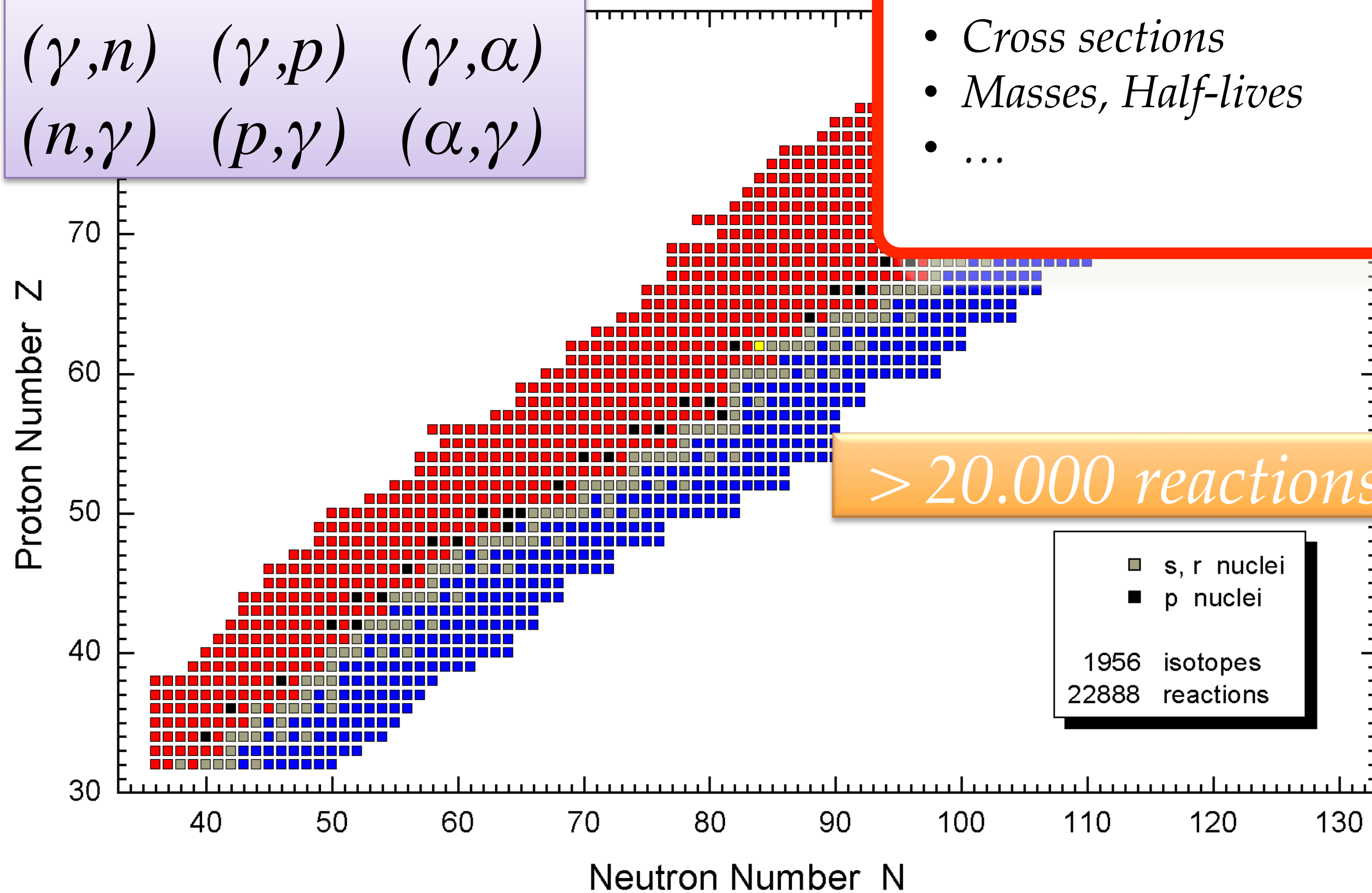
Nuclear Input

(γ,n) (γ,p) (γ,α)

(n,γ) (p,γ) (α,γ)

Nuclear

- *Reaction rates*
- *Cross sections*
- *Masses, Half-lives*
- …

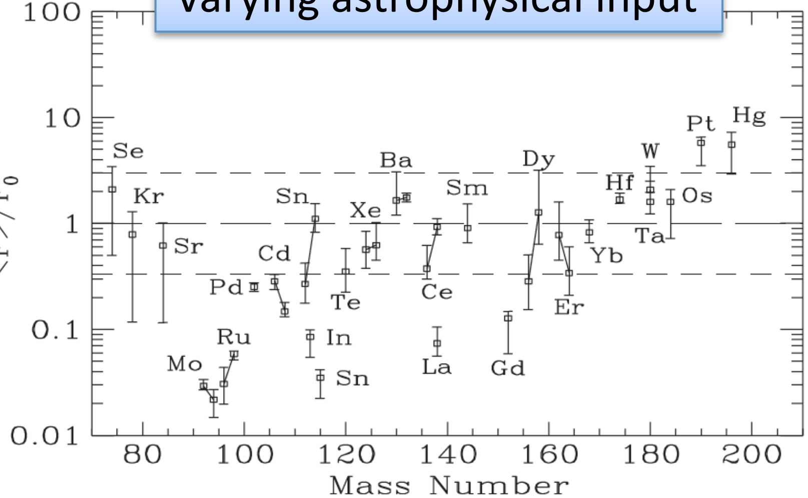


> 20.000 reactions

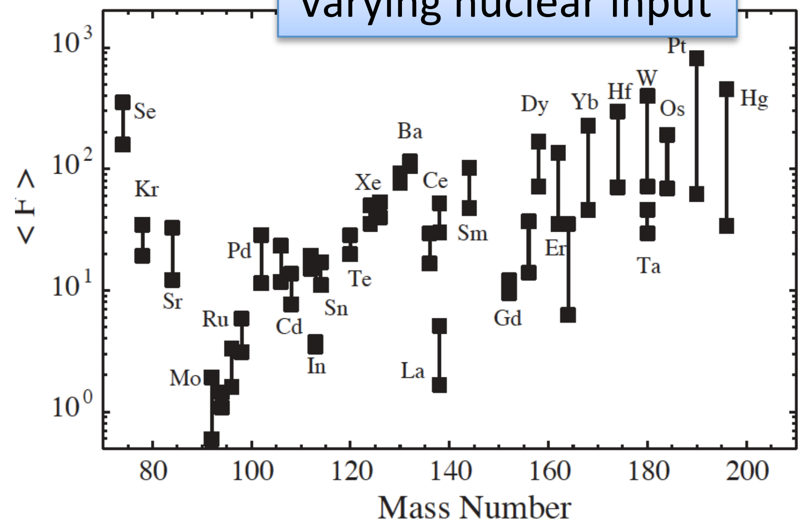
Uncertainties

Arnould – Goriely, Phys. Rep. 381 (2003) 1

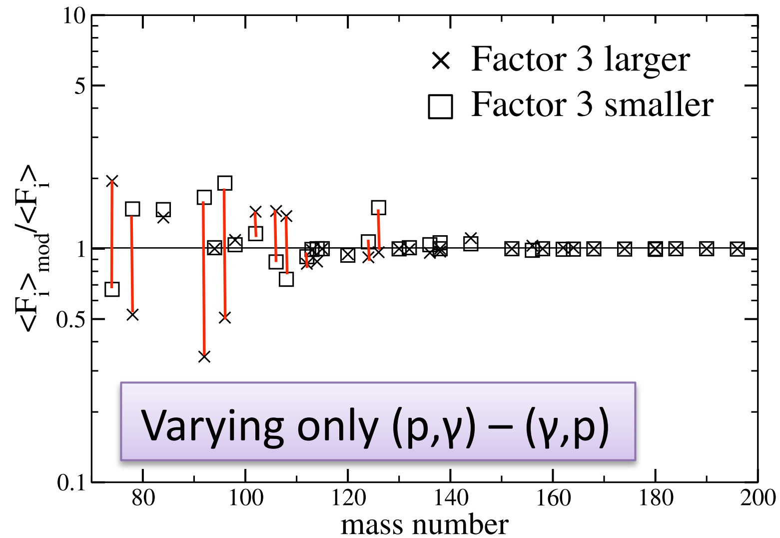
Varying astrophysical input



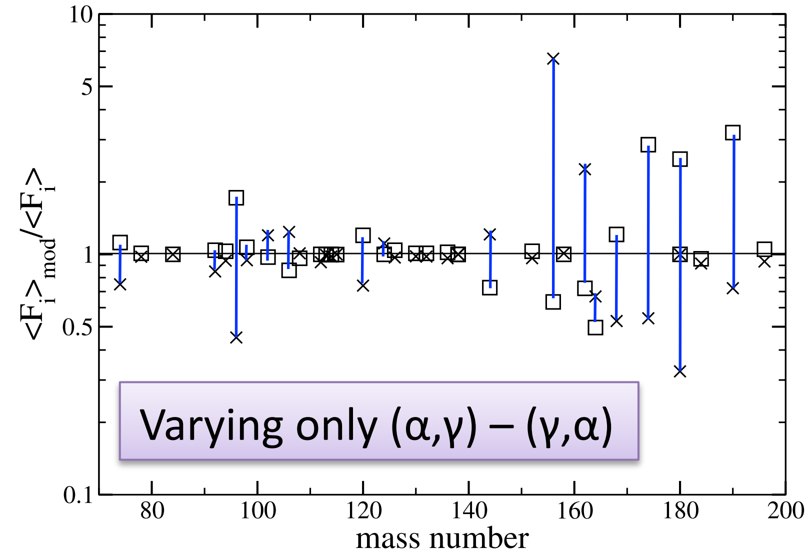
Varying nuclear input



Rapp et al. AJ 653 (2006) 474



Varying only (p,γ) – (γ,p)



Varying only (α,γ) – (γ,α)

Sensitivity studies

Only two studies in the market:

Rapp et al. AJ 653 (2006) 474

•*Type II SN explosion when shock front passes through the O/Ne layer of a* $M=25M_{\odot}$ *star*

•*Model dependent*

Rauscher et al. Phys. Rev. C 73 (2006) 015804

- *Model independent approach*
- *Reaction rate comparison*
- *Branching points*

Sensitivity studies

Rapp et al. AJ 653 (2006) 474

Reactions

^{126}Ba$(\gamma,p)^{125}$Cs*	^{92}Mo$(\gamma,p)^{91}$Nb*	^{75}Se$(n,p)^{75}$As*
^{110}Sn$(\gamma,p)^{109}$In*	^{86}Rb$(n,p)^{86}$Kr*	^{74}Se$(\gamma,p)^{73}$As*
^{106}Cd$(\gamma,p)^{105}$Ag	^{85}Sr$(n,p)^{85}$Rb*	^{76}As$(n,p)^{76}$Ge*
^{104}Cd$(\gamma,p)^{103}$Ag	^{84}Sr$(\gamma,p)^{83}$Rb*	^{75}As$(\gamma,p)^{74}$Ge*
^{100}Pd$(\gamma,p)^{99}$Rh	^{78}Kr$(\gamma,p)^{77}$Br*	^{73}As$(\gamma,p)^{72}$Ge
^{96}Ru$(\gamma,p)^{95}$Tc*	^{77}Se$(n,p)^{77}$As	^{71}Ge$(n,p)^{71}$Ga

Reaction Chains

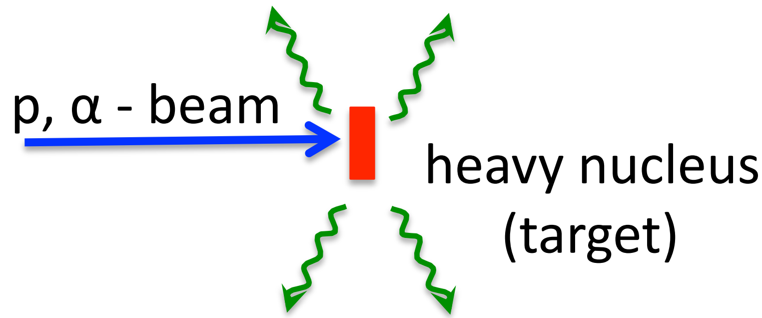
^{196}Pb$(\gamma,\alpha)^{192}$Hg*	^{166}Hf$(5\gamma,5\alpha)^{146}$Sm*
^{195}Pb$(3\gamma,3\alpha)^{183}$Os	^{156}Er$(3\gamma,3\alpha)^{144}$Sm*
^{190}Hg$(3\gamma,3\alpha)^{178}$W*	^{128}Ba$(\gamma,\alpha)^{124}$Xe
^{189}Hg$(3\gamma,3\alpha)^{177}$W	^{122}Xe$(\gamma,\alpha)^{118}$Te
^{188}Hg$(5\gamma,5\alpha)^{168}$Yb*	^{120}Te$(\gamma,\alpha)^{116}$Sn*
^{183}Pt$(3\gamma,3\alpha)^{171}$Hf	^{110}Sn$(\gamma,\alpha)^{106}$Cd*
^{178}Os$(4\gamma,4\alpha)^{162}$Er*	^{106}Cd$(\gamma,\alpha)^{102}$Pd
^{177}Os$(3\gamma,3\alpha)^{165}$Yb	^{96}Ru$(\gamma,\alpha)^{92}$Mo*
^{176}Os$(5\gamma,5\alpha)^{156}$Dy*	^{74}Se$(\gamma,\alpha)^{70}$Ge*
^{167}Hf$(\gamma,\alpha)^{163}$Yb	

1. Need to perform new measurements with stable beams
2. Need to develop techniques for measurements with radioactive beams

(γ,p), (γ,α) vs (p,γ), (α,γ)
Often better to measure in the time reverse direction

Experimental techniques

- Regular kinematics



<u>Facilities</u>: Tandem labs (ATOMKI, Athens, Notre Dame, Cologne, Bochum, etc)

<u>Equipment</u>: Gamma-ray detectors

<u>Techniques</u>: Activation – Angular distribution – Summing

<u>Advantages:</u>

•High intensity stable beams

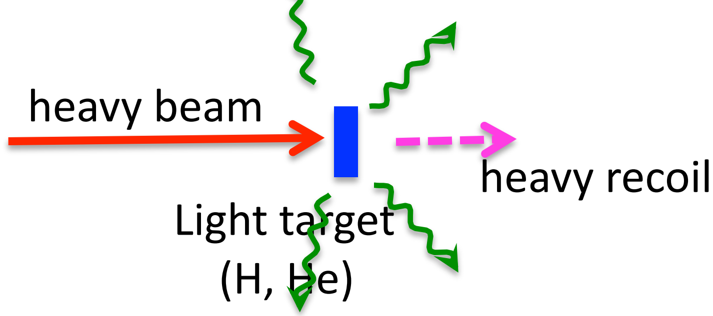
•Well developed techniques

<u>Disadvantages</u>

• Not applicable for all targets, in particular radioactive nuclei

Experimental techniques

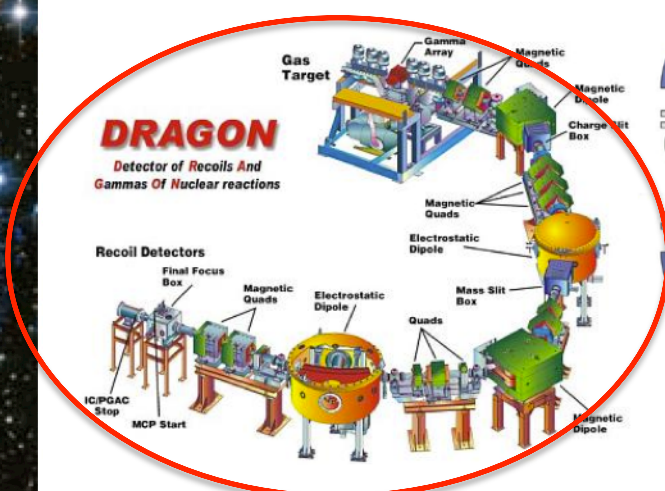
- Inverse kinematics

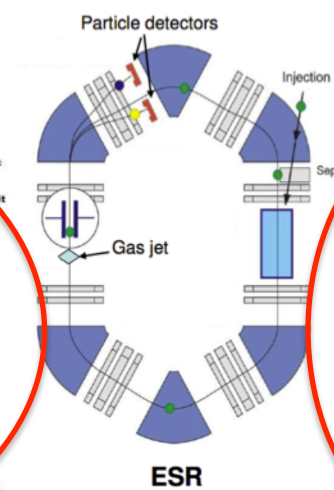


- ✓ recoil separators
- ✓ ring measurements
- ✓ γ-summing
- ✓ activation/implantation

Radioactive Beam Facilities: TRIUMF, MSU, GSI, GANIL, CERN…
Equipment: Dragon, SECAR, Storage ring, SuN, LISE, …

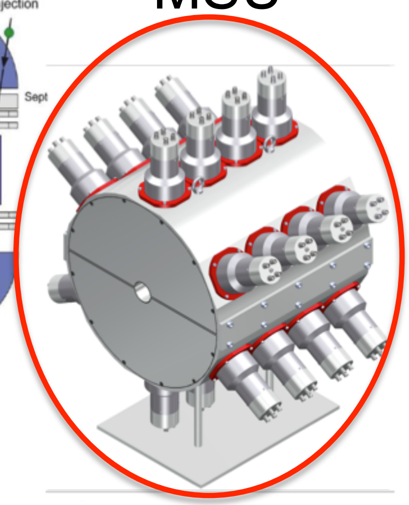
TRIUMF





GSI

MSU

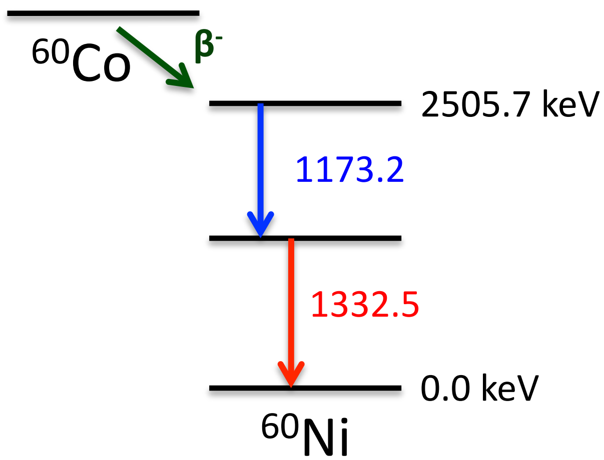


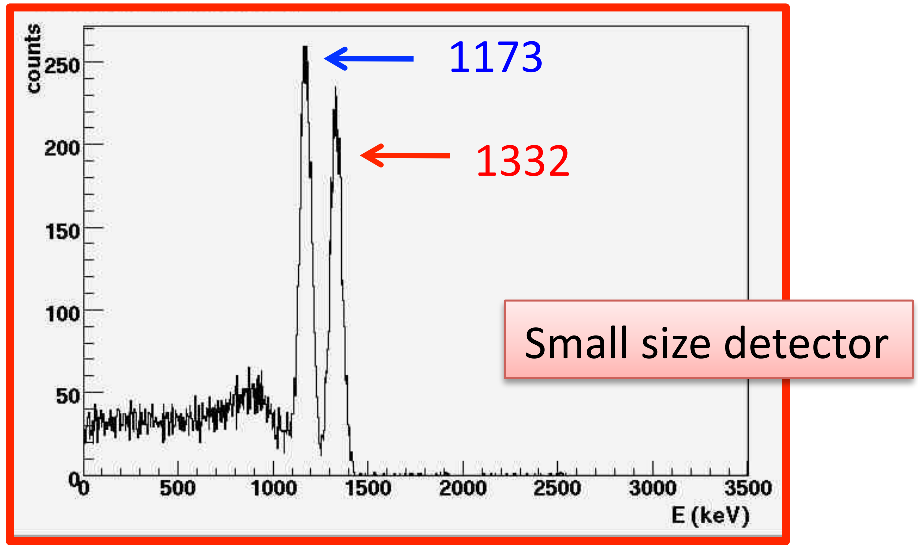
GANIL

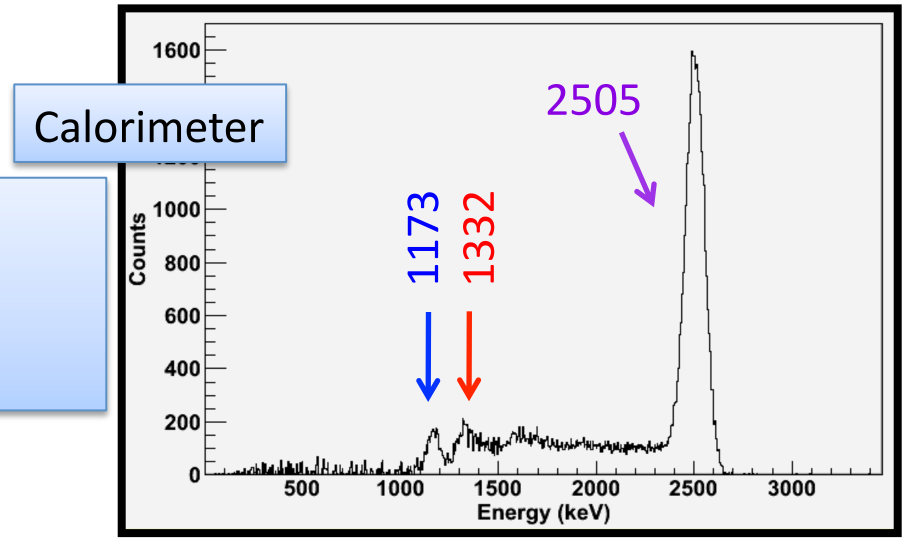
Regular Kinematics

the summing technique

The γ-Summing Method

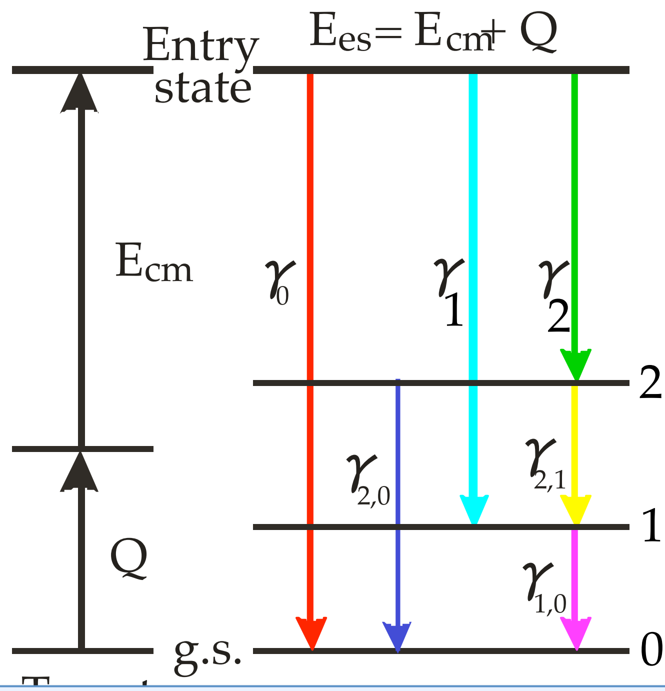




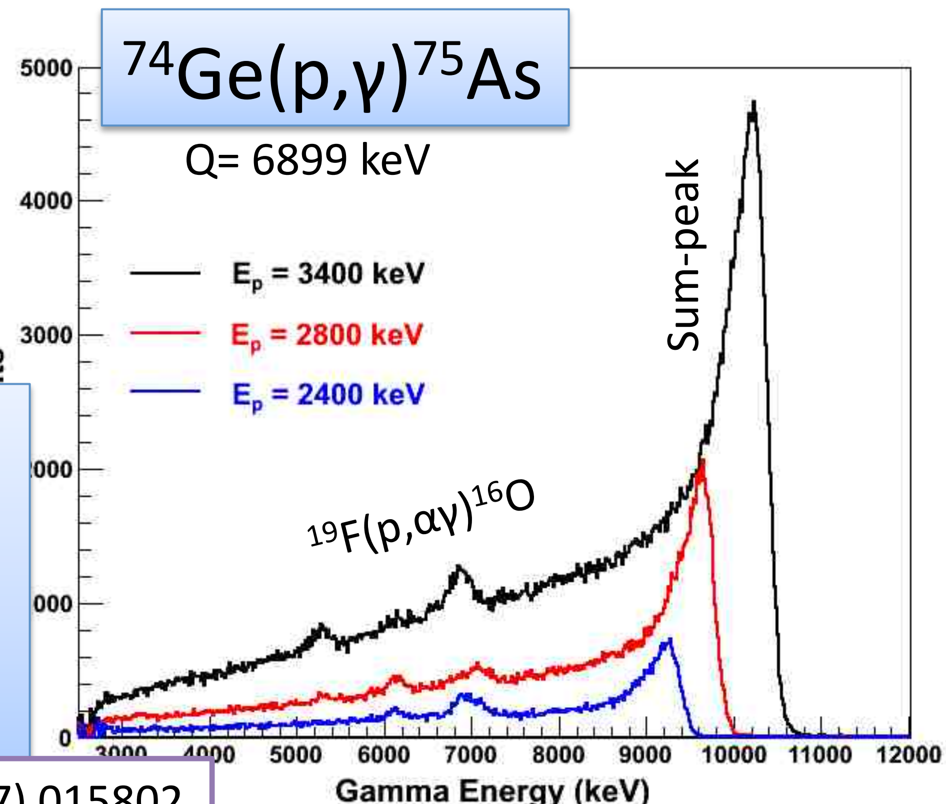


Total absorption spectroscopy used for beta-decays

4π γ - method - reactions

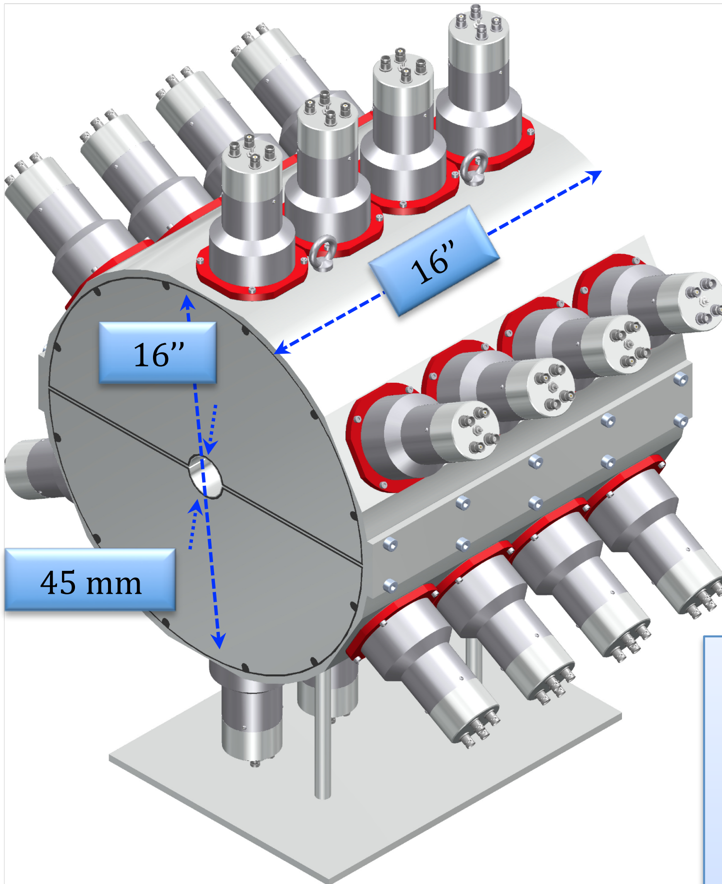


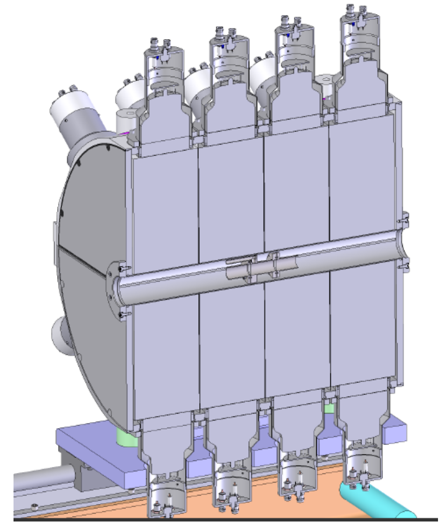
First experiments with summing technique done @ **University of Bochum, Germany** and **NCSR Demokritos, Greece**



A. Spyrou et al. Phys. Rev. C 76 (2007) 015802

SuN (Summing NaI) @ MSU





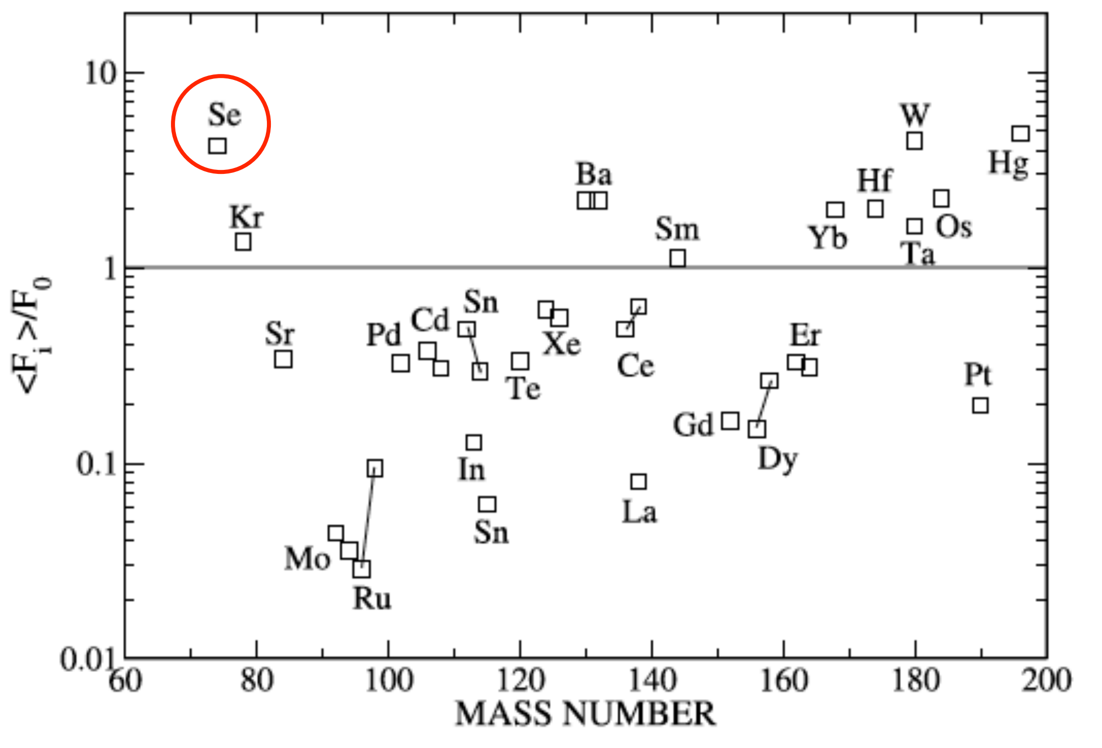
- 16x16 inch
- 45 mm borehole
- 2 pieces
- 8 segments
- 24 PMTs
- Efficiency > 85% for 1 MeV

Made by: SCIONIX

A. Simon, S.J. Quinn, A.S., et al., Nucl. Instr. Meth A 703, 16 (2013)

$^{74}Ge(p,\gamma)^{75}As$

Nucleosynthesis of the lightest p nucleus ^{74}Se



Rapp et al. AJ 653 (2006) 474

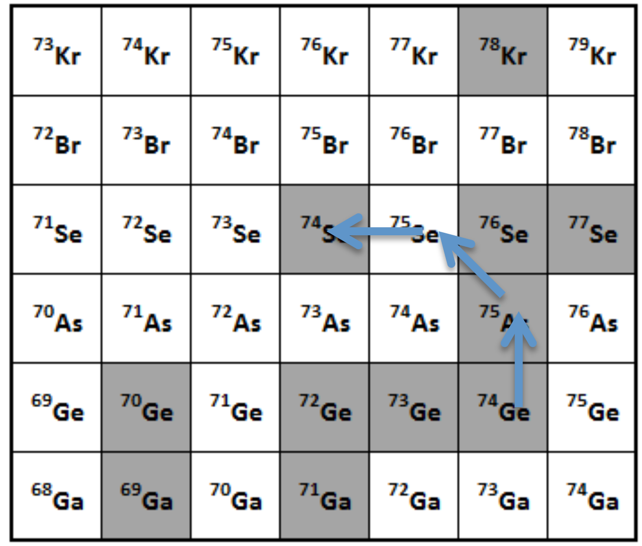
^{74}Ge(p,γ)^{75}As

Rapp et al. AJ 653 (2006) 474

TABLE 2

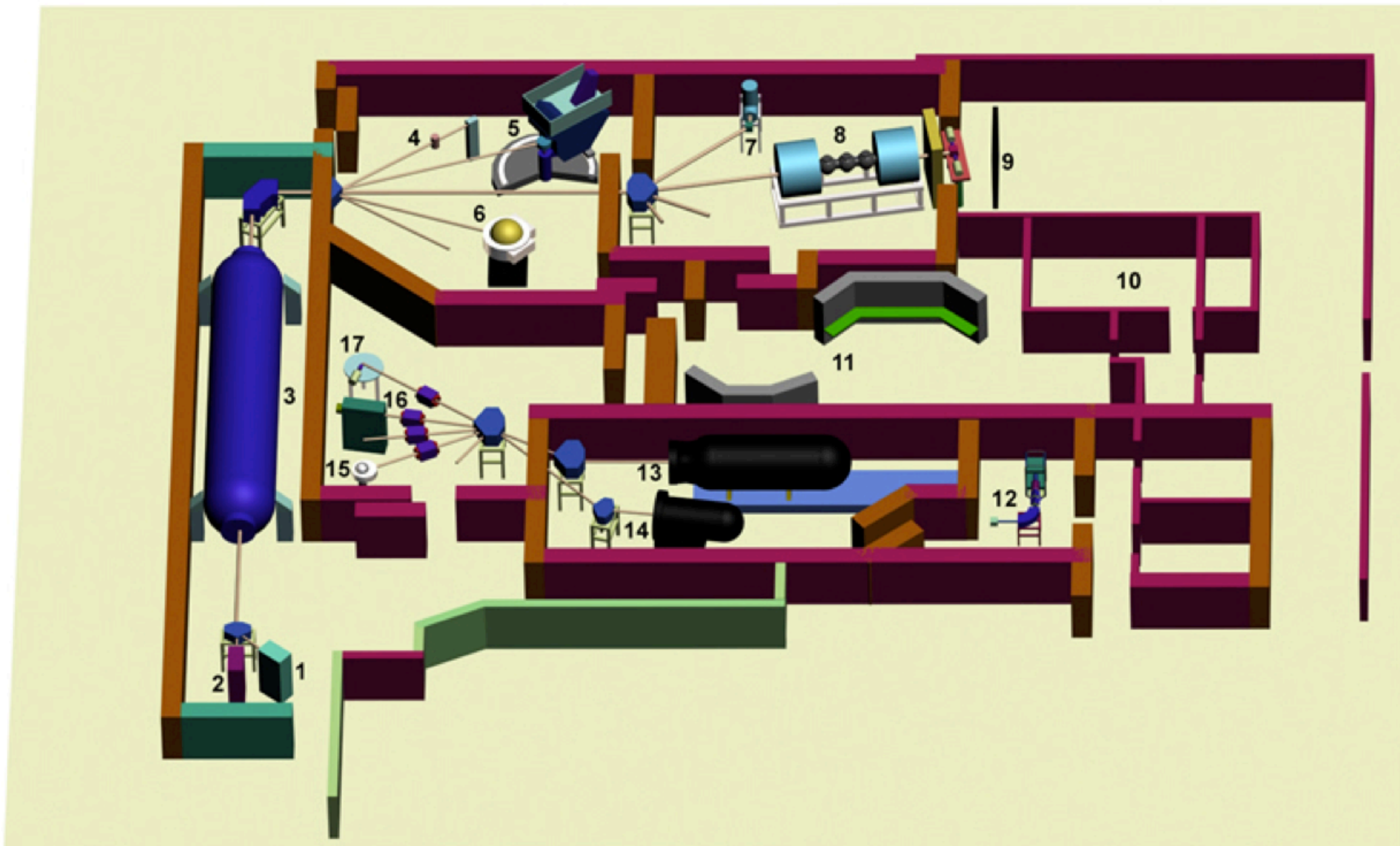
Selected (γ,p) or (n,p) Reactions

Reactions		
^{126}Ba$(\gamma,p)^{125}$Cs*	^{92}Mo$(\gamma,p)^{91}$Nb*	^{75}Se$(n,p)^{75}$As*
^{110}Sn$(\gamma,p)^{109}$In*	^{86}Rb$(n,p)^{86}$Kr*	^{74}Se$(\gamma,p)^{73}$As*
^{106}Cd$(\gamma,p)^{105}$Ag	^{85}Sr$(n,p)^{85}$Rb*	^{76}As$(n,p)^{76}$Ge*
^{104}Cd$(\gamma,p)^{103}$Ag	^{84}Sr$(\gamma,p)^{83}$Rb*	^{75}As$(\gamma,p)^{74}$Ge*
^{100}Pd$(\gamma,p)^{99}$Rh	^{78}Kr$(\gamma,p)^{77}$Br*	^{73}As$(\gamma,p)^{72}$Ge
^{96}Ru$(\gamma,p)^{95}$Tc*	^{77}Se$(n,p)^{77}$As	^{71}Ge$(n,p)^{71}$Ga



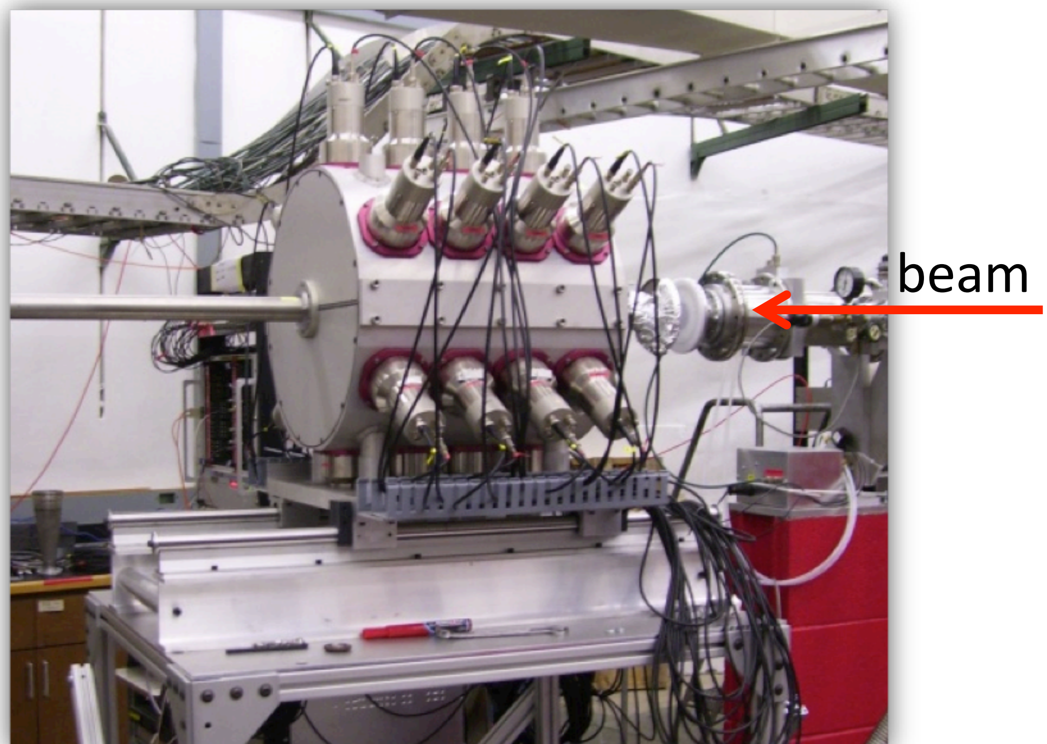
University of Notre Dame

10 MV Tandem Accelerator

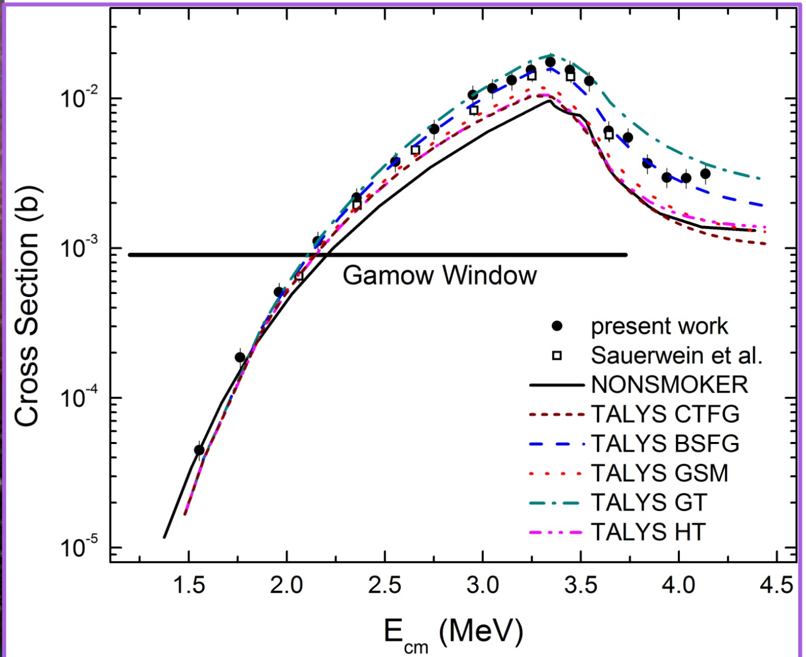


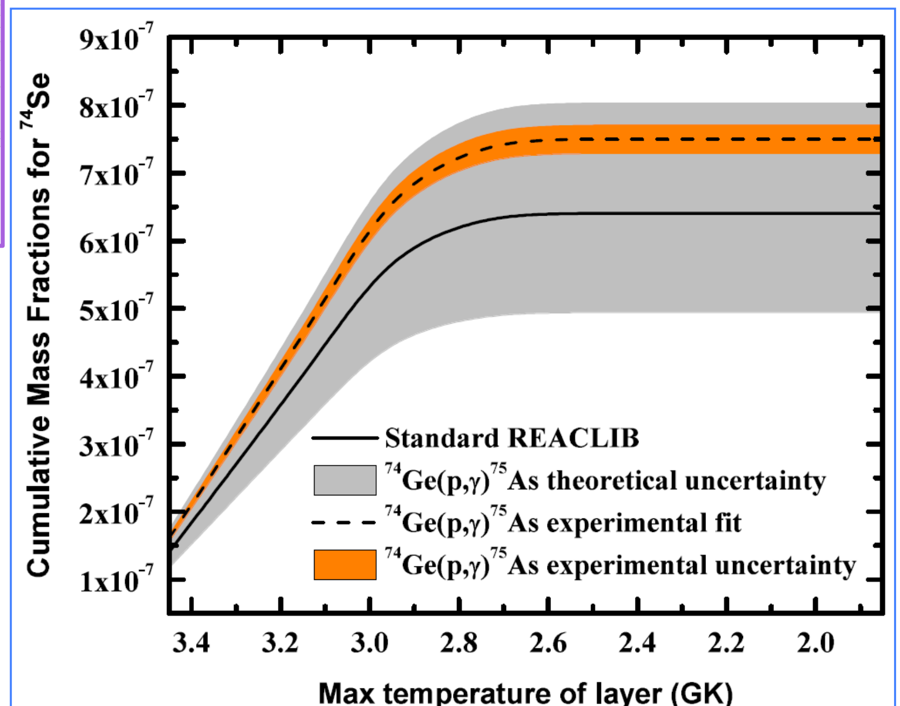
Summing NaI (SuN)

Target at center



$^{74}Ge(p,\gamma)^{75}As$



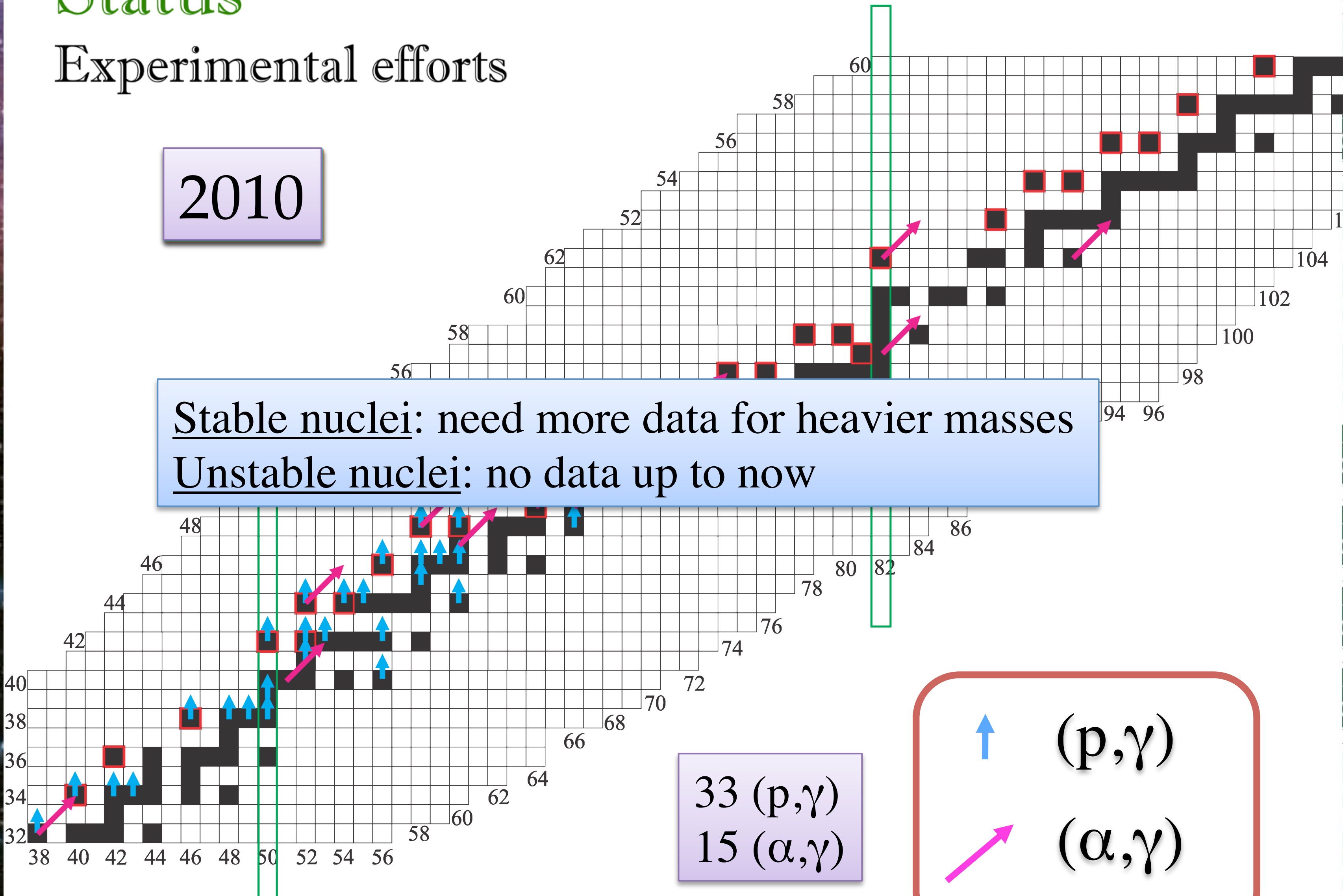


S. J. Quinn, A. Simon, A.S., et al., Phys. Rev. C 88, 011603 (R) (2013).

Status

Experimental efforts

2010



Stable nuclei: need more data for heavier masses

Unstable nuclei: no data up to now

33 (p,γ)
15 (α,γ)

↑ (p,γ)
↗ (α,γ)

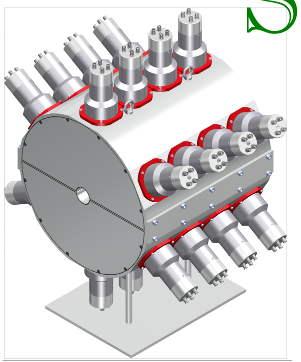
Inverse Kinematics

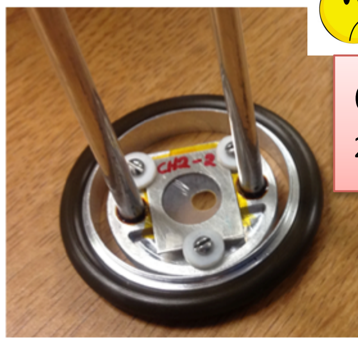
Stable beams

1. Measure reactions that are hard in regular kinematics
2. Develop techniques for future measurements with radioactive beams

- Efforts @ MSU using SuN
- Efforts @ TRIUMF using DRAGON

SuN in Inverse Kinematics

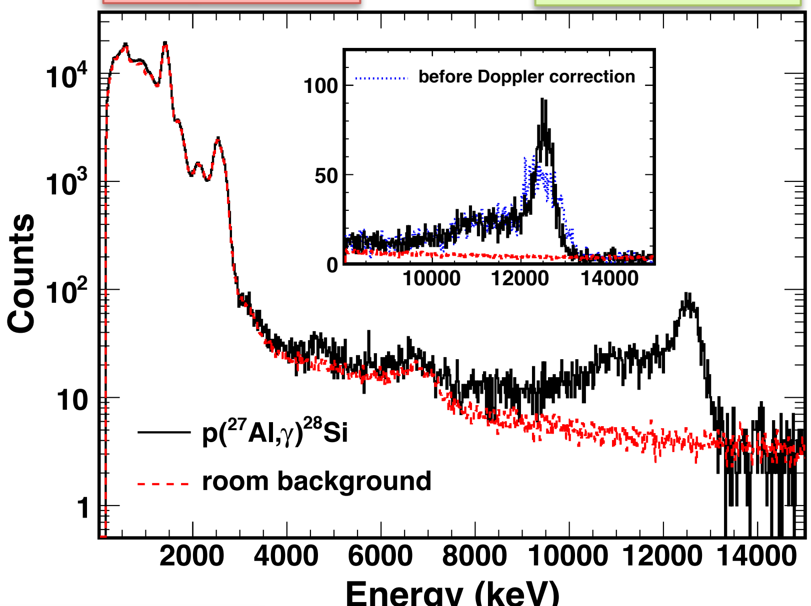




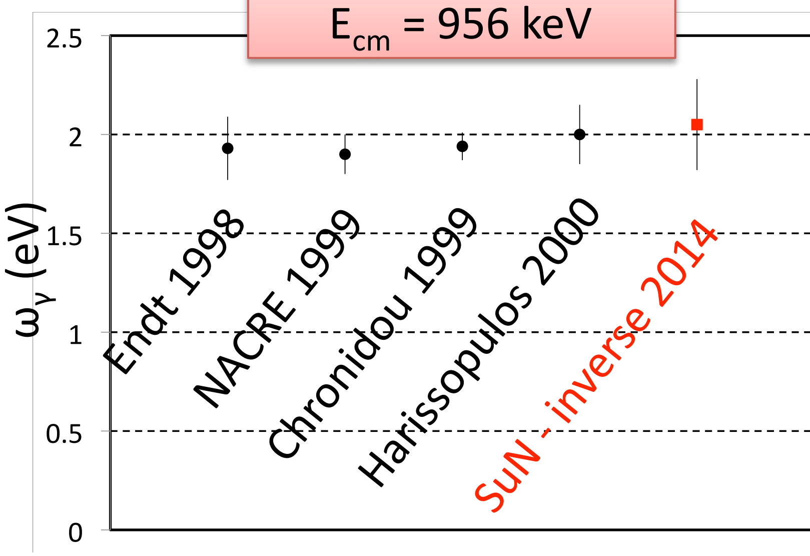
CH$_2$ target
^{27}Al beam

TiH$_2$ target

p(^{27}Al,γ)^{28}Si

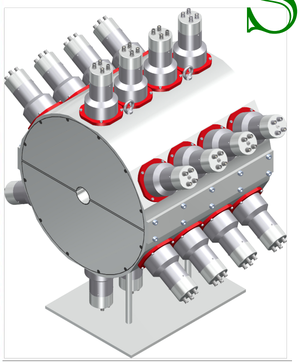


Resonance strength
E_{cm} = 956 keV

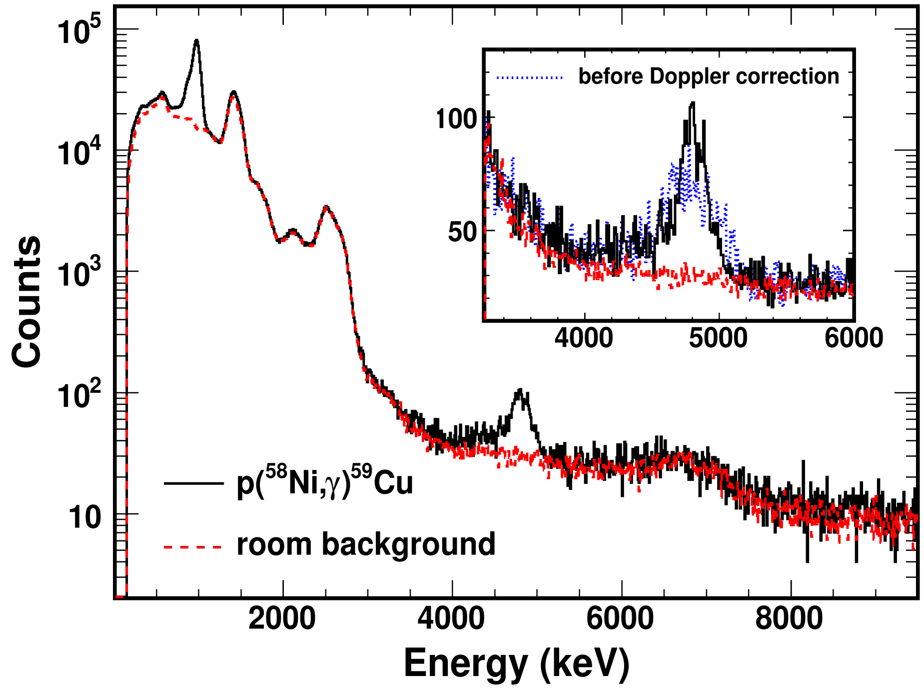


Steve Quinn

SuN in Inverse Kinematics



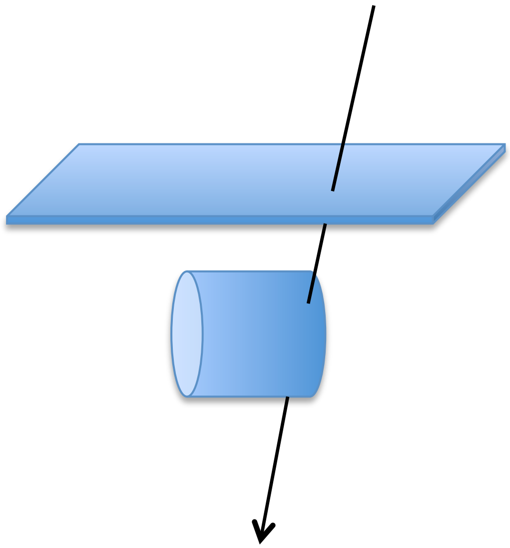
p(^{58}Ni,γ)^{59}Cu



- First application of summing technique in inverse kinematics
- Good agreement with previous measurements
- Technique applicable for measurements with stable or radioactive beams

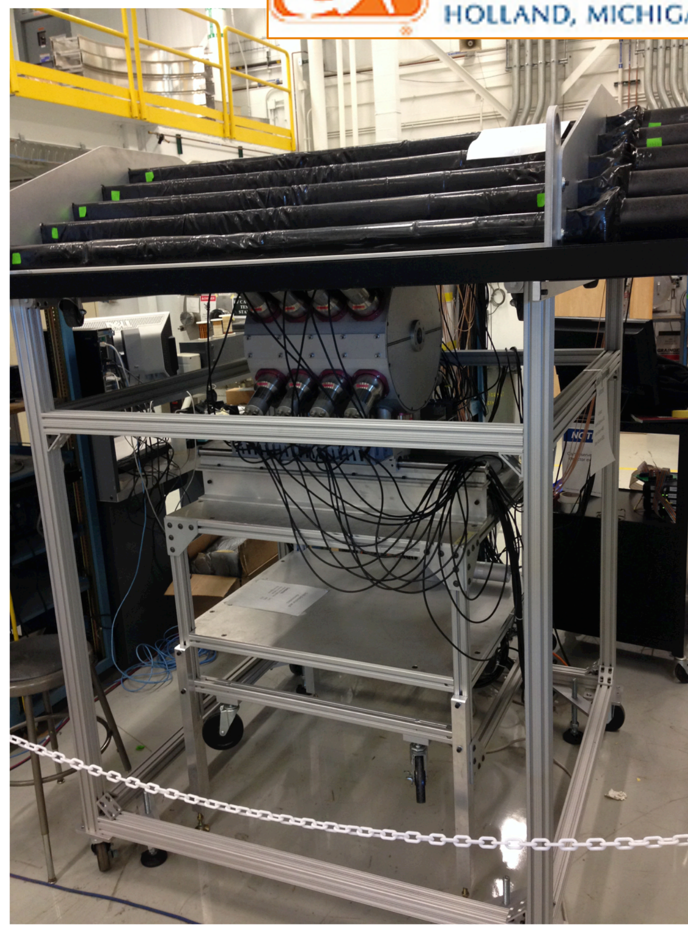
SuNSCREEN

HOPE COLLEGE
HOLLAND, MICHIGAN 49423



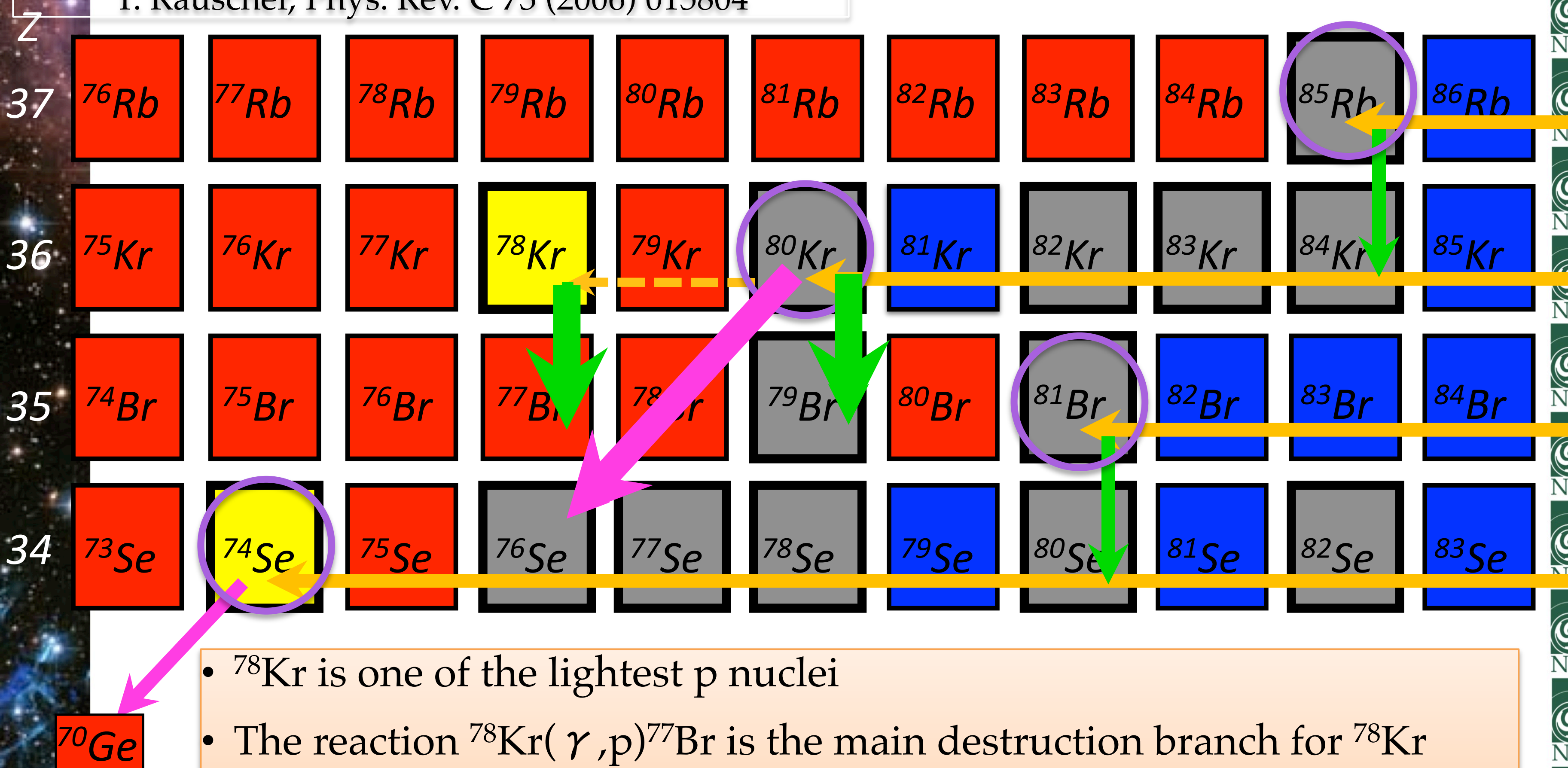
- 9 plastic scintillator bars
- Two PMTs on each bar
- Calibrated and optimized
- Rejection of ≈ factor 5

First stable beam test experiments at MSU end of 2014.



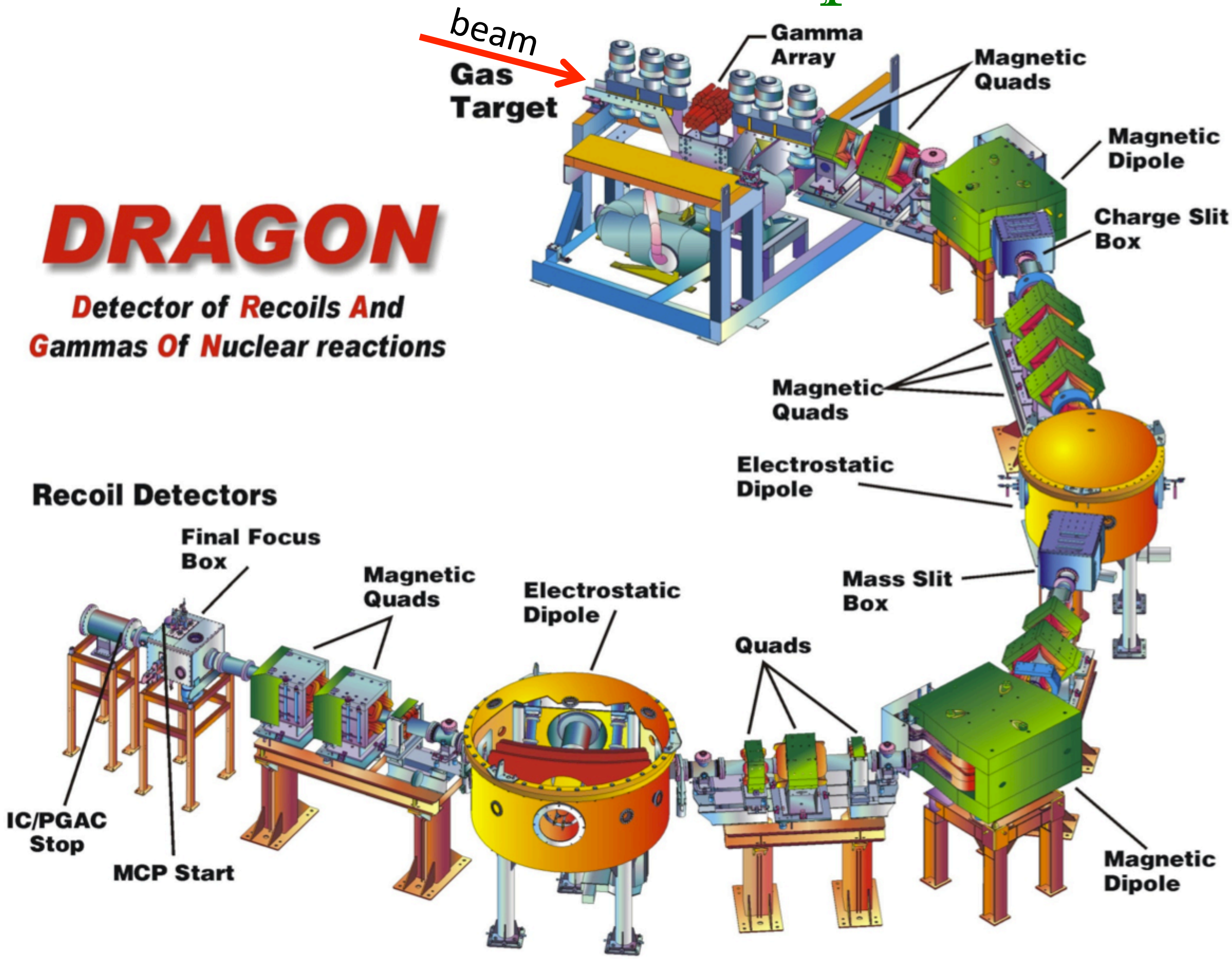
Inverse kinematics with DRAGON

T. Rauscher, Phys. Rev. C 73 (2006) 015804



- ^{78}Kr is one of the lightest p nuclei
- The reaction ^{78}Kr(γ,p)^{77}Br is the main destruction branch for ^{78}Kr
- The reactions ^{80}Kr(γ,p)^{79}Br and ^{80}Kr(γ,α)^{76}Se define whether the reaction flow will make it to ^{78}Kr

DRAGON recoil separator

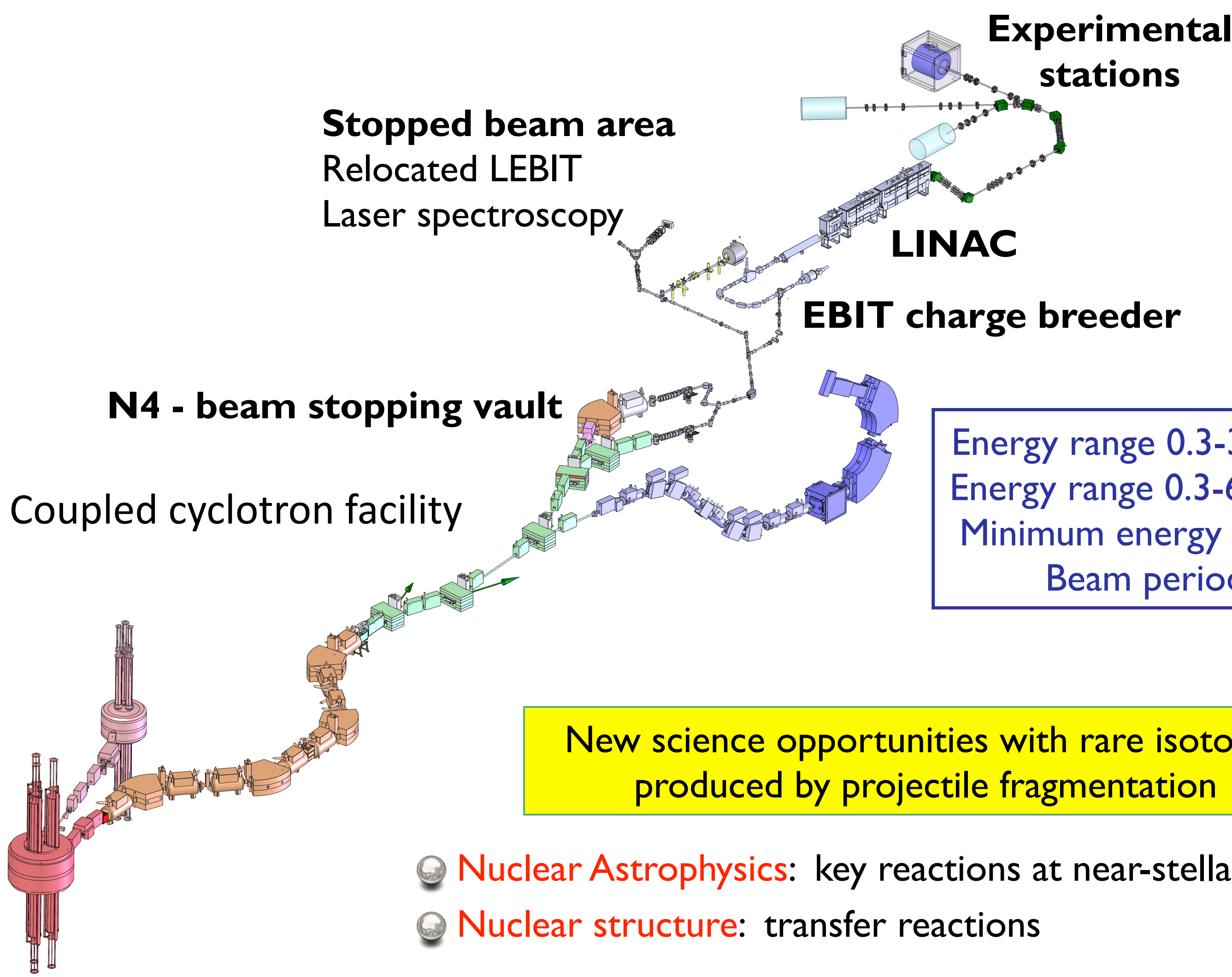


Inverse Kinematics

Radioactive beams

- Efforts at TRIUMF will continue
- New facility at MSU: ReA3

NSCL @ Michigan State University



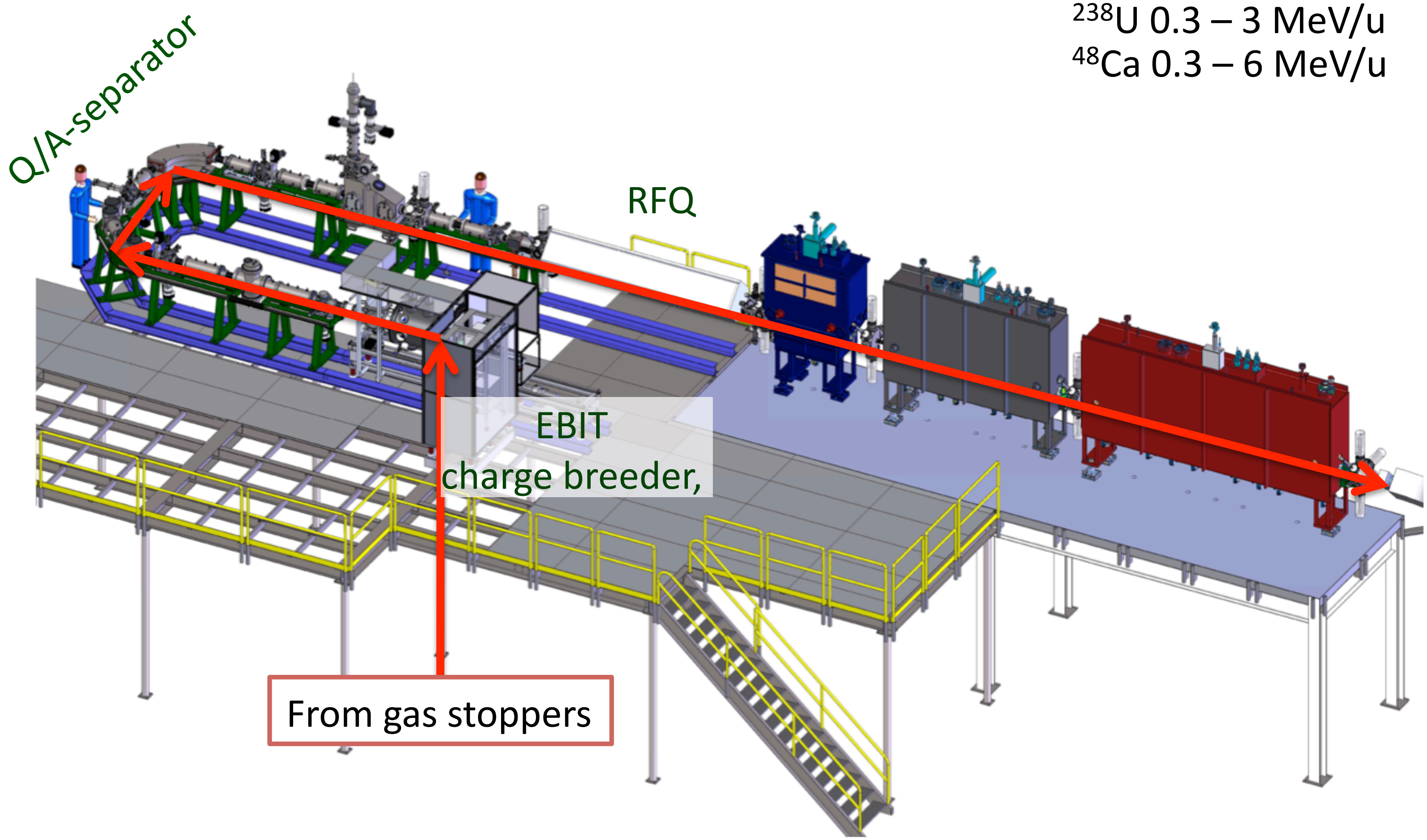
Energy range 0.3-3 MeV for ^{238}U
Energy range 0.3-6 MeV for ^{48}Ca
Minimum energy spread < 0.5%
Beam period 12.5 ns

New science opportunities with rare isotopes produced by projectile fragmentation

- Nuclear Astrophysics: key reactions at near-stellar energies
- Nuclear structure: transfer reactions

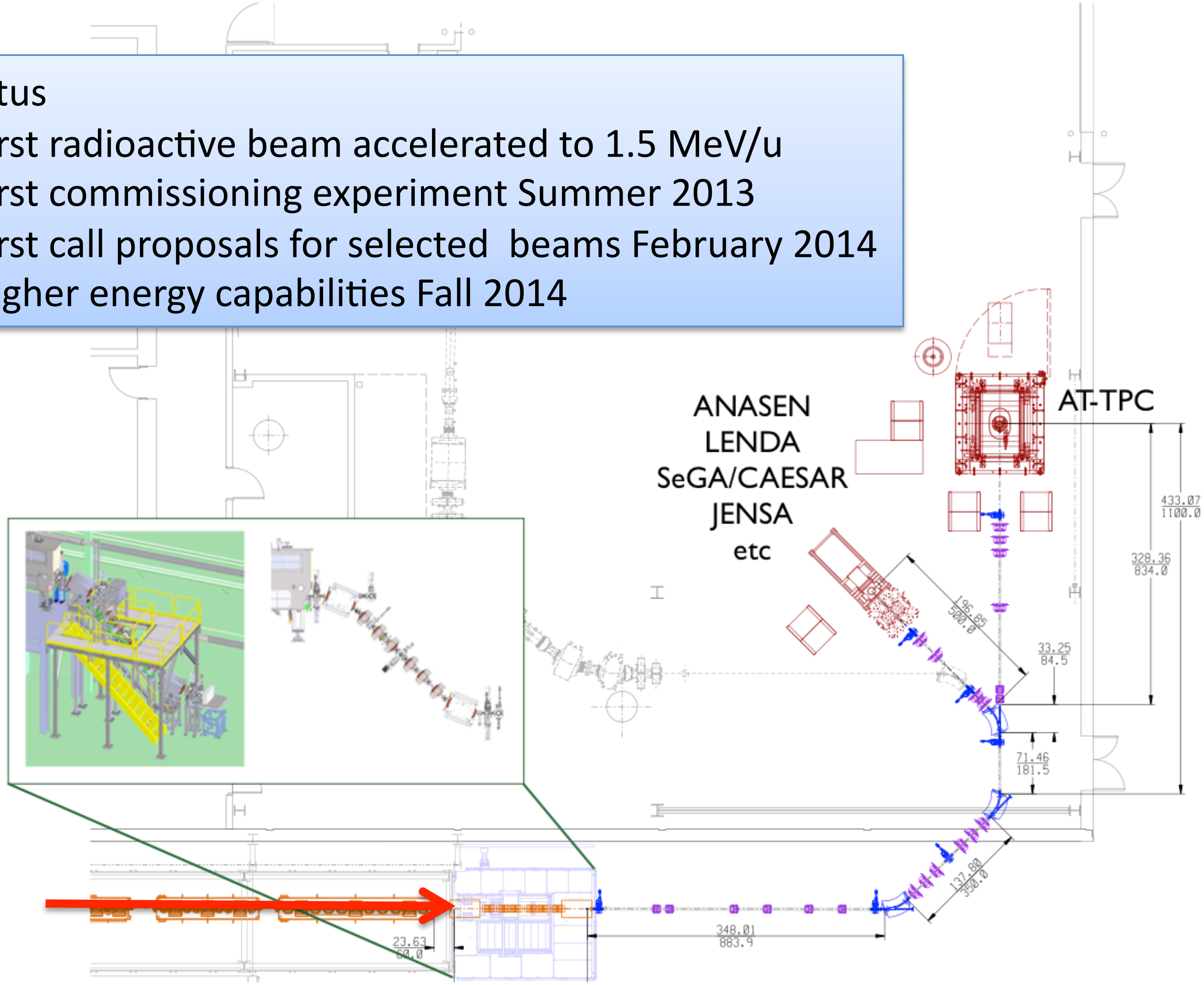
ReA3

^{238}U 0.3 – 3 MeV/u
^{48}Ca 0.3 – 6 MeV/u



Next Step: Experimental hall

Status
- First radioactive beam accelerated to 1.5 MeV/u
- First commissioning experiment Summer 2013
- First call proposals for selected beams February 2014
- Higher energy capabilities Fall 2014



Conclusions

- Making progress toward understanding the nuclear physics uncertainties in the p process
- (p,γ) reactions relatively well described (within factor 3)
- (α,γ) still large uncertainties (factor 10)
- Experimental data are limited to light masses
- Stable beams: need to extend to heavier regions
- Plans for radioactive beam experiments under way

Collaborators

- **Michigan State University / NSCL**

  Stephen Quinn, Anna Simon, Alexander Dombos, Sean Liddick, A. Kontos, +8 UG students

- **University of Notre Dame**

  T. Battaglia, A. Best, M. Bowers, B. Bucher, M. Couder, X. Fang, **J. Görres**, Q. Li, A. Long, S. Lyons, A. Roberts, D. Robertson, M. Smith, K. Smith, E. Stech, W. Tan, X. Tang**, M. Wiescher**

- **Hope College**

  Paul DeYoung

TRIUMF

C. Akers, J. Fallis, C. Ruiz, G. Christian, D. Hutcheon

University of York

A. Laird, B. Fulton