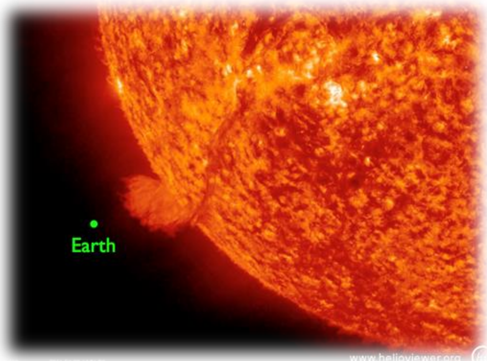
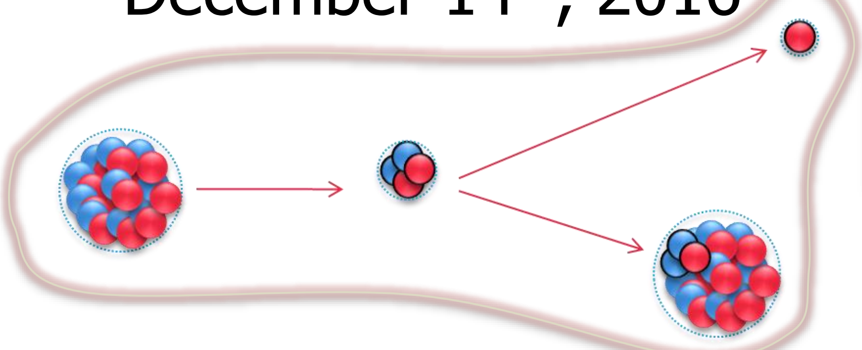
First Neutron-rich Beam Induced (*α*,*xn*) reaction studies with HabaNERO

HabaNERO

Sunghoon(Tony) Ahn
JINA-CEE, NSCL/MSU

December 14th, 2016





JINA-CEE
NSF Physics Frontiers Center

MICHIGAN STATE UNIVERSITY

HabaNERO

[Acknowledgements]

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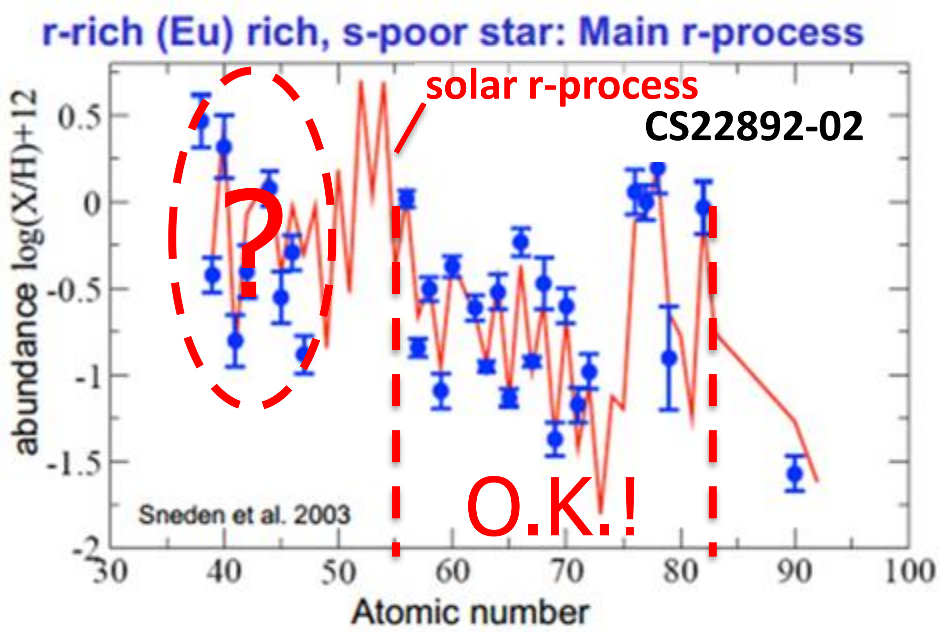
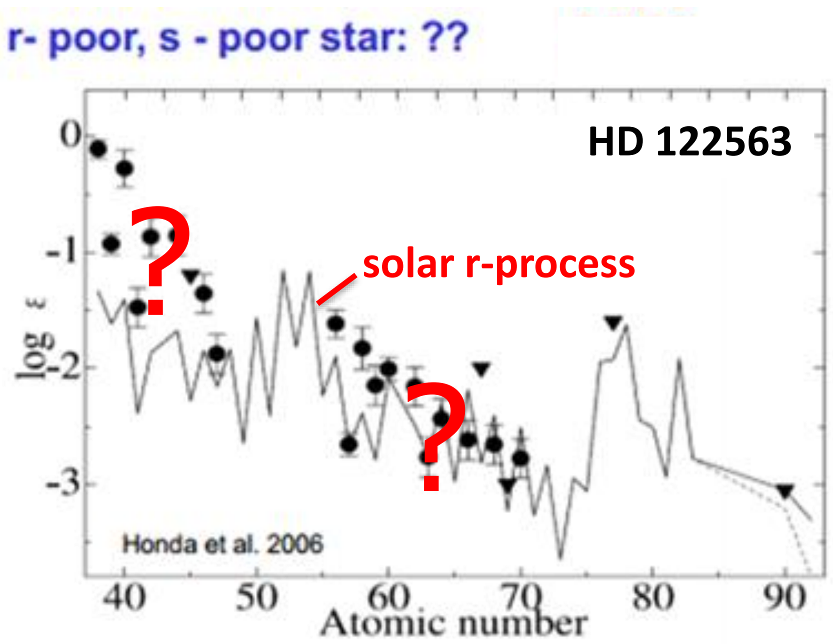
[9] *Department of Physics & Astronomy, University of Tennessee, Knoxville, USA*

Abundance Patterns of Metal Poor Halo Stars

- Sun formed ~10 billion years after big bang → accidental combination of many different processes?
- Metal poor halo stars are old and preserve in their photospheres the abundance composition at the location and time of their formation. → single event?

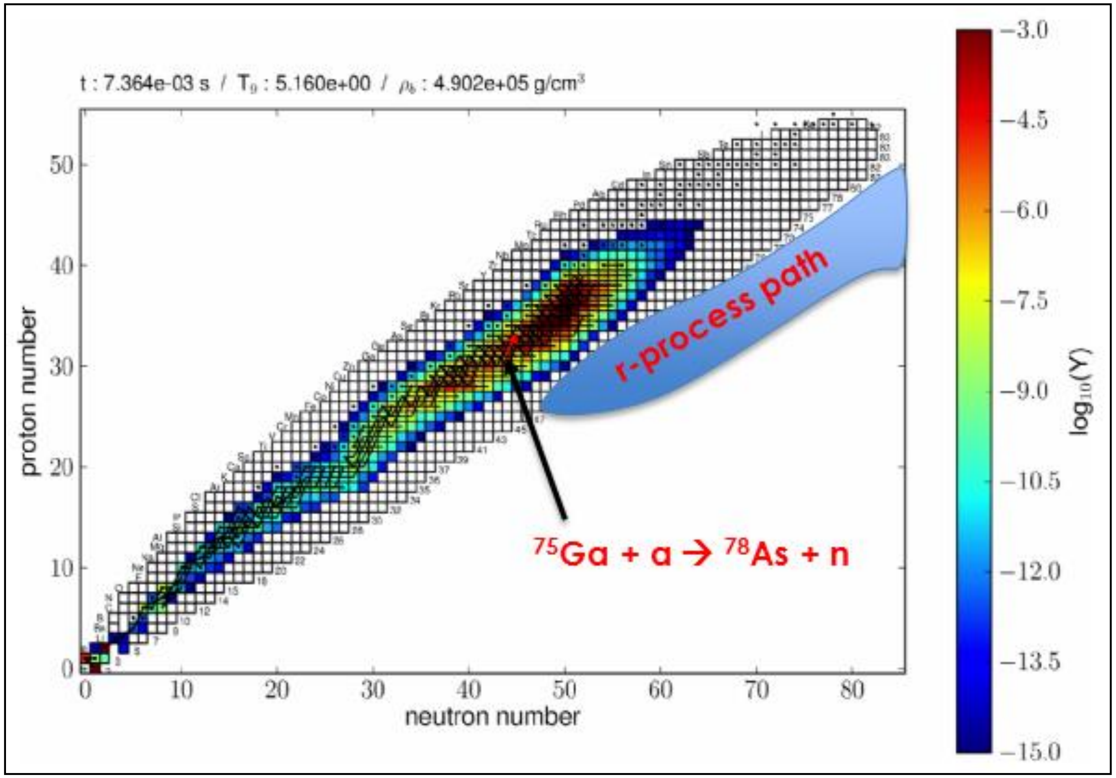
- **Many surprises found in the observations!**
  → Another nucleosynthesis needed!



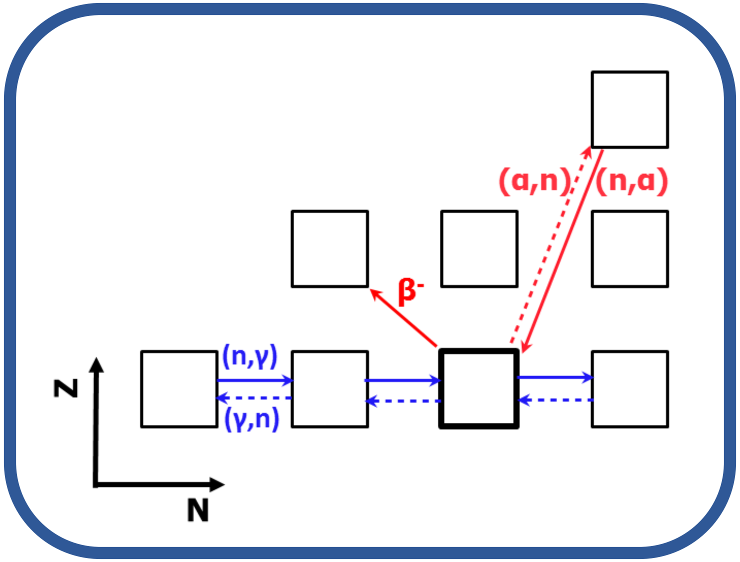


LEPP and (α,n) reactions

- In the neutrino driven wind at CCSN with T~4GK, charge particle reaction fall out of NSE.
- Good conditions for (*α,n*) and (*n,γ*) reactions with Iron seeds.
- (*α,n*) reactions provide enough abundances for low Z elements.



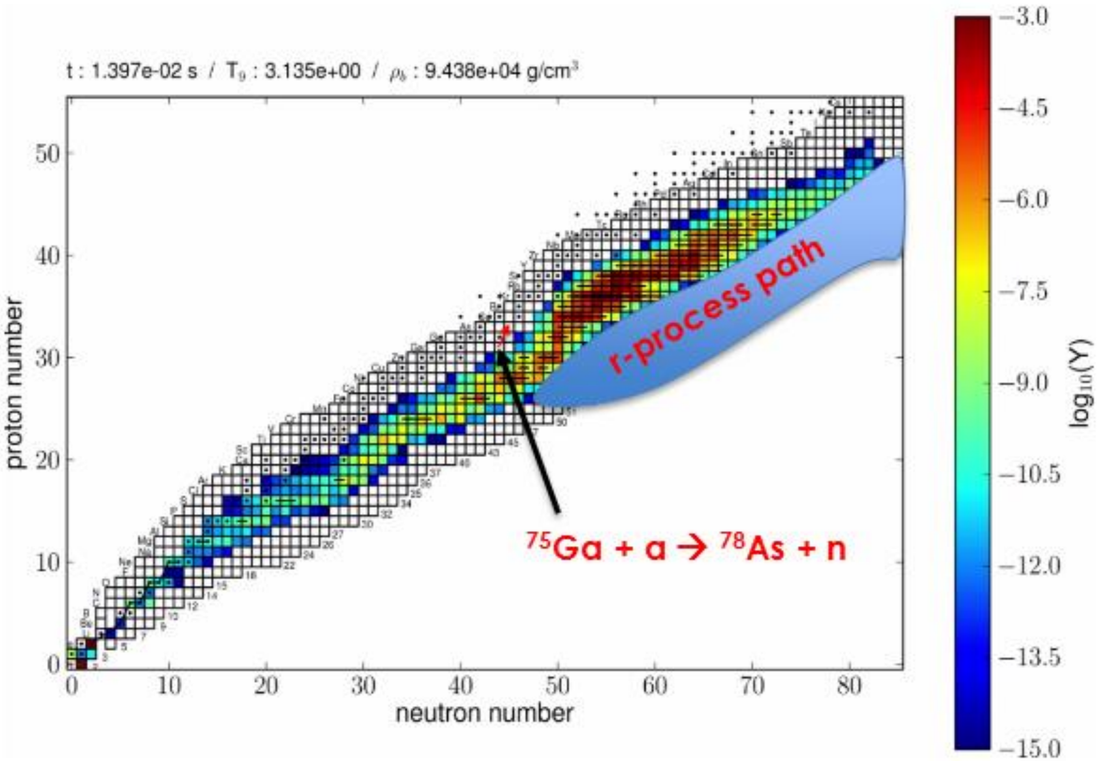
A Nucleosynthesis simulation in the incomplete r-process considering dominant (α,n) reactions



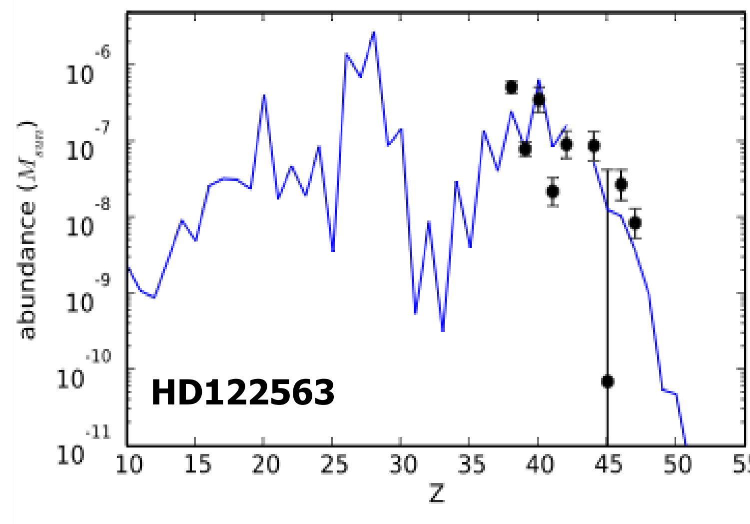
A diagram w/ (α,n) and (n,γ) reactions

Agreement between model and measurement

- In the neutrino driven wind at CCSN with T~4GK, charge particle reaction fall out of NSE.
- Good conditions for (*α,n*) and (*n,γ*) reactions with Iron seeds.
- (*α,n*) reactions provide enough abundances for low Z elements.



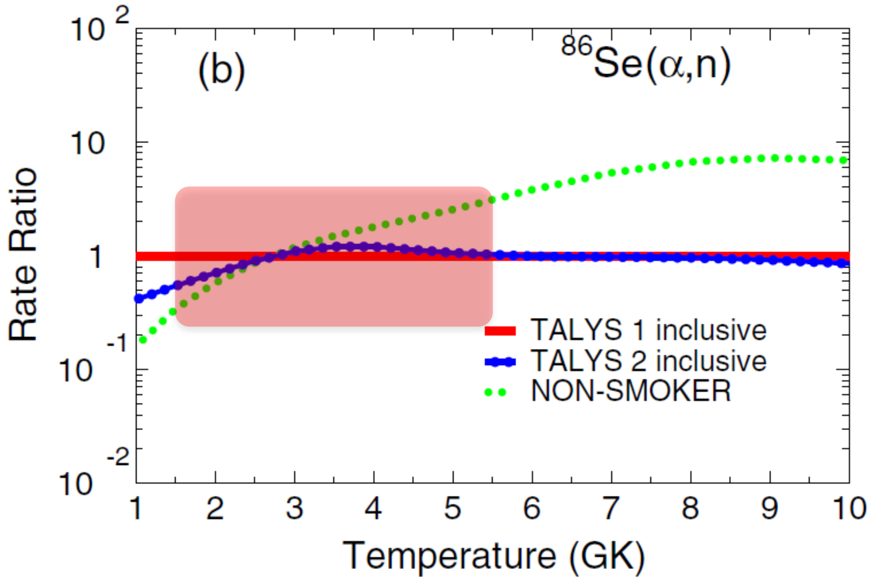
A Nucleosynthesis simulation in the incomplete r-process considering dominant (α,n) reactions



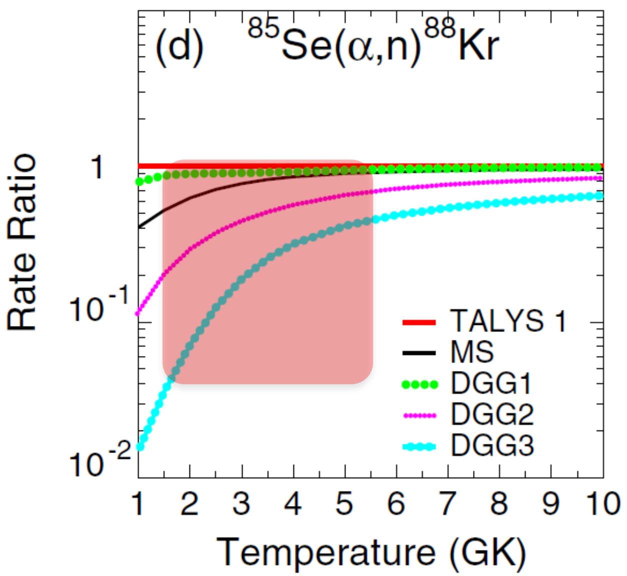
r-process abundances considering dominant (α,n) reactions
Bliss *et al*, In Preparation

Uncertain (α,n) cross sections for neutron-rich nuclei

- Theoretical (α,*n*) cross sections have large spread of predictions.
- (α,*n*) reaction rates largely depend on reaction codes and input parameters.



^{86}Se(*α*,*n*) reaction rate ratio w/ various HF code
J. Pereira and F. Montes, Phys Rev C 93, 034611 (2016)

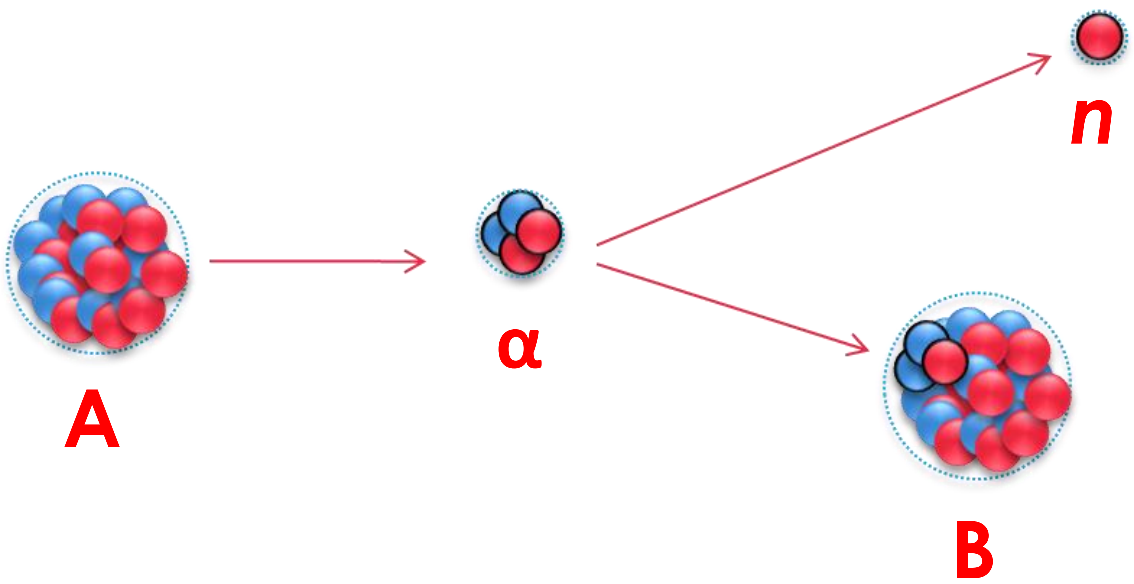


^{86}Se(*α*,*n*) reaction rate ratios w/ various alpha OMP
J. Pereira and F. Montes, Phys Rev C 93, 034611 (2016)

(α,*n*) reaction in inverse kinematics

- The neutron-rich nuclei live short.

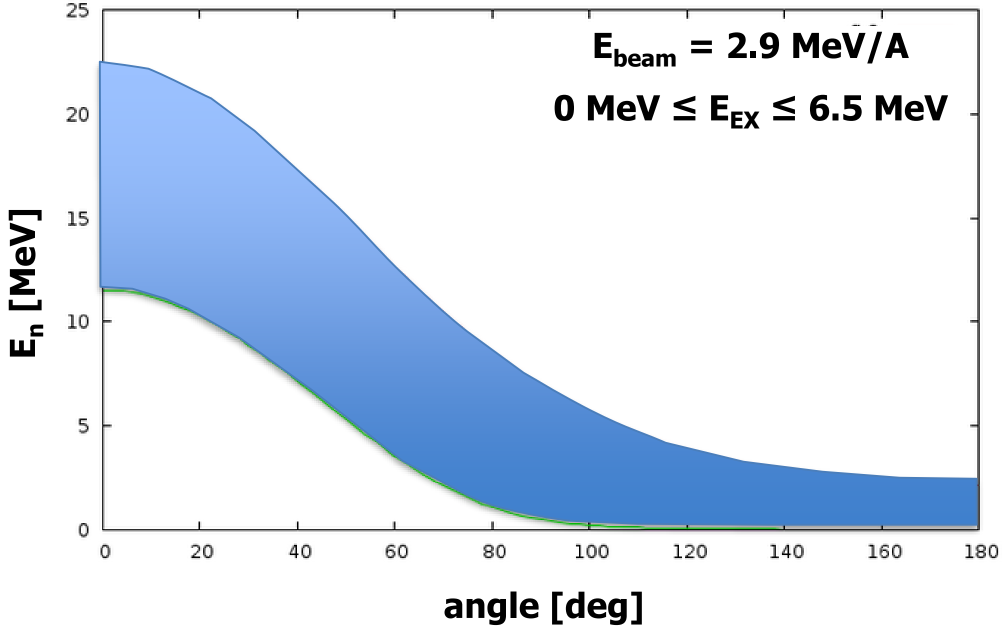
➔ A(**α**,*n*)B reaction in inverse kinematics: A = beam, **α** = target, *n* = ejectile, B = recoil



Kinematics diagram for A(a,*n*)B reaction in inverse kinematics

High efficient Neutron Detector for (α,n) reaction Study

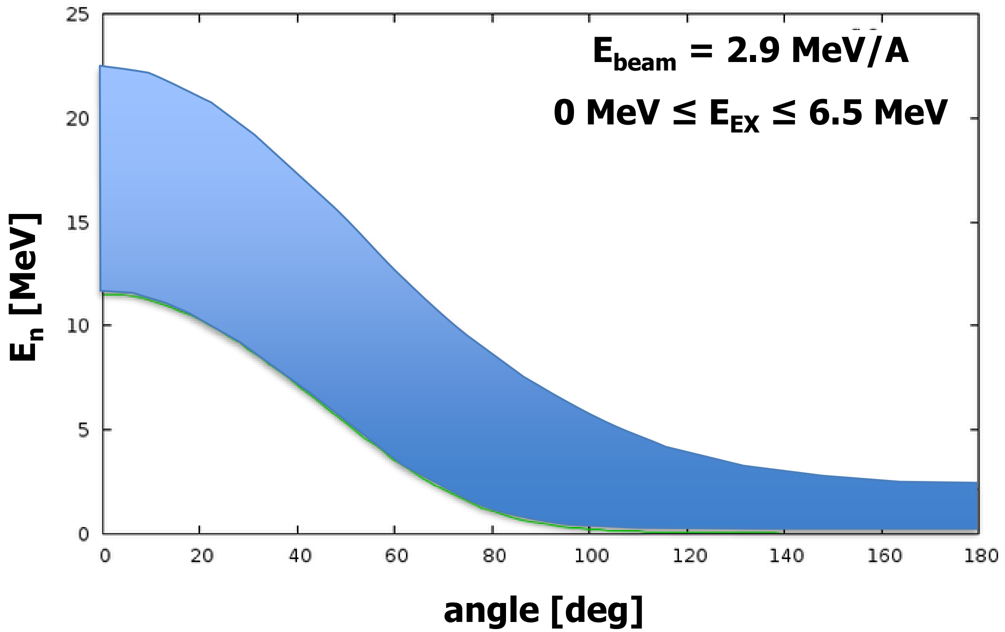
- Needs for a high efficient neutron detector for neutron energy up to 20 MeV



Simulated kinematics curves for ^{75}Ga(α,n)^{78}As reaction in inverse kinematics

A long counter System for (α,n) reaction Study

- Needs for a high efficient neutron detector for neutron energy up to 20 MeV



Simulated kinematics curves for ^{75}Ga(α,n)^{78}As reaction in inverse kinematics

➔ a long counter system, designed to be efficient for high energies and with flat efficiency curve as energy is not measured.

➔ **HABANERO**

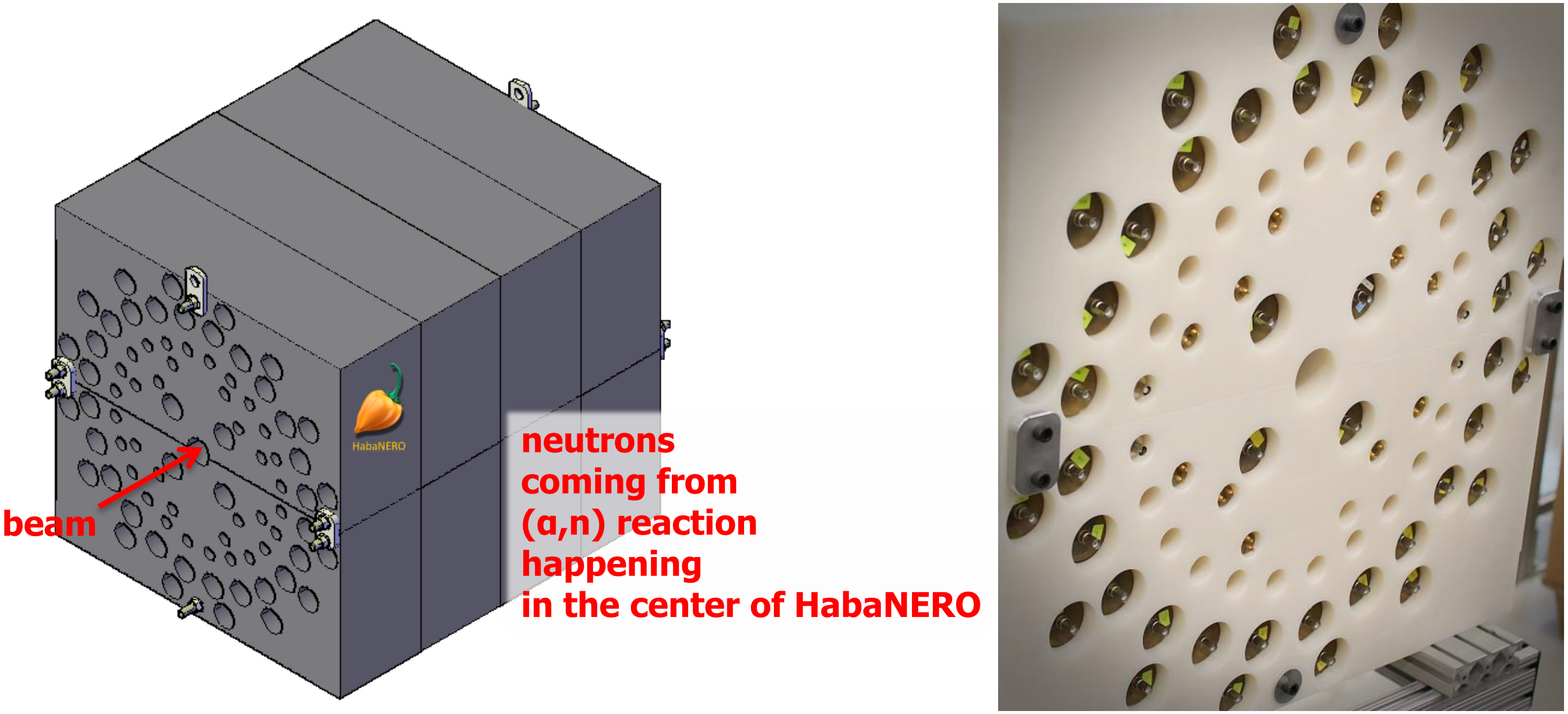
80 long counter tubes in HabaNERO

- HABANERO: Heavy ion Accelerated Beam induced (Alpha,Neutron) Emission Ratio Observer
- Properties:

1) Ultra High Molecular Weight Polyethylene (UHMWPE, ρ=0.945g/cm^3) box: L80 x W71 x H71 cm^3

2) 36 ^{3}He long counter tubes and 44 BF_3 tubes

HabaNERO



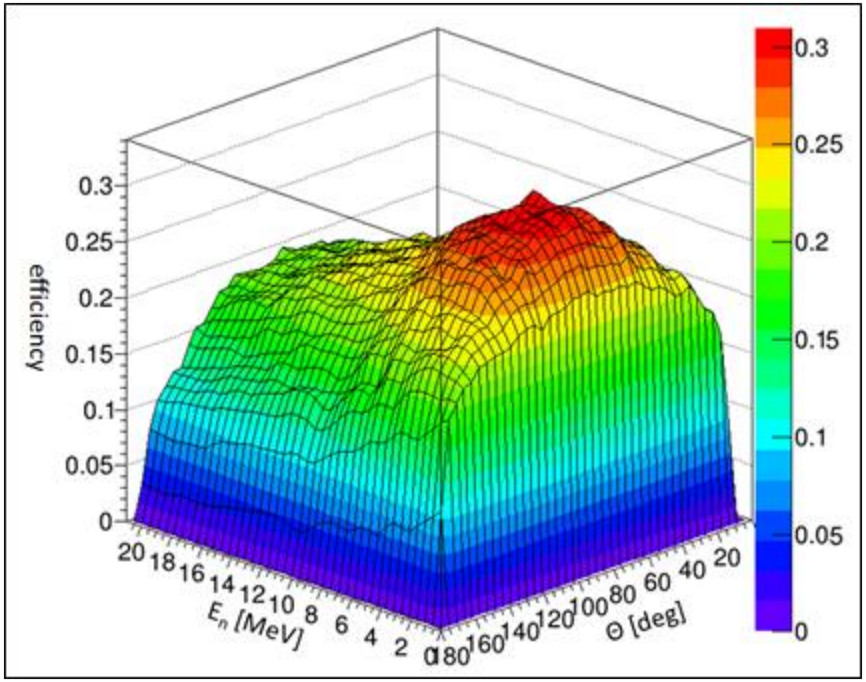
HABANERO neutron detector design (left) and real photo (right)

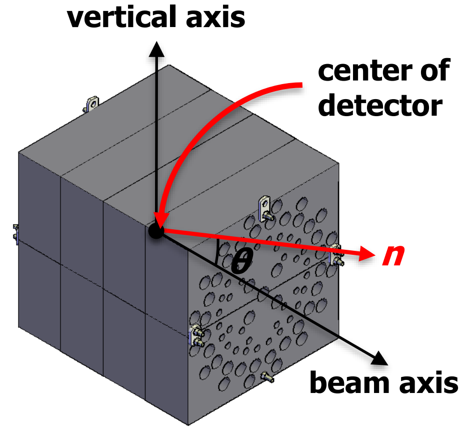
HabaNERO designed for high and flat efficiency

- HABANERO: Heavy ion Accelerated Beam induced (Alpha,Neutron) Emission Ratio Observer
- Properties:

1) Relatively high and flat efficiency for large energy range

2) For 0.1 MeV ≤ E_n ≤ 20 MeV, <ε>=22 %, ε_{max} = 27 %, ε_{min} = 17 %, δε = 5 %.

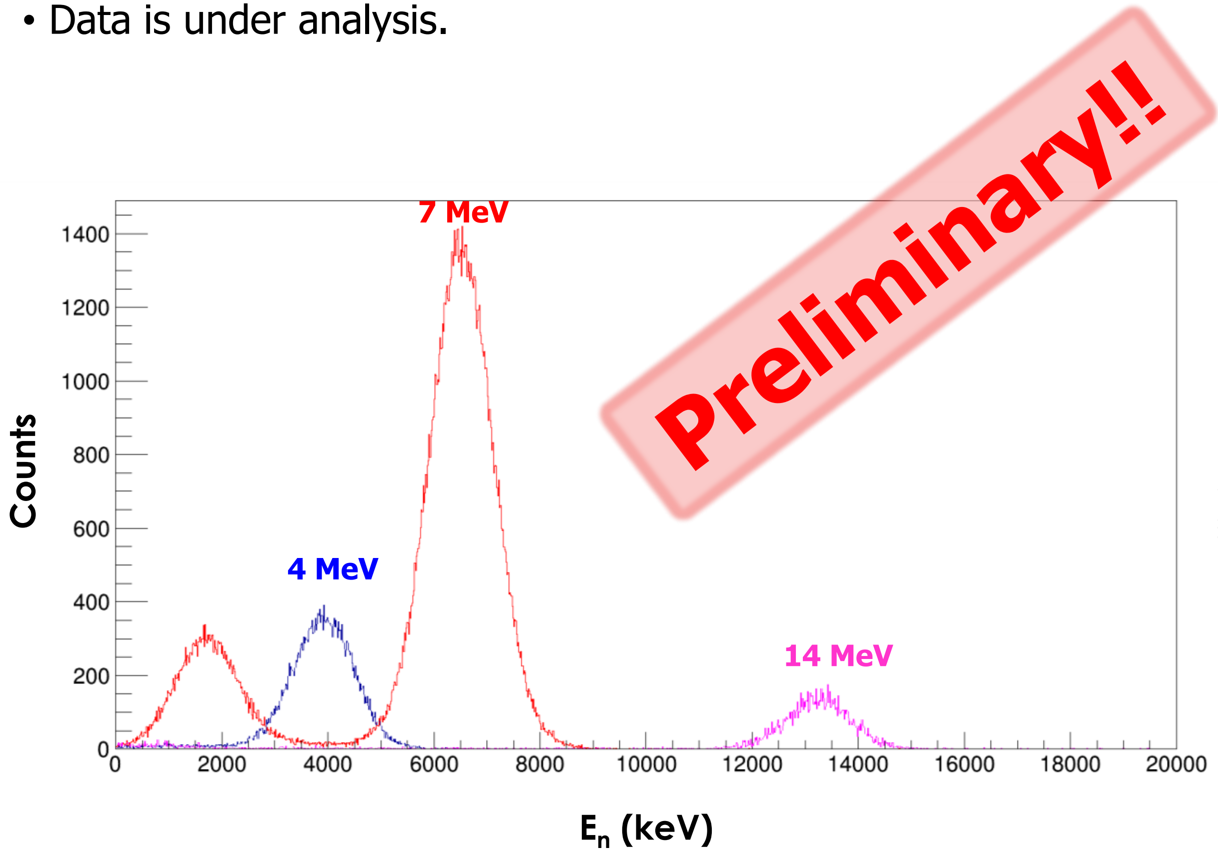




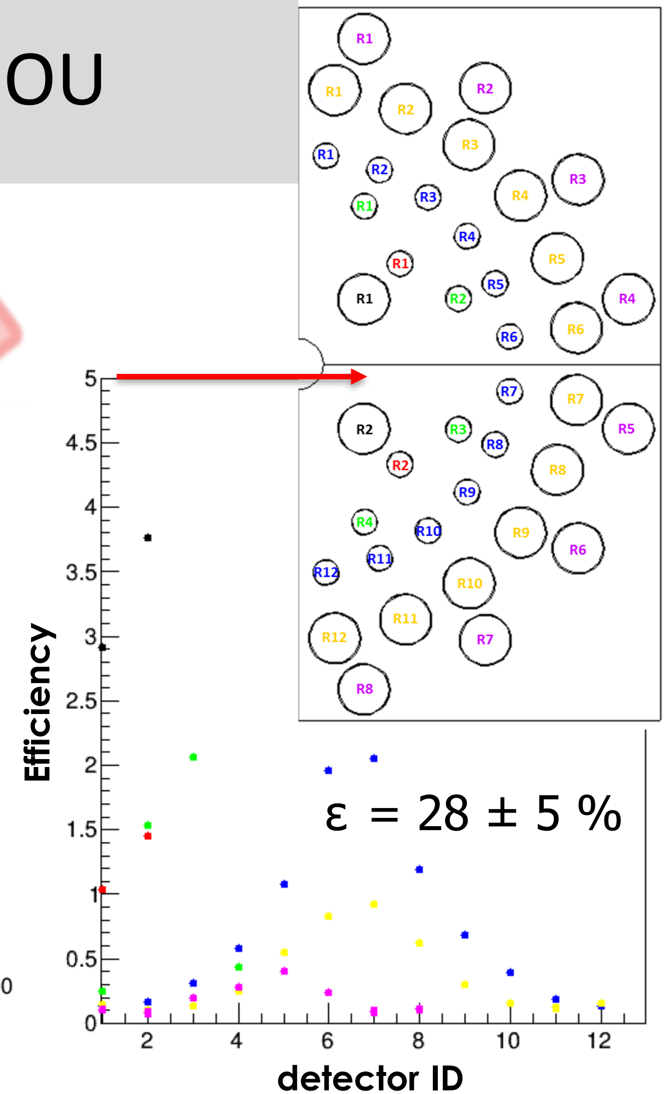
Neutron detection efficiency by MCNP simulation for neutrons having various theta angle

HabaNERO at OU

- Data is under analysis.



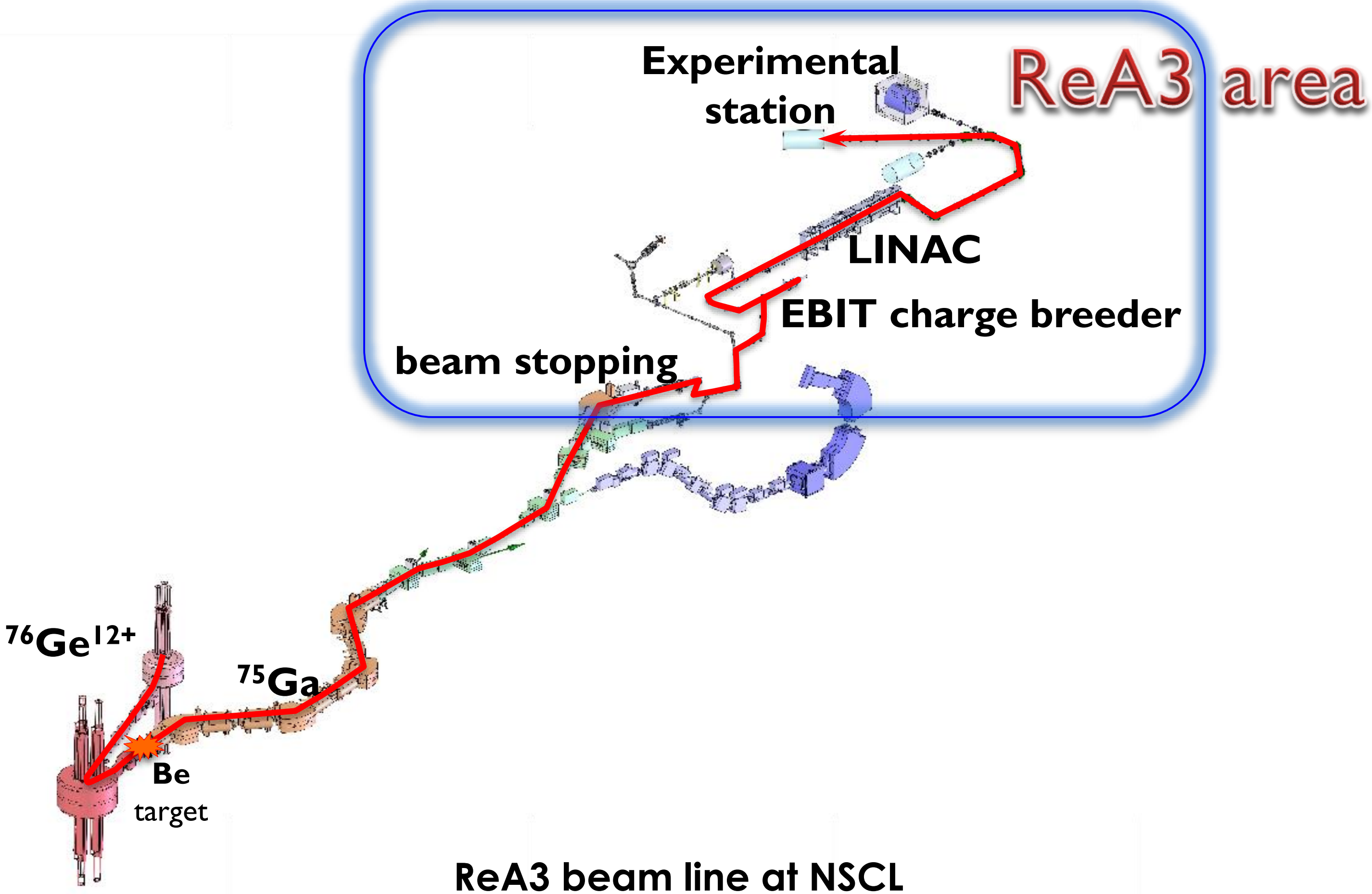
NE213 spectrum for three mono-energetic neutron beams ***(blue=4 MeV, red=7 MeV, purple=14 MeV)***



Efficiency plot for detector at En = 7 MeV, θ = 90 and φ = 90 deg

ReA3 reaccelerated beam facility

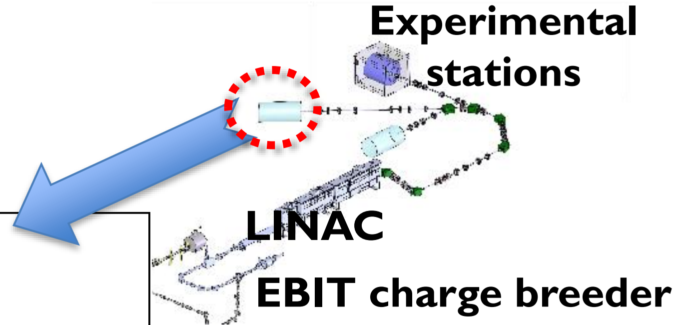
- ^{75}Ga beam with In-flight separation method and Gas Stopper/Reaccelerator at NSCL
- E_{beam} = 2.9 ~ 4.0 MeV/A (for T ~ 3.6-5.3 GK coverage), 5 beam energy steps

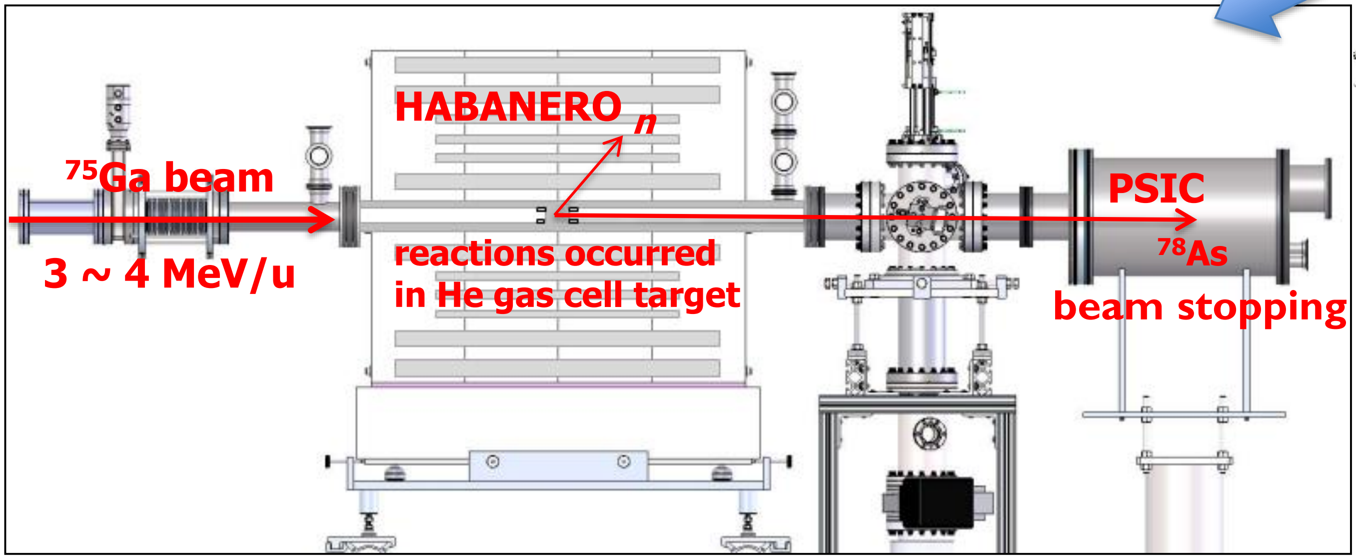


ReA3 beam line at NSCL

Experimental Setup for $^{75}Ga(\alpha,n)$ reaction

- ^{75}Ga reaccelerated beams by ReA3, NSCL, bombard ^{4}He gas target (T=355ug/cm^2) in the middle of the HABANERO.
- Position Sensitive Ionization Chamber (PSIC) provides beam current and PID.



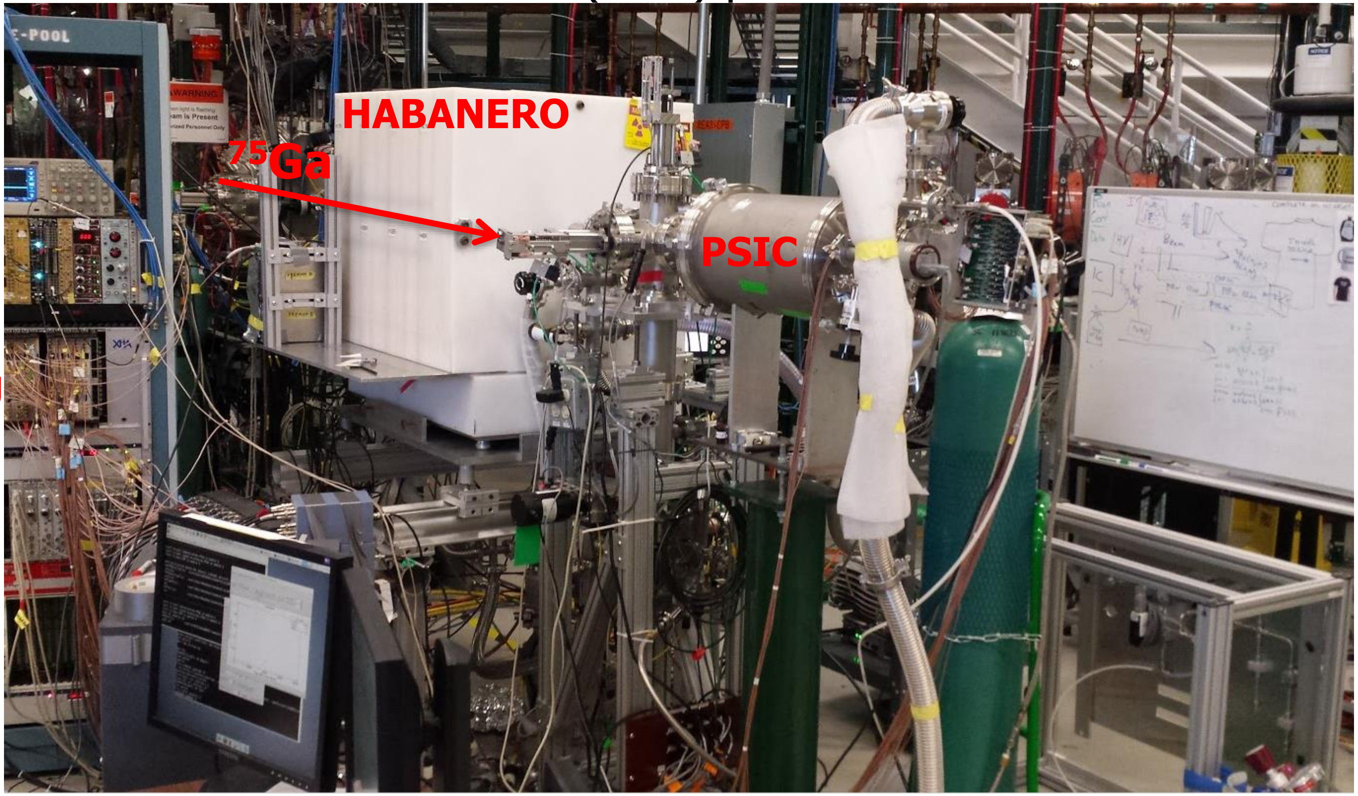


Experimental Setup Design

First measurement of ^{75}Ga(α,*n*) reaction at NSCL

- ^{75}Ga reaccelerated beams by ReA3, NSCL, bombard ^{4}He gas target (T=355ug/cm^2) in the middle of the HABANERO.
- Position Sensitive Ionization Chamber (PSIC) provides beam current and PID.

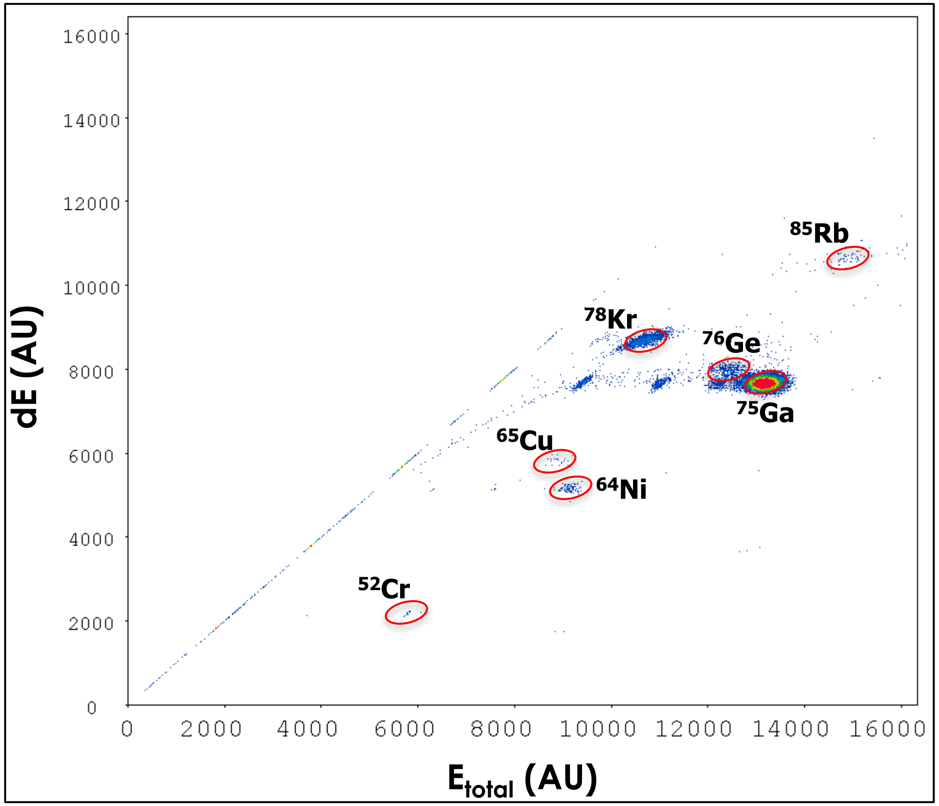
DDAS for Digital Signal Processing



Experimental Setup Photo

^{75}Ga beam purity

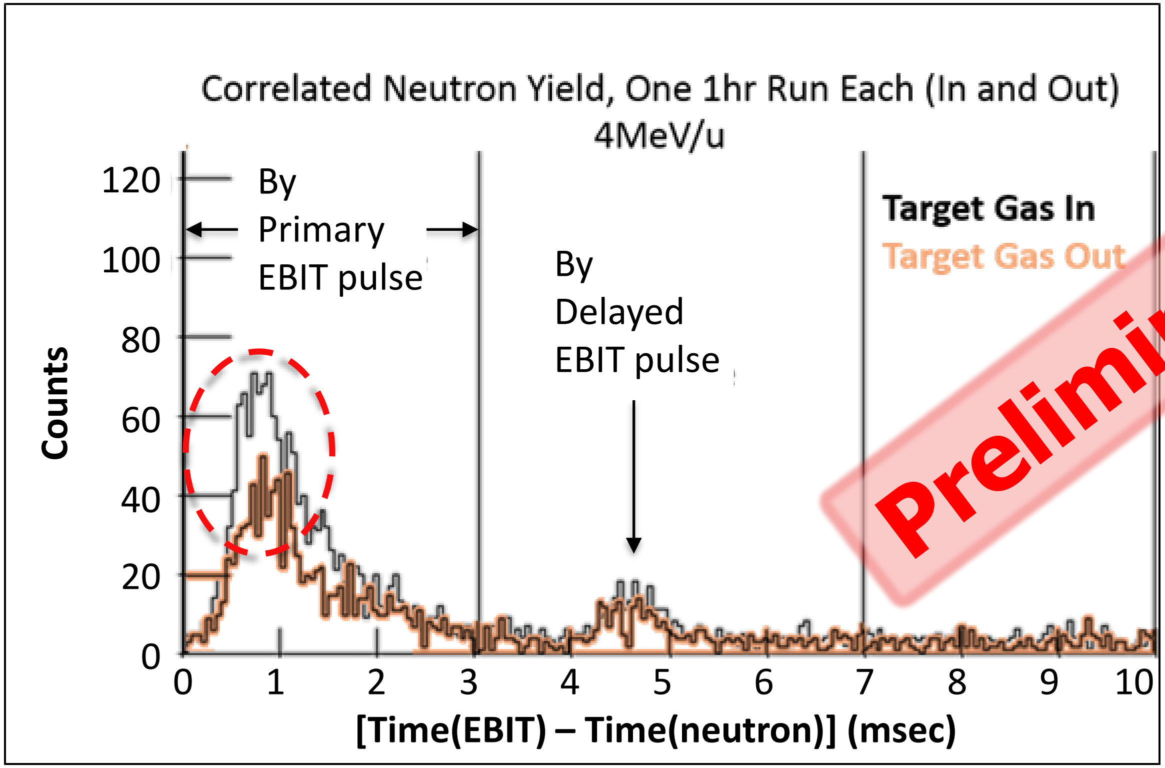
- RIB ($^{75}Ga^{26+}$) beam of five energies (4.0, 3.79, 3.58, 3.14 and 2.91 MeV/u)
- Purity: ^{75}Ga = 95%, ^{78}Kr = 4%, ^{75}Ge = 1%
- Beam intensity: more than 6000pps in average



PID plot in the PSIC

Neutrons from ^{75}Ga(α,*n*) reaction

- Neutron were detected in EBIT-HabaNERO correlation spectrum.
- Neutron excess of ^{75}Ga(a,n) reaction from comparison of 4He gas-in and gas-out run



Correlated neutron spectrum with the EBIT signal to compare between gas-in and out run

Summary

- Disagreements on the very metal poor halo stars for elements between Z=37 and 47.
- One proposal for the issue is a failed r-process to make (α,n) reactions happen to build up higher Z elements earlier than the r-process.
- (α,n) reaction rates are very uncertain and no experimental data exists.

➔ **Experimental (α,n) measurements are necessary to reduce the uncertainties.**

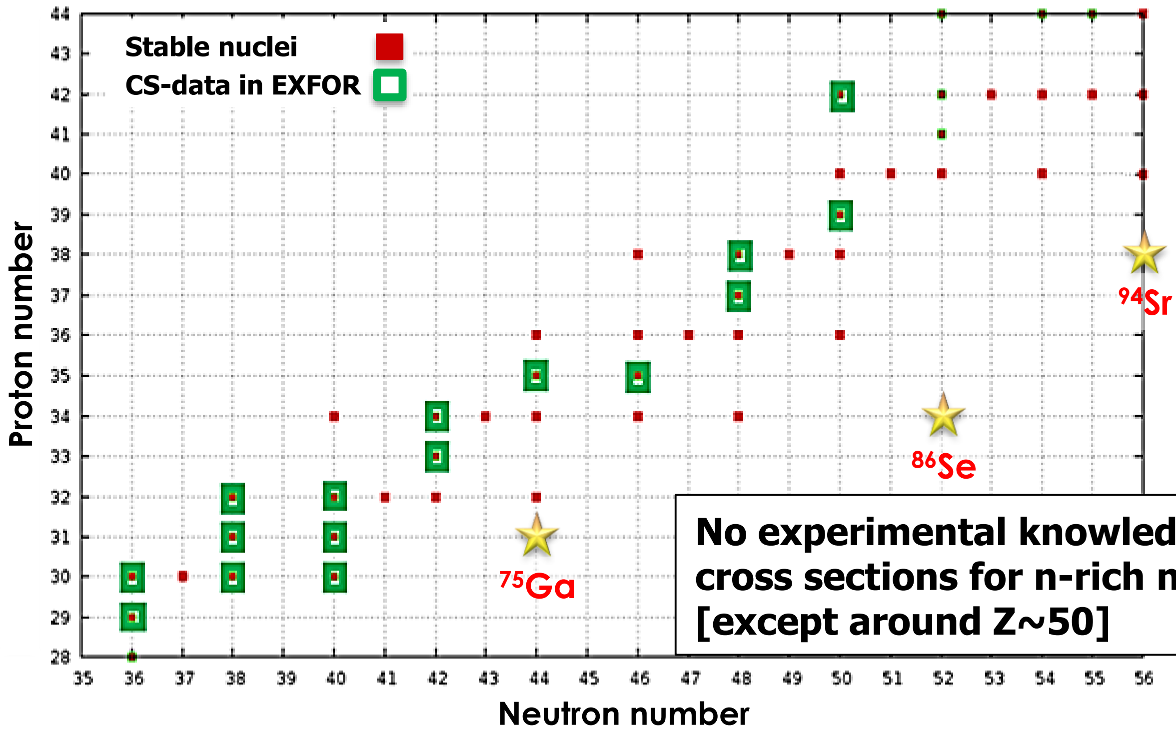
- **^{75}Ga(α,n) reaction in inverse kinematics experiment performed at ReA3, NSCL.**
- Neutron energy can go up to 20 MeV from the kinematics calculations.
- HABANERO is completed for the development and commissioned at Ohio University.
- RIB ($^{75}Ga^{26+}$) beam searching for neutrons from 4He gas cell target.
- Neutrons were seen in the EBIT-HabaNERO correlation spectrum.

- **Data Analysis is under progress.**
  - ✓ We are working on the efficiency of the HabaNERO using Ohio data.
  - ✓ Neutron cross section of stable beam will confirm the efficiency measurement.
  - ✓ One correlation code will be applied to both the stable beam data and RIB beam data.

[Back up Slides]

No Experimental data for (α,n) cross sections

- Some (α,*n*) reactions control the production of the dominant elements. e.g. ^{86}Se(α, x*n*), ^{75}Ga(α, x*n*), ^{94}Sr(α, x*n*) and so on.

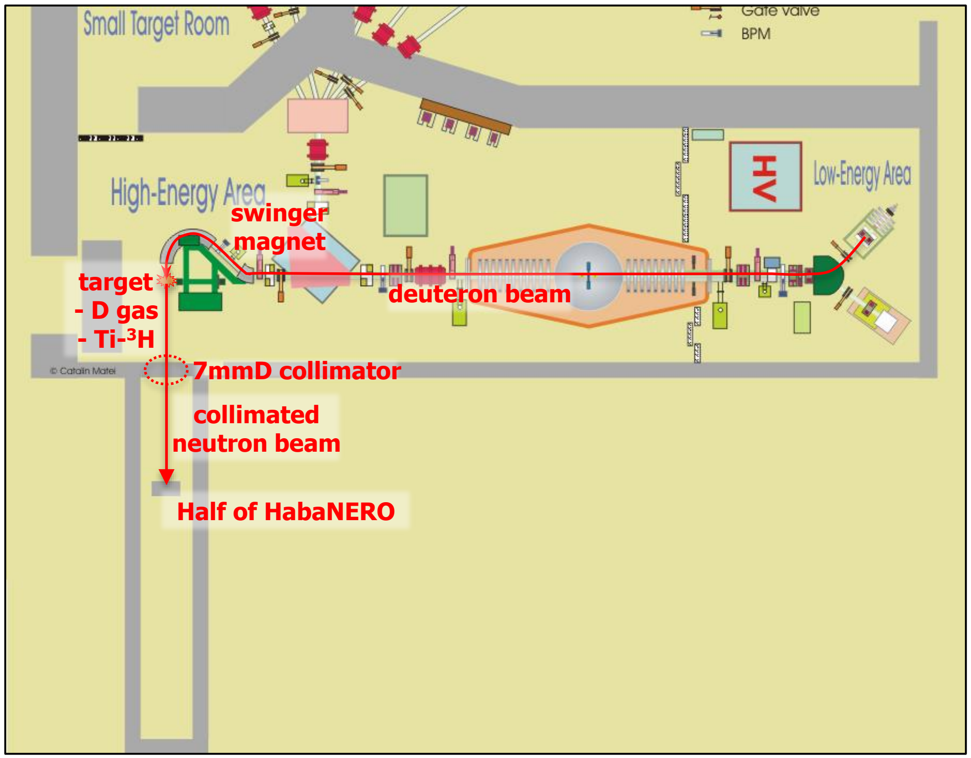


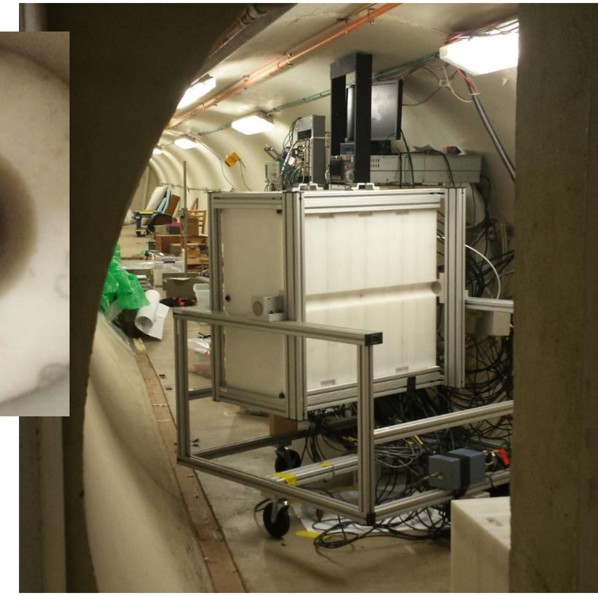
No experimental knowledge of (α,x*n*) cross sections for n-rich nuclei [except around Z~50]

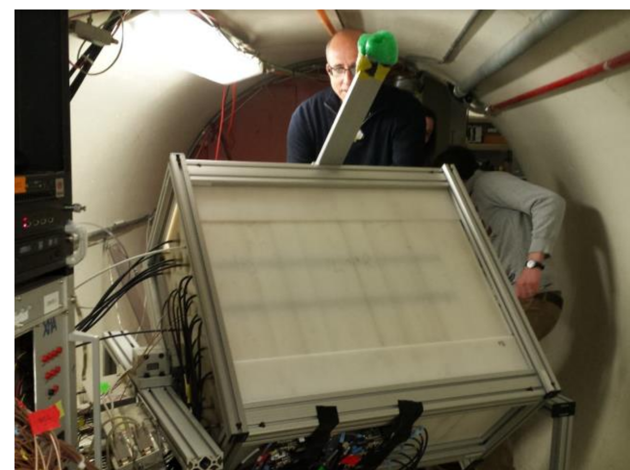
Experimental data for (*α*,*n*) reaction cross section
Compiled by Z. Meisel

HabaNERO Commissioning at OU

- Mono-energetic beam at EAL, Ohio University
- En = 4, 7 MeV by D(d,n) and 14 MeV by T(d,n)

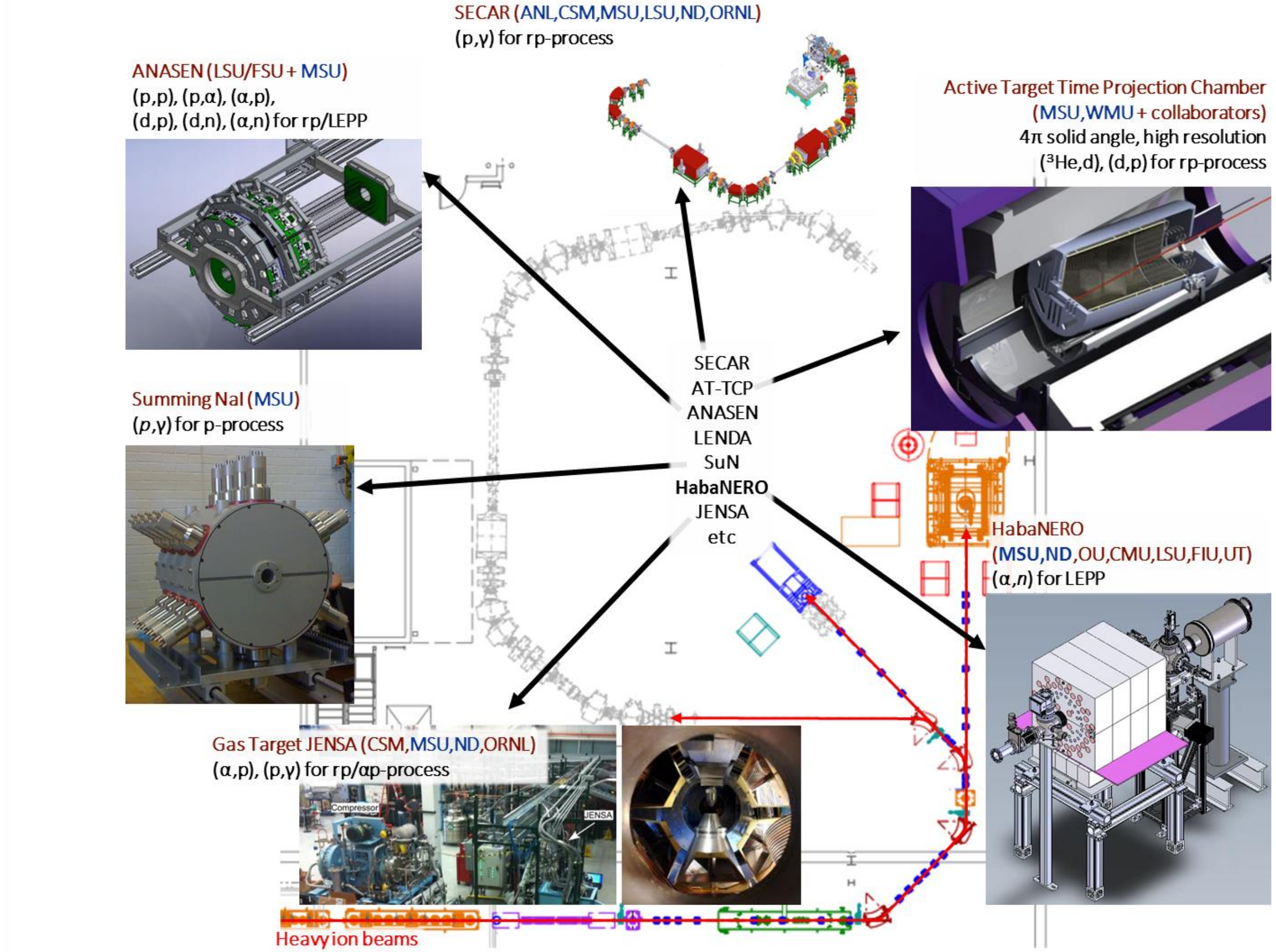






Collimator and Detector Setup Photos

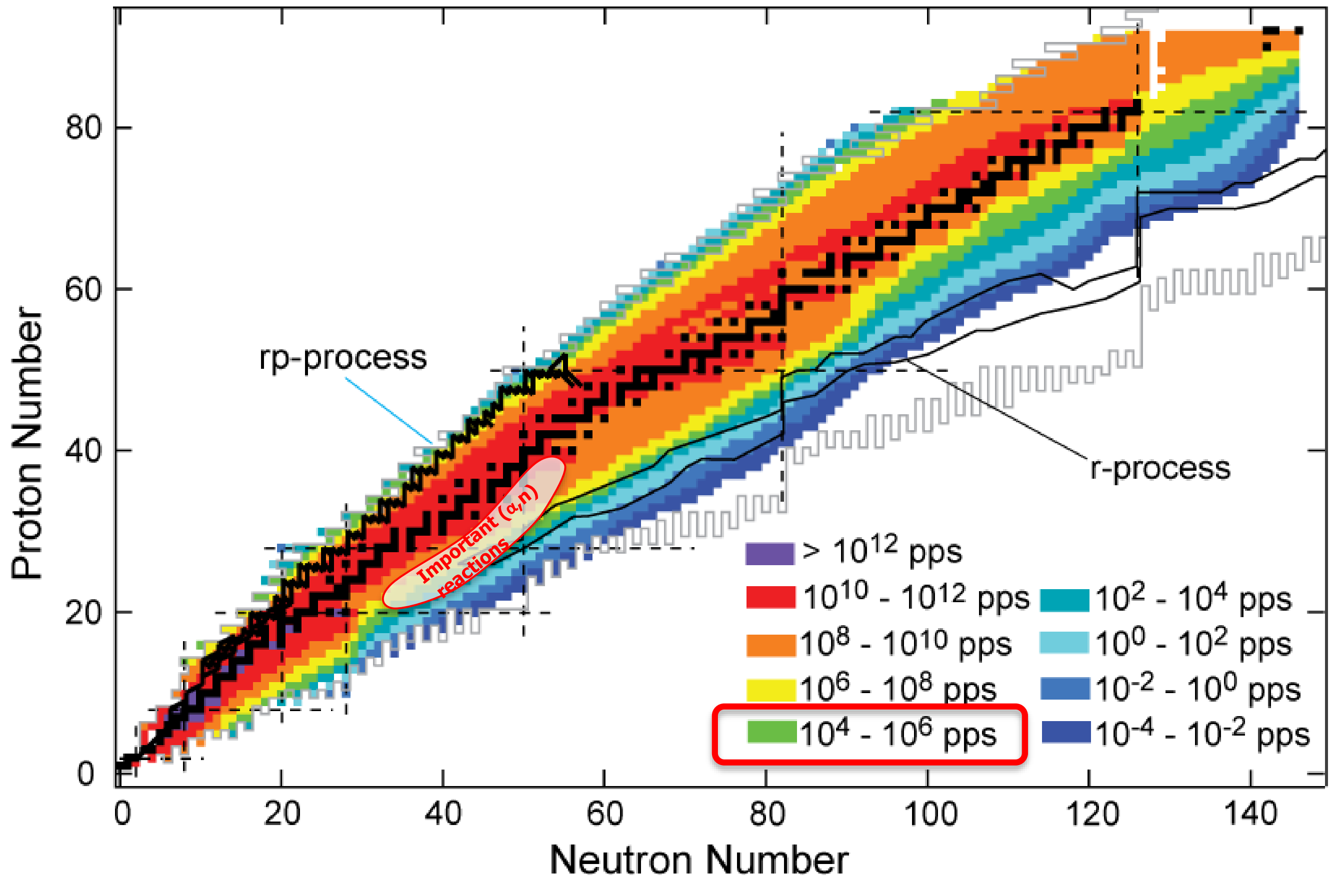
ReA3 Experimental Station



Experimental Devices in ReA3 beam line

Possible (α,*n*) reaction studies with FRIB

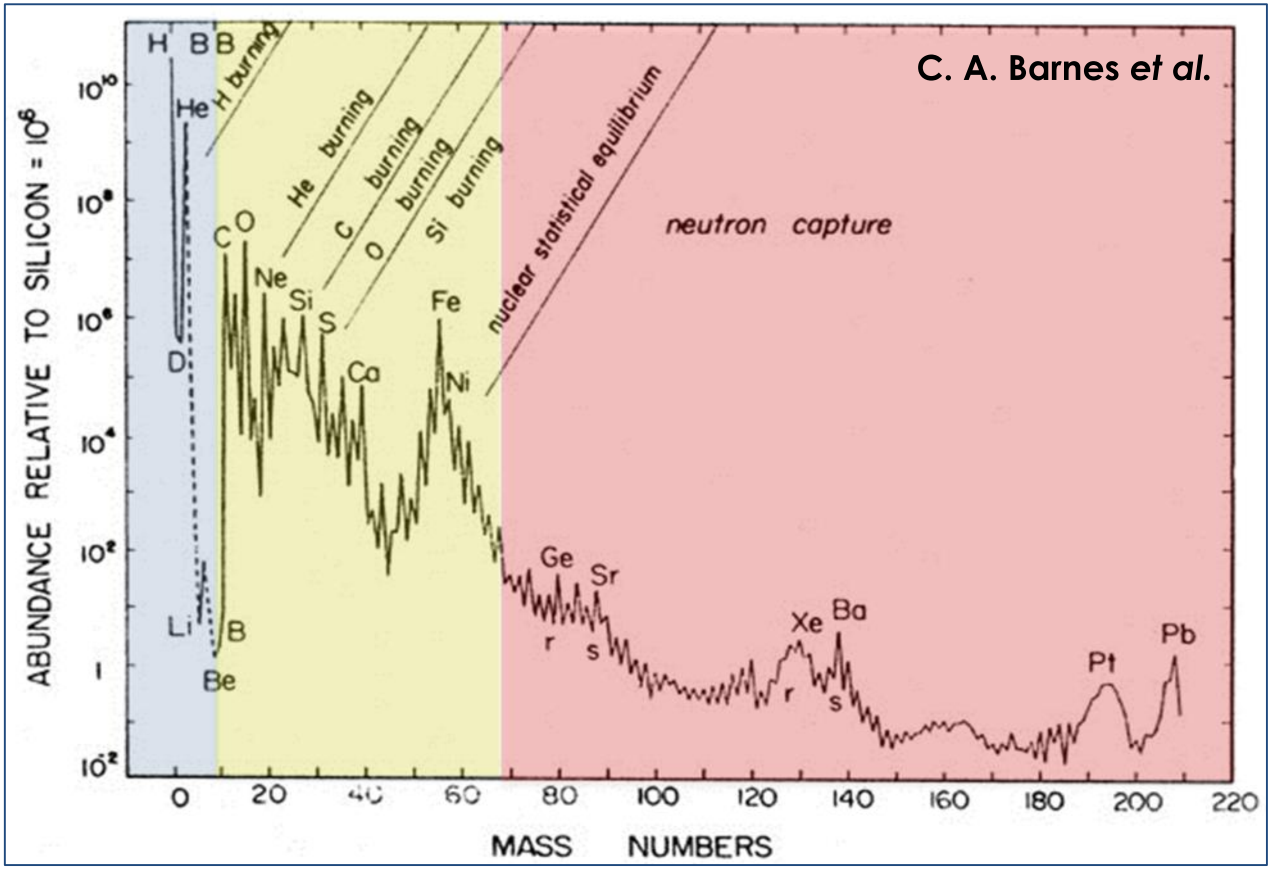
- FRIB will provide 1000-10000 times higher beam rates than current beam rates at NSCL.
- The beam rate of interesting (α,n) measurements > 10^3 pps



Projected beam rate by future FRIB

Solar Abundance Patterns

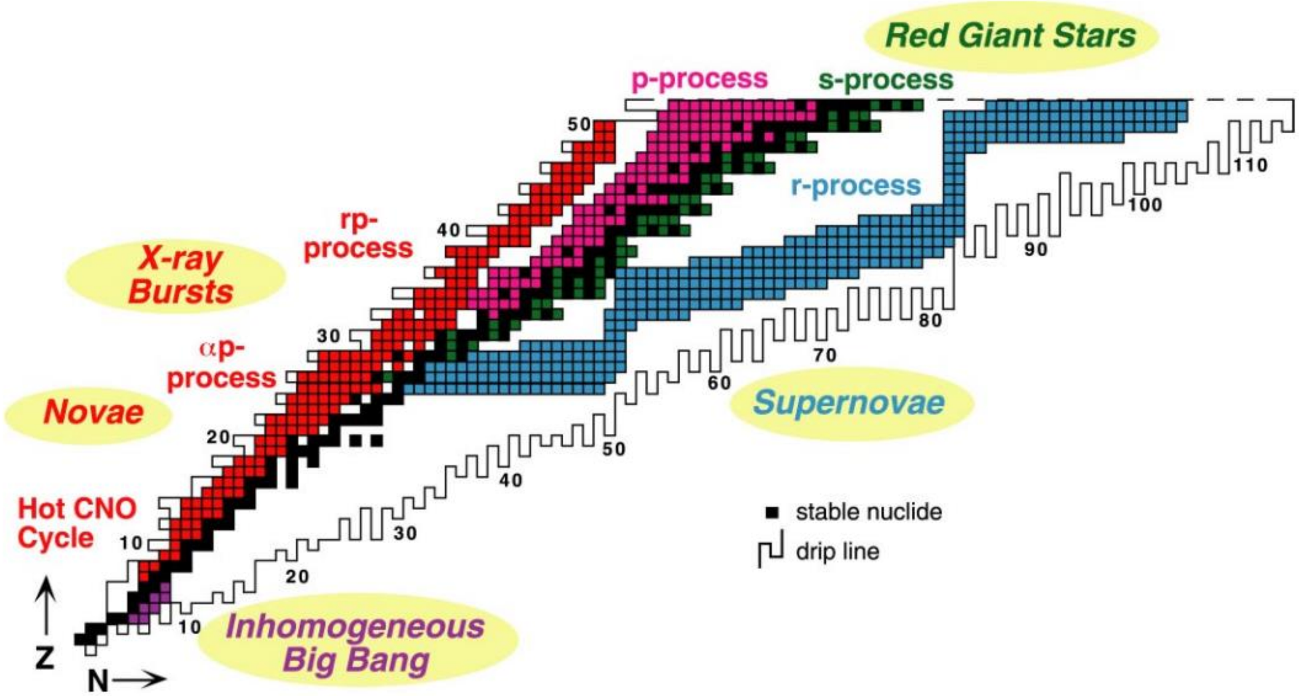
- "How and where were all of the elements created in the universe?"
- "How do stars burn and explode?"
- Abundance pattern = historical evidences of element formation



Solar abundance distribution

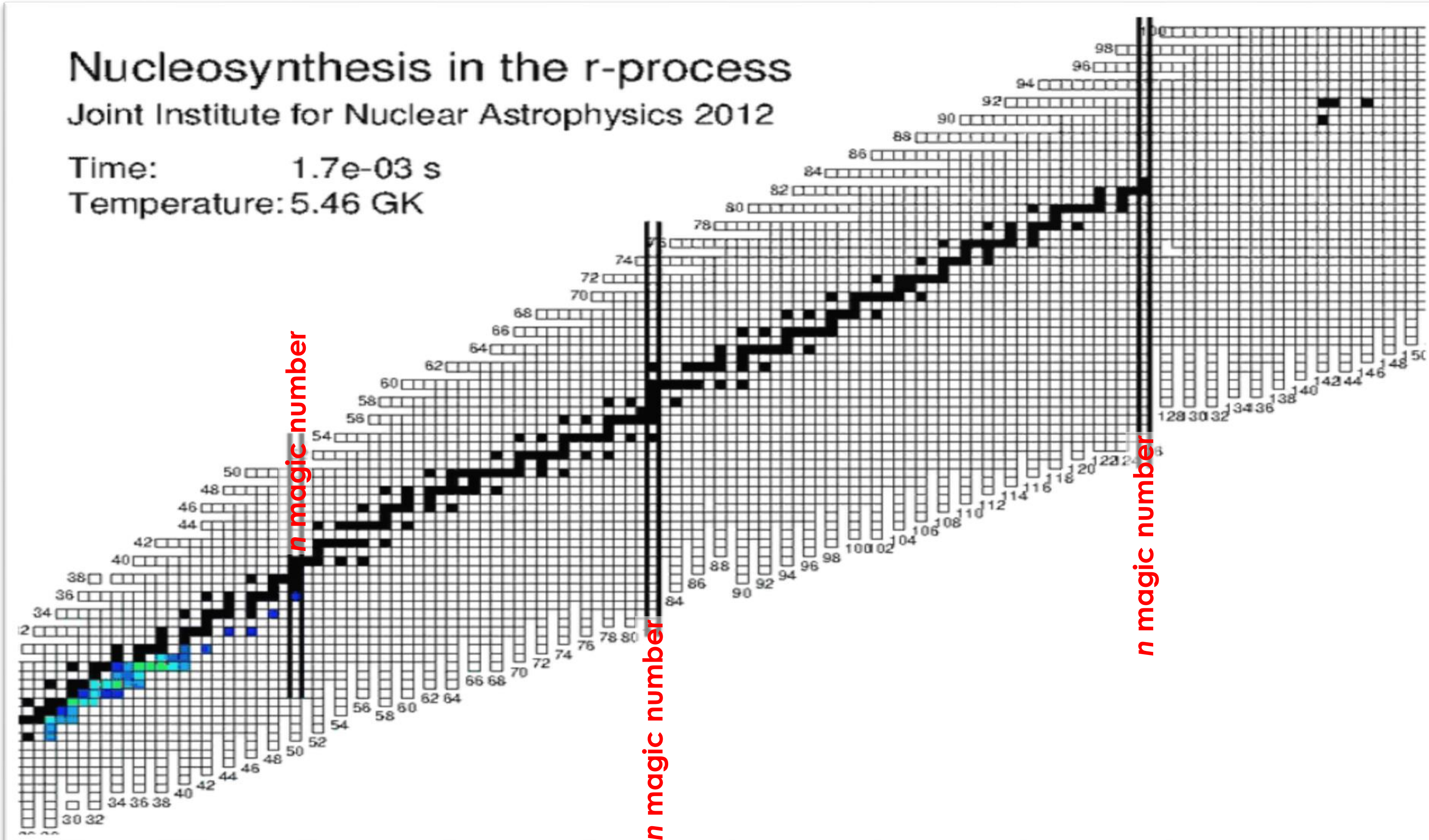
Nucleosynthesis Paths

- All of processes are suggested to explain heavy elements of the solar abundance pattern.
- What are major components to determine the path?
  - ✓ Astrophysics environment: T, *n* density, Y_e, time and neutrino presence
  - ✓ Nuclear Physics Properties: mass, Q-value, $T_{1/2}$, P_n, level densities and **reaction rates**

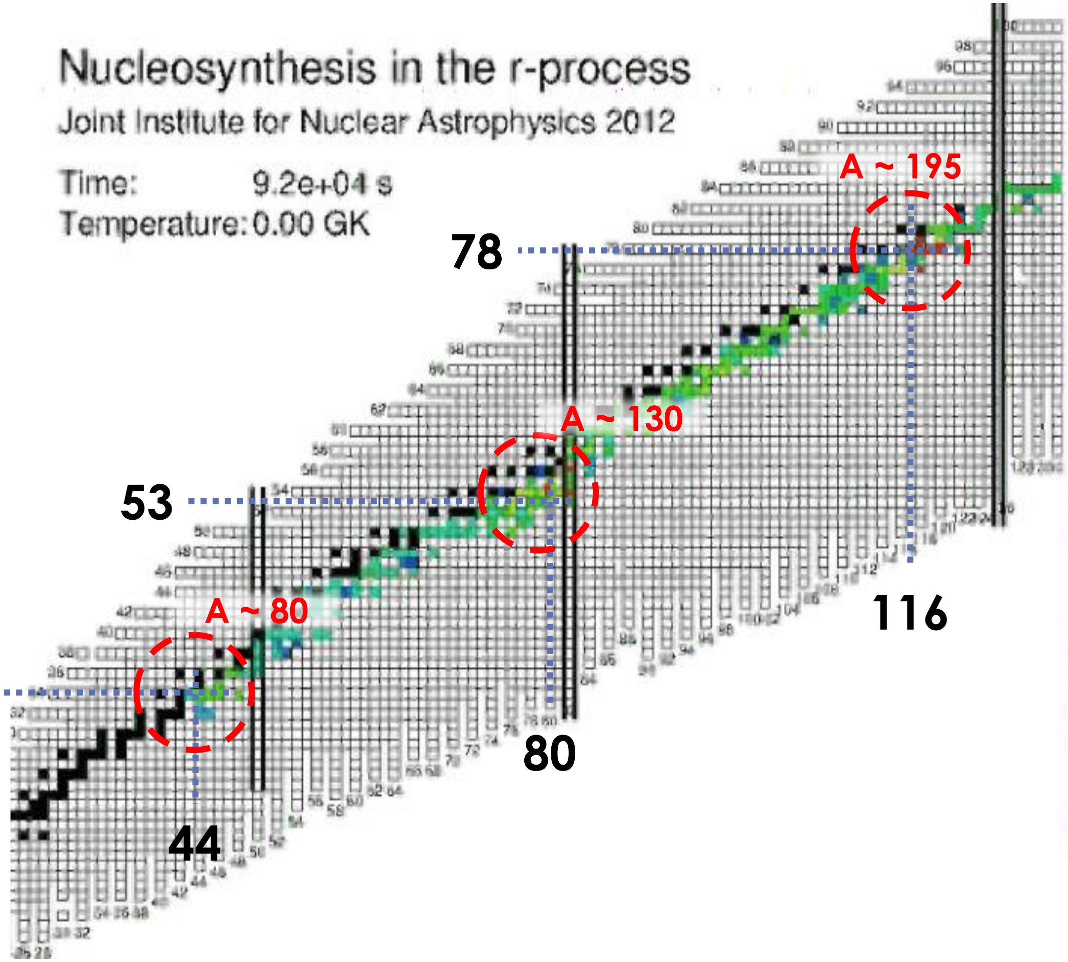


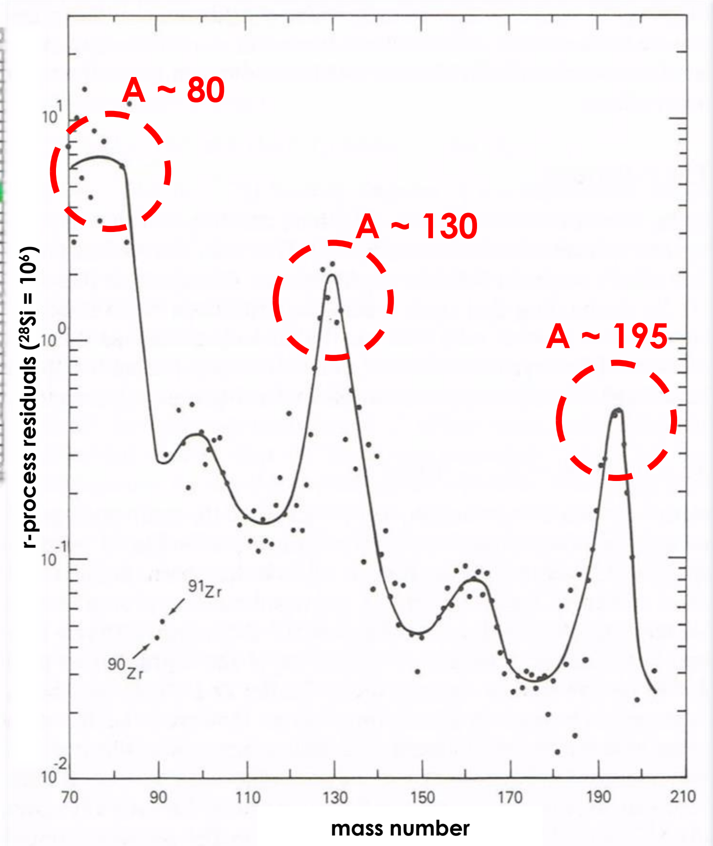
Nuclear Chart with nuclosynthesis paths
M. S. Smith and K. E. Rehm
Ann. Rev. of Nucl. Part. Sci., 51:91, 2001

Rapid Neutron Capture Process (r-process)



r-process Model Reproduces Abundance Peaks



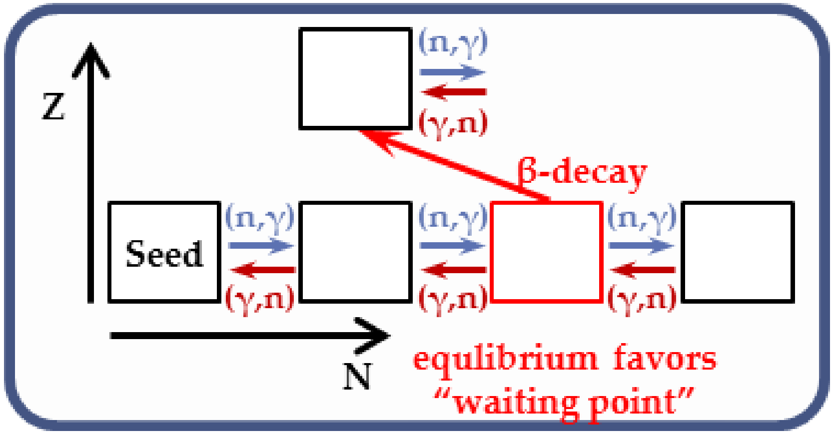


r-process yields
from solar abundance patterns
F. Kappeler *et al.*
Rep. Prog. Phys. 52 945 1989

What do we need for the r-process?

- Neutron capture physics set by two compositions:
  - ✓ neutron capture: n + (A,Z) ↔ (A+1,Z) + γ
  - ✓ β decay: (A,Z) ↔ (A,Z+1) + e^- + ν_e

- Requirements:
  - ✓ **Neutrons are very abundant (Y_n/Y_{seed} ~ 100).**
    - → Capture reactions occur even at small thermal speeds.
    - → No Coulomb barrier
  - ✓ Heavy seed nuclei (e.g. ^{56}Fe)



Neutron capture process diagram

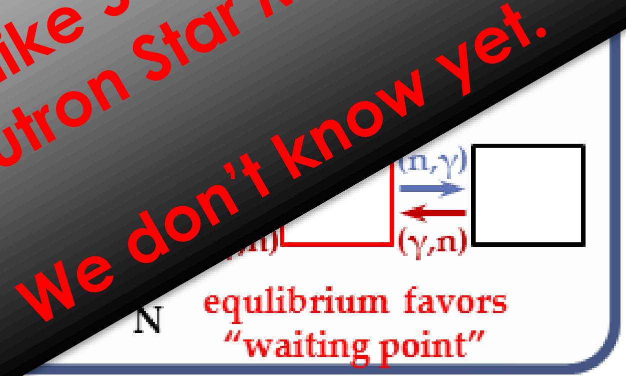
Any known site for the r-process yet?

- Requirements:
  - ✓ **Neutrons are very abundant (Y_n/Y_{seed} ~ 100).**
    - → Capture reactions occur even at small thermal speeds.
    - → No Coulomb barrier
  - ✓ Heavy seed nuclei (e.g. ^{56}Fe)

- Neutron capture physics set by two composi
  - ✓ neutron capture: n + (A,Z) ↔ (A+1
  - ✓ β decay: (A,Z) ↔ (A,Z+1) + e

Possible Astrophysical sites:
Core Collapse Supernovae?
Jet-like Supernovae?
Neutron Star Mergers?

We don't know yet.



Neutron capture process diagram

LEPP and (α,n) reactions

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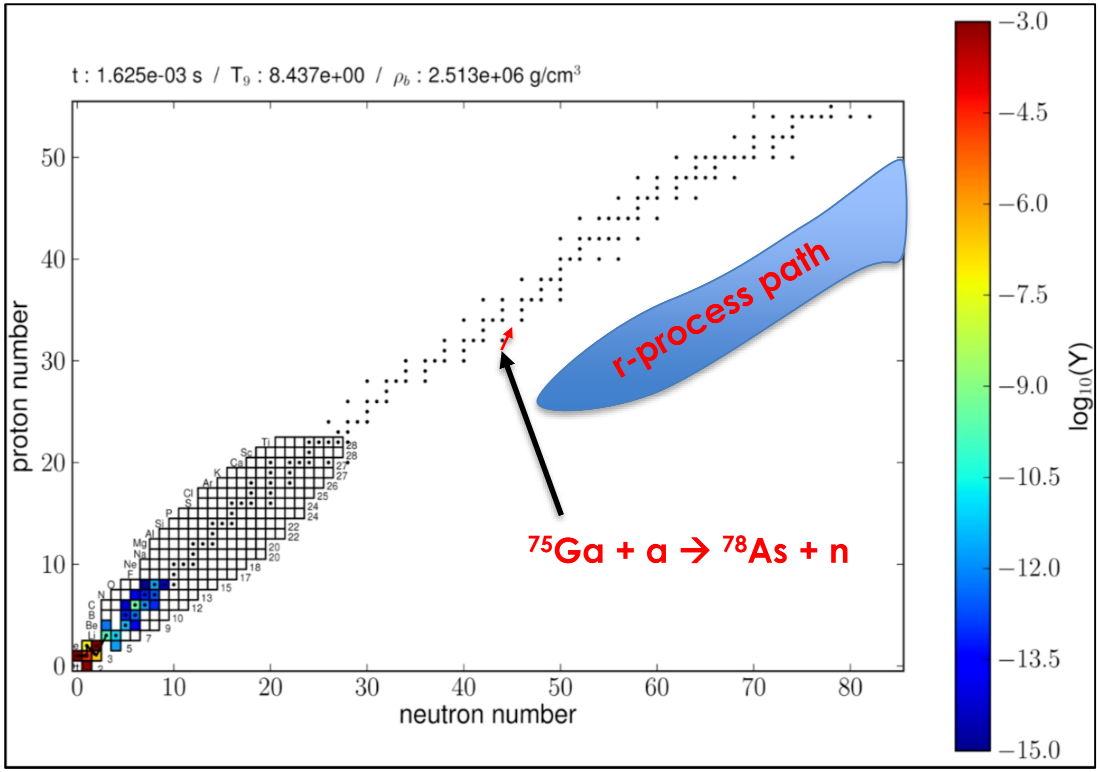
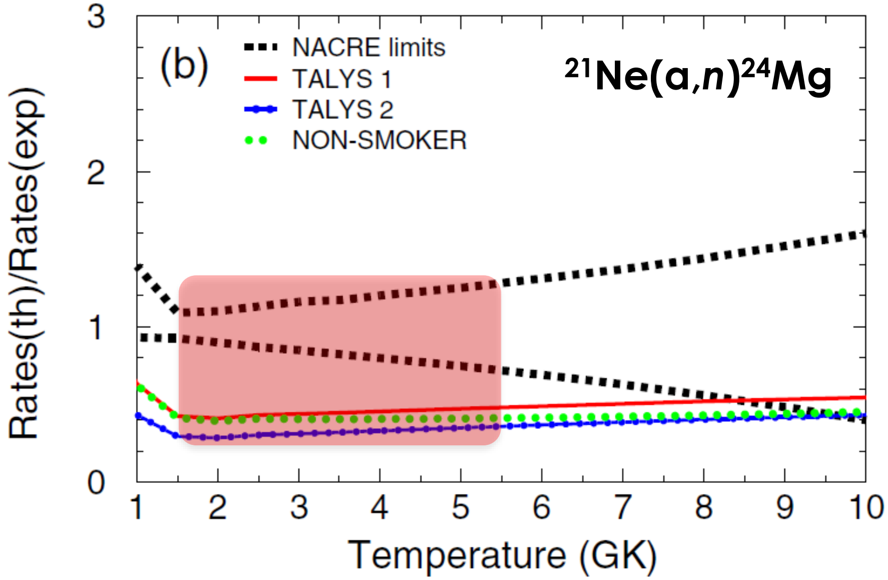
- (*α,n*) reactions provide enough abundances for low Z elements.



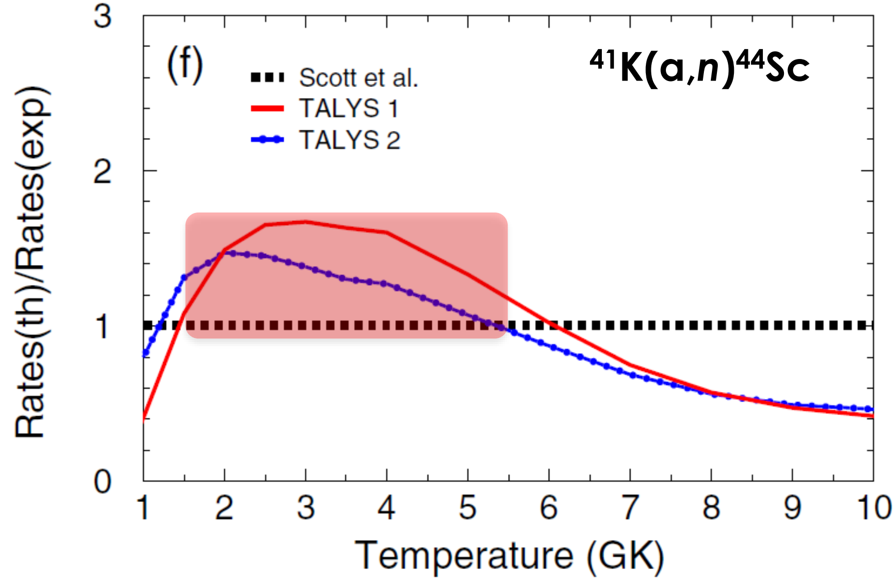
A Nucleosynthesis simulation in the incomplete r-process considering dominant (α,n) reactions

(α,n) cross sections from reaction code

- How accurate the (α,n) cross sections for the LEPP model?
- (α,*n*) reaction rates for **stable nuclei** looks good.



^{21}Ne(α,*n*)^{24}Mg reaction rate ratio w/ various HF code
J. Pereira and F. Montes, Phys Rev C 93, 034611 (2016)



^{41}K(α,*n*)^{44}Sc reaction rate ratios w/ various input
J. Pereira and F. Montes, Phys Rev C 93, 034611 (2016)

HabaNERO with OU people!

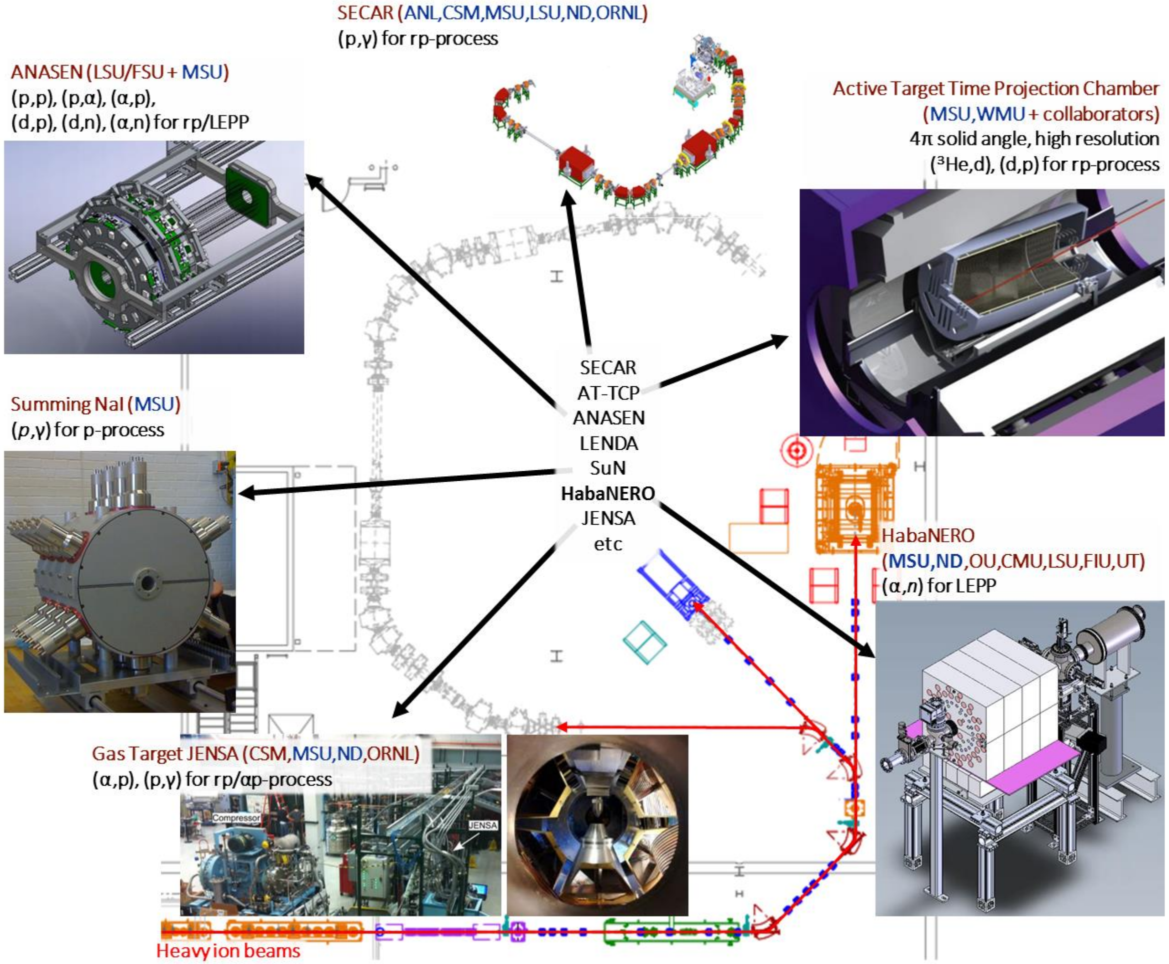
- Three weeks of experiment

Thank you!





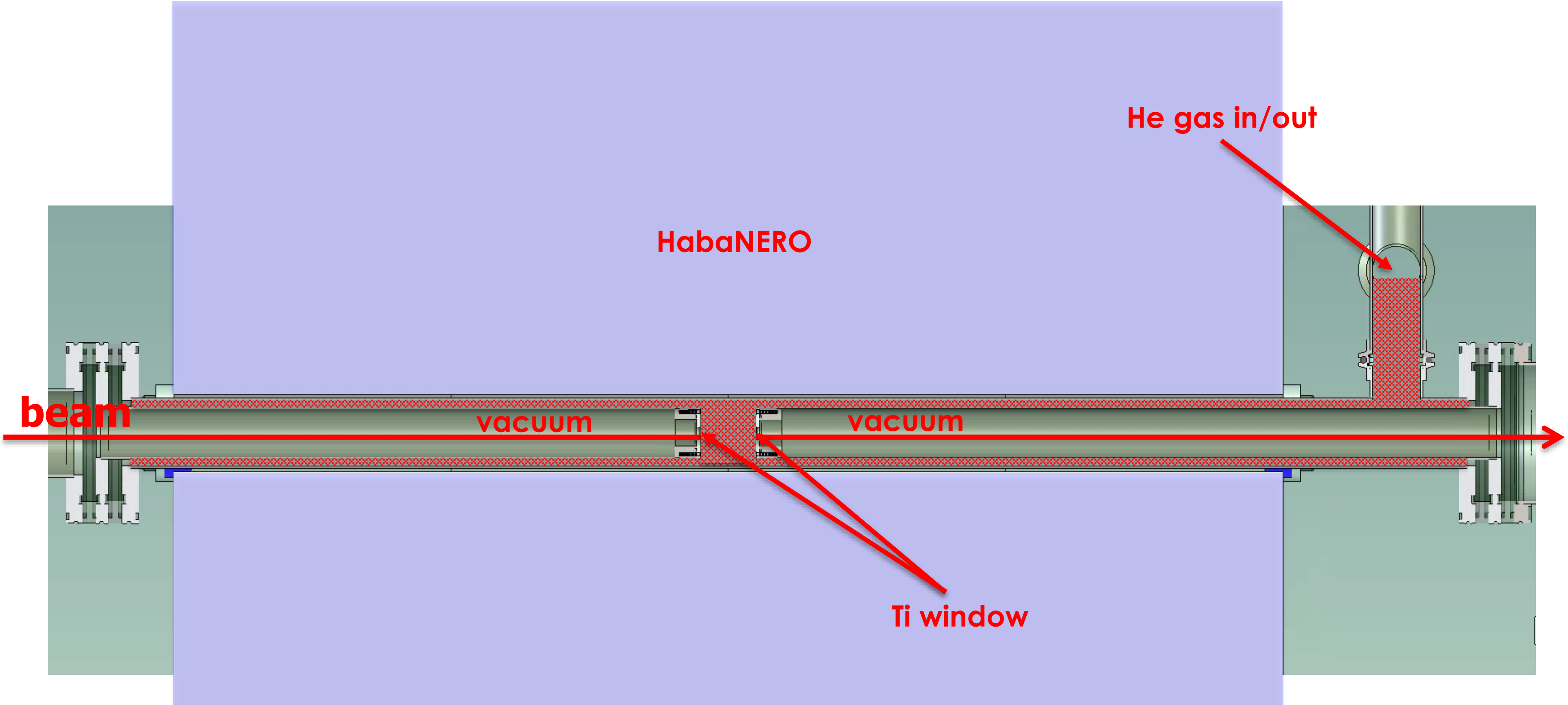
ReA3 Experimental Station



Experimental Devices in ReA3 beam line

He gas cell target

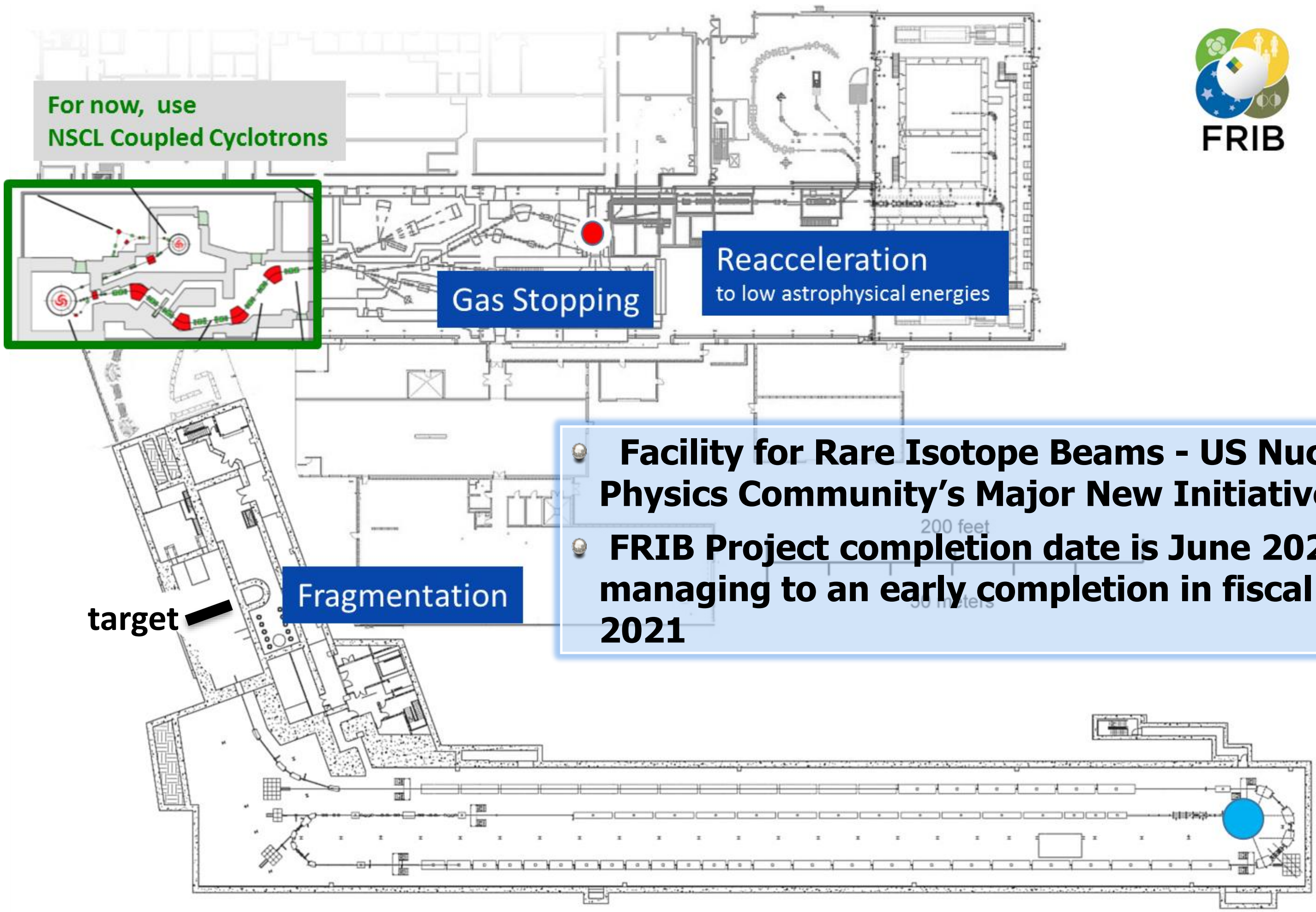
- 2um thickness Ti window foil
- large gas volume



Projection of the He gas cell target design

Great Opportunities with FRIB

FRIB

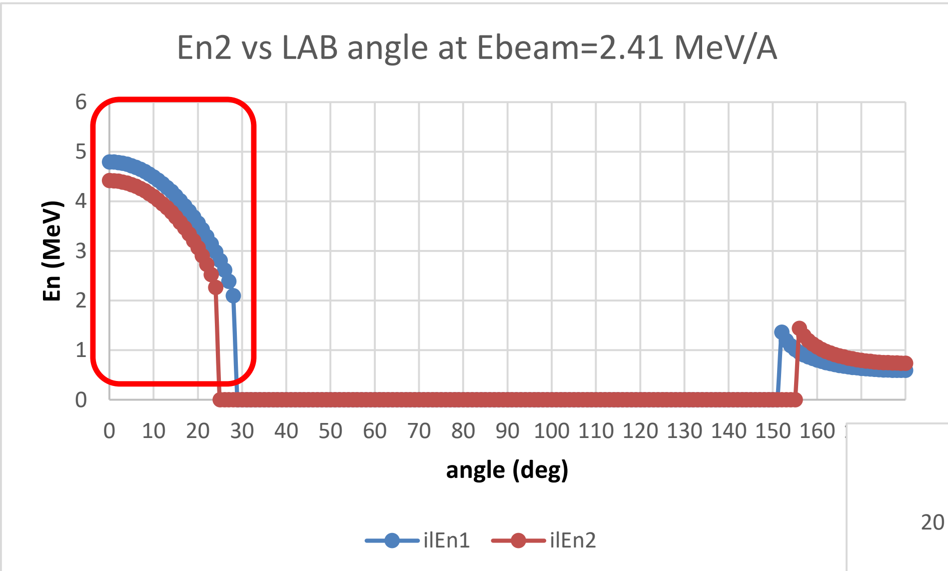


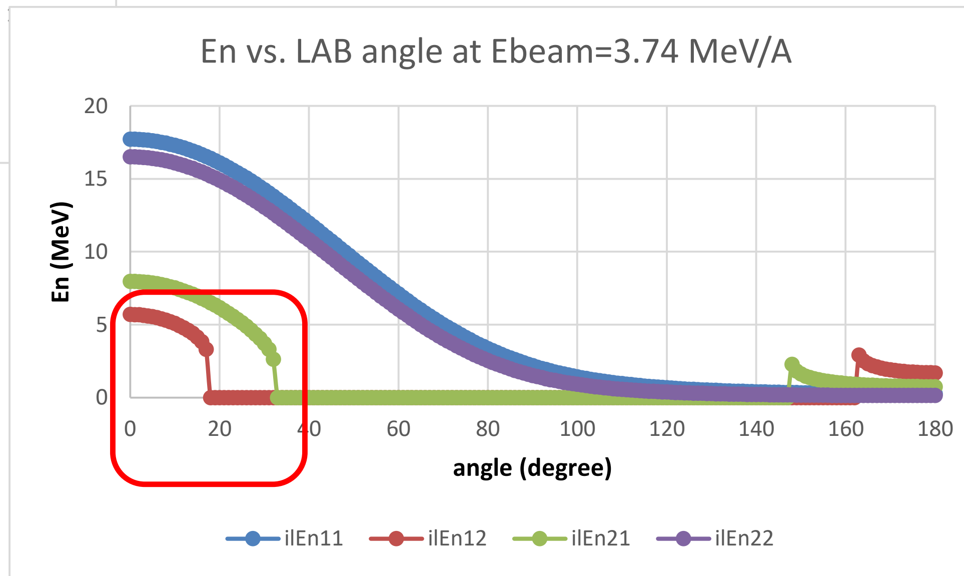
- Facility for Rare Isotope Beams - US Nuclear Physics Community's Major New Initiative
- FRIB Project completion date is June 2022, managing to an early completion in fiscal year 2021

FRIB layout

Angular dependency of efficiency on (α,2n) kinematics

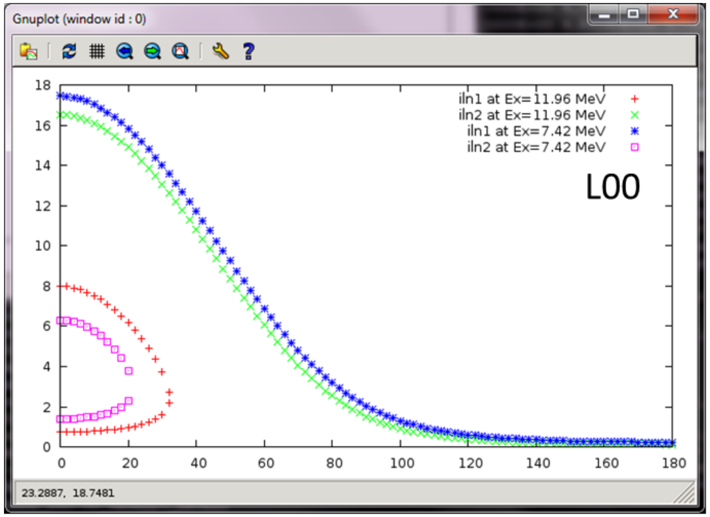
1. **As you lower the energy of neutron, it seems the angular dependency of the efficiency gets smaller.**

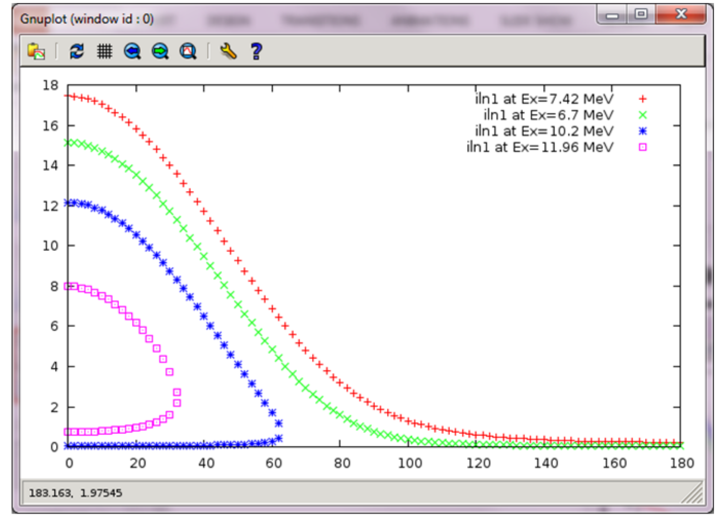


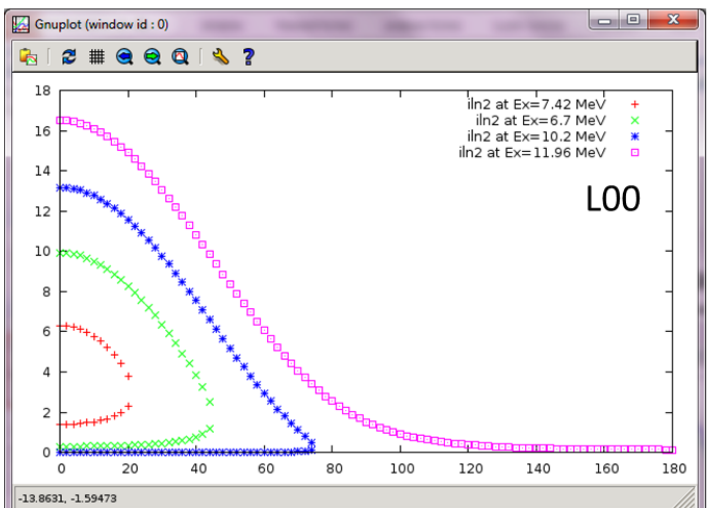


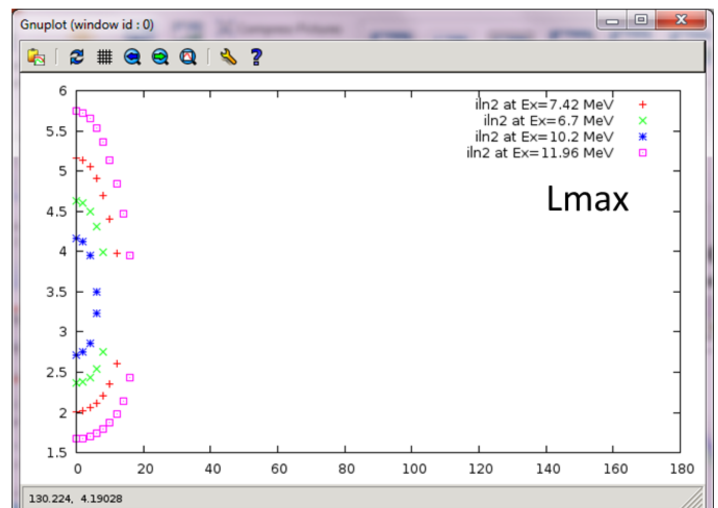
Angular dependency of efficiency on (α,2n) kinematics

1. E_{beam} = 3.74 MeV/A in inverse kinematics



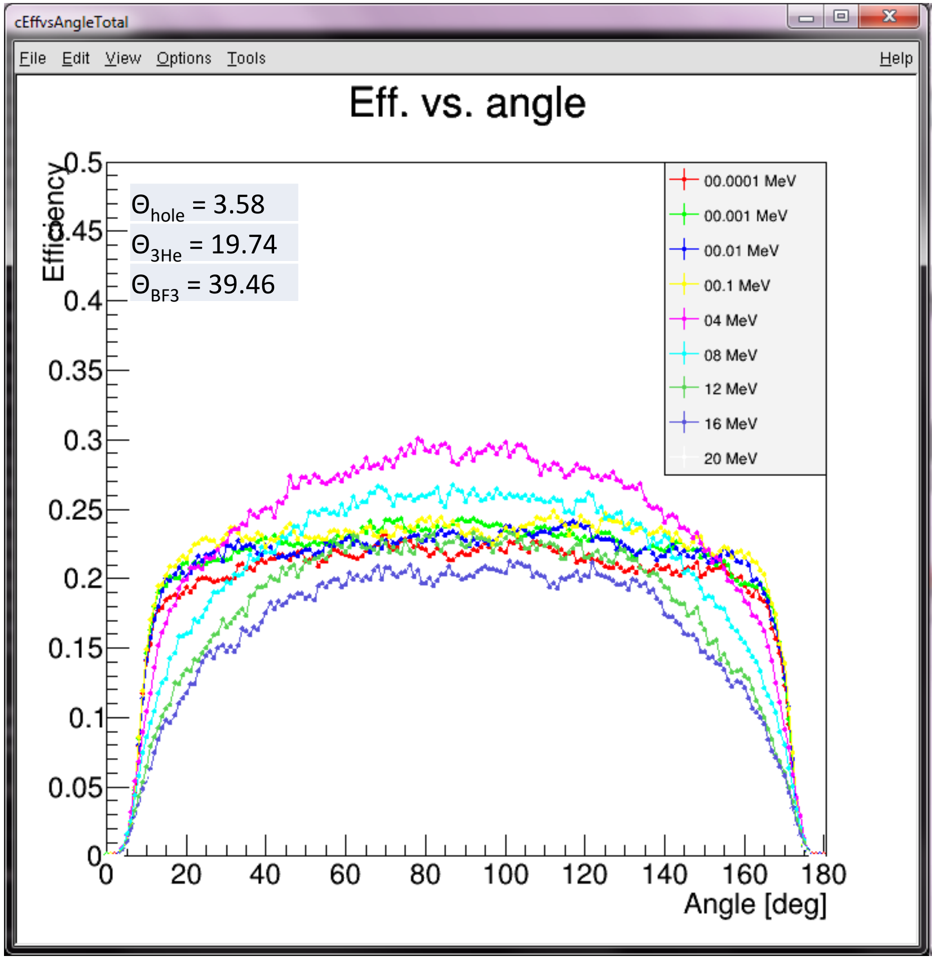


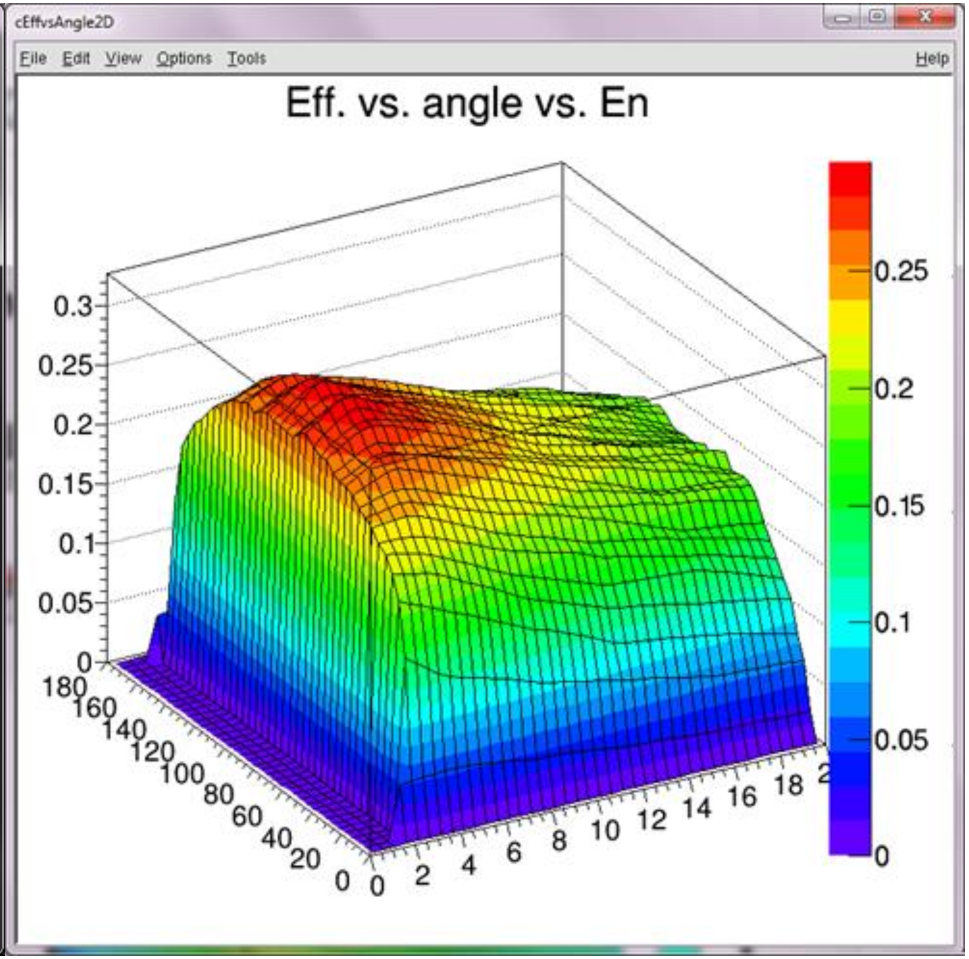




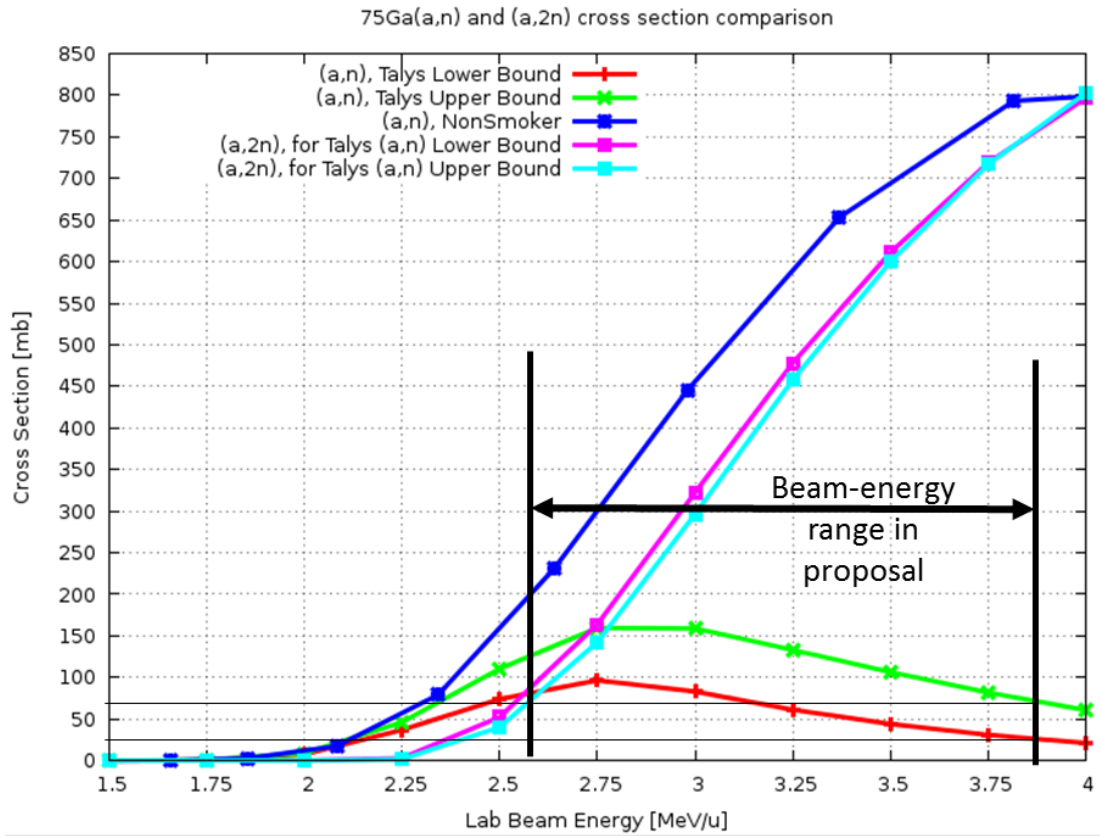
Angular dependency of efficiency down to 0.1keV

1. **As you lower the energy of neutron, it seems the angular dependency of the efficiency gets smaller.**





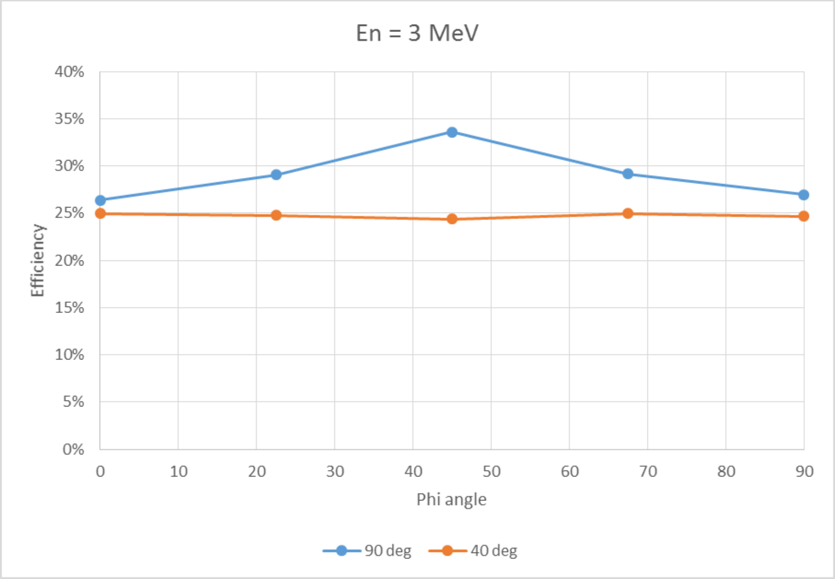
$^{75}Ga(\alpha,n)$ cross section by TALYS code

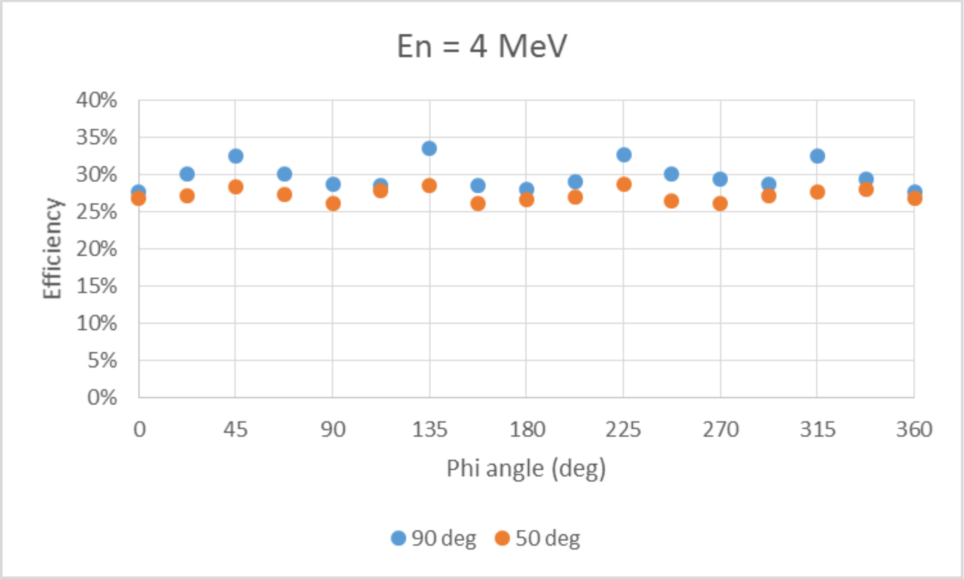


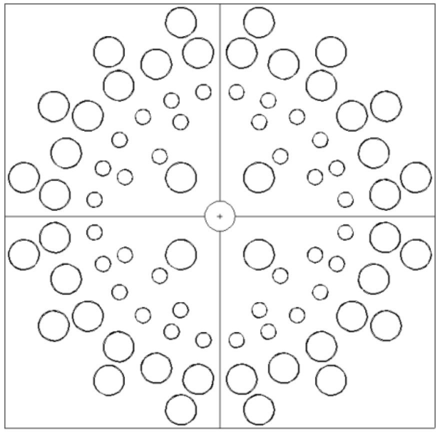
Calculated (a,n) and (a,2n) cross sections from TALYS code

Efficiency vs. Phi angle

- **Efficiency vs. Phi angle with En = 3 MeV and Theta = 40/90 deg (Left Top) and with En = 4 MeV and Theta = 40/90 deg (Right Top)**

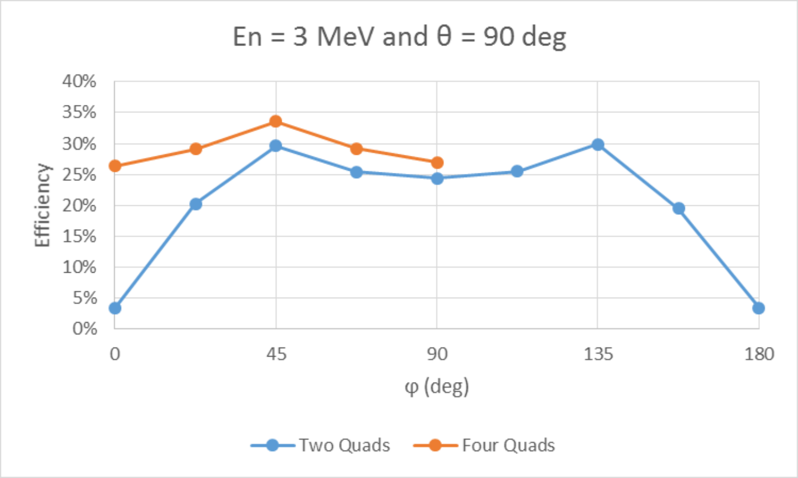


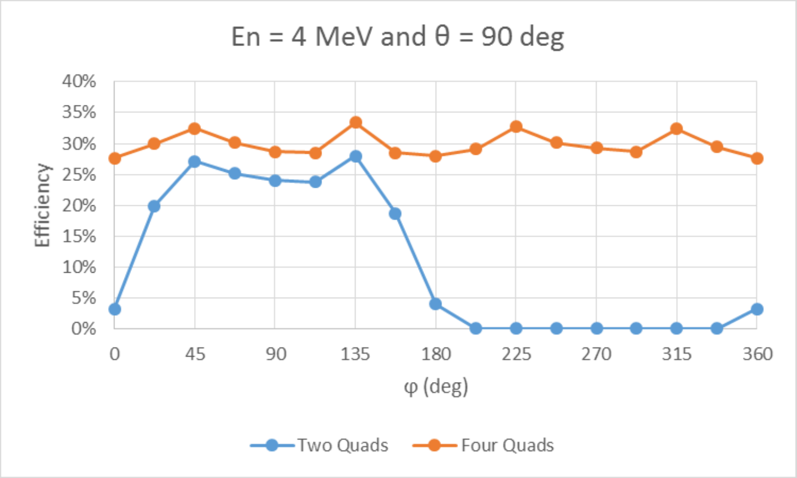


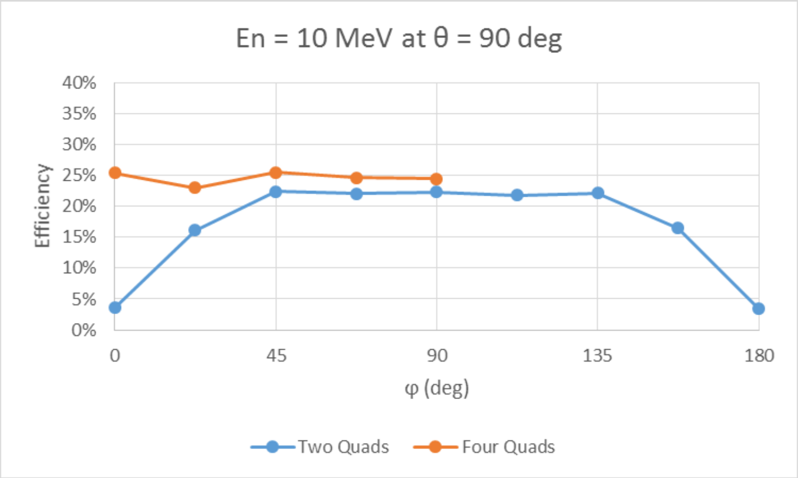


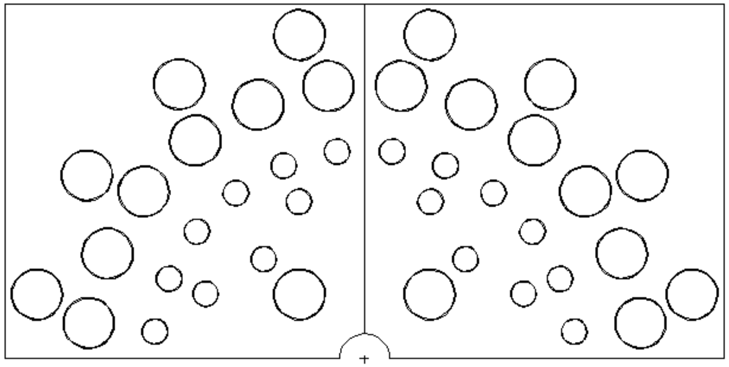
Differences on Efficiency vs. Polar angle

- Differences on Efficiency vs. Polar angle at a fixed En and theta angle between two quads and four quads



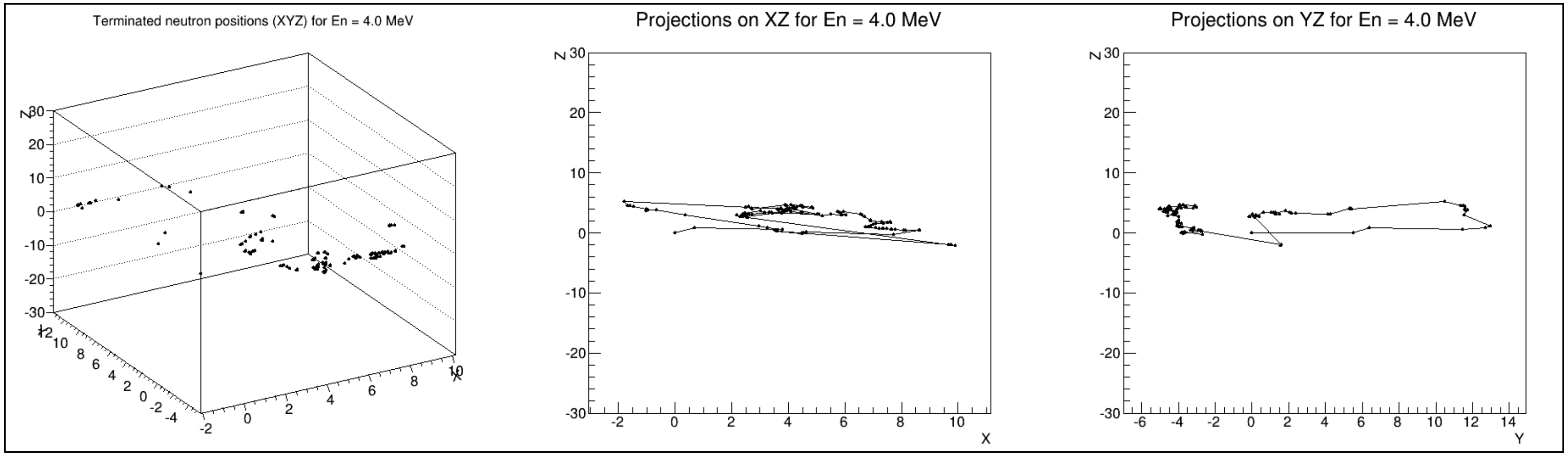


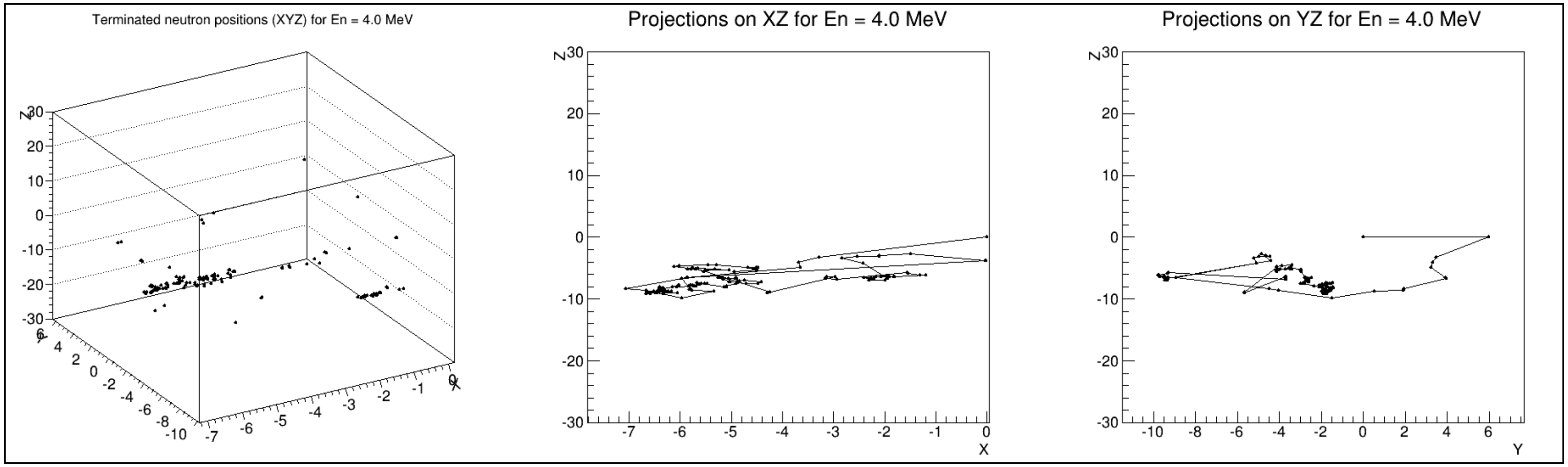




MCNP simulation result

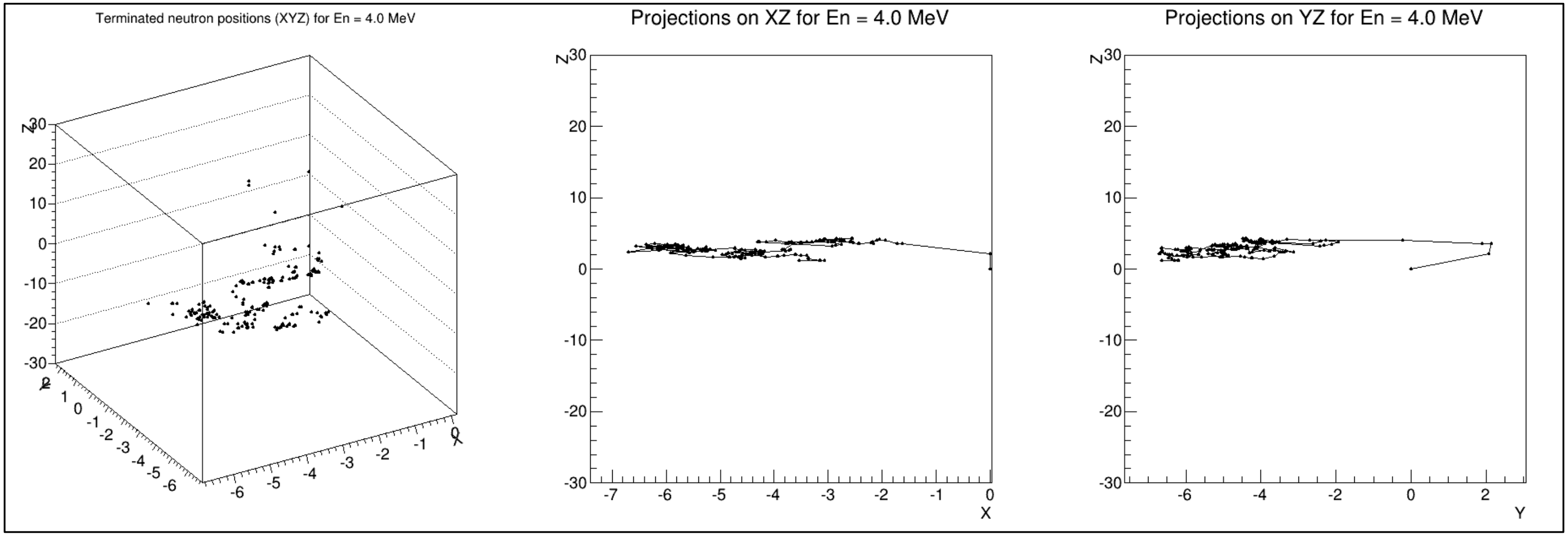
- **Particle Tracks for neutrons bouncing back to another side of quads (18 neutrons out of 76 generated at (theta,phi) = (90,90)**

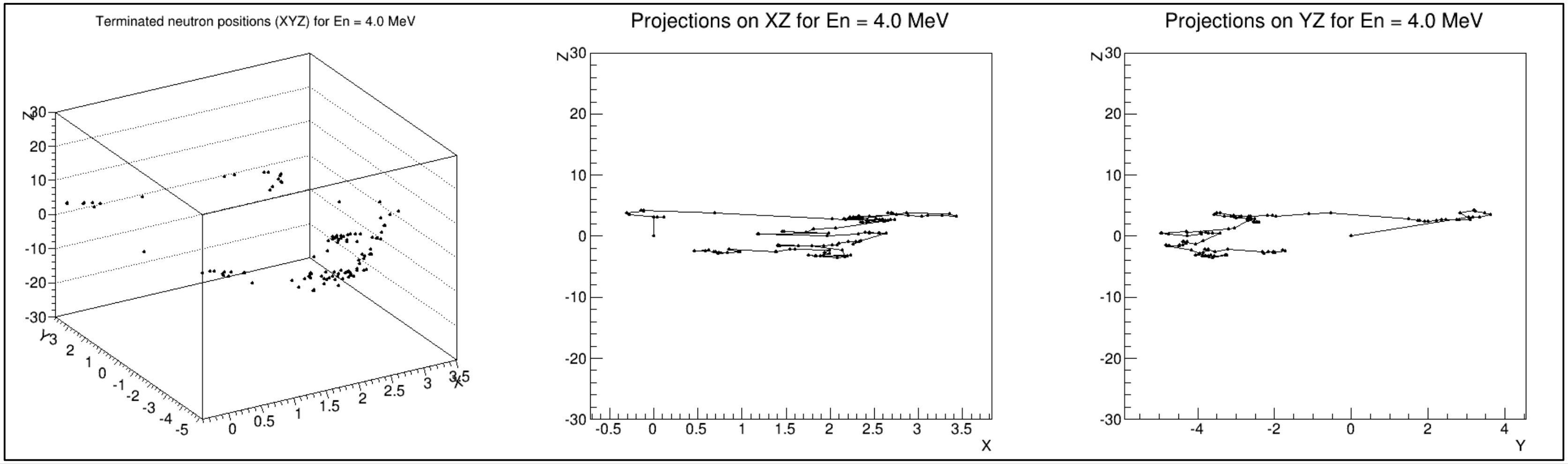




MCNP simulation result

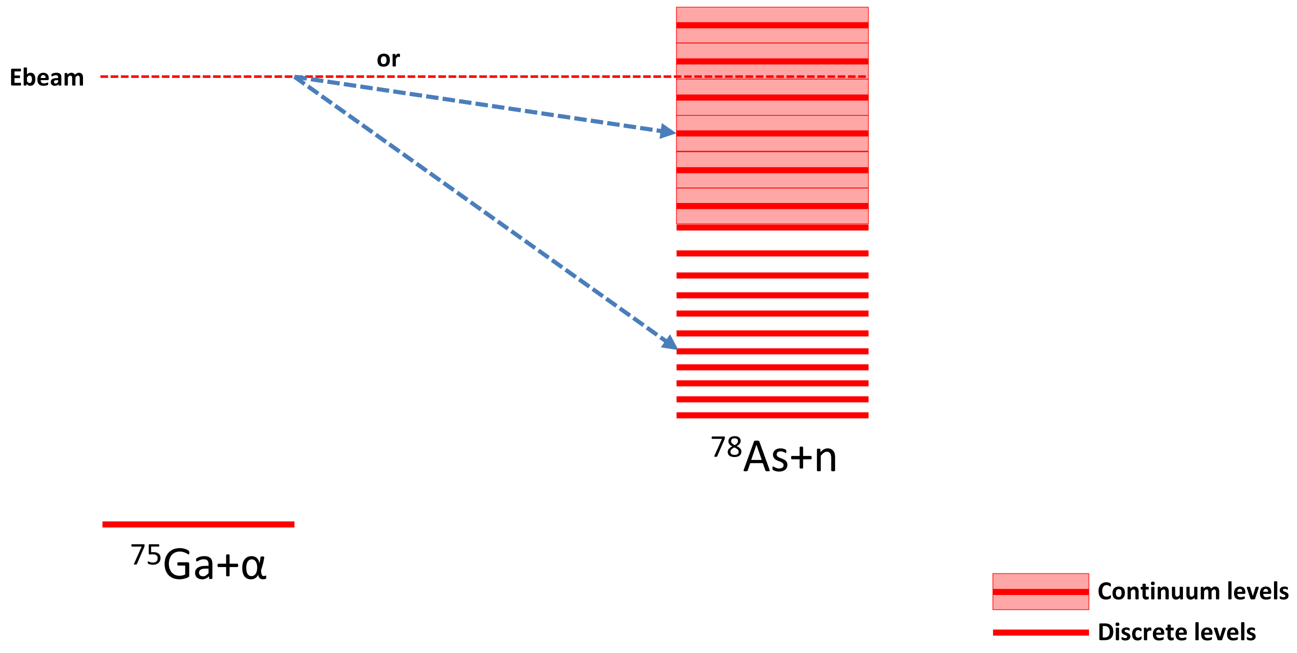
- **Particle Tracks for neutrons bouncing back to another side of quads (22 neutrons out of 97 generated at (theta,phi) = (90,45)**





Level Diagrams of $^{75}Ga(\alpha,n)$ reaction

1. Qg.s = -1.294 MeV

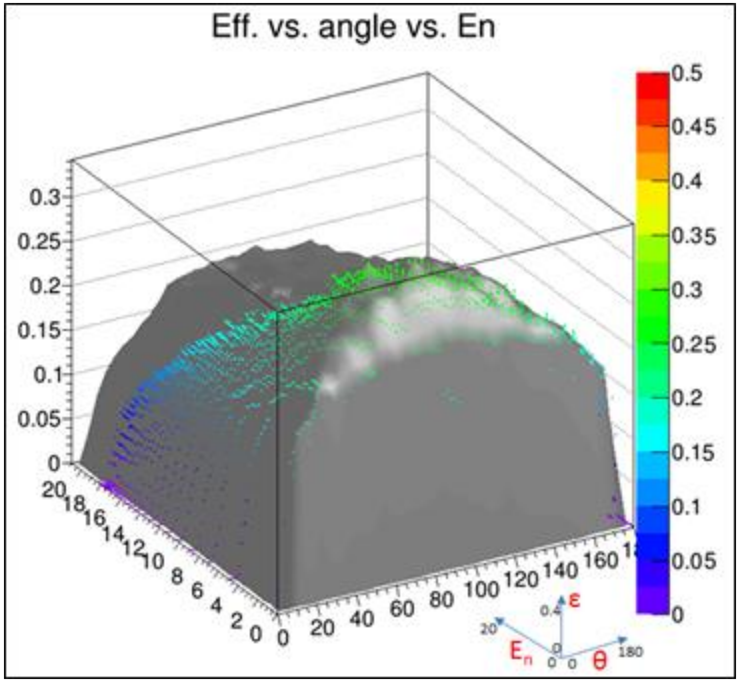


Efficiency curve for 75Ga(α,n) reaction

- HABANERO: Heavy ion Accelerated Beam induced (Alpha,Neutron) Emission Ratio Observer
- Properties:

1) Relatively high and flat efficiency for large energy range

2) For 0.1 MeV ≤ E_{n_isotr} ≤ 20 MeV, $<\varepsilon>=22$ %, $\delta\varepsilon=5$ %, $\varepsilon_{max}=27$ %, $\varepsilon_{E=0.1}=20$ %, $\varepsilon_{E=20}=17$ %.

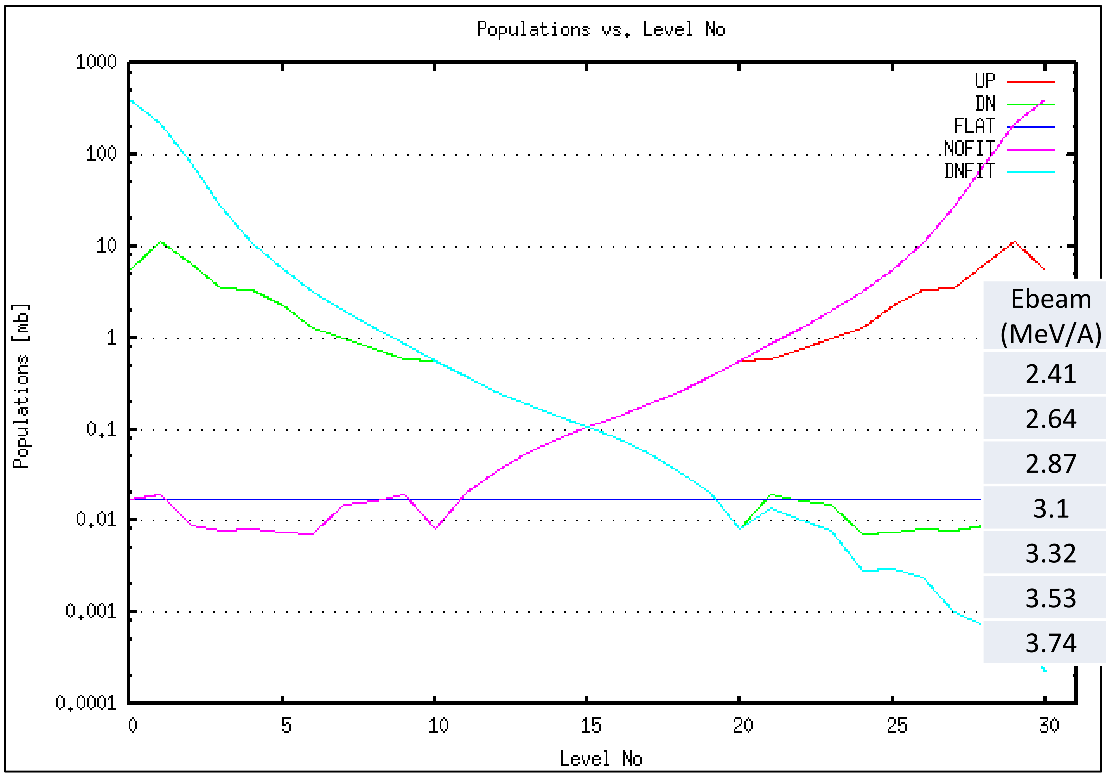


Neutron detection efficiency by MCNP simulation for ^{75}Ga(a,n) reaction

MCNP simulation result

1. **By varying populations of final states of ^{78}As/^{77}As, we can perform the sensitivity study of the efficiency.**
   1) **For (a,n) reaction: 19.8 % ≤ <ϵ> ≤ 24.5 % and 0.2 % ≤ δϵ ≤ 2.04 %**
   2) **For (a,2n) reaction:**
      - **The 1st neutron: 18.58 % ≤ $<\epsilon_{n1}>$ ≤ 20.83 % and 0.02 % ≤ $\delta\epsilon_{n1}$ ≤ 0.82 %**
      - **The 2nd neutron: 10.25 % ≤ $<\epsilon_{n2}>$ ≤ 15.4 % and 0.08 % ≤ $\delta\epsilon_{n2}$ ≤ 6.07 %**

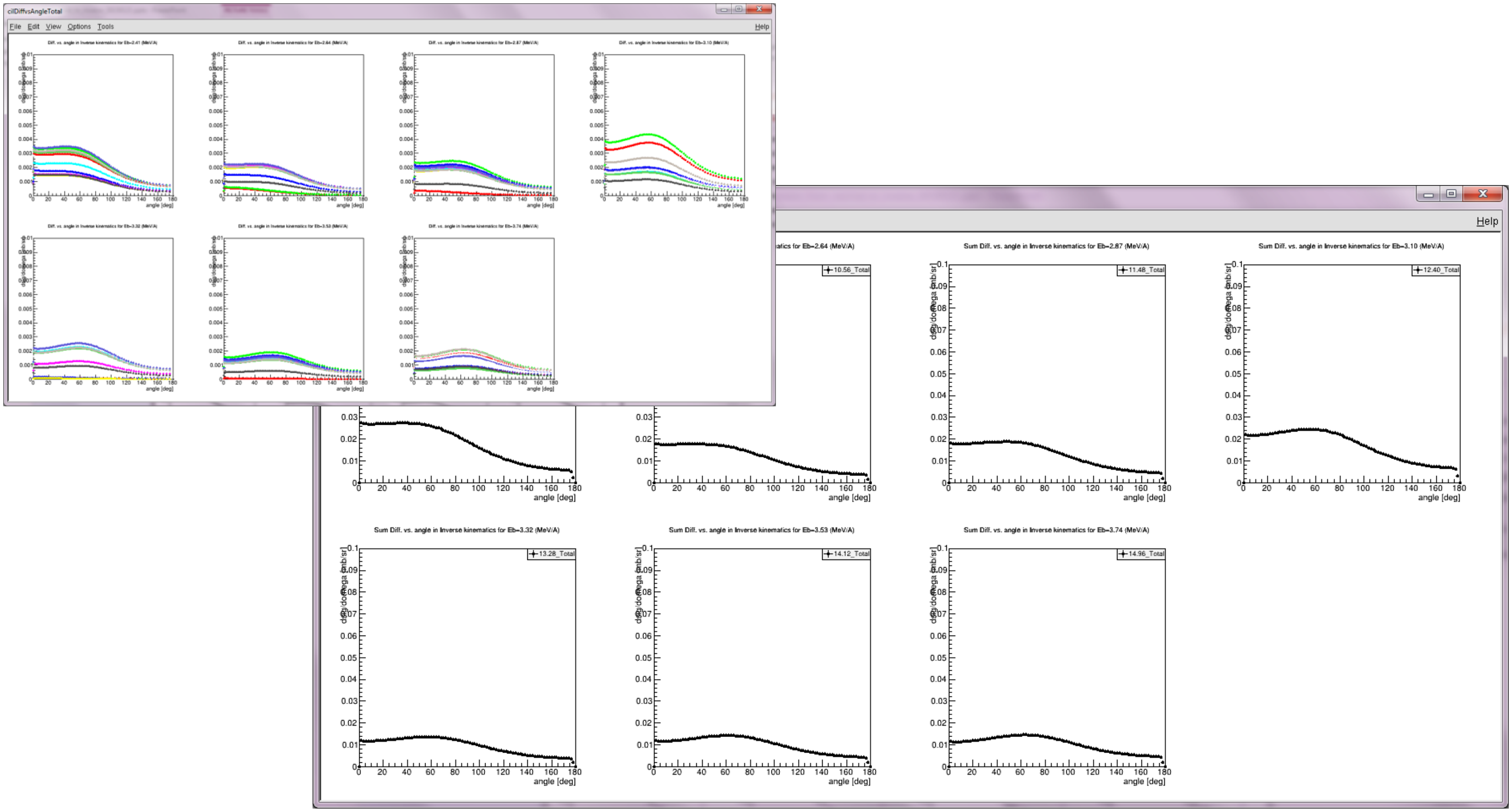
Ebeam (MeV/A)	<Eff>_M1 (%)	dEff_M1 (%)
2.41	20.97	±1.94
2.64	19.32	±2.52
2.87	20.63	±2.14
3.1	23.42	±1.39
3.32	21.91	±1.3
3.53	22.24	±1.03
3.74	24.5	±0.23



Ebeam (MeV/A)	<Eff> M1_n1 (%)	dEff M1_n1 (%)	<Eff> M1_n2 (%)	dEff M1_n2 (%)
2.41	18.58	±0.02	11.36	±0.08
2.64	20.02	±0.35	10.25	±3.16
2.87	20.64	±0.81	10.53	±5.59
3.1	19.65	±0.11	12.59	±3.67
3.32	20.4	±0.5	12.29	±6.07
3.53	20.67	±0.76	13.18	±5.64
3.74	20.83	±0.82	15.36	±4.69

Angular Distribution of $^{75}Ga(\alpha,n)$ reaction in inverse kinematics

- **dσ/dΩ vs. Angle (Discrete Levels) – Inverse Kinematics, LAB Frame**
- **An assuption of istropic differential cross section in CoM frame from compound reaction**

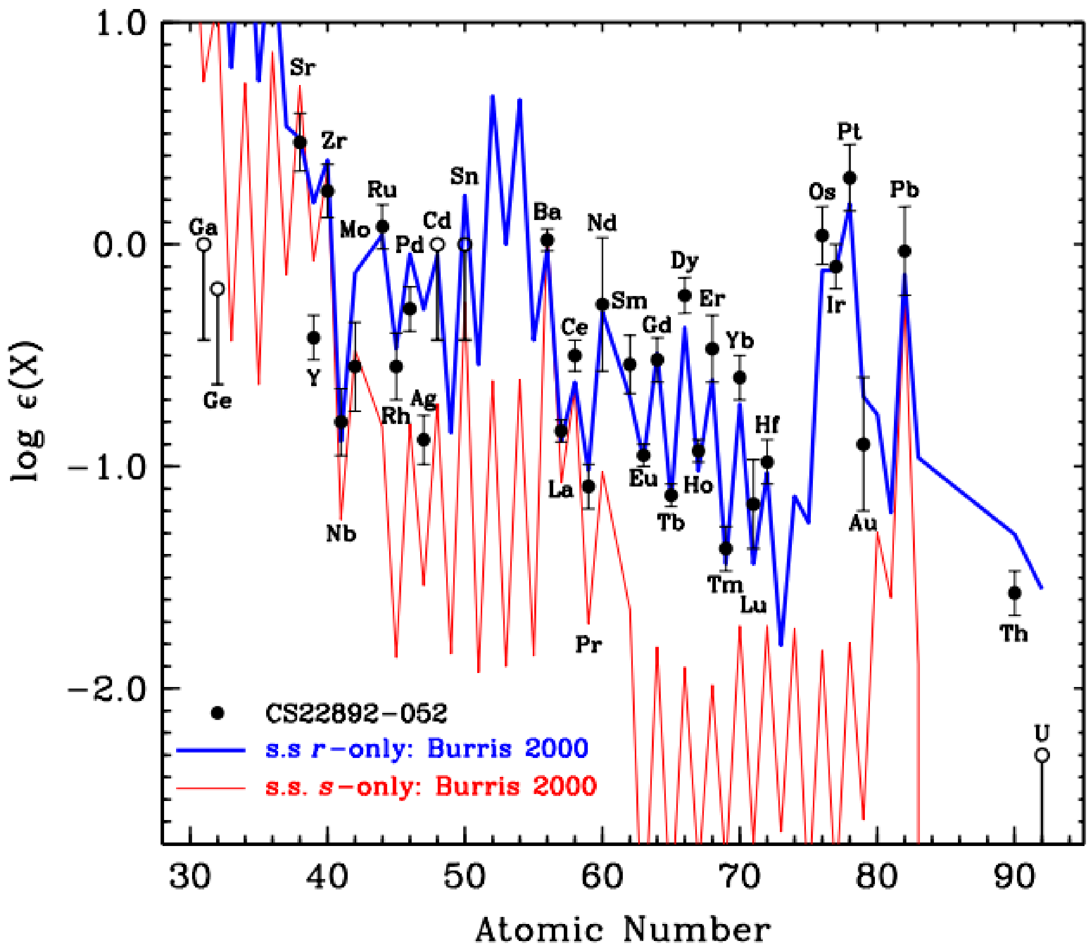


^{85}Rb Stable Beams

HabaNERO

- Stable ($^{85}Rb^{31+}$) beam for HabaNERO commissioning and confirmation of correlation technique.
  1) Two beam energies (4.17 and 3.93 MeV/u) of ^{85}Rb
  2) ^{4}He gas cell Pressure: 415 Torr (=355ug/cm^{2})

Abundance Patterns

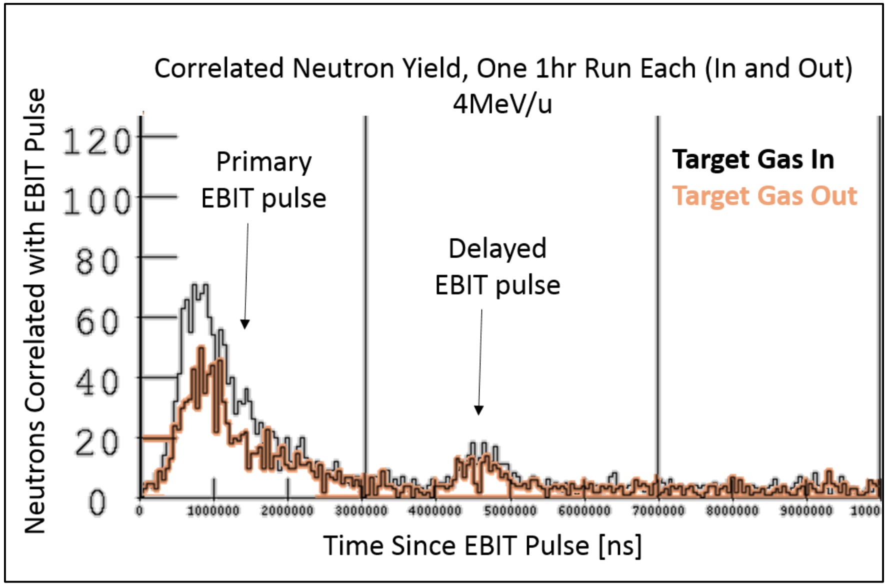


Observed *n*-capture abundances in CS 22892-02
C. Sneden *et al.*

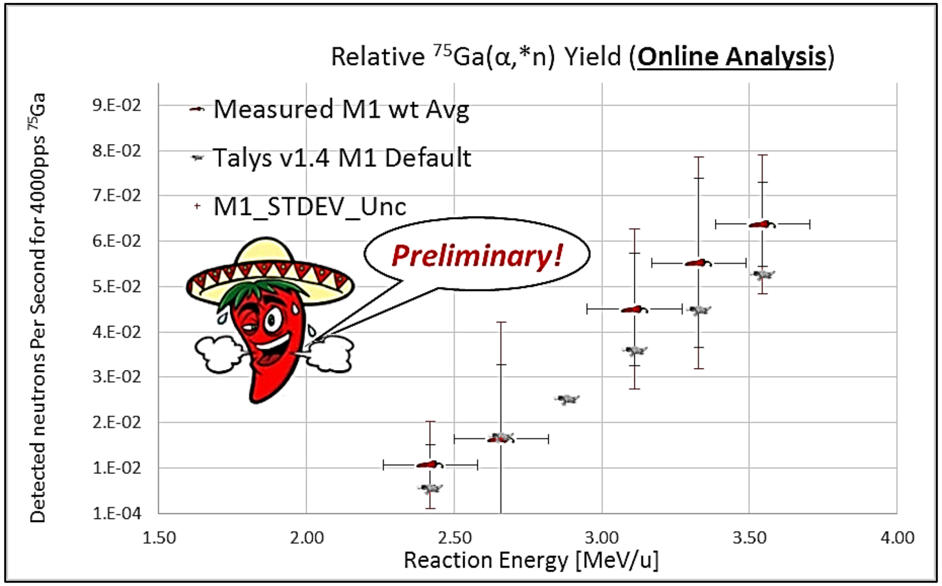
Neutrons!

HabaNERO

- Correlation between EBIT signal and neutron signal (from HabaNERO)
- Neutron excess from comparison of 4He gas-in and gas-out run to remove systematic fluctuation effect.
- Neutron excess were found in EBIT-HabaNERO correlation spectrum.



Correlated neutron spectrum with the EBIT signal to compare between gas-in and out run



Preliminary result of neutron yield over ^{75}Ga beam energy for the rate of 4000ps.