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Title: Nuclear reaction studies: Transfer and Neutron-induced reactions on medium-range nuclei.

Author(s): Georgiadou, Anastasia

Intended for: Invited Seminar at Lawrence Livermore National Laboratory

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Nuclear reaction studies: Transfer and Neutron-induced reactions on medium-range nuclei.

Anastasia Georgiadou, P-27

Why nuclear physics?

"What we do is understanding nature.

Understanding our origin and how matter forms"

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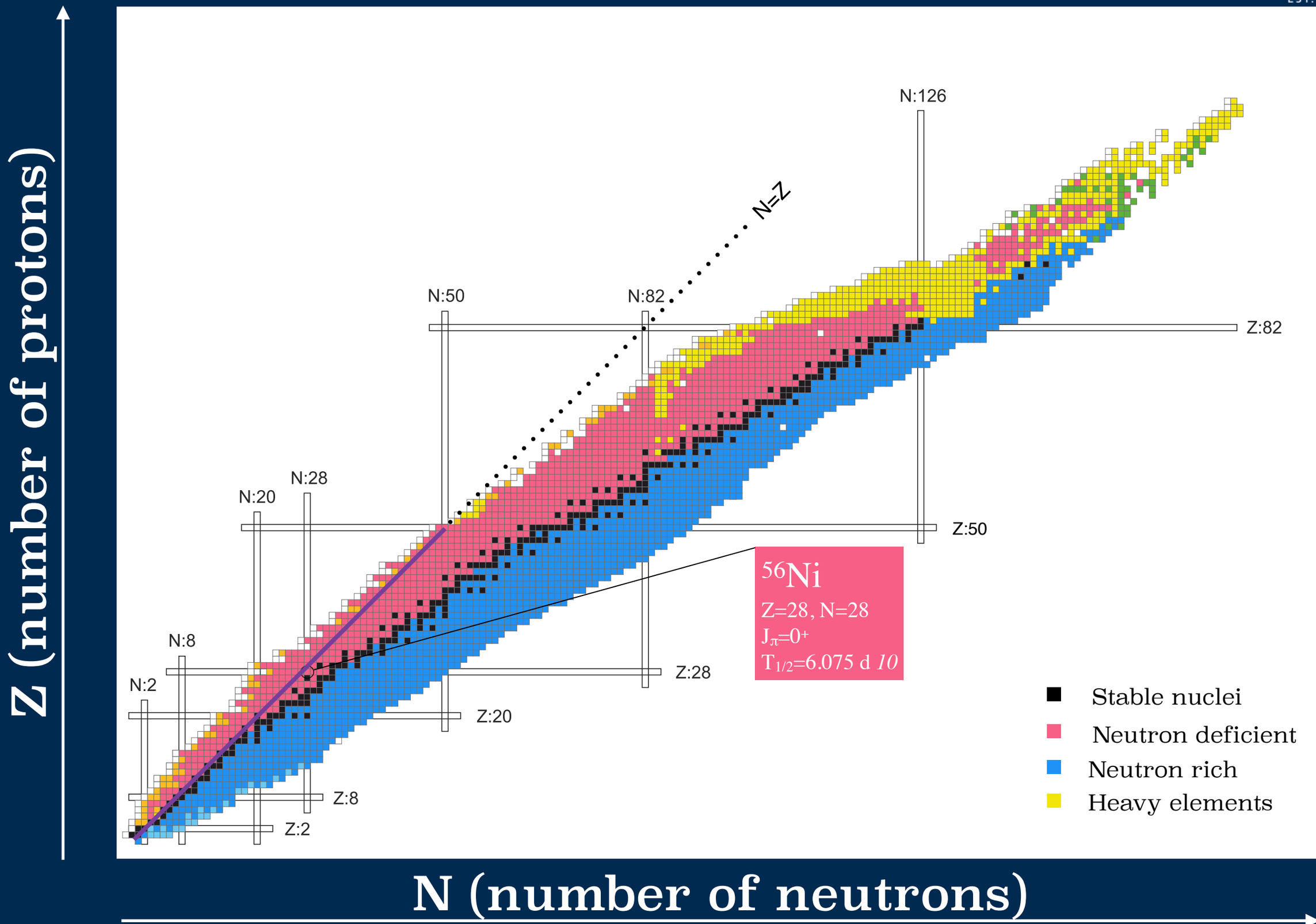

Why nuclear physics?

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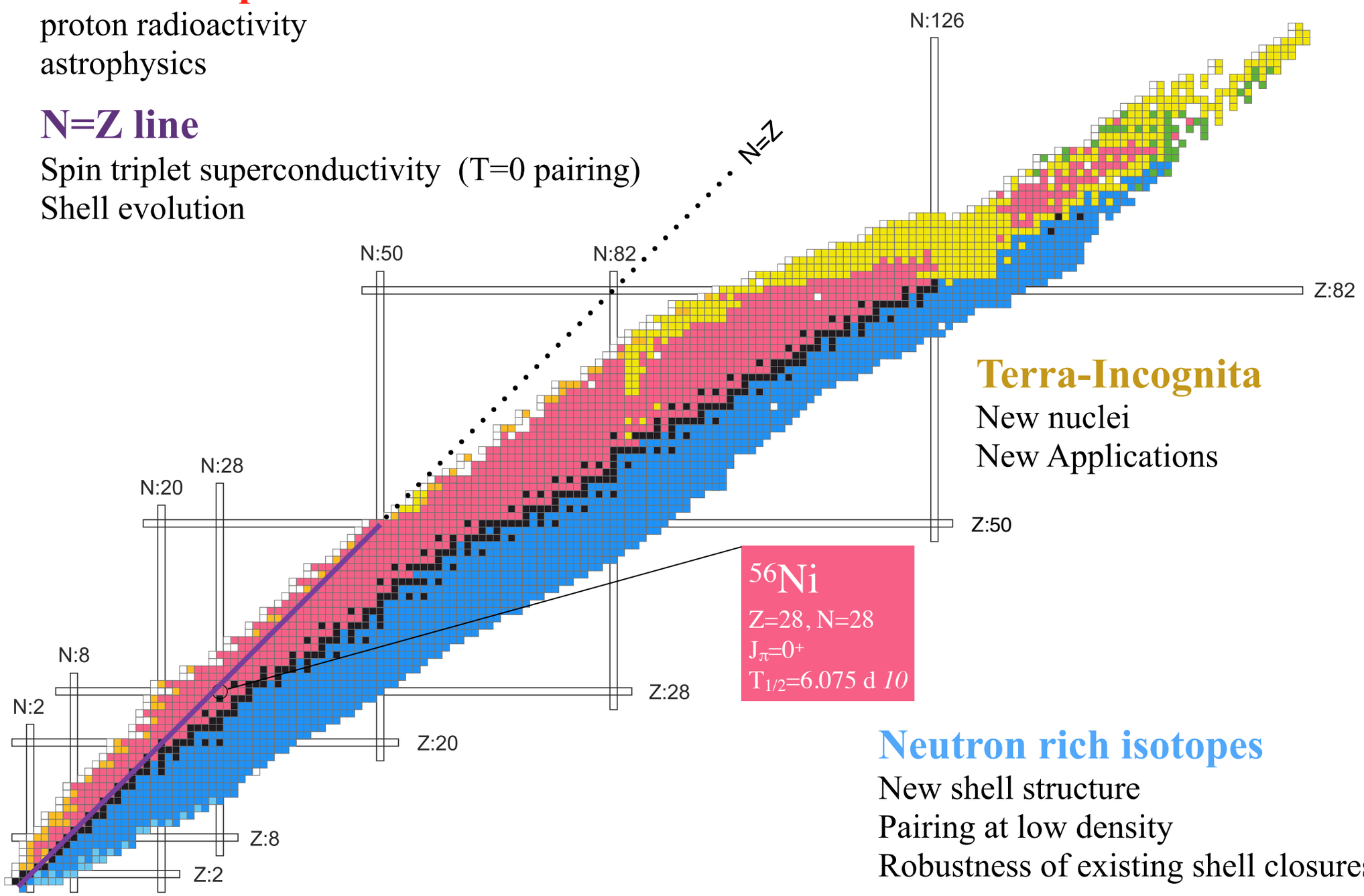
Z (number of protons)

Proton-Drip line

proton radioactivity
astrophysics

N=Z line

Spin triplet superconductivity (T=0 pairing)
Shell evolution



Terra-Incognita

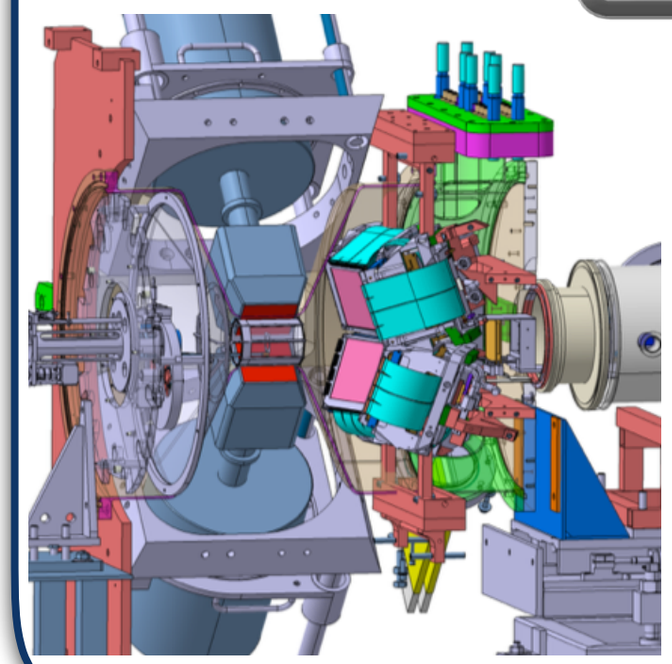
New nuclei
New Applications

Neutron rich isotopes

New shell structure
Pairing at low density
Robustness of existing shell closures

N (number of neutrons)

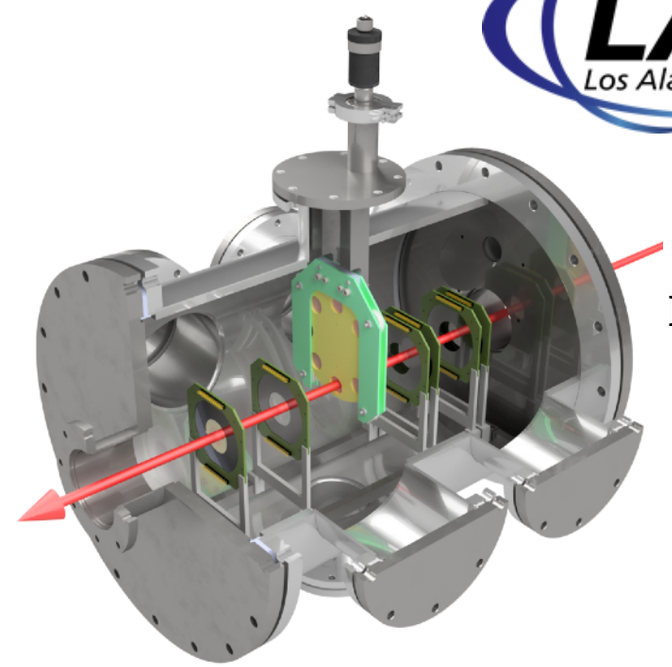
Outline



GANIL spiral2
laboratoire commun CEA/DSM CNRS/IN2P3

56Ni(p,d),(d,t),(d,α)

- One nucleon transfer
- Two-nucleon transfer

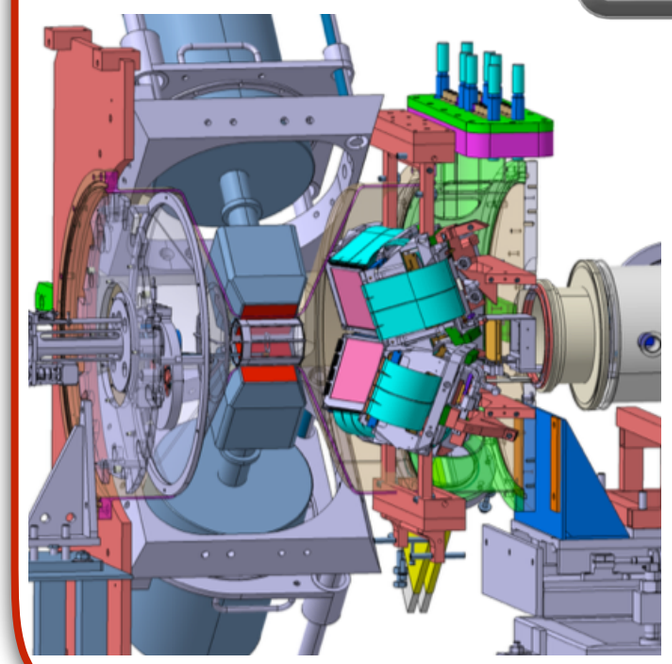


LANSCE
Los Alamos Neutron Science Center

54,56Fe(n,p),(n,a)

Low Energy Neutron-induced Charged-particle (Z) Chamber LENZ

Outline



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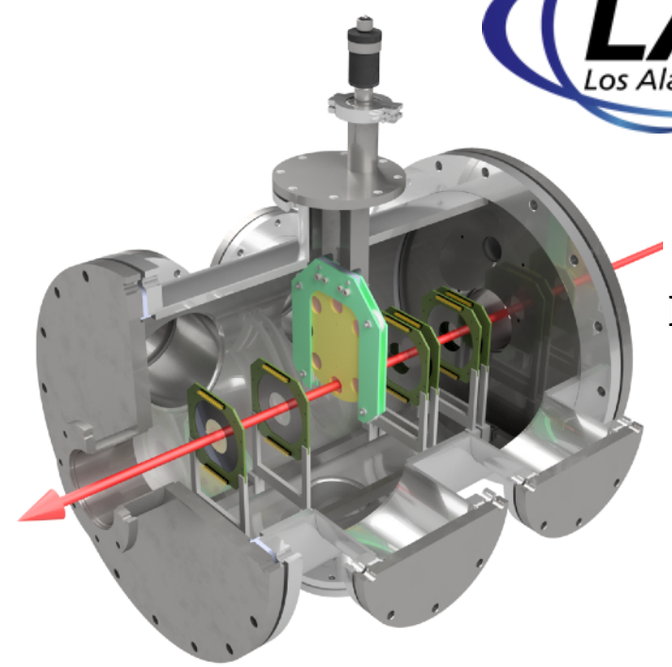


LANSCE
Los Alamos Neutron Science Center

54,56Fe(n,p),(n,a)

Low Energy Neutron-induced Charged-particle (Z) Chamber **LENZ**

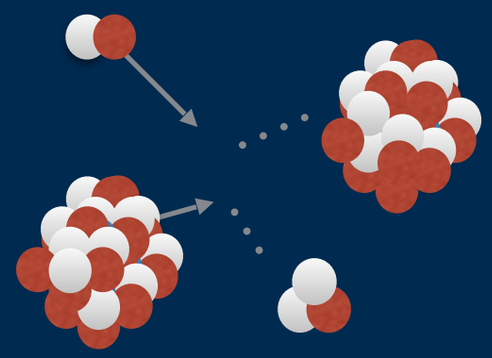
Team and Collaborations

NESTER Group

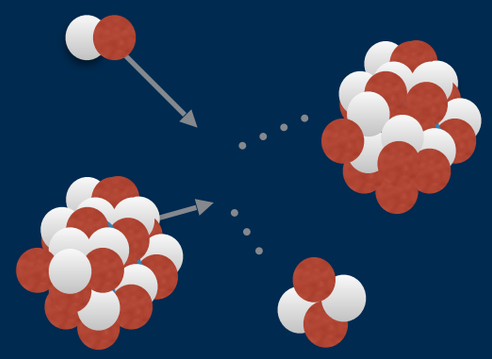
MUST2 Team: Yorick Blumenfeld, Didier Baumel,Marlène Assié, A.G, Benjamin LeCrom, Jacques Guillot, Freddy Flavigny, Laura Grassi

External Collaboration: Augusto Machiavelli (Lawrence Berkeley National Laboratory)

- Staff Scientist
- Post-Doc
- PhD Student

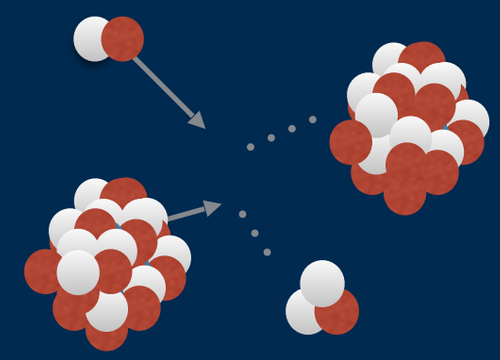


The one-nucleon transfer reactions
N=28 Shell closure



The two-nucleon transfer reaction
NP-Pairing in N=Z nuclei

LLNL Seminar 02/28/2020, A.Georgiadou, georgiadou@lanl.gov



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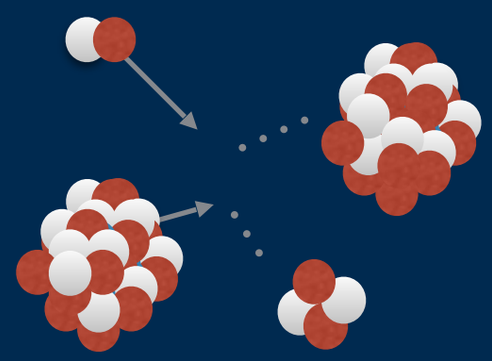
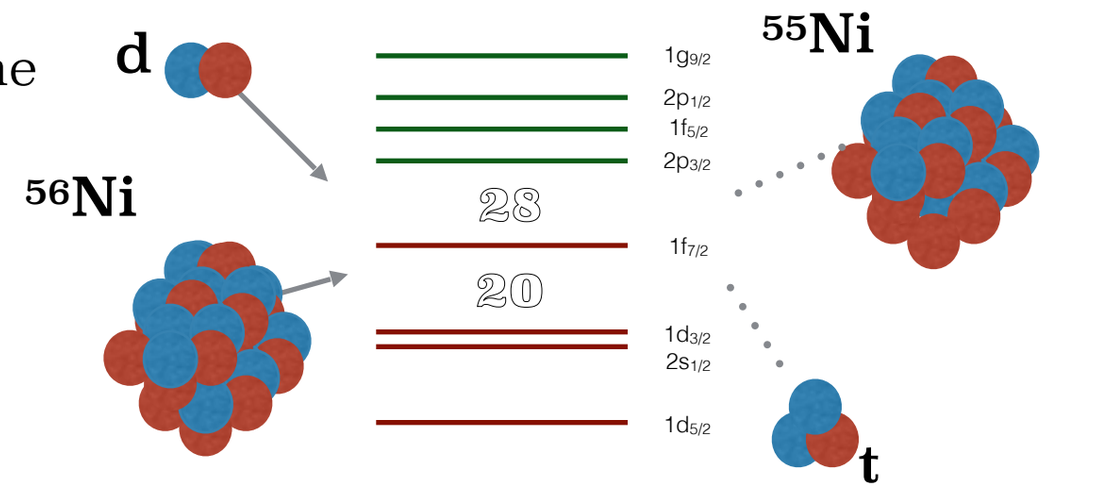


The two-nucleon transfer reaction
NP-Pairing in N=Z nuclei

LLNL Seminar 02/28/2020, A.Georgiadou, georgiadou@lanl.gov

N=28 Shell Closure

Transfer reactions play major role in our understanding of the nuclear elementary modes of excitation, particularly in the characterization of the **single particle degrees** of freedom and their correlations.



Single particle transfer reactions such as **(d,t) and (p,d)** give information about the **N=27 isotones.**

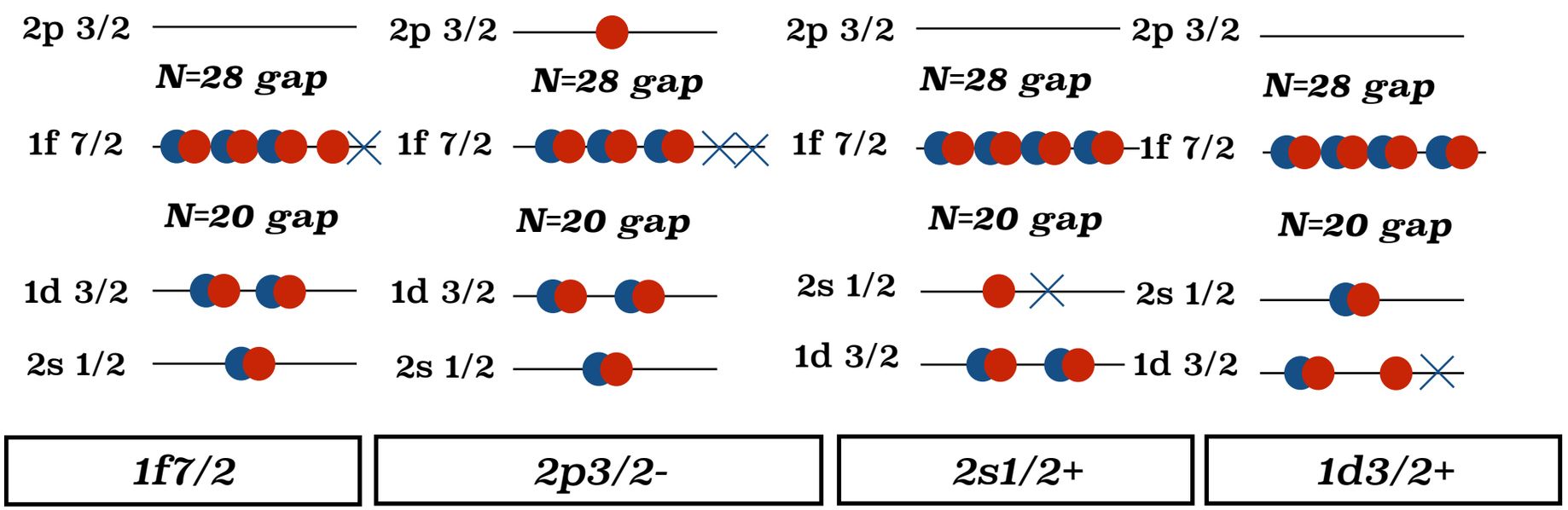
Extraction of the neutron **Spectroscopic Factor (SF)**, is a measure of the overlap between the initial and final state.

$$S_+ = \int |\langle \Psi_0^{A+1} | a^\dagger | \Psi_0^A \rangle| \quad , \quad C^2 S_{exp} = \frac{\sigma_{exp}}{\sigma_{th}^S P}$$

$$S_- = \int |\langle \Psi_0^{A-1} | a | \Psi_0^A \rangle|$$

N=28 Shell Closure

Single particle picture

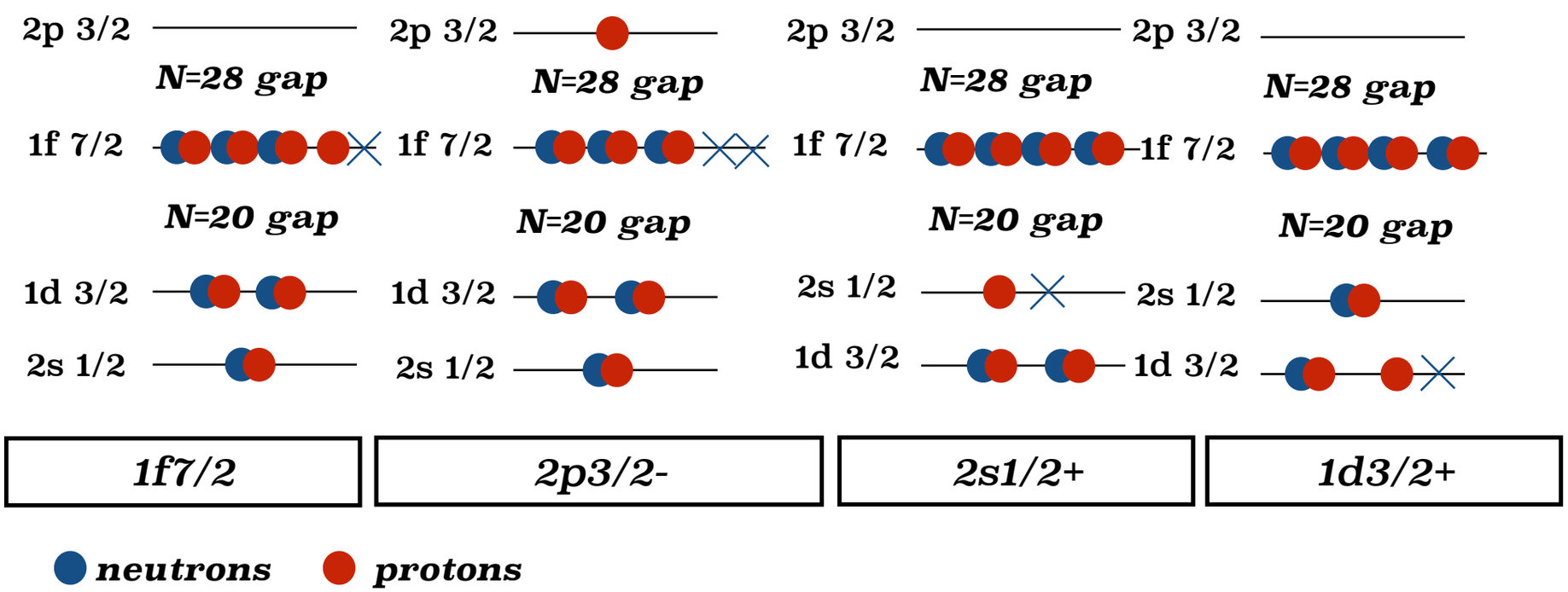


1f7/2	2p3/2-	2s1/2+	1d3/2+

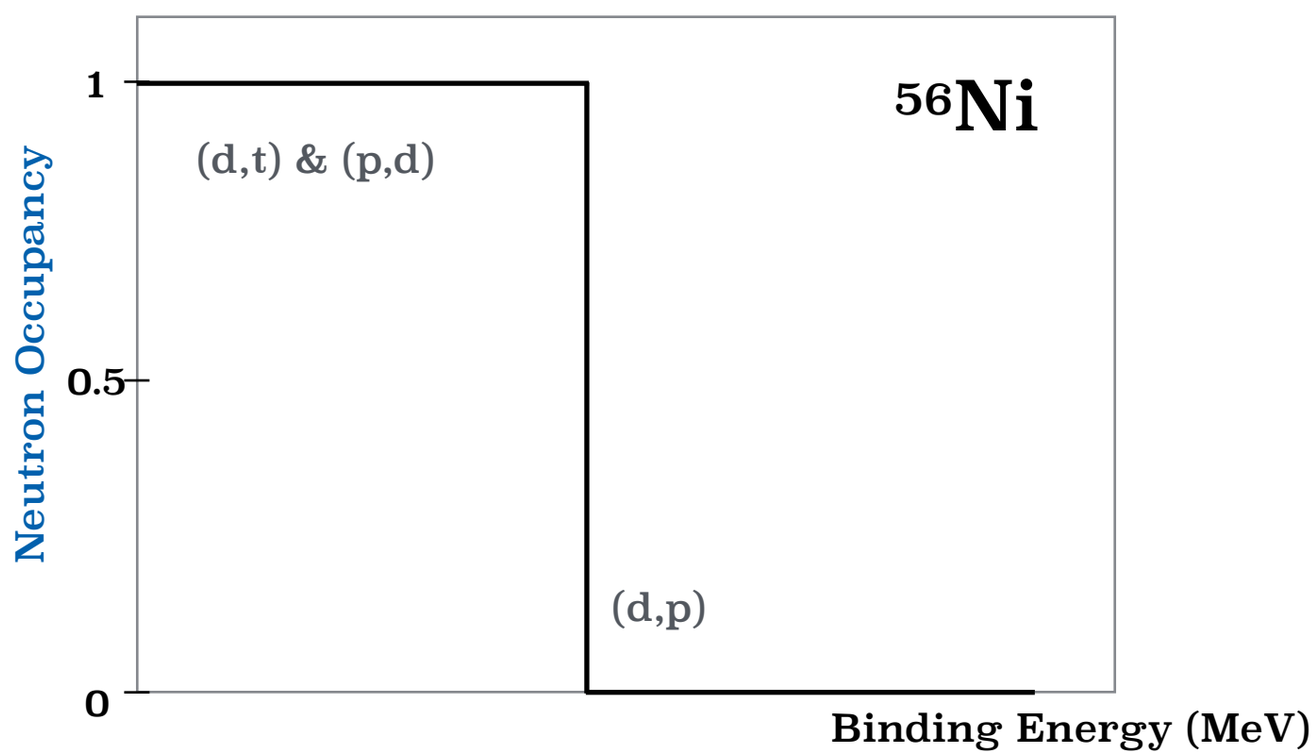
neutrons protons

N=28 Shell Closure

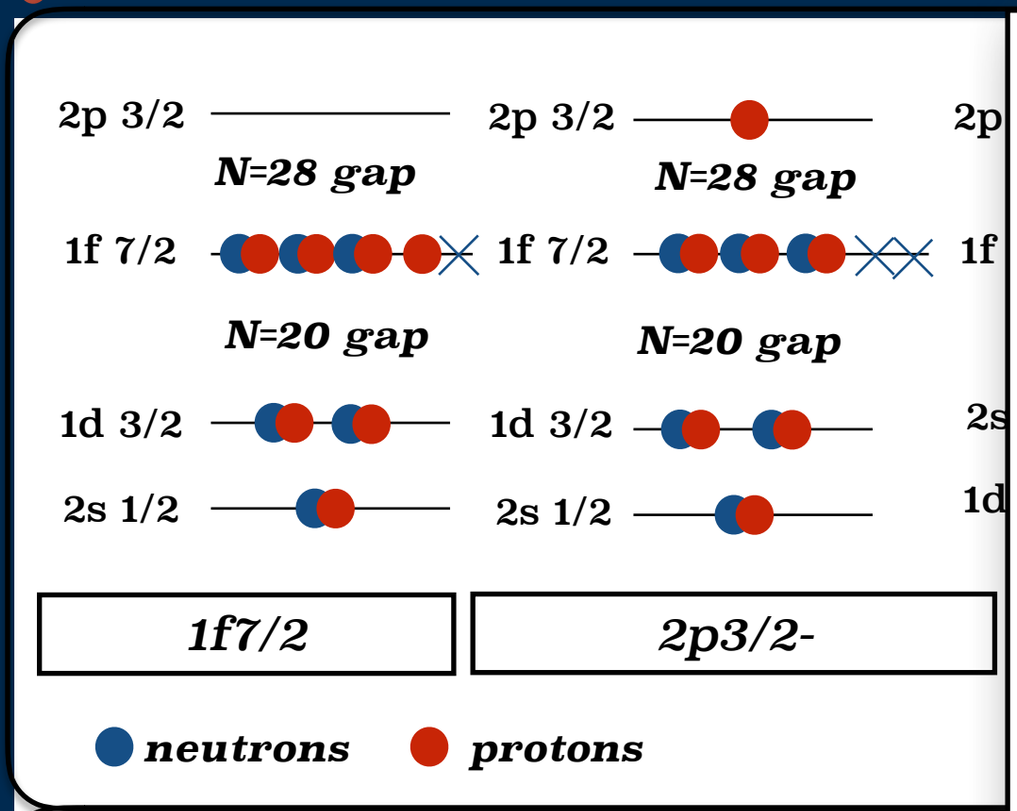
Single particle picture



56Ni Fermi surface



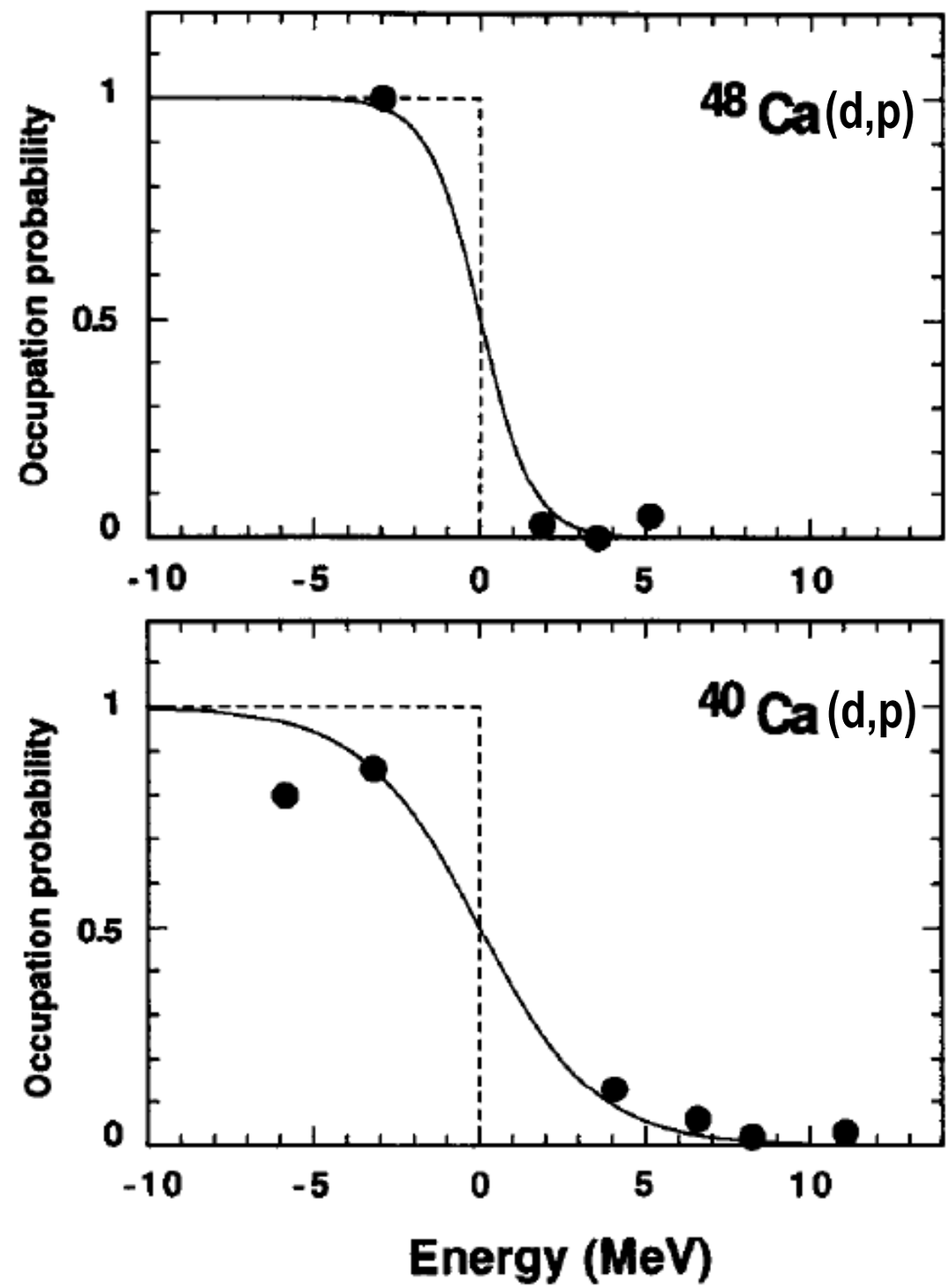
N=28 Shell Closure



Fermi-Distribution:

$$n(E_0) = \frac{1}{1 + exp\left[\frac{E}{\Delta}\right]}$$

Y. Uozumi et al. / Nuclear Physics A576 (1994) 123–137



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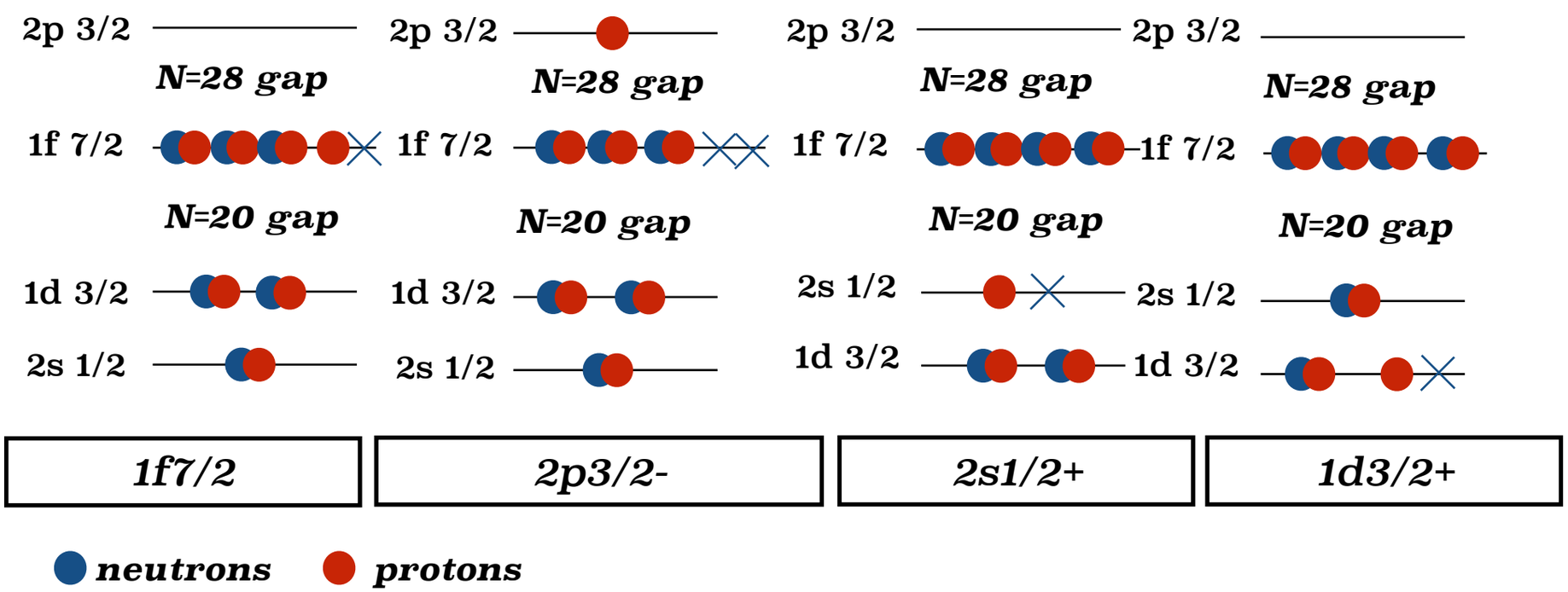
Single particle picture



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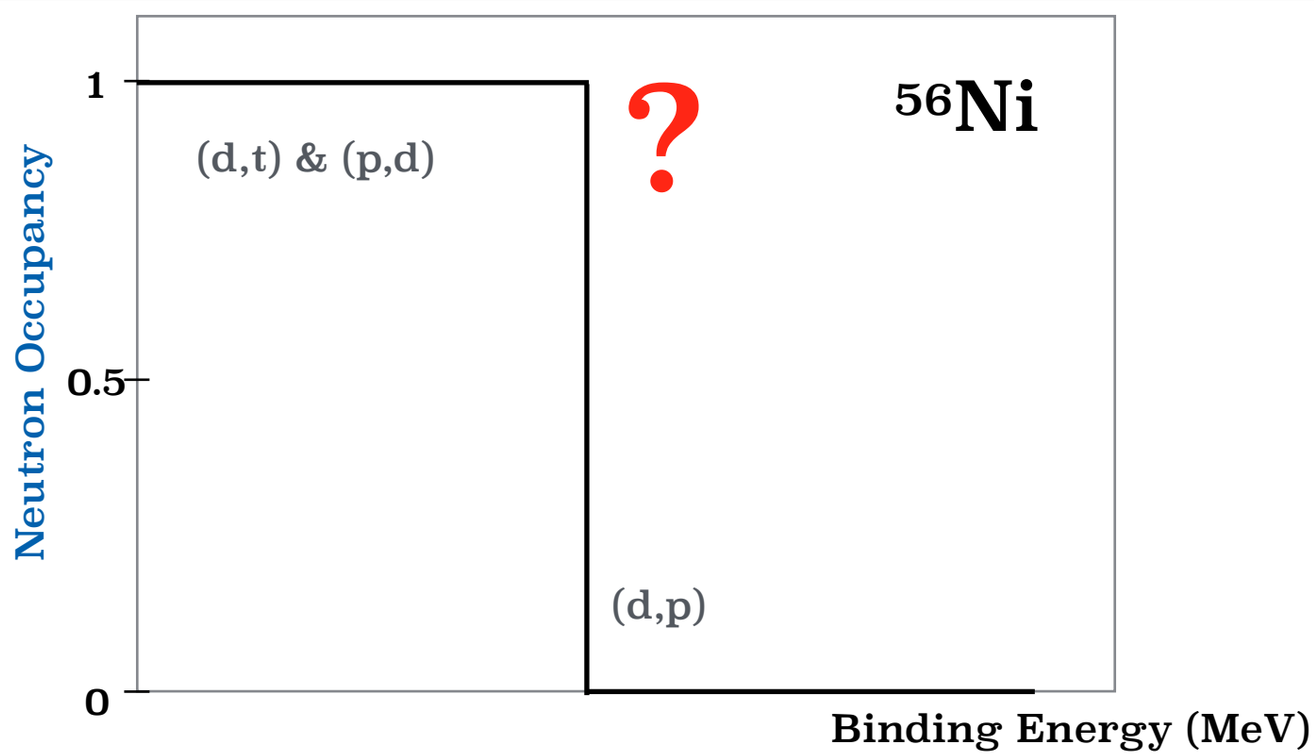
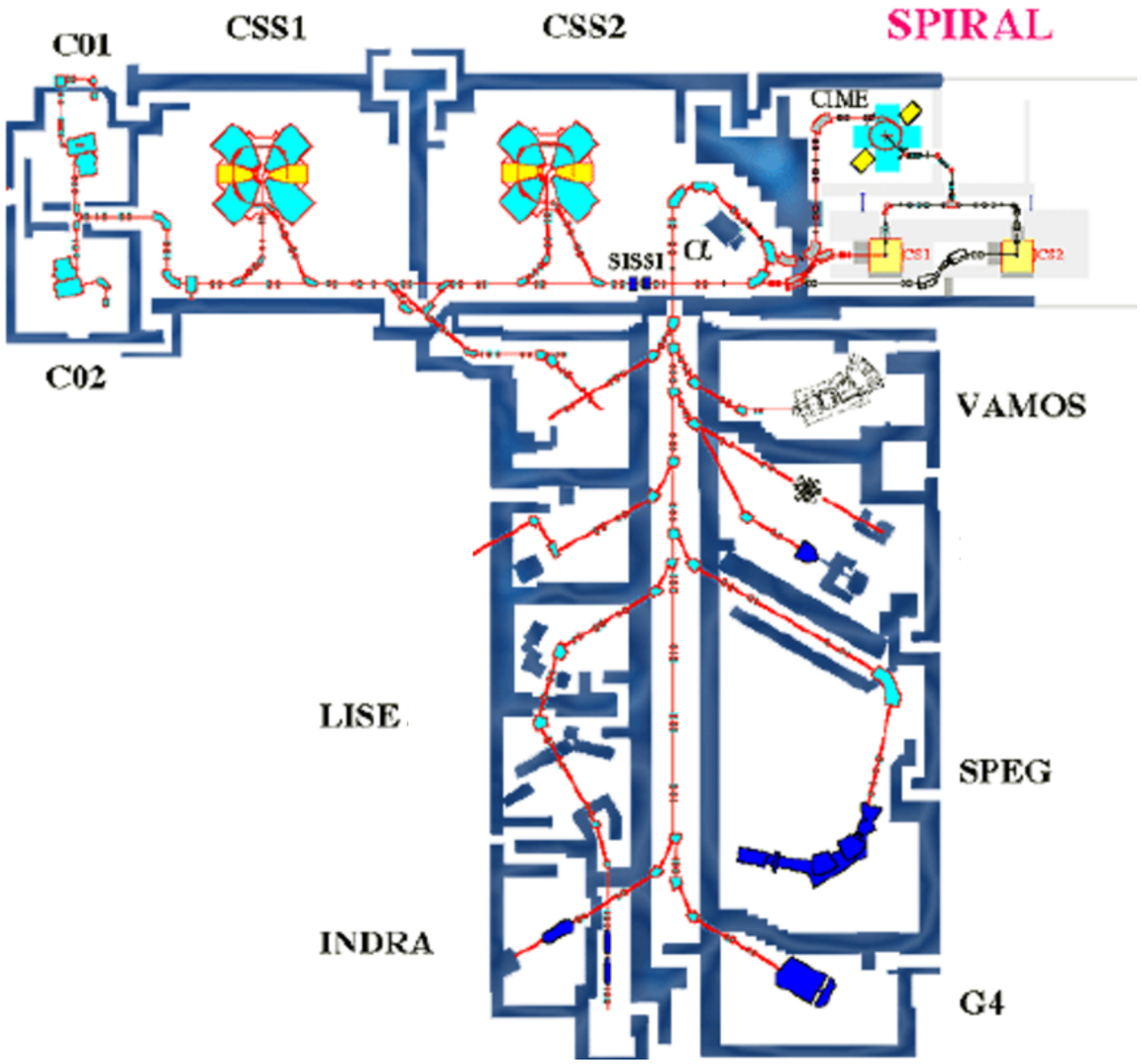


Experimental Set-Up

*The experiment "e644" was performed at GANIL, CAEN at Spring 2014.

Primary beam : ^{58}Ni at 74,5 MeV/υ

Rotating target (CLIM) : ^{9}Be (1 mm)



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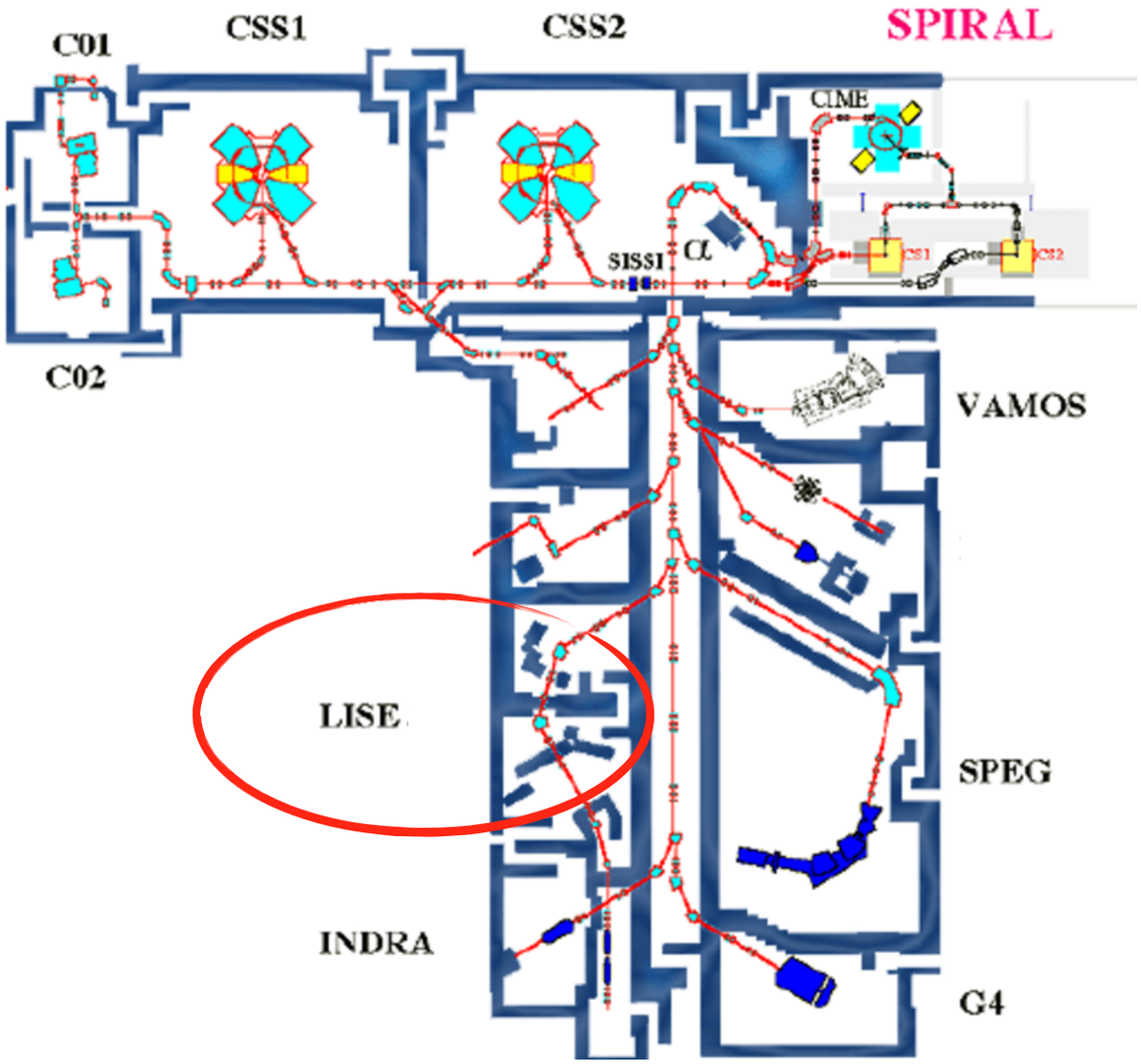
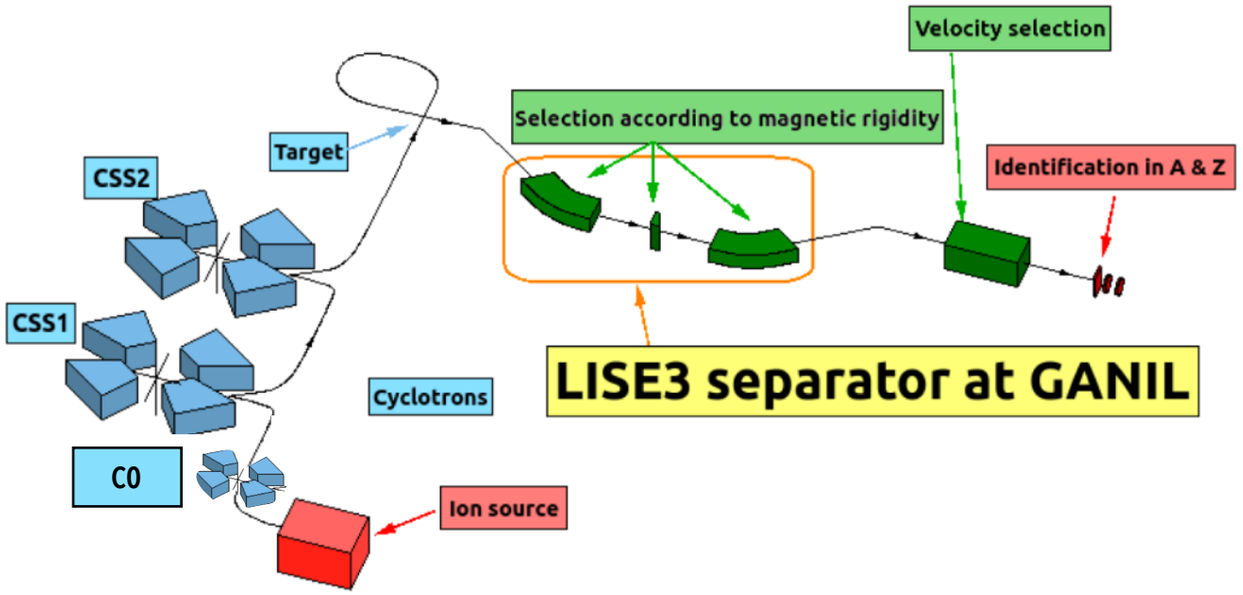


Experimental Set-Up

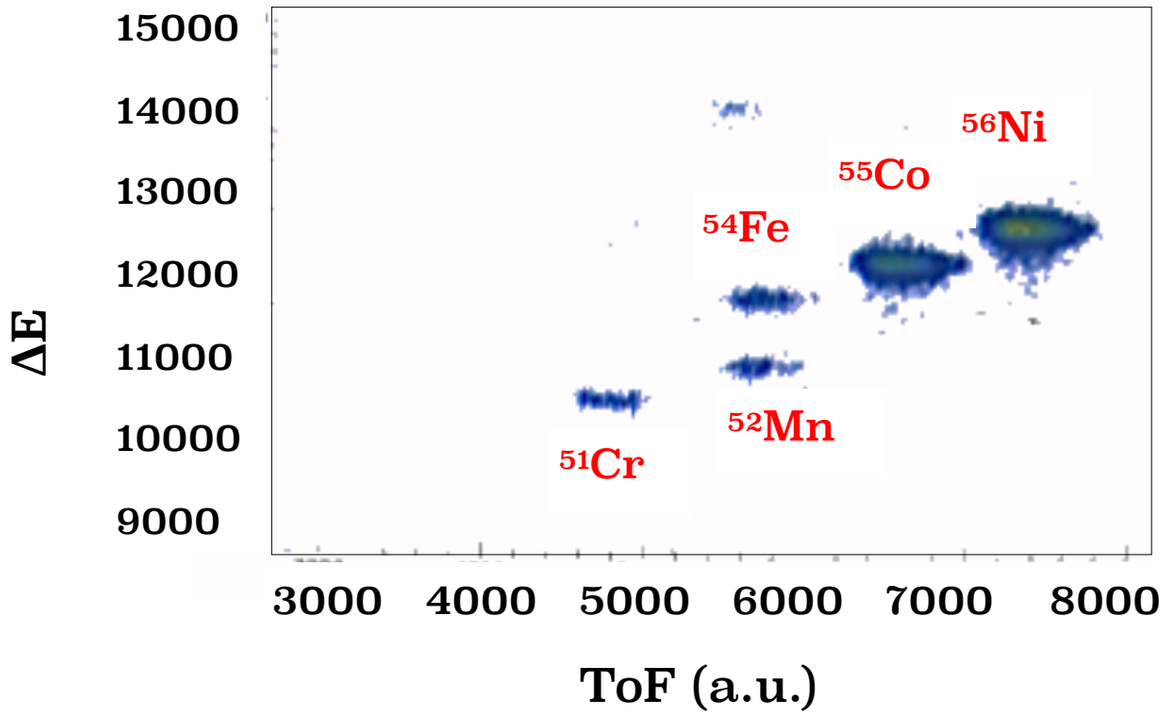
Fragment selection:

1. magnetic dipole: selection according to Bρ
2. achromatic degrader (Berilium) combined with a second magnetic dipole
3. Wien Filter: Velocity selection



Secondary beam :

^{56}Ni (30 MeV/u) 10^5 pps 68%



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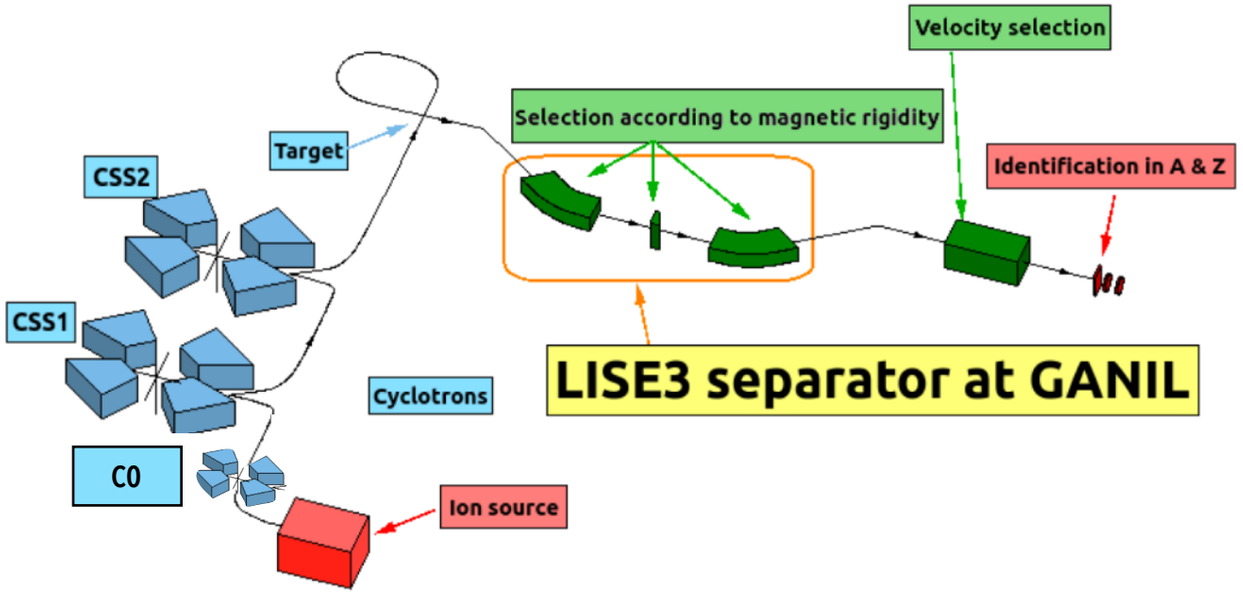
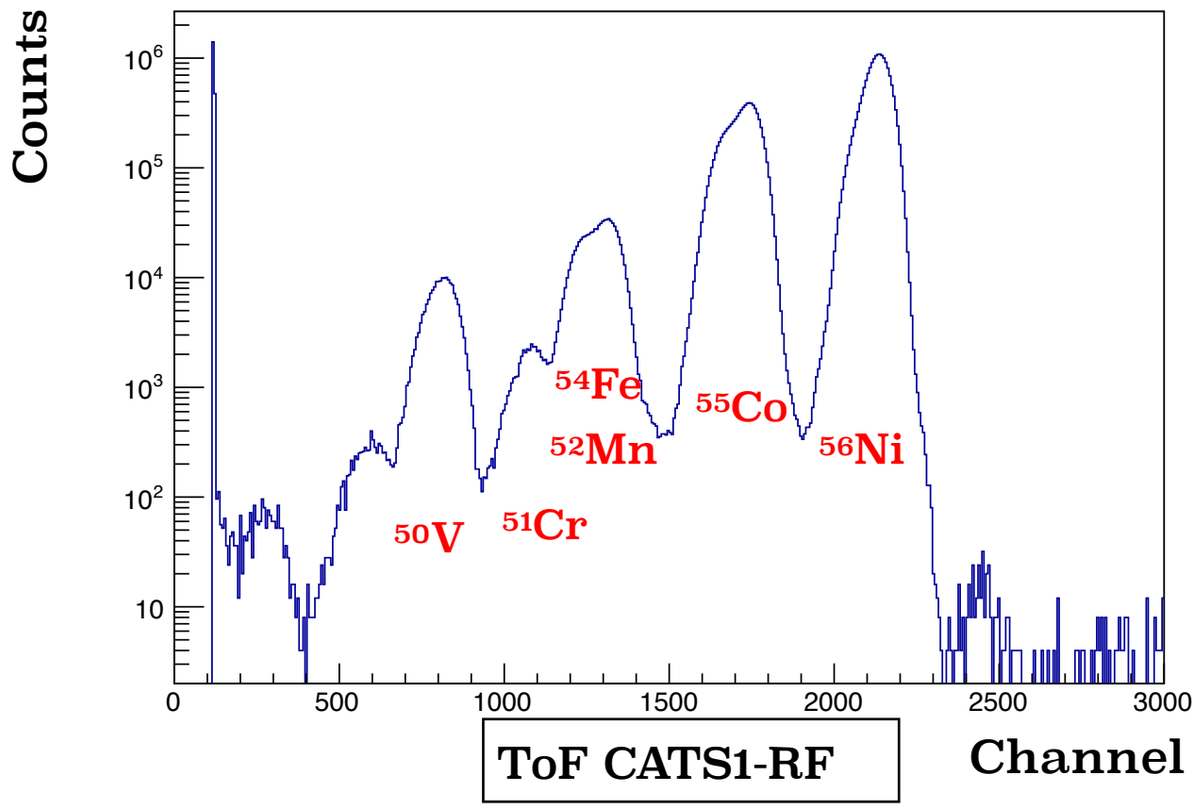


The RF-CATS time of flight spectrum: measurement between the cyclotron radio frequency and the first beam tracking device of the set-up



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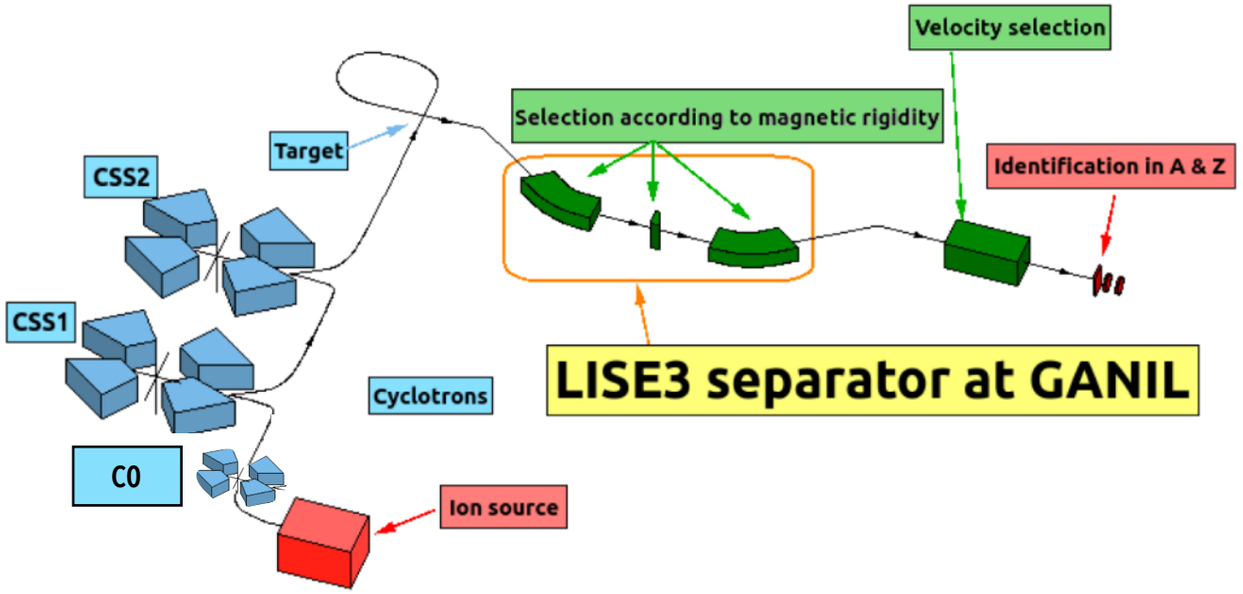

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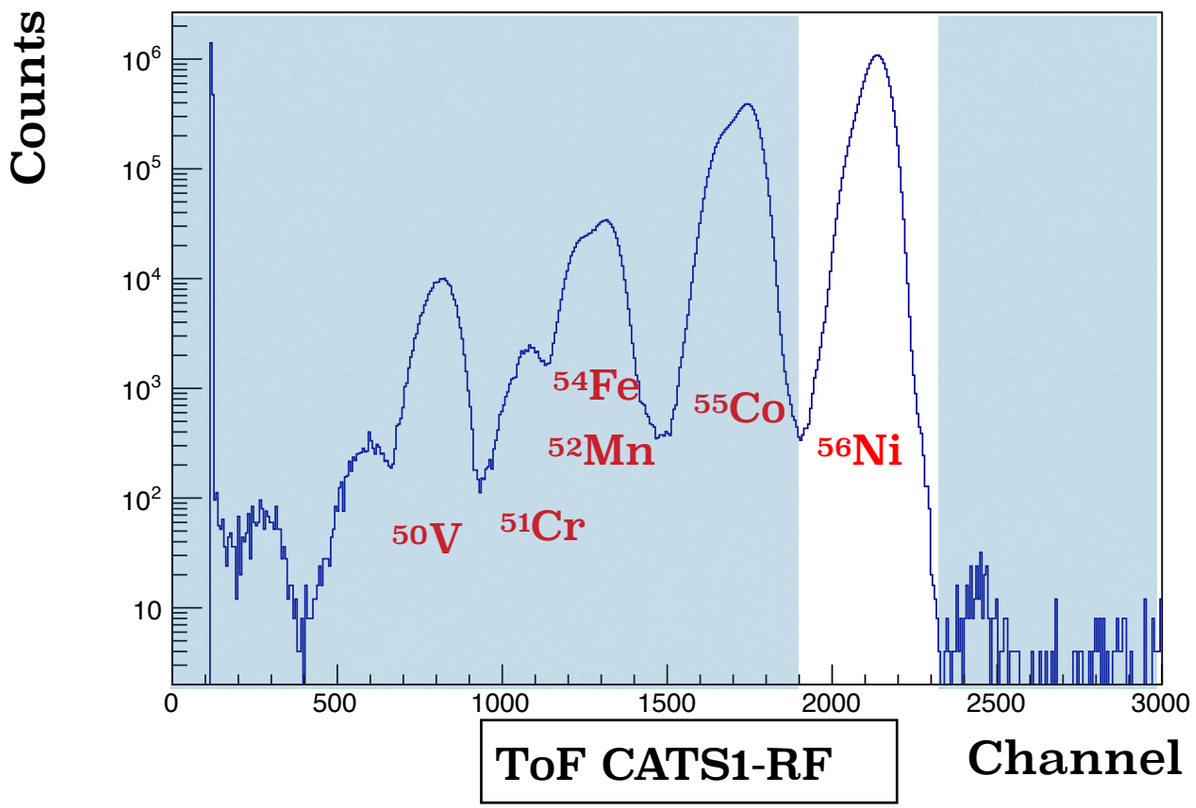


Experimental Set-Up

Reaction Targets: CH2 (6.9mg/cm²),

CD2 7mg/cm²

^{12}C (1.2mg/cm²)

One nucleon transfer

^{56}Ni(p,d)^{55}Ni

^{56}Ni(d,t)^{55}Ni

^{56}Ni(d,p)^{57}Ni

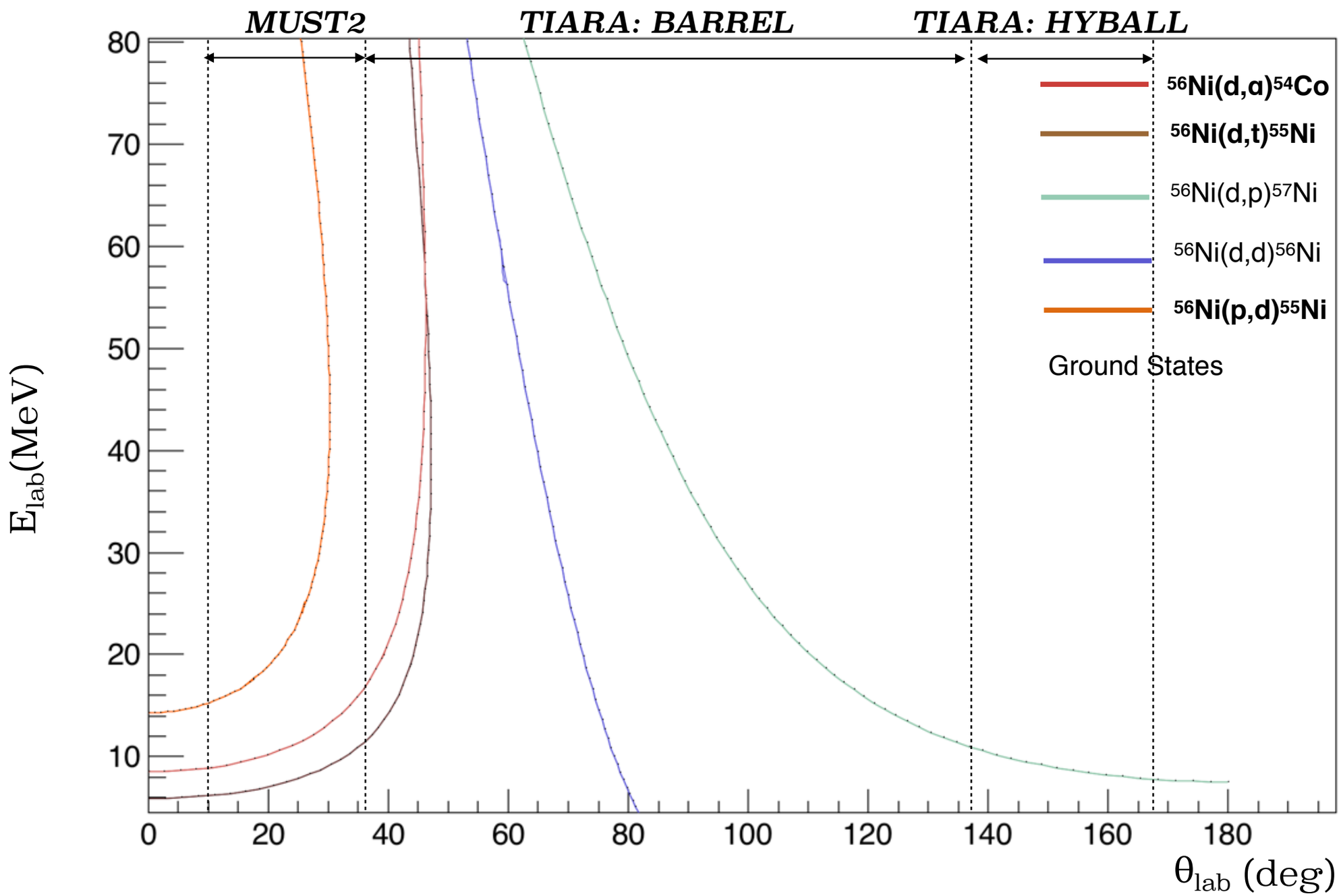
Two nucleon transfer

^{56}Ni(p,^{3}He)^{54}Co*

**Analysis Performed by B. Le Crom*

^{56}Ni(d,α)^{54}Co

The reaction Kinematics



Experimental Set-Up

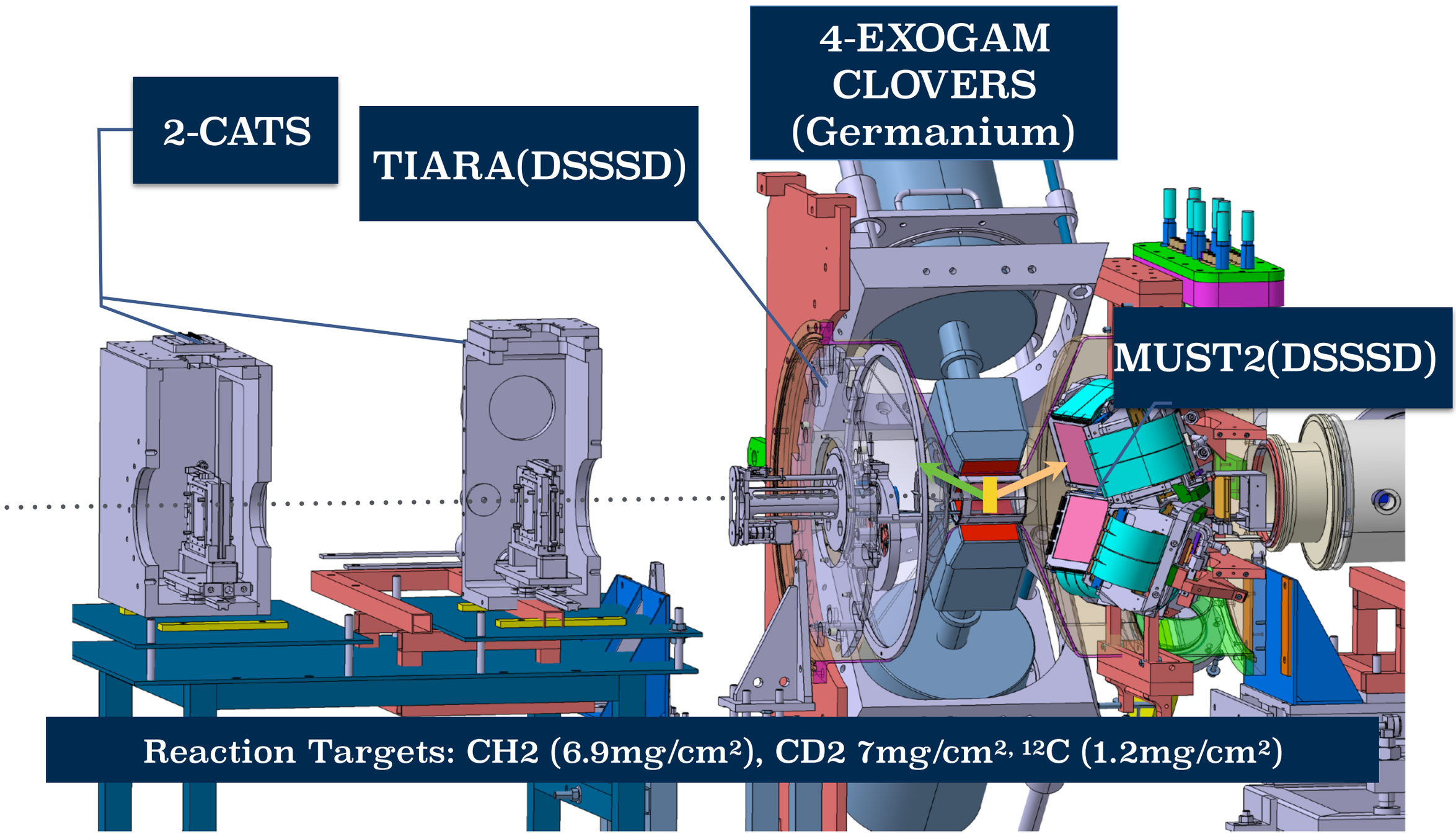
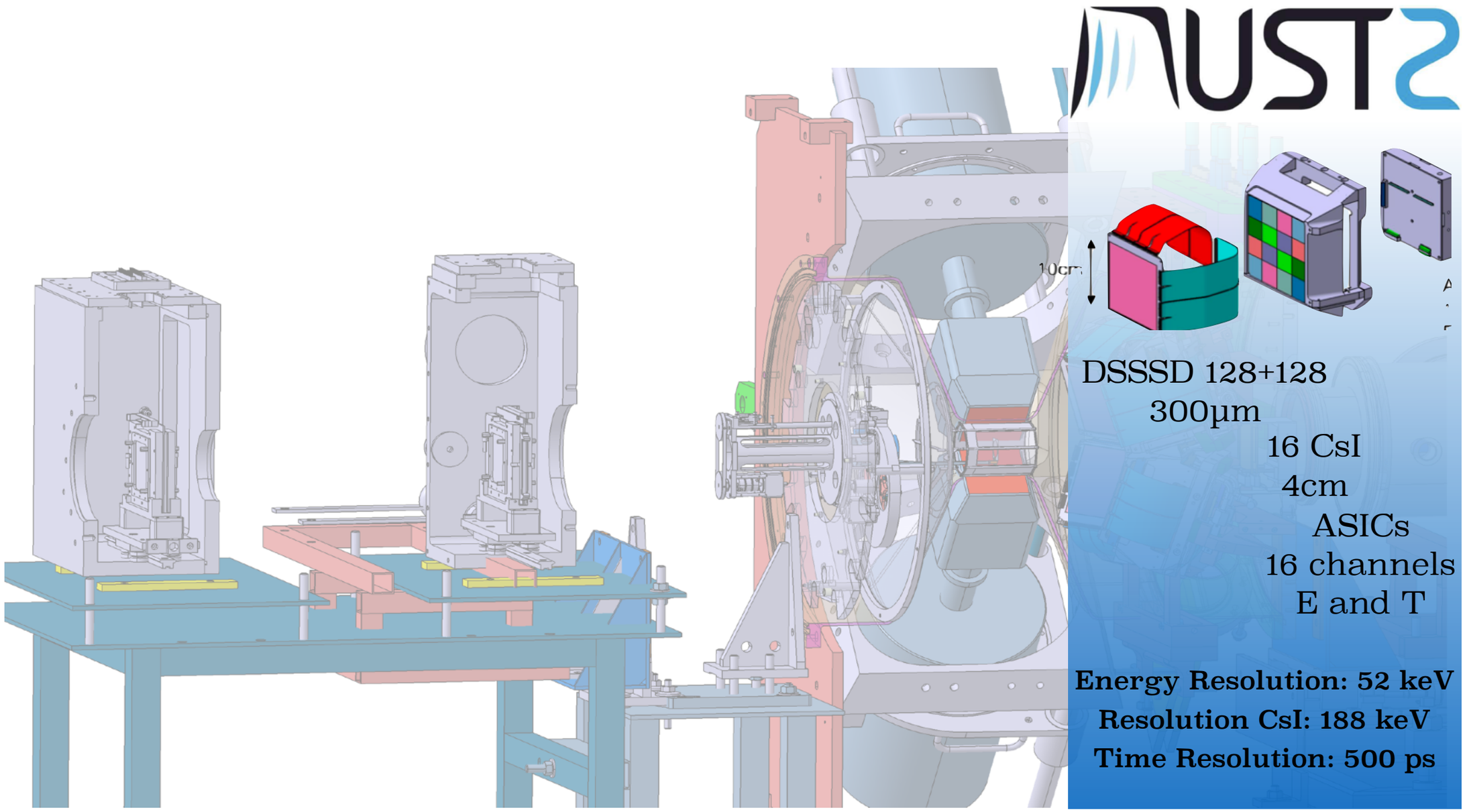


*Illustration by Emmanuel Rindel

Beam ^{56}Ni
tritons
protons

Experimental Set-Up



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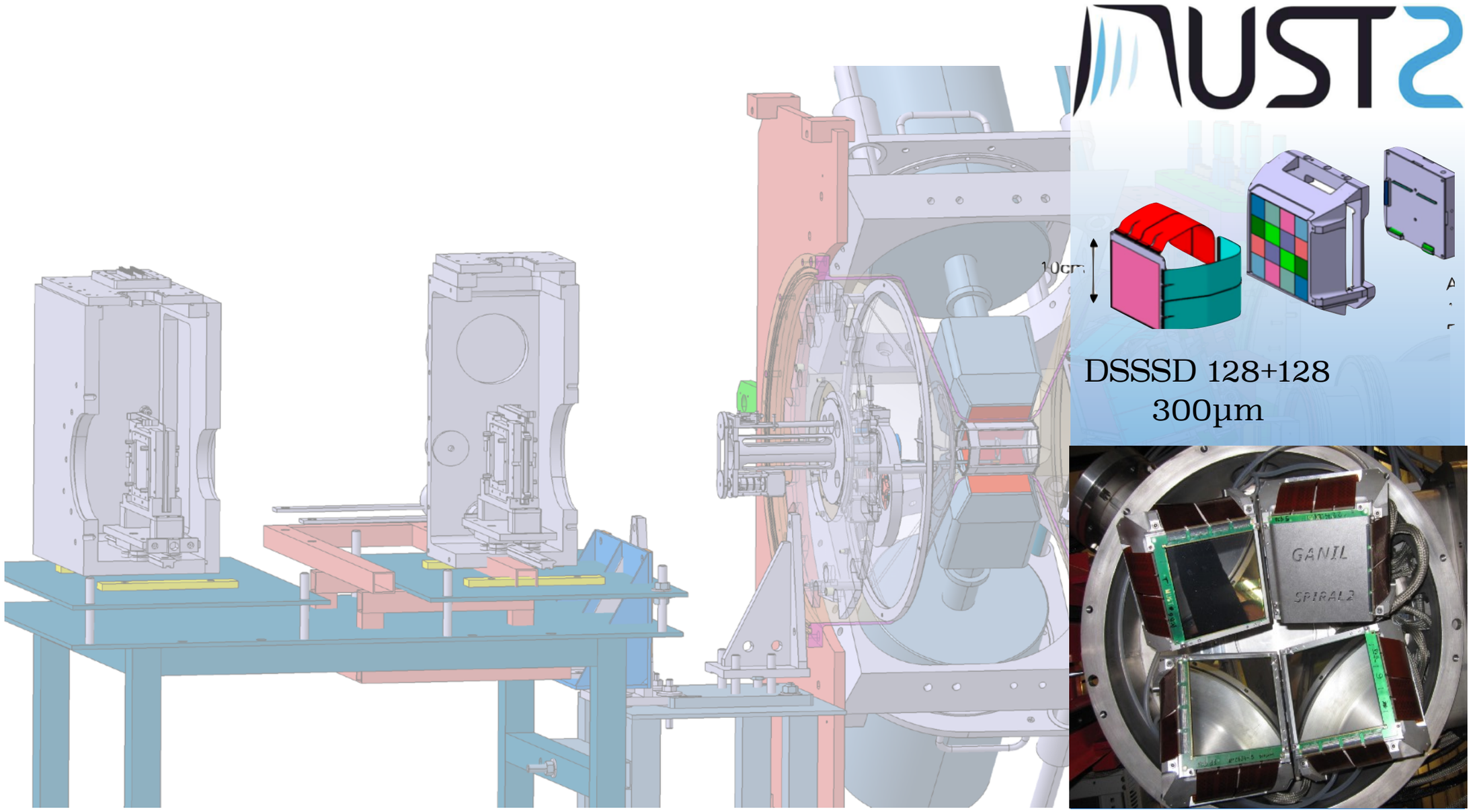

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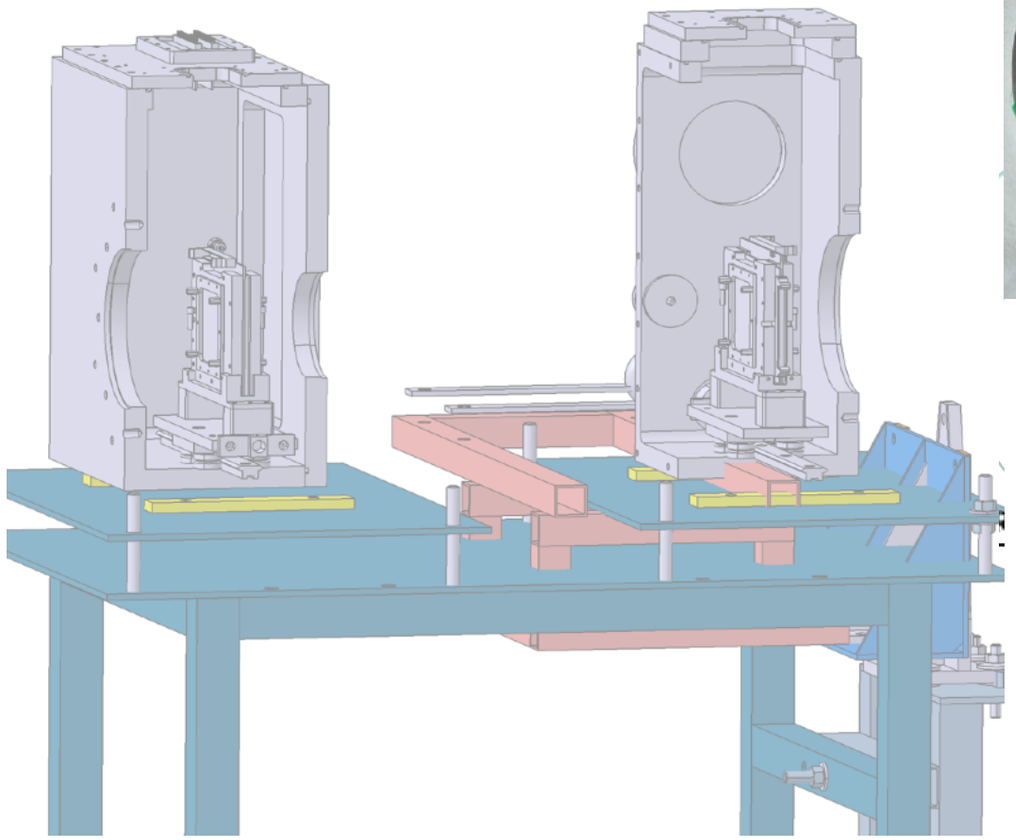
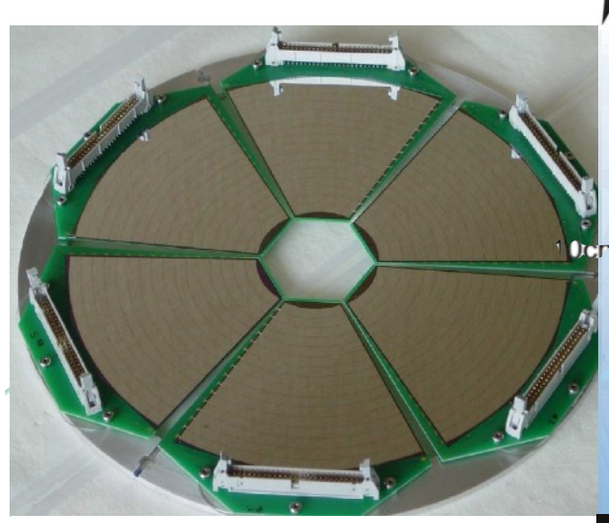
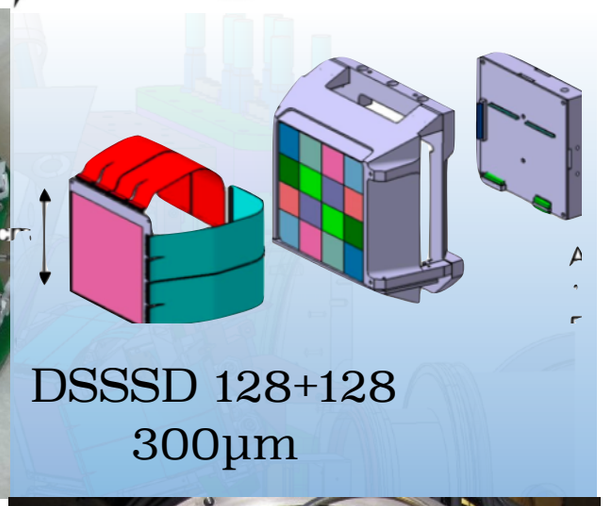


TIARA



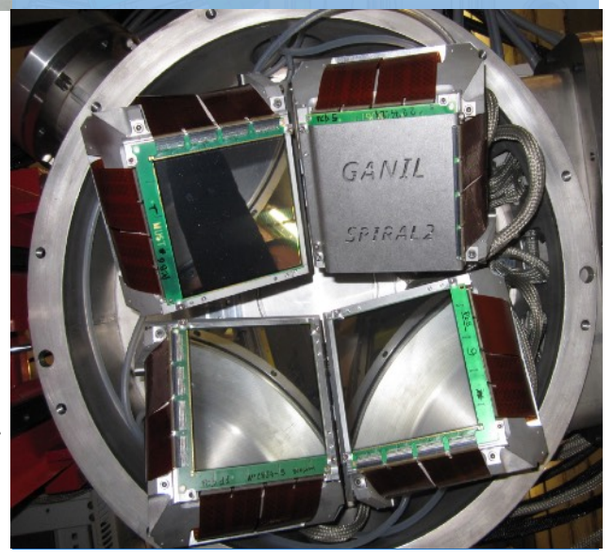


HYBALL

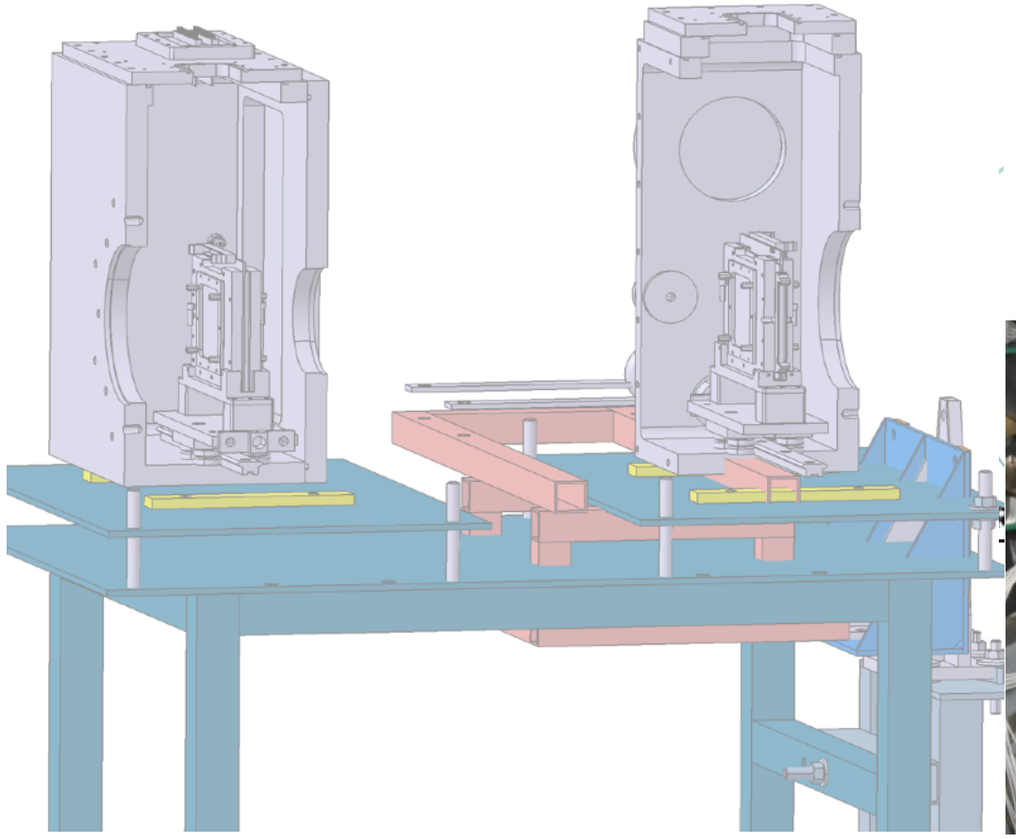
6 individual wedge-shaped DSSSD

Thickness: 400 µm

Active surface segmented in
16 rings of 40keV resolution
8 sectors of 70keV



Experimental Set-Up



TIARA MUSTS

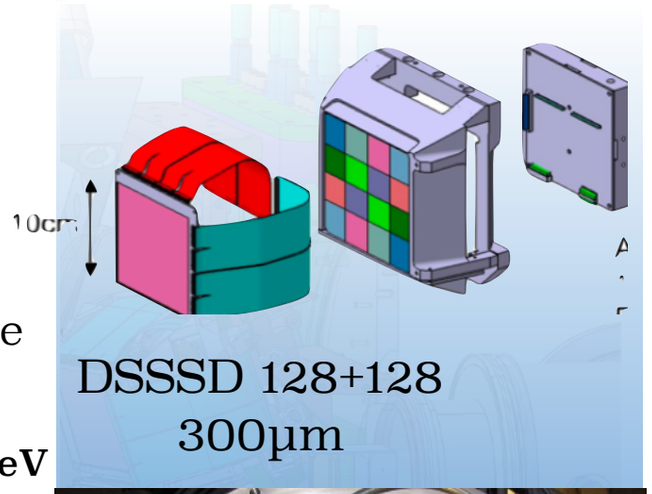
BARREL

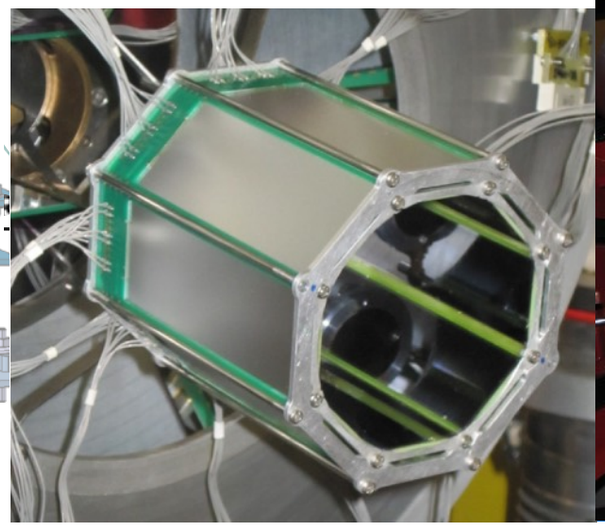
Thickness: 400 μm

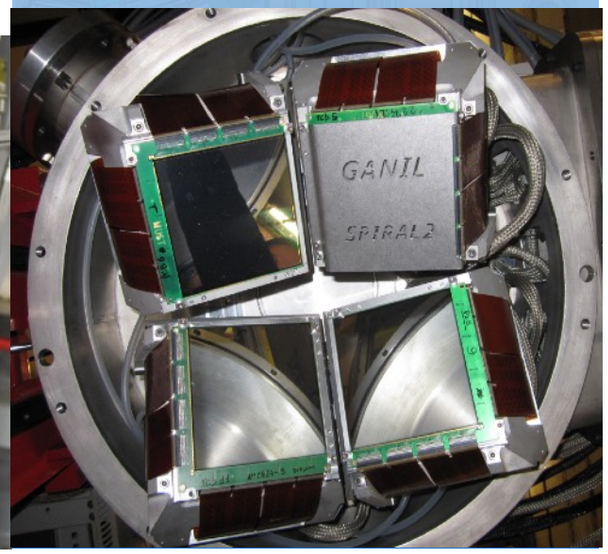
8 resistive charge division detectors

4 longitudinal resistive strips

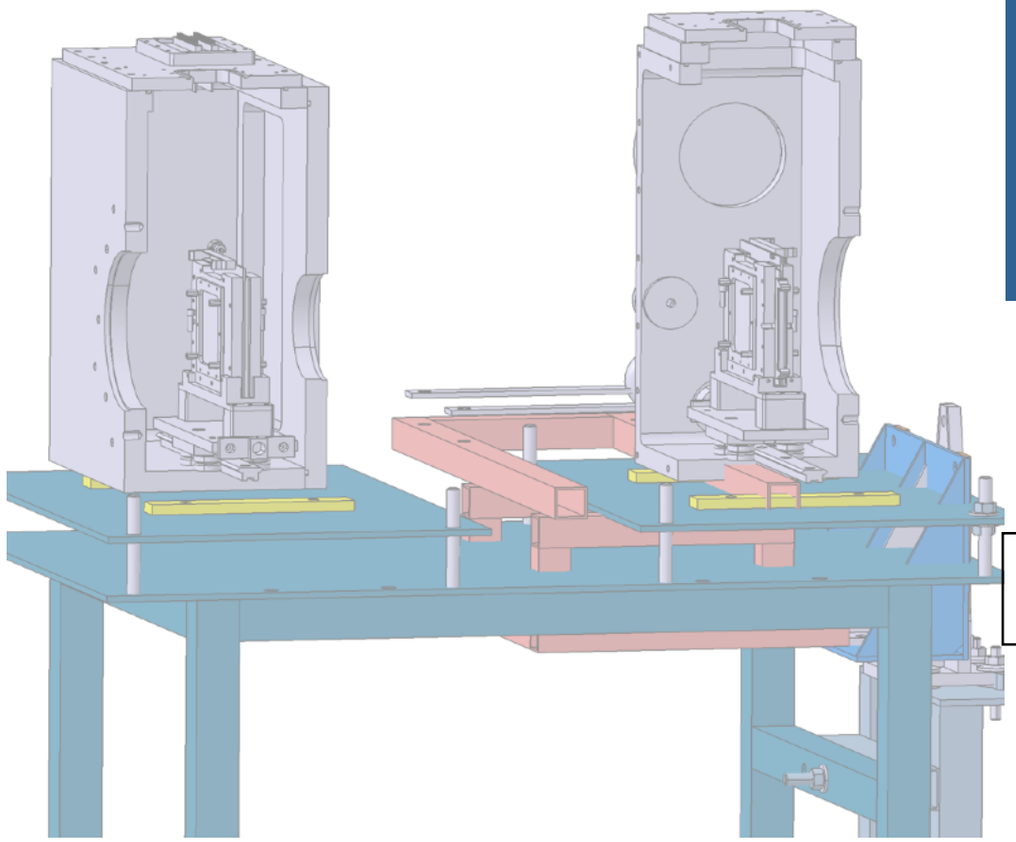
Energy Resolution: 140 keV



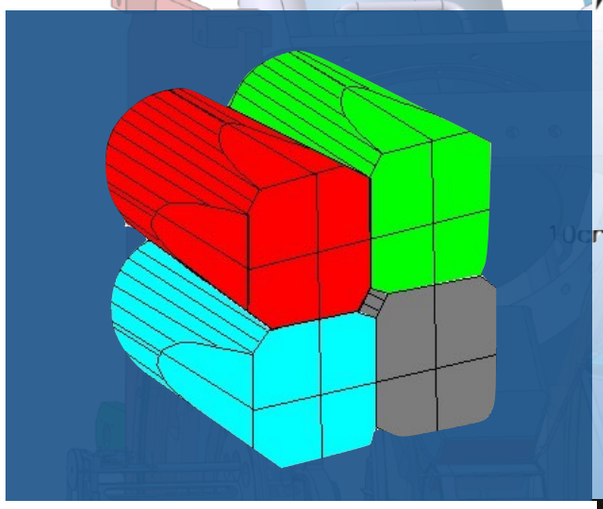


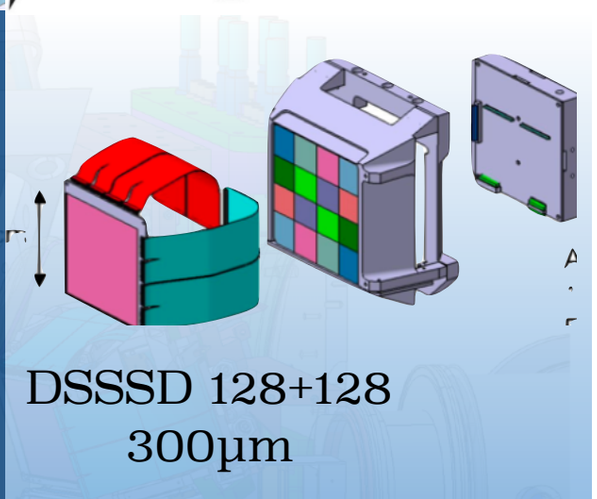


Experimental Set-Up



EXOGAM



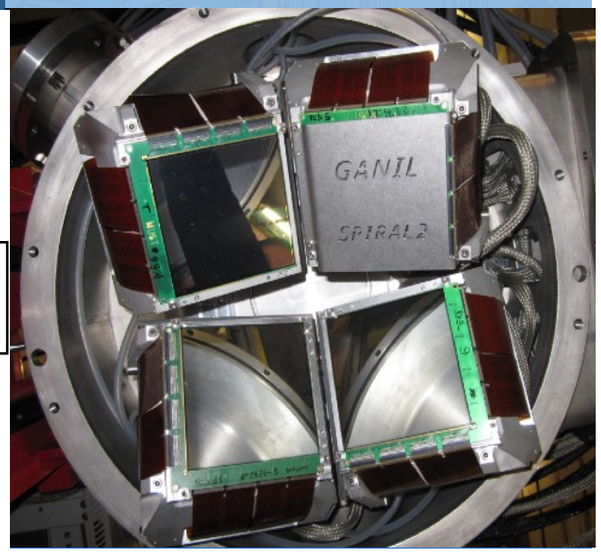


4 Germanium Clovers

3keV nominal resolution

8% efficiency at 1MeV

After Doppler Correction
~ 80 keV Resolution



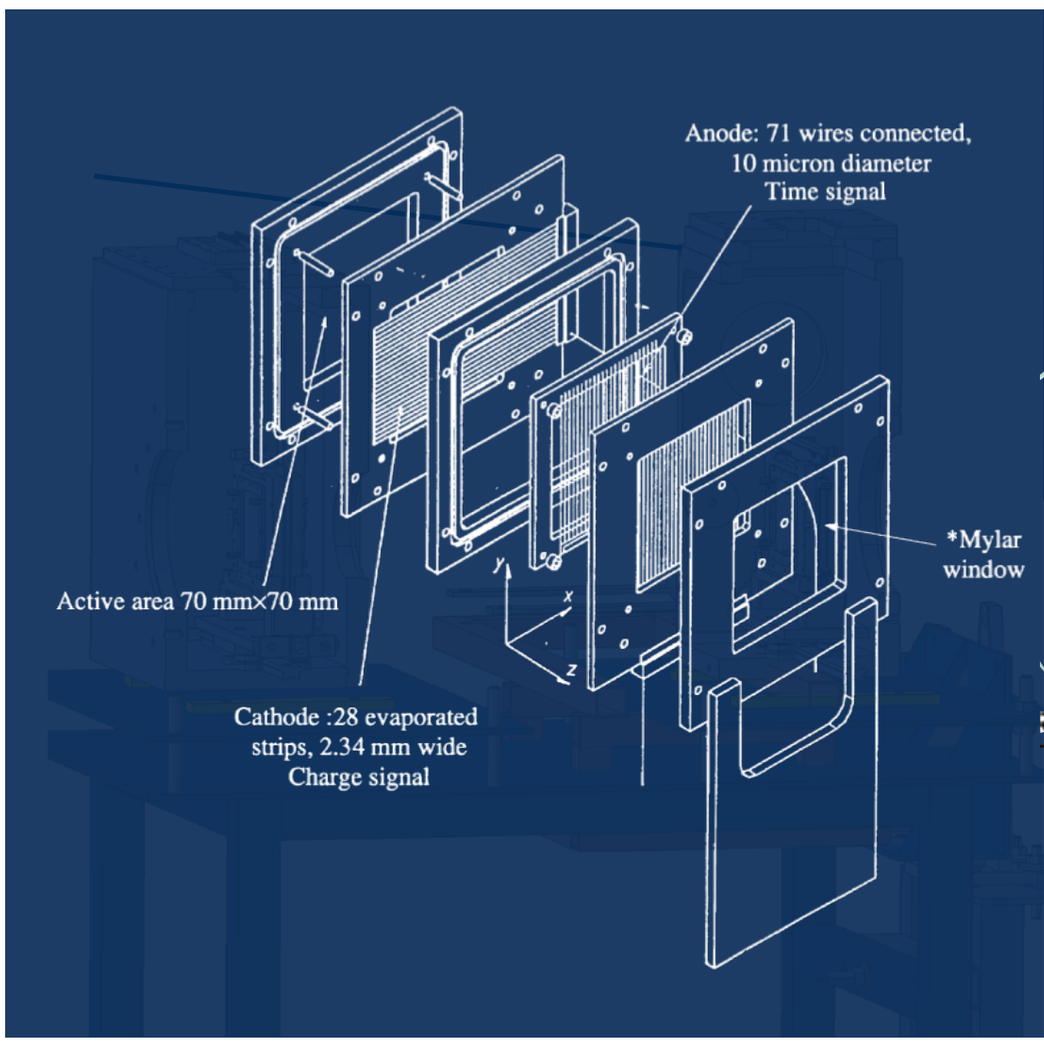
Add-back conditions

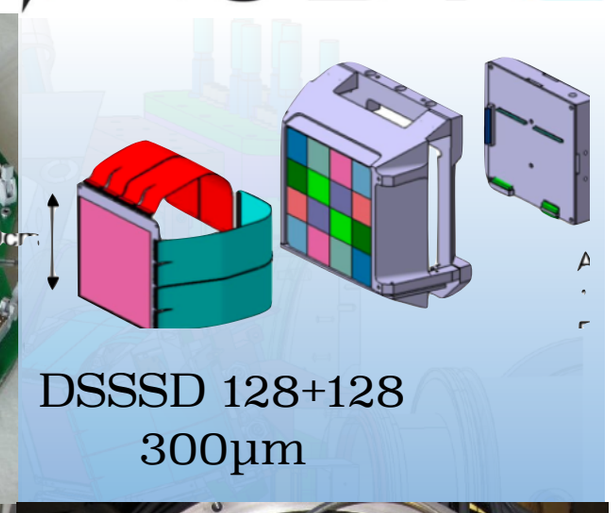
- Two events maximum
- No diagonal crystals

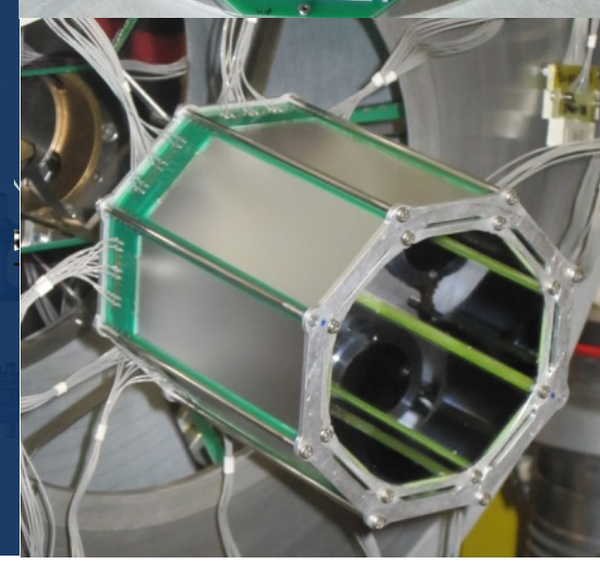
Experimental Set-Up

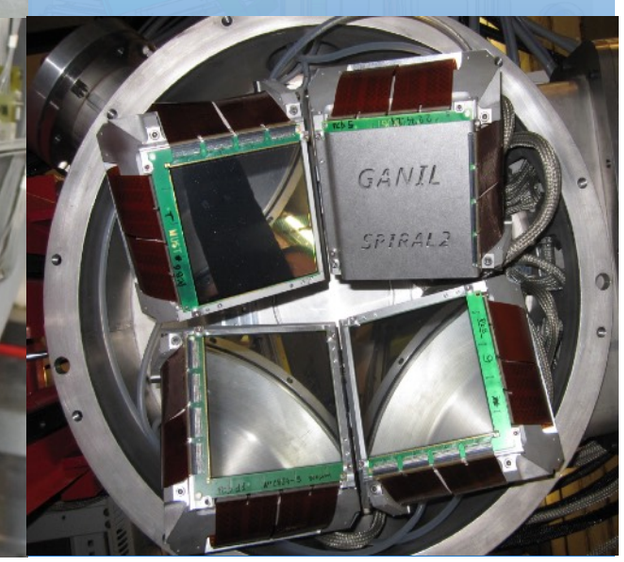
CATS

TIARA









Data Analysis-Mask reconstruction

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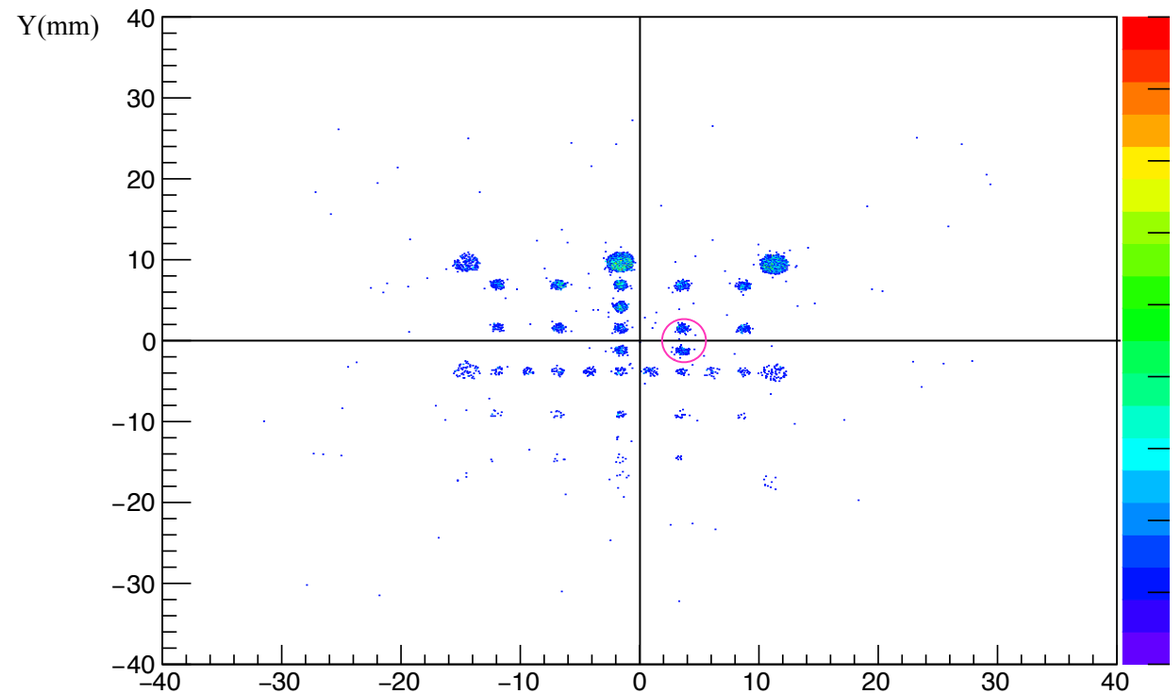
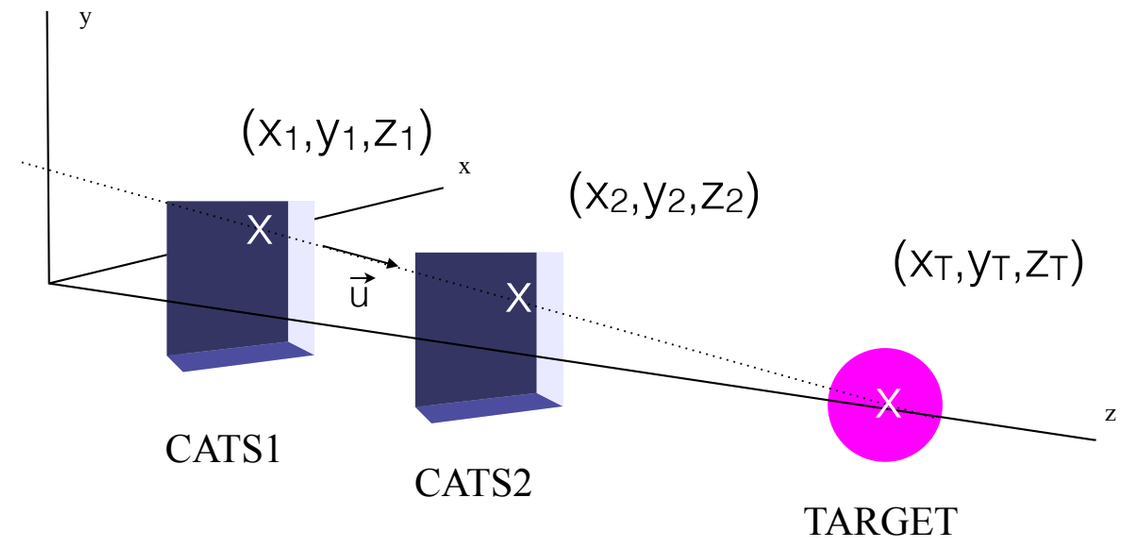
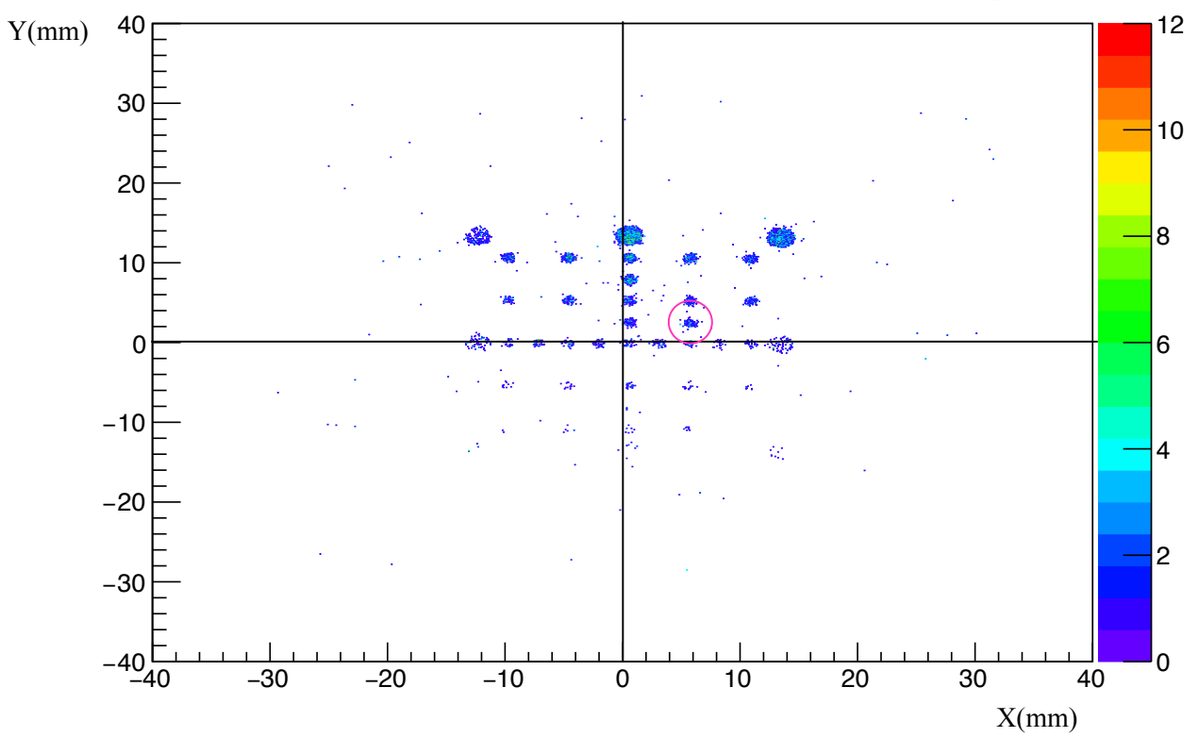
Mask reconstruction on CATS1 before alignment

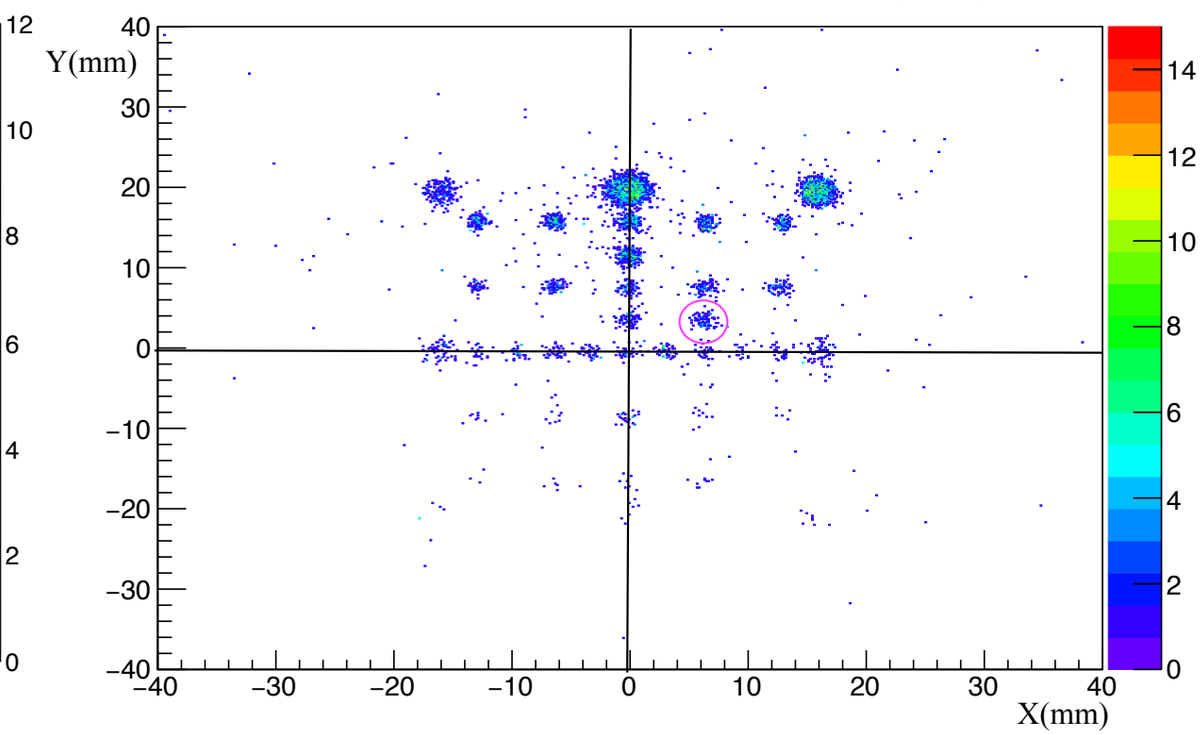




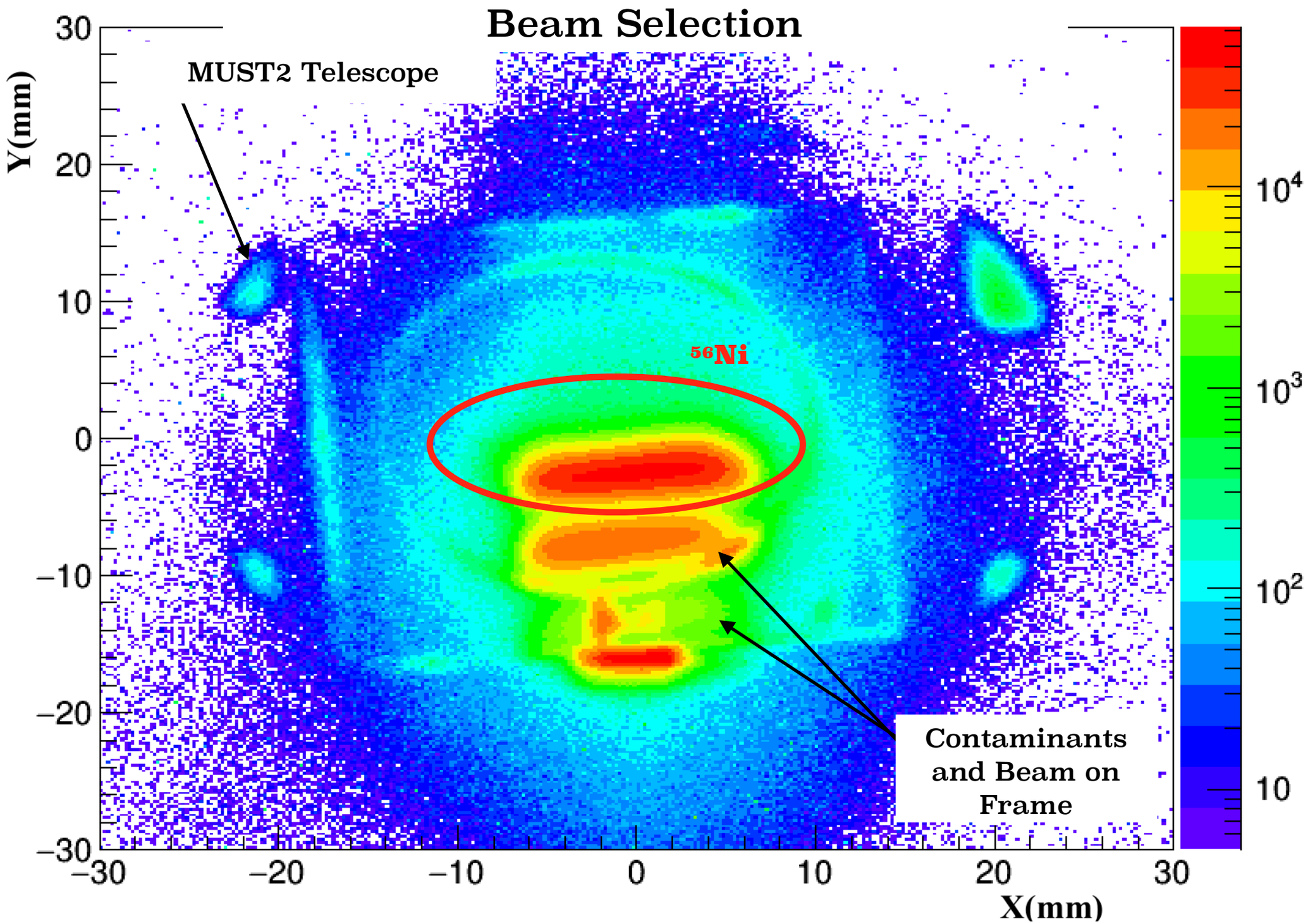
Mask reconstruction on CATS1 after alignment



Mask reconstruction on the target position.

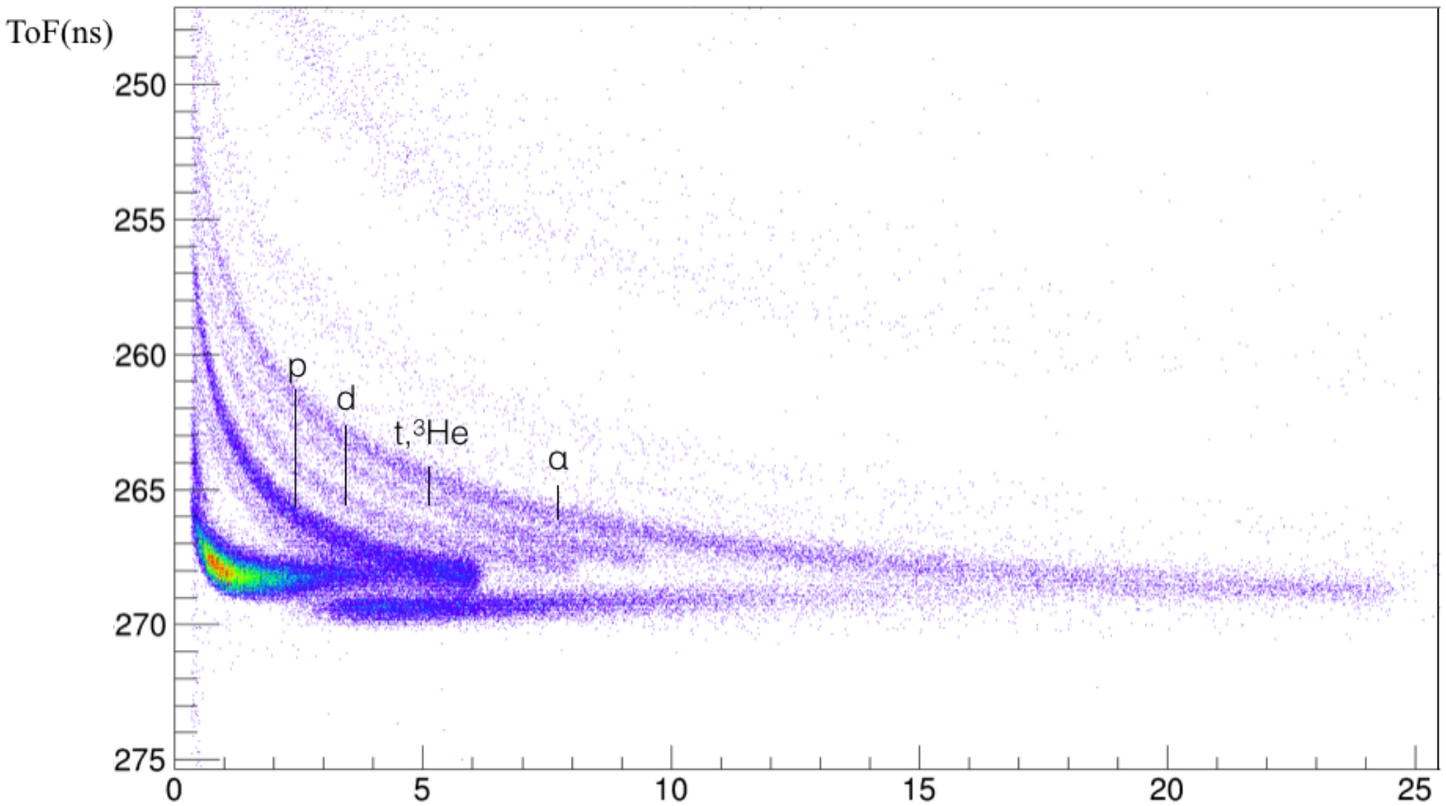


Data Analysis-Beam Selection



Beam reconstruction on the target position without ToF-HF condition.

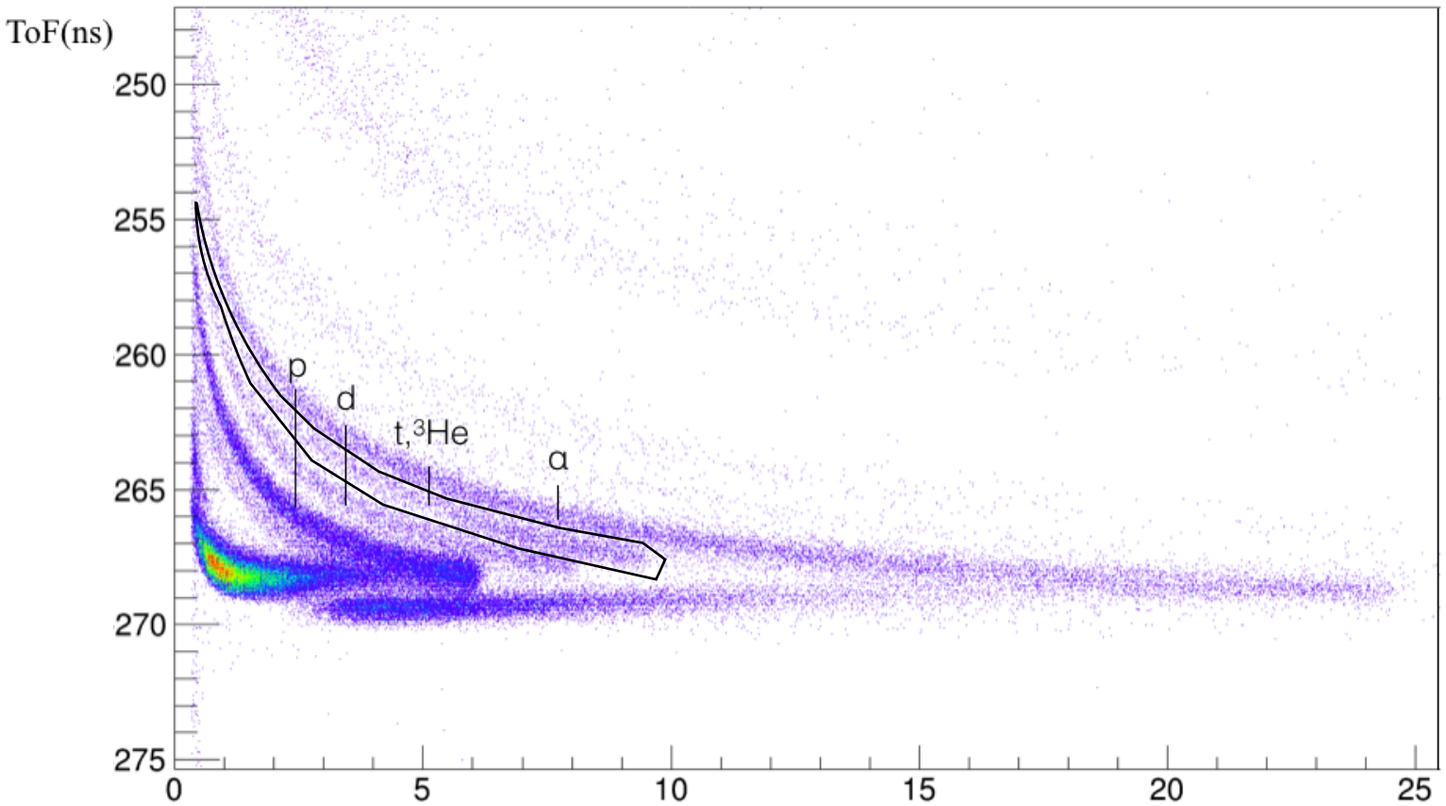
Data Analysis-Particle Selection



PID-ToF in the MUST2 Telescope 2

ΔE_{DSSD} (MeV)

Data Analysis-Particle Selection

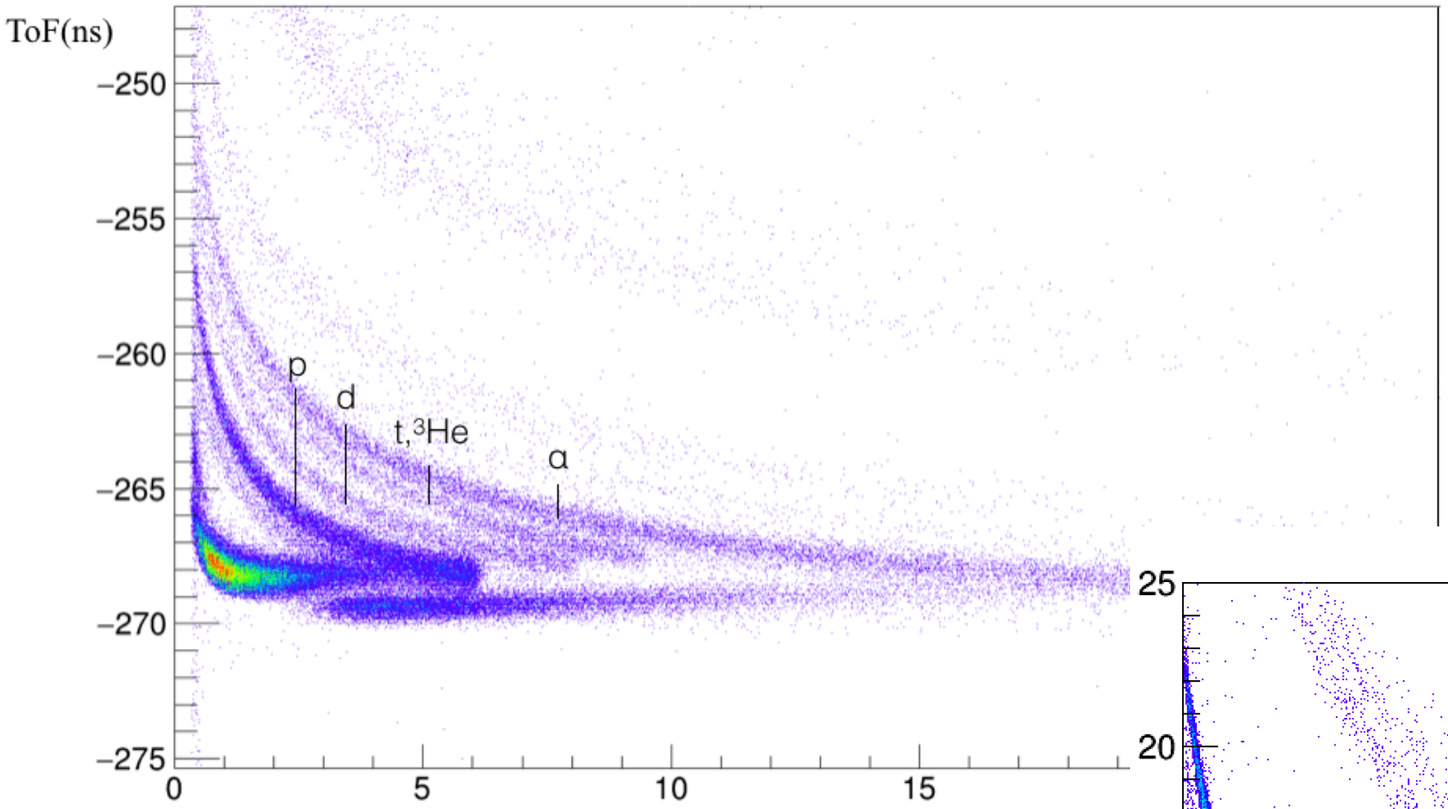


PID-ToF in the MUST2 Telescope 2

ΔE_{DSSD} (MeV)

$$\Delta t = \sqrt{\frac{mL^2}{2E}}$$

Data Analysis-Particle Selection

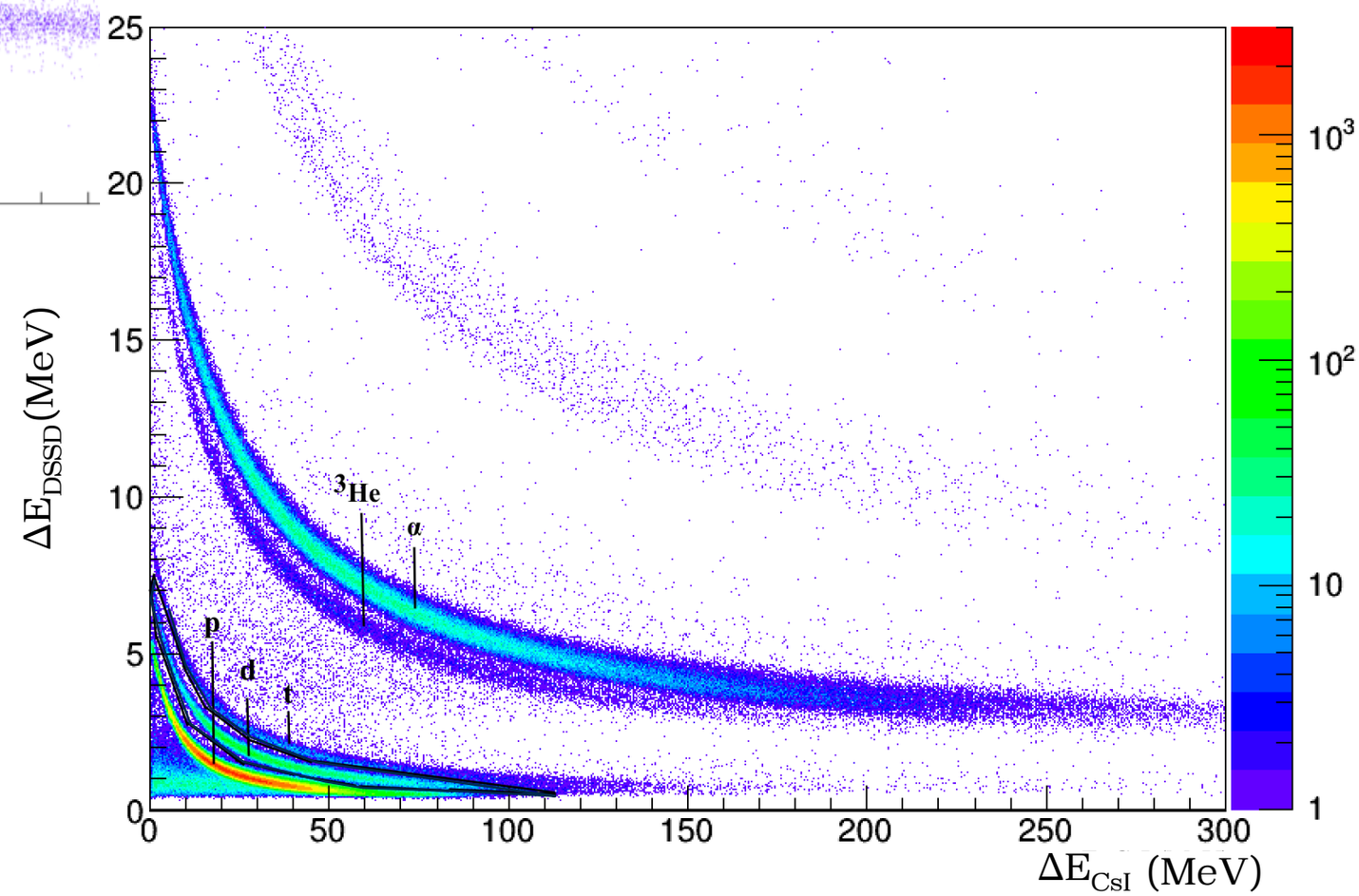


PID-ToF in the MUST2 Telescope 2

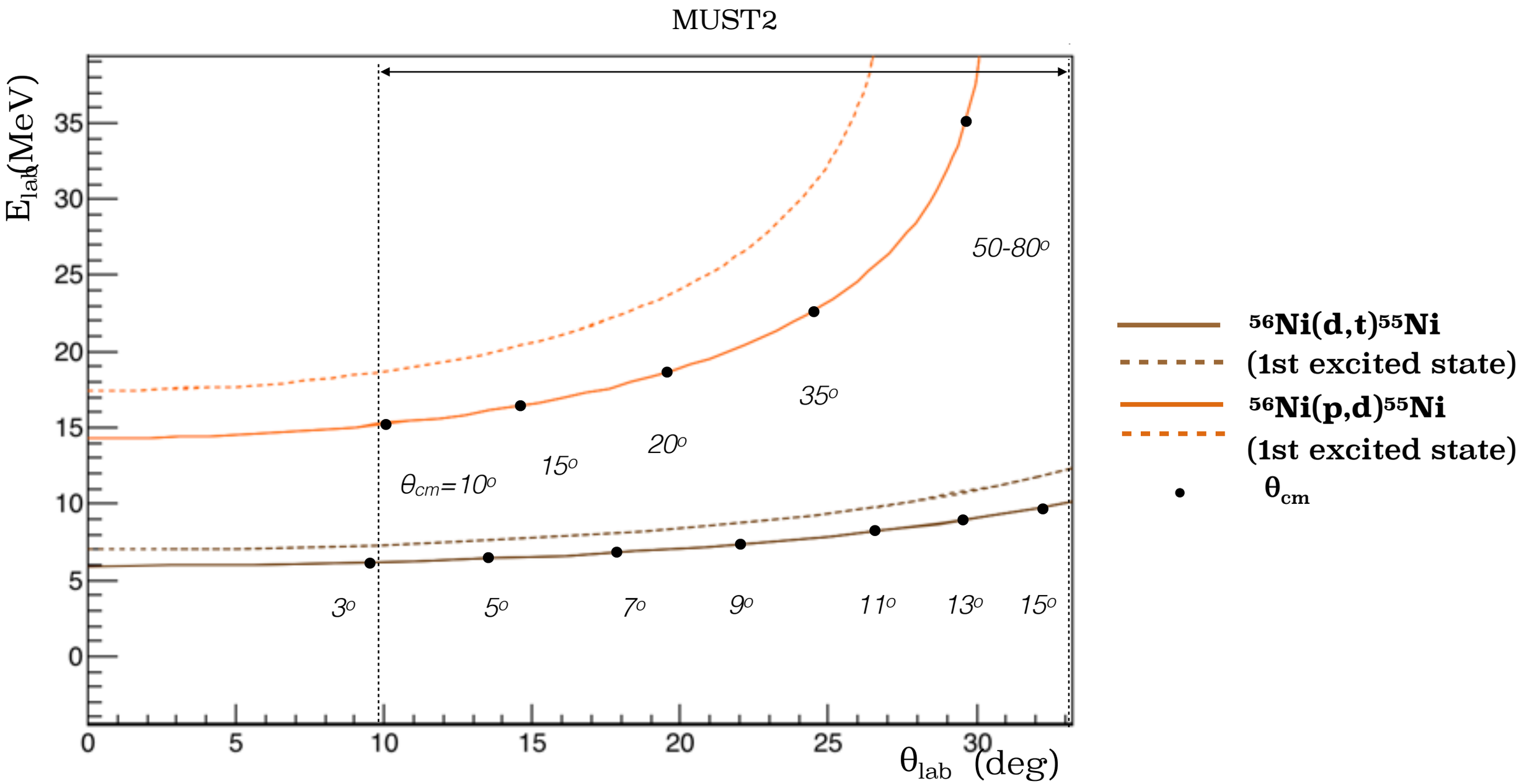
$$\Delta t = \sqrt{\frac{mL^2}{2E}}$$

$$\Delta E \approx \frac{AZ^2}{E}$$

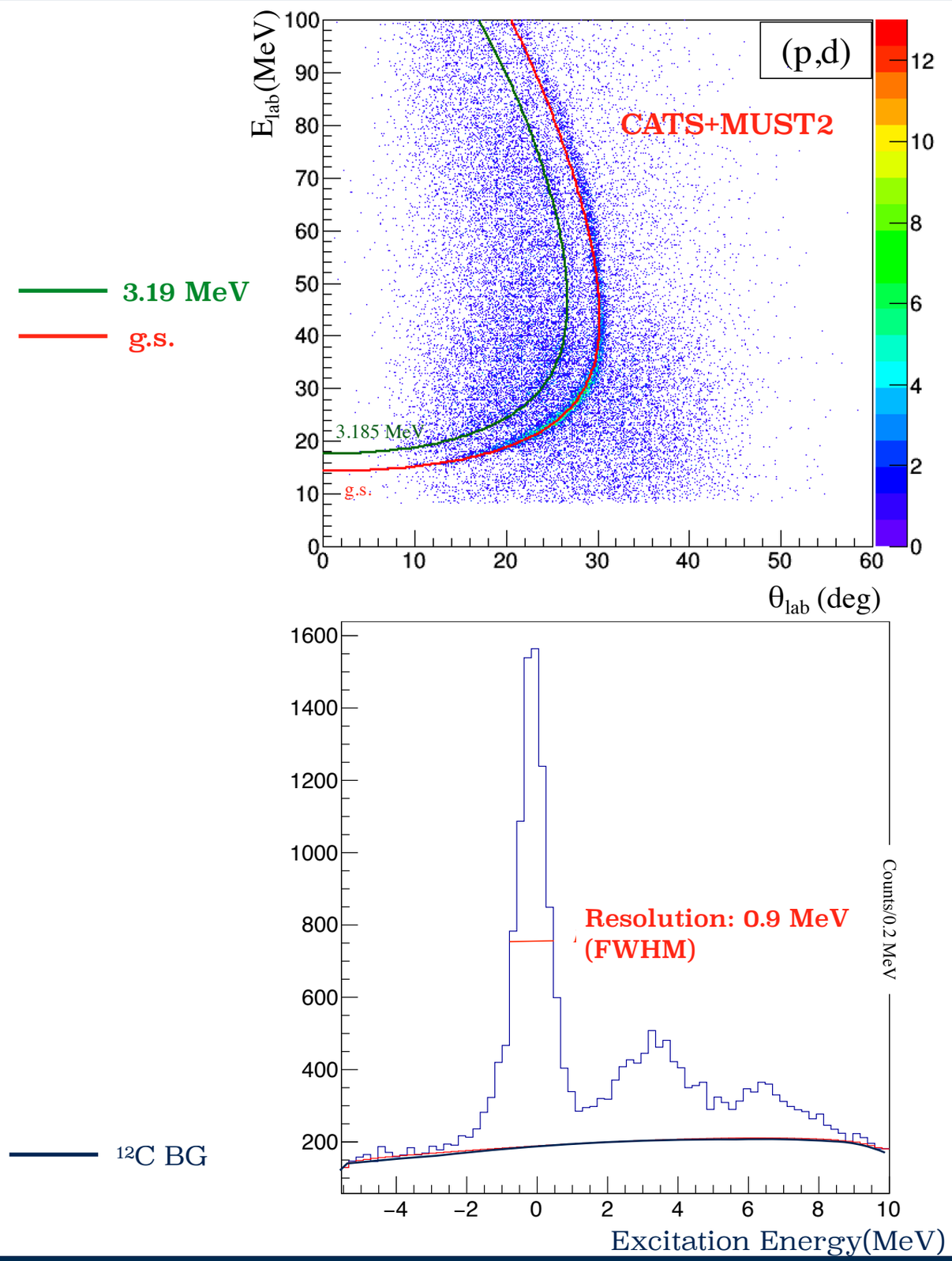
PID-ΔE vs E in the two layers of MUST2



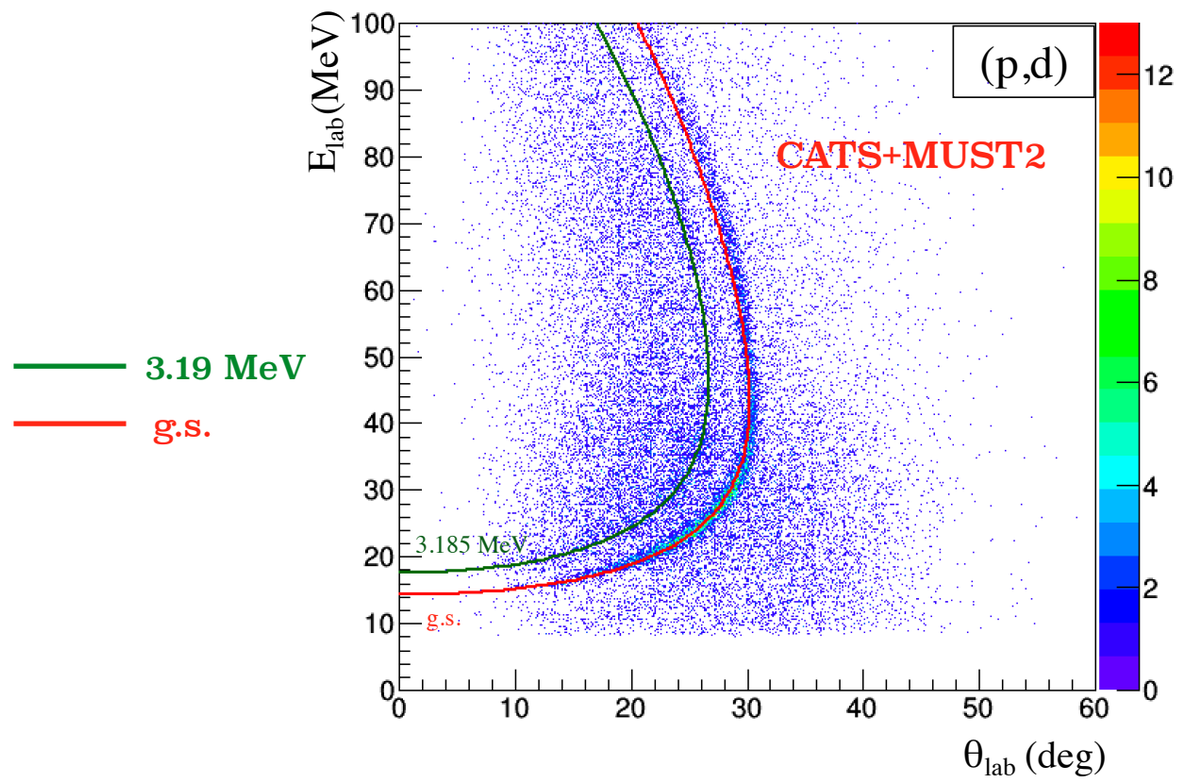
The reaction Kinematics

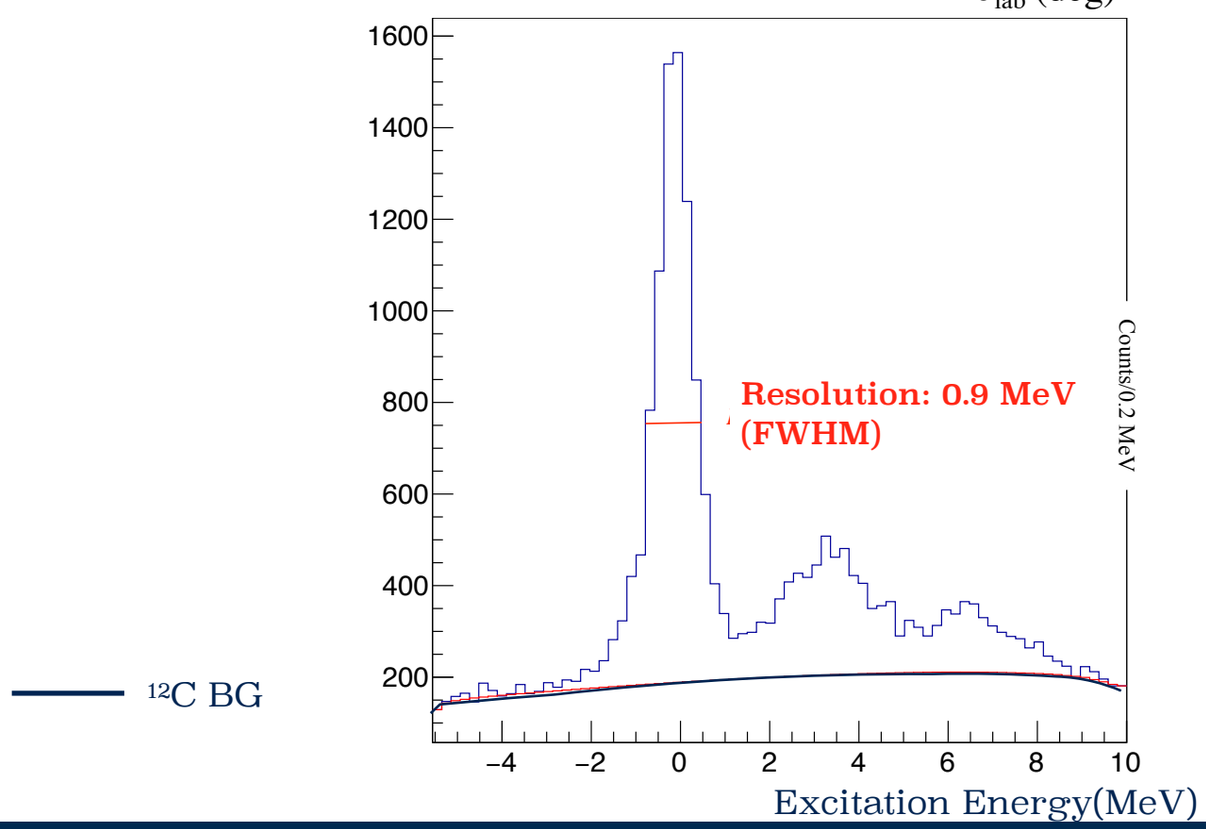


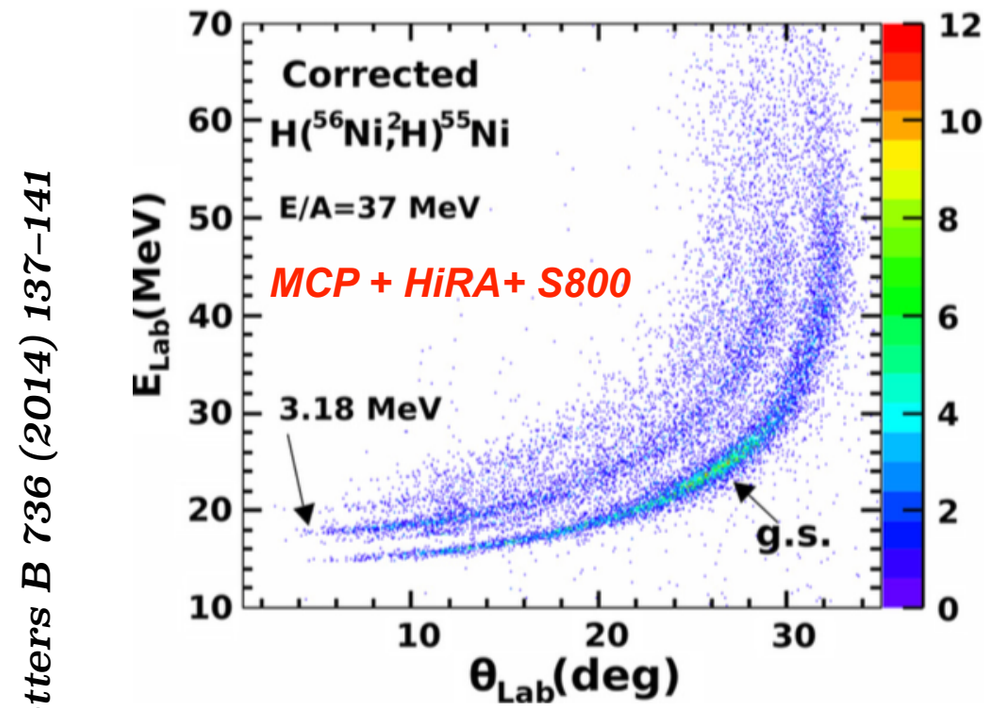
$^{56}Ni(p,d)^{55}Ni$

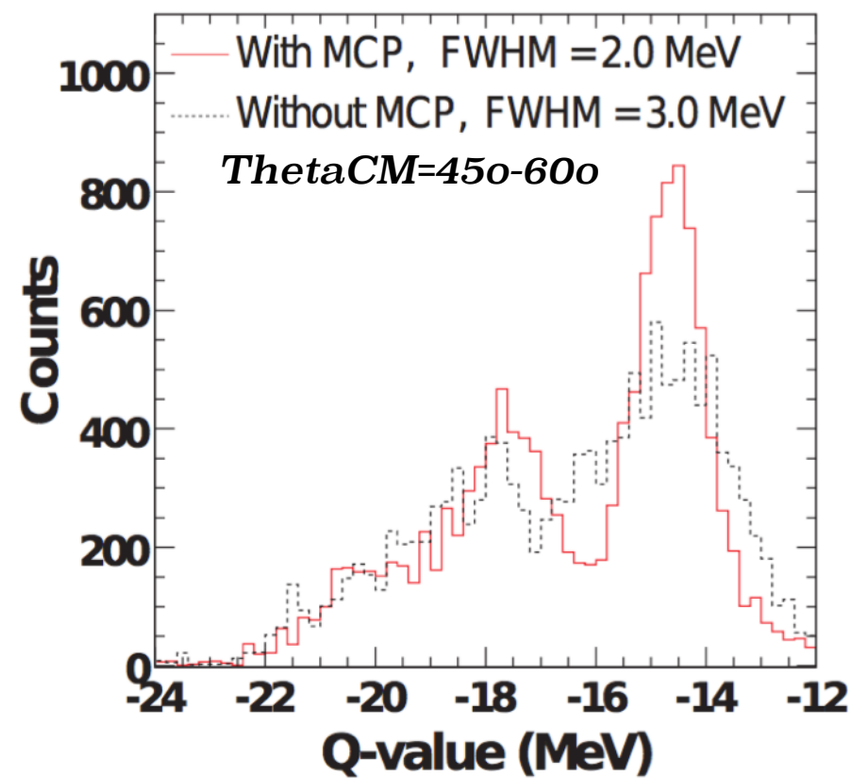

(p,d)
CATS+MUST2
3.19 MeV
g.s.
3.185 MeV
g.s.
E_{lab}(MeV)
θ_{lab} (deg)
Resolution: 0.9 MeV
(FWHM)
Counts/0.2 MeV
^{12}C BG
Excitation Energy(MeV)

$^{56}Ni(p,d)^{55}Ni$





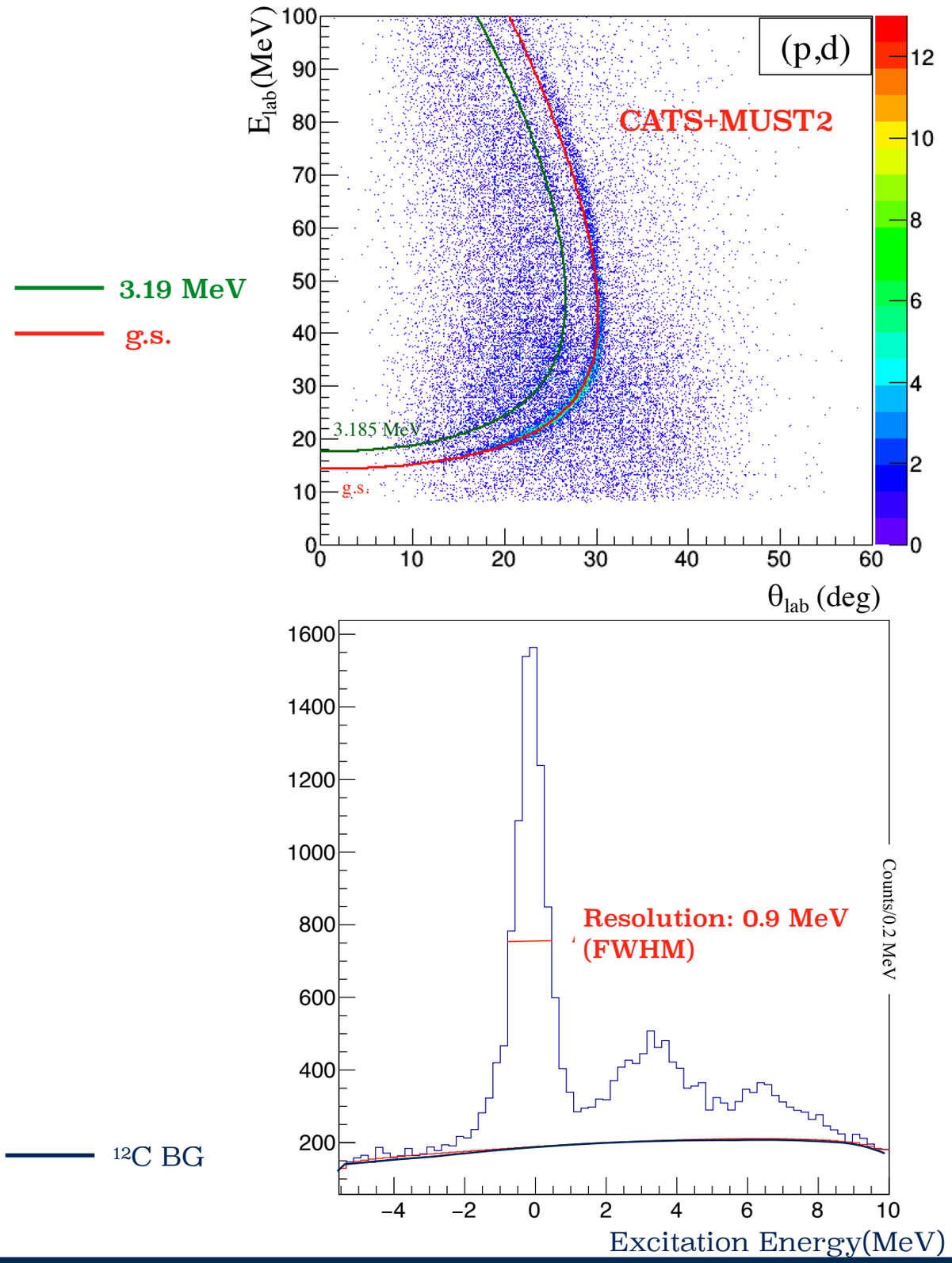


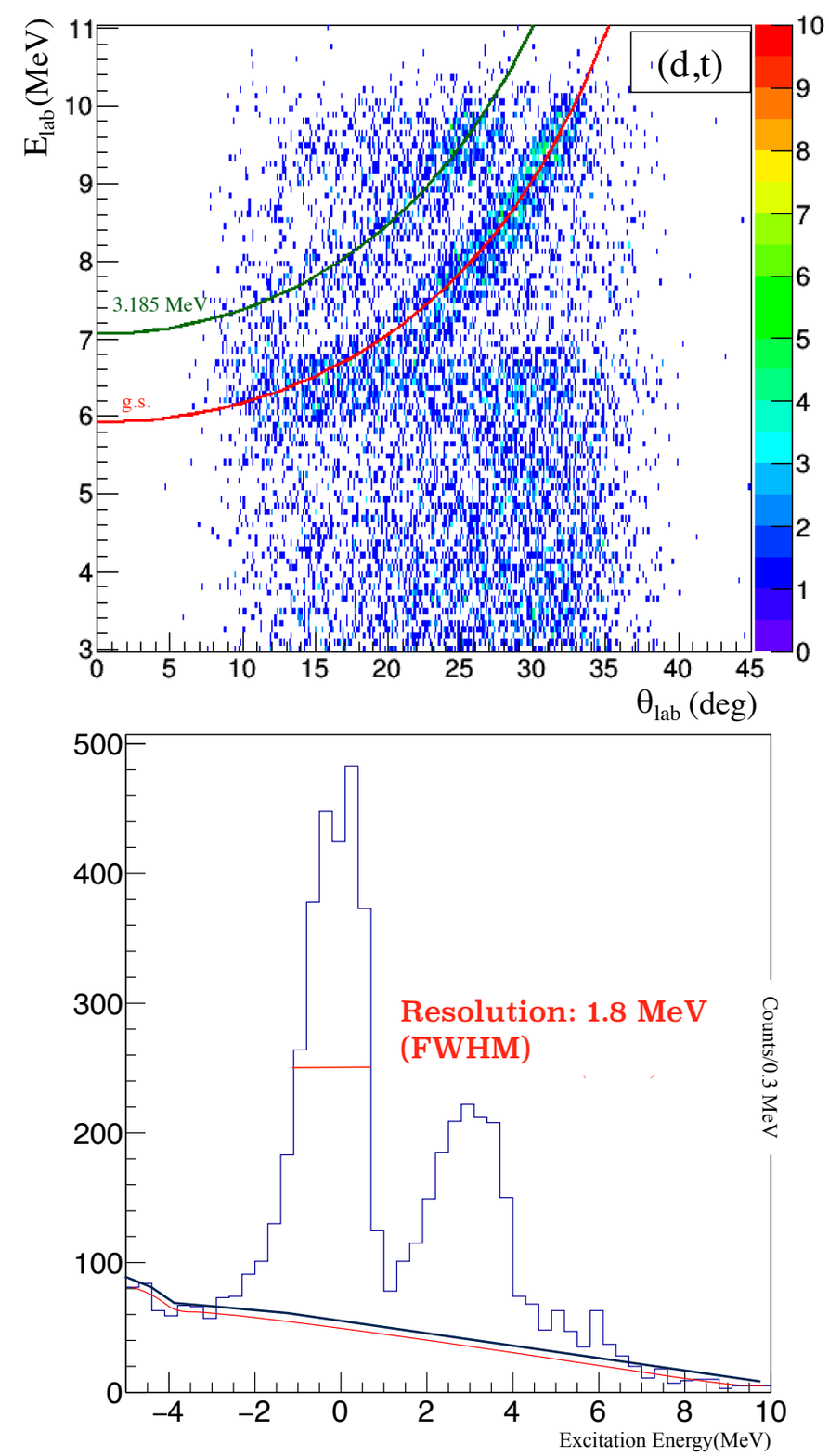


A. Sanetullaev et al. / Physics Letters B 736 (2014) 137–141

$^{56}Ni(p,d)^{55}Ni$

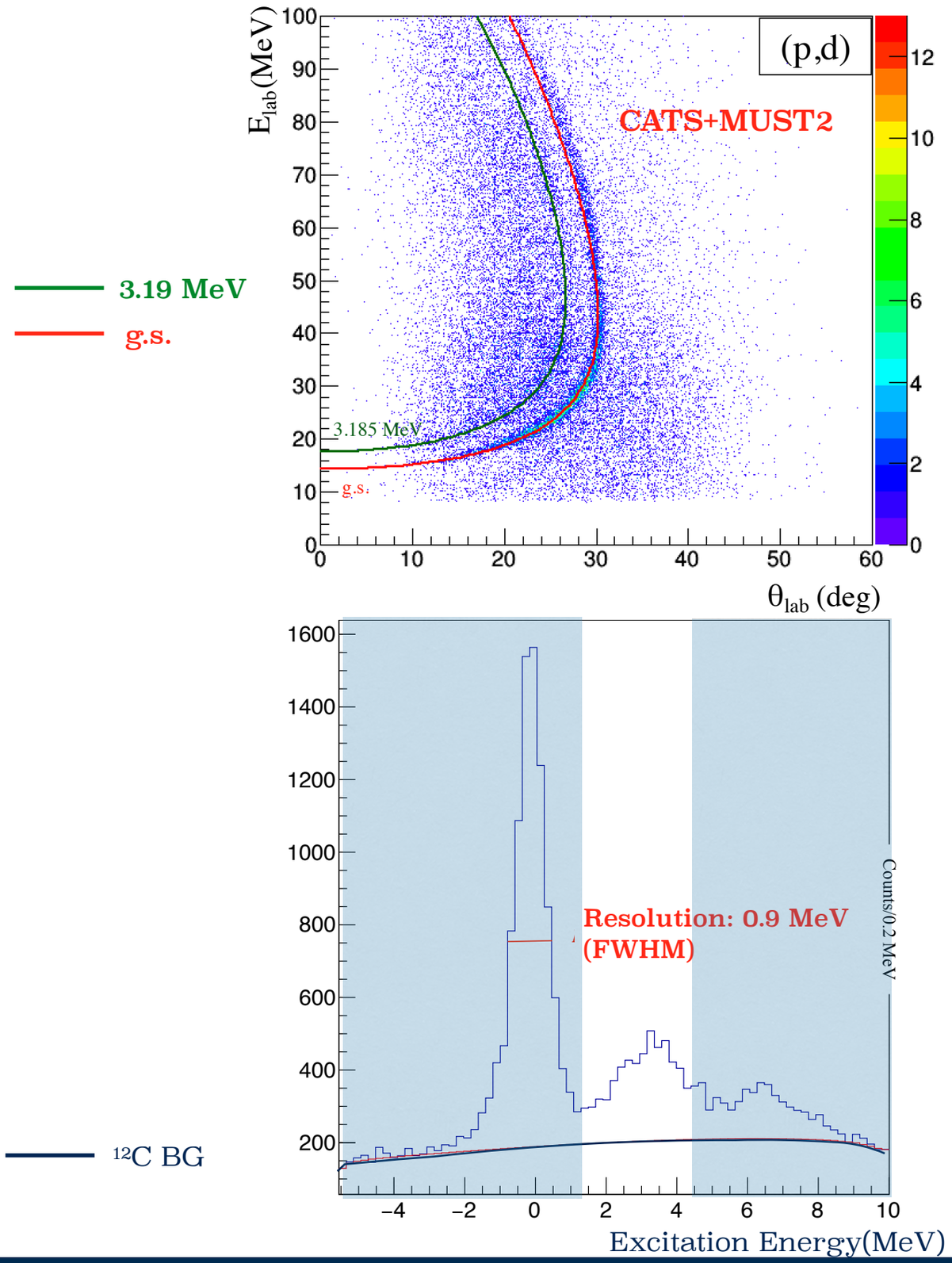
$^{56}Ni(d,t)^{55}Ni$

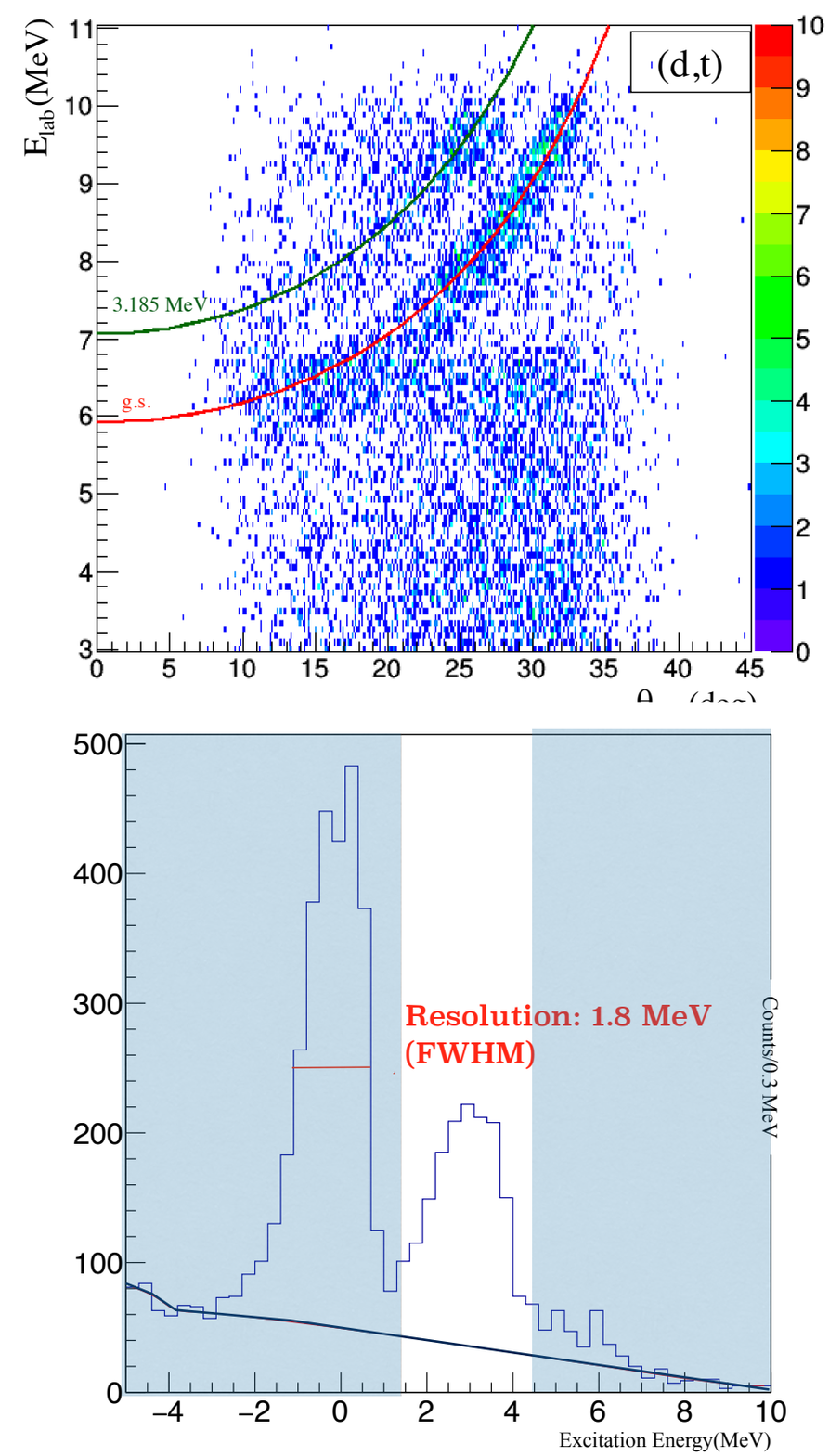




^{56}Ni(p,d)^{55}Ni

^{56}Ni(d,t)^{55}Ni

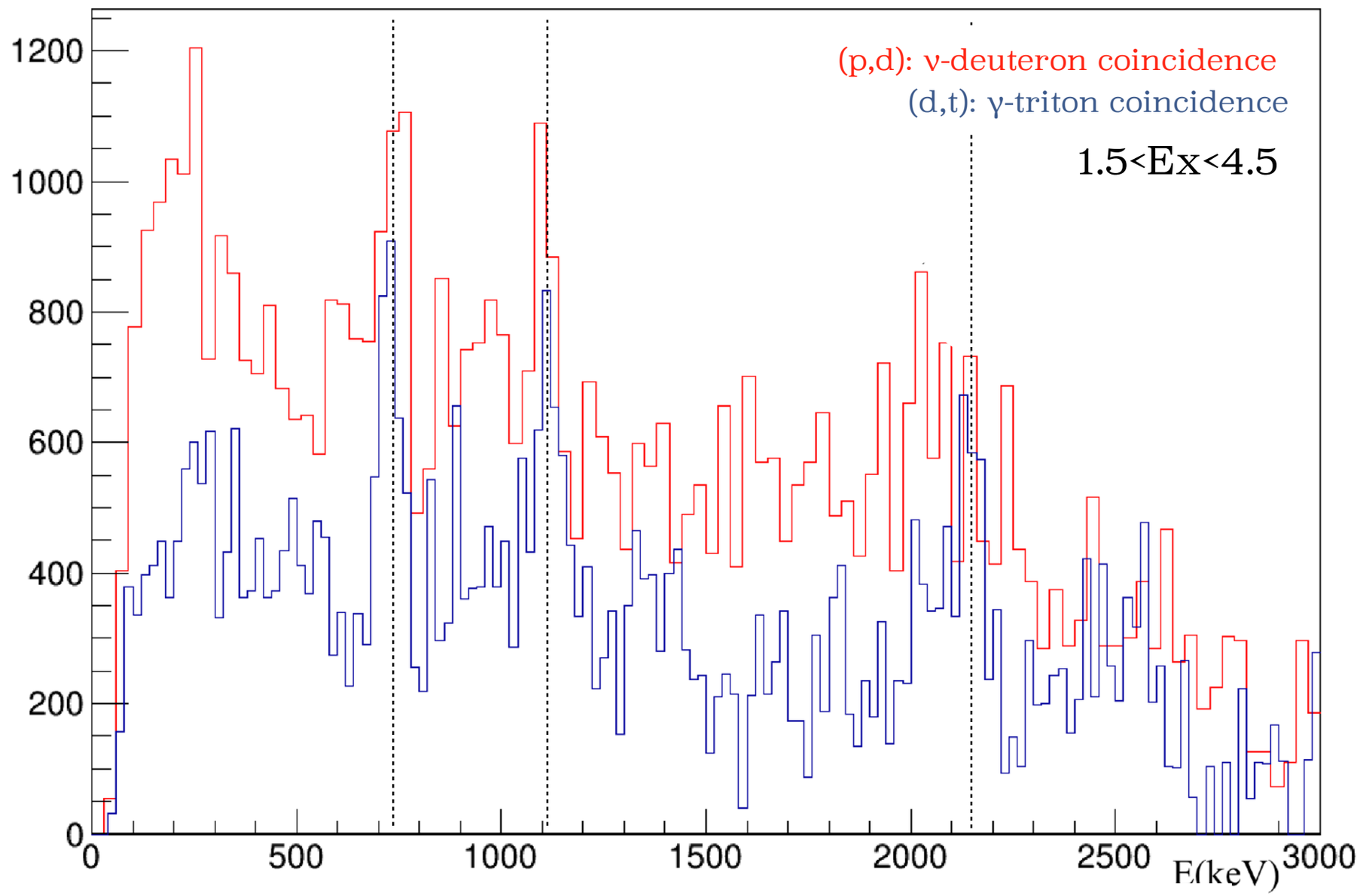




Data Analysis- Particle-γ coincidence

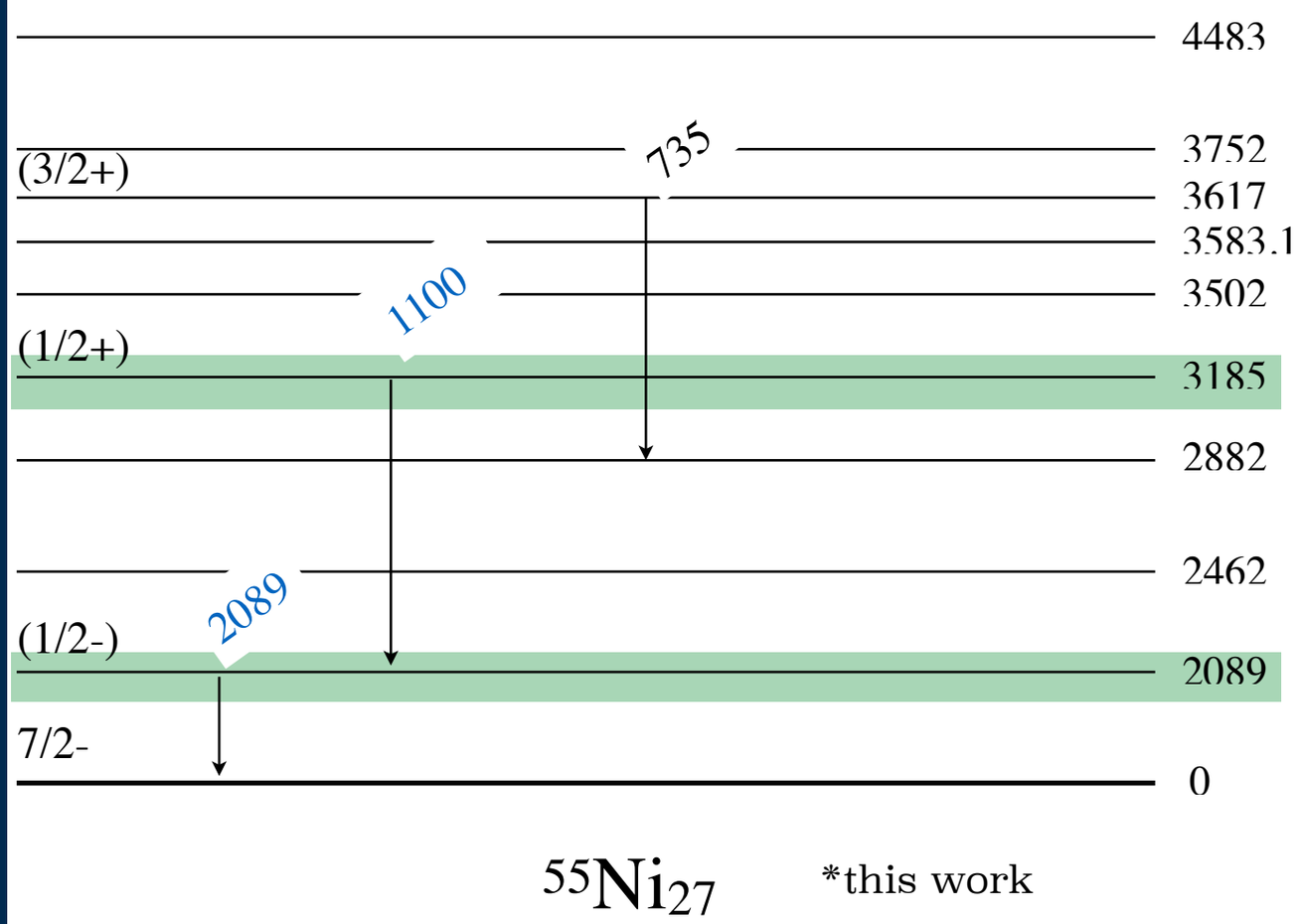
Particle-γ coincidence is used to:

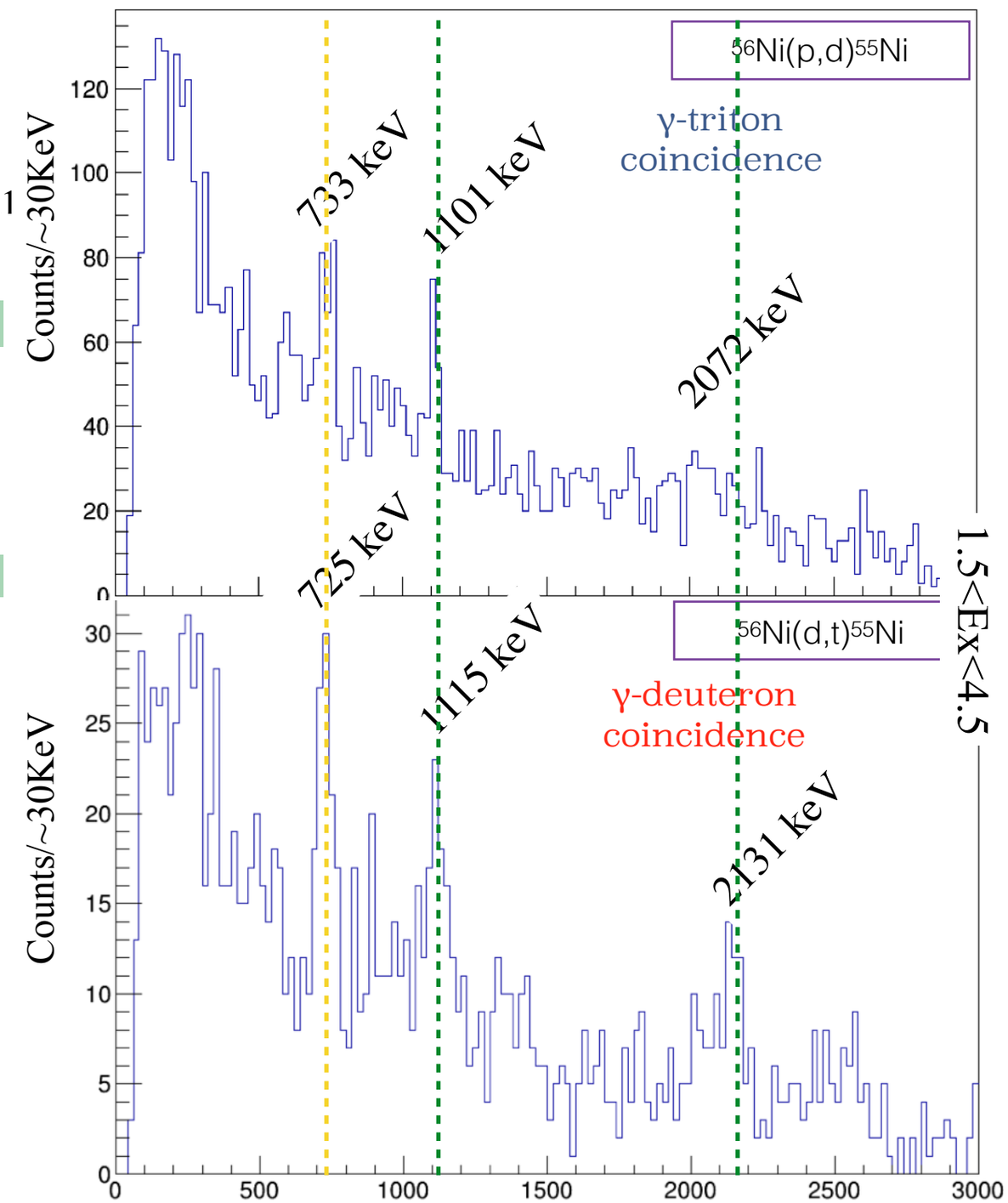
- Identify the populated states
- Get the relative ratios of the transitions



Doppler Corrected /Efficiency Corrected Energy

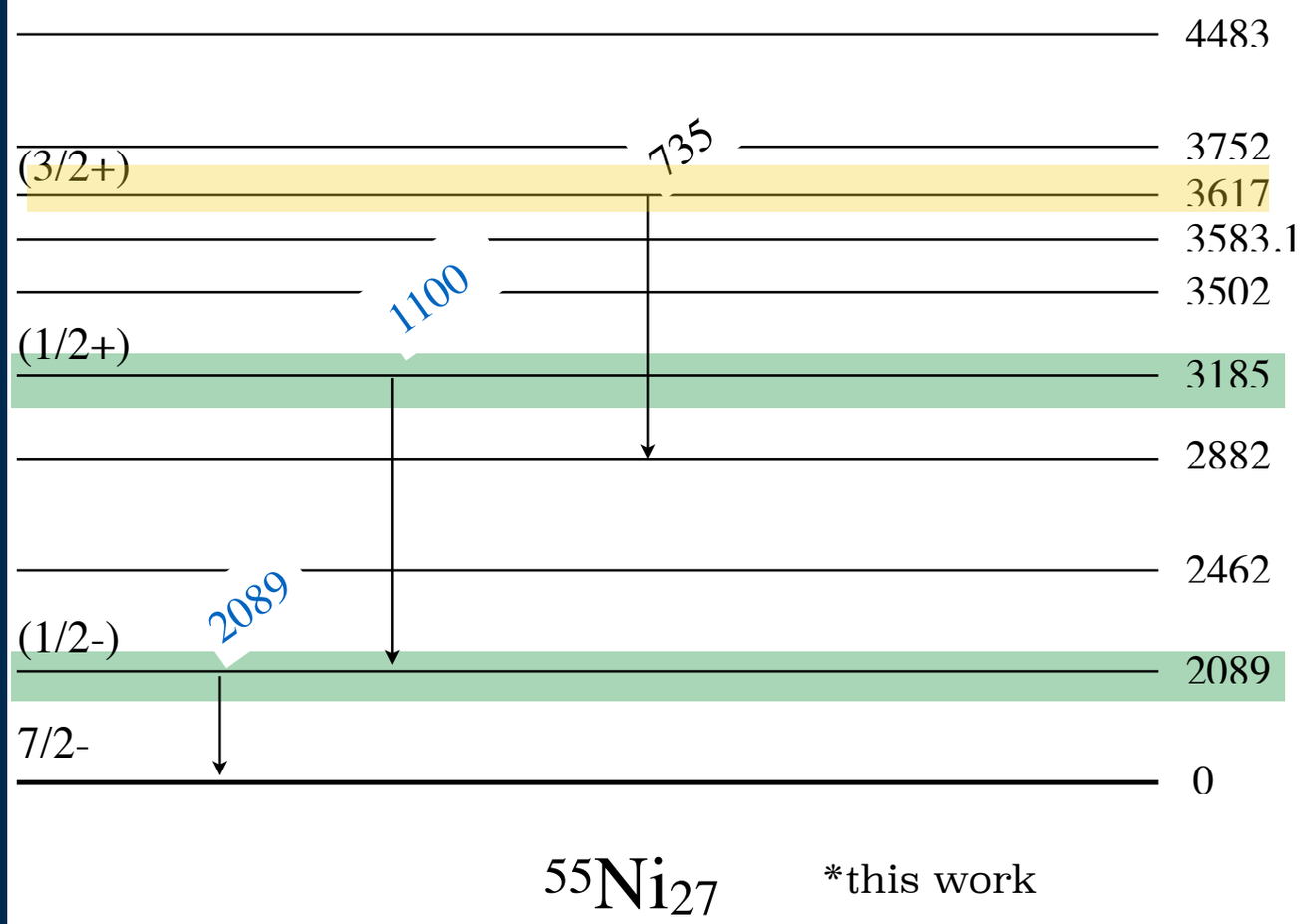
Data Analysis- Particle-γ coincidence

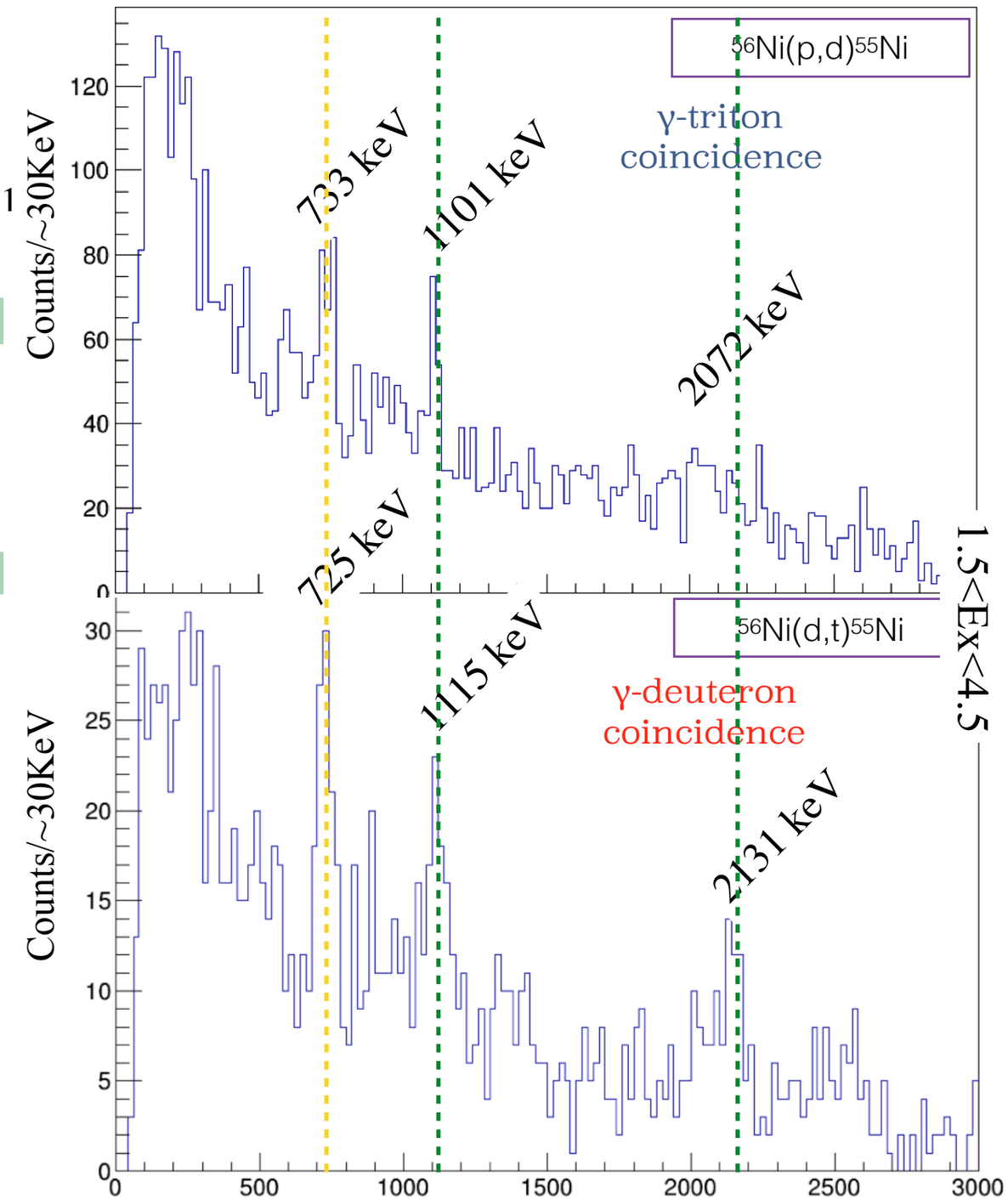




- **Populated States : 2089 keV, 3185 keV, 3617 keV**
- **Transfer reactions favour γ-transition to states with single particle character**
- **State 3617 populated and assigned to spin 3/2+**

Data Analysis- Particle-γ coincidence





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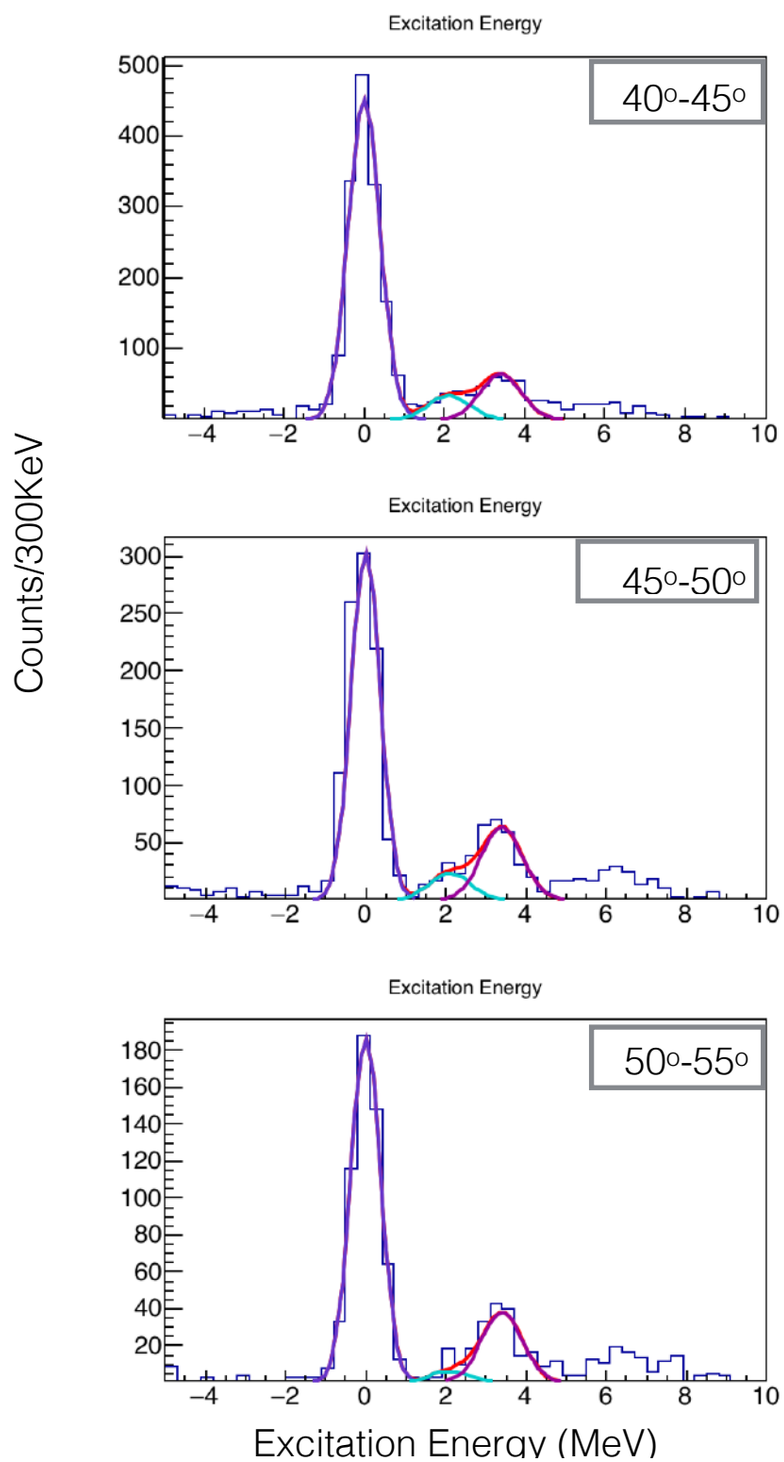
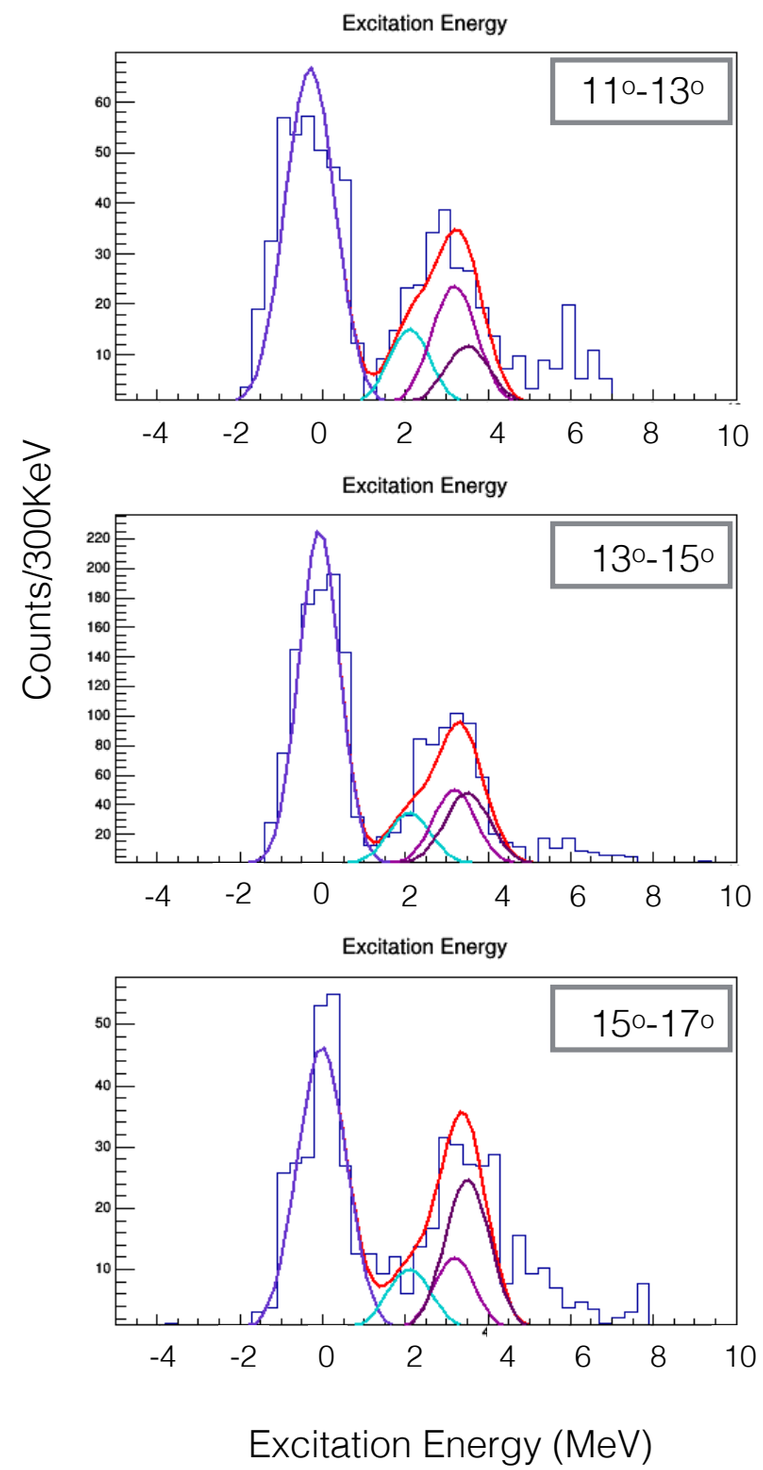
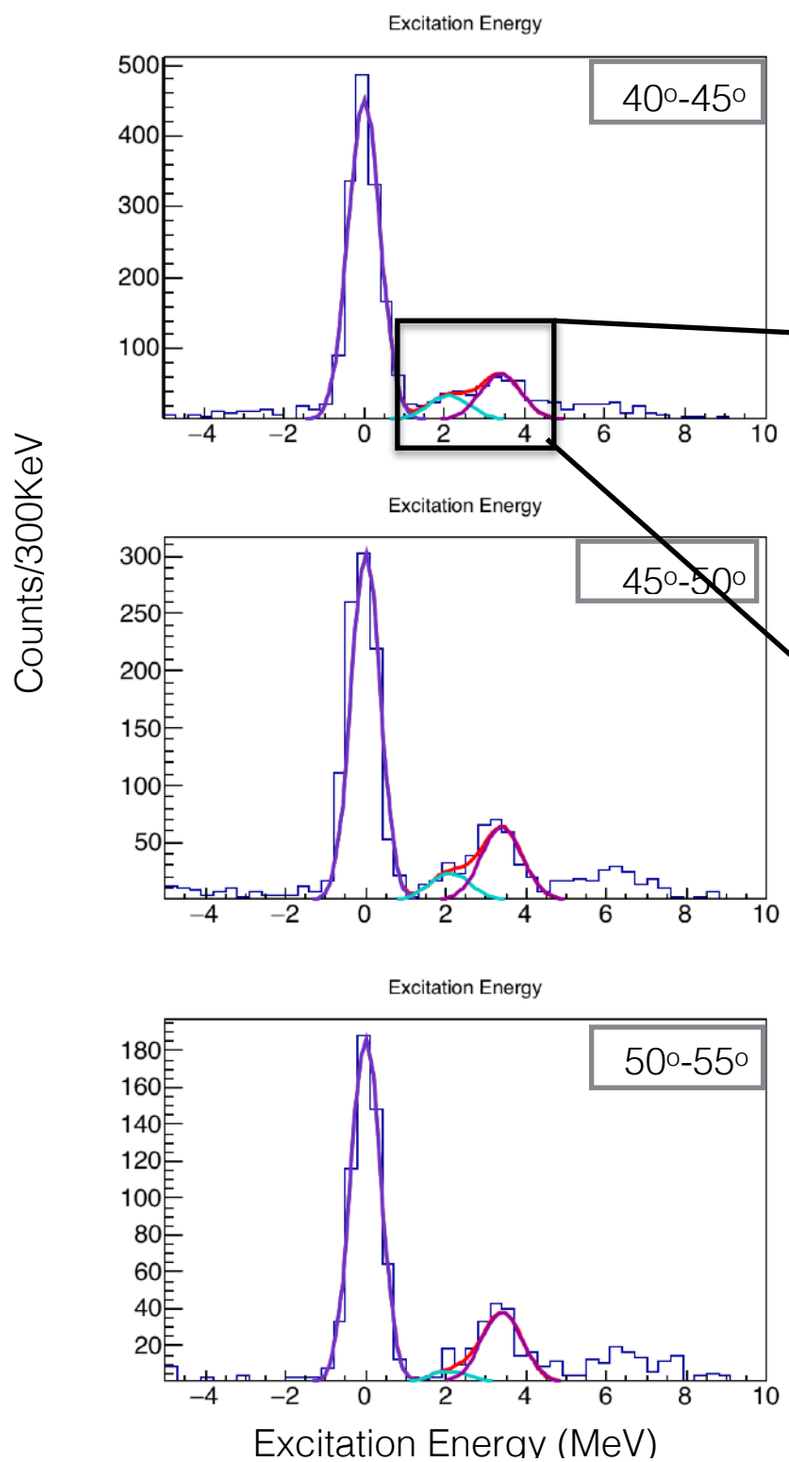
The excitation energy spectra in different angle range in the centre of mass

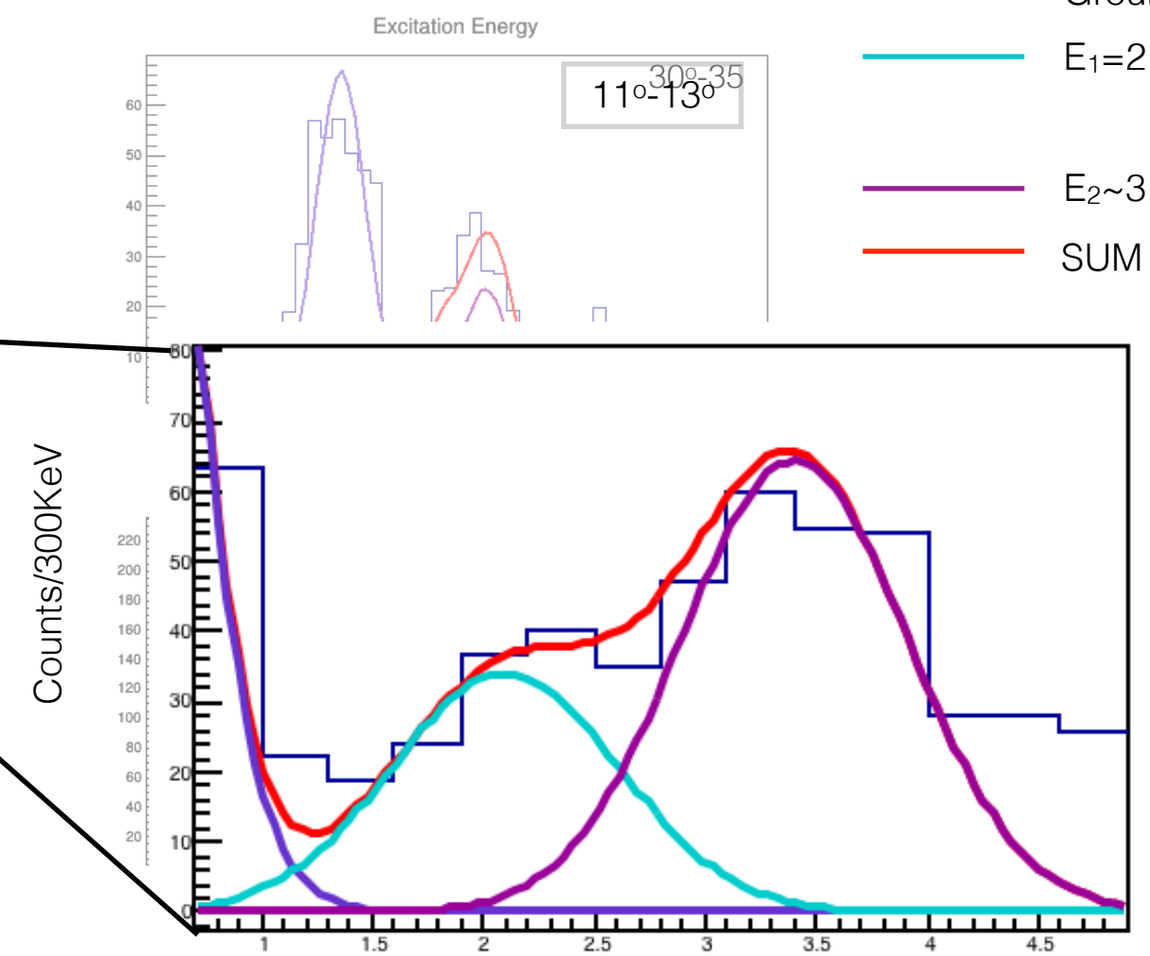




Ground State
E_1=2.1MeV
E_2~3.5 MeV
SUM

The excitation energy spectra in different angle range in the centre of mass





Ground State

E_1=2.1MeV

E_2~3.5 MeV

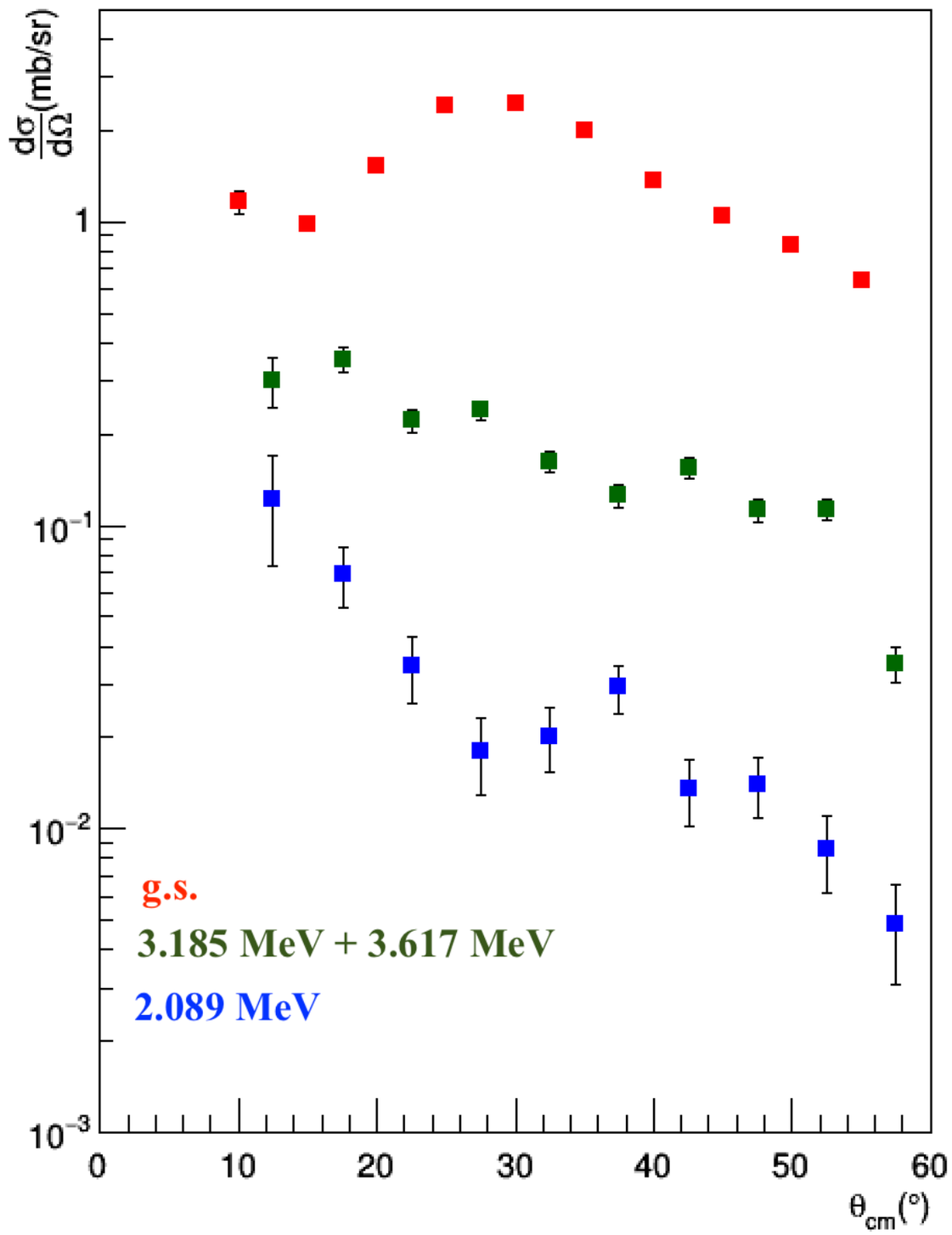
SUM

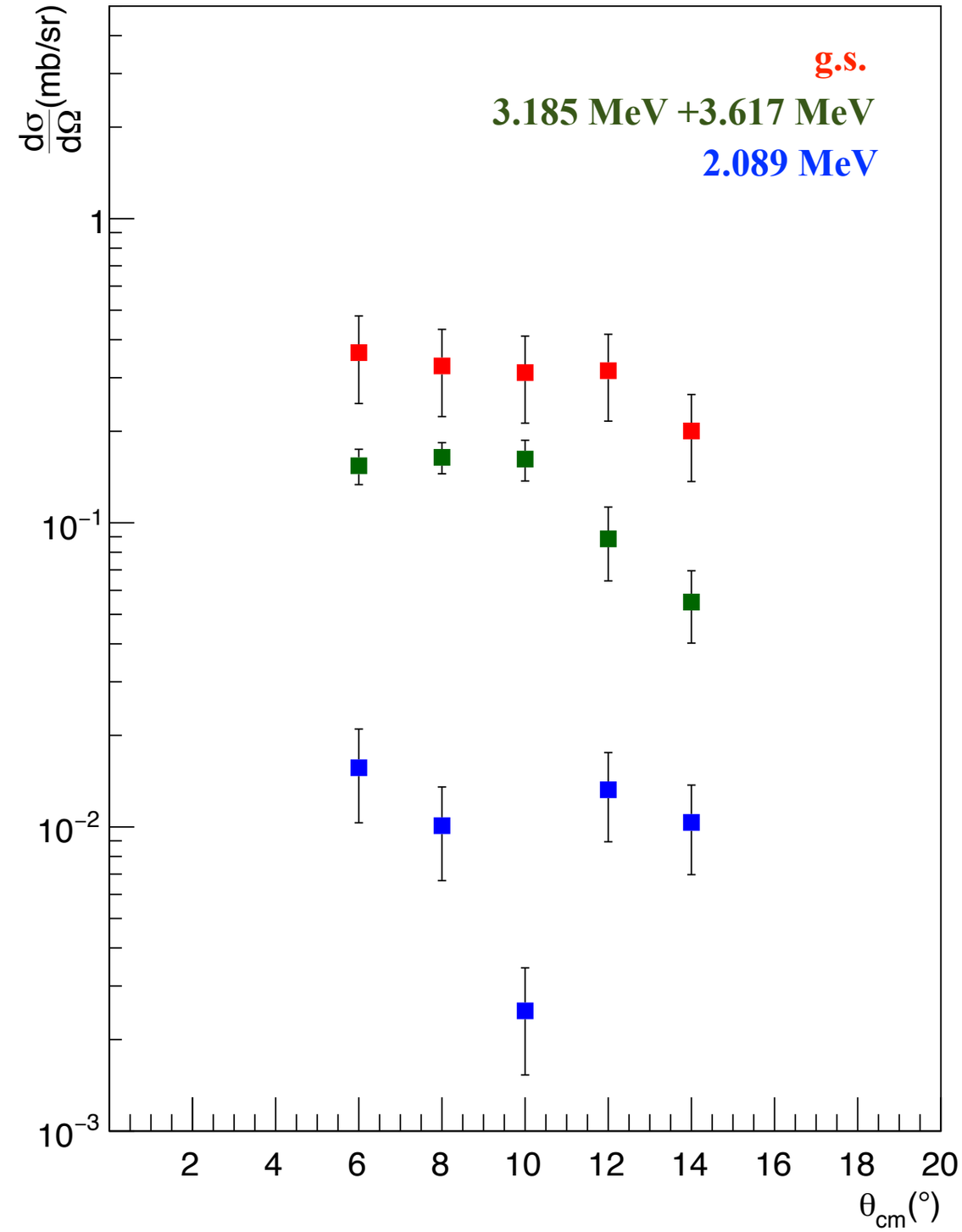
Gaussian Fit Drawing

- **Mean**: The energy level known from NNDC and observed in this experiment
- **Sigma**: The sigma of the Ground State
- **Amplitude**: Limited of the γ transitions and the population of the states.

$^{56}Ni(p,d)^{55}Ni$

$^{56}Ni(d,t)^{55}Ni$





$^{56}Ni(p,d)^{55}Ni$

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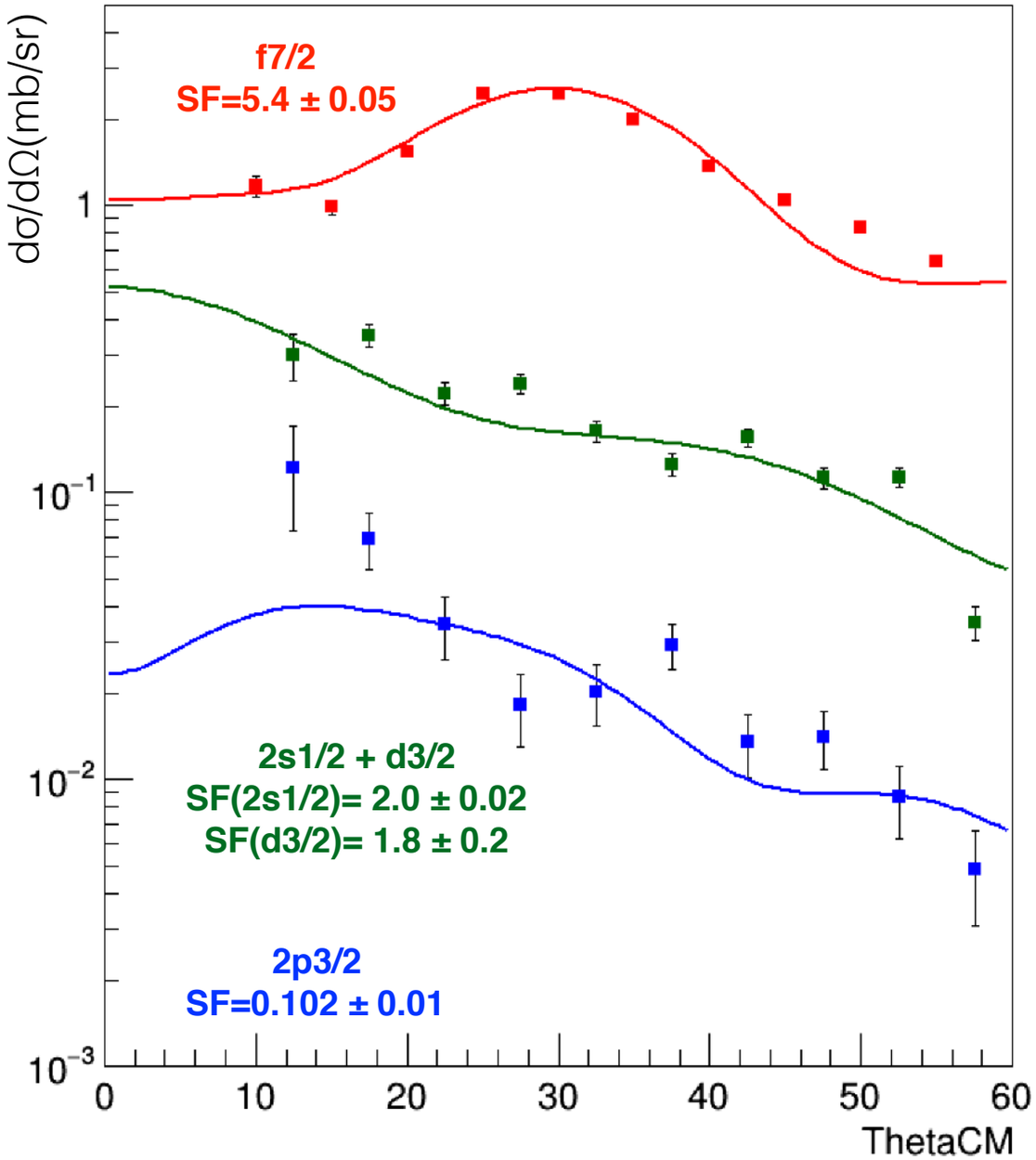
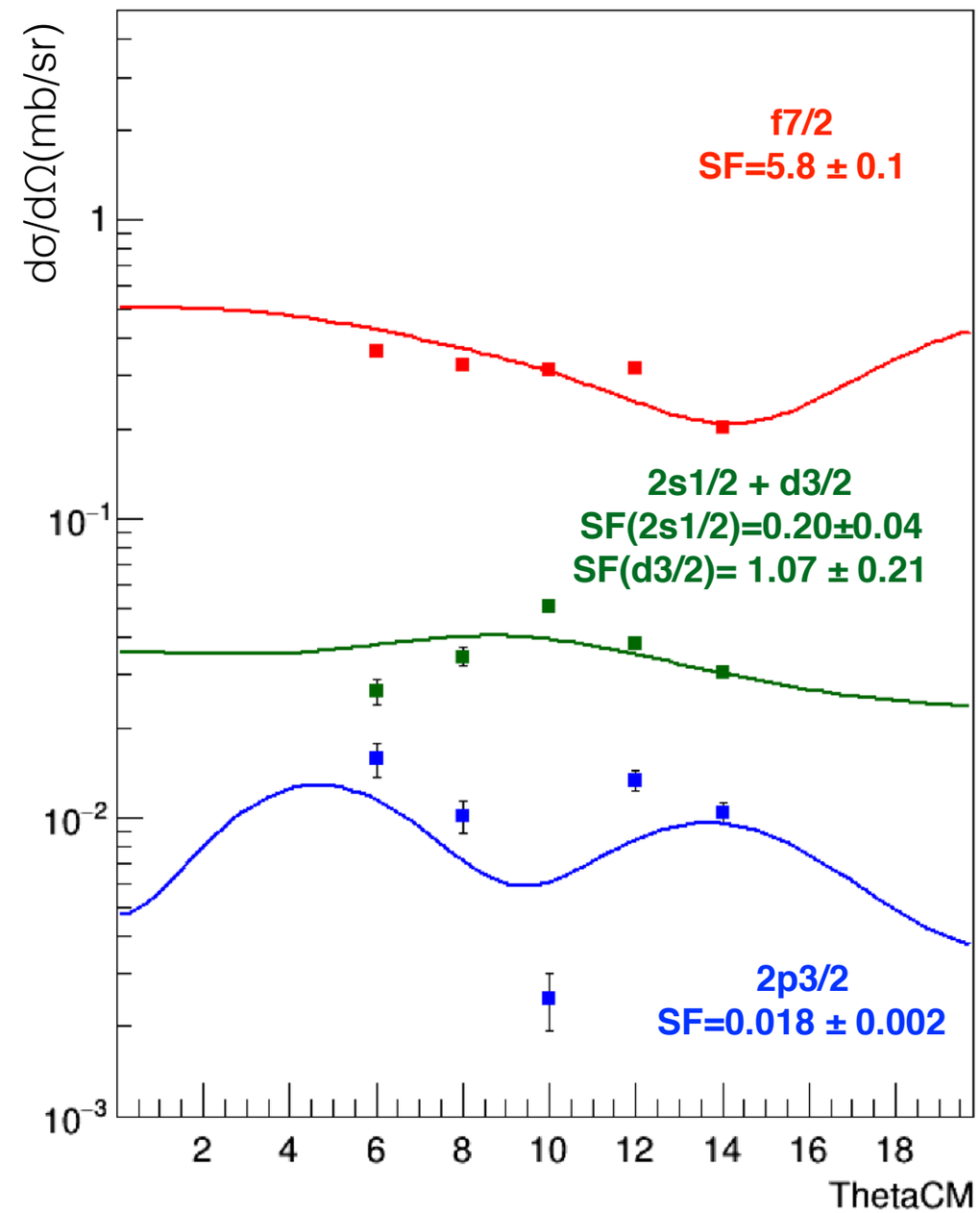


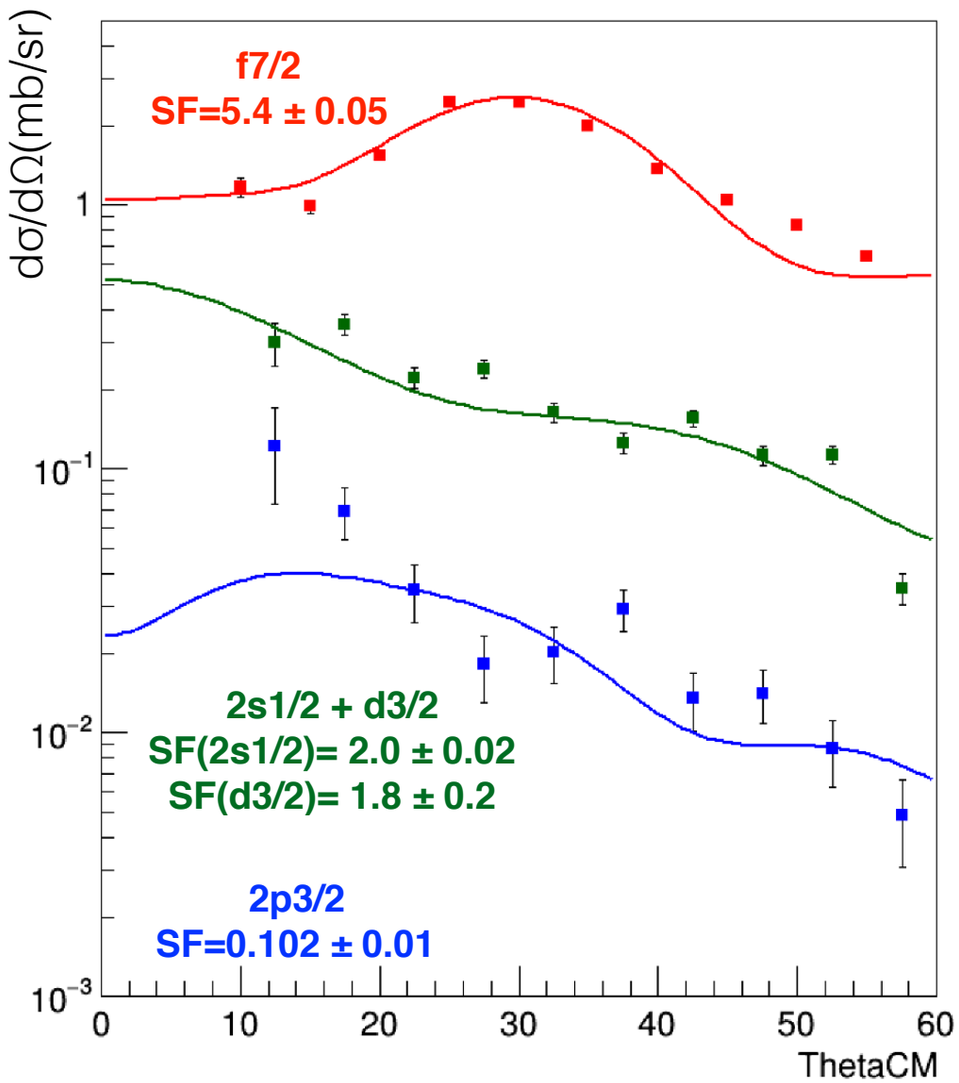


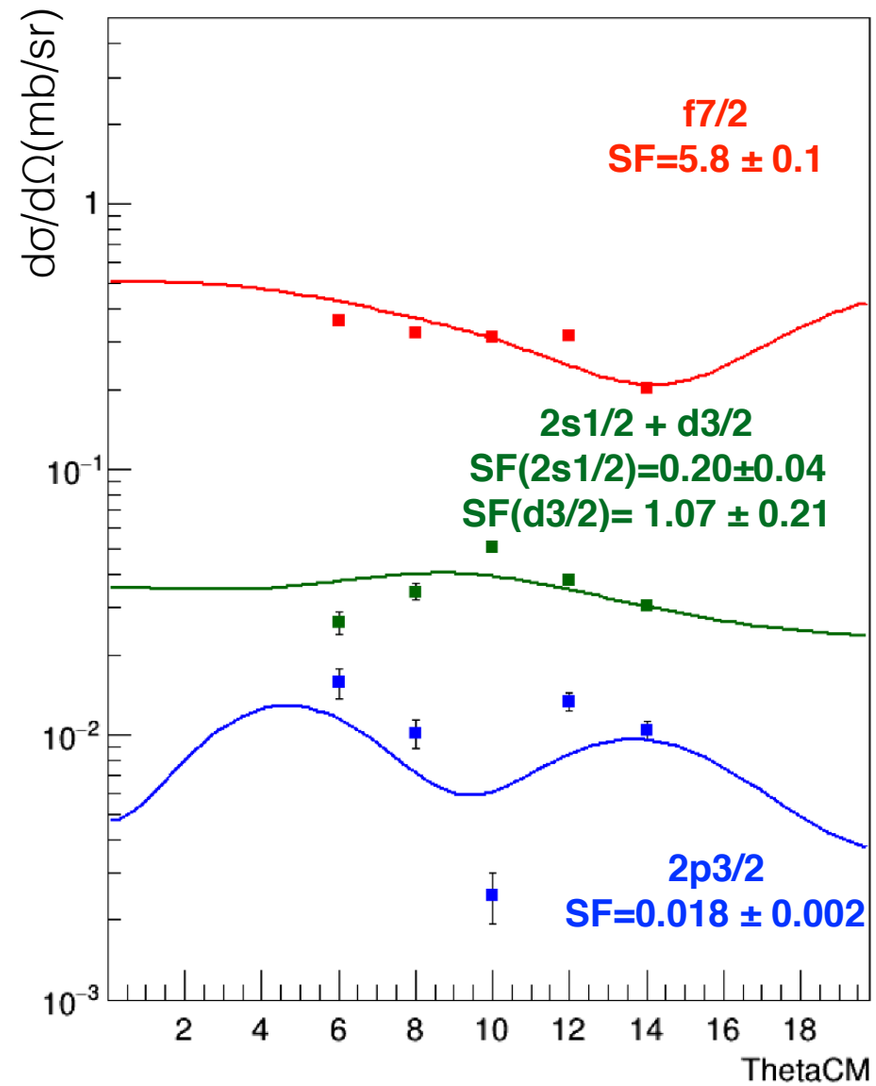
Calculation with DWBA: A.Georgiadou, J.Guillot

*Potential for **t** used by Pang et al. PRC, 79:024615, 2009.*
*Potential for **d** used by Daehnik et al. PRC, 21:2253–2274, Jun 1980.*
*Potential for **p** used by R.L. Varner, Physics Reports, 201(2):57 – 119, 1991.*

$^{56}Ni(p,d)^{55}Ni$

$^{56}Ni(d,t)^{55}Ni$



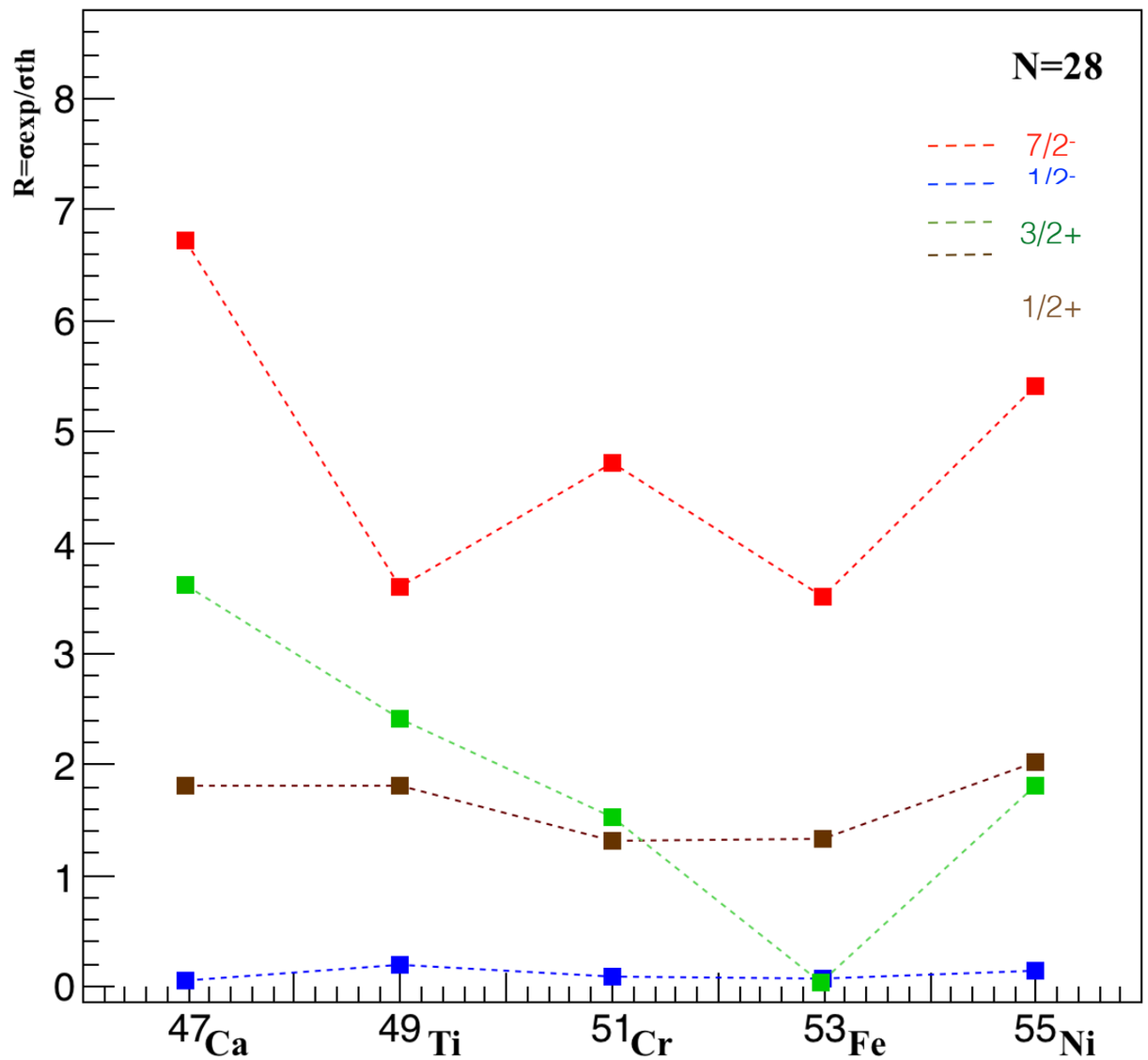


- E (MeV): Energy levels
- SF: Spectroscopic Factor

State	E_{exp}	$SF^{(p,d)}_{exp}$	$SF^{(d,t)}_{exp}$	SF[1]	SF_{SM1}
$1f_{7/2}$	0.0	5.4±1.0	5.8±1.2	6.7±0.7	6.75
$2p_{3/2}$	2.1	0.10±0.02	0.020±0.004	0.19±0.03	0.13
$2s_{1/2}$	3.2	2.0±0.4	0.20±0.04	1.0±0.2	1.57
$1d_{3/2}$	3.617	1.8±0.4	1.07±0.21	-	2.88

[1] *A. Sanetullaev et al. / Physics Letters B 736 (2014) 137–141*

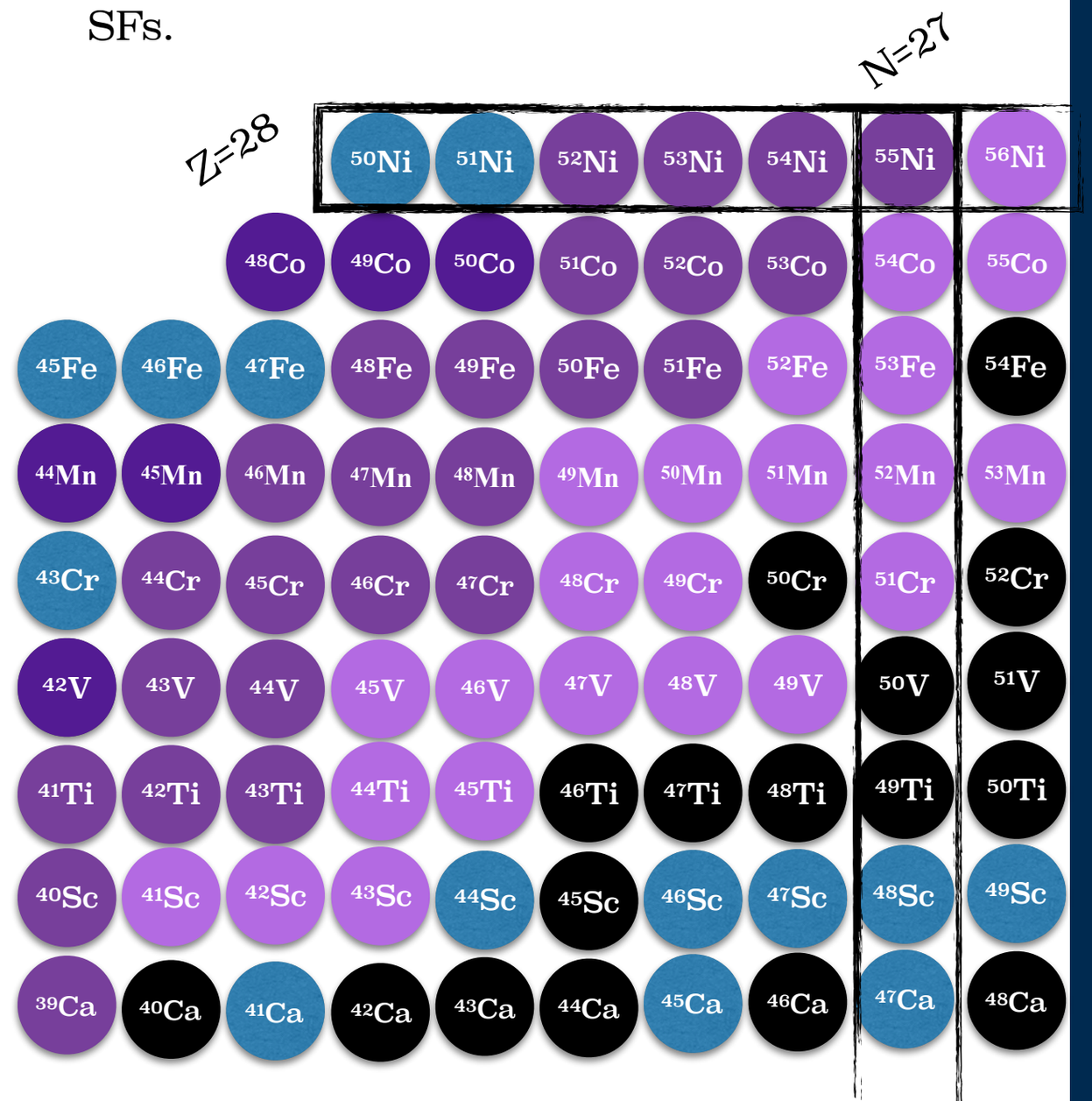
Results & Discussion



The Figure shows the spectroscopic factors for N = 27 isotones in the fp shell obtained from (p,d) reactions.

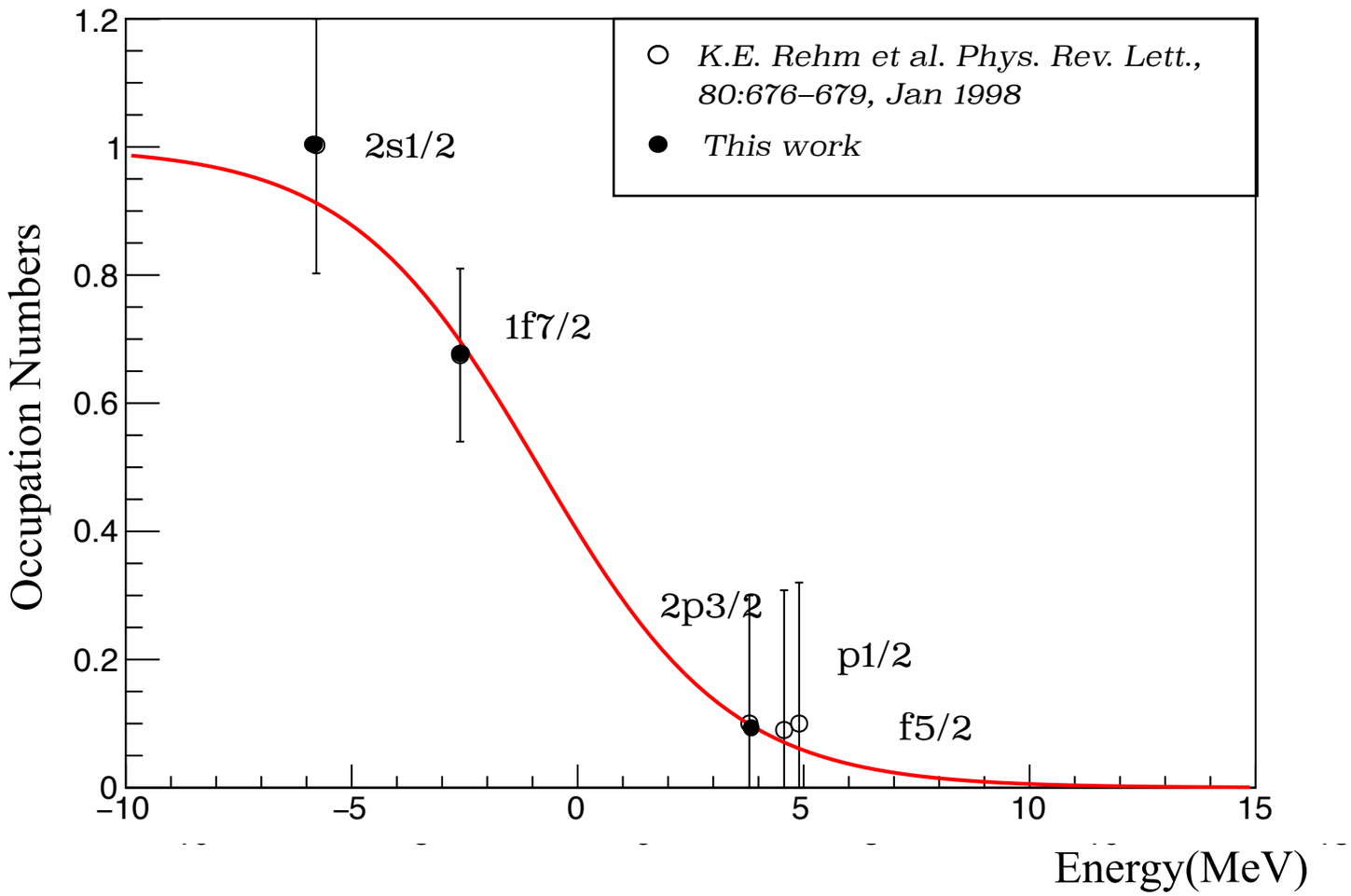
Shell evolution of N=28

- For the nuclei with shell closures at Z= 20 (^{47}Ca) and Z = 28 (^{55}Ni) we observe higher SFs.



Decay Q-value Range

Fermi surface of ^{56}Ni



Results & Discussion

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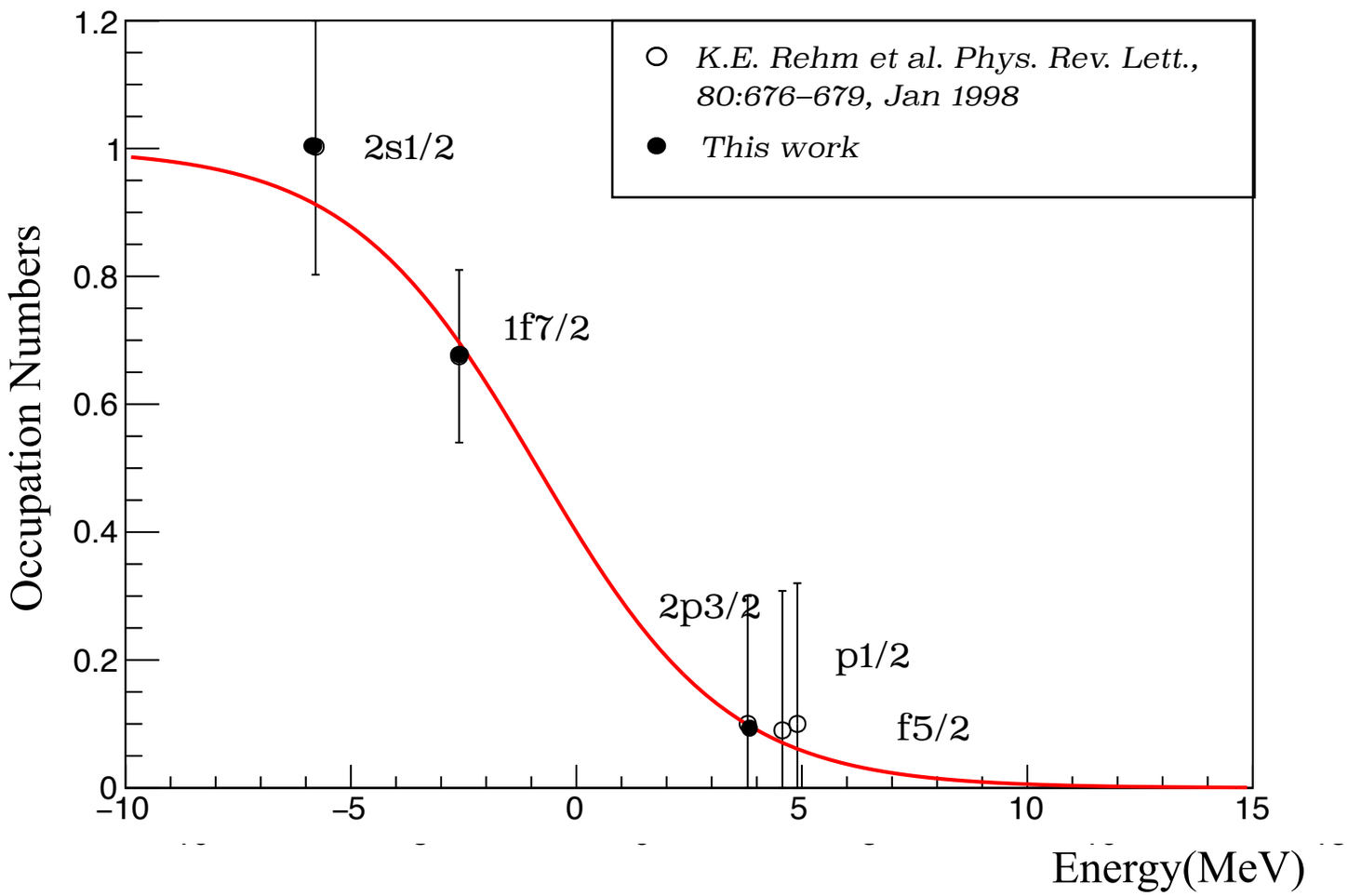
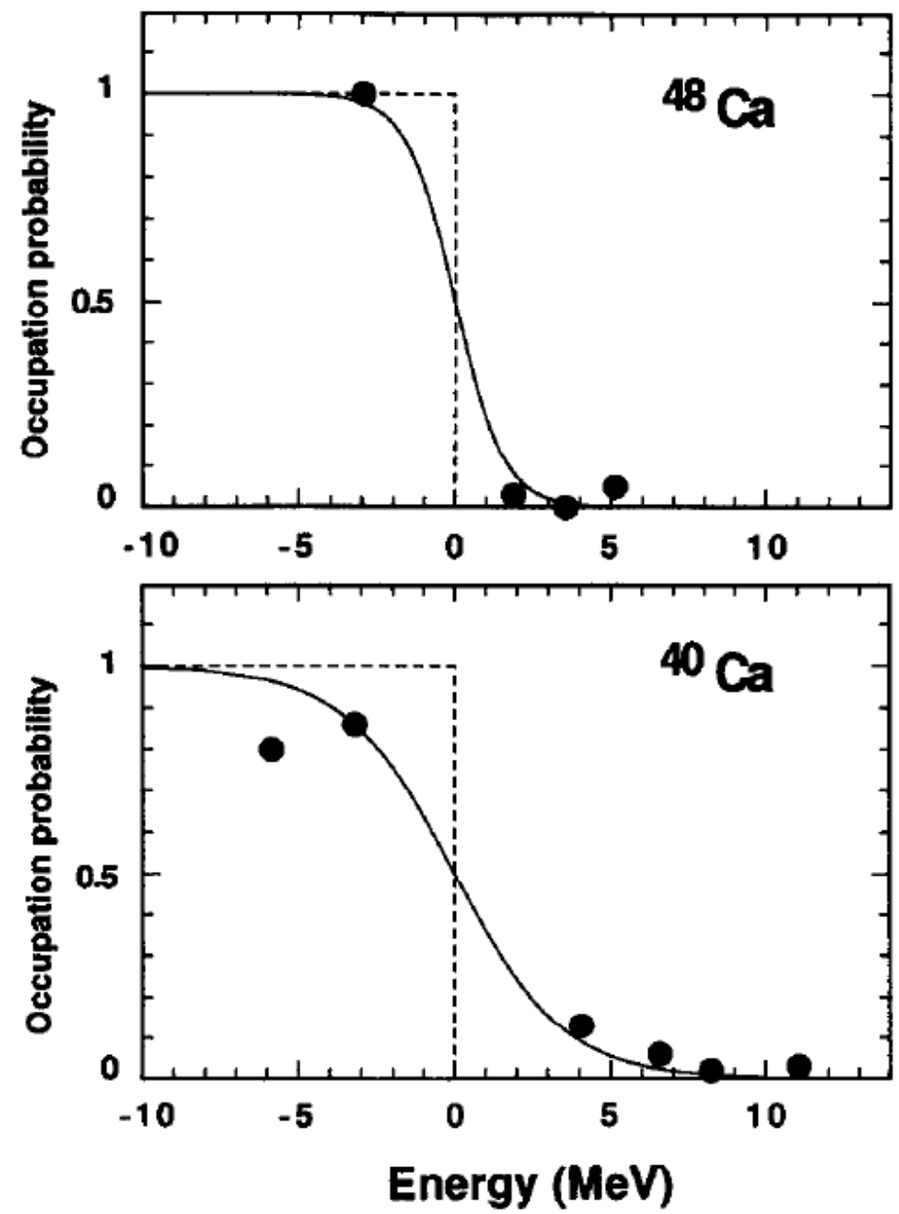
Fermi surface of ^{56}Ni



Nucleus	Diffuseness Factor (MeV)
^{56}Ni	2.1±0.4
^{40}Ca	1.7
^{48}Ca	0.59



N=28 shell closure not as robust as in other doubly magic nuclei.

Perspectives- One nucleon Transfer

High resolution silicon detector at backward angles plus higher efficiency gamma detection will allow the disentanglement of the excitation energy states.

AGATA+MUGAST

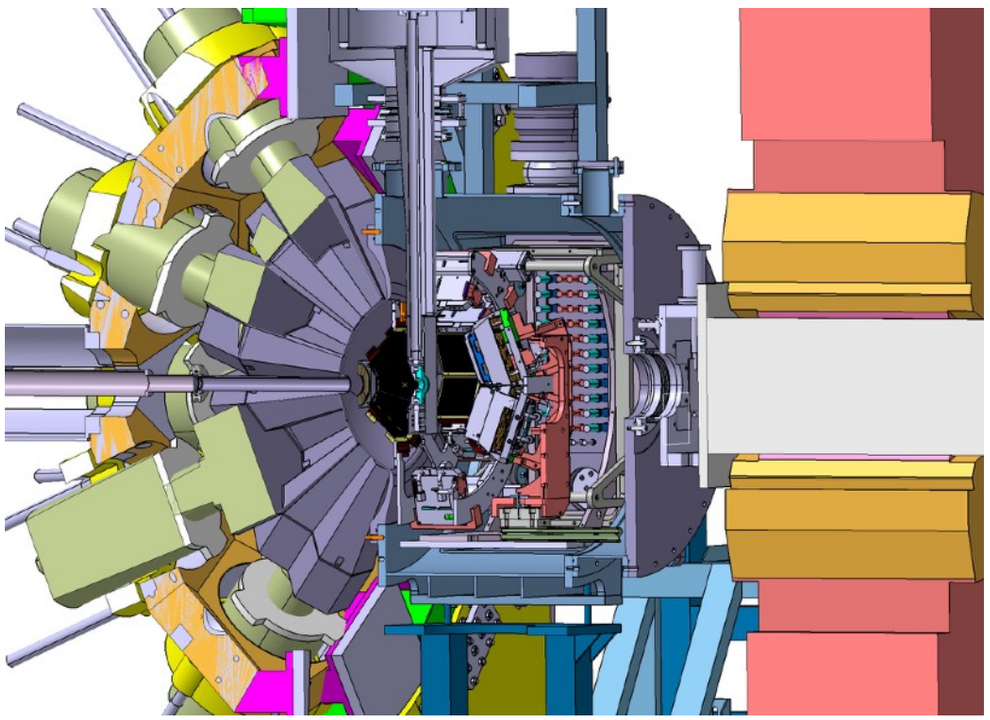
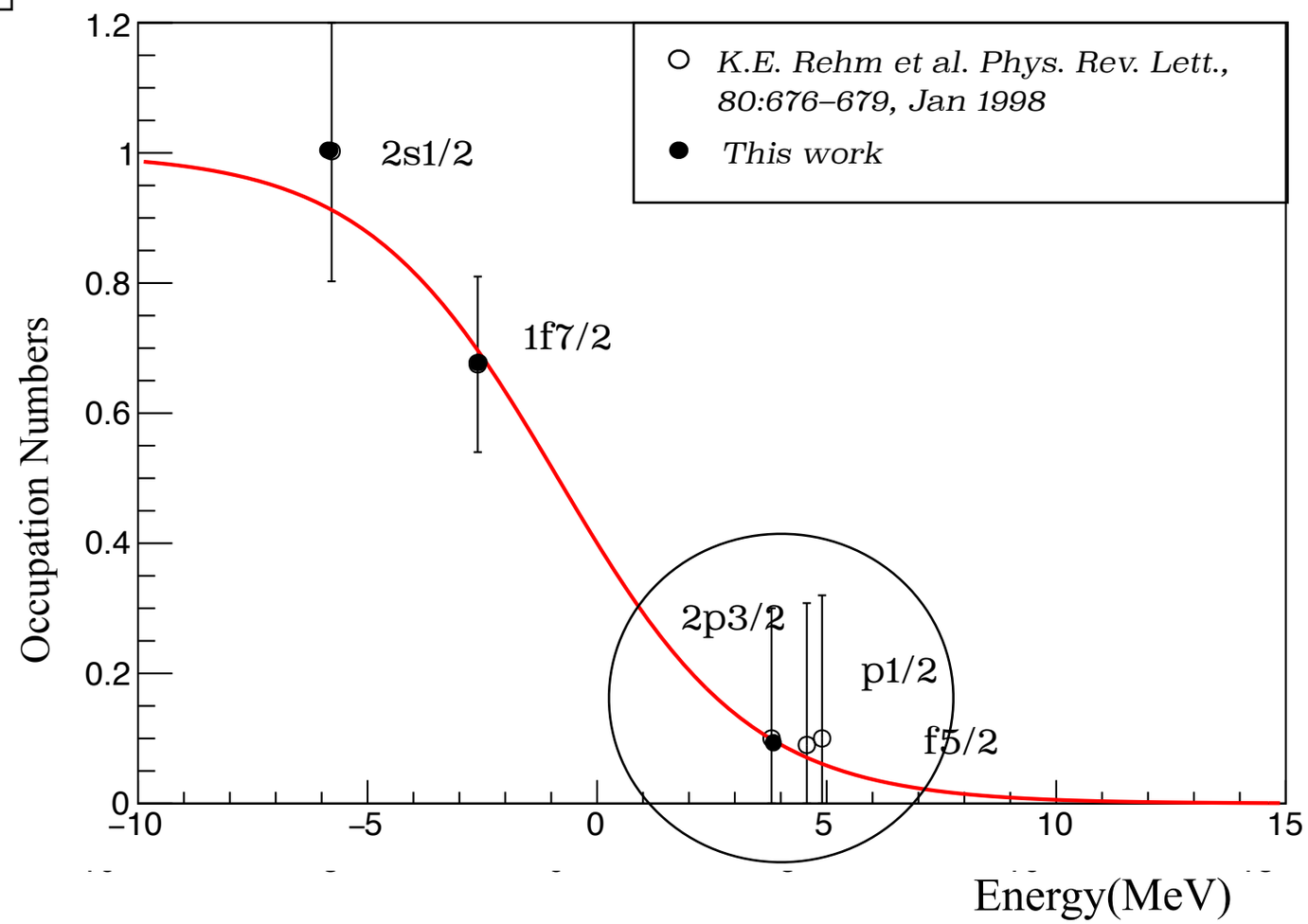
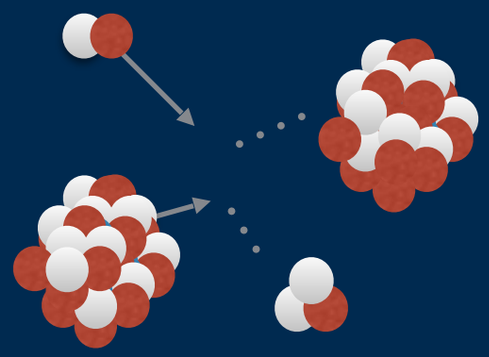


***Illustration by Emmanuel Rindel**

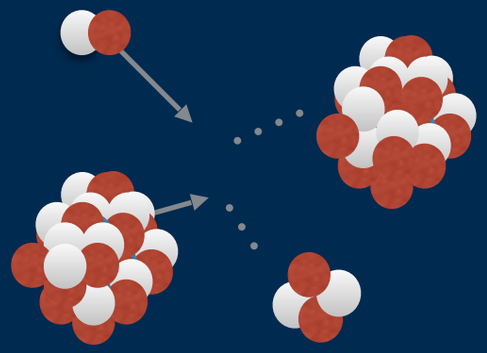
***L.O.I., F.Flavigny**

Fermi surface of ^{56}Ni





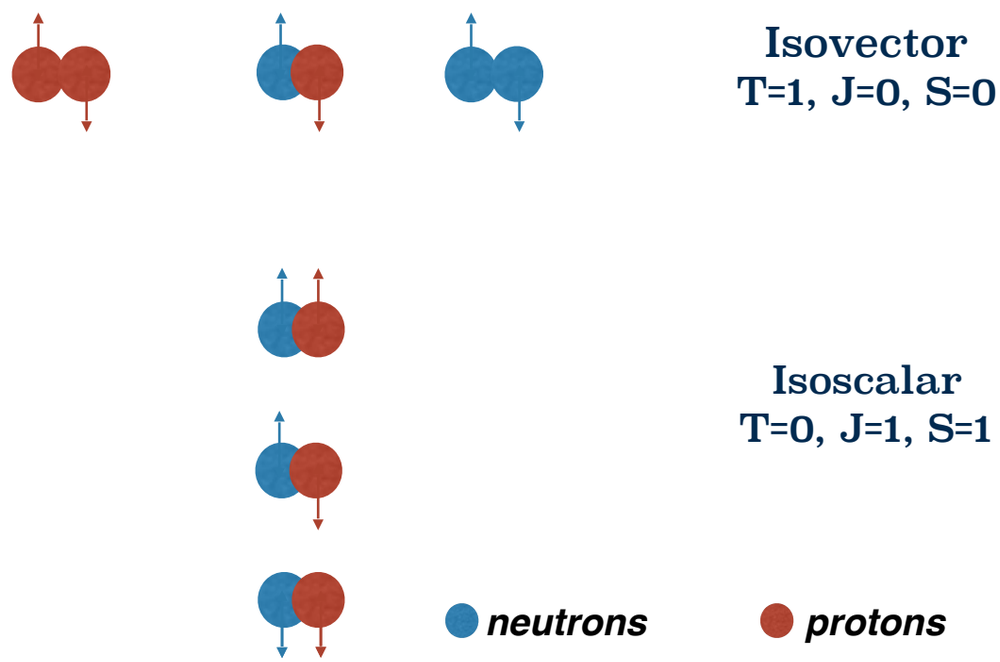
The one-nucleon transfer reactions
N=28 Shell closure



The two-nucleon transfer reaction
NP-Pairing in N=Z nuclei

LLNL Seminar 02/28/2020, A.Georgiadou, georgiadou@lanl.gov

neutron-proton pairing

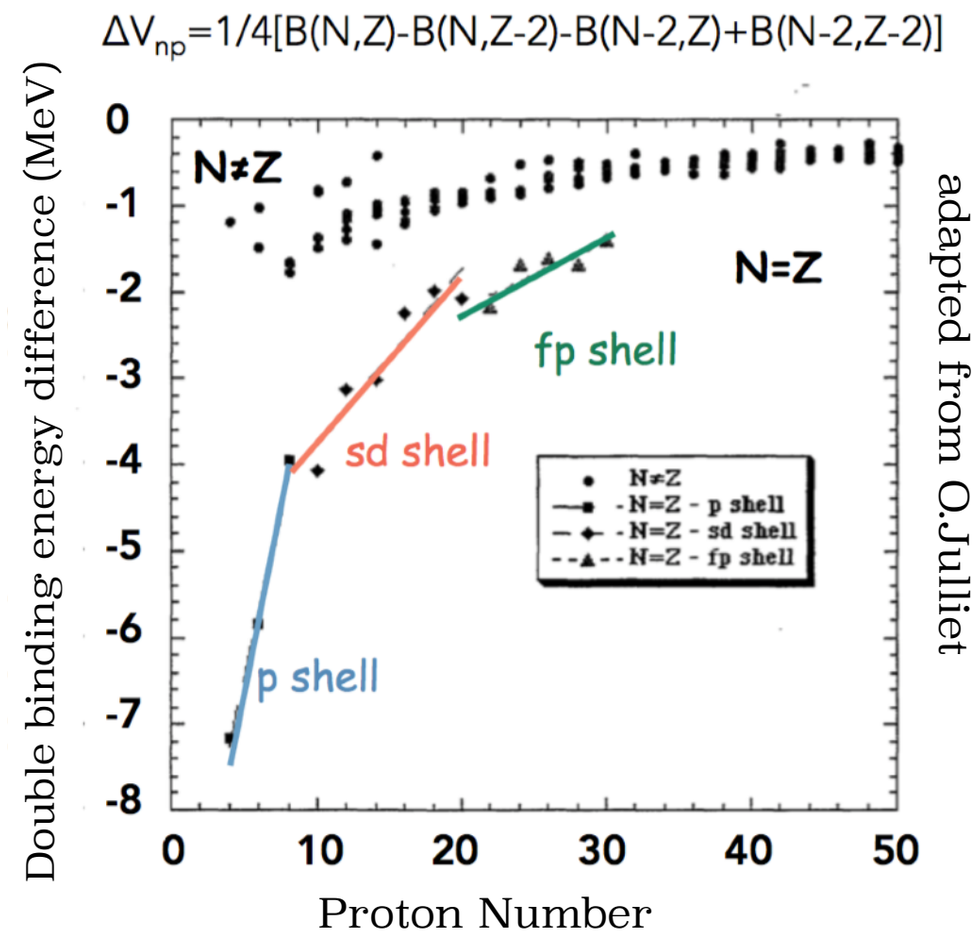


- **T=1 np pairing similar to nn and pp** pairing due to **charge independence.**
- **T=0 pairing** characteristics are **largely unknown.**
- In the **T=0** channel the **interaction** is expected to be **stronger** than in the T=1.
- **Proof**: the **existence of** the bound A=2 nucleus (**deuteron**).

neutron-proton pairing

Expected np pairing to be important in N=Z nuclei with **high J valence**.^{56}Ni : the N=Z nucleus for which we can do **transfer and study np** pairing

- For nuclei with N≠Z, nn and pp pairs are favoured.
- In the case of nuclei with N≈Z, n and p **occupy the same shell model orbit.**



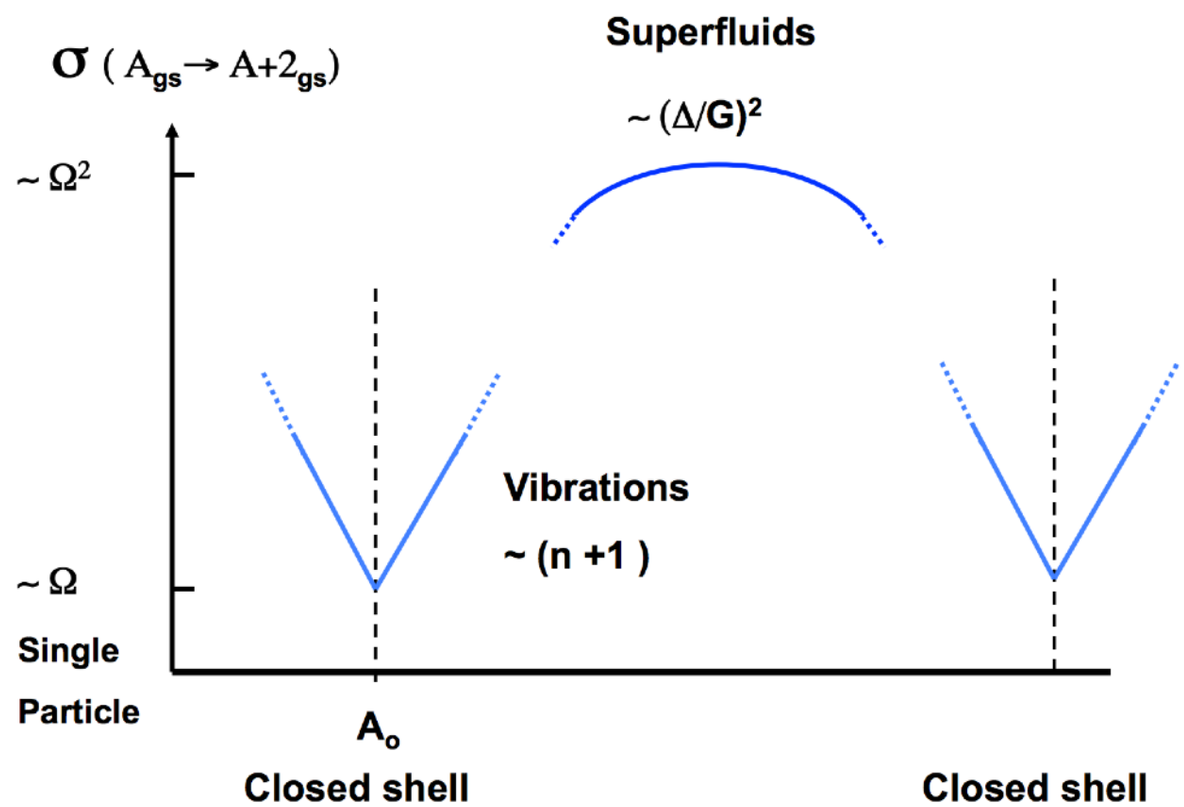
adapted from O.Julliet

- **np pairing mostly in N=Z nuclei**
- np pairing affected by shell effects

neutron-proton pairing

Schematic diagram depicting the behaviour of the 2-neutron transfer cross-sections.

adapted from Frauendorf & Macchiavelli Prog. in Part. and Nucl. Phys. 78 (2014) 24

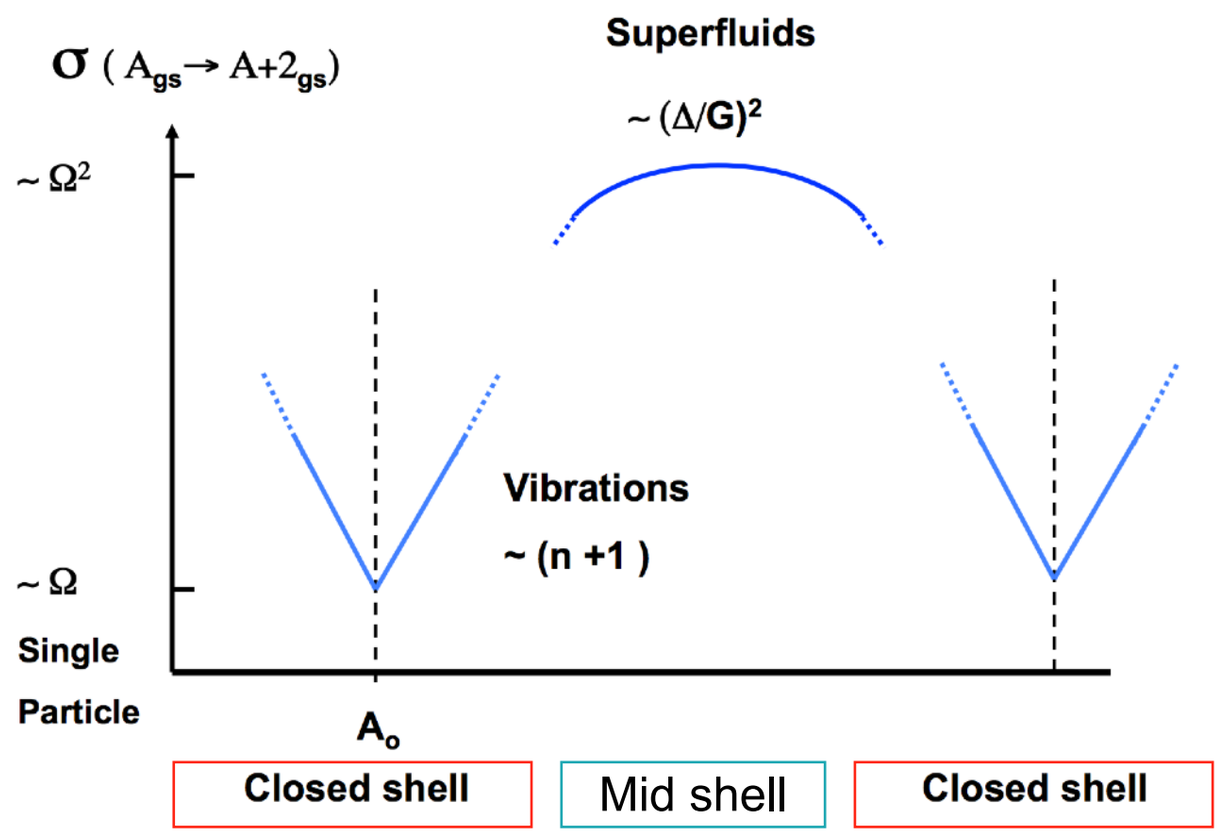


Cross section sensitive to the number of pairs in the nucleus.

neutron-proton pairing

Schematic diagram depicting the behaviour of the 2-neutron transfer cross-sections.

adapted from Frauendorf & Macchiavelli Prog. in Part. and Nucl. Phys. 78 (2014) 24

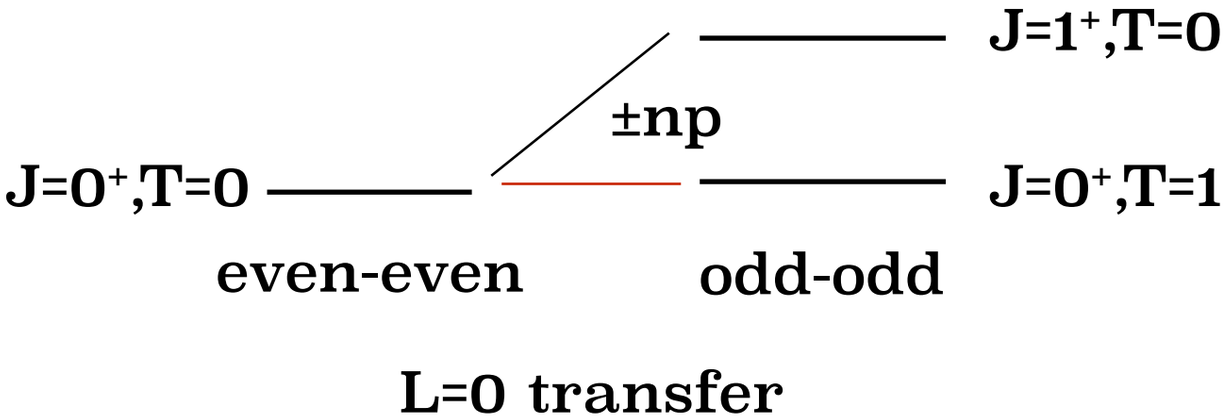


- "Normal" nuclei limit
- Vibrational-like spectrum
- Enhancement small relative to the single particle (SP) limit

- "Superfluid" limit
- Rotational-like spectrum for even-N neighbors
- Constant enhancement according to SP limit

neutron-proton pairing

σ (0+)/σ (1+) gives the relative strength of T=1/T=0 pairing



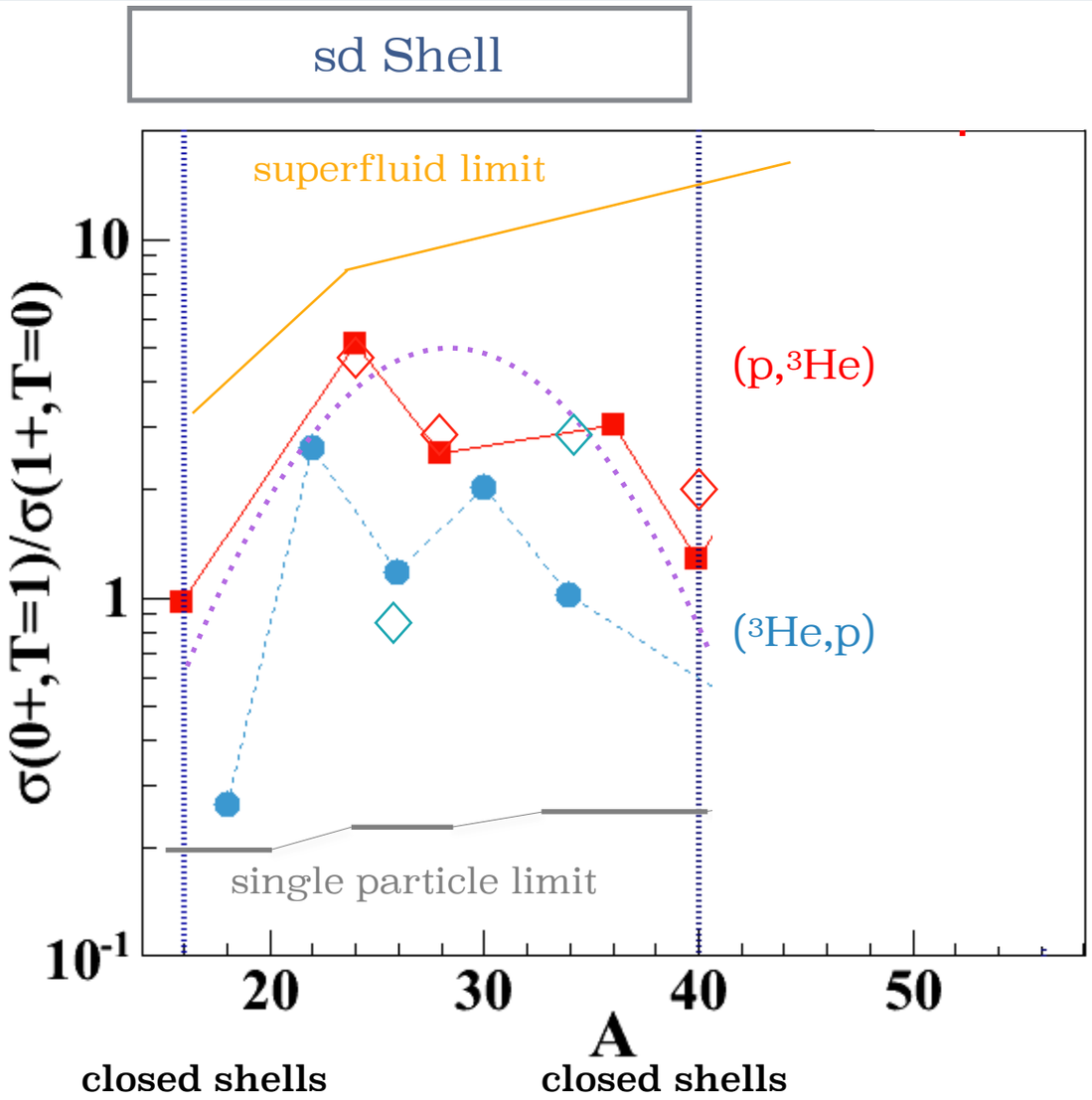
Schematic diagram depicting the use of two-particle transfer (np) reactions to study np correlations.

Deuteron transfer reaction:

Fröbrich (Phys. Lett. 1971) -> **2.5 enhancement factor in the cross section over the single particle estimate**

Piet Van Isacker PRL (2005) -> **Transfer proportional to the number of bosons=pairs**

neutron-proton pairing



Experimental data

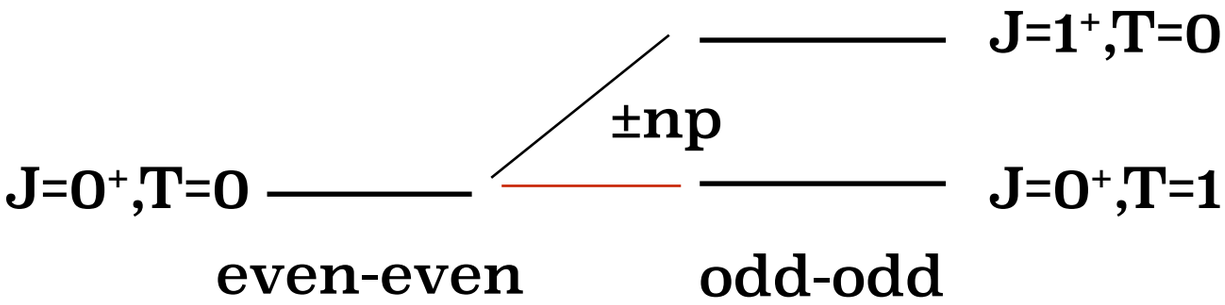
Y. Ayyad et al. PRC 96, 021303(2017)

Single particle estimate

Isovector superfluid limit

Parabolic shape

σ (0+)/σ (1+) gives the relative strength of T=1/T=0 pairing



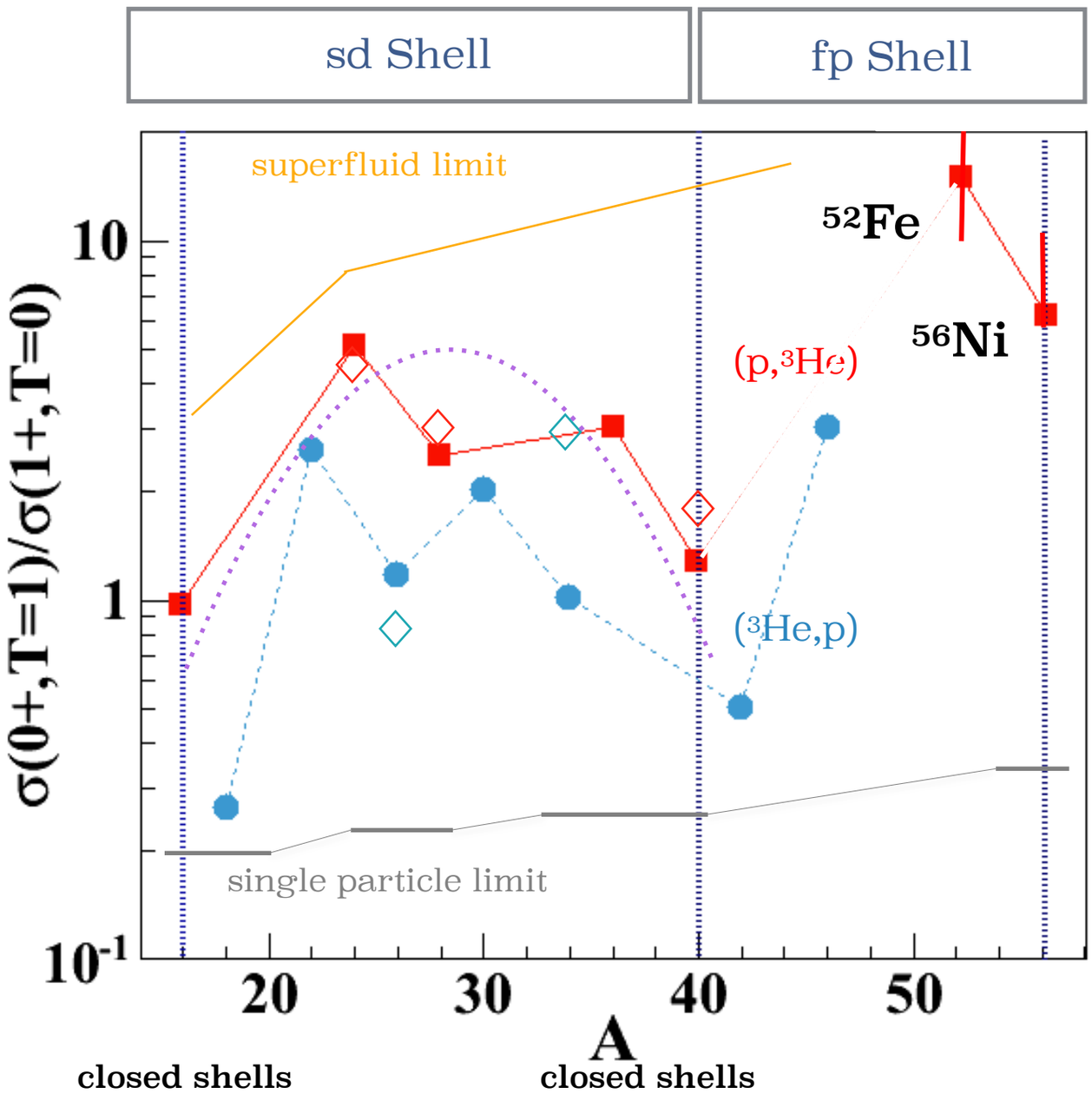
L=0 transfer

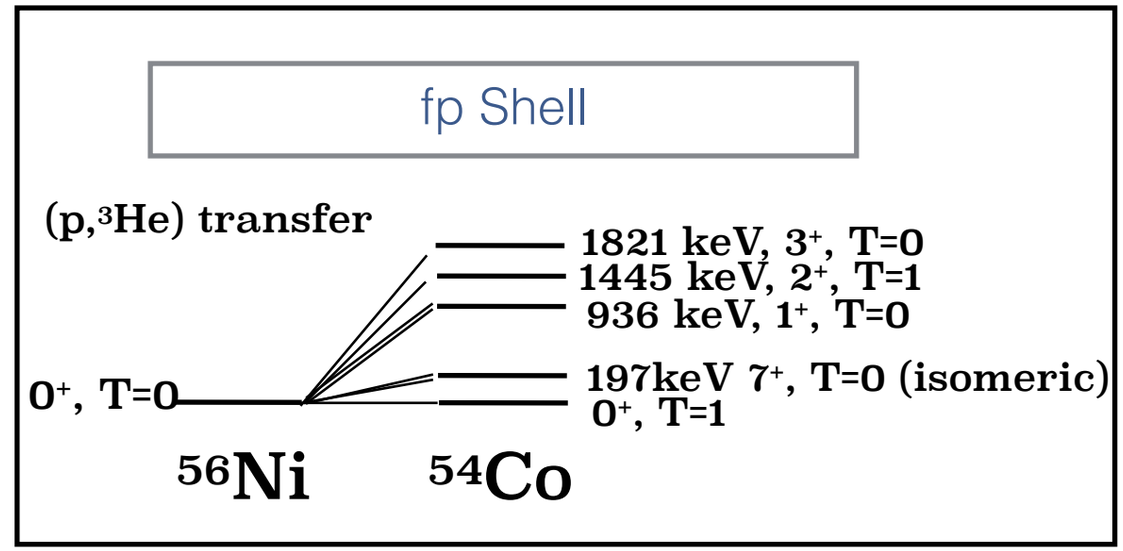
Schematic diagram depicting the use of two-particle transfer (np) reactions to study np correlations.

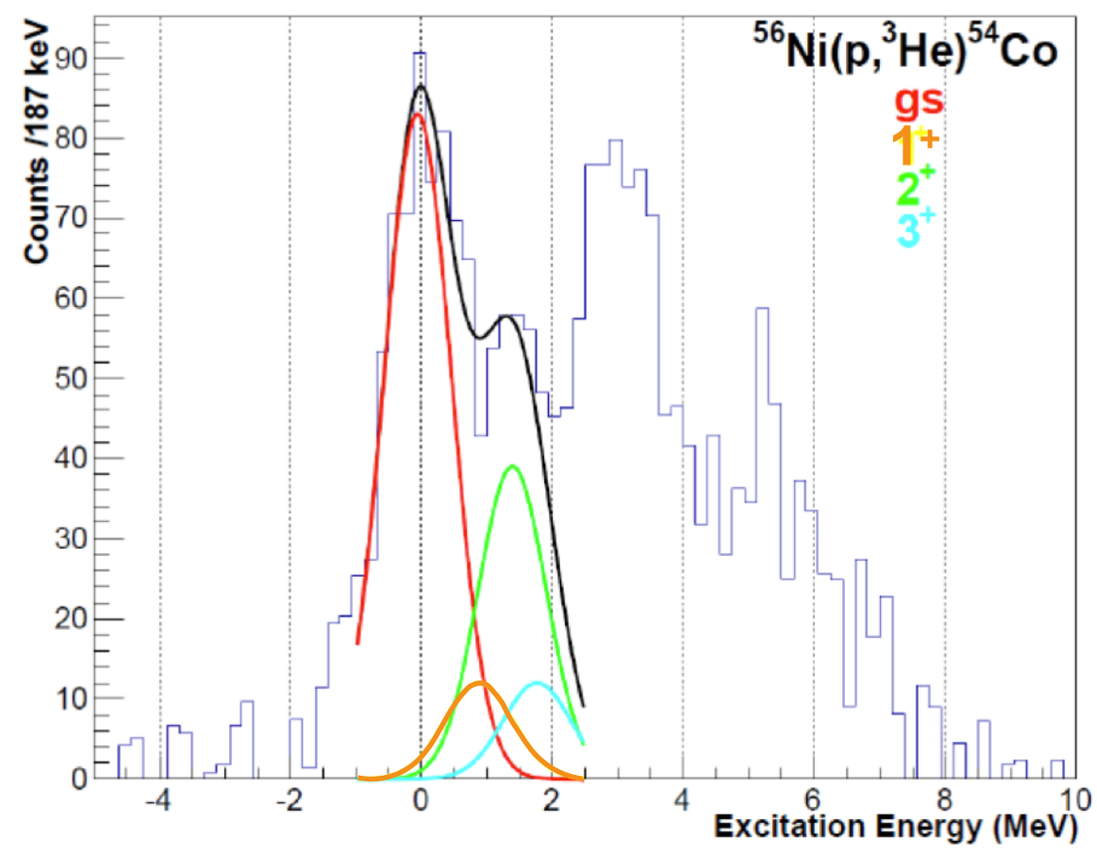
sd shell systematic

- from literature & ENSDF
  - max of cross-section at the lowest angle
  - measured in different energies, no error bars
- new measurements by Y. Ayyad, J. Lee, et al. PRC **96**, 021303® (2017)

neutron-proton pairing

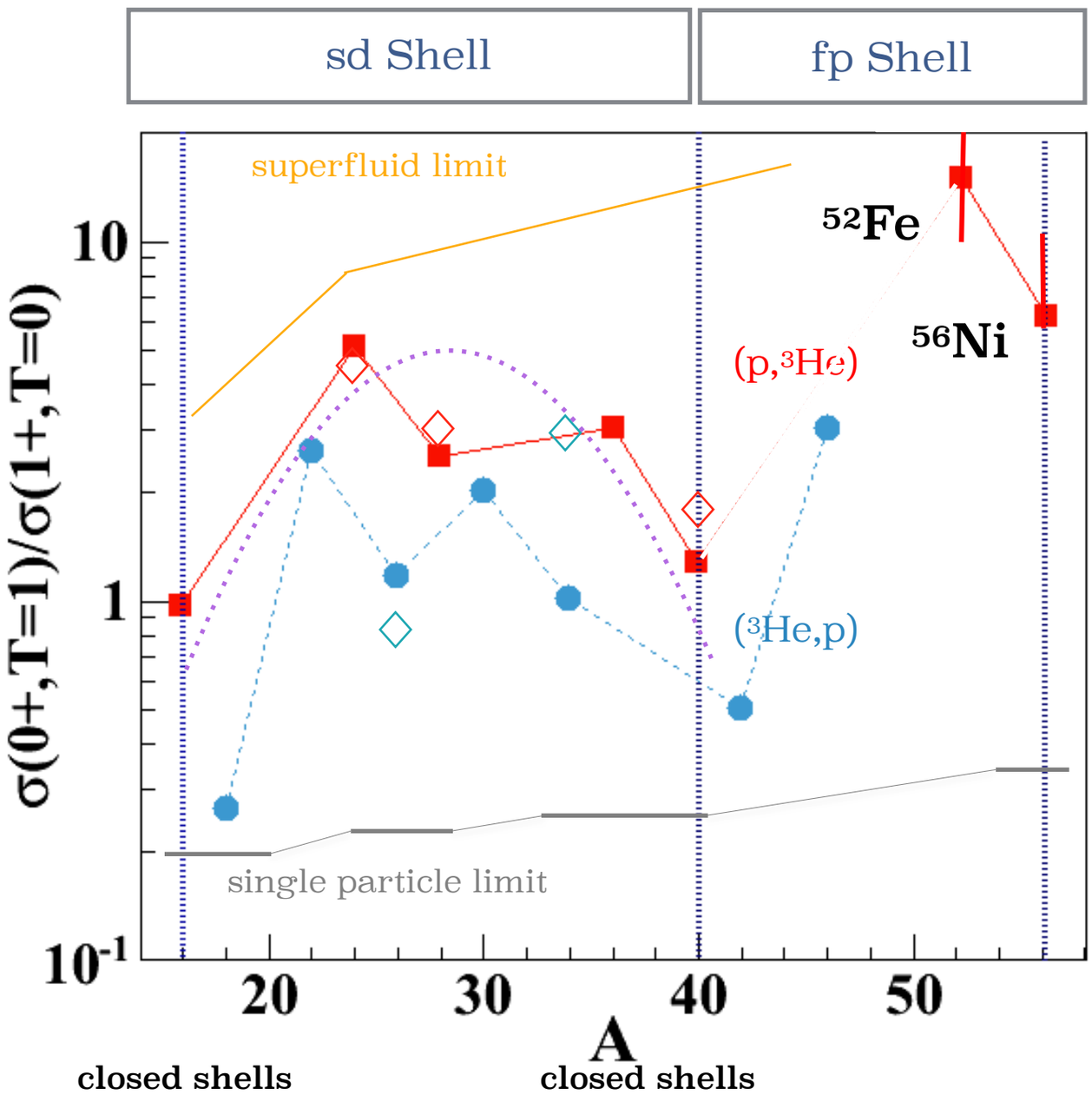


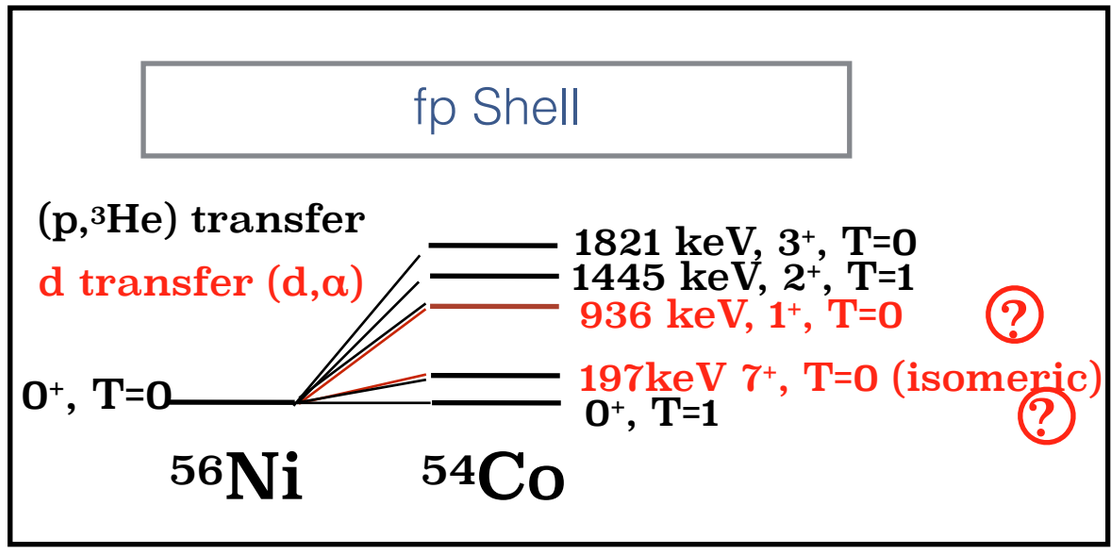




*B. Le Crom, Thesis, Université Paris-Saclay, 2016.

neutron-proton pairing





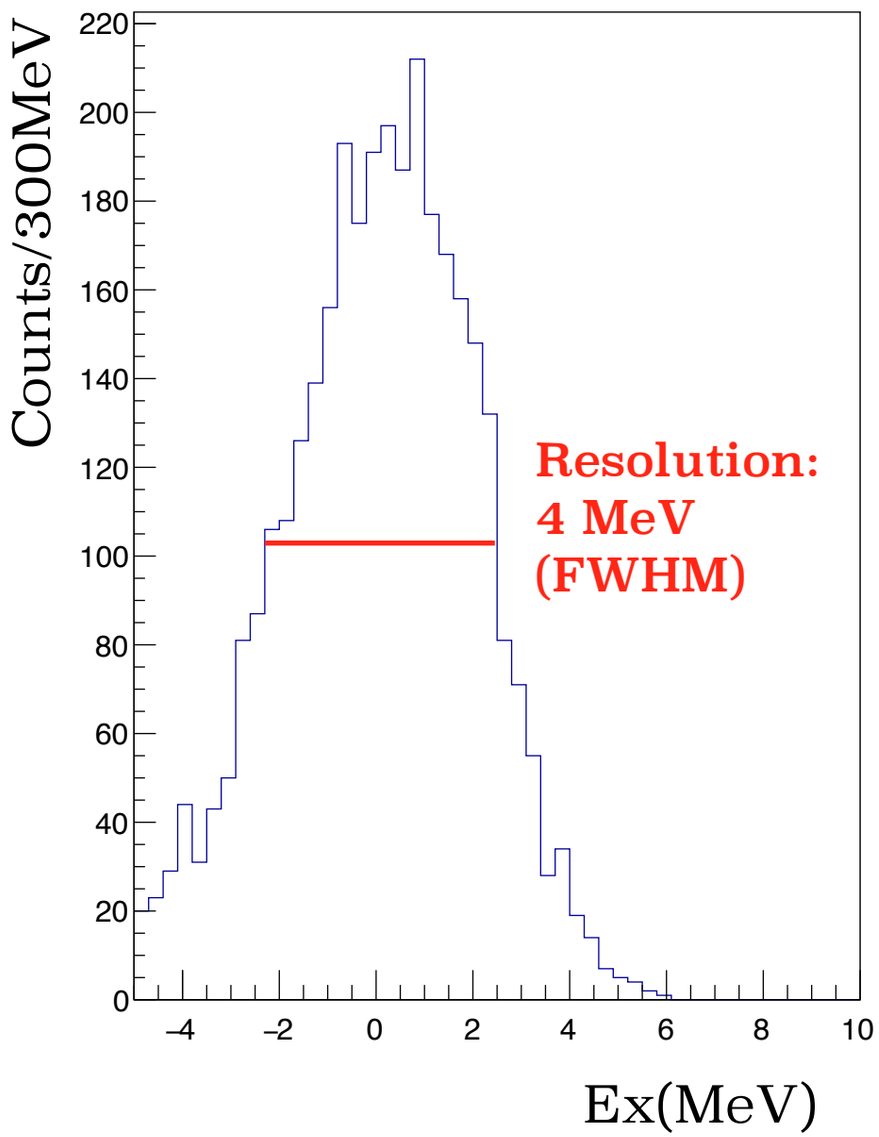
^{56}Ni (d,α) ^{54}Co, ΔT=0

Goals of the (d,α) analysis:

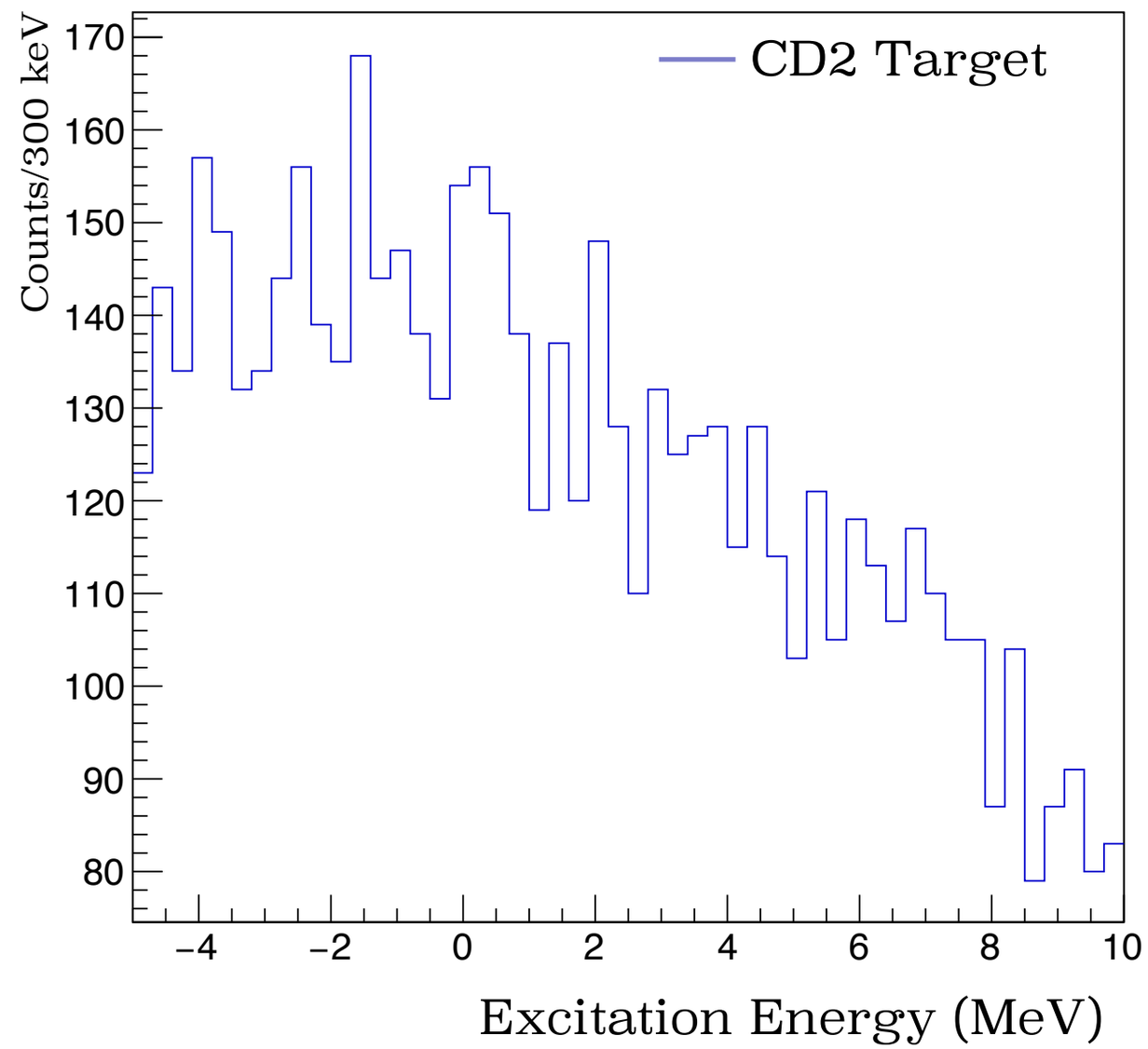
- Does this isomeric state contribute?
- Angular distribution of T=0 state at 0.936MeV

Data Analysis

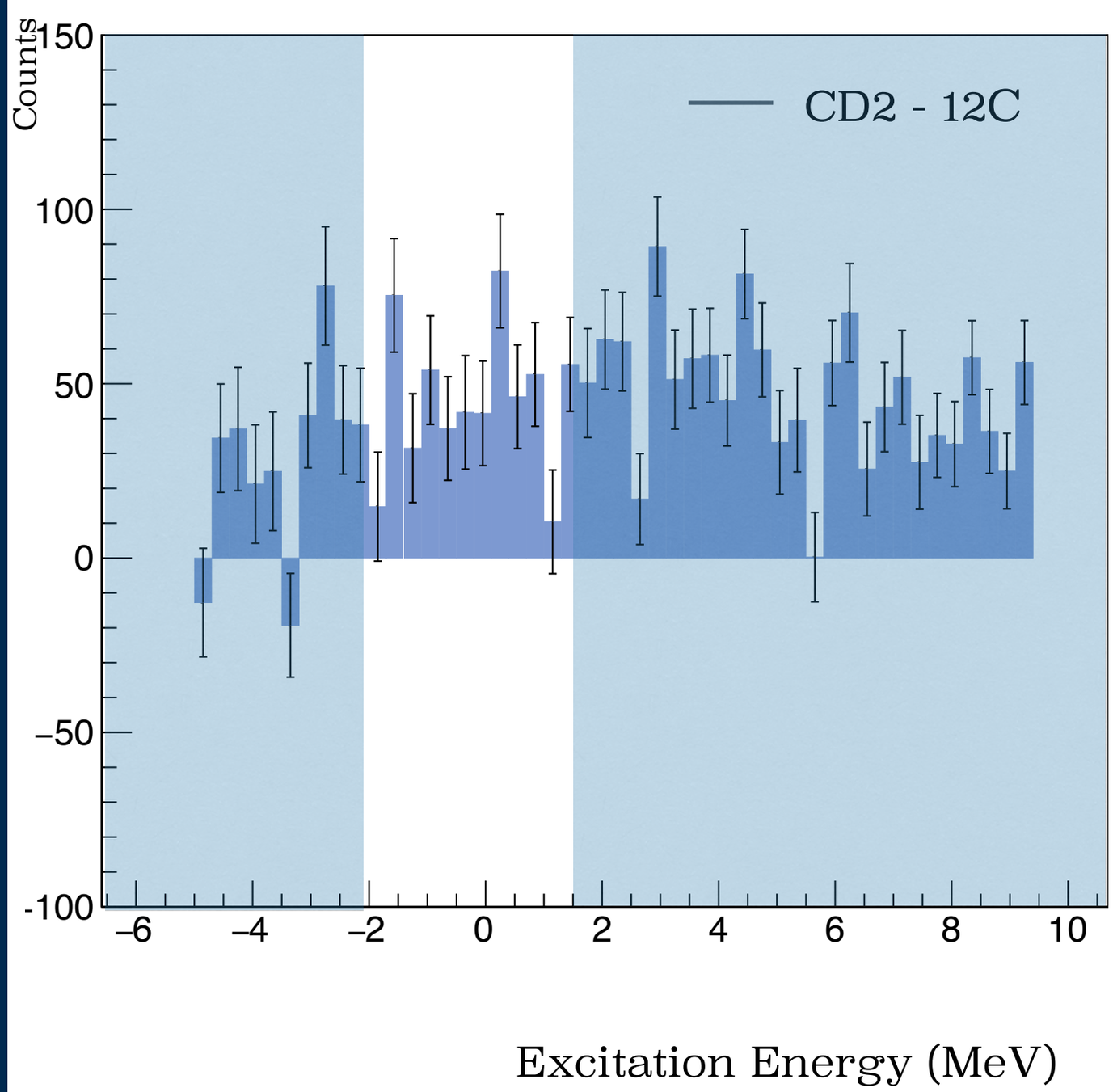
Simulation

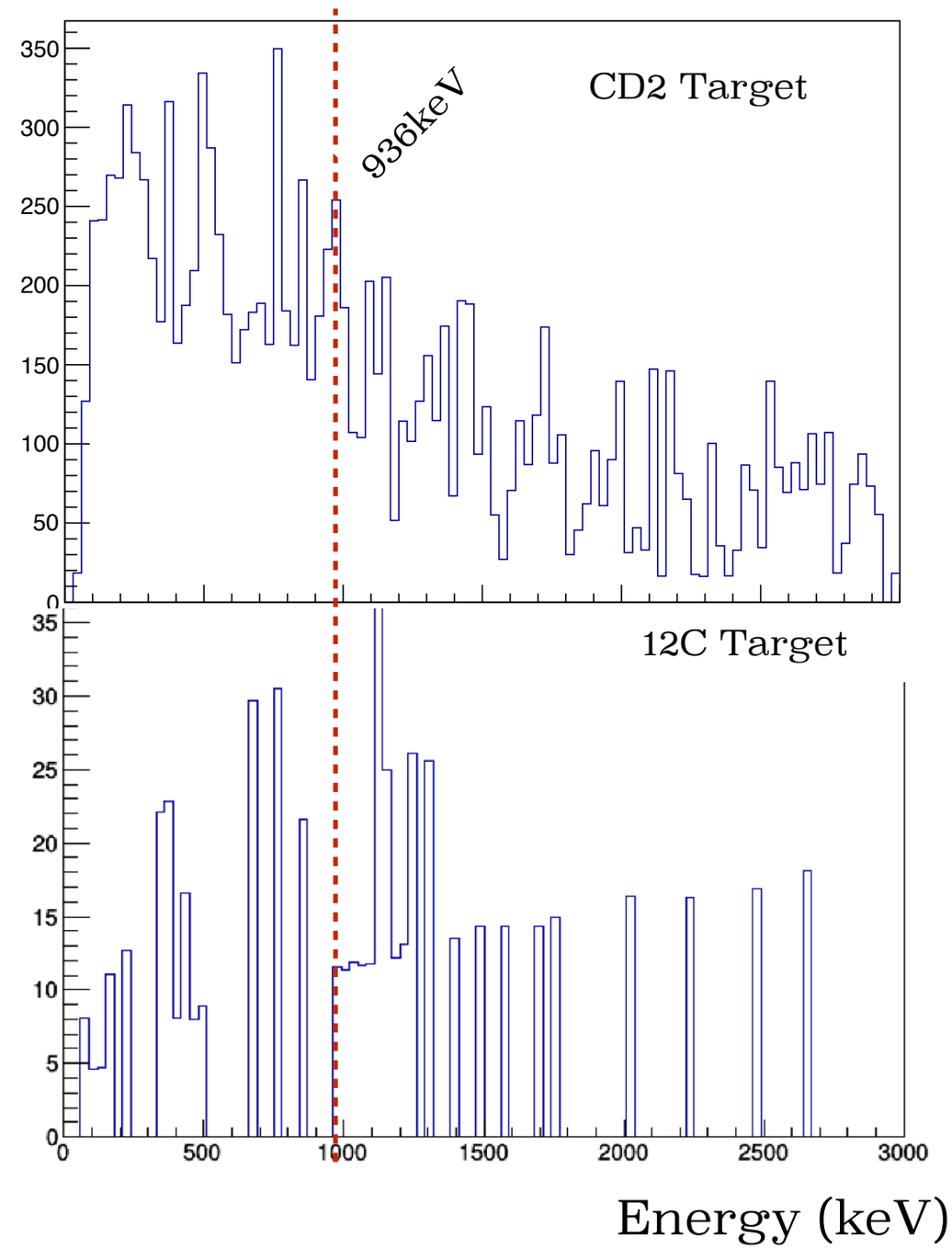


Experiment

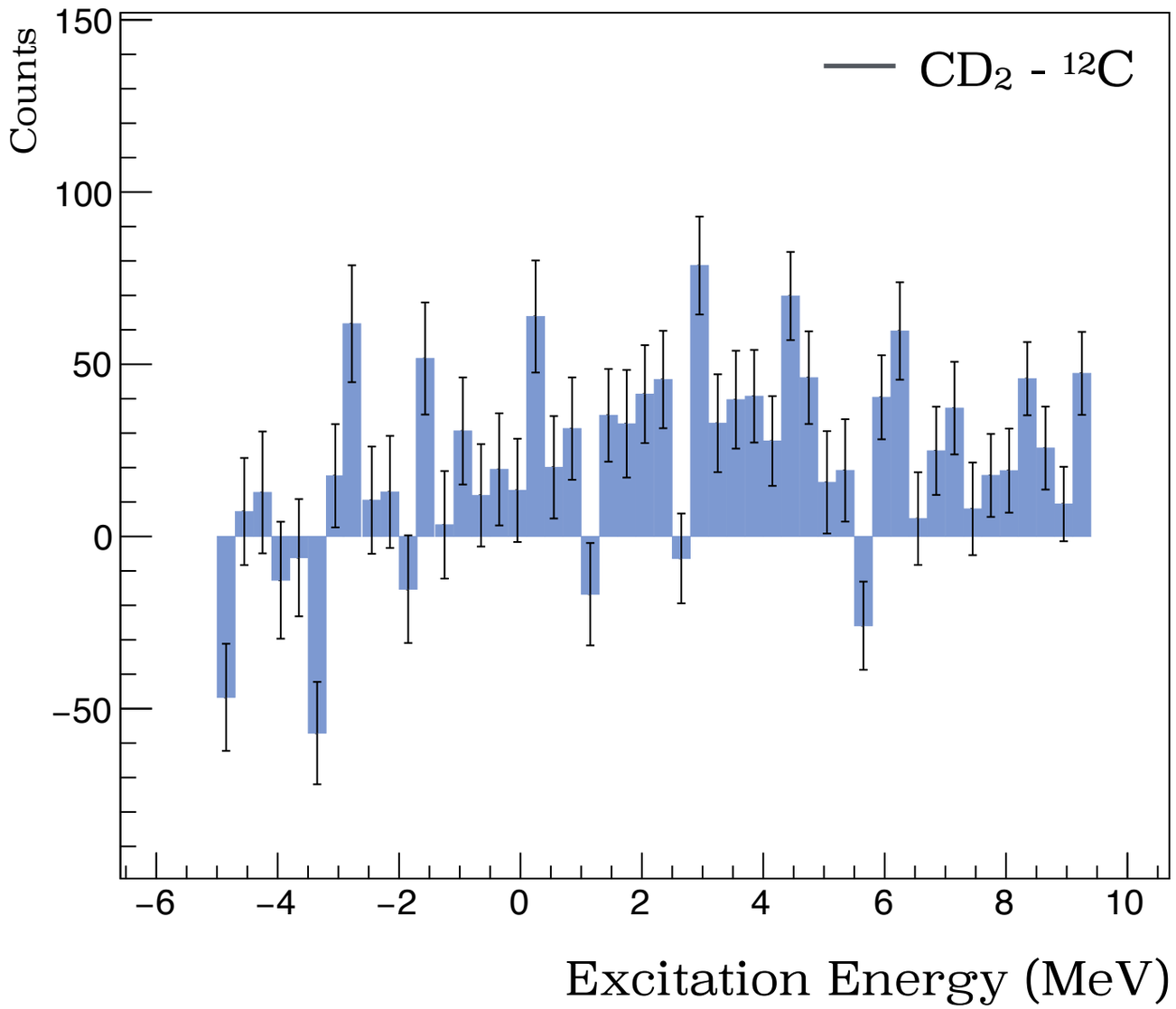


Particle-γ coincidence for the (d,α) reaction





Results & Discussion

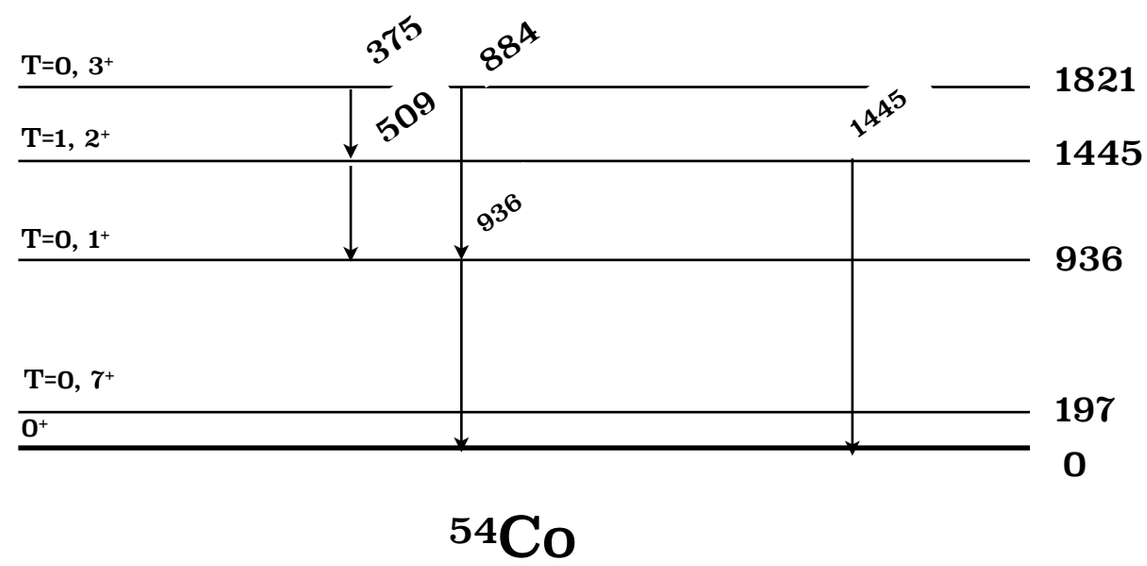


Upper Limit Cross Section

$\sigma_{tot}\,(1^+) < 3\ \mu b$

smaller than what (p,³He) measures

$\sigma_{tot}\,(1^+) = 11{,}5\ \mu b$



No peak structure revealing an isomeric state, confirming the ratio

$\frac{T=1}{T=0} = 6.3\ ^{+2.8}_{-0.8}$ obtained from (p,³He) for ⁵⁶Ni

Submitted in PRL, ***"Pair transfer as a probe of neutron proton pairing in unstable fp-shell nuclei" B. Le Crom, M. Assié, Y. Blumenfeld, J. Guillot, M-C. Delattre, N. De Seréville, S. Franchoo, A. Georgiadou, F. Hammache, P. Morfouace, L. Perrot, I. Stefan, and D. Suzuki.***

Conclusions

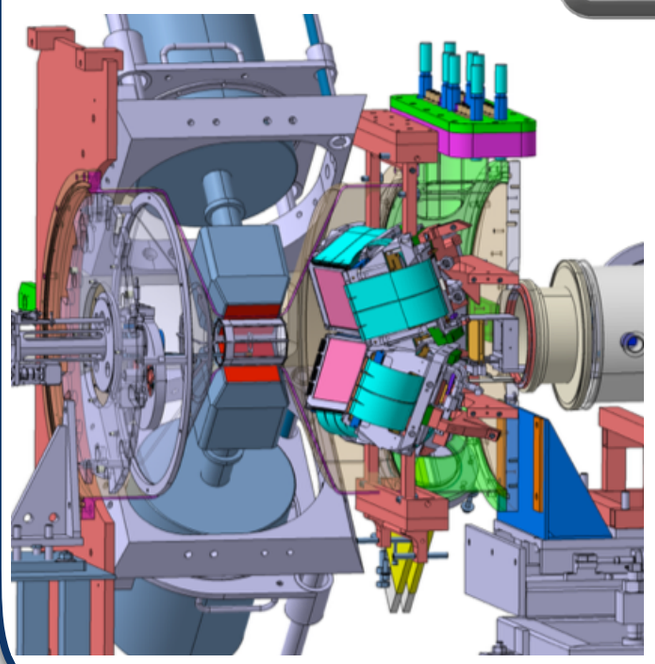
One-nucleon Transfer

- The analysis of the ***(d,t) & (p,d)*** reaction adds information on the level scheme of **^{55}Ni**
- The shell closure in the ***N=28 region*** showing a ***large SF for the f7/2*** and a ***smooth Fermi surface*** comparable with the one of ***^{40}Ca.***

Two-nucleon Transfer

- While the angular distribution for the first **J=1+,T=0** was not extracted we got the upper limit in the cross section.
- no isomeric state contributing, this confirms the ratio $\frac{T=1}{T=0} = 6.3\ ^{+2.8}_{-0.8}$ obtained from (p,^{3}He) for ^{56}Ni

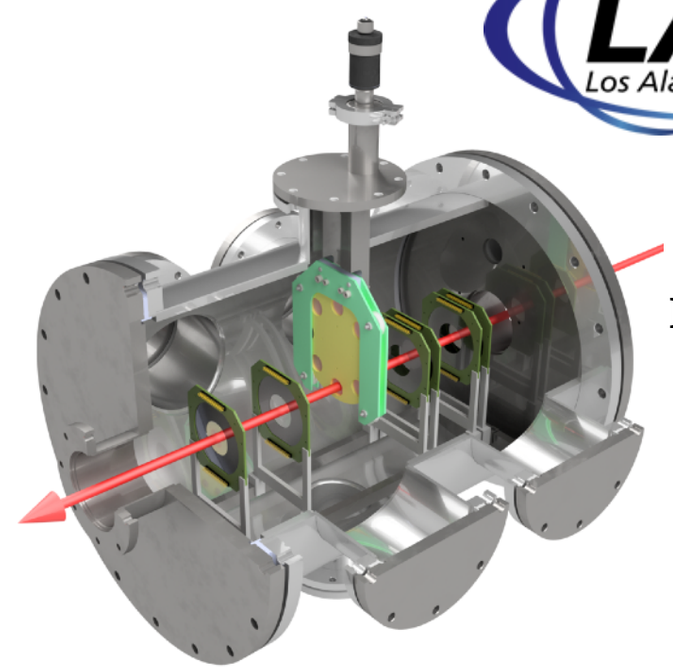
Outline



GANIL spiral2
laboratoire commun CEA/DSM CNRS/IN2P3

56Ni(p,d),(d,t),(d,α)

- **One nucleon transfer**
- **Two-nucleon transfer**



LANSCE
Los Alamos Neutron Science Center

54,56Fe(n,p),(n,a)

Low Energy Neutron-induced Charged-particle (Z) Chamber LENZ

Team and Collaborations

P-27 Group

LENZ Group: Hye Young Lee, Lukas Zavorka, Brad DiGiovine, A.G., Sean Kuvin, Daniel Votaw

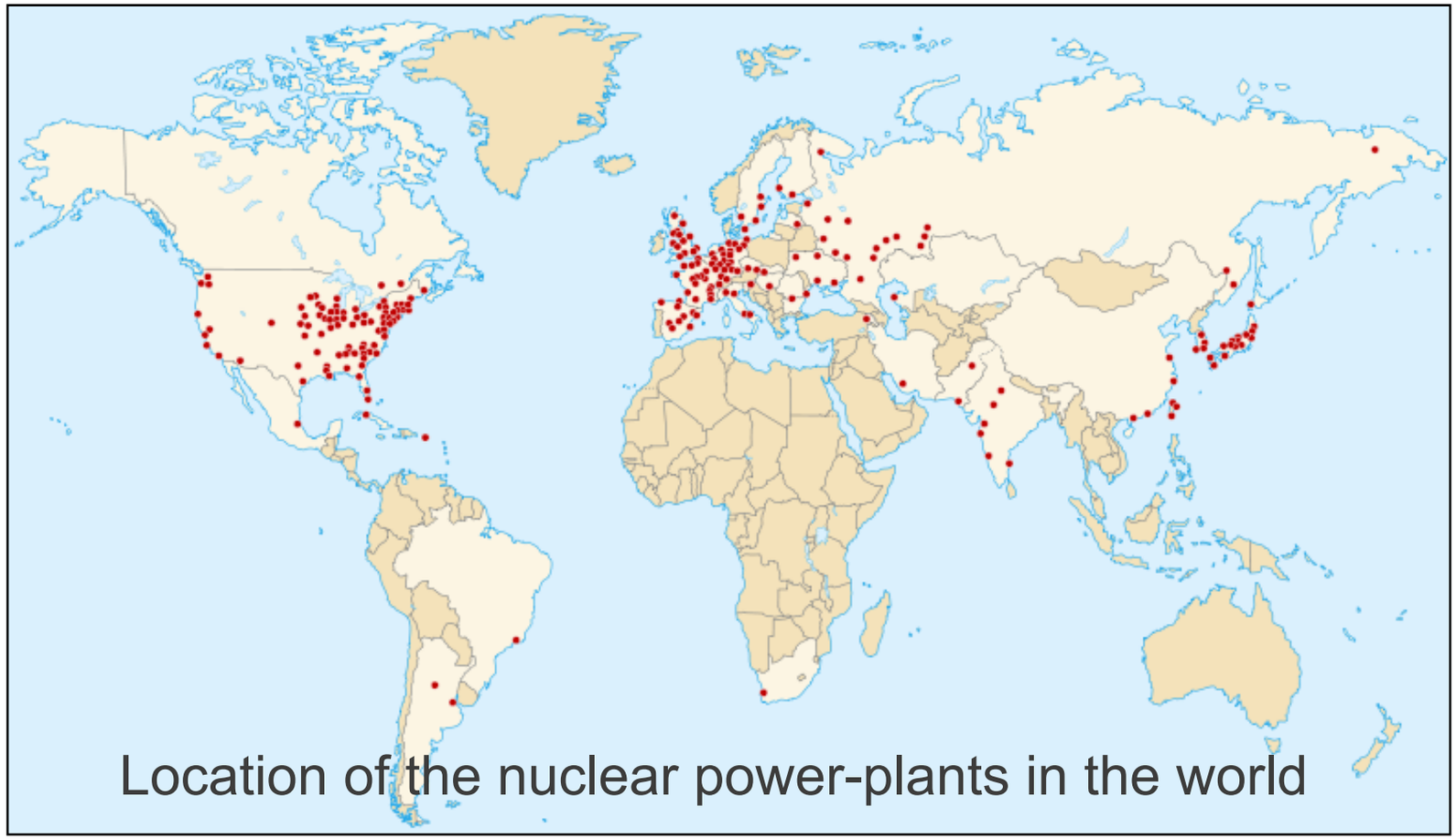
T-2 Collaboration: Toshihiko Kawano, Mike Herman

External Collaboration: Hyeong Il Kim (KAERI Korea), Georgios Perdikakis(CMU), Peli Tsintari (CMU)

Staff Scientist
Post-Doc
PhD Student

Structural materials cross sections input for statistical models…

Structural materials used in application where radiation damage may occur.

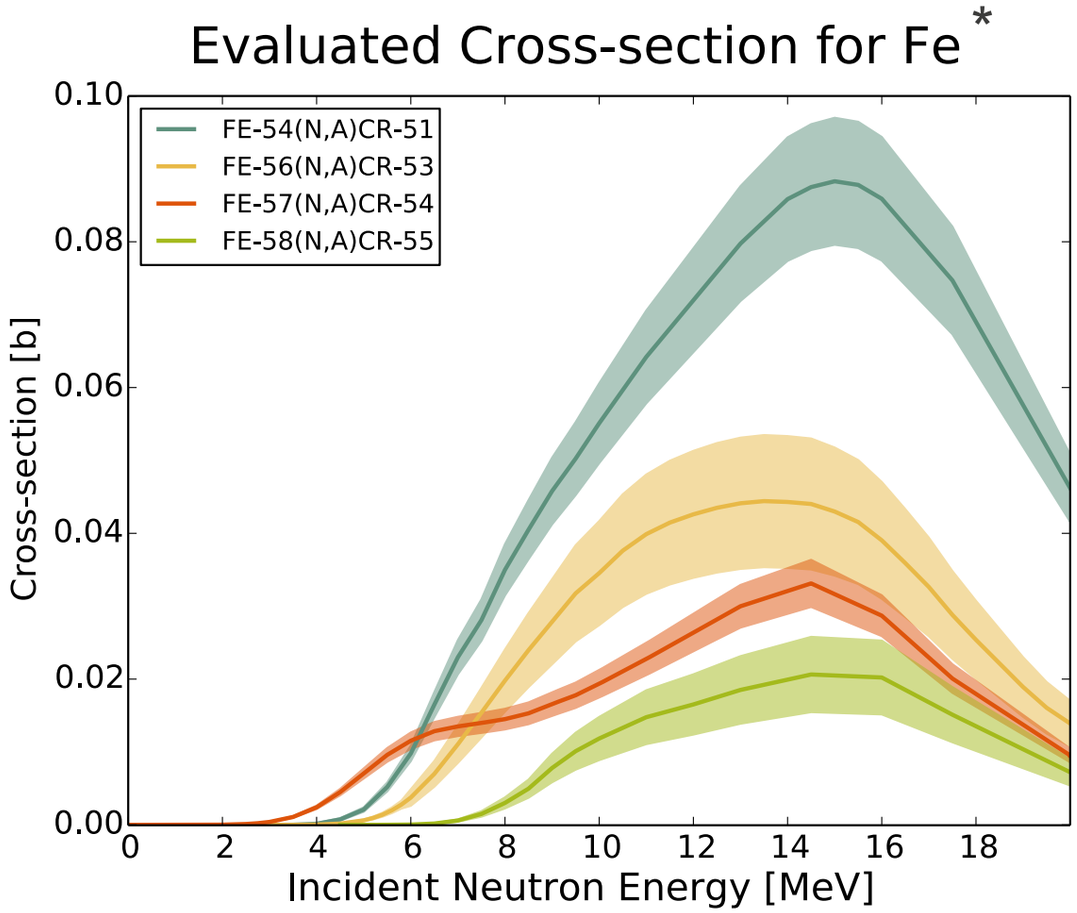


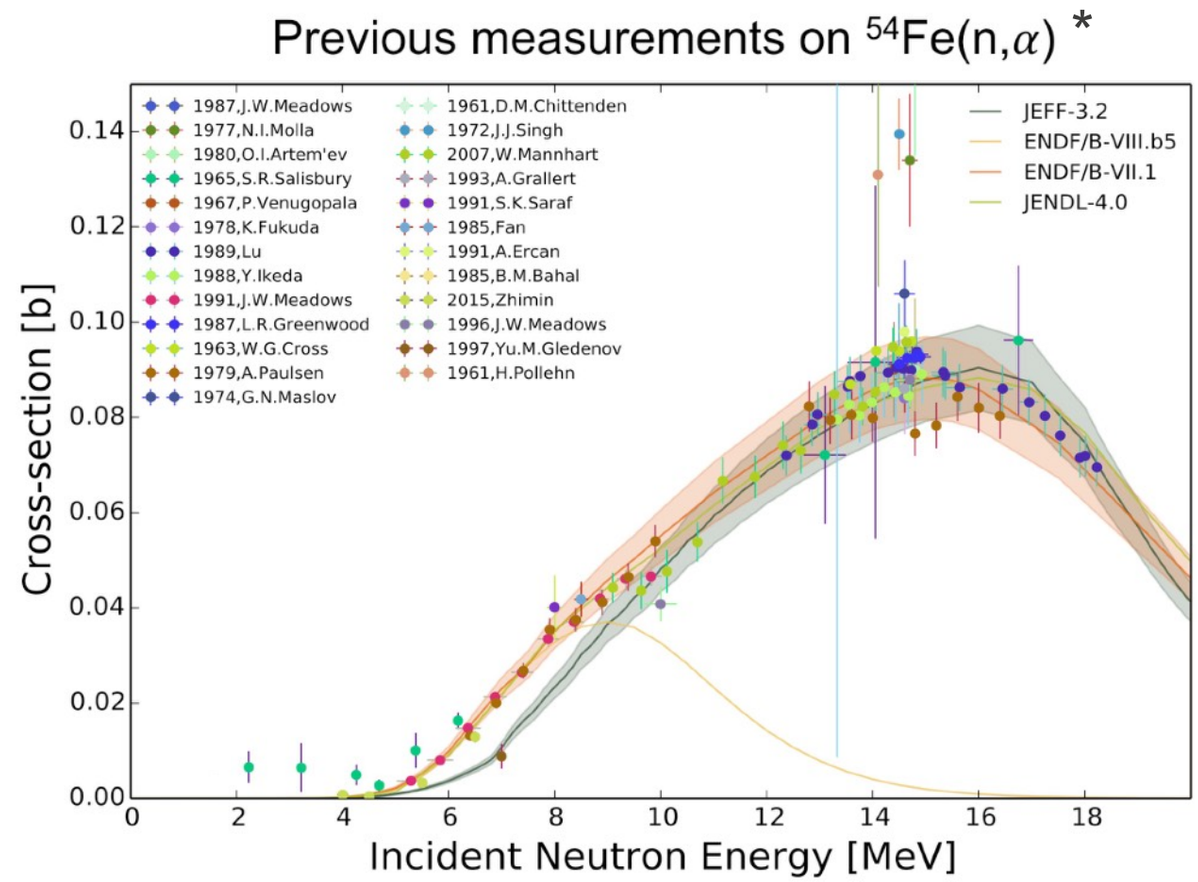
There are a lot of cases where the reaction cross section of the medium mass range isotopes derive from the statistical models such as the Hauser-Feshbach (HF) formalism

While HF in general provides a reasonable estimate, one often has to re-scale the calculated cross section to the available experimental data, to meet the precision needed in cases such as reactor design.

Structural materials cross sections input for statistical models…

Better understanding of nuclear input parameters is one of the key improvements in the HF modeling, since there are sparse data sets available for many nuclear reactions.



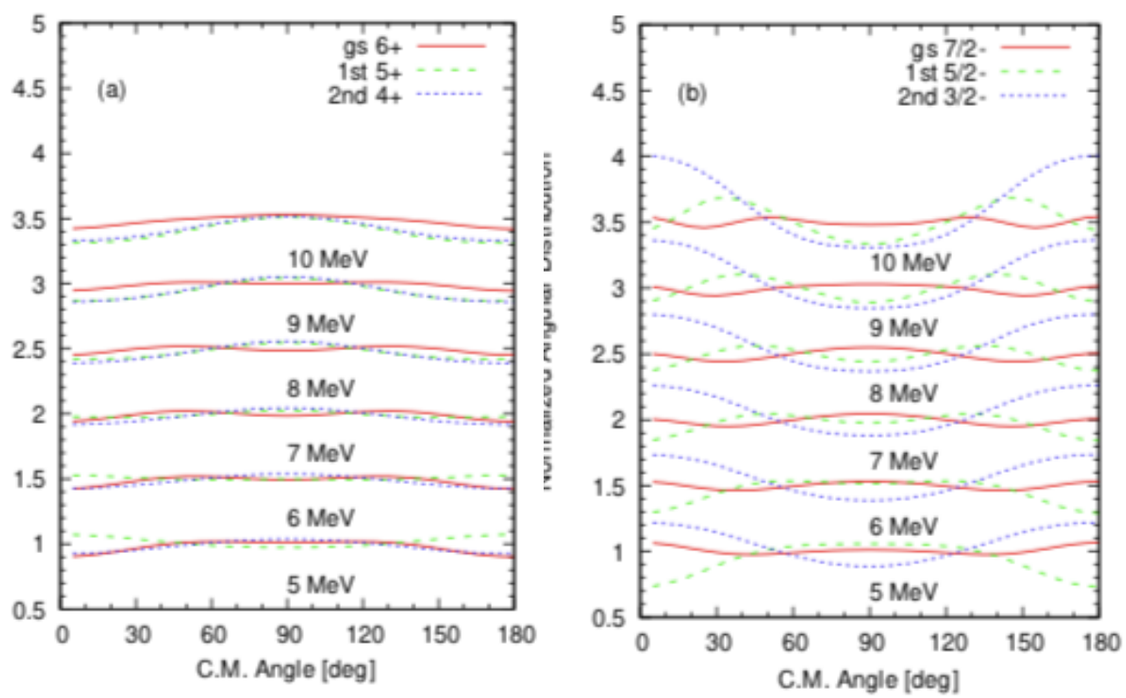


*Courtesy A.Long

Our effort is to supply this missing information of the angular distributions, especially for the charged particles, to the current ENDF/B-VIII.0 library!!!

Structural materials cross sections input for statistical models…

Angular distribution shape according to angle and energy



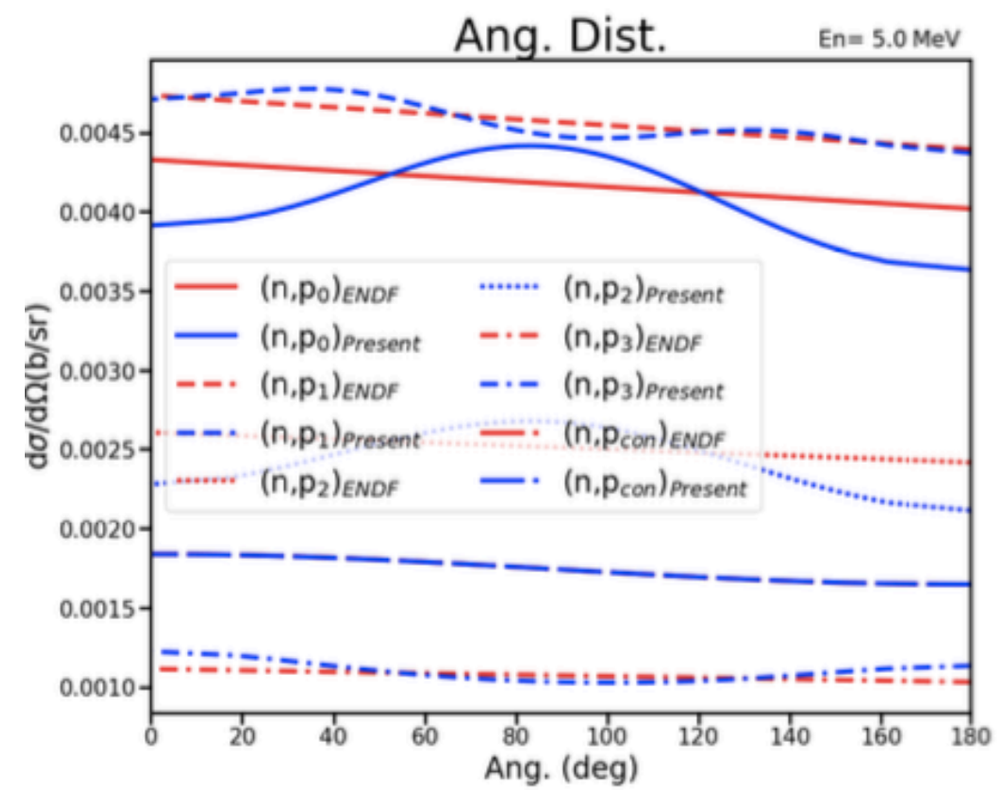
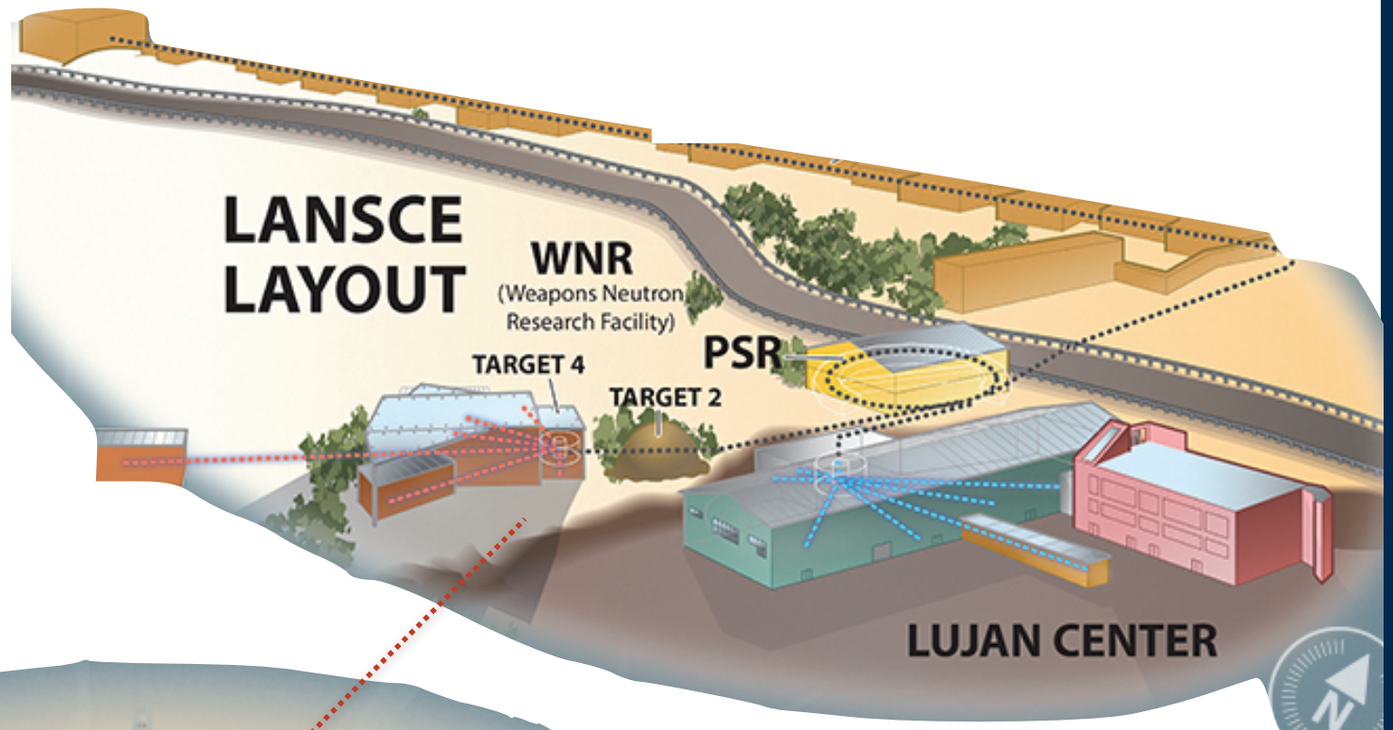


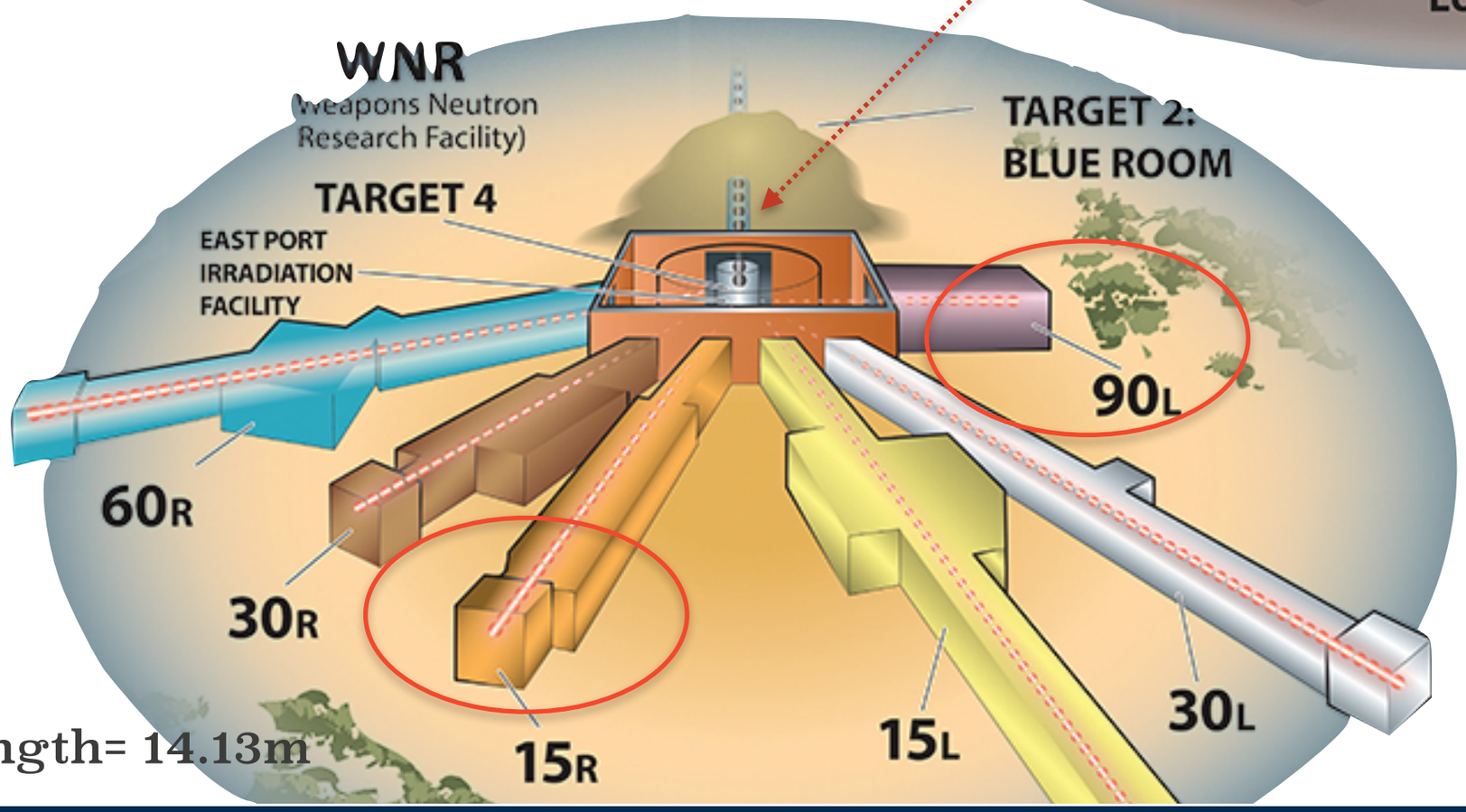
Figure 1: Normalized angular distributions of (a) **proton** and (b) **α-particle** for the neutron-induced reaction on ^{48}Ti. For better visibility, the angular distributions at different incident energies are shifted by 0.5.

Figure 2: Angular distributions for **discrete levels of (n,p)** reaction in the Lab system are compared to those of for ^{54}**Fe.** Most of the distributions of new evaluations are 90-degree symmetric in the center-of-mass system while those of ENDF/B-VIII are isotropic.

Submitted in NIM A *"New Evaluation on Angular Distributions and Energy Spectra for Neutron-Induced Charged-Particle Measurements" H.I. Kim, H.Y. Lee, A. Georgiadou, S.A. Kuvin, L. Zavorka, T. Kawano ,M.W. Herman*

LENZ at LANSCE



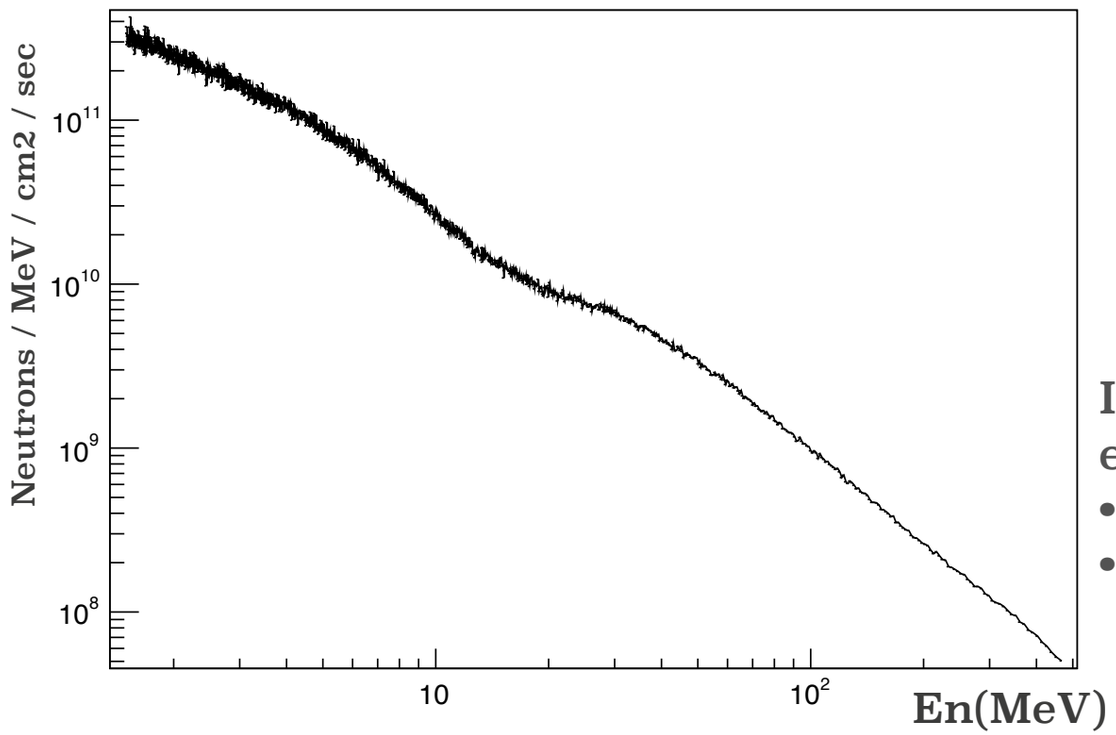


Flight Path Length= 14.13m

LENZ at LANSCE

Los Alamos NATIONAL LABORATORY EST. 1943

Neutron Flux at the 15R flight path

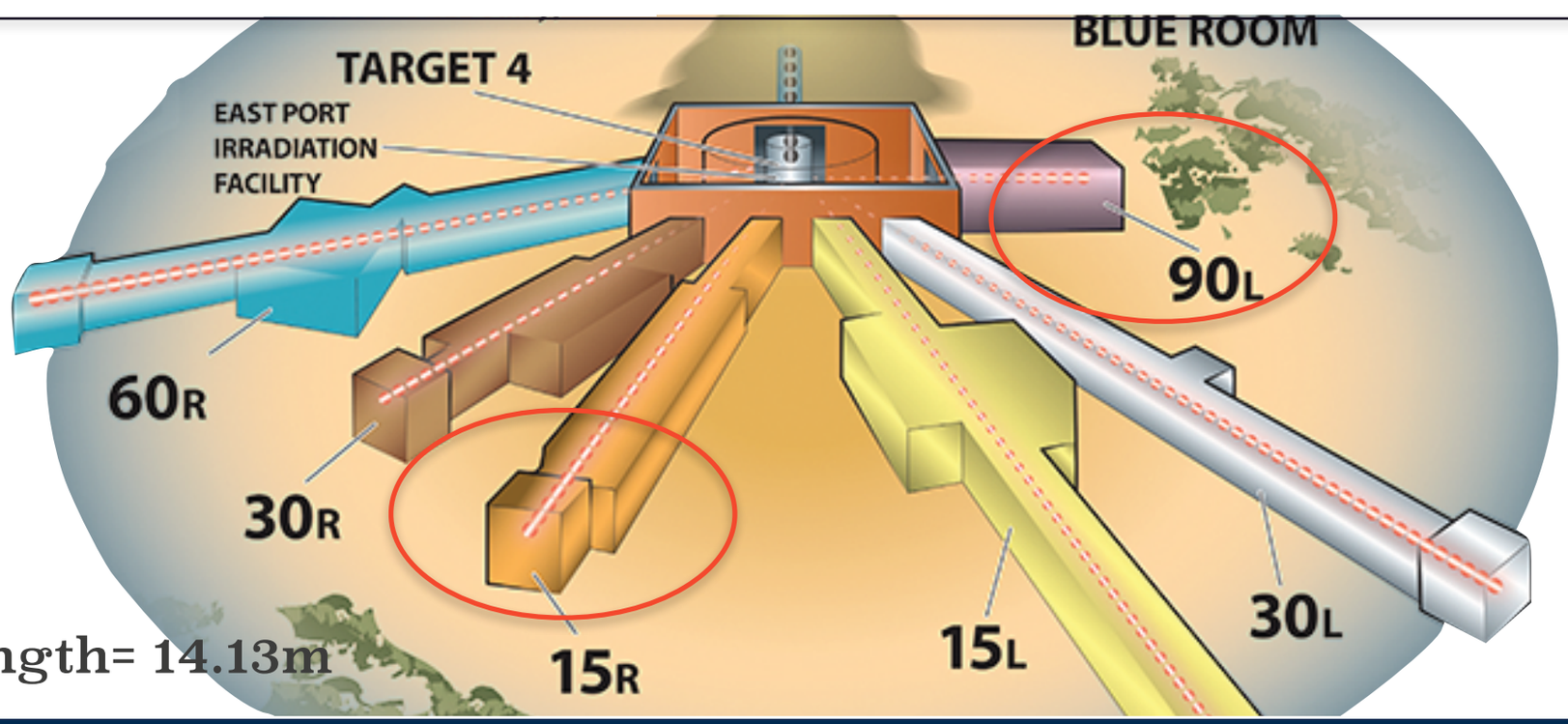


Sweeper magnets located after the shutter and the last collimator in the flight path to deflect charged particles generated from:

- the spallation neutron target
- along the flightpath in beam collimation materials.

Implementation of state-of-the-art **waveform digitizers** enhance the power of the experimental system :

- separating and identifying different charged particles,
- obtaining improved timing- and energy- resolutions, processing high data rates.

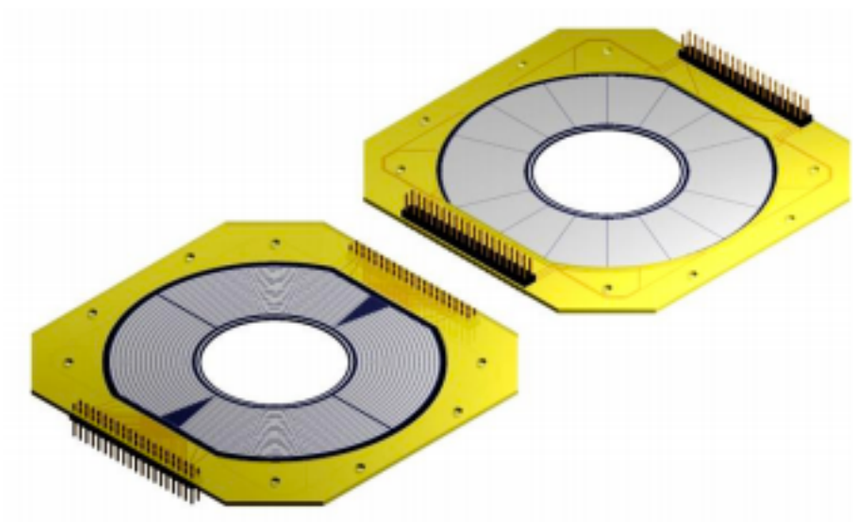


Flight Path Length= 14.13m

LENZ at LANSCE: LENZ (Low Energy Neutron-induced Charged-particle (Z) Chamber)

LENZ (Low Energy Neutron-induced Charged-particle (Z) Chamber)

DSSD: S1 Micron Detectors
From 65μm-1500μm thick



Energy Resolution: ~40KeV
Efficiency ~90%
3-α source

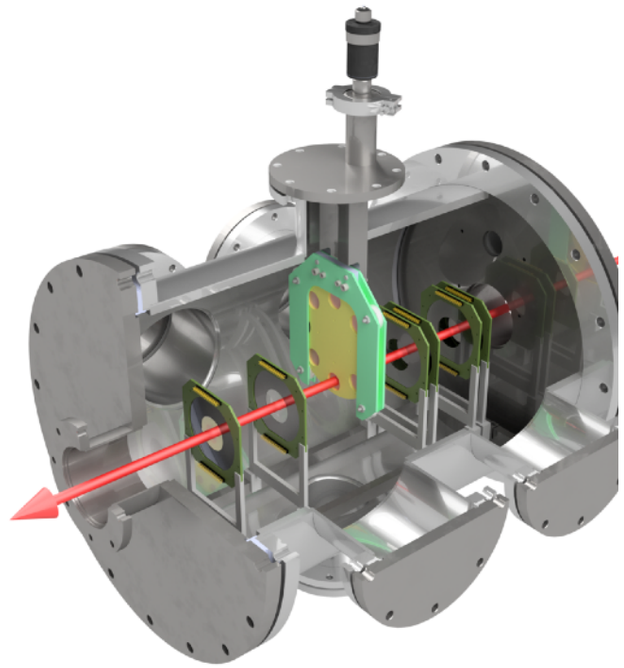
LENZ at LANSCE: LENZ (Low Energy Neutron-induced Charged-particle (Z) Chamber)

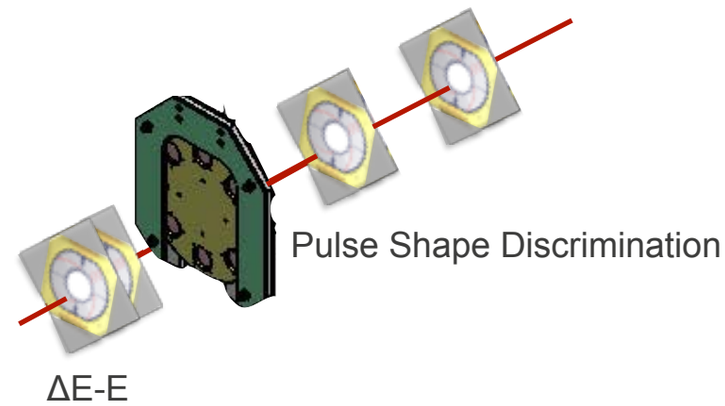
LENZ (Low Energy Neutron-induced Charged-particle (Z) Chamber)

LENZ

$^{54}Fe, ^{56}Fe$

09/2019

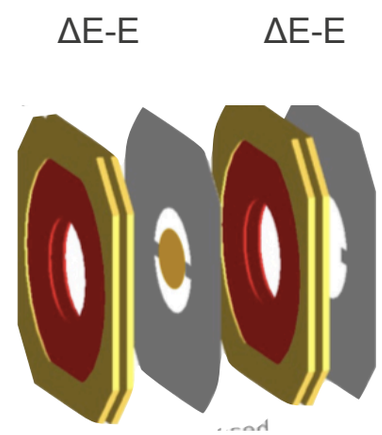




Also-LENZ

$^{54}Fe, ^{56}Fe$

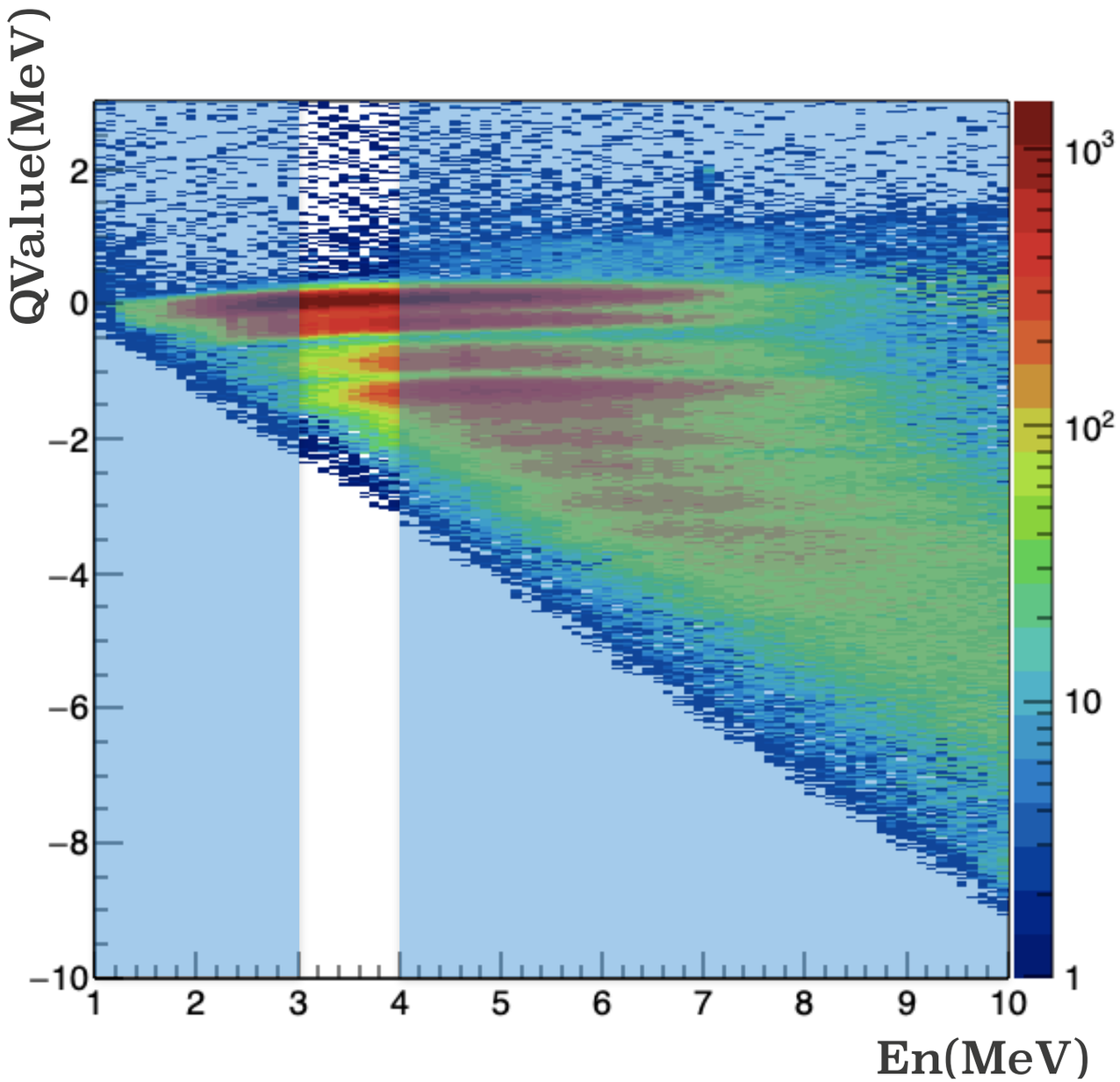
06/2018

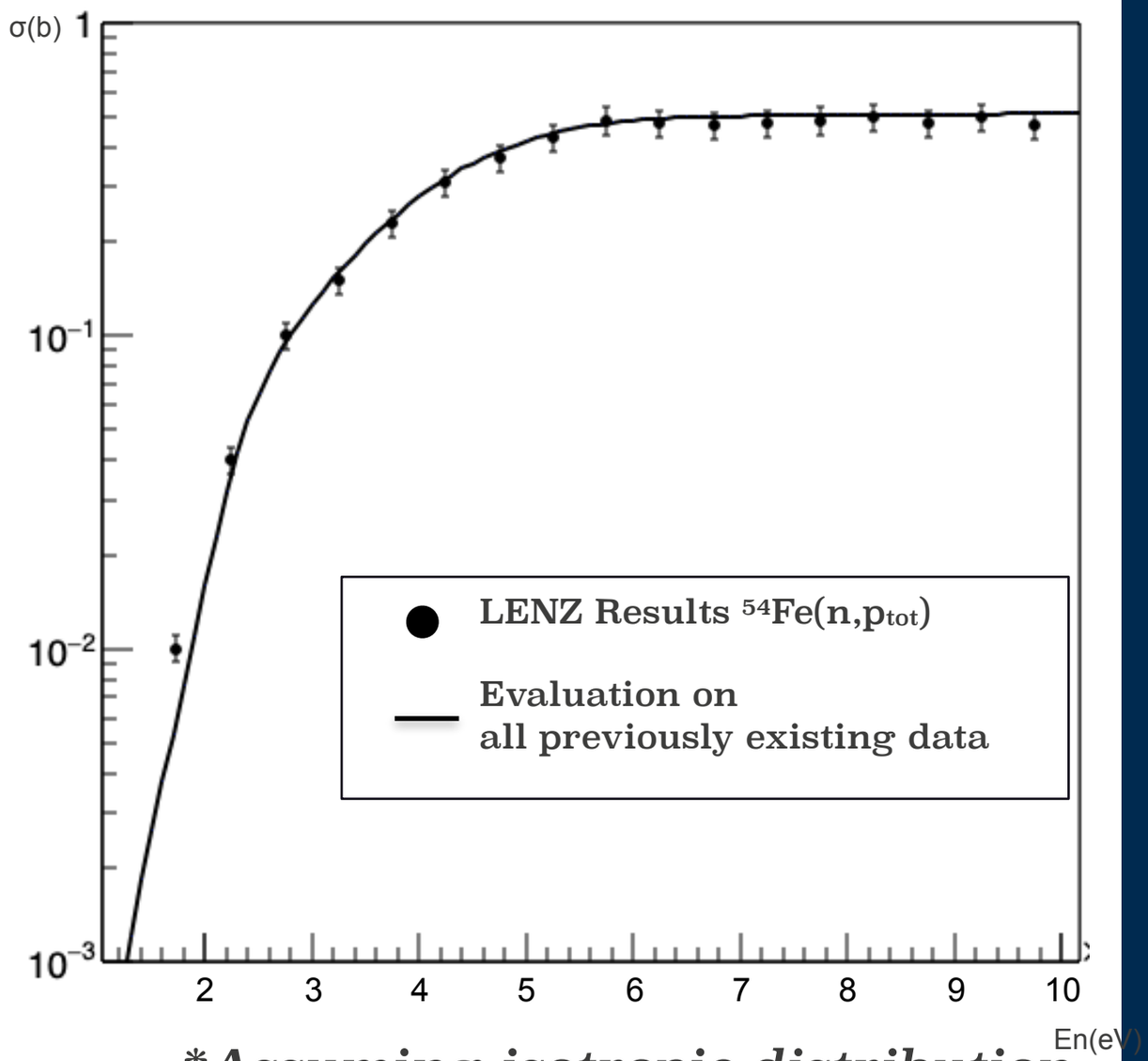


^{54}Fe(n,p) Reaction Study

Comparing the Total CrossSection with already existing data

^{54}Fe(n,p$_{tot}$)^{54}Mn:





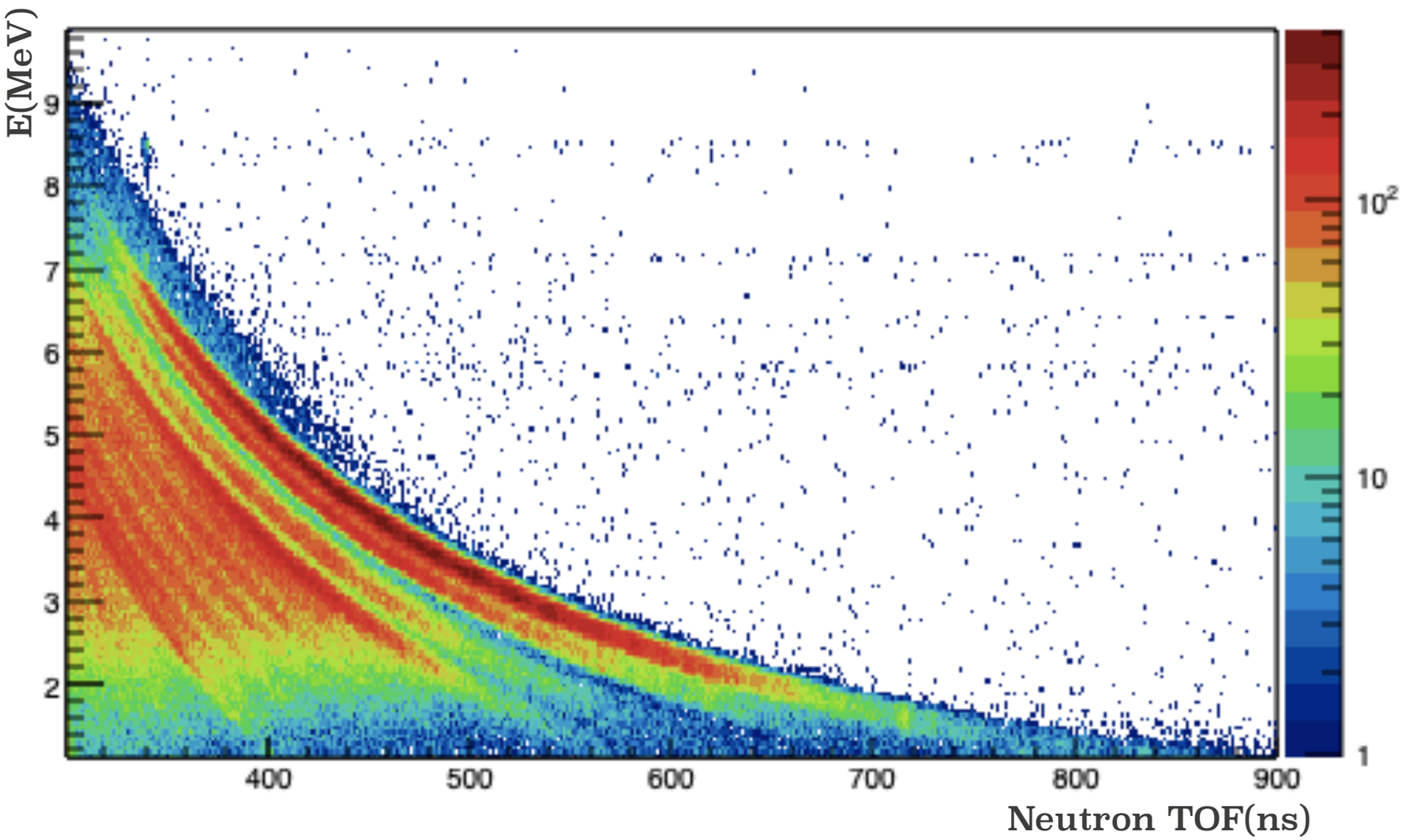
***Assuming isotropic distribution**

*from NNDC

^{54}Fe(n,p) Reaction Study

Looking at the discrete levels…

Particle E vs Neutron TOF



^{54}Mn Level Scheme*

E_{Levels}(MeV)	Q_{Value}(MeV)
0.000	0.085
0.055	0.032
0.156	-0.071
0.368	-0.283
0.408	-0.323
0.839	-0.754
1.009	-0.924
1.073	-0.988
1.137	-1.052
1.375	-1.290
1.392	-1.307
1.454 …	-1.369
1.461	-1.376
1.508	-1.423

*from NNDC

^{54}Fe(n,p) Reaction Study

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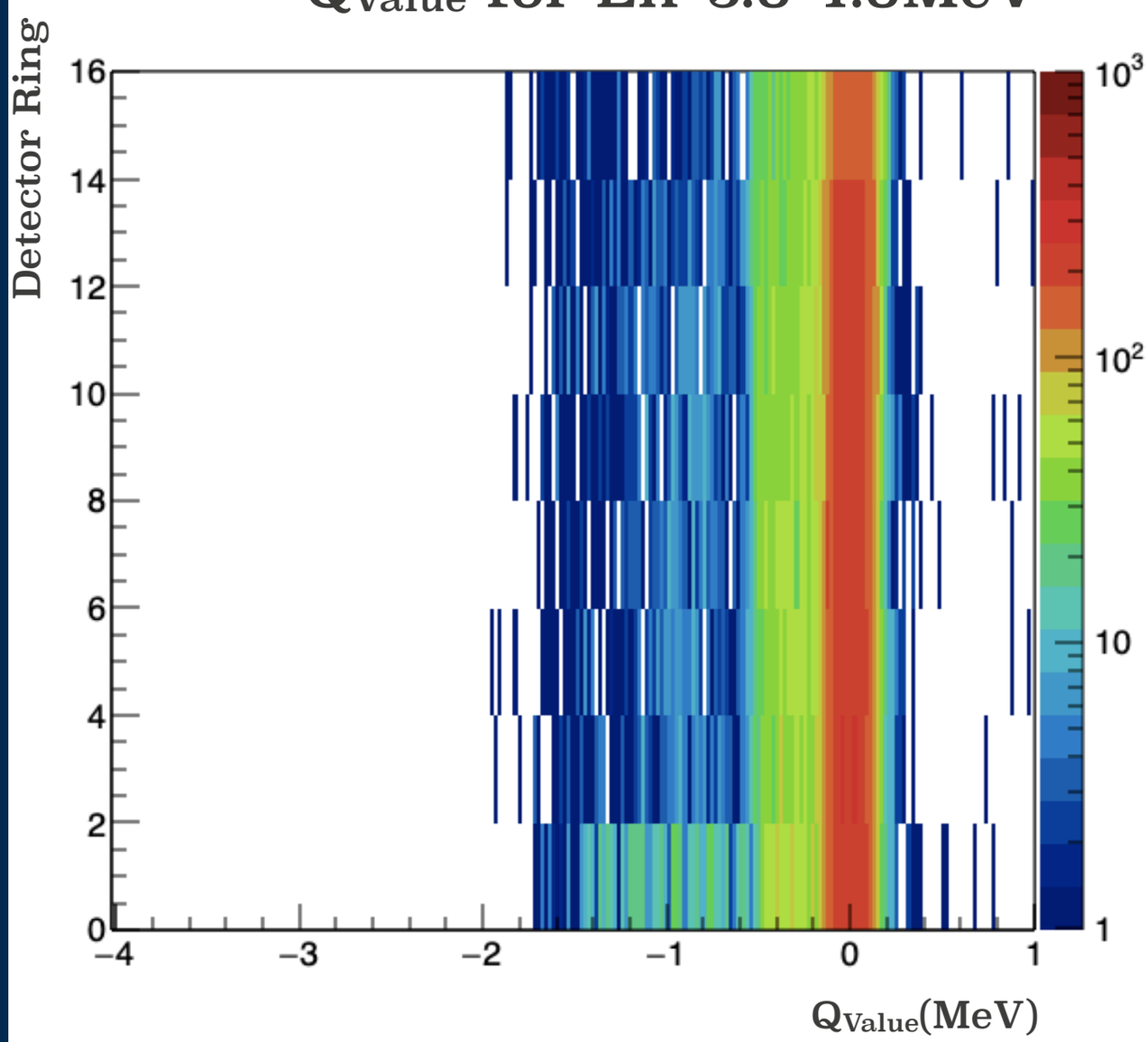
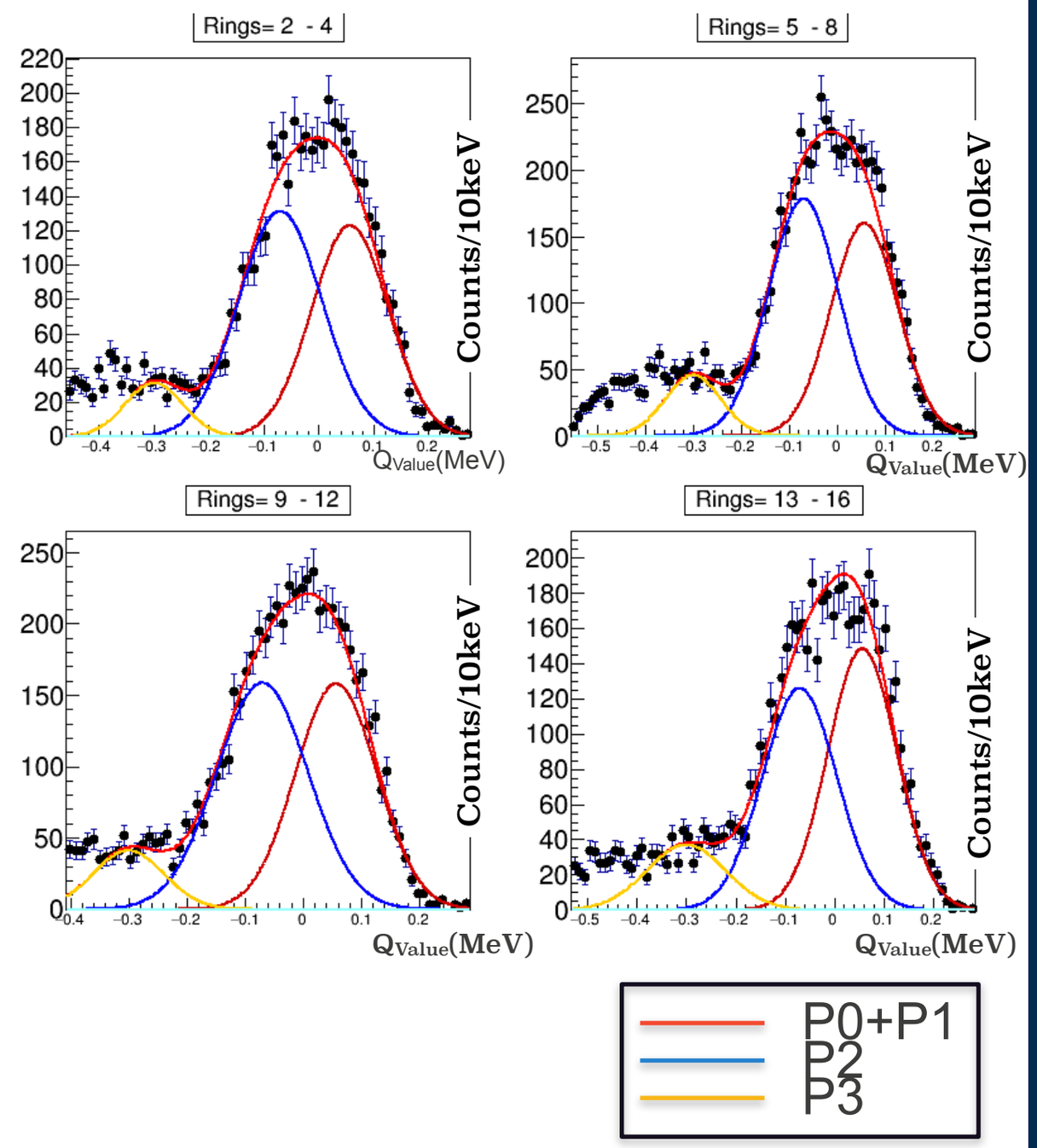
First Approach on the data analysis

Q_{Value} for En=3.0-4.0MeV

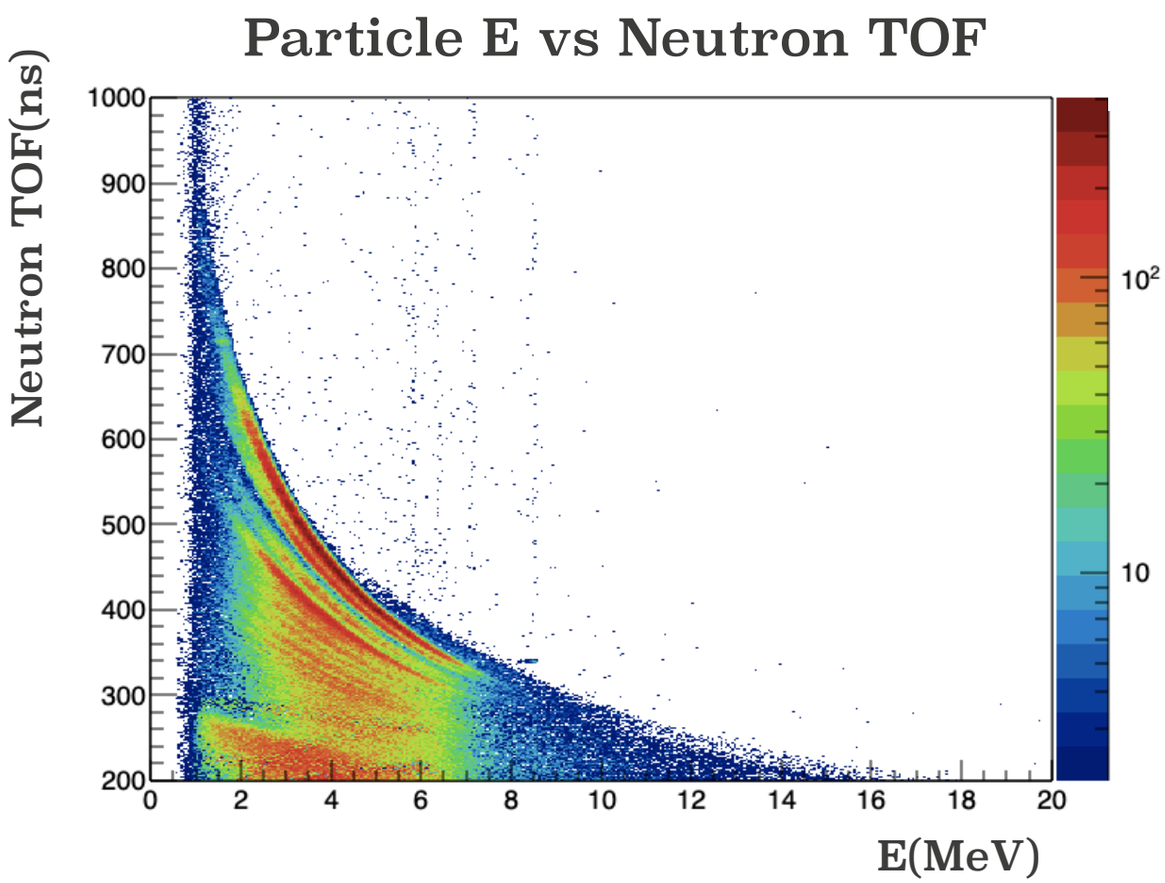




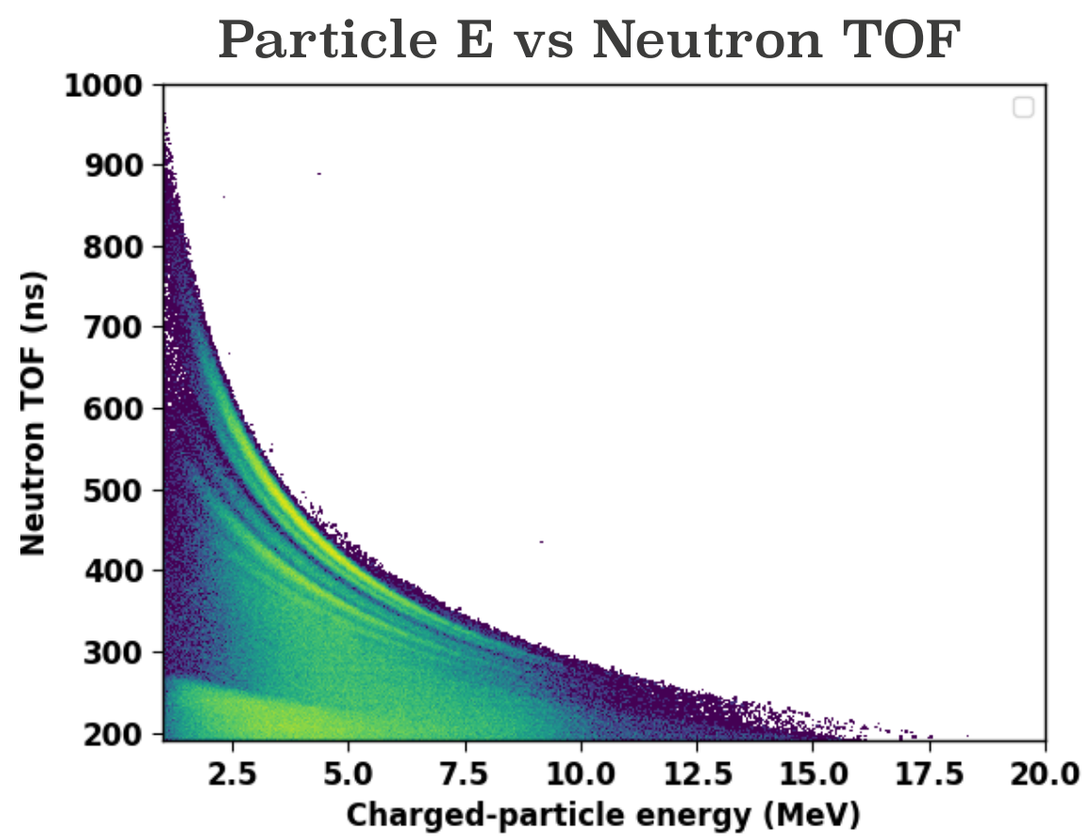
^{54}Fe(n,p) Reaction Study

Looking at the discrete levels…

Experiment



Simulation

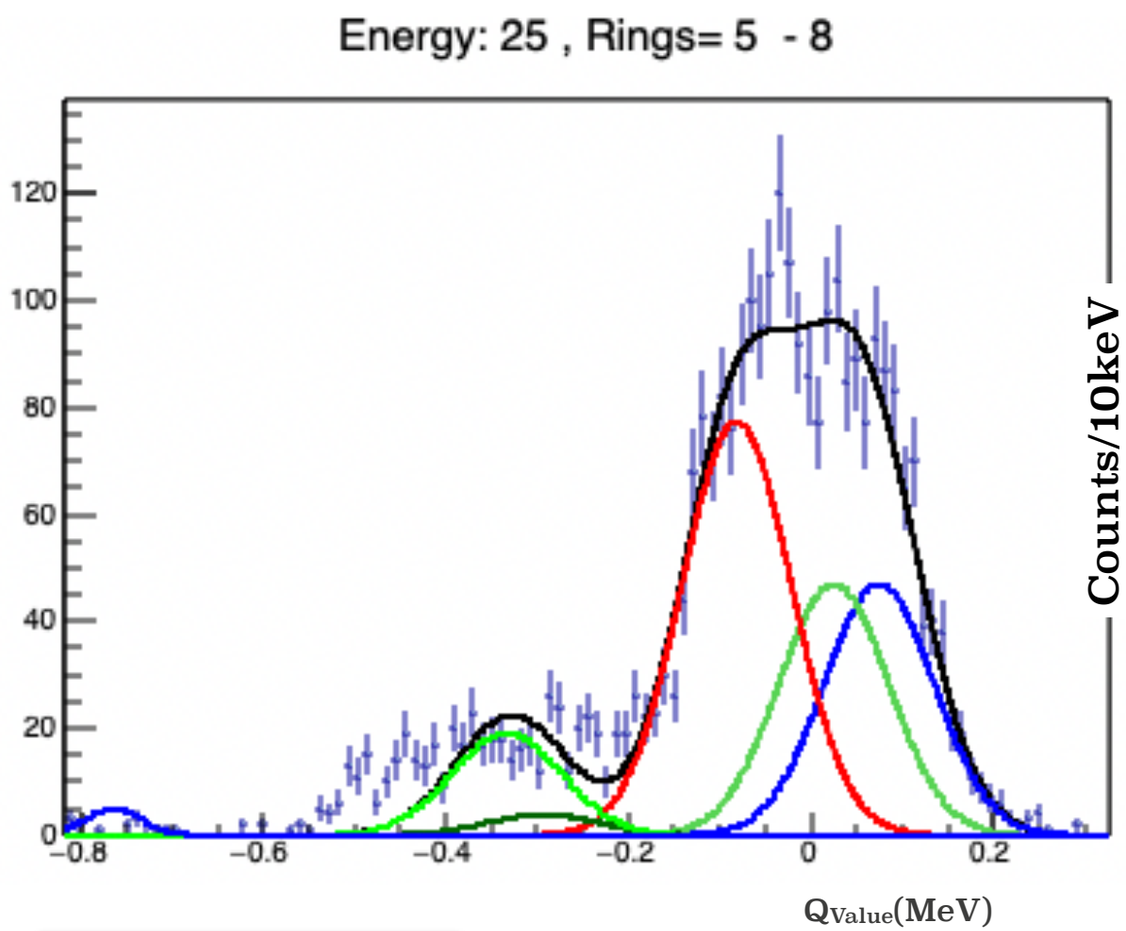


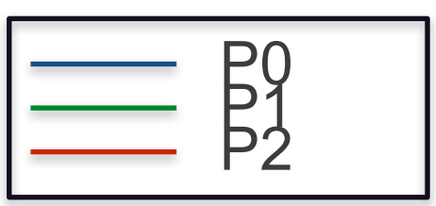
**MCNP6 calculations: L.Zavorka*

^{54}Fe(n,p) Reaction Study

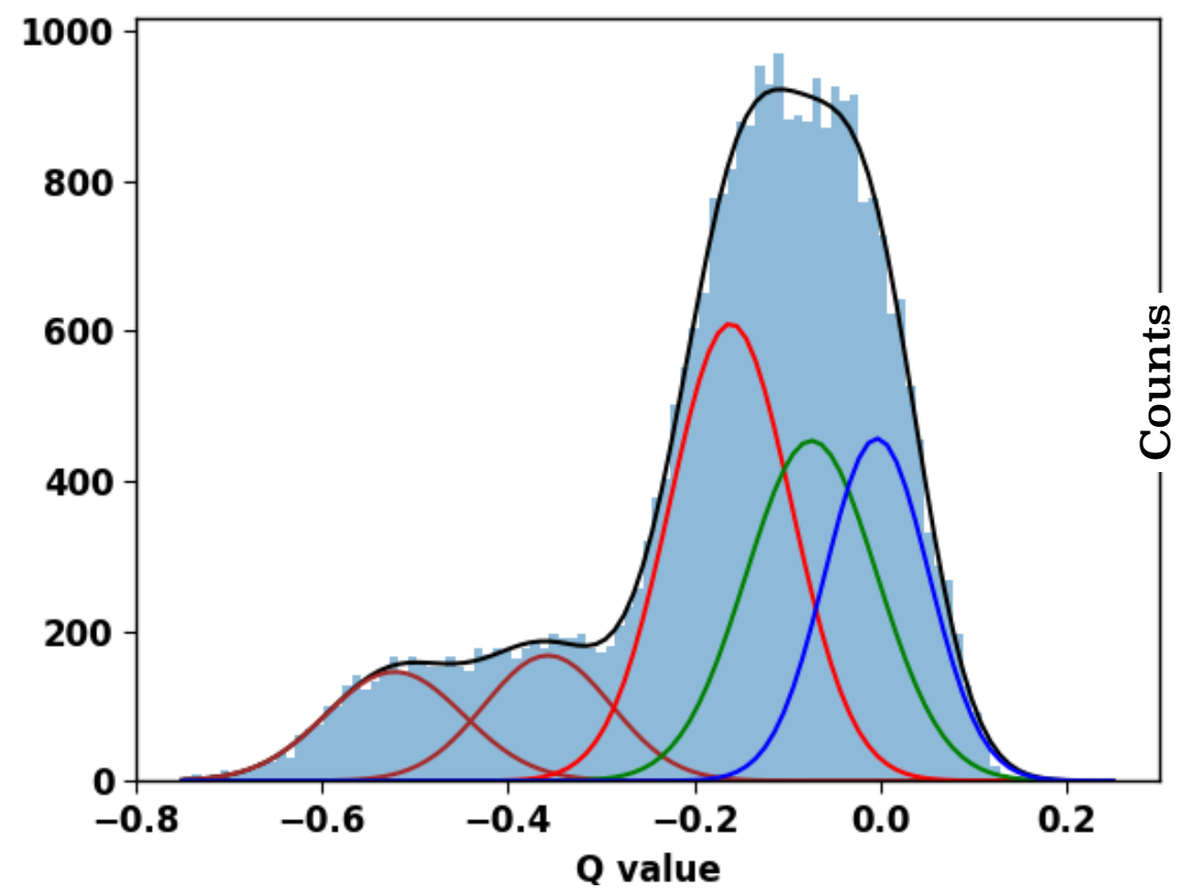
Looking at the discrete levels…

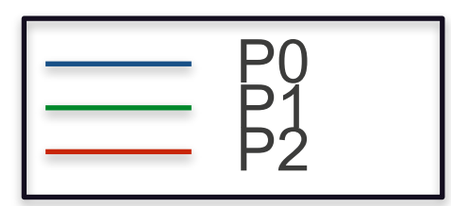
Experiment





Simulation





^{54}Fe(n,p) Reaction Study

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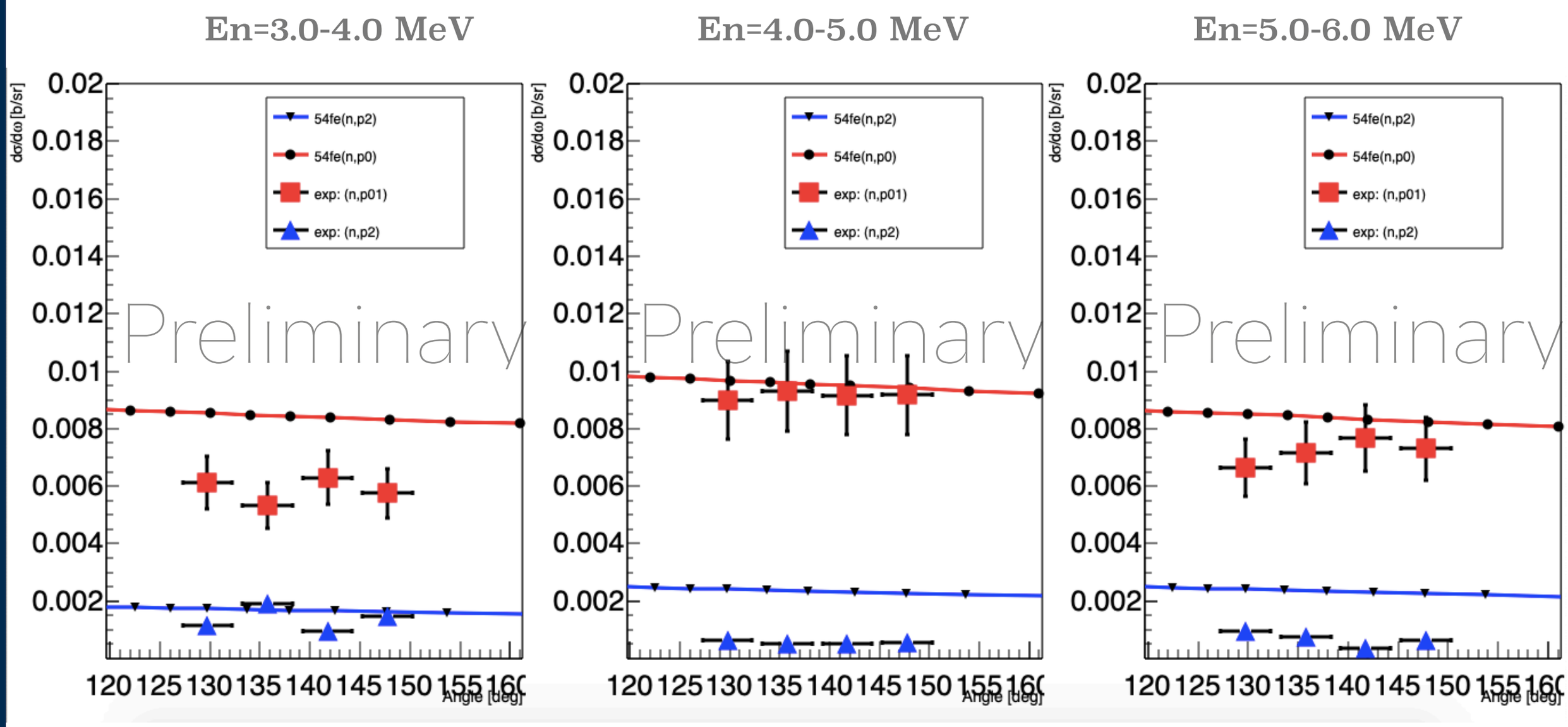
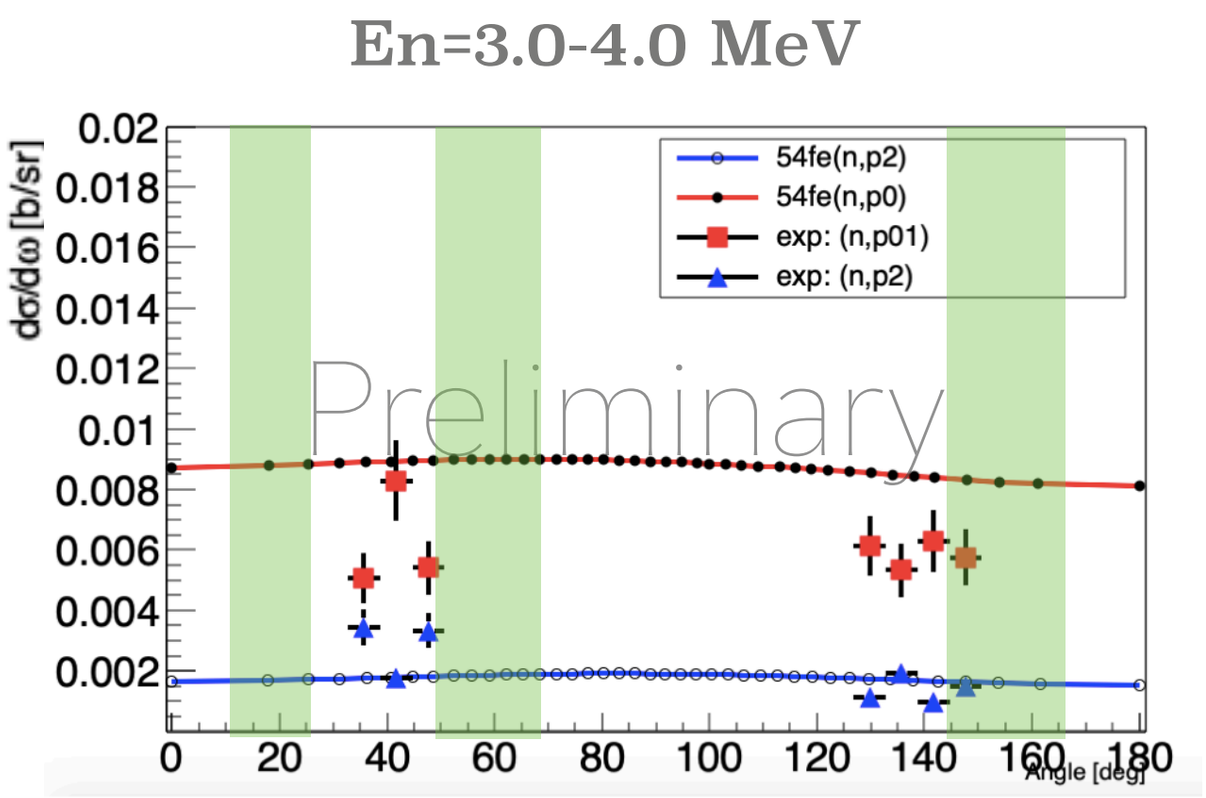
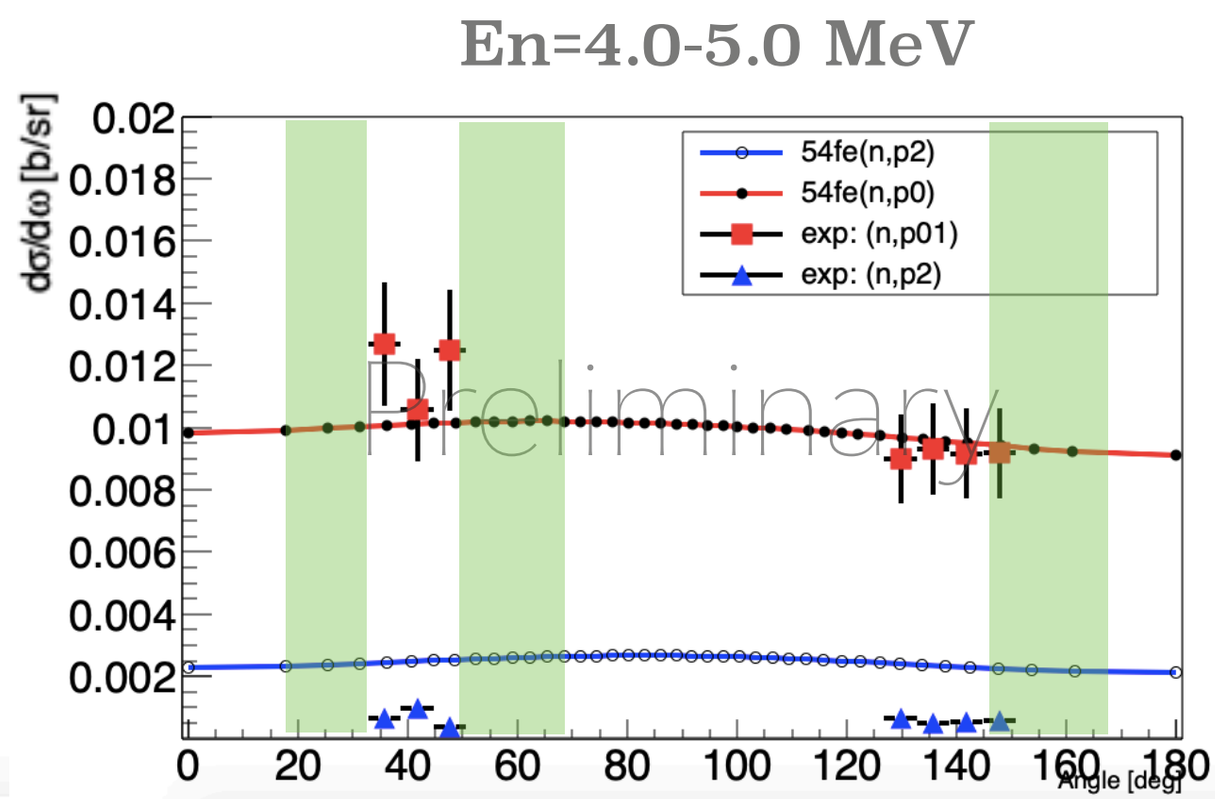
Backward Angles



Evaluations from Dr. Hyeong Il Kim

Conclusion





- With the analysis of already taken data we will cover a wider angular range
- Campaign of experiments studying these structural material: ^{58,60}Ni, ^{56}Fe (n,p) and (n,α)
- Aiming to supply this missing information of the angular distributions, especially for the charged particles, to the current ENDF/B-VIII.0 library
- Experiments with radioactive samples in the near future: ^{56,59}Ni.

Proposal RunCycle2020-
Particle-γ coincidences

Properties	Enhanced $LaBr_3$ (Ce+Sr)
Energy Resolution @ 662KeV	2.2%
Photoelectron yield [% of NaI(Tl)] (for γ-rays)	>190
Wavelength of emission max [nm]	385
Primary decay time [μs]	0.025
Light yield [photons/keVγ]	73
Refractive index @ emission max.	~2.0

$^{54}Fe(n,p)^{54}Mn$

E(level) (keV)	E(γ) (keV)
0.0	
54.88 *12*	54.4 *3*
156.29 *8*	156.27 *11*
368.22 *15*	211.98 *14* 368.2 *8*
407.55 *8*	251.2 *1* 352.7 *3* 407.5 *1*
839.10 *19*	470.75 *25* 682.5 *5* 838.8 *4*
1009.7 *3*	853.1 *5* 954.9 *5*
1073.11 *20*	704.88 *17* 916.7 *20*
1136.99 *19*	297.7 *2* 768.87 *17* 980.7 *7*
1375.00 *14*	967.3 *2* 1320.3 *4* 1375.1 *2*
1391.0 *3*	1336.0 *5*
1454.4 *3*	1399.6 *6* 1454.0 *7*
1460.6 *6*	387.5 *5*

$^{56}Fe(n,p)^{56}Mn$

E(level) (keV)	E(γ) (keV)
0.0	
26.6045 *13*	26.6043 *14*
110.5041 *18*	83.8990 *15* 110.505 *4*
212.026 *5*	212.017 *6*
215.1282 *24*	104.6234 *20* 188.524 *6* 215.134 *7*
335.529 *6*	123.502 *4* 335.540 *15*
340.989 *6*	125.90 *3* 128.961 *4* 314.395 *10* 340.990 *25*
454.337 *7*	113.348 *4* 242.36 *10* 454.30 *6*
486.310 *7*	145.320 *20* 271.175 *9* 274.28 *3* 459.71 *5* 486.74 *8*
541 *5* ?	
661 *5* ?	
716.178 *8*	229.867 *7* 375.180 *20* 716.180 *14*
753.46 *8*	299.11 *13* 541.42 *13*

$^{54}Fe(n,\alpha)^{51}Cr$

E(level) (keV)	E(γ) (keV)
0.0	
749.10 *8*	749.07 *9*
776.95 *17*	27.85 *19* 776.95 *17* S
1164.59 *14*	1164.5 *1*
1352.65 *17*	575.6 *1* 603.5 *3* 1353.7 *6*
1480.07 *16*	315.60 *20* 1480.3 *3*
1557.26 *13*	204.0 *8* 808.19 *21* 1557.5 *3*
1899.2 *3*	1124.0 *9* 1149.4 *9* 1899.41 *25*
2001.91 *21*	2001.35 *12*
2255.5 *3*	775.4 *2*
2312.58 *17*	1148.0 *3* 2312.52 *23*
2379.46 *14*	822.3 *3* 899.9 *5* 1026.7 *2* 1215.5 *5* 2379.3 *2*
2385.4 *4*	905.3 *3*
2500	
2699 *10*	

CNR*20
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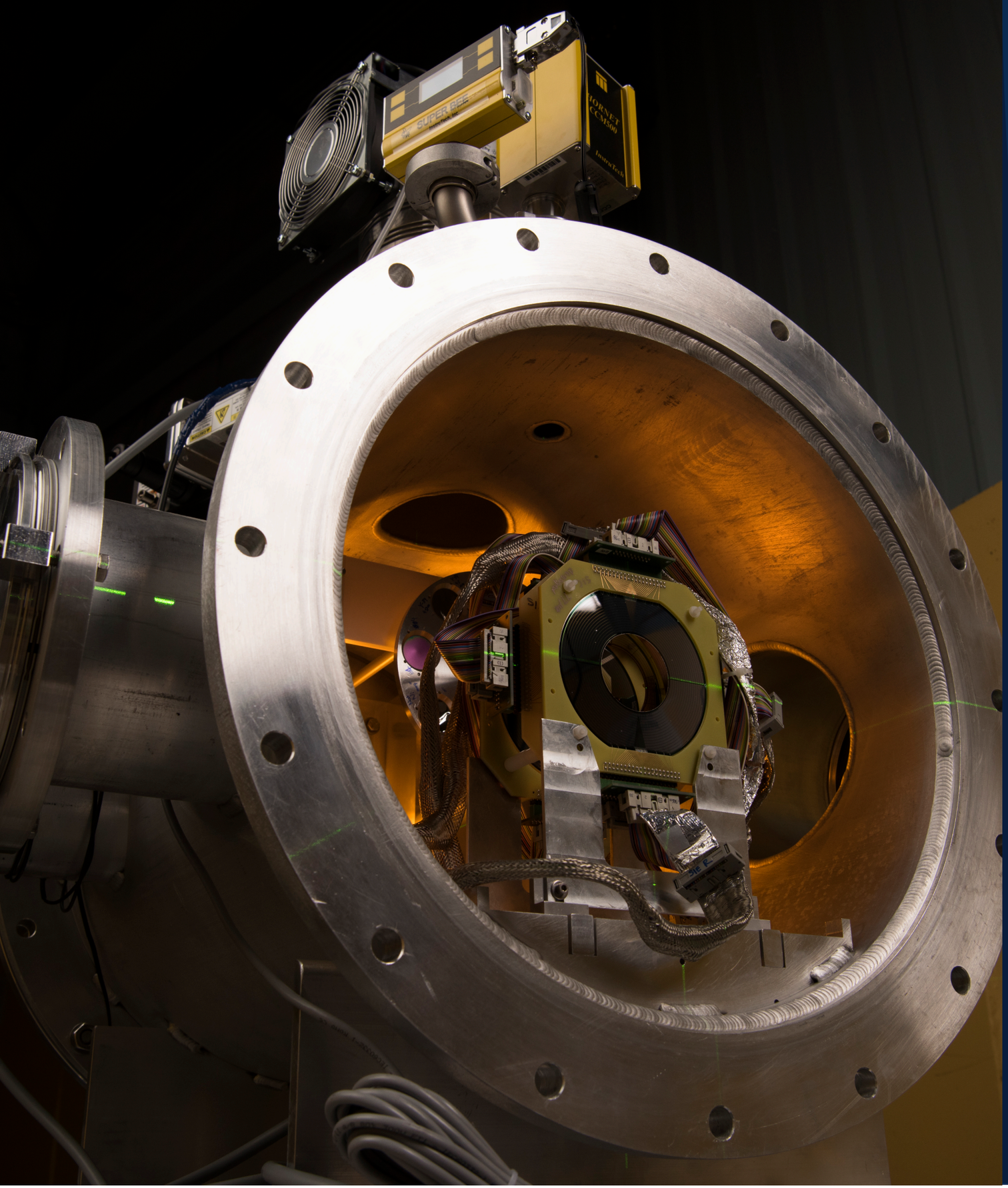
Athens, Greece



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Thank you!