# Multinucleon Transfer in Peripheral Collisions below the Fermi energy. Recent experiment on 11.5 MeV/nucleon ^{48}Ti+^{48}Ti

Georgios A. Souliotis

Laboratory of Physical Chemistry, Department of Chemistry, National and Kapodistrian University of Athens, Athens, Greece

HINPw7 Workshop
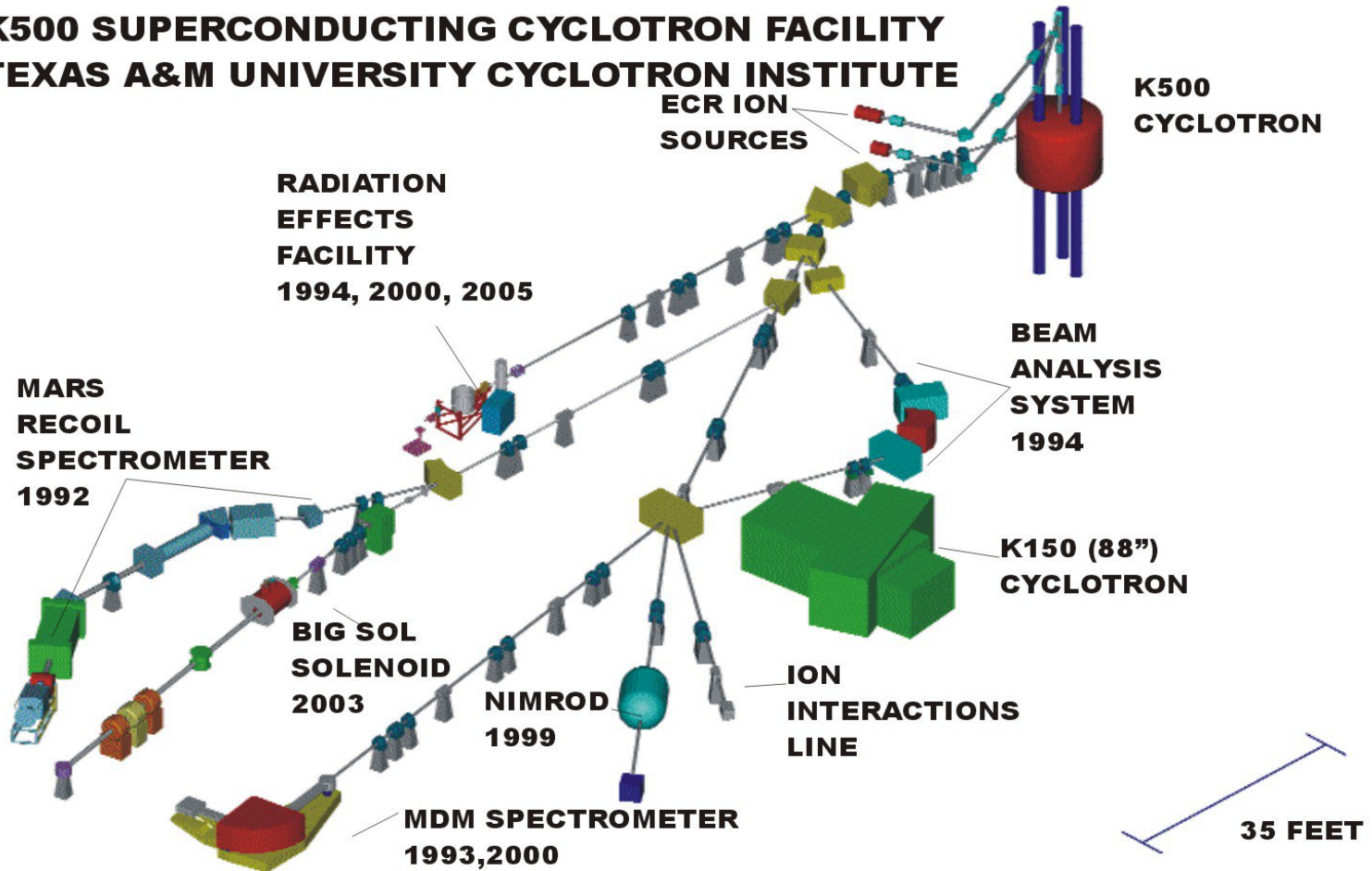**University of Ioannina**
31 May-1 June, 2024

HINP
ΕΙΠΦ

ΕΘΝΙΚΟΝ & ΚΑΠΟΔΙΣΤΡΙΑΚΟΝ
ΠΑΝΕΠΙΣΤΗΜΙΟΝ ΑΘΗΝΩΝ

NATIONAL & KAPODISTRIAN
UNIVERSITY OF ATHENS
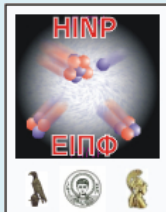
Outline

- Experimental work at Texas A&M. MARS separator (2-stage): $^{40}Ar, ^{86}Kr + Ni, Sn$

- Experimental work at Texas A&M. BigSol Line Separator: $^{64}Ni + ^{64}Ni, ^{124}Sn, ^{208}Pb$

- Experimental work at: LNS/INFN Italy with MAGNEX: $^{70}Zn + ^{64}Ni$

- Recent work with the MARS Separator (3-stage) : $^{48}Ti + ^{48}Ti$

- Reaction/Dynamics simulations with DIT and CoMD followed by GEMINI
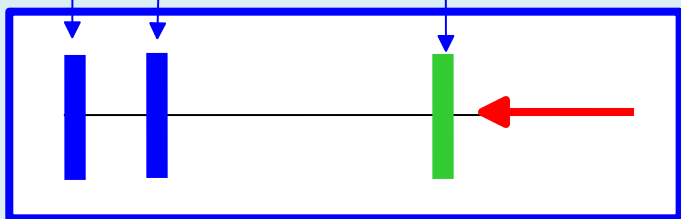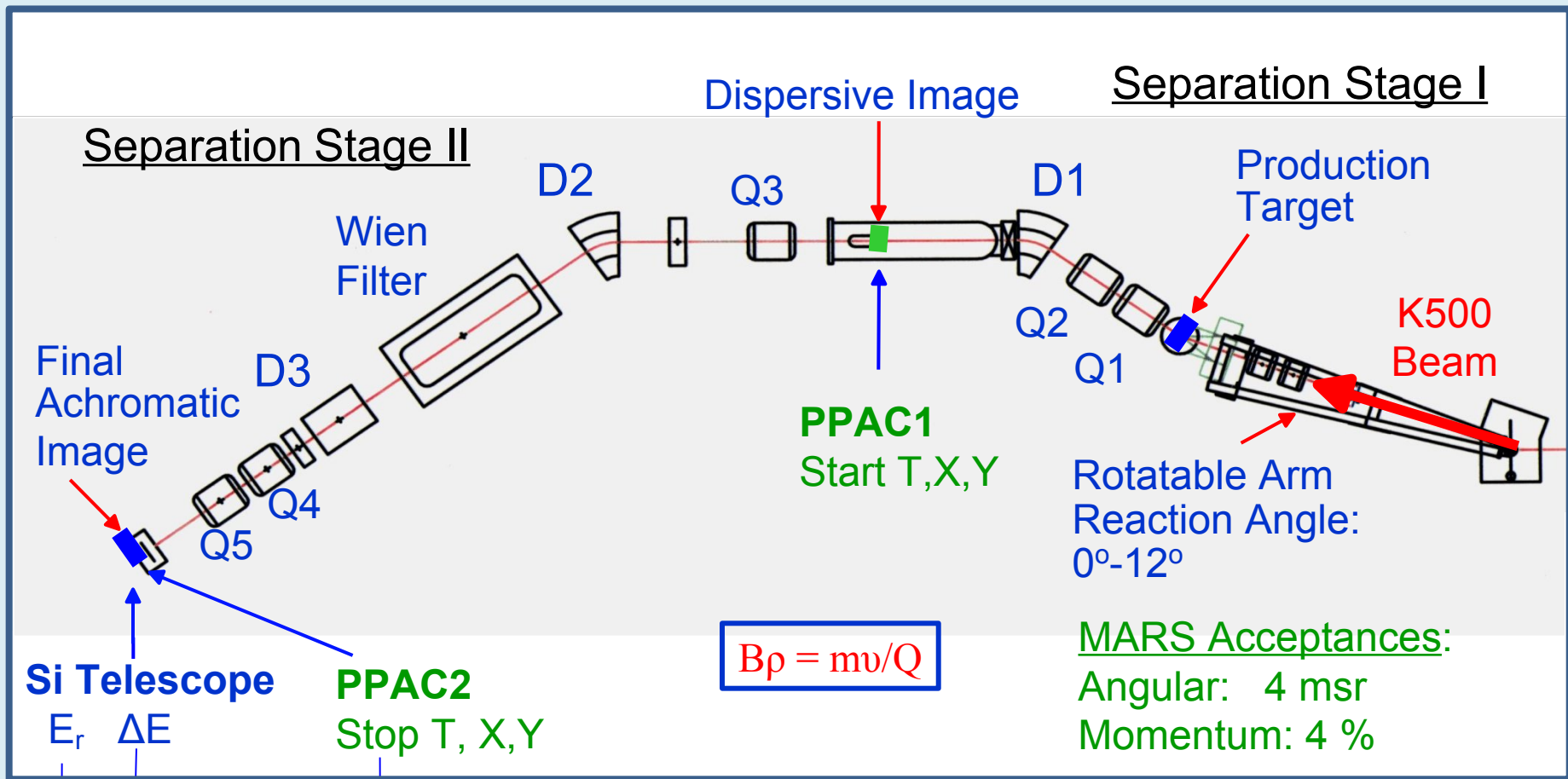- Detailed filtering for the spectrometer acceptance

 Conclusions and future steps

Cyclotron Institute at Texas A&M University

K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY CYCLOTRON INSTITUTE

ECR ION SOURCES

K500 CYCLOTRON

RADIATION EFFECTS FACILITY 1994, 2000, 2005

BEAM ANALYSIS SYSTEM 1994

MARS RECOIL SPECTROMETER 1992

K150 (88") CYCLOTRON

BIG SOL SOLENOID 2003

NIMROD 1999

ION INTERACTIONS LINE

MDM SPECTROMETER 1993, 2000

35 FEET

ΕΘΝΙΚΟΝ & ΚΑΠΟΔΙΣΤΡΙΑΚΟΝ ΠΑΝΕΠΙΣΤΗΜΙΟΝ ΑΘΗΝΩΝ
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MARS Recoil Separator for Heavy Rare Isotope Studies*

Dispersive Image

Separation Stage I

Separation Stage II

D2   Q3   D1   Production Target

Wien Filter

K500 Beam

Final Achromatic Image

D3

Q2
Q1

Q4

Q5

PPAC1
Start T,X,Y

Rotatable Arm
Reaction Angle:
0°-12°

$B\rho = m\upsilon/Q$

MARS Acceptances:
Angular: 4 msr
Momentum: 4 %

Si Telescope
E_r ΔE

PPAC2
Stop T, X,Y

*G. A. Souliotis et al.,
Nucl. Instr. Methods B, 266, 4692 (2008)
and references therein

ΕΘΝΙΚΟΝ & ΚΑΠΟΔΙΣΤΡΙΑΚΟΝ
ΠΑΝΕΠΙΣΤΗΜΙΟΝ ΑΘΗΝΩΝ
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Reactions Studied with MARS

^{86}Kr (15MeV/u) + ^{64}Ni, ^{58}Ni   (**4º** and **7º** data) [1,2,3]

^{86}Kr (15MeV/u) + ^{124}Sn, ^{112}Sn   (**4º** and **7º** data) [1,2,3]

^{86}Kr (25MeV/u) + ^{64}Ni   (**2º** and **4º** data) [3,4,5]

^{86}Kr (25MeV/u) + ^{124}Sn, ^{112}Sn   (**4º** data)   [3,4,5]

^{40}Ar (15MeV/u) + ^{64}Ni, ^{58}Ni   (**4º** data) [6,7]

[[1] G.A. Souliotis, M. Veselsky et al., *Phys. Rev. C*, 84, 064607 (2011)
[2] P. Fountas, G.A. Souliotis et al., *Phys. Rev. C*, 90, 064613 (2014)
[3] G.A. Souliotis, M. Veselsky et al., *Phys. Lett. B* 543, 163 (2002)
[4] G.A. Souliotis, M. Veselsky et al., *Phys. Rev. Lett.* 91, 022701 (2003)
[5] O. Fasoula, G.A. Souliotis et al, arXiv: 2103.10688 (nucl-ex 2021)

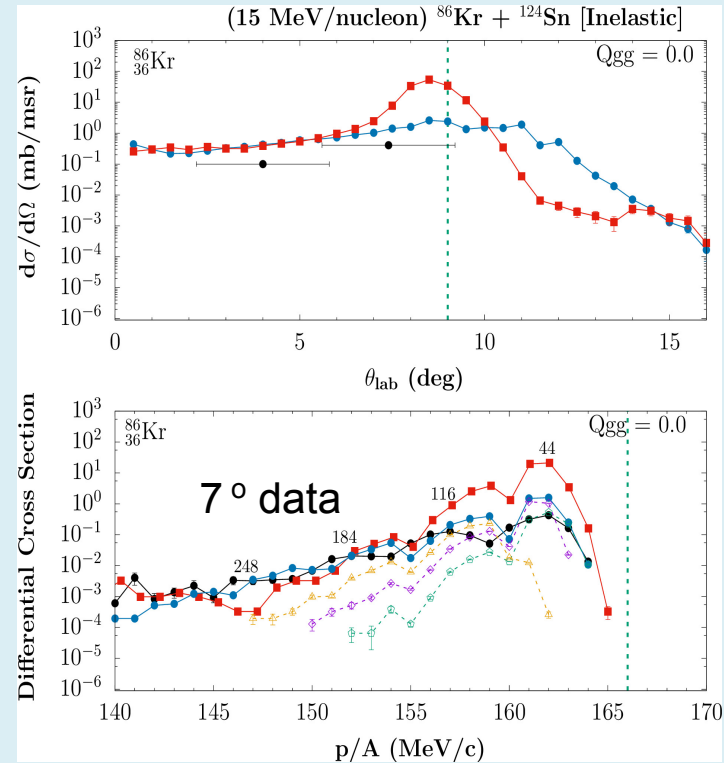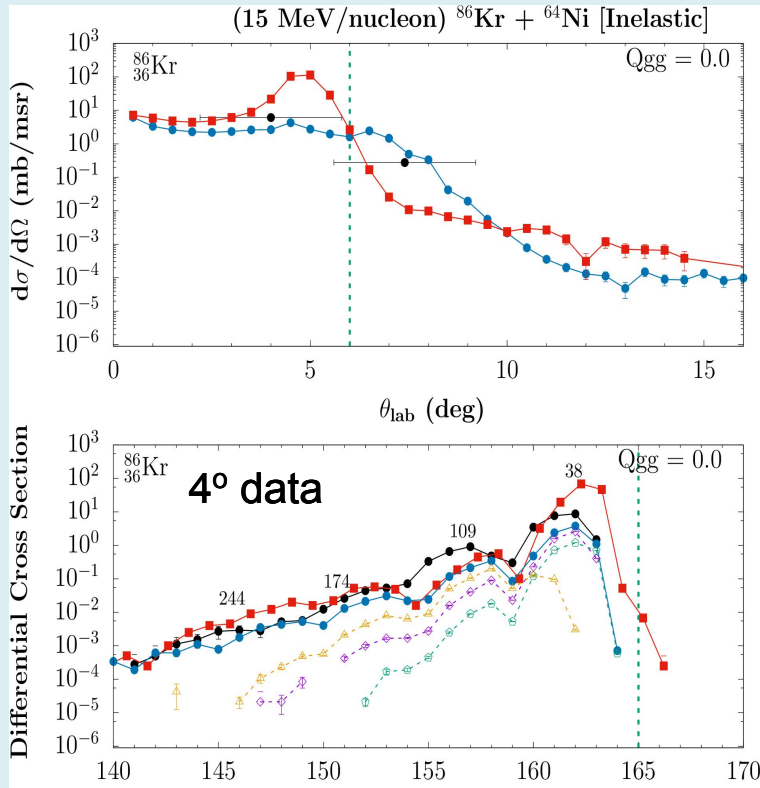[6] A. Papageorgiou, G.A. Souliotis et al., *J. Phys. G* 45, 095105 (2018)
[7] K. Palli, G.A. Souliotis et al., *Eur. Phys. J. WoC* 252, 07002 (2021)

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15 MeV/nucleon ⁸⁶Kr + ⁶⁴Ni / ¹²⁴Sn – Inelastic Channel

Angular and p/A Distributions
- ● Exp. Data
- ● DIT/Gemini
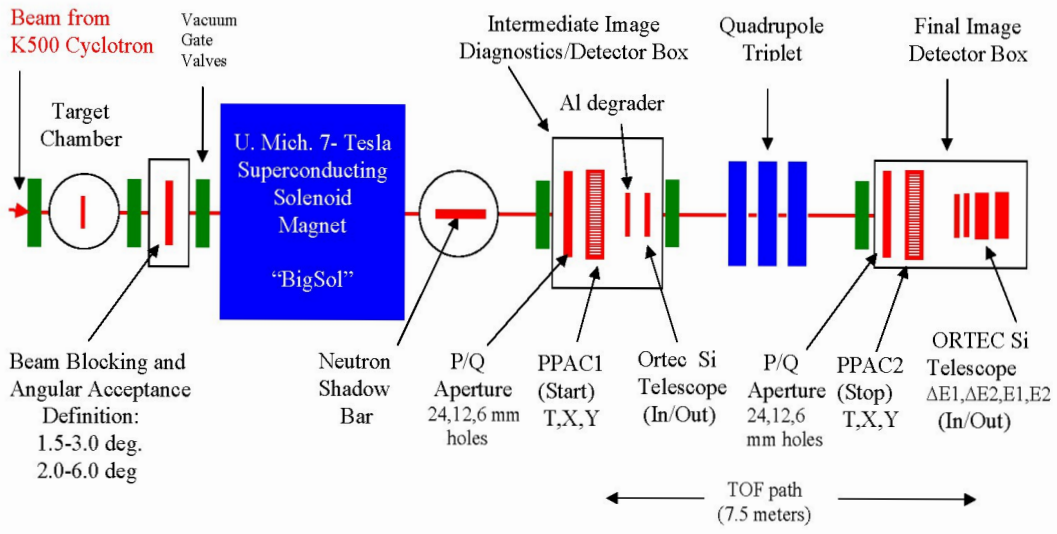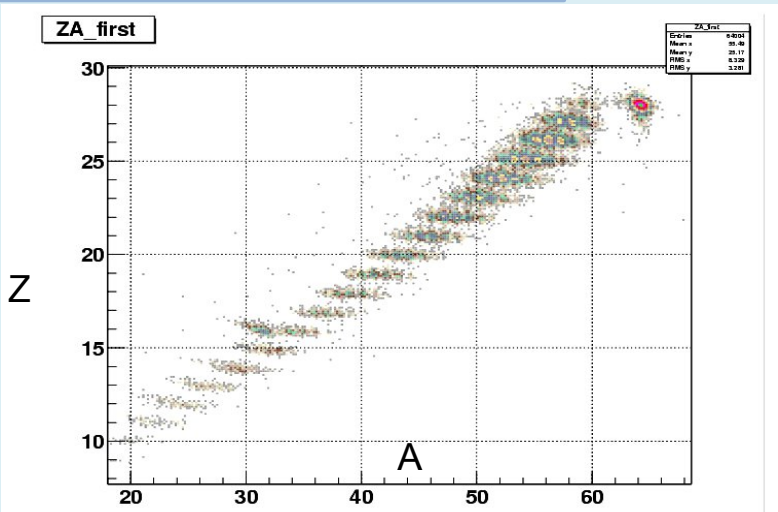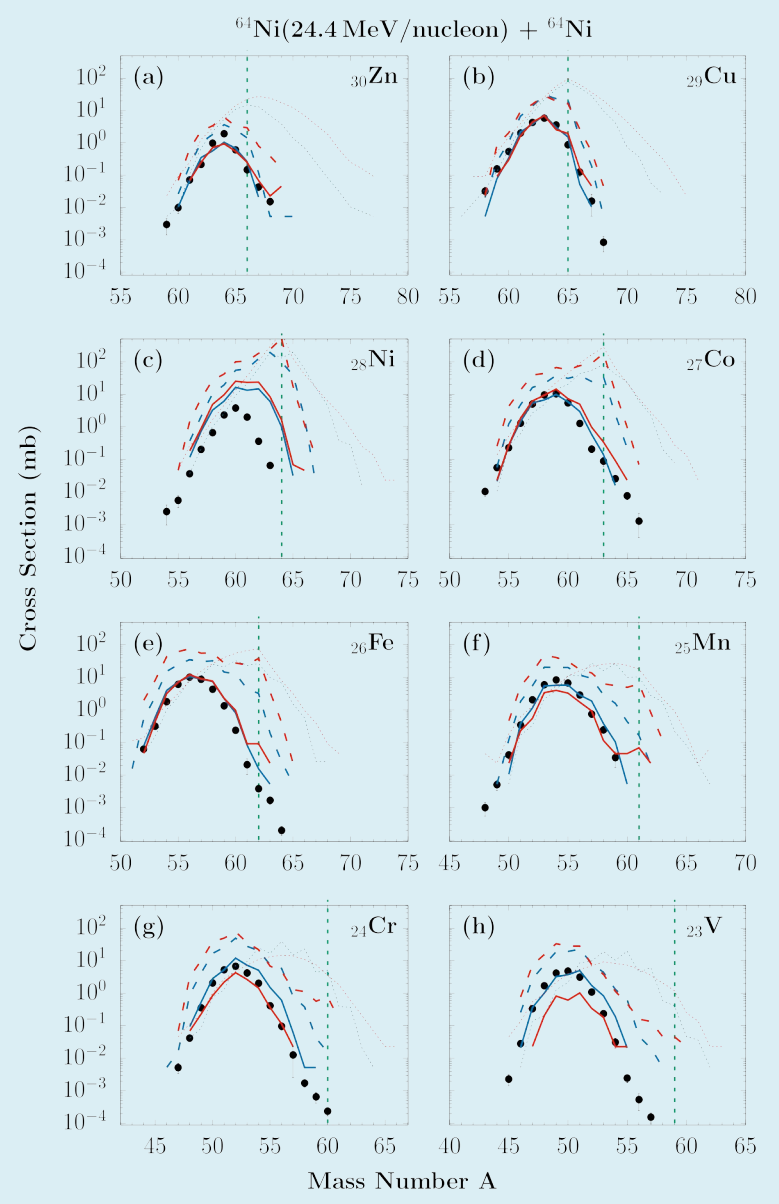- ■ CoMD/Gemini
- ★ Experimental points 4° and 7°

*Olga. Fasoula, G. A. Souliotis, et al., in preparation

DIT Quasiprojectile
(QP) Analysis
- ● QP – 0N
- ● QP – 1N
- ● QP – 2N

Beam from K500 Cyclotron

Vacuum Gate Valves

Intermediate Image Diagnostics/Detector Box

Al degrader

Quadrupole Triplet

Final Image Detector Box

Target Chamber

U. Mich. 7- Tesla Superconducting Solenoid Magnet

"BigSol"

Beam Blocking and Angular Acceptance Definition:
1.5-3.0 deg.
2.0-6.0 deg

Neutron Shadow Bar

P/Q Aperture 24,12,6 mm holes

PPAC1 (Start) T,X,Y

Ortec Si Telescope (In/Out)

P/Q Aperture 24,12,6 mm holes

PPAC2 (Stop) T,X,Y

ORTEC Si Telescope ΔE1,ΔE2,E1,E2 (In/Out)

TOF path (7.5 meters)

References
[1] G.A. Souliotis, D.V. Shetty, A. Keksis et al., Phys. Rev. C **73**, 024606 (2006).
[2] G.A. Souliotis, B. Stein, M. Veselsky et al., Nucl. Instum. Methods B **266**, 4692 (2008).

ZA_first

Z

A

$^{64}Ni(24.4\,MeV/nucleon) + ^{64}Ni$

Cross Section (mb)

Mass Number A

Eirini Kontogianni, G. A. Souliotis et al.,   (see poster}

MAGNEX Spectrometer at LNS

S800 Cyclotron Beam:
^{70}Zn (15 MeV/nucleon)
^{64}Ni target 1.18 mg/cm^2
$\theta_{MAGNEX} = 9^o$
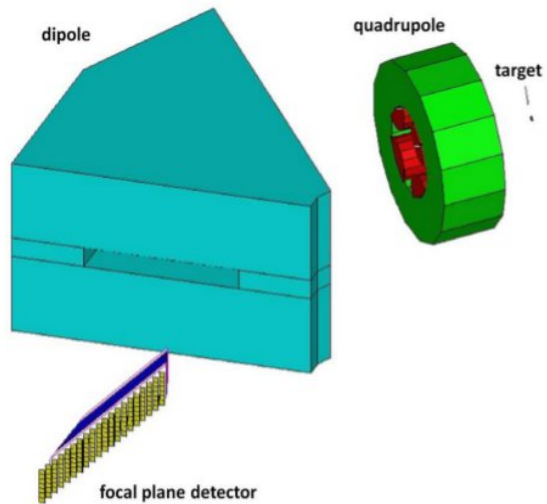
F. Cappuzzello, C. Agodi, D. Carbone and M. Cavallaro, Eur. Phys. J. A., 52:167 (2016)

G.A.. Souliotis, S. Koulouris, F. Cappuzzello, D. Carbone, A. Pakou et al., Nucl. Instrum. Methods A 1031 (2022) 166588

Angular distributions of ejectiles from ^{70}Zn (15 MeV/nucleon) + ^{64}Ni
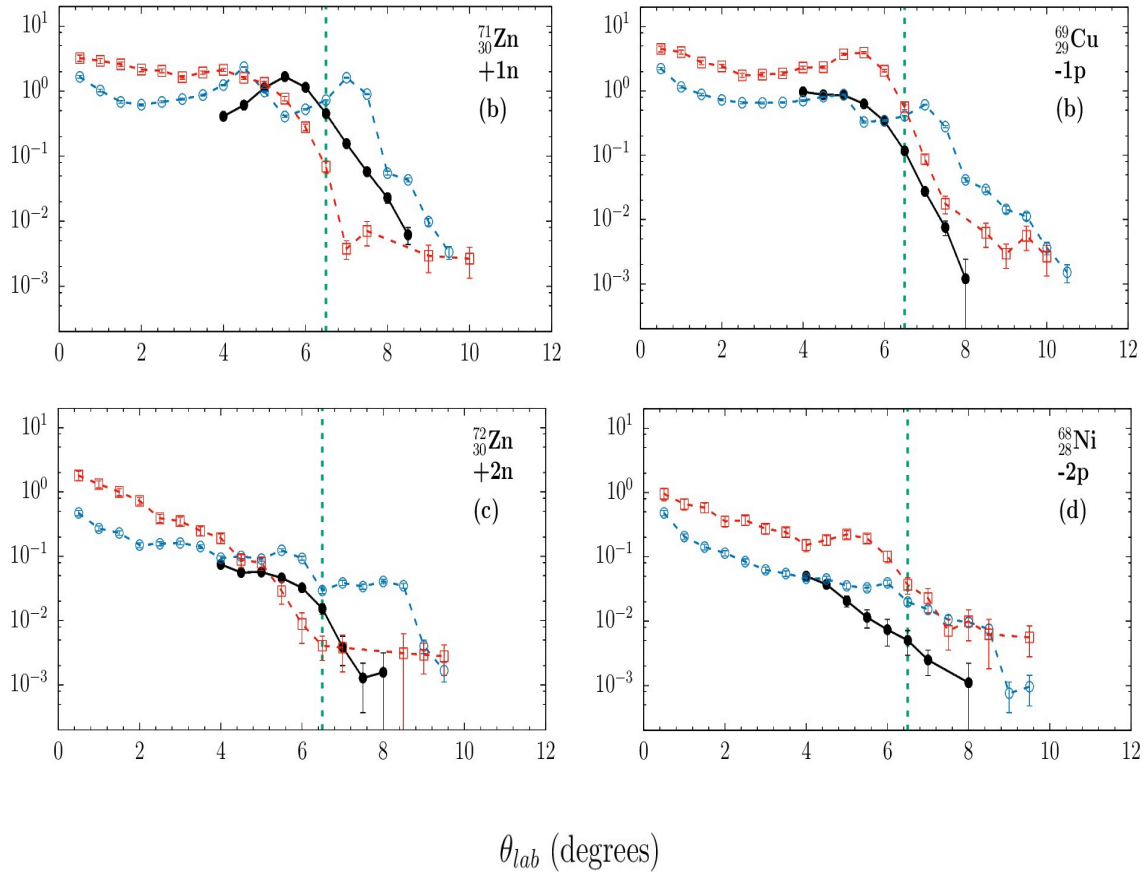
Experimental data: (closed black circles)
Calculations

DIT/GEMINI (dotted blue line)
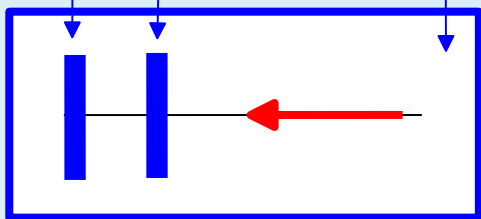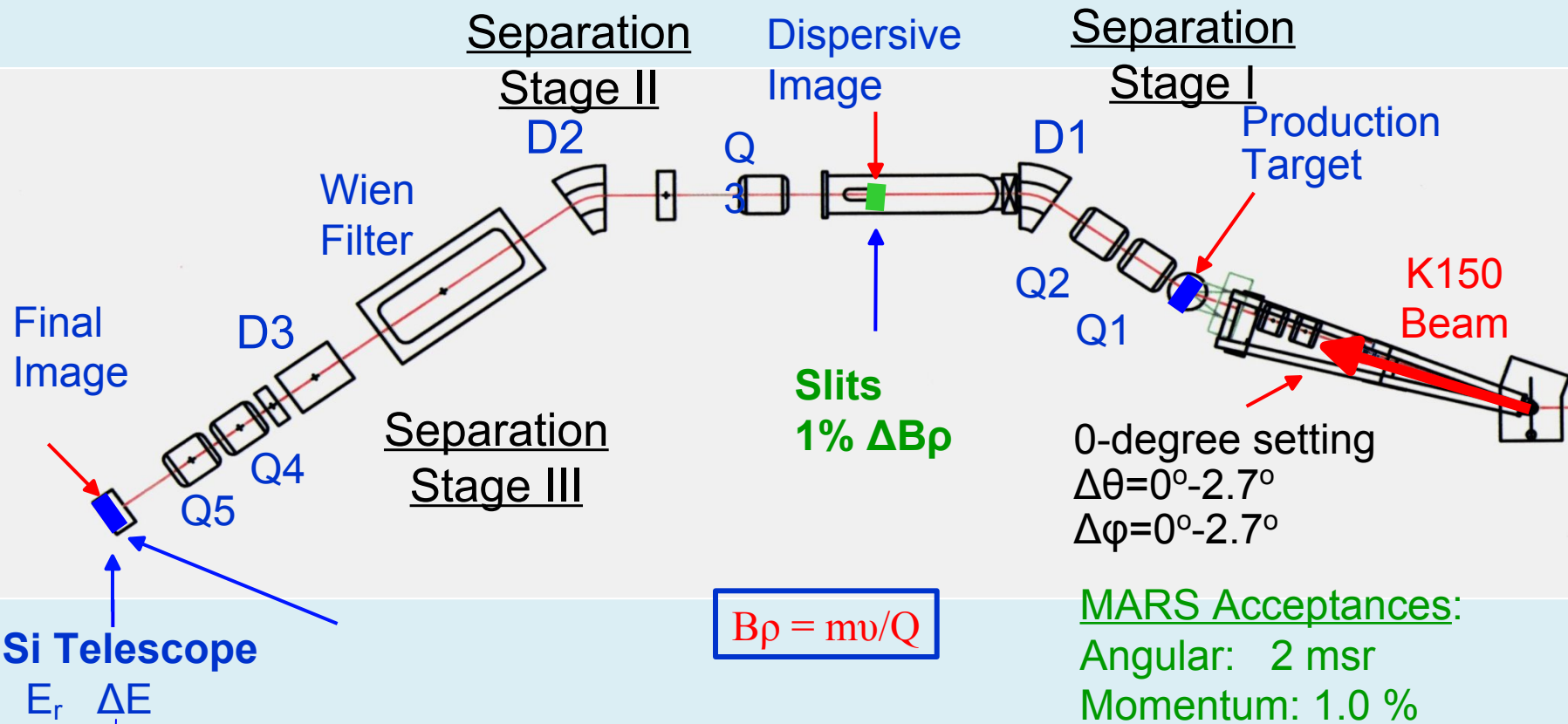
CoMD/GEMINI (dotted red line)

Dashed green line
Grazing Angle $\theta_{gr} = 6.5°$

θ_{lab} (degrees)

Stergios. Koulouris, G.A. Souliotis F. Cappuzzello, D. Carbone, A. Pakou et al., Phys. Rev. C 108, 044612 (2023)

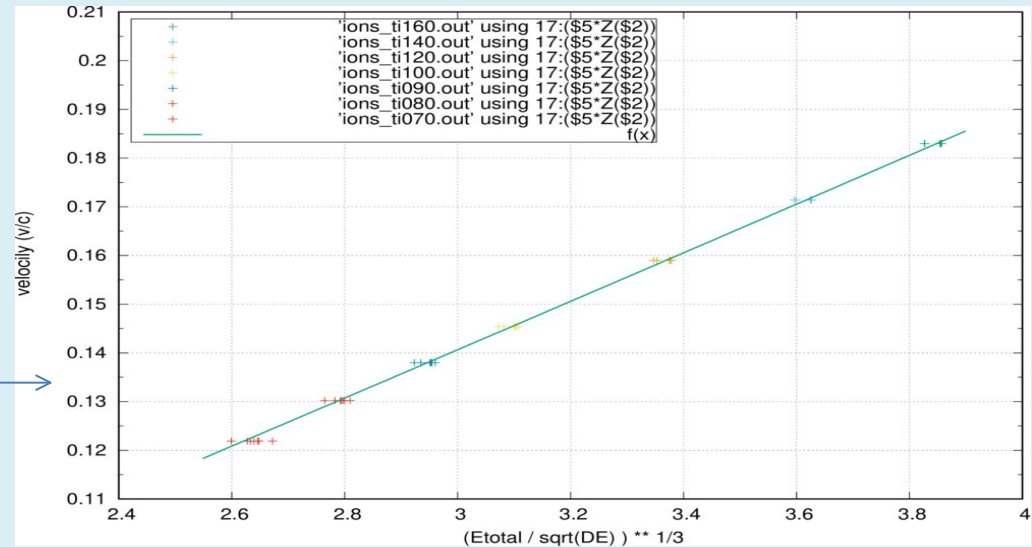**MARS Recoil Separator (standard 3-stage).** ^{48}Ti **beam from the K150 Cyclotron**

Separation
Stage II

Dispersive
Image

Separation
Stage I

D2

Q 3

D1

Production
Target

Wien
Filter

Q2

K150
Beam

Final
Image

Q1

D3

Slits
1% ΔBρ

0-degree setting
Δθ=0°-2.7°
Δφ=0°-2.7°

Separation
Stage III

Q4

Q5

$B\rho = mv/Q$

MARS Acceptances:
Angular: 2 msr
Momentum: 1.0 %

Si Telescope

E_r ΔE

Extracted quantities :

Energy loss (ΔE),

Total Energy E=ΔE +E$_r$

Velocity (from ΔE,E)

Mass-to-charge ratio: A/Q   Bρ = p/A * A/Q

Atomic Number Z   Z ~ υ ΔE$^{1/2}$
Ionic charge Q   Q ~ f(E, υ, Bρ)

Mass number A   A = A(Y)

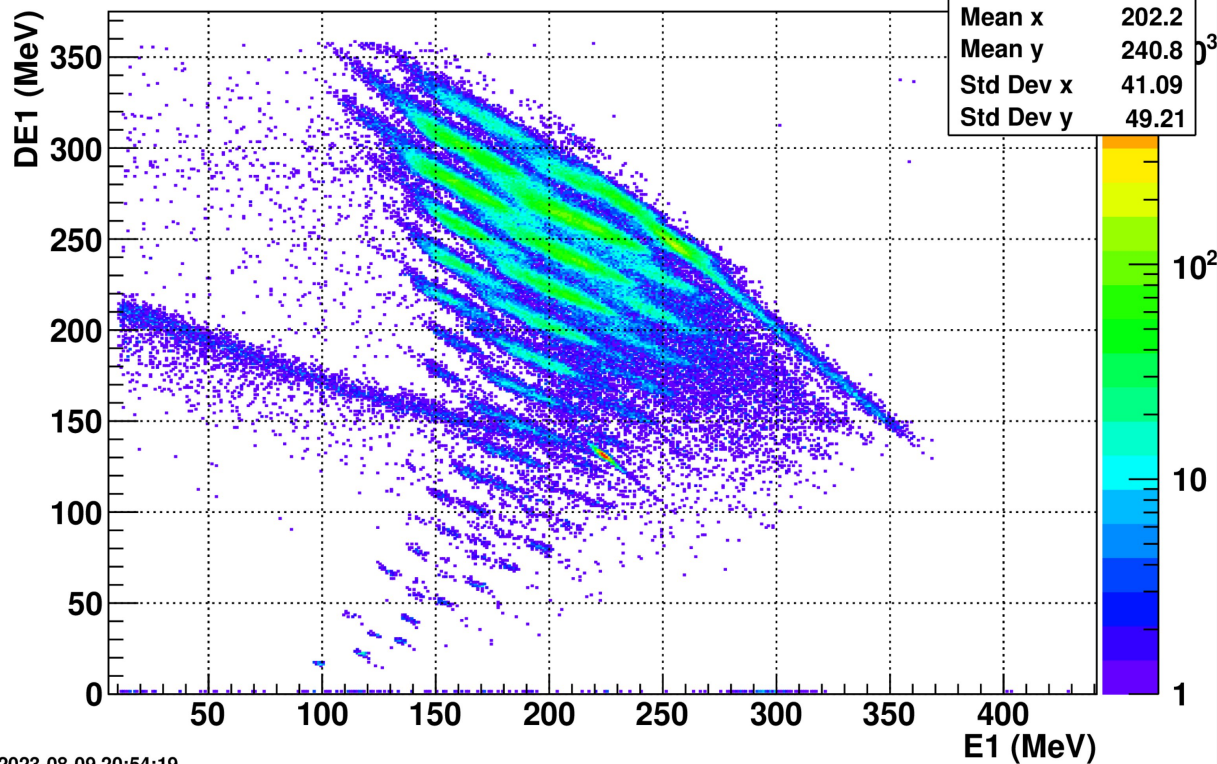**Reconstructed: Fragment Yield Distribution Y(Z, A, p/A)**

ΔE, Er Calibrations

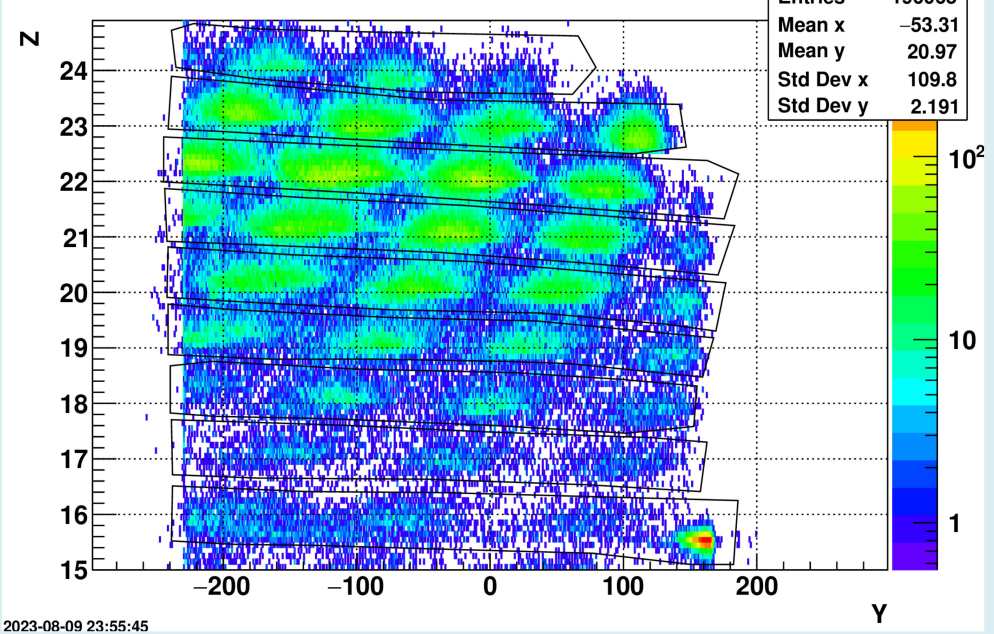Energy loss   ΔE

Residual Energy Er

Total Energy
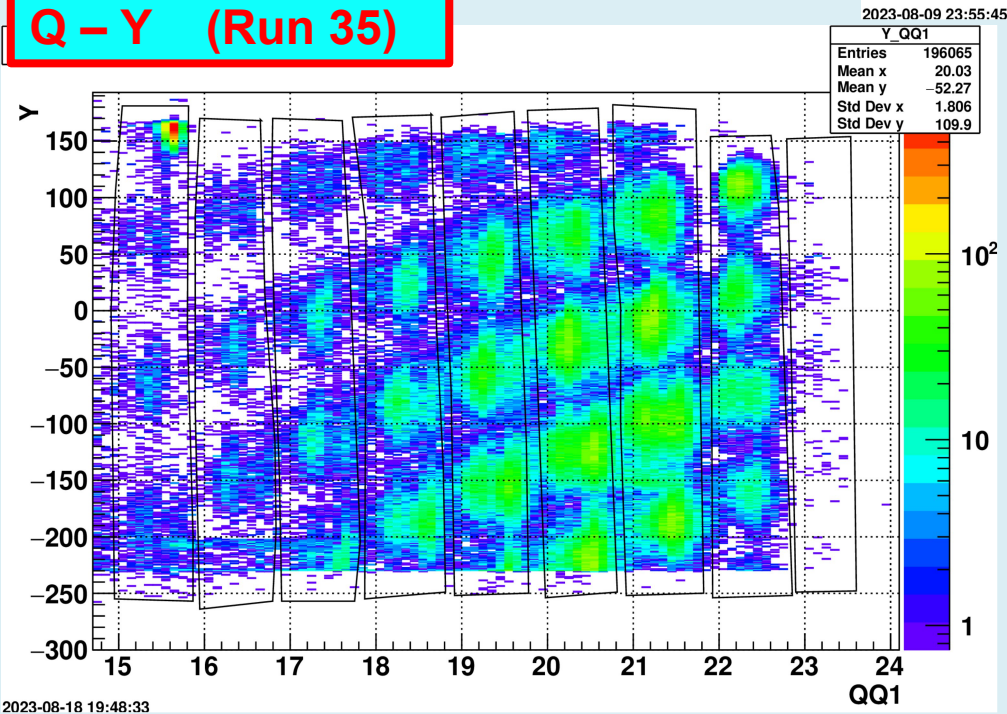
Z and Q separation and gating. Mass identification

Z reconstruction
Q reconstruction

Correlated Z and Q with the Y
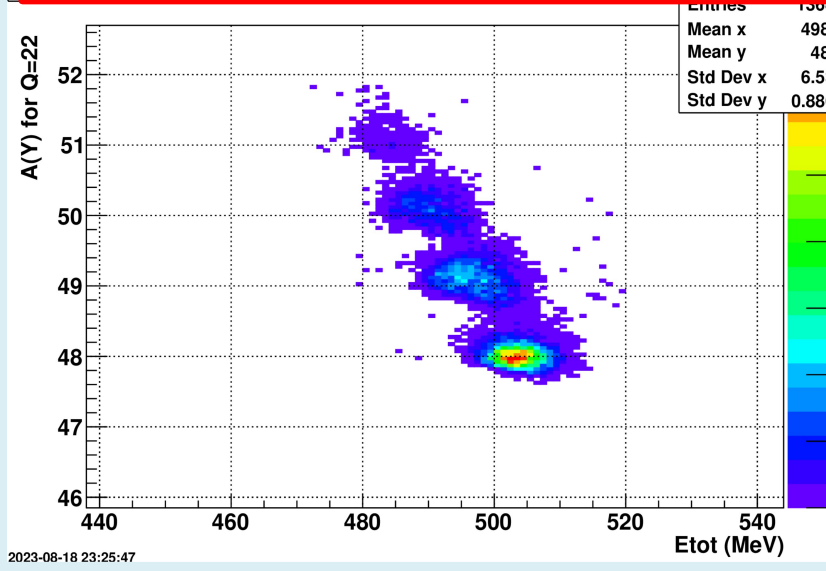position at the tail of MARS
Set Z and Q gates !

Z – Y   (Run 35)

Z_Y	
Entries	196065
Mean x	−53.31
Mean y	20.97
Std Dev x	109.8
Std Dev y	2.191

2023-08-09 23:55:45

Q – Y   (Run 35)

Y_QQ1	
Entries	196065
Mean x	20.03
Mean y	−52.27
Std Dev x	1.806
Std Dev y	109.9

2023-08-18 19:48:33

Mass for Z=23 and Q=22   (Run 35)

Entries	13...
Mean x	498...
Mean y	48...
Std Dev x	6.5...
Std Dev y	0.88...

2023-08-18 23:25:47

Yield distributions: Data, Calculations: 48Ti (11.1 MeV/u) + ^{48}Ti

(11.1 MeV/nucleon) ^{48}Ti+^{48}Ti
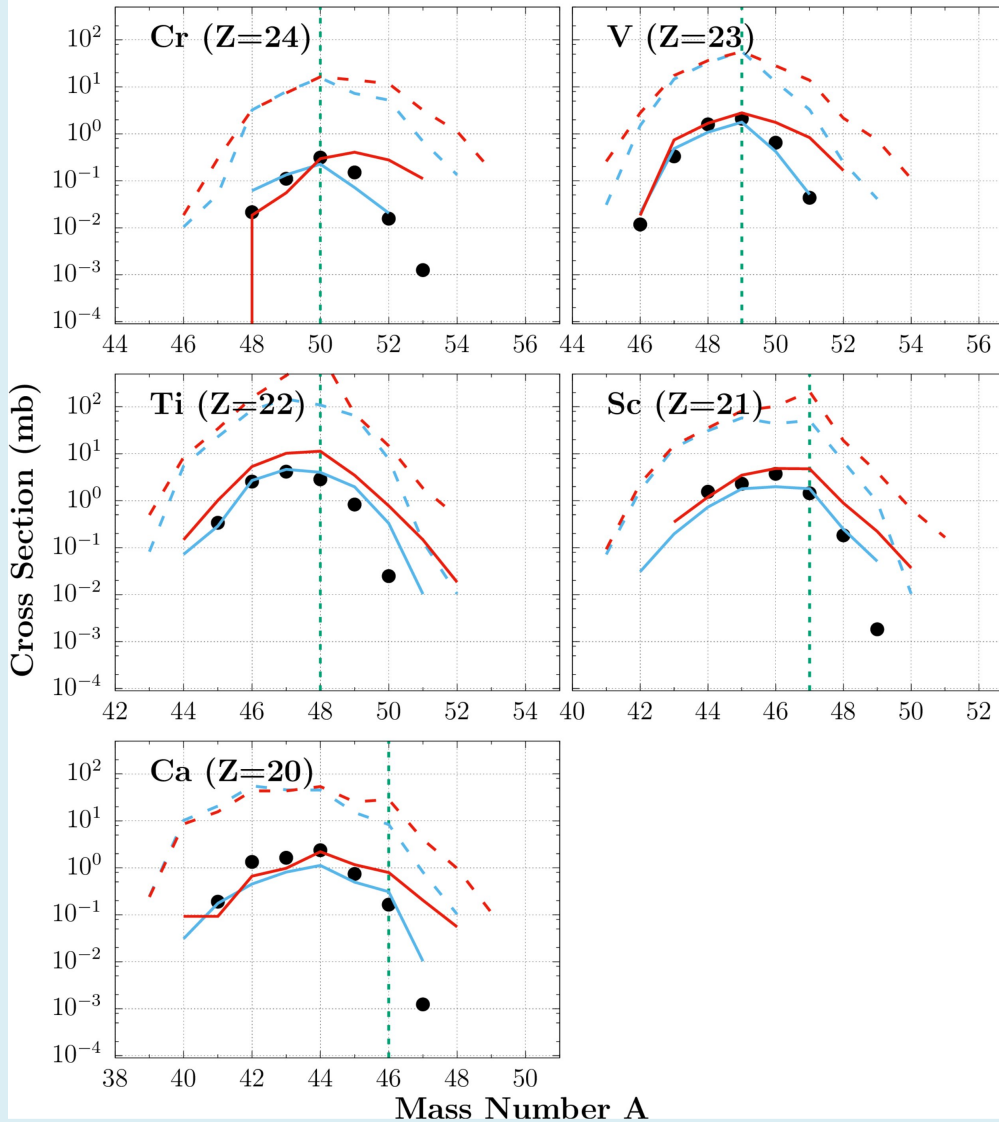
- • ^{48}Ti+^{48}Ti(11.1 MeV/u) exp. data

- - - - CoMD/GEM (total)

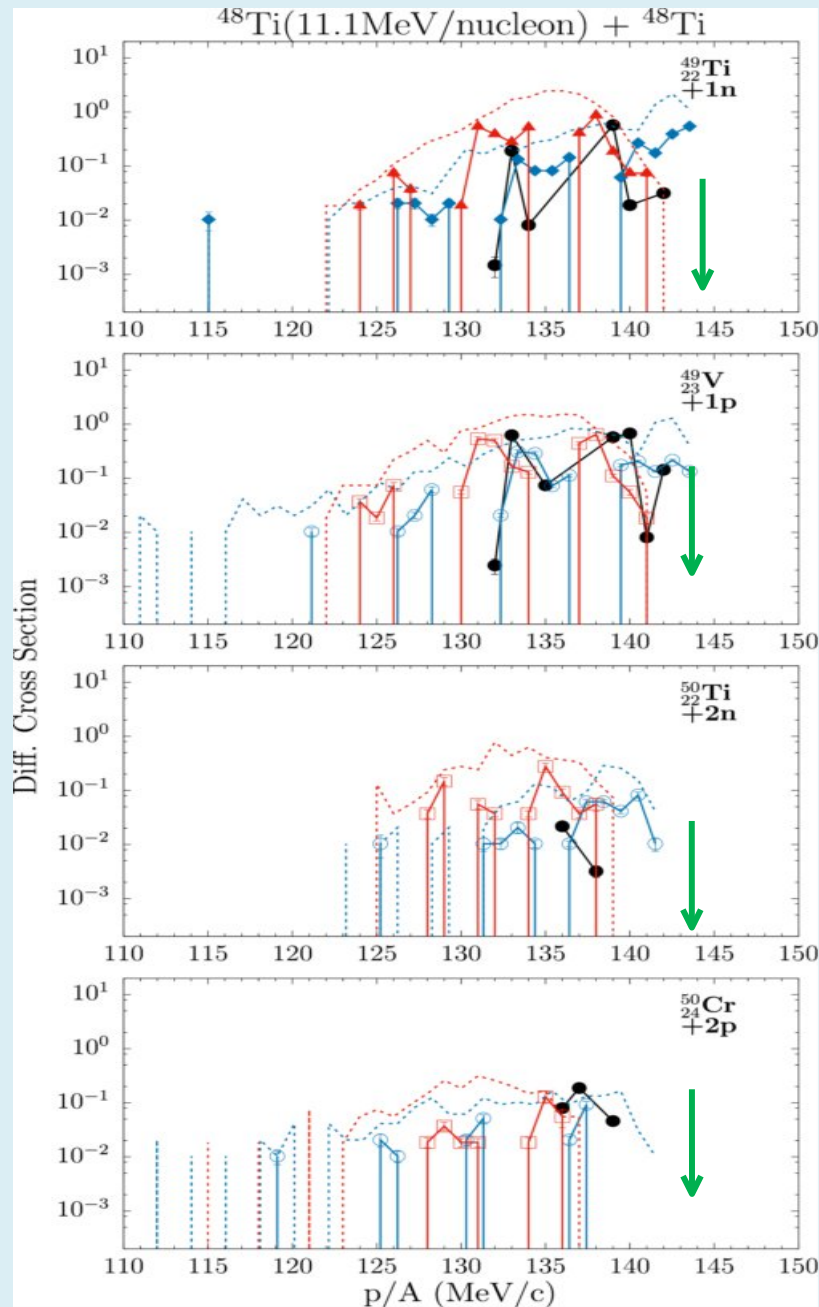- —— CoMD/GEM with angular + BRHO filter

- -- - - DIT/GEM (total)

- ——-DIT/GEM with angular + BRHO filter

Angular acceptance: 0º-2.7º

⁴⁸Ti(11.1MeV/nucleon) + ⁴⁸Ti

- **⁴⁸Ti+⁴⁸Ti(11.5 MeV/u) exp. data**

- - - - **CoMD/GEM (total)**

—— **CoMD/GEM with angular + BRHO filter**

- - - **DT/GEM (total)**

—— **DIT/GEM with angular + BRHO filter**

Angular acceptance: 0°-2.7°

Beam: p/A = 144. MeV/c

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^{48}Ti(11.1MeV/nucleon) + ^{48}Ti

$^{48}_{21}$Sc
−1p,+1n

$^{48}_{23}$V
+1p,−1n

Diff. Cross Section

p/A (MeV/c

- ^{48}Ti+^{48}Ti(11.5 MeV/u) exp. data

- - - - CoMD/GEM (total)

———— CoMD/GEM with angular + BRHO filter
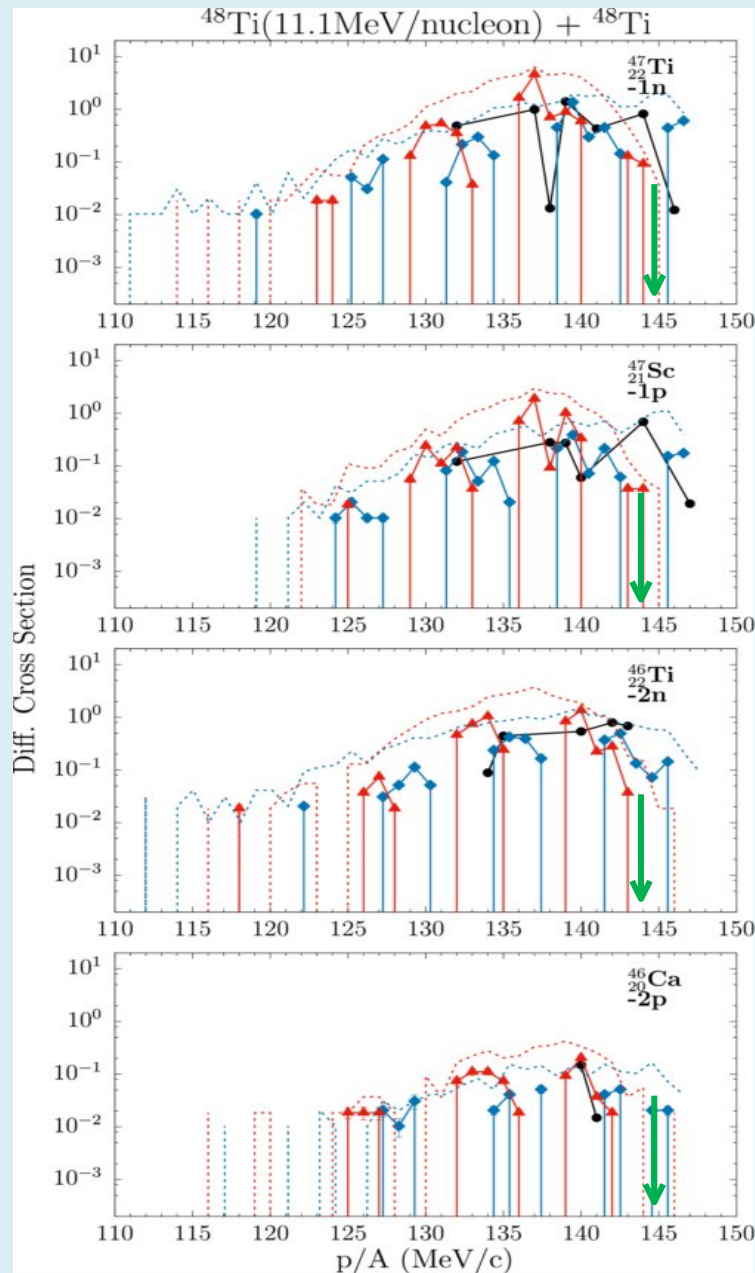
- - - -DT/GEM (total)

———-DIT/GEM with angular + BRHO filter

Angular acceptance: 0°-2.7°

Beam: p/A = 144. MeV/c

The filled points from the calculations are to the measured data (black filled points).

ΕΘΝΙΚΟΝ & ΚΑΠΟΔΙΣΤΡΙΑΚΟΝ
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p/A distribution: 48Ti (11.5 MeV/u) + ^{48}Ti

- ^{48}Ti+^{48}Ti(11.5 MeV/u) exp. data

-- - - CoMD/GEM (total)

—— CoMD/GEM with angular + BRHO filter

- - - - DT/GEM (total)

—— DIT/GEM with angular + BRHO filter

Angular acceptance: 0°-2.7°

Beam: p/A = 144. MeV/c

Summary - Discussion

Systematic studies of peripheral collisions with a variety of beams, targets and spectrometers at energies below the Fermi energy.

Recent measurements and analysis of ^{48}Ti(11.5MeV/u) + ^{48}Ti

Extraction of cross sections, momentum p/A distributions and angular distributions. Binary kinematical analysis.

Detailed calculations and analysis with DIT and CoMD models.
Details of the mechanisms to be disentangled:
– Nucleon exchange
– Charge exchange
– pair transfer (nn,pp)
– Cluster transfer (mainly alpha)

Pathways to neutron rich isotopes

Collaborations and Acknowledgments

- **Professor Sherry Yennello and her group**
  Texas A&M University, Cyclotron Institute

- **Professor Aldo Bonasera and his group**
  Texas A&M University, Cyclotron Institute

- **Professor Athena Pakou and her group**
  University of Ioannina, Ioannina, Greece

- **Professor Francesco Cappuzzello and his group**
  University of Catania and LNS/INFN, Catania, Italy

University of Athens Nuclear Chemistry Group Members:

- **Olga Fasoula (PhD Candidate)**
- **Stergios Koulouris (PhD Candidate)**
- **Chryssi Gianitsa (MSc candidate)**
- **Konstantinos Gatzogias (MSc Candidate)**
- **Eirini Kontogianni (MSc candidate)**
- **Eleftheria Travlou (senior undergraduate student)**
- **Nikos Korakis (senior undergraduate student)**

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Thank you !

Momentum Distributions

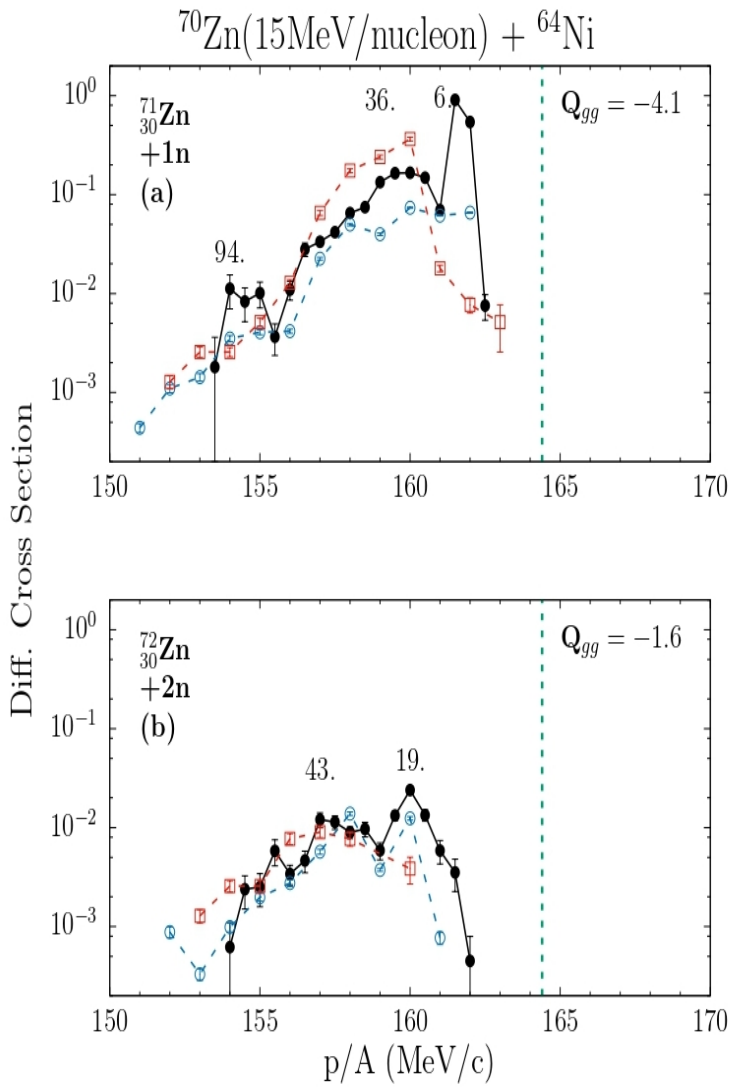$^{70}Zn(15MeV/nucleon) + ^{64}Ni$

Calculations
DIT/GEMINI (dotted blue line,   )
CoMD/GEMINI   (dotted   red
line,   )

Vertical dashed green line (   ) —
p/A of the projectile

$\Delta\theta = 4 - 6^o$

Numbers above peaks: Total
Excitation Energy (in MeV) from
binary   kinematics   from   the
corresponding p/A values.

Diff. Cross Section: $d^2\sigma$ / $d\Omega d(p/A)$
[mb / (MeV/c) msr]

eral feature of the momentum

per nucleon distributions

Quasielastic peak

Direct Processes

Broad region (lower

values of P/A)

Deep Inelastic

Processes/

Multinucleon Transfer

Reactions
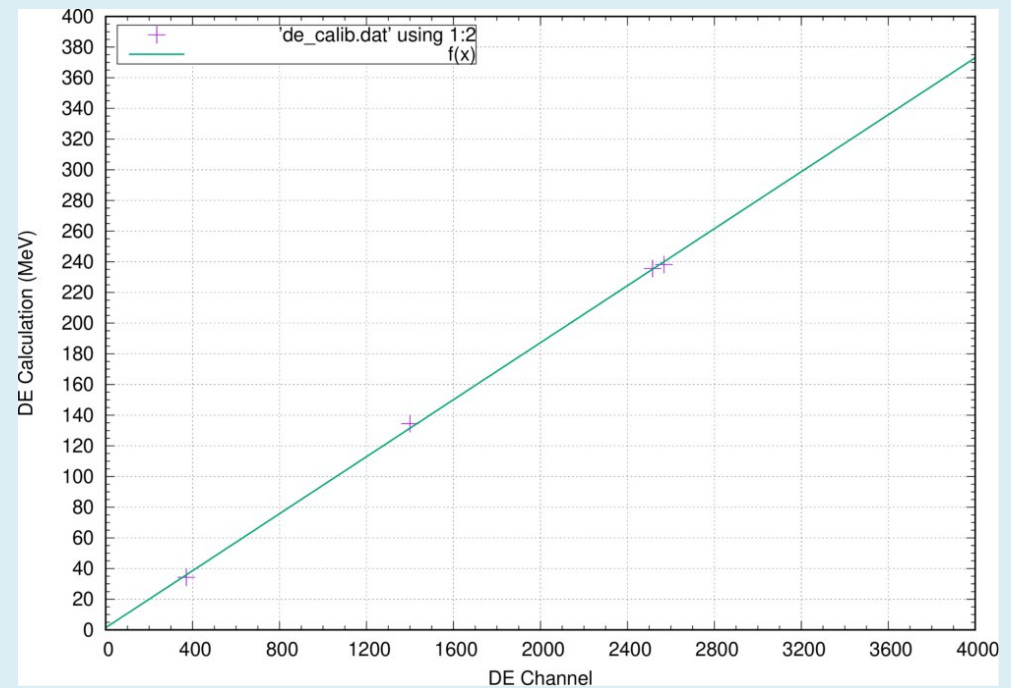
Momentum per nucleon distributions
of ejectiles from nucleon pickup channels from the
reaction of ^{70}Zn (15 MeV/nucleon) + ^{64}Ni.

S. Koulouris, G.A. Souliotis F. Cappuzzello, D. Carbone, A. Pakou et al., Phys. Rev. C 108, 044612 (2023), doi:
10.1103/PhysRevC.108.044612

ΔE, Er Calibrations

Energy loss   ΔE

Residual Energy Er
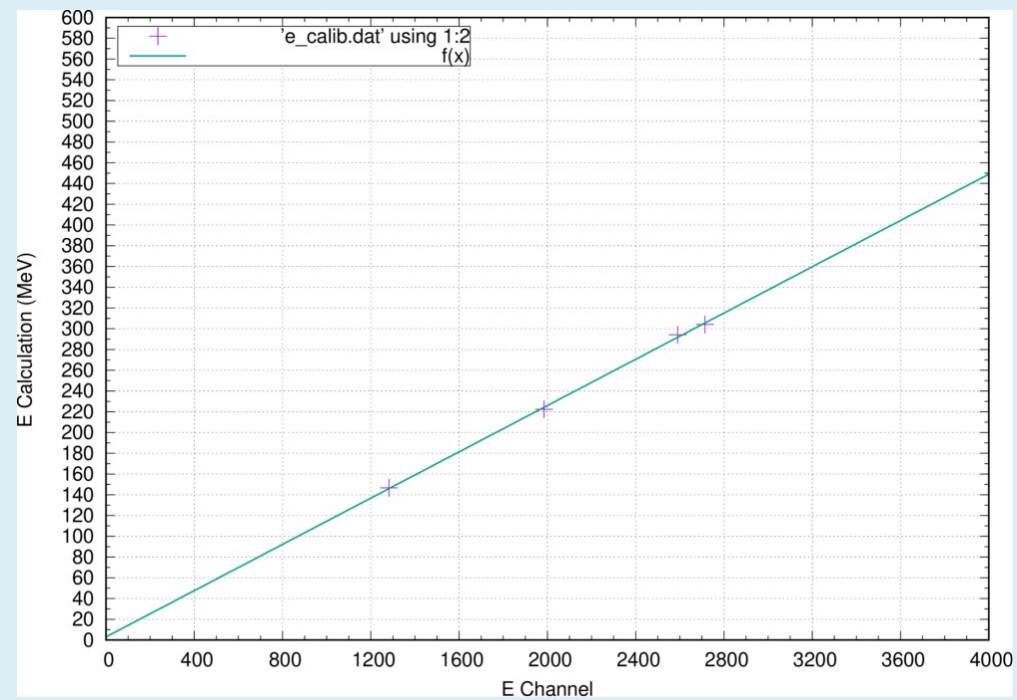
Total Energy

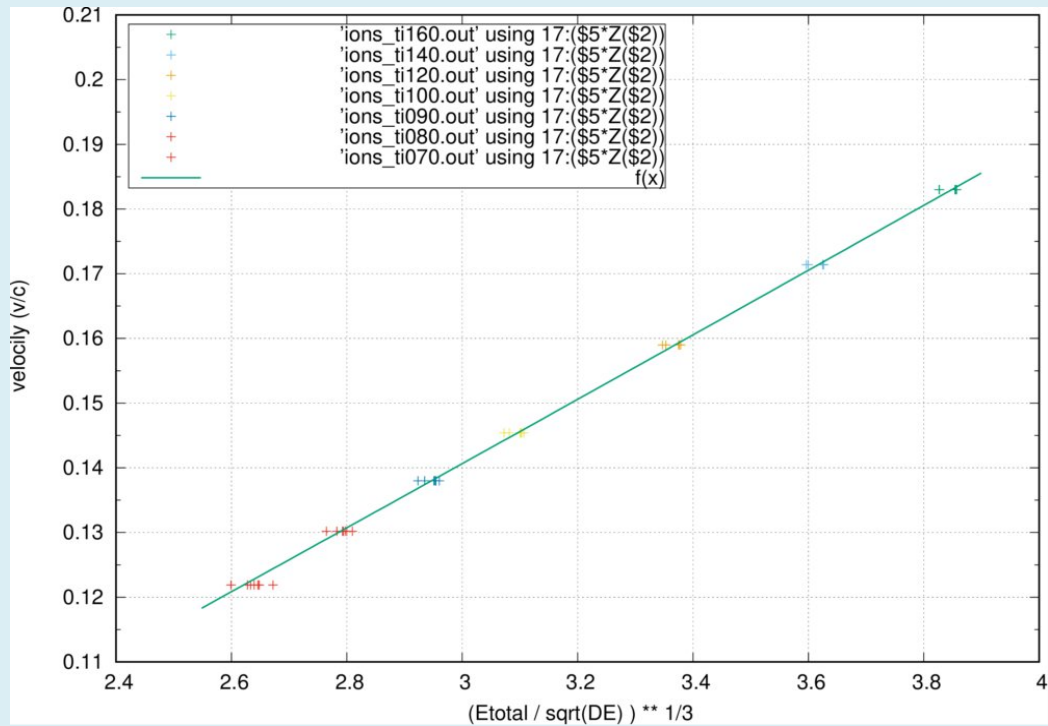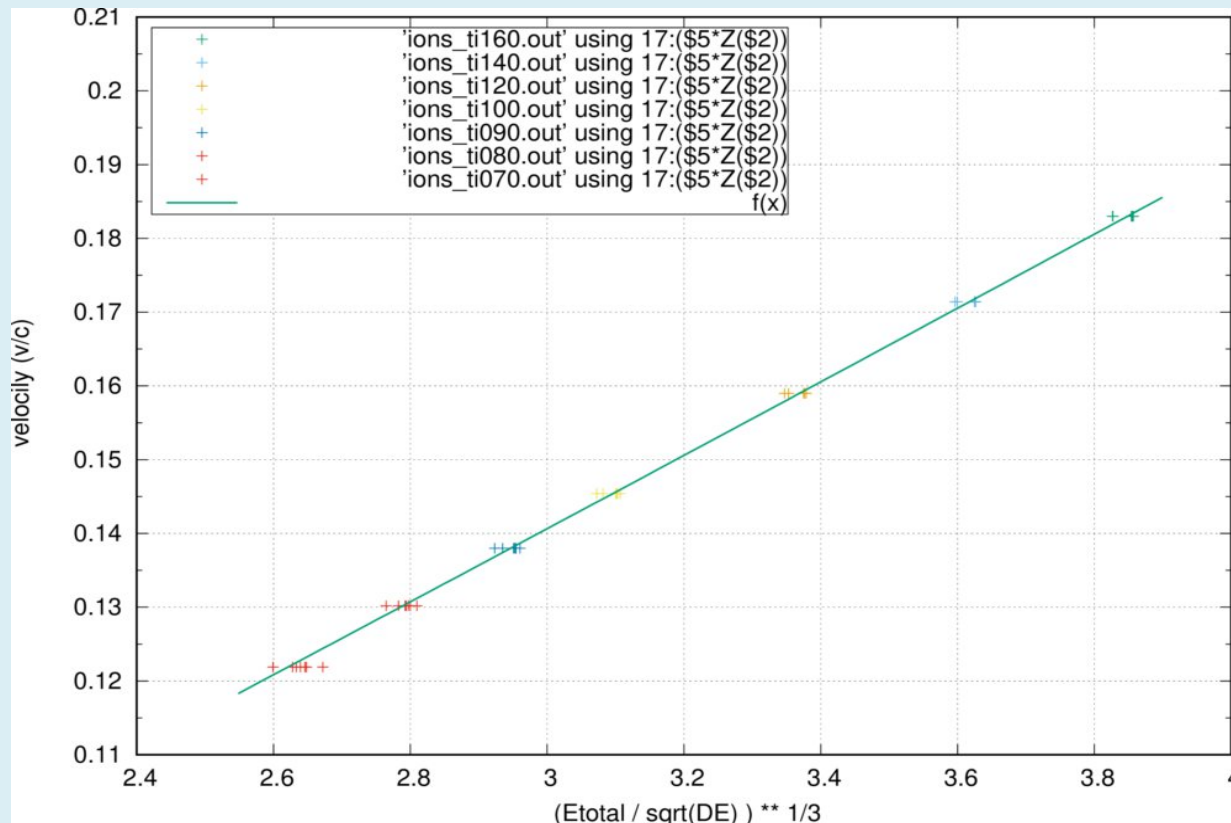## Calibrations

<u>Extracted physical quantities :</u>

Velocity (TOF) from   Energy loss and Total Energy
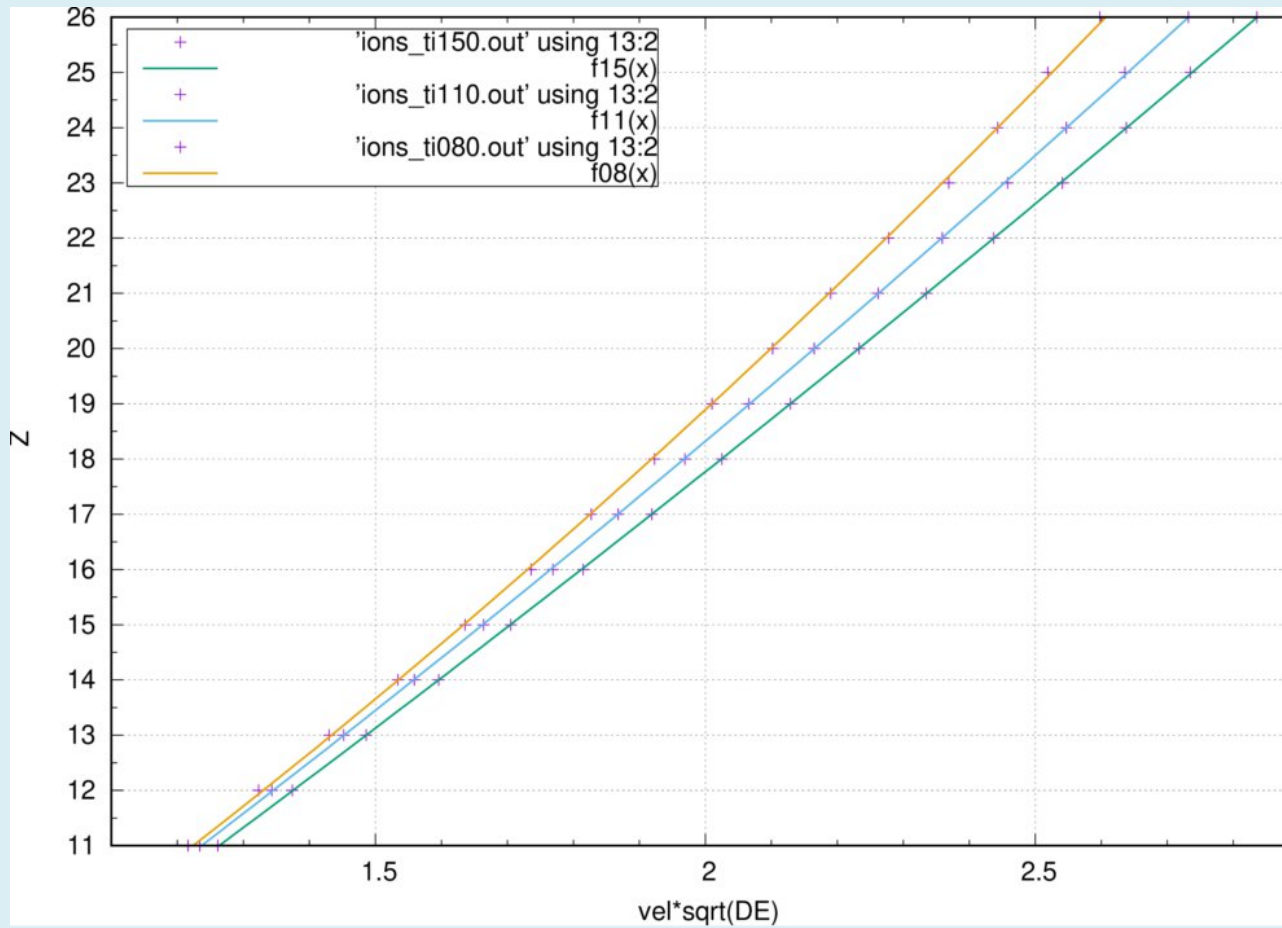
Extracted physical quantities :
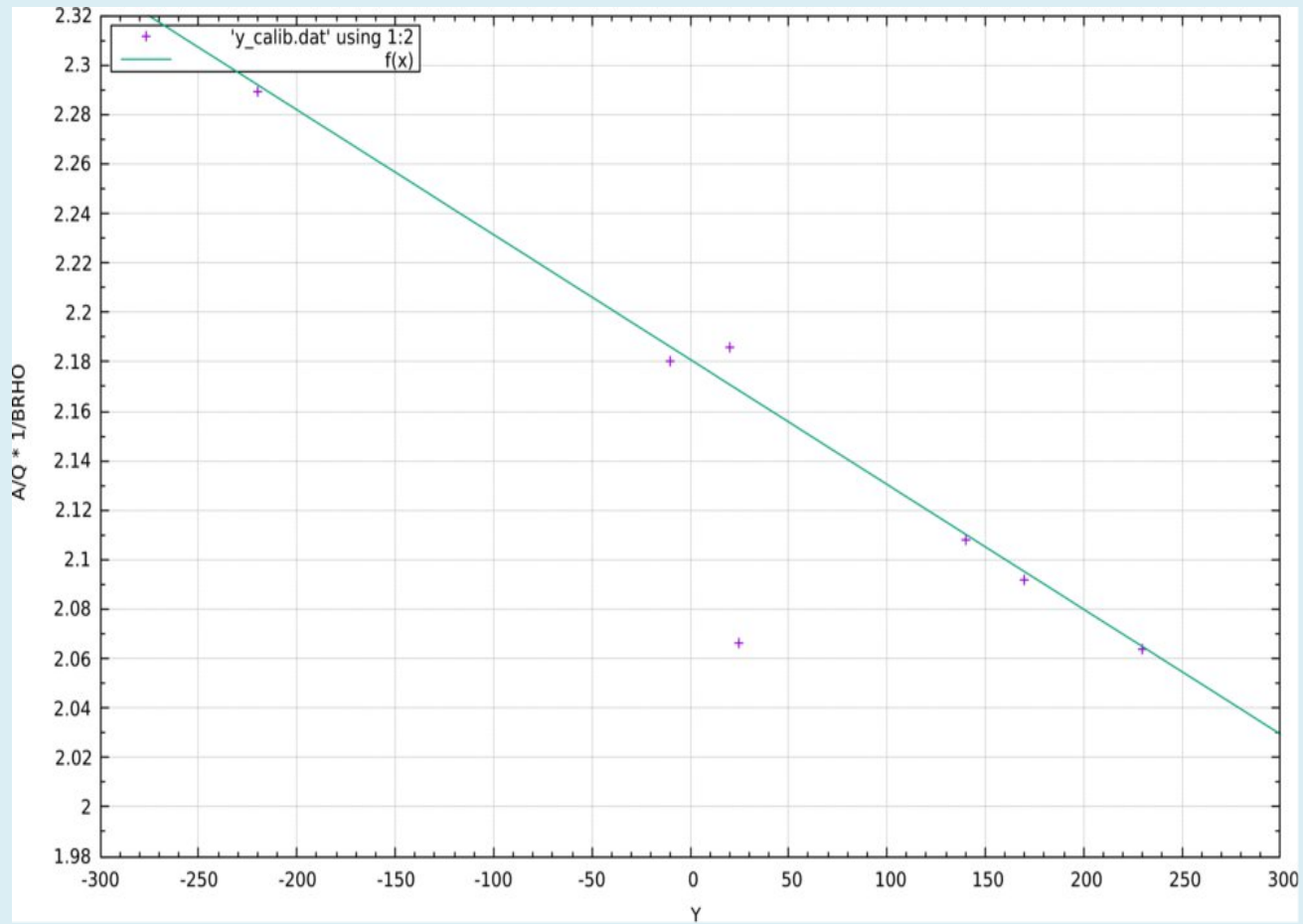
Velocity (TOF) from   Energy loss and Total Energy

Y   Calibration

Mass ID

Z=24

Run 35