Multinucleon Transfer Studies of the ^{70}Zn (15 MeV/nucleon) + ^{64}Ni System

S. Koulouris[1], G. A. Souliotis[1], F. Cappuzzello[2,3], D. Carbone[3], A. Pakou[4], C. Agodi[3], G. Brischetto[2,3], S. Calabrese[3], M. Cavallaro[3], I. Ciraldo[2,3], O. Fasoula[1], O. Sgouros[3], V. Soukeras[3], A. Spatafora[2,3], D. Torresi[3], M. Veselsky[5]

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

[2] Dipartimento di Fisica e Astronomia "Ettore Majorana", Universita di Catania, Italy

[3] Laboratori Nazionali del Sud, INFN, Catania, Italy

[4] Department of Physics and HINP, The University of Ioannina, Ioannina, Greece

[5] Institute of Experimental and Applied Physics, Czech Technical University, Prague, Czech Republic

7th Hellenic Institute Of Nuclear Physics Workshop
31st May - 1st June 2024, Ioannina, Greece

HELLENIC REPUBLIC
National and Kapodistrian University of Athens

UNIVERSITY OF IOANNINA

INFN

HINP
ΕΙΠΦ

Outline of the Talk

- Introduction
- Experimental setup
- Particle Identification Procedure
- Presentation of experimental results - Comparison with theoretical calculations
- Summary and next steps

Motivation of present work

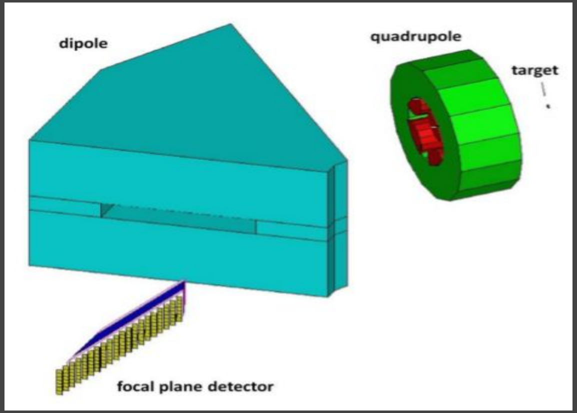
- Production and identification of neutron-rich nuclides ⟶ One of the main concurrent challenges of the nuclear community
- Systematic studies of production of neutron-rich nuclides far from the line of beta stability in peripheral collisions below the Fermi energy (15-20 MeV/nucleon)
- Multinucleon transfer and deep inelastic collisions mostly dominate this energy regime
- A large acceptance spectrometer is essential ⟶ Efficient collection of the produced fragments

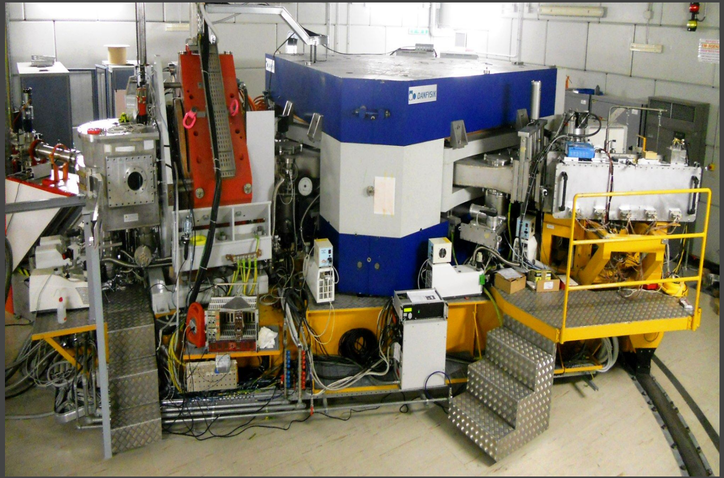
S. Heinz, H. M. Devaraja, Eur. Phys. J. A., 58:114 (2022)
M. Thoennessen, Rep. Prog. Phys. 76, 056301 (2013)

MAGNEX Spectrometer at INFN/LNS, Catania

S800 Cyclotron Beam:
^{70}Zn (15 MeV/nucleon)
^{64}Ni target 1.18 mg/cm^2
$\theta_{MAGNEX} = 9^o$

The ejectiles passed through a 6 μm Mylar foil and were detected by the spectrometer's FPD





G.A. Souliotis, S. Koulouris, F. Cappuzzello, D. Carbone, A. Pakou et al., Nucl. Instrum. Methods A 1031 (2022) 166588
F. Cappuzzello, C. Agodi, D. Carbone and M. Cavallaro, Eur. Phys. J. A., 52:167 (2016)

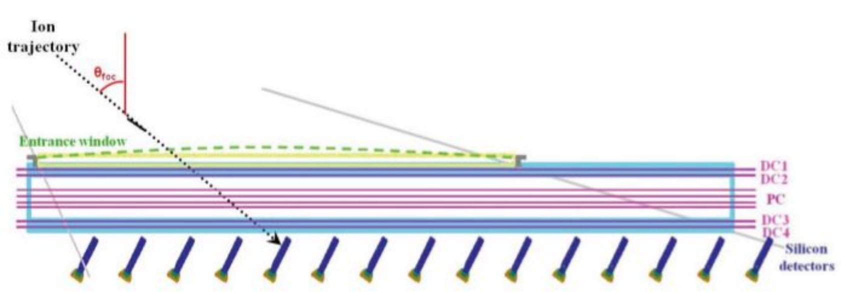
MAGNEX Spectrometer

Focal Plane Detector (FPD)

- Gas-filled hybrid detector (isobutane of 40 mbar pressure)
- Wall of 60 large silicon detectors (7 Si detectors were used for this experiment)
- Proportional Drift Chamber spanning at six sequential planes

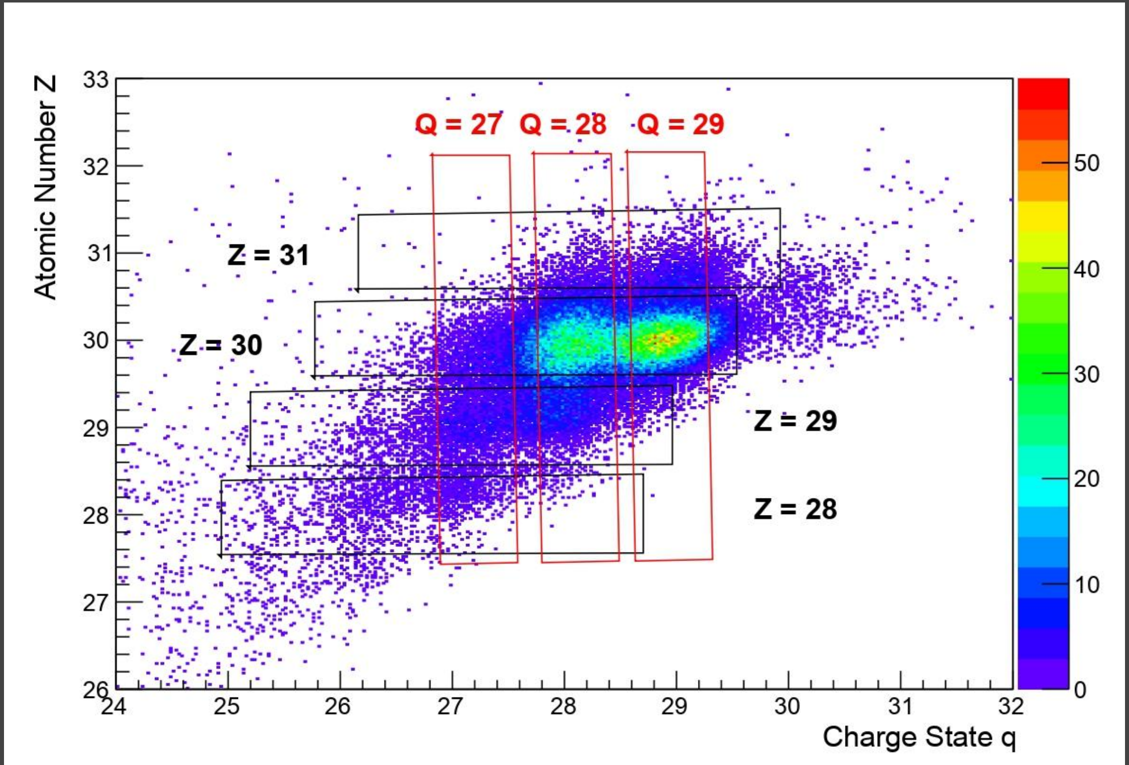
↓

- Determination of horizontal and vertical coordinates
- Determination of the angles θ and φ of the ion's trajectory
- Energy loss of the reaction products in the gas and the residual energy of the fragments in the Si detectors



F. Cappuzzello, C. Agodi, D. Carbone and M. Cavallaro, Eur. Phys. J. A., 52:167 (2016)
D. Torresi, O. Sgouros, V. Soukeras et al., Nuclear Inst. and Methods in Physics Research, A 989 (2021) 164918

Z vs Q correlation



Reconstructed Z vs charge state q correlation of ejectiles from the reaction ^{70}Zn (15 MeV/nucleon) + ^{64}Ni corresponding to the same silicon detector.

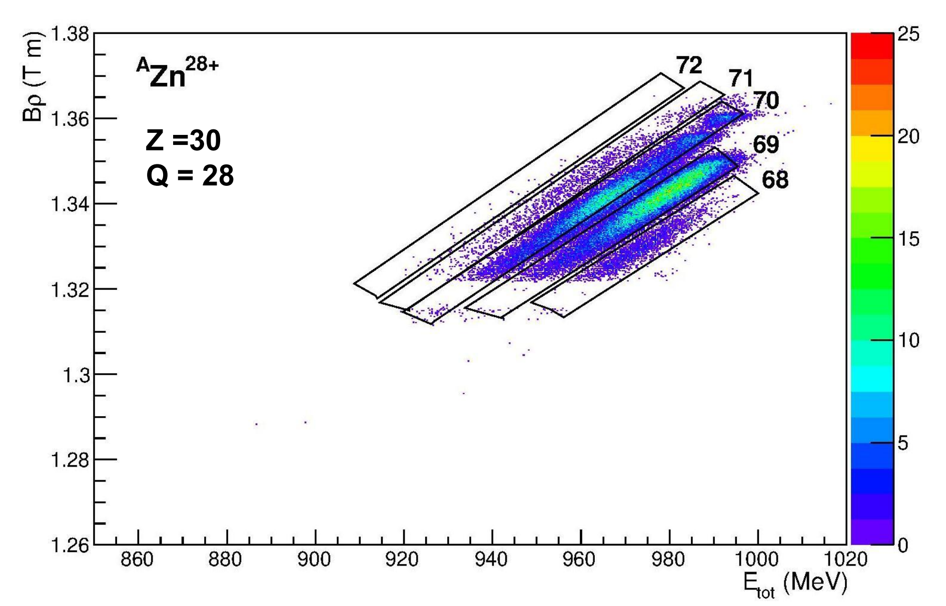
Graphical contours are shown on each band corresponding to the atomic numbers Z (horizontal bands) and the ionic charge states q (vertical bands) of the ejectiles.

G.A. Souliotis, S. Koulouris, F. Cappuzzello, D. Carbone, A. Pakou et al., Nucl. Instrum. Methods A 1031 (2022) 166588
S. Koulouris, G.A. Souliotis et al., EPJ Web of Conferences **252**, 07005 (2021)

Mass Determination

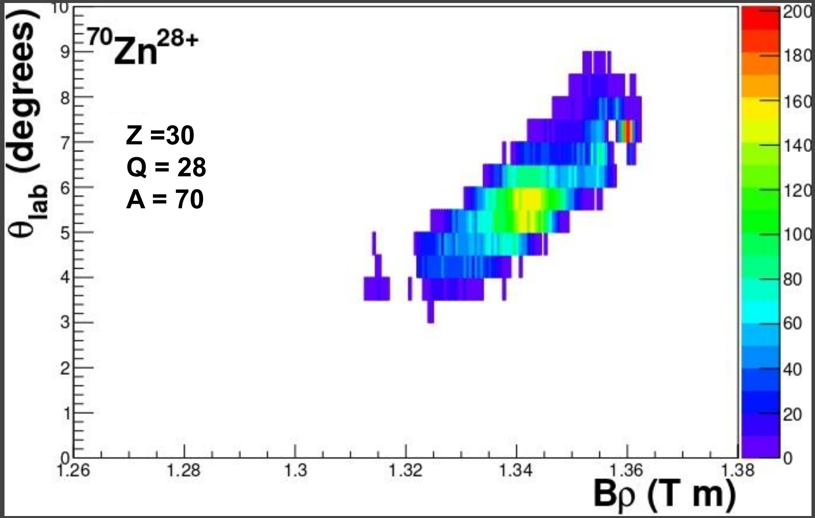
$$B\rho = \frac{\sqrt{m}}{Q}\sqrt{2Etot}$$

For each Z, Q, A gate:



Magnetic rigidity vs total energy correlation of ejectiles with Z = 30 and Q = 28 from the reaction ^{70}Zn (15 MeV/nucleon) + ^{64}Ni

Graphical contours: Isotopes of Zn^{28+} (A = 68-72)



Reaction angle vs magnetic rigidity plot for Z = 30, Q = 28, A = 70

Obtain cross section (Z, A, theta, P/A)

Overview of PID Procedure

PID Procedure for particle identification of the reaction products

↓

Systematic approach: Z,Q reconstruction based on previous works

↓ Correlation of the reconstructed Z and Q in a 2D correlation

Identification of particles with specific Z and Q

↓ Correlation of Bρ and E_{tot} for each Si detector

Separation of different isotopes of a specific element

↓ Correlation of Bρ and the reaction angle (θ_r) for events of a given Z,Q,A, Si detector and experimental run

Obtain cross section (Z, A, theta, P/A)

Theoretical Models

DIT - Deep Inelastic Transfer model (Phenomenological)

- Peripheral and semi-peripheral collisions
- Stochastic nucleon exchange

L. Tassan-Got and C. Stephan, Nucl. Phys. A, **524**, 121 (1991)

CoMD - Constrained Molecular Dynamics (Microscopic)

- Nucleon: Gaussian wavepackets
- Pauli principle imposed via a phase-space constraint

M. Papa, A. Bonasera et al., Phys. Rev. C, **64**, 024612, (2001)
Konstantina Palli, G.A. Souliotis et al., Eur. Phys. J. WoC, **252**, 07002 (2021)
Teo Depastas, G.A. Souliotis, A. Bonasera et al, Eur. Phys. J. WoC, **252**, 07003 (2021)

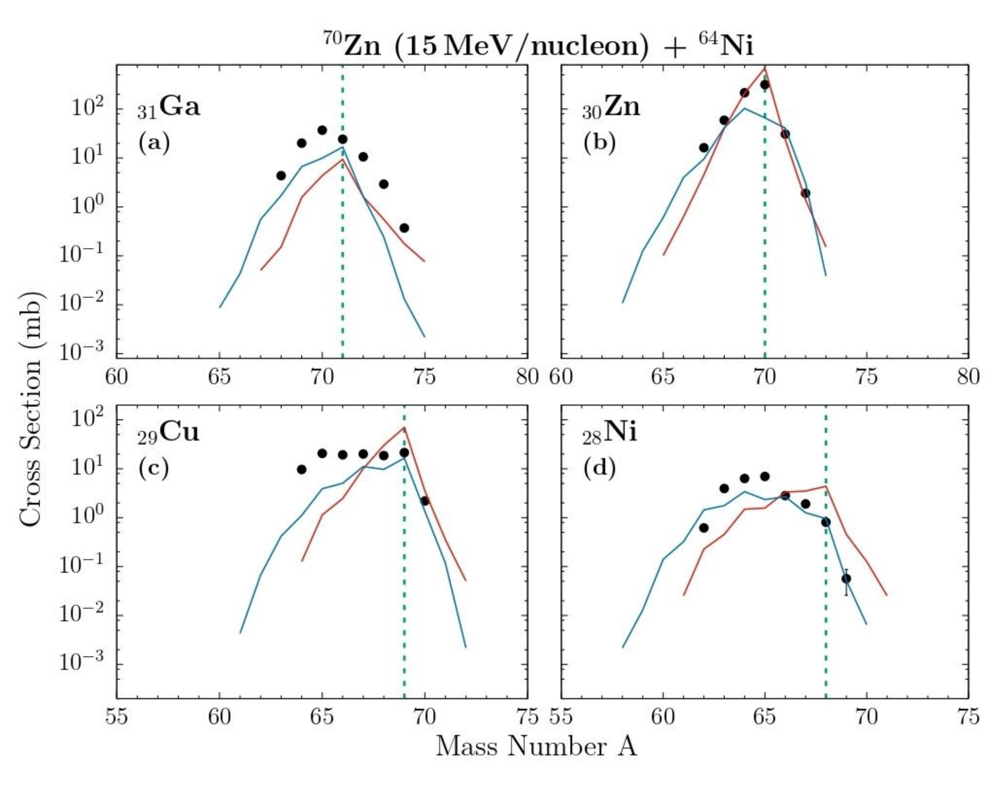
GEMINI - De-excitation

- Binary decay model

R. J. Charity et.al, Nucl. Phys. A, **483**, 371 (1988), R. J. Charity, Phys. Rev. C **58**, 1073 (1998)

Experimental Results

Mass Distributions



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

Experimental Data (Closed Black Circles)

$\Delta\theta$ = 4 - 15°
Bρ range: 1.260 - 1.425 Tm

Calculations
DIT/GEMINI (solid blue line, ——)
CoMD/GEMINI (solid red line, ——)
Green vertical line: - - starting point of neutron pickup.

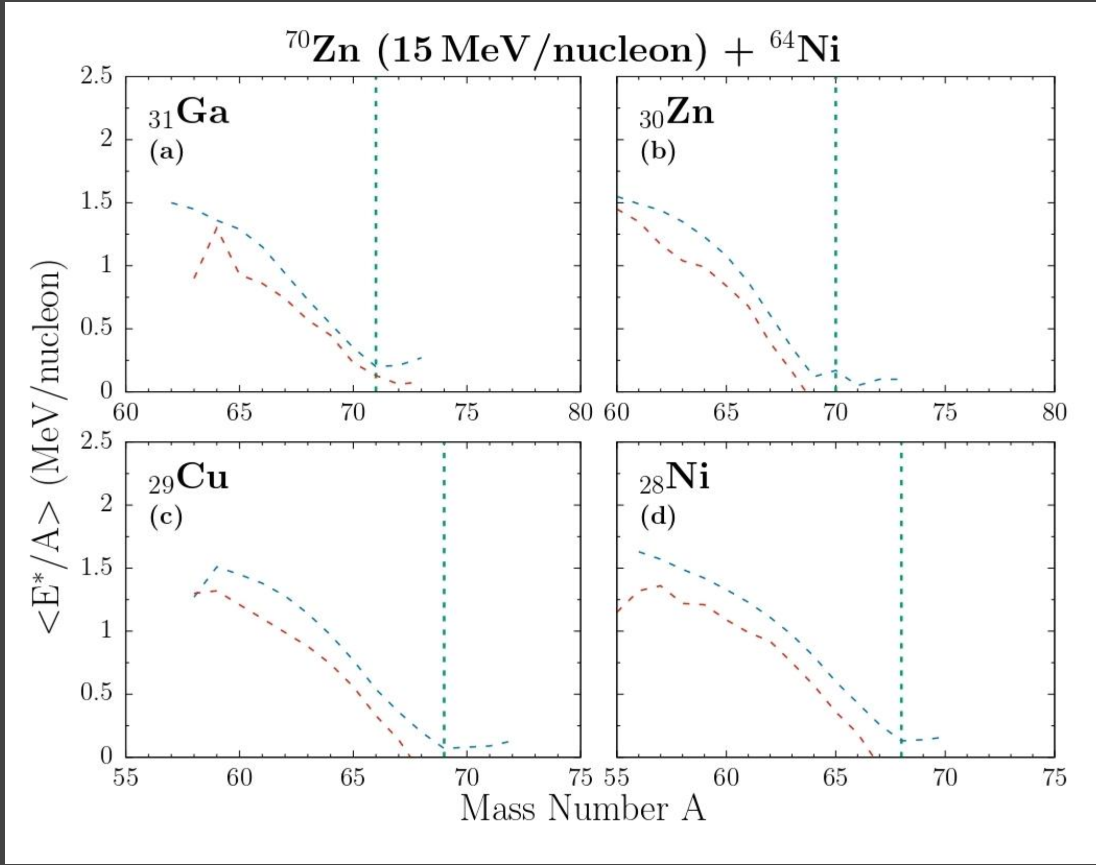
S. Koulouris, G.A. Souliotis F. Cappuzzello, D. Carbone, A. Pakou et al., Phys. Rev. C 108, 044612 (2023)

Calculated Mean Excitation Energy

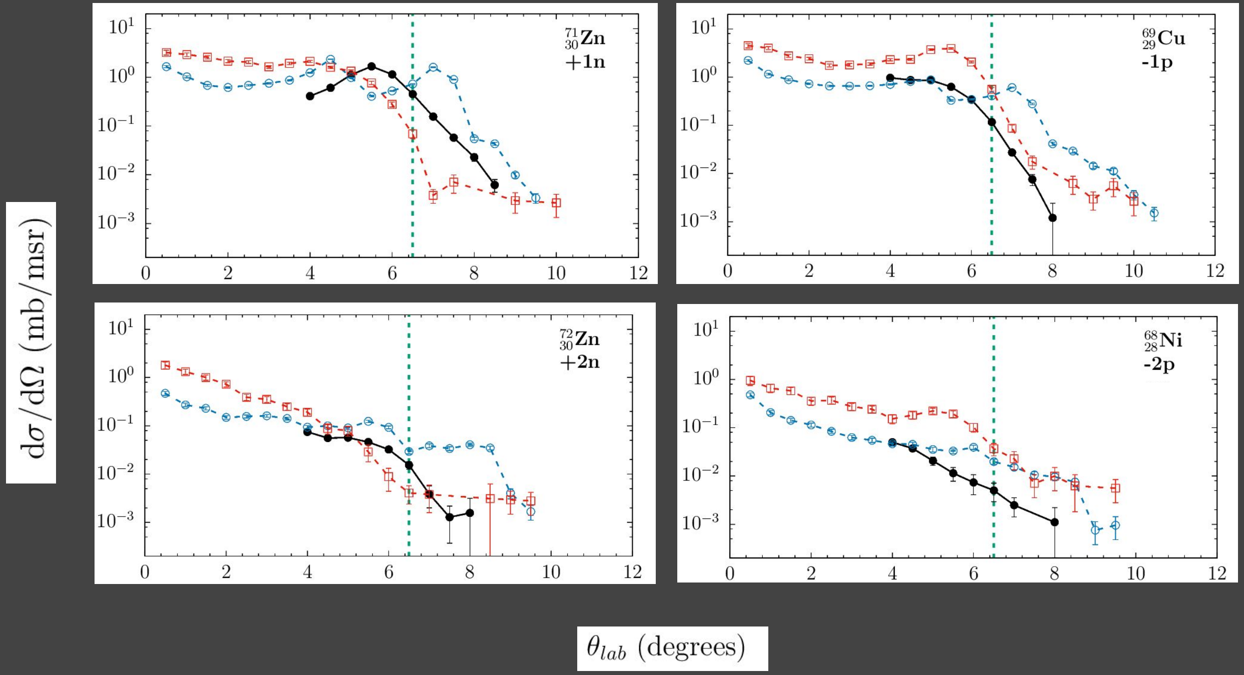
Distributions of Primary Fragments

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

Vertical dashed green line (- - -)
starting point of neutron pickup.



Angular Distributions



Angular distributions
of ejectiles from the reaction of ^{70}Zn
(15 MeV/nucleon) + ^{64}Ni.

General feature of the angular distributions:

Bell-shaped pattern

Peak near the grazing angle ($\theta_{gr} = 6.5^{o}$)

Experimental data: (closed black circles)
Calculations
DIT/GEMINI (dotted blue line, - -)
CoMD/GEMINI (dotted red line, - -)

Dashed green line (- -)
Grazing Angle $\theta_{gr} = 6.5^{o}$

Diff. Cross Section: dσ / dΩ (mb / msr)

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

Experimental data: (closed black circles)
Calculations
DIT/GEMINI (dotted blue line, - - -)
CoMD/GEMINI (dotted red line, - - -)

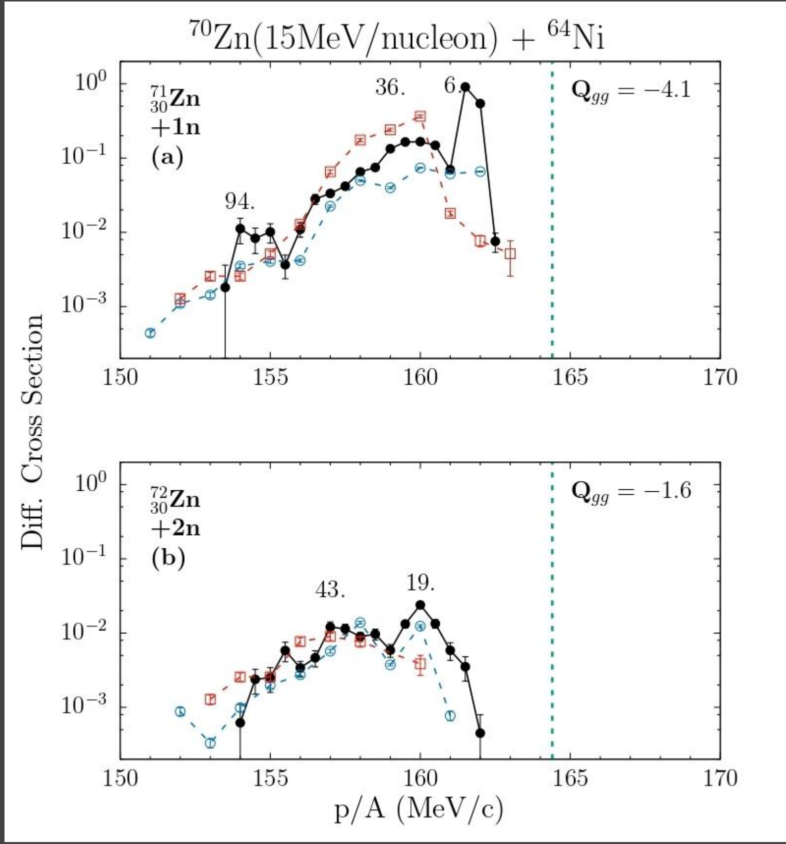
Vertical dashed green line (- - -) p/A of the projectile

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

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

$$E^*_{tot} = Q_{gg} - Q$$

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



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

Momentum Distributions

General feature of the momentum per nucleon distributions

Quasielastic peak

↓

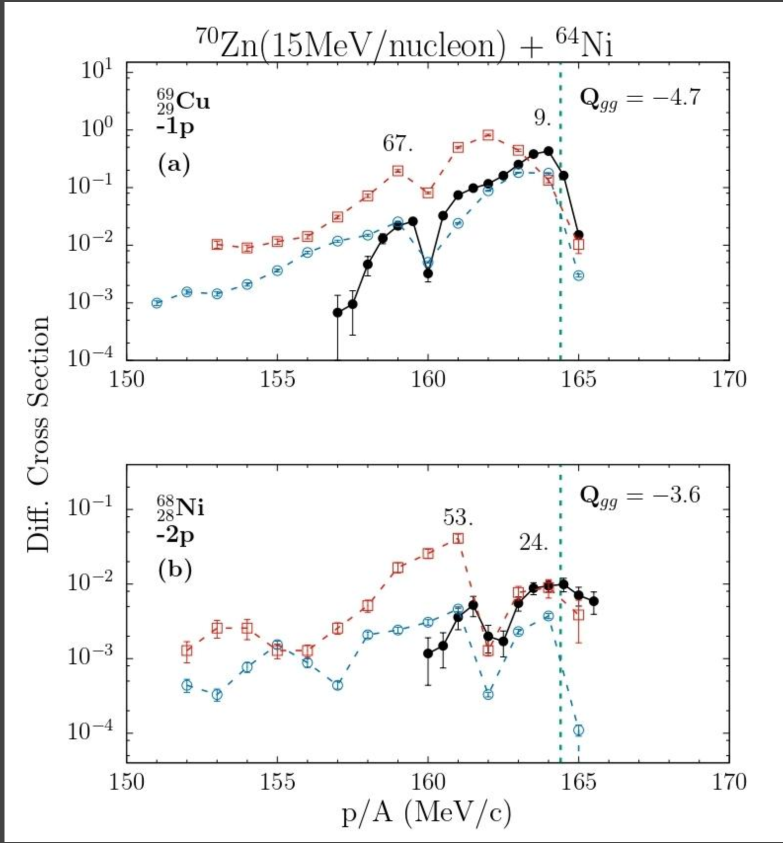
Direct Processes

Broad region (lower values of P/A)

↓

Deep Inelastic Processes/ Multinucleon Transfer Reactions

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



Momentum per nucleon distributions
of ejectiles from proton removal 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

Summary

- Detailed experimental study of ejectiles from the reaction with the MAGNEX spectrometer: Production of neutron-rich nuclides

- Obtained → Mass Distributions, Momentum Distributions, Angular Distributions

Channels leading to n-rich products

Neutron Pickup	Proton Removal
+1n	-1p
+2n	-2p
…	…

- Trying to understand these complex distributions via comparisons with theoretical models

DIT
CoMD (further developments needed)
other direct reaction models (e.g. FRESCO, Ptolemy)

G.A. Souliotis, S. Koulouris, F. Cappuzzello, D. Carbone, A. Pakou et al., Nucl. Instrum. Methods A 1031 (2022) 166588
S. Koulouris, G.A. Souliotis F. Cappuzzello, D. Carbone, A. Pakou et al., Phys. Rev. C 108, 044612 (2023)

Thank you very much for your attention!