# Studies of peripheral heavy-ion reactions with the MAGNEX spectrometer for the production of neutron-rich isotopes

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# Outline of the talk

- Introduction
- Experimental setup
- Particle Identification Procedure
- Presentation of preliminary experimental results
- Summary and conclusions

# Purpose of heavy-ion reaction studies

- 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 to the limit of the neutron-drip line in peripheral collisions below the Fermi energy (15-20 MeV/nucleon)

- This energy regime is mostly dominated by multinucleon transfer and deep inelastic collisions

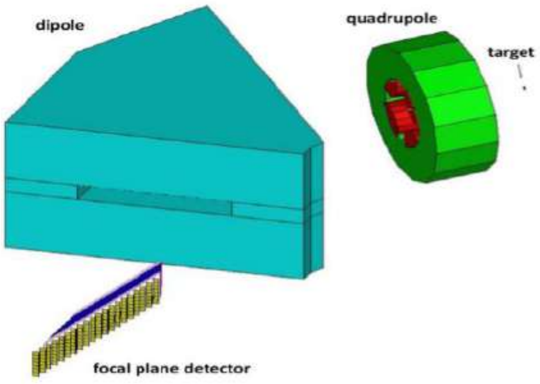
- For the efficient collection of the produced fragments a large acceptance spectrometer is essential

G. A. Souliotis, M. Veselsky et al., Phys. Rev. C 84, 064607 (2011)
P. N. Fountas, G. A. Souliotis, M. Veselsky, A. Bonasera, Phys. Rev. C 90, 064613 (2014)

# MAGNEX Spectrometer

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




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 (seven were used for this experiment)
- Proportional Drift Chamber spanning at six sequential planes

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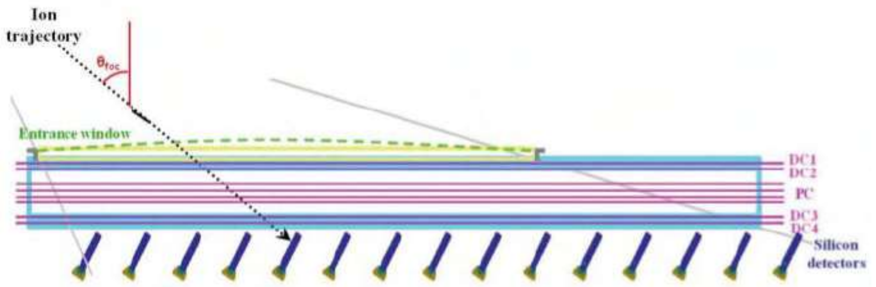
- Determination of horizontal and vertical coordinates
- Determination of the angles θ and φ of the ion's trajectory
- Energy loss of the reaction products in the gas and the residual energy of the fragments in the Si detectors




F. Cappuzzello, C. Agodi, D. Carbone and M. Cavallaro, Eur. Phys. J. A., 52:167 (2016)

# TOF measurement

Inverse TOF measurement

- Start: Signals of Si detectors
- Stop: Radiofrequency of the cyclotron

Following the TOF measurement, a proper calibration was carried out

Using also the trajectory length of the particles which was calculated (obtained from optical reconstruction), their velocity has been extracted

Typical values of TOF and velocity of the projectile-like fragments:

**TOF ~ 120 ns**

**u ~ 0.17c**

# PID Procedure

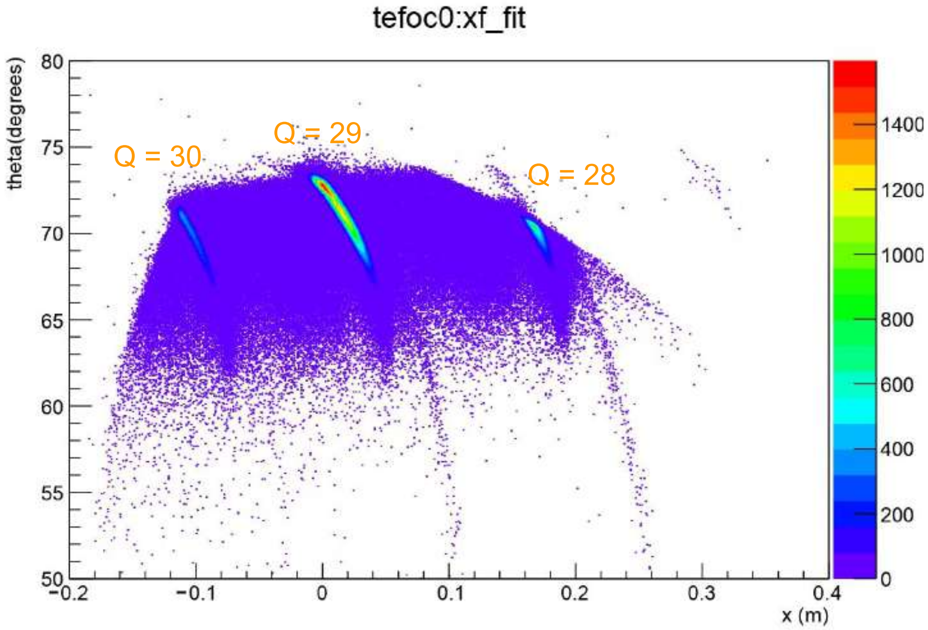
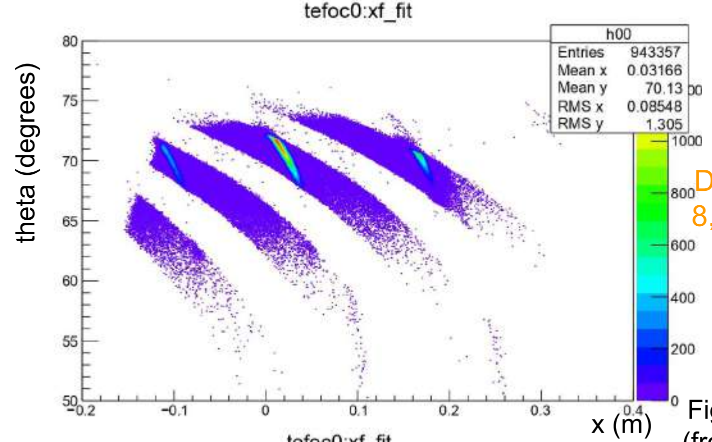
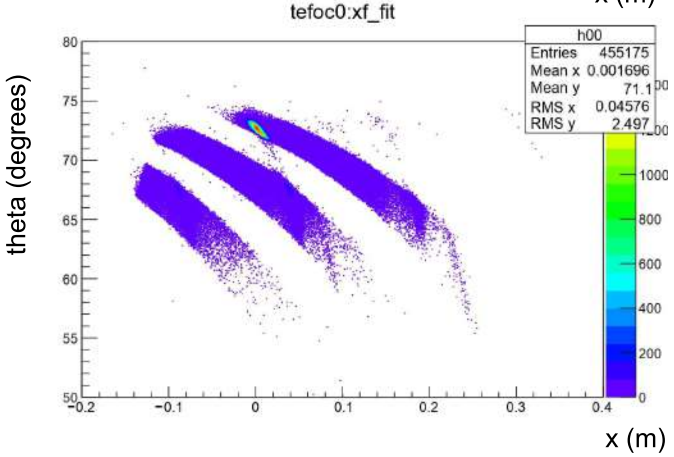



Fig. 1: Plot of the horizontal angle versus the horizontal position measured at the FPD. In Fig. 1, experimental data of products from the reaction $^{70}Zn$ + $^{64}Ni$ distributed on all seven Si detectors.




Si Detectors: 8,14,20,26

Fig. 1a, 1b (from top to bottom)




Si Detectors: 11,17,23

# PID Procedure

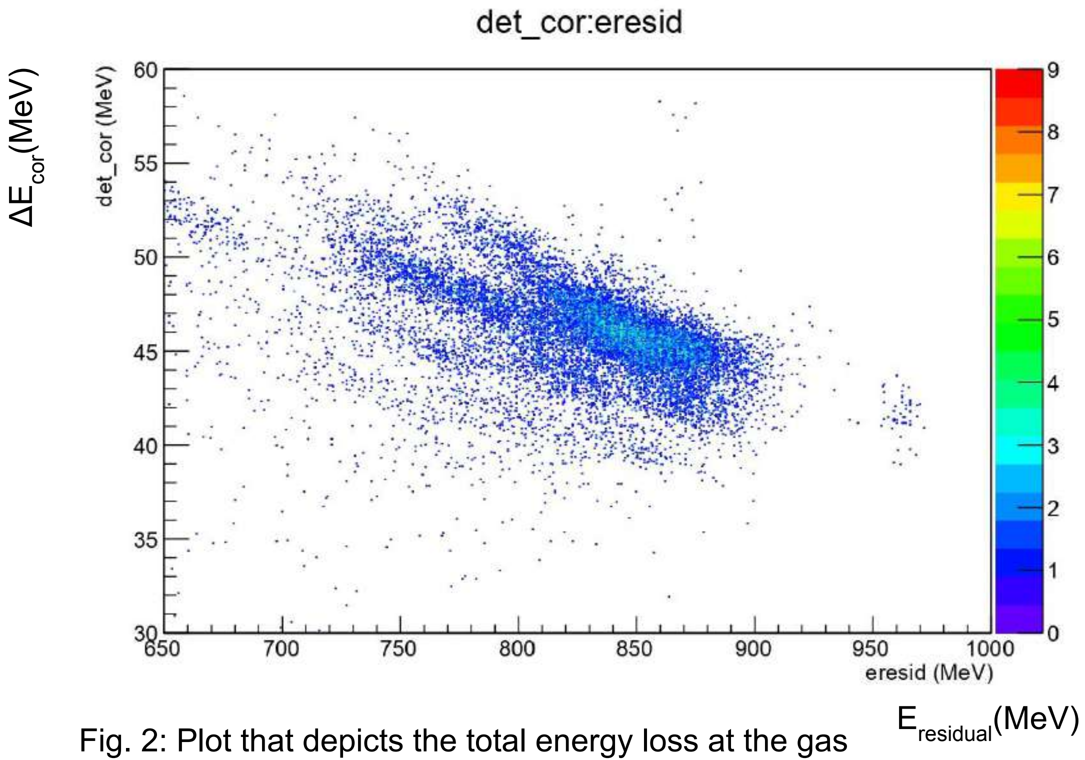



Fig. 2: Plot that depicts the total energy loss at the gas section of the FPD vs the residual energy measured by a single silicon detector.

- The ΔE-E correlation is a standard method for the determination of the atomic number of the ejectiles
- However, for heavier ions this method leads to rather complex results as can be seen in Fig. 2 due to an intermix of Z and Q bands.
- Systematic approach to determine Z

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Z-reconstruction

F. Cappuzzello, C. Agodi, D. Carbone and M. Cavallaro, Eur. Phys. J. A., 52:167 (2016)

# Z Reconstruction

- Detailed approach of Z determination based mainly on Bethe's stopping power formula:

$$Z \propto u\sqrt{\Delta E}$$

- Guided by this equation, we empirically expressed Z as a quadratic function of the product $u\sqrt{\Delta E}$ with velocity-dependent coefficients:

$$Z = \alpha_0(u) + \alpha_1(u)\, u\sqrt{\Delta E} + \alpha_2(u)\, (u\sqrt{\Delta E})^2$$

- To obtain the coefficients of this equation for Z values close to the projectile (Z = 30) we employed a least-squares fitting procedure in the energy range of 8-23 MeV/nucleon in steps of 0.5 MeV/nucleon
- Subsequently, the values of each coefficient at the various energies were fitted with polynomial functions of velocity
- Finally, Z was calculated from the above equation using the measured values of ΔE and u

G.A. Souliotis, K. Hanold, W. Loveland et al., Phys. Rev. C 57, 3129 (1998)

# Z Reconstruction

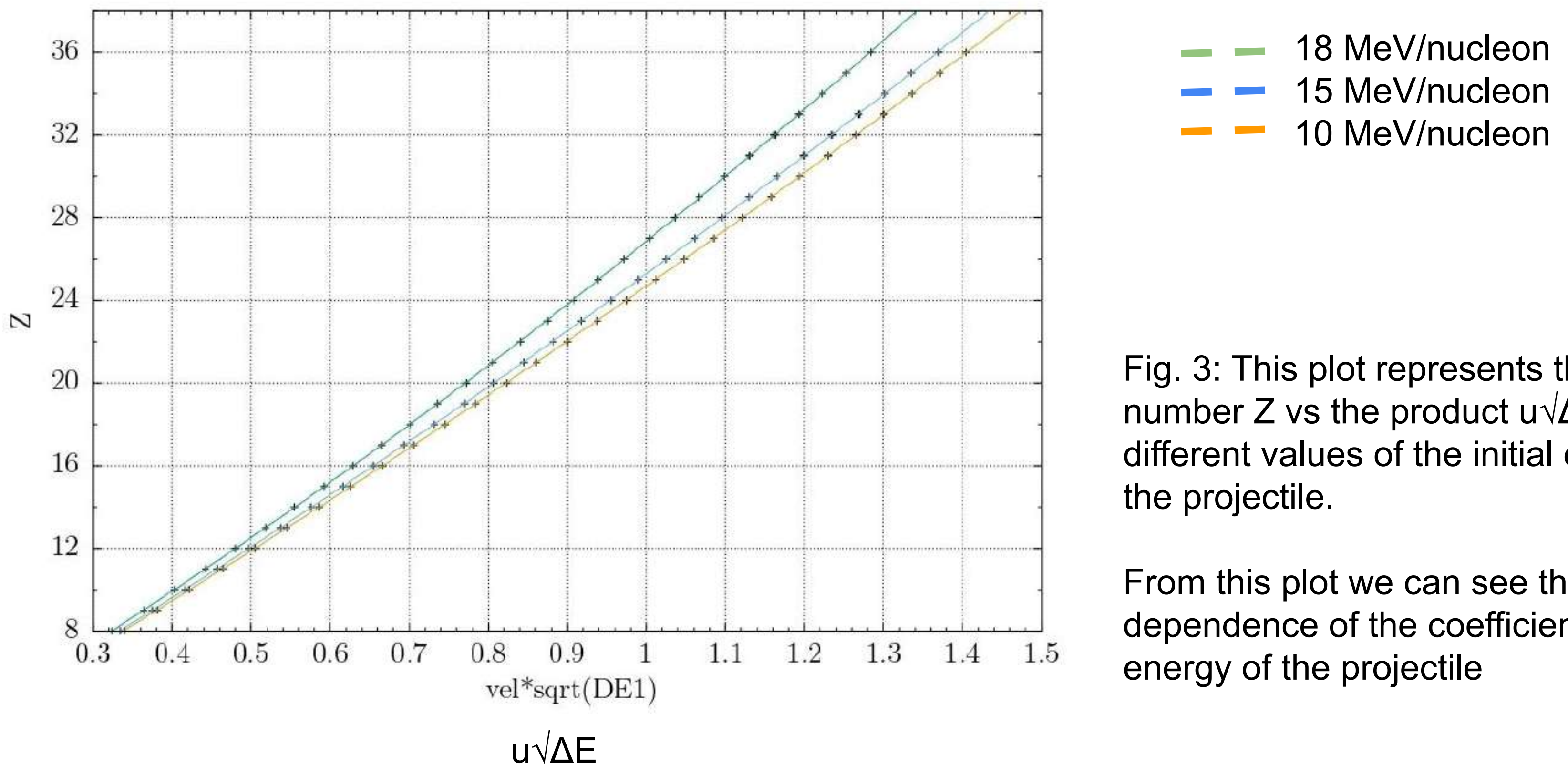


Fig. 3: This plot represents the atomic number Z vs the product $u\sqrt{\Delta E}$, for different values of the initial energy of the projectile.

From this plot we can see the dependence of the coefficients on the energy of the projectile

# Ionic Charge State (Q) Reconstruction

- The TOF measurement, along with the trajectory length, enabled us to calculate the charge state from the equation:

$$Q = \frac{2Etot}{B\rho}\frac{L}{TOF}$$

$$B\rho = B\rho_0(1+\delta)$$

$B\rho_0$ : Magnetic rigidity at the central trajectory
$\delta$ : fractional deviation from the central trajectory

- By reconstructing Q and Z, we initiated a new approach for the identification of the ejectiles

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Correlation of Z and Q of the products in a two dimensional plot

F. Cappuzzello, C. Agodi, D. Carbone and M. Cavallaro, Eur. Phys. J. A., 52:167 (2016)

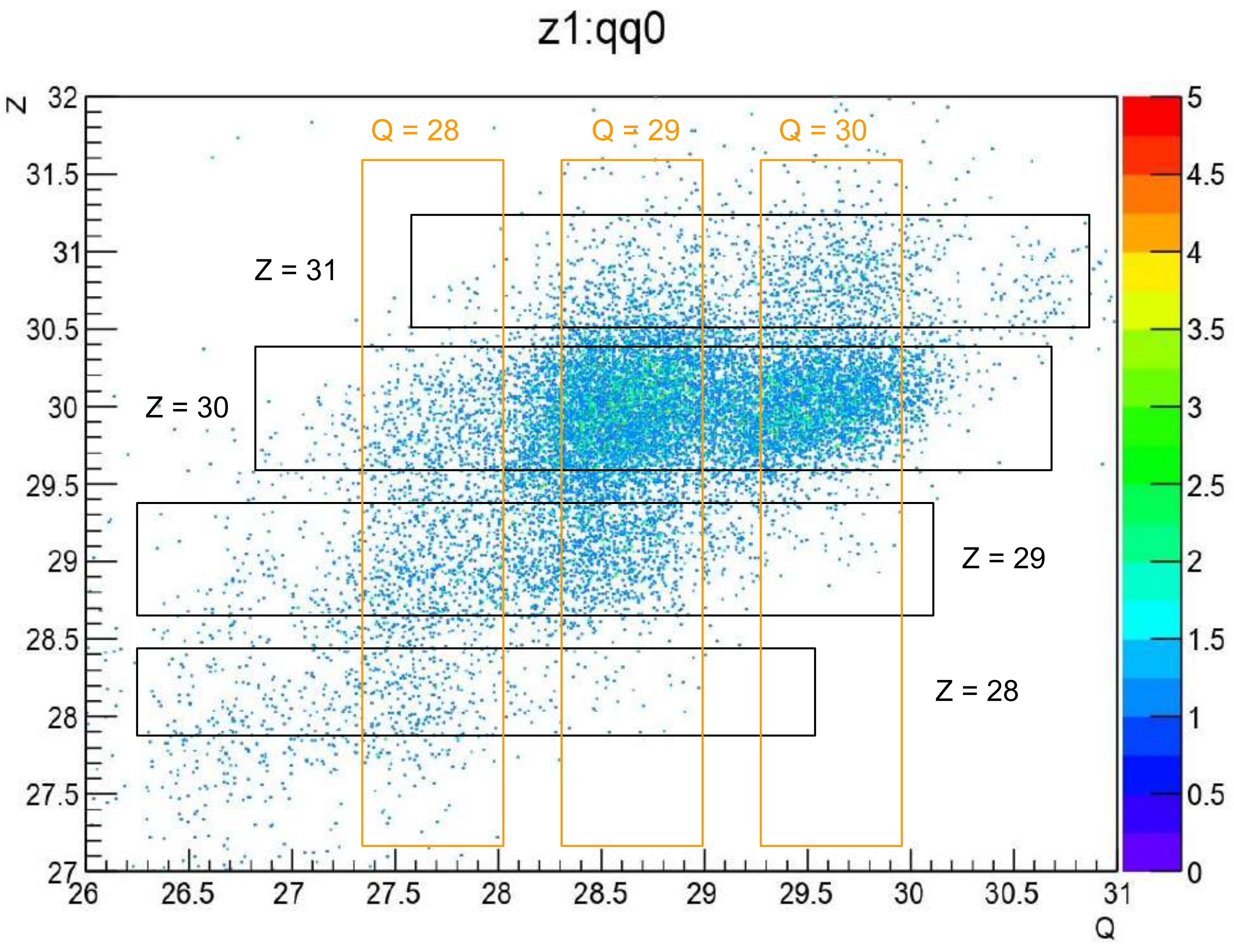


Fig. 4: Plot that depicts the atomic number vs the charge state of the products that were collected by a single silicon detector.

We can see the presence of different areas, corresponding to elements with also specific charge states.

We were in position to select events of a specific Z and Q, leading us subsequently to a rather clear mass determination.

# Mass Determination

- For the mass determination, our technique is based on the relationship between total kinetic energy and magnetic rigidity as shown in this equation:

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

- Using the Z vs Q plot, we have achieved the identification of products with specific Z and Q. So, for a given Q, the dependence is only on the mass. Thus, in a Bρ vs $E_{tot}$ representation, the particles are distributed on different bands according to their $\sqrt{m}$

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Successful separation and identification of isotopes

F. Cappuzzello, C. Agodi, D. Carbone and M. Cavallaro, Eur. Phys. J. A., 52:167 (2016)

# Mass Determination

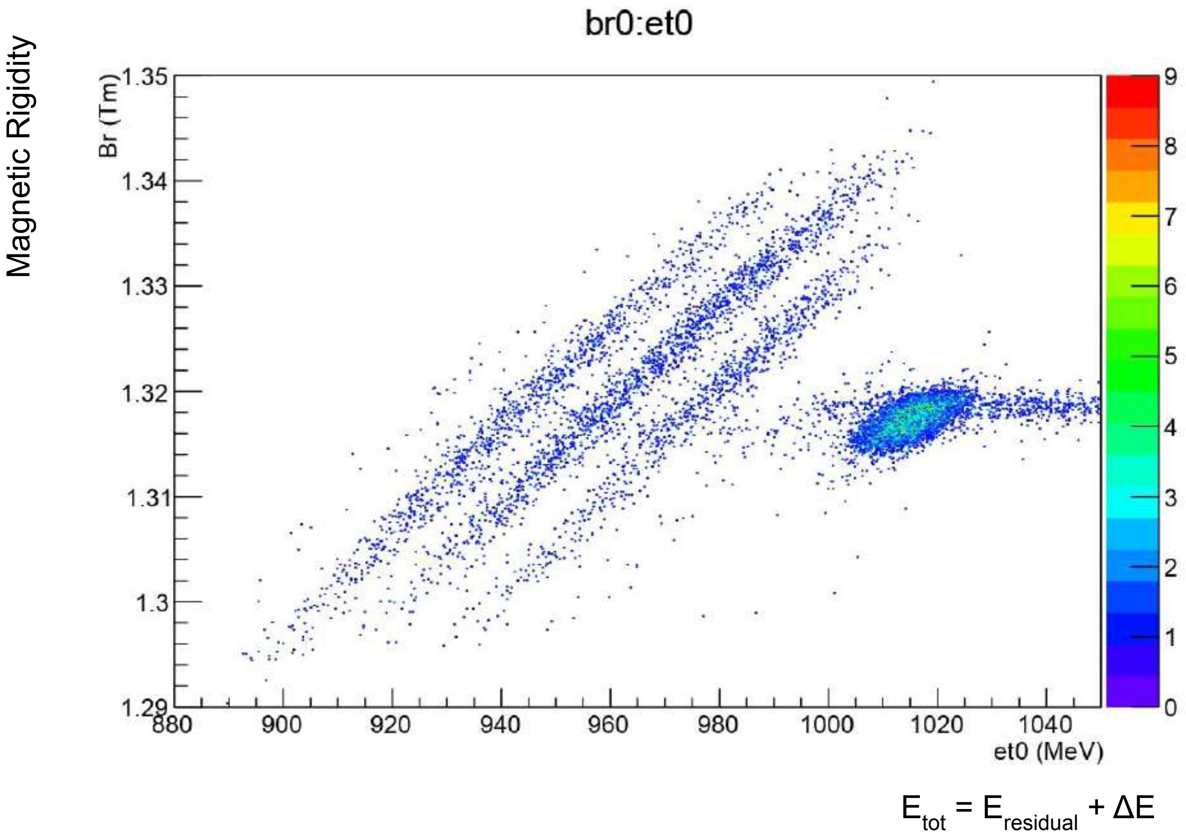
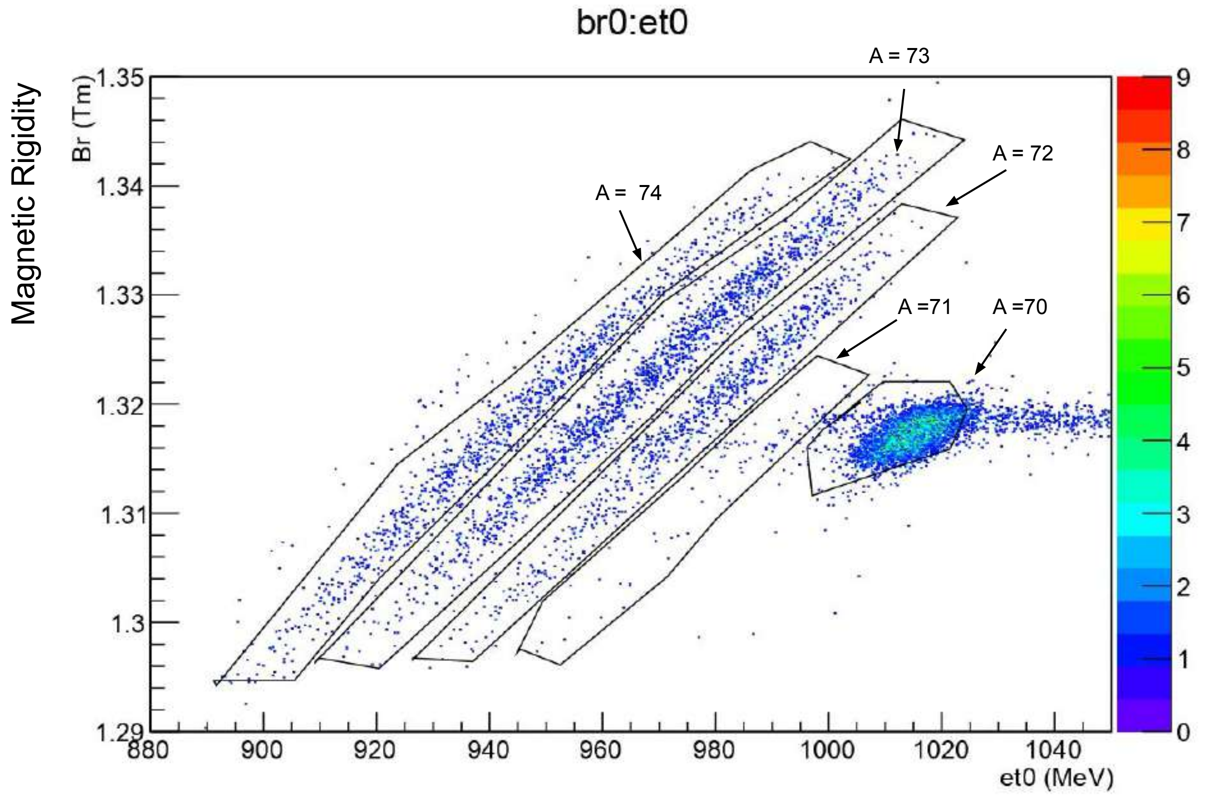



Fig. 5: Plot that depicts the magnetic rigidity vs the total energy (ΔE + residual energy) of products with Z = 30 and Q = 29 that were collected by a single silicon detector.

The presence of distinct areas is evident, corresponding to different isotopes of Zn.




$E_{tot} = E_{residual} + \Delta E$

Fig. 6: Plot that depicts the magnetic rigidity vs the total energy (ΔE + residual energy) of products with Z = 30 and Q = 29 that were collected by a single silicon detector.

Five of the isotopes of Zn (Z =30) with their corresponding graphical contours are indicated.

# Conclusions and Summary

- Study of the reaction $^{70}Zn$(15 MeV/nucleon) + $^{64}Ni$ at INFN/LNS with MAGNEX spectrometer
- ΔE-E correlation rather inadequate for the Z identification of the reaction products

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Systematic approach: Z reconstruction based on previous works

↓ Correlation of the reconstructed Z and Q

Identification of particles with specific Z and Q

↓ Correlation of Bρ and $E_{tot}$

Preliminary separation of different isotopes of a specific element

# Conclusions and Summary

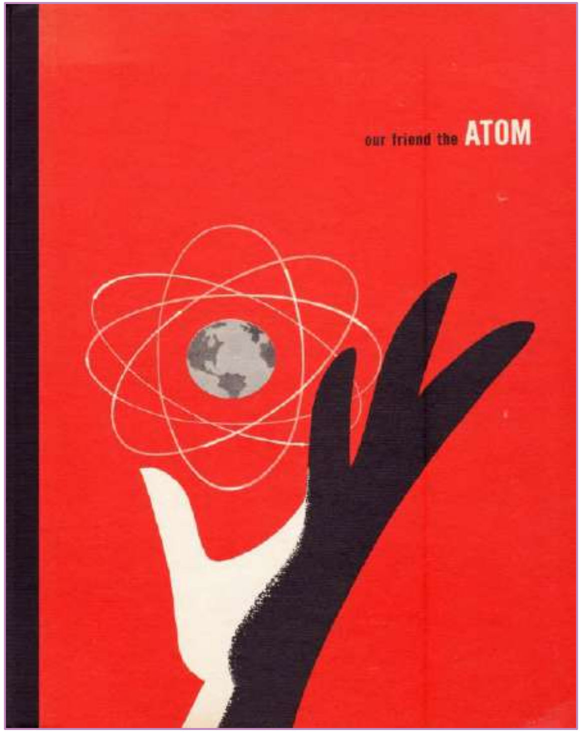
Plans for future work:

- After the proper identification of the ejectiles, we plan to obtain their production cross sections, their angular and momentum distributions

- Thorough analysis of the data along with comparisons with theoretical models (CoMD, DIT, GEMINI)

- A better understanding of the complex reaction mechanisms that dominate this energy regime

# Thank you very much for your attention!

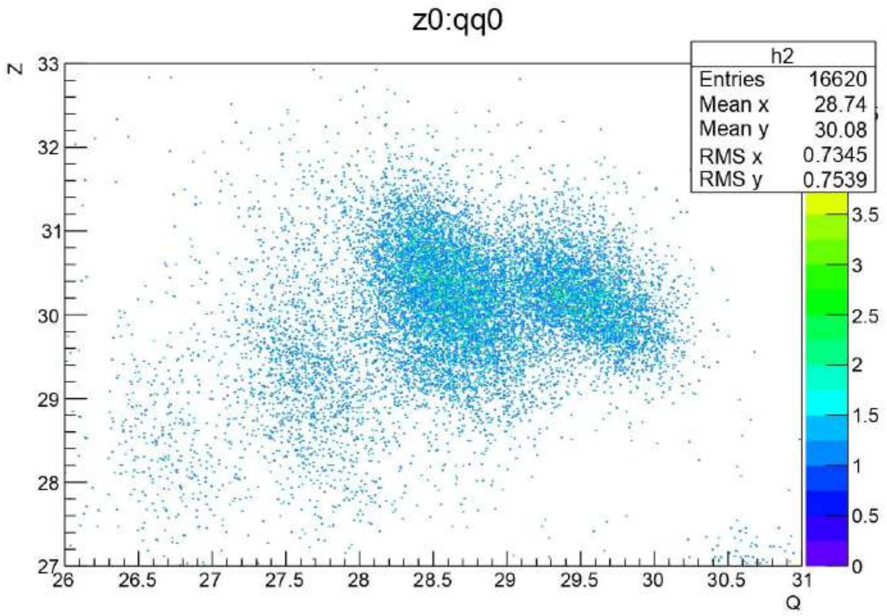


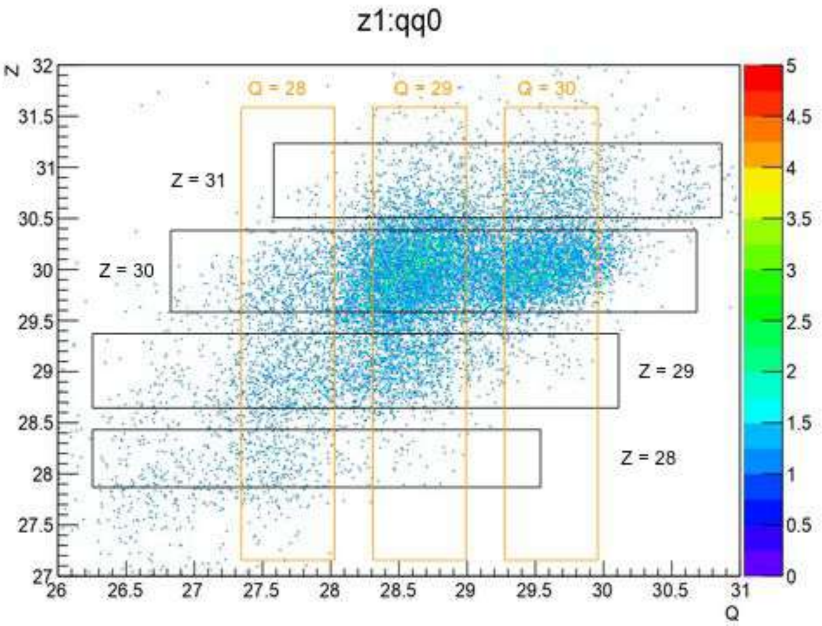
# Extras

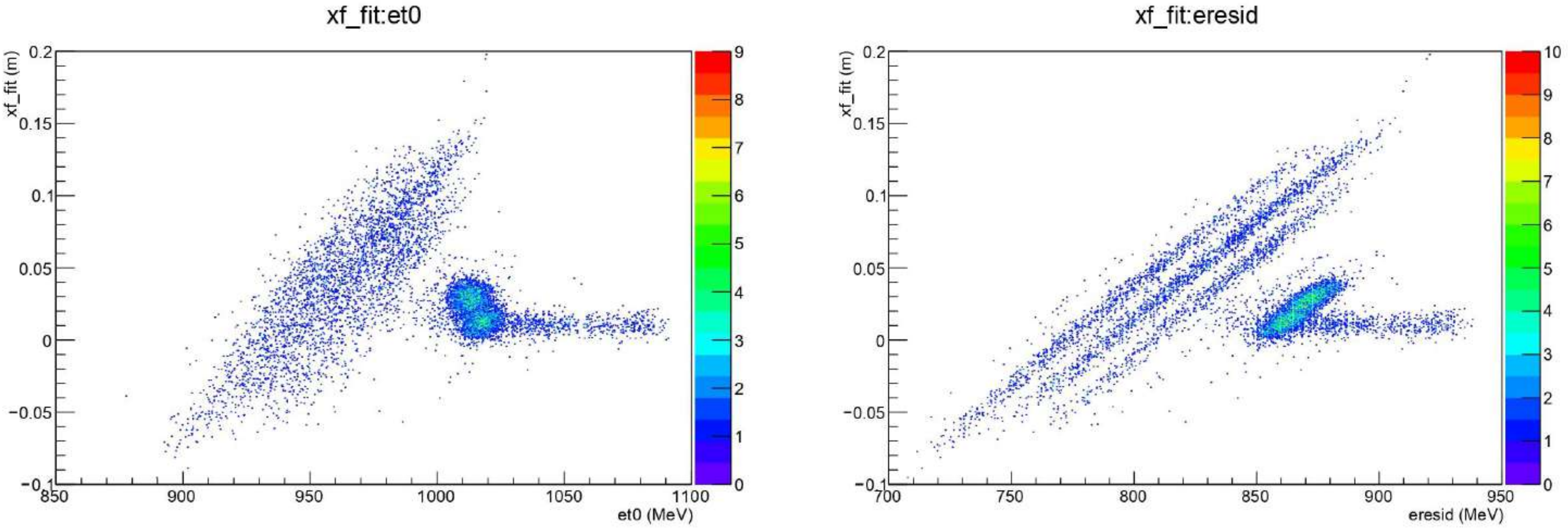
# Ongoing Efforts of Z-Reconstruction

$$Z = \alpha_0(u) + \alpha_1(u)\, u\sqrt{\Delta E} + \alpha_2(u)\, (u\sqrt{\Delta E})^2$$

$$Z = \alpha_0(u) + \alpha_1(u)\, \sqrt{(E_{tot}\Delta E)} + \alpha_2(u)\, (\sqrt{E_{tot}}\Delta E)^2$$





xf_fit:et0
xf_fit (m)
et0 (MeV)
xf_fit:eresid
xf_fit (m)
eresid (MeV)

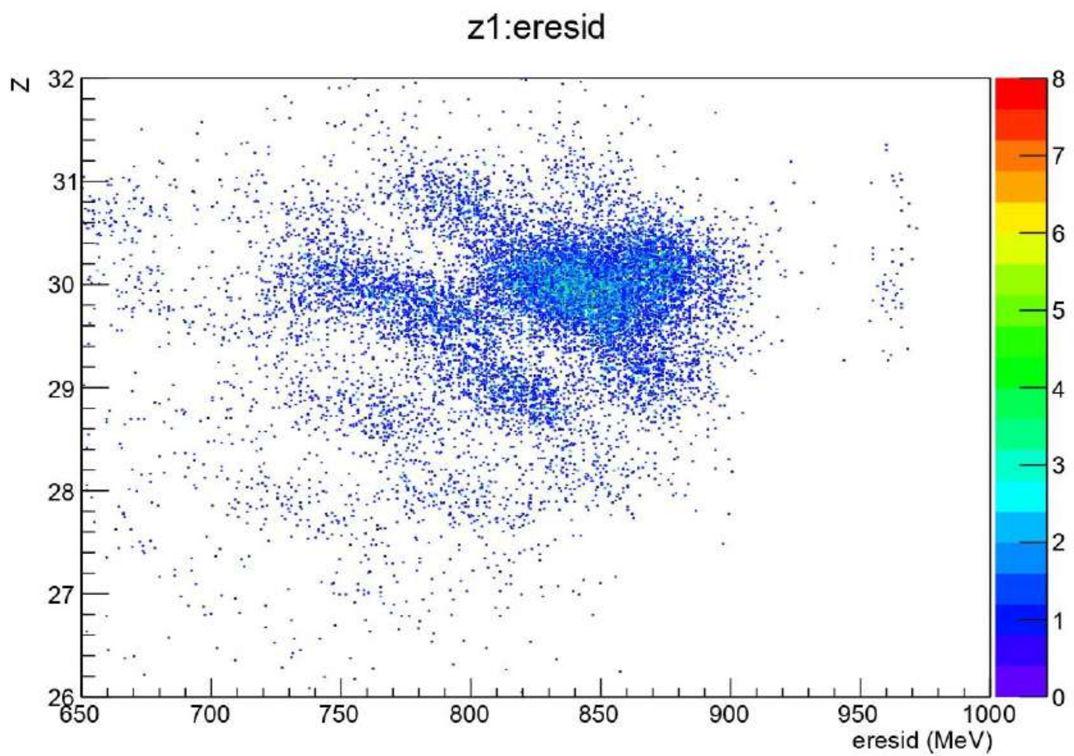
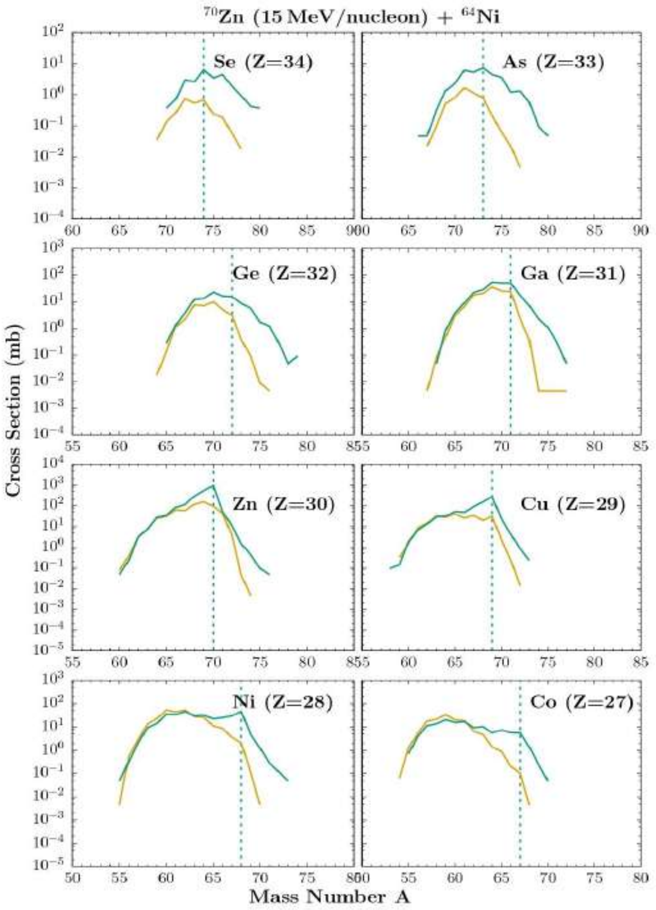



Fig. 4: Plot that represents the atomic number vs the residual energy of the products that were collected by a single silicon detector.

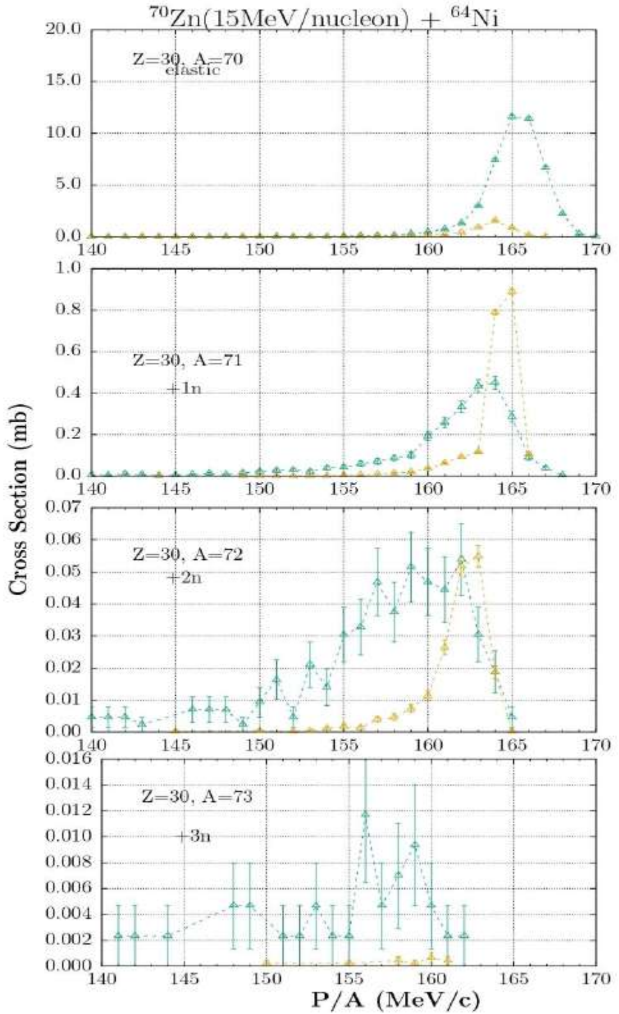
We can see that the identification is rather difficult, due to the presence of different charge states of the products.

This observation led to the reconstruction of Q and the Z vs Q plots

# Preliminary Calculations for $^{70}Zn$(15 MeV/nucleon) + $^{64}Ni$




Comparison of calculated mass distributions (lines) of projectile fragments with Z = 33–40 from the reaction $^{70}Zn$(15 MeV/nucleon) + $^{64}Ni$.
The calculations shown are: DIT/GEMINI (solid yellow line) and CoMD/GEMINI (solid green line). The green line indicates the starting point of neutron pickup.




Momentum distributions depicting the elastic channel ($^{70}$Zn) and the products of the pickup of up to three neutrons from the target.
The calculations shown are:
DIT/GEMINI (solid yellow line) and CoMD/GEMINI (solid green line).