Recent developments in the study of peripheral collisions below the Fermi energy

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Outline

- Exotic Nuclides => toward the driplines
  Nuclear Reactions: energy regimes

- Fermi Energy peripheral collisions

- Neutron-Rich Rare Isotope Production
- Experimental efforts at Texas A&M and Catania
- Dynamical simulations with CoMD
- Ground States, GMR and GDR dynamics via CoMD

ΕΘΝΙΚΟΝ & ΚΑΠΟΔΙΣΤΡΙΑΚΟΝ ΠΑΝΕΠΙΣΤΗΜΙΟΝ ΑΘΗΝΩΝ
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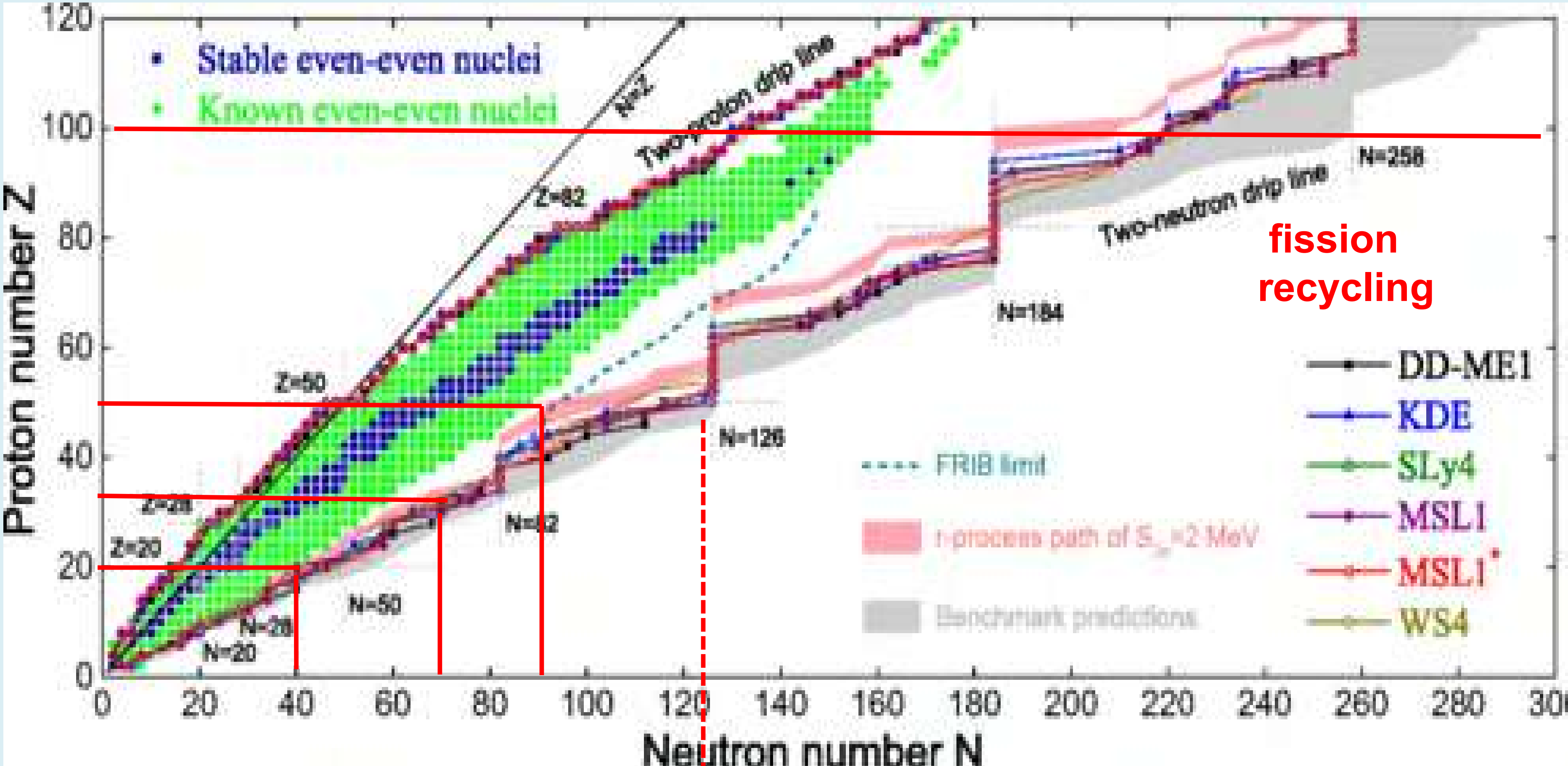
The Nuclear Landscape and the location of the driplines



^{60}Ca ^{106}Kr ^{140}Sn

^{118}Kr ^{176}Sn

FRIB : Facility for Rare Isotope Beams, Michigan State University

R. Wang, L.W. Chen, Phys. Rev. C **92**, 031303 (2015)

R. Utama et. al., Phys. Rev. C **96**, 044308 (2017)

Energy Regimesof Nuclear Reactions:

- **Low Energy:** < 10 MeV/u ($\upsilon < 0.15$ c)
- **Fermi Energy:** 10 - 50 MeV/u ($\upsilon = 0.15 - 0.3$ c)
- **Medium Energy:** 50 -200 MeV/u ($\upsilon = 0.3 - 0.6$ c)
- **High Energy:** > 200 MeV/u ($\upsilon > 0.6$ c)

ΕΘΝΙΚΟΝ & ΚΑΠΟΔΙΣΤΡΙΑΚΟΝ ΠΑΝΕΠΙΣΤΗΜΙΟΝ ΑΘΗΝΩΝ
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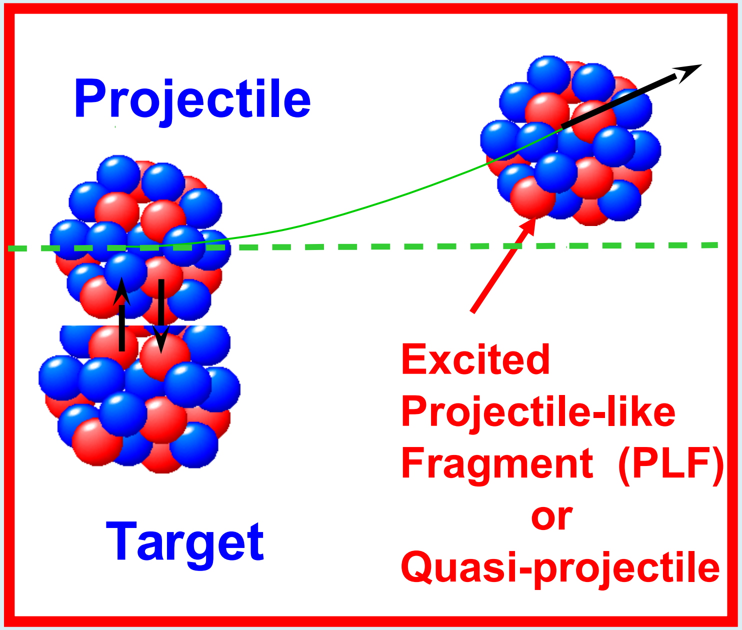
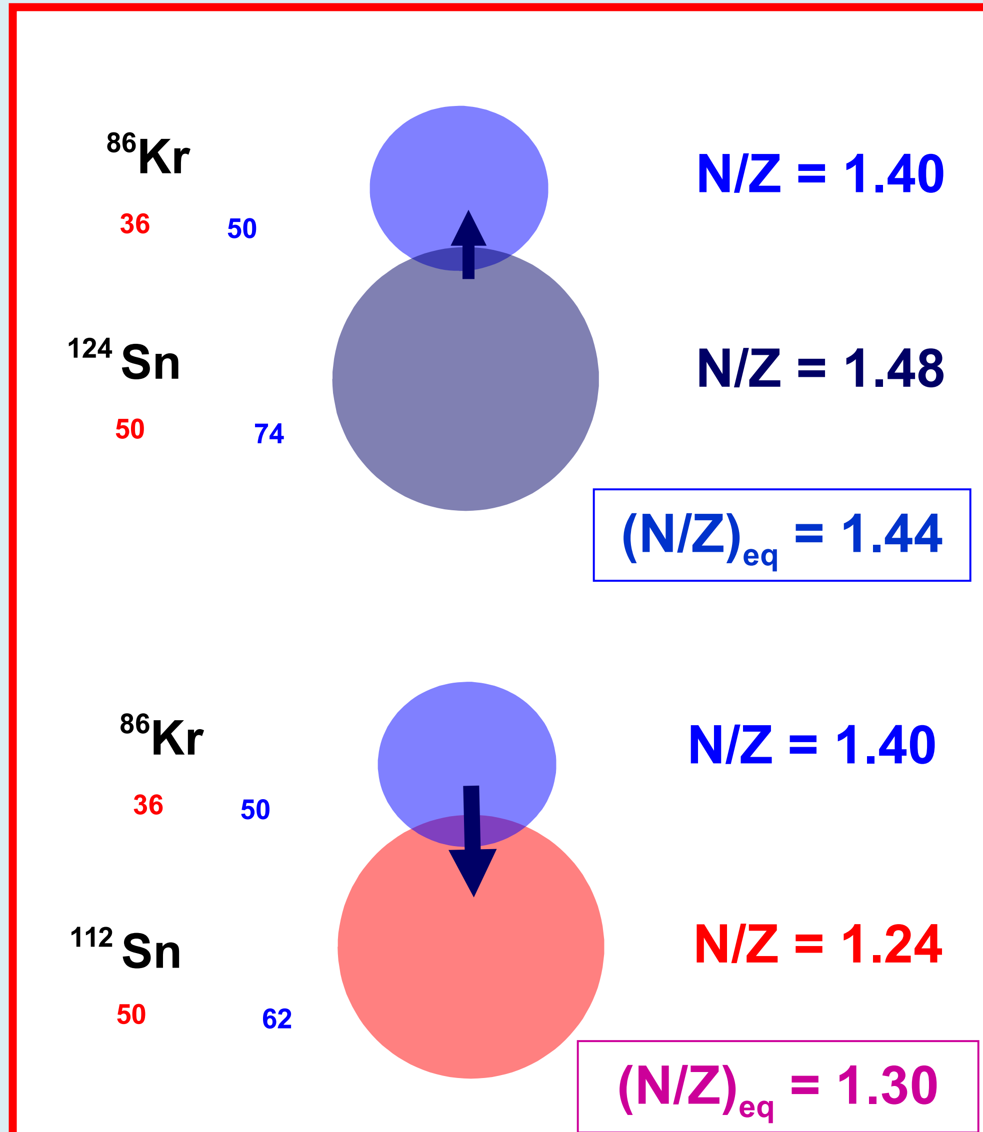
Picture of a peripheral collision (DIT - nucleon-exchange)



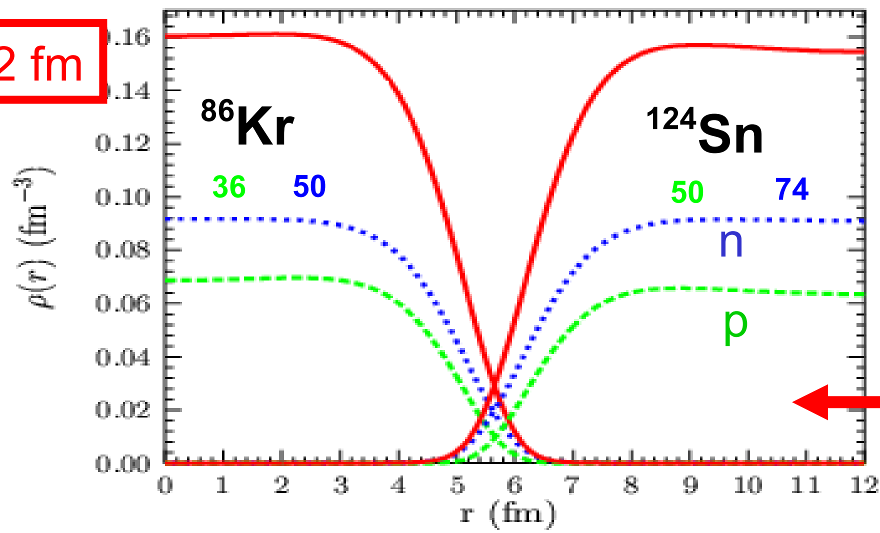


Deep Inelastic Transfer Model: semi-classical nucleon-exchange Model

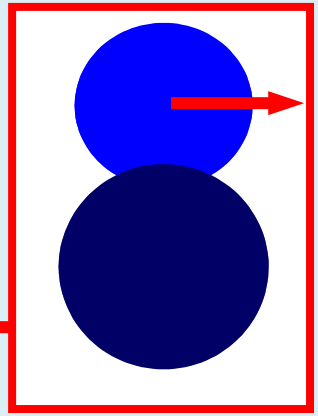
DIT : L. Tassan-Got, C. Stephan, Nucl. Phys. A 524, 121 (1991)
M. Veselsky, G.A. Souliotis, Nucl. Phys. A 765, 252 (2006)

Density Profile Overlap in a Peripheral Collision: $^{86}Kr + ^{124}Sn$

R =12 fm



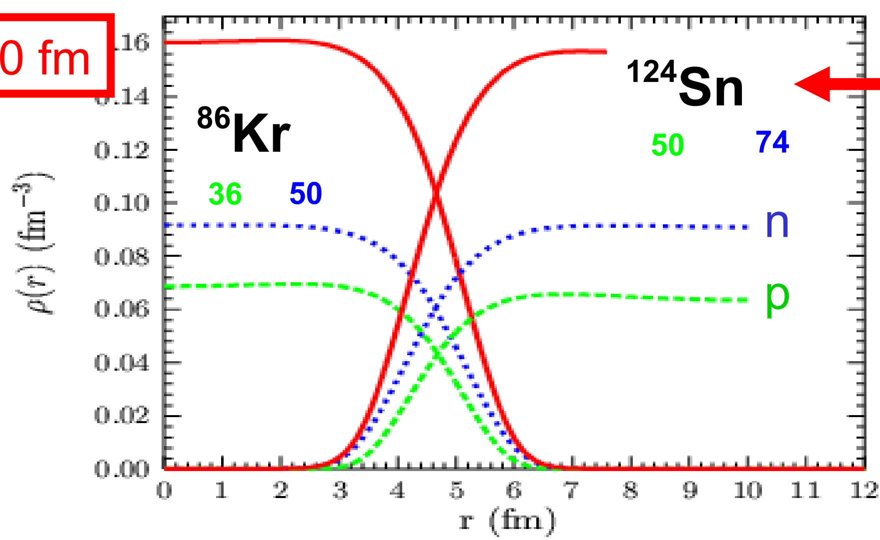
$\rho_{overlap} = \rho_{projectile} + \rho_{target}$

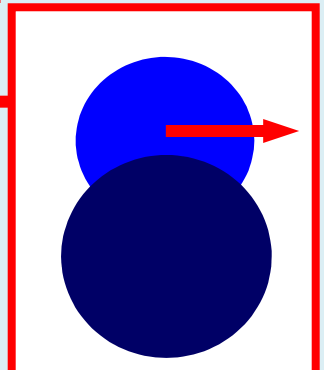


$\rho_{overlap} \sim 1/4\ \rho_o$

Peripheral collision:
$t_{interaction}$ short

R =10 fm





$\rho_{overlap} \sim 1.5\ \rho_o$

Semi-peripheral collision:
$t_{interaction}$ longer

Peripheral Collisions:

may provide information on the nucleon-nucleon interaction on a wide range of densities

Calculations with the Thomas-Fermi code of V. Kolomietz, Phys. Rev. C 64, 024315 (2001)

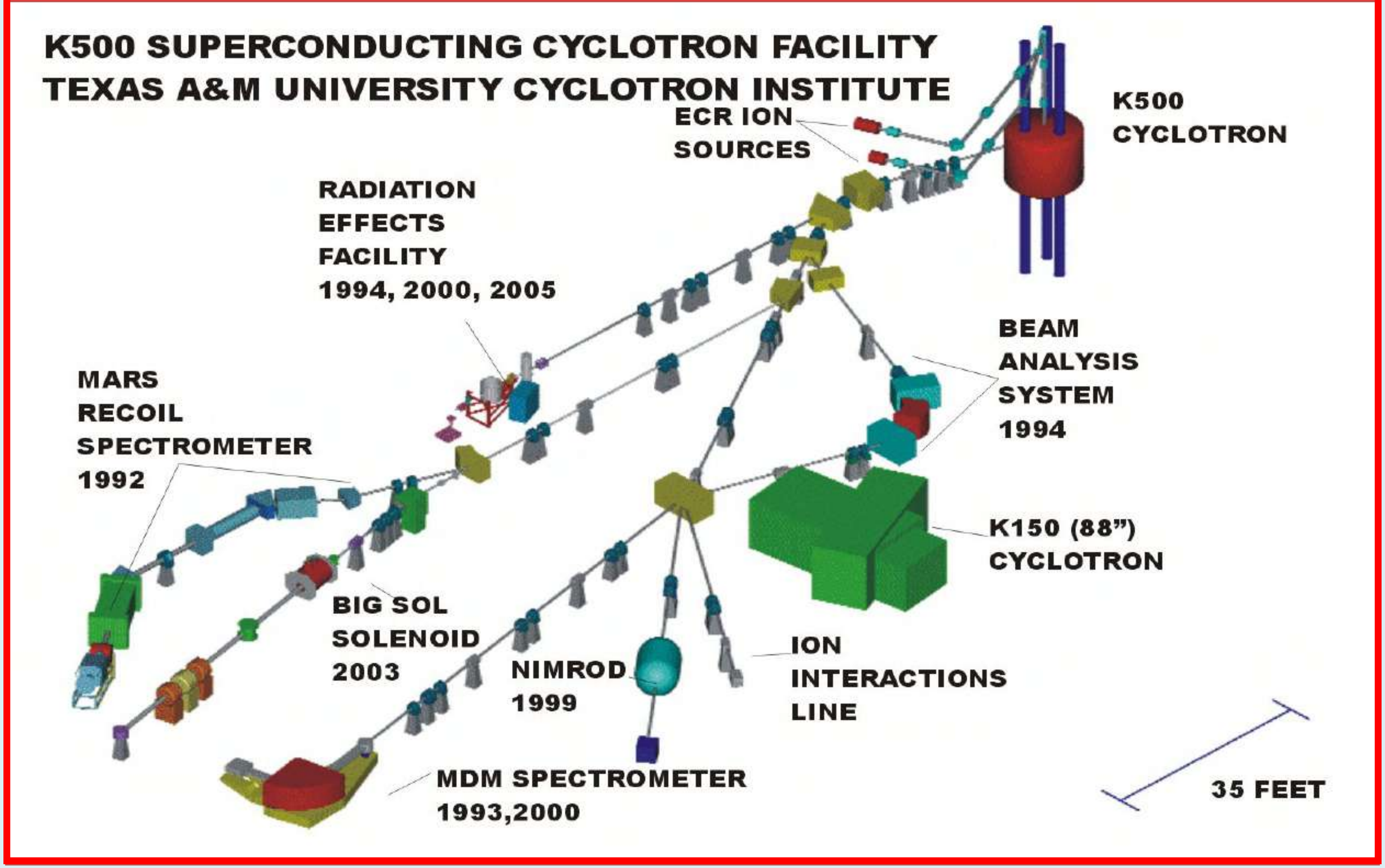
Microscopic Calculations: Constrained Molecular Dynamics Model (CoMD)

CoMD: Quantum Molecular Dynamics (Semi classical)

- Nucleons considered as gaussian wavepackets
- Solution of the classical Hamilton's equations for the centroids
- **Phenomenological N-N interaction (Skyrme-type)**
- Symmetry potential depending on the nuclear density
- Surface potential (can be isospin dependent)
- Emulation of Pauli principle through appropriate restriction in phase space (phase space constraint)
- **Recognition of cluster (fragment) formation** (R_{N-N} = 2.4 fm)
- Simulation of a large number of events (Monte Carlo approach)
- Continue evolution for 300-500 fm/c.
- Obtain properties of primary fragments

M. Papa, A. Bonasera et al., Phys. Rev. C 64, 024612 (2001)

Cyclotron Institute at Texas A&M University



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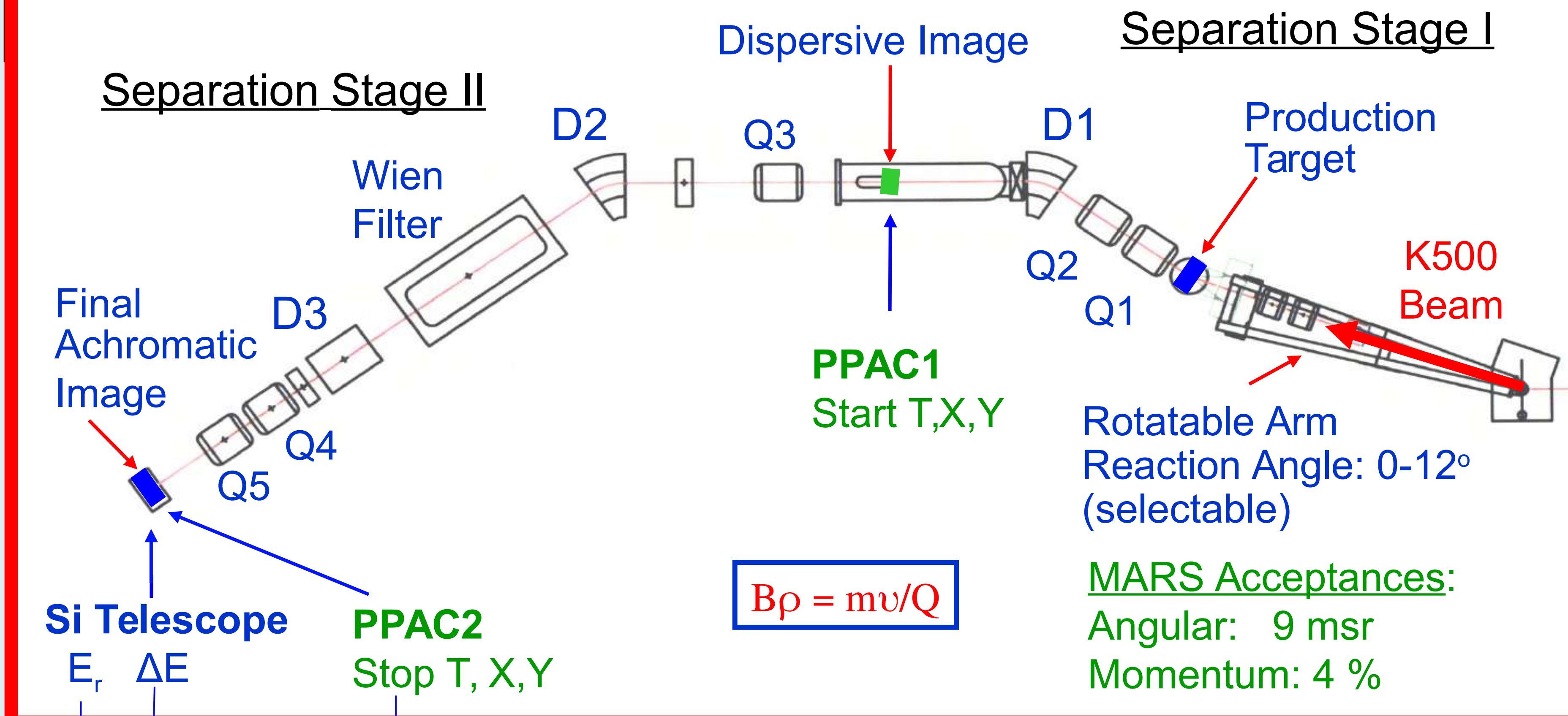
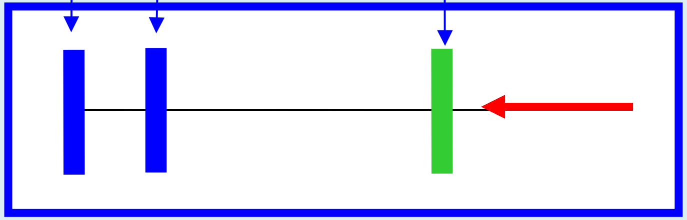
MARS Recoil Separator and Setup for Heavy Rare Isotope Studies*



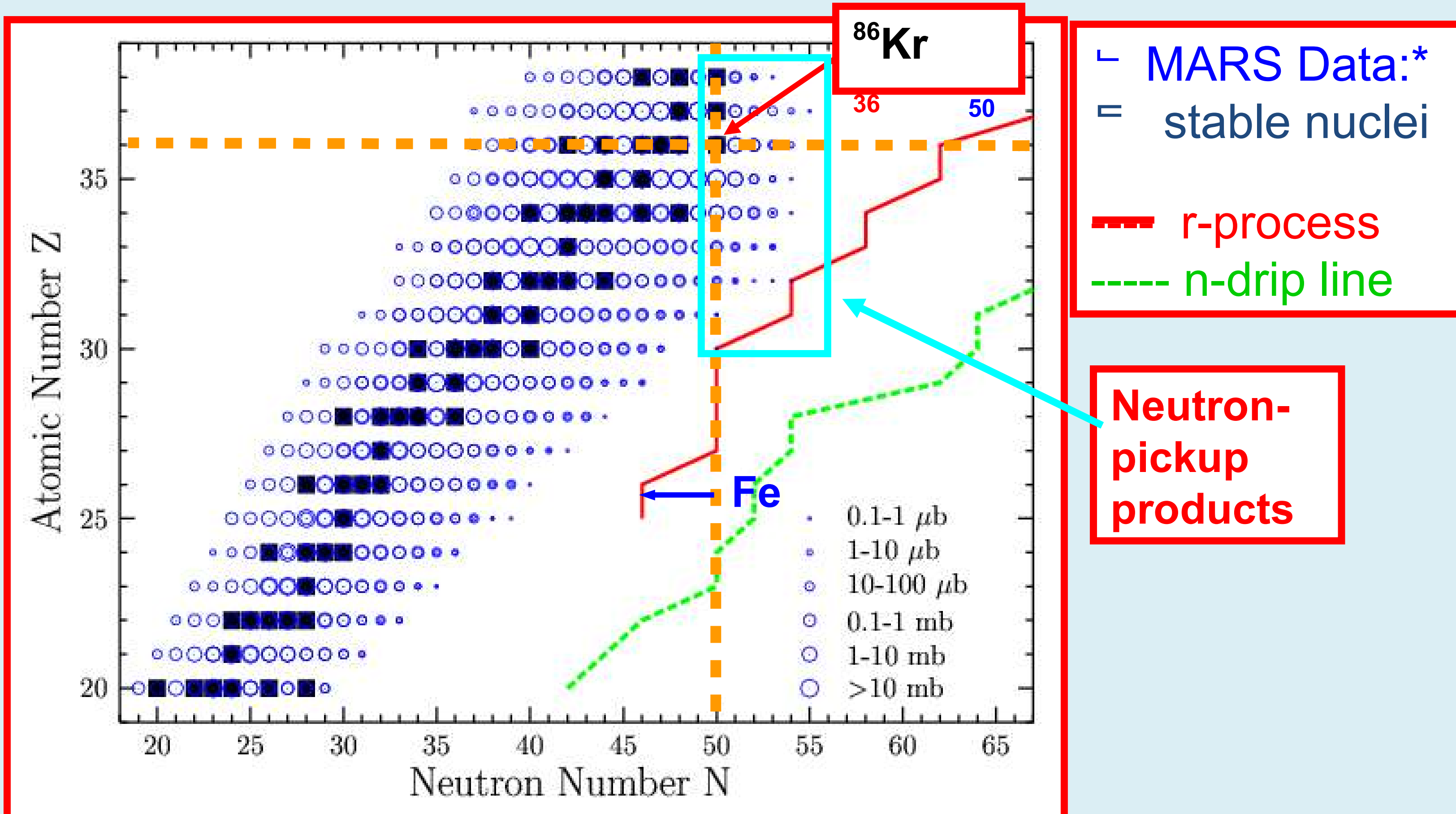
$$B\rho = m\upsilon/Q$$



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

Rare Isotope Production below the Fermi Energy

^{86}Kr (15 MeV/nucleon) + ^{64}Ni



Neutron-Rich Rare Isotopes near and above the **Fe-Ni region** play a critical role in supernova nucleosynthesis (e.g., r-process)

*G. A. Souliotis et al., Phys. Rev C 84, 064607 (2011)

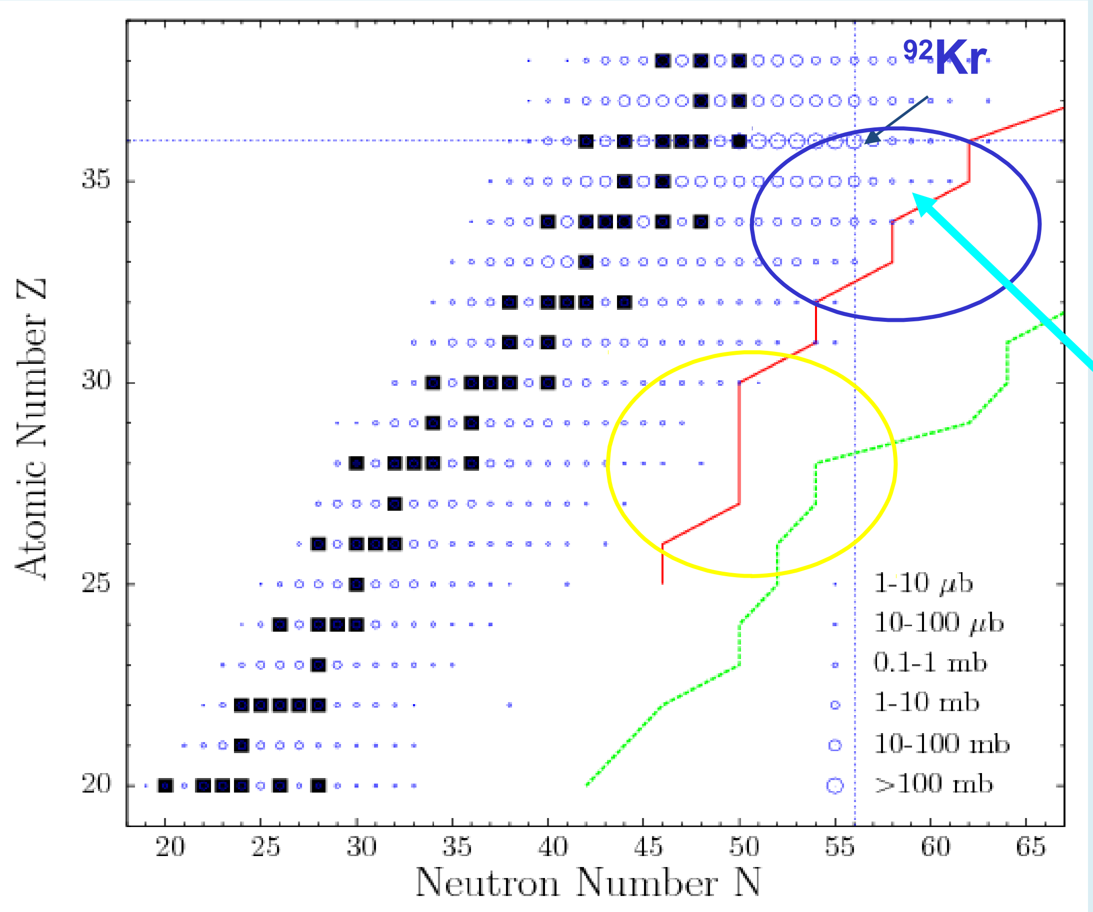
Example of nuclide production using RIBs:

Calculated nuclide cross sections:

Very important:

Neutron-pickup channels !!! along with proton stripping

^{92}Kr (15 MeV/u) + ^{64}Ni



Calculations*: CoMD/SMM

stable nuclides

---- r-process

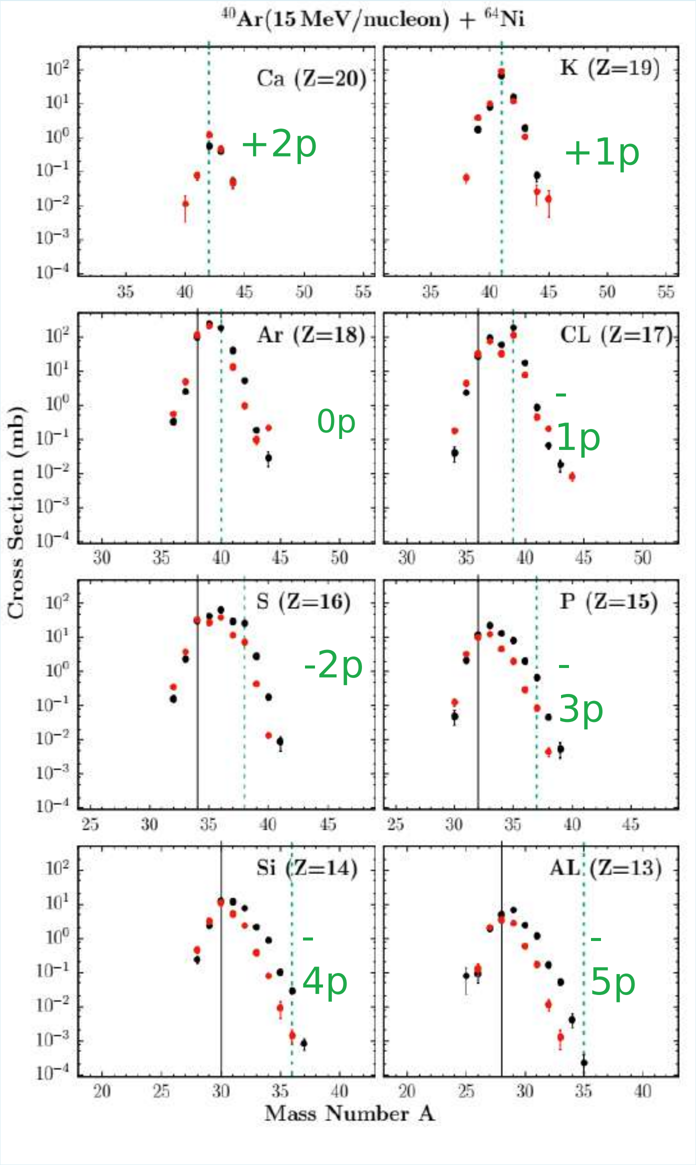
----- n-drip line

Neutron-pickup products

Rate estimates: ^{92}Kr from RIB-facility at 0.5pnA (~3x10^{9}pps), ^{64}Ni (20mg/cm^{2}) :
1mb => 600 pps (pps = particles per second)

- P.N. Fountas, G.A. Souliotis et al, Phys. Rev. C 90, 064613 (2014)
- O. Fasoula, G.A. Souliotis et al, arXiv: 2103.10688 (nucl-ex 2021)

Experimental Data from ^{40}Ar (15MeV/nucleon)+^{64}Ni



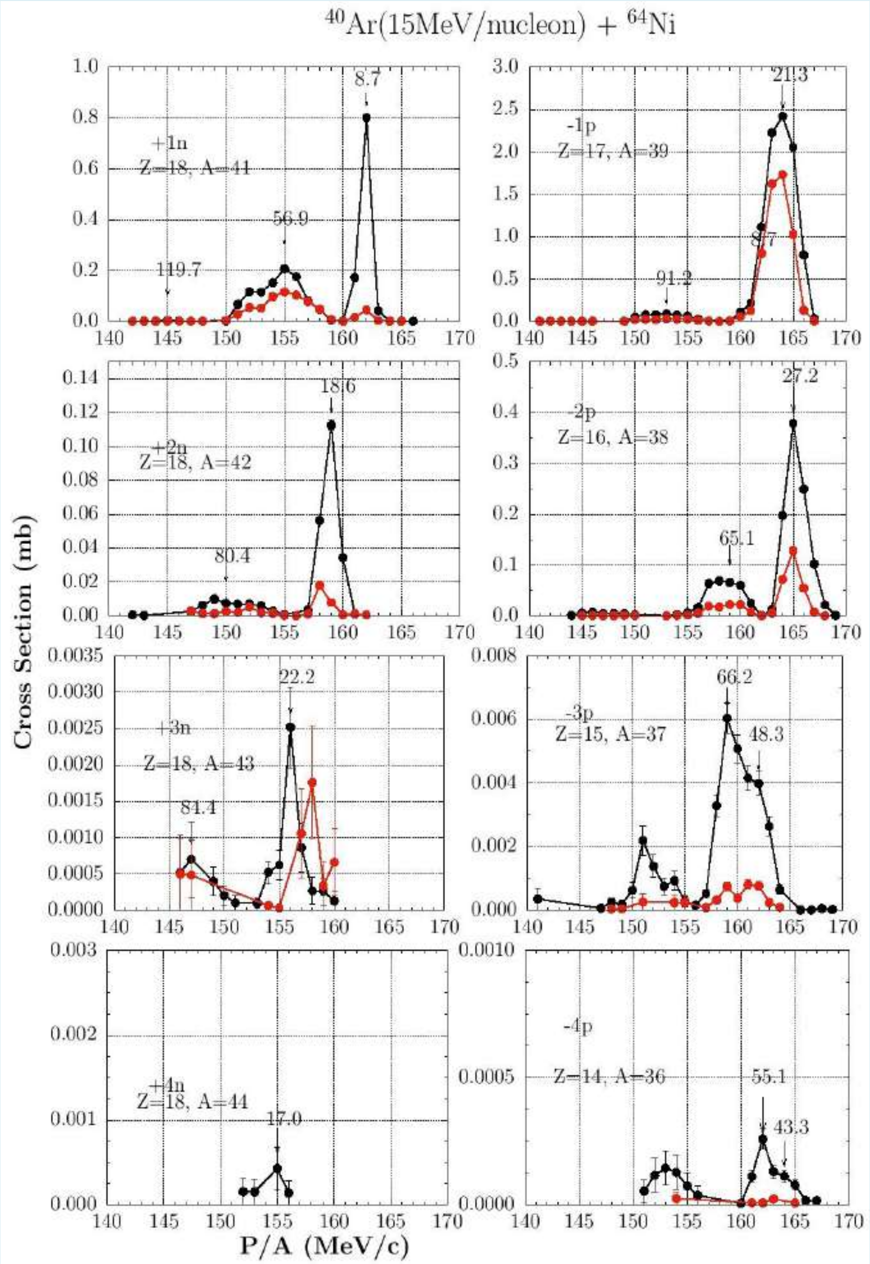
$^{40}Ar + ^{64}Ni$

$^{40}Ar + ^{58}Ni$

- The experimental data were obtained by the MARS Spectrometer at the Cyclotron Institute of Texas A&M University

georgiou, G. Souliotis et al., J. Phys. G: Nucl. Part. Phys. 45 095105 (2018)

Experimental Data : Momentum Distributions

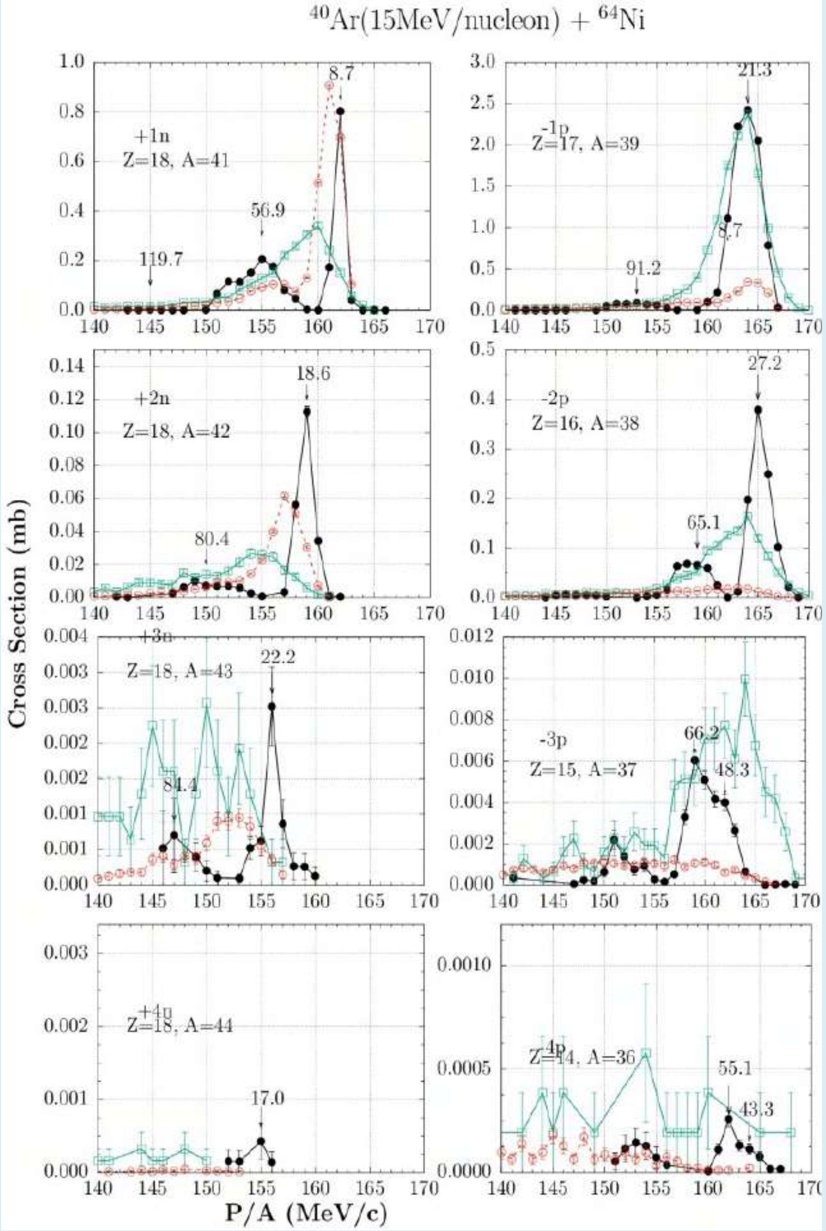


^{40}Ar + ^{64}Ni

^{40}Ar + ^{58}Ni

- The experimental data were obtained by the MARS Spectrometer at the Cyclotron Institute of Texas A&M University
- P/A Resolution: 0.3%
- K. Palli, G.A. Souliotis et al, in progress

Comparison of best calculations DIT vs CoMD Momentum Distributions



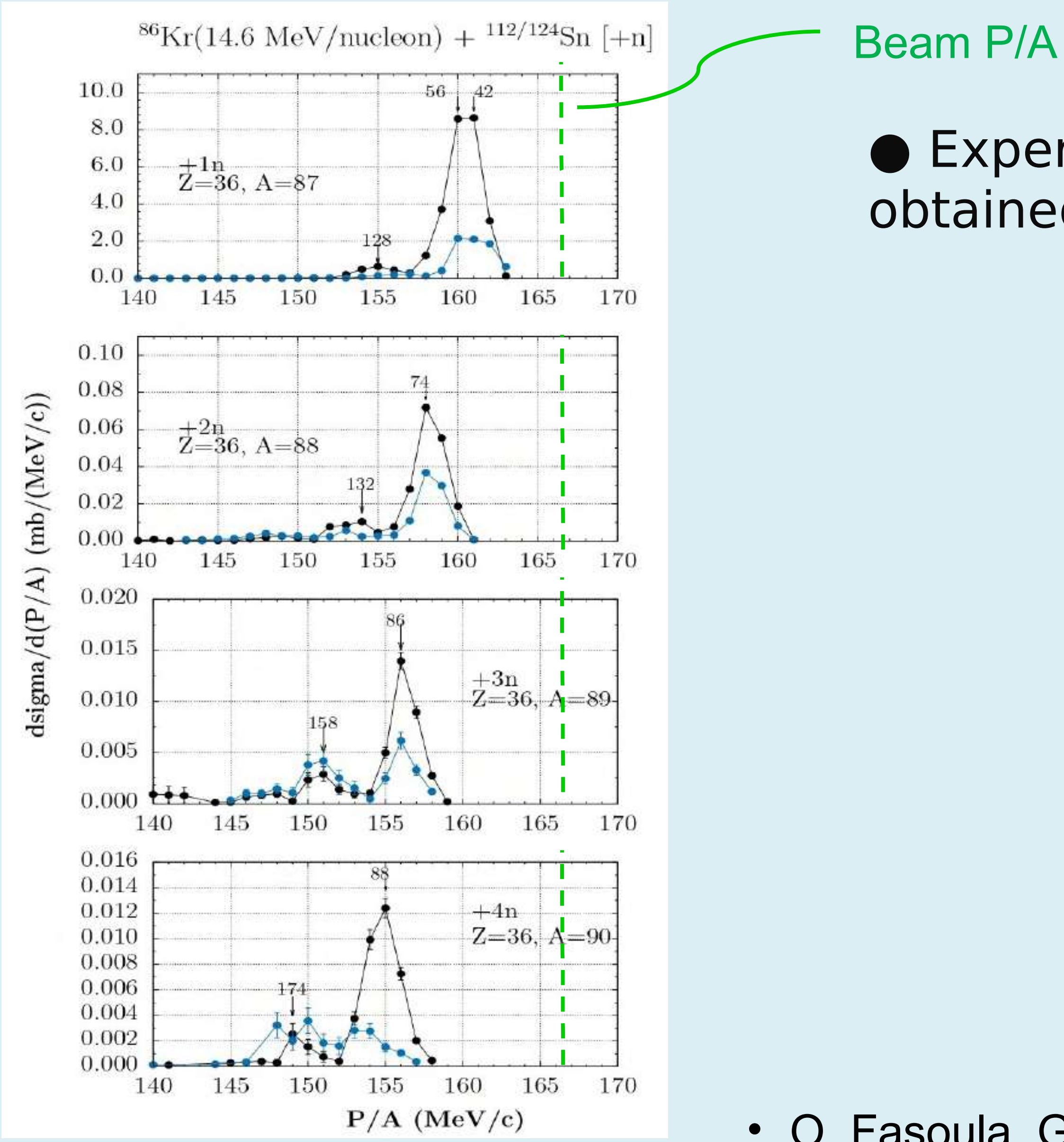
● Experimental Data

Calculations:

- Red dashed line: DIT
- Green full line: CoMD (paulm=87)

• K. Palli, G.A. Souliotis et al, in progress

Experimental Data from ^{86}Kr (15MeV/nucleon)+^{124}Sn, ^{112}Sn
Recent Efforts: Momentum Distributions



● Experimental Data obtained with MARS at 7°

- O. Fasoula, G.A. Souliotis et al, in progress

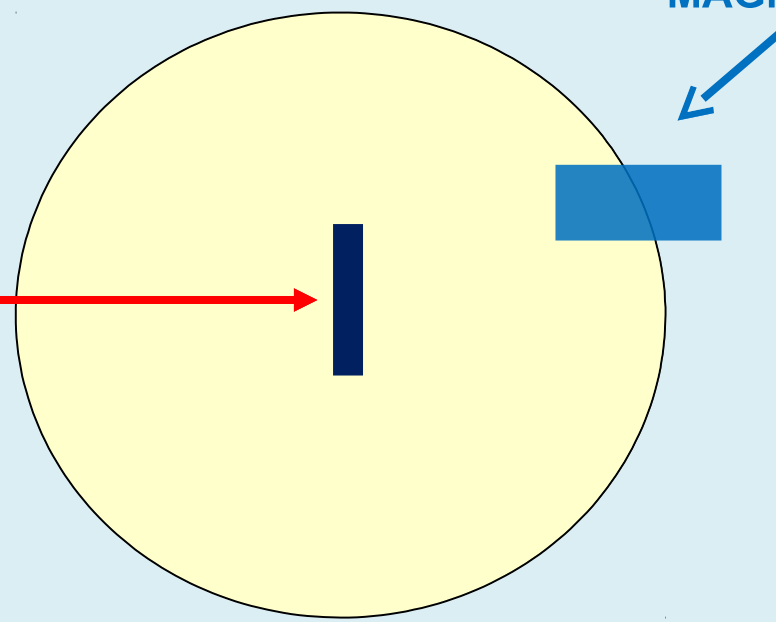
Experimental Efforts at LNS Catania: MAGNEX spectrometer

$\theta_{MAGNEX} = 9^{o}$ $\Delta\theta = 4^{o}\text{-}16^{o}$

F. Cappuzzello et al.,
Eur. Phys. J. A 52, 167 (2016)

Experimental setup: MAGNEX target chamber

MAGNEX 4^0-16^0



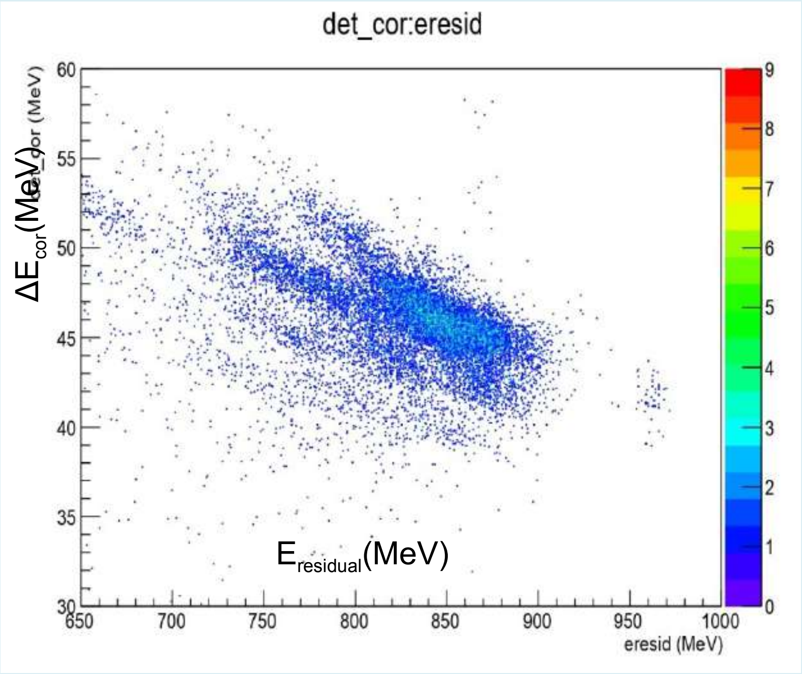
K800 Cyclotron Beam:
^{70}Zn (15 MeV/nucleon)

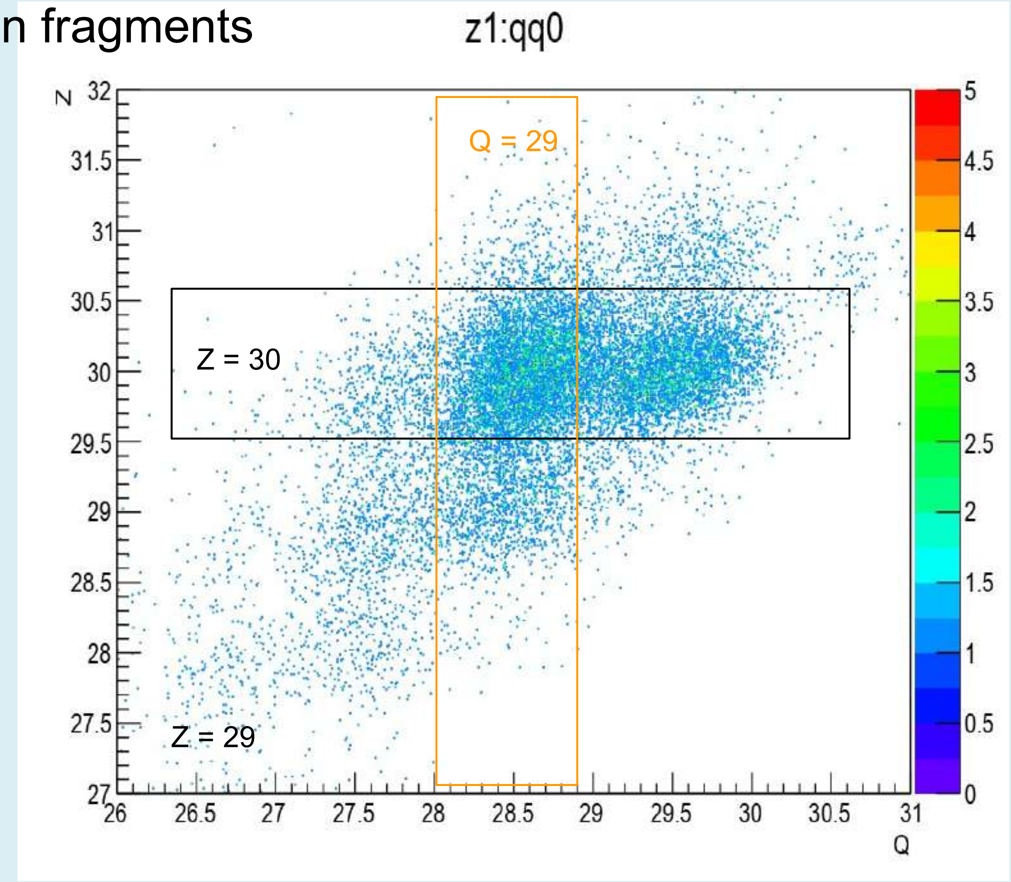
0.5 pnA (3 x 10^9 pps)

^{64}Ni target 1.0 mg/cm^2

Standard MAGNEX setup plus TOF measurement relative to cyclotron RF

Atomic Number Z identification for ^{70}Zn fragments



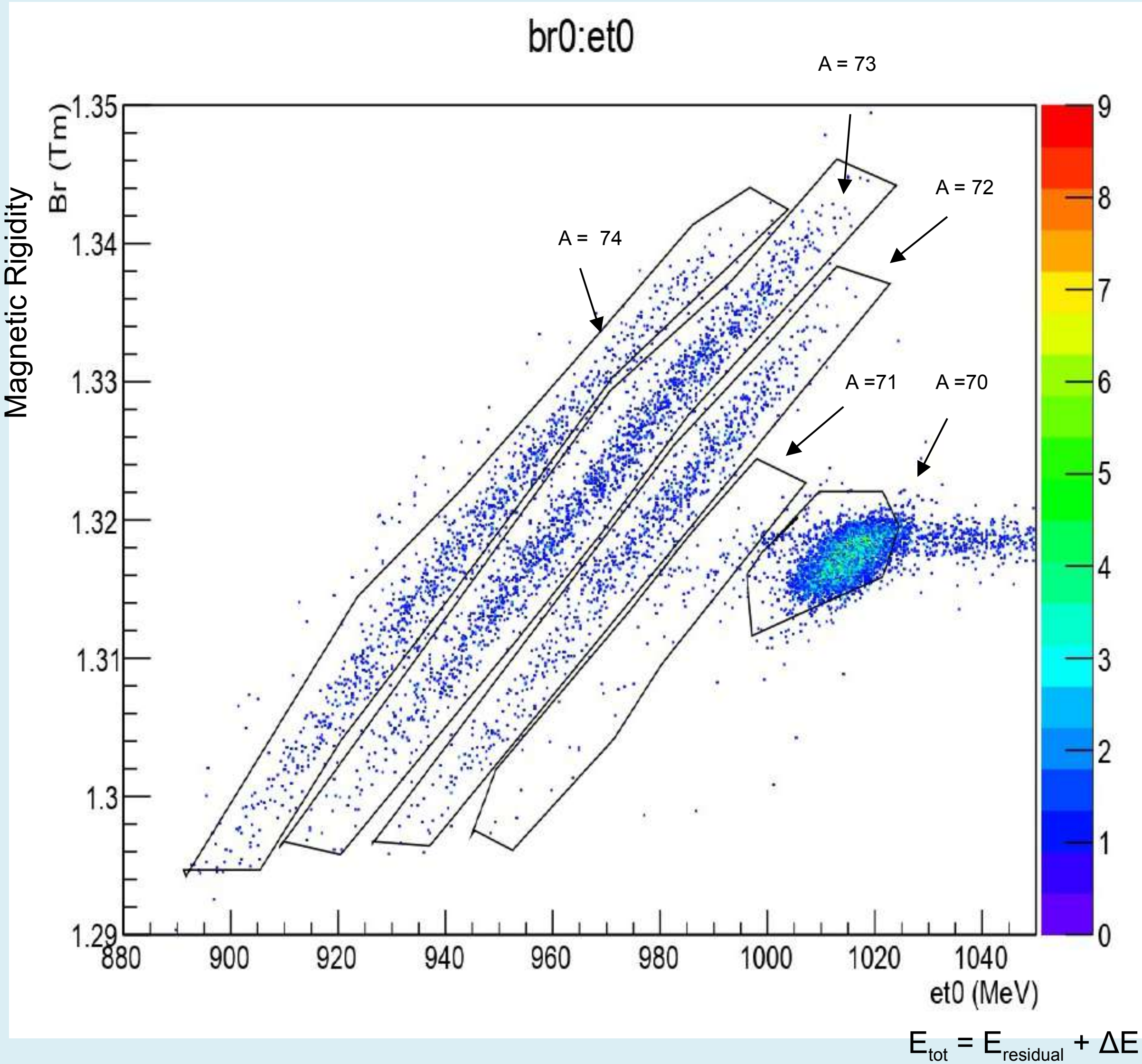


Z = 28

Z reconstruction
Combination of DE, TOF (relative to RF) and trajectory reconstruction

- S. Koulouris, G.A. Souliotis et al, in progress

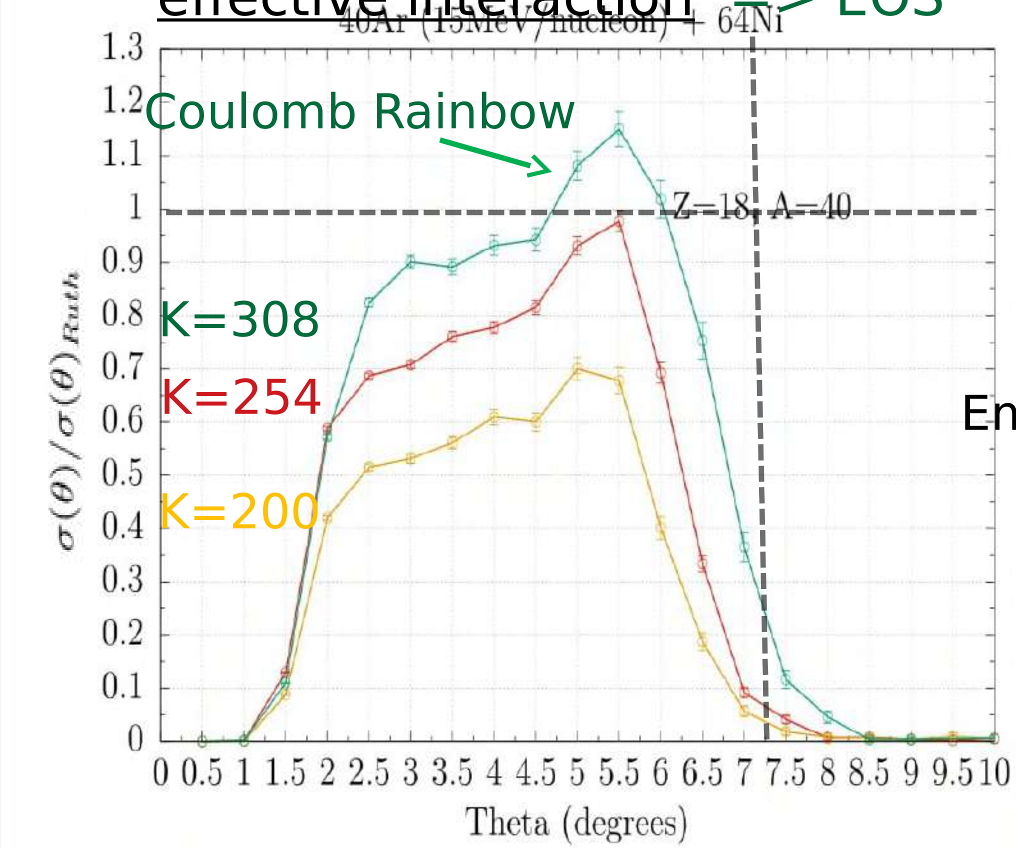
Mass separation and identification of $^{70}Zn + ^{64}Ni$ fragments



- S. Koulouris, G.A. Souliotis et al, in progress

CoMD Calculations: Elastic Scattering

- Angular Distribution Ratio: $(d\sigma/d\Omega)/(d\sigma/d\Omega)_{Ruth}$
- Effect of compressibility K = 200, 254, 308
- Possibility to connect experimental data of **Elastic Scattering** of **medium-mass heavy-ions** to the CoMD effective interaction => EOS



Elastic Channel: Z=18, A=40
b = 0-40 fm
Yellow: K=200
Red: K=254
Green: K=308

Empirical value of $\theta_{1/4} \approx 7.2^{o}$

Next Steps:
Detailed CoMD Calculations
Optical Model Calculations

Obtain DATA from MAGNEX from Zn+Ni run and future runs

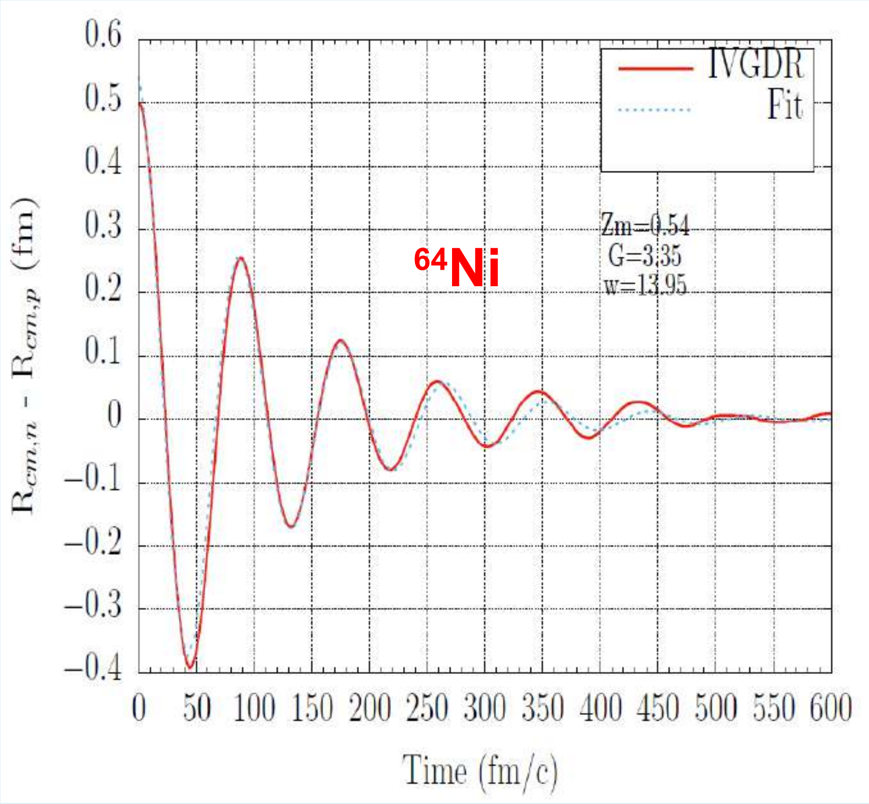
- K. Palli, G.A. Souliotis et al, in progress

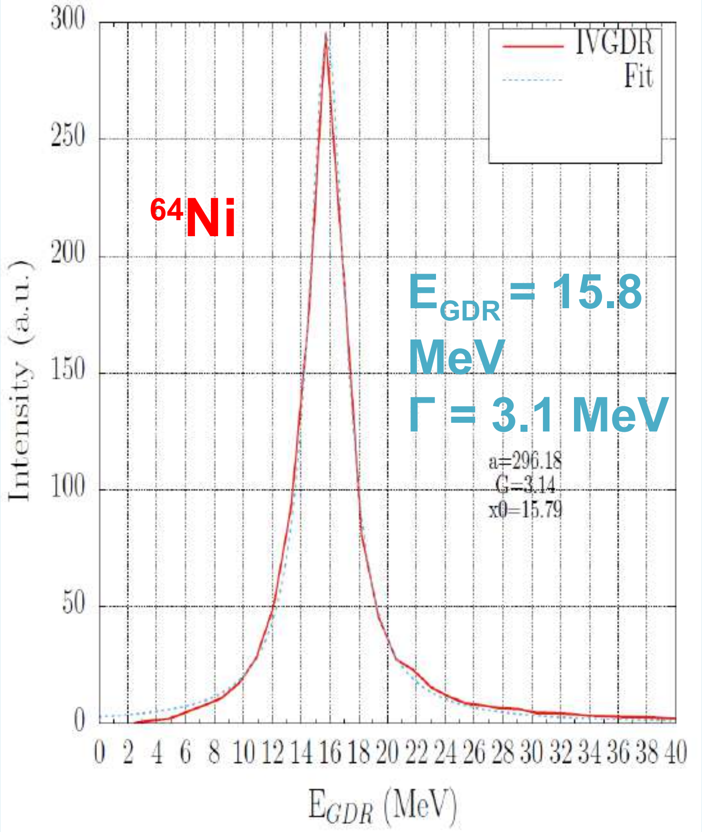
GDR description with the CoMD

$$D(t) = D_0 e^{bt/2} \cos \omega t$$

$$b = \frac{\Gamma}{\hbar} \sim \sigma_{NN}$$

$$I = \frac{(\Gamma/2)\, D_0 \hbar}{(\Gamma/2)^2 + (E - E_D)^2}$$

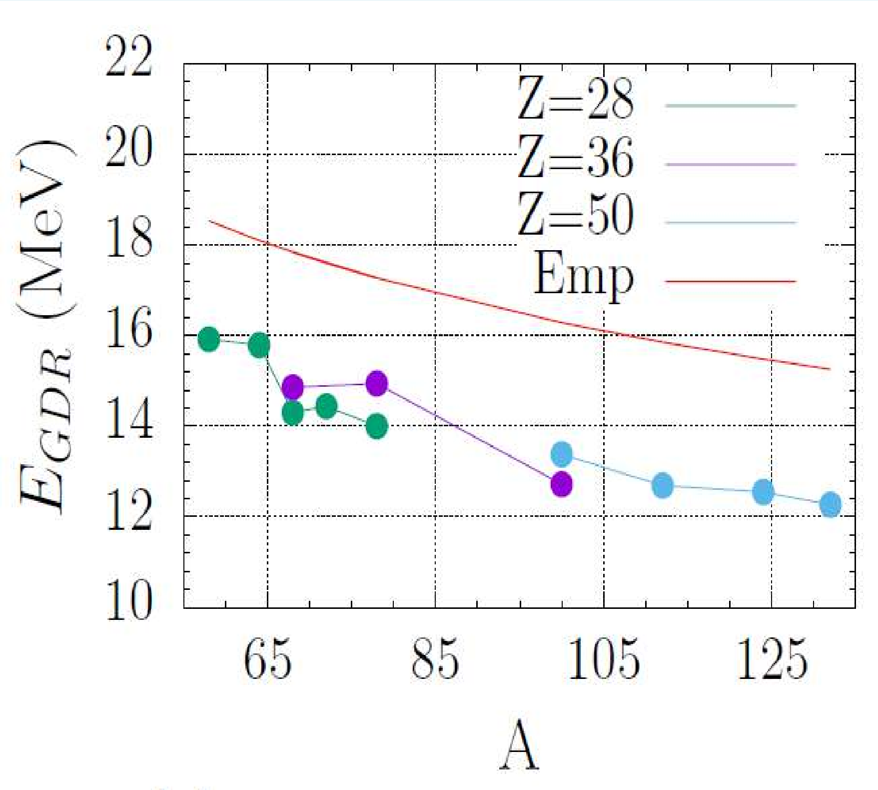




- T. Depastas, G.A. Souliotis et al, in progress

Mass Dependence of GDR & Skin in CoMD

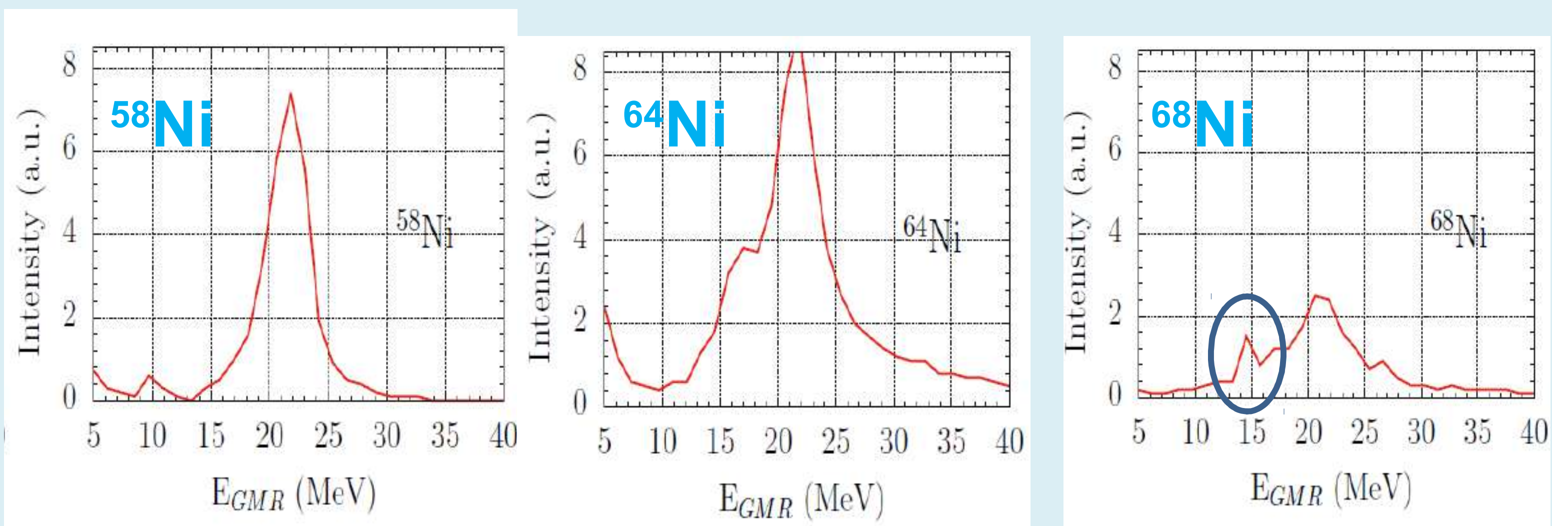
- ❖ GDR ▭ Correct dependency upon $A^{-1/6} + A^{-1/3}$
- ❖ Difference from empirical parameterization by about 2-3 MeV
- ❖ Skin ▭ Linearly dependent upon A



- T. Depastas, G.A. Souliotis et al, in progress

Giant Monopole Resonances in CoMD

- ❖ Momentum Space Iso-Scalar Perturbation
- ❖ Fourier Transform of Radius over time ▭ GMR Spectrum
- ❖ ^{58,64,68}Ni ▭ E_{GMR} ~ 22 MeV (experimental 21.1 ± 1.9 MeV)
- ❖ Soft monopole for ^{68}Ni ▭ E_{soft} ~ 14.5 MeV (experimental 12.9 ± 1.0 MeV)X. Sun, *Phys Rev C*, **103** 044603 (2021)



- T. Depastas, G.A. Souliotis et al, in progress

NUCLEAR PHYSICS

From nuclear clusters to neutron stars

Measurements of α cluster formation in nuclear "skins" can improve neutron star models

By **Or Hen**

When neutron stars are formed, their massive gravitational pressure "crushes" most of their protons and electrons into neutrons. Understanding the interaction between the remaining protons (~5%) and neutrons in the star's core is required to model the neutron star equation of state, which relates its pressure and density and determines many of its macroscopical properties. These proton-neutron interactions are governed by the extremely complex strong nuclear force that challenges direct EOS calculations. This problem is traditionally overcome by using effective mean-field models. Although overall instructive, the important impact of nucleon-nucleon correlations and nuclear clusters are usually not explicitly included in these calculations. On page 260 of this issue, Tanaka *et al.* (*1*) now report precise measurements of α cluster (helium-4 nuclei) formation in the outer neutron "skin" of a wide range of neutron-rich tin isotopes that should help constrain models.

A neutron star is born when a massive star runs out of nuclear fuel. After all of the matter at the very center of the star has been transformed into iron or similar elements through nuclear fusion, it collapses under its own gravitational pressure and leaves an extremely compact remnant (*2*). A typical neutron star is about as big as Manhattan (~10 km radius) but has about 1.4 times the mass of the Sun (~10^6 times the mass of Earth). The density inside their core ranges from about two to five times that of atomic nuclei.

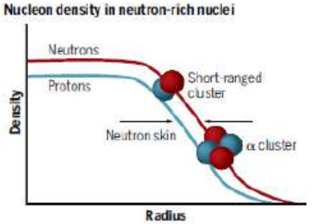
energy between symmetric nuclear matter (in which the number of protons equals the number of neutrons) and pure neutron matter at density ρ. The density dependence of the symmetry energy is then described by its slope, $L(\rho) = 3\rho\, dE_{sym}(\rho)/d\rho$. The symmetry energy is well constrained at the density of terrestrial atomic nuclei (ρ_0), but its density dependence $L(\rho_0)$ is not (*3, 4*).

Determining *L* would greatly improve modeling of the matter inside the cores of neutron stars. Usually, the method used to constrain *L* is to measure nuclear neutron

Probing neutron skins

The neutron skin, the region where neutron density exceeds proton densities in nuclei, is affected by α cluster formation in the outer low-density regions (as measured by Tanaka *et al.*) and short-ranged clusters at higher-density regions.

Nucleon density in neutron-rich nuclei



skins, which are the differences between the radii of the neutron and proton distributions in neutron-rich nuclei (*2, 5*). This method is based on the density decrease of atomic nu-

increasing mass number, are directly sensitive to the abundance of α clusters. Their dependence on the proton-neutron asymmetry of the measured isotopes showed excellent agreement with the mean-field models that include cluster effects (*8, 9*). The same calculations also show that cluster formation affects the correlation between the neutron skin and the density dependence of the symmetry energy. This finding is supported by the recent chiral dynamics study of Miller *et al.* (*10*), which found that a different type of clustering—two-nucleon short-range correlations (*11, 12*)—can also potentially affect the thickness of the neutron skin.

The impact of such cluster correlations was previously considered but deemed to be negligible compared with the large experimental uncertainties in the determination of the neutron skin. This assumption is now being challenged by a new generation of high-precision experiments. Most notably, the PREX (^{208}Pb Radius Experiment) collaboration (*13*) at the U.S. Jefferson Lab accelerator uses parity-violating elastic electron scattering to directly measure the neutron radius of lead and recently reported achieving 1% accuracy. Along with precision measurements made with pion photoproduction reactions (*14*) by the Crystal Ball collaboration at the German Mainz Microtron (MAMI) accelerator, future measurements may reach 0.5% accuracy. The results of Tanaka *et al.* call for new precision theoretical calculations that directly account for nuclear correlations and clusters. Such theoretical advances are in progress (*15*) and will enable a precise extraction of the density dependence of the symmetry energy from the

REPORT

NUCLEAR PHYSICS

Formation of α clusters in dilute neutron-rich matter

Junki Tanaka[1,2,3]*, Zaihong Yang[3,4]*, Stefan Typel[1,2], Satoshi Adachi[4], Shiwei Bai[5], Patrik van Beek[1], Didier Beaumel[6], Yuki Fujikawa[7], Jiaxing Han[5], Sebastian Heil[1], Siwei Huang[5], Azusa Inoue[4], Ying Jiang[5], Marco Knösel[1], Nobuyuki Kobayashi[4], Yuki Kubota[3], Wei Liu[5], Jianling Lou[5], Yukie Maeda[8], Yohei Matsuda[9], Kenjiro Miki[10], Shoken Nakamura[4], Kazuyuki Ogata[4,11], Valerii Panin[3], Heiko Scheit[1], Fabia Schindler[1], Philipp Schrock[12], Dmytro Symochko[1], Atsushi Tamii[4], Tomohiro Uesaka[3], Vadim Wagner[1], Kazuki Yoshida[13], Juzo Zenihiro[3,7], Thomas Aumann[1,2,14]

The surface of neutron-rich heavy nuclei, with a neutron skin created by excess neutrons, provides an important terrestrial model system to study dilute neutron-rich matter. By using quasi-free α cluster–knockout reactions, we obtained direct experimental evidence for the formation of α clusters at the surface of neutron-rich tin isotopes. The observed monotonous decrease of the reaction cross sections with increasing mass number, in excellent agreement with the theoretical prediction, implies a tight interplay between α-cluster formation and the neutron skin. This result, in turn, calls for a revision of the correlation between the neutron-skin thickness and the density dependence of the symmetry energy, which is essential for understanding neutron stars. Our result also provides a natural explanation for the origin of α particles in α decay.

Table 1. Experimental and theoretical values of the tin isotope parameters. Target thicknesses and enrichments of the tin-isotope targets, the experimental and theoretical cross sections, the effective number of α clusters, and the theoretical neutron-skin thicknesses Δr_{np} from the gRDF prediction (*23*). The calculations were performed with the DD2 parameters (*5*) for the effective interaction without and with the α clusters. In the last column, the value is the percentage by which Δr_{np} is reduced when α clusters are included. nb, nanobarn.

Tin isotope	Target thickness (mg/cm²)	Isotopic enrichment (%)	Experimental cross sections (nb)	Theoretical cross sections (nb)	Effective number of α clusters	Theoretical Δr_{np} without α (fm)	Theoretical Δr_{np} with α (fm)	Relative Δr_{np} change (%)
^{112}Sn	40.2(4)	95.1(1)	0.157(12)	0.160	0.3876	0.0495	0.0277	−44
^{116}Sn	39.3(4)	97.8(2)	0.129(16)	0.127	0.3304	0.0843	0.0580	−31
^{120}Sn	39.9(4)	99.6(1)	0.090(13)	0.095	0.2668	0.1179	0.0912	−23
^{124}Sn	40.7(4)	97.4(2)	0.073(10)	0.065	0.1958	0.1505	0.1275	−15

Tanaka *et al.*, *Science* **371**, 260–264 (2021) 15 January 2021

232 15 JANUARY 2021 • VOL 371 ISSUE 6526 sciencemag.org SCIENCE

MOTIVATION: Explore signatures of a-clustering in the peripheral collisions ^{86}Kr+^{112}Sn,^{124}Sn

Summary and Conclusions

- Investigation of peripheral reactions at 15 MeV/nucleon: production of neutron-rich nuclides.
- Study of the experimental mass distributions and the recently extracted momentum distributions with the theoretical models: phenomenological model DIT, microscopical model CoMD.
- Experimental work on MAGNEX data that will provide yields, angular and momentum distributions
- CoMD work on ground state and giant resonance dynamics
- <u>**Future Goals:**</u>
- In the CoMD framework: compressibility K, symmetry energy, in-medium NN scattering cross sections.
- DWBA-type calculations with the FRESCO code (elastics, 1, 2 nucleon transfer)
- Presence and role of cluster transfer (a, 3He, t, heavier-clusters??)
- Develope a theoretical framework for predictions of the production of neutron-rich nuclei.
- In parallel, use this framework to obtain information on the effective NN interaction

Experimental: identidy key reactions in the Fermi energy region (10-3[illegible] MeV[illegible]

Propose experiment(s) to obtain high-resolution data in the upgraded [illegible] M[illegible]

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NATIONAL & KAPODISTRIAN UNIVERSITY OF ATHENS

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University of Catania and LNS/INFN

Prof. Francesco Cappuzzello and his group

Texas A&M Cyclotron Institute

Prof. Sherry Yennello (director) and her group

End of Talk: Additional slides here

PHYSICAL REVIEW LETTERS **126**, 172502 (2021)

Editors' Suggestion | Featured in Physics

Accurate Determination of the Neutron Skin Thickness of ^{208}Pb through Parity-Violation in Electron Scattering

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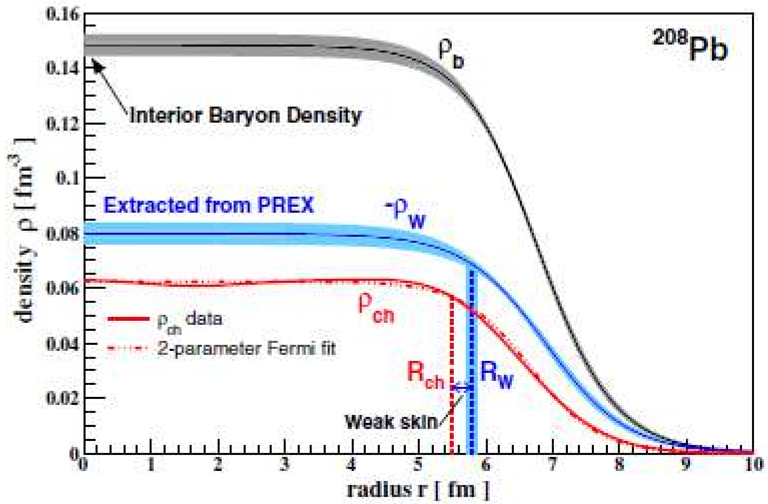

FIG. 4. ^{208}Pb weak and baryon densities from the combined PREX datasets, with uncertainties shaded. The charge density [46] is also shown.

TABLE III. PREX-1 and -2 combined experimental results for ^{208}Pb. Uncertainties include both experimental and theoretical contributions.

^{208}Pb Parameter	Value
Weak radius (R_W)	5.800 ± 0.075 fm
Interior weak density (ρ_W^0)	-0.0796 ± 0.0038 fm^{-3}
Interior baryon density (ρ_b^0)	0.1480 ± 0.0038 fm^{-3}
Neutron skin ($R_n - R_p$)	0.283 ± 0.071 fm

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Editors' Suggestion

Implications of PREX-2 on the Equation of State of Neutron-Rich Matter

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Laboratory experiments sensitive to the equation of state of neutron rich matter in the vicinity of nuclear saturation density provide the first rung in a "density ladder" that connects terrestrial experiments to astronomical observations. In this context, the neutron skin thickness of ^{208}Pb ($R^{208}_{\rm skin}$) provides a stringent laboratory constraint on the density dependence of the symmetry energy. In turn, an improved value of $R^{208}_{\rm skin}$ has been reported recently by the PREX collaboration. Exploiting the strong correlation between $R^{208}_{\rm skin}$ and the slope of the symmetry energy L within a specific class of relativistic energy density functionals, we report a value of $L = (106 \pm 37)$ MeV—which systematically overestimates current limits based on both theoretical approaches and experimental measurements. The impact of such a stiff symmetry energy on some critical neutron-star observables is also examined.

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The updated Lead Radius EXperiment (PREX-2) has delivered on the promise to determine the neutron radius of ^{208}Pb with a precision of nearly 1%. By combining the original PREX result [1,2] with the newly announced PREX-2 measurement, the following value for the neutron skin thickness of ^{208}Pb was reported [3]:

$$R_{\rm skin} = R_n - R_p = (0.283 \pm 0.071)\ {\rm fm}, \qquad (1)$$

tribution for L displayed in Fig. 1(b). Using the same analysis on both J and $\tilde{L}$—the latter representing the slope of the symmetry energy at $\tilde{\rho}_0$—we derive the following limits:

$$J = (38.1 \pm 4.7)\ {\rm MeV}, \qquad (5a)$$

$$L = (106 \pm 37)\ {\rm MeV}, \qquad (5b)$$

$$\tilde{L} = (71.5 \pm 22.6)\ {\rm MeV}. \qquad (5c)$$

As indicated in Fig. 1(b), these limits are systematically larger than those obtained using either purely theoretical approaches or extracted from a theoretical interpretation of experimental data [14,19–25]. We underscore that the models used in this Letter represent a particular class of relativistic EDFs.

We note that theoretical interpretations of elastic nucleon-nucleus scattering cross sections together with quasielastic reactions to isobaric analog states obtained limits on L that are consistent with our findings [26]. The PREX-2 result is also considerably larger—and in many