Production of Neutron-Rich Rare Isotopes toward the astrophysical r-proceess

Georgios A. Souliotis

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

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ΕΘΝΙΚΟΝ & ΚΑΠΟΔΙΣΤΡΙΑΚΟΝ ΠΑΝΕΠΙΣΤΗΜΙΟΝ ΑΘΗΝΩΝ
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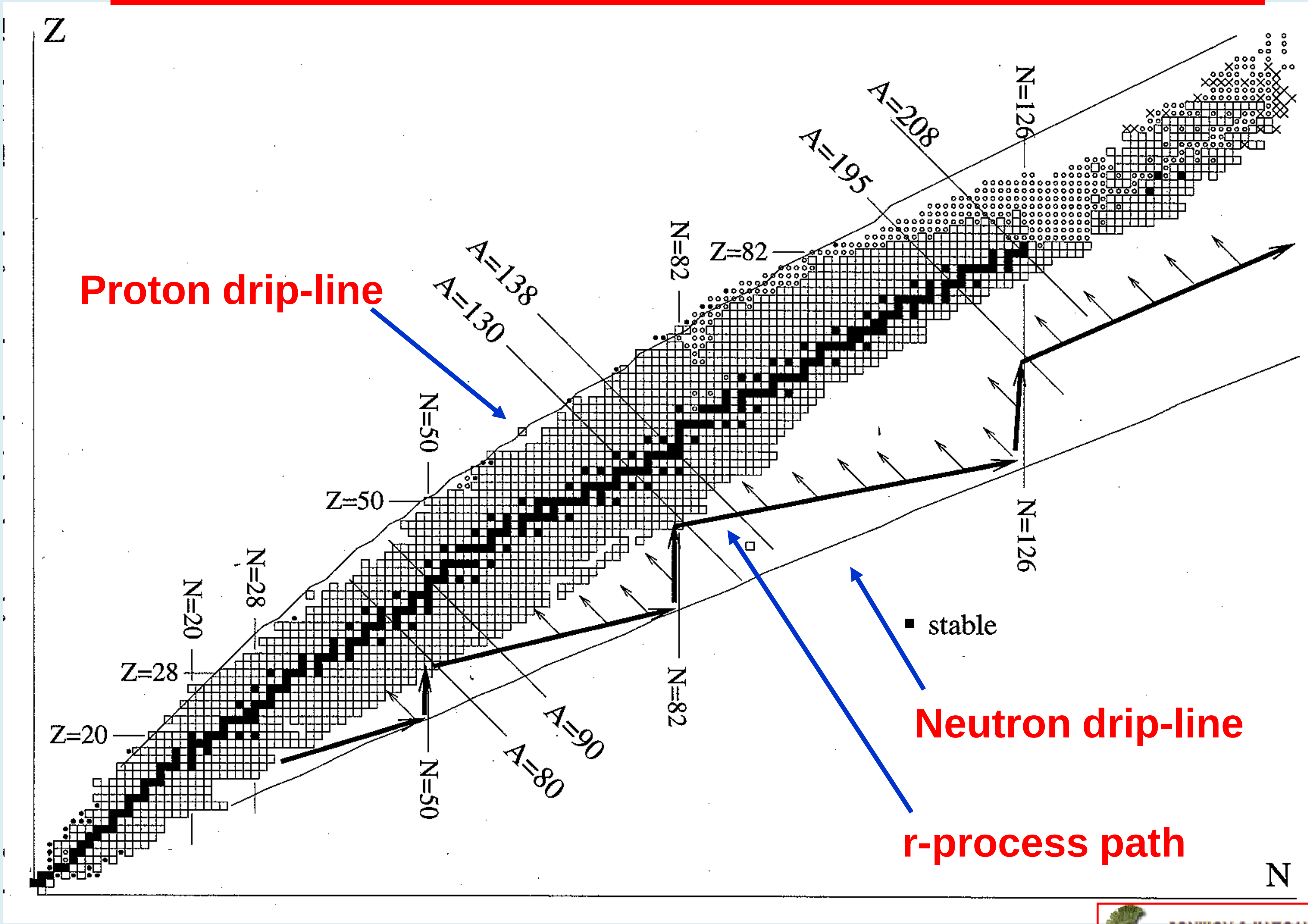
Outline

- **Introduction**
  - **Chart of Nuclides**
  - **Nucleosynthesis processes: focus on trans-Fe elements**
- **Research Results and Directions**
  - **Rare Isotope Production**
  - **Nuclear Fission – Spallation**
- **Summary-Conclusions**

The Nuclear Landscape and the r-process path



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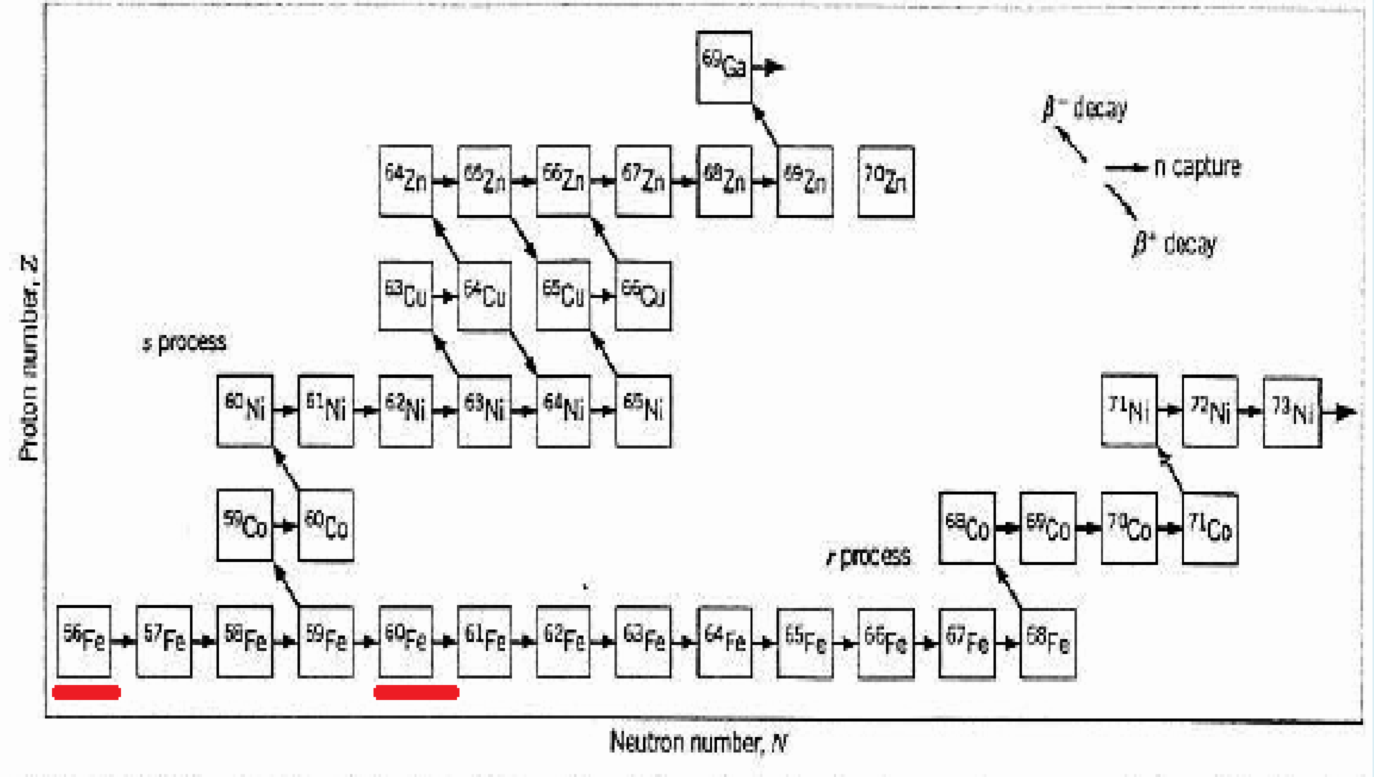
Rapid Neutron capture process (r-process)

•$\rho_n = 10^{22} – 10^{24}$ cm^{-3}
• T = 1.0-3.0*10^9 K

$t_{r\text{-}proc} \sim$ 1-10 s

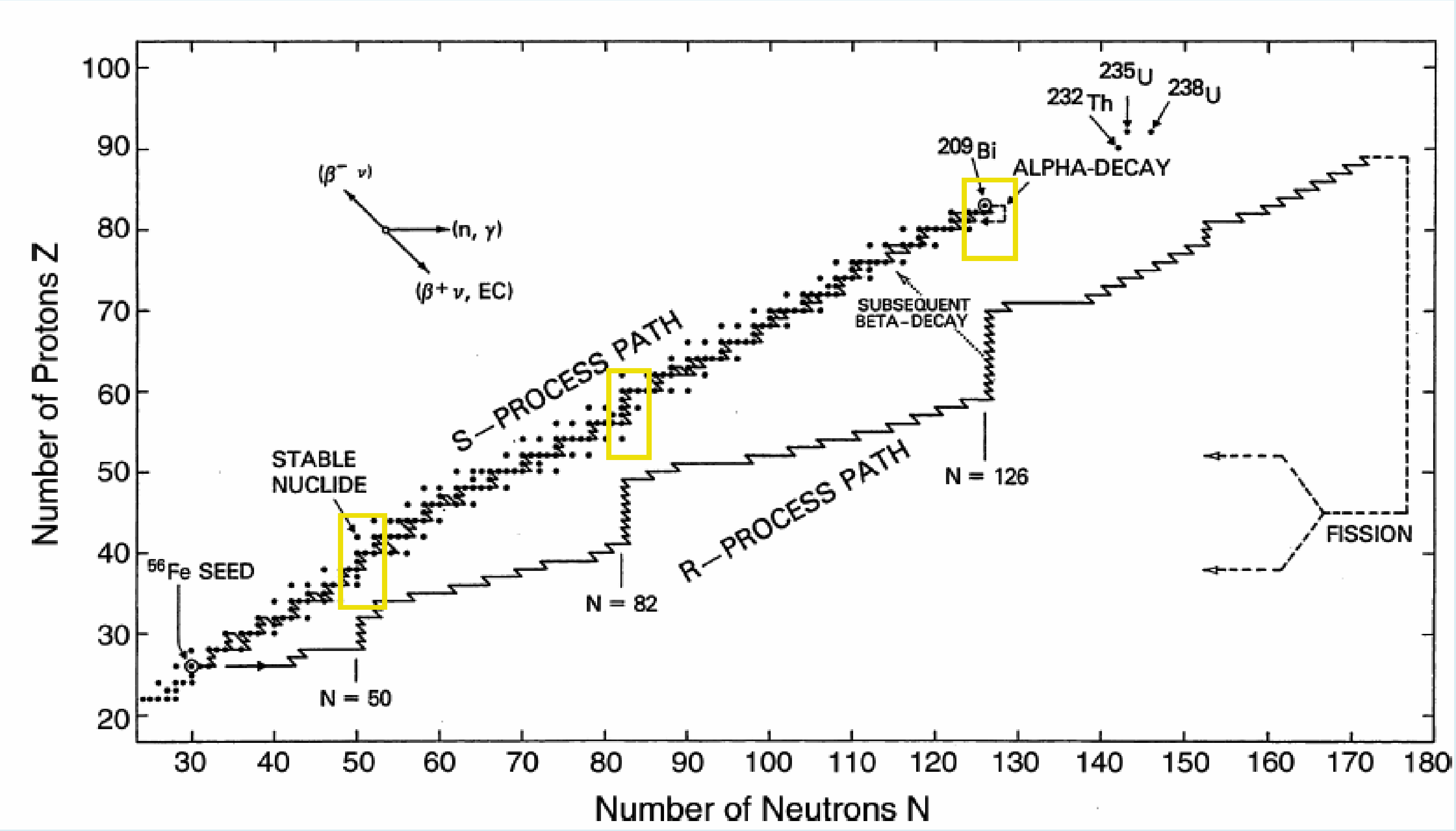
$t_{r\text{-}proc} \ll t_{\beta\text{-}decay.}$



^{59}Fe $t_{1/2}$ = 44.5 d,
^{68}Fe $t_{1/2}$ = 0.019 s, ^{71}Co $t_{1/2}$ =0.09 s, ^{76}Ni $t_{1/2}$ = 0.24 s

* e.g. C.A. Bertulani, T. Kajino, Prog. Nucl. Part. Physics 89, 56 (2016)

s,r processes

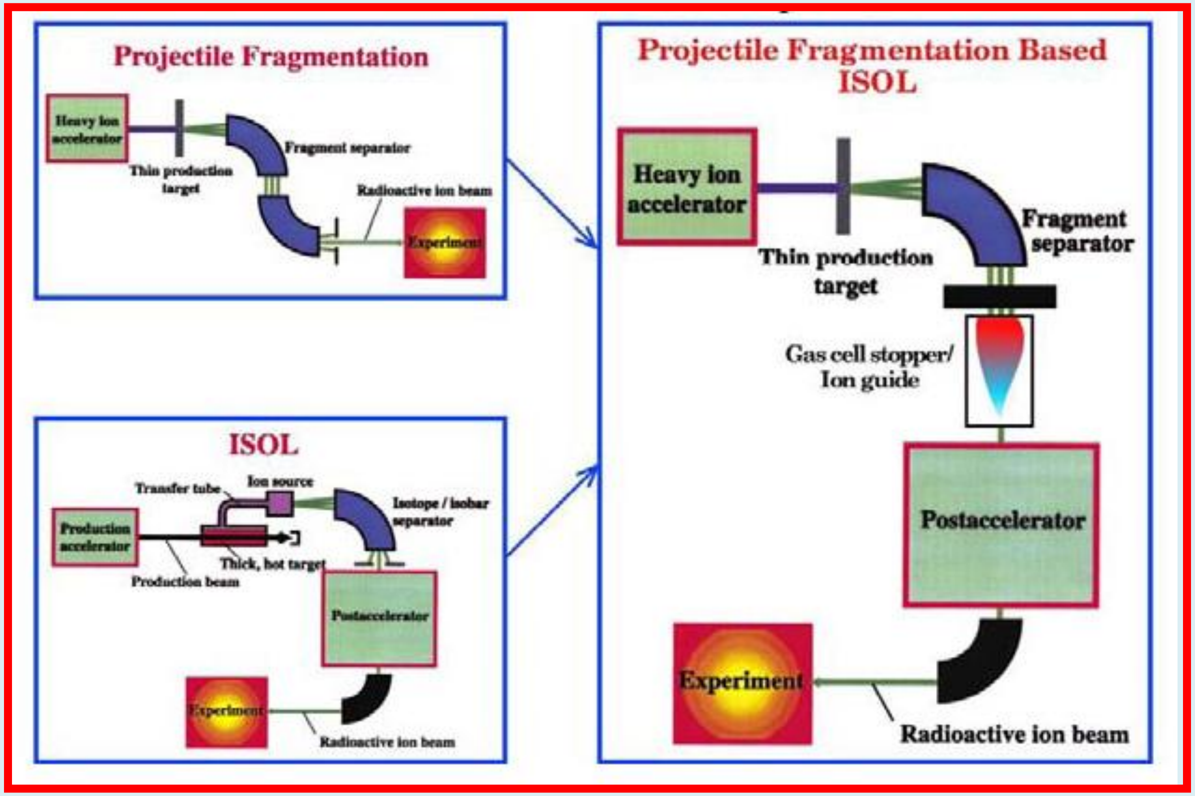


* e.g. C.A. Bertulani, T. Kajino, Prog. Nucl. Part. Physics 89, 56 (2016)

Production Methods of Rare Isotope Beams[1]

Projectile Fragmentation

(In-Flight) Techniques



Isotope Separation On-Line

ISOL Techniques

Combination Method

Main Mechanisms to Produce Neutron-Rich Nuclides:

- **Projectile (or target) fission**
- **Projectile (or target) fragmentation**

[1] H. Geissel, Ann. Rev. Nucl. Part. Sci., **1995,** *45,* 163.

[2] D. Geesaman, Ann. Rev. Nucl. Part. Sci., **2006,** *56,* 53.

*http://www.sc.doe.gov/np/nsac/nsac.html

RIB facility @ S. KOREA: Raon

Raon: 라온 meaning happy/joyful in Korean

Raon: Heavy ion accelerator planned to be constructed by 2021 in South Korea

RISP (Rare Isotope Science Project): Research facility of the **IBS** (Institute for Basic Science), Daejeon, South Korea

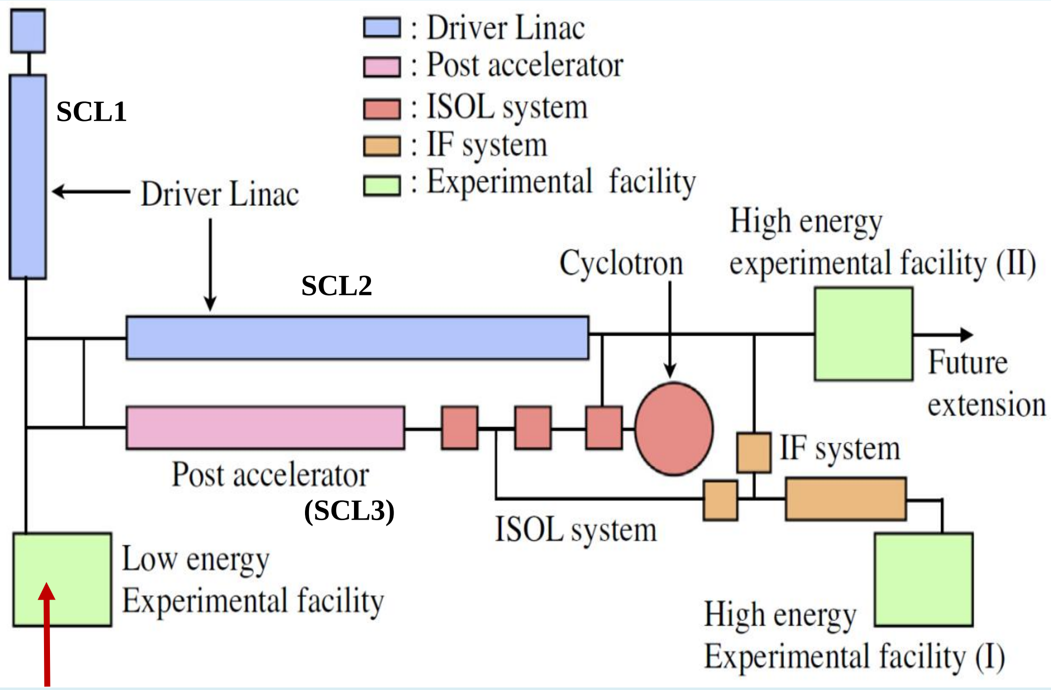
https://www.ibs.re.kr/eng/sub01_05.do

FUTURE ACCELERATOR COMPLEX IN RAON

Innovative feature: ISOL + IF facilities (ideally coupled)

For IF: ~200 MeV/nucleon
From ISOL: ~20 MeV/nucleon
SCL: Superconducting linear accelerator

Initial phase of operation:
stable beams 15-25 MeV/nucleon
KOBRA separator



KOBRA
Korea Broad acceptance Recoil spectrometer and Apparatus

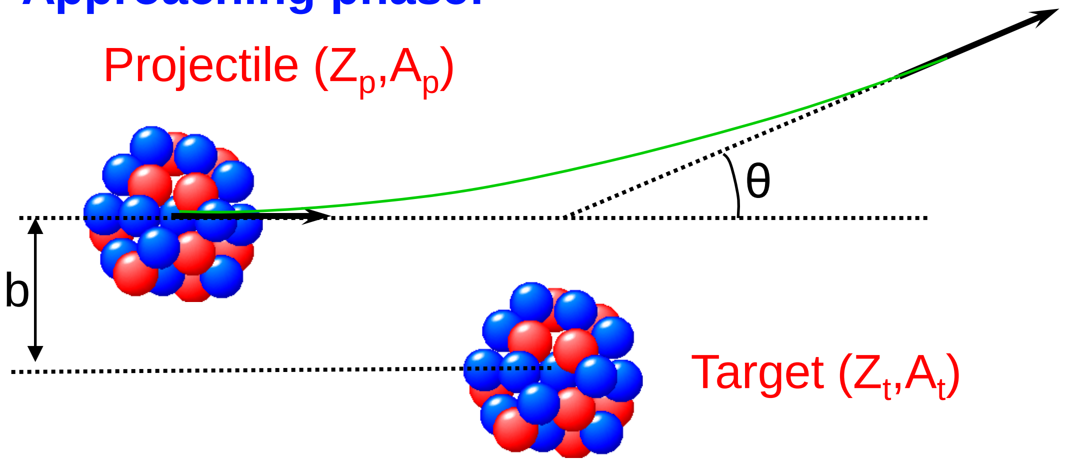
http://risp.ibs.re.kr/eng/orginfo/info_blds.do

Characteristics of Nuclear Reactions: Energy Regimes

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

Collisions between Heavy Ions at Fermi Energies (E/A < 50MeV)

Approaching phase:



- Neutrons
- Protons

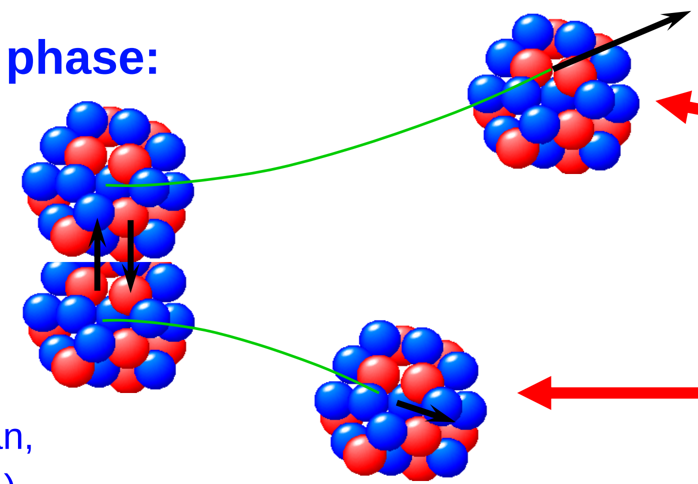
b: impact parameter

θ: scattering angle

Grazing angle, θ_{gr}:
nuclei in touching configuration

Overlap (interaction) phase:

exchange of nucleons:



excited projectile-like fragment (PLF) or quasi-projectile

excited target-like fragment (TLF) or quasi-target

Deep Inelastic Transfer (DIT) Model

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

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)

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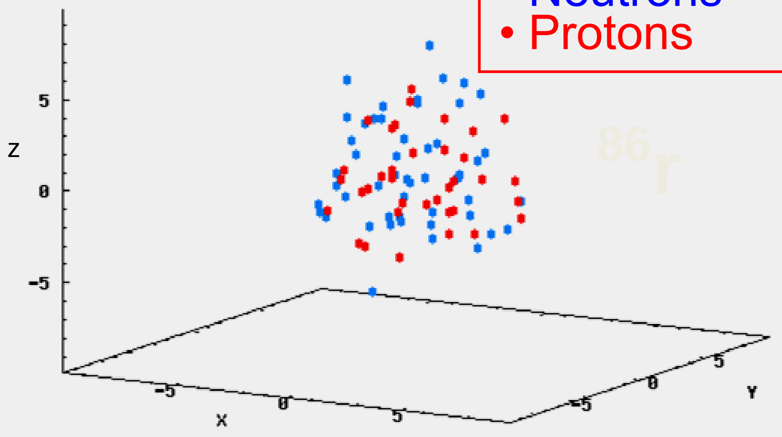
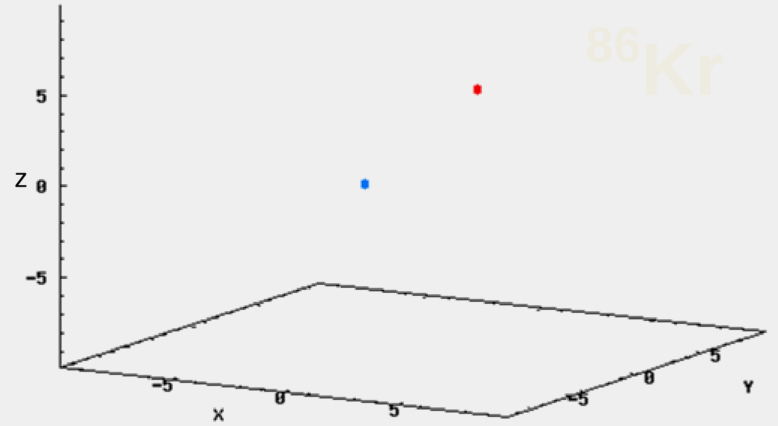
Microscopic Calculations: Constrained Molecular Dynamics (CoMD)*

CoMD Evolution of ^{86}Kr Nucleus:
t = 0-500 fm/c   Δt = 10 fm/c

- Neutrons
- Protons



Nucleon Trajectories in ^{86}Kr



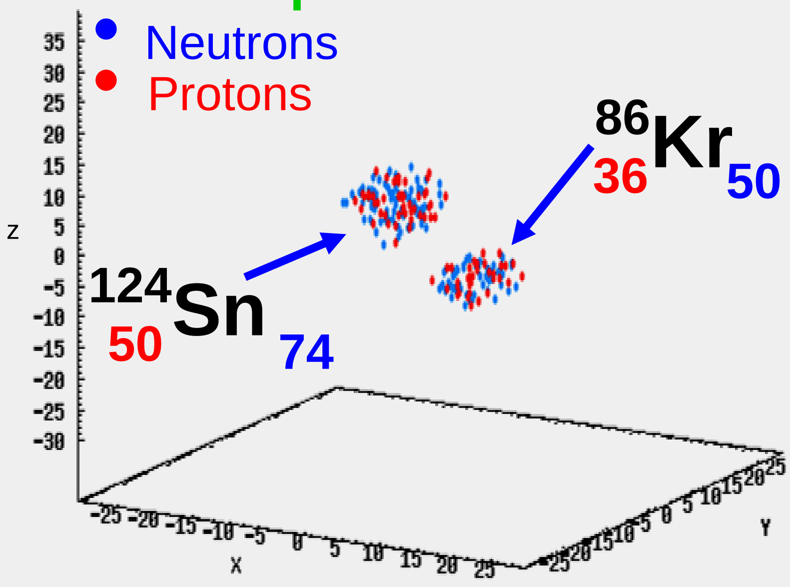
*M. Papa, A. Bonasera et al.,
Phys. Rev. C 64, 024612 (2001)

CoMD Calculations: ^{86}Kr (15 MeV/nucleon) + ^{124}Sn

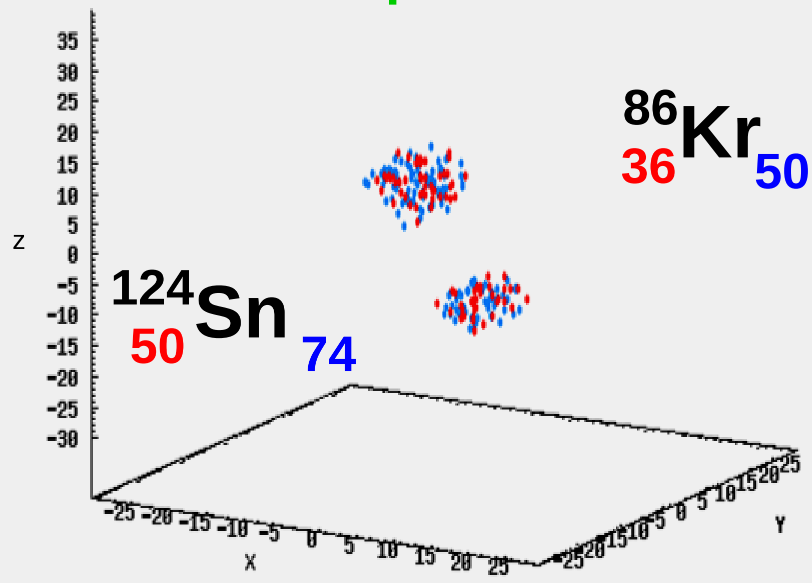
b = 10 fm
t = 0-300 fm/c Δt = 10 fm/c

b = 8 fm
t = 0-300 fm/c Δt = 10 fm/c

Peripheral Collision



Semi-Peripheral Collision



CoMD: Constraint Molecular Dynamics; M. Papa, A. Bonasera,
Phys. Rev. C 64, 024612 (2001)

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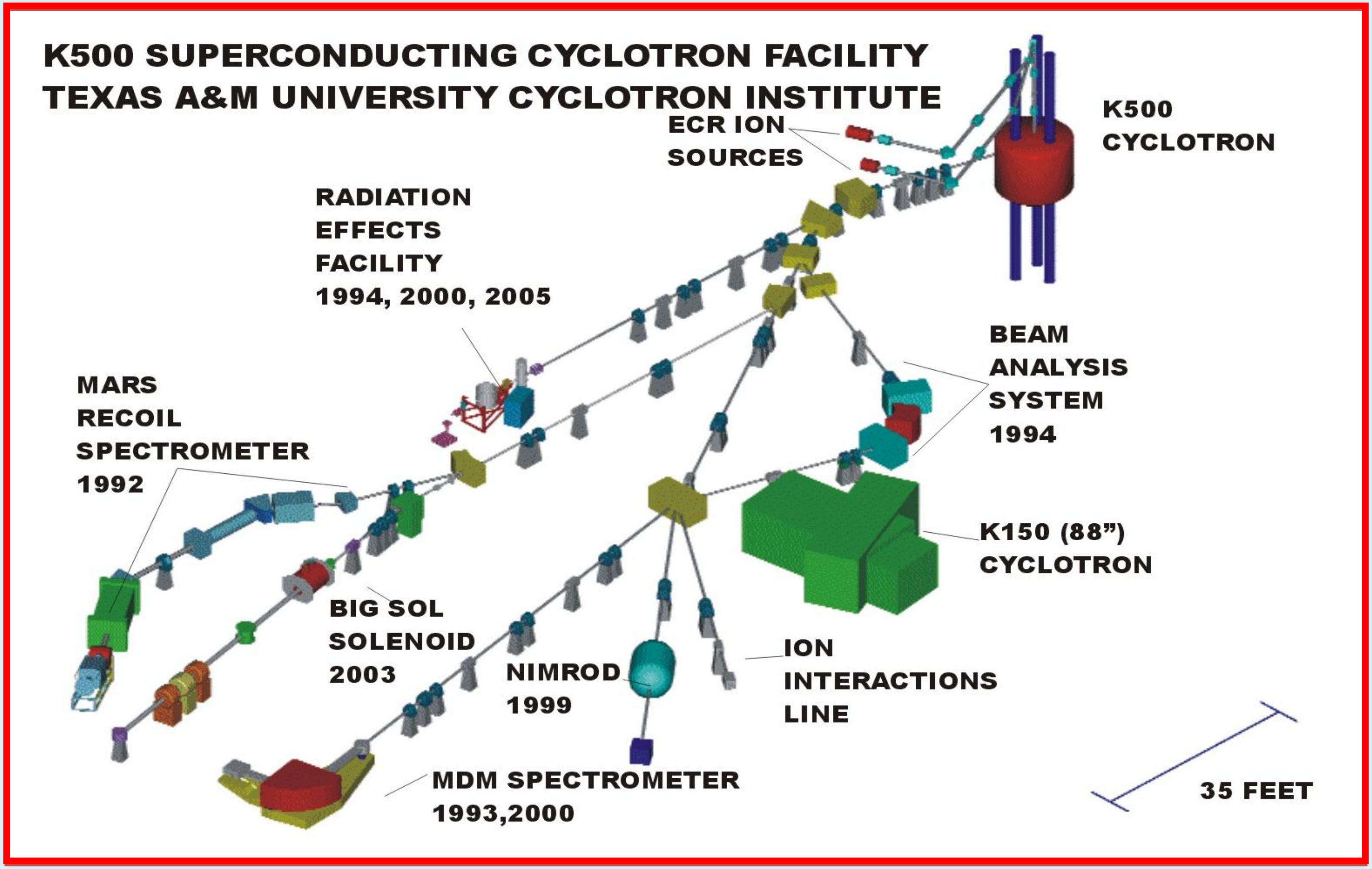
Cyclotron Institute at Texas A&M University



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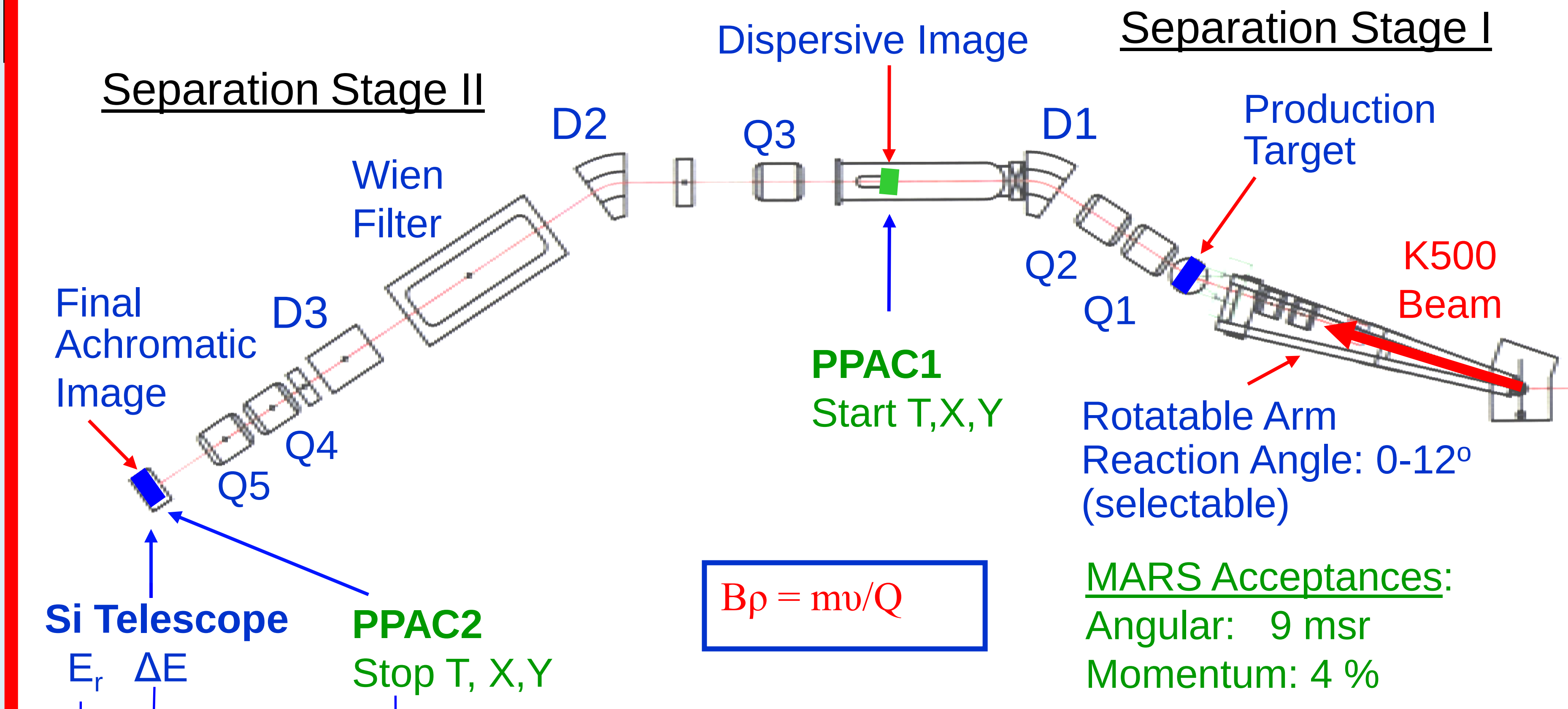
CYCLOTRON INSTITUTE
Texas A&M University

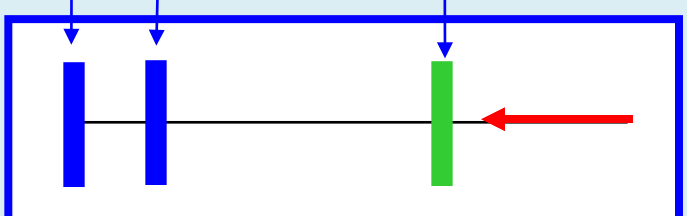
MARS Recoil Separator and Setup for Heavy Rare Isotope Studies*

CYCLOTRON INSTITUTE
Texas A&M University



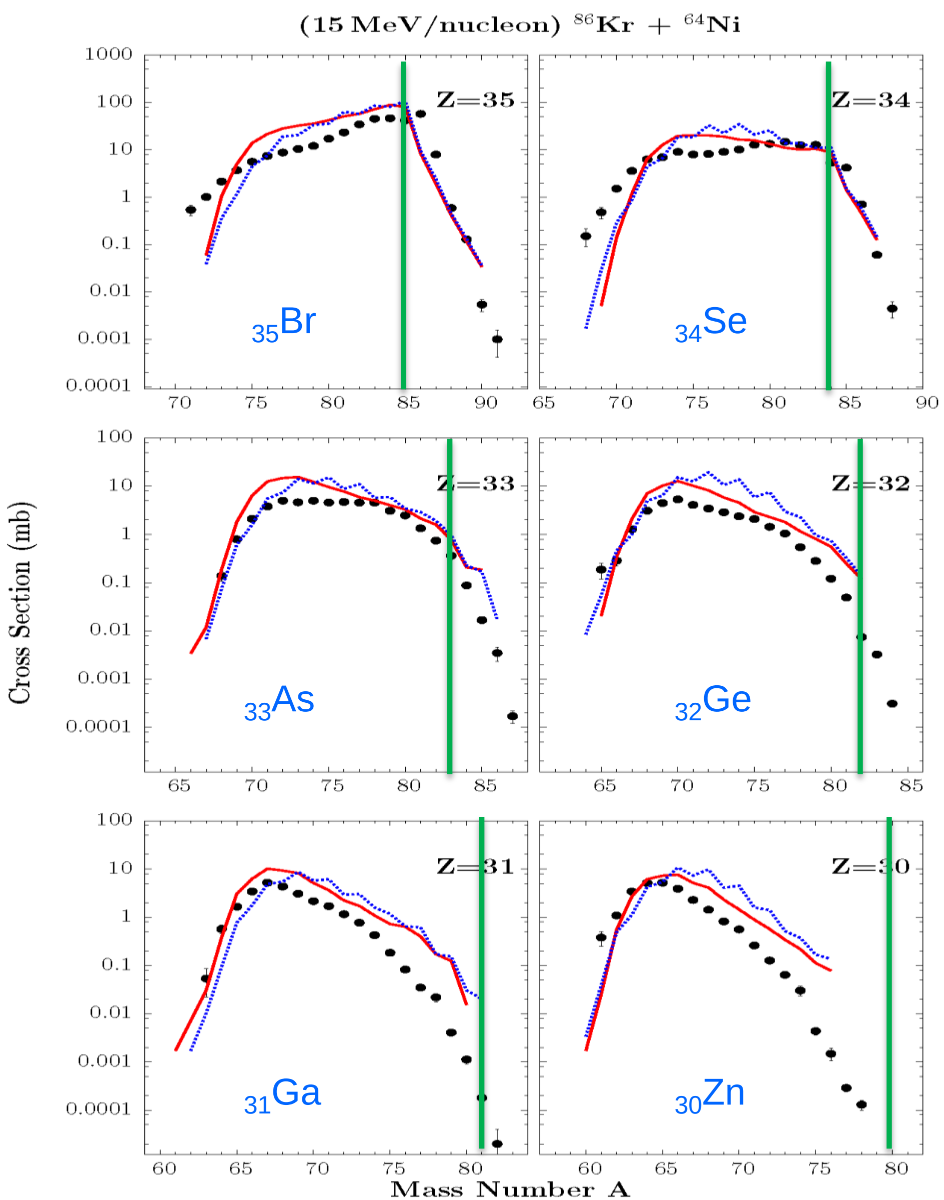
$B\rho = m\upsilon/Q$

MARS Acceptances:
Angular: 9 msr
Momentum: 4 %



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

Comparison: Data, Calculations: ^{86}Kr (15 MeV/nucleon) + ^{64}Ni



- ^{86}Kr + ^{64}Ni (15 MeV/u)*

— CoMD/SMM

----- CoMD/GEMINI

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

CoMD: Constrained Molecular Dynamics:
M.Papa et. al., Phys. Rev. C 64, 024612 (2001)

GEMINI: Binary Decay Code:
R. Charity, Nucl. Phys. A 483, 391 (1988)

SMM: Statistical Multifragmentation Model:
A. Botvina et al., Phys. Rev. C 65, 044610 (2002);
Nucl. Phys. A 507, 649 (1990)

* P.N. Fountas, G.A. Souliotis et al., Phys. Rev C 90, 064613 (2014)

^{92}Kr RNB Cross Sections and Rate estimates

Rare isotope	Reaction Channel	Cross Section (mb)	Rates (s^{-1})
^{93}Kr	- 0p + 1n	18.8	1.1×10^4
^{94}Kr	- 0p + 2n	2.3	1.3×10^3
^{95}Kr	- 0p + 3n	0.63	3.8×10^2
^{96}Kr	- 0p + 4n	0.20	1.2×10^2
^{92}Br	- 1p + 1n	4.5	2.7×10^3
^{93}Br	- 1p + 2n	0.75	4.5×10^2
^{94}Br	- 1p + 3n	0.078	47
^{95}Br	- 1p + 4n	0.039	23
^{96}Br	- 1p + 5n	0.008	5
^{90}Se	- 2p + 0n	2.70	1.6×10^3
^{91}Se	- 2p + 1n	0.60	3.5×10^2
^{92}Se	- 2p + 2n	0.12	70
^{93}Se	- 2p + 3n	0.039	23

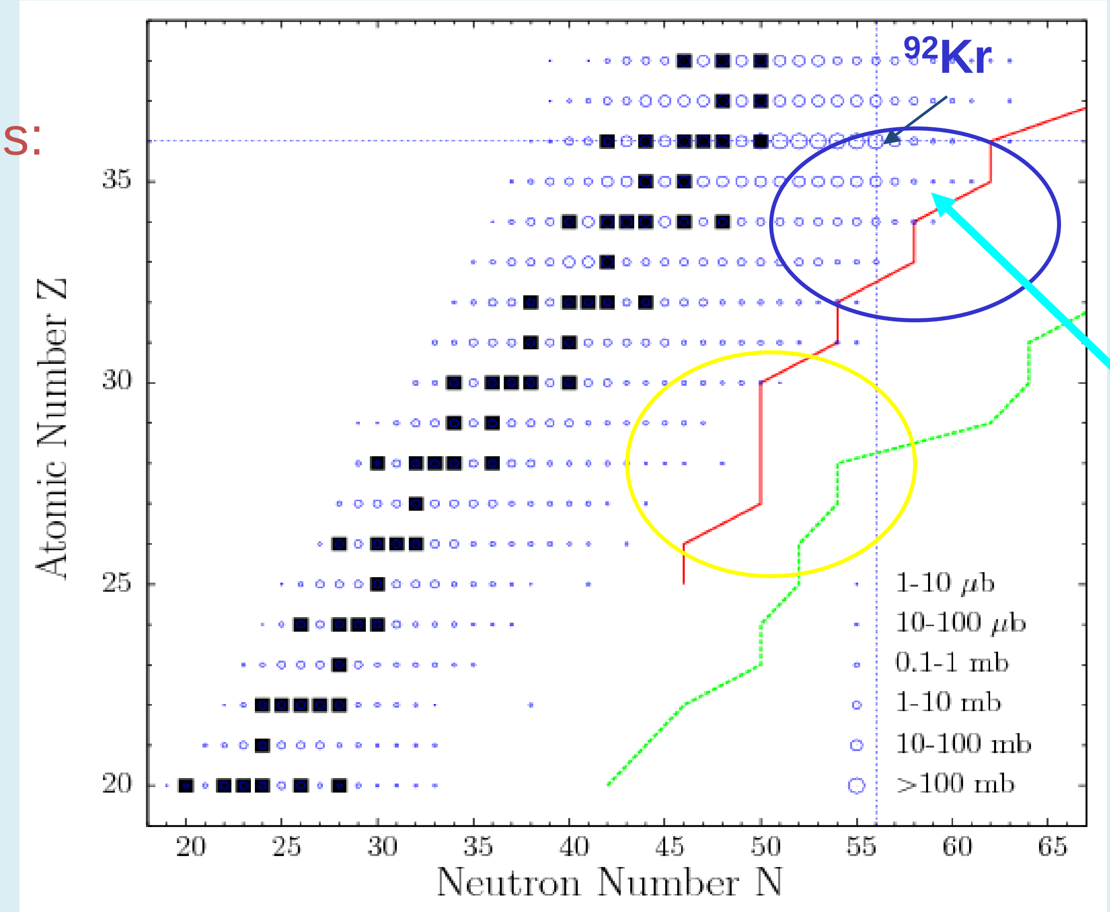
- **Cross sections and rate estimates of neutron-rich isotopes from ^{92}Kr (15 MeV/nucleon) + ^{64}Ni**
- **Beam of ^{92}Kr with intensity 0.5 pnA (3 x 10^9 particles/s)**
- **^{64}Ni target with a thickness of 20 mg/cm^2**

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

Example of nuclide production in DIC with RIBs:

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

Calculated nuclide cross sections:



Very important:

Neutron-pickup channels !!! along with proton stripping

❍ Calculations*: CoMD/SMM

■ stable nuclides

---- r-process

----- n-drip line

Neutron-pickup products

Rate estimates: ^{92}Kr from RAON at 0.5pnA (~3x10^{9}pps), ^{64}Ni (20mg/cm^2) :

1mb => 600 pps

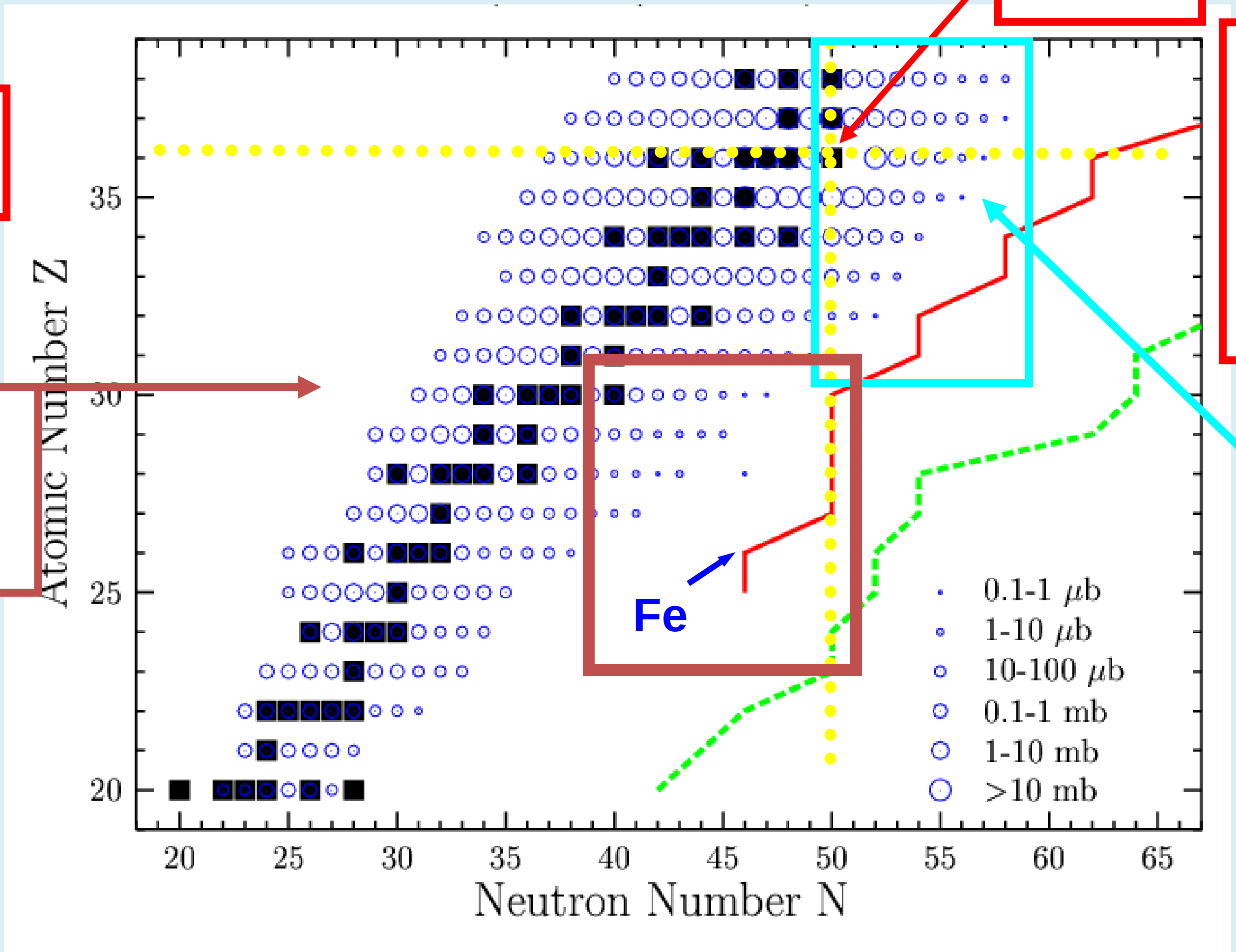
* P.N. Fountas, G.A. Souliotis et al, Phys. Rev. C 90, 064613 (2014)

Rare Isotope Production at 15MeV/nucleon :

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

^{86}Kr

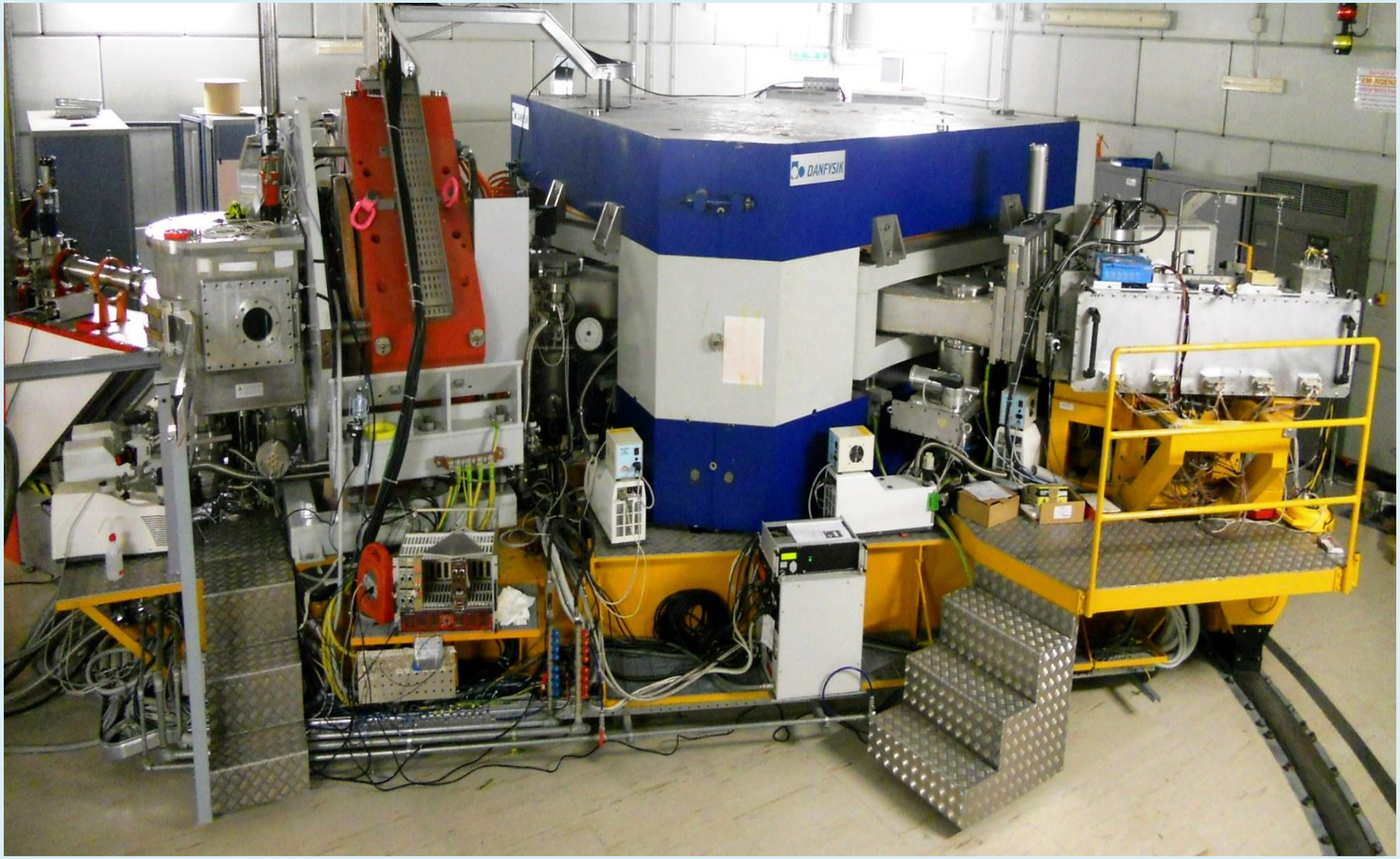
PROPOSED ^{70}Zn



Neutron-Rich Rare Isotopes near and above the **Fe-Ni region**

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

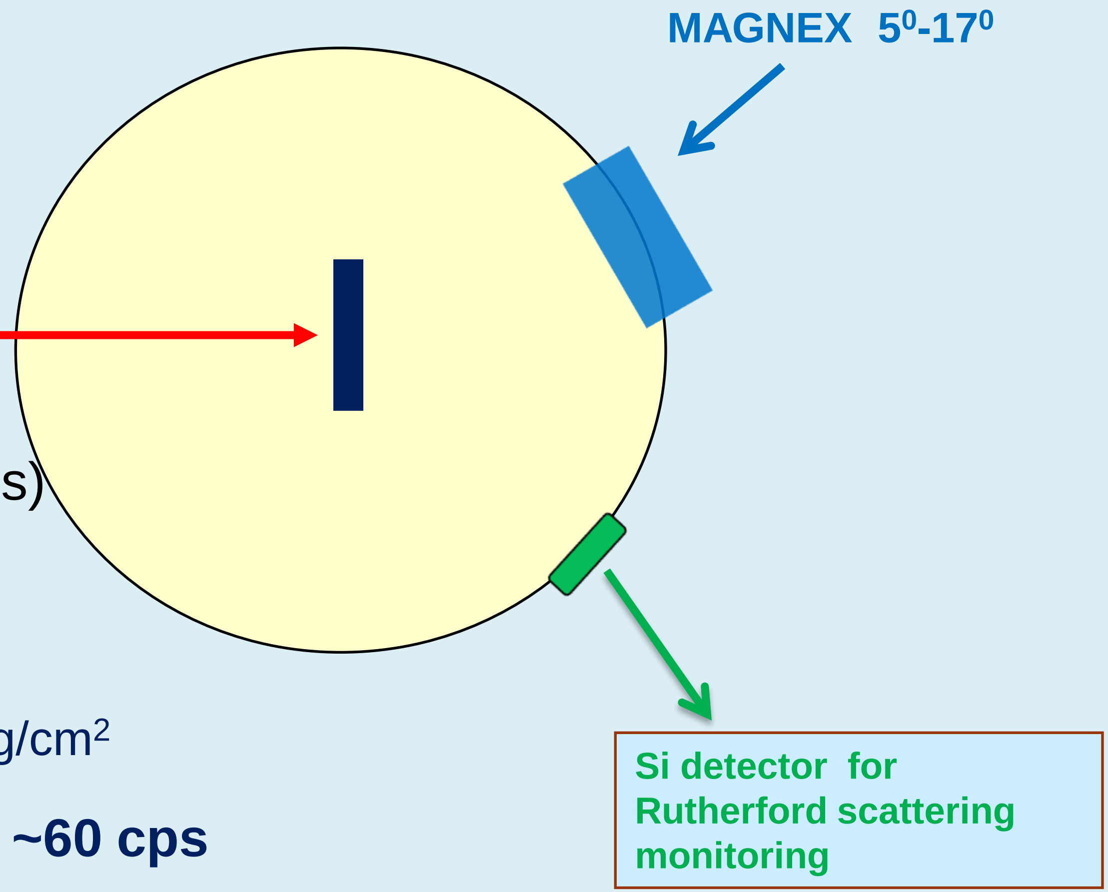
Experimental setup: The MAGNEX spectrometer



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

Experimental setup: MAGNEX target chamber

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



0.5-1.0 pnA (3-6 x 10^{9} pps)

^{64}Ni, ^{208}Pb targets 1.0-2.0 mg/cm^{2}

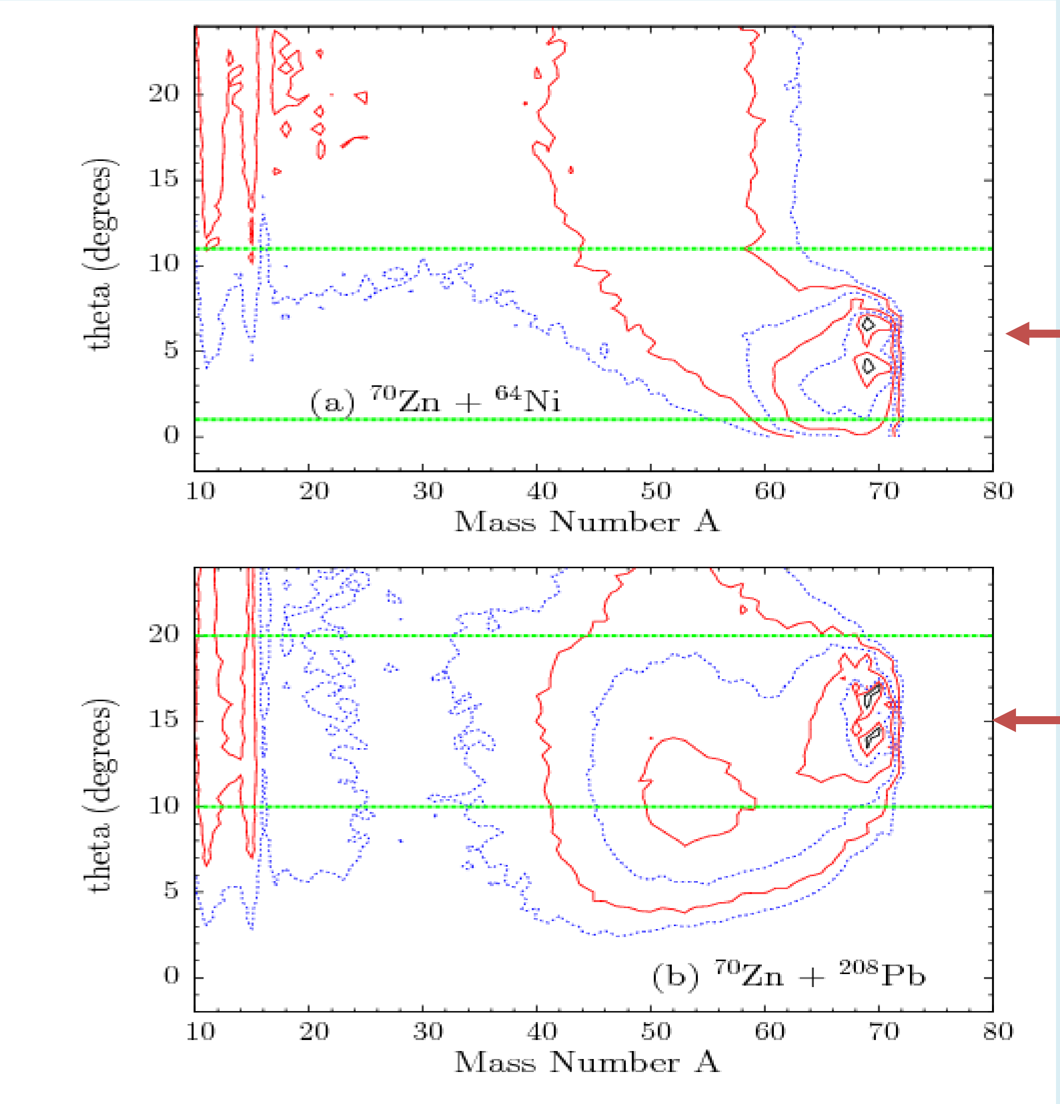
Count estimate: 1mb => ~60 cps

For rare isotopes   : 1μb => ~ 3.6 cpm

1nb =>   ½ BTU

Calculations: DIT/SMM: ^{70}Zn (15 MeV/nucleon) + ^{64}Ni, ^{208}Pb

Mass-resolved angular distributions



$\theta_{gr} = 6^o$

$\theta_{gr} = 15^o$

For this test run : one angle setting $\theta_{MAGNEX} = 9^o$ $\Delta\theta = 4^o$-16^o

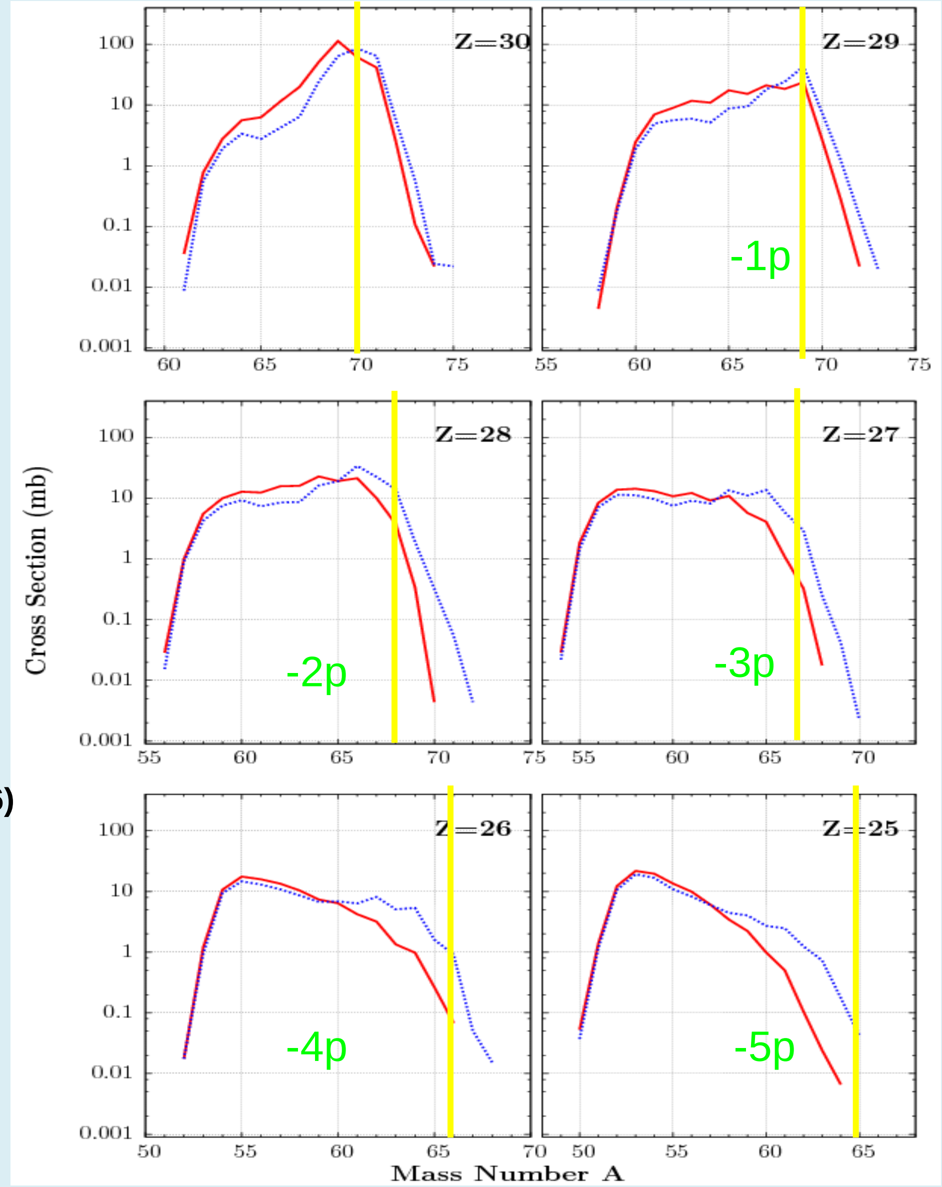
Preliminary DIT/SMM Calculations: ^{70}Zn (15 MeV/nucleon) + ^{64}Ni

Mass distributions of near-projectile isotopes

DIT : L. Tassan-Got,
NPA 524, 121 (1991)

**DITm: M. Veselsky,
G.A. Souliotis,
NPA 765, 252 (2006)**

SMM: Statistical Multifragmentation Model:
A. Botvina et al.,
PRC 65, 044610 (2002);
NPA 507, 649 (1990)



Expected rate:

1μb => ~ 4 cpm

ΕΘΝΙΚΟ ΚΑΙ ΚΑΠΟΔΙΣΤΡΙΑΚΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΘΗΝΩΝ

Plans for MAGNEX experiments

- Experimental study of peripheral reactions at energy ~10-30 MeV/nucleon
  Beams: ^{48}Ca, ^{70}Zn, ^{82}Se (targets: ^{64}Ni, ^{124}Sn, ^{208}Pb, ^{238}U, look ~ θ_{gr})

- Projectile fission of ^{238}U (15 MeV/nucleon)

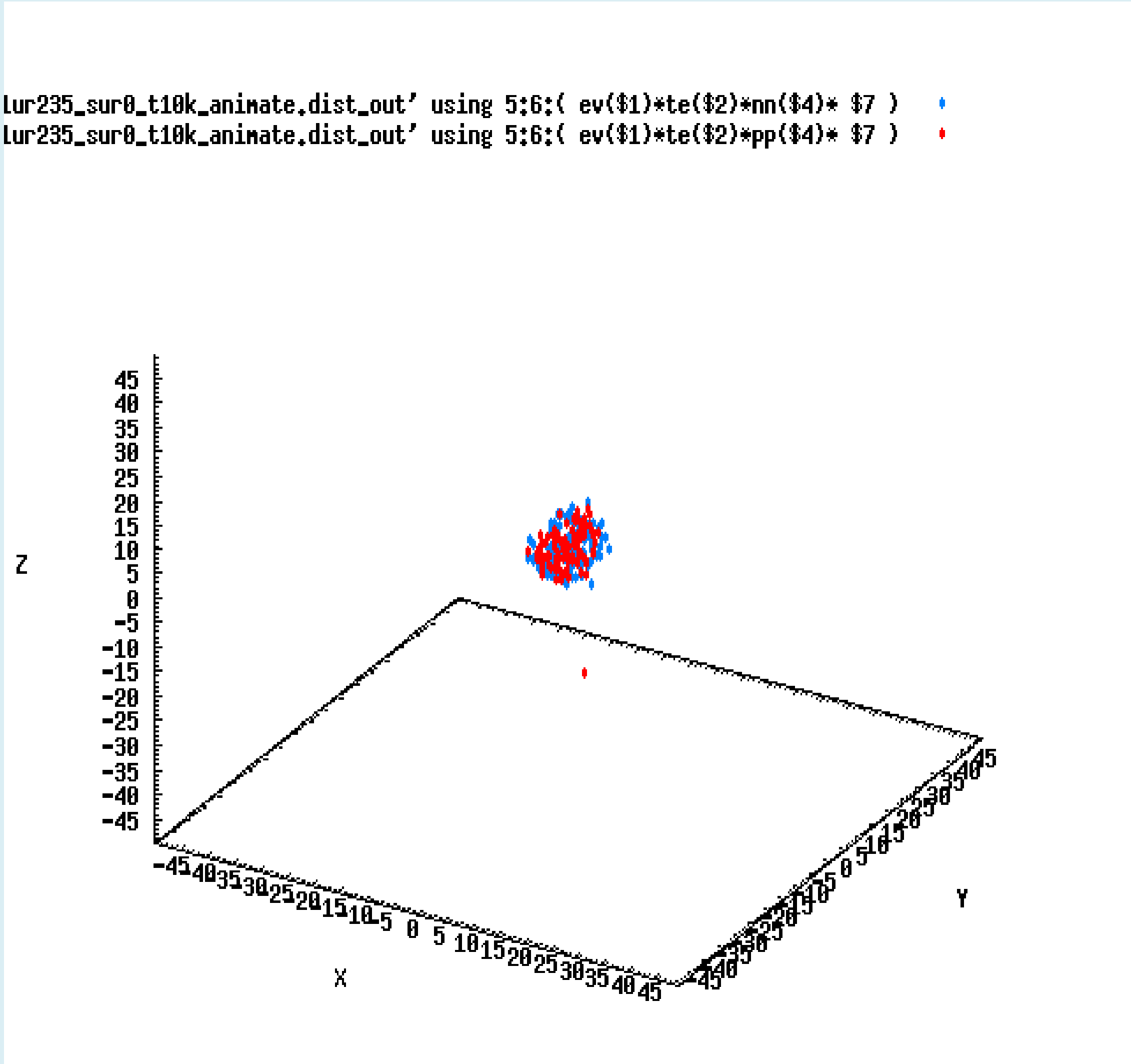
- Excitation-energy reconstruction and study (10-30 MeV/nucleon data)

Experience for experimental studies using neutron-rich RIBs
(FRIBS/LNS, FRIB/MSU, RISP/Korea)

Access the neutron-drip line near Z~26-28 with RIBs of Zn, Ni

Nuclear Fission Studies with CoMD

p (30 MeV) + ^{235}U



*N. Vonta, G.A. Souliotis, *et al.*, *Phys. Rev C* **87, 014001** (2015).

ΕΘΝΙΚΟΝ & ΚΑΠΟΔΙΣΤΡΙΑΚΟΝ ΠΑΝΕΠΙΣΤΗΜΙΟΝ ΑΘΗΝΩΝ
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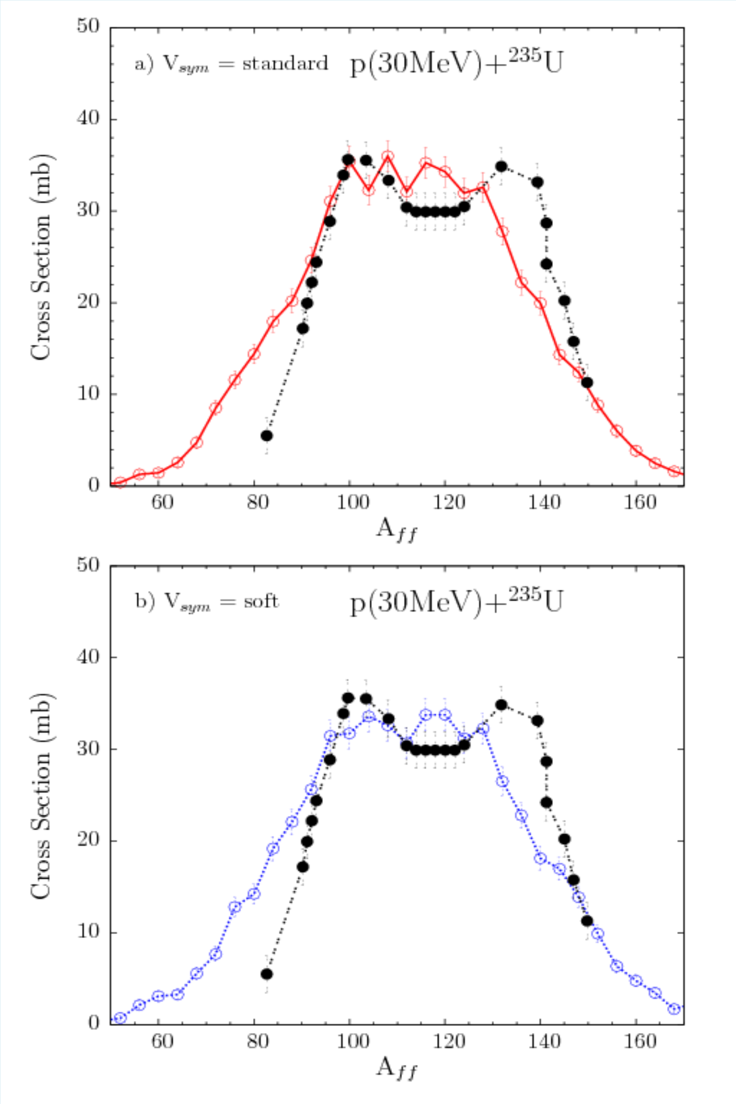
Comparison between Theoretical and Experimental Results: p (30 MeV) + ^{235}U



Red line: standard V_{sym} ~ ρ

Blue line: soft V_{sym} ~ $\rho^{1/2}$

Grey points: experimental data:
S.I. Mulgin et al., Nucl. Phys. A 824, 1 (2009)

*N. Vonta, G.A. Souliotis, *et al.*, *Phys. Rev C* **87, 014001** (2015).

ΕΘΝΙΚΟΝ & ΚΑΠΟΔΙΣΤΡΙΑΚΟΝ ΠΑΝΕΠΙΣΤΗΜΙΟΝ ΑΘΗΝΩΝ
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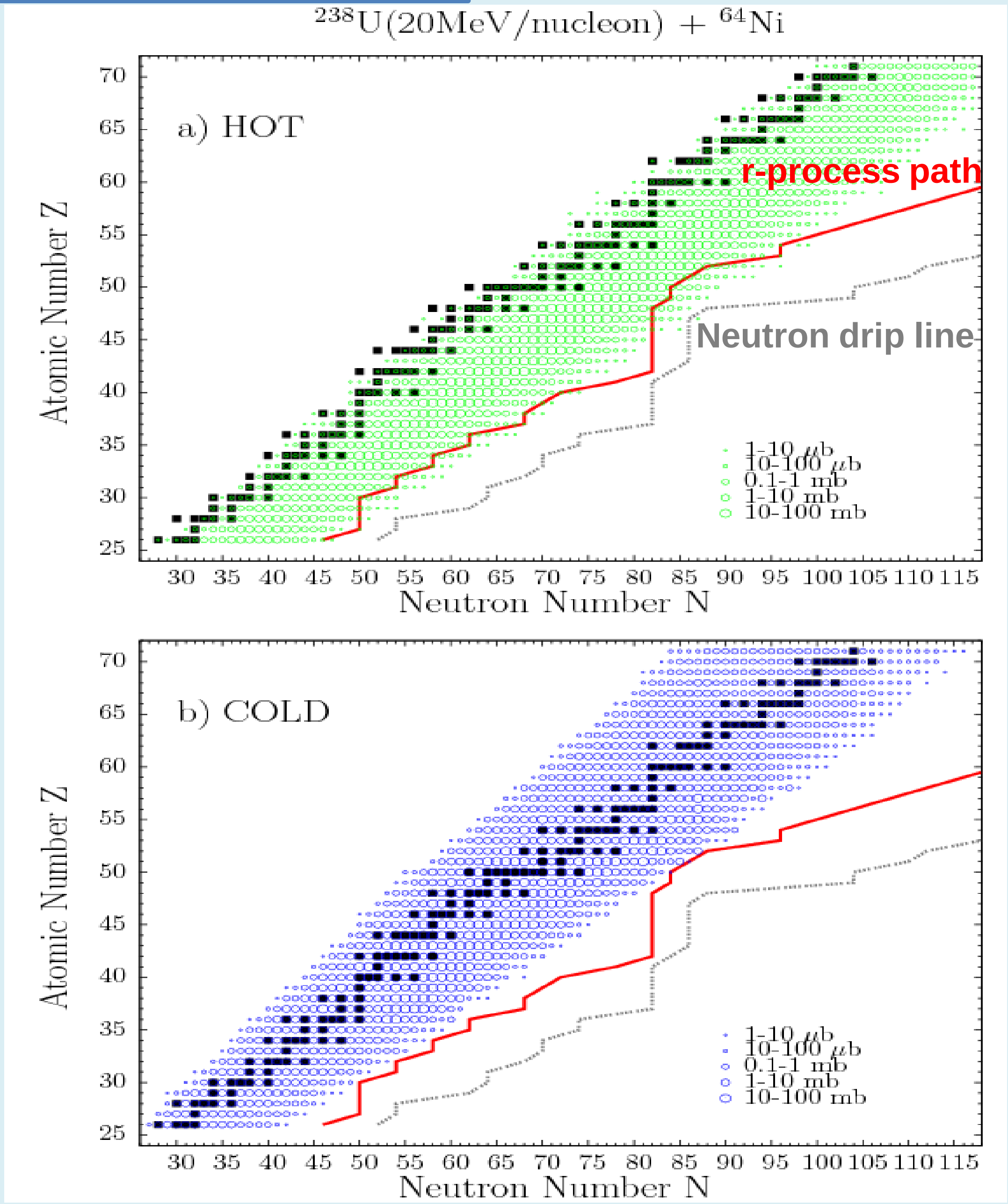
Fission Calculations: ^{238}U (20 MeV/nucleon) + ^{64}Ni



Production cross sections of neutron-rich nuclides

*N. Vonta, G.A. Souliotis, *et al.*, *Phys. Rev C* (Dec.2016).

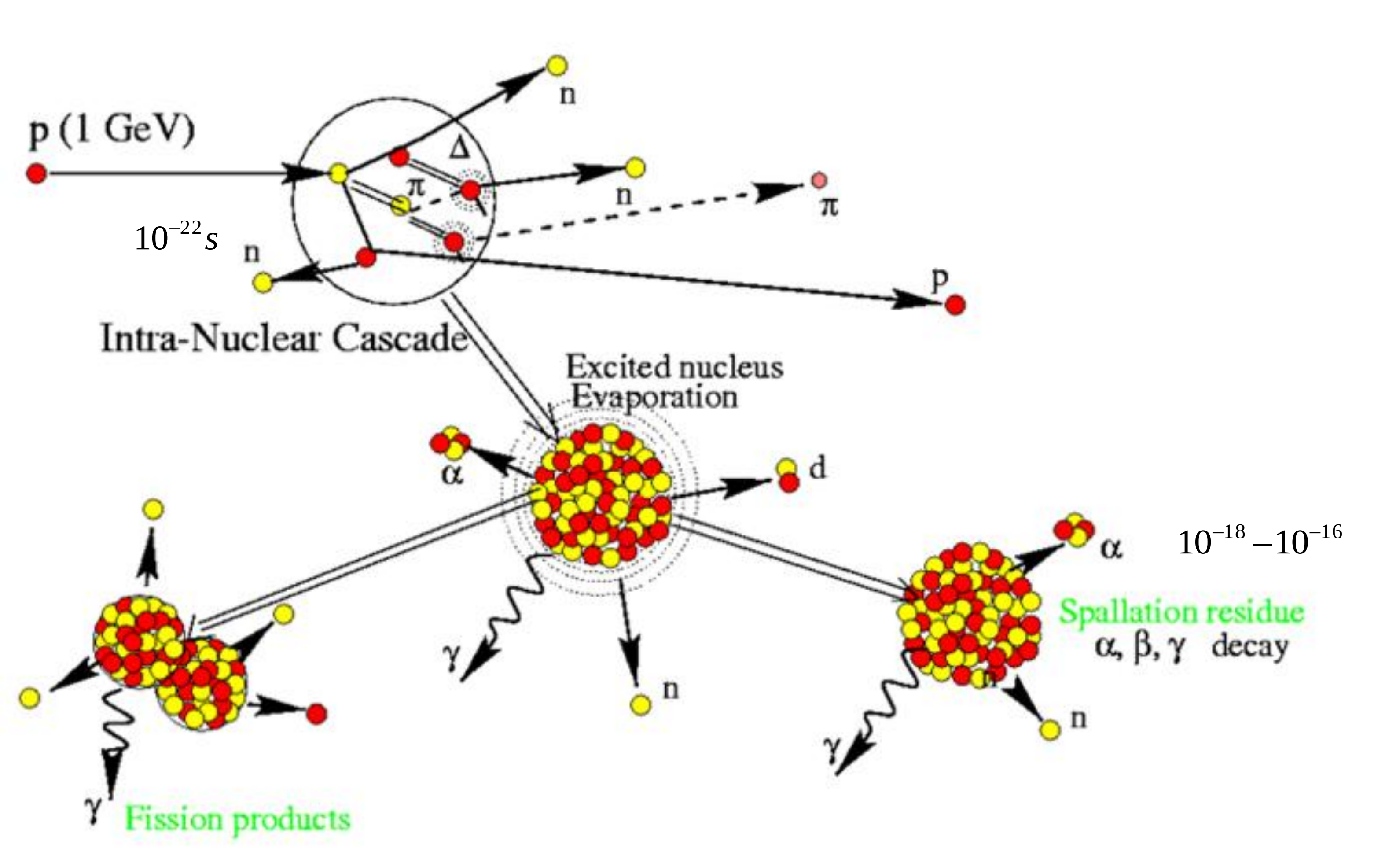
Overview of spallation and its applications

- Astrophysics (reactions induced by cosmic rays in interstellar medium)
- Accelerator-driven systems (ADS) (“Energy amplification”)
- Transmutation of nuclear waste

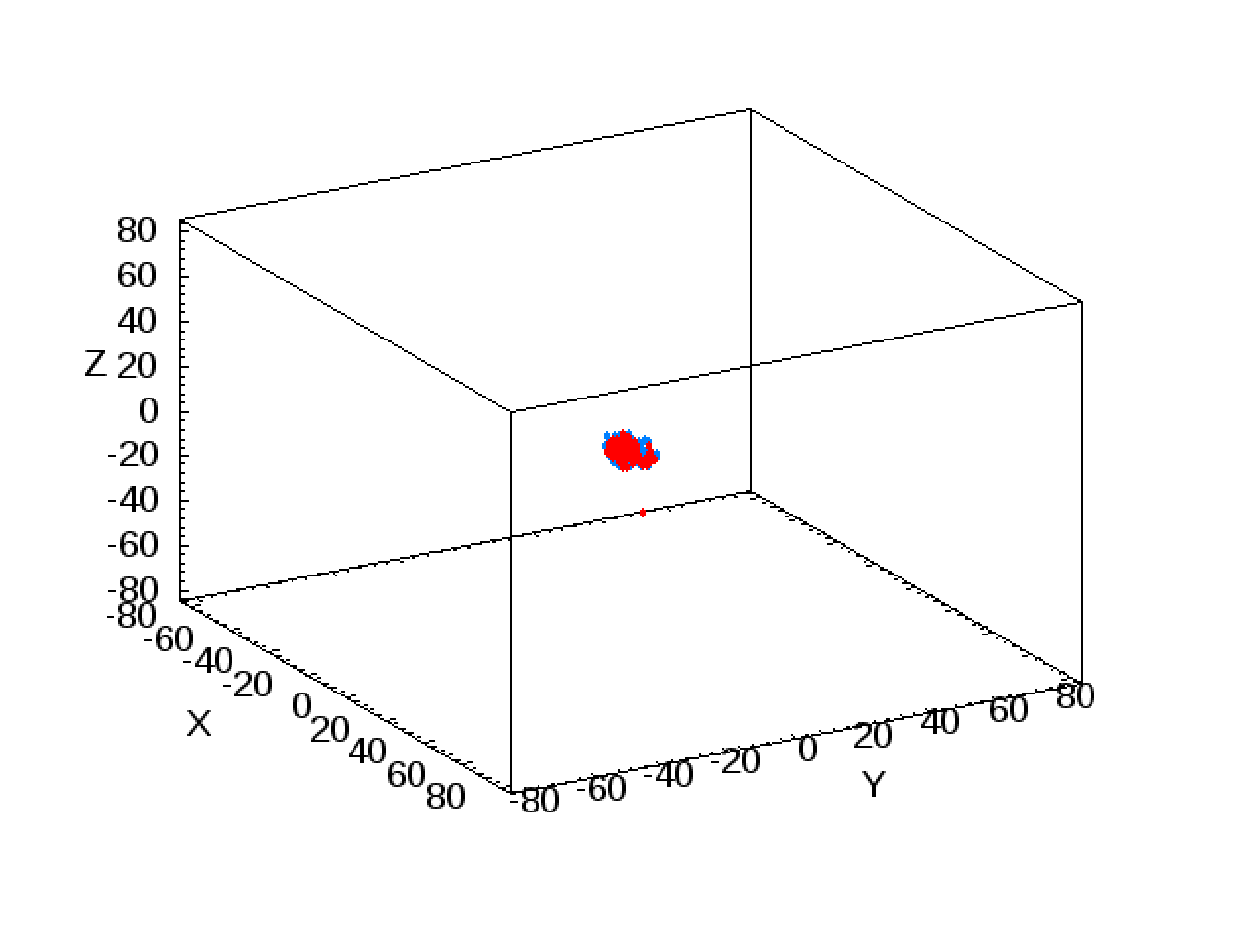
- Sources (Facilities) of spallation neutrons

- Production of rare isotopes (ISOL facilities)

Spallation reaction mechanism



Spallation: p(500MeV) + ^{208}Pb



*A. Assimakopoulou, G.A. Souliotis, *A. Bonasera, M. Veselsky, in preparation*
(Aug. 2016).

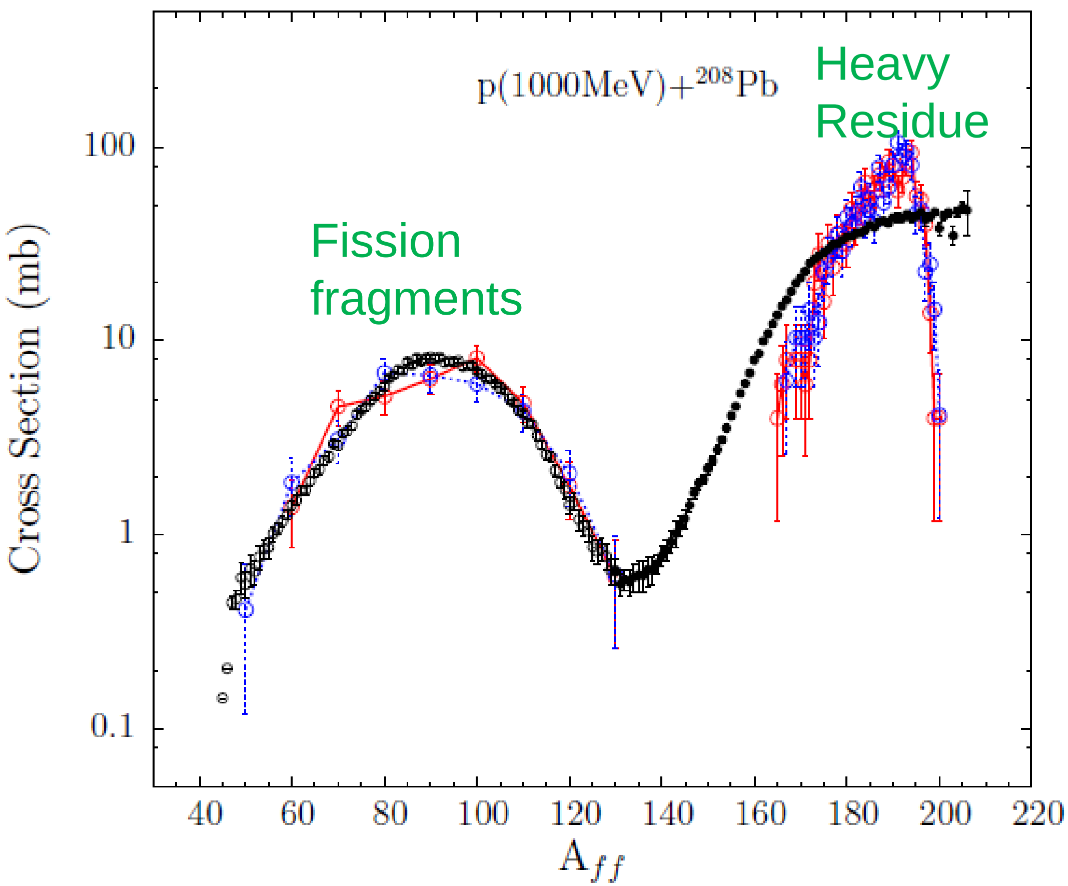
Comparison between theoretical results and experimental data: p(1000 MeV) + ^{208}Pb

CoMD calculations

Red line: standard $V_{sym} \sim \rho$

Blue line: soft $V_{sym} \sim \sqrt{\rho}$

Black points:experiment



CoMD calculations agree with the experimental data

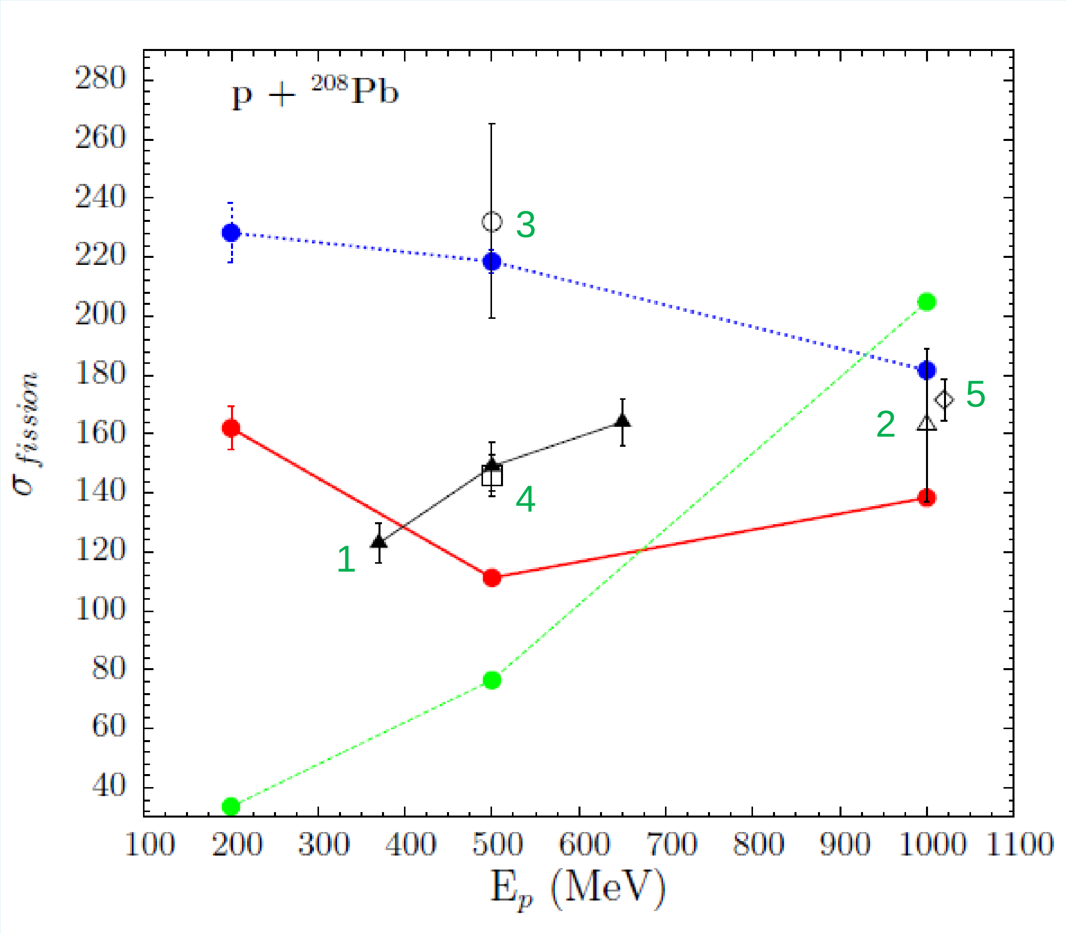
Exp. Data: T. Enqvist et al., Nucl. Phys. A 686, 481 (2001)

*A. Assimakopoulou, G.A. Souliotis, *et al.*,

Fission Cross Section of ^{208}Pb

- CoMD calculations: Red line: standard
- Blue line: soft

Black points: experimental data



1)J. L. Rodriguez et al., Phys. Rev. C 90, 064606 (2014)

2)T. Enqvist et al., Nucl. Phys. A 686, 481-524 (2001)

3)B. Fernandez et al., Nucl. Phys. A 747, 227-267 (2005)

4)K. -H. Schmidt et al., Phys. Rev. C 87, 034601 (2013)

5)A. V. Prokofiev, Nucl. Instr. Meth. A 463 557-575 (2001)

Fission cross section/residue cross section

CoMD calculations

Red line: standard

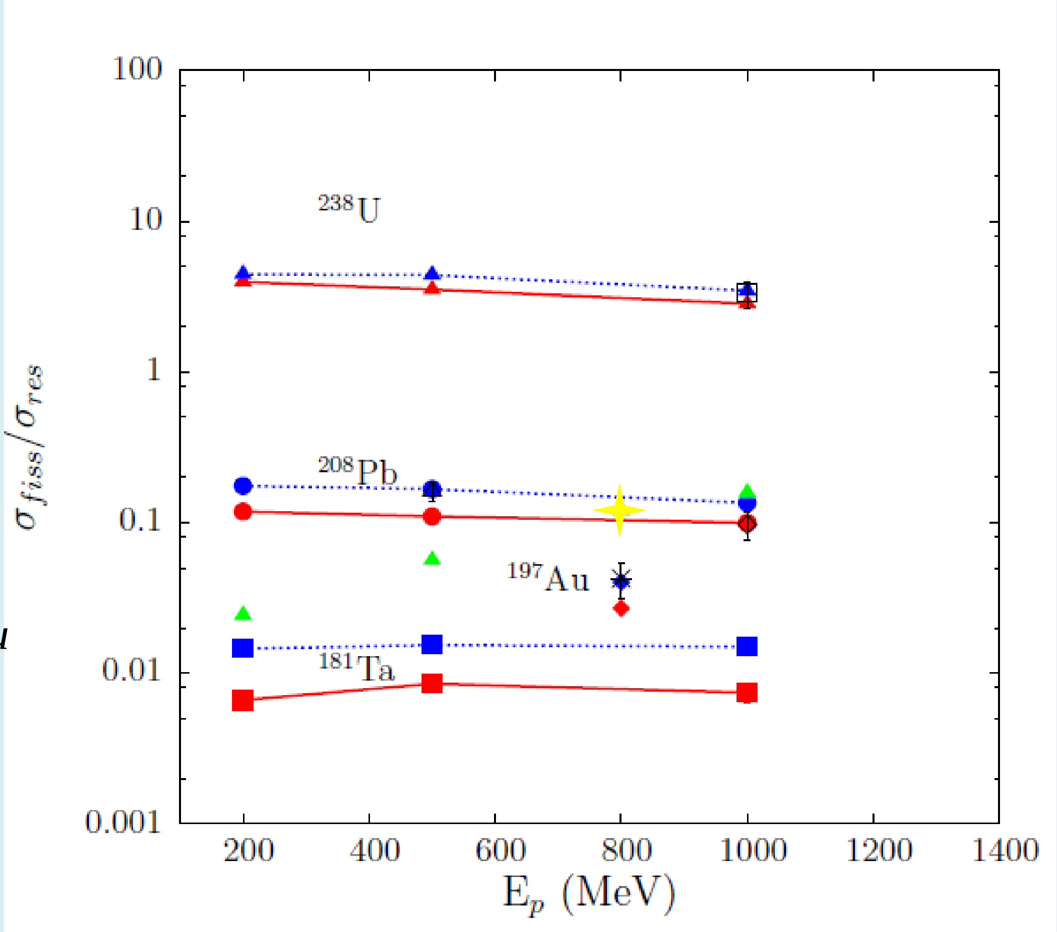
Blue line: soft

Green points:

INC/SMM calculations for ^{208}Pb

Yellow point:

INC/SMM calculations for ^{197}Au



High fissility

Modest fissility

Low fissility

1)T. Enqvist et al., Nucl. Phys. A 686, 481-524 (2001)

2)B. Fernandez-Dominguez et al., Nucl. Phys. A 747, 227-267 (2005)

3)M. Bernas et al., Nucl. Phys. A 725, 213-253 (2003)

4)J. Benlliure, P. Armbruster et al., Nucl. Phys. A 700 469-491 (2002)

5)F. Rejmund et al., Nucl. Phys. A 683 540-565 (2001)

Summary

- **Overview of Nuclear Studies**
  - Nuclear Chart-Nuclear Stability
  - Overview of Nucleosynthesis. Focus on r-process
- **Research Results and Directions**
  - Rare Isotope Production
  - Nuclear Multifragmentation: hot nuclei
  - Nuclear Fission, Spallation

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Dr. Alex Botvina, GSI

TAMU Cyclotron Institute Collaborators

Prof. Sherry Yennello, CI Director

Dr. Brian Roeder

RISP/IBS Collaborators, Korea

Dr. Y.K. Kwon, Low Energy Group Leader

Dr. K. Tshoo

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