Neutron-rich rare isotope production with stable and radioactive beams in the mass range A ~ 40-60 at 15 MeV/nucleon

A. Papageorgiou[1], G.A. Soulotis[1], M. Veselsky[2], A. Bonasera[3,4]

[1]Laboratory of Physical Chemistry, Department of Chemistry, National and Kapodistrian University of Athens
[2]Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia
[3]Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA
[4]Laboratori Nazionali del Sud, INFN, via Santa Sofia 62, I-95123 Catania, Italy

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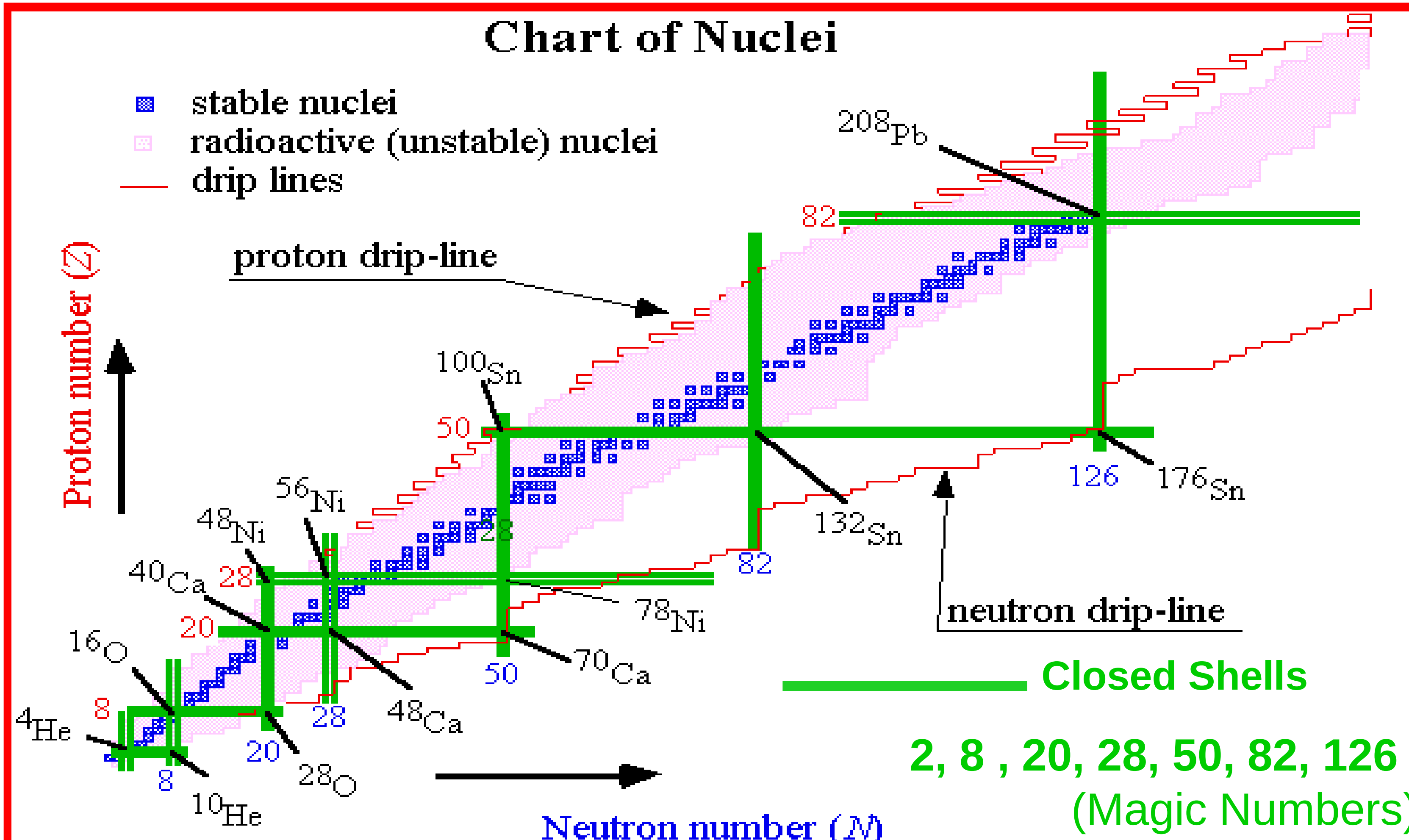
Overview:

- Introduction
- Explanation of the models
- Comparison of our calculations with experimental results
- Summary and conclusions

The Nuclear Landscape



- **281 nuclei are stable**
- **~ 3300 short-lived (radioactive) nuclei synthesized to date**
- **large region of neutron-rich nuclei is still unexplored (~4000 nuclei)**

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Rare isotope production study: Why?

Investigation of very neutron nuclei offers:

•Understanding of the **nuclear structure** with increasing N/Z

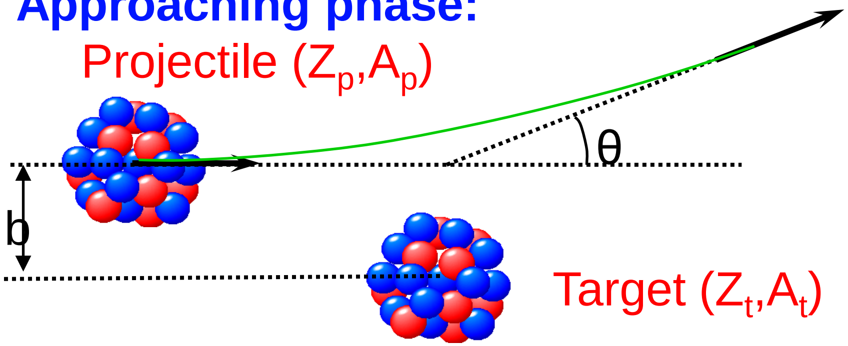
•Insight in nucleosynthesis processes (i.e. rapid neutron capture process, **r-process**)

•Reactions induced by n-rich nuclei:
isospin dependence N-N interaction, equation of state of asymmetric nuclear matter.

Production of very neutron-rich nuclides is a central issue in current and future **rare isotope beam facilities (GSI, Ganil, NSCL/FRIB, TRIUMF, RISP/Korea etc)**.

Peripheral Collisions, Deep Inelastic Transfer (DIT)*

Approaching phase:

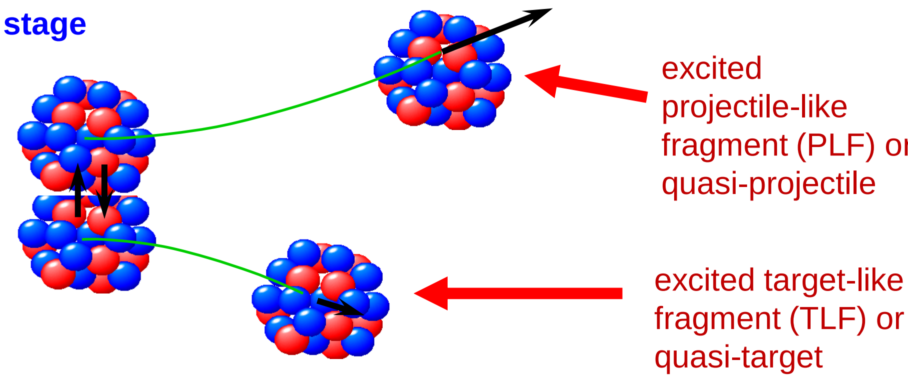


Neutrons
Protons

b: impact parameter
θ: scattering angle

Overlapping (interaction) stage

Exchange of nucleons:



Deep Inelastic Transfer (DIT) Model
L. Tassan-Got and C. Stephan, Nucl. Phys. A 524, 121 (1991)

DIT : Phenomenological model (Monte Carlo implementation)

- Formation of a di-nuclear configuration
- Exchange of nucleons through a “window” formed by the superimposition of the nuclear potentials in the neck region
- Dissipation of Kinetic energy into internal degrees of freedom

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

Microscopic Calculations: Constrained Molecular Dynamics (CoMD)*

CoMD: Quantum Molecular Dynamics model (Semiclassical)

- Nucleons are considered as Gaussian wavepackets
- **N-N effective interaction** (Skyrme-type with K=200 MeV/fm^3)
- Several forms of **N-N symmetry potential V_{sym} (ρ)**
- **Pauli principle** imposed via a phase-space constraint
- **Fragment recognition algorithm** (R_{min} = 3.0 fm)
- **Monte Carlo** implementation

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

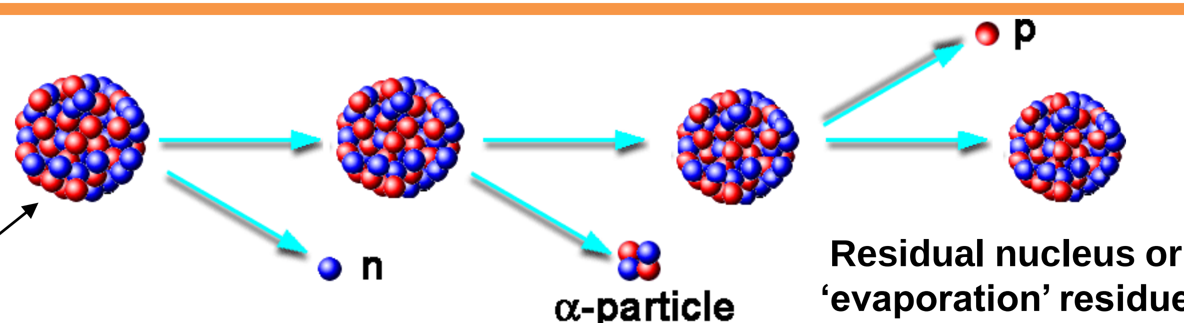
Nuclear De-excitation Mechanisms

I. Sequential Evaporation

$E^*/A < 2$ MeV

$T < 4$MeV

Initial nucleus

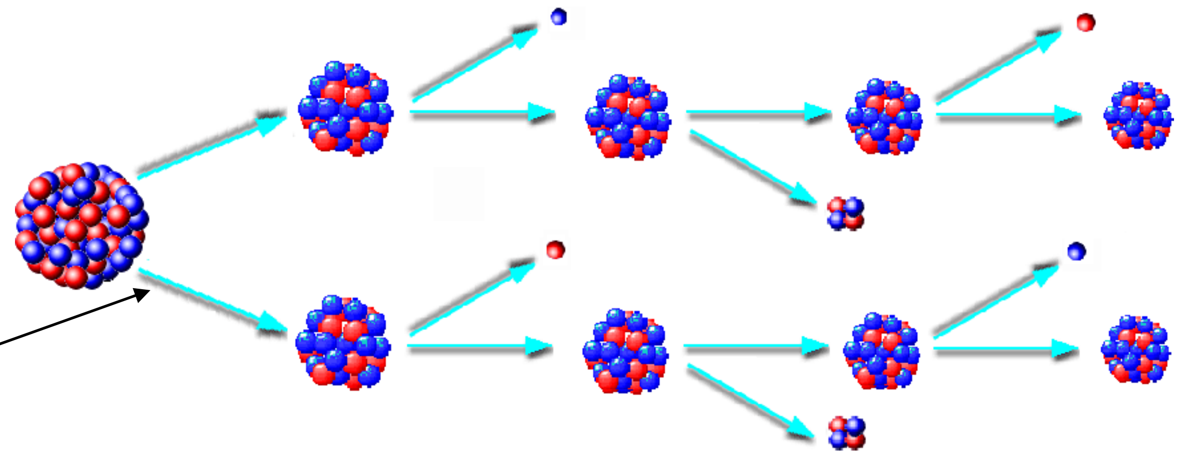


II. Sequential Binary Decay

$E^*/A \sim 2\text{-}3$ MeV

$T \sim 4\text{-}5$ MeV

Binary splitting
(like fission)

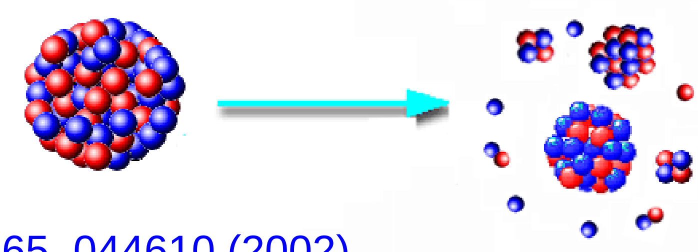


III. Multifragmentation

$E^*/A > 4$ MeV

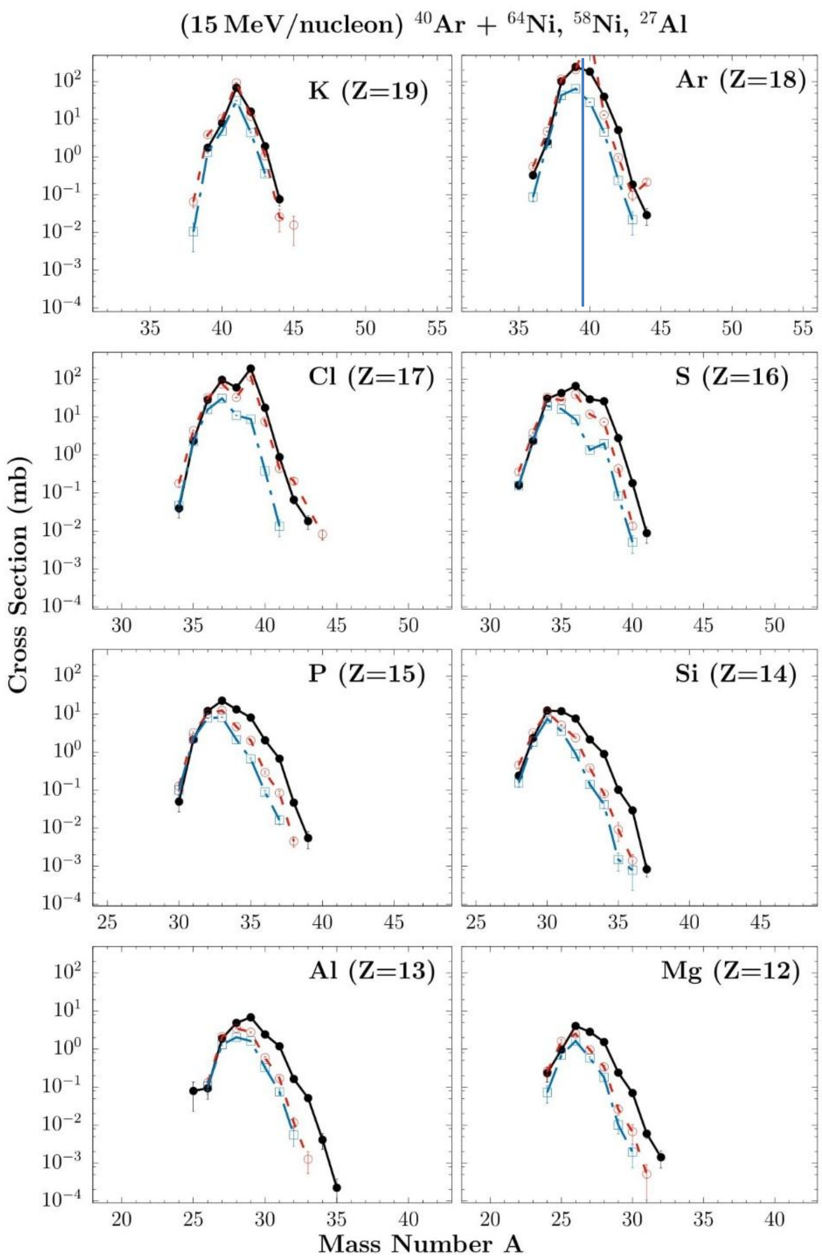
$T > 6$ MeV

Simultaneous emission of
several fragments, Δt = 50 fm/c (10^{-22} sec)



SMM Code: A. Botvina et al., Phys. Rev. C 65, 044610 (2002)

Comparison of data: ^{40}Ar (15 MeV/nucleon) + ^{64,58}Ni, ^{27}Al

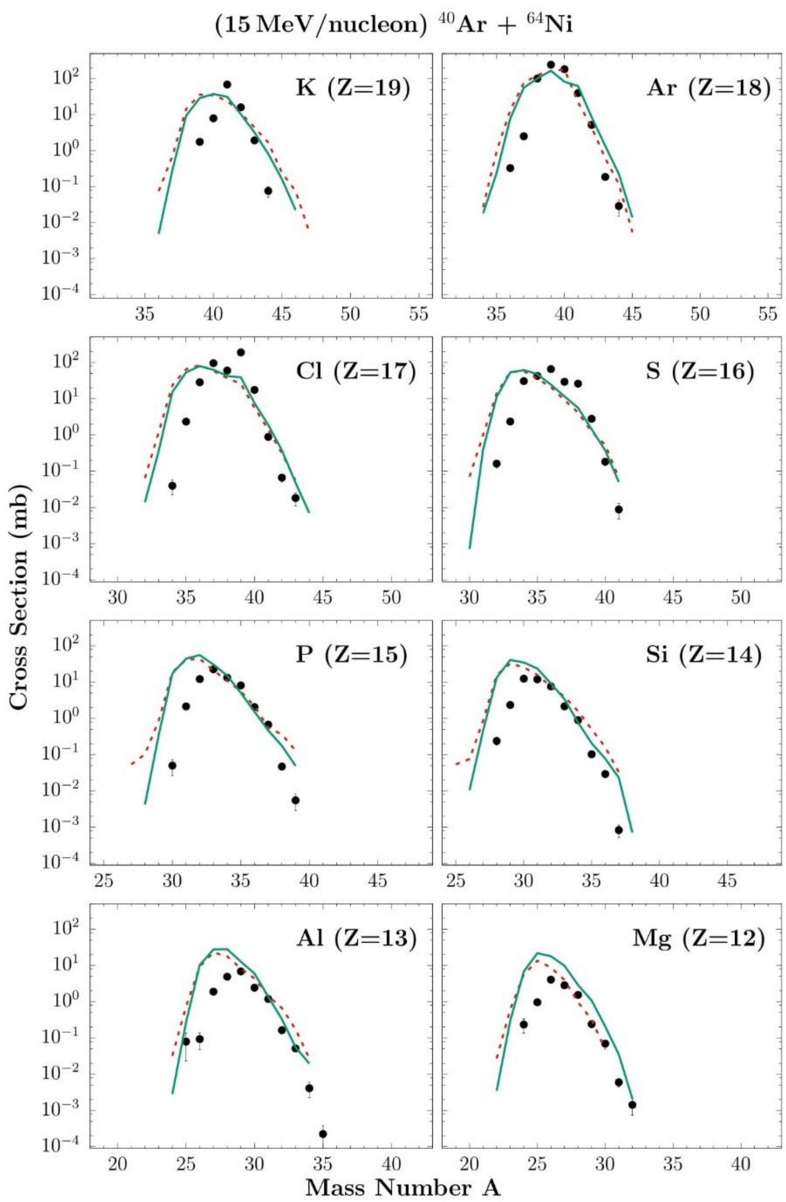


- ^{40}Ar+ ^{64}Ni (15 MeV/u)*
- ^{40}Ar+ ^{58}Ni (15 MeV/u)*
- ^{40}Ar+ ^{27}Al (15 MeV/u)*

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

Data from Texas A&M University

Comparison: Data, Calculations: ^{40}Ar (15 MeV/nucleon) + ^{64}Ni



• ^{40}Ar+ ^{64}Ni (15 MeV/u)*

----- CoMD/SMM (slow)

— DIT/SMM (fast)

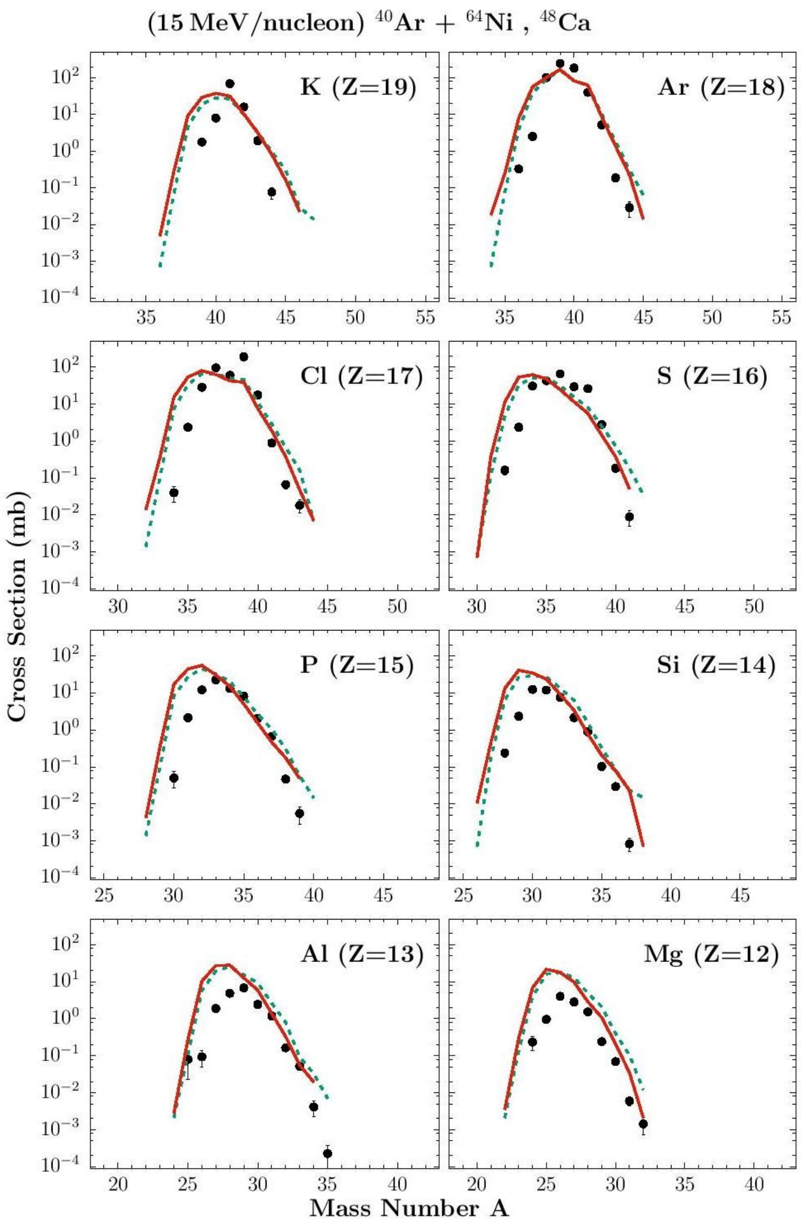
*G.A. Souliotis et al., Phys. Rev. C 84, 064607 (2011)

DIT : Deep inelastic transfers L. Tassan-Got and C. Stefan, Nucl. Phys A 524, 121 (1991)

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

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

Calculations: ^{40}Ar(15 MeV/u) + ^{64}Ni, ^{48}Ca



● ^{40}Ar + ^{64}Ni (15 MeV/u)* data

— DIT/SMM ^{40}Ar + ^{64}Ni (N/Z = 1.28)

----- DIT/SMM ^{40}Ar + ^{48}Ca (N/Z = 1.40)

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

DIT : Deep inelastic transfers L. Tassan-Got and C. Stefan, Nucl. Phys A 524, 121 (1991)

SMM: Statistical Multifragmentation Model:
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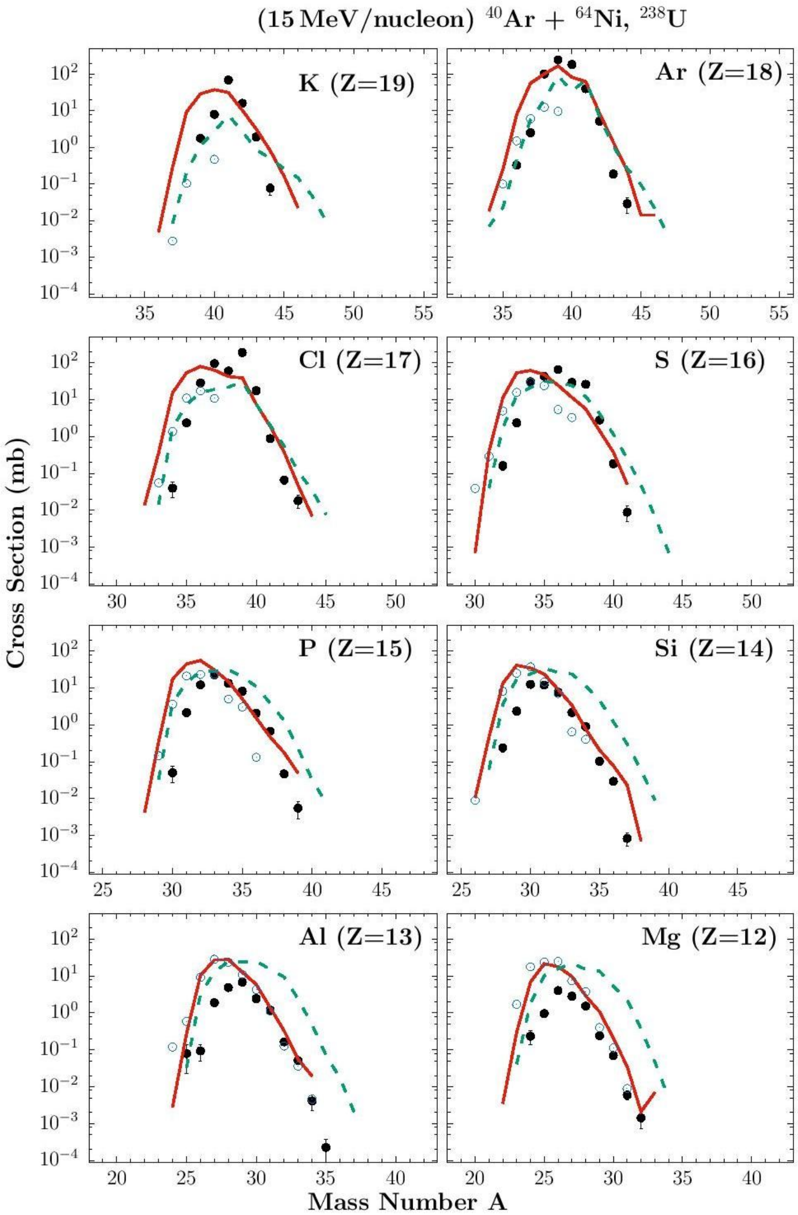
Nucl. Phys. A 507, 649 (1990)

Calculations: ^{40} Ar(15 MeV/nucleon) + ^{238}U



- ^{40}Ar + ^{64}Ni (15 MeV/u)*
- ^{40}Ar + ^{181}Ta (90 MeV/u)**
- DIT/SMM ^{40}Ar + ^{64}Ni (N/Z = 1.28)
- ----- DIT/SMM ^{40}Ar + ^{238}U (N/Z = 1.59)

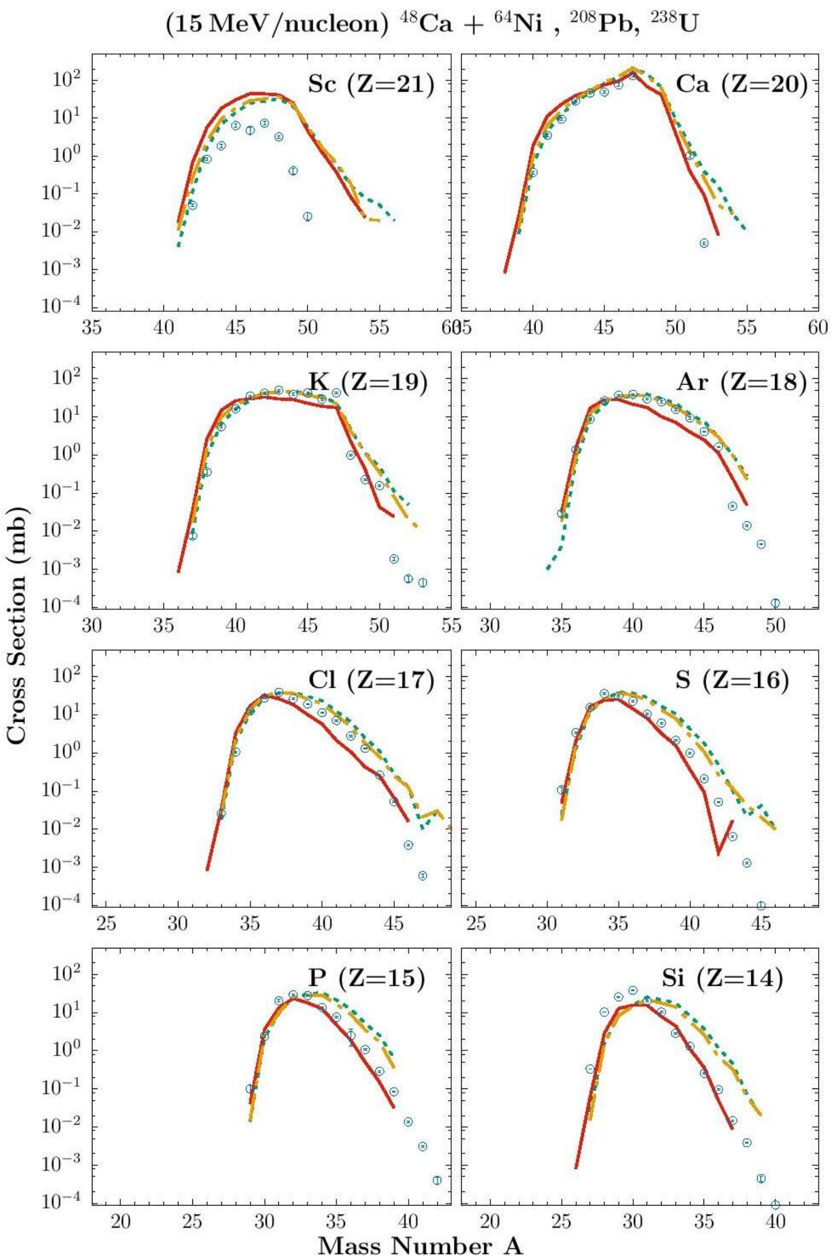
*G.A. Souliotis et al., Phys. Rev. C 84, 064607 (2011)

**Projectile Frgmentation reactions and Production of Nuclei near the neutron drip-line, Masahiro Notani, University of Tokyo

DIT : Deep inelastic transfers L. Tassan-Got and C. Stefan, Nucl. Phys A 524, 121 (1991)

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

Calculations: ^{48}Ca(15 MeV/nucleon) + ^{64}Ni, ^{238}U, ^{208}Pb



o ^{48}Ca + ^{181}Ta (140 MeV/u)*

— DIT/SMM ^{48}Ca + ^{64}Ni (N/Z = 1.28)

….. DIT/SMM ^{48}Ca + ^{238}U (N/Z = 1.59)

----- DIT/SMM ^{48}Ca+ ^{208}Pb (N/Z = 1.54)

* M. Mocko et al., Phys. Rev. C 74, 054612 (2006)

DIT : Deep inelastic transfers L. Tassan-Got and C. Stefan, Nucl. Phys A 524, 121 (1991)

SMM: Statistical Multifragmentation Model:
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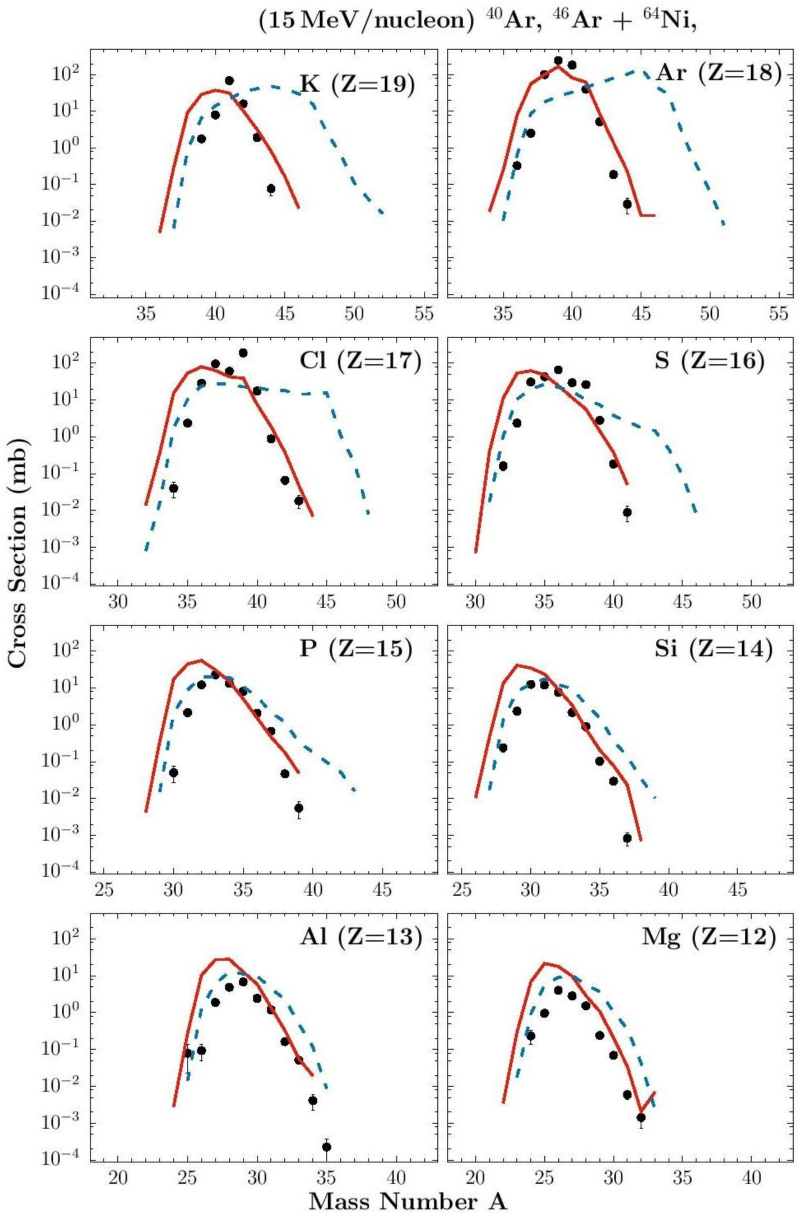
Nucl. Phys. A 507, 649 (1990)

Comparison of RIB ^{46}Ar with stable beam ^{40}Ar



- ^{40}Ar + ^{64}Ni (15 MeV/u)*

— DIT/SMM ^{40}Ar + ^{64}Ni

….. DIT/SMM ^{46}Ar + ^{64}Ni

DIT : Deep inelastic transfers L. Tassan-Got and C. Stefan, Nucl. Phys A 524, 121 (1991)

SMM: Statistical Multifragmentation Model:
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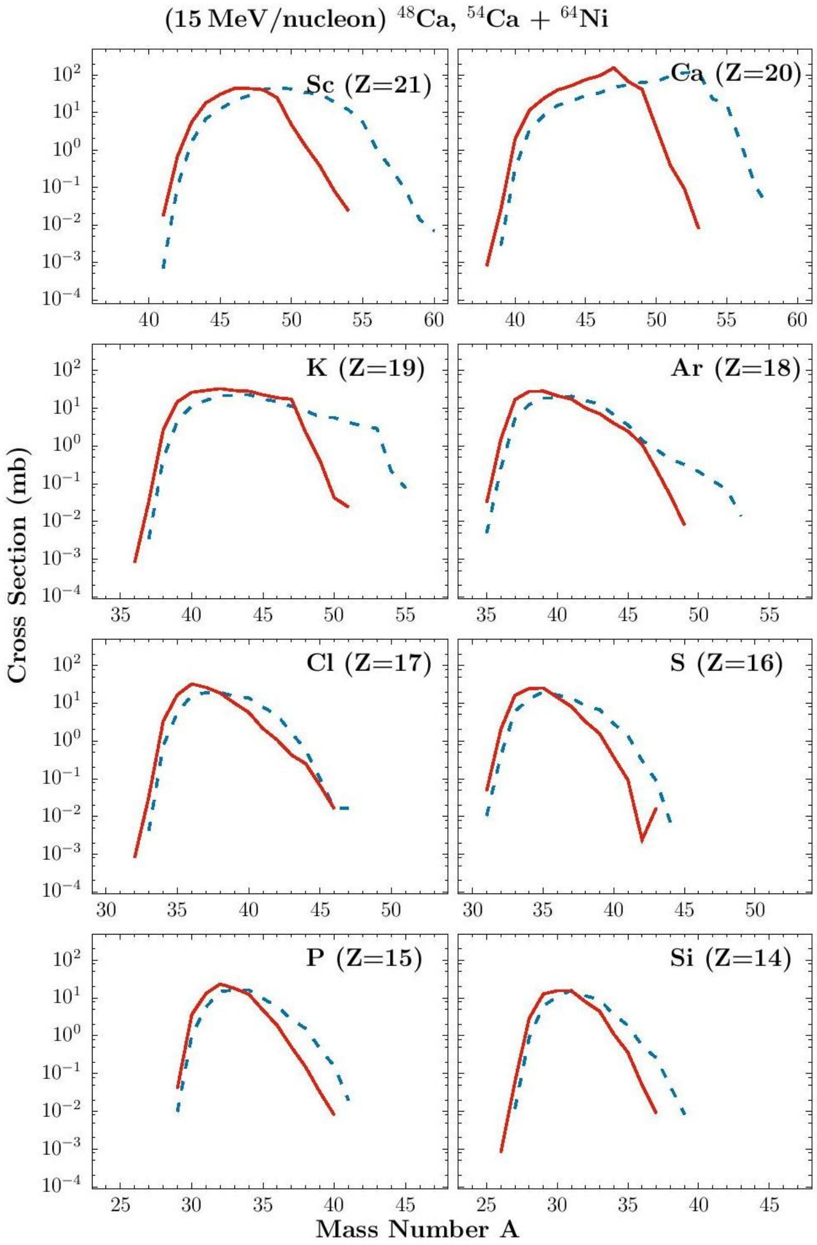
Nucl. Phys. A 507, 649 (1990)

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

Comparison of RIB ^{54}Ca with stable beam ^{48}Ca



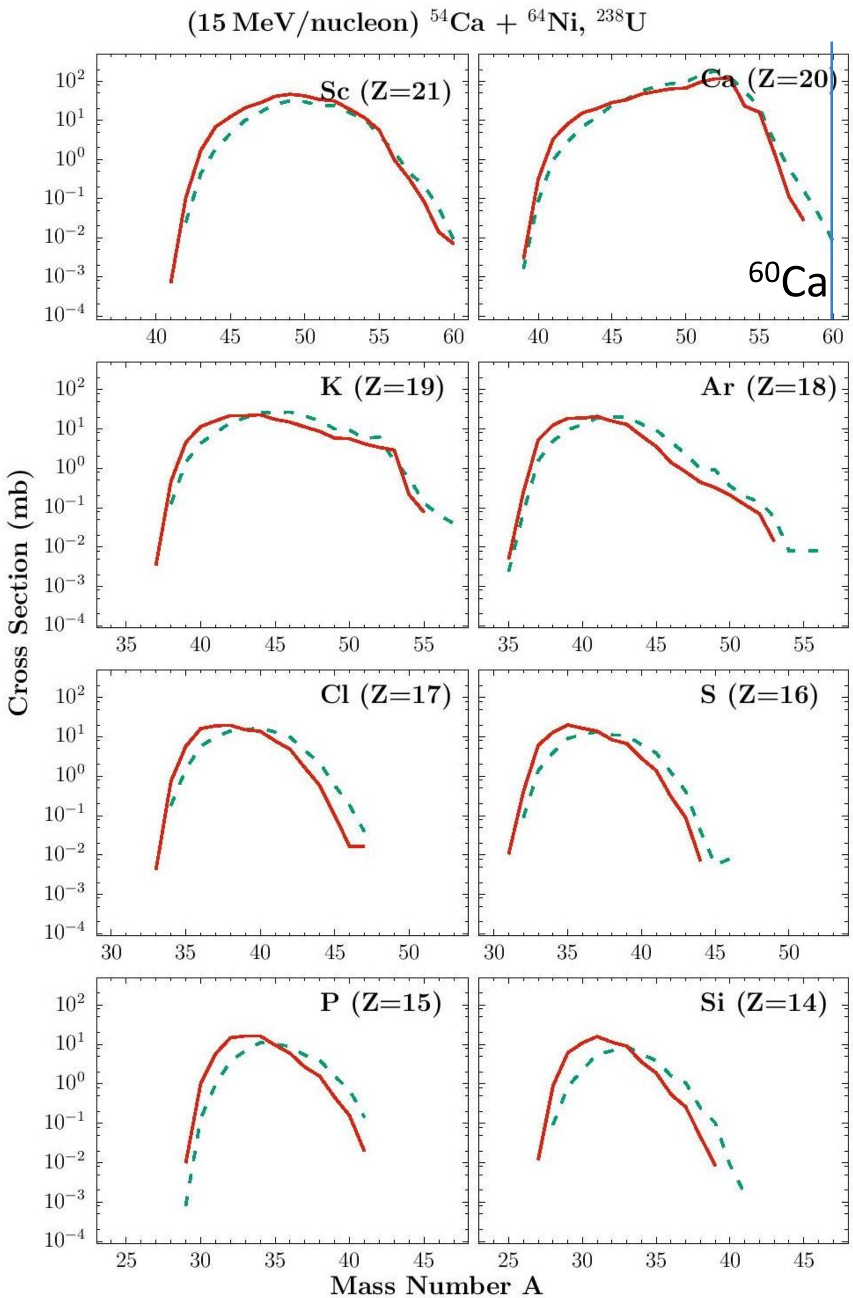
— DIT/SMM $^{48}Ca + ^{64}Ni$

….. DIT/SMM $^{54}Ca + ^{64}Ni$

DIT : Deep inelastic transfers L. Tassan-Got and C. Stefan, Nucl. Phys A 524, 121 (1991)

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

Calculations with RIB ^{54}Ca(15 MeV/nucleon) + ^{64}Ni, ^{238}U



— DIT/SMM ^{54}Ca + ^{64}Ni (N/Z = 1.28)

….. DIT/SMM ^{54}Ca + ^{238}U (N/Z= 1.59)

DIT : Deep inelastic transfers L. Tassan-Got and C. Stefan, Nucl. Phys A 524, 121 (1991)

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Cross Sections and RIB Rate estimates

^{48}Ca (15 MeV/nucleon) + ^{238}U

Rare isotope	Reaction Channel	Cross Section (mb)	Rates (s^{-1})
^{54}Ca	- 0p + 6n	0,03	4.6×10^{3}
^{46}Ar	- 2p - 0n	2.88	4.4×10^{5}
^{55}Sc	+1p + 6n	0.051	7.8×10^{3}
^{52}K	- 1p + 5n	0.05	17.6×10^{3}

- **Beam of ^{48}Ca with intensity 500 pnA (3 x 10^{12} particles/s)**
- **Beams of ^{46}Ar and ^{54}Ca with intensities taken from the rates of the reaction ^{48}Ca (15 MeV/nucleon) + ^{238}U**
- **^{238}U target with a thickness of 20 mg/cm^{2}**

^{46}Ar (15 MeV/nucleon) + ^{238}U

Rare isotope	Reaction Channel	Cross Section (mb)	Rates (s^{-1})
^{51}Ar	- 0p + 5n	0,064	1.4×10^{-3} (5 $hour^{-1}$)
^{52}Ar	- 0p - 06n	0.008	1.8×10^{-4} (15 day^{-1})
^{48}Cl	-1p + 3n	0.24	5.4×10^{-3} (19 $hour^{-1}$)
^{49}Cl	- 1p + 4n	0.06	1.3×10^{-3} (5 $hour^{-1}$)

^{54}Ca (15 MeV/nucleon) + ^{238}U

Rare isotope	Reaction Channel	Cross Section (mb)	Rates (s^{-1})
^{57}Ca	- 0p + 3n	0.59	1.4×10^{-4} (12 day^{-1})
^{58}Ca	-0p +4n	0..16	3.75×10^{-5} (3 day^{-1})
^{59}Ca	-op +5n	0.04	9.75×10^{-6} (6 $week^{-1}$)
^{60}Ca	- 0p + 6n	0.008	1.9×10^{-6} (1 $week^{-1}$)
^{54}K	-1p + 1n	0.58	1.4×10^{-4} (12 day^{-1})
^{57}K	- 1p + 4n	0.04	9.4×10^{-6} (6 $week^{-1}$)

Summary and Conclusions:

- Systematic study of production of neutron-rich rare isotopes in peripheral reactions below the Fermi energy in mass range A ~40-60
- Satisfactory agreement with available experimental results
- Predictions of RIB rates using the calculated cross sections
- Predictions of extremely neutron rich isotopes towards ^{60}Ca

Plans for future work:

- Further theoretical investigation with CoMD, DIT, SMM
- Experimental work with ^{70}Zn stable beam at 15 MeV/nucleon at LNS Catania with the MAGNEX spectrometer

Acknowledgements

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THANK YOU !