Production of Rare Isotopes toward the astrophysical r-process path

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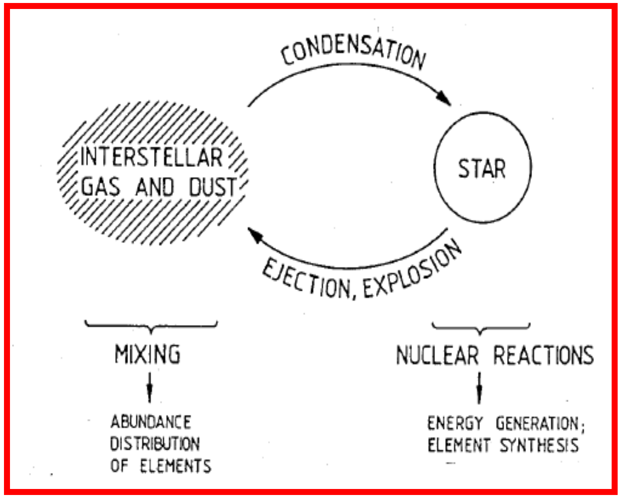
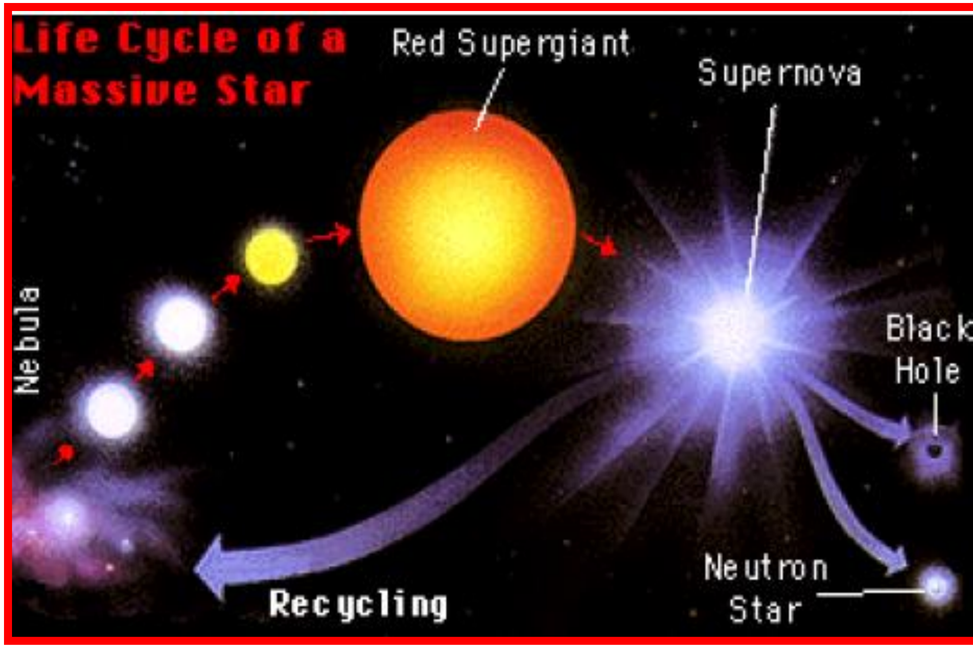
Nucleosynthesis in the Universe and the Stars

Big Bang Nucleosynthesis

$$\underbrace{{}^1H,\ {}^2H,\ {}^3He,\ {}^4He}_{\sim 98\%\ \text{by}\ mass},\ {}^6Li,\ {}^7Li$$

Star formation, Nucleosynthesis





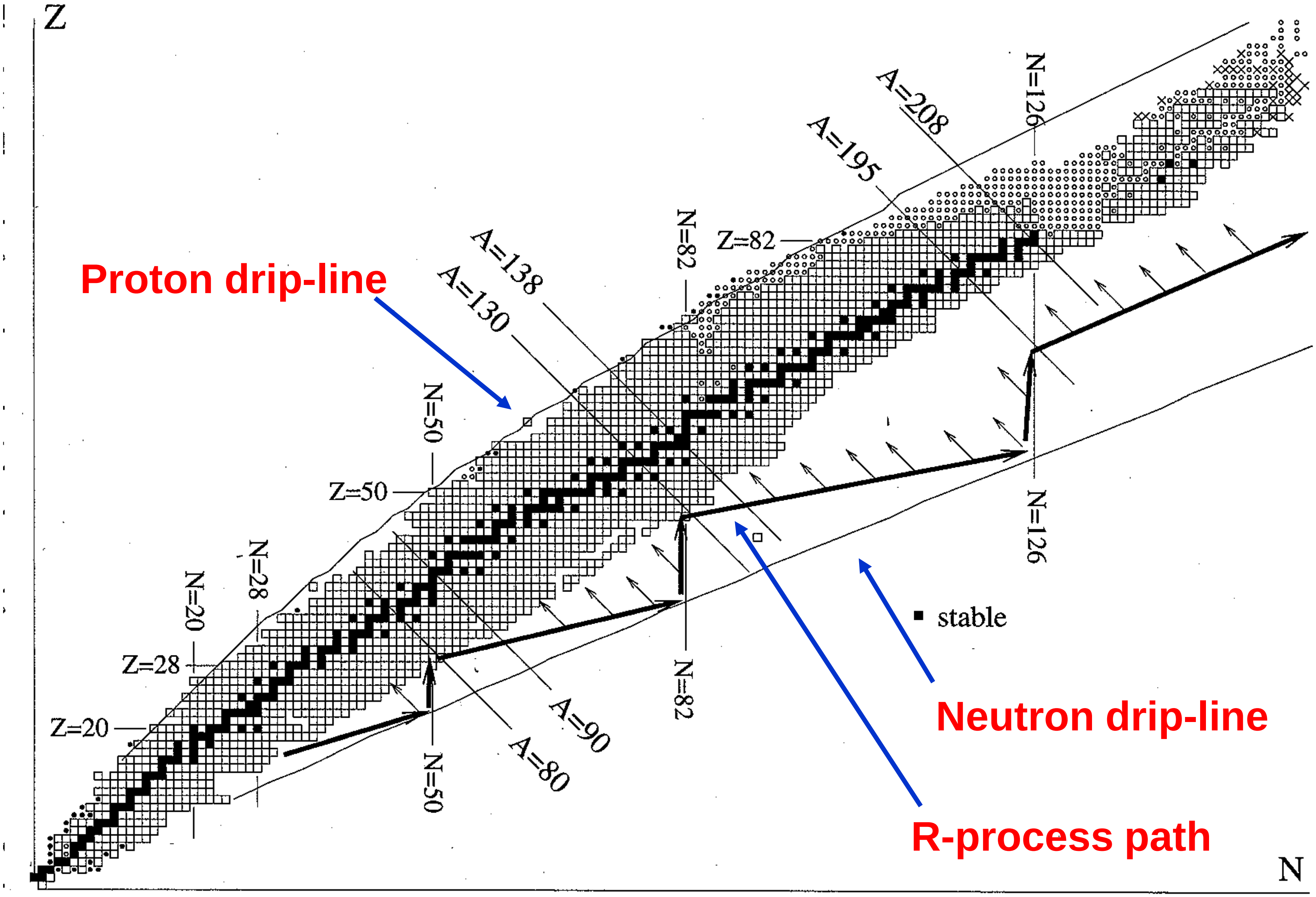
The properties of nuclei play key roles in the life and evolution of stars

Elements up to Fe synthesized in thermonuclear fusion reactions

Elements above Fe: n-capture/β-decay
s-process (slow neutron capture)
r-process (rapid neutron capture)

Stars from birth to death: cosmic laboratories for “exotic” nuclei

The Nuclear Landscape and the r-process path

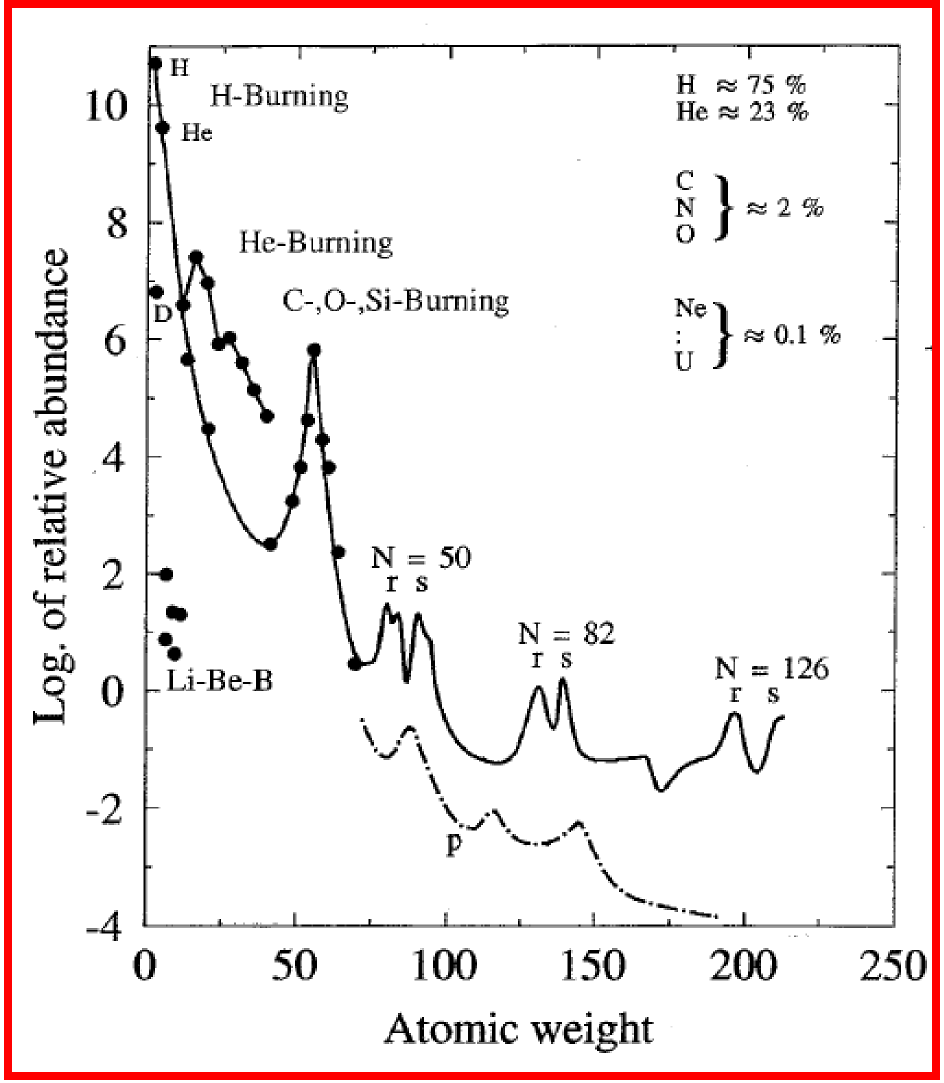


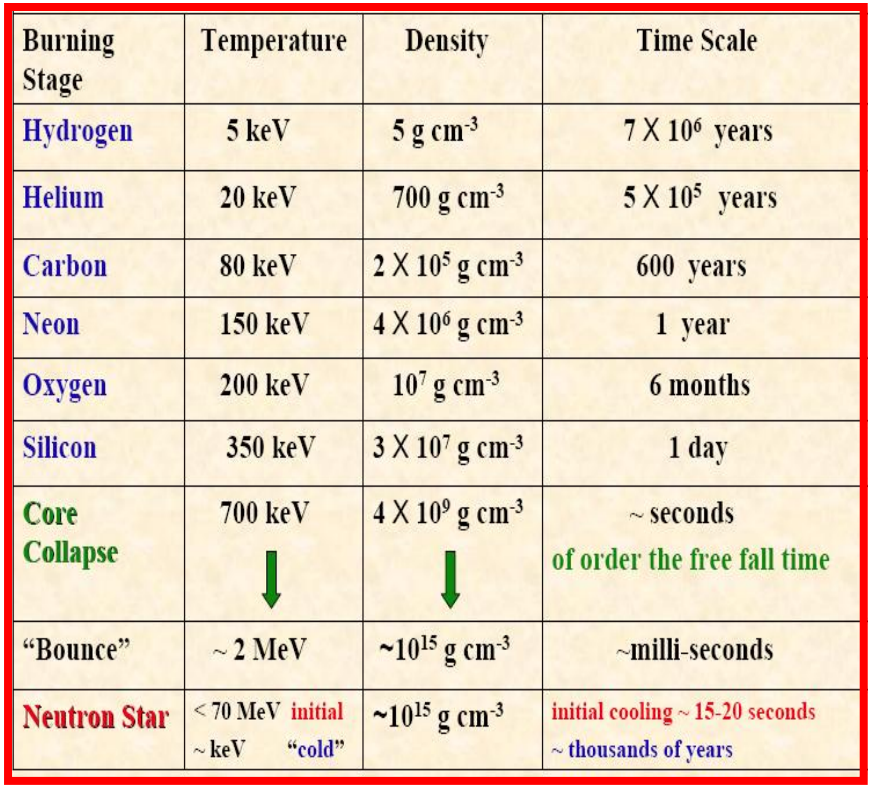
Proton drip-line

Neutron drip-line

R-process path

Abundance Distribution of the Elements*





Burning Stage	**Temperature**	**Density**	**Time Scale**
Hydrogen	5 keV	5 g cm^{-3}	7 X 10^{6} years
Helium	20 keV	700 g cm^{-3}	5 X 10^{5} years
Carbon	80 keV	2 X 10^{5} g cm^{-3}	600 years
Neon	150 keV	4 X 10^{6} g cm^{-3}	1 year
Oxygen	200 keV	10^{7} g cm^{-3}	6 months
Silicon	350 keV	3 X 10^{7} g cm^{-3}	1 day
Core Collapse	700 keV ↓	4 X 10^{9} g cm^{-3} ↓	~ seconds of order the free fall time
"Bounce"	~ 2 MeV	~10^{15} g cm^{-3}	~milli-seconds
Neutron Star	< 70 MeV initial ~ keV "cold"	~10^{15} g cm^{-3}	initial cooling ~ 15-20 seconds ~ thousands of years

* G. M. Fuller, UCSD

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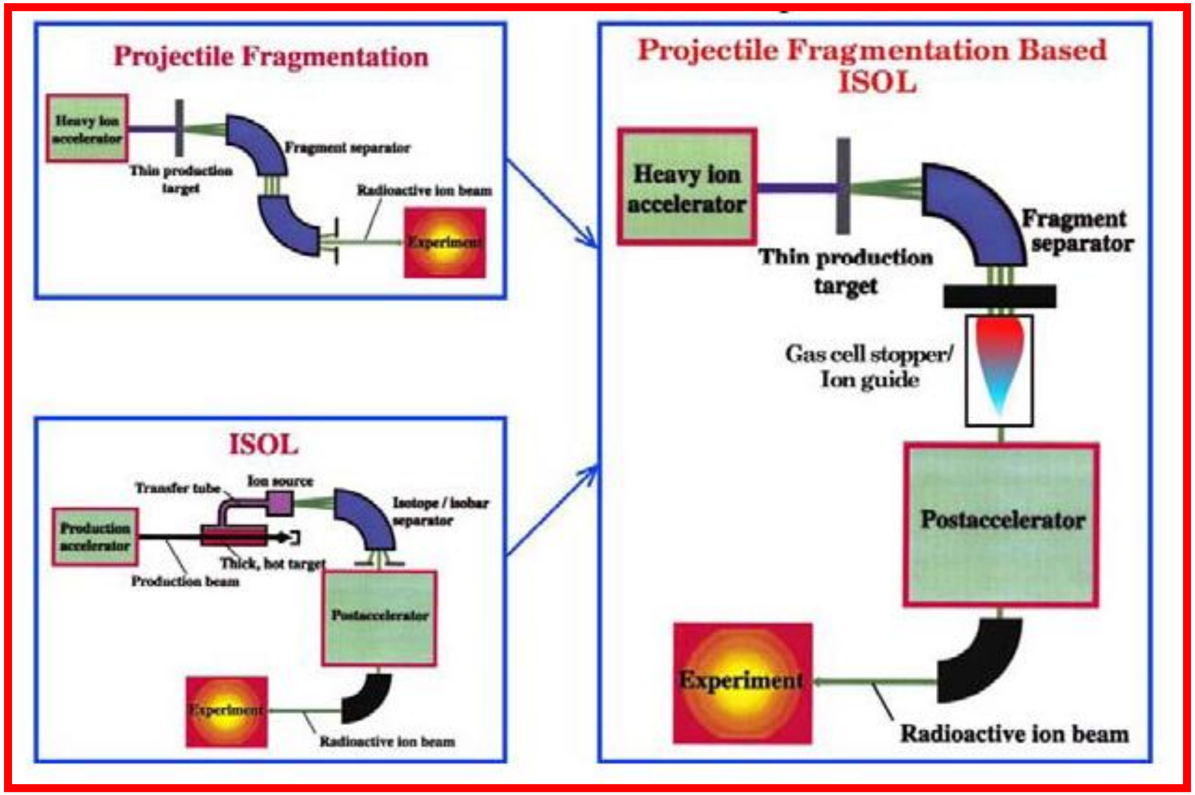
Production Methods of Rare Isotope Beams[1]

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

Overview :

Previous work at Texas A&M:

- deep inelastic collisions at Fermi energies:
- ^{86}Kr(25MeV/nucleon) + ^{64}Ni, PLB 543, 163 (2002)
- ^{86}Kr + ^{124}Sn, ^{112}Sn, PRL 91, 022701 (2003)

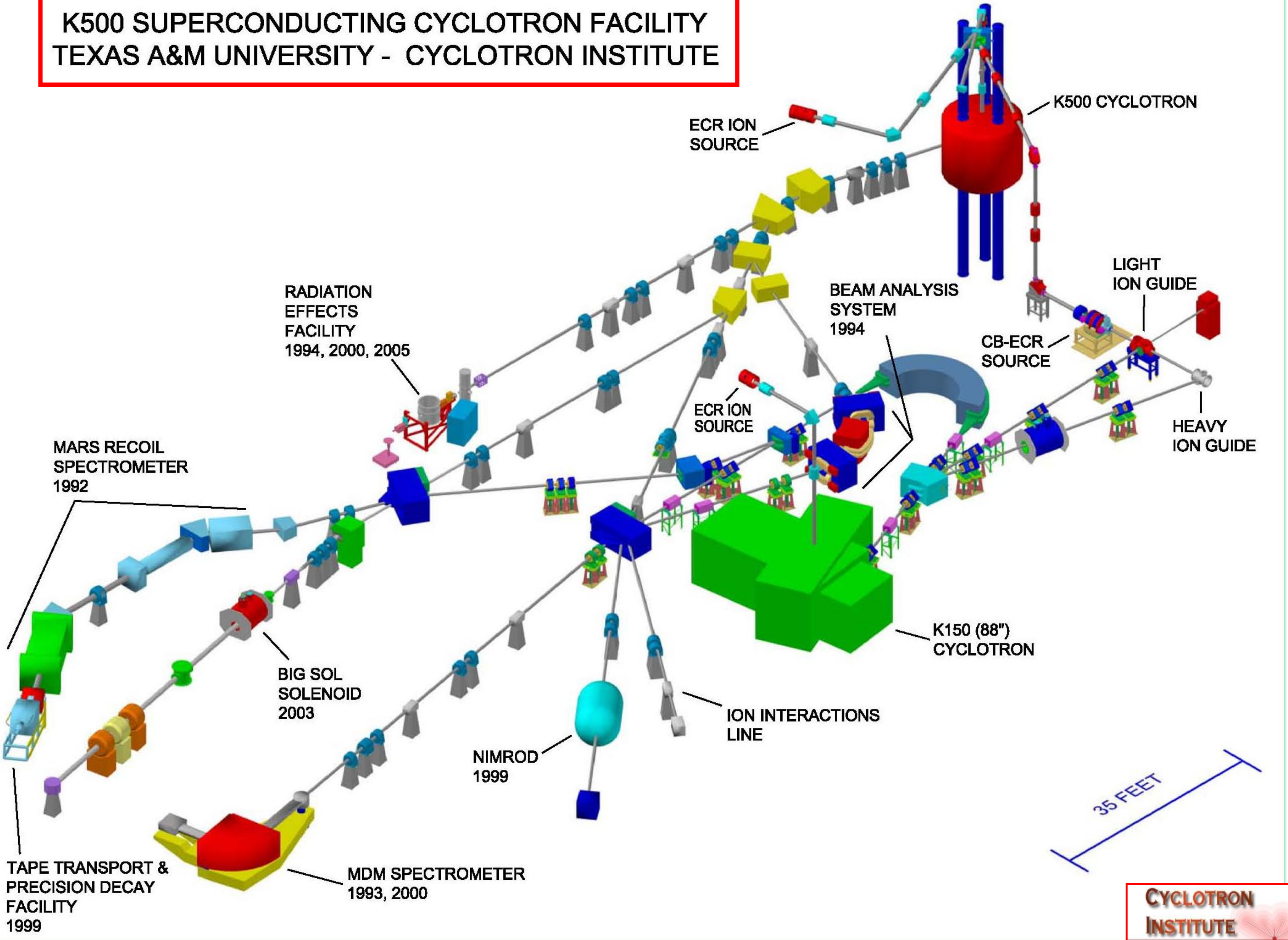
Findings:

- Peripheral collisions: enhanced production of neutron-rich nuclei, neutron skin effect
- Heavy Residues as EOS probes:
  - N/Z equilibration [PLB 588, 35 (2004)]
  - $C_{sym}(\varepsilon^*)$ in hot nuclei [PRC 73 024606 (2006)]
  - Emphasis on $S_{sym}(\rho)$ via CoMD calculations
  - Phys. Rev C, 90, 064612 (2014)

Current focus: Investigation at 15MeV/u to produce
n-rich isotopes: Phys. Rev C, 84, 064607 (2011)
P. Fountas, G.S. et al. Phys. Rev C, 90, 064613 (2014)
Systematic description of the mechanisms with
DIT and CoMD models. Fission description:

N. Vonta, G.S. et al., Phys. Rev C 92, 024616 (2015)

K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE



K500 CYCLOTRON

ECR ION
SOURCE

RADIATION
EFFECTS
FACILITY
1994, 2000, 2005

BEAM ANALYSIS
SYSTEM
1994

LIGHT
ION GUIDE

CB-ECR
SOURCE

ECR ION
SOURCE

HEAVY
ION GUIDE

MARS RECOIL
SPECTROMETER
1992

K150 (88")
CYCLOTRON

BIG SOL
SOLENOID
2003

ION INTERACTIONS
LINE

NIMROD
1999

35 FEET

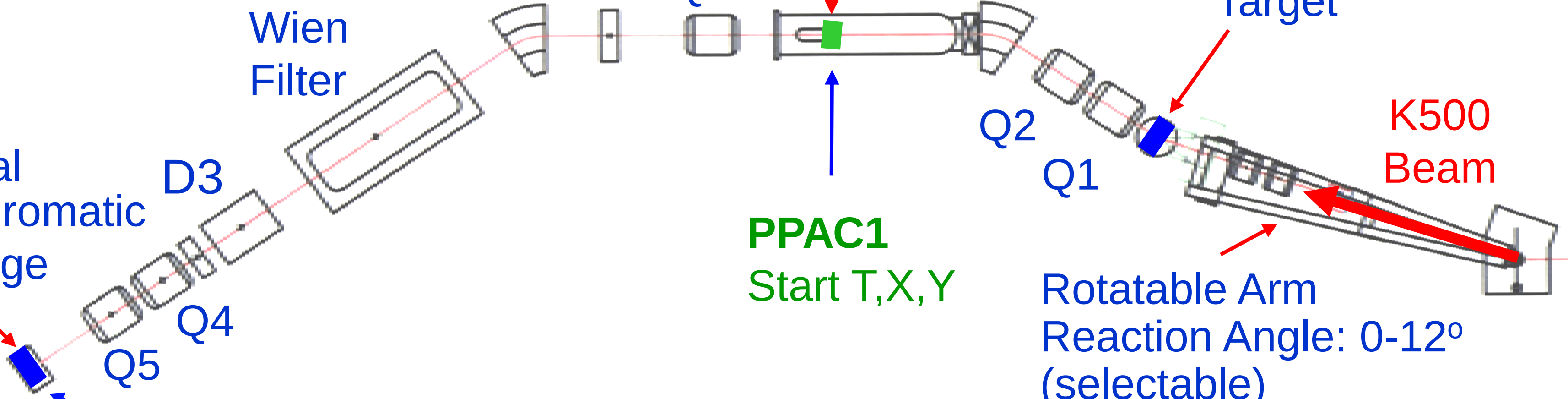
TAPE TRANSPORT &
PRECISION DECAY
FACILITY
1999

MDM SPECTROMETER
1993, 2000

CYCLOTRON
INSTITUTE
Texas A&M University

MARS Recoil Separator and Setup for Heavy Rare Isotope Studies*

Cyclotron Institute
Texas A&M University



Separation Stage I

Dispersive Image

Separation Stage II

D2

Q3

D1

Production Target

Wien Filter

K500 Beam

Q2

Q1

Final Achromatic Image

D3

PPAC1
Start T,X,Y

Rotatable Arm
Reaction Angle: 0-12º
(selectable)

Q4

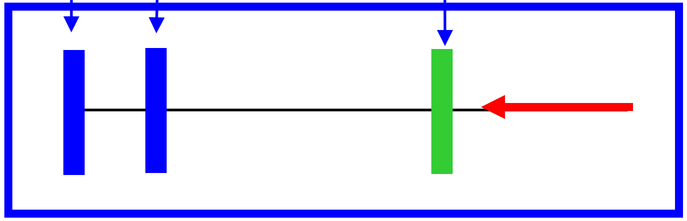
Q5

$B\rho = m\upsilon/Q$

MARS Acceptances:
Angular: 9 msr
Momentum: 4 %

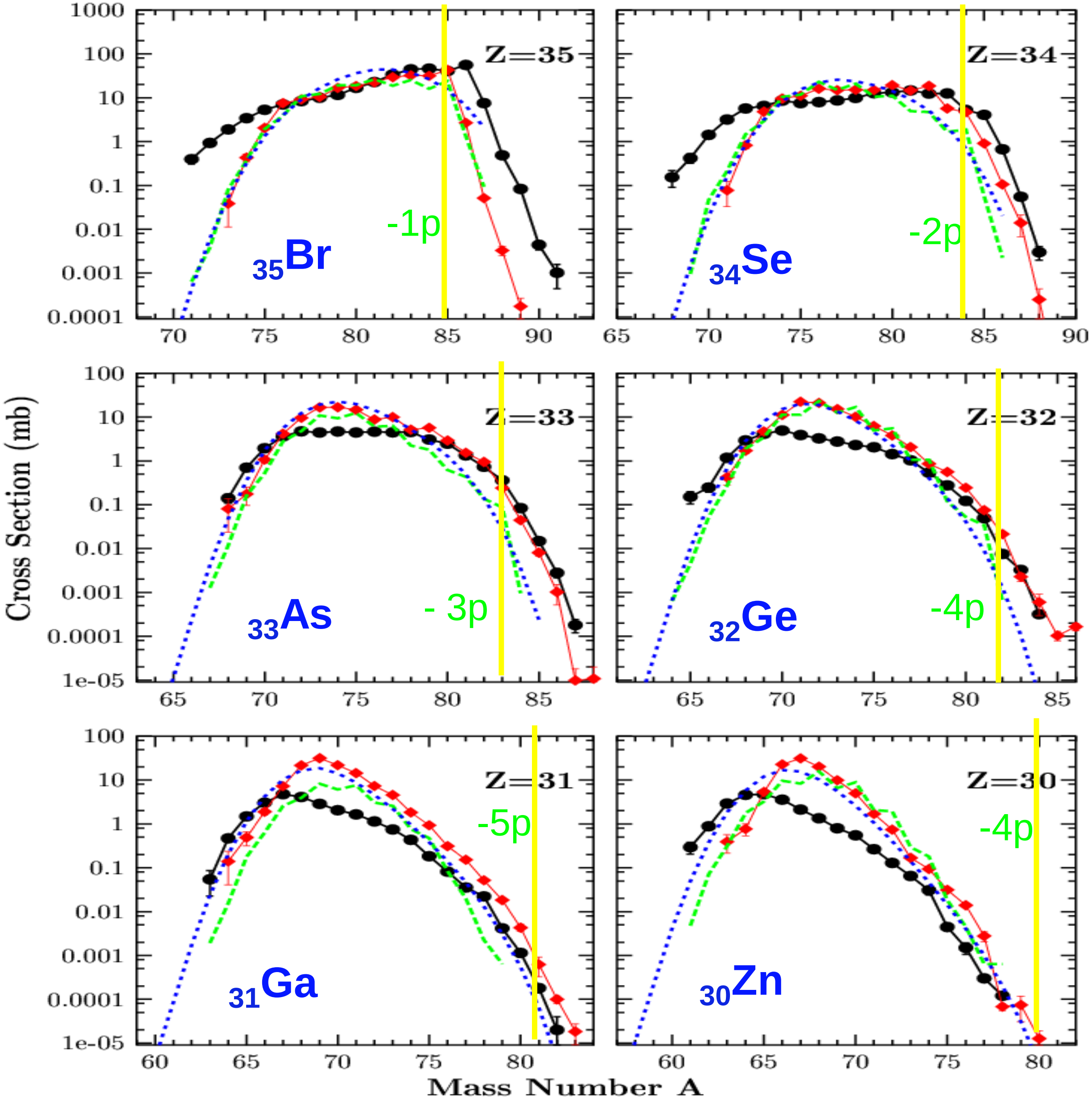
Si Telescope
E_r ΔE

PPAC2
Stop T, X,Y



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

Mass Distributions: ^{86}Kr + ^{64}Ni



● ^{86}Kr + ^{64}Ni (15 MeV/u)

● ^{86}Kr + ^{64}Ni (25 MeV/u)*

----- DIT/GEMINI

----- EPAX

Large cross sections of n- pickup products

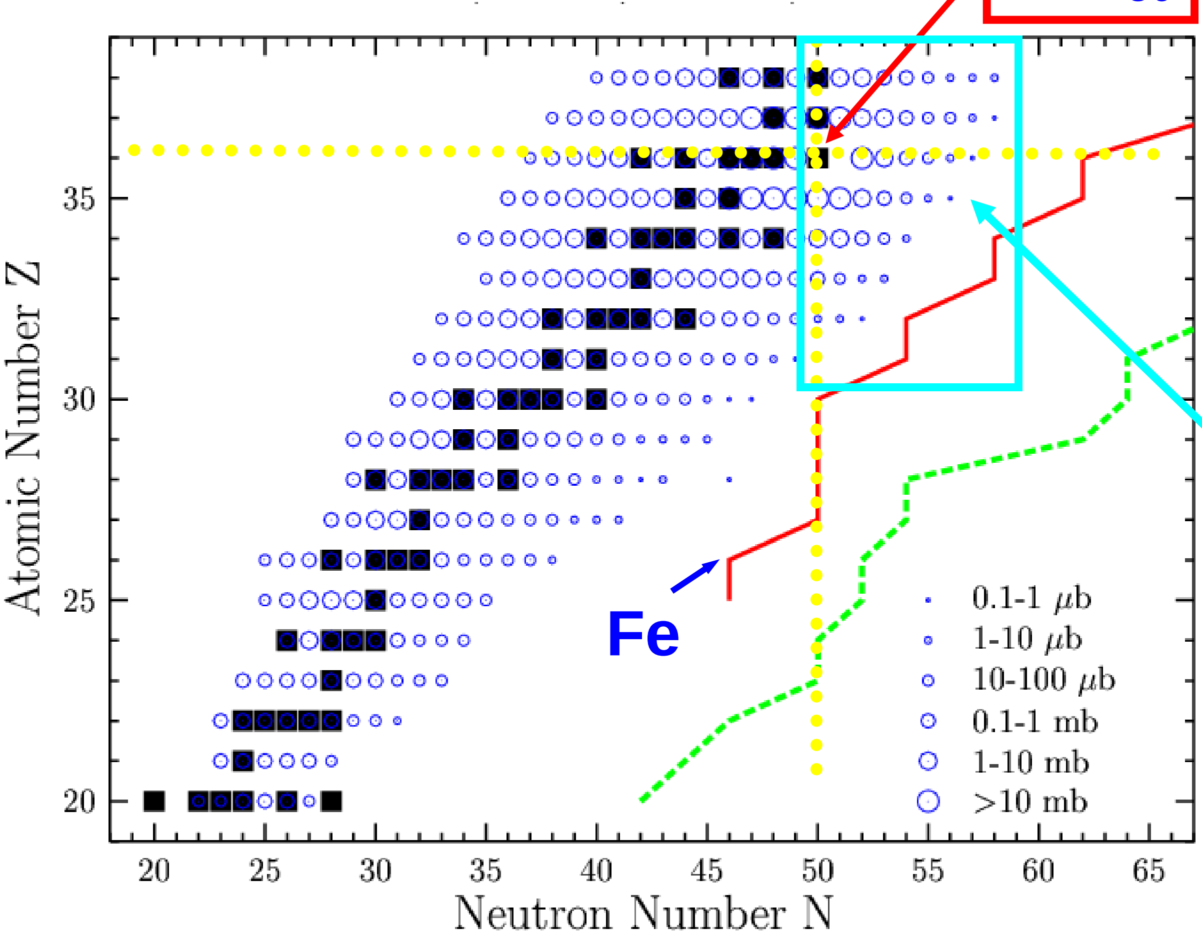
*G. A. Souliotis et al., Phys. Rev. C 84, 064607 (2011)

*G. A. Souliotis et al., Phys. Lett. B 543, 163 (2002)

Rare Isotope Production at 15MeV/nucleon :

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

$^{86}_{36}\text{Kr}_{50}$



Fe

❍ MARS Data:*

■ stable nuclei

— r-process

----- n-drip line

Neutron-pickup products

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

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

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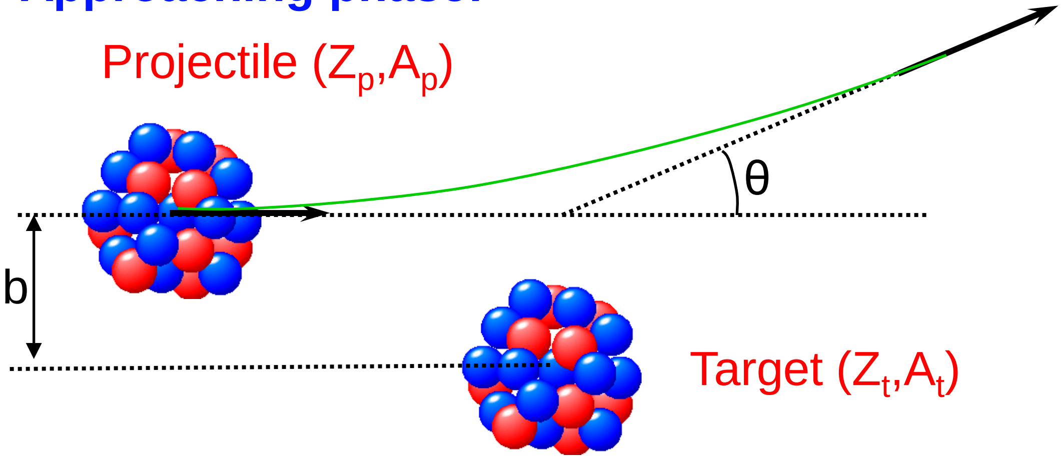
Collisions between Heavy Ions at Fermi Energies (10<E/A < 40MeV)

Approaching phase:



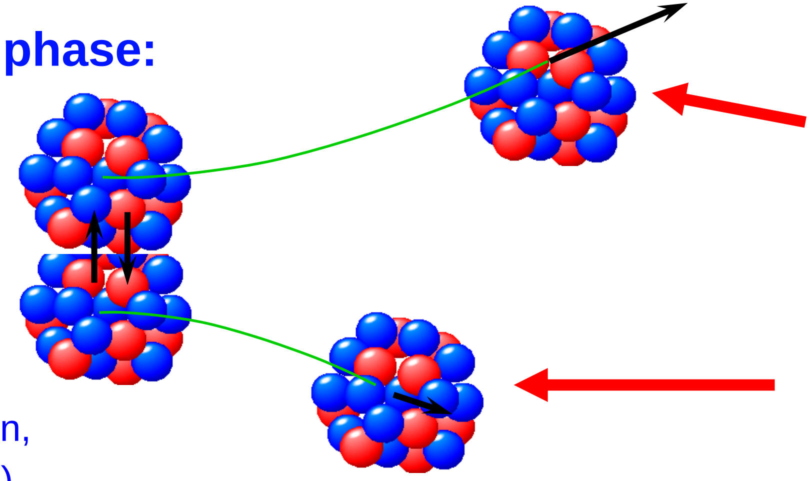
● Neutrons
● Protons

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)

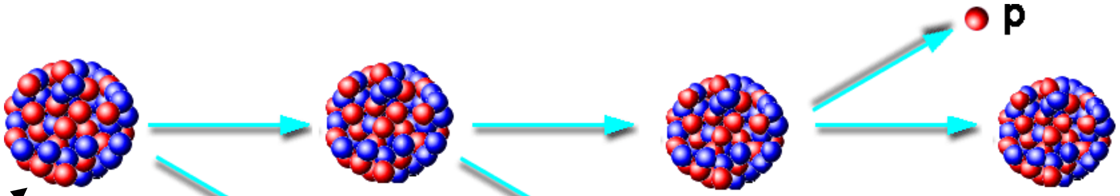
DITm: M. Veselsky, G.A. Souliotis, Nucl. Phys. A 765, 252 (2006)

Nuclear De-excitation Mechanisms

I. Sequential Evaporation

E*/A < 2 MeV

T < 4MeV



Initial nucleus

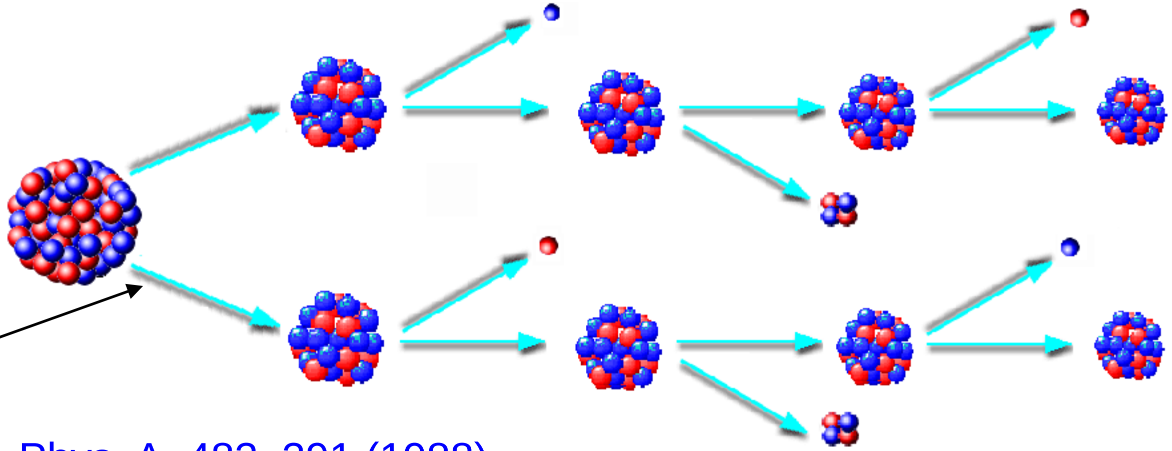
α-particle

Residual nucleus or
'evaporation' residue

II. Sequential Binary Decay

E*/A ~ 2-3 MeV

T ~ 4-5 MeV



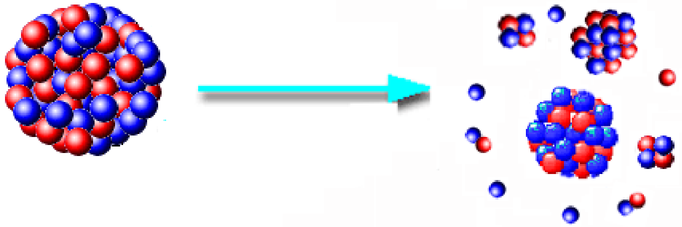
Binary splitting
(like fission)

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

III. Multifragmentation

E*/A > 4 MeV

T > 6 MeV



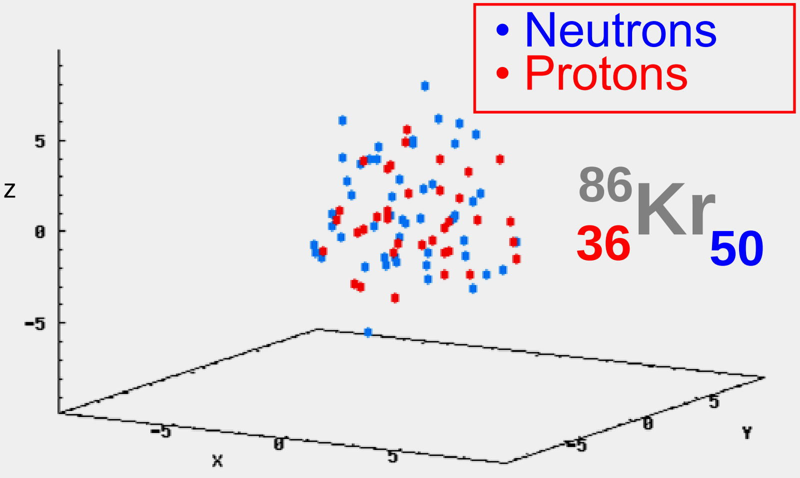
Simultaneous emission of
several fragments
Δt = 50 fm/c (10^{-22} sec)

Microscopic Calculations: Constrained Molecular Dynamics (CoMD)*

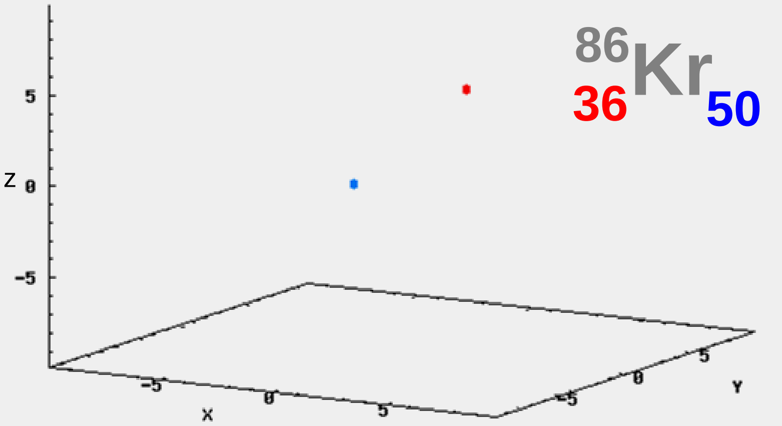
CoMD : Quantum Molecular Dynamics model (Semiclassical)

- Nucleons are considered as Gaussian wavepackets
- **N-N effective interaction** (Skyrme-type with K = 200 or K = 380)
- Several forms for **N-N symmetry potential $V_{sym}(\rho)$**
- **Pauli principle** imposed (via a ‘constraint’ algorithm)
- **Fragment recognition algorithm** (minimum spanning tree, R_{min} = 3.0 fm)

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



Nucleon Trajectories in ^{86}Kr



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

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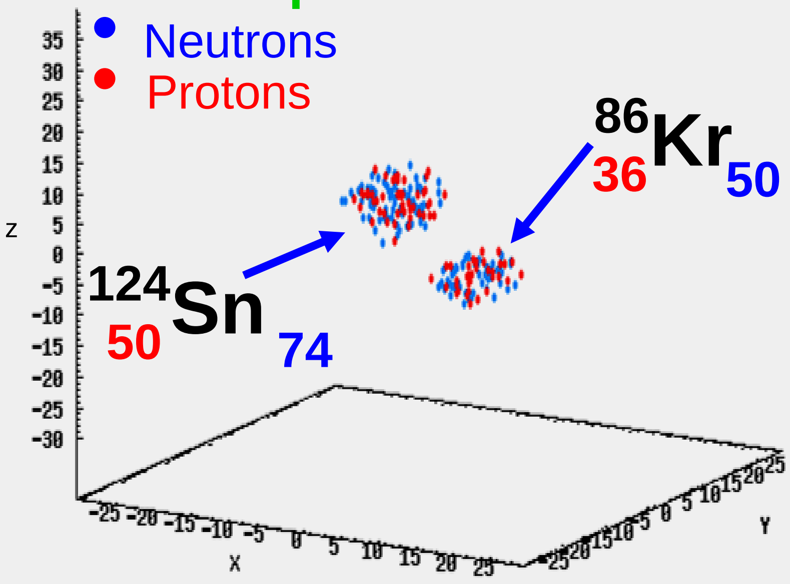
CoMD Calculations: ^{86}Kr (15 MeV/nucleon) + ^{124}Sn

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

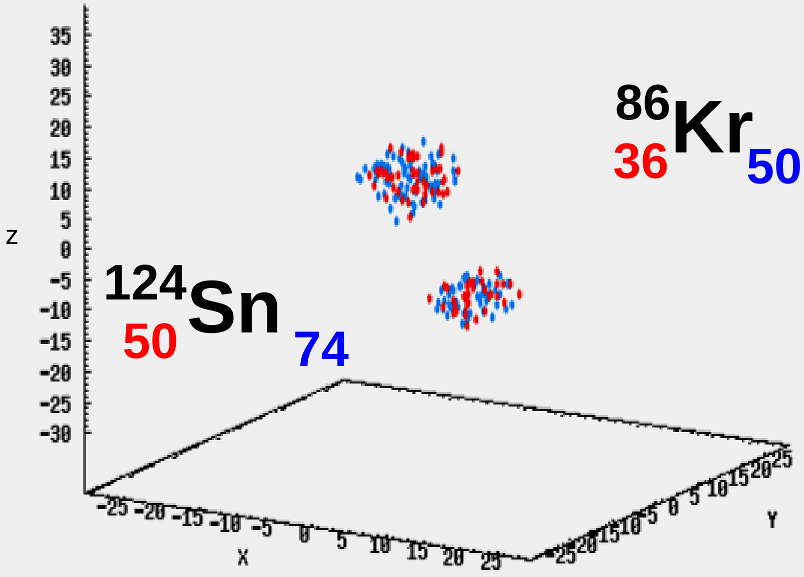


● Neutrons
● Protons

$^{86}_{36}\mathrm{Kr}_{50}$

$^{124}_{50}\mathrm{Sn}_{74}$

Semi-Peripheral Collision



$^{86}_{36}\mathrm{Kr}_{50}$

$^{124}_{50}\mathrm{Sn}_{74}$

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

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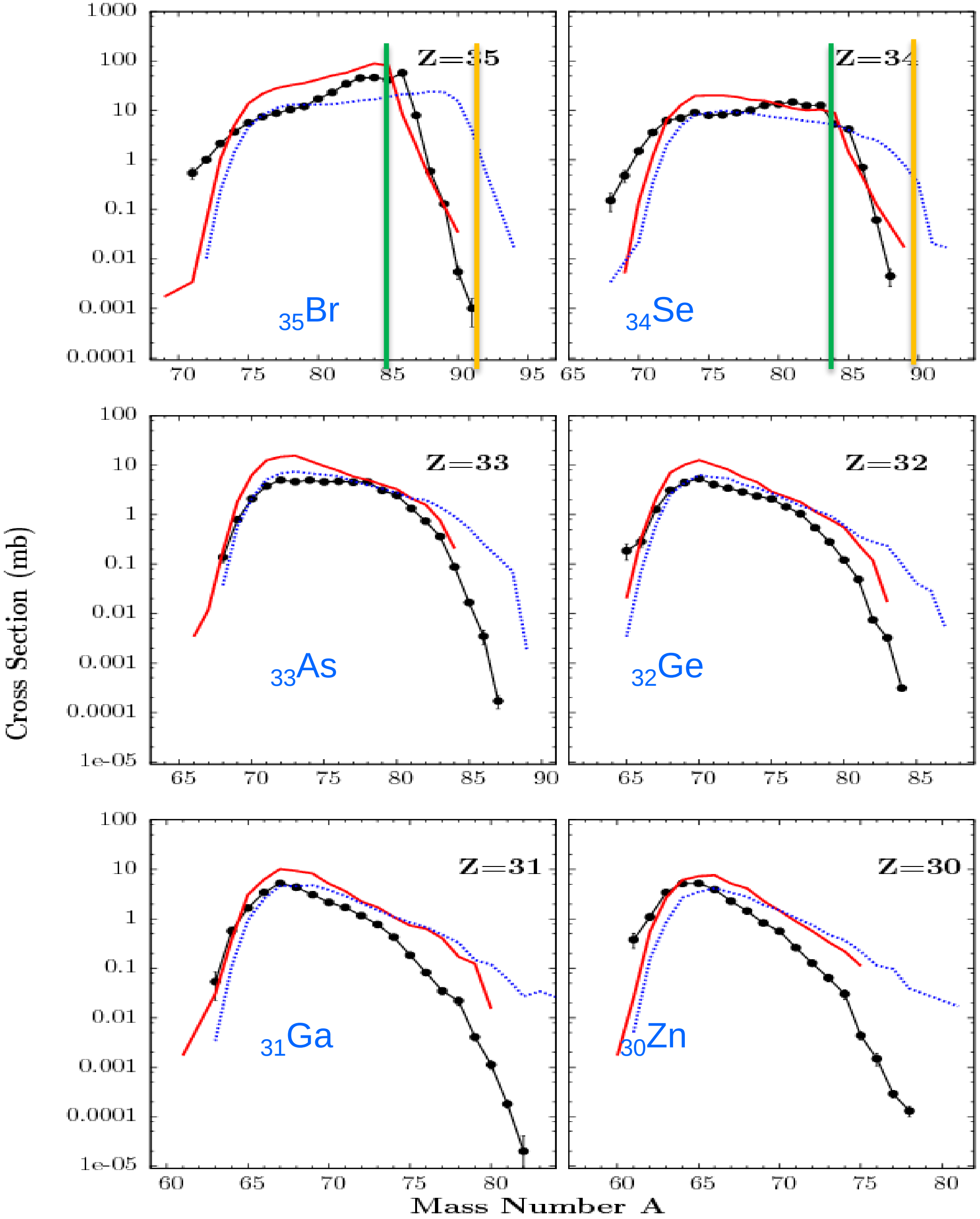
Prediction: ^{92}Kr (15 MeV/nucleon) + ^{64}Ni



● ^{86}Kr + ^{64}Ni (15 MeV/u)*

— CoMD/SMM (^{86}Kr)

----- CoMD/SMM (^{92}Kr)

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

Example of nuclide production in DIC with RIBs:

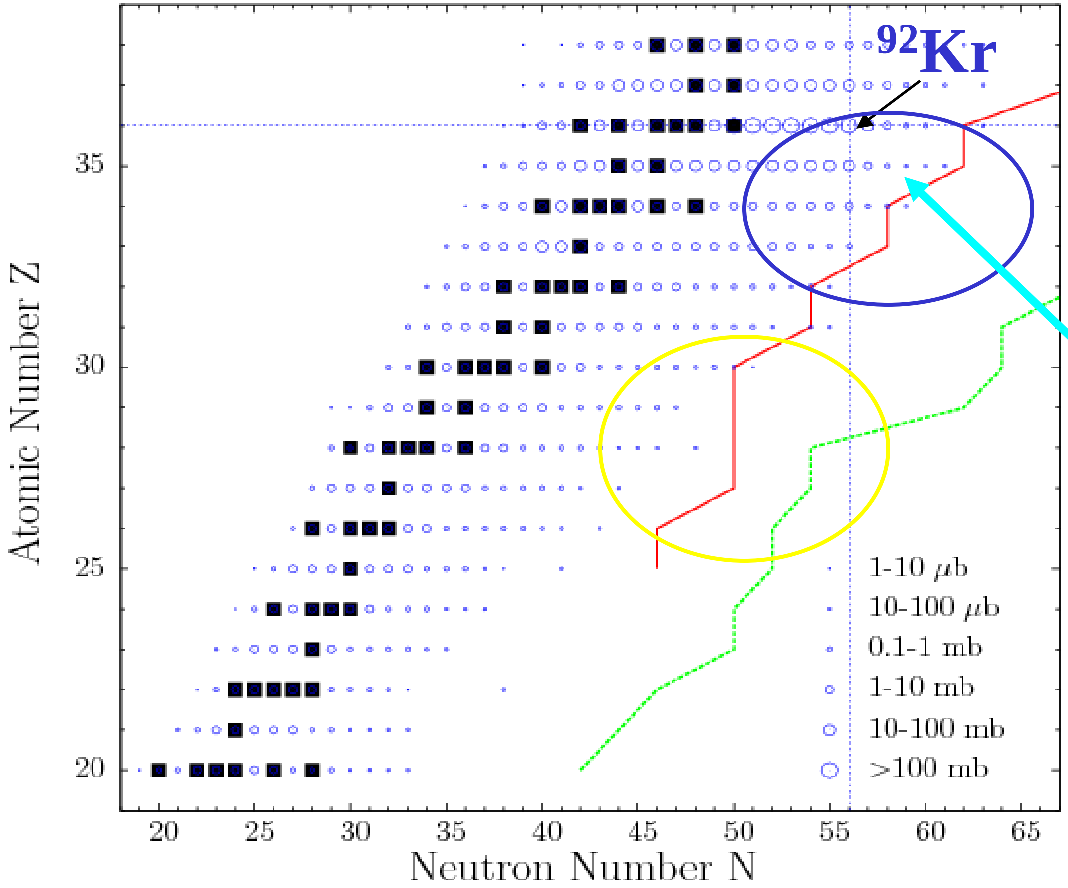
^{92}Kr (15 MeV/u) + ^{64}Ni

❍ Calculations*:
CoMD/SMM

Calculated
nuclide
cross sections:

Very important:

Neutron-pickup
channels !!!
along with
proton stripping



■ 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, M. Veselsky, et al, Phys. Rev. C 90, 064613 (2014)

Summary and Conclusions

- Study of projectile fragment distributions from peripheral collisions: production of very neutron-rich nuclei. Attempts to understand mechanism.
- **Microscopic calculations** of peripheral collisions with DIT and CoMD

Plans for future work (to be discussed futher in this workshop !):

- Comparisons with theoretical codes (DIT, CoMD, GEMINI, SMM)
- Excitation-energy reconstruction and study (15-25 MeV/nucleon data)
- Experimental study of peripheral reactions at energy ~10-20 MeV/nucleon
  Beams: ^{48}Ca, ^{64}Ni, ^{70}Zn, ^{82}Se (also w/ heavy targets: ^{208}Pb, ^{238}U, look ~ θ_{gr})

Extension of experimental studies using neutron-rich RIBs from RISP and TAMU upgrade.

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

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S. Wuenschel, **S.J. Yennello**, Texas A&M

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