Separation of neutron-rich DIR products with MARS

Decay Spectroscopy Workshop

ORNL – Aug. 18-19, 2003

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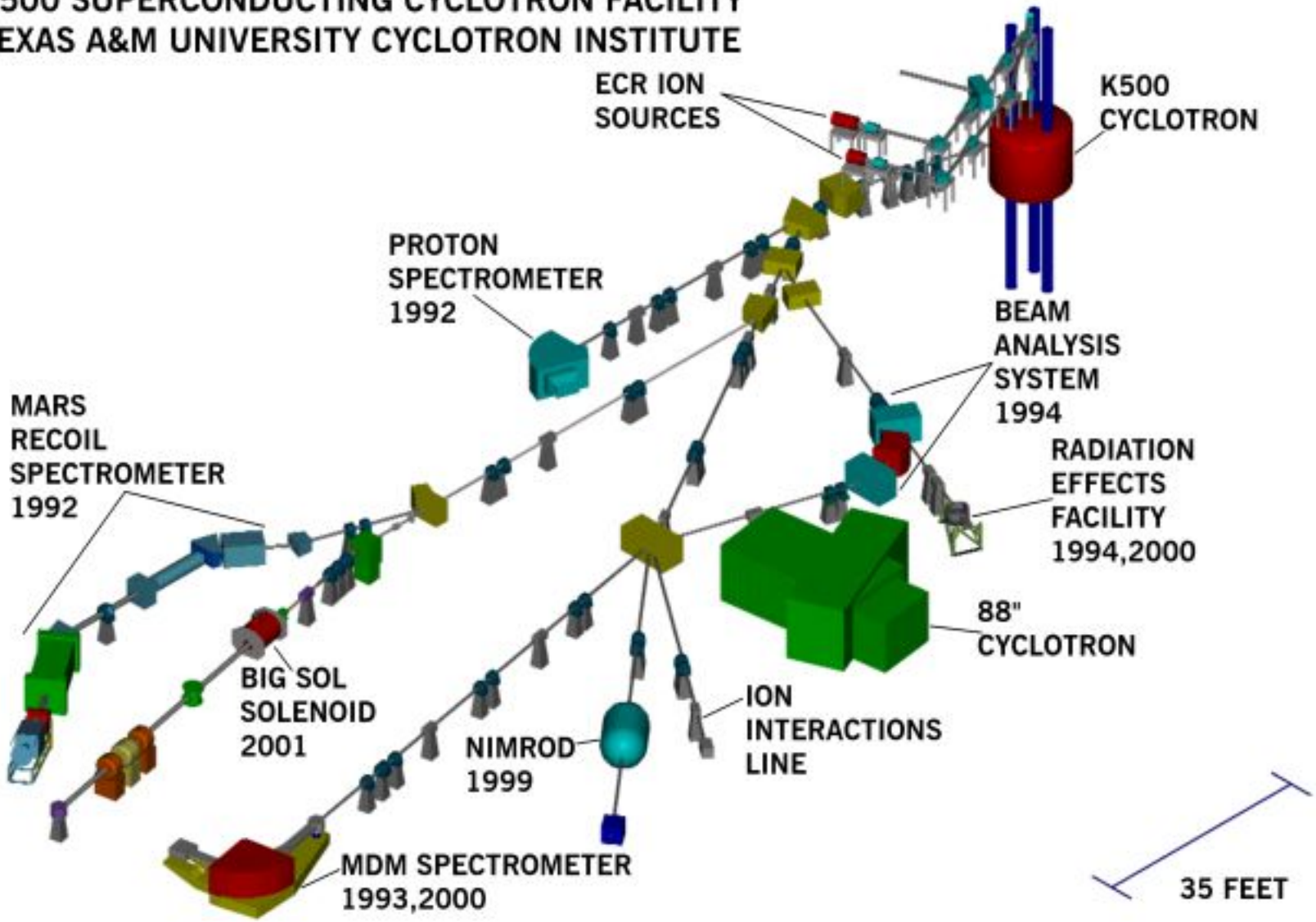
Texas A&M University

K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY CYCLOTRON INSTITUTE



Momentum Achromat Recoil Separator

design: R. E. Tribble, R. H. Burch, C. A. Gagliardi, *Nucl. Instr. Meth.* **A285** (1989)441; NIM **B56/57** (1991)956

Design characteristics:

- On-line recoil mass separator
- For low and intermediate energy HI recoils E=5-50 MeV/u (match to K500)
- Best in inverse kinematics
- Measures recoils or PLF at $\theta_{lab} = 0^o$ or off-0° (up to 30 deg.)
- Momentum achromat + mass separator (two dispersive planes)
- High beam rejection factor $> 10^{15}$-10^{17}
- Low cost

MARS used for:

- production of secondary RIBeams:

  - nuclear astrophysics (RET group –main use)

  - reaction mechanism studies (JB Natowitz, SJ Yennello, G. Viesti - Legnaro group)
- production and separation of high purity samples of exotic nuclei for off-beam β-decay studies (^{57}Cu and with JC Hardy group $0^+ \rightarrow 0^+$ transitions ^{22}Mg, ^{30}S, ^{34}Ar, ^{62}Ga - tape transport)
- in-beam γ–ray spectroscopy (^{57}Cu)
- Off-beam spectroscopy of short-lived isotopes
- Reaction mechanism studies (MARS as detector!)

Production Techniques

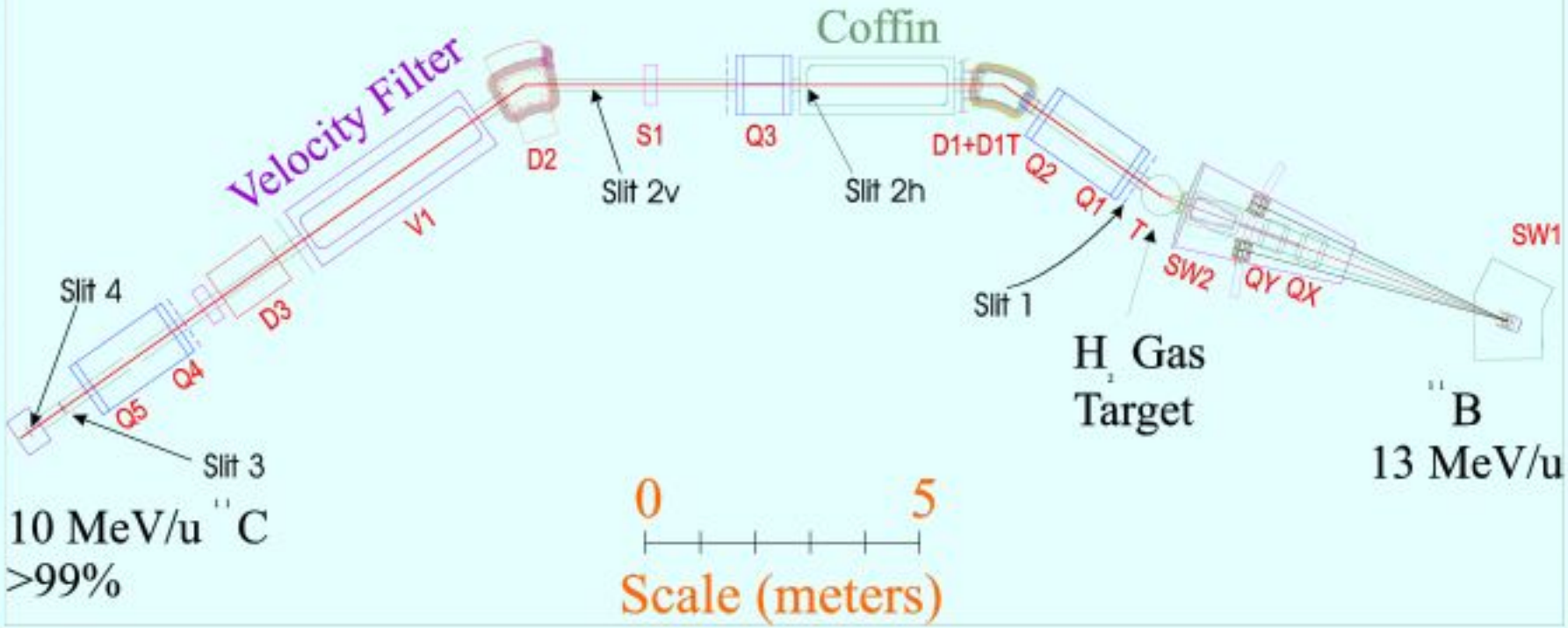
Inverse kinematics (fusion-evaporation or transfer):

- heavy-ion beams
- gas targets (^{1}H, ^{2}H, ^{3}He)
- solid targets

Fragmentation or deep inelastic transfer:

- ^{86}Kr, ^{124}Sn beams on Al, Ni and Sn targets

Momentum Achromat Recoil Separator



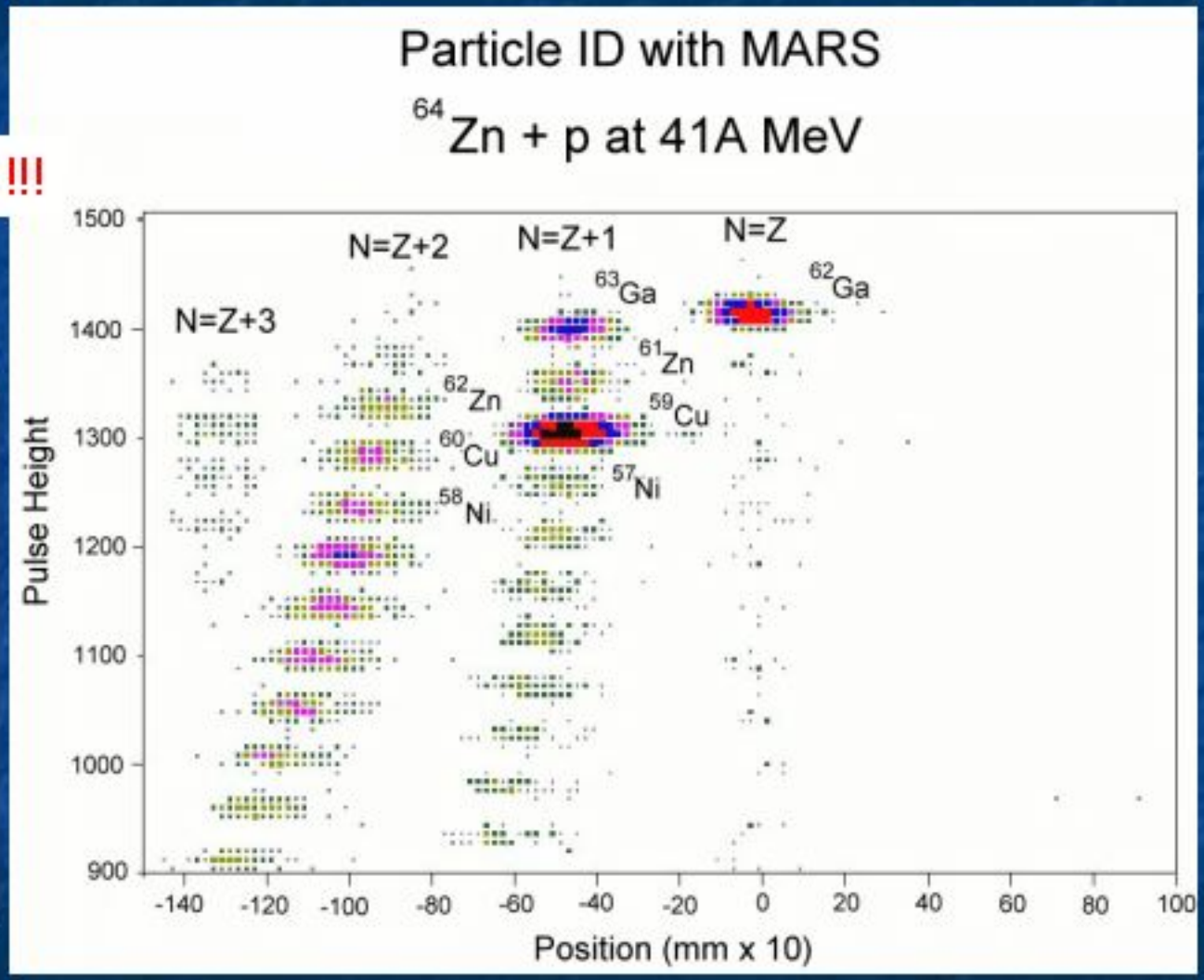
E vs. Y on Focal Plane

Fully stripped recoils !!!

$$E = \frac{1}{2}\left(\frac{p}{q}\right)^2 \left(\frac{q}{m}\right)^2 m$$

$$Y \propto \frac{q}{m}$$

Here p/q is cst.



BC Hyman ea, PR C **68**, 015501 (2003)

Study of ^{57}Cu excited states showed that *in-beam* γ-ray spectroscopy – difficult because v/c=0.25

 Phys Rev C 53, 982 (1996) 53

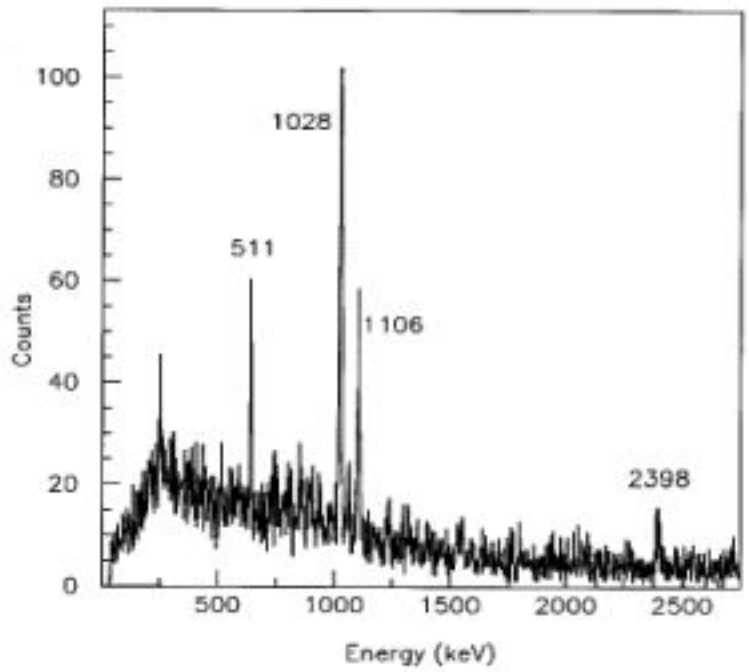


FIG. 2. The summed γ-ray spectrum from the 155° detectors, gated on ^{57}Cu recoil nuclei, after gain matching and Doppler shift corrections have been applied. The small line between the 1028 keV and 1106 keV transitions is the 847 keV line from ^{56}Fe.

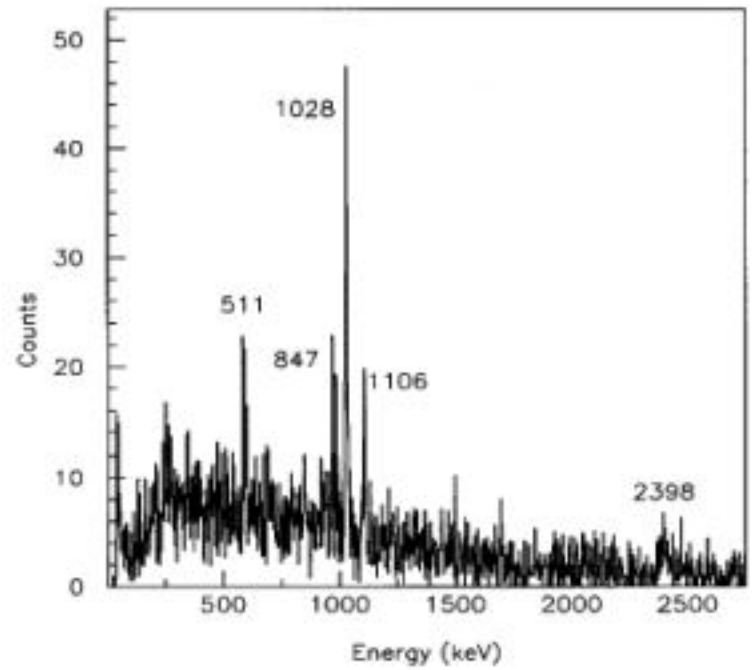


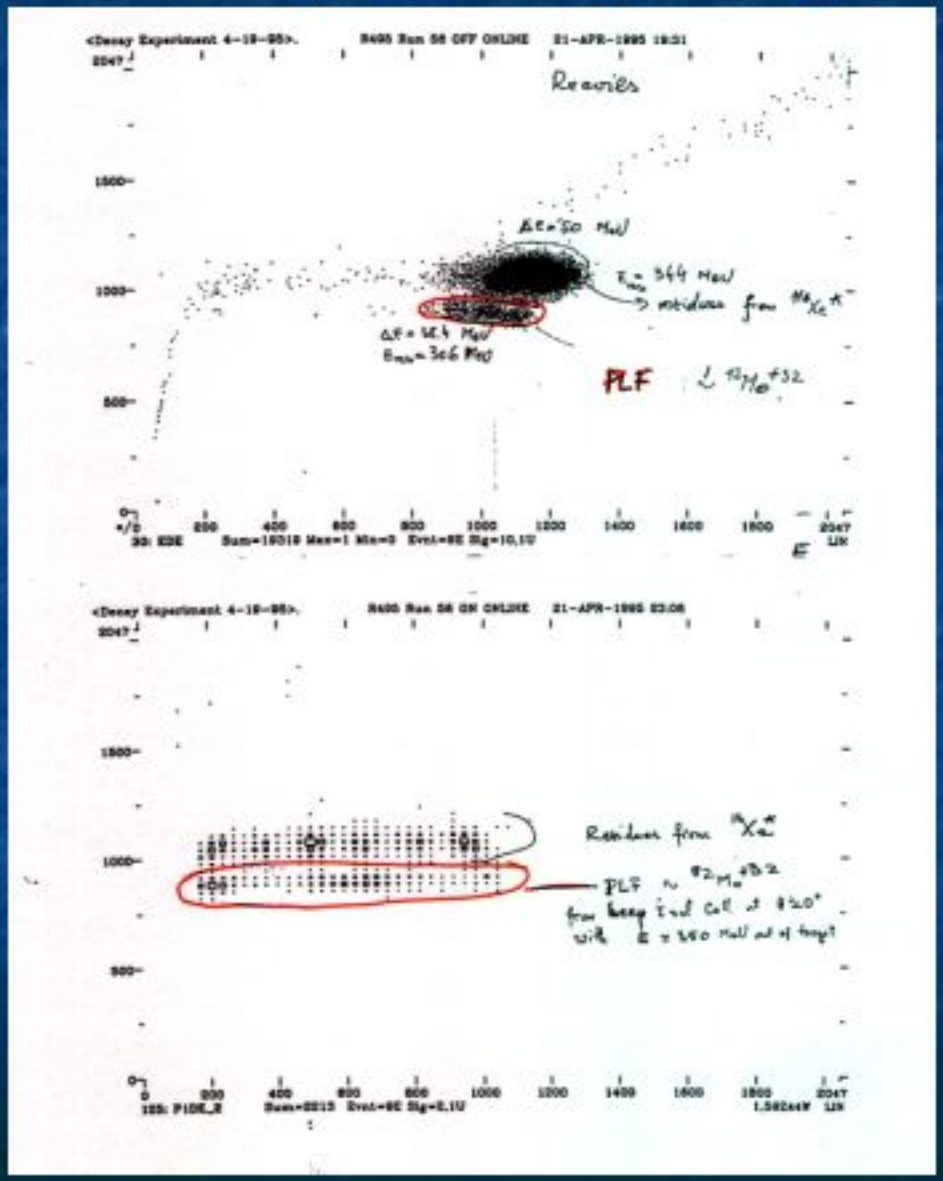
FIG. 3. The summed γ-ray spectrum from the 120° detectors, gated on ^{57}Cu recoil nuclei, after gain matching and Doppler shift corrections have been applied. The 511 and 847 keV lines appear fragmented because the three 120° detectors were not aligned at the same angle, and so they had different Doppler shift factors.

More complex separation: ^{92}Mo (644 MeV)+^{24}Mg

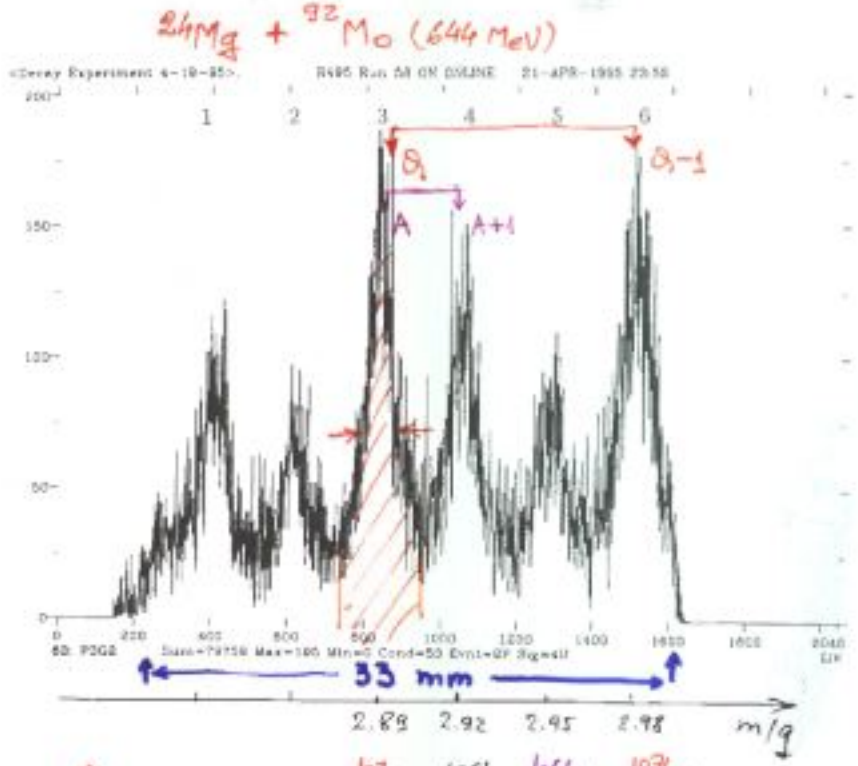
Not fully stripped !!!

E-ΔE →

E – pos →



More complex separation: ^{92}Mo (644 MeV)+^{24}Mg

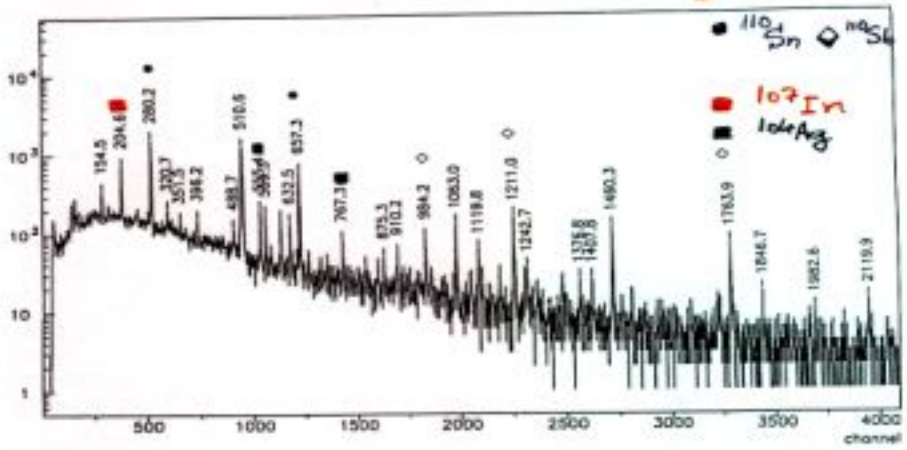


$\frac{A}{Z_i}$ =

107/37	105/36	106/36	107/36
110/38	108/37	109/37	110/37
104/36	111/38	112/38	104/35

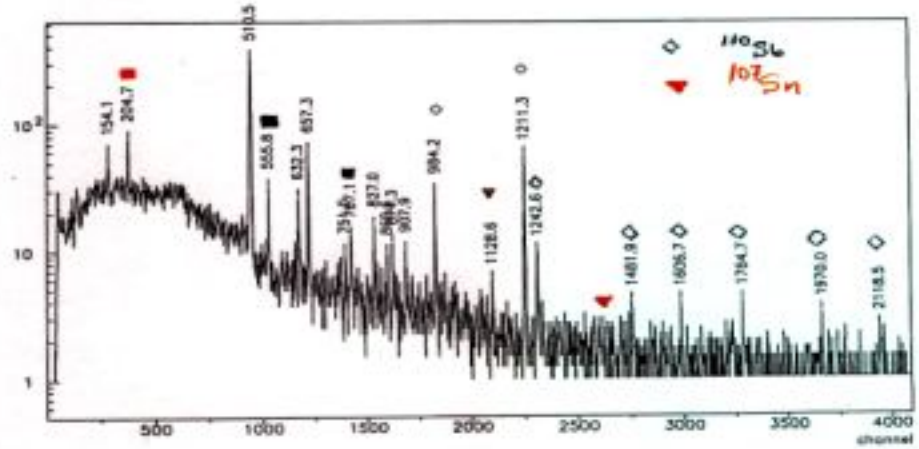
$$\frac{\delta A}{A} \simeq \frac{1}{250}$$

γ-singles



γ-γ coinc

495fr12.det



Reaction mechanism studies

a) Neutron-Rich Rare Isotope Production in the Fermi Energy Domain

b) Heavy Residue Properties, Isoscaling and N/Z Equilibration

George A. Souliotis

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E. Martin, D.V. Shetty, S.J. Yennello

Recent research results presented at:
The International Conference of Nucleus-Nucleus Collisions (NN03),
Moscow, June 17-22, 2003

Production of Neutron-Rich Nuclides (methods):

! target, projectile fission
! cold projectile fragmentation (medium to high energy)
! deep inelastic collisions (low to medium energies)
! multinucleon transfer reactions (around V_b)

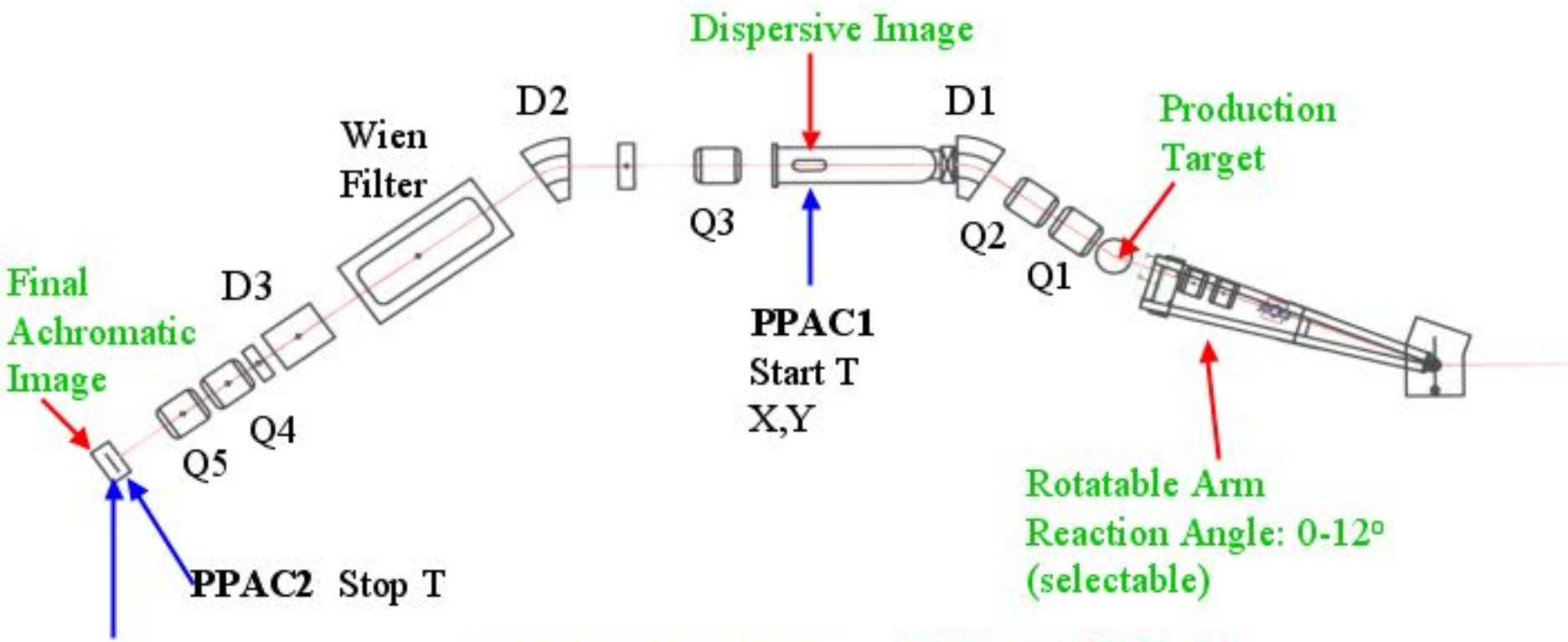
Present work: deep inelastic collisions at Fermi energies:

! ^{86}Kr(25MeV/nucleon) + ^{64}Ni, (**PLB 543**, 163 (2002))
! ^{86}Kr + ^{124}Sn, ^{112}Sn (**PRL 91**, 022701 (2003)
! ^{124}Sn (20 MeV/u) + ^{124}Sn, ^{124}Sn + ^{27}Al (**NPA** (2003))
! Heavy-Residue Yield Scaling (nucl-ex/0305027)

Findings: ! Enhanced production of neutron-rich species, neutron skin effect
! Heavy-Residue Yield Ratios probing N/Z equilibration

Applications with RIB from TAMU upgrade and RIA

MARS Recoil Separator and Setup



Silicon Telescope:

$_E_1$, X,Y (Strips)

$_E_2$, $E_{residual}$

MARS Acceptances:

Angular: 9 msr

Momentum: 4 %

Beam angle set to:

0° (1.0-3.0°) for Kr+Ni (θ_{gr} = 3.5°)

4° (2.5-5.5°) for Kr+Sn (θ_{gr} = 6.5°)

Experimental Details:

Reactions studied:

! $^{86}Kr^{22+}$ (25 MeV/u, 1-5 pnA) + ^{64}Ni (4 mg/cm^2) PLFs in 1.0-3.0° (θ_{gr} = 3.5°)

! $^{86}Kr^{22+}$ (25 MeV/u, 1-5 pnA) + $^{124,112}Sn$ (2 mg/cm^2) PLFs in 2.5-5.5° (θ_{gr} = 6.5°)

Measured quantities:

! _E_1, __$_2$, _$_r$, (x,y) strips

! time of flight (START-STOP)

! x-position at First Image (B_ information)

Extracted physical quantities:

! Velocity, Energy loss, Total Energy

! Mass-to-charge ratio: A/Q $B\rho \sim A/Q \times \upsilon$

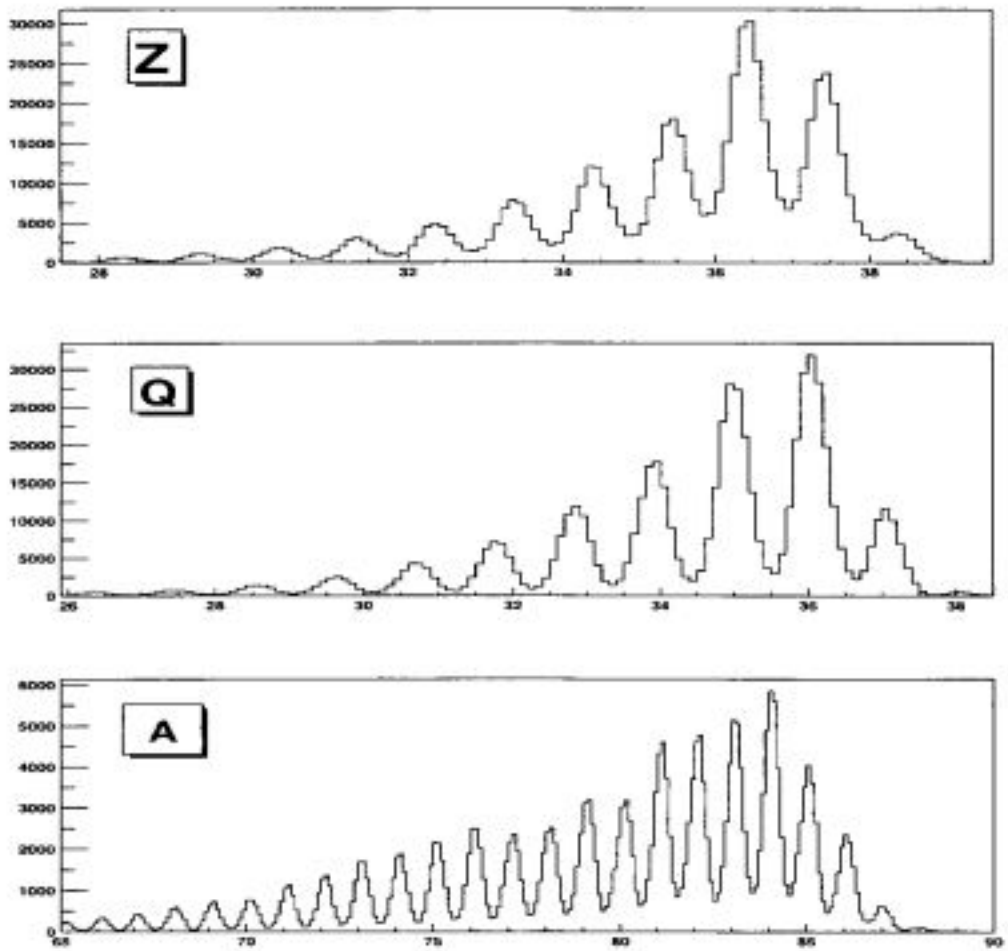
! Atomic Number Z $Z \sim \upsilon$ _$E^{1/2}$

! Ionic charge Q $Q \sim f(E, \upsilon)$

! Mass number A $A = Q_{int} \times A/Q$

Yield distribution (Z,A,_)

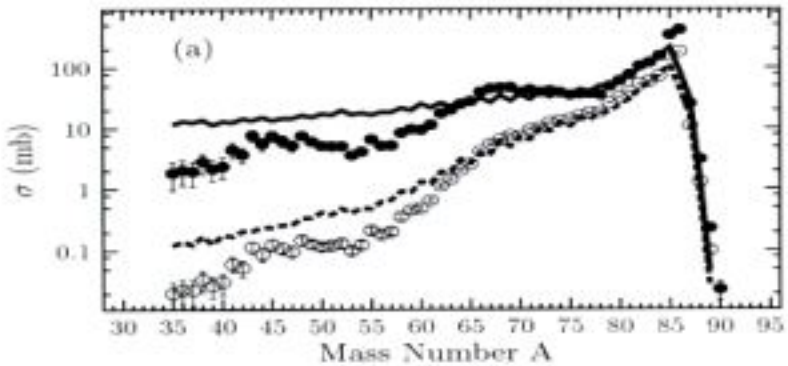
Z, Q, _ spectra (one run): ^{86}Kr (25 MeV/u) + ^{64}Ni



Resolutions (FWHM) : _Z = 0.5
_Q = 0.4
_A = 0.5

Gross Distributions: ^{86}Kr (25 MeV/u) + ^{64}Ni

Isobaric Yield Distribution

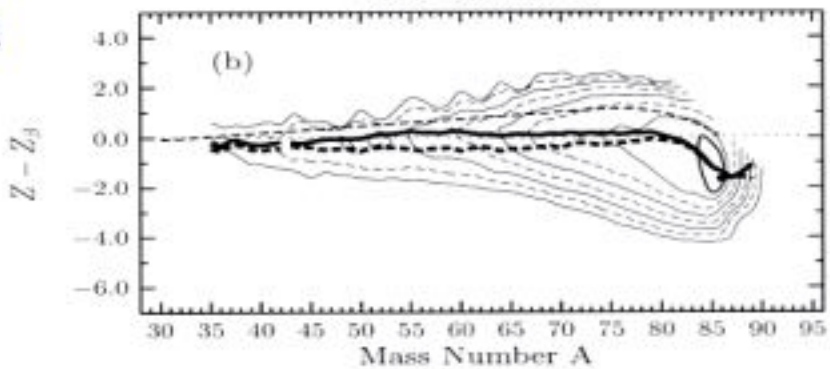


----- DIT/GEMINI

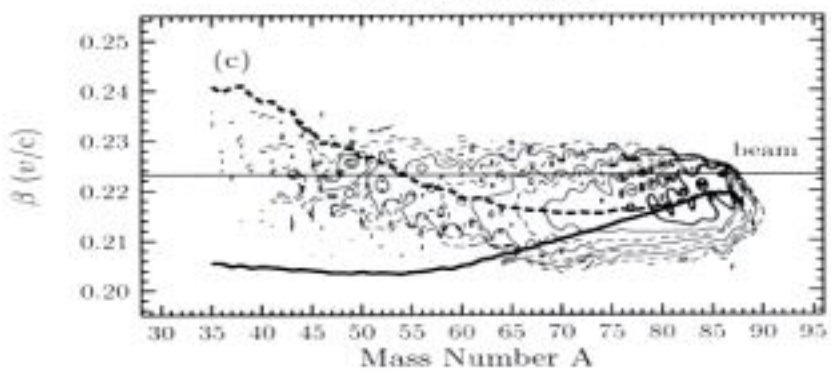
- - - DIT/GEMINI (filtered)

Z - A Distribution

(relative to Z_β)



Velocity - mass Distribution



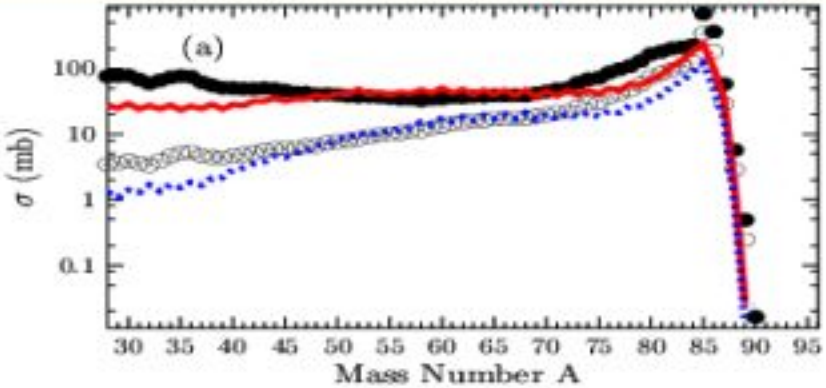
References:

DIT: L. Tassan-Got and C. Stephan, Nucl. Phys. A524 121 (1991)

GEMINI: R. Charity et al., Nucl. Phys. A483 391 (1988)

Gross Distributions: ^{86}Kr (25 MeV/u) + ^{124}Sn

Isobaric Yield Distribution

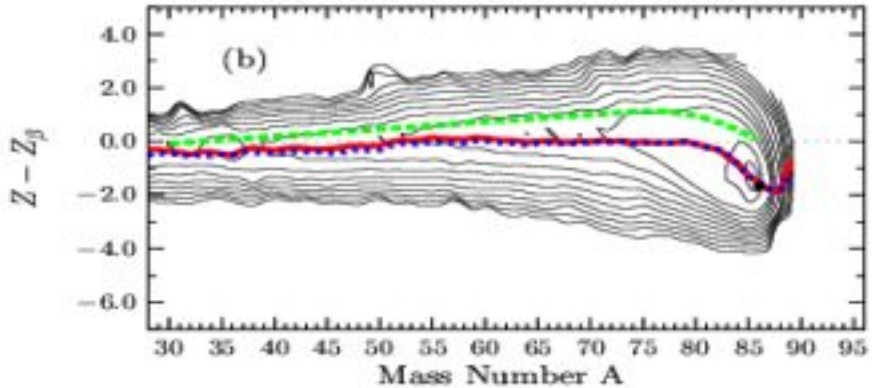


Data
! Data
Corrected (_, B_)

-- DIT/GEMINI

Z - A Distribution

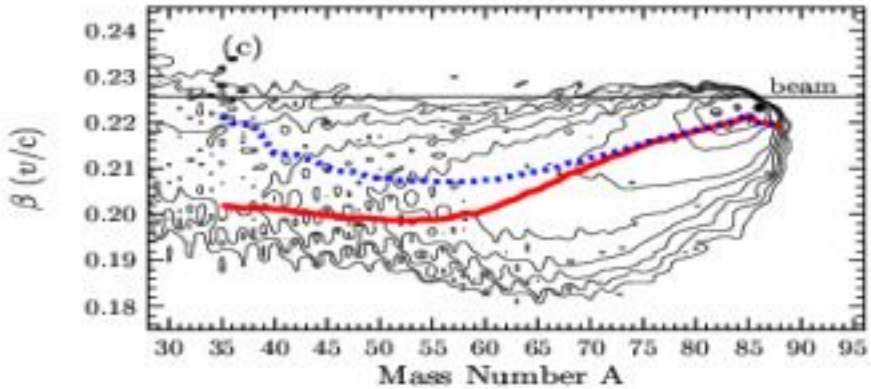
(relative to Z_β)



-- DIT/GEMINI filtered (_,B_)

-- EPAX2

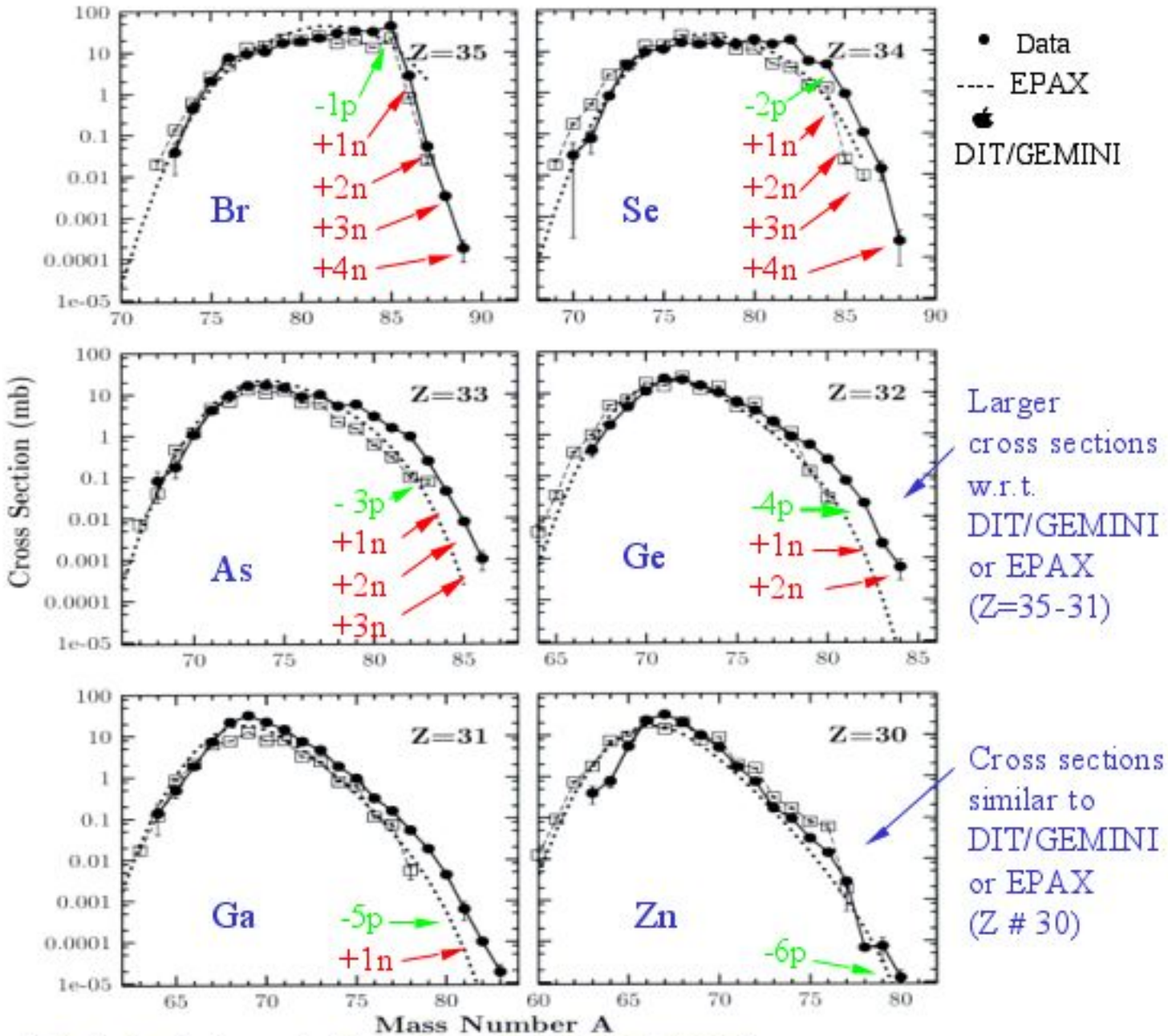
Velocity - mass Distribution



References:

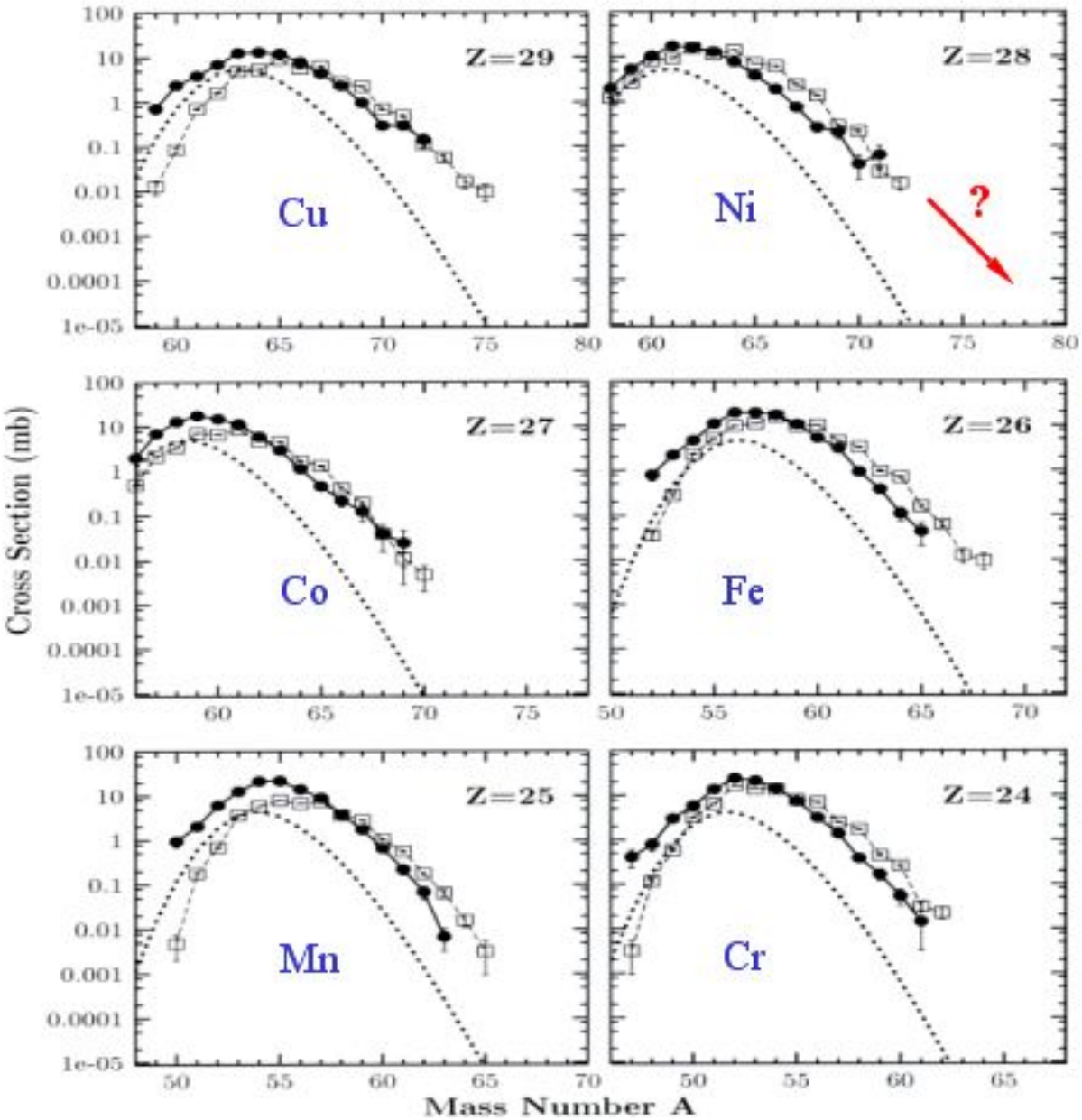
DIT: L. Tassan-Got and C. Stephan, Nucl. Phys. A524 121 (1991)
GEMINI: R. Charity et al., Nucl. Phys. A483 391 (1988)
EPAX2: K. Summerer and B. Blank, Phys. Rev. C61 034607 (2000).

Mass distributions: ^{86}Kr (25 MeV/u) + ^{64}Ni*



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

Mass distributions : ^{124}Sn (20 MeV/u) + ^{124}Sn



- Data
- EPAX
- DIT/GEMINI

Measured cross sections agree with DIT/GEMINI

They are 10-100 larger than

EPAX predictions

Estimates of Production Rates: $^{86}Kr+^{64}Ni$

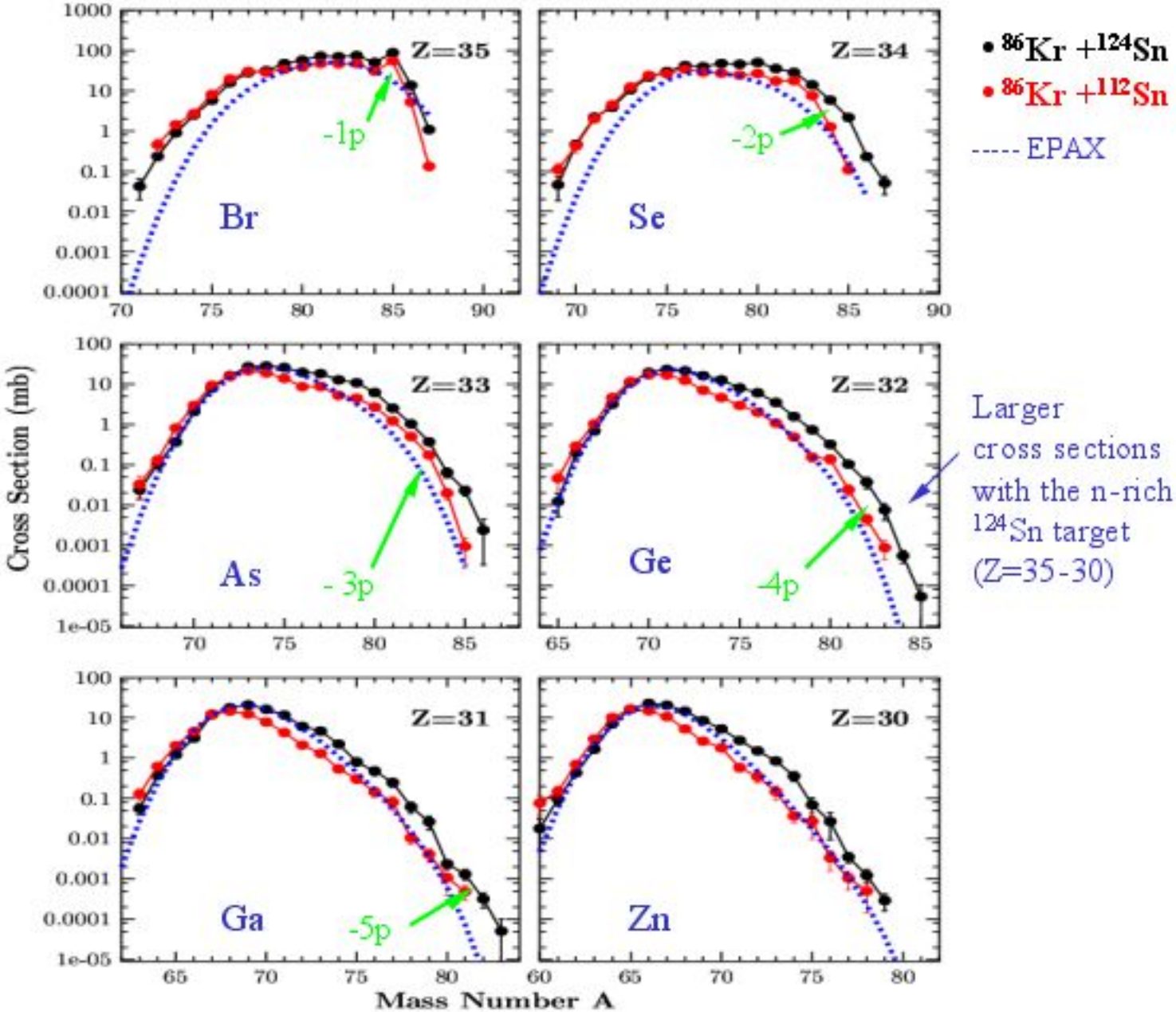
Use cross sections of this work, assume:

^{86}Kr beam (25MeV/u) 100 pnA
^{64}Ni target (20 mg/cm^2)

Rare Isotope:	Reaction channel	Cross Sections Experiment: This work	Calculated DIT/GEMINI	High Energy Data	Rate(sec^{-1})
				*	
^{84}Se	-2p+0n	4.7 mb	0.8 mb	2 mb	5.6×10^5
^{85}Se	-2p+1n	900 μb	60 μb	8 μb	1.1×10^5
^{86}Se	-2p+2n	100 μb	3 μb	–	1.2×10^4
^{87}Se	-2p+3n	14 μb	–	–	1.7×10^3
^{88}Se	-2p+4n	0.3 μb	–	–	3×10^1
^{82}Ge	-4p+0n	22 μb	2 μb	3 μb	2.6×10^3
^{83}Ge	-4p+1n	2.3 μb	–	0.04 μb	2.8×10^2
^{84}Ge	-4p+2n	0.4 μb	–	–	4.8×10^1

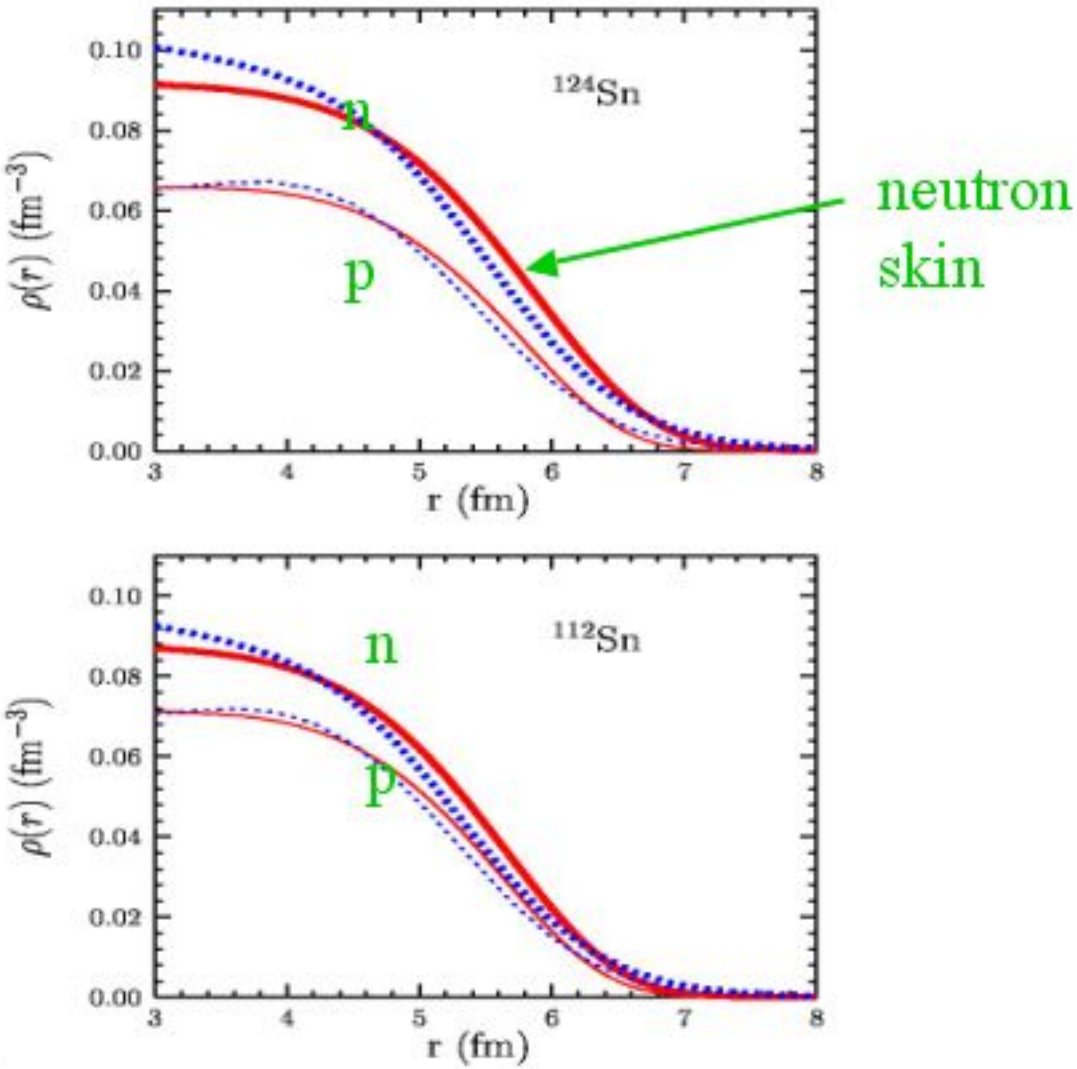
* GSI data: M. Weber et al. Nucl. Phys. A 578 (1994) 659

Mass distributions: ^{86}Kr (25 MeV/u) + ^{124}Sn, ^{112}Sn*



* G.A. Souliotis et al., **Phys. Rev. Lett. 91**, 022701 (2003)

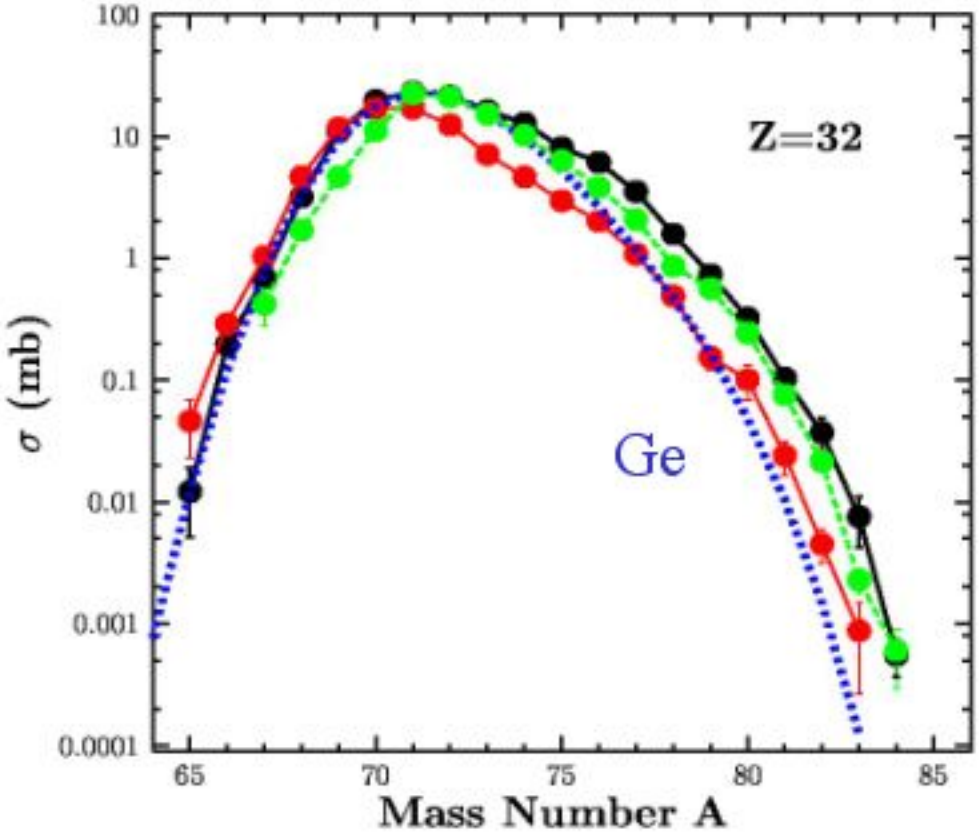
Neutron-Proton Density Calculations for ^{124}Sn, ^{112}Sn



Thomas-Fermi : V.M. Kolomietz, A.I. Sanzhur et al., PRC 64, 024315 (2001)

Skyrme-Hartree-Fock: J. Friedrich, P. Reinhard, PRC 33, 335 (1986)

Mass Distribution of Germanium from $^{86}Kr(25MeV/u) + {}^{124}Sn, {}^{112}Sn, {}^{64}Ni$



Data using targets:

! ^{124}Sn

! ^{112}Sn

! ^{64}Ni

------ EPAX2

Target	N/Z		Valley of stability
^{124}Sn	1.48	n-rich	^{118}Sn
^{112}Sn	1.24	n-poor	
^{64}Ni	1.29	n-rich	^{60}Ni

Summary and Outlook

Measured charge, mass, velocity distributions of residues from:
^{86}Kr (25 MeV/u) + ^{64}Ni, ^{124}Sn, ^{112}Sn, Studies inside θ_{gr}

Reaction simulations: DIT/Gemini: reasonable description,
Effect of the **Neutron Skin** (very n-rich products)

Scaling of Heavy-Residue Yields: **N/Z Equilibration**

Plans for future work :

! Investigate reactions with heavier targets: ^{208}Pb, ^{238}U (look ~ θ_{gr})
! Study the process of N/Z equilibration, E/A dependence

Tools at Texas A&M:

! MARS Line (High Resolution)
! Superconducting Solenoid Rare Isotope Line (Large Acceptance)
! Future: Re-accelerated beams via a Gas-Cell based ISOL concept*

Application in studies using high-N/Z beams from RIA

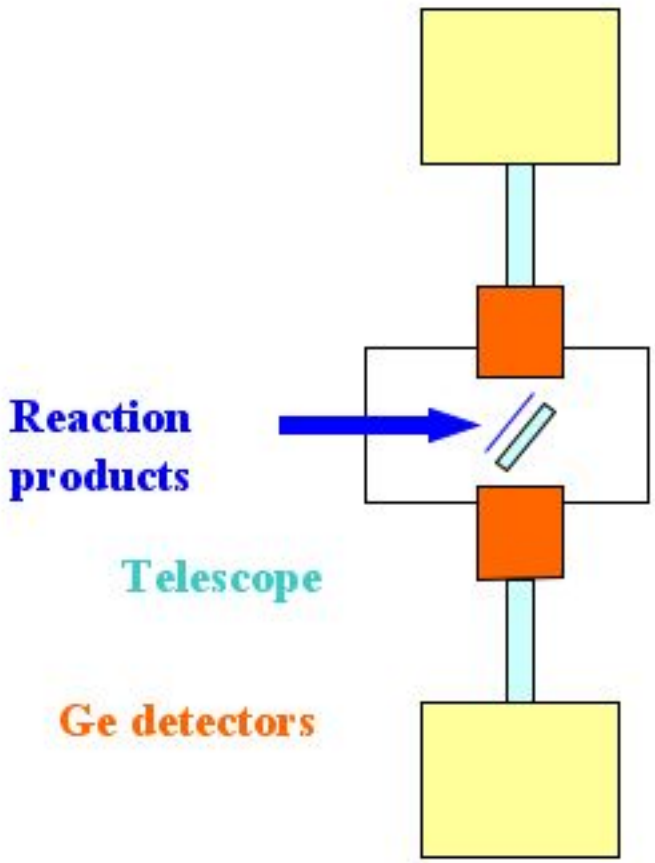
* TAMU Cyclotron White Paper in : http://cyclotron.tamu.edu

Lessons learned with MARS

- Versatile
- Easy to tune
- Good purity – need fully stripped recoils at high energy
- Good angular and energy resolution for RIBs
- Can do beam cocktails (from fragmentation or deep inelastic), but no beam tagging used so far
- Can be used for in-beam γ– recoil coincidences, but a large granularity gamma ray detector array needed (due to large Doppler broadening at $v/c>0.25$)
- Best for use in off-beam decay studies
- MARS config available for LISE++

Near future "perspectives"

- Look for gamma-rays after the beta-decay of identified products using simplest detector arrangements
- Regions out of reach to fission product studies - around Pb and higher?!?
- Induce outside groups with good gamma-ray detection systems to come measure with MARS



Collaborators

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