

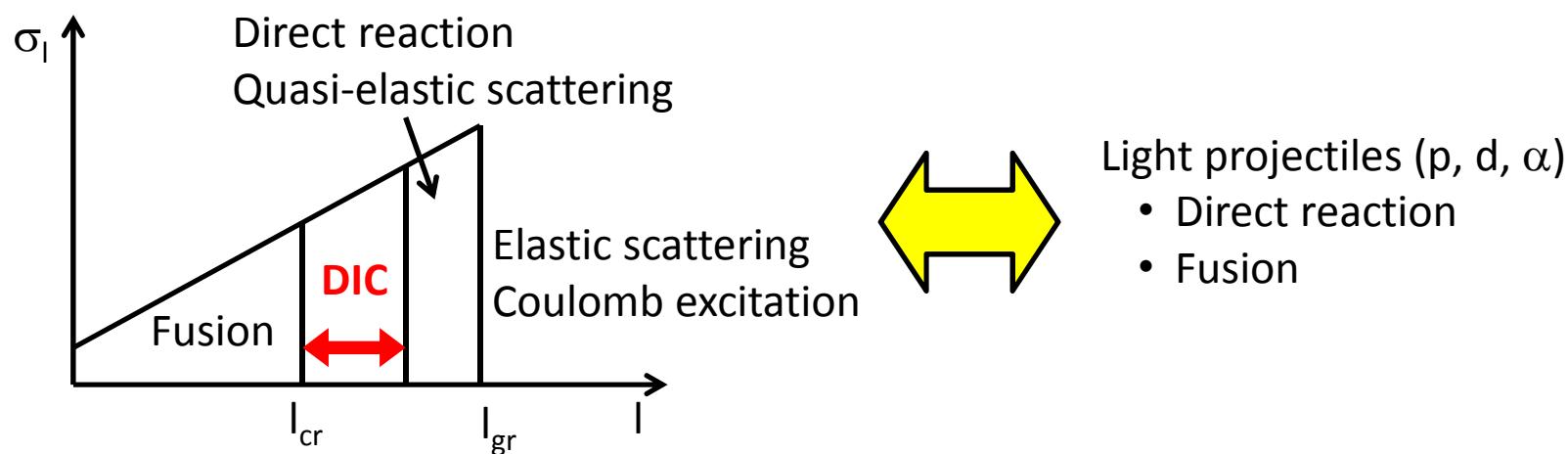
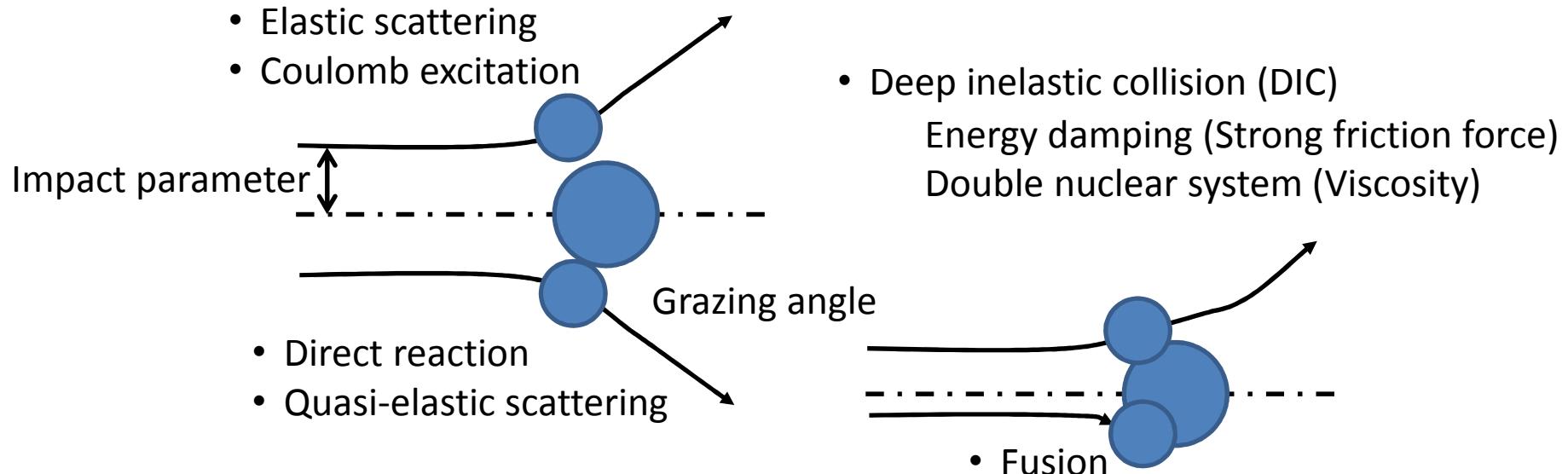
Experimental study of nuclear production by multinucleon transfer reaction

Y.X. Watanabe (IPNS, KEK)

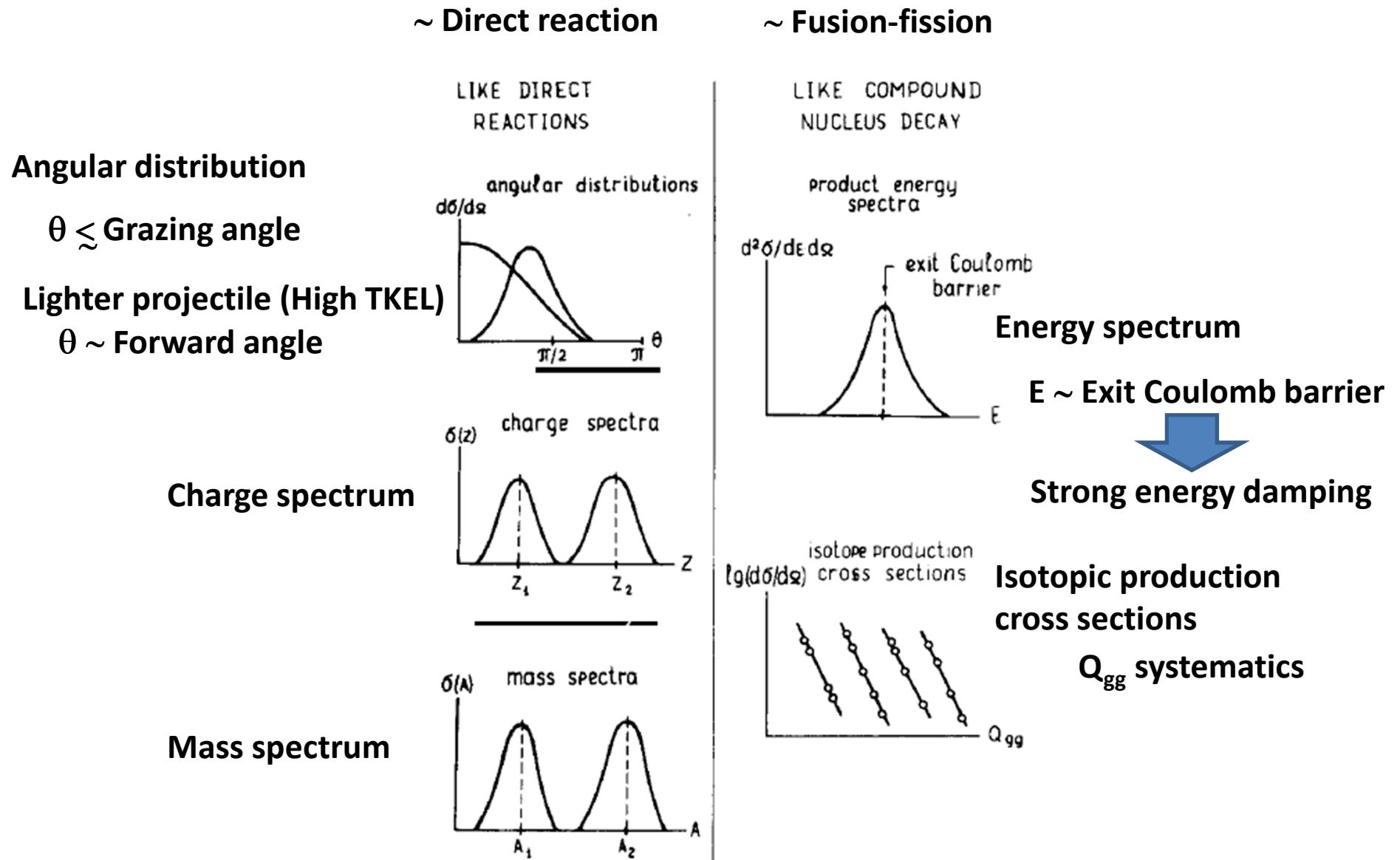
Contents

1. Introduction: Low energy heavy ion reaction
2. Production of $N = 126$ nuclei by MNT
3. Measurements of $^{136}\text{Xe} + ^{198}\text{Pt}$
4. Summary

Low energy heavy ion reactions

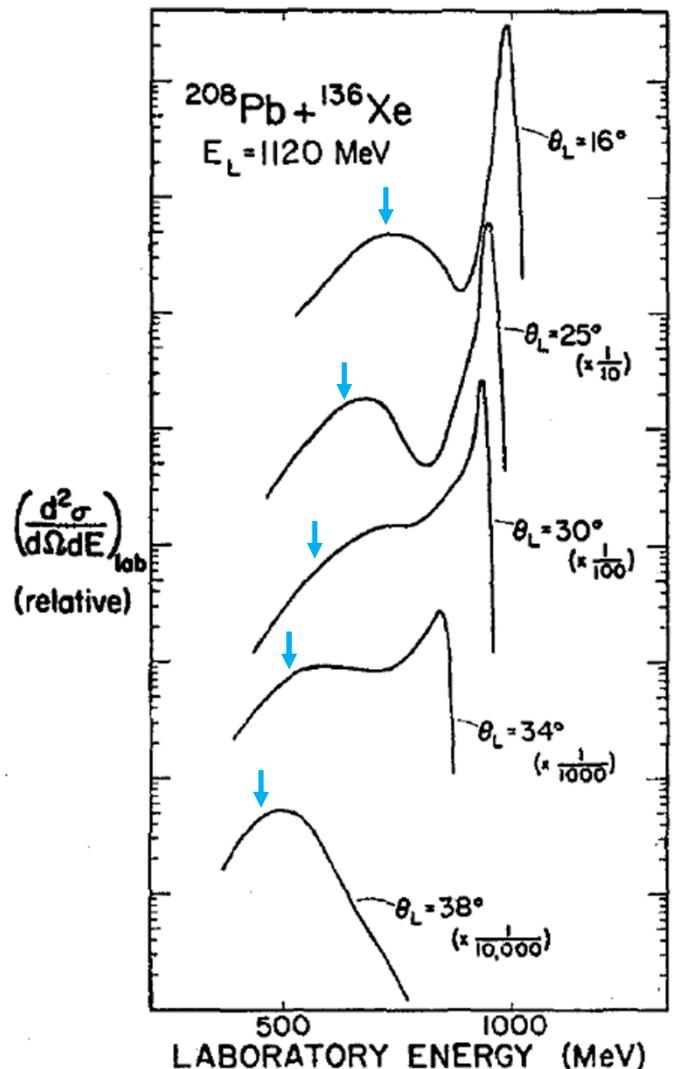


Features of deep inelastic collision

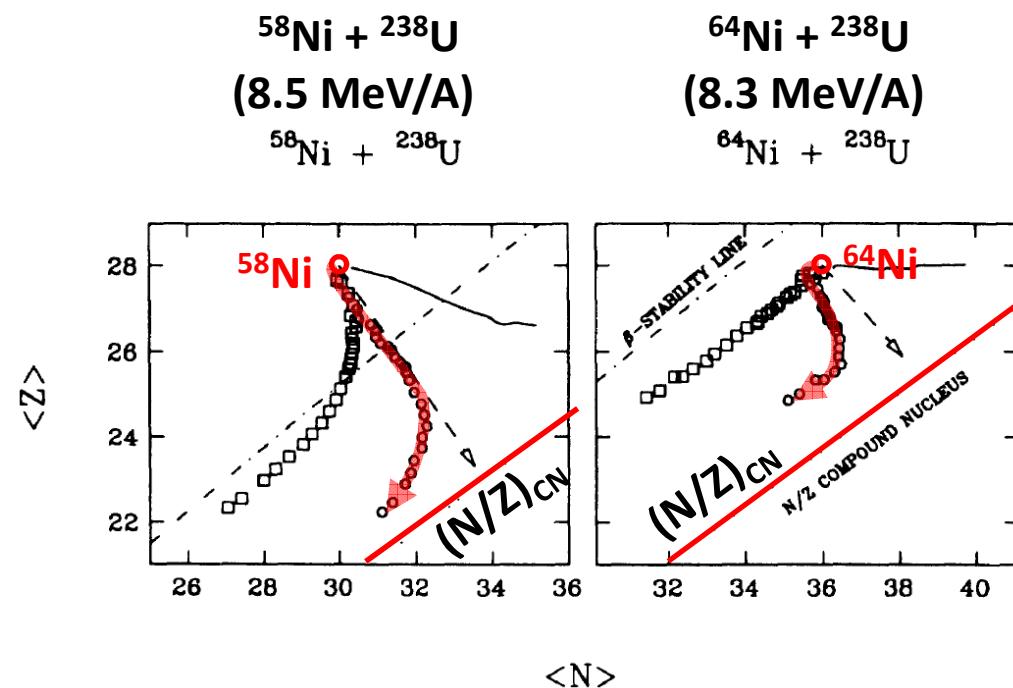


Deep inelastic collision: Energy damping and N/Z equilibration

$^{136}\text{Xe} + ^{208}\text{Pb}$ (8.2 MeV/A)



N/Z equilibration is a monotonic and continuous process according to energy damping



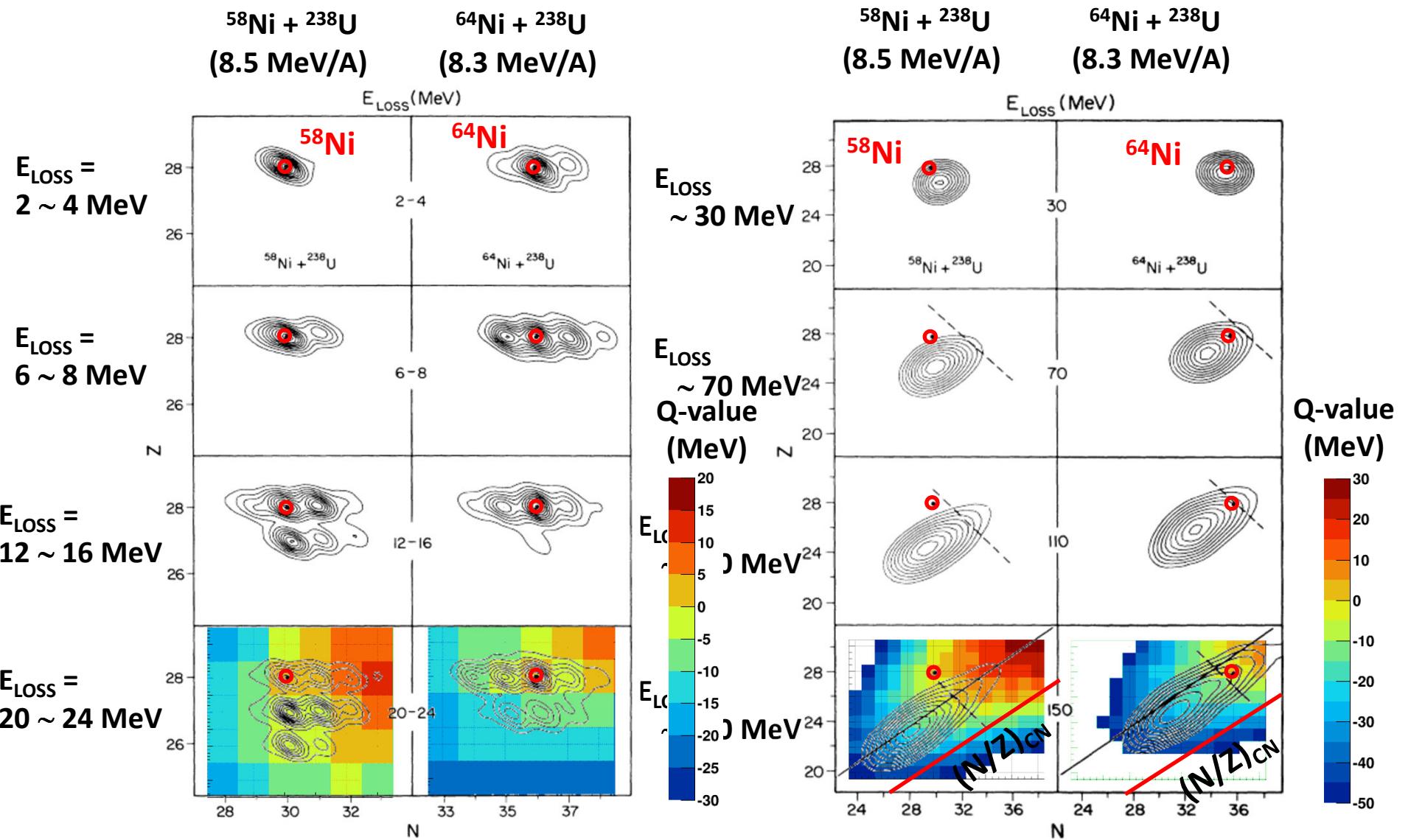
R. Vandenbosch et al., Nucl. Phys. A269 (1976), 210 – 222.

R. Planeta et al., Phys. Rev. C38 (1988), 195 – 209.

↓ Energy of symmetric fission from Viola systematics

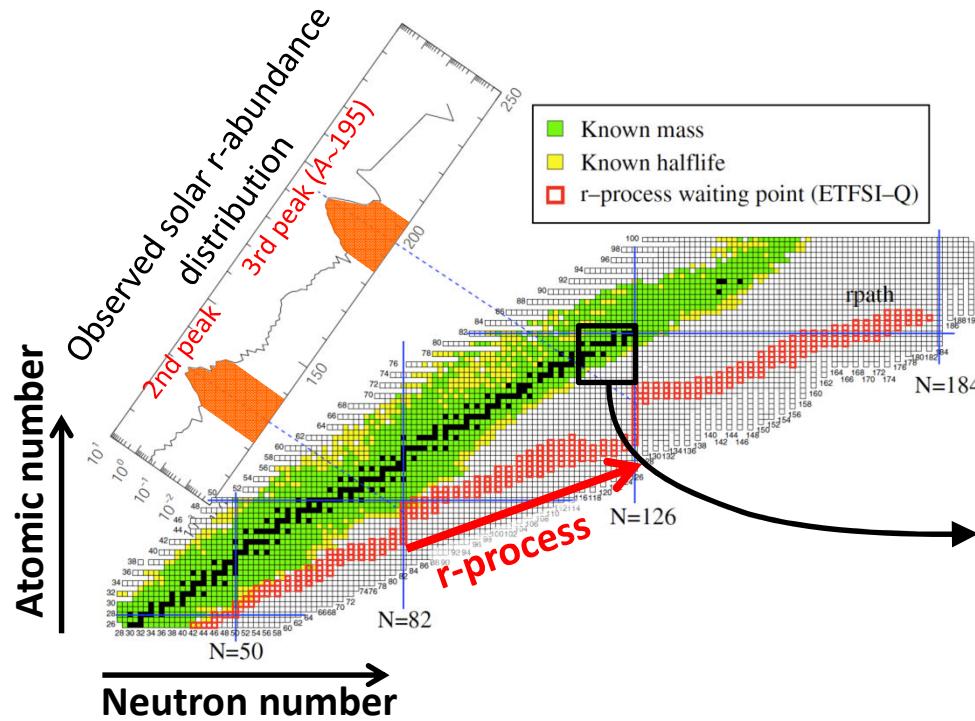
V.E. Viola, K. Kwiatkowski and M. Walker, Phys. Rev. C (1985), 1550 – 1552.

Deep inelastic collision: Isotopic distribution



R. Planeta et al., Phys. Rev. C38 (1988), 195 – 209.

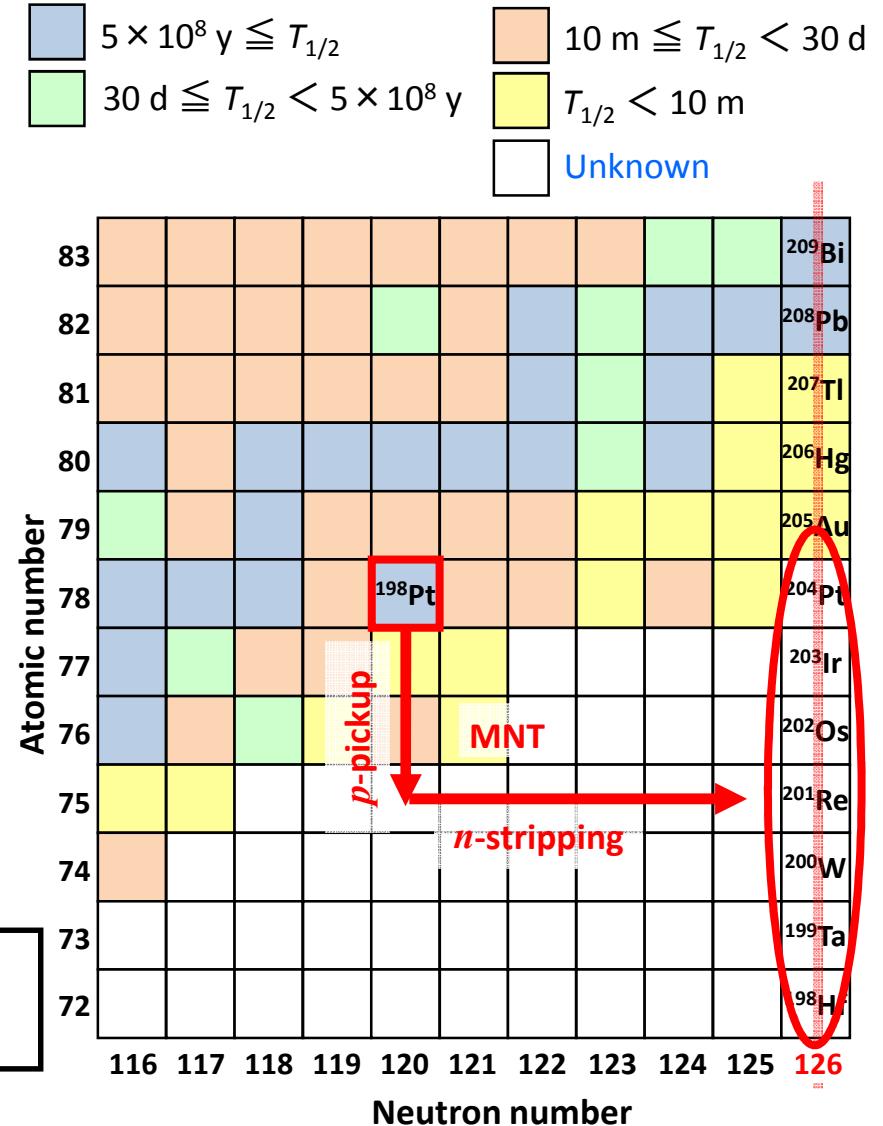
Neutron-rich nuclei around N = 126



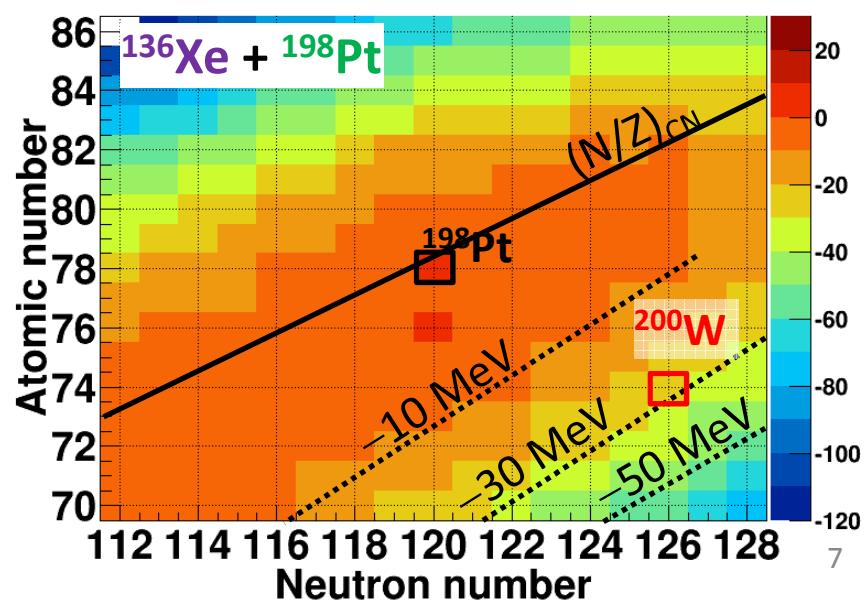
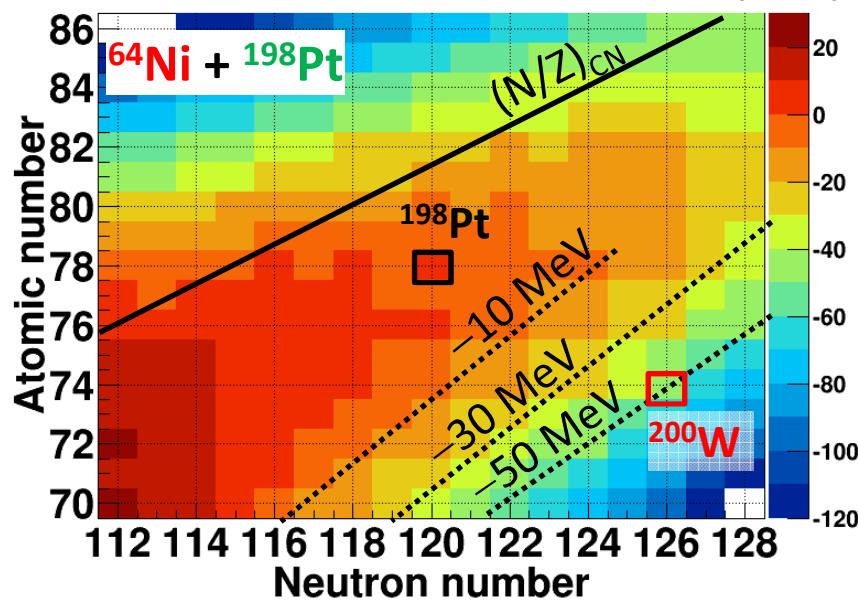
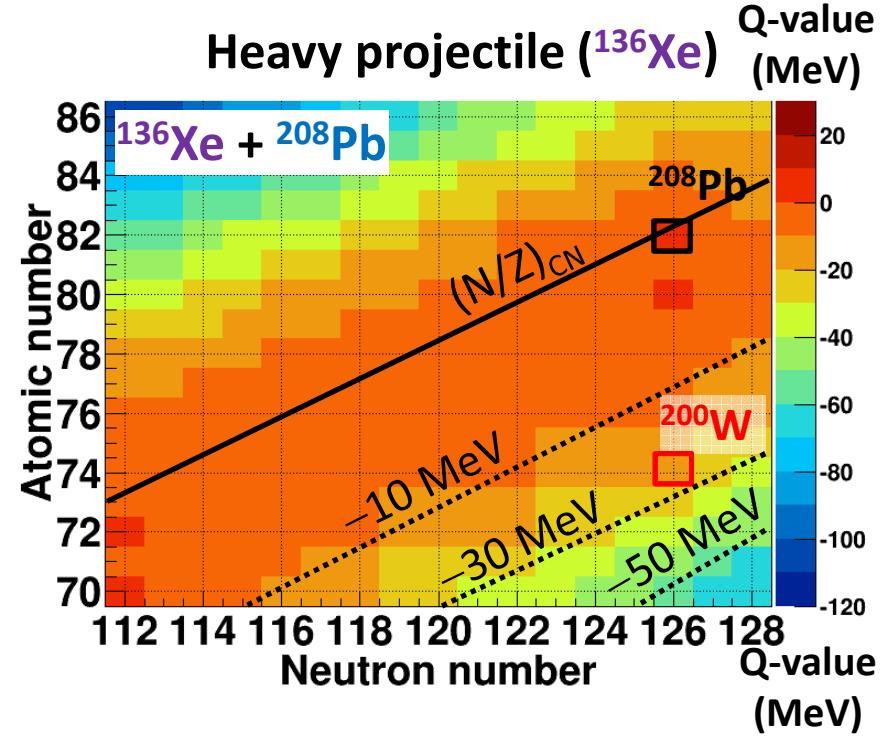
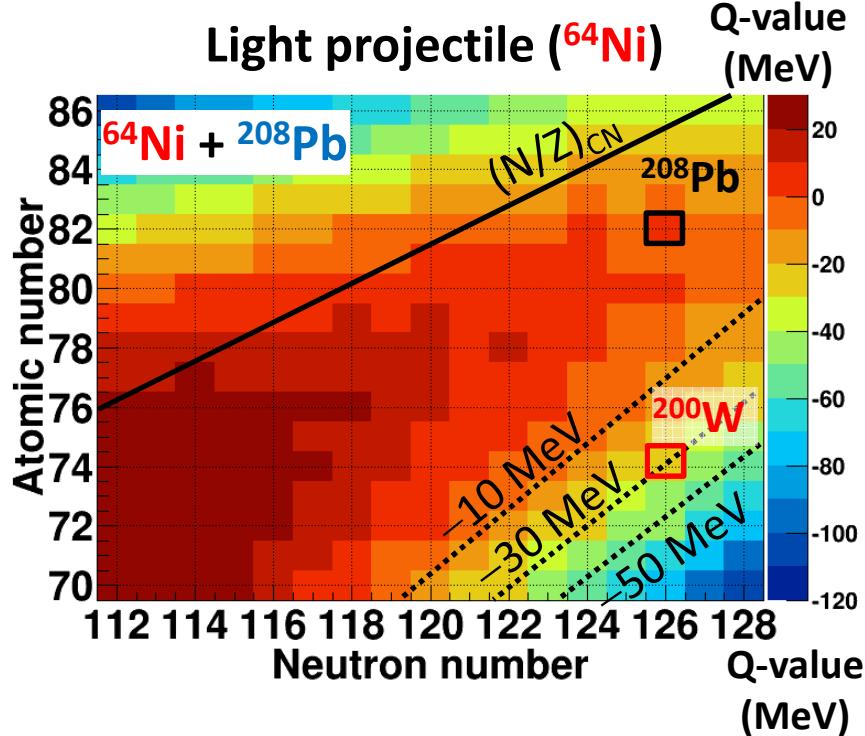
H. Grawe et al., Rept. Prog. Phys. 70 (2007), 1525 – 1582.

KISS project

Lifetime measurements around $N=126$
→ Astrophysical environments of r-process

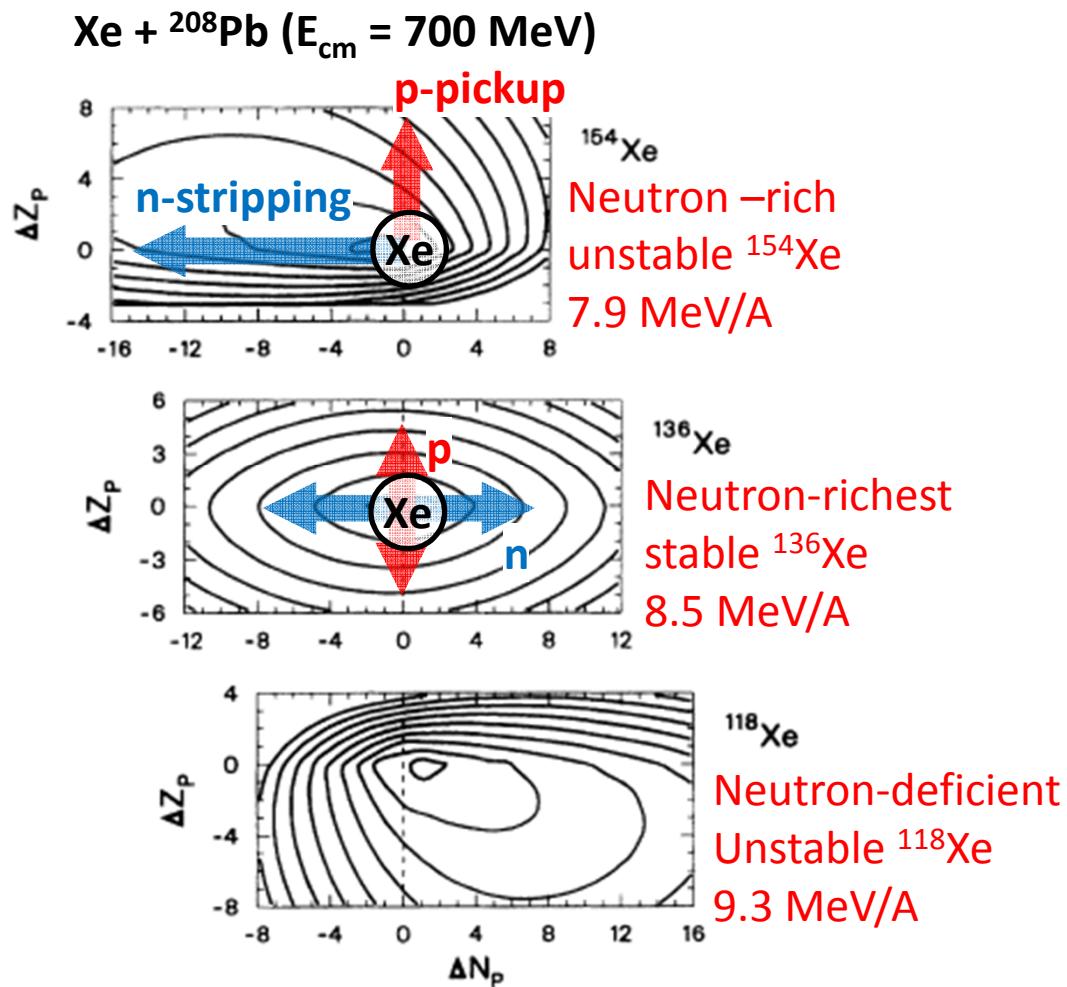


Projectile dependence



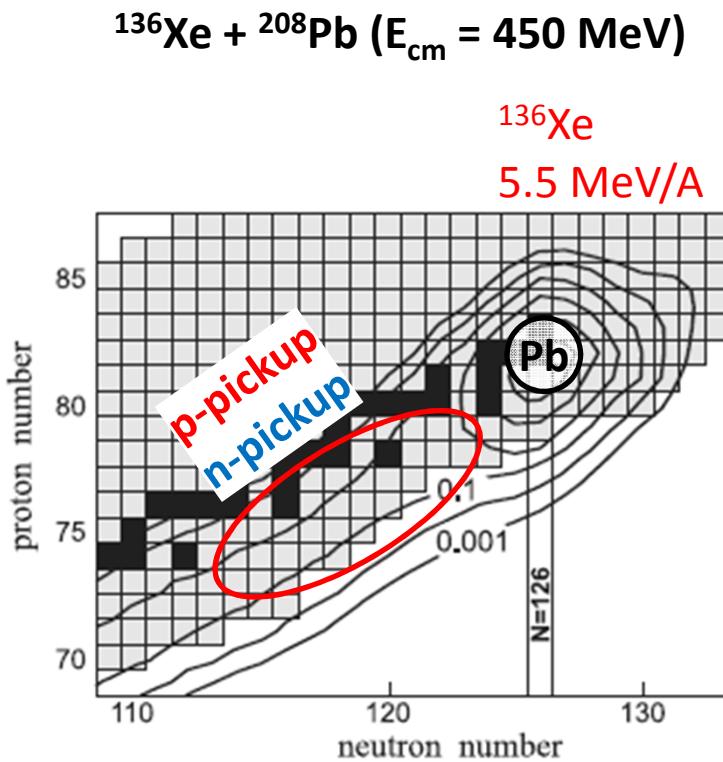
Nuclear production by MNT reactions

Semi-classical approach
Single-particle transfer probability



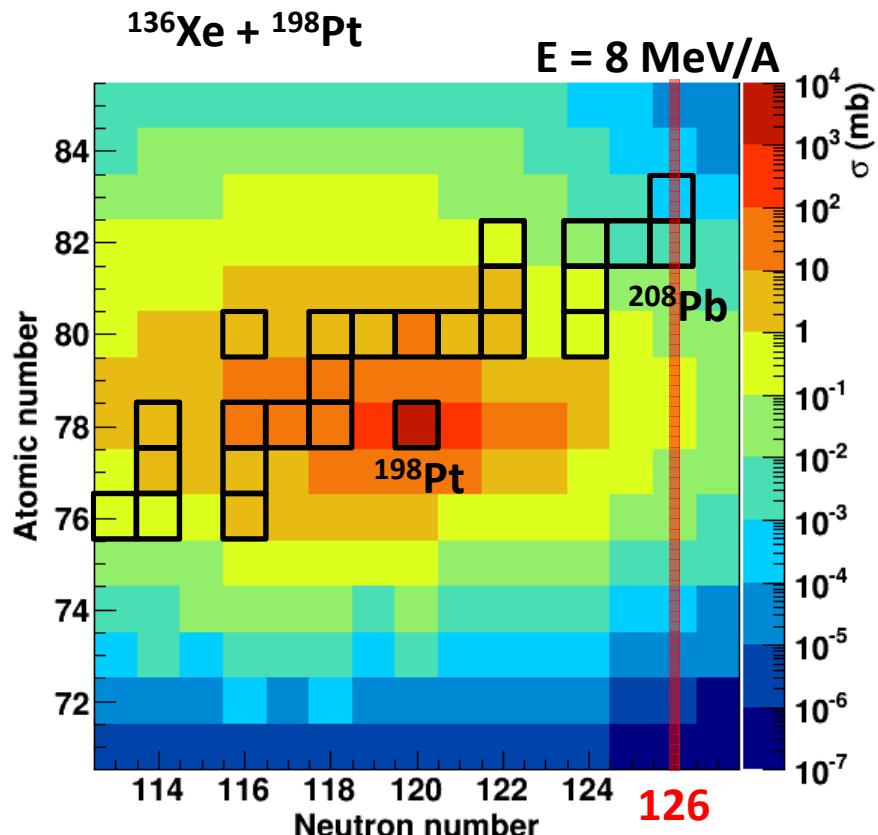
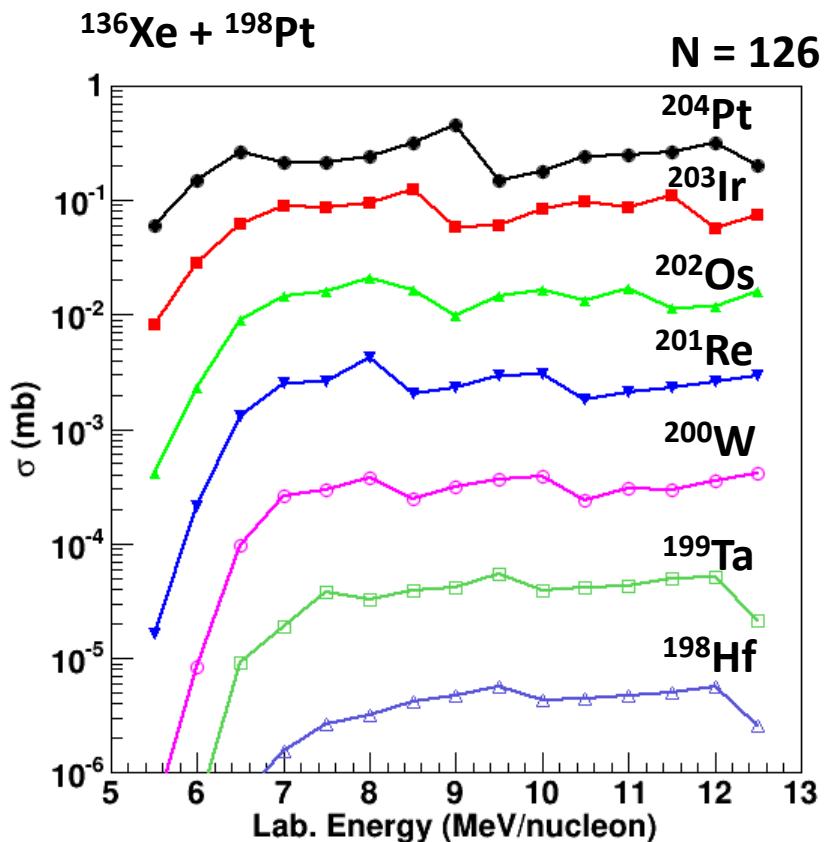
C.H. Dasso, G. Pollaro and A. Winther,
Phys. Rev. Lett. 73 (1994), 1907 – 1910.

Macroscopic approach
Langevin-type dynamical equation of motion



V. Zagrebaev and W. Greiner,
Phys. Rev. Lett. 101 (2008), 122701.

MNT reaction of $^{136}\text{Xe} + ^{198}\text{Pt}$



GRAZING calculation

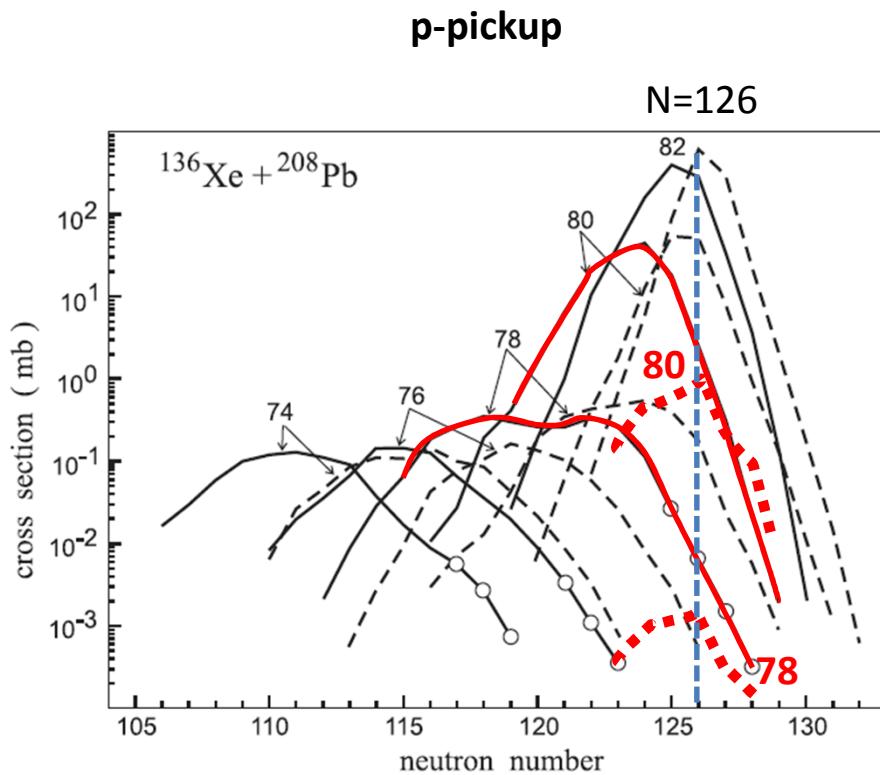
A. Winther, Nuclear Physics A572 (1994), 191 – 235;

A. Winther, Nuclear Physics A594 (1995), 203 – 245;

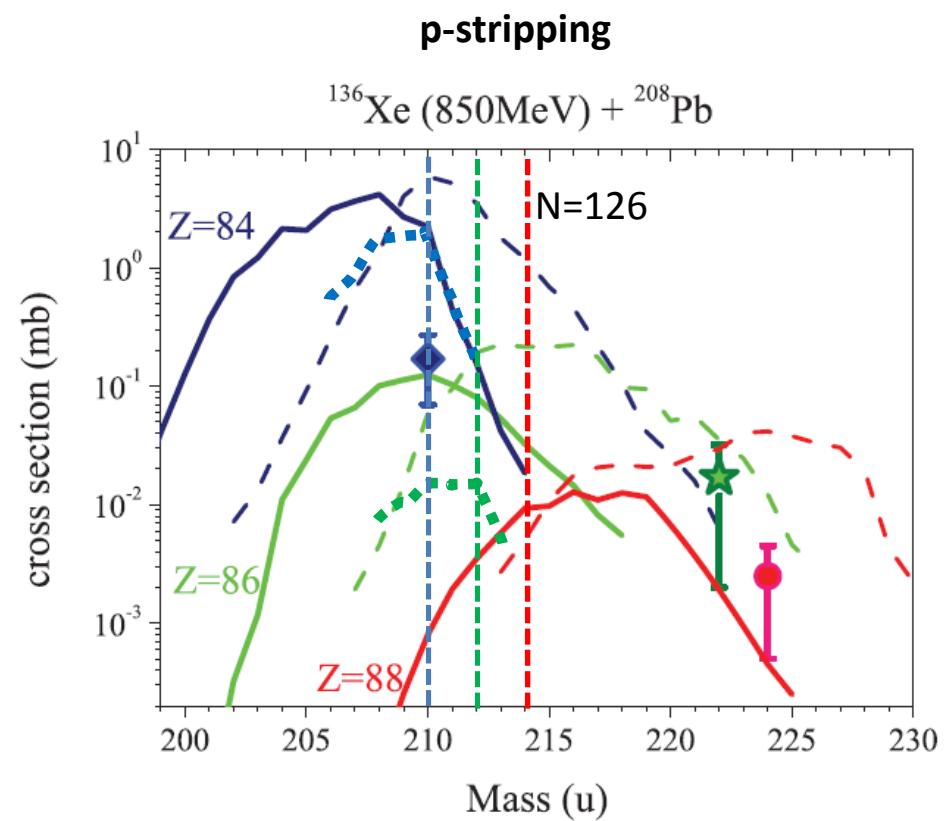
<http://personalpages.to.infn.it/~nanni/grazing/>

Comparison with measurements: $^{136}\text{Xe} + ^{208}\text{Pb}$

$^{136}\text{Xe} + ^{208}\text{Pb}$ (5.47 MeV/A)



$^{136}\text{Xe} + ^{208}\text{Pb}$ (6.25 MeV/A)



V. Zagrebaev and W. Greiner, Phys. Rev. Lett. 101 (2008), 122701.

E.M. Kozulin et al., Phys. Rev. C86 (2012), 044611.

----- GRAZING calculation

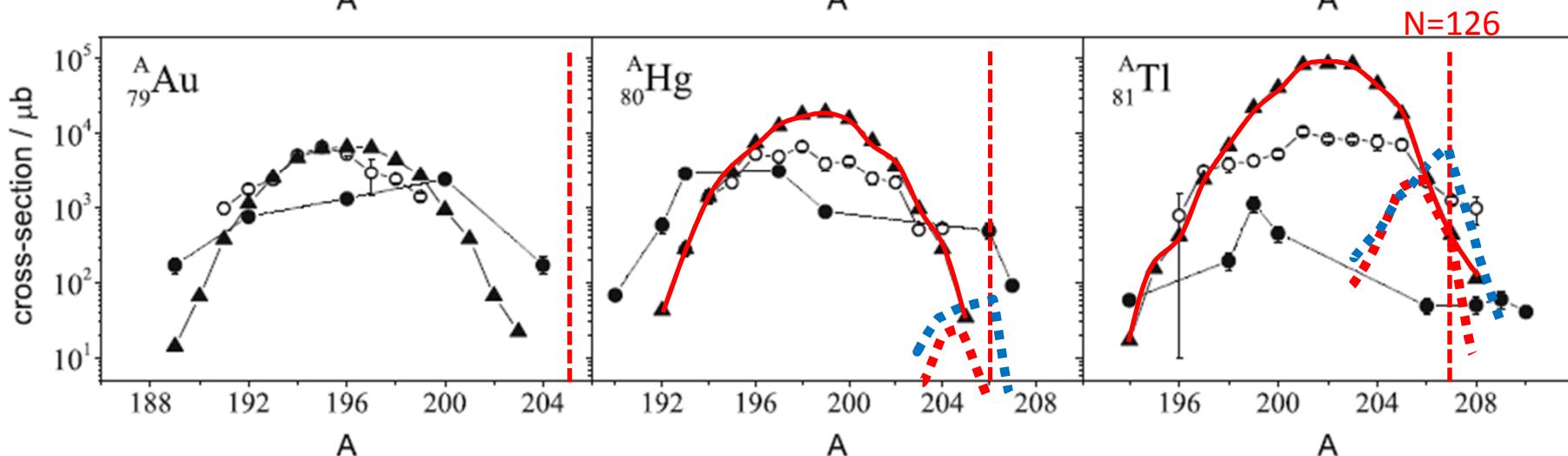
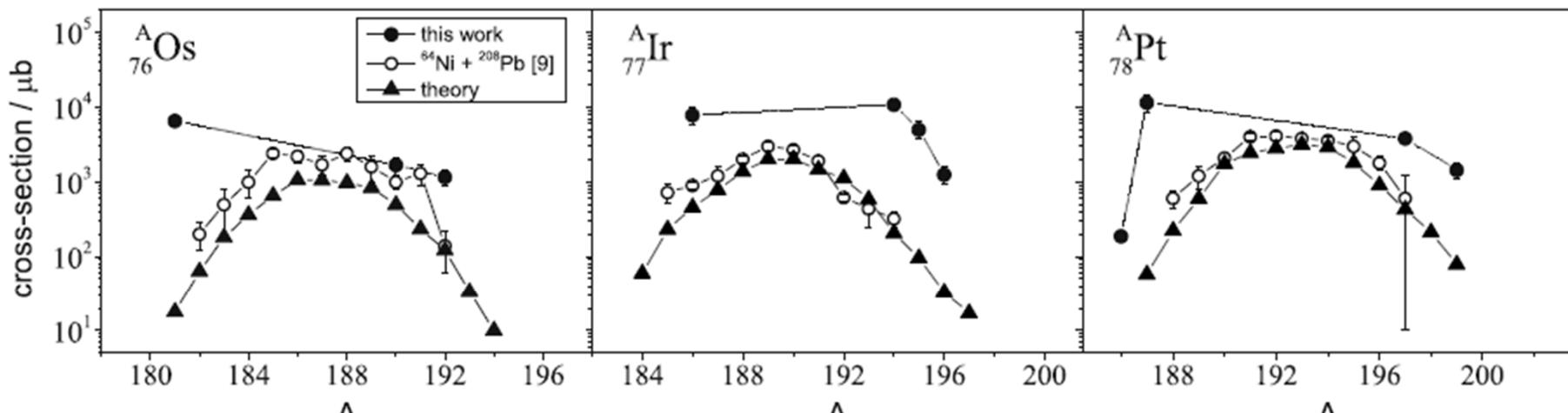
— V. Zagrebaev and W. Greiner

Comparison with measurements: $^{64}\text{Ni} + ^{207,208}\text{Pb}$

● $^{64}\text{Ni} + ^{207}\text{Pb}$ (5.0 MeV/A)

○ $^{64}\text{Ni} + ^{208}\text{Pb}$ (5.5 MeV/A)

p-pickup



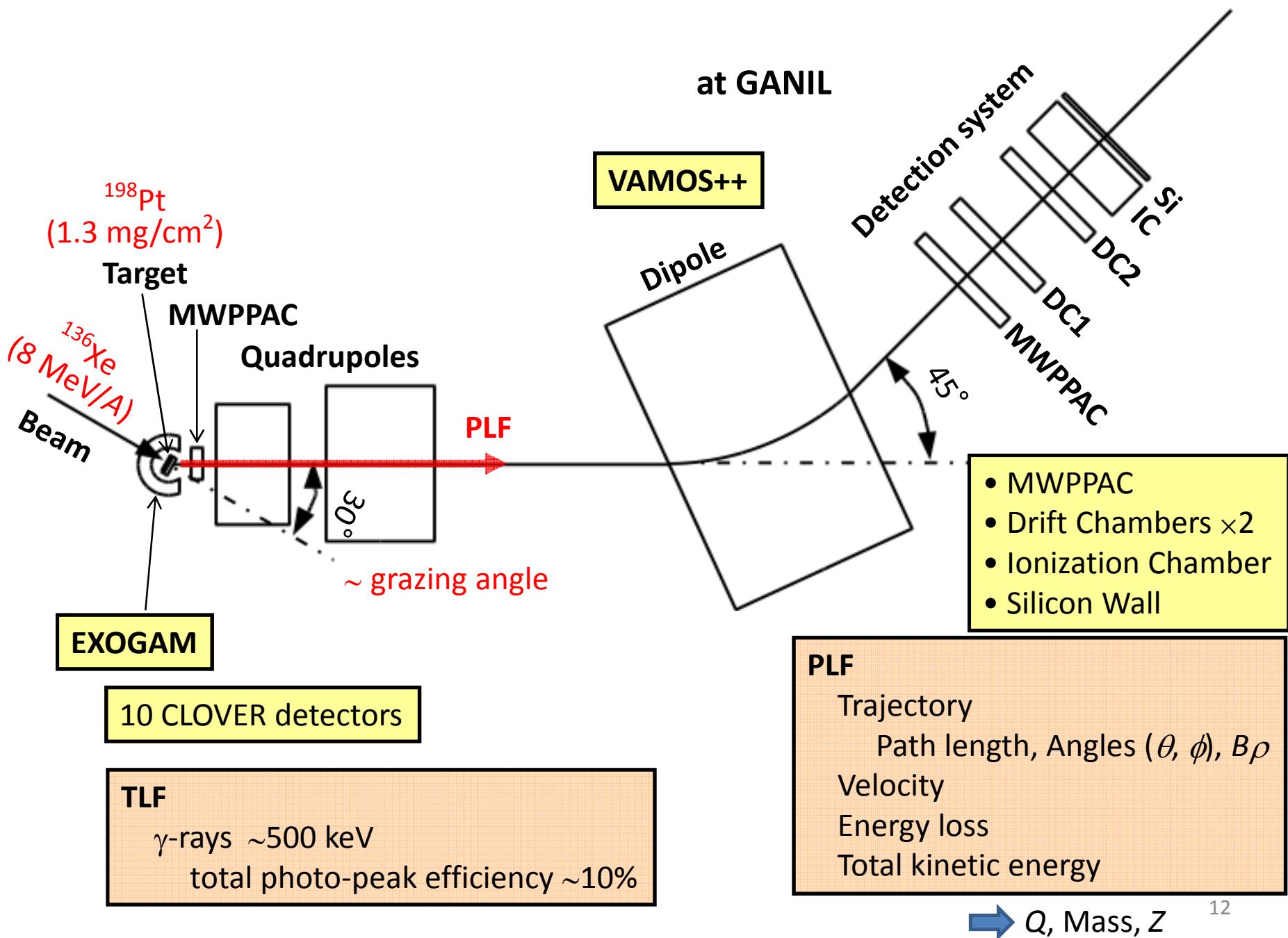
---- GRAZING calculation ($^{64}\text{Ni} + ^{207}\text{Pb}$)

---- GRAZING calculation ($^{64}\text{Ni} + ^{208}\text{Pb}$)

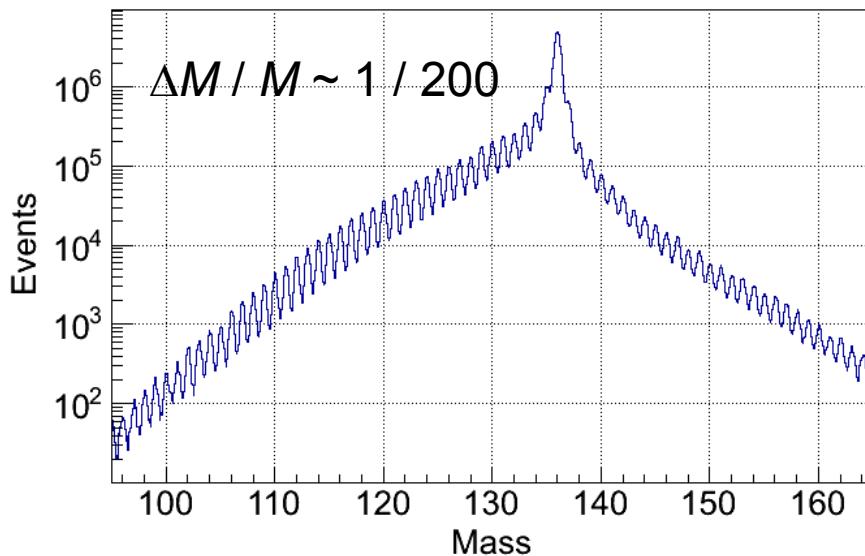
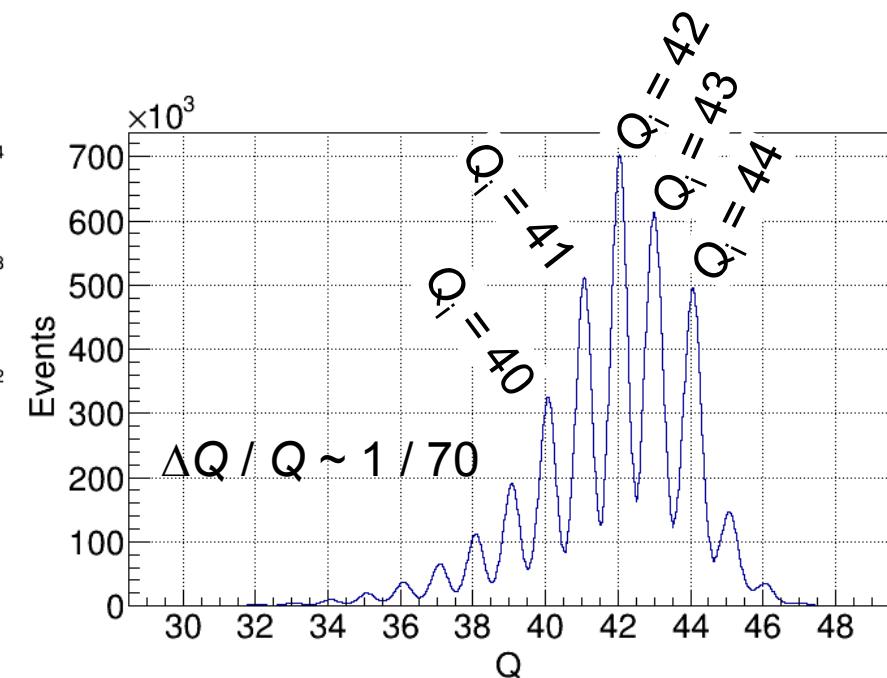
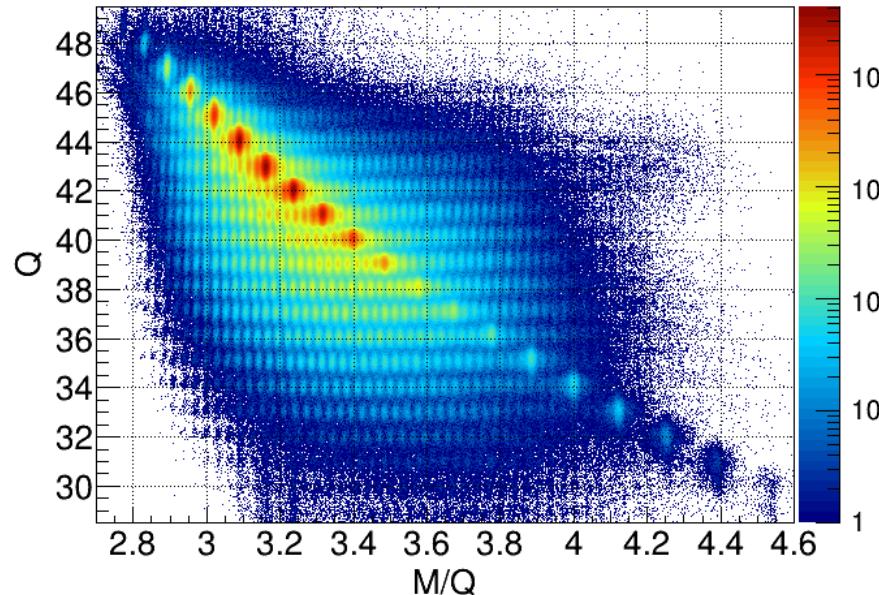
▲ V. Zagrebaev and W. Greiner ($^{64}\text{Ni} + ^{207}\text{Pb}$)

O. Beliuskina et al., Eur. Phys. J. A50 (2014), 161.

MNT measurement of $^{136}\text{Xe} + ^{198}\text{Pt}$



Charge and mass distributions of PLF

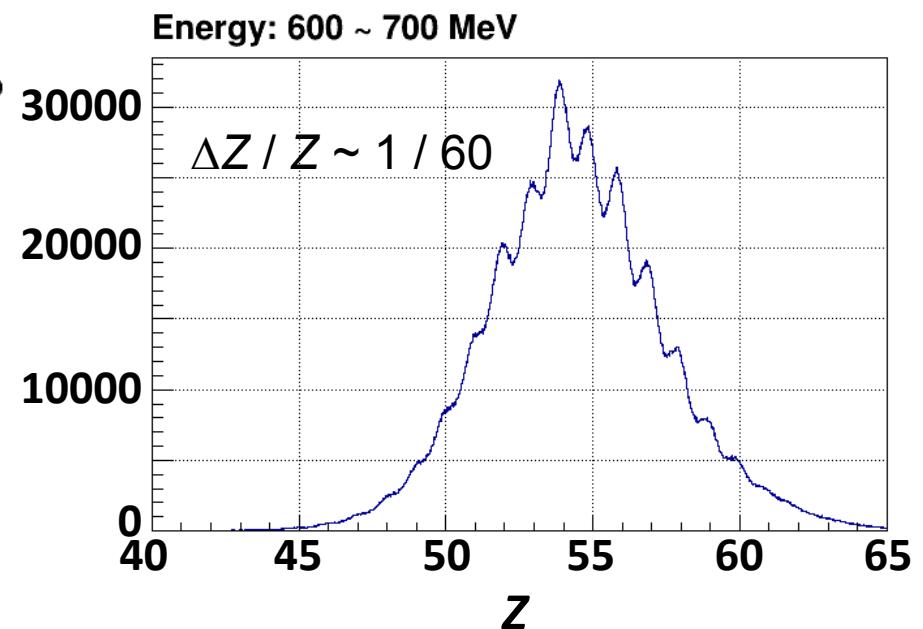
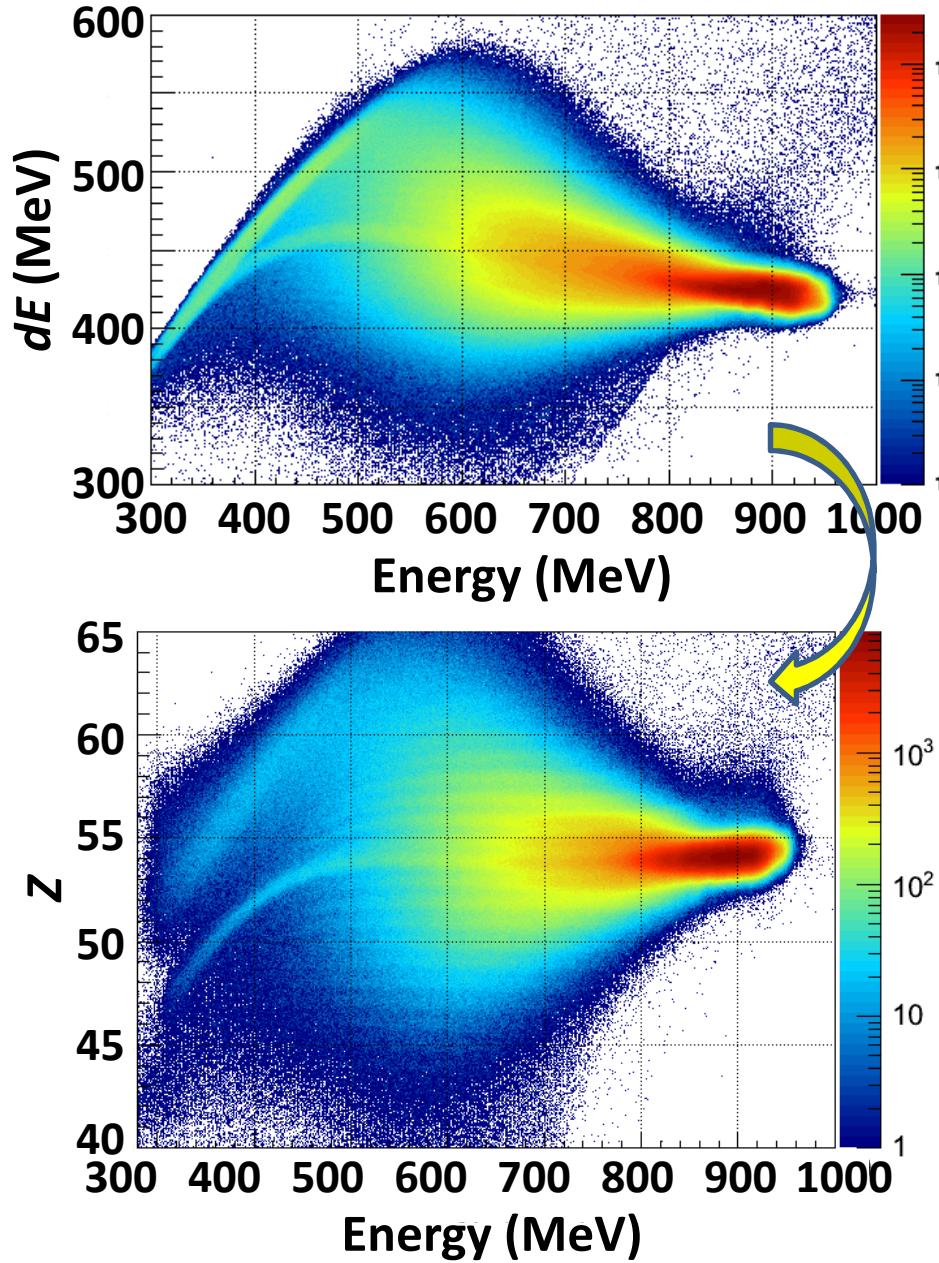


$$M / Q = B\rho / v$$

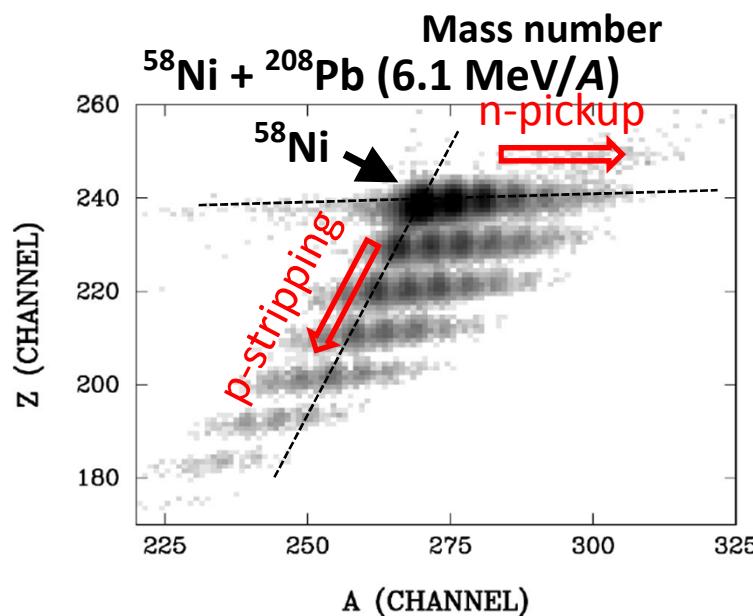
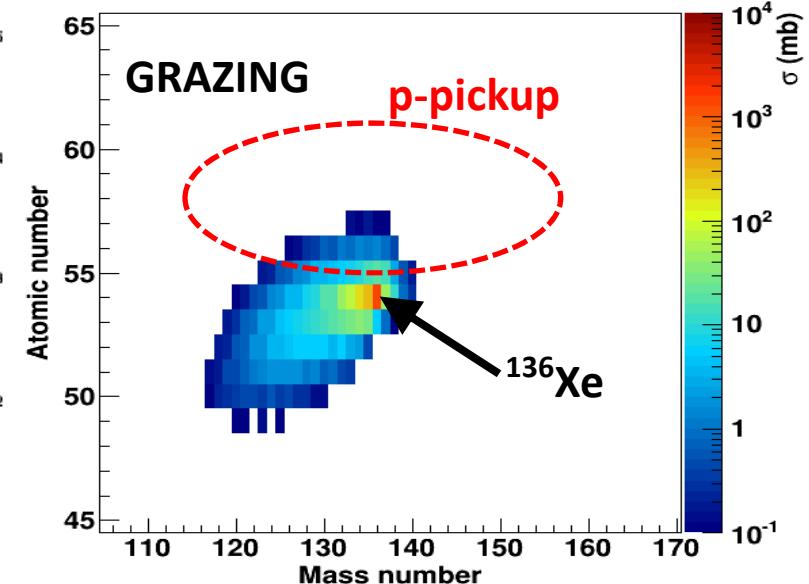
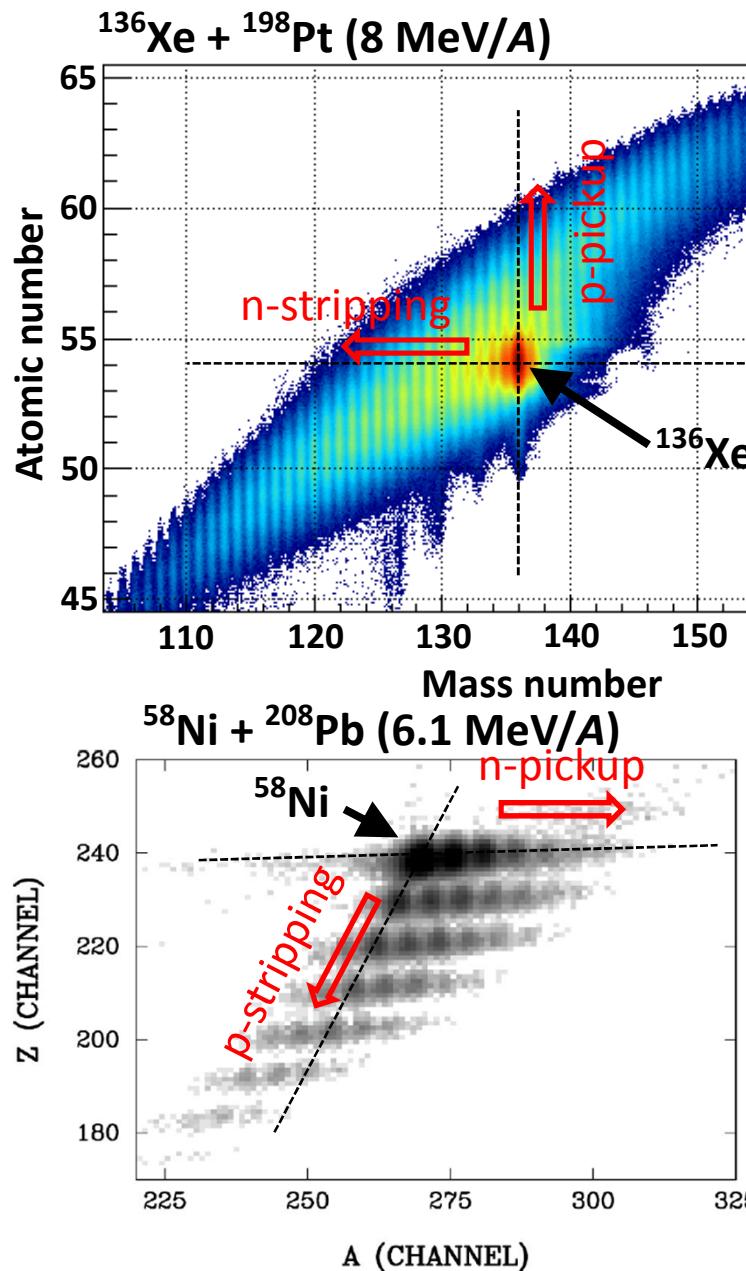
$$Q = 2 E / B\rho v$$

$$M = Q_i M / Q$$

Z identification of PLF



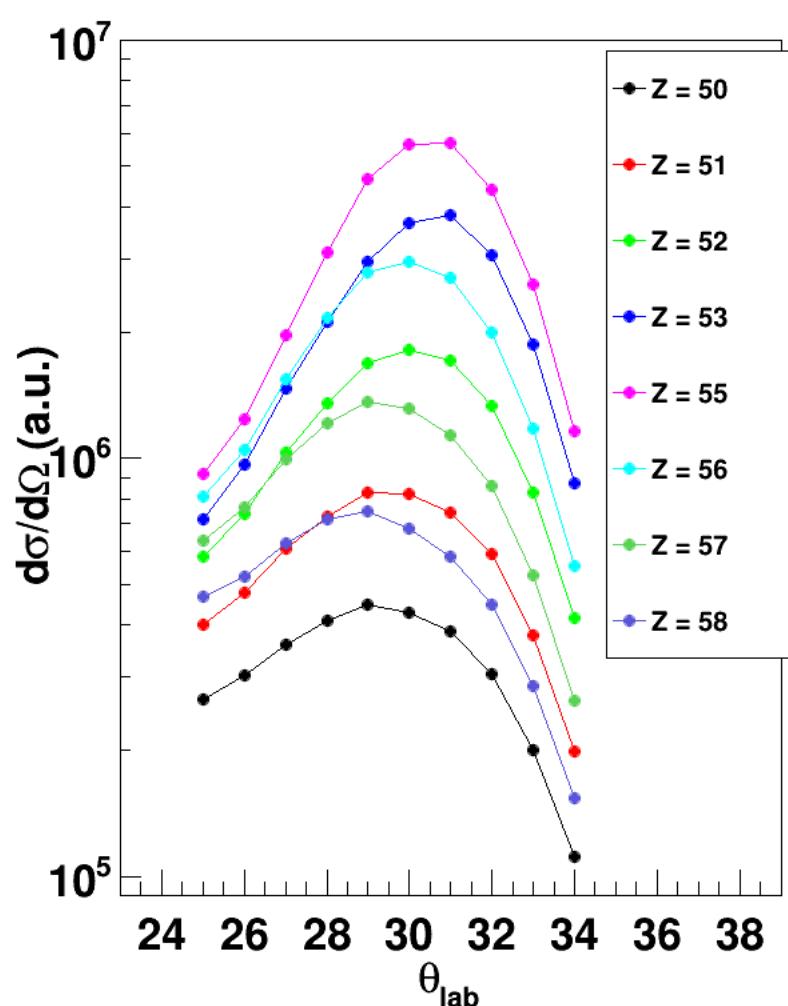
Z-A distribution of PLF



Contribution of *p*-pickup and *n*-stripping channels was observed.

c.f. *n*-pickup and *p*-stripping channels dominate in $^{58}\text{Ni} + ^{208}\text{Pb}$.

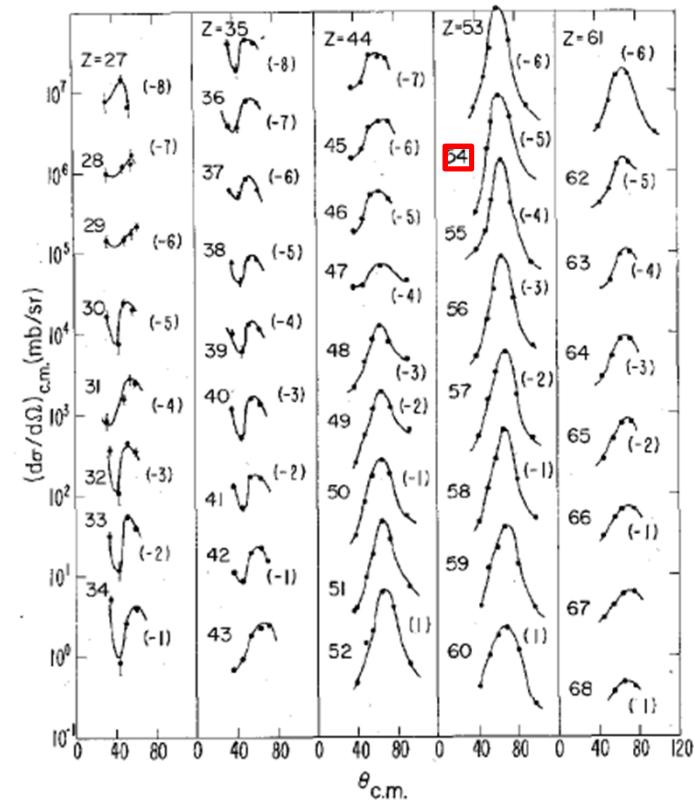
Angular distributions



Focusing effect

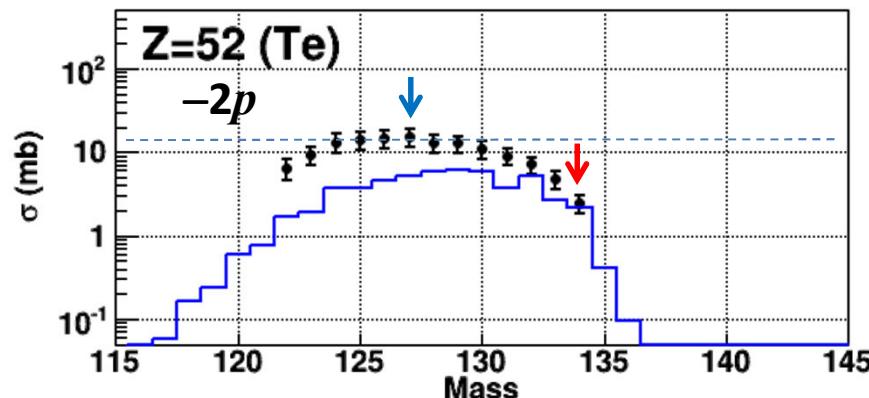
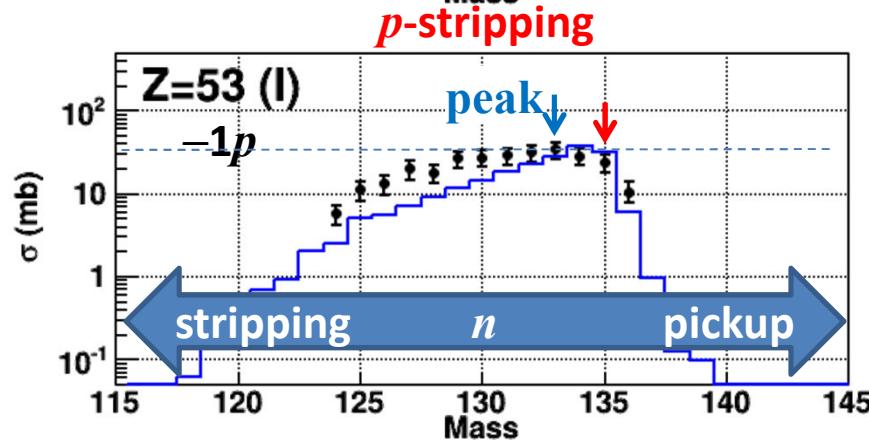
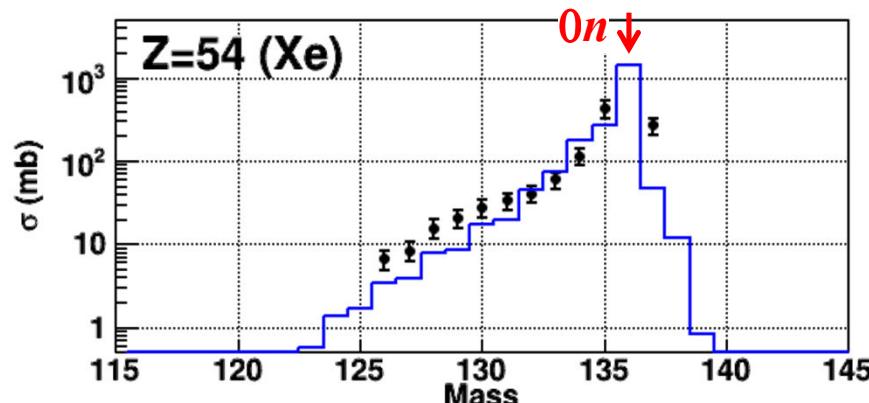
$$\theta \lesssim \theta_{\text{grazing}}$$

$^{136}\text{Xe} + ^{197}\text{Au}$ (7.2 MeV/A)



P. Russo et al., Phys. Lett. 67B (1977), 155 – 157.

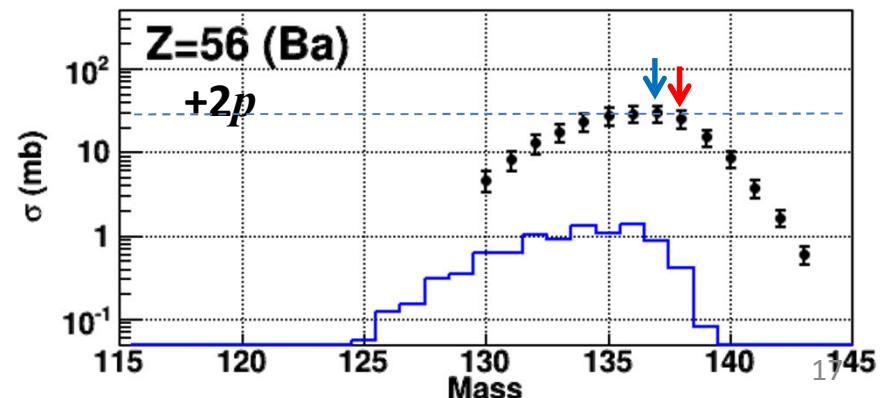
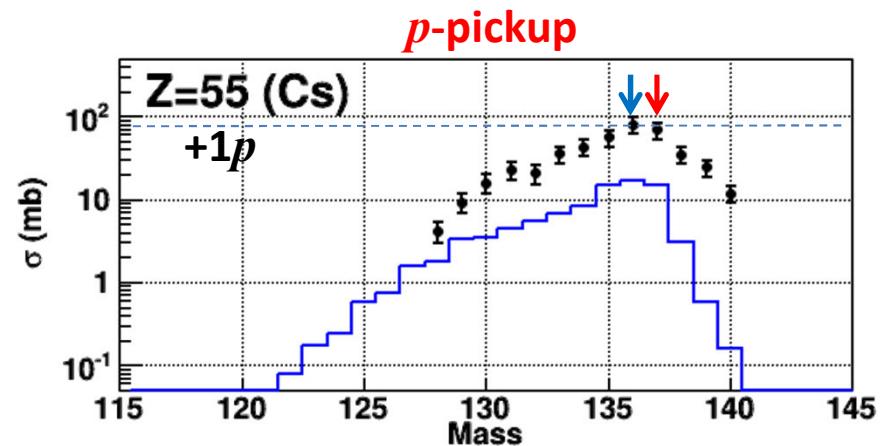
Isotopic distributions of PLF (0 , $\pm 1p$, $\pm 2p$ transfer)



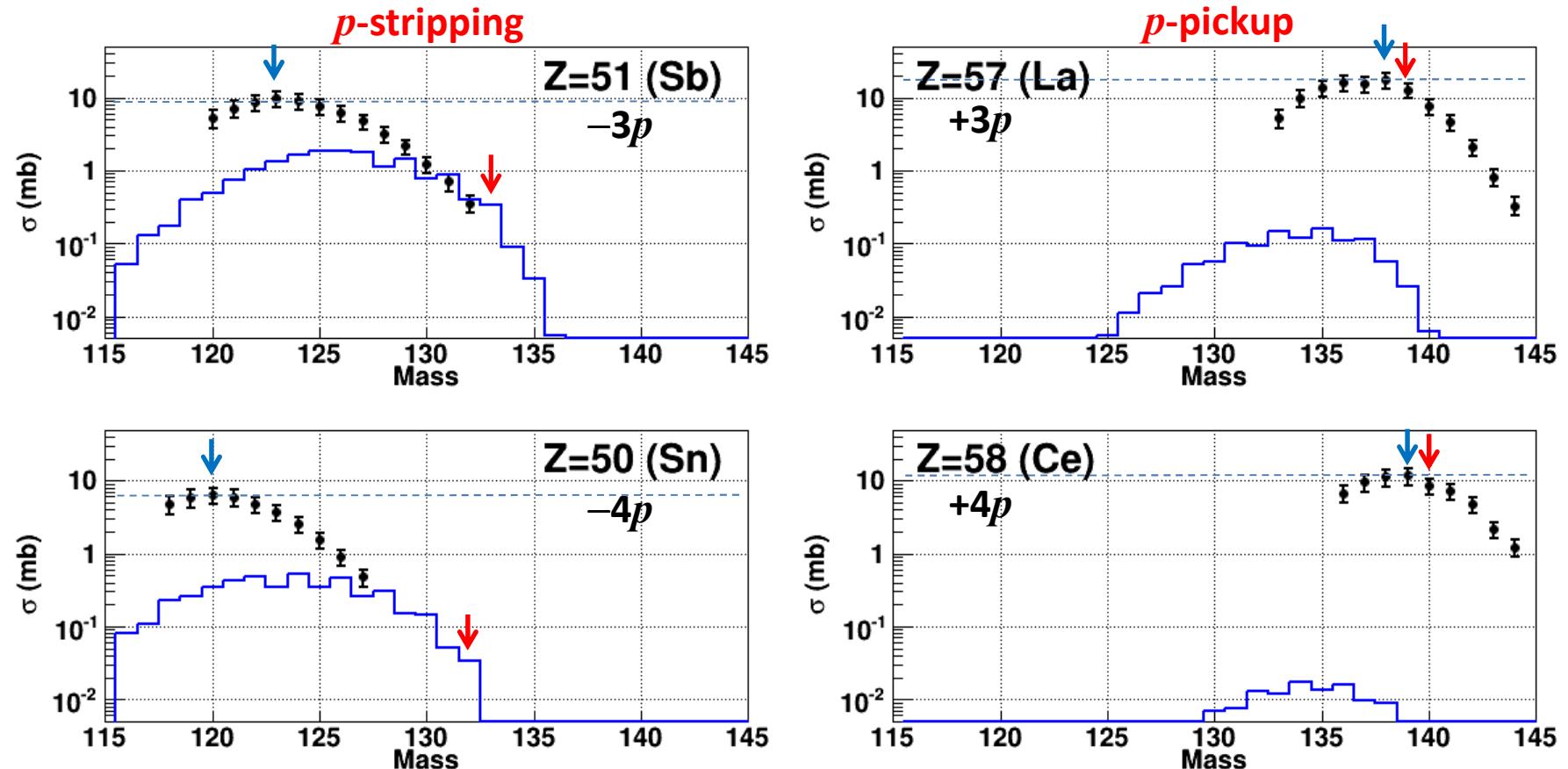
- Measurements
- GRAZING after evaporation

p-pickup: Larger cross section

p-stripping: Lighter distribution



Isotopic distributions of PLF ($\pm 3p$, $\pm 4p$ transfer)



$E_{\text{lab}} = 8 \text{ MeV/A}$

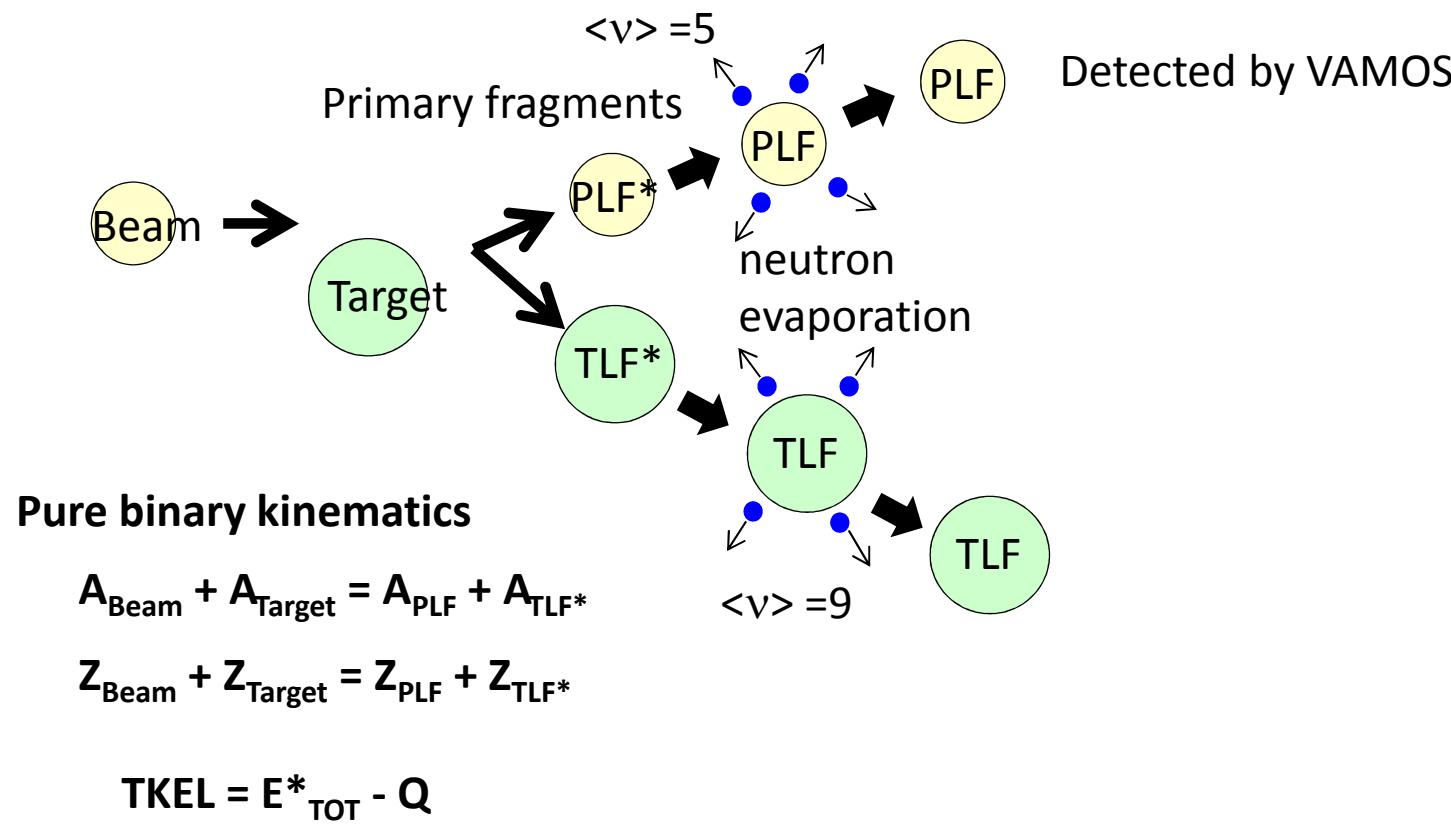
(55% higher than the Coulomb barrier)

Deep-inelastic components

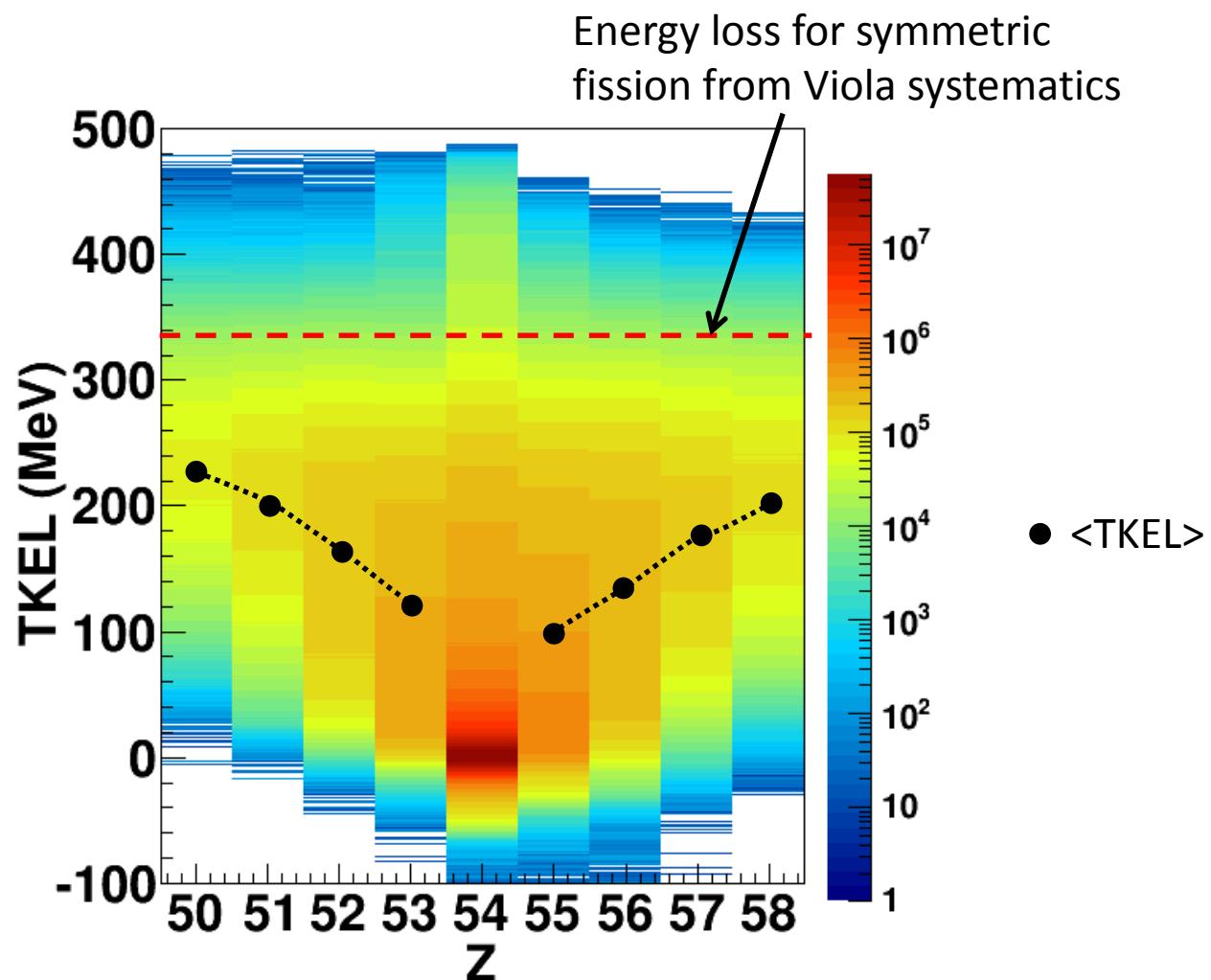
N/Z Equilibration

- Measurements
- GRAZING after evaporation

Evaluation of TKEL (Total Kinetic Energy Loss)

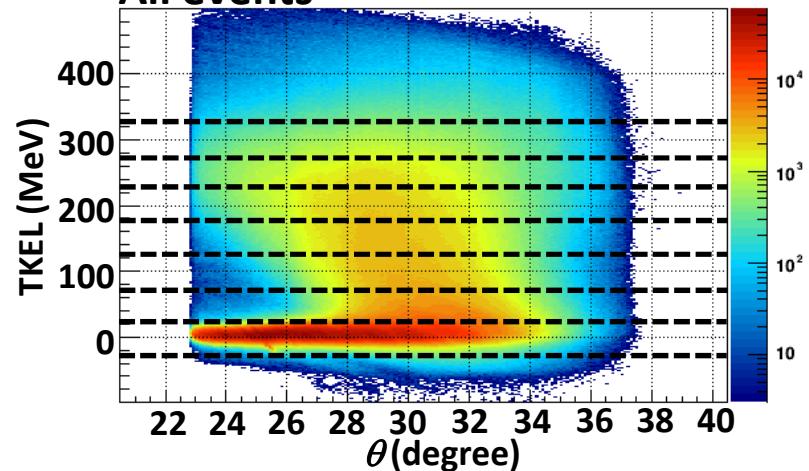


TKEL distributions



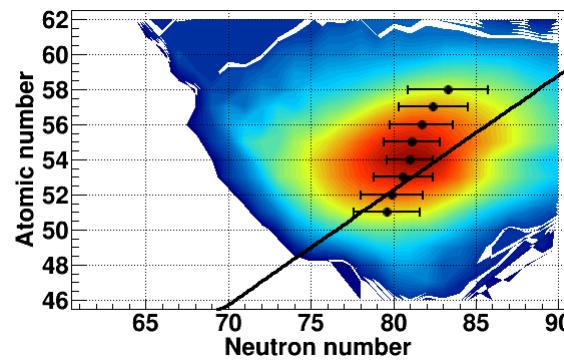
Z – N distribution of PLF for different TKEL

All events

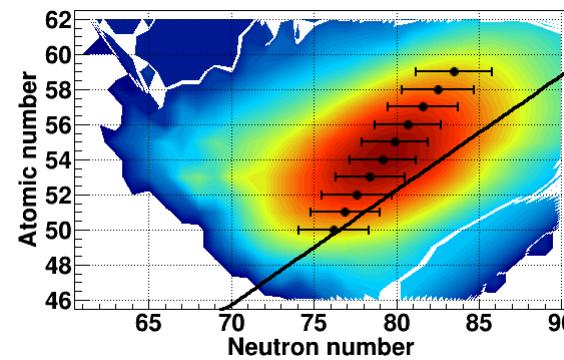


Evolution of Z-N
distribution (50 MeV
window)

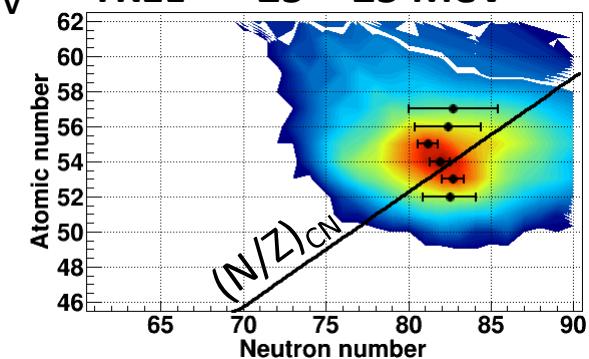
TKEL = 25 – 75 MeV



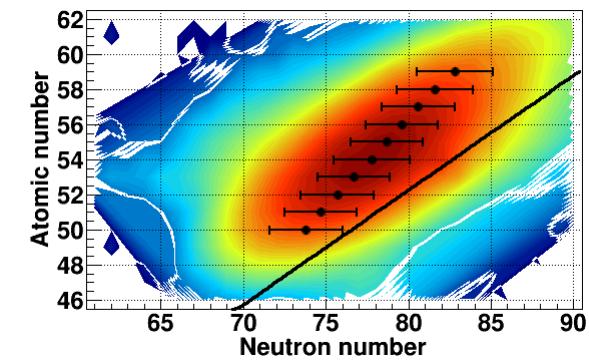
TKEL = 75 – 125 MeV



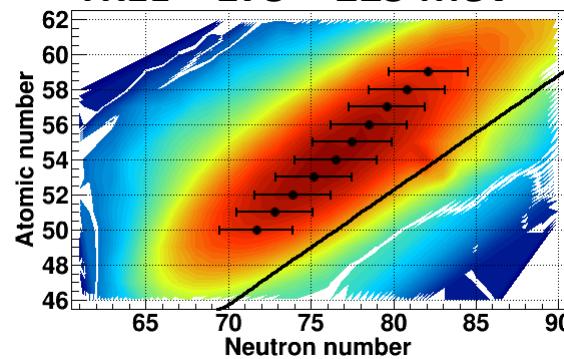
TKEL = -25 – 25 MeV



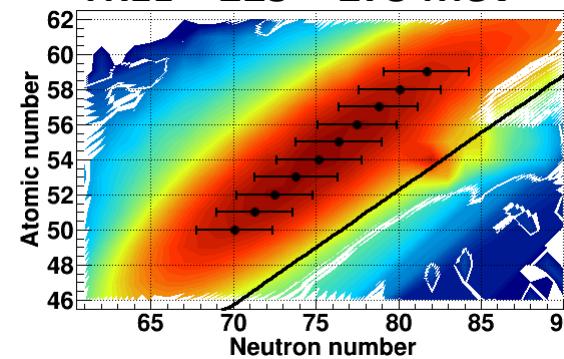
TKEL = 125 – 175 MeV



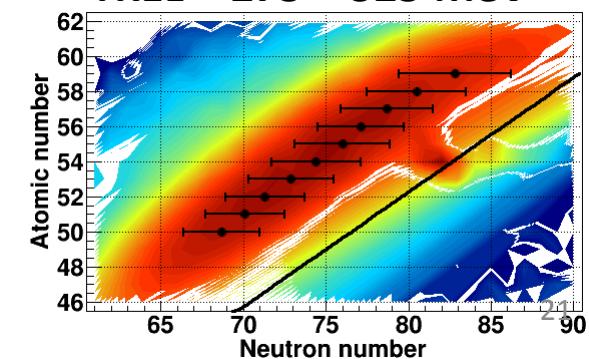
TKEL = 175 – 225 MeV



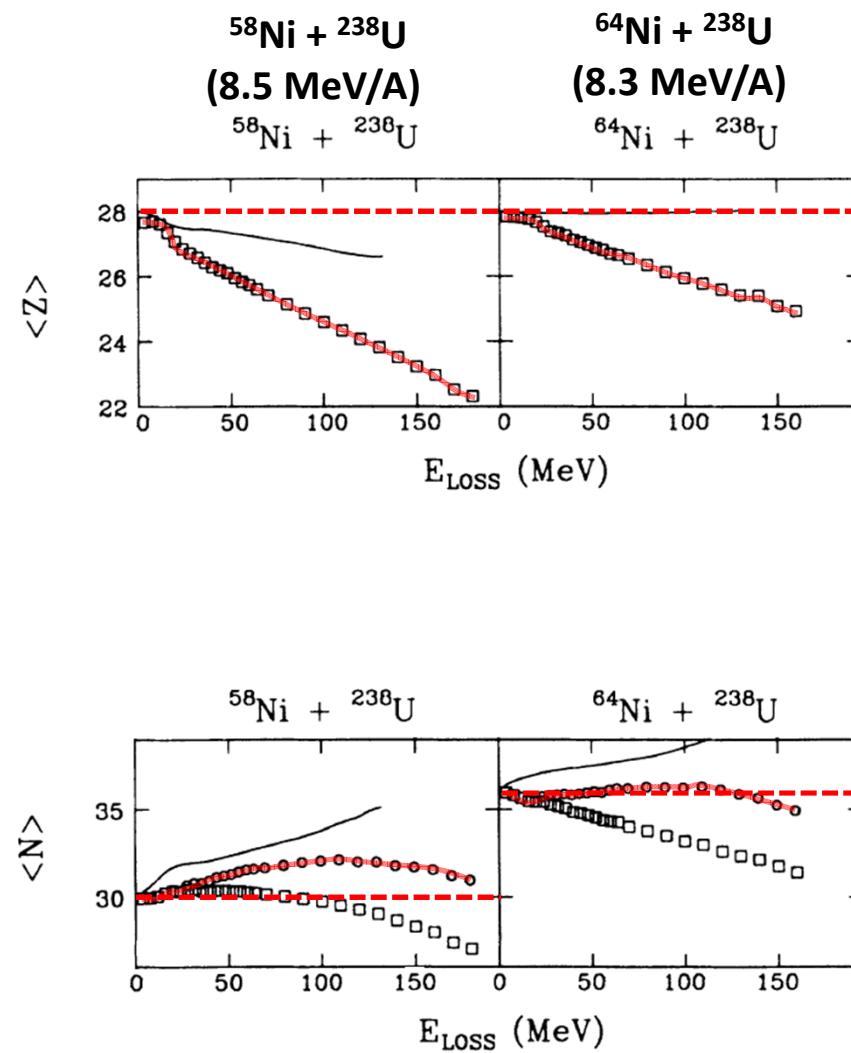
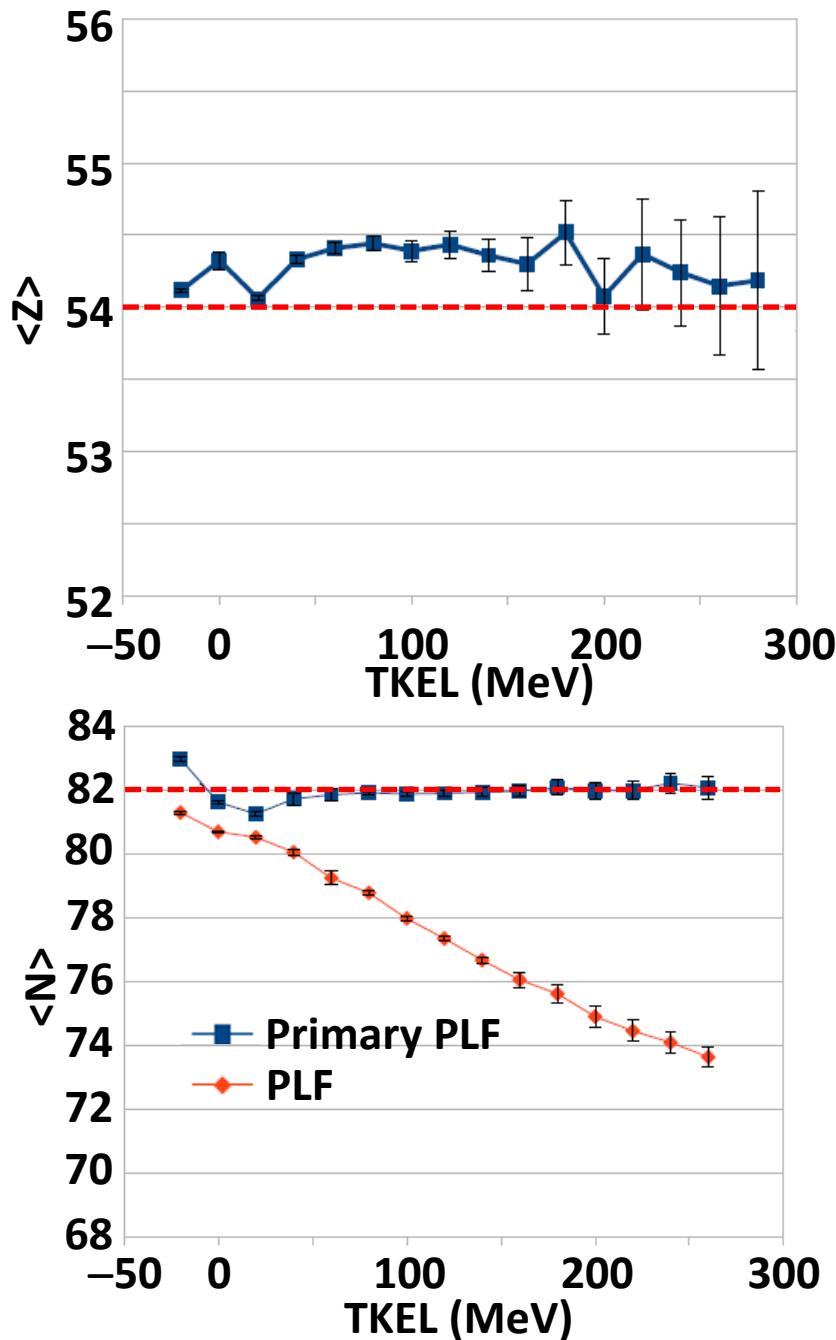
TKEL = 225 – 275 MeV



TKEL = 275 – 325 MeV

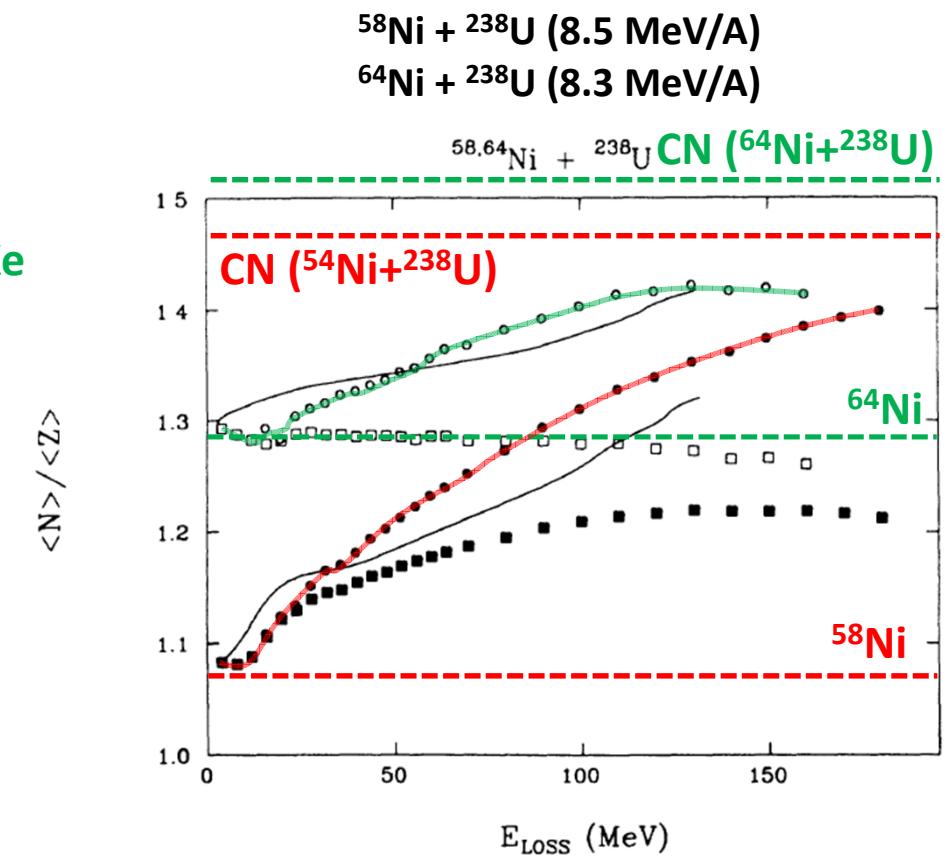
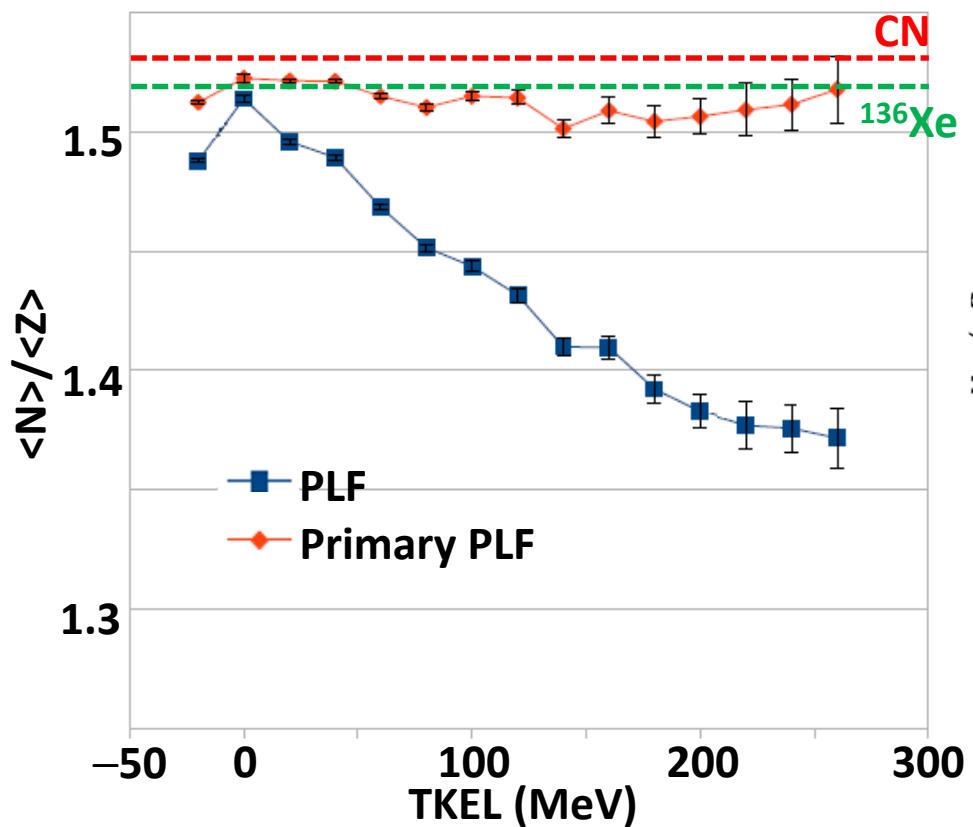


Evolution of centroids of distributions



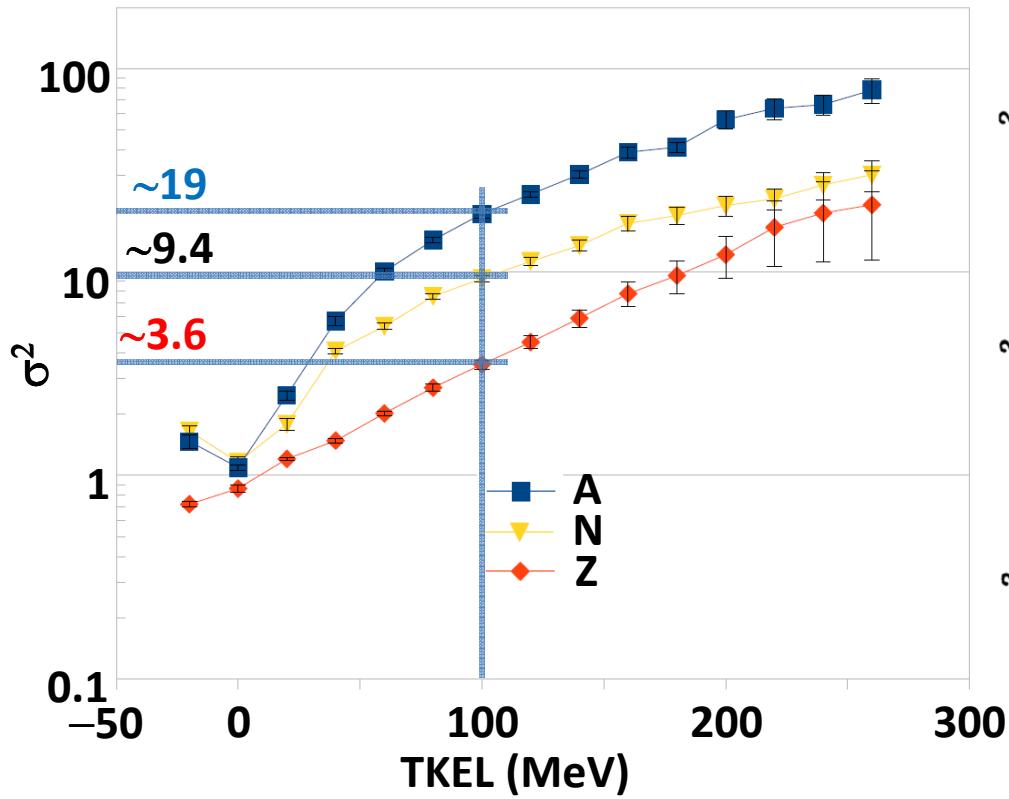
R. Planeta et al., Phys. Rev. C38 (1988), 195 – 209.

N/Z equilibration

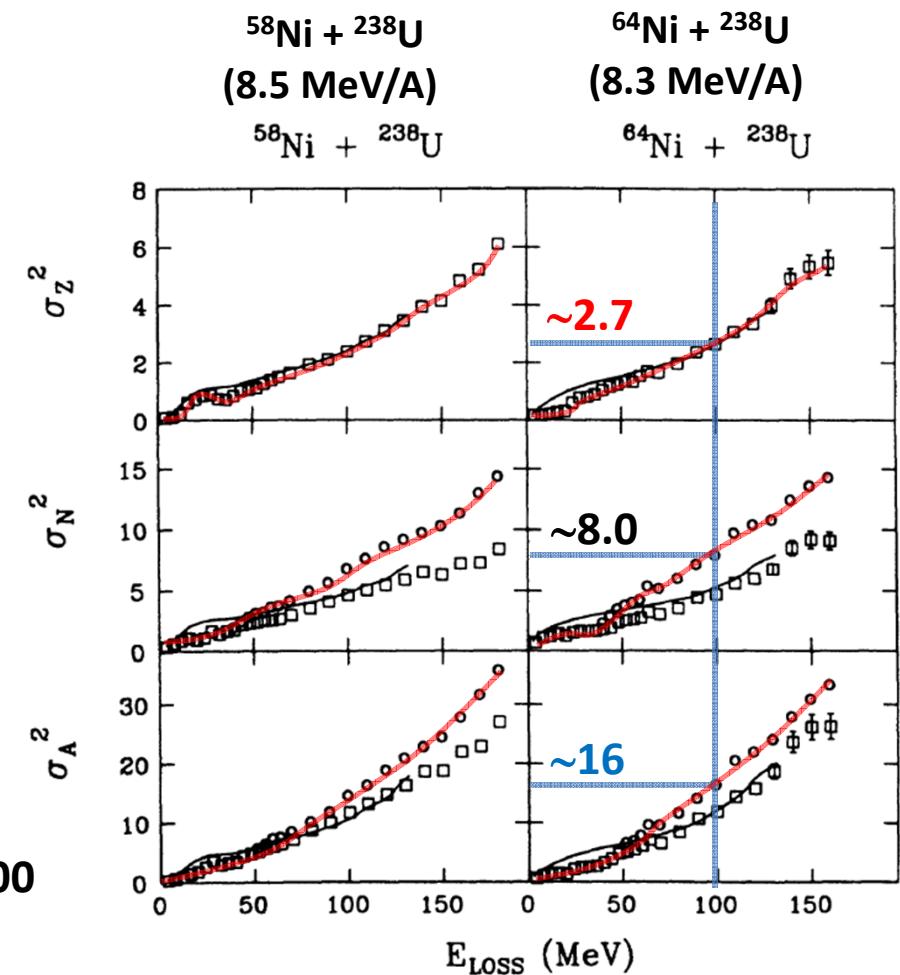


R. Planeta *et al.*, Phys. Rev. C38 (1988), 195 – 209.

Variances

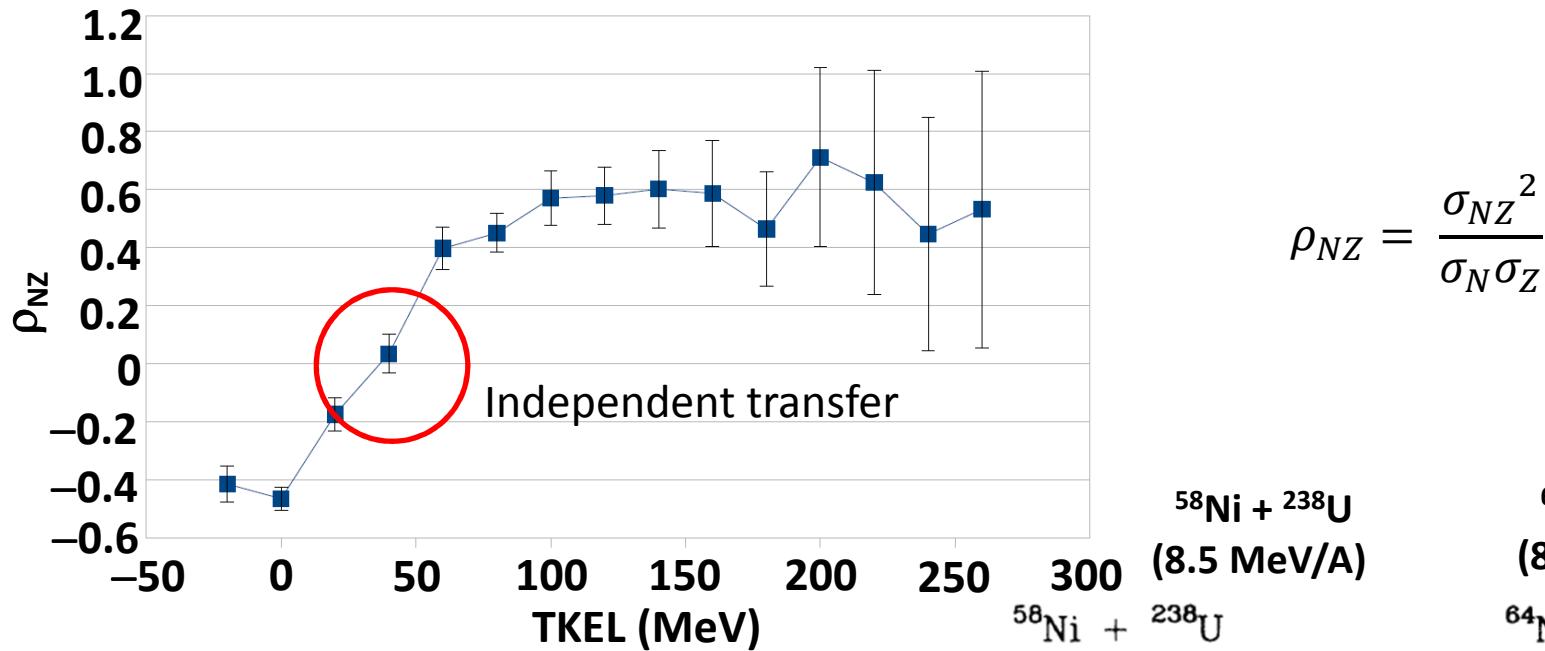


Angular distributions, TKEL distributions,
 $\langle Z \rangle$, $\langle N \rangle$, σ_Z^2 , σ_N^2 , σ_A^2 follow the past
 studies



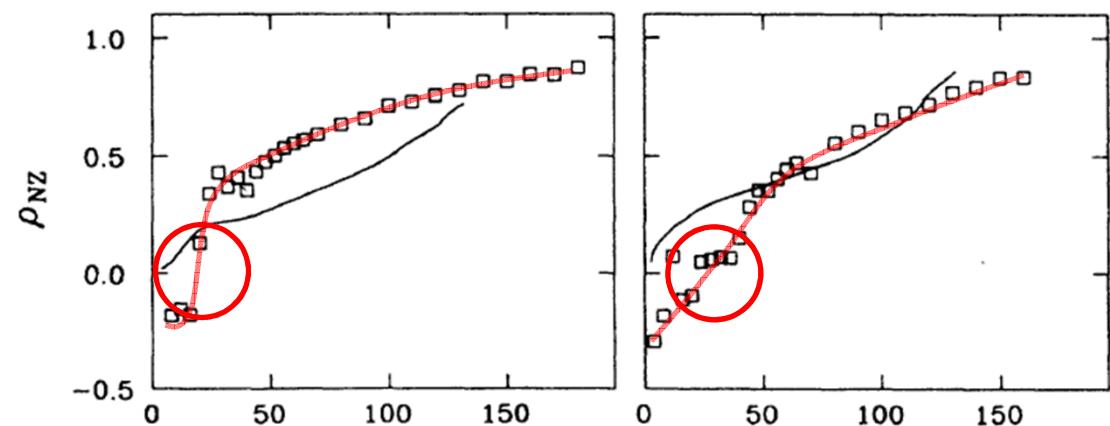
R. Planeta et al., Phys. Rev. C38 (1988), 195 – 209.

Correlation coefficient

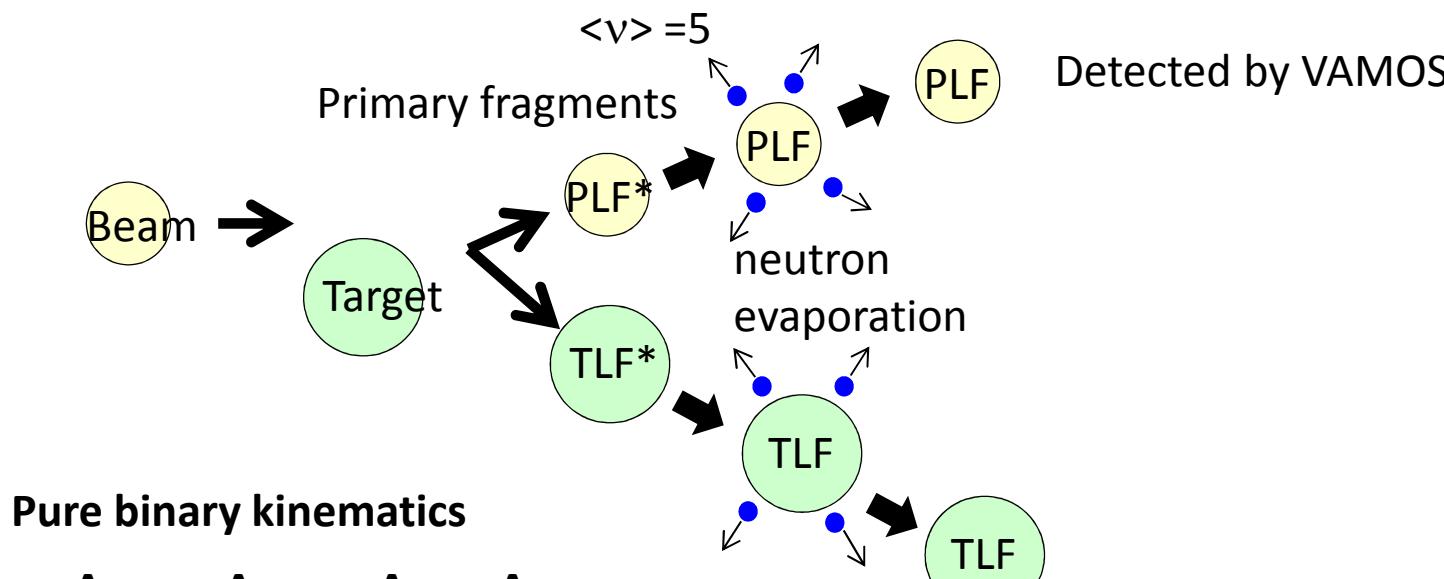


$^{64}\text{Ni} + ^{238}\text{U}$
(8.3 MeV/A)

$^{64}\text{Ni} + ^{238}\text{U}$



Evaluation of TLF distribution



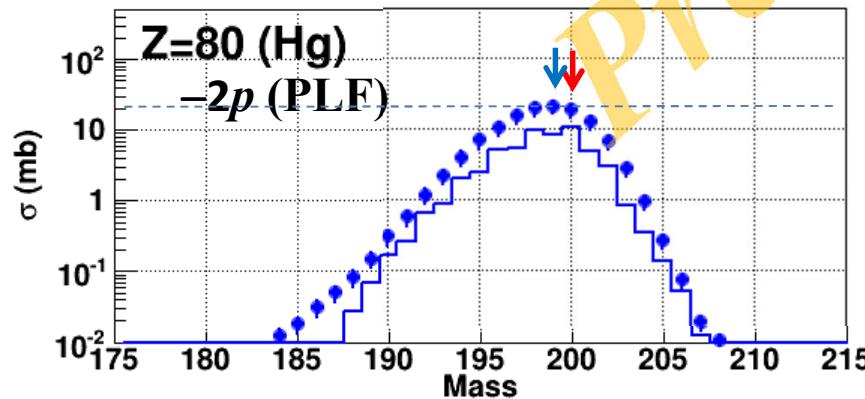
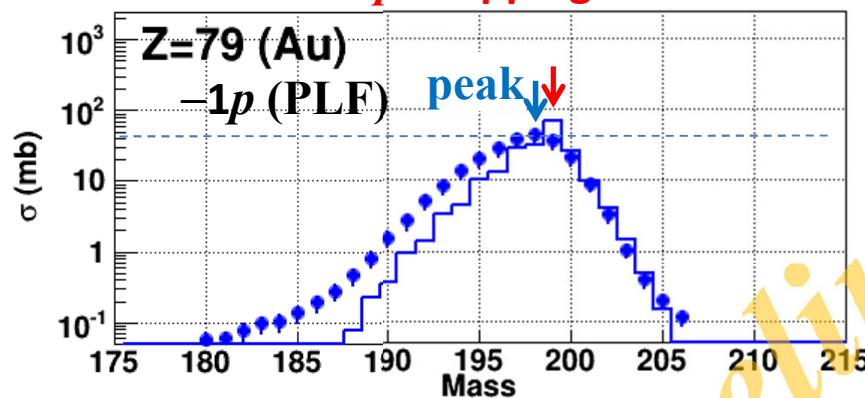
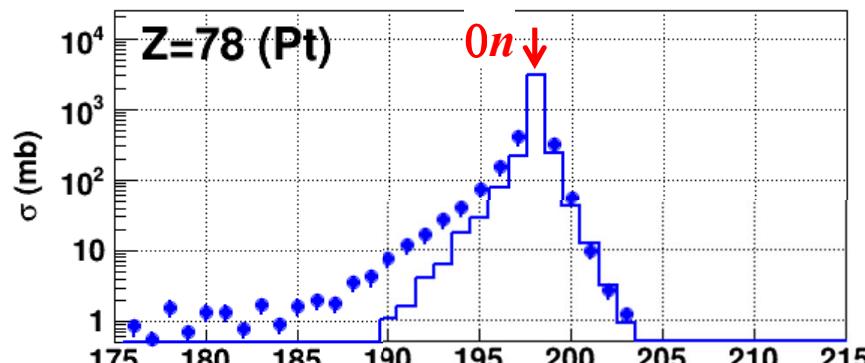
Excitation energy sharing in mass ratio

$$\text{TKEL} = E^*_{\text{TOT}} - Q$$

$E^*_{\text{PLF}} = E^*_{\text{TOT}} \times M_{\text{PLF}} / (M_{\text{PLF}} + M_{\text{TLF}^*})$
 $\rightarrow v_{\text{PLF}} \rightarrow \text{Primary PLF A} \rightarrow \text{Primary TLF A}$

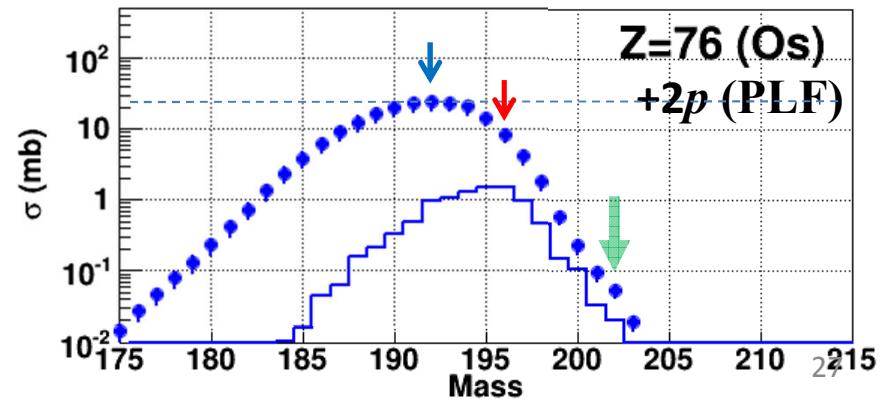
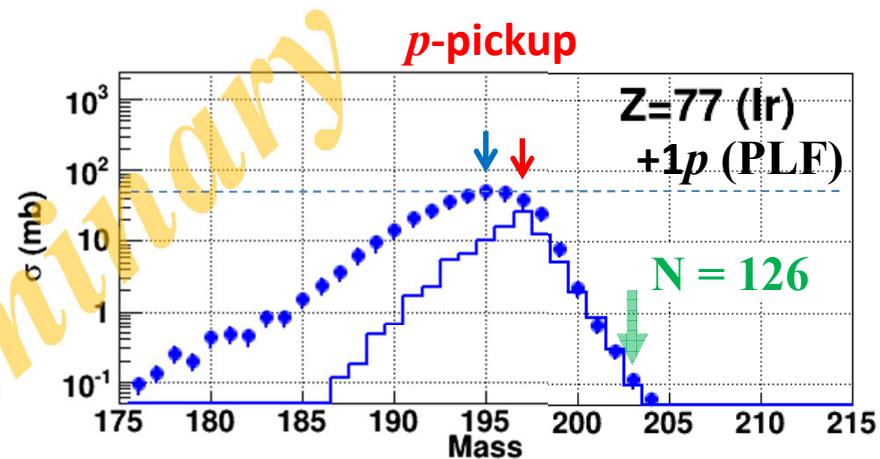
$E^*_{\text{TLF}^*} = E^*_{\text{TOT}} \times M_{\text{TLF}^*} / (M_{\text{PLF}} + M_{\text{TLF}^*})$
 $\rightarrow v_{\text{TLF}} \rightarrow \text{TLF A}$

Isotopic distributions of TLF (0, $\pm 1p$, $\pm 2p$ transfer)



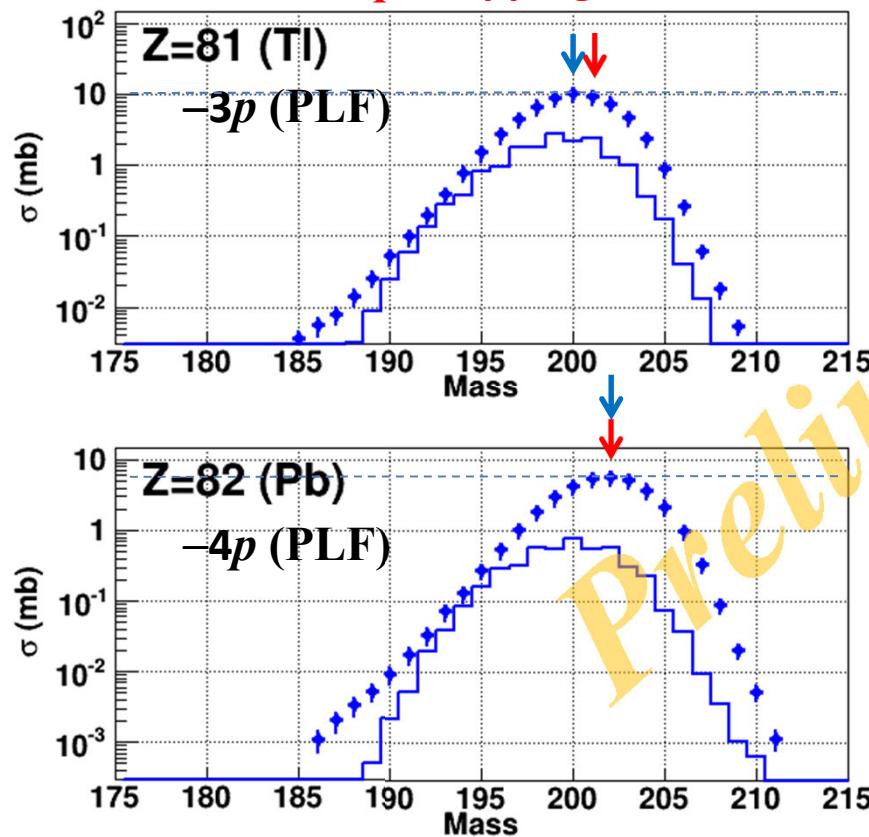
- Measurements after evaporation
- GRAZING after evaporation
- p*-pickup: Larger cross section
Lighter distribution
N/Z equilibrium & evaporation

^{202}Os : $\sigma_{\text{GRAZING}} \sim 20 \mu\text{b} \rightarrow \sim 50 \mu\text{b} (\times 2.5)$

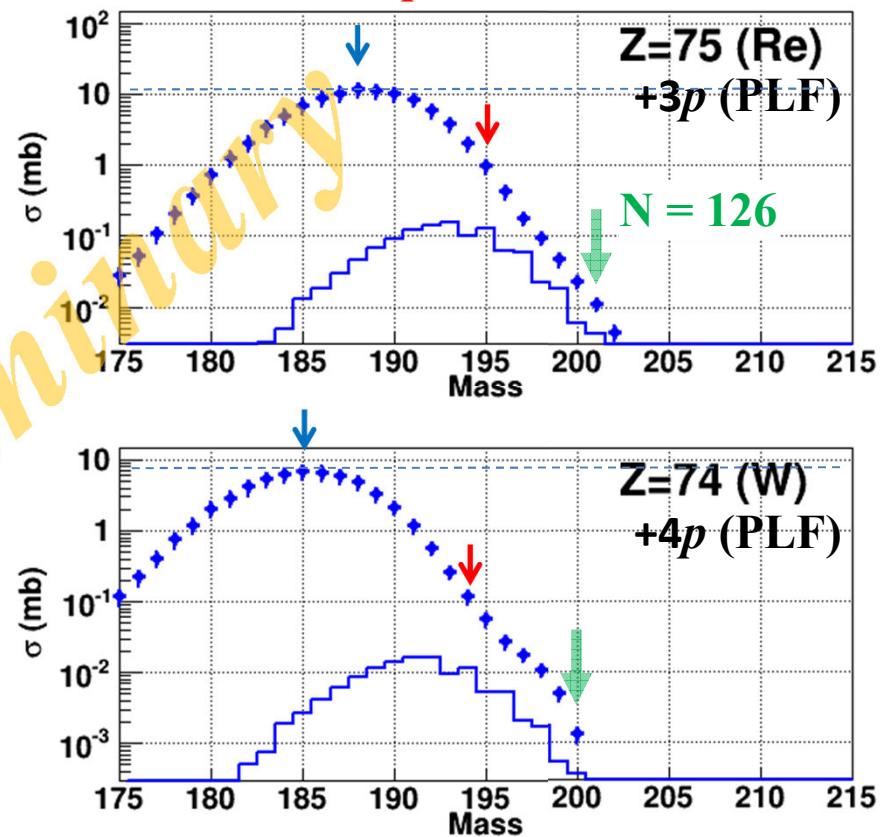


Isotopic distributions of TLF ($\pm 3p$, $\pm 4p$ transfer)

p-stripping



p-pickup

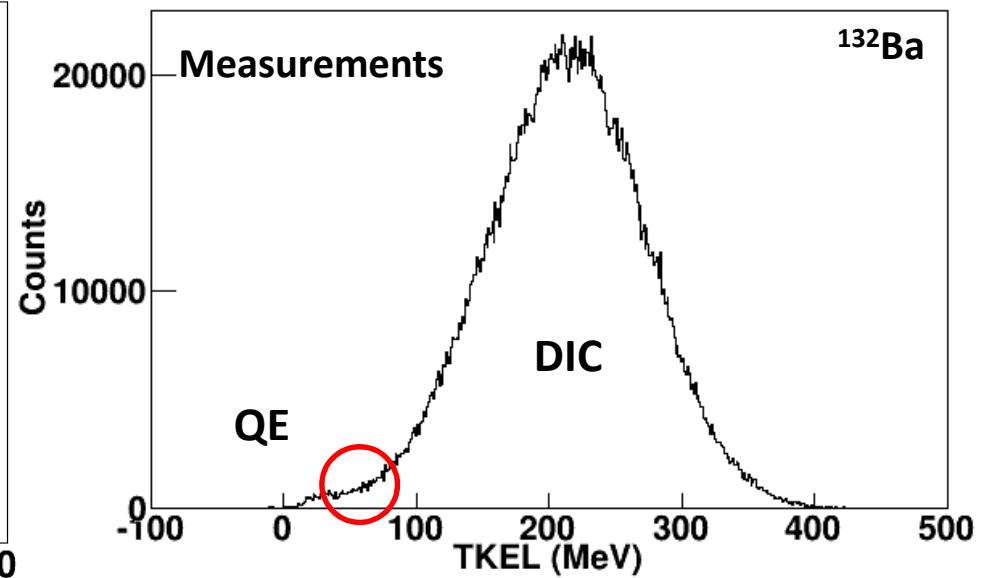
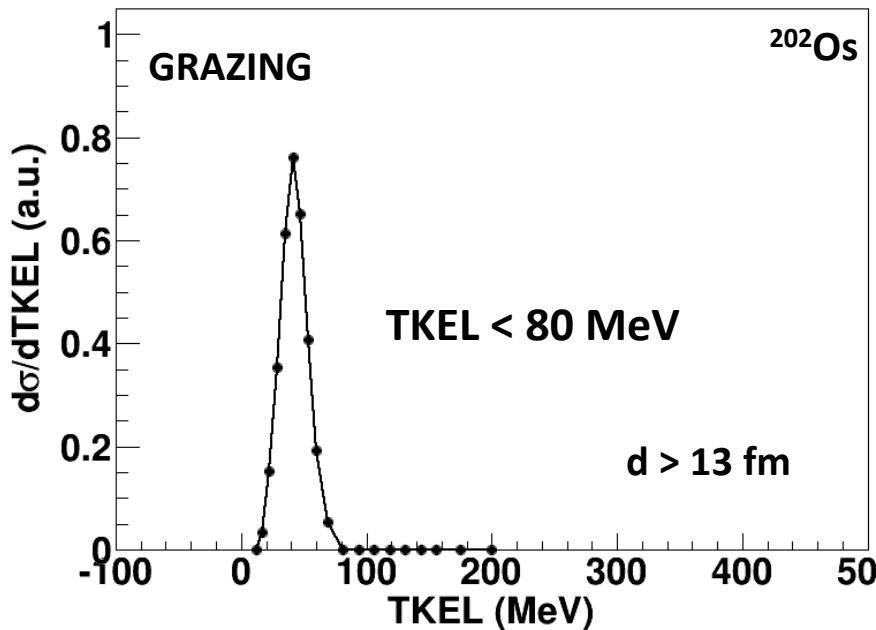
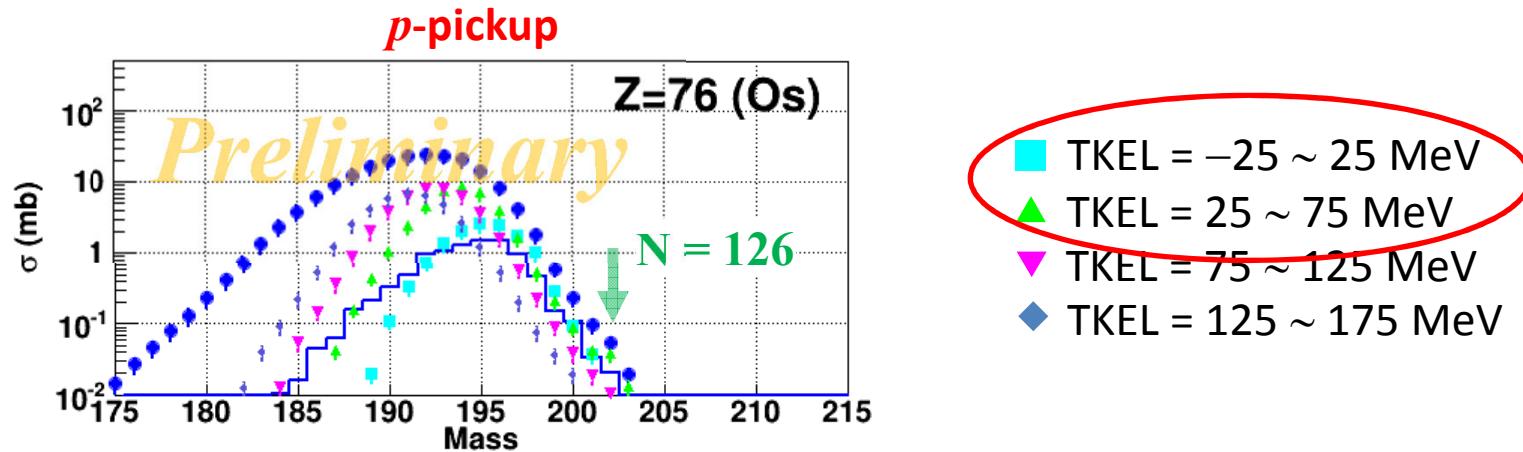


- Measurements after evaporation

- GRAZING after evaporation

^{200}W : $\sigma_{\text{GRAZING}} \sim 0.4 \mu\text{b} \rightarrow \sim 1.3 \mu\text{b} (\times 3)$

TKEL dependence of isotopic distribution



Summary

- Low energy heavy ion reaction
 - Deep inelastic collision
 - Direct reaction-like : Angular distribution, Charge and mass spectrum
 - Fusion-fission-like : Energy spectrum
- Deep inelastic collision
 - $\langle N \rangle, \langle Z \rangle$: N/Z equilibration is a monotonic and continuous process according to energy dumping
 - Isotopic distribution (nucleon exchange): Q-values , Dynamical effect
- Production of neutron-rich nuclei around $N = 126$
 - $^{136}\text{Xe} + ^{198}\text{Pt}$: Q-values, $(N/Z)_{\text{Xe}} \sim (N/Z)_{\text{Pt}}$
- Experimental study of $^{136}\text{Xe} + ^{198}\text{Pt}$
 - PLFs were detected
 - Angular distributions, TKEL distributions, $\langle Z \rangle, \langle N \rangle, \sigma_Z^2, \sigma_N^2, \sigma_A^2$ follow past studies
 - $\rho_{ZN} \sim 0$ for TKEL $\lesssim 70$ MeV
 - TLF distributions were deduced
 - $\sigma \gtrsim \sigma_{\text{GRAZING}}$ around $N = 126 \leftarrow \text{TKEL} < 75$ MeV
 - Relatively large orbital angular momentum at the border between QE and DIC would contribute to the n-rich and p-deficient TLF production

Collaboration

KISS project

KEK	Y. Hirayama, H. Ishiyama, H. Miyatake, H.S. Jung, M. Oyaizu, Y.X. Watanabe
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Tsukuba University	S. Kimura, M. Mukai
RIKEN	Y. Matsuo, M. Wada, T. Sonoda
K.U. Leuven	P. Van Duppen , Yu. Kudryavtsev, M. Huyse

MNT measurements at GANIL

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LNL	L. Corradi, E. Fioretto
Padova University	D. Montanari
IPN	M. Niikura, D. Suzuki
Osaka University	H. Nishibata, J. Takatsu