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Dispersive and Deflective Effect in Transverse Momentum Distribution of Fragments at Intermediate Energies

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r280n collaboration, RIKEN-RRC
p178 collaboration, NIRS-HIMAC

Heavy-ion beam of intermediate energies

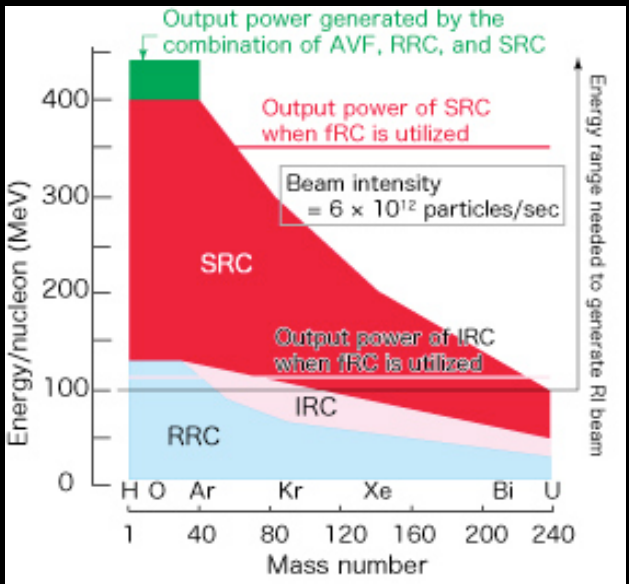
Accelerator facility

for basic science : Nuclear physics , …

for application : Cancer therapy , …

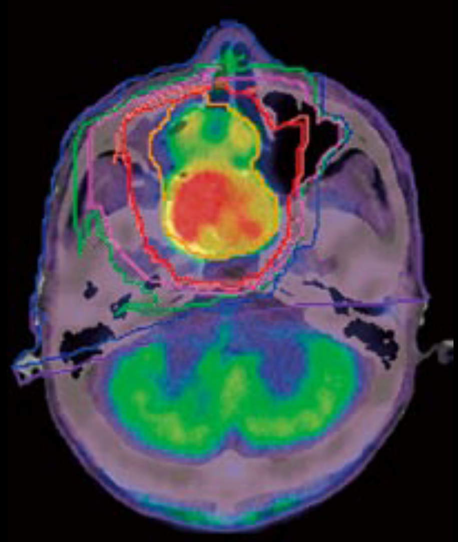
From galaxy : Galactic cosmic ray (GCR)

at RI-beam facility



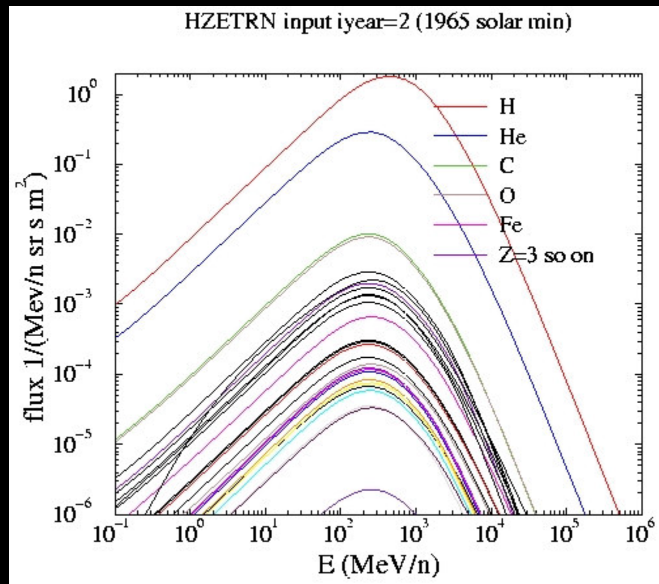
RI beam factory, RIKEN

Cancer therapy



J. Mizoe, Radiological Sciences, 50 (2007) 26.

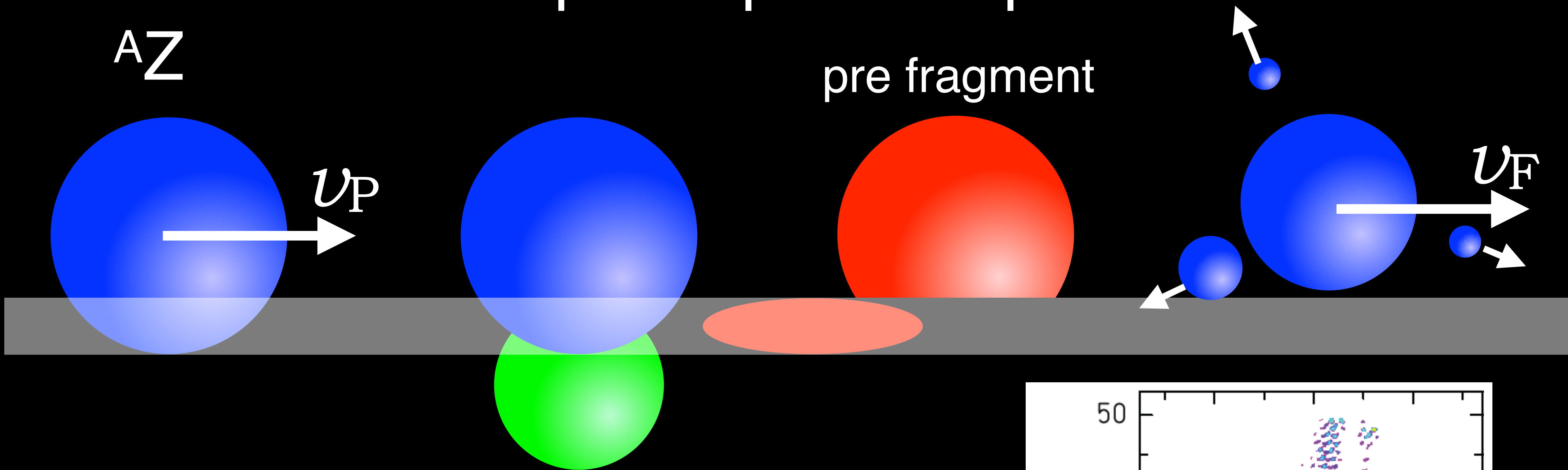
E-spectrum of GCR



Zi-Wei Lin, UAH / NASA Space Radiation Shielding Program, MSFC (2004).

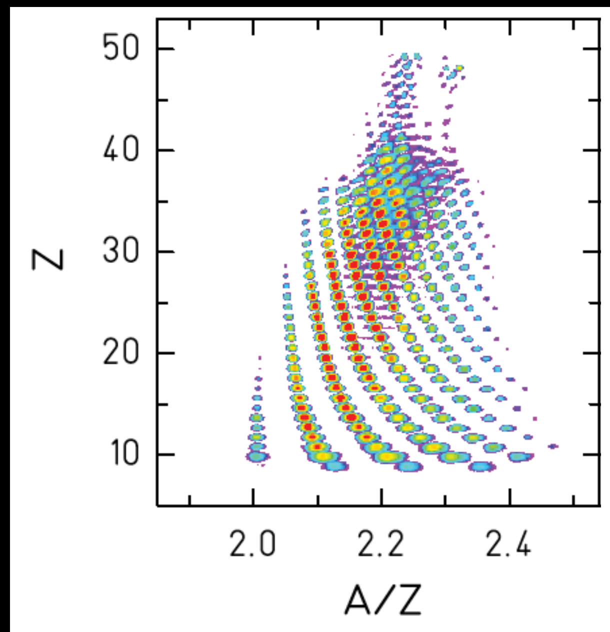
Fragmentation process ; E > 100 MeV/u

Participant-spectator picture



Frequently utilized at RNB facilities

1) Productivity for wide range of isotopes
2) High beam quality



V. Föhr et al., Phys. Rev. C 84, 054605 (2011).

P_T distribution of fragments

Simple @*E* > 1GeV/u

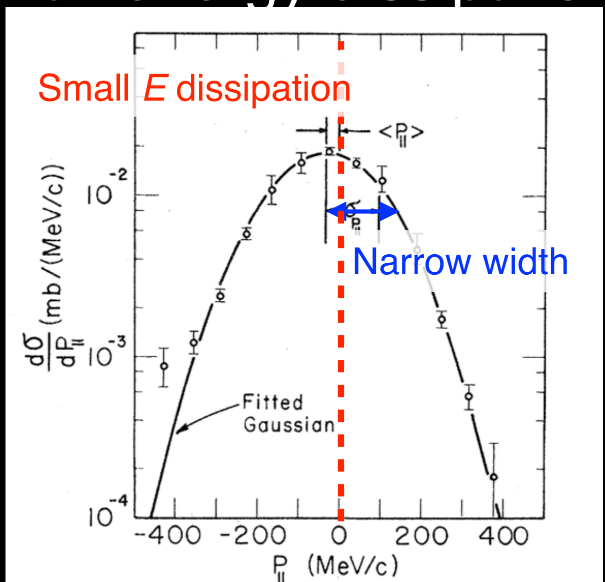
1. Isotropic Gaussian-type distribution

$$\sigma_T = \sigma_L = \sigma_{GH}$$

$$\sigma_{GH} = \sigma_0 \sqrt{\frac{A_F(A_P - A_F)}{A_P - 1}}$$

$$\sigma_0 \sim 100\,(\mathrm{MeV/c})$$

2. Small energy dissipation



D.E. Greiner et al., Phys. Rev. Lett. 35 (1975) 152.

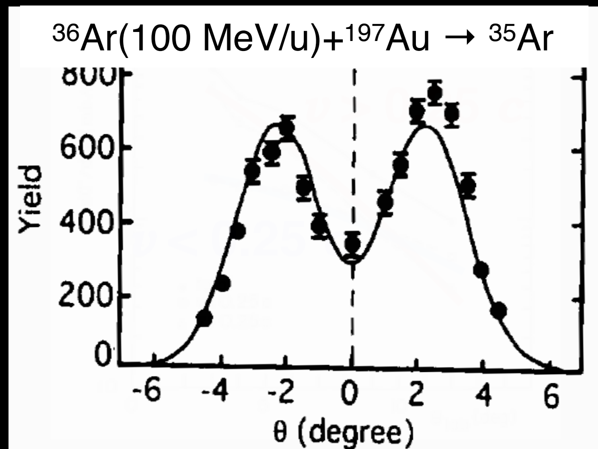
Additional contributions @*E* ~ 100 MeV/u

1. Additional transverse width

$\sigma_T > \sigma_L$

Experimental studies are deficient or fragmentary.

2. Velocity dependence @44MeV/u
3. Deflective effect in peripheral reactions @100 MeV/u



K. Matsuta et al., Nucl. Phys. A 701 (2002) 383.

Object of this talk

Dispersive and deflective nature in P_T distribution of fragmentation products at E=100~300 MeV/u

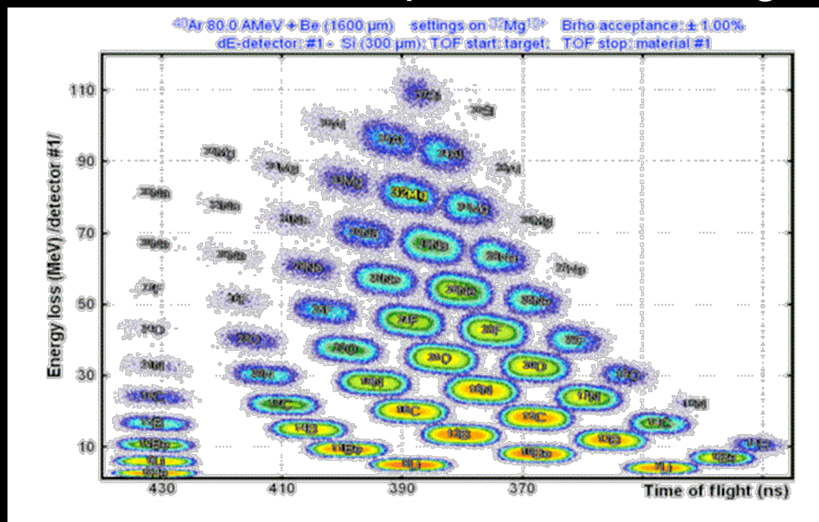
Systematic investigation and formulation of

1. Additional transverse width
2. Velocity dependence
3. Deflective effect in peripheral reactions

→ Improvement of simulation code for HI beam transportation

e.g. FLUKE, PHITS, LISE++, MOCADI, …

^{40}Ca(80 AMeV) + Be optimized for ^{32}Mg



LISE++ : http://lise.nscl.msu.edu/introduction.html

Experimental

Reaction system

95 MeV/u & 290 MeV/u

95MeV/u : $^{40}Ar + ^{9}Be$

RIPS fragment separator(RIKEN)

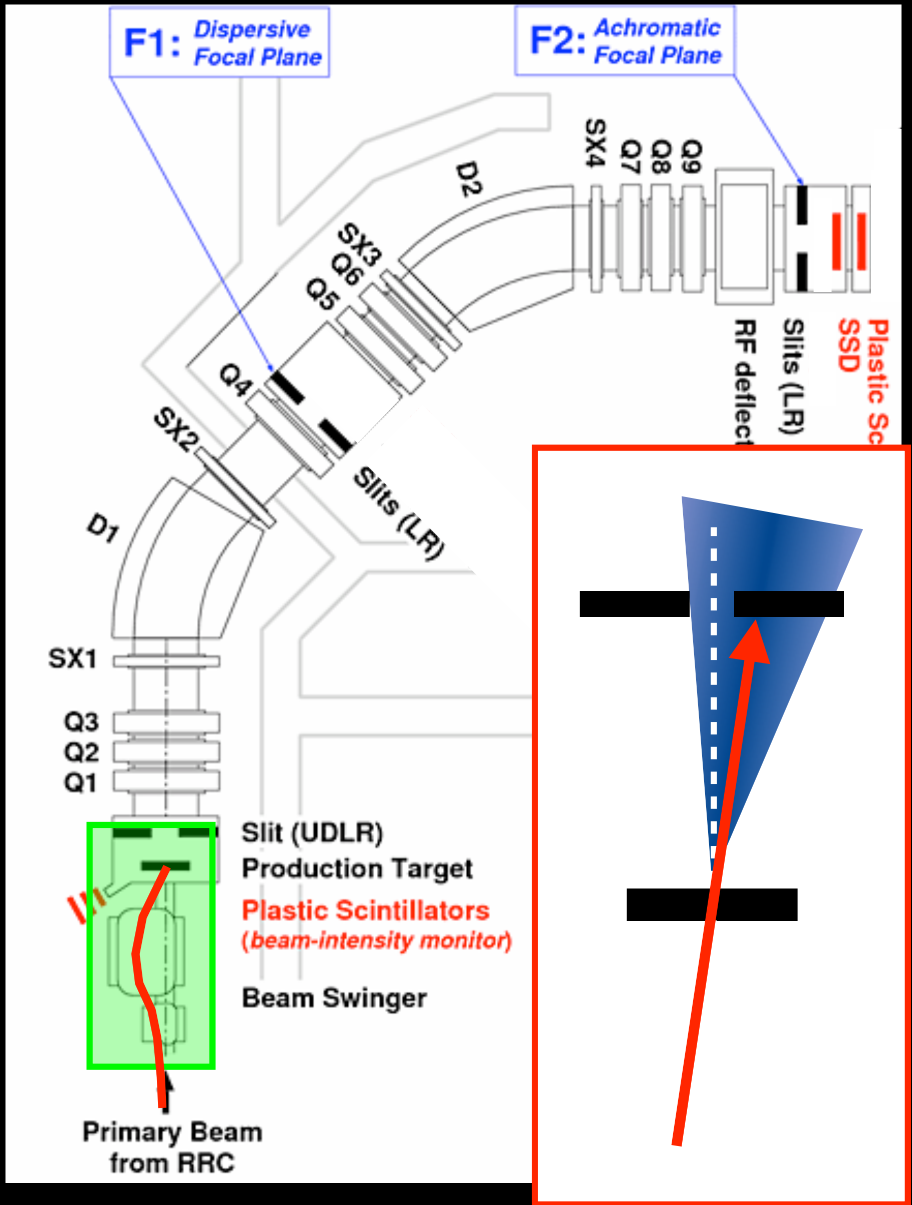
290MeV/u : $^{40}Ar + ^{27}Al, ^{93}Nb, ^{159}Tb, ^{197}Au$

$^{84}Kr + ^{12}C, ^{27}Al, ^{93}Nb, ^{159}Tb, ^{197}Au$

SB2 fragment separator(NIRS)

Experimental : fragment separator

RIKEN Ring cyclotron + RIPS



Reaction : ^{40}Ar (95 MeV/u) + ^{9}Be

Identification : TOF, ΔE, $B\rho$

Acceptance :

P_T : Slit after target

P_L : Slit @ F1

Beam intensity monitor : @target

Ambiguity of beam intensity : ~ ± 5 %

Angular distribution :

Beam swinger + slit after target

Keep optical axis of RIPS at any angle setting

→ Reduce ambiguities in transmission and detection efficiencies of fragmentation products.

Results & analysis

Width of P_T distribution

Well-defined width obtained from angular distribution

Fitting with a Gaussian function

$$N(\theta) = A\exp\left\{-\frac{\theta^2}{2{\sigma_\theta}^2}\right\}$$

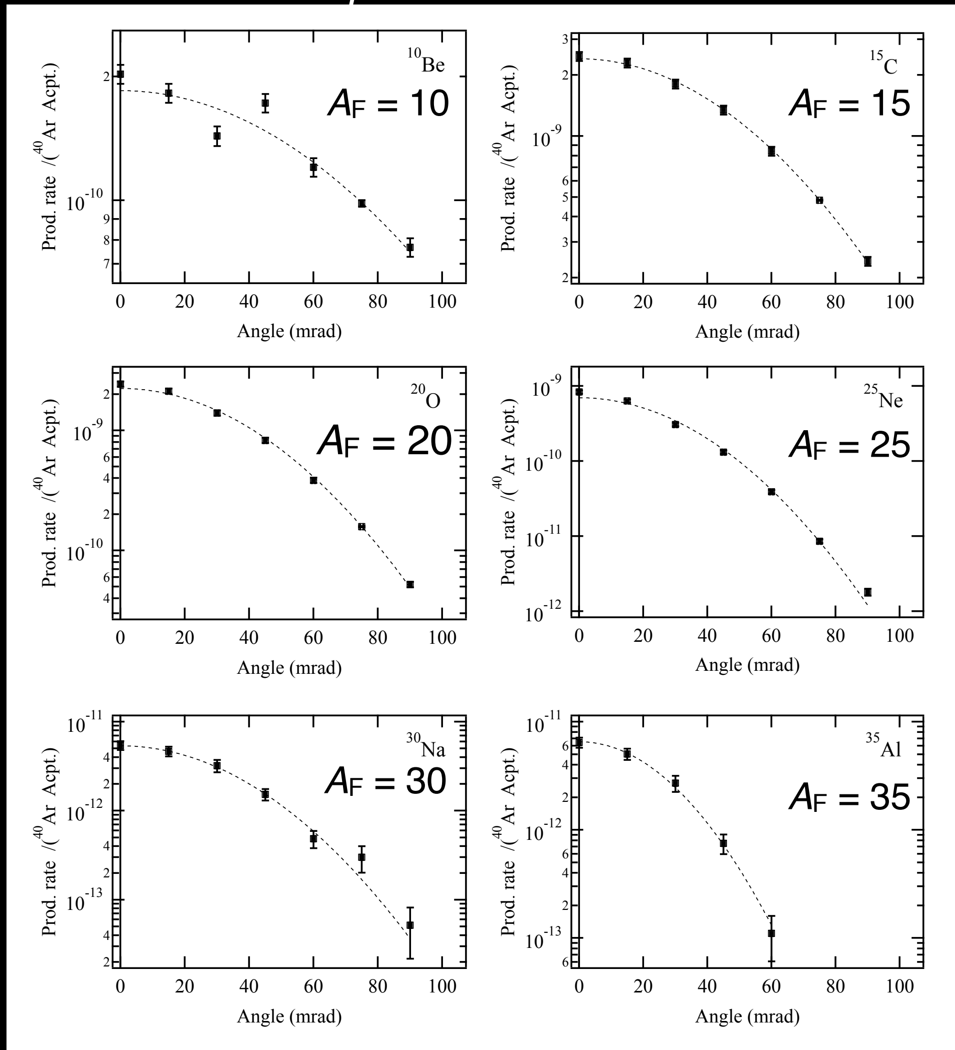
Width of P_T distribution

$$\boldsymbol{\sigma}_T = P_L \times \boldsymbol{\sigma}_{\boldsymbol{\theta}}$$

Considering

1) Finite angular acceptance ± 7.5 mrad
2) Angular struggling in target evaluated by ATIMA
3) Emittance of primary beam assumed to be neglected

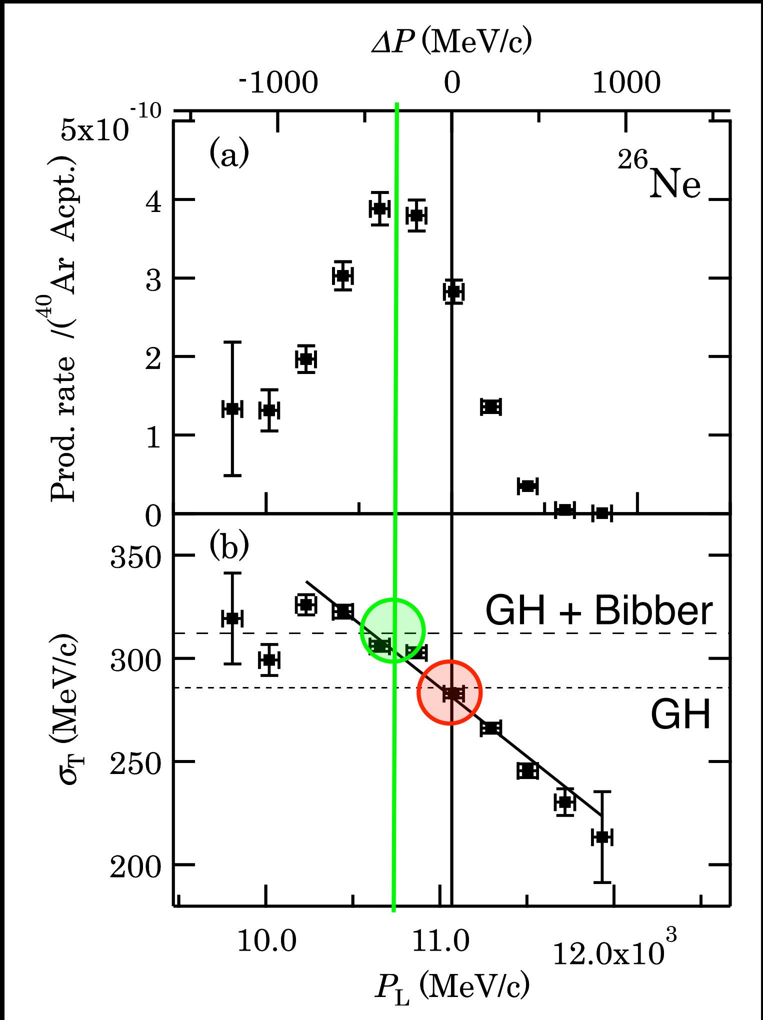
$B\rho$ = 3.600 Tm



S. Momota et al., Phys. Rev. C 92, 024608 (2015).

σ_T vs. velocity : Ar+Be@95 MeV/u

^{40}Ar + Be → ^{26}Ne + X



S. Momota et al., Phys. Rev. C 92, 024608 (2015).

ΔP : shift from primary beam velocity

P_L distribution

ΔP = ~ - 300 MeV/c

Clear correlation between σ_T and fragment velocity

Observed σ_T agrees with literature values.

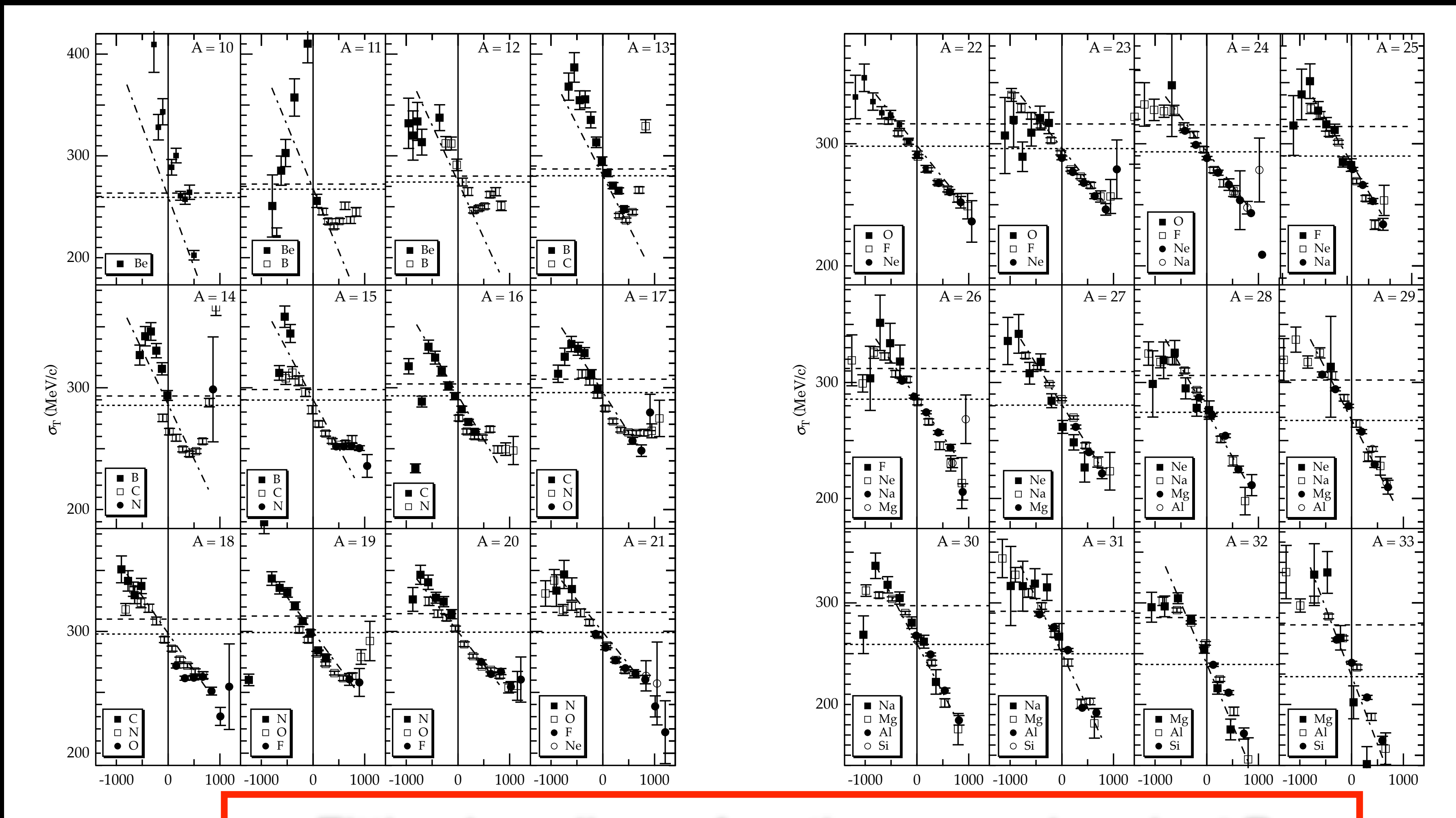
$\sigma_T = \sigma_{GH}$ @primary beam velocity

$= \sigma_{Bibber}$ @center of P_L dist.

Observed correlation between σ_T and ΔP

Correlation identified for wide range of fragments

$A_F = 10 \sim 21$ $A_F = 22 \sim 33$

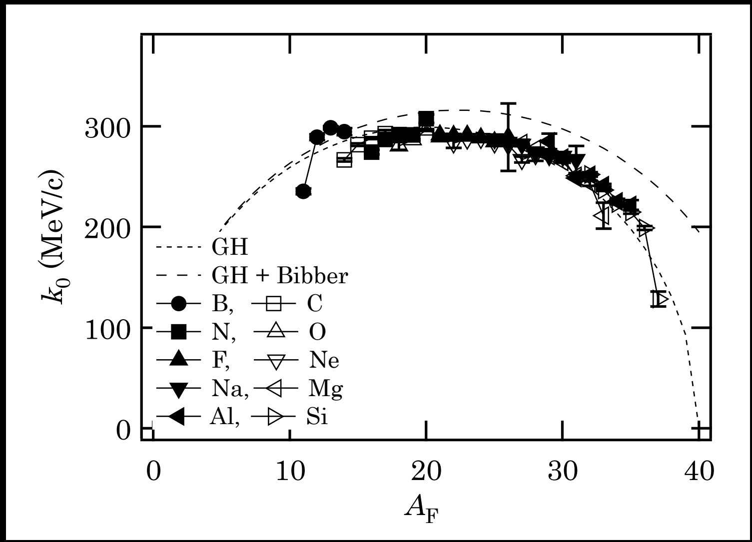


Fitting by a linear function : $\sigma_T = k_0 + k_1 \Delta P$

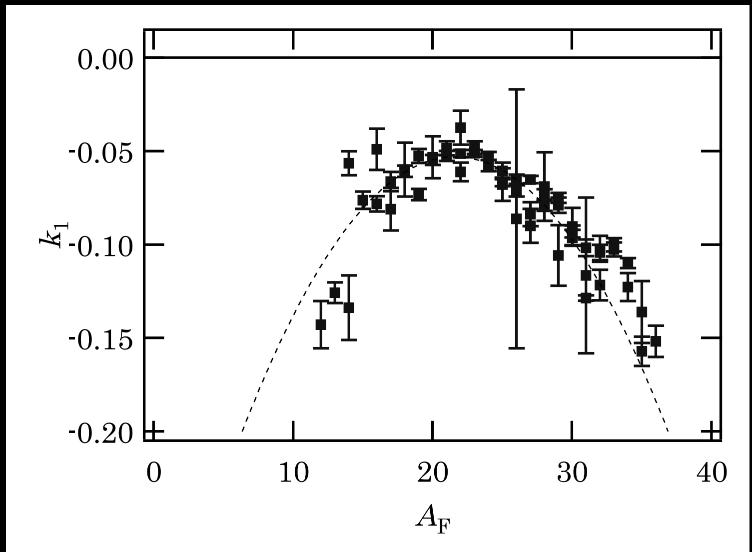
S. Momota et al., Phys. Rev. C 92, 024608 (2015).

Formulation of velocity dependence

k_0 : $\boldsymbol{\sigma}_T$ at projectile velocity



k_1 : Slope parameter



S. Momota et al., Phys. Rev. C 92, 024608 (2015).

Well reproduced by Goldhaber formulation $k_0 = \sigma_{GH}$,

$$\sigma_{GH} = \sigma_0 \sqrt{\frac{A_F(A_P - A_F)}{A_P - 1}}$$

σ_0 = 93.6 ± 1.3 MeV/c

σ_0 = 93.5 ± 2.6 MeV/c

obtained from P_L dist., ^{40}Ar(90 MeV/u) + Be
M. Notani et al., Phys. Rev. C 76 (2007) 044605.

Formulated with quadratic function

$$k_1 = -0.384 + 0.0273 A_F + 0.000631 A_F^2$$

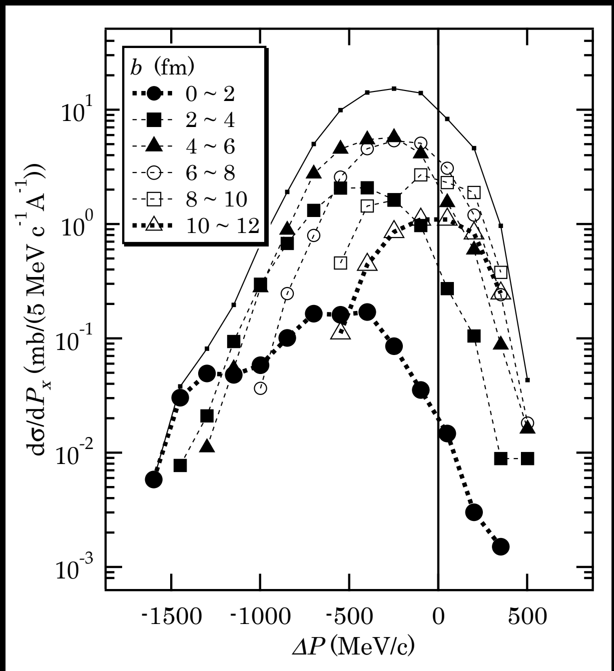
Contribution of impact parameter

Microscopic model calculation

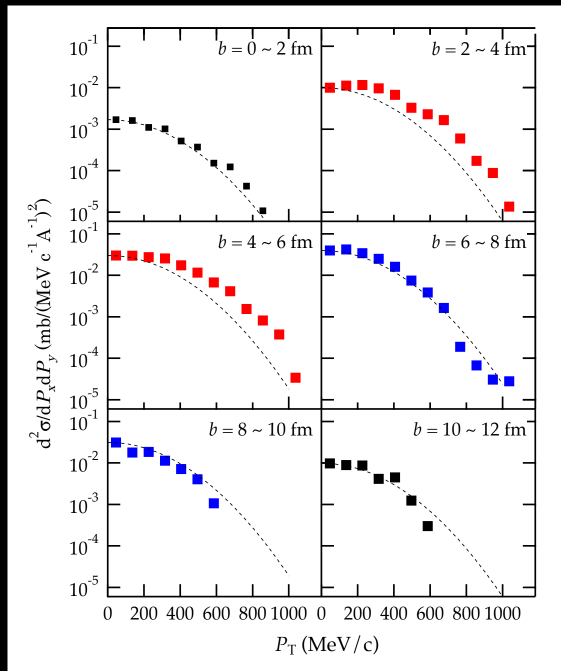
1) Production of pre-fragments
AMD calculation with
Gogny type interaction
A. Ono, Phys. Rev. C 59, 853 (1999).

2) Evaporation
Statistical decay
T. Maruyama et al.,
Prog. Theor. Phys. 87, 1367 (1992).

P_L distribution

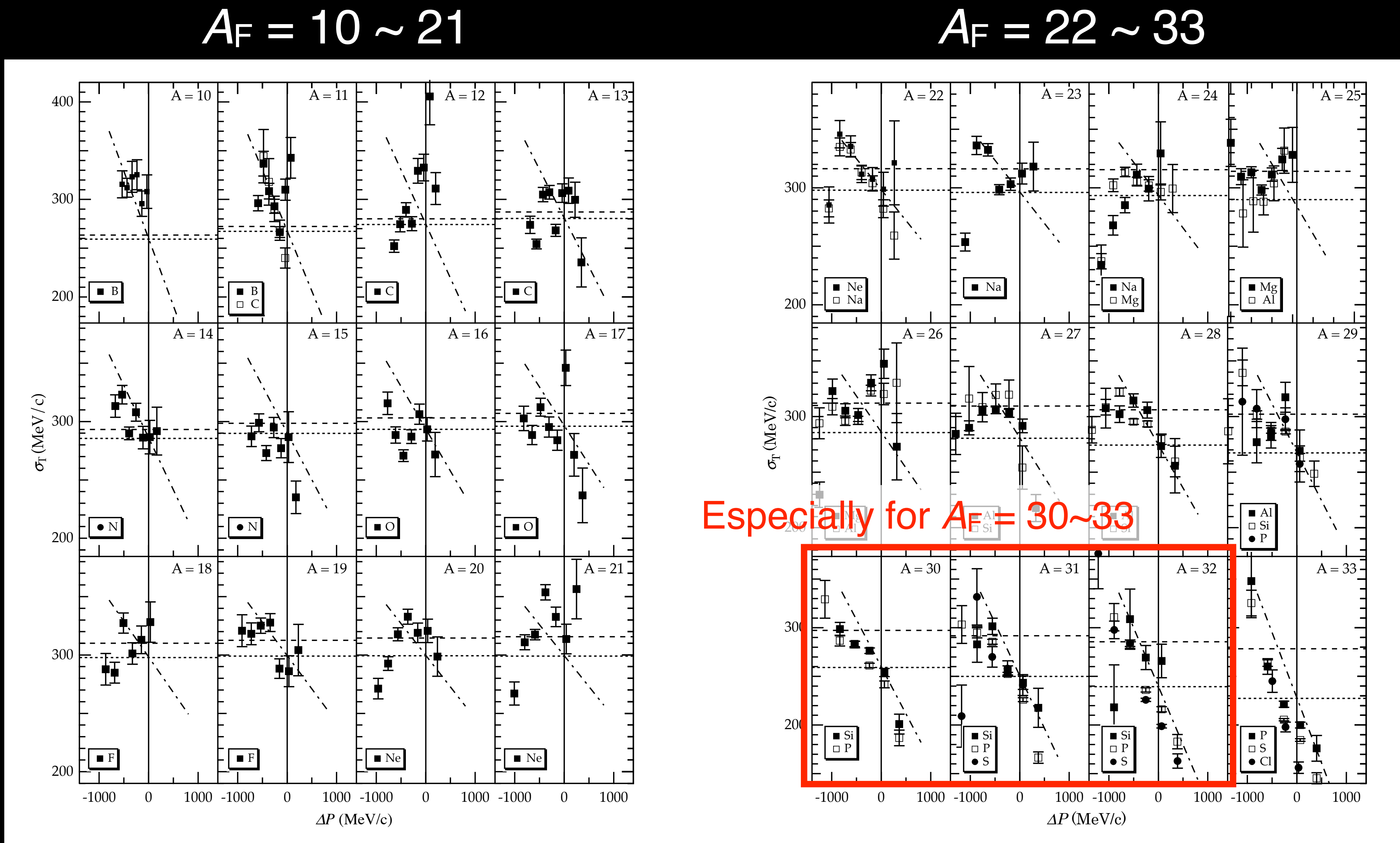


P_T distribution



S. Momota et al., Phys. Rev. C 92, 024608 (2015).

Calculated correlation between σ_T and ΔP

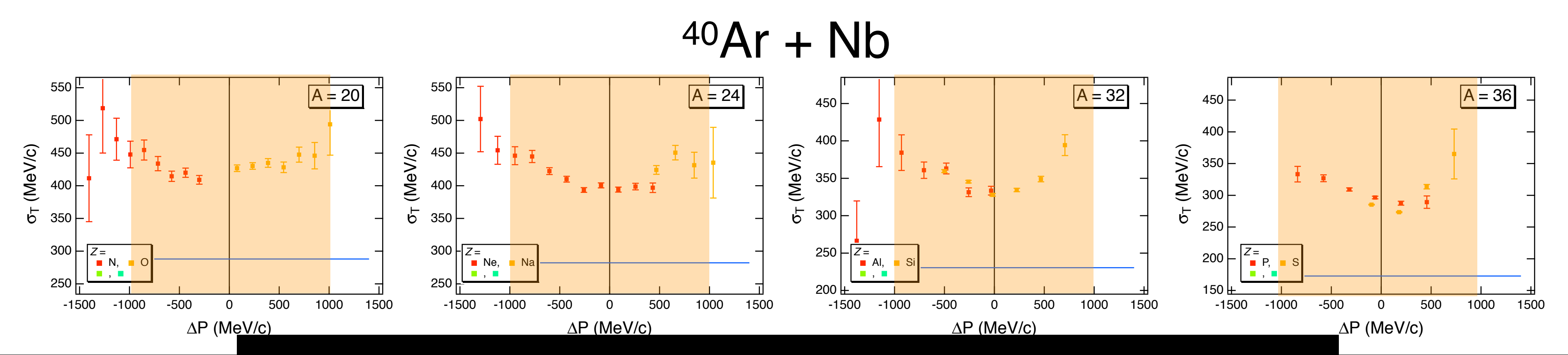


S. Momota et al., Phys. Rev. C 92, 024608 (2015).

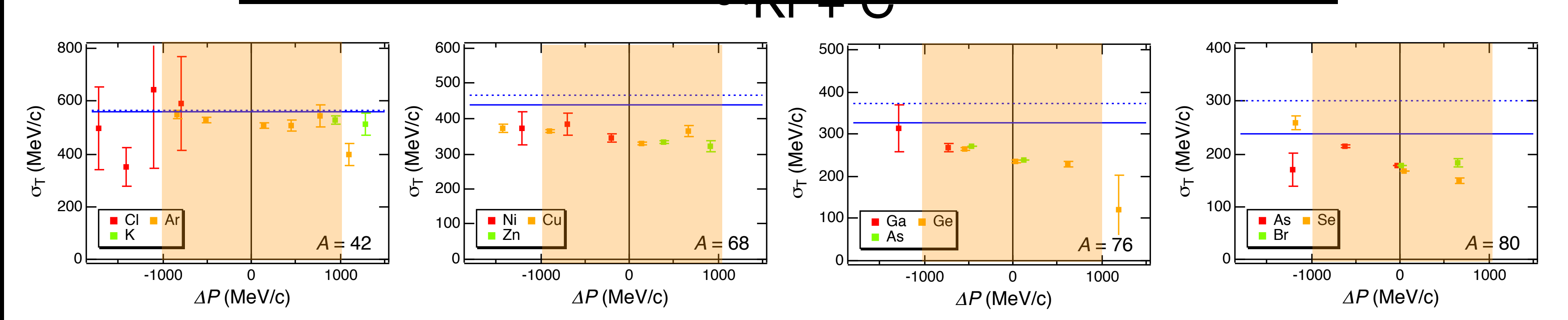
AMD calculation roughly reproduces behaviors of σ_T.

σ_T vs. velocity : Ar+Nb, Kr+C@290 MeV/u

$A_F = A_P/2$ | ΔA = -16 | ΔA = -8 | ΔA = -4

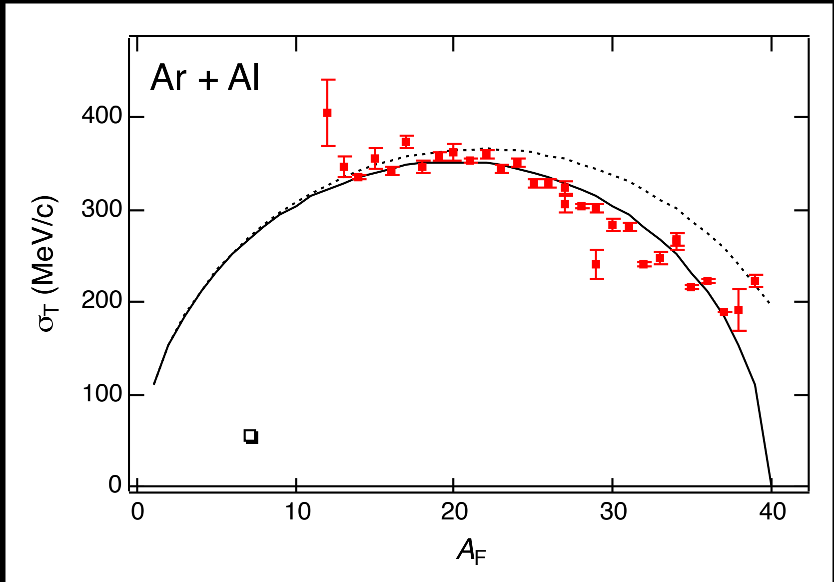


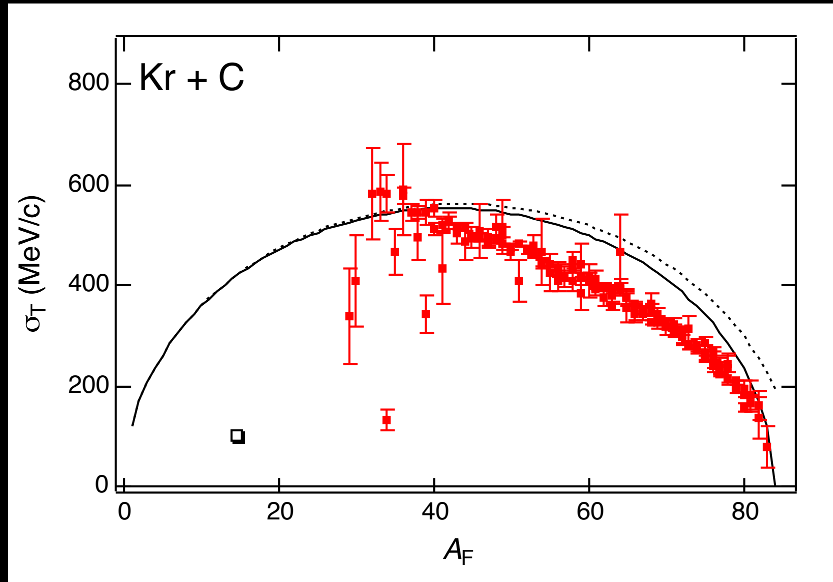
Average over ΔP = -1000 ~ +1000 MeVc



- Velocity dependence is not remarkable.
- Moderate correlation is identified in small $-\Delta A$ reactions.

σ_T vs. A_F : Ar, Kr+light target@290 MeV/u





σ_0 = 110 MeV/c

σ_L in Ar(290MeV/u)+Al

reported in ND2010

σ_0 = 120 MeV/c

σ_L in Kr(290MeV/u)+C

$$\sigma(P_T) = \sqrt{\sigma(P_L)^2 + \frac{A_F(A_F-1)}{A_P(A_P-1)}\sigma_{D0}{}^2}$$

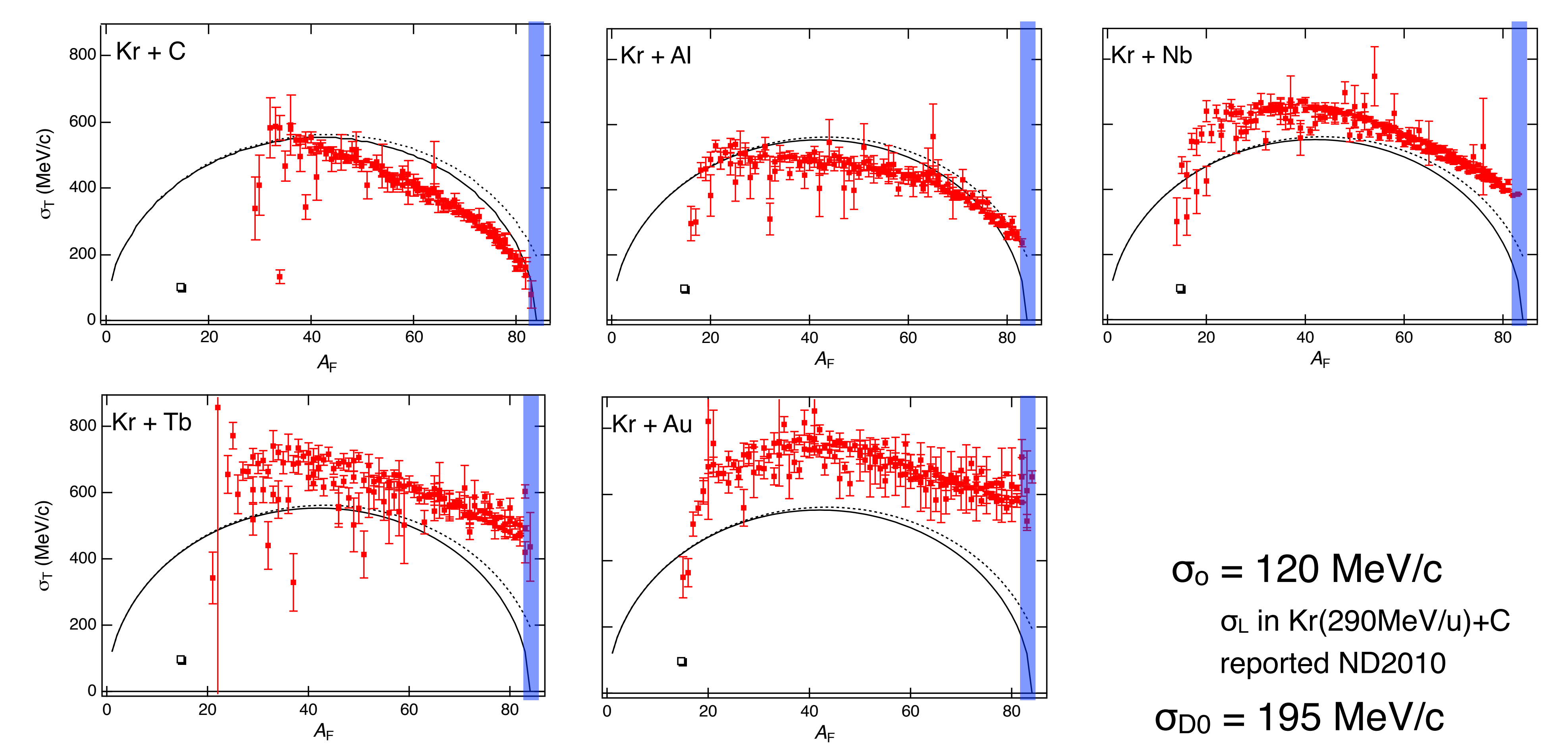
σ_{D0} = 195 MeV/c

K. Van Bibber et al., Phys. Rev. Lett. 43 (1979) 840.

$\sigma_T = \sigma_L$

$\sigma_T < \sigma_L$

σ_T vs. A_F : Kr+C, Al, Nb, Tb, Au@E=290 MeV/u



σ_0 = 120 MeV/c

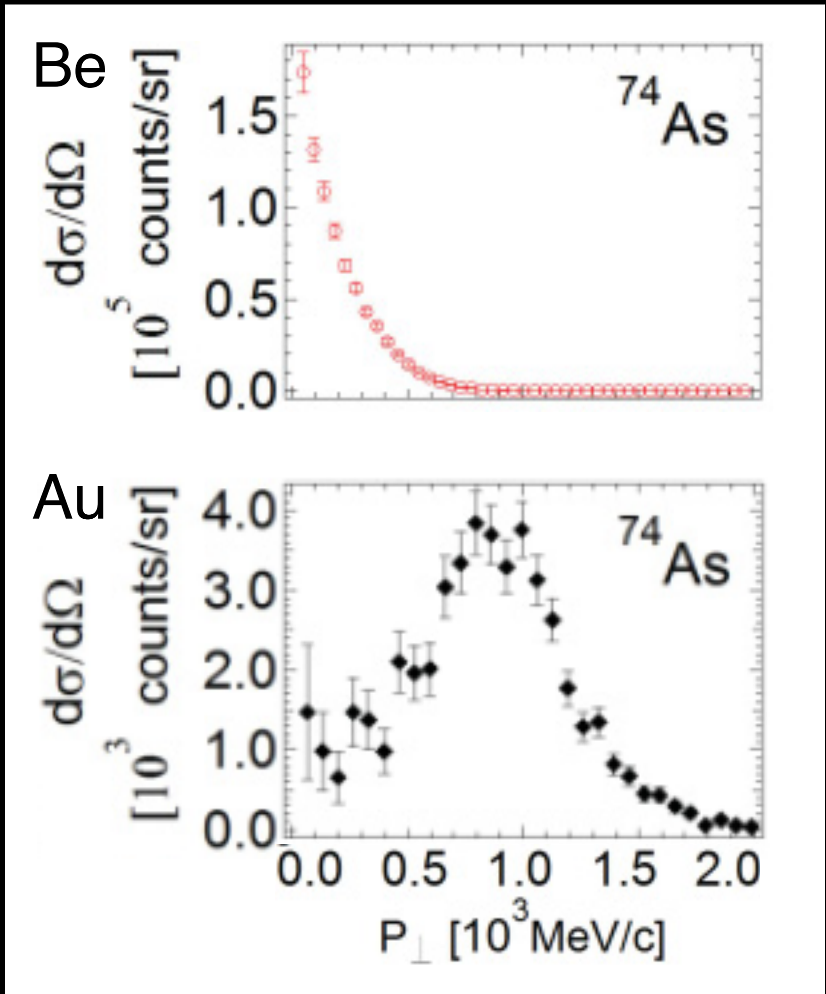
σ_L in Kr(290MeV/u)+C reported ND2010

σ_{D0} = 195 MeV/c

- Width of angular distribution increases with A_T.
- Extraction of deflective effect from observed angular distribution for intermediate mass fragments has not been achieved yet.

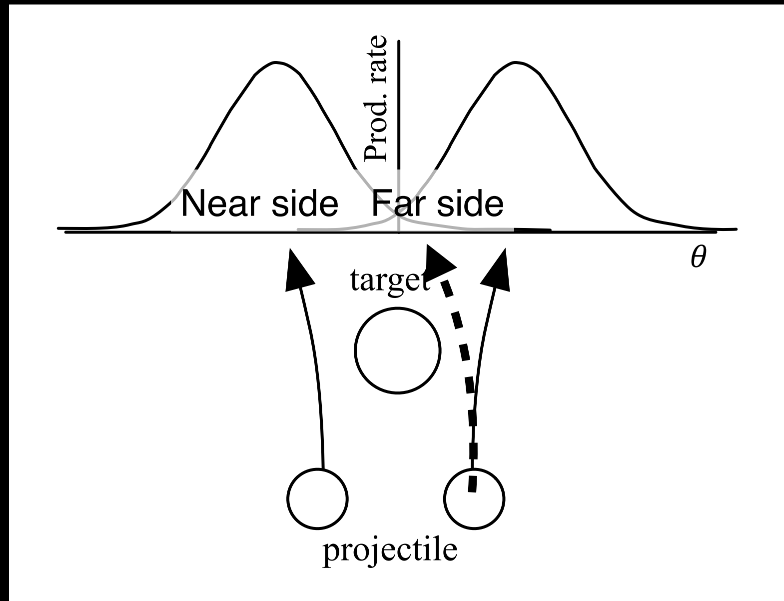
Orbital deflection @E=130 MeV/u

^{76}Ge+Be, Au@MSU



K. Meierbachtol et al., Phys. Rev. C 85 (2012) 034608.

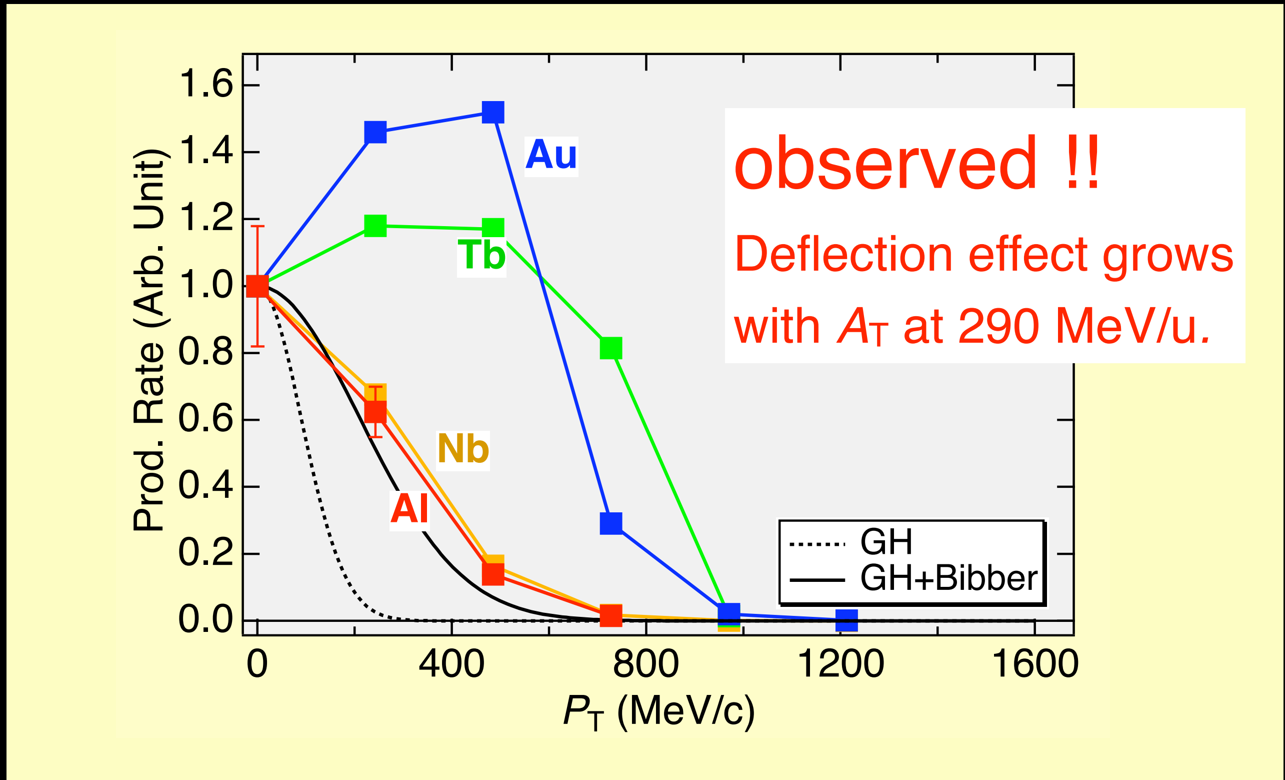
Orbital deflection induced by Coulomb+Nuclear pot.



1) Well-defined impact parameter ; b
2) Sum of contributions of near-side and far-side.

Orbital deflection @ E=290 MeV/u

1-p removal reaction : ^{40}Ar+Al, Nb, Tb, Au → ^{39}Cl



Near side Far side

$$Y(\theta) = k\left\{\exp\left(-\frac{(\theta-\theta_{def})^2}{2\sigma_\theta{}^2}\right)+\exp\left(-\frac{(\theta+\theta_{def})^2}{2\sigma_\theta{}^2}\right)\right\}$$

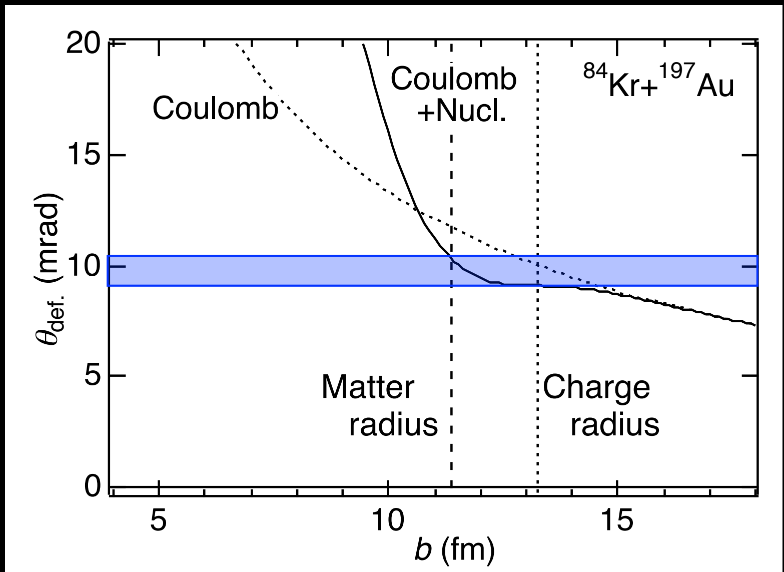
Deflection angle in peripheral reactions

Deflection angle for exchange or 1-nucleon removal reactions

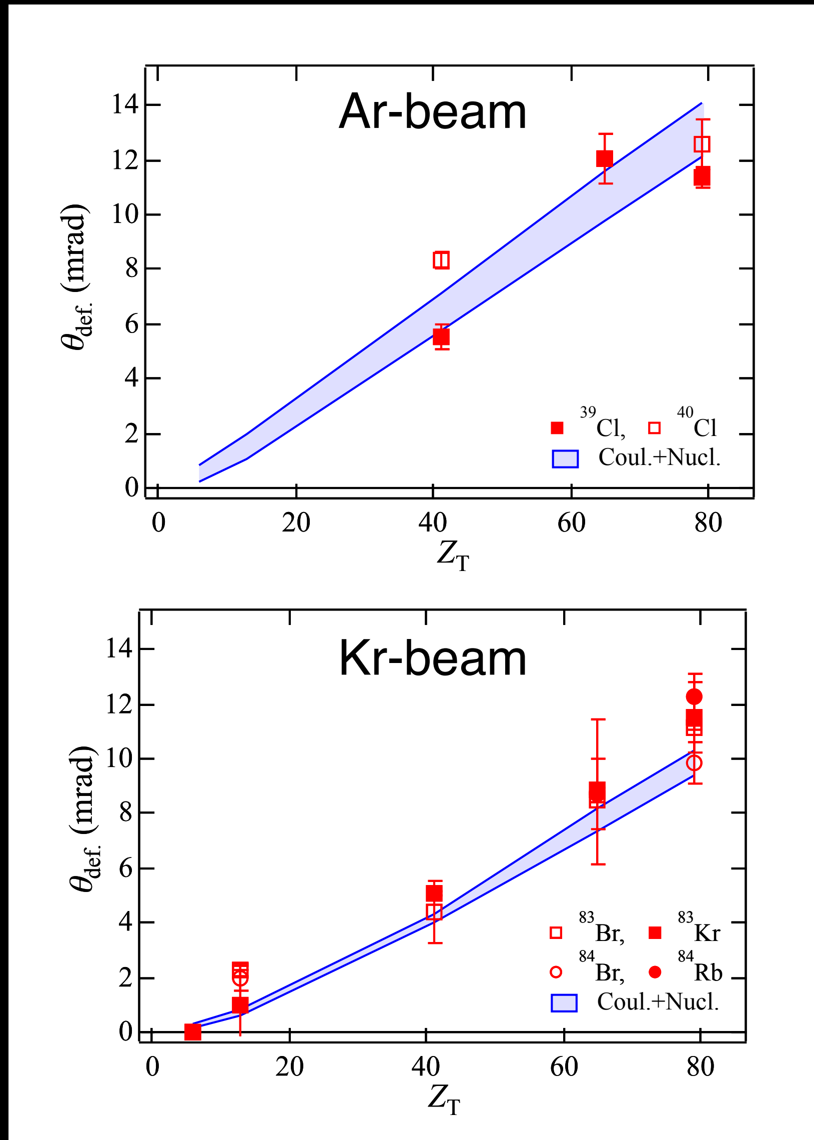
$\Delta A = 0$ or -1

increases with A_T.

Calculated $\theta_{def.}$ vs. b



S. Momota et al., Nucl. Phys. A (in press)



S. Momota et al., Nucl. Phys. A (in press)

Conclusions

Dispersive and deflective effect in fragmentation process at 95 and 290 MeV/u was studied.

1. Correlation between σ_T and velocity
   - Remarkable and systematic correlation at 95 MeV/u :
     $\sigma_T = k_0 + k_1\, \Delta P$
   - No significant correlation at 290 MeV/u

2. Deflective effect at E=290 MeV/u
   - grows with target mass.
   - agrees with simple calculation for peripheral reactions.

Analysis of deflective effect for intermediate mass fragments is now in progress.

Acknowledgements

- **r280n@RIPS collaboration**

  RCNP, Japan : I. Tanihata
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  RIKEN Ring Cyclotron staff and crew

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  NIRS : M. Kanazawa, A. Kitagawa, S. Sato
  HIMAC staff and crew

- **AMD calculation**

  Tohoku Univ., Japan : A. Ono