5th International Conference on Nuclear Fragmentation
Oct./04-11/2015, Kemer, Turkey

Velocity-dependent transverse momentum distribution of projectile-like fragments at 95 MeV/u

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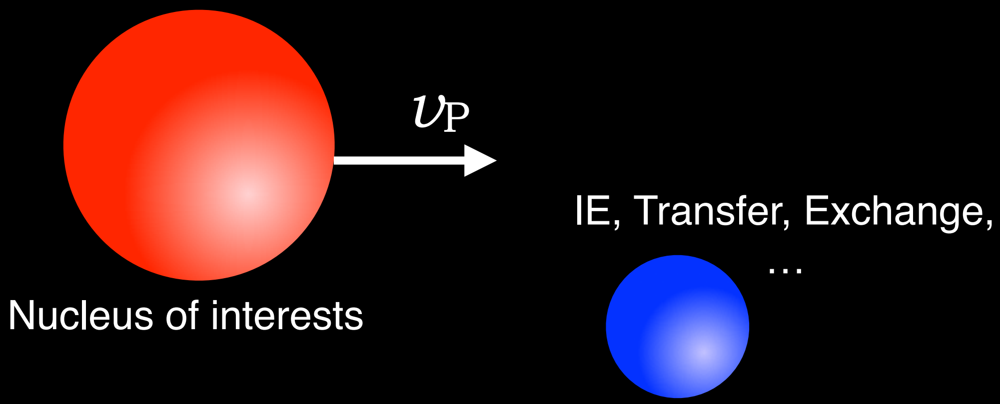
r280n collaboration

Introduction

Investigation of unstable nuclei

Inverse kinematics scheme

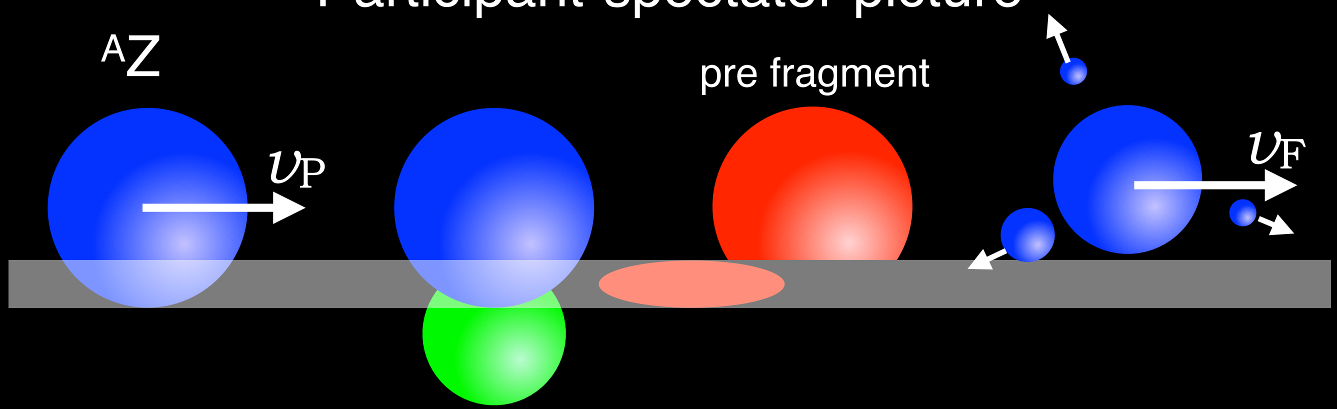


Preparation of radioactive nuclear beams (RNBs)

1) Wide range in nuclear chart
2) High quality as a beam

Fragmentation process

Participant-spectator picture



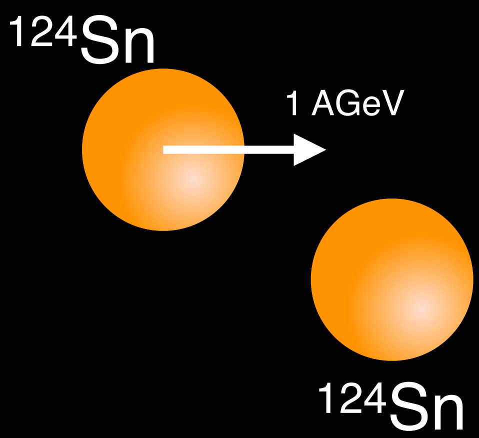
Satisfies two requirements

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

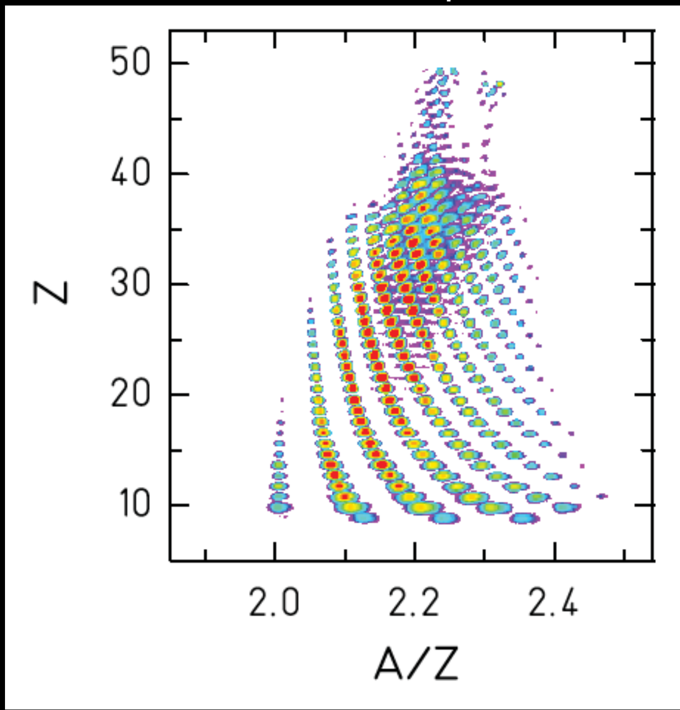
→Usually applied at RNB facilities

Production of a wide range of isotopes

Fragments prod. from $^{124}Sn+^{124}Sn$ at 1 AGeV
V. Föhr et al., Phys. Rev. C 84, 054605 (2011).



Produced isotopes

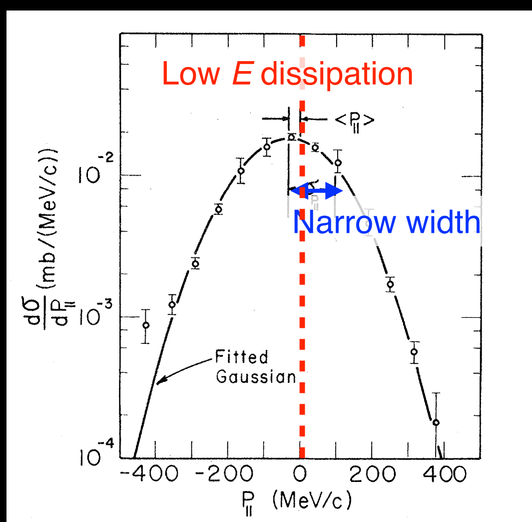


High quality as secondary beam

Momentum distribution of fragments
- ***E* dissipation : low**
- **Narrow width**
- **Simple & well studied at relativistic *E***

Therefore
- **Separation of objective isotope with high efficiency**

P_L distribution of ^{10}Be produced from ^{12}C (2.1 GeV/nucleon)+^{9}Be
D.E. Greiner et al., Phys. Rev. Lett. 35(1975) 152



P_0=2880 MeV/c/A

Formulation for practical use

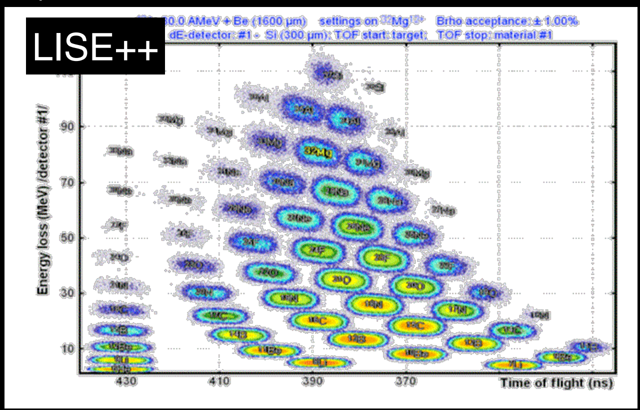
Transportation/separation of fragments through fragment separator

Performance of separator is simulated by means of

LISE++, MOCADI, …

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

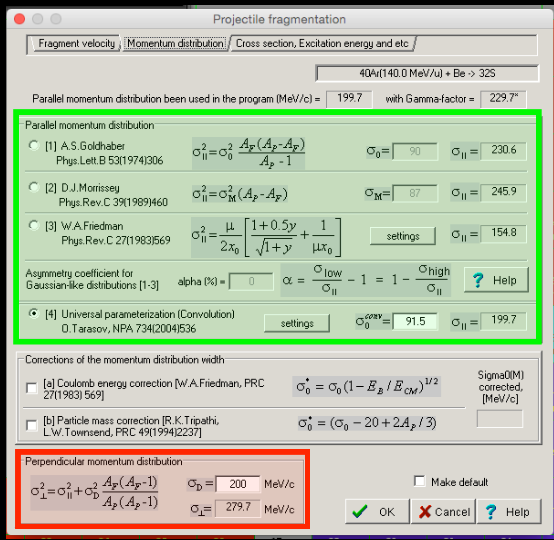
http://lise.nscl.msu.edu/introduction.html



Key parameters for simulation

$\boldsymbol{\sigma}_{\mathrm{prod.}}$

P_L, P_T distribution



Few systematic studies on P_T

Object of this talk

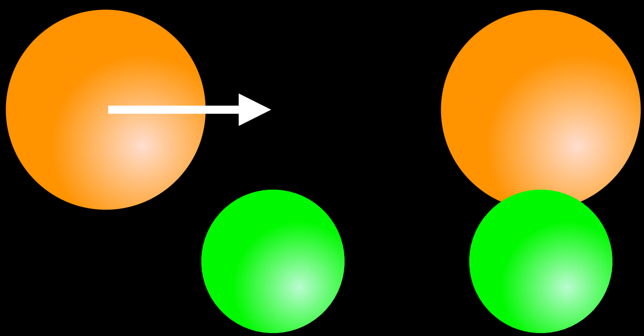
Remarkable and systematic correlation between P_T distribution and P_L of fragmentation products at E~100 MeV/u

1. Earlier works on P_L, P_T distributions
2. Experimental (RIPS-RIKEN)
3. Correlation obtained from experimental results
4. Comparison with microscopic dynamic model
5. Conclusions

Previous studies on momentum distributions

Isotropic distribution at relativistic *E*

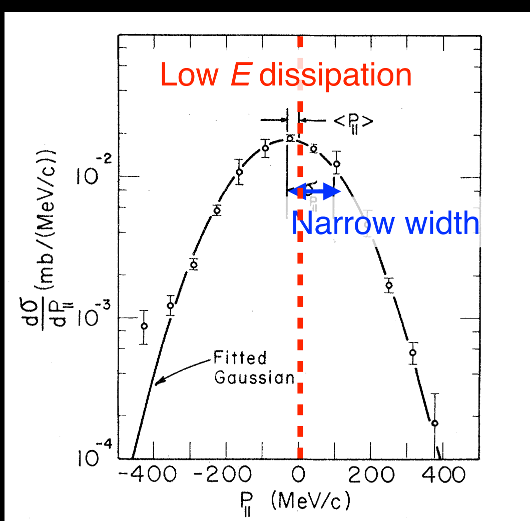
$E \gtrsim 1$ GeV/u



P_L distribution of ^{10}Be

^{12}Ca(2.1 GeV/nucleon)+^{9}Be

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



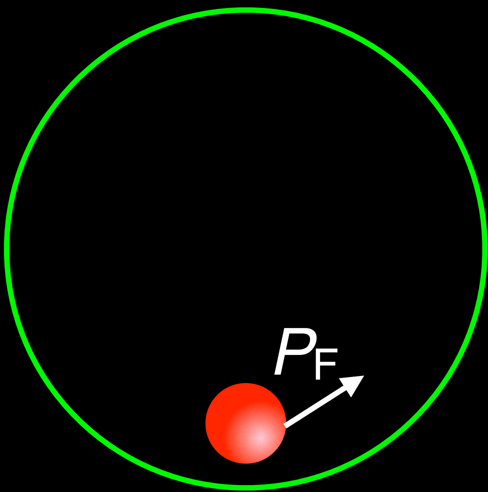
- Gaussian-type distribution with small energy dissipation
- Isotropic distribution
  $\sigma_L = \sigma_T$ to an accuracy of 10%

→ Contribution of Fermi momentum

Model based on Fermi momentum

Assumption :
Independent removal of nucleons in projectile

→ Momentum distribution of fragments corresponds to statistical sum of Fermi momentum for each removed nucleon.



P_F : Fermi momentum of nucleon in projectile

Formulation proposed by Goldhaber

$$\sigma_{GH}{}^2 = \frac{A_F(A_P - A_F)}{A_P - 1}\sigma_0{}^2$$

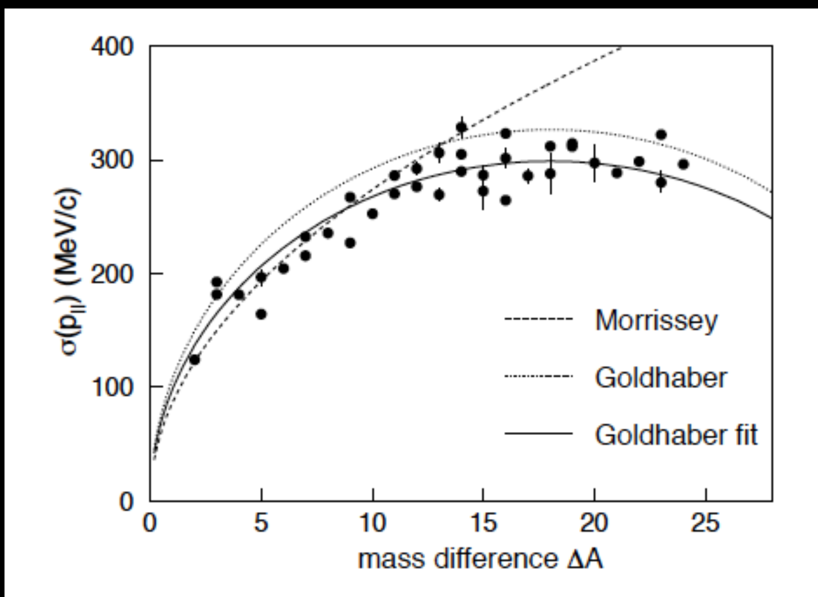
$$\sigma_0 = \frac{P_F}{\sqrt{5}} \sim 100 \text{ MeV/c}$$

A.s. Goldhaber, Phys. Lett. B 53, 306 (1974).

Simple and successfully applied to a wide range of reaction system

Success of Goldhaber model

Width of P_L distribution of fragments
^{36}Ar(1.05 GeV/nucleon)+^{9}Be
M. Caamano et al., Nucl. Phys. A 733(2004) 187.



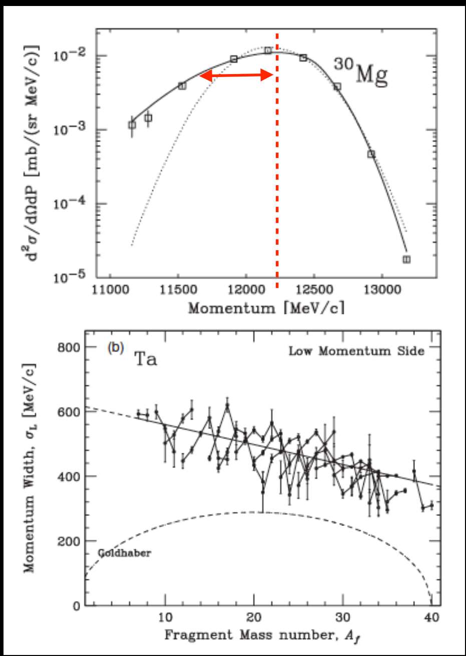
$$\sigma_0 = 98.2 \text{ MeV/c} \qquad \frac{P_F}{\sqrt{5}} \sim 100 \text{ MeV/c}$$

Deviation from isotropic dist. at $E \sim 100$ MeV/u

P_L distribution : Low momentum tail

P_L distribution at 90 MeV/u

$^{40}Ar + {}^{9}Be \rightarrow {}^{30}Mg + X$



M. Notani et al., Phys. Rev. C 76 (2007) 044605.

Universal parametrization obtained from experimental results

O. Tarasov, Nucl. Phys. A 734 (2004) 536.

$$f(P_L) = \exp\left(\frac{P_L}{\tau}\right) \cdot \left[1 - erf\left(\frac{P_L - P_0 + \sigma_{pf}{}^2/\tau - s \cdot \tau}{\sqrt{2}\sigma_{pf}}\right)\right]$$

$$\tau = coef \cdot \frac{\sqrt{A_F \cdot E_S}}{\beta}$$

$$\sigma_{pf} = \beta \sigma_{pf}{}^2 \frac{A_F (A_P - A_F)}{A_P - 1}$$

Formulated momentum distributions have been incorporated into simulation.

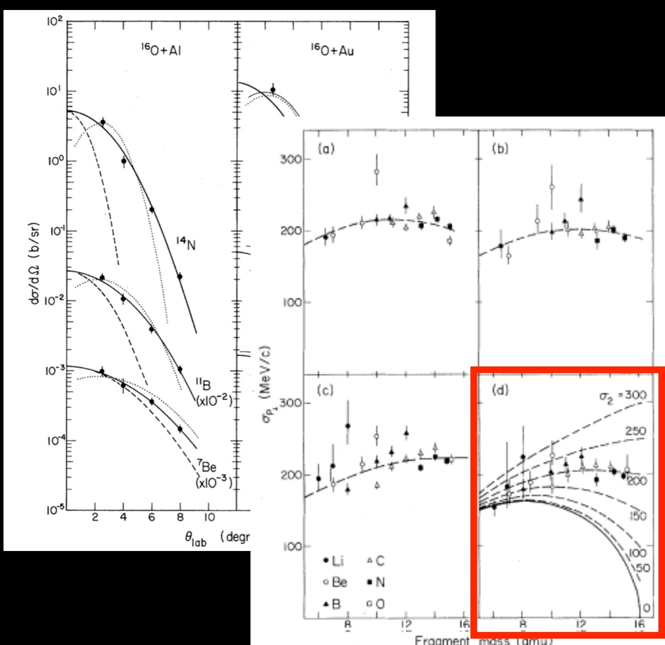
Deviation from isotropic dist. at $E \sim 100$ MeV/u

P_T distribution : Additional width

P_T distribution observed at 90 MeV/u

$^{16}O + {}^{27}Al \rightarrow {}^{A}Z + X$

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



Additional width due to orbital deflection by target nucleus

$$\sigma_T{}^2 = \sigma_{GH}{}^2 + \sigma_D{}^2$$

Empirical formulation for σ_D

$$\sigma_D{}^2 = \frac{A_F(A_F - 1)}{A_P(A_P - 1)} \sigma_2{}^2$$

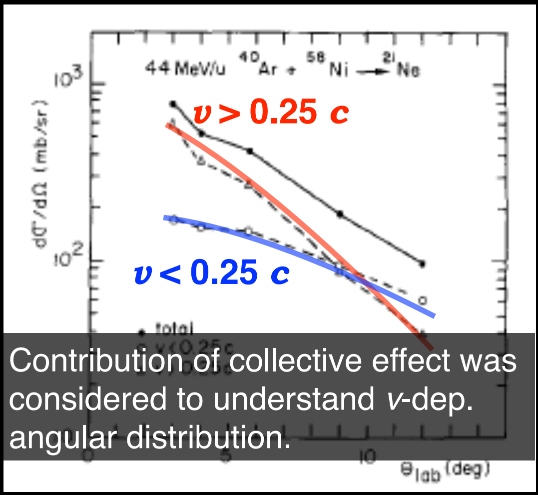
Usually applied with $\boldsymbol{\sigma_2} \sim 200$ MeV/c.

However, the reliability of the formulation is doubtful

- scarce systematic measurements at $E \sim 100$ MeV/u
- no measurements as a func. of v. suggested from asymmetric P_l dist.

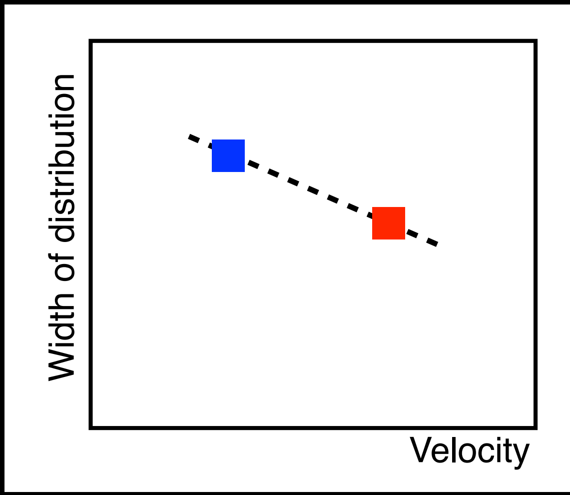
Velocity dependent P_T distribution

Angular dist. observed at 44 MeV/u
$^{40}Ar + ^{58}Ni \rightarrow ^{21}Ne + X$



V. Borrel et al., Z. Phys. A 314 (1982) 191.

Expected trend for width of P_T distribution

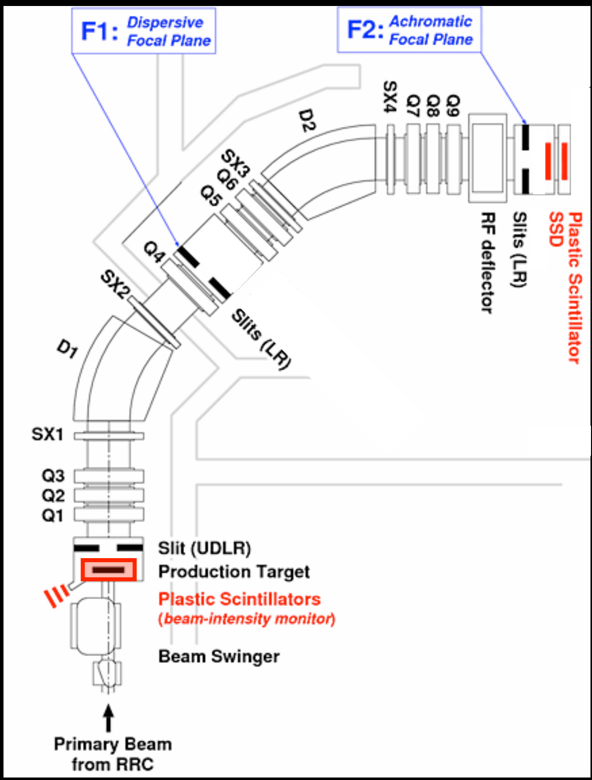


It is suggestive, but further investigations are needed to
1) formulate *v*-dependent behavior
2) understand based on reaction process.

Experimental

Experimental : fragment separator

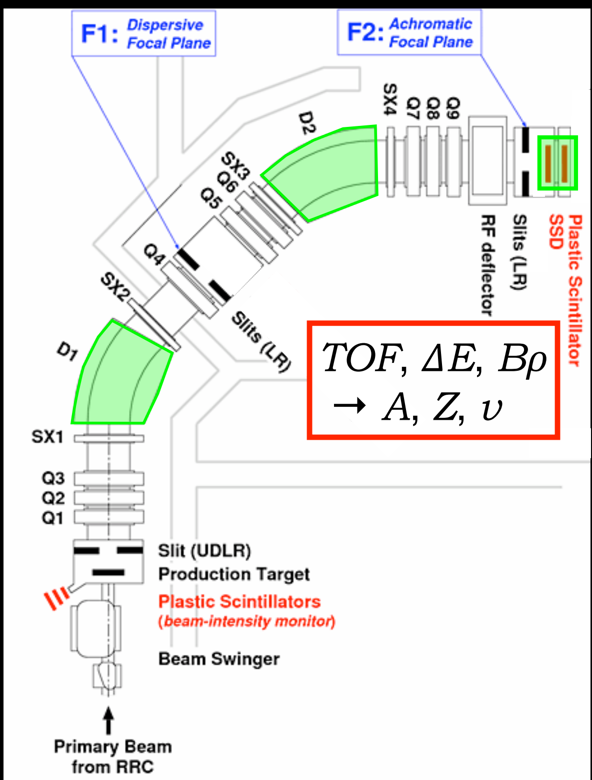
RIKEN Ring cyclotron + RIPS



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

Experimental : fragment separator

RIKEN Ring cyclotron + RIPS

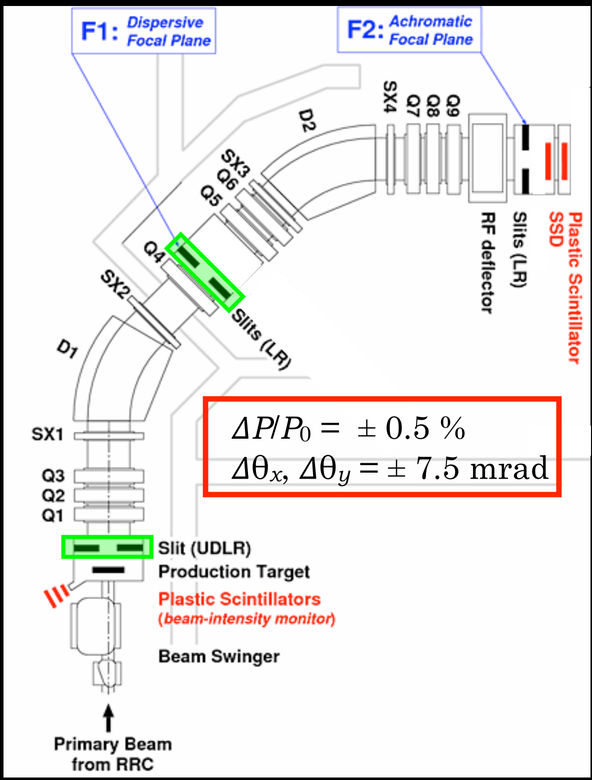


Reaction : ^{40}Ar (95 MeV/u) + ^{9}Be

Identification : TOF, ΔE, $B\rho$

Experimental : fragment separator

RIKEN Ring cyclotron + RIPS



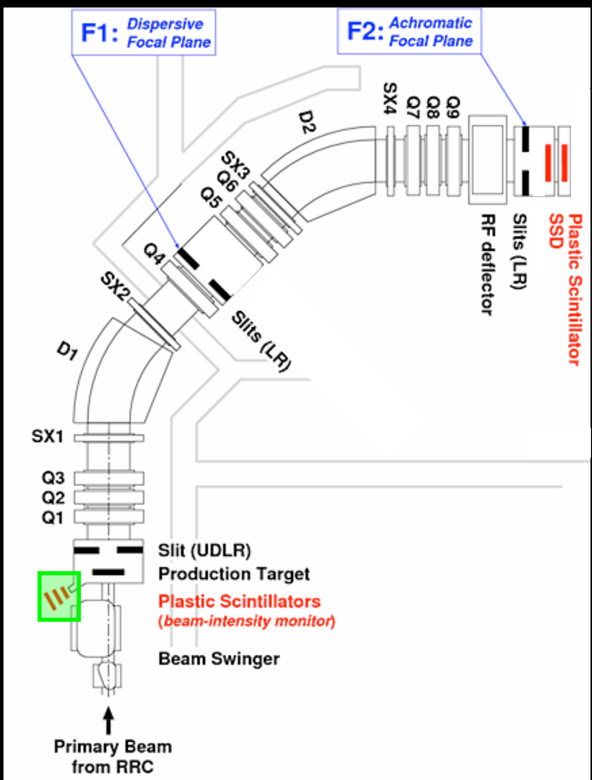
Reaction : ^{40}Ar (95 MeV/u) + ^{9}Be

Identification : TOF, ΔE, $B\rho$

Acceptance : Slit after target, F1

Experimental : fragment separator

RIKEN Ring cyclotron + RIPS



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

Identification : TOF, ΔE, $B\rho$

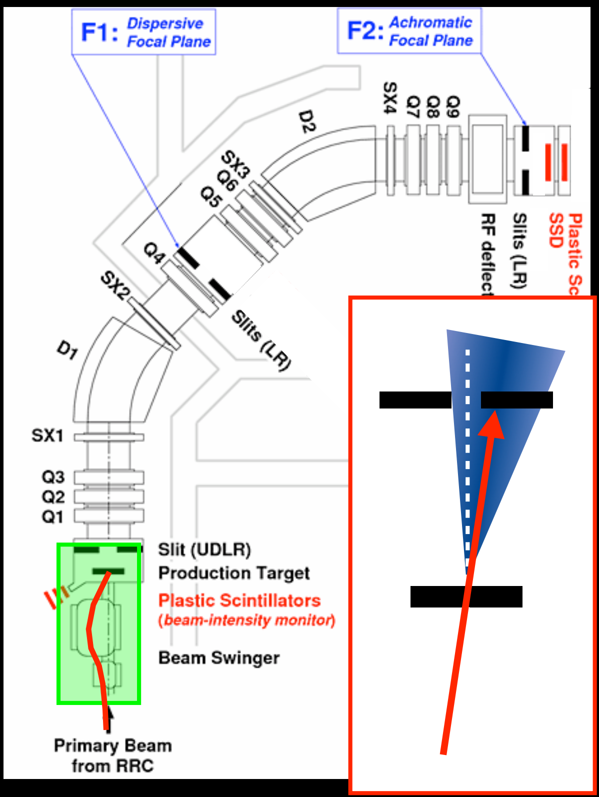
Acceptance : Slit after target, F1

Beam intensity monitor : PL@target

Ambiguity of beam intensity : ~ ± 5 %

Experimental : fragment separator

RIKEN Ring cyclotron + RIPS



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

Identification : TOF, ΔE, $B\rho$

Acceptance : Slit after target, F1

Beam intensity monitor : PL@target

Ambiguity of beam intensity : ~ ± 5 %

Angular distribution :

Beam swinger + slit after target

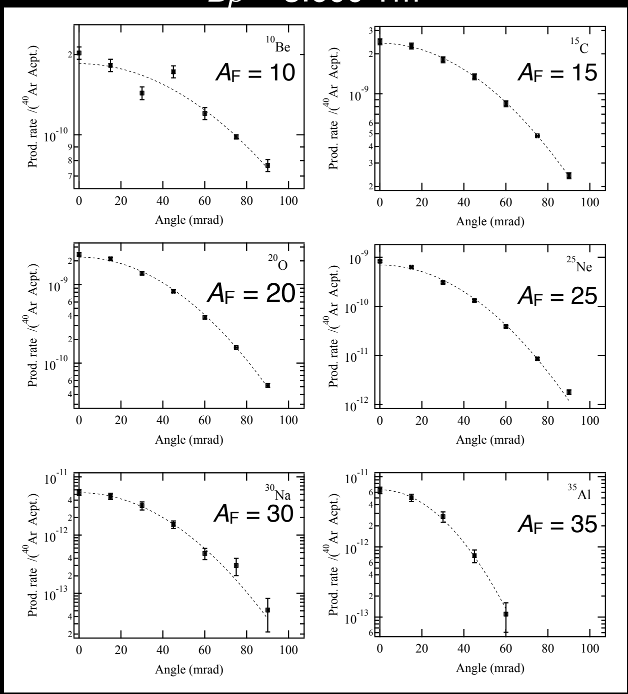
Keep optical axis of RIPS at any angle setting → Constant values for transmission and detection efficiencies of fragmentation products.

Results & Analysis

Width of P_T distribution

Obtained from angular distribution

$B\rho$ = 3.600 Tm



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

Fitting with a Gaussian function

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

with considering

1) Finite angular acceptance
± 7.5 mrad

2) Angular struggling in target
evaluated by ATIMA

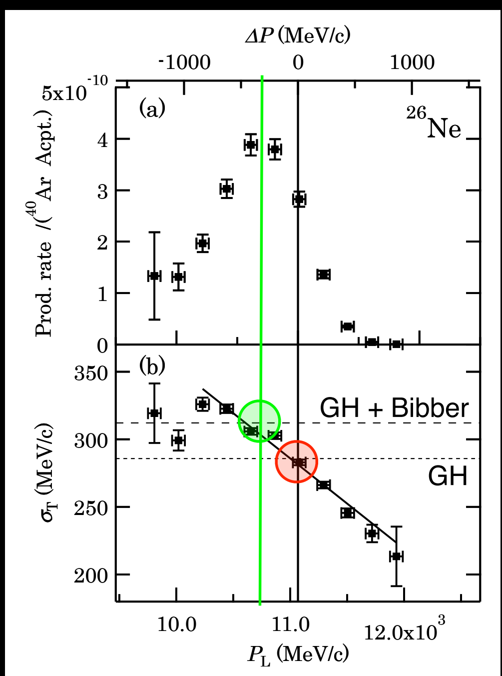
3) Emittance of primary beam
assumed to be neglected

Width of P_T distribution

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

Correlation between σ_T and velocity

^{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
Deceleration : ~ 300 MeV/c
Larger width for low P_L

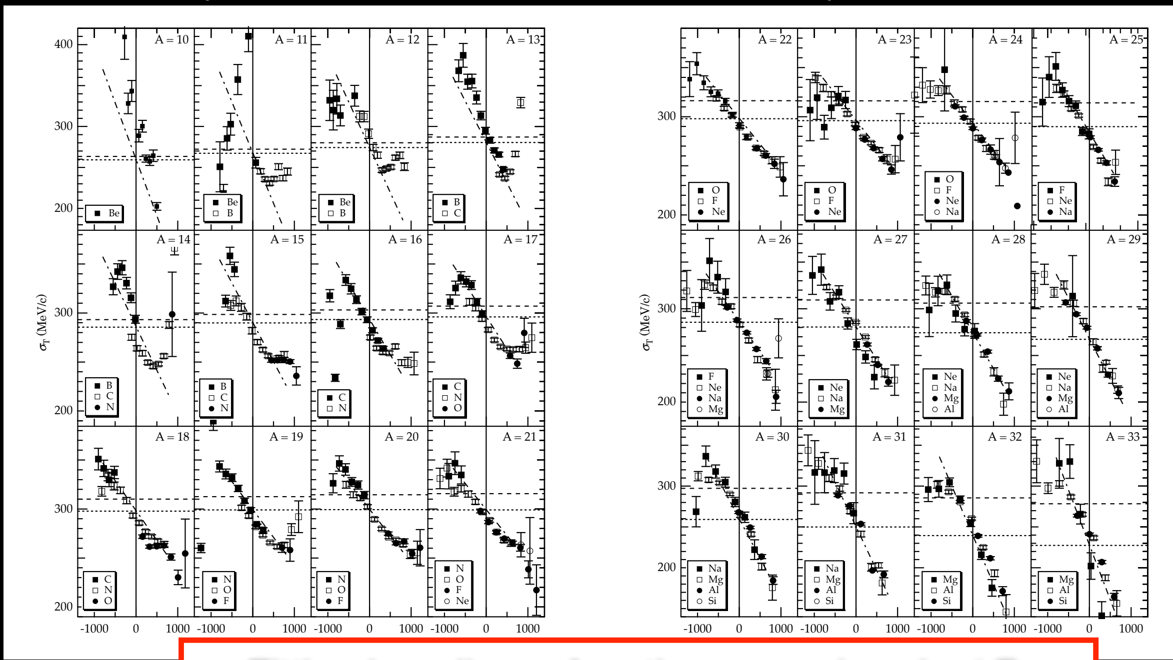
Remarkable decreasing trend

Agreement with reference values
GH@primary beam velocity
GH+Bibber@center of P_L dist.

Correlation between σ_T and ΔP_L

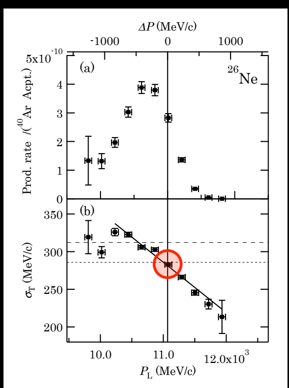
Universal behaviors of σ_T

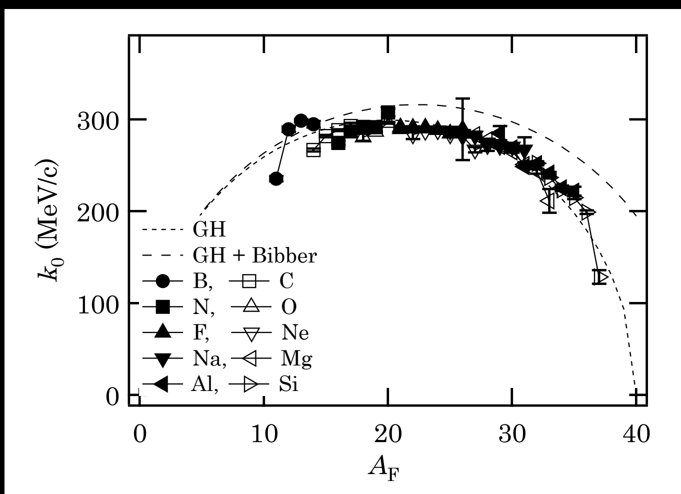
A_F = 10 ~ 21 A_F = 22 ~ 33



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

σ_T at projectile velocity : k_0

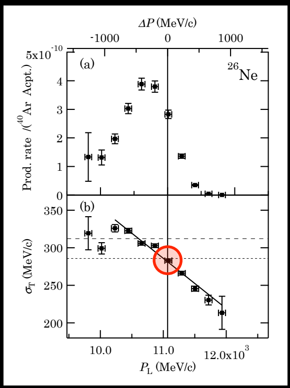




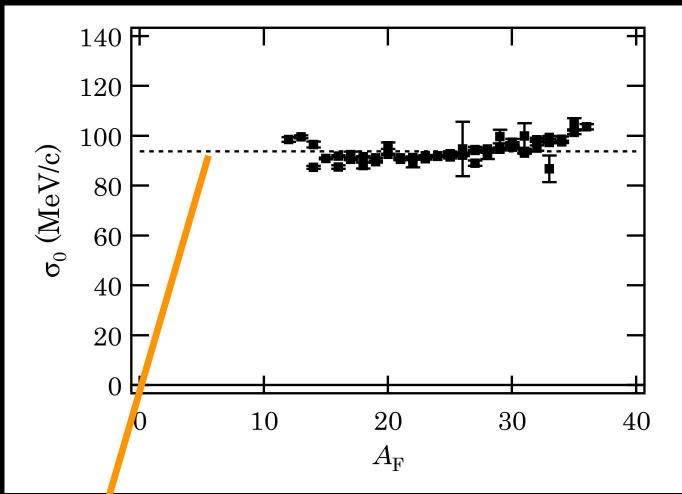
✓ Good agreement with Goldhaber formulation

No additional dispersions are not needed.

Reduced width : σ_0



$$\sigma_{GH}{}^2 = \frac{A_F(A_P - A_F)}{A_P - 1}\sigma_0{}^2$$

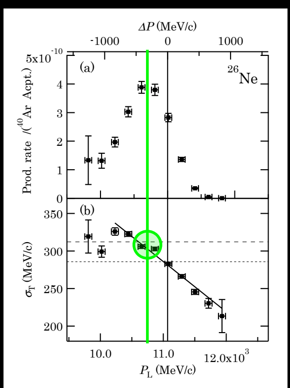


Av. = 93.6 ± 1.3 MeV/c

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.

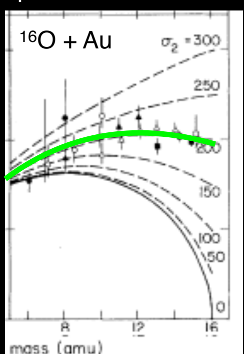
✓ Good agreement with σ_0 obtained from P_L dist.

σ_T at center of P_L distribution

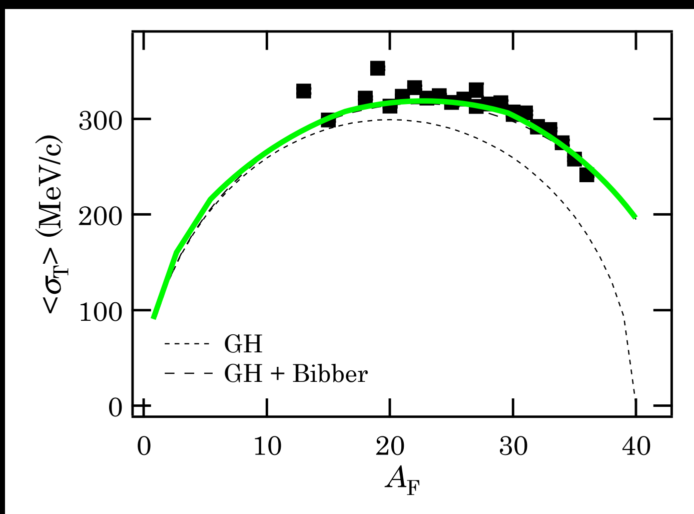


In order to compare with the previous results, most probable σ_T, $\langle\sigma_T\rangle$, is introduced.
$\langle\sigma_T\rangle$: σ_T at center of P_L distribution

σ_T at E=92.5 MeV/u

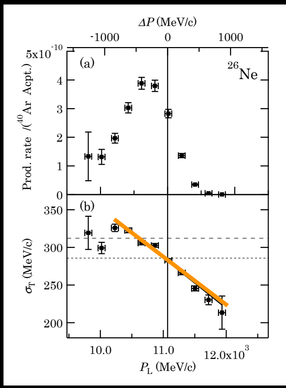


K van Bibber et al.,
Phys. Rev. Lett. 43 (1979) 840.



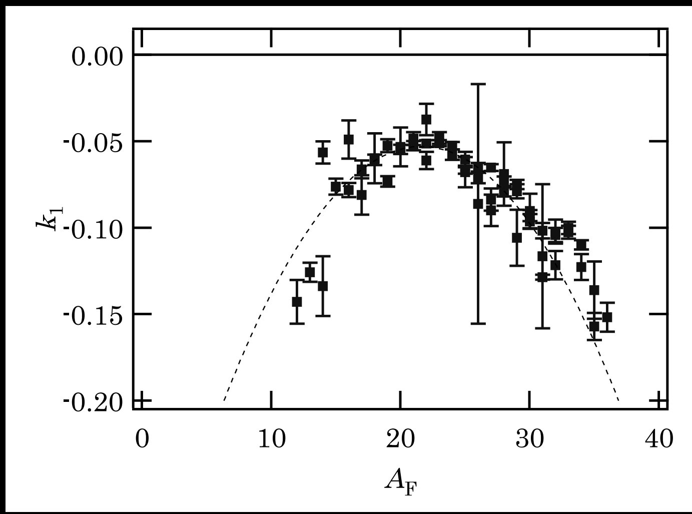
✓ Consistent with previous results on σ_T

Slope parameter : k_1



Parameter to characterize decreasing trend

Parabolic behavior of k_1



Fitting by a quadratic function :

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

Empirical formulation of σ_T

Width of P_T distribution : σ_T

Monotonically decreasing with velocity

$\sigma_T = k_0 + k_1 \Delta P_L$

σ_T at projectile velocity : k_0

$\sigma_T(\Delta P_L=0) = \sigma_L = \sigma_{GH}$

Slope parameter : k_1

Depends on A_F

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

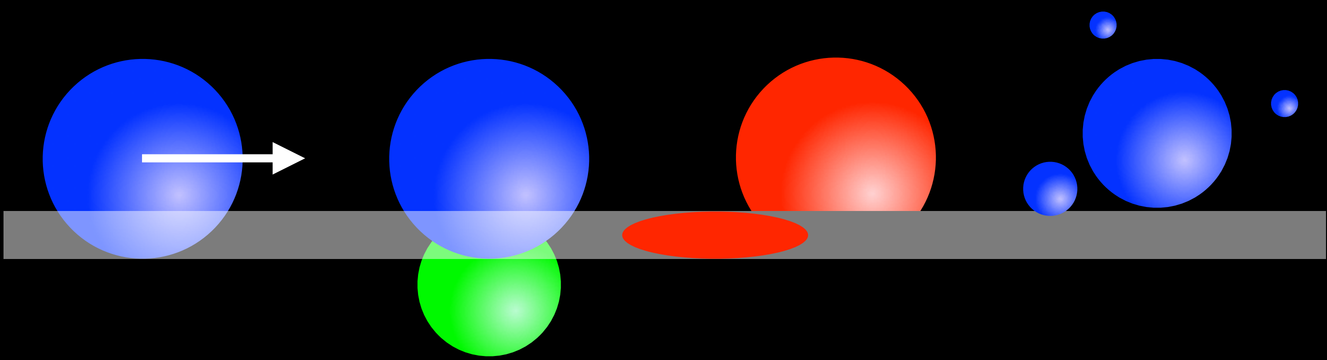
Microscopic reaction model

can reproduce behaviors of σ_T?

can reveal origin of the behaviors?

Microscopic reaction model

Collective features
-> Additional dispersion and deceleration effect



Abrasion, Excitation

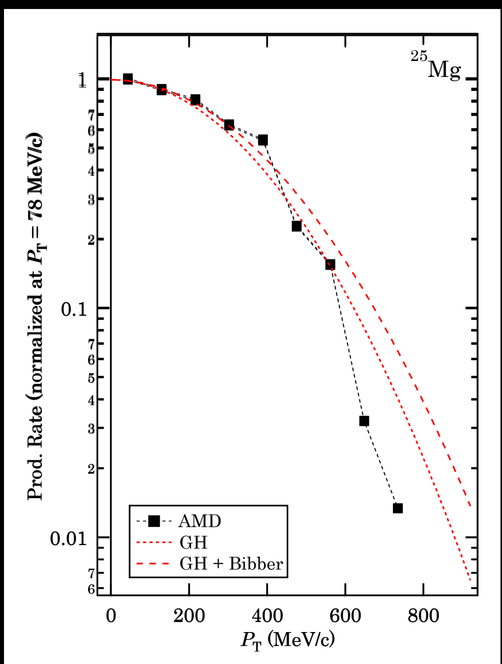
AMD
^{40}Ar(87.4 MeV/A)+^{9}Be
b = 0 ~ 12 fm
Gogny type int.
A. Ono, Phys. Rev. C 59, 853 (1999).

Evaporation

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

P_T distribution obtained by simulation

^{40}Ar + Be → ^{25}Mg + X



P_T distribution obtained from AMD + SD calculation

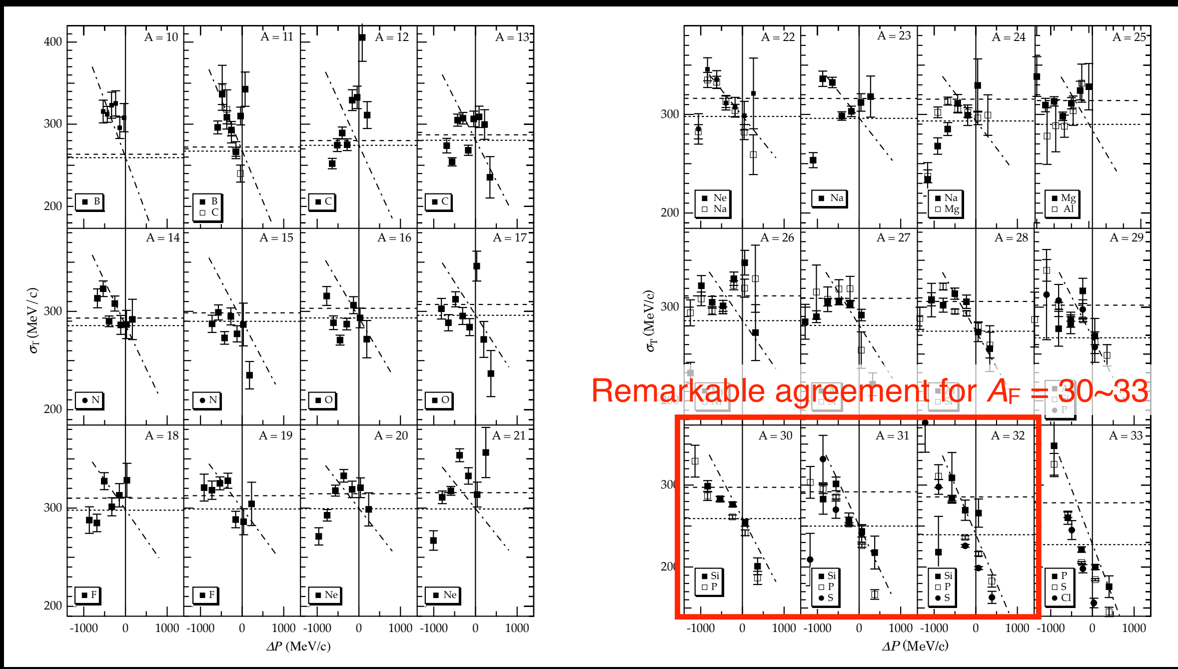
Gaussian-like distribution

Width is consistent with conventional values

Fitting with a Gaussian function as for experimental results
→ σ_T(AMD)

Correlation between σ_T and ΔP_L

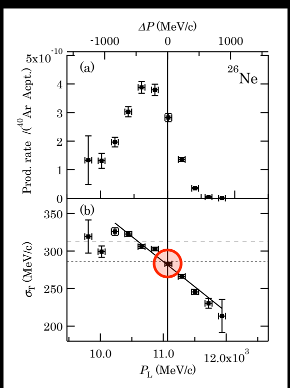
A_F = 10 ~ 21 A_F = 22 ~ 33

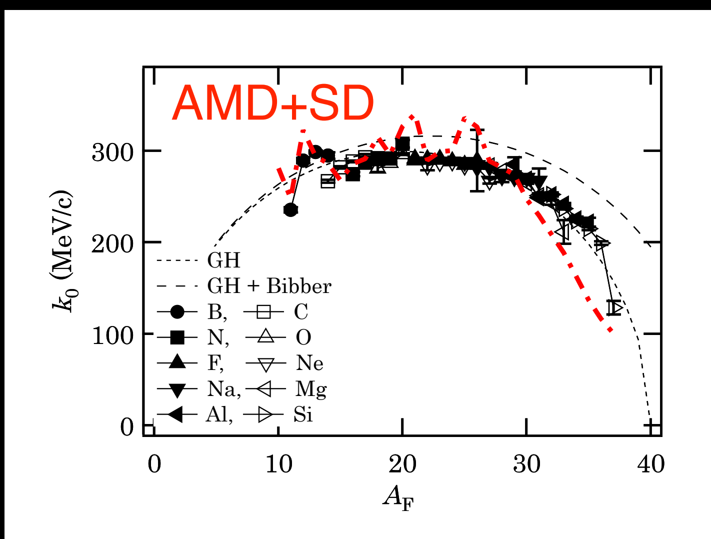


AMD calculation roughly reproduces behaviors of σ_T.

Fitting with a linear function → k_0, k_1

σ_T at projectile velocity : k_0

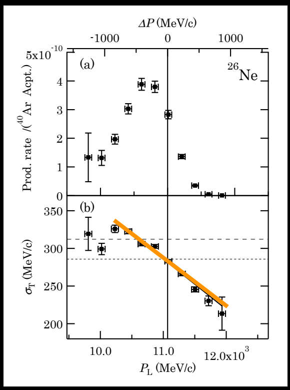




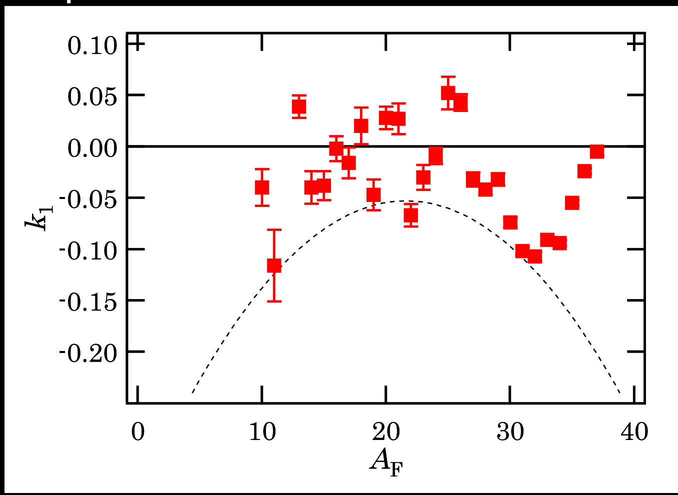
Not so bad,

but systematically underestimate k_0 at A_F > 30.

Slope parameter : k_1



Parabolic trend of k_1 obtained from experimental results

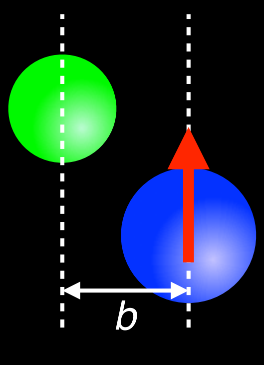


AMD calculation roughly reproduces negative values for k_1.
Large scattering prevents further investigations on k_1.

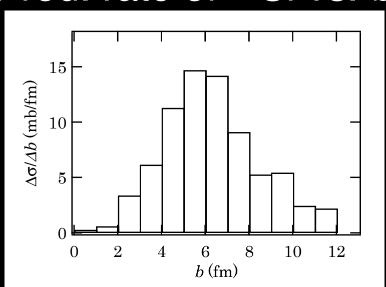
b-dependent P_L distribution

Impact parameter ↔ Collective/dissipative nature

Therefore, P_L distribution is expected to depends on impact parameter.

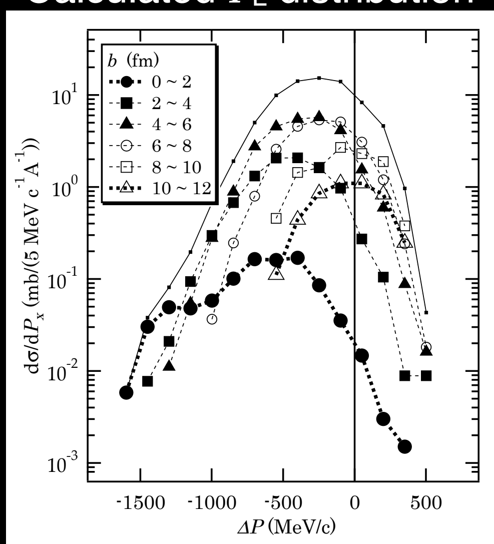


Prod. rate of ^{30}Si vs. b



r (^{40}Ar) + r (^{9}Be) = 6.6 fm
$r = r_0 A^{1/3}$, r_0 = 1.2 fm

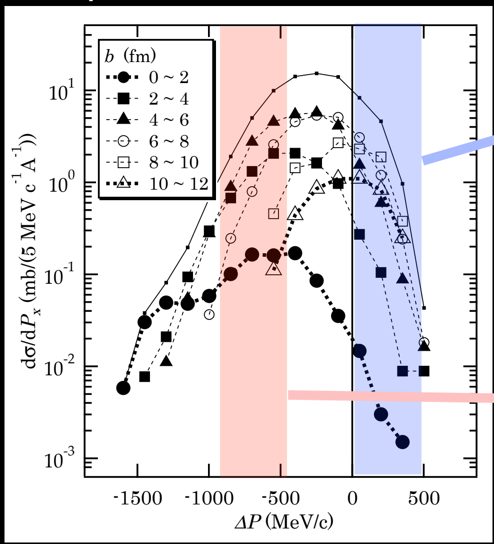
Calculated P_L distribution

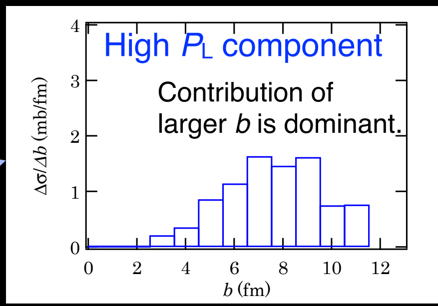


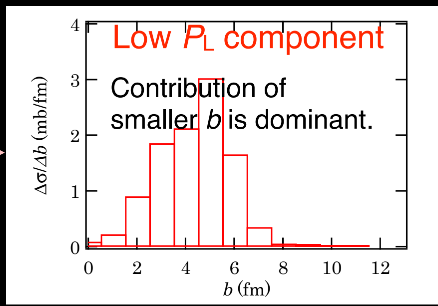
E-dissipation is promoted for small *b*.

Contribution of impact parameter

b-dependent P_L distribution



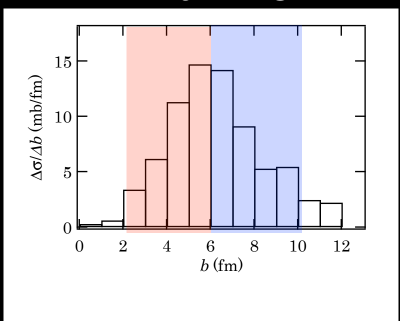




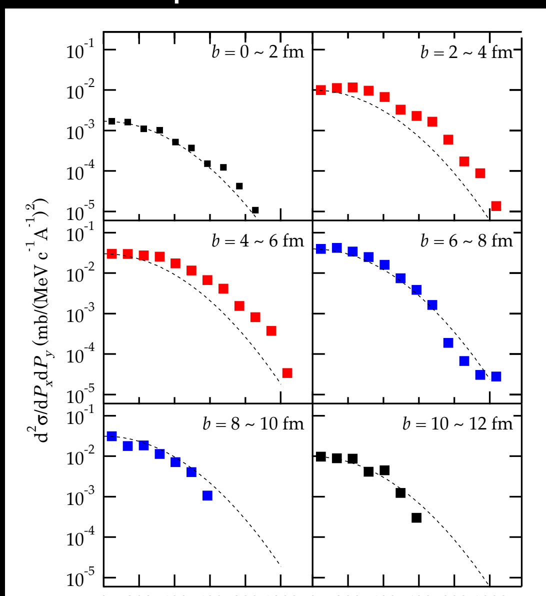
b-dependent P_T distribution

Prod. rate vs. *b*

$^{40}Ar + ^{9}Be \rightarrow ^{30}Si + X$



b-dependent P_T dist.

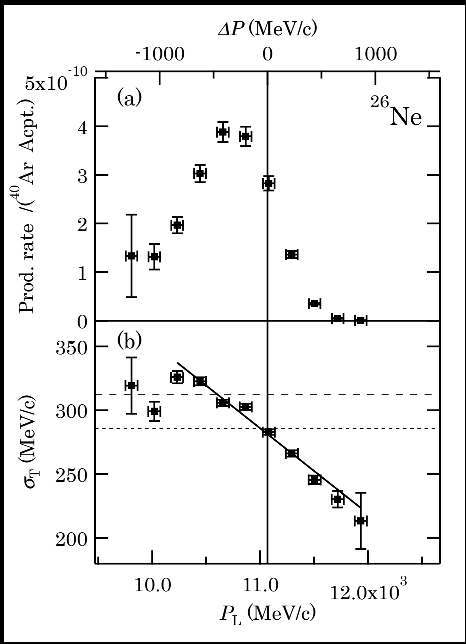


The width of P_T distribution is larger for small *b*.

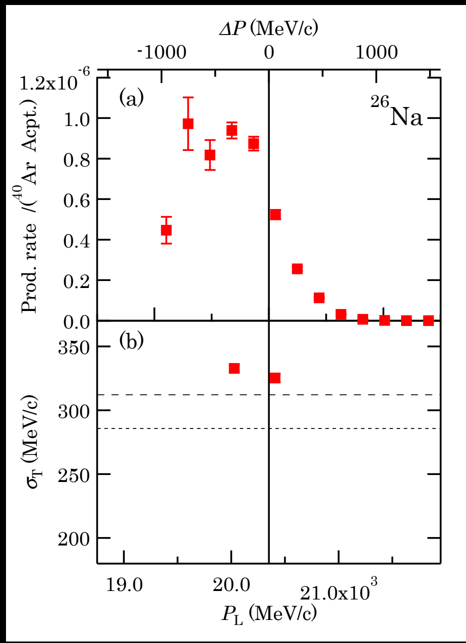
→ *v*-dependent σ_T would be originated from contribution of impact parameters.

P_T distribution at higher energy

E = 95 MeV/u
^{40}Ar + Be → ^{26}Ne + X



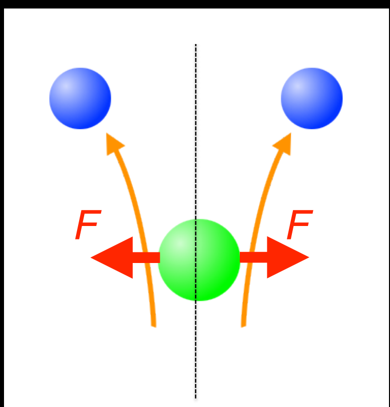
E = 290 MeV/u
^{40}Ar + Al → ^{26}Na + X



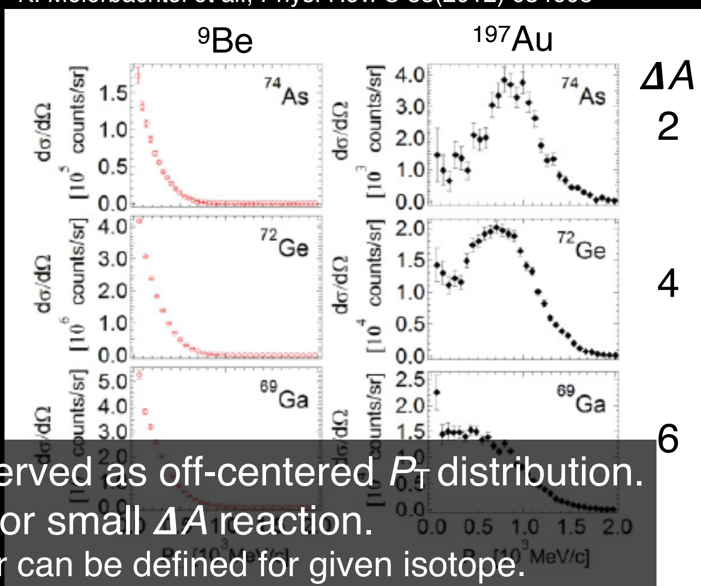
Velocity dependence is not remarkable.

P_T distribution with heavier target

Dominant contribution of repulsive Coulomb force



P_T distribution of fragments
^{76}Ge(130 MeV/nucleon)+^{9}Be, ^{197}Au
K. Meierbachtol et al., Phys. Rev. C 85(2012) 034608



- Deflection effect was observed as off-centered P_T distribution.
- Deflection is remarkable for small ΔA reaction.
  Specified impact parameter can be defined for given isotope.

Possibility to investigation proximity potential for heavy reaction system

Conclusions

- Remarkable **correlation** between width of P_T distribution (σ_T) and fragment velocity (ΔP_L) has been observed at E = 95 MeV/u.

1. Simple formulation : $\sigma_T = k_0 + k_1 \Delta P_L$
2. Comparison with previous results
   $\sigma_T(\Delta P_L = 0) = \sigma_{GH}$
   Width of P_L distribution
   σ_T at center of P_L dist. = σ_D
   Conventionally used value
3. Important contribution of impact parameter to understand observed correlation

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