Projectile Fragmentation

modern route to exotic nuclei

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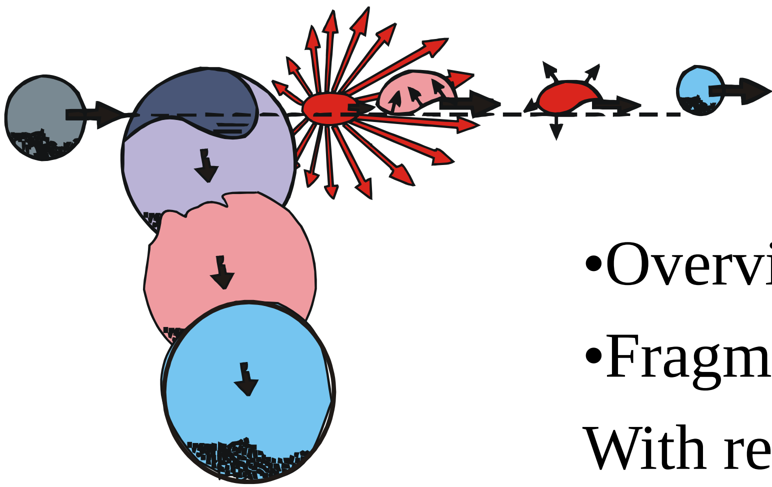


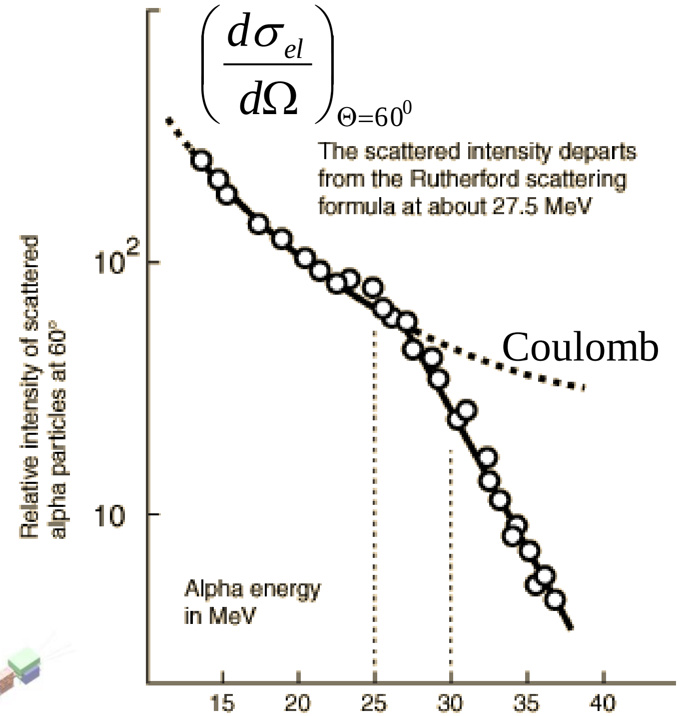
- Overview of Reaction Mechanism
- Fragment Separators

With references and estimates of typical values

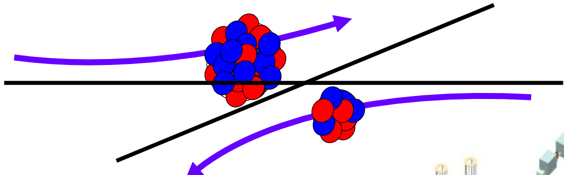
Why the fast beams ?
(a) Rutherford Scattering

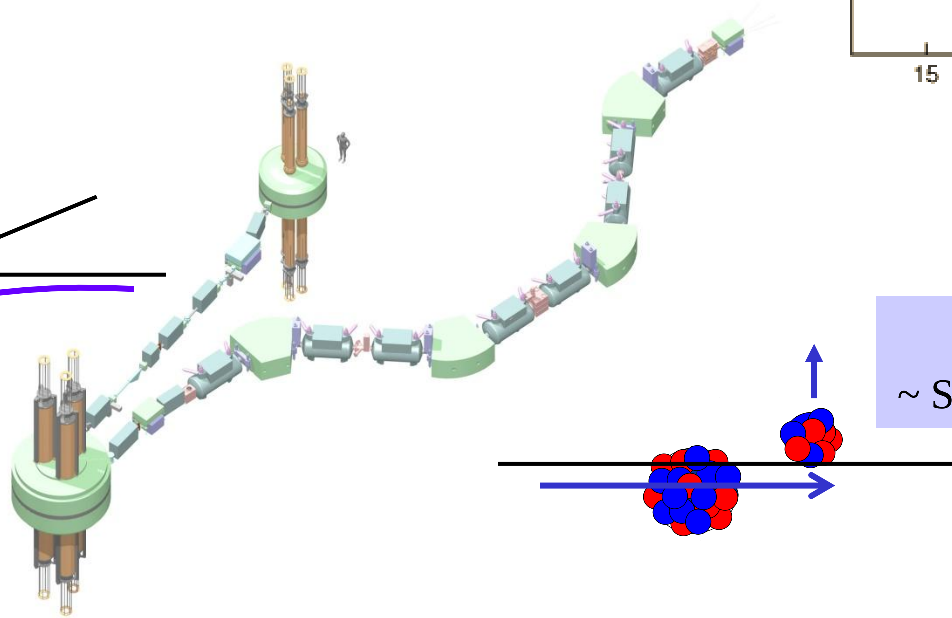
$$\frac{d\sigma}{d\cos\theta} = \frac{\pi}{2} z^2 Z^2 \alpha^2 \left(\frac{\hbar c}{KE}\right)^2 \frac{1}{(1-\cos\theta)^2}$$

e.g., He + Pb, Eisberg and Porter, Rev. Mod. Phys. **33**(1961)190



KE ~ V_{coul}
Coulomb Trajectories

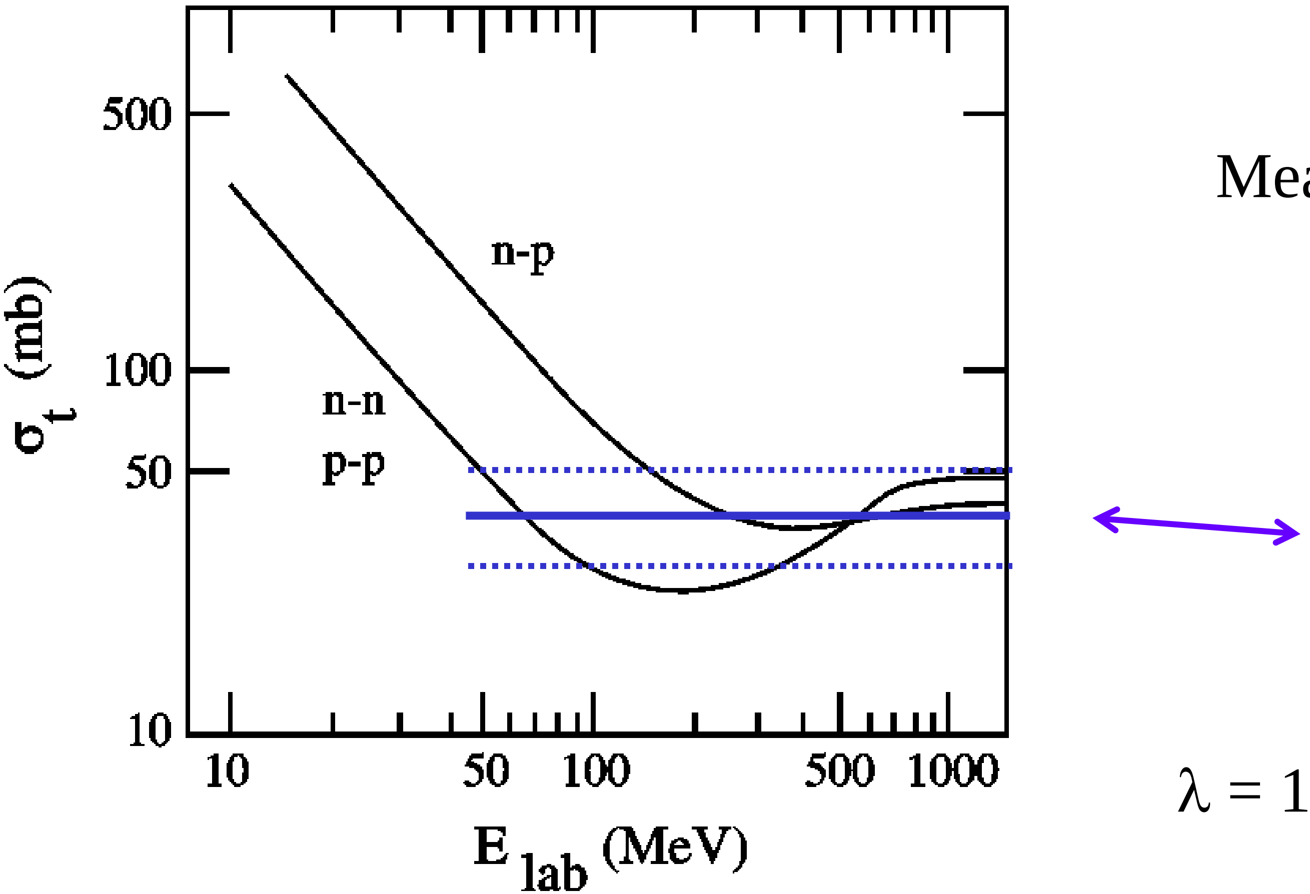




KE >> V_{coul}
~ Straight-line Trajectories

Why the fast beams ? (b) geometrical cross sections

Nucleon-nucleon scattering Cross sections



Mean free path, λ:
$\lambda = 1 / (\rho\,\sigma)$

$\rho = 0.15\ fm^{-3}$

$\sigma \sim 40$ mb
(+/- 25%)

$\lambda = 1.7\ fm < R_{nucleus}$

Empirical Production Cross Sections

Target Fragments:
G. Rudstam,
Z. Naturforsch. <u>21a</u> (1966) 1027

Cosmic Rays:
R. Silverberg and C.H. Tsao,
Ap. J. Suppl. <u>25</u> (1973) 313, <u>58</u> (1985) 873

Unified Systematics:
K. Suemmerer, et al., EPAX
Phys. Rev. **C**<u>42</u> (1990) 2546

B.Blank & KS, EPAX2
Phys. Rev **C**<u>61</u> (2000) 034607

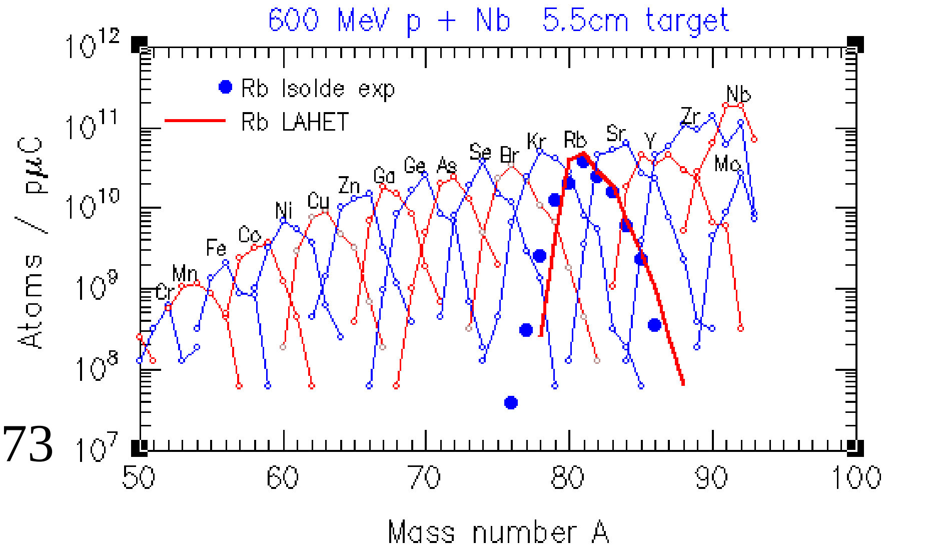
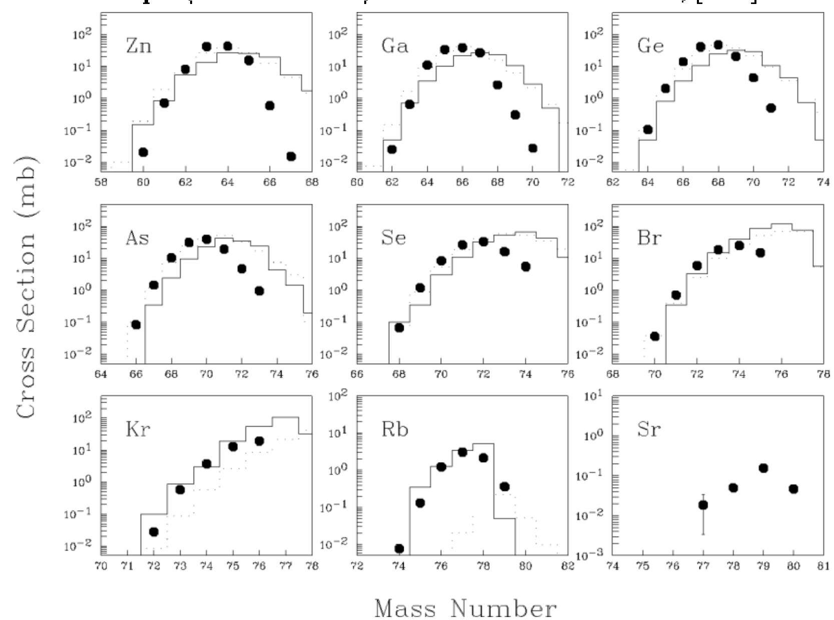
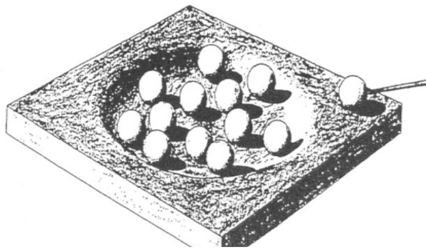


Fig. II.13: LAHET prediction (solid curves) for 600 MeV p+Nb are compared to experimental data for Rb isotopes (solid blue circles) obtained from ISOLDE at CERN, [RA88].



R. Pfaff, et al.,
Phys. Rev. ***C****<u>53</u> (1996) 1753*

Aside: Reaction Models

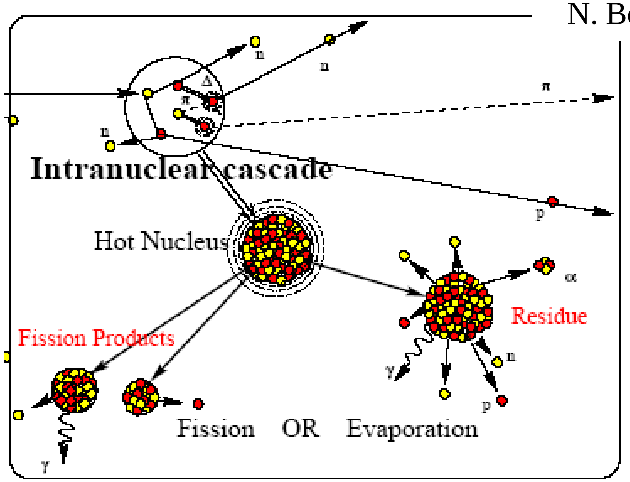


N. Bohr, Nature **137** (1936) 351

Intranuclear Cascade:

VEGAS by K. Chen, Z. Fraenkel, et al.,
Phys. Rev. 166 (1968) 949

ISABEL by Yariv and Fraenkel,
Phys. Rev. **C**20 (1979) 2227
INCL4 by Cugnon, et al.
Phys. Rev. **C**66 (2002) 044615

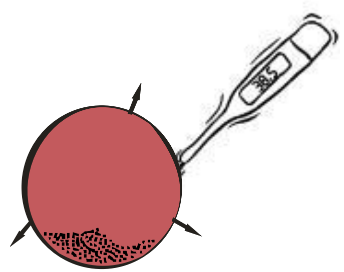


"Macroscopic"

Abrasion/Ablation by J.D. Bowman,
W.J. Swiatecki, and C.F. Tsang, LBL-2908
FIREBALL by J. Gossett, et al.,
Phys. Rev. **C**16 (1977) 2227
FIRESTREAK by W.D.Myers,
Nucl. Phys. **A296** (1978) 177

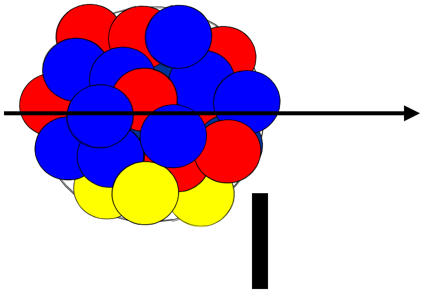
ABRABLA by J.-J. Gaimard, et al.,
Nucl. Phys. A531 (1991) 709.

Unresolved problem:
What's the E* ?



K-H Schmidt, 2001
www-wnt.gsi.de/kschmidt/thermome.htm

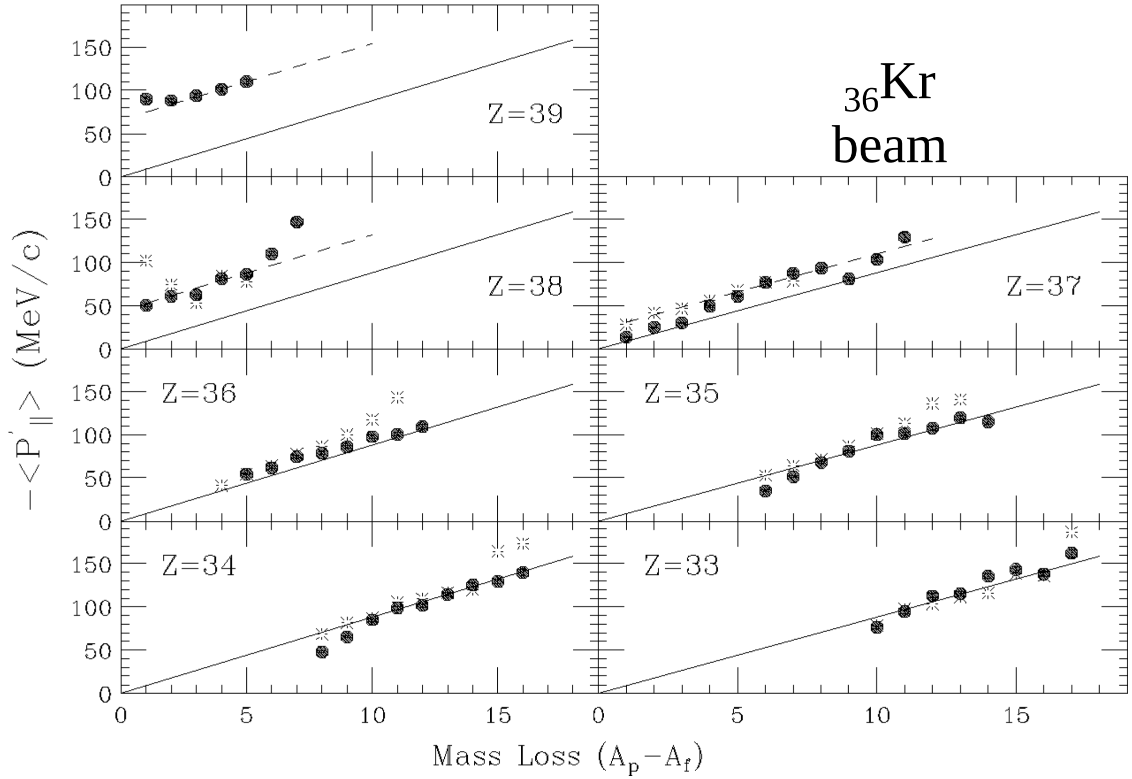
Momentum Distribution, (a) centroids



Removal of bound nucleons:

$$q_i\, c \sim \Delta E_i\, (\gamma + 1) / \beta\gamma$$

$$-\langle P_{\|} \rangle \sim 8\, \Delta A\ (\mathrm{MeV}/c)$$



$_{36}$Kr beam

^{86}Kr + ^{9}Be data:

R. Pfaff, et al., Phys. Rev. ***C**<u>51</u>* *(1995) 1348*

Pickup of target nucleons:

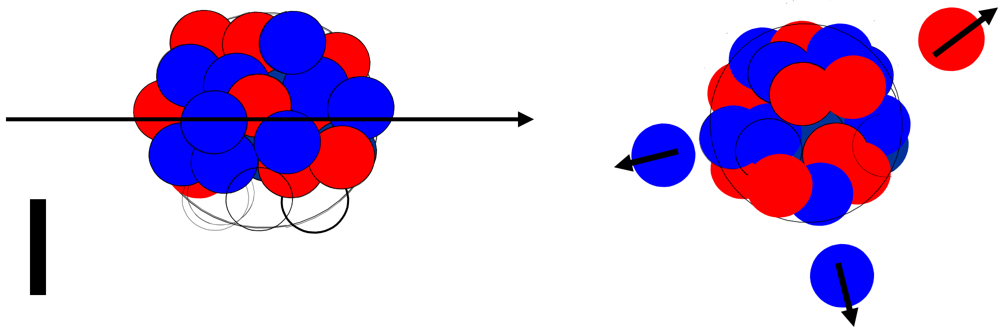
$$\langle p_f \rangle = [\, (A_f - \Delta A_t) P_B / A_B + \Delta A_t\, p_{Fermi}]$$

Models:

DJM, Phys. Rev. ***C**<u>39</u>* *(1989) 460*

G.A. Souliotis, et al., Phys. Rev. ***C**<u>46</u>* *(1992) 1383*

Momentum Distribution, (b) de-excitation widths



Isotropic Recoils

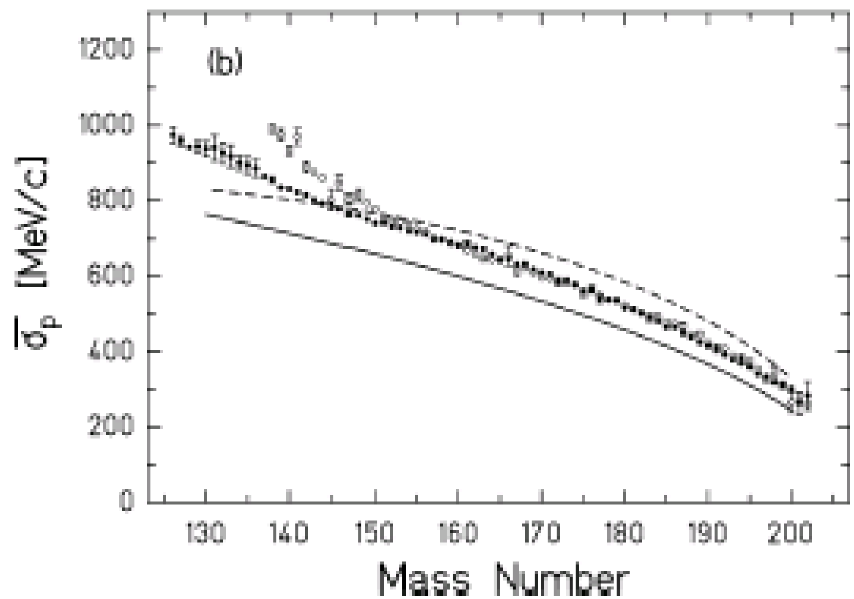
-- from initial process [Goldhaber]

-- from de-excitation [evaporation]

$$\sigma^2_{\|} = \sigma^2_0[\,(A_B - A_f)\, A_f / (A_B - 1)]$$

$$\sigma^2_{\|} \sim \Delta A \;\; (A_f / (A_B - 1)$$

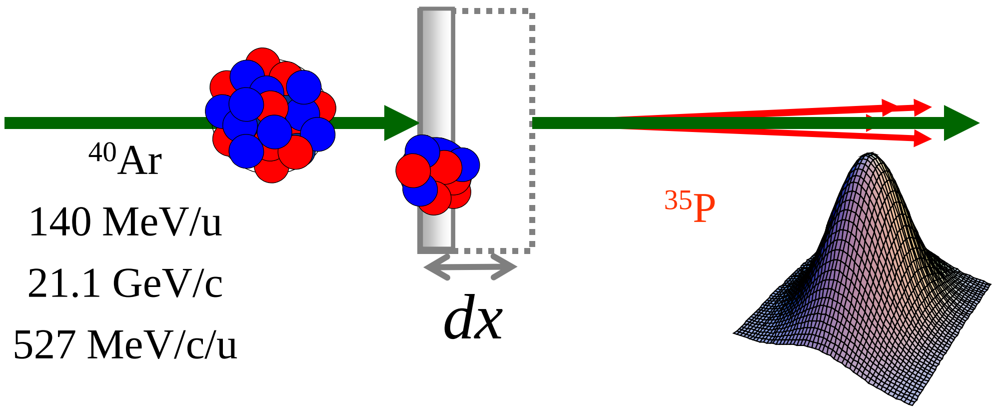
$$\sigma^2_{\|} \sim \;\Delta A$$



^{208}Pb + ^{1}H (open), ^{2}H data (full symbols):
T. Enqvist, et al., Nucl. Phys. ***A703*** *(2oo2) 435*

dashed: Goldhaber, Phys.Lett. ***B**53 (1974) 306*
solid: DJM, Phys. Rev. ***C**39 (1989) 460*

Cartoon of Projectile Fragmentation



$s\,(p_\wedge, p_\parallel)$ » gaussian

$p_\parallel$ » 18,000 MeV/c

» 520 MeV/c/u

(Strong dependence on *dx*)

$s_\parallel$ » 300 MeV/c (1.7% of $p_\parallel$)

(Weak dependence on *dx*)

Fraction converted, *f*

$$f = \frac{\text{Production Rate}}{\text{Beam Flux}} = \frac{R}{\Phi} = N_0 \sigma_{rxn}$$

$$f = \left(\frac{\rho_{\text{tgt}} \; N_A}{\text{AW}_{\text{tgt}}} dx \right) \sigma_{rxn}$$

$$f \approx \left(\frac{2\left(\text{g/cm}^3\right)\, 6x10^{23}\left(\text{/mole}\right)}{9\left(\text{g/mole}\right)} 0.1\left(\text{cm}\right) \right) 10^{-24} \left(\frac{\text{cm}^2}{barn} \right)$$

$$f \approx 0.013 \,/\, barn$$

(e.g., ^{35}P σ ~ 0.002 barn, *f* ~ 10^{-5})

Thumbnail of Projectile Fragmentation Facilities

First Experiments – LBL BEVALAC [late 70's]

First Generation, used existing device: – LISE @ GANIL

Second Generation, construct specific device:

A1200 @ NSCL, $K=K_{accel}$
superconducting, begins beamlines

FRS @ GSI, $K=K_{accel}$
'full acceptance', begins beamlines

RIPS @ RIKEN, $K= 1.65\ K_{accel}$
'large acceptance'

Lithium, A/q
11/3 vs. 7/3 => 1.6
Tin,
132/50 vs. 118/50 => 1.1

K1200 accel => A1900 sep.

Third Generation, construct improved high-resolution device:

LISE3 @ GANIL, post selection in Wien filter

A1900 @ NSCL, $K=1.6\ K_{accel}$ superconducting, begins beamlines

Fourth Generation – preselection before high resolution separator:

A1900 & S800 beamline – recently tested

bigRIPS @ RIKEN – just finished

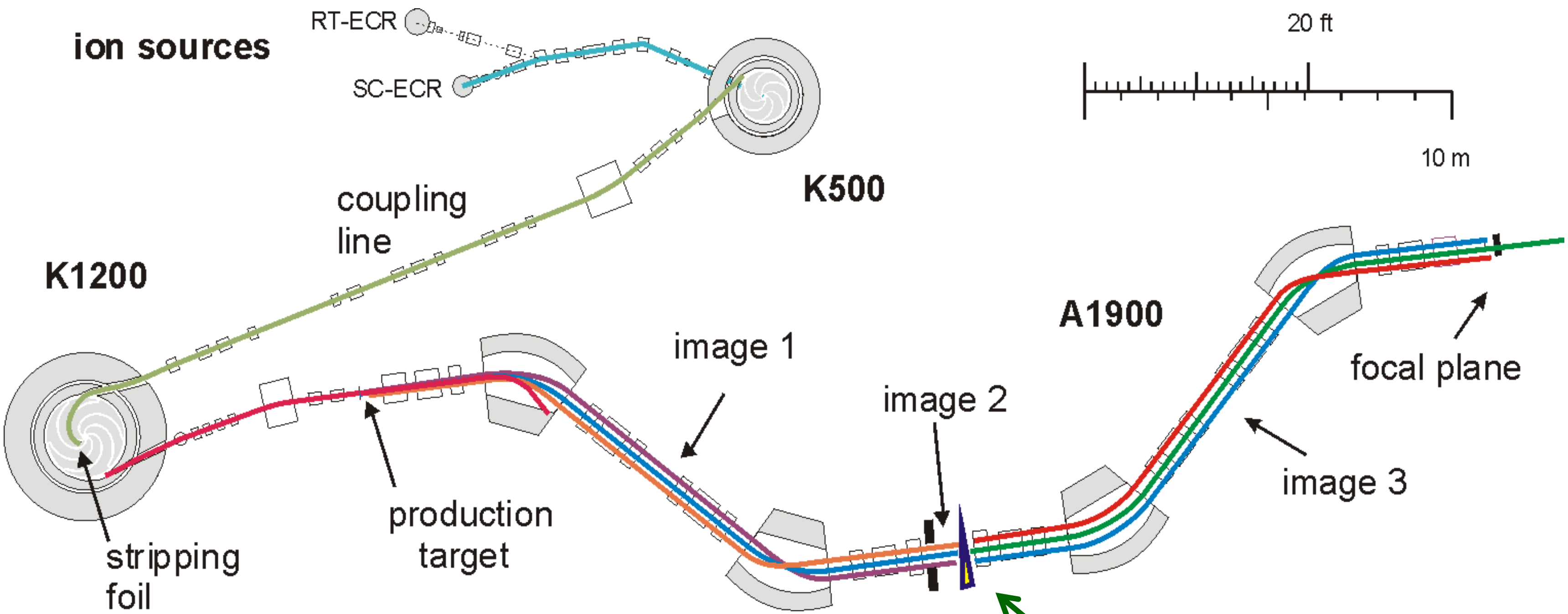
superFRS @ GSI – in design

A2400 @ F.RIB – in design

NSCL

Production in 0° Spectrometer

Example: ^{86}Kr $\rightarrow {}^{78}_{28}$Ni$_{50}$ (doubly magic …)



d Ω = 8 msr

Δp/p = 5%

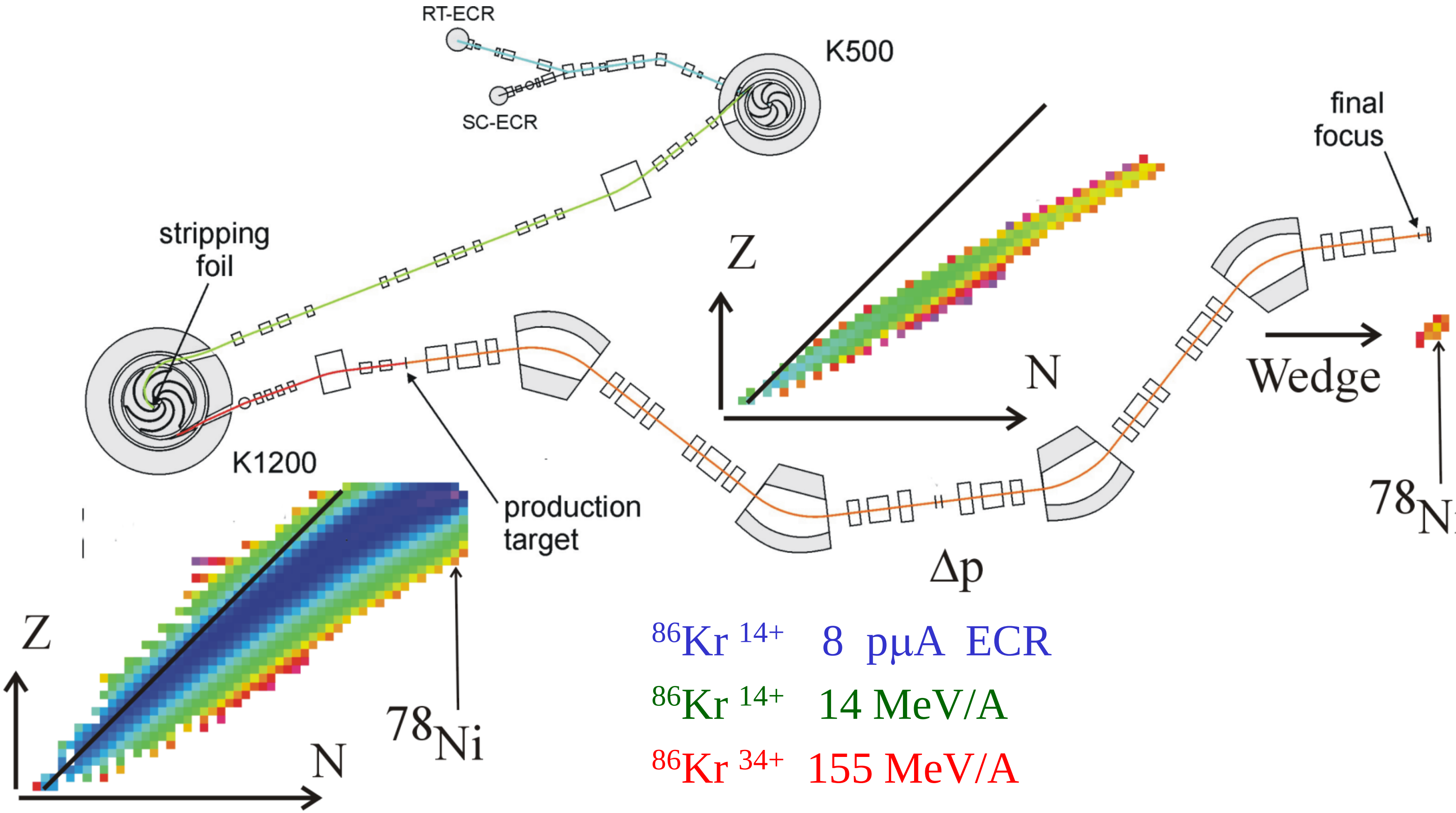
Wedge location

Dispersion = 5 cm/%

Resolution = 2500 p/Δp

Fragment Separation Example

^{86}Kr $\rightarrow$ ^{78}Ni, battle conditions



^{86}Kr $^{14+}$ 8 pμA ECR

^{86}Kr $^{14+}$ 14 MeV/A

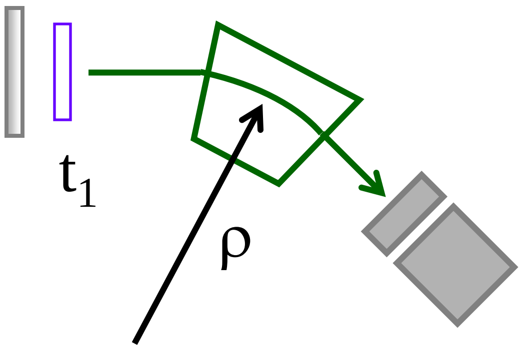
^{86}Kr $^{34+}$ 155 MeV/A

→ 65% of the ^{78}Ni is transmitted

Max (NSCL): 100 pnA (1.3 kW power) ~ 10^{-2} /s

PRL 94(2oo5) 112501: 15 pnA (0.2kW)

Particle Identification Concept, $^{A}Z^{q+}$



Magnetic Rigidity

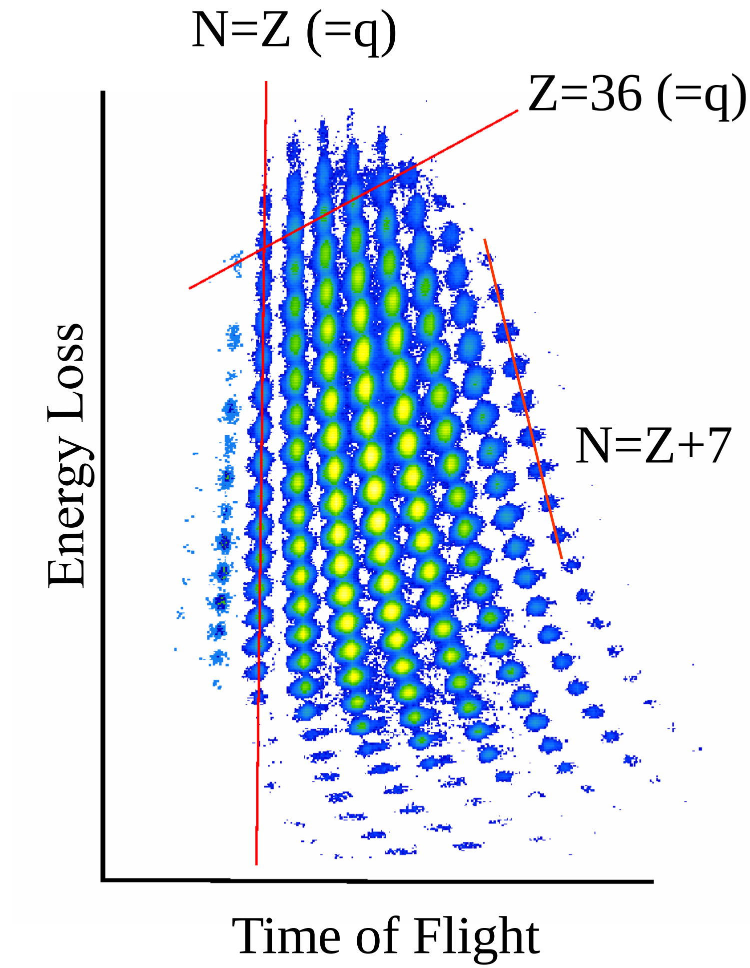
$$B\rho = p/q = m\,\beta\gamma\,/\,q$$

$$\beta \;\alpha\; 1/(t_2 - t_1)$$

$$Z \;\alpha\; \mathrm{Sqrt}(\Delta E\,(\gamma + 1)\,)$$

$$q \;\alpha\; \mathrm{TKE}\,\beta\,\gamma\,/\,B\rho\,(\,\gamma - 1)$$

$$A = q\,B\rho\,/\,\beta\,\gamma$$



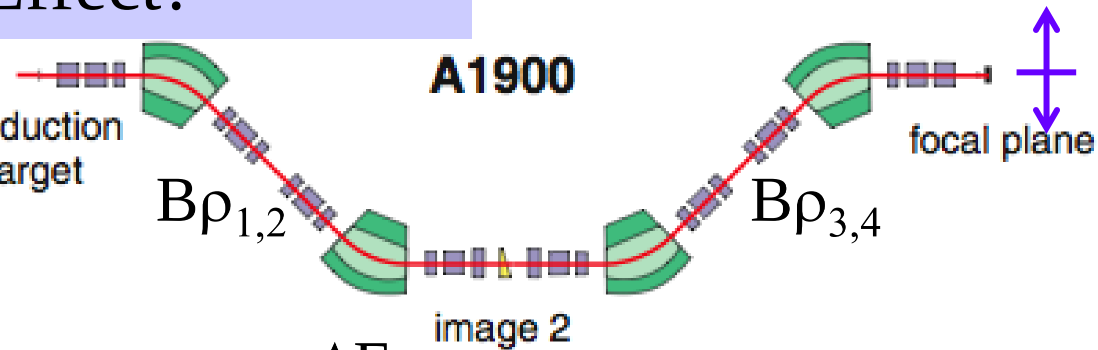
(no wedge)

Auxiliary measurement: positions/angles

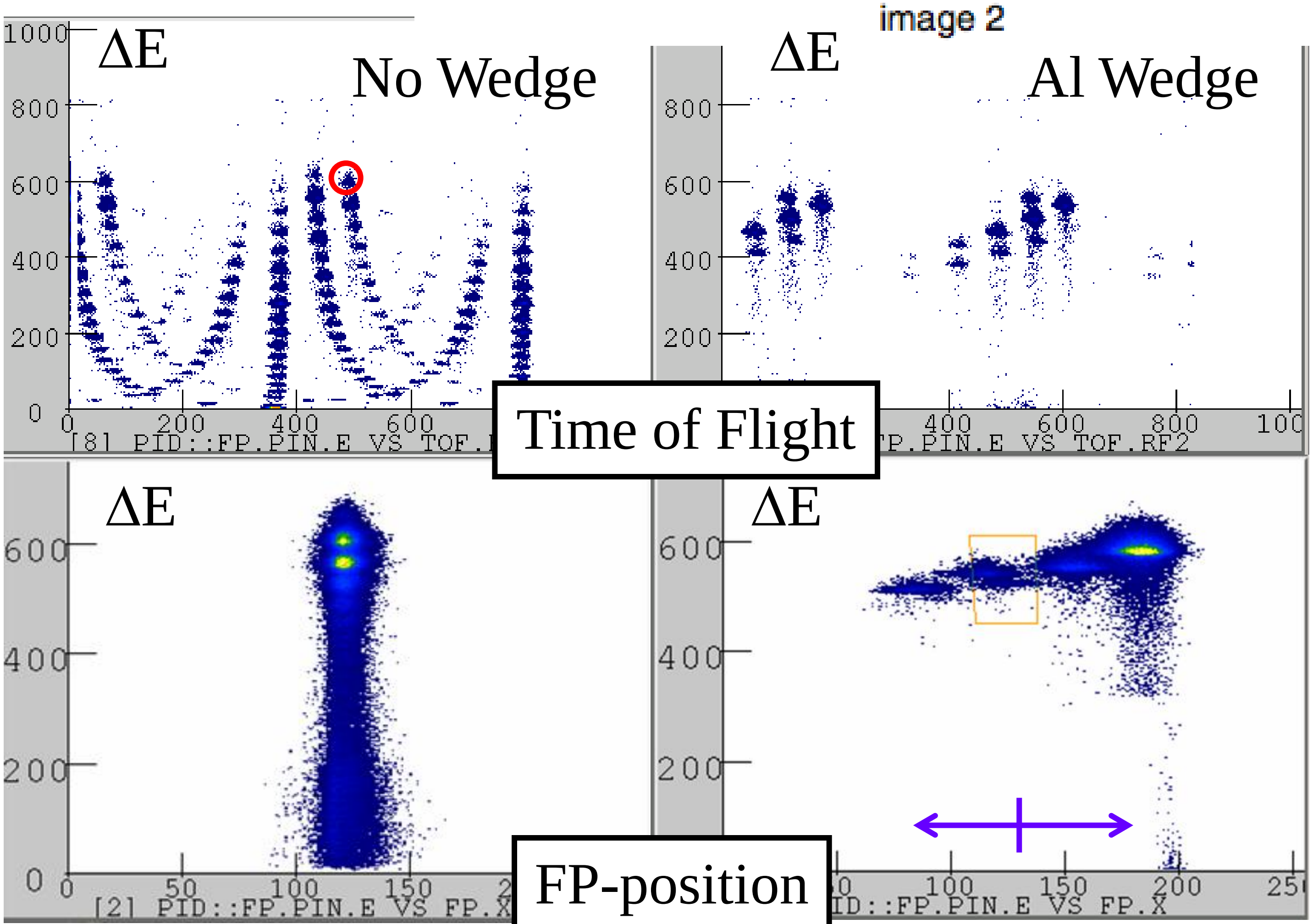
Details: Wedge Effect?

Example:

$^{40}Ca \rightarrow {}^{38}_{20}Ca_{18}$



$B\rho_{1,2} = B\rho_{3,4}$



$B\rho_{1,2} > B\rho_{3,4}$

Summary

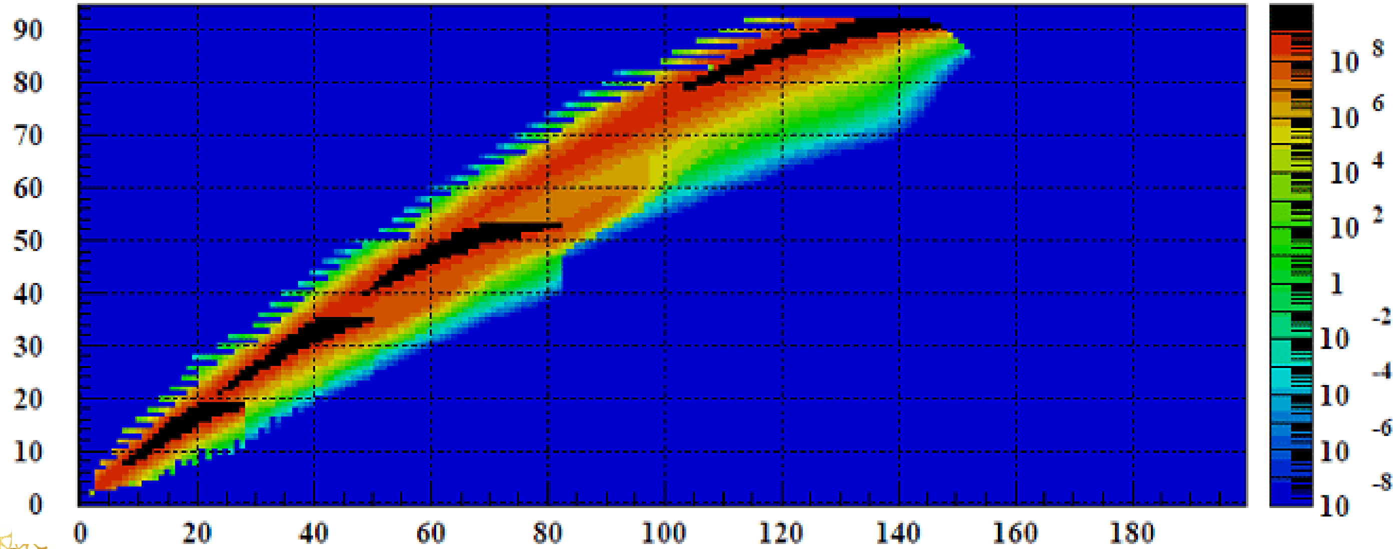
•Simple nuclear reactions provide a broad range of nuclei

•General features of the reactions are well-known but some details are not

•Projectile fragments are produced at nearly the speed of light

•Projectile fragments:

- Rapid physical separation of fragment in a magnetic system
- Requires: Z, A, and q identification/separation in 0^{o} spectrometer



A few beams or targets produce a broad range of products

http://www.rarf.riken.go.jp/UsersGuide/BigRIPS/intensity.html