Multi-nucleon transfer basics

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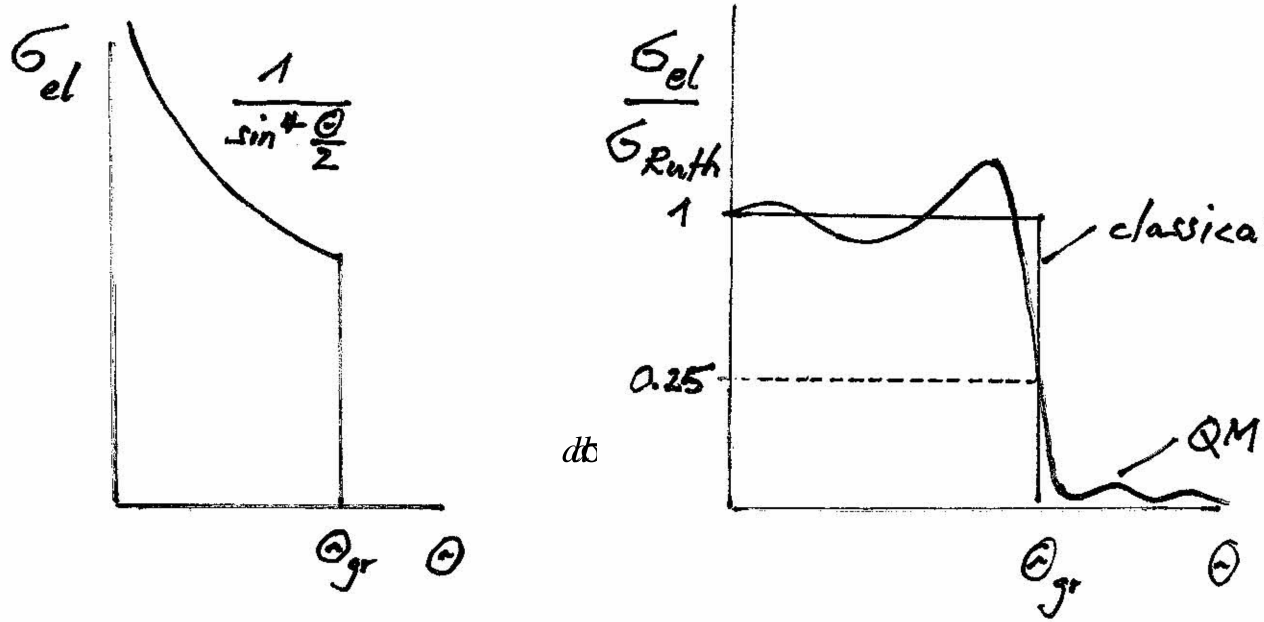
Grazing angle θ_{gr}



$$\left(\frac{d\sigma}{d\Omega}\right)_c = |f_c(\theta)|^2$$

$f_c(\theta)$ Coulomb scattering amplitude

Analogy to black disk: scattering amplitude of light at the border falls to 0.5 => cross section to 0.25

<u>Quarterpoint Method</u>

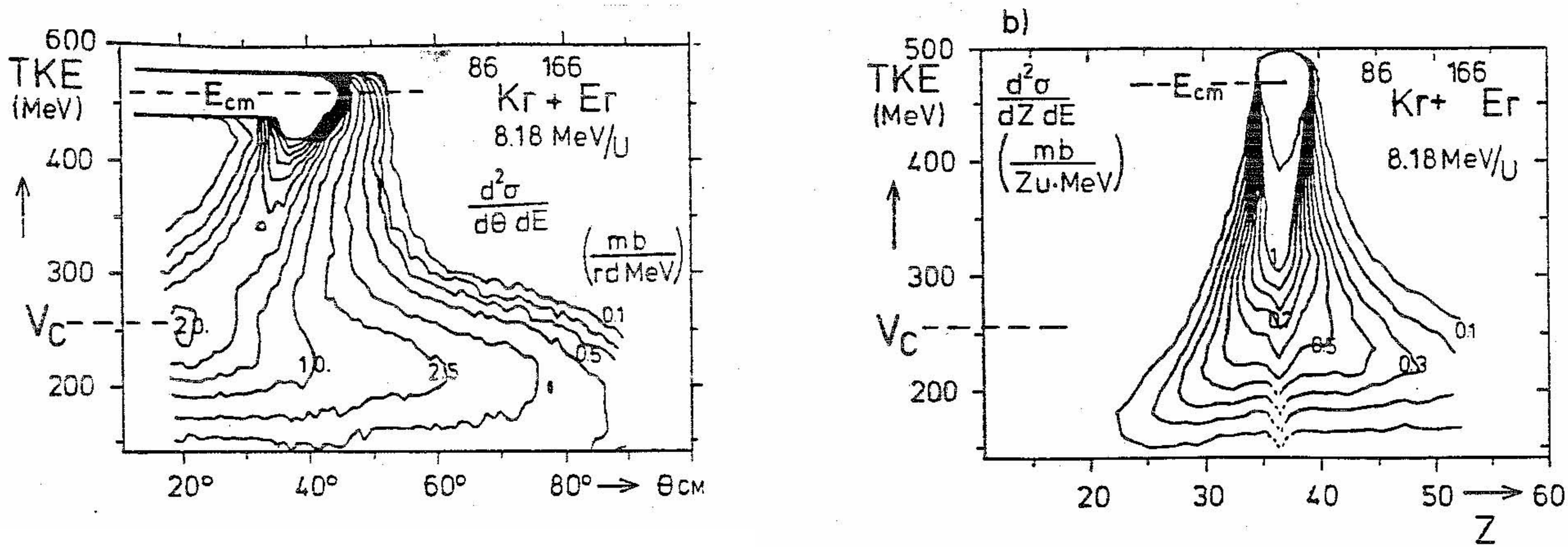


Fig. 3.7. Contour plots for the Wilczynski diagram (part a) and for the diffusion plot (part b) of the ^{86}Kr + ^{166}Er collision. The absolute cross section is indicated on the contour lines.

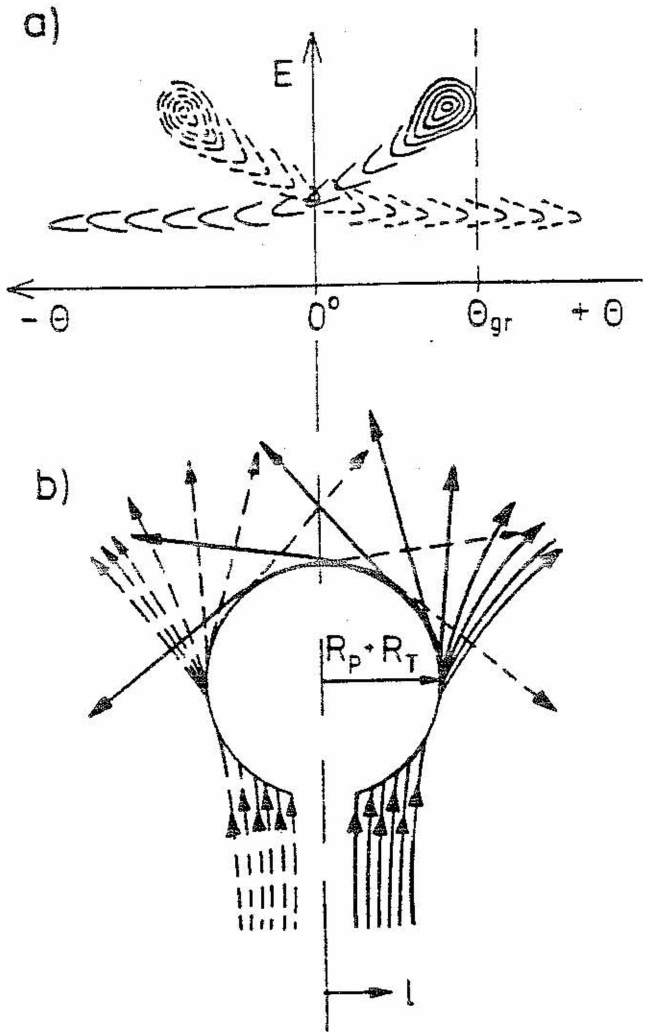


Fig. 3.9. Wilczynski diagram: part (a) sketches, in an energy versus scattering angle plot, the contour lines of constant cross section. In a reaction plane defined by the beam axis and the detection angle two components are possible: (i) for impact parameters on the right hand side of the beam axis (solid lines) and (ii) on the left hand side (dashed lines). Part (b) of the figure illustrate the corresponding trajectories leading to the energy–angle correlation of part (a). The ingoing angular momentum is denoted by *l*.

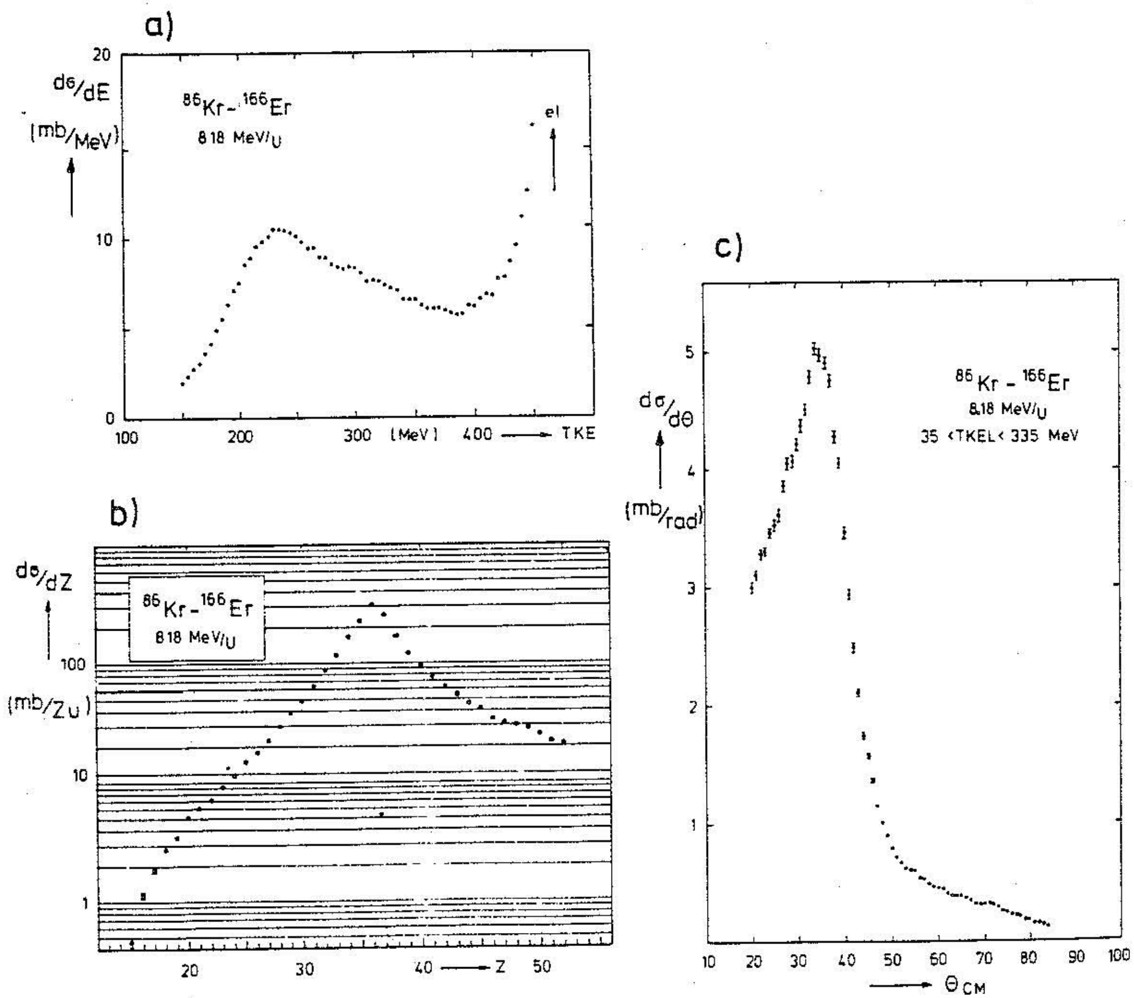


Fig. 3.8. One dimensional projection of all inelastic events for energy losses TKEL > 35 MeV as a function of energy (part a), charge (part b) and scattering angle (part c). Same data as in fig. 3.7. From Rudolf (1979).

Deflection functions

orbiting

focussing

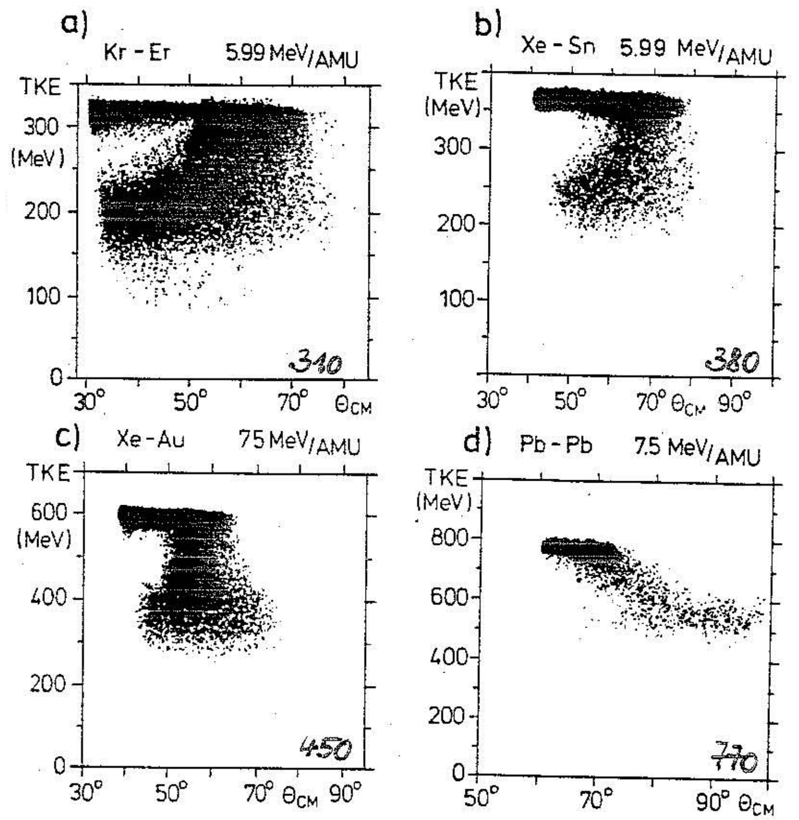
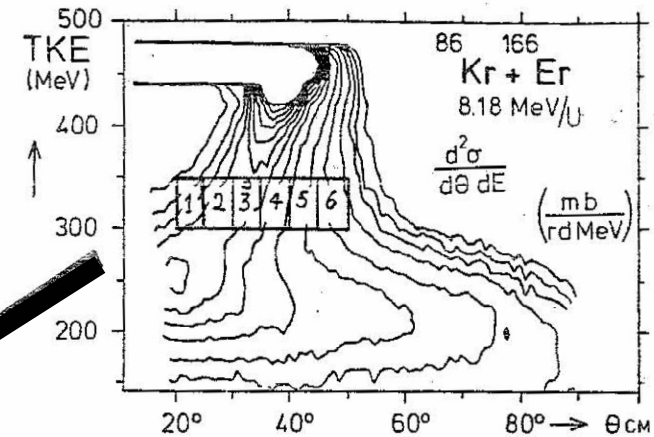
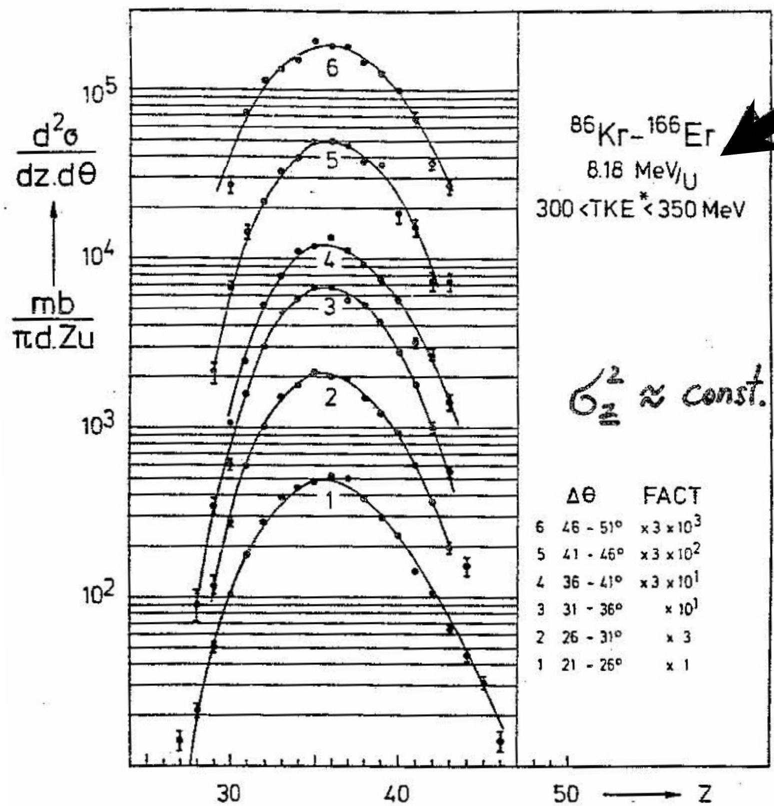


Fig. 3.10. Wilczynski diagrams for four different target–projectile combinations gained as scatter-plot in overview type of experiments. From Sann et al. (1977).

$$\eta' = \frac{Z_1 Z_2 e^2}{\hbar v_{cB}}$$

Coulomb trajectory





Use of $\Delta\Theta$ as a clock?

$$\frac{\Delta\Theta}{\Delta t} = \frac{\ell\hbar}{\mathcal{J}\,\tau_{int}}$$

$$\Delta\Theta = \int_0 \frac{\ell\hbar(t)}{\mathcal{J}_{rel}(t)}\,dt$$

$$\tau_{int} \sim (\Theta_{gr} - \Theta)/\ell_{gr}$$

Fig. 3.15. Analysis of the element distributions as a function of energy loss and scattering angle. In part (a) Wilczynski diagram with (superimposed) a raster indicating the bins in energy and in angle (bin 1 to 6) for which the element distribution is displayed in part (b) of the figure.From Rudolf (1979).

$$P(z,t) = \frac{1}{\sqrt{2\pi\sigma_z^2}} \exp\left\{-\frac{(z-z_0)^2}{2\sigma_z^2}\right\}$$

Gaussian Z distribution widens with TKEL

Diffusion model:

$$P(z,t) = \frac{1}{\sqrt{4\pi D_z t}} \exp\left\{-\frac{(z-z_0-vt)^2}{4 D_z t}\right\}$$

i.e. $\sigma_z^2 = 2 D_z t$

TKEL as internal clock

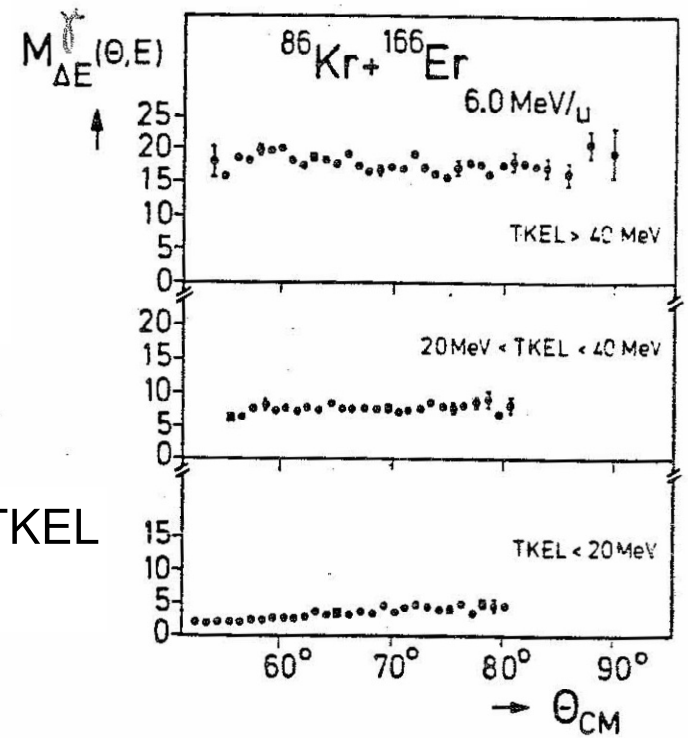


Fig. 3.16. Average gamma multiplicity $\langle M \rangle$ as a function of center of mass scattering angle for selected bins in energy loss TKEL. The investigated reaction is ^{86}Kr on ^{166}Er at an incident energy of 6.0 MeV/u.

Energy loss caused by the recoil momentum associated with each nucleon exchange

$$F_{ex} = -k_{ex} |\dot{r}|$$

$\dot{r} = v$ velocity of relative motion (Fermi momentum neglected)

Momentum transfer

$$\Delta p = m |\dot{r}|$$ m nucleon mass

The system must counteract with an equal recoil momentum

$\curvearrowright$ $$\delta E_{ex} = \frac{m}{\mu} E_{av}$$

$E_{av} = E_{cm} - V_c - TKEL$

μ reduced mass

$m = 1$

$\curvearrowright$ $$\boxed{-\frac{dE_{av}}{dN_{ex}} = \frac{E_{av}}{\mu}}$$ "Recoil formula"

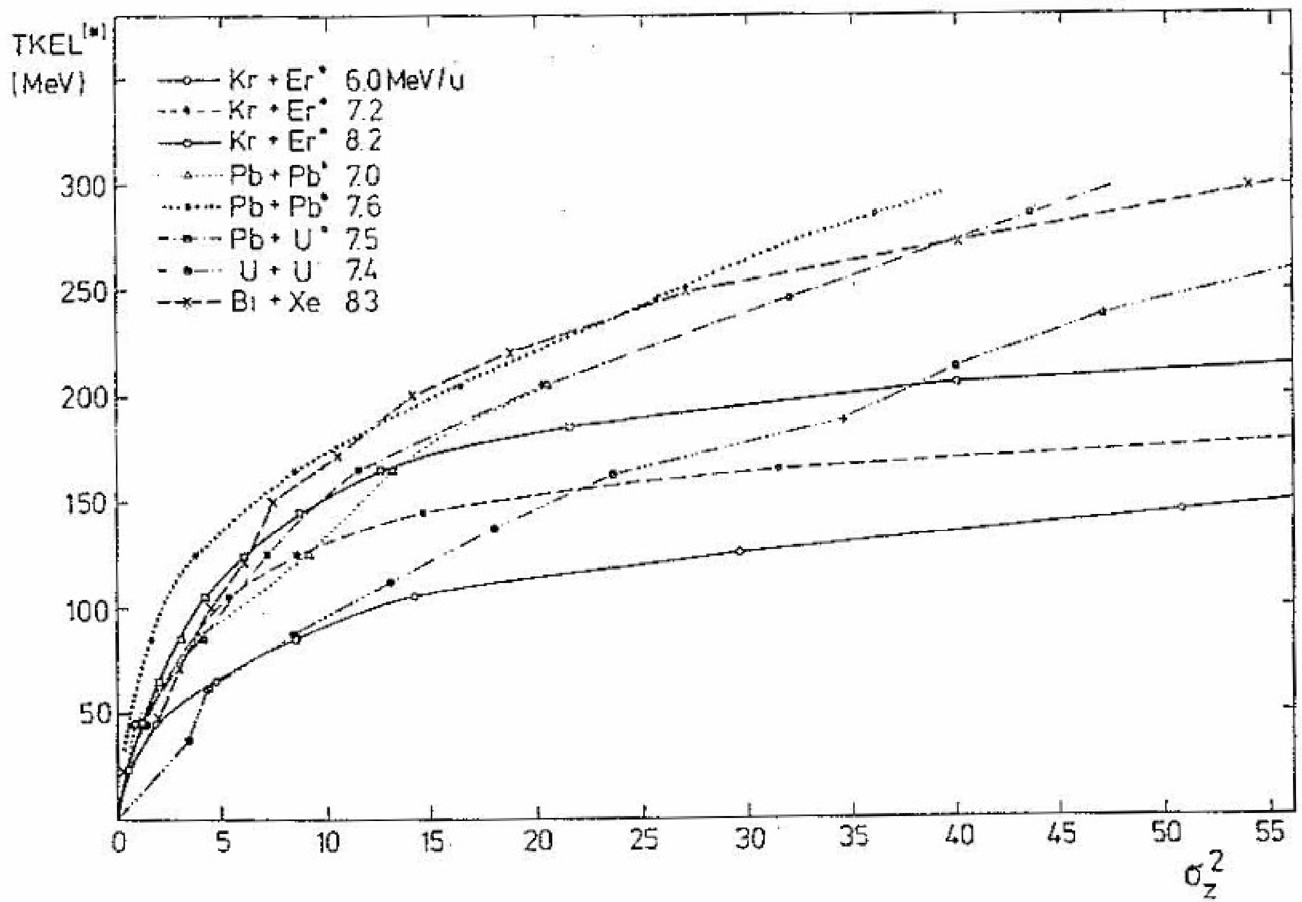
$$N_{ex} = \sigma_A^2$$

$$\sigma_A^2 = \sigma_Z^2 + \sigma_N^2 + 2\rho_{NZ}\,\sigma_Z\,\sigma_N$$

Nuclear structure dependence

$$-\frac{dE_{av}}{d(\sigma_A^2)} = \frac{E_{av}}{\mu} + DE(TKEL)$$

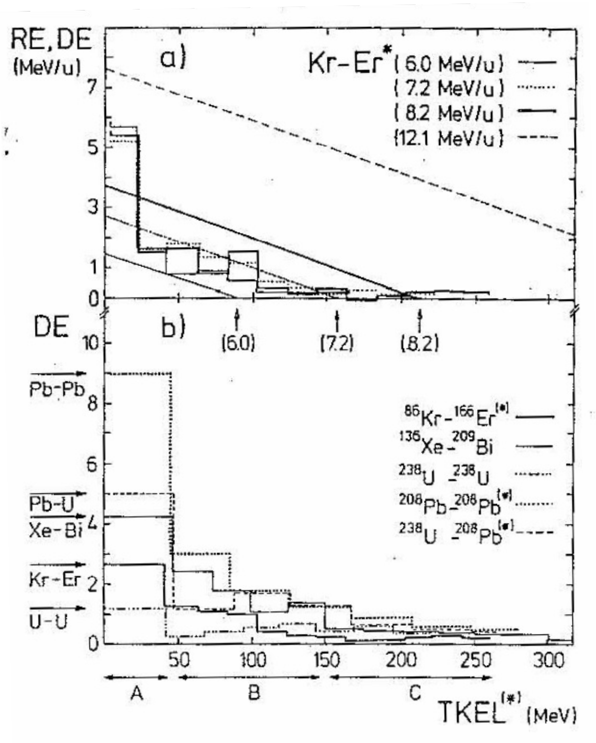
$\frac{E_{av}}{\mu}$ = RE; $DE(TKEL)$ = "shell" correction



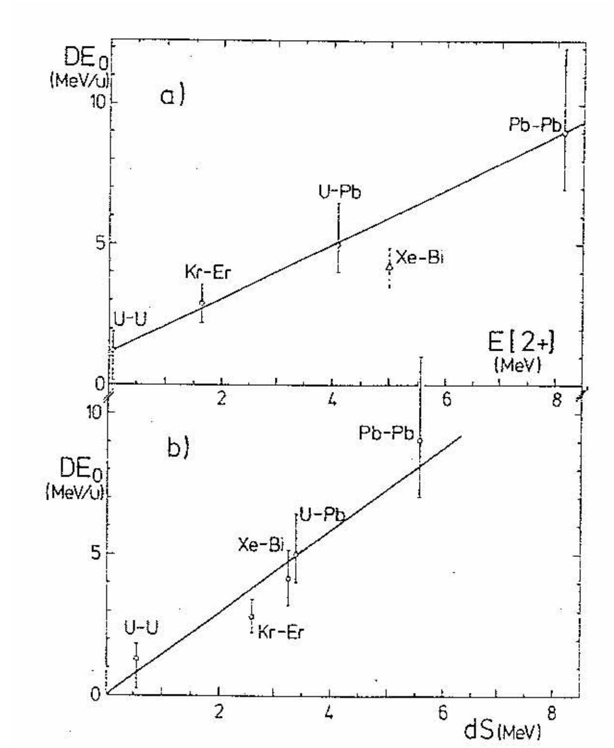
No universal dissipated energy curve !

nuclear structure !

Subtract RE = E_{av}/μ from the measured TKEL to obtain DE



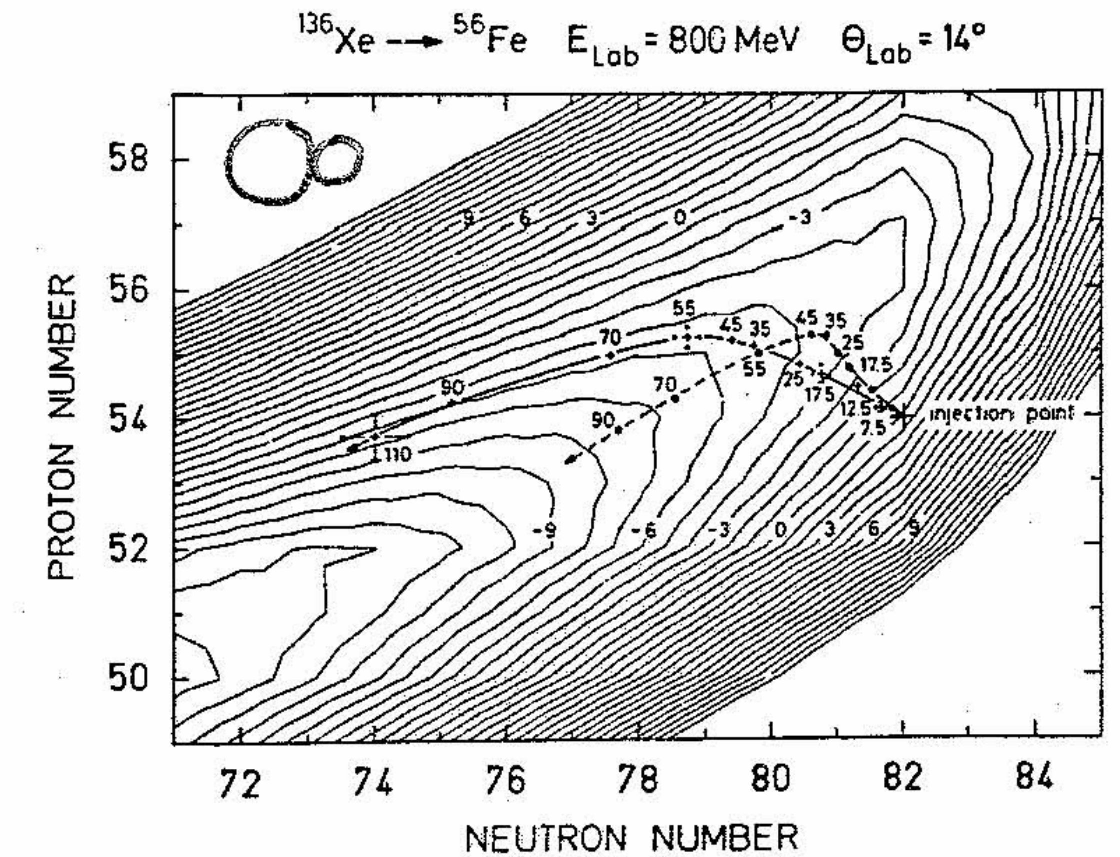
DE = f(TKEL)
DE ≠ f(MeV/u)
DE = system dependent



$$dS = \frac{1}{4}\sum_{i=1}^{4} Q_{gg}(i)$$

A Nuclear structure
B Vanishing shell structure
C Deformability

Schüll et al.



PES + Shell corr.

Drift path for 1st moments
+ uncorrected
▪ corrected for neutron evap.

N/Z equilibration before mass equilibration
Is this process intrinsically faster ?

Instrinsically faster than nucleon exchange ? Collective mode ?

E1 giant resonance shows quantum mechanical zero point motions at T = 0

$$V(z_3)\Big|_{A_3} = \frac{1}{2} c \left(z_3 - \bar{z}_3\right)^2 + const$$

Harmonic oscillator with little damping => weak coupling to intrinsic degrees of freedom that constitute a heat bath (temperature T). This gives certain enery eigenvalues

$$\varepsilon(T,\omega) = \frac{1}{2}\hbar\omega + \frac{\hbar\omega}{\exp(\hbar\omega/T - 1)}$$

c an ω are connected via the moment of inertia
$c = B\,\omega^2$

With these eigenvalues, we obtain the variance

$$\sigma_z^2\Big|_{A_3} = \frac{1}{c}\left(\frac{1}{2}\hbar\omega + \frac{\hbar\omega}{\exp(\hbar\omega/T - 1)}\right)$$

Two extreme cases

$\hbar\omega \gg T$

$$\sigma_z^2\Big|_{A_3} = \frac{\hbar\omega}{2c} = const$$

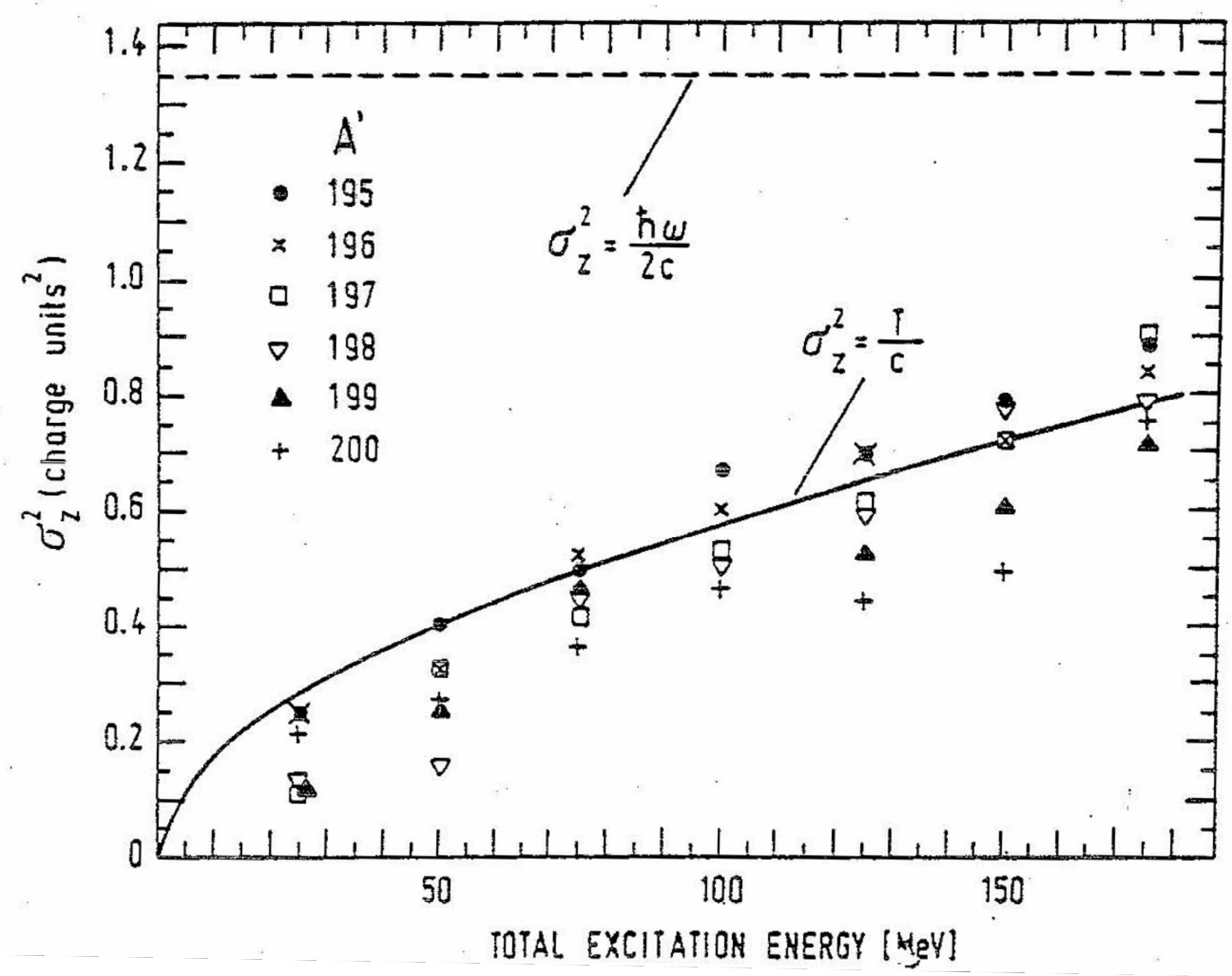
Quantum fluctuations

$\hbar\omega \ll T$

$$\sigma_z^2\Big|_{A_3} = \frac{T}{c}$$

Statistical fluctuations

J. V. Kratz et al. $^{132}Xe + ^{197}Au$



Transport Theory (W. Nörenberg)

Assumption: Slow macroscopic variables (Z, A, TKEL…) and fast intrinsic degrees of freedom. The latter reach a local statistical equilibration after each perturbation (change of a macroscopic variable), i.e. are occupied according to their statistical weight.

=> Markov approximation

=> Fokker-Planck equation

$$\frac{df(y,t)}{dt} = -\frac{\partial}{\partial y}(vf) + \frac{\partial^2}{\partial y^2}(Df)$$

f probability to find the system at time t with the property y

tranport coefficients

v drift velocity

D diffusion coefficient

solution

$$f(y,t) = \frac{1}{\sqrt{4\pi D t}} \exp\left\{-\frac{(y-vt)^2}{4Dt}\right\}$$

$$\sigma_y^2 = 2Dt$$

$$\sigma_Z^2 = 2 D_{ZZ} \tau_{int}$$

$$\frac{df(N,Z,t)}{dt} = -\frac{\partial}{\partial N} v_N(N,Z,t)f - \frac{\partial}{\partial Z} v_Z(N,Z,t)f + \frac{\partial^2}{\partial N^2} D_{NN}(N,Z,t)f + \frac{\partial^2}{\partial Z^2} D_{ZZ}(N,Z,t)f$$

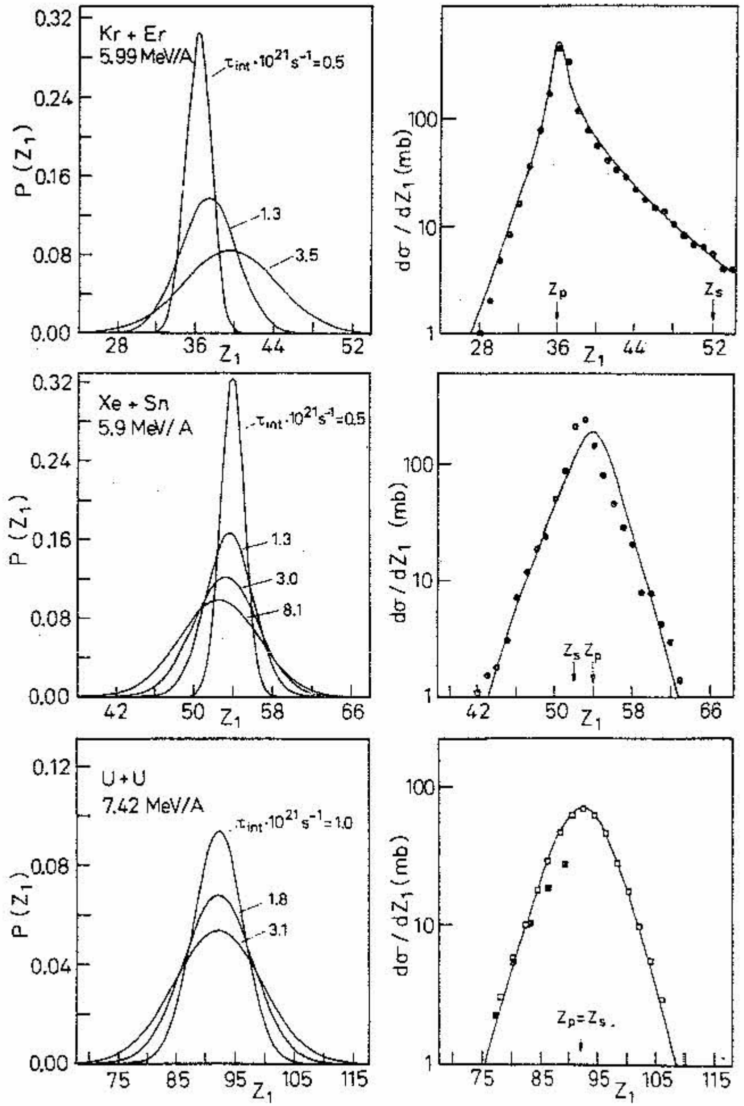
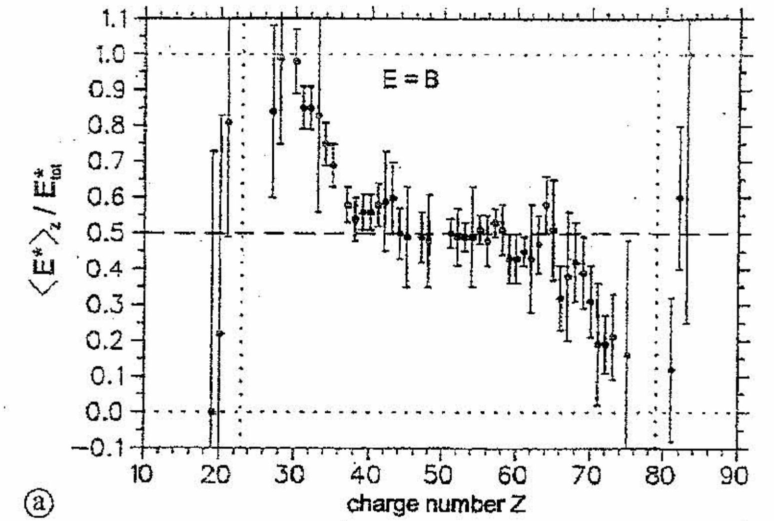
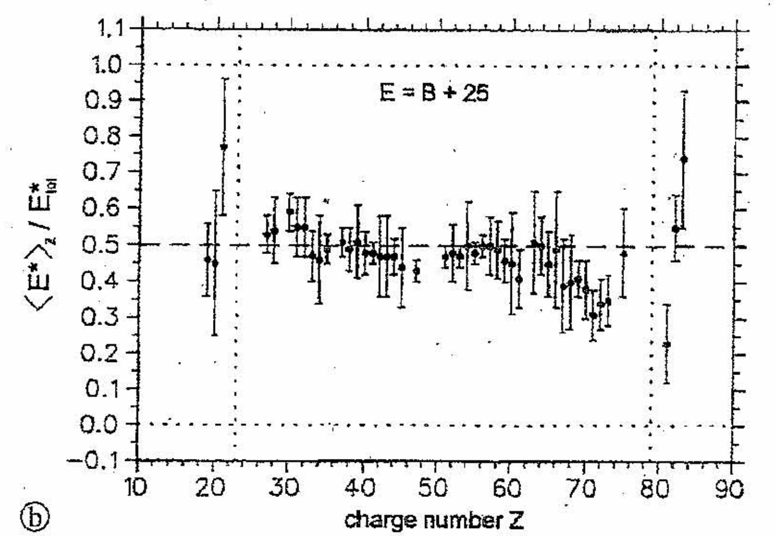


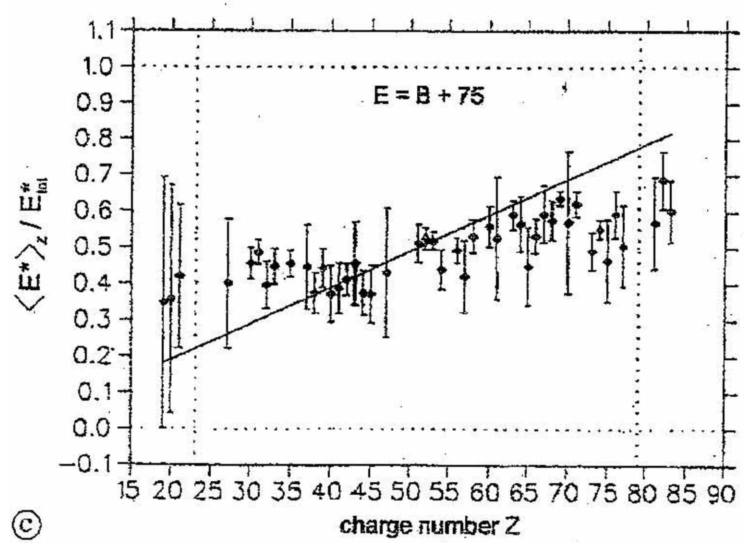
Fig. 3.66. Element distributions for dissipative heavy-ion collisions. The fitted values for the drift and diffusion coefficients are (in units of 10^{-22} s^{-1}) $v_A = 0.3$, $D_{AA} = 1.9$ for ^{86}Kr (5.99 MeV/u) + ^{166}Er, $v_A = -0.1$, $D_{AA} = 1.6$ for ^{132}Xe (5.9 MeV/u) + ^{120}Sn and $v_A = 0$, $D_{AA} = 7.5$ for ^{238}U (7.42 MeV/u) + ^{238}U. From Wolschin (1977).

$^{51}V + ^{197}Au$

Ch. Wirtz et al.







U. Brosa: Random neck rupture