

Multifragmentação Nuclear

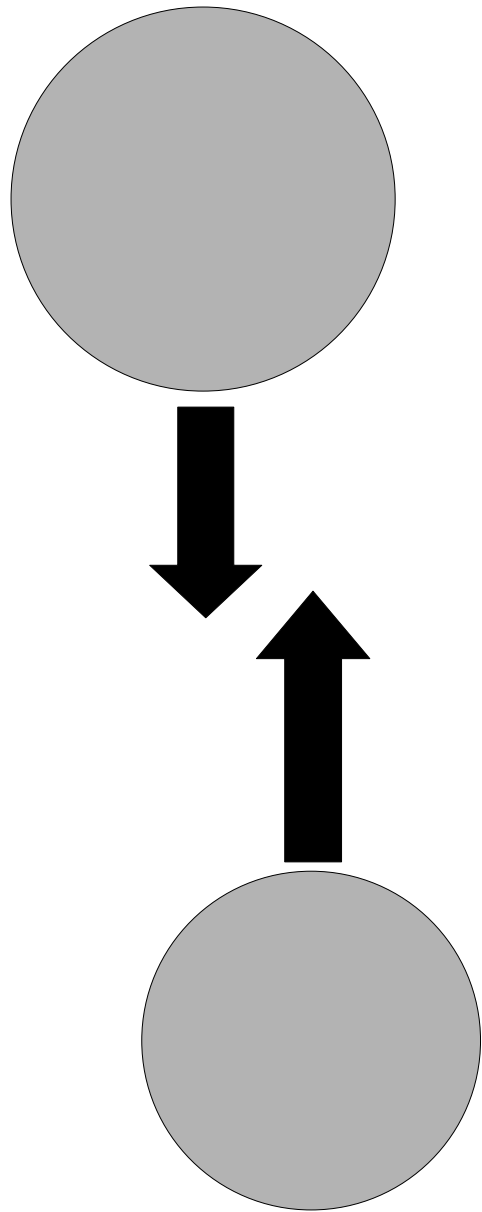
Principais colaborações

- UFRJ - Raul Donangelo
 - Michigan State University
- M. Betty Tsang
- William G. Lynch

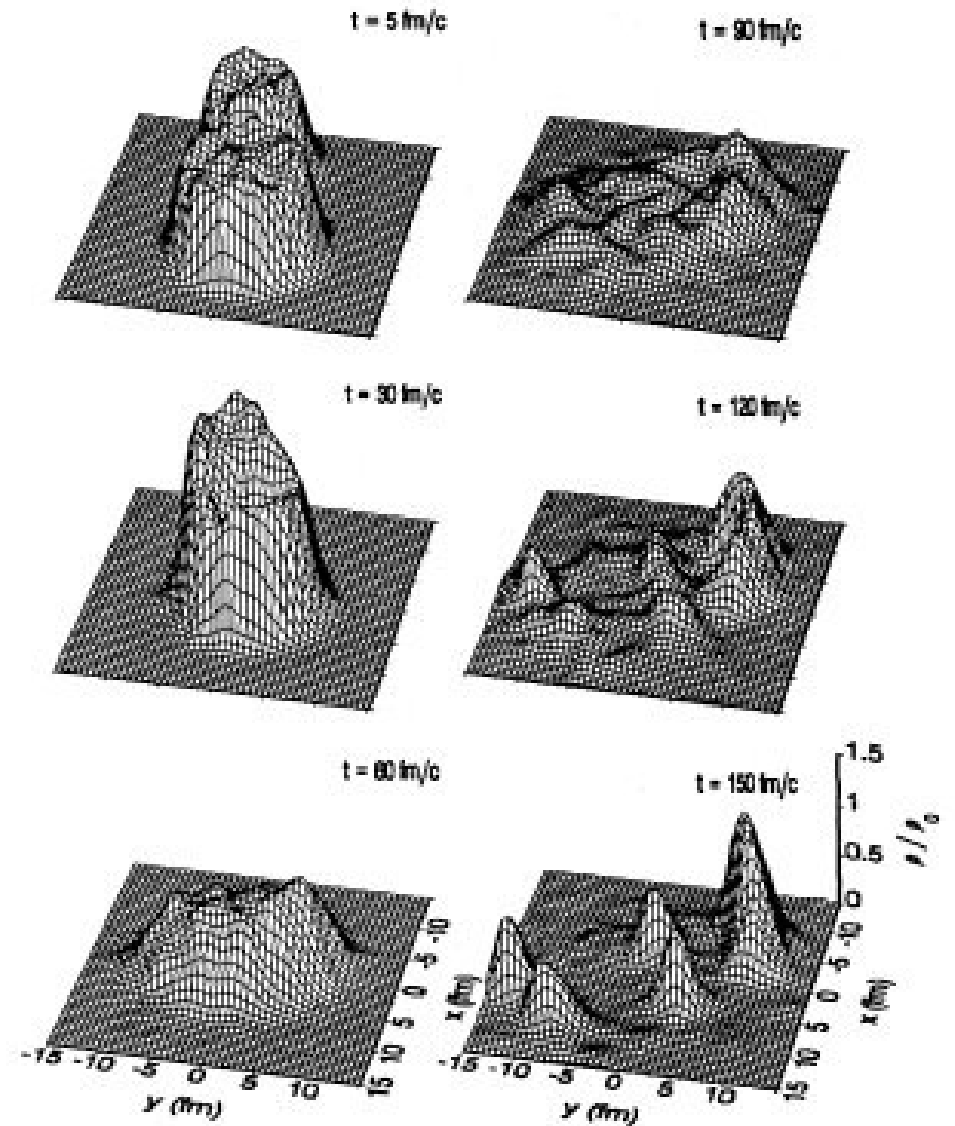
Aplicação à Física de Super-Novas

- M. Famiano (WMU)
- Helio Dias (USP)
- E. Brown (MSU)
- A. Steiner (MSU)

poucas dezenas $\leq E_{Lab}/A <$ *poucas centenas*



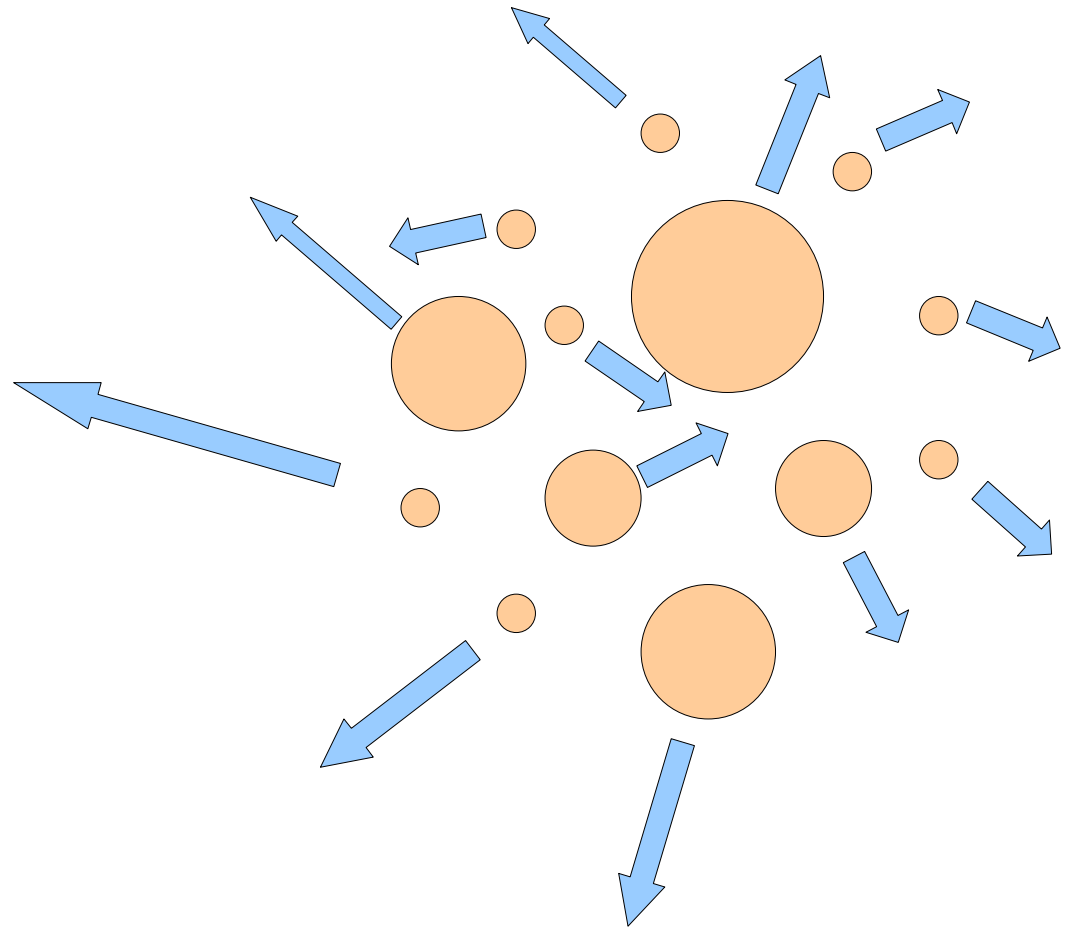
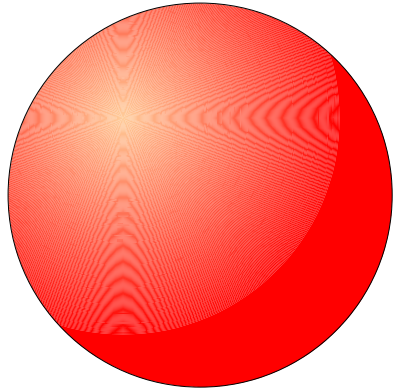
Kr (65 MeV per Nucleon) + Au



S.R. Souza and C. Ngô,
Phys. Rev. C48, R2555 (1993)

$T \neq 0$

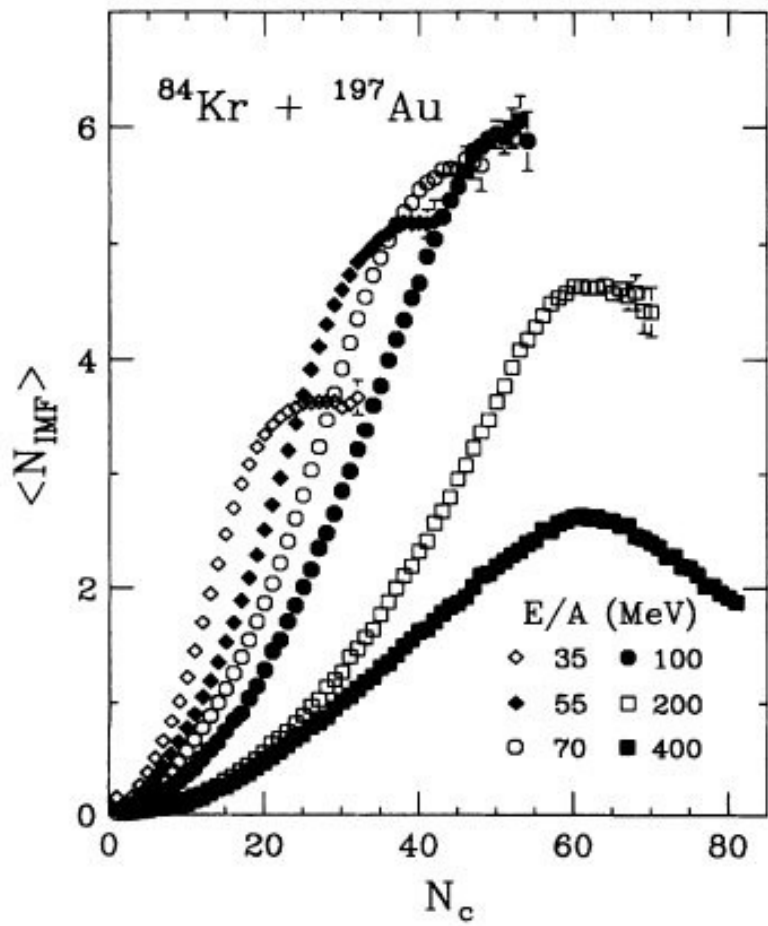
$\rho / \rho_0 < 1/3$



Algumas dezenas de fragmentos carregados

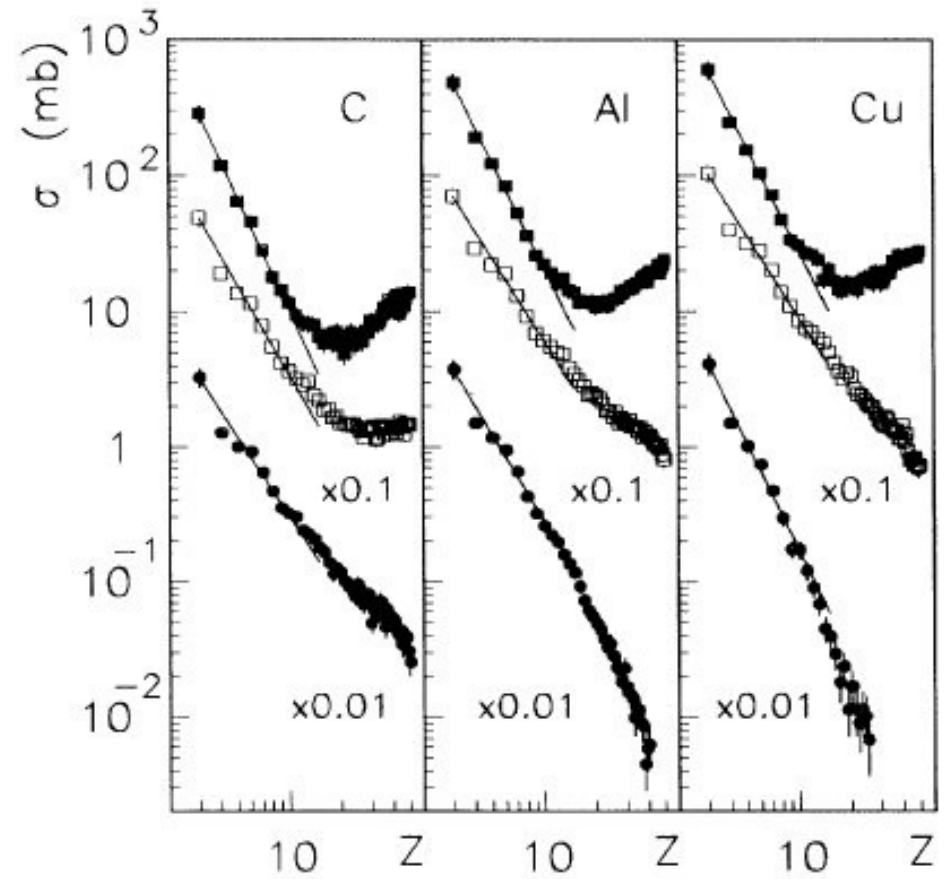
B. Jakobsson et al, Z. Phys. A 307, 293 (1982)

J. E. Finn et al, Phys. Rev. Lett. 49, 1321 (1982)



G. Peaslee et al, Phys. Rev. C49, R2271 (1994)

MSU



C. Ogilvie et al, Phys. Rev. Lett. 67, 1214 (1991)

GSI

Interferometria

S. Pratt e S.E. Koonin
W. Bauer

Escala de tempo: $\tau \approx 100 \text{ fm}/c$

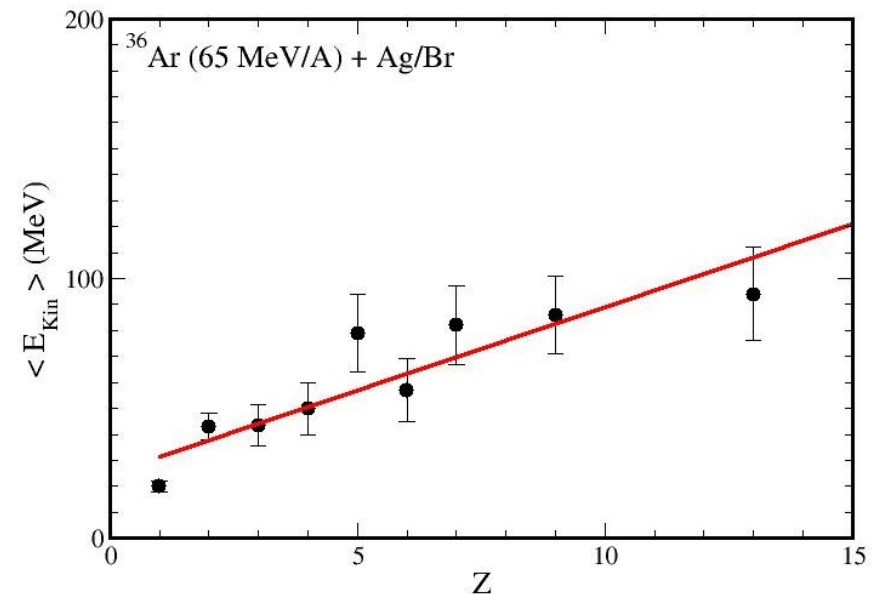
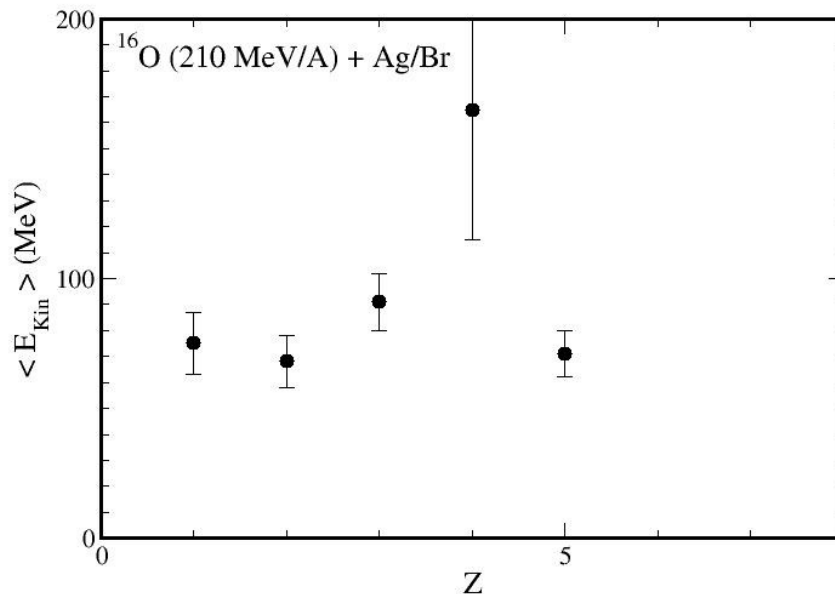
Densidade/Tamanho: $1/3 - 1/6 \rho/\rho_0$

D. Fox et al, Phys. Rev. C 50, 2424 (1994)

J.P. Bondorf, A. S. Botvina, I.N. Mishustin e S.R. Souza,
Phys. Rev. Lett. 73, 628 (1994)

J.B. Natowitz et al, Phys. Rev. C 66, 031601 (2002)

F. Schussler et al., Nucl. Phys. A531, 452 (1991)



Motivação

- Equação de estado da matéria nuclear

$F(\rho, T, x)$  Energia livre de Helmholtz

$$x = (A - 2Z) / A$$

- Transição de fase líquido-gás na matéria nuclear

P.J. Siemens, Nature 305, 410 (1983)

Tratamentos teóricos

● Dinâmicos:

- **Dinâmica molecular:** Equações de movimento clássicas, com ingredientes quânticos, tais como o princípio de Pauli, introduzidos de modo aproximado...

J. Aichelin, Phys. Rep. 202, 233 (1991)

C. Dorso, S. Duarte e J. Randrup, Phys. Lett. B 188, 161 (1987)

S.R. Souza et al, Nucl. Phys. A 571, 159 (1994)

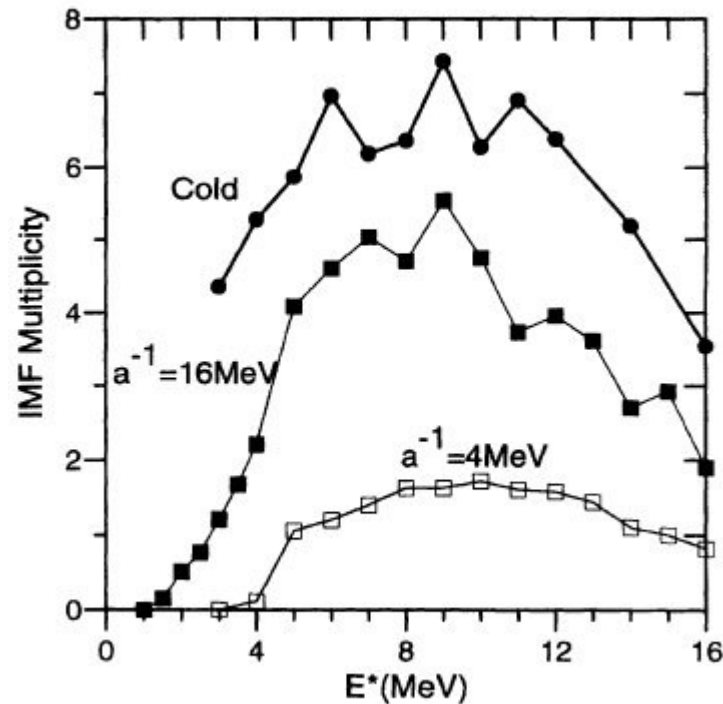
- Virtudes:** Descreve qualitativamente (as vezes quantitativamente) diversas características, como distribuição de carga, fluxo radial, etc.

Problemas

System	DR	QMD	Data
O($E/A = 210$ MeV) + AgBr	1.8	1.6	5.6
Ar($E/A = 65$ MeV) + AgBr	4.1	2.3	7.4
Kr($E/A = 95$ MeV) + AgBr	3.3	4.3	4.4
Au($E/A = 100$ MeV) + Au	9.8	9.5	9.8

R. Donangelo e S.R. Souza, Phys. Rev. C52, 326 (1995)

Capacidade térmica incorreta...

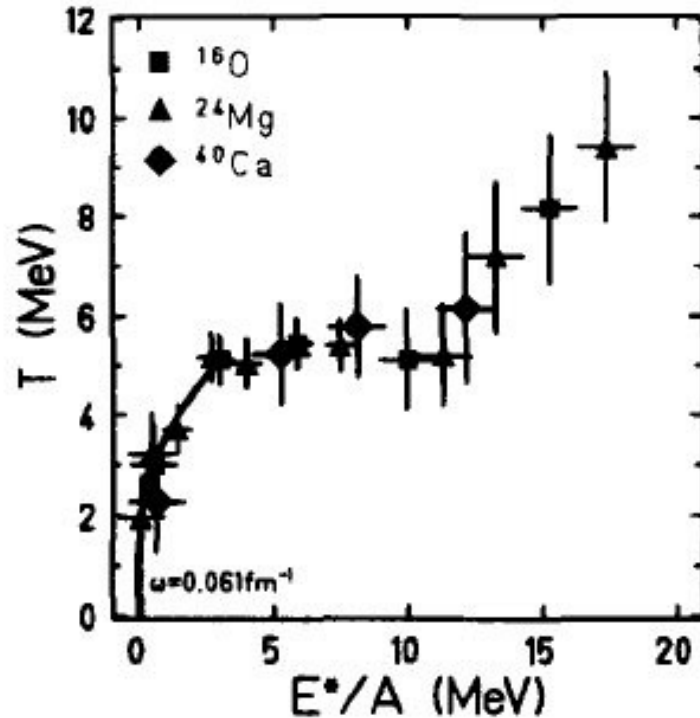


R. Donangelo, H. Schulz, K. Sneppen e S. R. Souza,
Phys. Rev. C50, R563 (1994)

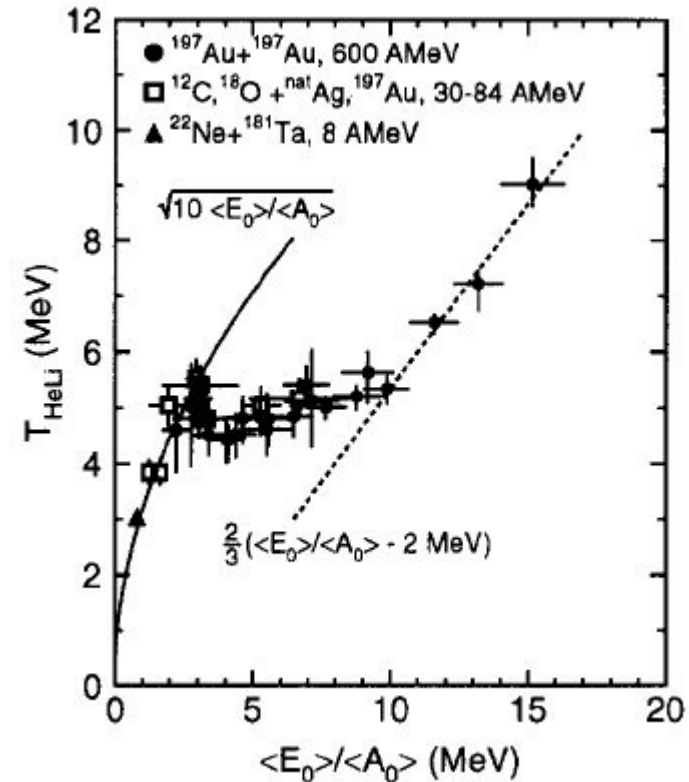
- Dinâmica molecular fermiônica:

H. Feldmeier e J. Schnack, Rev. Mod. Phys. 72, 655 (2000).

Virtudes: Sistema quântico de muitos corpos! Ainda que aproximado... Possui a capacidade térmica correta, reproduz as energias de ligação dos núcleos, etc.



H. Feldmeier e J. Schnack,
Prog. Part. Nucl. Phys. 39, 393 (1997).



J. Pochodzalla et al,
Phys. Rev. Lett. 75, 1040 (1995).

Problemas: Até hoje não pode ser aplicada a um sistema grande...

- Boltzmann-Uhlen-Uhlenbeck (BUU):

$$\frac{\partial}{\partial t} f(\vec{r}, \vec{p}) + \frac{\partial}{\partial \vec{r}} f(\vec{r}, \vec{p}) \cdot \frac{\partial}{\partial \vec{p}} h(\vec{r}, \vec{p}) - \frac{\partial}{\partial \vec{p}} f(\vec{r}, \vec{p}) \cdot \frac{\partial}{\partial \vec{r}} h(\vec{r}, \vec{p}) = I_{coll}$$

$f(\vec{r}, \vec{p})$ \longrightarrow Densidade a 1-corpo

$$h(\vec{r}, \vec{p}) = \frac{\vec{p}^2}{2m} + U[f(\vec{r}, \vec{p})] \longrightarrow \text{Hamiltoniana a 1-corpo}$$

$U[f(\vec{r}, \vec{p})]$ \longrightarrow Potencial a 1-corpo - autoconsistente

$$I_{coll} = \frac{1}{\pi^3 m^2 \hbar^3} \int d^3 \vec{p}_2 d^3 \vec{p}_3 d^3 \vec{p}_4 \delta(\epsilon + \epsilon_2 - \epsilon_3 - \epsilon_4) \delta(\vec{p} + \vec{p}_2 - \vec{p}_3 - \vec{p}_4) \frac{d\sigma}{d\Omega} [f_{\vec{p}_3} f_{\vec{p}_4} (1 - f_{\vec{p}}) (1 - f_{\vec{p}_2}) - f_{\vec{p}} f_{\vec{p}_2} (1 - f_{\vec{p}_3}) (1 - f_{\vec{p}_4})]$$

S.R. Souza and C. Ngô,
Phys. Rev. C48, R2555 (1993)

Virtudes: Retem diversos ingredientes quânticos, como a ocupação máxima do espaço de fase, leva a distribuição de Fermi-Dirac no equilíbrio, etc.

Problemas: Implementação numérica:

Espaço de fase em 6 dimensões impossibilita a utilização de métodos numéricos confiáveis. Os utilizados não garantem as propriedades desejadas.

Descrição a 1-corpo de um fenômeno de muitos corpos.

Avanços: Boltzmann-Langevin: Inclusão de flutuações térmicas na distribuição a 1-corpo

J. Randrup e B. Rermaud, Nucl. Phys. A514, 339 (1990).

Ph. Chomaz, G.F. Burgio and J. Randrup, Phys. Lett. B 254 340 (1991).

G.F. Burgio, Ph. Chomaz and J. Randrup, Nucl. Phys. A 529 , 157 (1991).

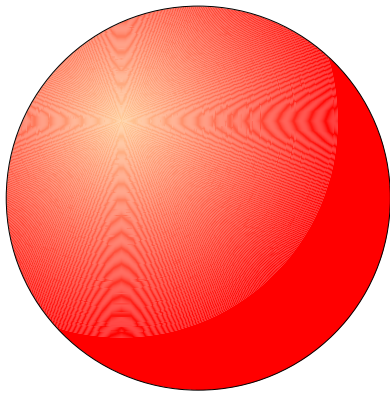
F.S. Zhang, SURAUD E. Suraud, Phys. Lett. B319, 35 (1993).

Modelos Estatísticos

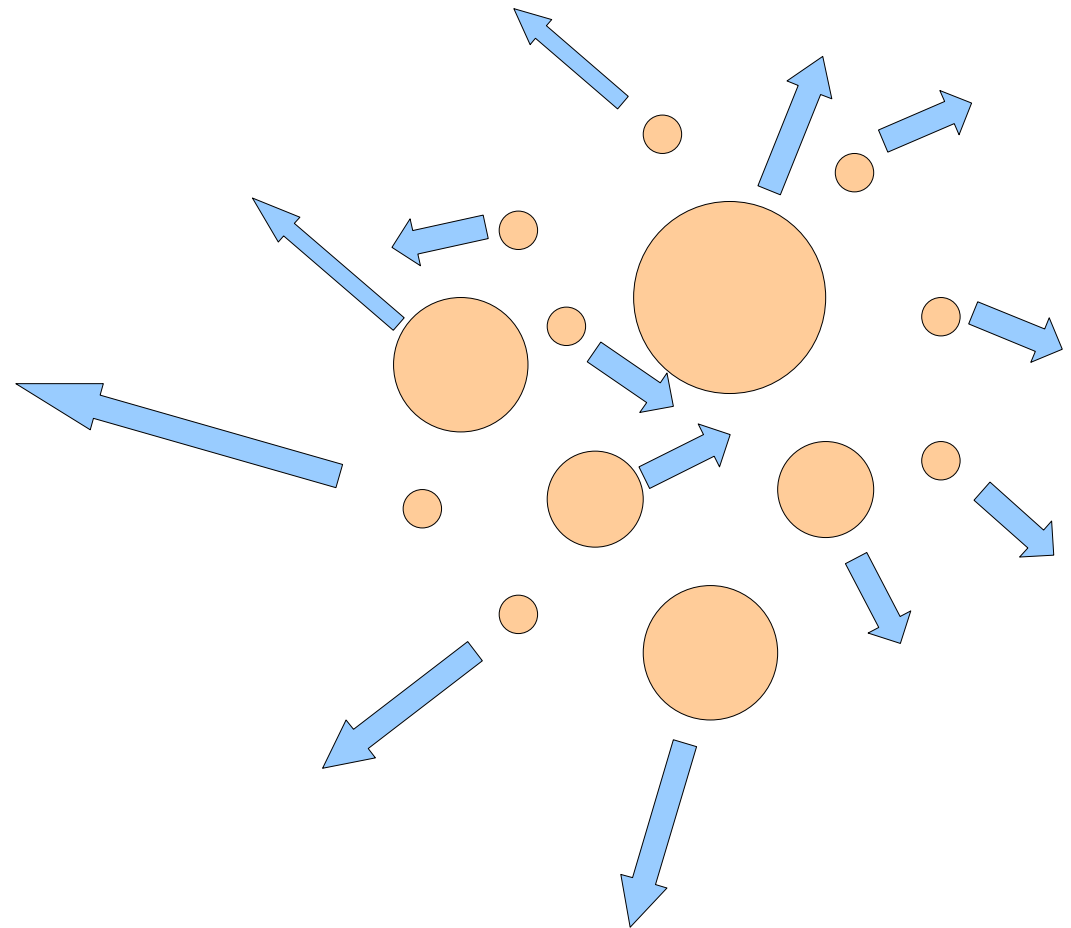
J. P. Bondorf et al, Phys. Rep. 257, 133 (1995).

D.H.E. Gross, Phys. Rep. 279, 120 (1997).

Equilíbrio térmico



Quebra simultânea



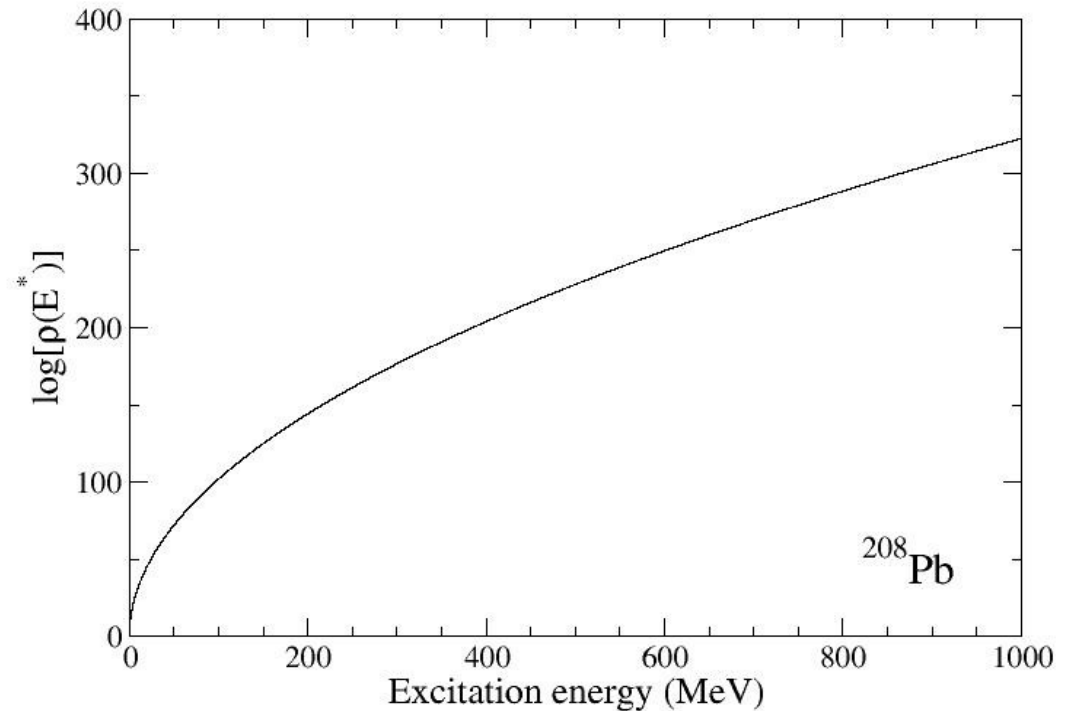
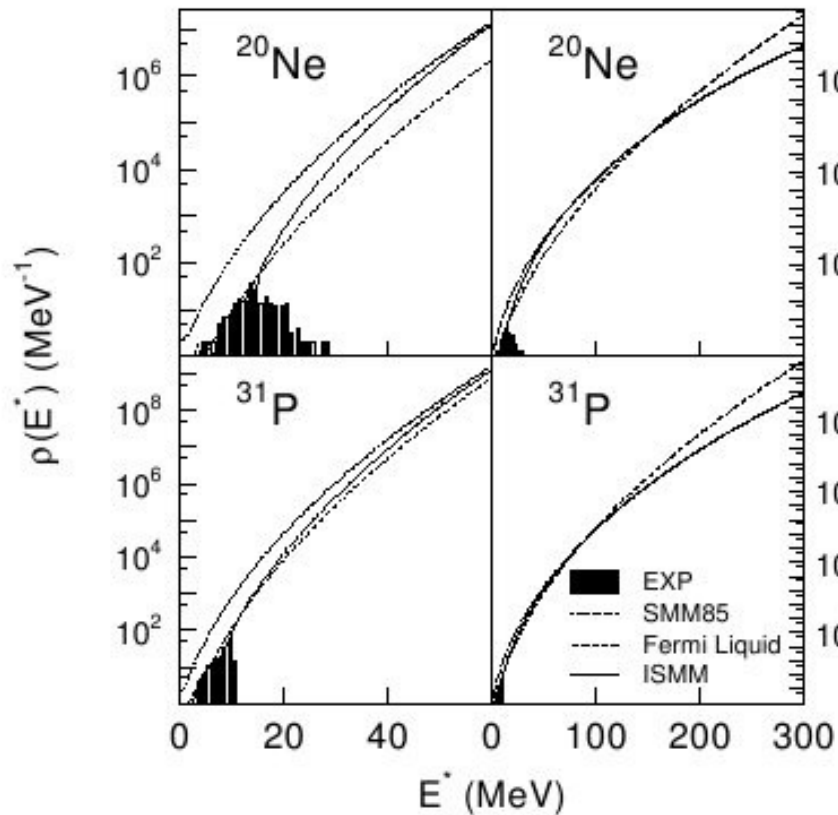
Justificativa

Niels Bohr, Nature 137, 344 (1936)

—► Decaimento do “núcleo composto”

V. Weisskopf, Phys. Rev. 52, 295 (1937)
Phys. Rev. 57, 472 (1940)

—► Primeiro tratamento estatístico



S.R. Souza et al, Phys. Rev. C68, 034609 (2003)

The Statistical Multifragmentation Model - SMM

J.P. Bondorf et al, Nucl. Phys. A443, 321 (1985), Nucl. Phys. A444, 460 (1985)
 K. Sneppen, Nucl. Phys. A470, 213 (1987)

$$A_0 = \sum_i A_i n_i \qquad Z_0 = \sum_i Z_i n_i \qquad \longrightarrow \qquad \text{Conservação de massa e carga}$$

$$-B_{A_0, Z_0} + E^* = a_{Coul} \frac{Z_0^2}{A_0^{1/3}} \frac{1}{(1+\chi)^{1/3}} + \sum_i n_i E_i \qquad \longrightarrow \qquad \text{Conservação de energia}$$

$$E = F + TS$$

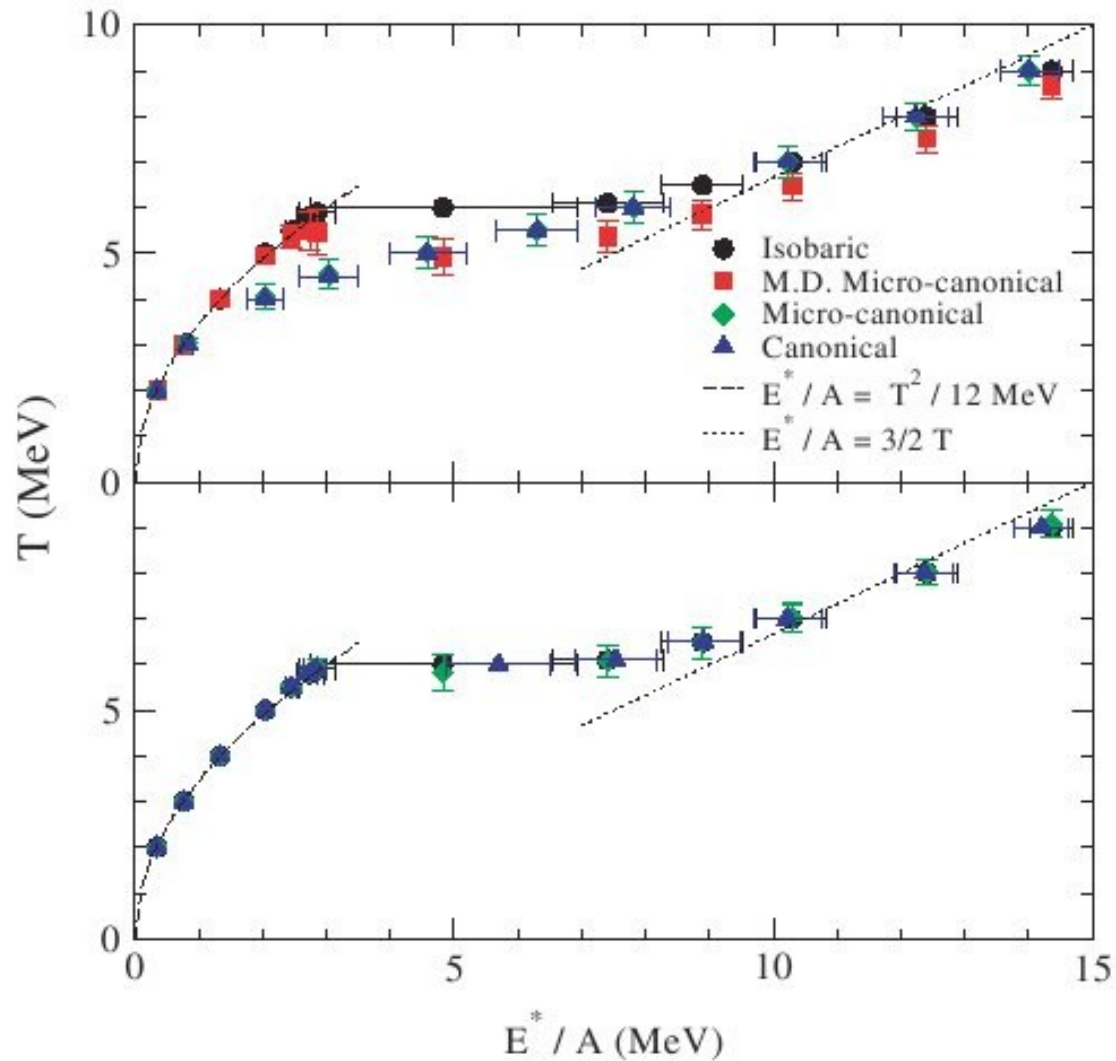
$$S = -\frac{dF}{dT}$$

$$F = \sum_i n_i (f_i - B_i)$$

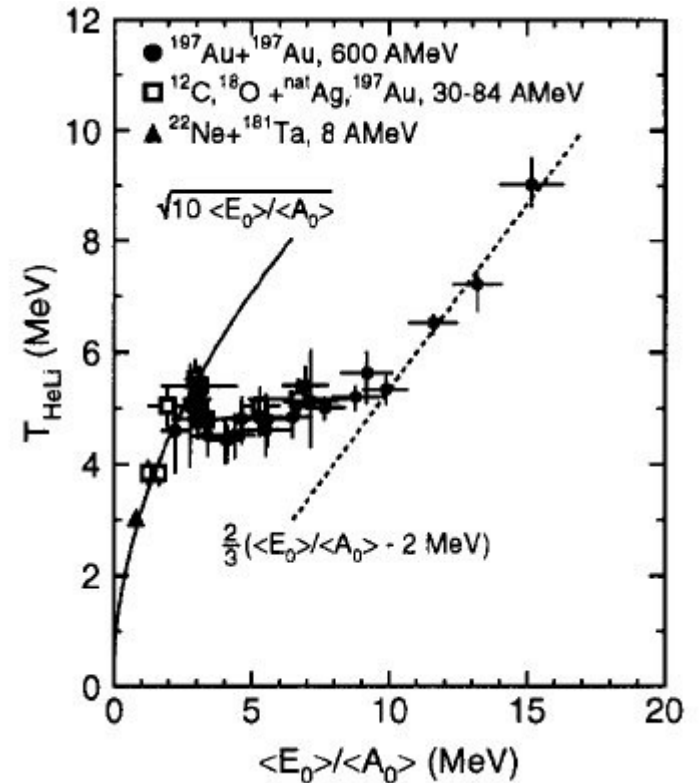
$$f_{bulk}(T) = -a_{ld} T^2 \qquad f_{surf}(T) = \beta_0 \left[\left(\frac{T_c^2 - T^2}{T_c^2 + T^2} \right)^{5/4} - 1 \right] \qquad f_{Coul} = a_{Coul} \frac{Z_i^2}{A_i^{1/3}} \left[1 - \frac{1}{(\chi + 1)^{1/3}} \right]$$

$$f_{trans}(T) = -T \ln \left[\frac{g_i V_0}{1 + \chi} \left(\frac{m A_i T}{2 \pi \hbar} \right)^{3/2} \right] + T \ln (n_i!) / n_i$$

J.P. Bondorf et al, Nucl. Phys. A444, 460 (1985).



C.E. Aguiar, R. Donangelo e S.R. Souza,
 Phys. Rev. C73, 024613-1 (2006).



J. Pochodzalla et al,
 Phys. Rev. Lett. 75, 1040 (1995).

S. Albergo et al, Nuovo Cimento 89, 1 (1985).

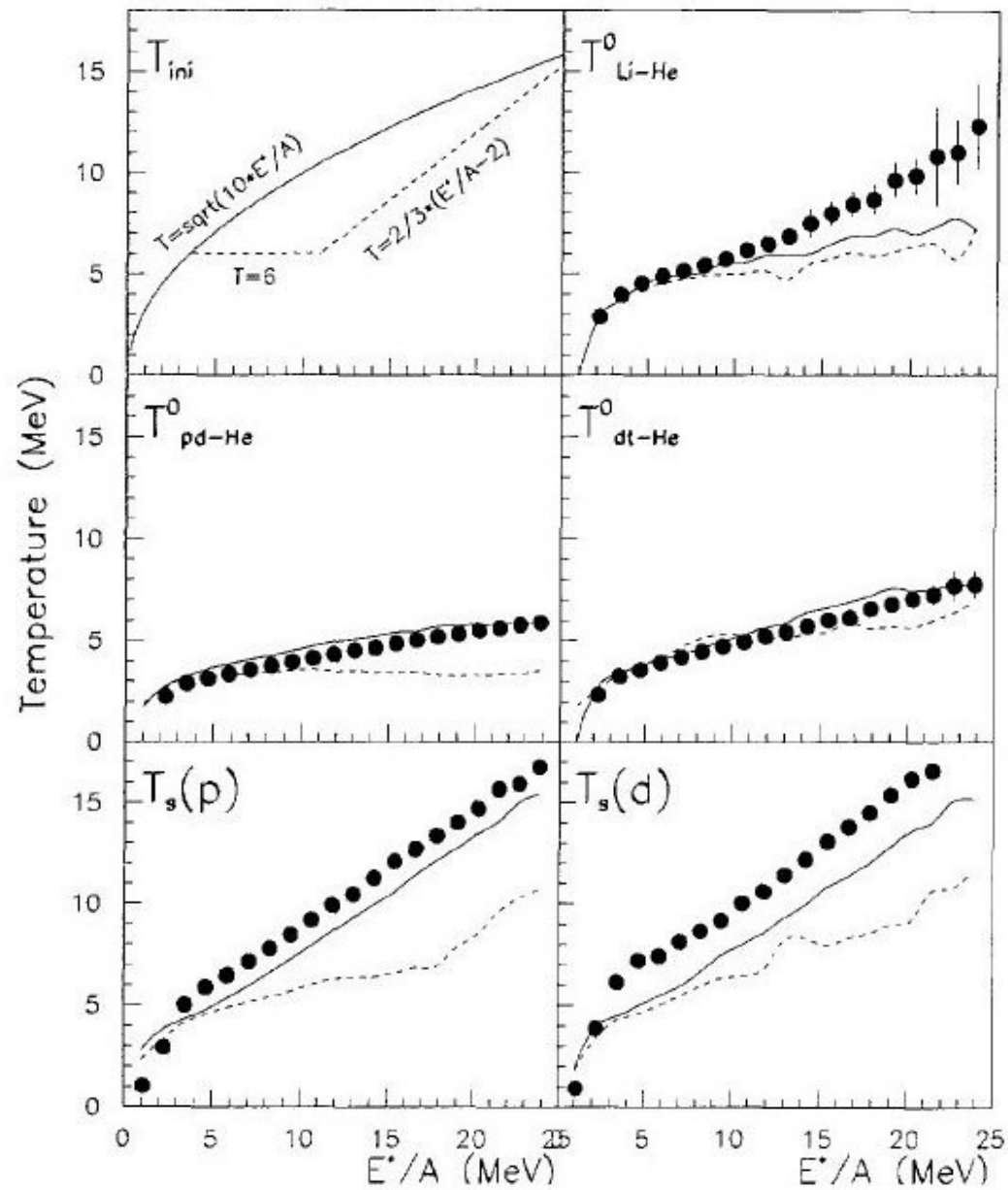
$$Y(N, Z) = V_f \frac{A^{3/2}}{\lambda_T} \zeta_{AZ}(T, V_f) \exp\left[\frac{\mu_p Z + \mu_n N}{T}\right] \quad \zeta_i = \sum_j g_i^{(j)} \exp\left[-\frac{\Delta E_j}{T}\right]$$

$$\lambda_T = \sqrt{2\pi \hbar^2 / mT}$$

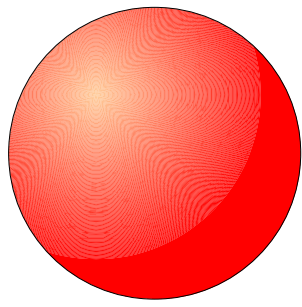
$$\frac{Y(A_1, Z_1)/Y(A_1+1, Z_1)}{Y(A_2, Z_2)/Y(A_2+1, Z_2)} = C \exp(\Delta B/T)$$

Isótopos escolhidos cuidadosamente para maximizar:

$$\Delta B = B(A_1, Z_1) - B(A_1+1, Z_1) - B(A_2, Z_2) + B(A_2+1, Z_2)$$

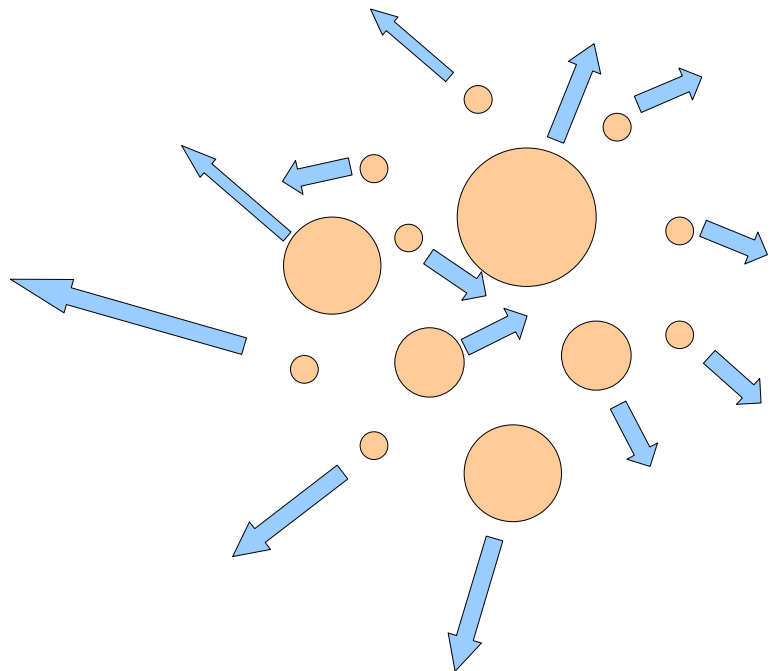
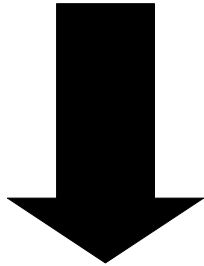


Y.-G. Ma et al., Phys. Lett. B390, 41 (1997).

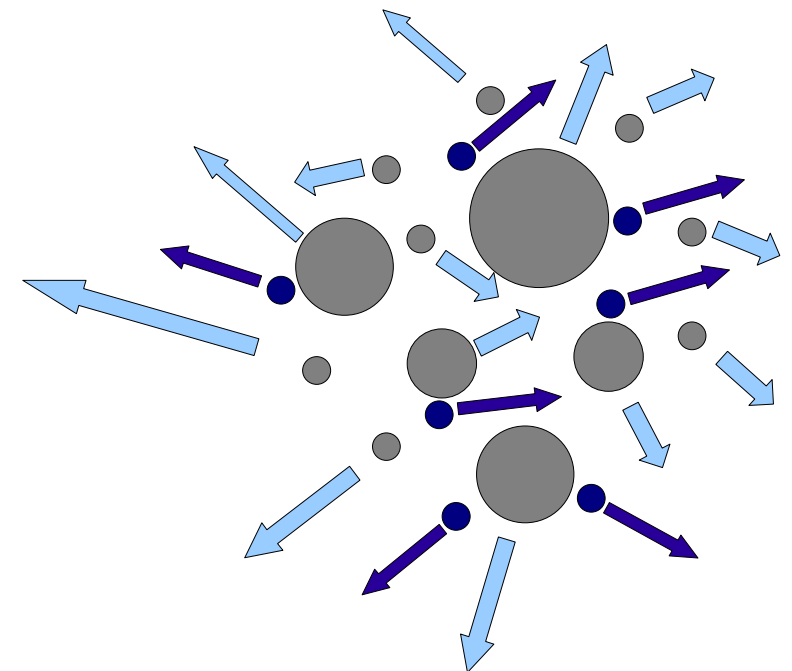
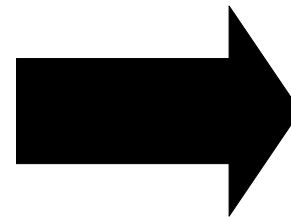


S.R. Souza et al., Phys. Rev. C62, 064607 (2000).

A. Kelic, J.B. Natowitz e .H. Schmidt,
Eur. Phys. J. A 40, 203 (2006).

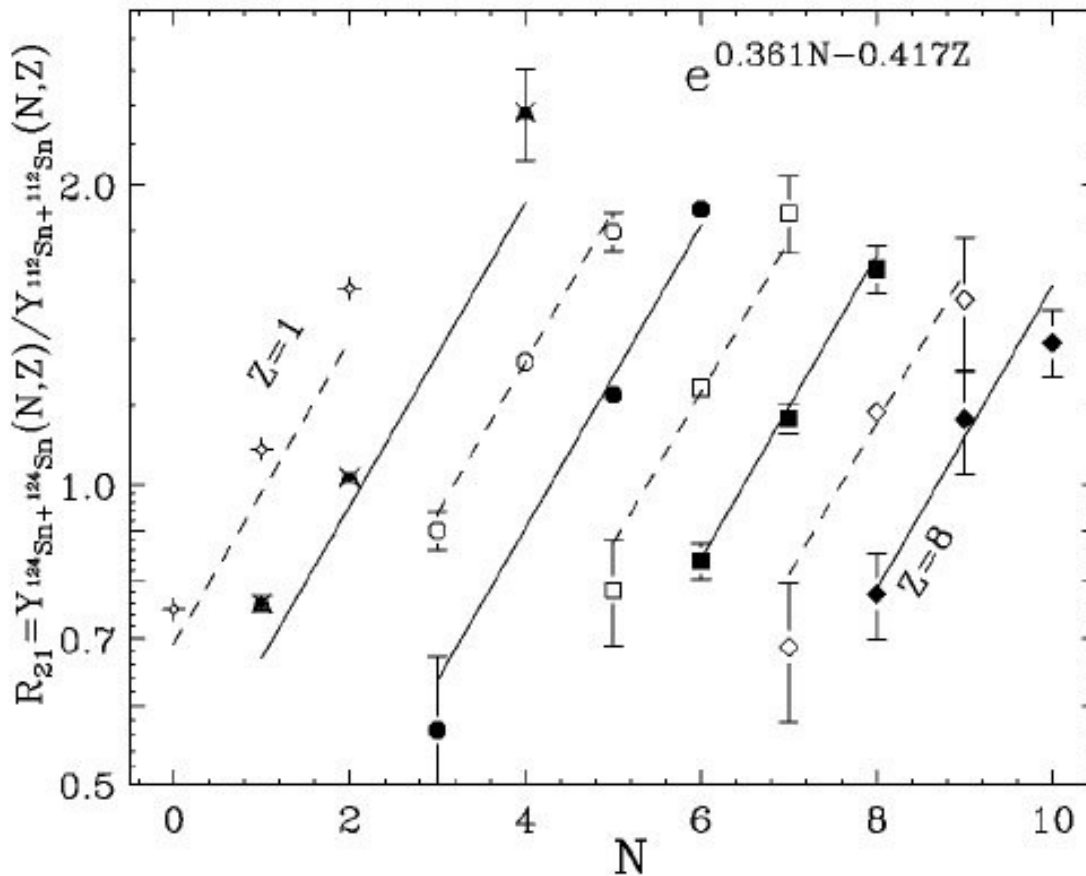


Decaimento secundário



Isoscaling

$$R_{21} = Y_2(N, Z) / Y_1(N, Z) = C \exp(\alpha N + \beta Z)$$



M.B. Tsang et al., Phys. Rev. C64, 054615 (2001).

Ensemble grand-canônico

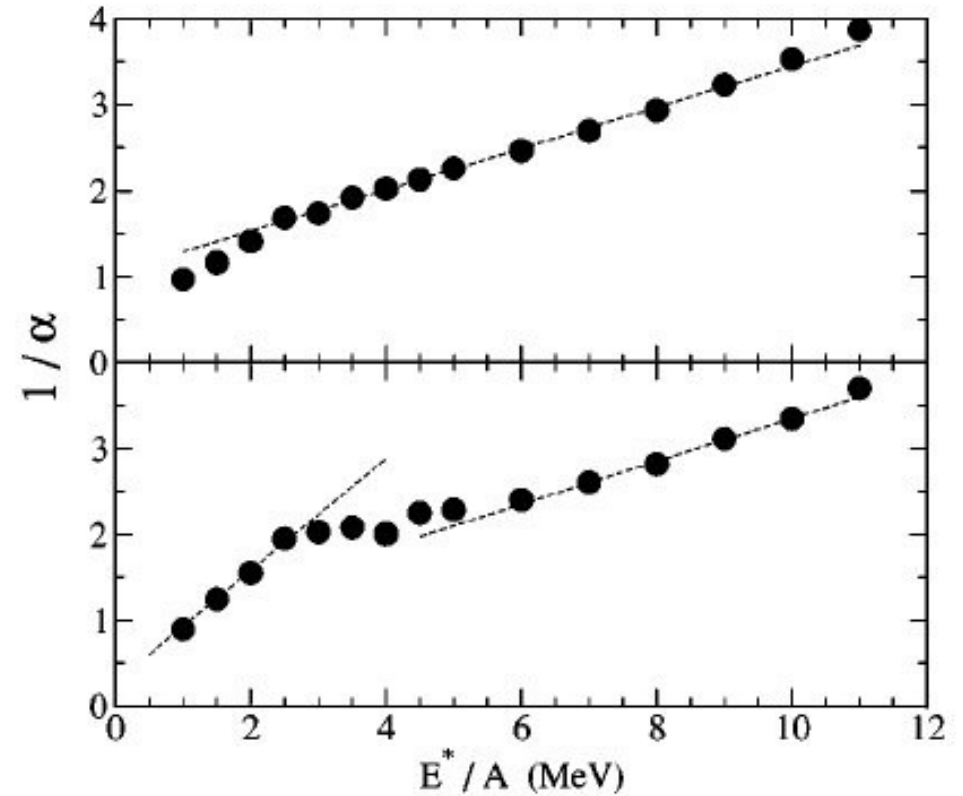
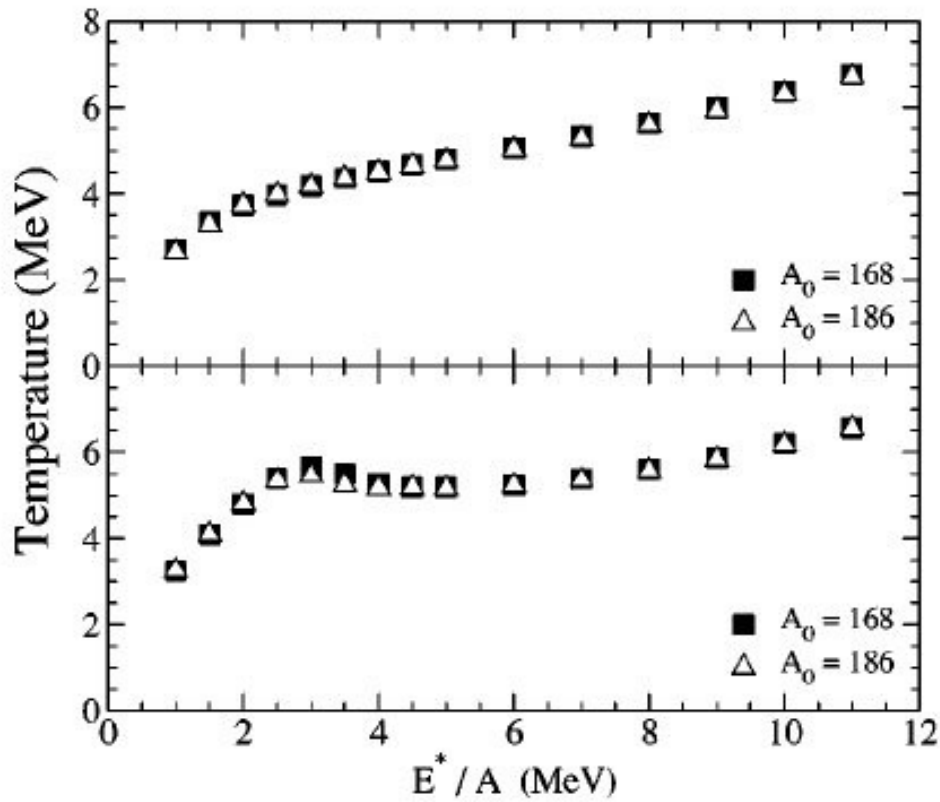
$$Y(N, Z) = \zeta_{AZ}(T, V_f) \exp\left[\frac{\mu_p Z + \mu_n N}{T}\right]$$

$$\zeta_{AZ} = g_{AZ} \frac{V_f}{\lambda_T^3} A^{3/2} \exp\left[\frac{B_{AZ} - f_{AZ}(T)}{T}\right]$$

$$\alpha = \frac{\mu_n^{(2)} - \mu_n^{(1)}}{T}$$

$$\beta = \frac{\mu_p^{(2)} - \mu_p^{(1)}}{T}$$

Statistical Multifragmentation Model



S.R. Souza et al., Phys. Rev. C69, 031607 (2004).

Considerações Finais

- O comportamento qualitativo da curva calórica nuclear é um **problema em aberto**.
- É necessário o desenvolvimento de métodos confiáveis para a determinação da energia de excitação e da temperatura de breakup.
- Efeitos de não equilíbrio podem ser importantes
[T.X. Liu et al, Eur. Phys. Lett. 74, 806 \(2006\)](#).
- O fluxo radial contém informações importantes sobre não equilíbrio e sobre a geometria do sistema
[S.R. Souza et al., Phys. Rev. C76, 024614 \(2007\)](#).