ANGULAR-MOMENTUM DEPENDENCE OF CLUSTER-GAMMA COMPETITION IN PRE-EQUILIBRIUM REACTIONS

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Pre-equilibrium reactions *(exciton model)*:

Pre-eq. cross sections and energy spectra

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon_x} = \sigma_{\mathrm{R}} \sum_n \tau_n \lambda_x^c(n, E, \varepsilon_x)$$

where the time spent by a nucleus in an *n*-exciton state is given by the time integral of the occupation probabilities,

$$\tau_n = \int_0^\infty P(n, E, t)\mathrm{d}t$$

The occupation probabilities are obtained from the set of master equations *(written here with all couplings necessary for sequential decays and for γ cascades)*

$$
\begin{aligned}
\frac{\mathrm{d}P(i,n,E,J,t)}{\mathrm{d}t} &= P(i,n-2,E,J,t)\,\lambda^{+}(i,n-2,E,J) \\
&+ P(i,n+2,E,J,t)\,\lambda^{-}(i,n+2,E,J) \\
&- P(i,n,E,J,t)\,\Big[\lambda^{+}(i,n,E,J)+\lambda^{-}(i,n,E,J) \\
&\qquad\qquad +L(i,n,E,J)\Big] \\
&+ \sum_{i',J',n',x} \int P(i',n',E',J',t) \\
&\qquad\qquad \times\lambda_x^c([i',n',E',J'] \xrightarrow{\varepsilon} [i,n,E,J])\mathrm{d}\varepsilon,
\end{aligned}
$$

Nucleon emission is associated with Δ *n = -1.* In the spin-independent case, the nucleon emission rates are

$$\lambda_x^c(n, E, \varepsilon_x) = \frac{2s_x + 1}{\pi^2 \hbar^3} \mu_x \varepsilon_x \sigma^*_{\mathrm{INV}}(\varepsilon_x) \frac{\omega(p-1, h, U)}{\omega(p, h, E)} \mathcal{R}_x(p)$$

Gamma emission in pre-equilibrium reactions:

First attempt (Plujko & Prokopets) **?**

Single-particle radiative mechanism $\Delta n = 0, -2$
(Běták & Dobeš, Akkermans & Gruppelaar)

Spin variables (Obložinský & Chadwick)

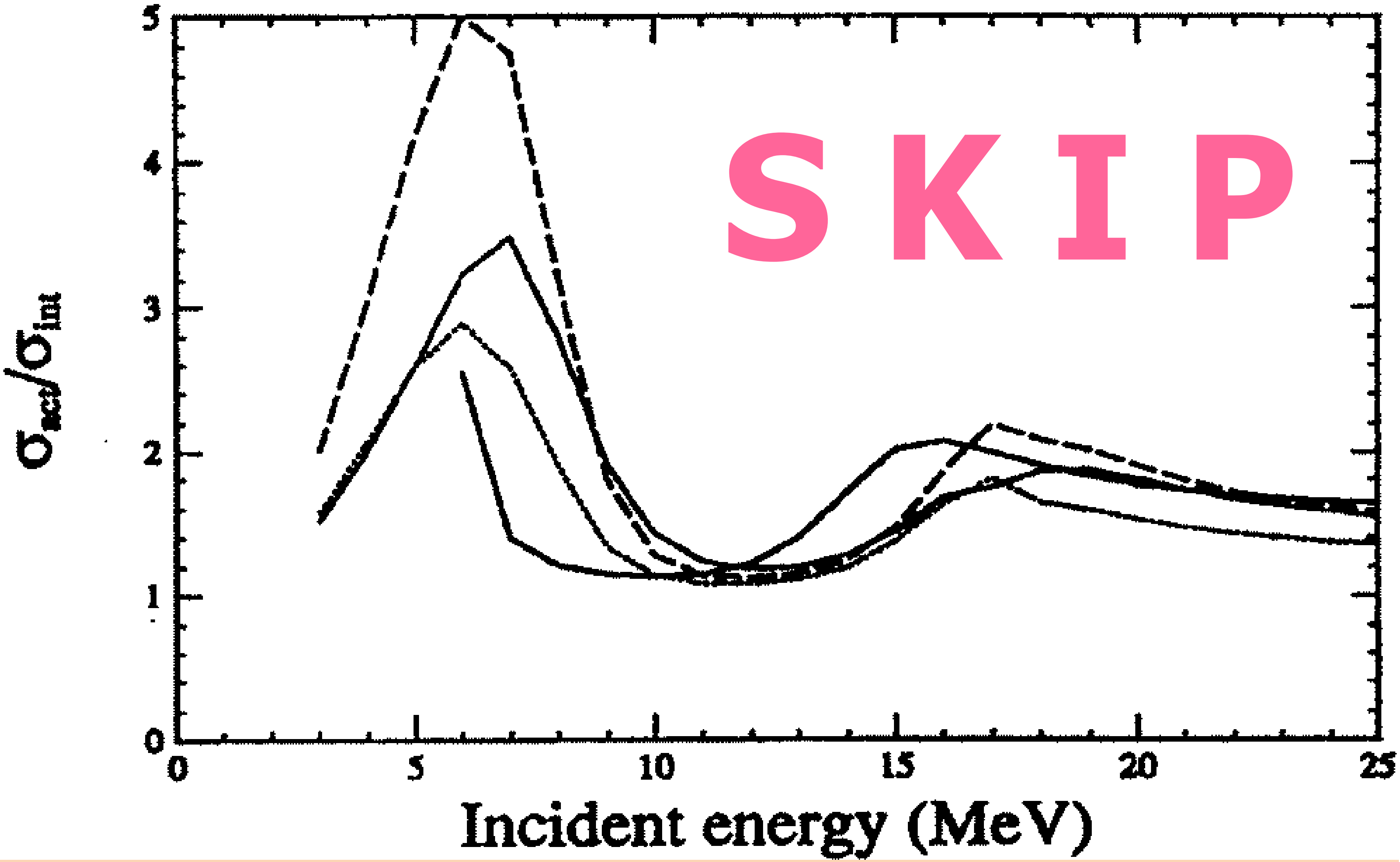
At excitation energies above 30 MeV – also quasideuteron mechanism (Obložinský)

The γ emission is possible for Δ *n* = *-2* or *0.* These rates *(in the spin-independent case and for E1)* are

$$\lambda_\gamma(n,E,\varepsilon_\gamma) = \frac{\varepsilon_\gamma^2 \sigma_{\rm GDR}(\varepsilon_\gamma)}{\pi^2 \hbar^3 c^2} \frac{\sum_{m=n,n-2} b(m,\varepsilon_\gamma)\omega(m,E-\varepsilon_\gamma)}{\omega(n,E)}$$

$$\begin{aligned} b(n-2,\varepsilon_\gamma) &= \frac{\omega(2,\varepsilon_\gamma)}{g(n-2)+\omega(2,\varepsilon_\gamma)} \\ b(n,\varepsilon_\gamma) &= \frac{gn}{gn+\omega(2,\varepsilon_\gamma)} \end{aligned}$$

and *b*'s are the branching ratios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$\sigma_{act}/\sigma_{int}$
Incident energy (MeV)
0
1
2
3
4
5
0
5
10
15
20
25

$$\lambda^{\pm}(n, E) = \frac{2\pi}{\hbar} |M_{\mathrm{nonspin}}|^2 \omega_{\mathrm{f}}(n \pm 2, E)$$

$$\lambda^{\pm}(n, E, J) = \frac{2\pi}{\hbar} |M|^2 \omega_{\mathrm{f}}(n \pm 2, E) X_{nJ}{}^{\downarrow}.$$

Spin variables (Obložinský & Chadwick)

$$X_{nJ}{}^{\downarrow} = \frac{1}{R_n(J)} \sum_{j_4 Q} R_1(Q)\tilde{F}(Q)R_{n-1}(j_4)\Delta(Qj_4J)$$

$$\tilde{F}(Q) = \sum_{j_3 j_5} (2j_5+1)R_1(j_5)(2j_3+1)F(j_3) \begin{pmatrix} j_5 & j_3 & Q \\ \frac{1}{2} & 0 & -\frac{1}{2} \end{pmatrix}^2$$

$$F(j_3) = \sum_{j_1 j_2} (2j_1+1)R_1(j_1)(2j_2+1)R_1(j_2) \begin{pmatrix} j_1 & j_2 & j_3 \\ \frac{1}{2} & -\frac{1}{2} & 0 \end{pmatrix}^2$$

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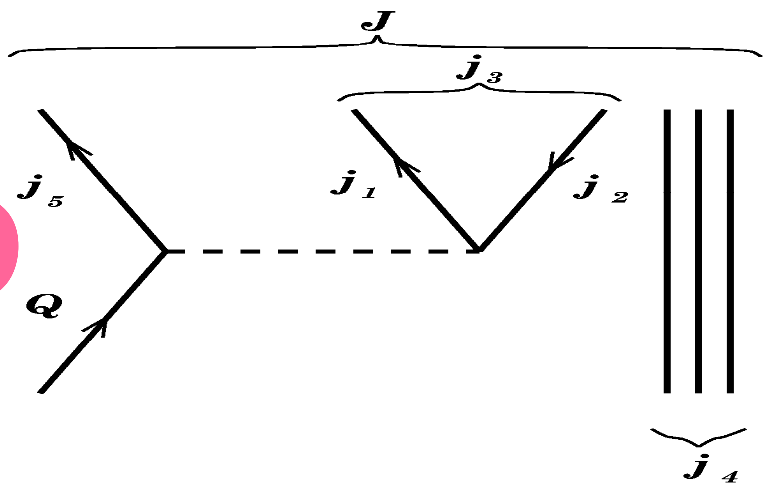

gamma emission rates with spin

$$\lambda_\gamma([E,n,J] \stackrel{\varepsilon_\gamma,\lambda}{\rightarrow} [U,m,S]) = \frac{\varepsilon_\gamma^{2\lambda}\sigma_{\mathrm{GDR}}(\varepsilon_\gamma)}{3\pi^2\hbar^3c^2}\frac{b_{nS}^{nJ}\,\omega(m,E-\varepsilon_\gamma,S)}{\omega(n,E,J)}$$

$$b_{mS}^{nJ} = \frac{y_m^n x_{mS}^{nJ}}{y_m^m x_{mS}^{mJ} + y_m^{m+2} x_{mS}^{m+2J}}$$

$$x_{nS}^{nJ} = \frac{(2\lambda+1)(2J+1)}{R_n(S)} \sum_{j_1 j_2 j_3} (2j_1+1)R_1(j_1)(2j_2+1)R_1(j_2)R_{n-1}(j_3) \times \begin{pmatrix} j_2 & \lambda & j_1 \\ \frac{1}{2} & 0 & -\frac{1}{2} \end{pmatrix}^2 \begin{Bmatrix} j_2 & j_3 & S \\ J & \lambda & j_1 \end{Bmatrix}^2$$

$$x_{nS}^{n+2J} = \frac{2J+1}{2S+1} \sum_{j_1 j_2} (2j_1+1)R_1(j_1)(2j_2+1)R_1(j_2) \times \begin{pmatrix} j_2 & j_1 & \lambda \\ \frac{1}{2} & -\frac{1}{2} & 0 \end{pmatrix}^2 \Delta(Si\lambda J)$$

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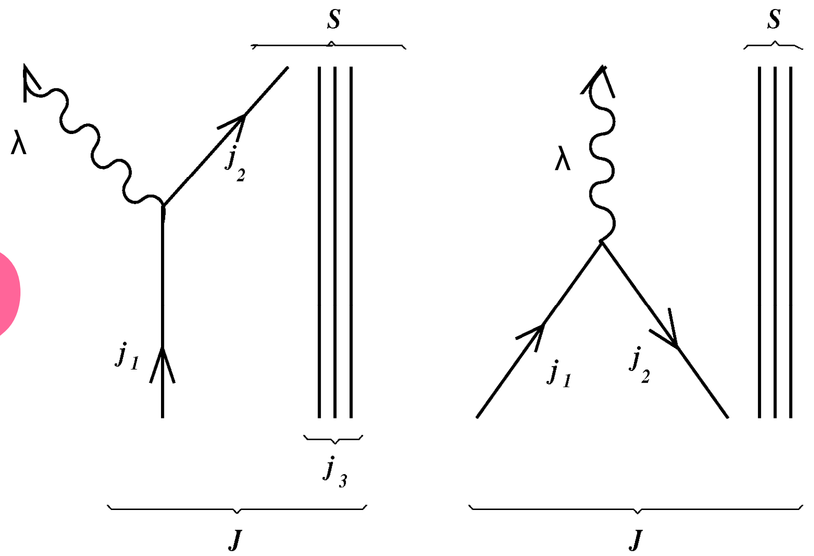
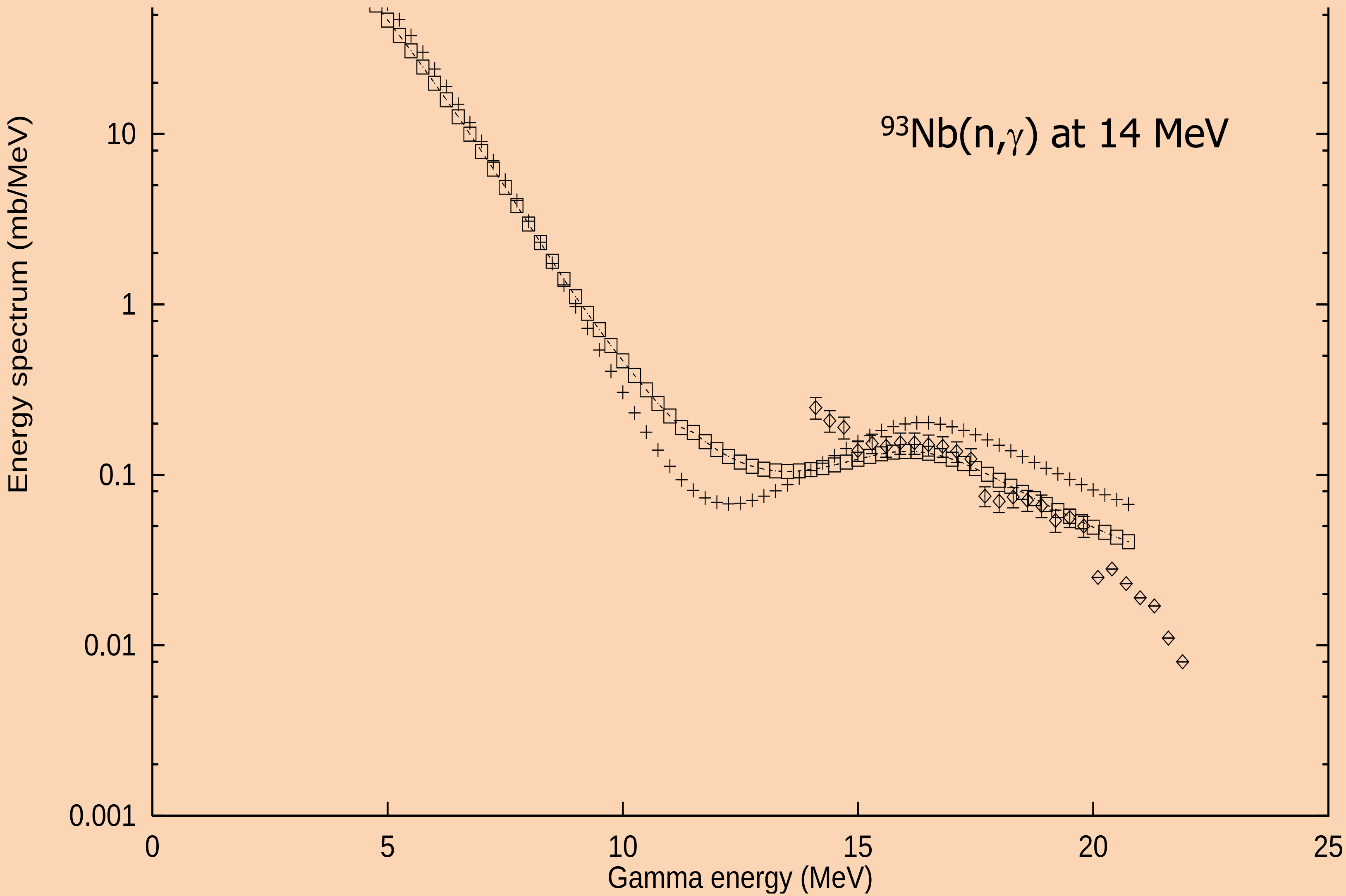



^{93}Nb(n,γ) at 14 MeV
Energy spectrum (mb/MeV)
10
1
0.1
0.01
0.001
0
5
10
15
20
25
Gamma energy (MeV)

- **Light clusters: d to α**
- **Coalescence model:**

Kalbach (Cline, Kalbach-Cline, Kalbach-Walker), Ribanský & Obložinský

Emision rate (nucleons):

$$\lambda_x^c(n,E,\varepsilon_x) = \frac{2s_x+1}{\pi^2\hbar^3}\; \mu_x \varepsilon_x \sigma^*_{INV}(\varepsilon_x) \frac{\omega(p-1,h,U)}{\omega(p,h,E)} R_x(p)$$

Coalescence clusters:

$$\lambda_x^c(n,E,\varepsilon_x) = \frac{2s_x+1}{\pi^2\hbar^3}\; \mu_x \varepsilon_x \sigma^*_{INV}(\varepsilon_x) \frac{\omega(p-p_x,h,U)}{\omega(p,h,E)} R_x(p)\gamma_x \frac{\omega(p_x,0,\varepsilon_x+B_x)}{g_x}$$

- **Generalized (coalescence + pickup)**

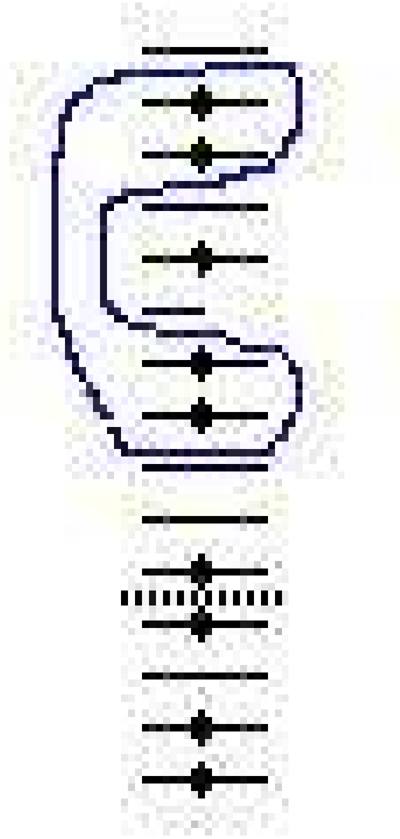
Iwamoto & Harada, Dobeš & Běták, Bisplinghoff

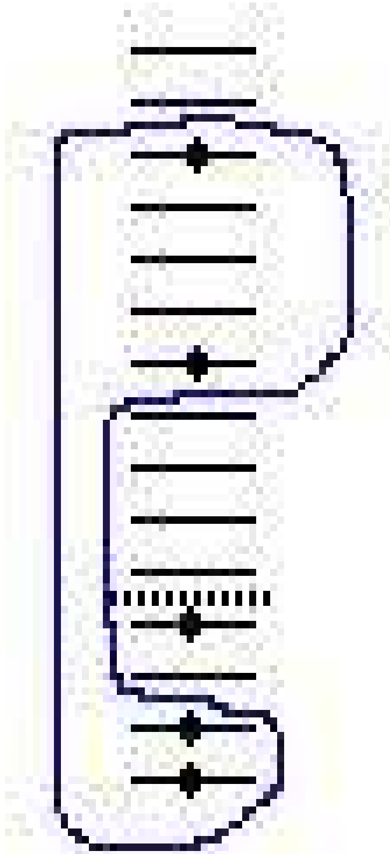
$$\omega(p-p_x,h,U)\omega(p_x,0,\varepsilon_x+B_x)$$

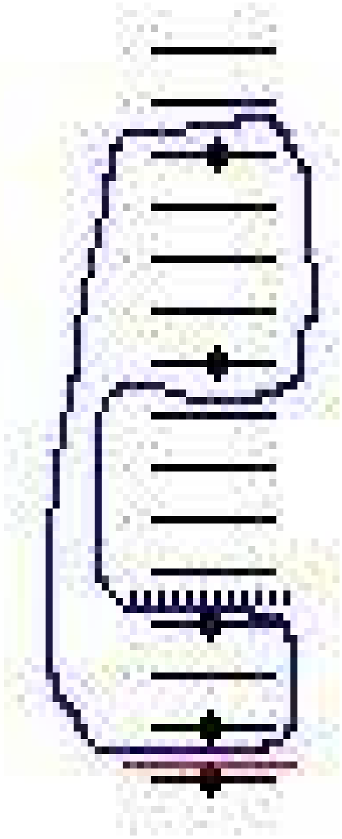
$$\rightarrow$$

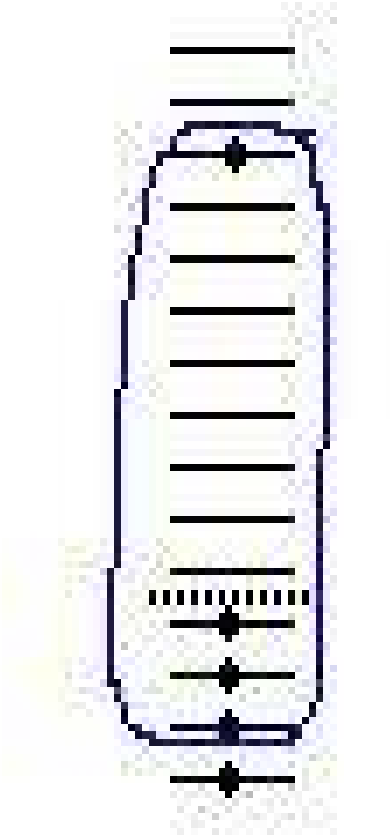
$$\sum_{p^*=1}^{p_x}\int_{\varepsilon_x+B_x}^{E}\omega(p-p^*,h,E-\varepsilon_1)\omega(p^*,0,\varepsilon_1)\omega(0,p_x-p^*,\varepsilon_2)d\varepsilon_1$$

PARAMETERLESS !









coalescence *IH model* *IHB model* *knock-out*

- *Bisplinghoff*

Pickup limited by the binding energy of nucleons in the cluster (i.e. about 28 MeV for alphas and 2 MeV for deuterons)

- ***Now***

Limitation due to binding energy for all clusters

Only low-exciton configurations with pickup (CN limit!)

Thermal “blurring” considered

Admixture allowed for whole nuclear potential well

Possibility of knockout (initial stage only) for alphas

$$\propto \int_0^E \omega(0,4,U-\varepsilon)\omega(1,0,\varepsilon)d\varepsilon$$

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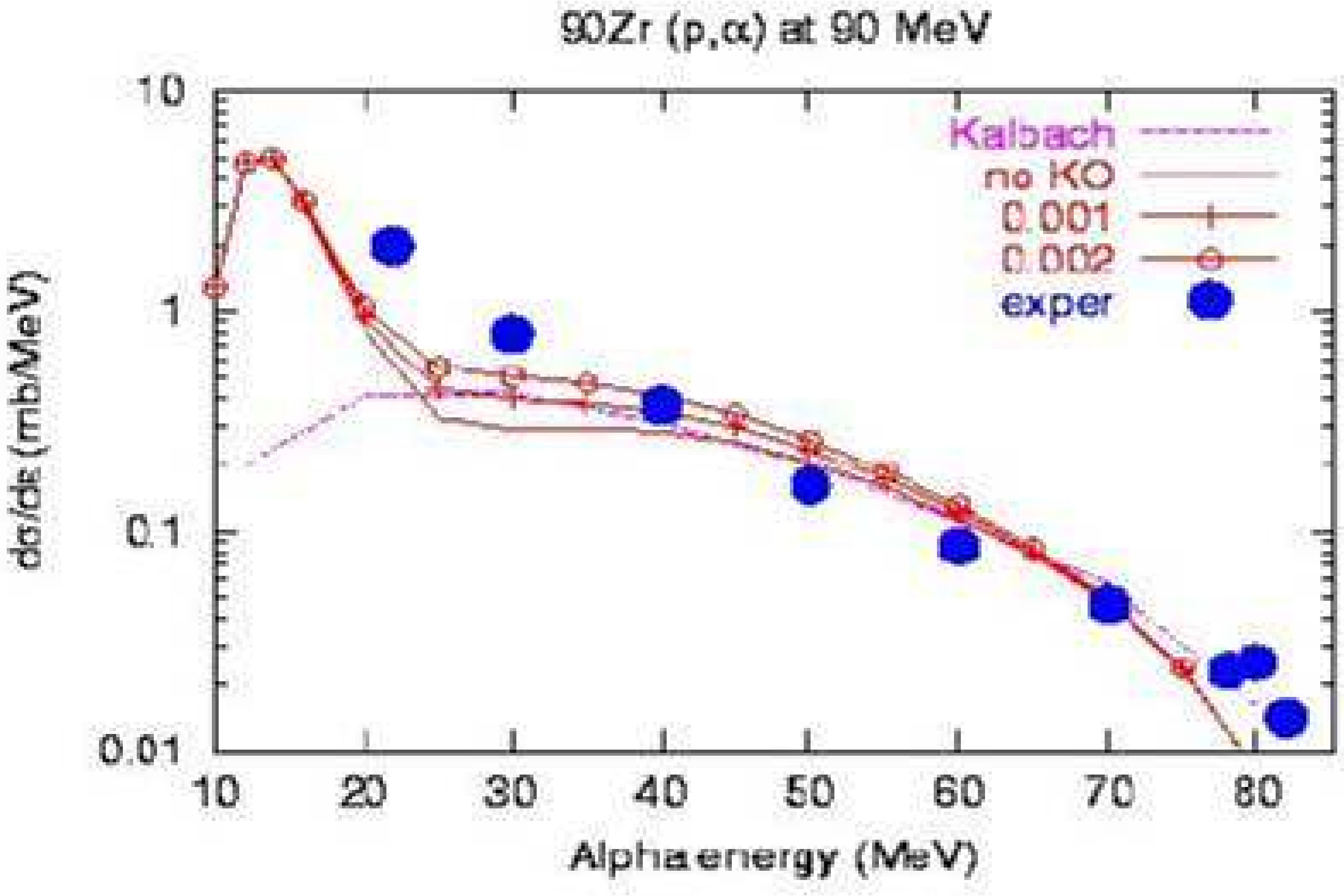
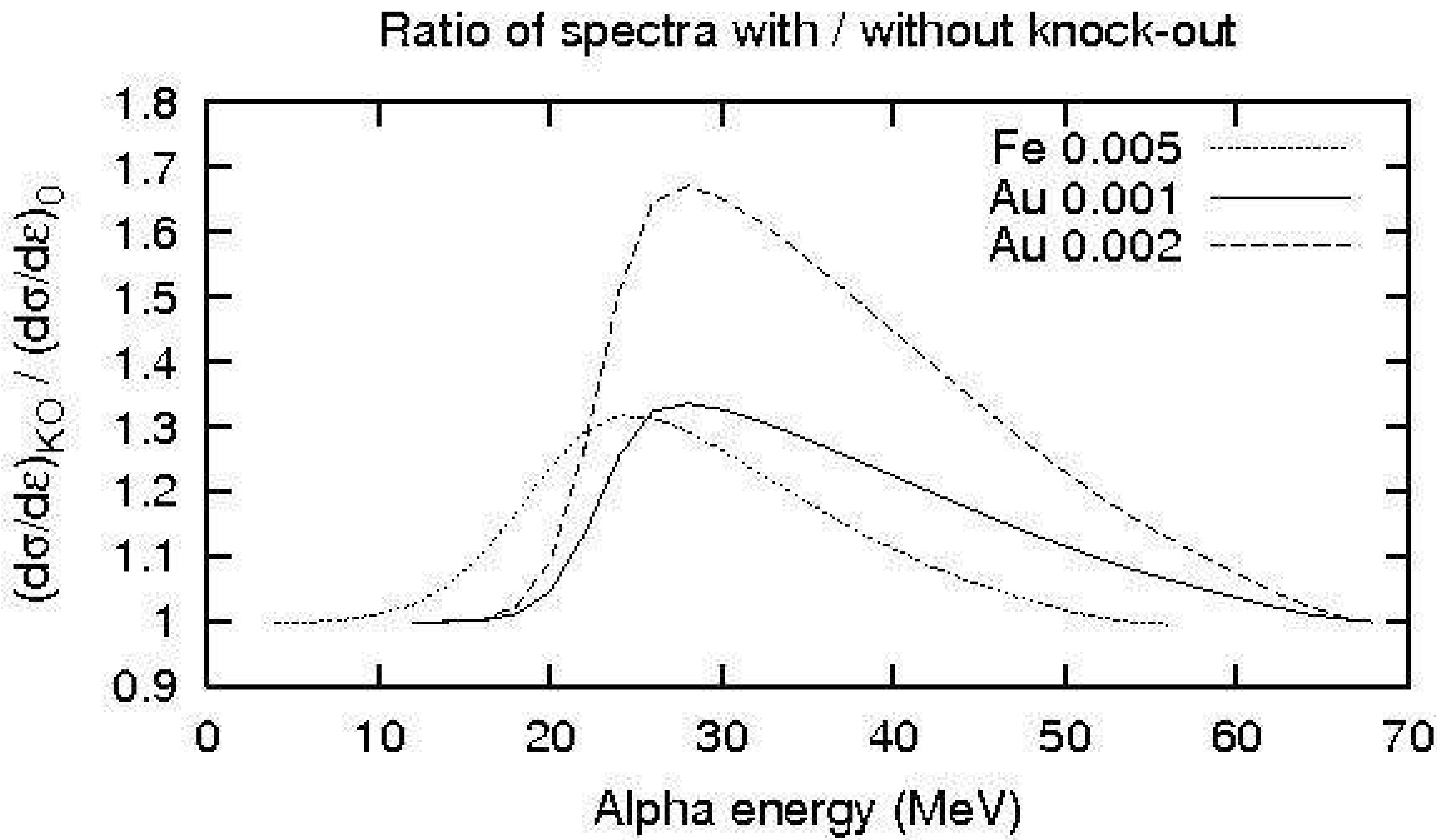


90Zr (p,α) at 90 MeV
dσ/dε (mb/MeV)
Alpha energy (MeV)
Kalbach
no KO
0.001
0.002
exper
10
1
0.1
0.01
10
20
30
40
50
60
70
80



Ratio of spectra with / without knock-out
$(d\sigma/d\varepsilon)_{KO}$ / $(d\sigma/d\varepsilon)_0$
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0
10
20
30
40
50
60
70
Alpha energy (MeV)
Fe 0.005
Au 0.001
Au 0.002

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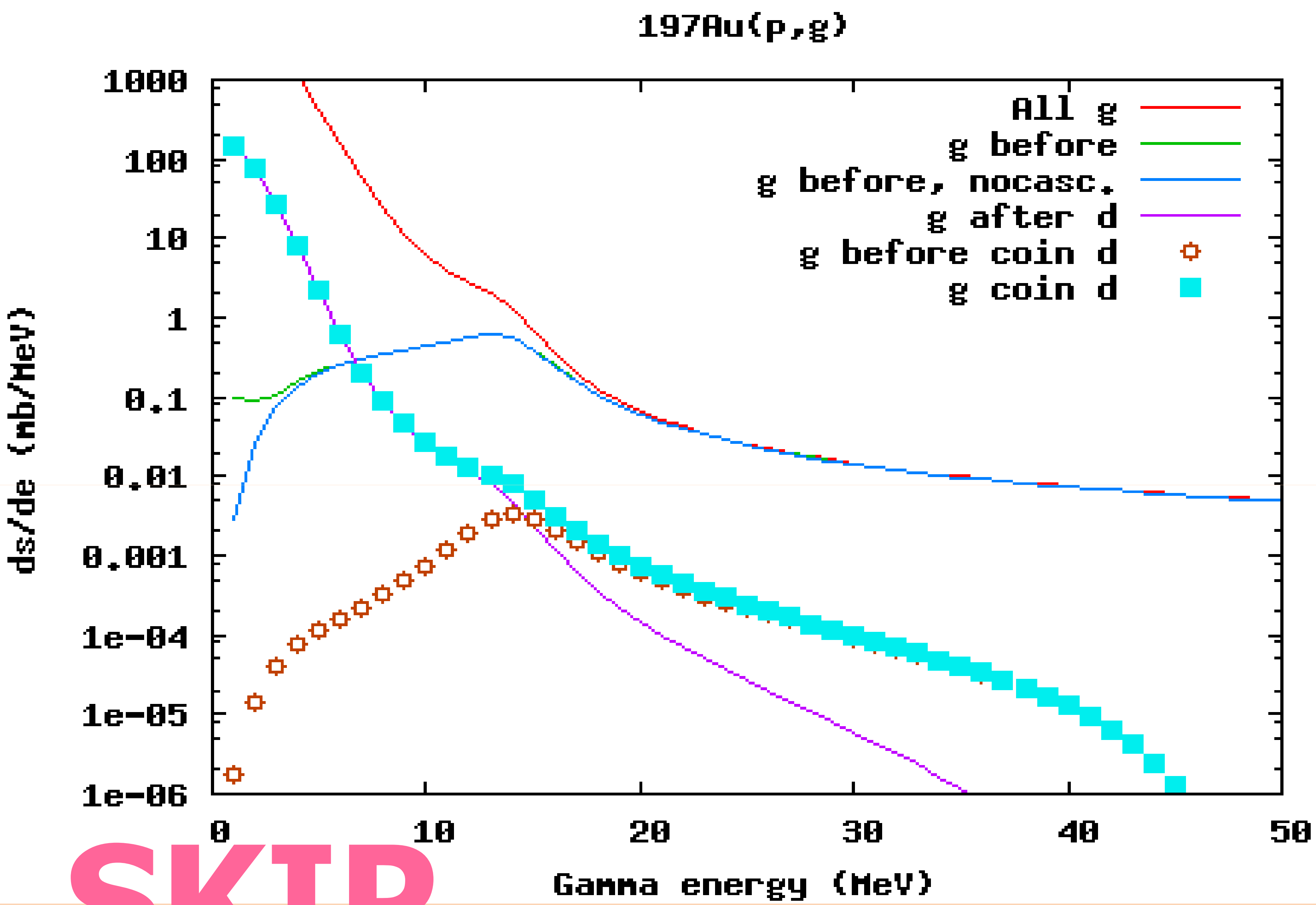
197Au(p,g)
All g
g before
g before, nocasc.
g after d
g before coin d
g coin d
ds/de (mb/MeV)
Gamma energy (MeV)
1000
100
10
1
0.1
0.01
0.001
1e-04
1e-05
1e-06
0
10
20
30
40
50

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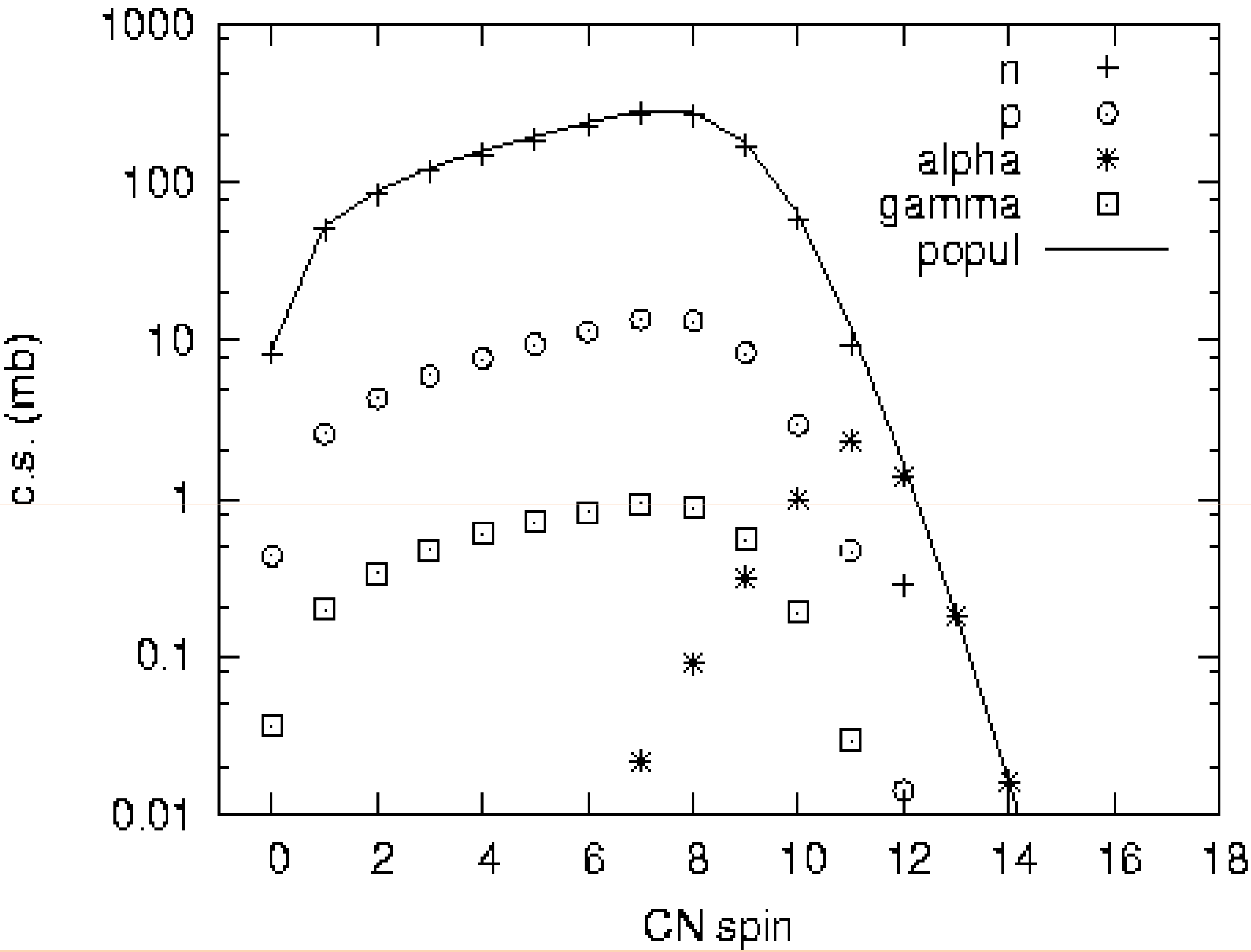
1000
100
10
1
0.1
0.01
c.s. (mb)
0
2
4
6
8
10
12
14
16
18
CN spin
n
p
alpha
gamma
popul

CONCLUSIONS

- Formulated spin-dependent pre-equilibrium cluster emission for the Iwamoto-Harada model. Spin couplings enter the cluster creation probability, therefore spin dependence formally the same as it is for nucleons (but different densities and T_l). Emission mainly from higher spins.
- Primary gamma emission influenced only weakly. Visible on cascades, as clusters take away more spin.

Thank you