Manifestation of clustering in fission of heavy nuclei

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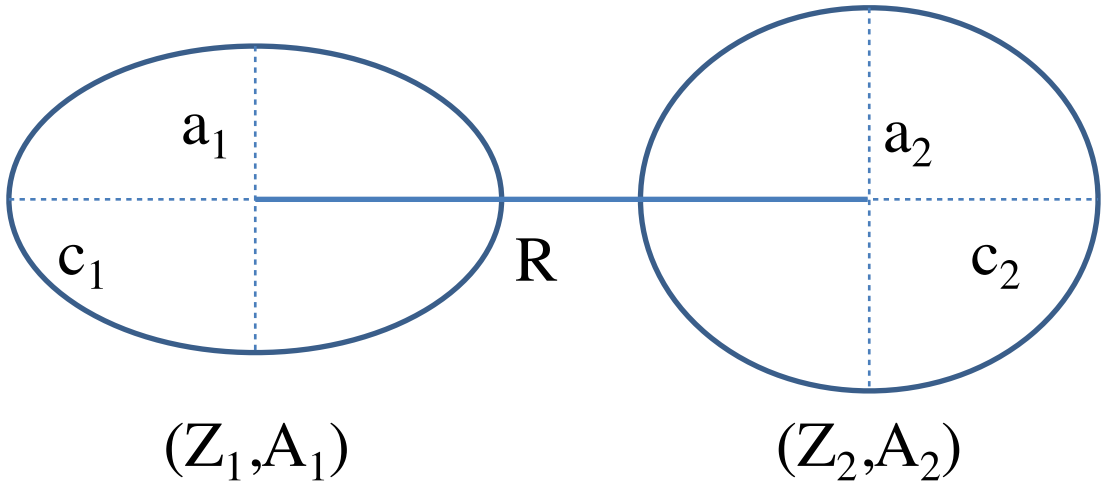
Contents

Model

Parameters Z_1, A_1, β_1, β_2 and R completely describe the geometry of the system.



The interaction potential between the fragments: $V(R,Z,A,J,\beta_1,\beta_2)=V_N+V_C$

$$V_c(R,Z_1,Z_2,\beta_1,\beta_2)=\frac{e^2Z_1Z_2}{R}+\left(\frac{9}{20\pi}\right)^{1/2}\frac{e^2Z_1Z_2}{R^3}\sum_{i=1}^{2}R_i^2\beta_i\left[1+\frac{2}{7}\left(\frac{5}{\pi}\right)^{1/2}\beta_i\right]P_2(cos\theta_i)$$

$$V_N=\int\rho_1(r_1)\rho_2(R-r_2)F(r_1-r_2)dr_1dr_2$$

$$F(r_1-r_2)=C_0[F_{in}\frac{\rho_1(r_1)}{\rho_{00}}+F_{ex}(1-\frac{\rho_1(r_1)}{\rho_{00}})]\delta(r_1-r_2)$$

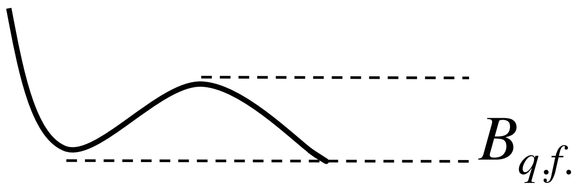
$$\rho_0(r)=\rho_1(r)+\rho_2(R-r)$$

$$F_{in,ex}=f_{in,ex}+f'_{in,ex}\frac{(N-Z)(N_2-Z_2)}{(N+Z)(N_2+Z_2)}$$

$$C_0=300MeVfm^3$$

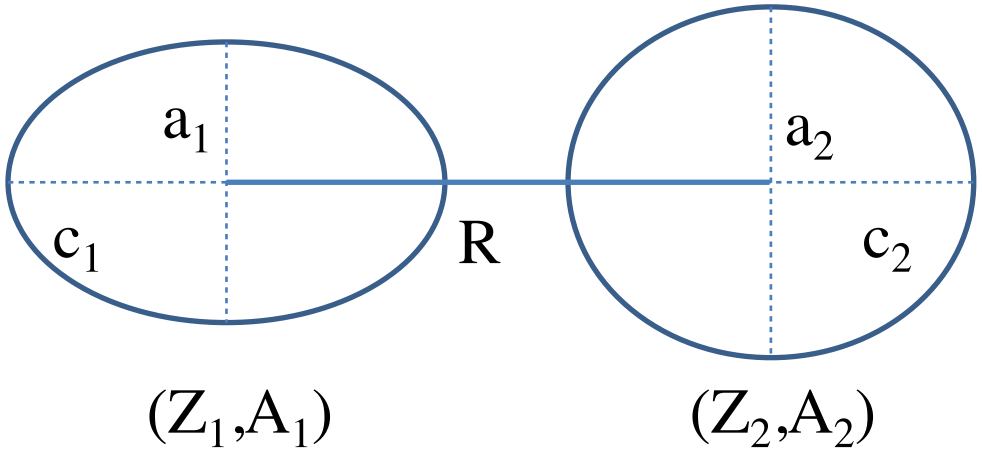
$$f_{in}=0.09, f_{ex}=-2.59$$

$$\rho_{00}=0.17fm^{-3}, a=0.51-0.56fm$$



Sh. A. Kalandarov, G.G. Adamian, N.V. Antonenko, W. Scheid, Phys. Rev. C 82, 044603 (2010)

Model



- *The total energy:*

$$U(A_i,Z_i,\beta_i,d)=$$

$$=U_{macro}(A_i,Z_i,\beta_i,d)+\delta U^{shell}(A_i,Z_i,\beta_i)=$$

$$=\sum_{i=1,2}U_i^{LD}(A_i,Z_i,\beta_i)+\sum_{i=1,2}\delta U_i^{shell}(A_i,Z_i,\beta_i',E_i^*)+$$

$$+V_N(A_i,Z_i,\beta_i,d)+V_C(A_i,Z_i,\beta_i,d).$$

$$U_i^{L.D.}(A_i,Z_i,\beta_i)=U_i^{Surface}(A_i,Z_i,\beta_i)+U_i^{C}(A_i,Z_i,\beta_i)+U_i^{Sym}(A_i,Z_i)$$

- *Liquid drop terms:*

$$U_i^{sym}(A_i,Z_i)=27.612\frac{(N_i-Z_i)^2}{A_i}$$

$$U_i^{C}(A_i,Z_i,\beta_i)=\frac{3}{5}\frac{(Z_ie)^2}{R_{0,i}}\frac{\beta_i^{1/3}}{\sqrt{\beta_i^2-1}}ln(\beta_i+\sqrt{\beta_i^2-1})$$

Model

Surface energy with variable surface tension:

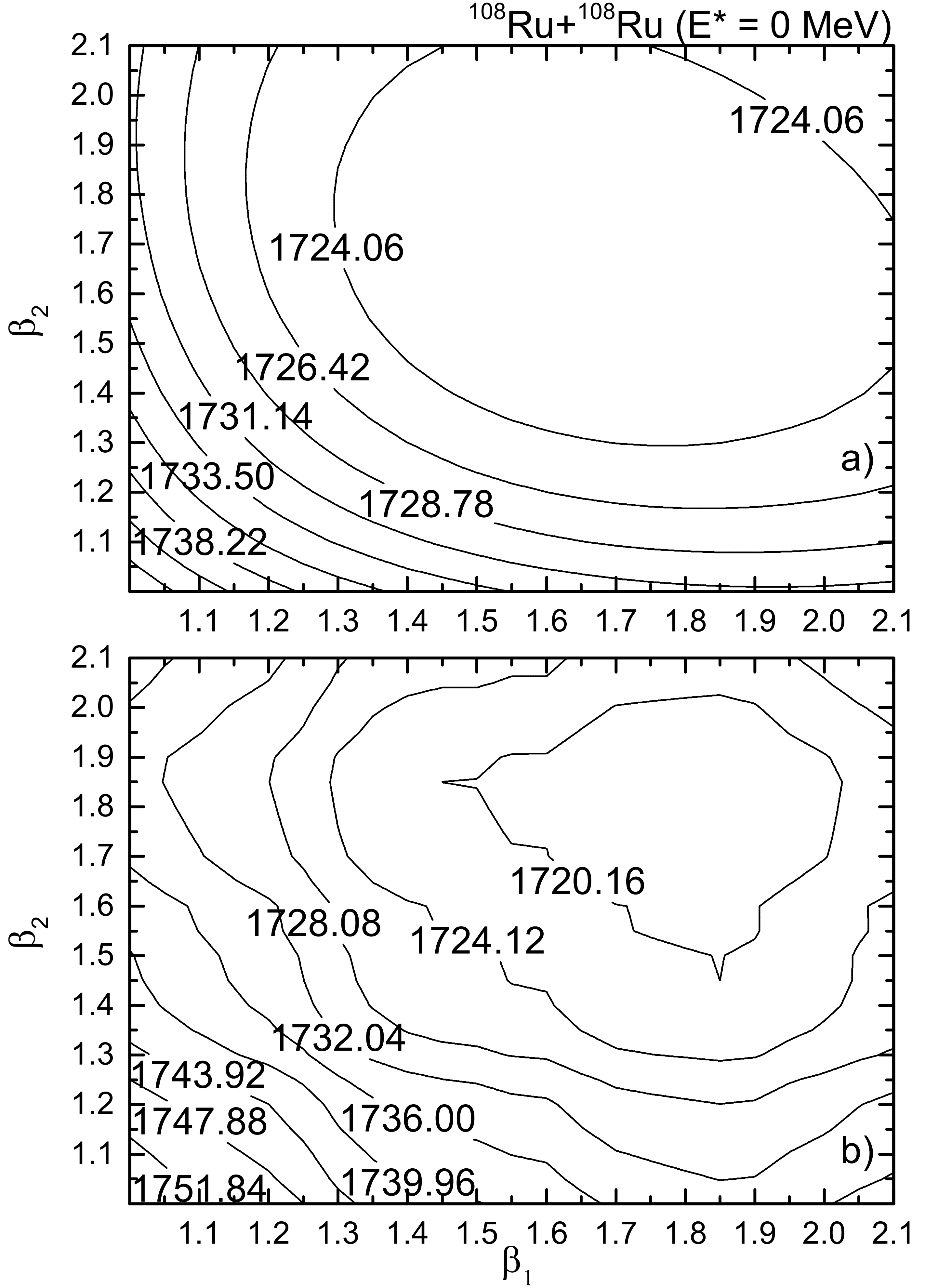
$$U_i^{Surface}(A_i, Z_i, \beta_i) = \sigma_i S_i$$

$$\sigma_i = \sigma_{0,i}(1 + k_i(\beta_i - \beta_i^{g.s.})^2)$$
$$\sigma_{0,i} = 0.9517(1 - 1.7826((N_i - Z_i)^2)/A_i)^2)$$

$$k_i = \frac{1}{1+exp[-0.063(C_{vib}(Z_i,A_i)-67)]}$$

$$C_{vib}(Z_i, A_i) = \frac{\hbar\omega_{vib}^i(3Z_i e R_{0,i}^2/(4\pi))^2}{2B(E2)_{vib}^i}$$

$$B(E2)_{vib} = E_{2^+}^i B(E2)_{rot}^i/(\hbar\omega_{vib}^i)$$



Shell corrections are calculated as in :

J. Maruhn and W. Greiner, Z. Phys. ***251****, 431 (1972).*

Model

Excitation energy of the scission configuration can be calculated as a sum of the initial excitation energy of the fissioning nucleus and the difference of the potential energies of the fissioning nucleus and scission configuration:

$$E^*(A_i, Z_i, \beta_i, R_m) = E^*_{CN} + \left[U_{CN}(A, Z, \beta) - U(A_i, Z_i, \beta_i, R_m)\right].$$

$$T_{DNS}(E^*) = \sqrt{E^*/a}\ , a = A/12\, MeV^{-1}$$

Temperature dependence of LD terms:

$$U_i^{sym}(A_i, Z_i, T) = U_i^{sym}(A_i, Z_i, T=0)(1 + 6 * 10^{-4} E_i^*/A_i),$$

$$U_i^{C}(A_i, Z_i, \beta_i, T) = U_i^{C}(A_i, Z_i, \beta_i, T=0)(1 - 0.12 E_i^*/A_i)$$

$$U_i^{Surf}(A_i, Z_i, \beta_i, T) = U_i^{Surf}(A_i, Z_i, \beta_i, T=0)(1 + 0.102 E_i^*/A_i).$$

$$k_i(E_i^*) = k_i * exp\left[-E_i^*/E_k\right]$$

Shell damping:

$$\delta U_i^{shell}(A_i, Z_i, \beta_i', E_i^*) = \delta U_i^{shell}(A_i, Z_i, \beta_i', E_i^* = 0) exp[-E_i^*/E_D]$$

G. Sauer, H. Chandra, U. Mosel, Nucl. Phys. A ***264*** *(1976) 221-243*

Model

Yields:

Using
$$P_{Z,A}(E^*_{CN},\beta_1,\beta_2) \sim exp\{-U(R_m,Z,A,\beta_1,\beta_2)/T\}$$
$$P^{decay}_{Z,A,\beta_1,\beta_2} \sim exp\{-B_{qf}(Z,A,\beta_1,\beta_2)/T\}$$

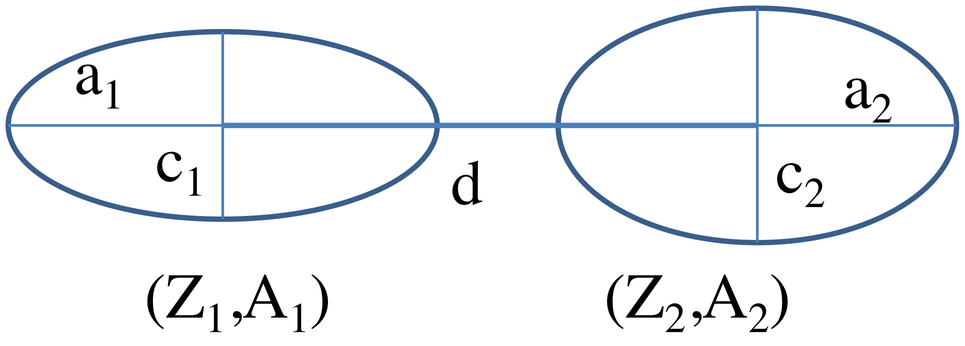
$$w(A_i,Z_i,\beta_i,E^*) = N_0 exp[-\frac{U(A_i,Z_i,\beta_i,R_m)+B_{qf}(A_i,Z_i,\beta_i)}{T}]$$

The different yields can be calculate by integrating over the deformations:

$$Y(A_i,Z_i) = N_0 \int\int w(A_i,Z_i,\beta_1,\beta_2,E^*)\,\mathrm{d}\beta_1\mathrm{d}\beta_2,$$

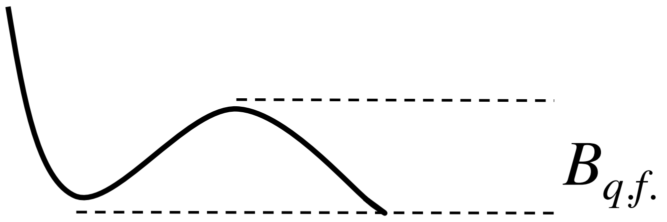
$$Y(A_i) = N_0 \sum_{Z_i}\int\int w(A_i,Z_i,\beta_1,\beta_2,E^*)\,\mathrm{d}\beta_1\mathrm{d}\beta_2,$$

$$Y(Z_i) = N_0 \sum_{A_i}\int\int w(A_i,Z_i,\beta_1,\beta_2,E^*)\,\mathrm{d}\beta_1\mathrm{d}\beta_2,$$

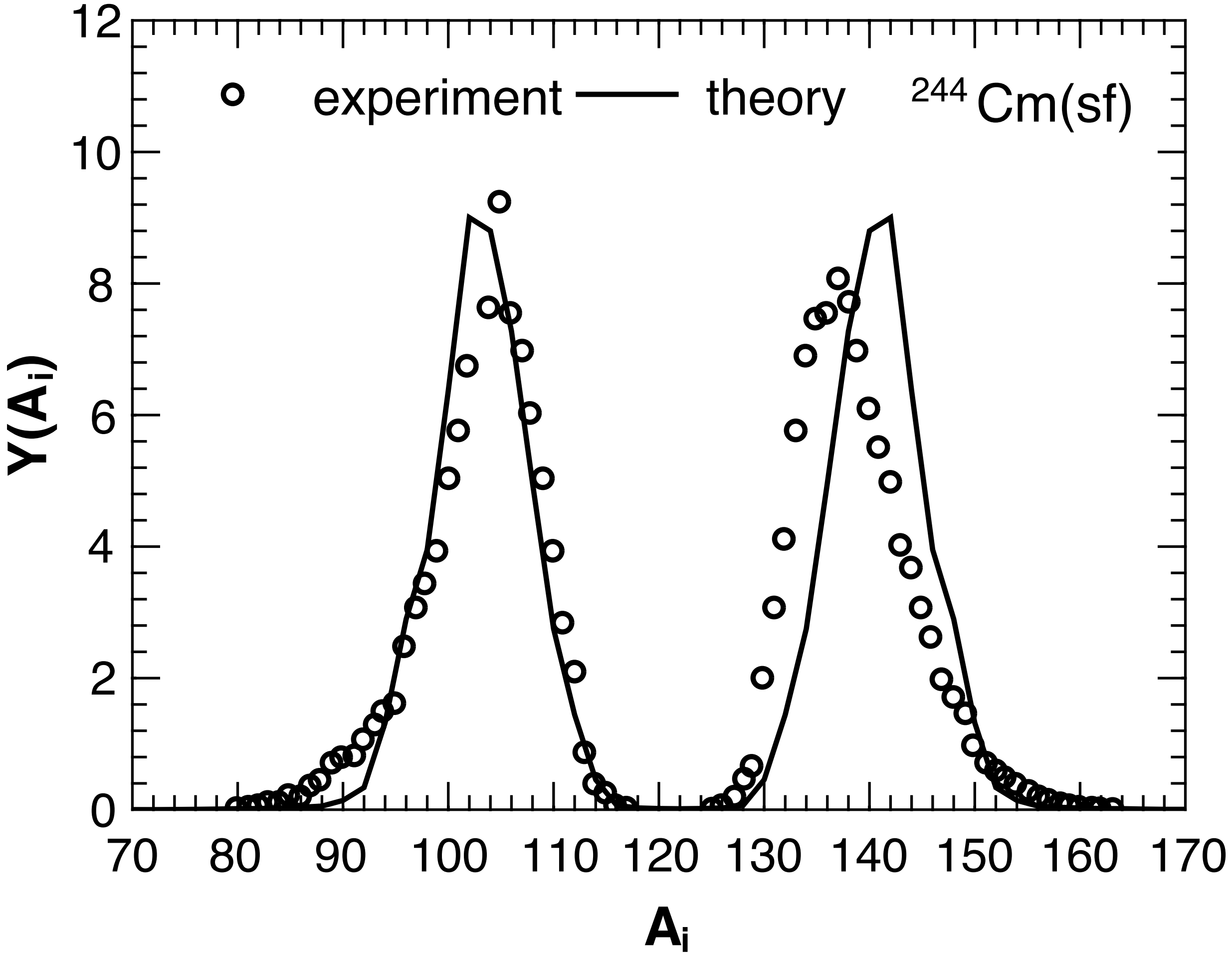


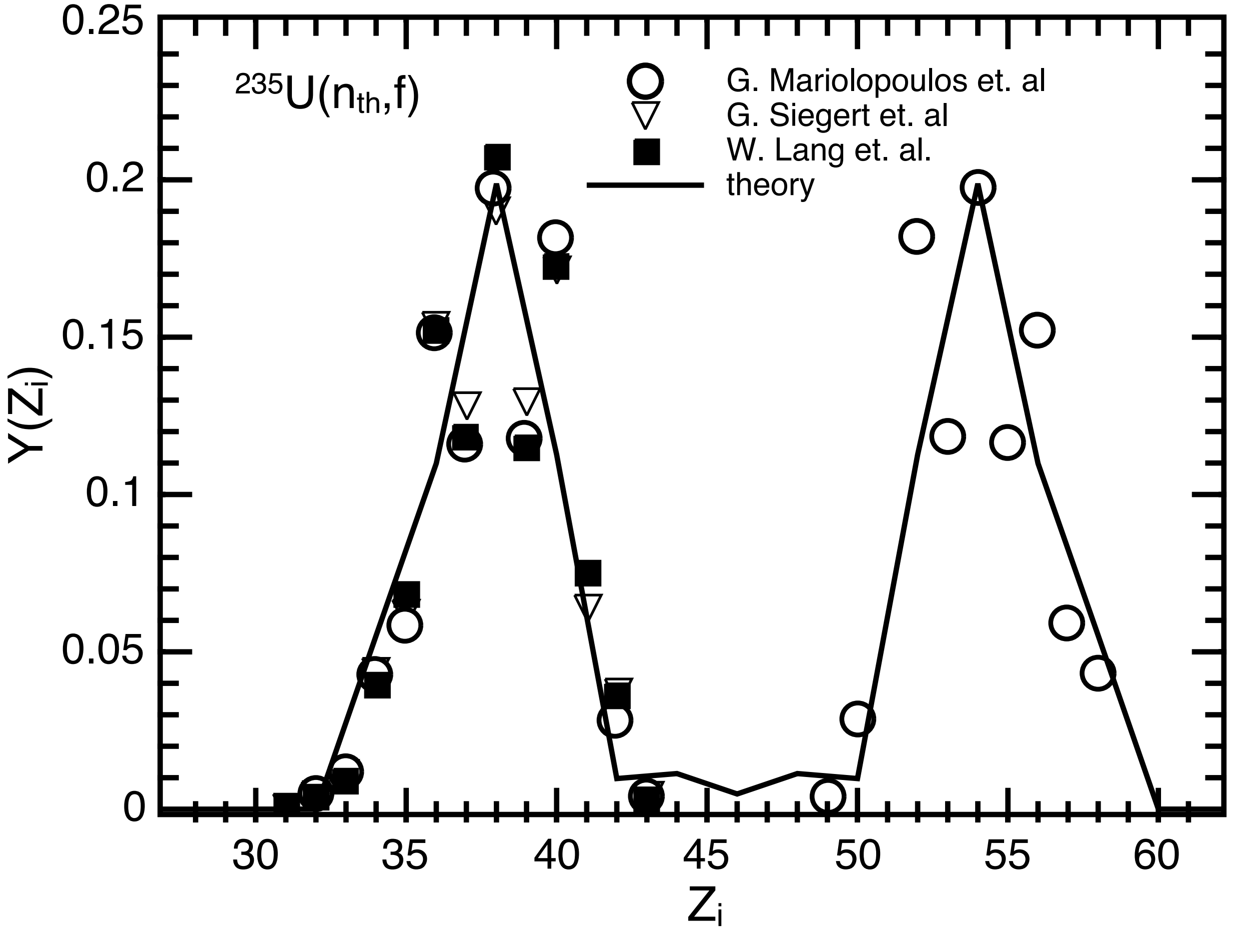
$$TKE(A_i,Z_i) = V_c(A_i,Z_i,\beta_1,\beta_2) + V_n(A_i,Z_i,\beta_1,\beta_2)$$

$$<TKE>(A_i) = \frac{\sum_{Z_i}\int TKE(A_i,Z_i,\beta_1,\beta_2)\,w(A_i,Z_i,\beta_1,\beta_2,E^*)d\beta_1 d\beta_2}{\sum_{Z_i}\int w(A_i,Z_i,\beta_1,\beta_2,E^*)d\beta_1 d\beta_2}$$



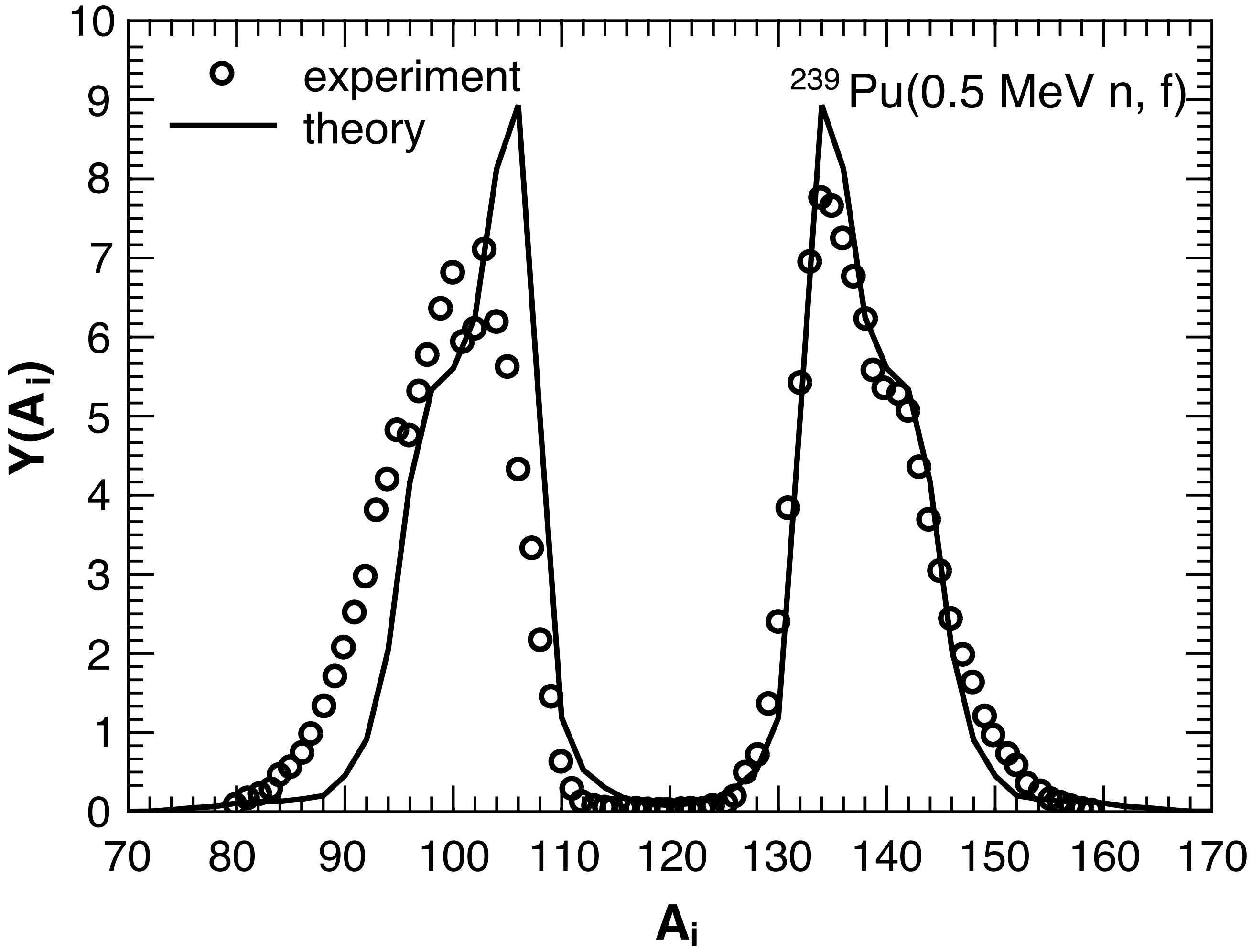
Results

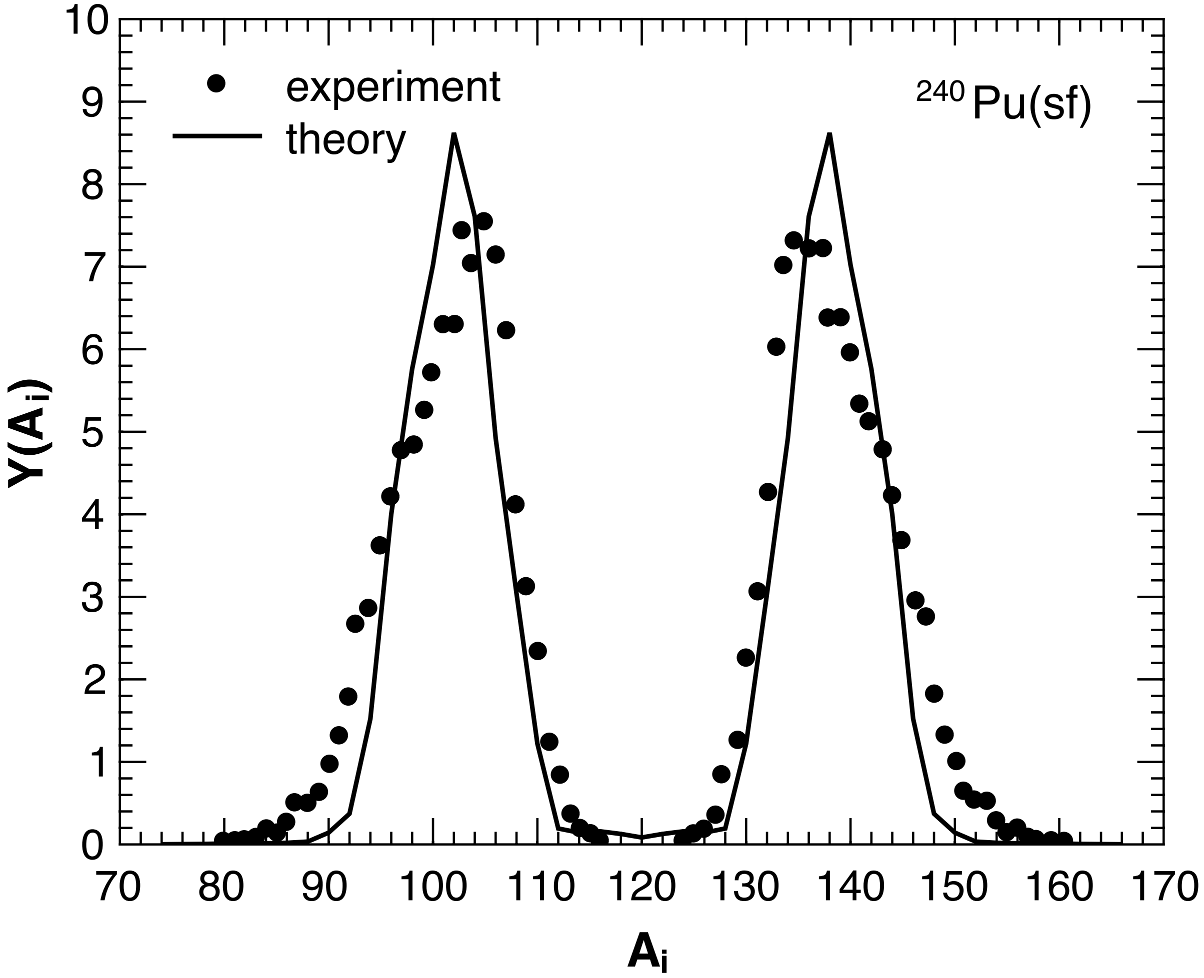




- W. Lang, H.G. Clerc, W. Wohlfarth, H. Schrader, and K.-H. Schmidt, Nucl. Phys. A 345, 34(1980);
- G. Siegert, H. Wollnik, J. Grief, R. Decker, G. Fiedler, and B. Pfeiffer, Phys.Rev.C 14, 1864 (1976);
- G. Mariolopoulos, Ch. Hamelin, J. Blachot, J.P. Boucqet, B. Brissot, J. Crancon, H. Nifenecker, and Ch. Ristori, Nucl. Phys. A 361, 213 (1981).
- T.R. England and B.F. Rider, LANL report no. LA-UR-94-3106 (1994).
- P. Schillebeeckx, C. Wagemans, A.J. Deruytter, and R. Barthelemy, Nucl. Phys. A 545, 623 (1992).
- R. Schmidt and H. Henschel, Nucl. Phys. A 395, 15 (1983).

Results





- W. Lang, H.G. Clerc, W. Wohlfarth, H. Schrader, and K.-H. Schmidt, Nucl. Phys. A 345, 34(1980);
- G. Siegert, H. Wollnik, J. Grief, R. Decker, G. Fiedler, and B. Pfeiffer, Phys.Rev.C 14, 1864 (1976);
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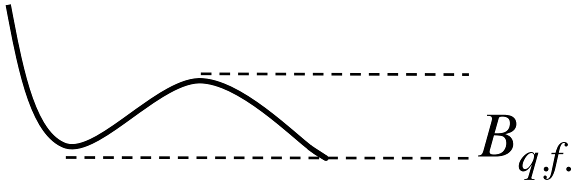
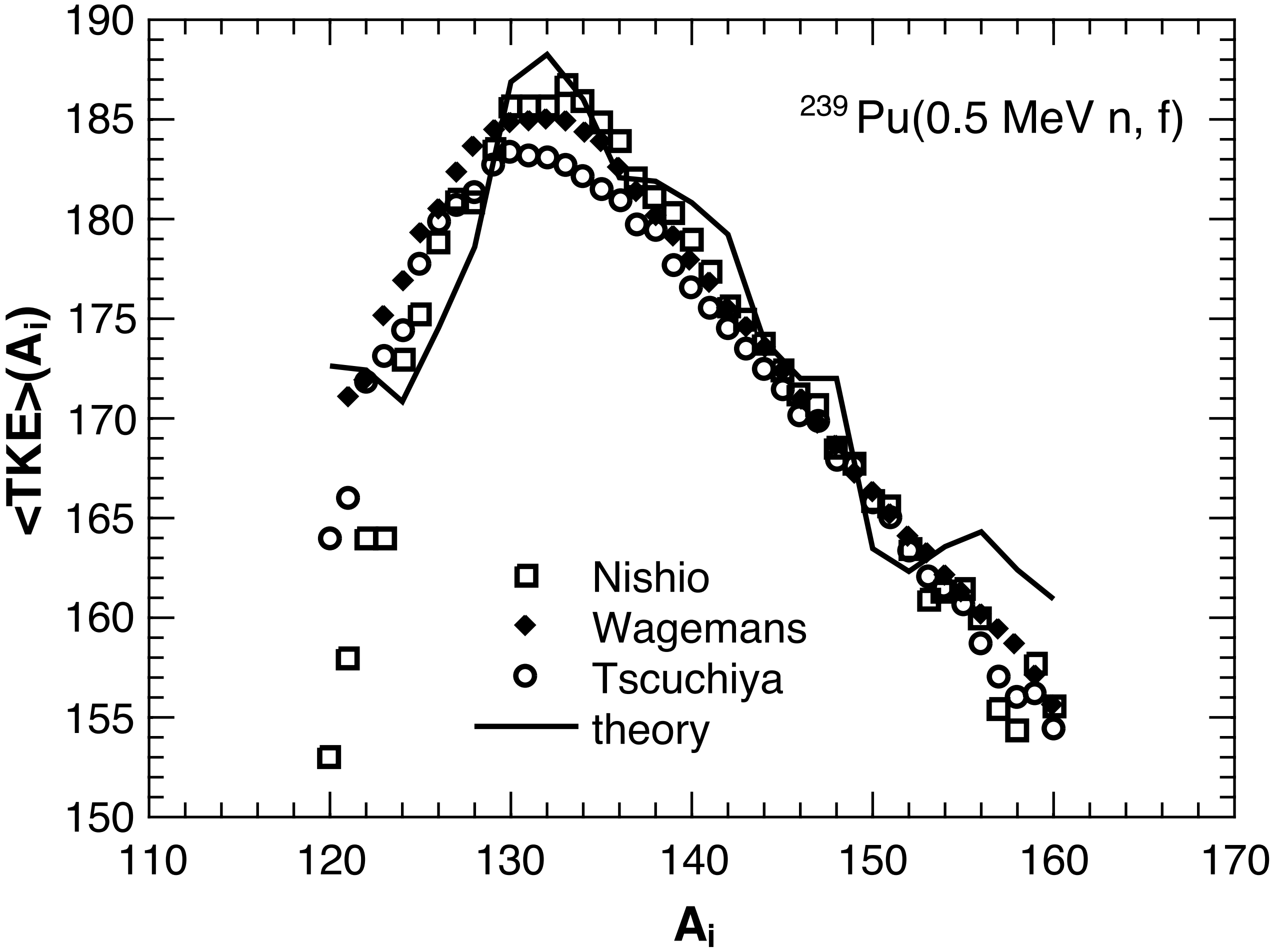
- T.R. England and B.F. Rider, LANL report no. LA-UR-94-3106 (1994).
- P. Schillebeeckx, C. Wagemans, A.J. Deruytter, and R. Barthelemy, Nucl. Phys. A 545, 623 (1992).

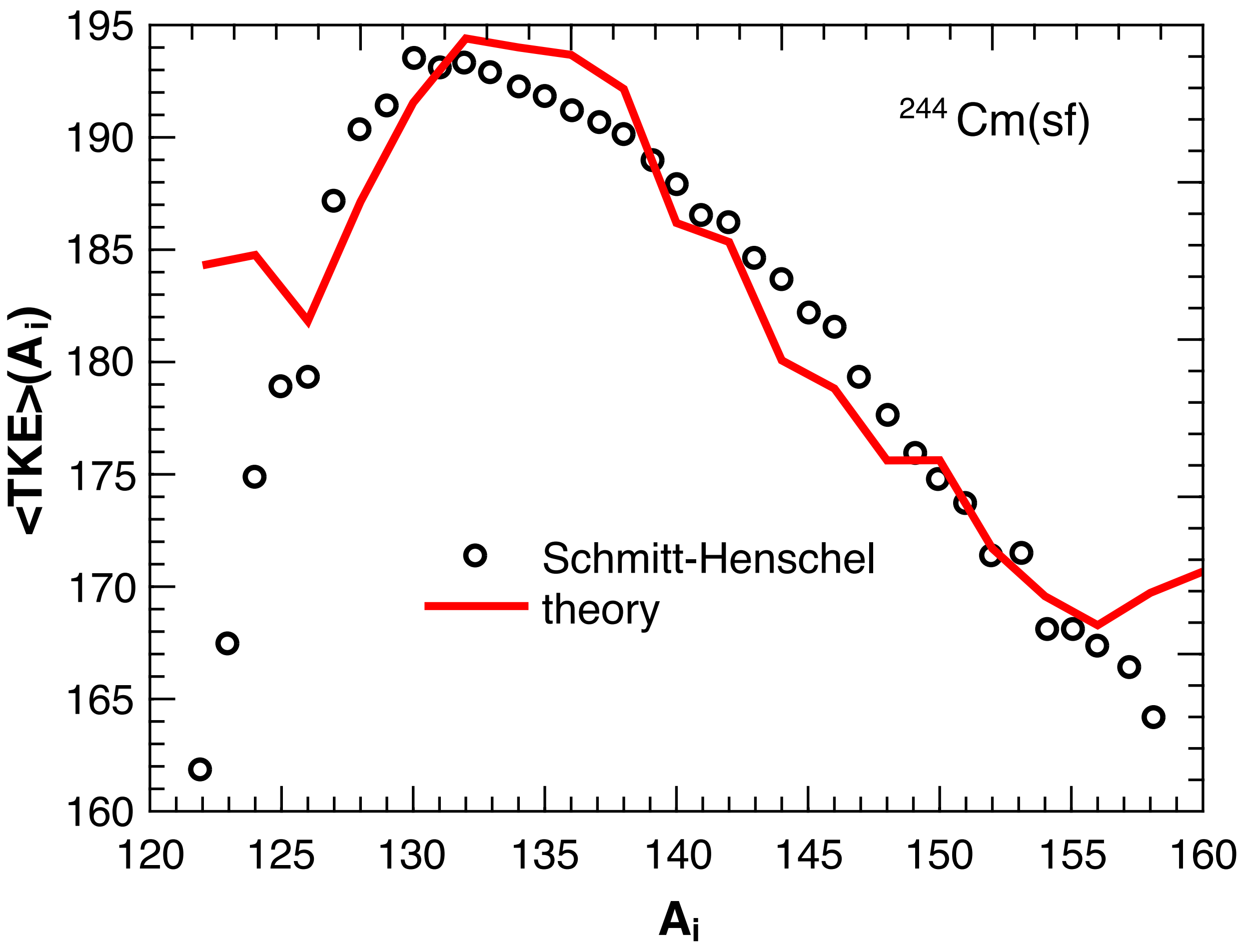
Results (and more modelling)

$$\langle TKE\rangle(A_i) = \frac{\sum_{Z_i}\int d\beta_L d\beta_H TKE(A_i, Z_i, \beta_i) w(A_i, Z_i, \beta_i, E^*)}{\sum_{Z_i}\int d\beta_L d\beta_H w(A_i, Z_i, \beta_i, E^*)}.$$

$$TKE(\{A_i, Z_i, \beta_i\}) = V^N(\{A_i, Z_i, \beta_i\}) + V^C(\{A_i, Z_i, \beta_i\})$$







- R. Schmidt and H. Henschel, Nucl. Phys. A 395, 15 (1983).
- C. Wagemans, E. Allaert, A. Deruytter, R. Barthelemy, and P. Schillebeeckx, Phys. Rev. C 30, 218 (1984).
- T.R. England and B.F. Rider, LANL report no. LA-UR-94-3106 (1994).

Results (and more modelling)

The probability of emitting exactly *x* neutrons (Jackson model):

$$P_{xn}(E_i^*) = P(x) - P(x+1)$$

$$P(x) = 1 - e^{-\Delta_x}\left(1 + \sum_{k=1}^{2x-3}\frac{(\Delta_x)^k}{k\,!}\right)$$

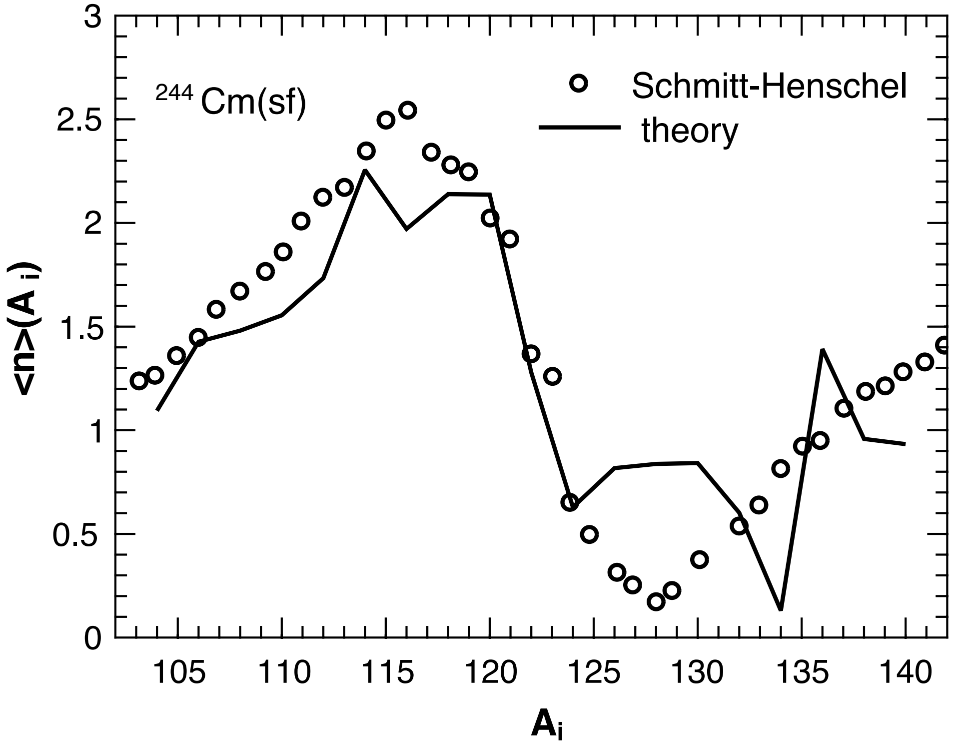
$$P(x+1) = 1 - e^{-\Delta_{x+1}}\left(1 + \sum_{k=1}^{2x-1}\frac{(\Delta_{x+1})^k}{k\,!}\right)$$

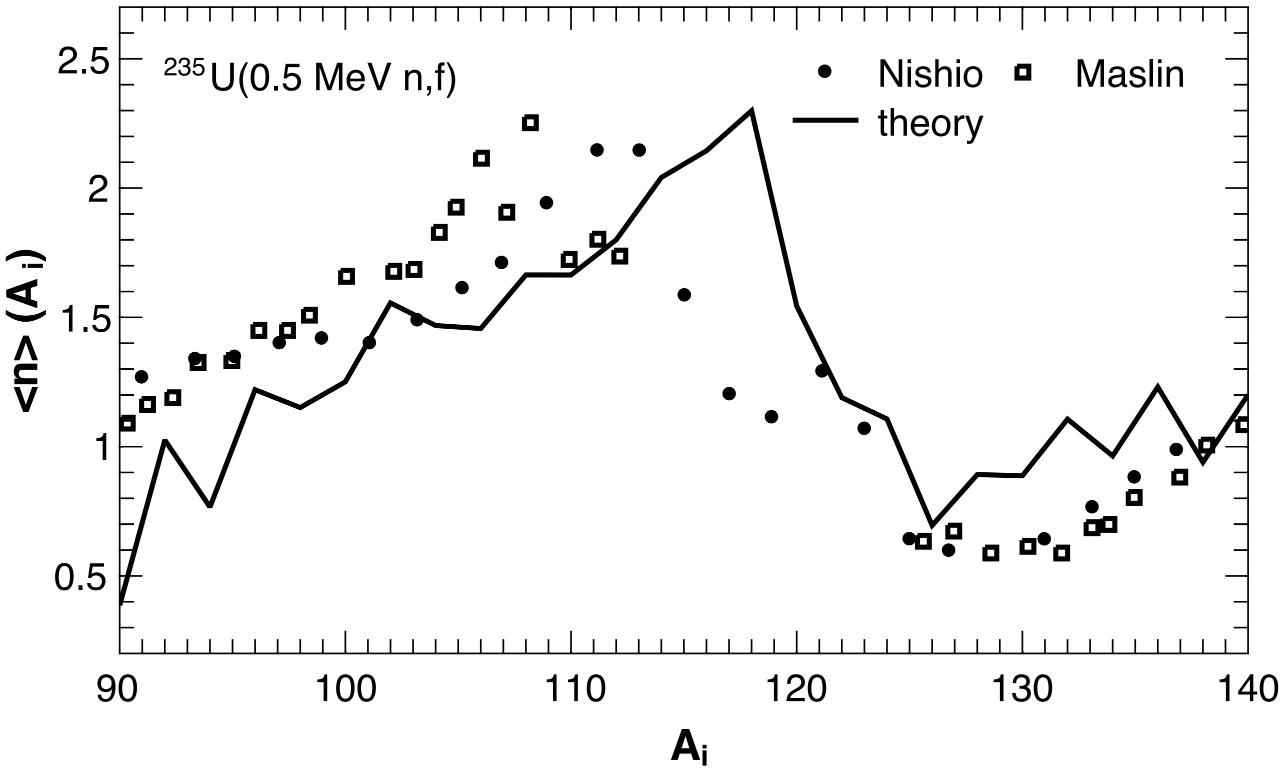
$$\Delta_x = \left(E_i^* - \sum_{k=1}^{x} B_k\right)/T_i$$

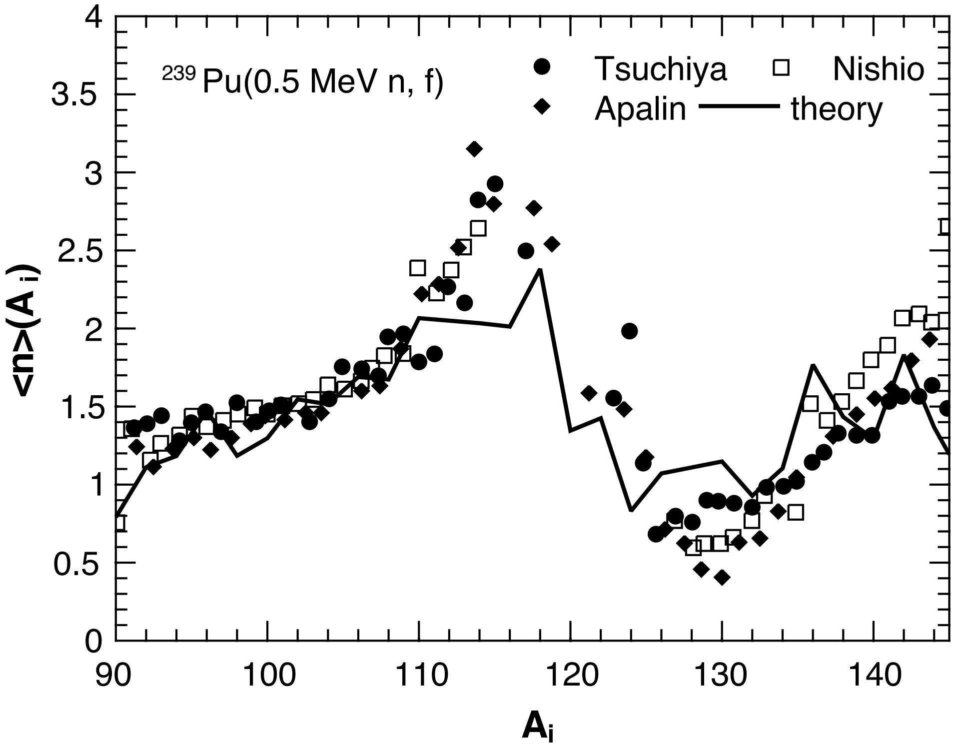
$$P_L(E_L^*) \sim \rho_L(E_L^*)\rho_H(E^* - E_L^*),$$

$$\rho_i(E_i^*) \sim \exp[2(a_i E_i^*)^{1/2}]\,.$$

$$P_L(x) = \frac{\int_0^{E^*} dE_L^* P_{xn}^L(E_L^*)\rho_L(E_L^*)\rho_H(E^* - E_L^*)}{\int_0^{E^*} dE_L^* \rho_L(E_L^*)\rho_H(E^* - E_L^*)}$$

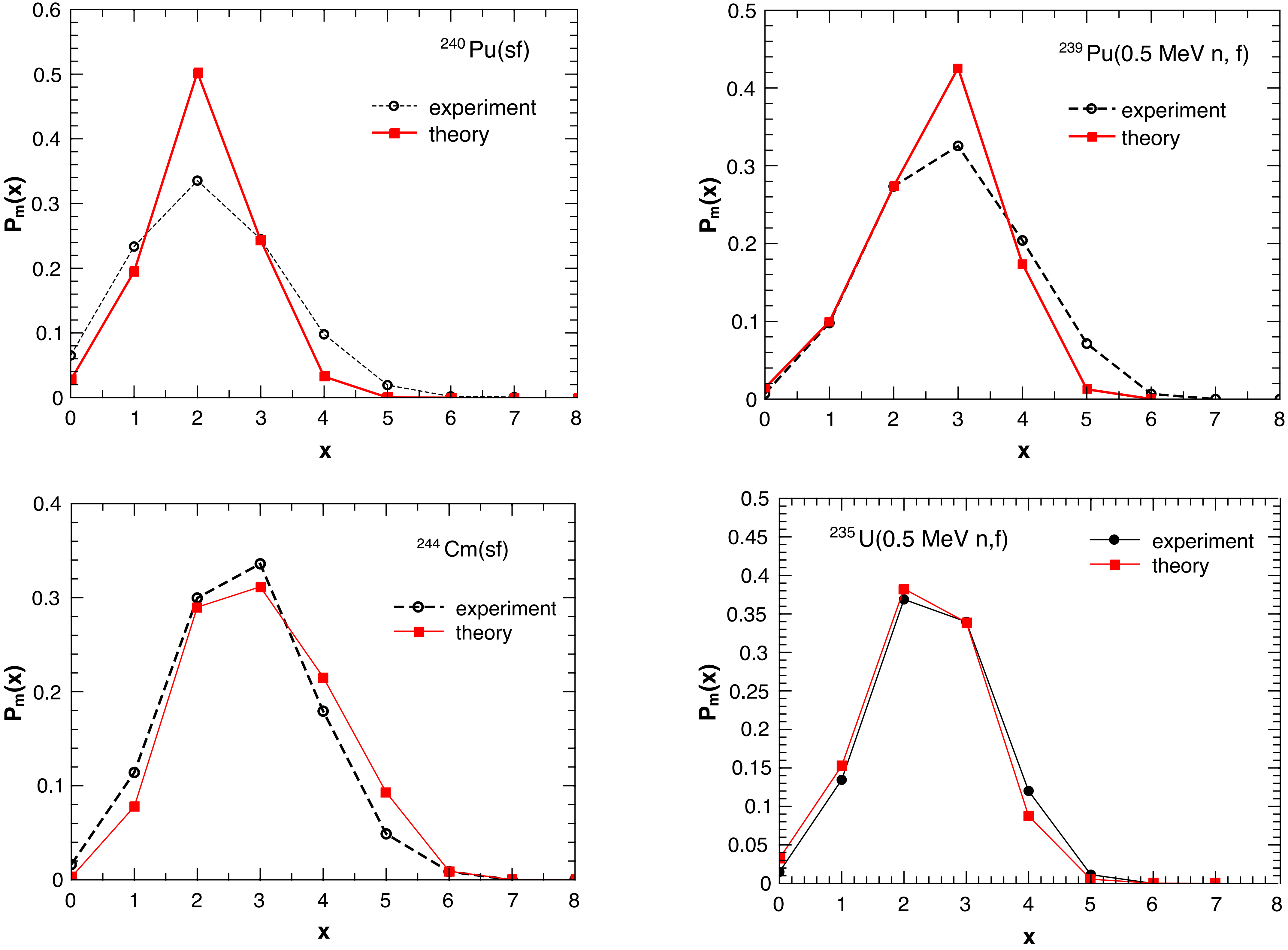






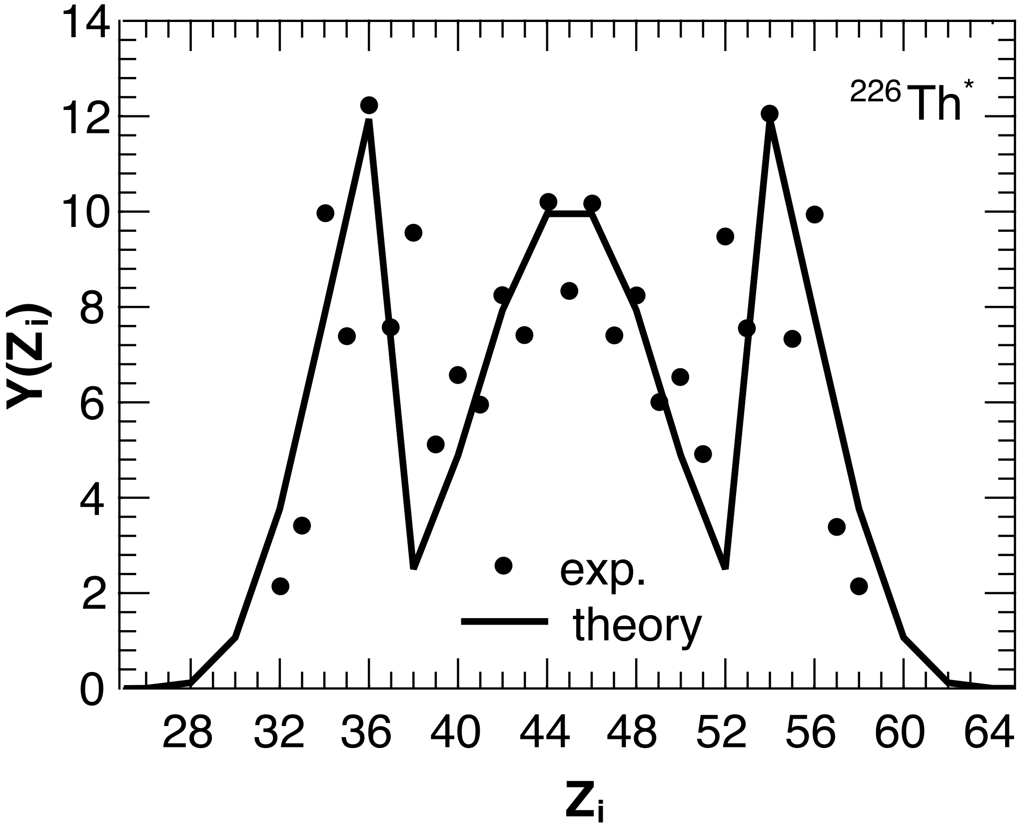
- K. Nishio, , et.al., Nucl. Phys. A 632, 540 (1998); K. Nishio, et.al., J. Nucl. Sci. Technol. 32, 404 (1995); C. Tsuchiya, , et.al., J. Nucl. Sci. Technol. 37, 941 (2000); V.F. Apalin, , et.al. Nucl. Phys. A 71, 553 (1965).
- R. Schmidt and H. Henschel, Nucl. Phys. A 395, 29 (1983).

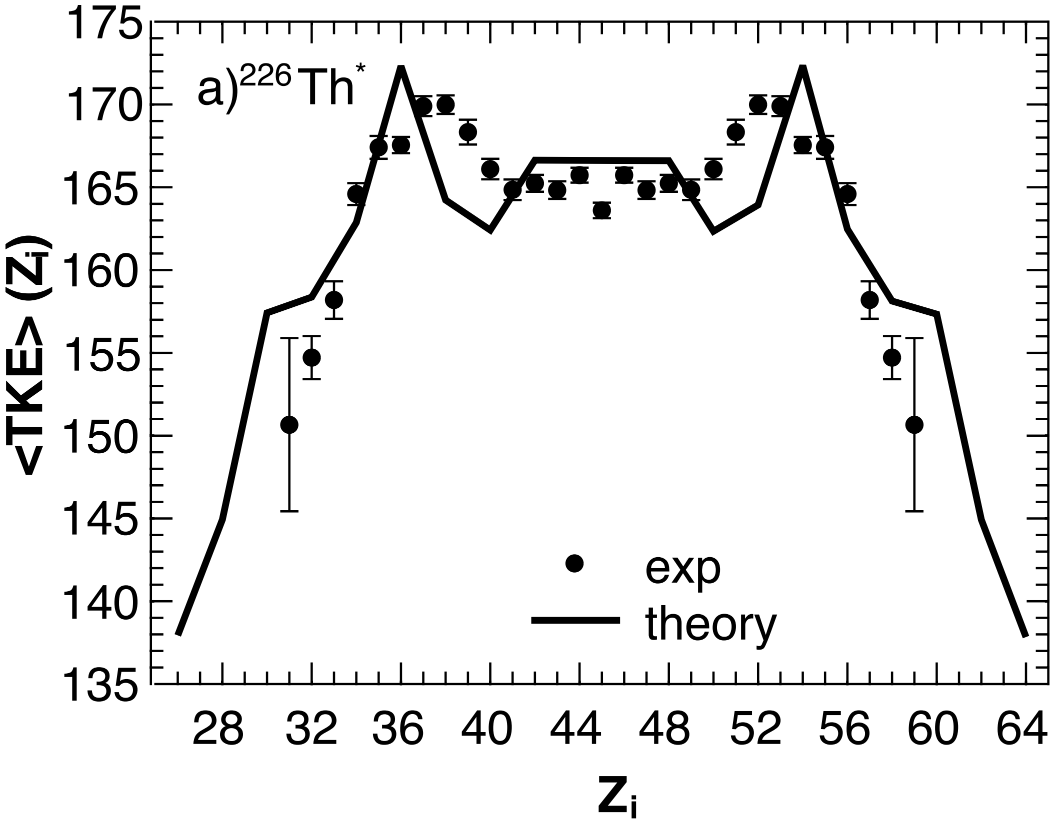
Results (and more modelling)

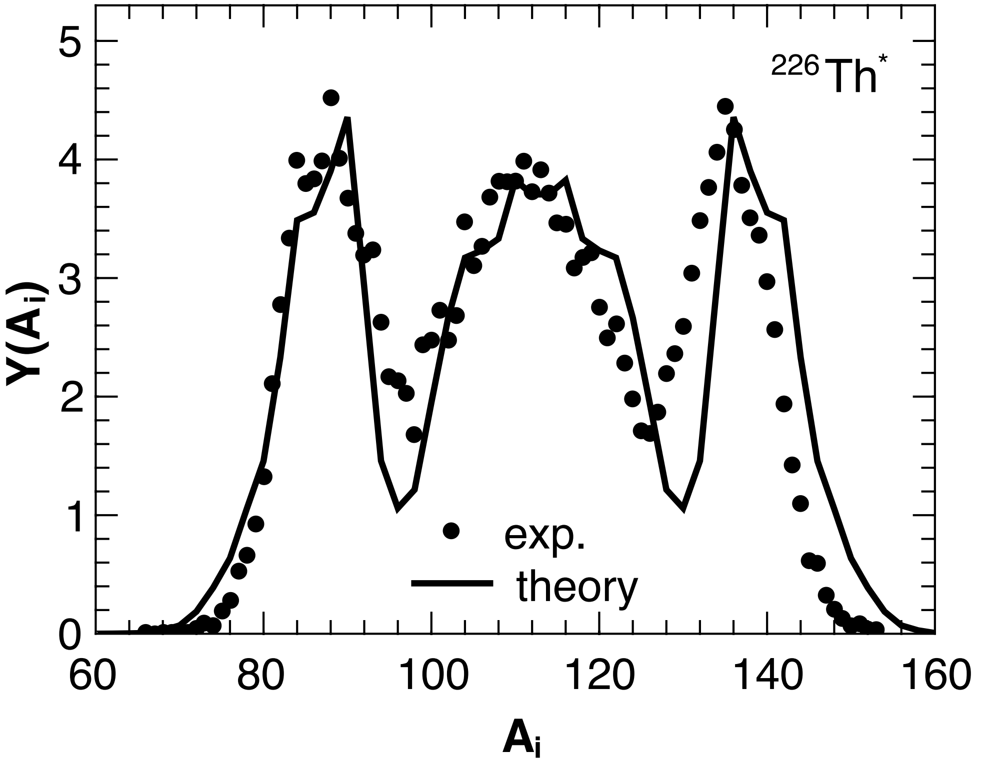


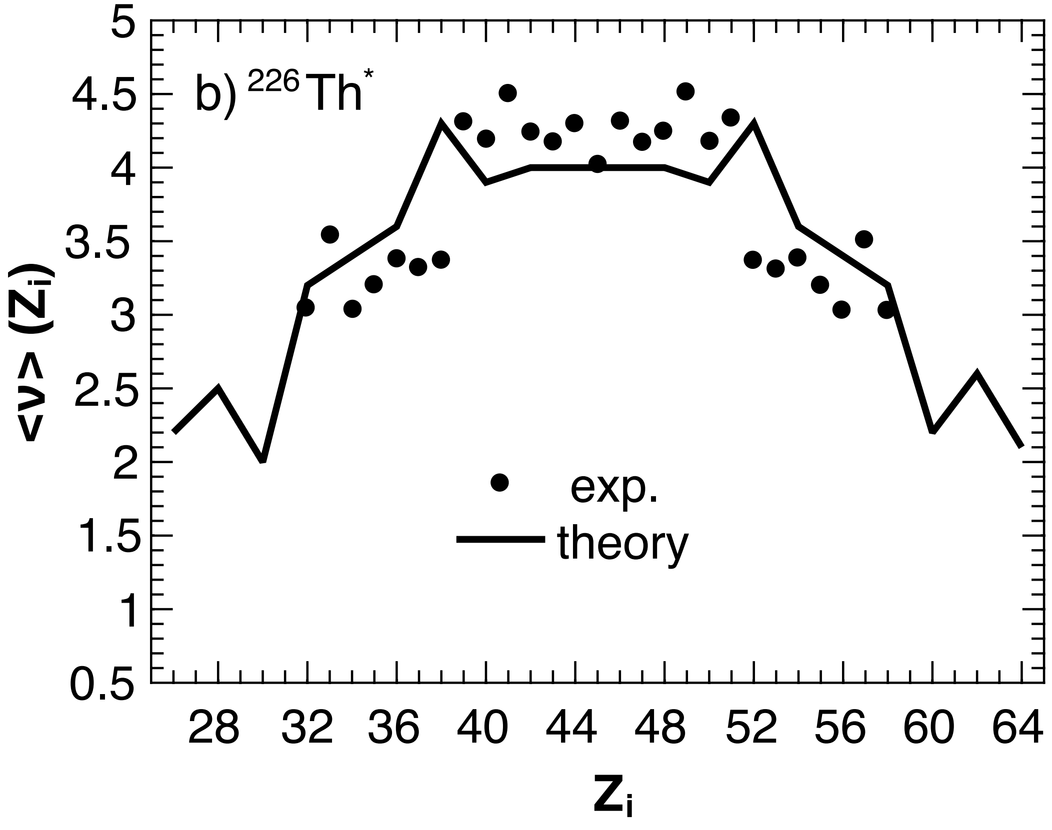
- B.C. Diven, H.C. Martin, R.F. Taschek, and J. Terrell, Phys. Rev. 101, 1012 (1956).
- N. E. Holden andM. S.Zucker, Brookhaven National Laboratory Report No. BNL-NCS-35513 (1985).
- Z. Huanqiao, L. Zuhua, D. Shengyao, and L. Shaoming, Nucl. Sci. Eng. 86, 315 (1984).

Results - thorium isotopes



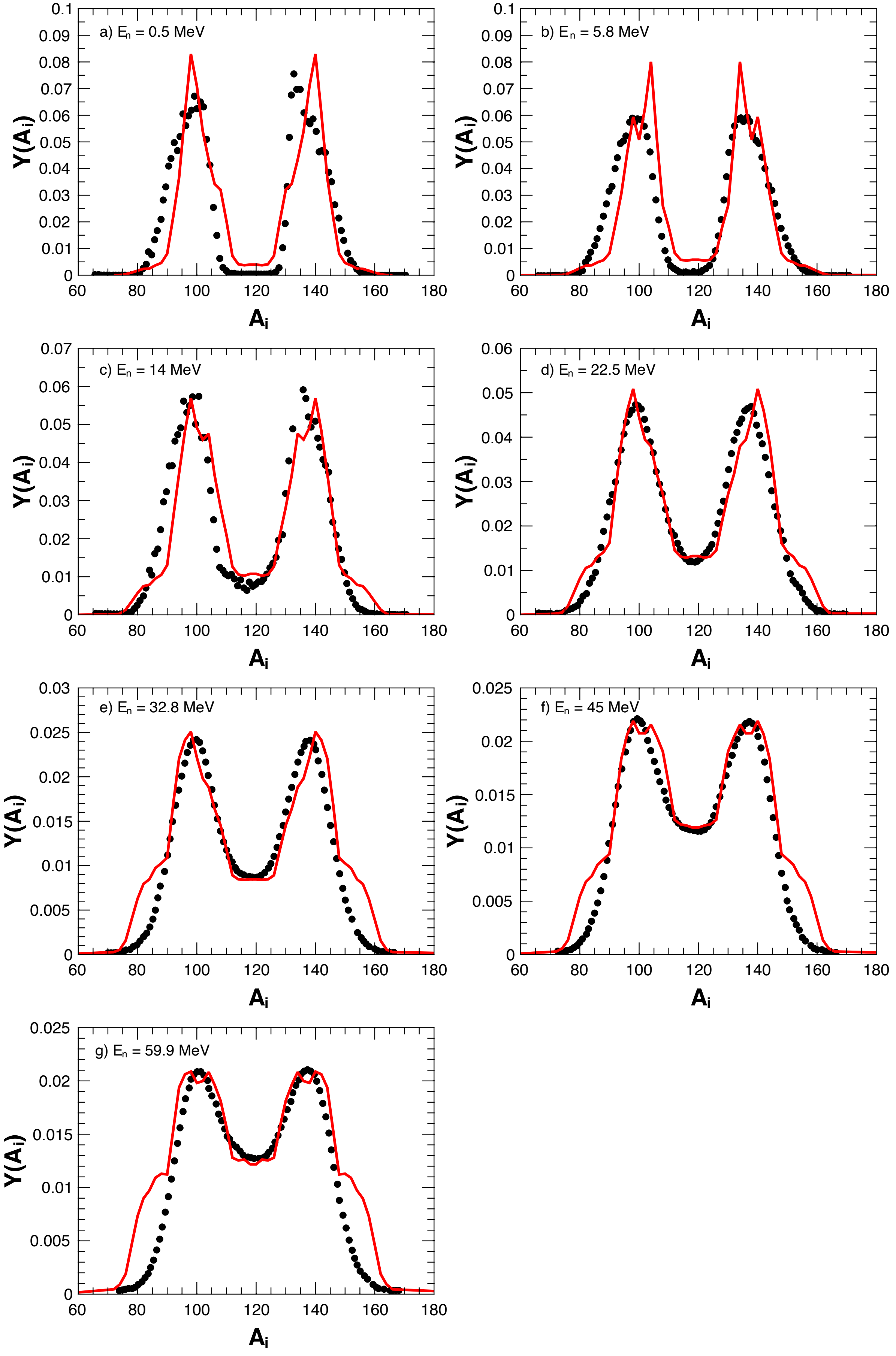


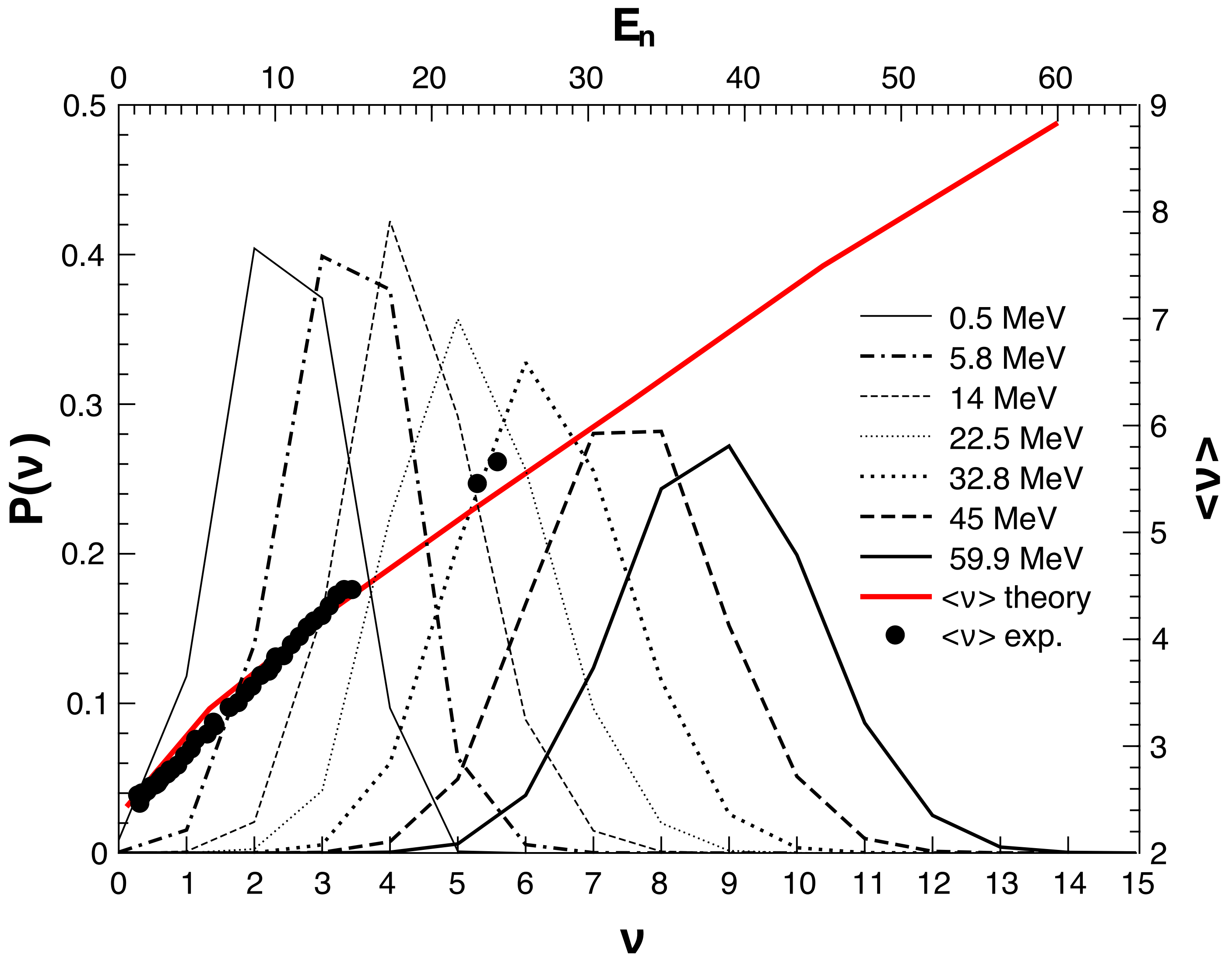




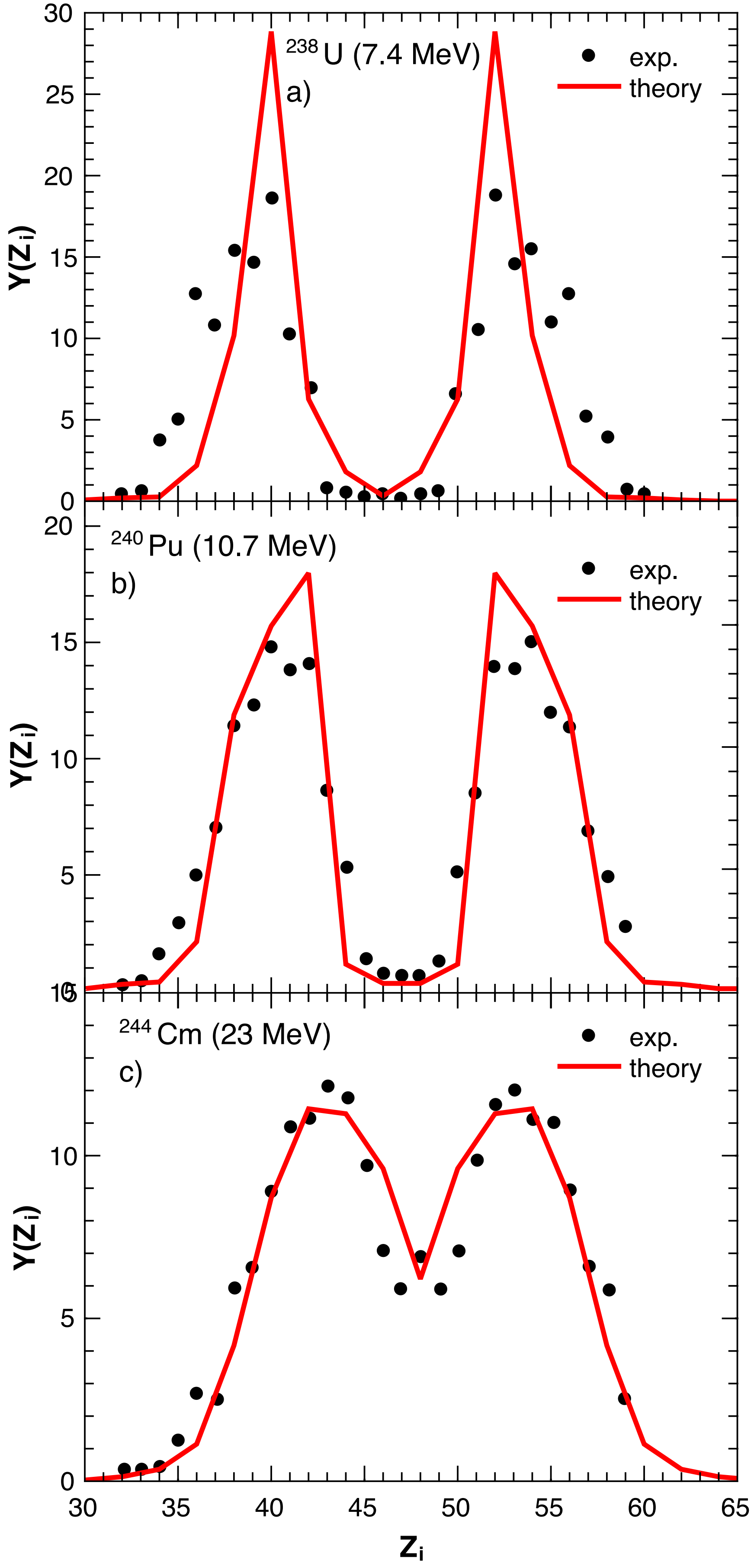
- K.-H. Schmidt et al., Nucl. Phys. A 665, 221 (2000); 693, 169 (2001).
- A. Chatillon et al., Phys. Rev. Lett. 124, 202502 (2020)

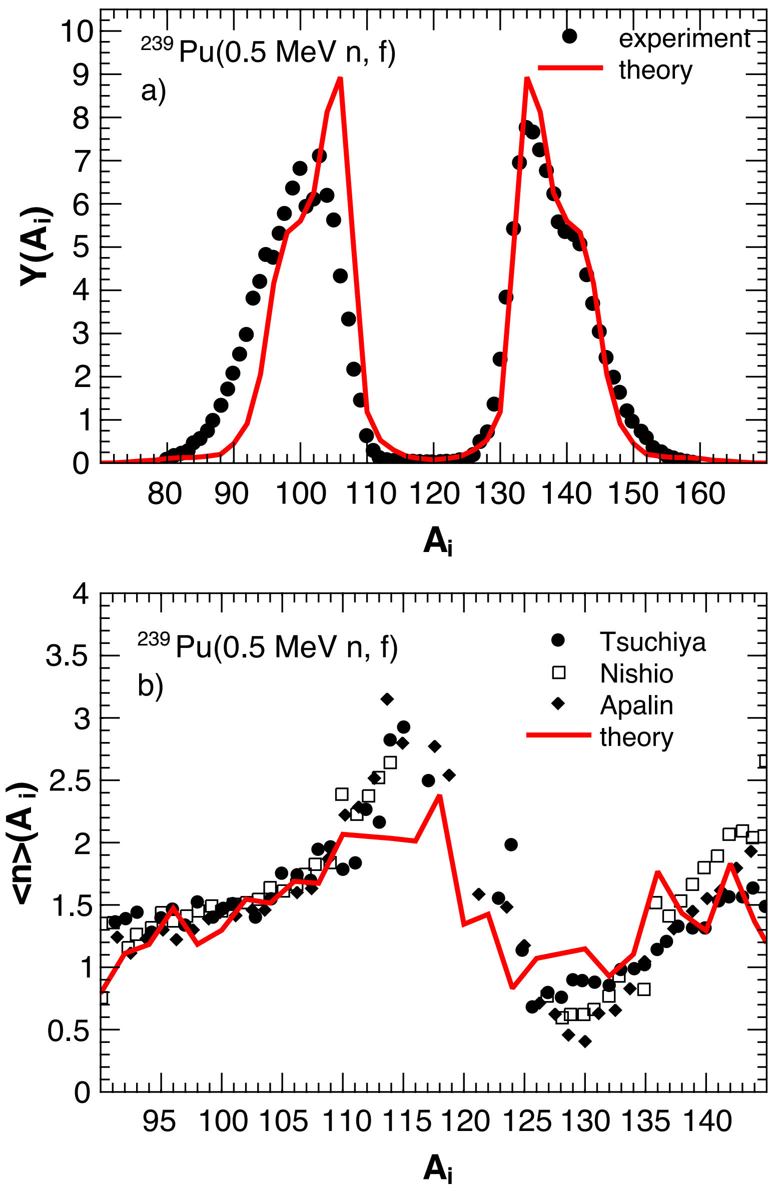
What about excitation energy of CN? $^{238}U(n,f)$

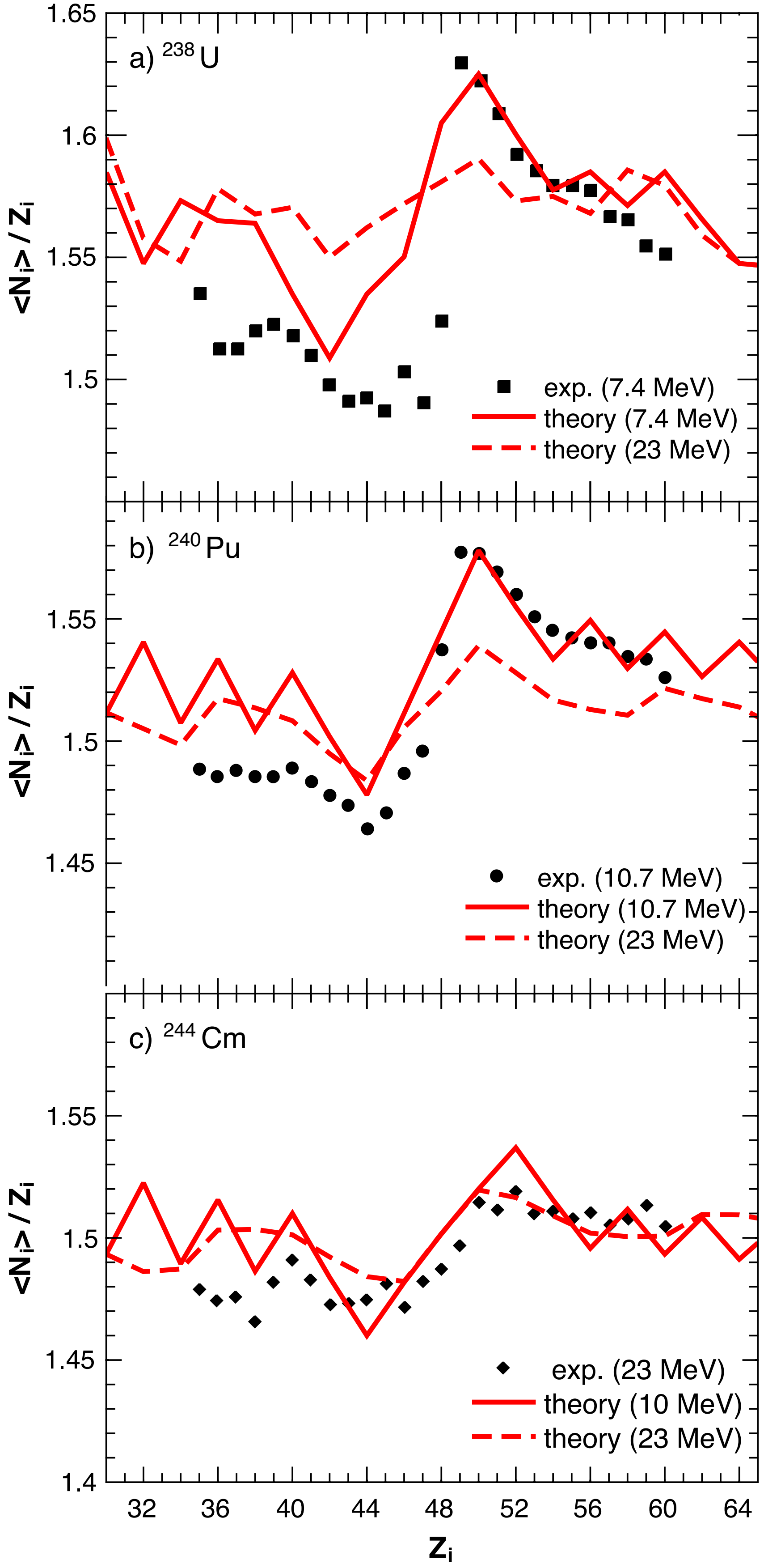




Results - <N/Z> ratios in primary fragments







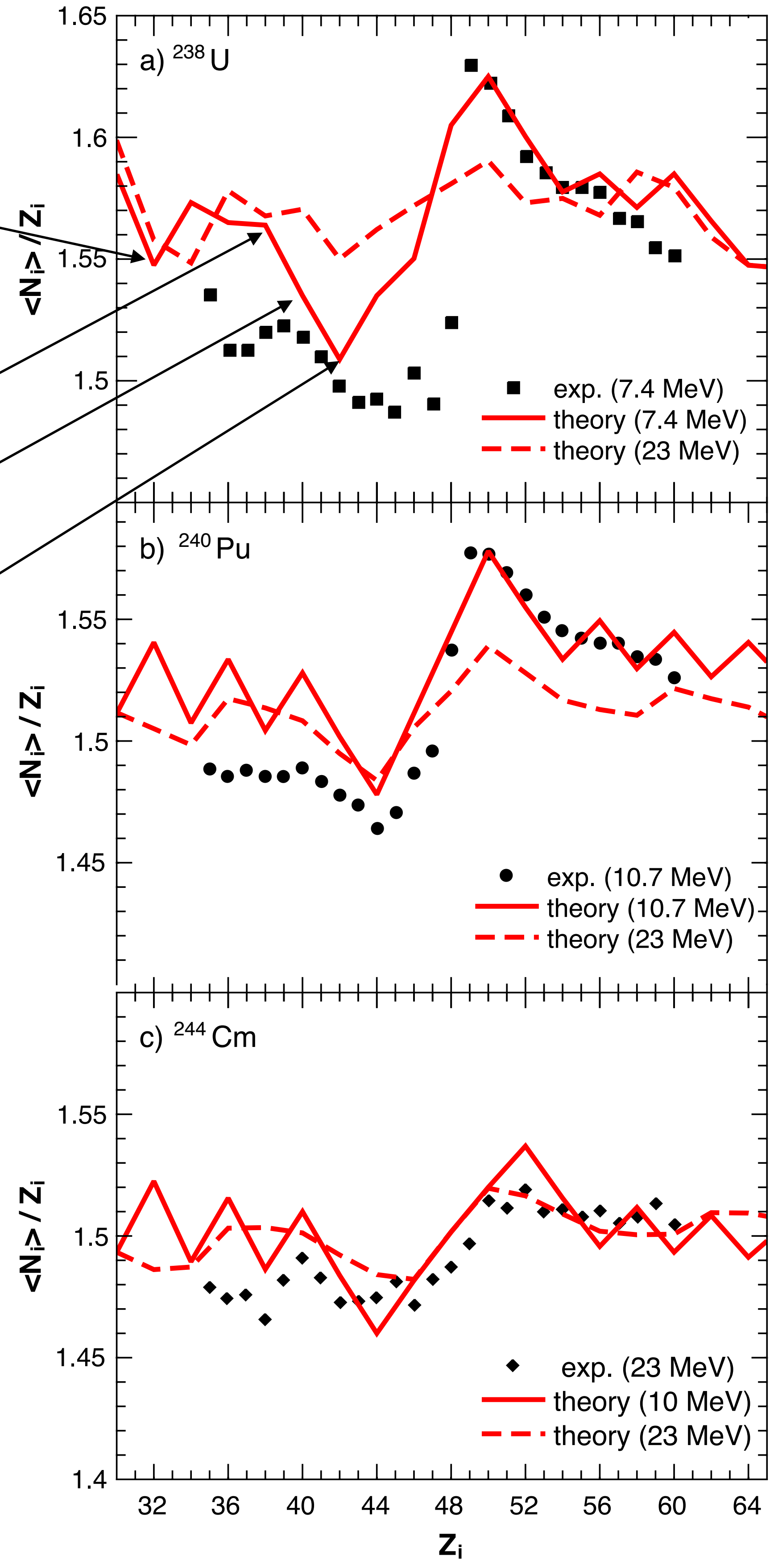
Results - <N/Z> ratios in primary fragments

$Z_L=32 \rightarrow$ ^{82}Ge ($N_L=50$)+ ^{156}Nd

$Z_L=38 \rightarrow$ ^{102}Sr + ^{136}Xe ($N_H=82$), ^{100}Sr + ^{138}Xe ($N_H=84$), ^{98}Sr + ^{140}Xe ($N_H=86$)

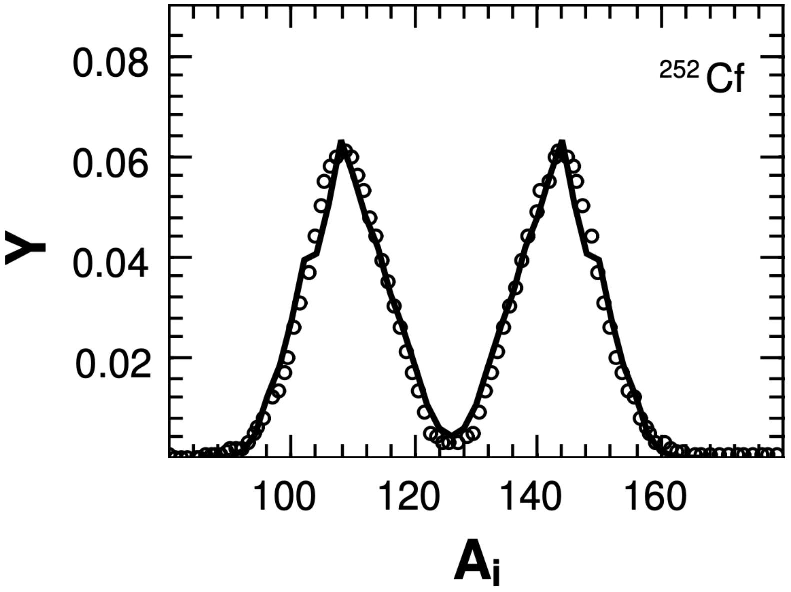
$Z_L = 40 \rightarrow$ ^{102}Zr + ^{136}Te, ^{104}Zr + ^{134}Te, ^{106}Zr + ^{132}Te

$Z_L = 42 \rightarrow$ ^{106}Mo + ^{132}Sn (double magic)



Focus: ^{252}Cf

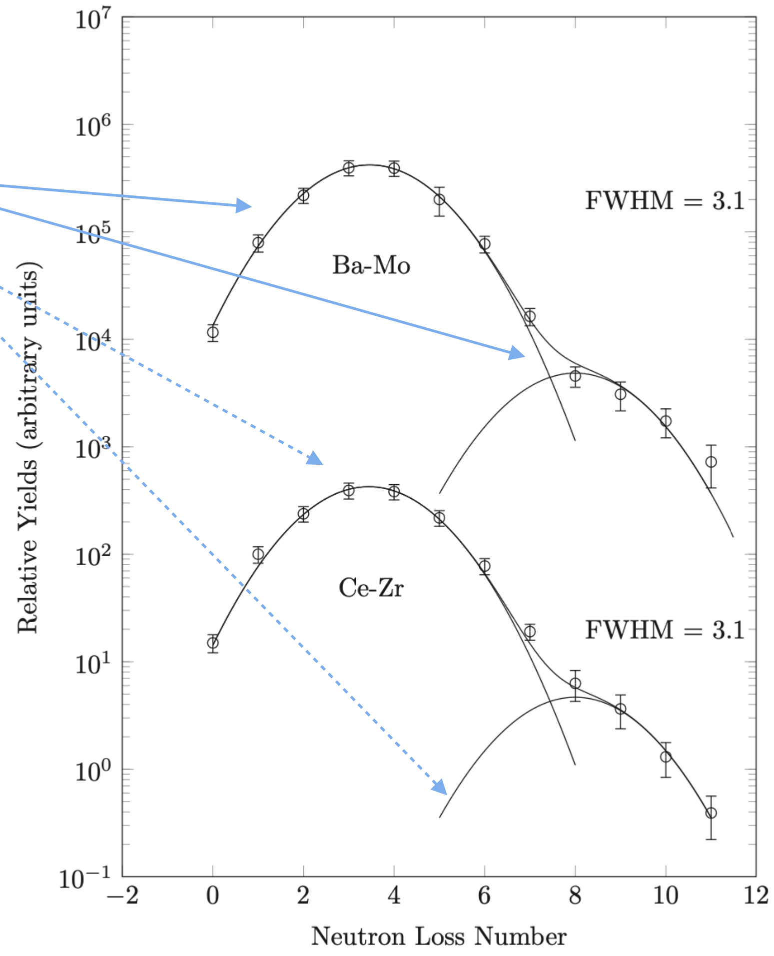
Paşca et. al, PRC **99**, 064611 (2019)



Two fission modes?

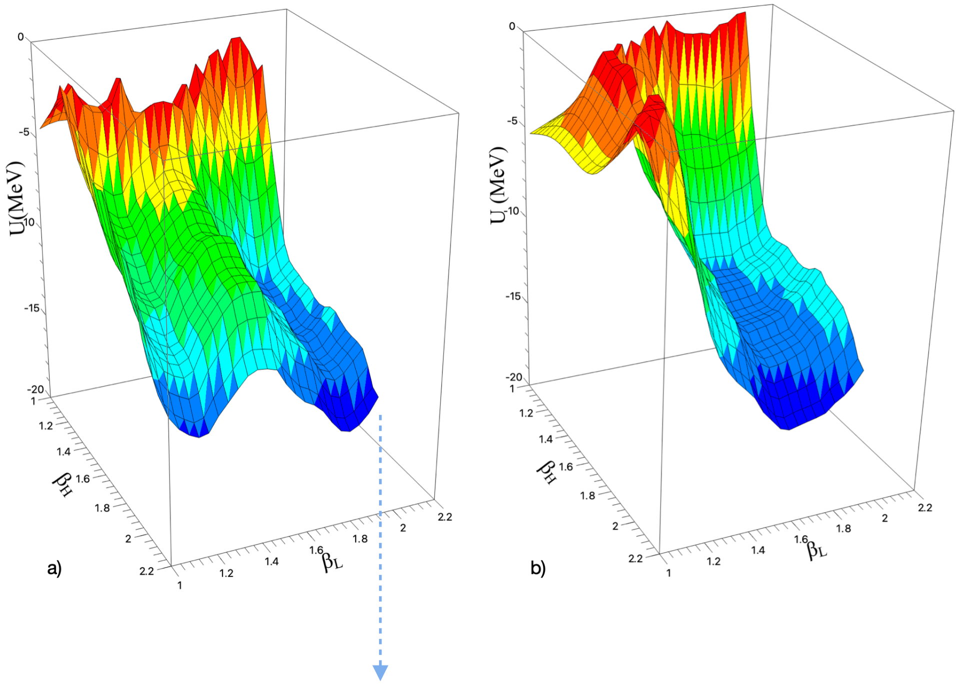
Ba-Mo: 1st mode: $< TKE > = 189 \pm 1$ MeV
$< \nu > = 3 - 4$

2nd mode: $< TKE > = 153 \pm 3$ MeV
$< \nu > \simeq 8$



B. M. Musangu et.al., PRC **101**, 034610 (2020)
see also: G.M. Ter-Akopian et.al., PRL**77**, 32 (1996)
and G.M. Ter-Akopian et.al., PRC**55** 1146 (1997)

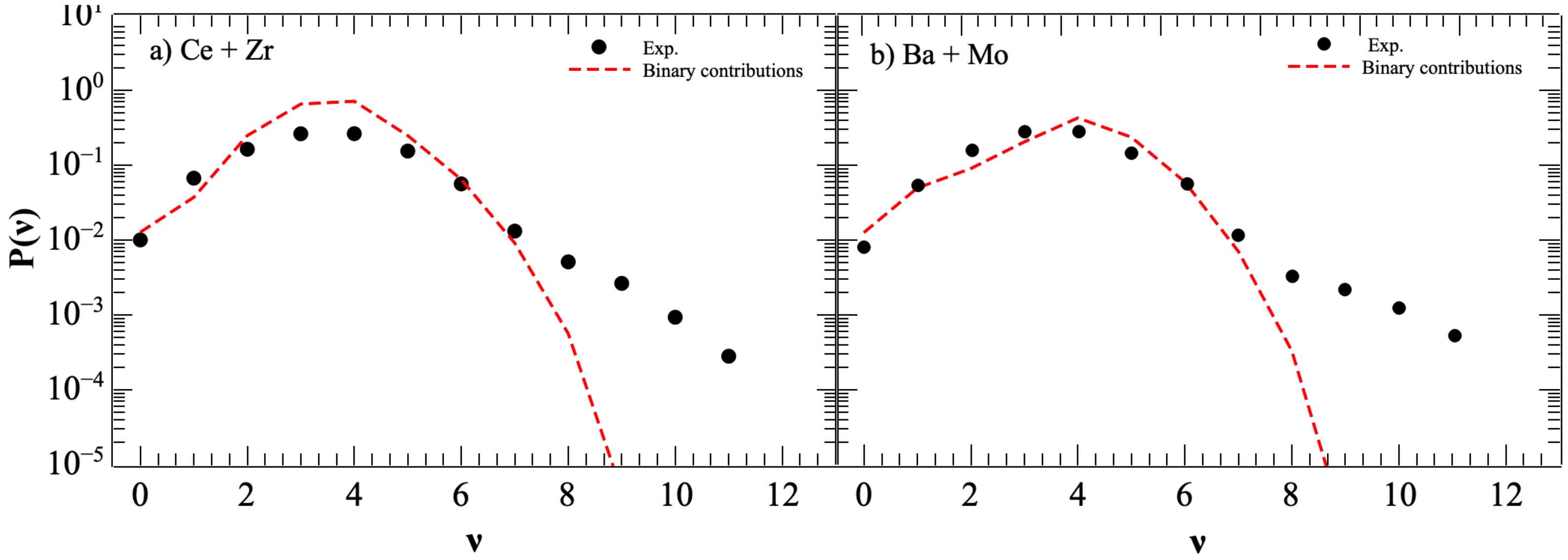
G.M. Ter-Akopian et.al., PRC**55** 1146 (1997): "(…) *data clearly indicate that most of the neutrons in the high neutron emission events come out of the Ba fragments – not the Mo fragments*."



Theory: $TKE(\beta_1 = \beta_2 = 2.2) = 173.4$ MeV (Ba-Mo) and 171.0 MeV (Ce-Zr), respectively.

Maximum excitation energy: $\epsilon^*_{Ba} = E^*_{Ba} + U^{def}_{Ba} = 28.1$ MeV and $\epsilon^*_{Ce} = E^*_{Ce} + U^{def}_{Ce} = 24.1$ MeV, respectively.

Theory: $< TKE > = 192.4$ MeV (Ba-Mo)
$< TKE > = 189.1$ MeV (Ce-Zr)
$< \nu > \simeq 3.5$

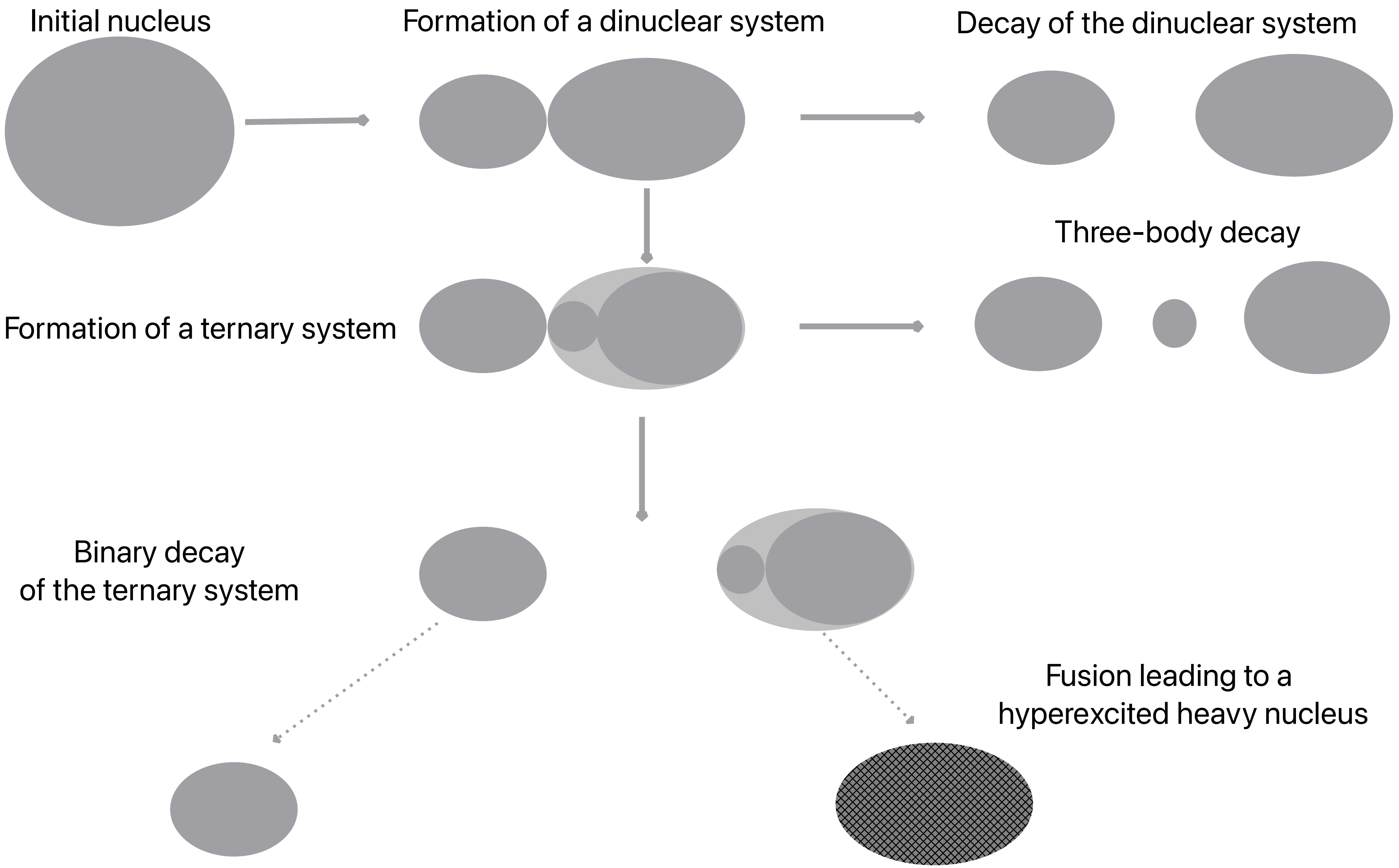


To obtain $TKE \sim 153$ MeV one needs $\beta_{Ba,Mo} \geq 2.5$ (>3 PRC55 1146 (1997)) - unrealistic.

Focus: ^{252}*Cf*

Competing mechanisms?

Ideea supported by: I. Tsekhanovich *et. al*., PRC**67** 034610 (2003), Yu.V. Pyatkov *et.al*., Physics of Atomic Nuclei **86**/4 (2023), …



Initial nucleus

Formation of a dinuclear system

Decay of the dinuclear system

Three-body decay

Formation of a ternary system

Binary decay
of the ternary system

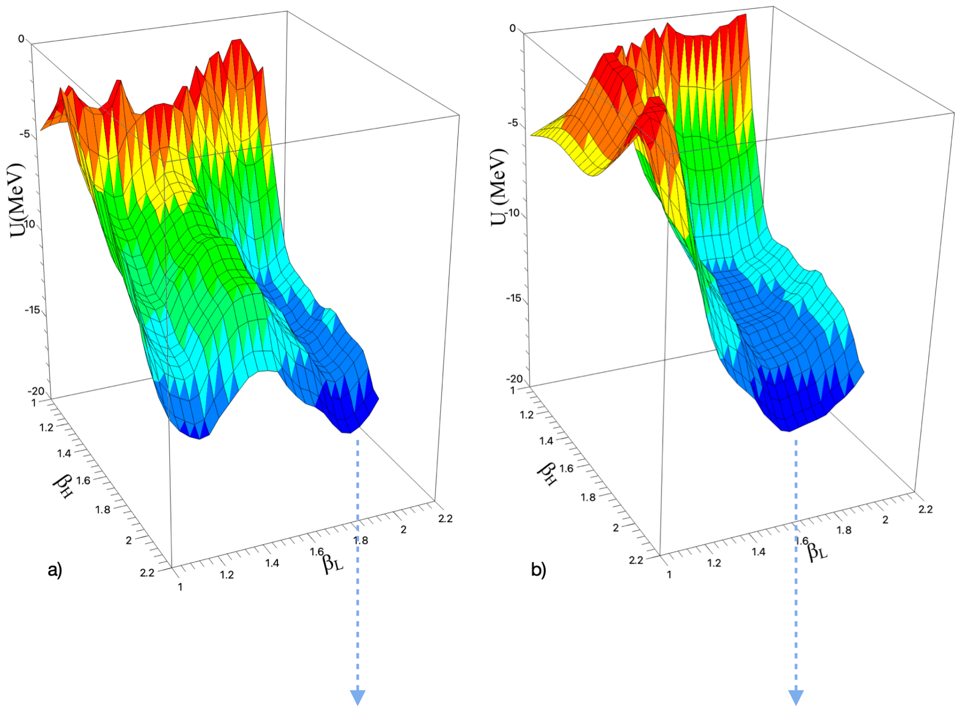
Fusion leading to a
hyperexcited heavy nucleus

Schematic illustration of normal binary decay and ternary fission processes, as well as the ternary cluster mechanism leading to a hyperexcited heavy fragment.

Focus: ^{252}Cf

Competing mechanisms?

Ideea supported by: I. Tsekhanovich *et. al.*, PRC**67** 034610 (2003), Table I (right)



Ba (left) and Ce (right) nuclei have sufficient ϵ^* to be energetically feasible to be represented as clusters.

Notable third fragments: α, ^{10}Be, ^{14}C, ^{20}O, $^{24,26}Ne$ (neutron rich nuclei).

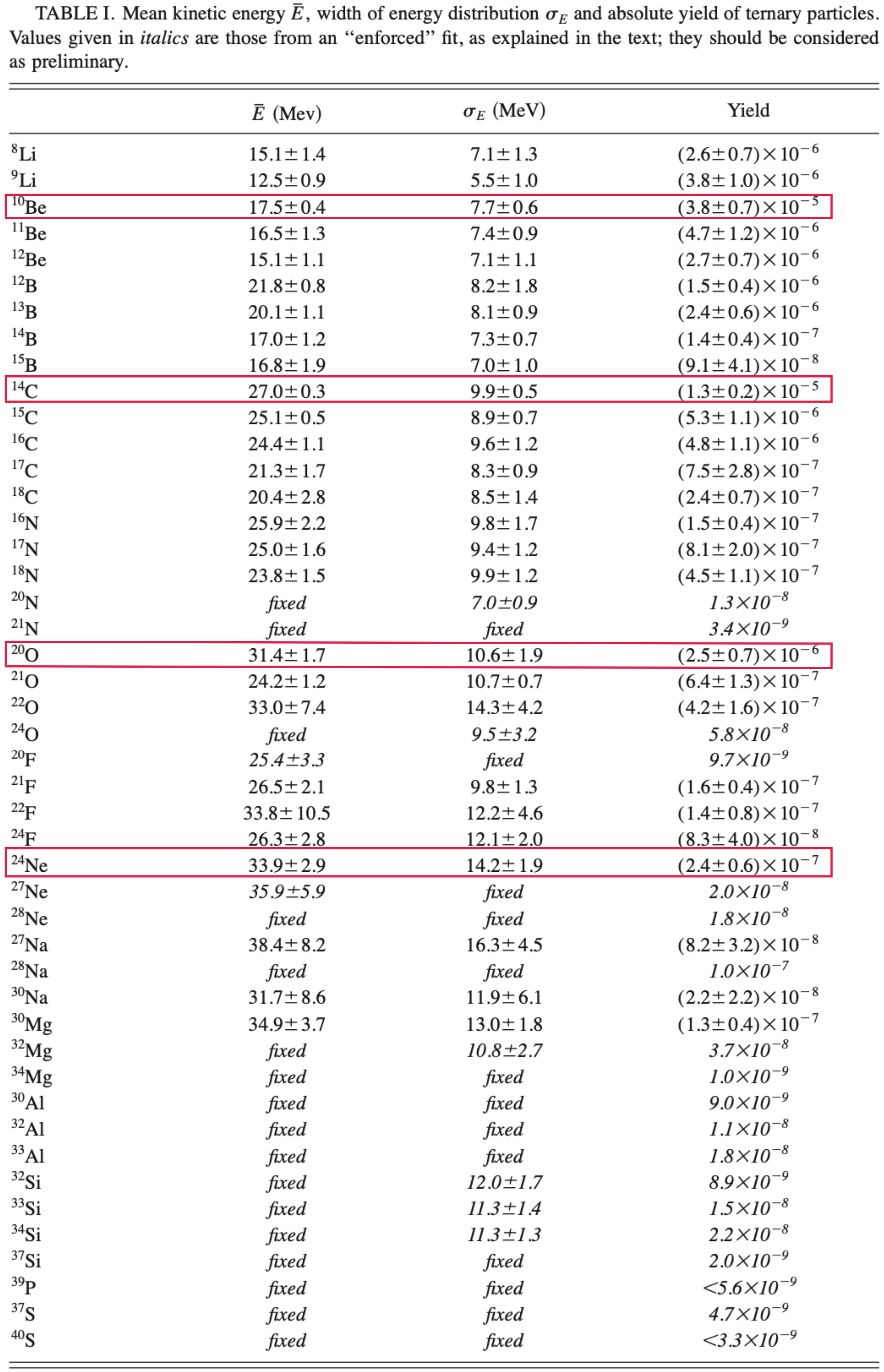


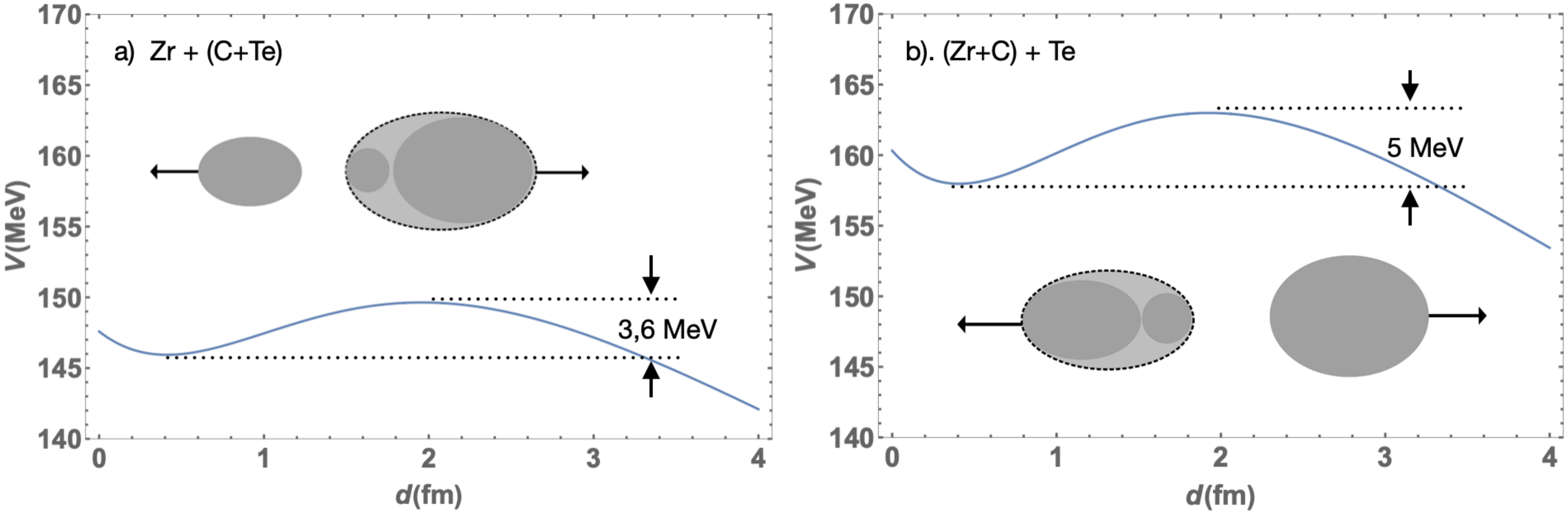
TABLE I. Mean kinetic energy $\bar{E}$, width of energy distribution σ_E and absolute yield of ternary particles. Values given in *italics* are those from an "enforced" fit, as explained in the text; they should be considered as preliminary.

	$\bar{E}$ (Mev)	σ_E (MeV)	Yield
^{8}Li	15.1 ± 1.4	7.1 ± 1.3	$(2.6\pm0.7)\times10^{-6}$
^{9}Li	12.5 ± 0.9	5.5 ± 1.0	$(3.8\pm1.0)\times10^{-6}$
^{10}Be	17.5 ± 0.4	7.7 ± 0.6	$(3.8\pm0.7)\times10^{-5}$
^{11}Be	16.5 ± 1.3	7.4 ± 0.9	$(4.7\pm1.2)\times10^{-6}$
^{12}Be	15.1 ± 1.1	7.1 ± 1.1	$(2.7\pm0.7)\times10^{-6}$
^{12}B	21.8 ± 0.8	8.2 ± 1.8	$(1.5\pm0.4)\times10^{-6}$
^{13}B	20.1 ± 1.1	8.1 ± 0.9	$(2.4\pm0.6)\times10^{-6}$
^{14}B	17.0 ± 1.2	7.3 ± 0.7	$(1.4\pm0.4)\times10^{-7}$
^{15}B	16.8 ± 1.9	7.0 ± 1.0	$(9.1\pm4.1)\times10^{-8}$
^{14}C	27.0 ± 0.3	9.9 ± 0.5	$(1.3\pm0.2)\times10^{-5}$
^{15}C	25.1 ± 0.5	8.9 ± 0.7	$(5.3\pm1.1)\times10^{-6}$
^{16}C	24.4 ± 1.1	9.6 ± 1.2	$(4.8\pm1.1)\times10^{-6}$
^{17}C	21.3 ± 1.7	8.3 ± 0.9	$(7.5\pm2.8)\times10^{-7}$
^{18}C	20.4 ± 2.8	8.5 ± 1.4	$(2.4\pm0.7)\times10^{-7}$
^{16}N	25.9 ± 2.2	9.8 ± 1.7	$(1.5\pm0.4)\times10^{-7}$
^{17}N	25.0 ± 1.6	9.4 ± 1.2	$(8.1\pm2.0)\times10^{-7}$
^{18}N	23.8 ± 1.5	9.9 ± 1.2	$(4.5\pm1.1)\times10^{-7}$
^{20}N	*fixed*	7.0 ± 0.9	1.3×10^{-8}
^{21}N	*fixed*	*fixed*	3.4×10^{-9}
^{20}O	31.4 ± 1.7	10.6 ± 1.9	$(2.5\pm0.7)\times10^{-6}$
^{21}O	24.2 ± 1.2	10.7 ± 0.7	$(6.4\pm1.3)\times10^{-7}$
^{22}O	33.0 ± 7.4	14.3 ± 4.2	$(4.2\pm1.6)\times10^{-7}$
^{24}O	*fixed*	9.5 ± 3.2	5.8×10^{-8}
^{20}F	25.4 ± 3.3	*fixed*	9.7×10^{-9}
^{21}F	26.5 ± 2.1	9.8 ± 1.3	$(1.6\pm0.4)\times10^{-7}$
^{22}F	33.8 ± 10.5	12.2 ± 4.6	$(1.4\pm0.8)\times10^{-7}$
^{24}F	26.3 ± 2.8	12.1 ± 2.0	$(8.3\pm4.0)\times10^{-8}$
^{24}Ne	33.9 ± 2.9	14.2 ± 1.9	$(2.4\pm0.6)\times10^{-7}$
^{27}Ne	35.9 ± 5.9	*fixed*	2.0×10^{-8}
^{28}Ne	*fixed*	*fixed*	1.8×10^{-8}
^{27}Na	38.4 ± 8.2	16.3 ± 4.5	$(8.2\pm3.2)\times10^{-8}$
^{28}Na	*fixed*	*fixed*	1.0×10^{-7}
^{30}Na	31.7 ± 8.6	11.9 ± 6.1	$(2.2\pm2.2)\times10^{-8}$
^{30}Mg	34.9 ± 3.7	13.0 ± 1.8	$(1.3\pm0.4)\times10^{-7}$
^{32}Mg	*fixed*	10.8 ± 2.7	3.7×10^{-8}
^{34}Mg	*fixed*	*fixed*	1.0×10^{-9}
^{30}Al	*fixed*	*fixed*	9.0×10^{-9}
^{32}Al	*fixed*	*fixed*	1.1×10^{-8}
^{33}Al	*fixed*	*fixed*	1.8×10^{-8}
^{32}Si	*fixed*	12.0 ± 1.7	8.9×10^{-9}
^{33}Si	*fixed*	11.3 ± 1.4	1.5×10^{-8}
^{34}Si	*fixed*	11.3 ± 1.3	2.2×10^{-8}
^{37}Si	*fixed*	*fixed*	2.0×10^{-9}
^{39}P	*fixed*	*fixed*	$<5.6\times10^{-9}$
^{37}S	*fixed*	*fixed*	4.7×10^{-9}
^{40}S	*fixed*	*fixed*	$<3.3\times10^{-9}$

Focus: $^{252}\mathit{Cf}$

Competing mechanisms?

Ideea supported by: I. Tsekhanovich *et. al*., PRC**67** 034610 (2003), Yu.V. Pyatkov *et.al*., Physics of Atomic Nuclei **86**/4 (2023), …



Interaction potentials favor the formation of the cluster composing of the heaviest nucleus with the third particle.

G.M. Ter-Akopian et.al., PRC**55** 1146 (1997): “(…) *data clearly indicate that most of the neutrons in the high neutron emission events come out of the Ba fragments – not the Mo fragments*.”

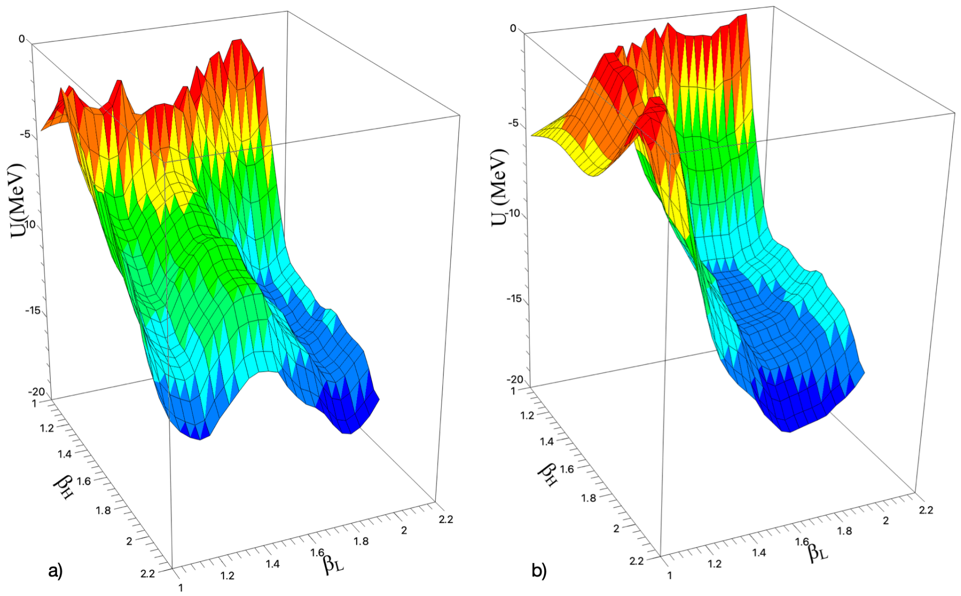
Focus: ^{252}Cf

Final excitation energy of the heavy fragment is: $\varepsilon^{**} = \varepsilon^{*} + \Delta V - Q$,

where $\varepsilon^{*} = E_i^{*} + U^{def}$;

ΔV - the reduction of the interaction potential due to the third fragment;

Q is the fusion Q-value.



^{148}Ce + ^{104}Zr $\qquad \epsilon^{*}_{Ce} = E^{*}_{Ce} + U^{def}_{Ce} = 24.1$ MeV

	ΔV (MeV)	Q (MeV)	ε^{**}_H (MeV)	TKE (MeV)
$(^{144}\mathrm{Ba}+\alpha)+^{104}\mathrm{Zr}$	8.3	1.1	31.3	162.0
$(^{138}\mathrm{Xe}+^{10}\mathrm{Be})+^{104}\mathrm{Zr}$	13.9	2.9	35.1	140.5
$(^{134}\mathrm{Te}+^{14}\mathrm{C})+^{104}\mathrm{Zr}$	30.8	-9.2	64.0	150.3
$(^{128}\mathrm{Sn}+^{20}\mathrm{O})+^{104}\mathrm{Zr}$	39.6	-9.2	72.7	153.6
$(^{122}\mathrm{Cd}+^{26}\mathrm{Ne})+^{104}\mathrm{Zr}$	47.4	-9.9	81.4	144.5
$(^{124}\mathrm{Cd}+^{24}\mathrm{Ne})+^{104}\mathrm{Zr}$	45.8	-11.0	80.9	144.2

Large variations in ΔV, especially for heavy third nuclei.

^{146}Ba + ^{106}Mo $\qquad \epsilon^{*}_{Ba} = E^{*}_{Ba} + U^{def}_{Ba} = 28.1$ MeV

	ΔV (MeV)	Q (MeV)	ε^{**}_H (MeV)	TKE (MeV)
$(^{142}\mathrm{Xe}+\alpha)+^{106}\mathrm{Mo}$	12.7	2.0	38.8	166.6
$(^{136}\mathrm{Te}+^{10}\mathrm{Be})+^{106}\mathrm{Mo}$	13.7	3.2	38.6	144.4
$(^{132}\mathrm{Sn}+^{14}\mathrm{C})+^{106}\mathrm{Mo}$	30.5	-8.5	67.1	155.9
$(^{126}\mathrm{Cd}+^{20}\mathrm{O})+^{106}\mathrm{Mo}$	39.0	-3.5	70.6	160.6
$(^{120}\mathrm{Pd}+^{26}\mathrm{Ne})+^{106}\mathrm{Mo}$	45.0	-4.7	77.8	157.1
$(^{122}\mathrm{Pd}+^{24}\mathrm{Ne})+^{106}\mathrm{Mo}$	44.8	-5.6	78.5	158.0

Focus: ^{252}Cf

Final excitation energy of the heavy fragment is: $\varepsilon^{**} = \varepsilon^{*} + \Delta V - Q$,

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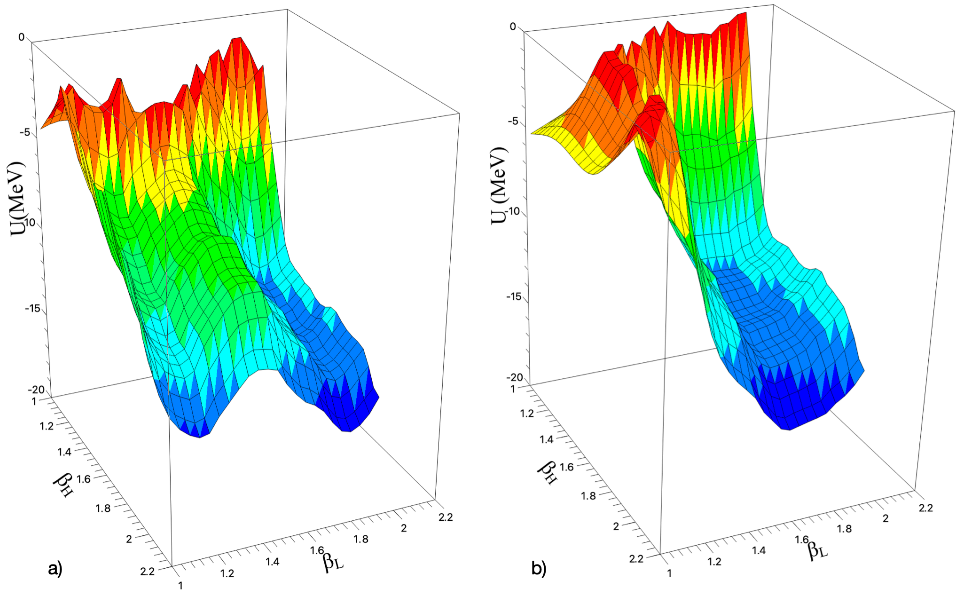

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(^{124}Cd+^{24}Ne)+^{104}Zr	45.8	-11.0	80.9	144.2

^{146}Ba + ^{106}Mo

$\epsilon^{*}_{Ba} = E^{*}_{Ba} + U^{def}_{Ba} = 28.1$ MeV

	ΔV (MeV)	Q (MeV)	ε^{**}_H (MeV)	TKE (MeV)
(^{142}Xe+α)+^{106}Mo	12.7	2.0	38.8	166.6
(^{136}Te+^{10}Be)+^{106}Mo	13.7	3.2	38.6	144.4
(^{132}Sn+^{14}C)+^{106}Mo	30.5	-8.5	67.1	155.9
(^{126}Cd+^{20}O)+^{106}Mo	39.0	-3.5	70.6	160.6
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(^{122}Pd+^{24}Ne)+^{106}Mo	44.8	-5.6	78.5	158.0

Large variations in ΔV, especially for heavy third nuclei.

Large negative Q-values enhance ε^{**}, especially for heavy third nuclei.

Focus: ^{252}Cf

Final excitation energy of the heavy fragment is: $\varepsilon^{**} = \varepsilon^{*} + \Delta V - Q$,

where $\varepsilon^{*} = E_i^{*} + U^{def}$;

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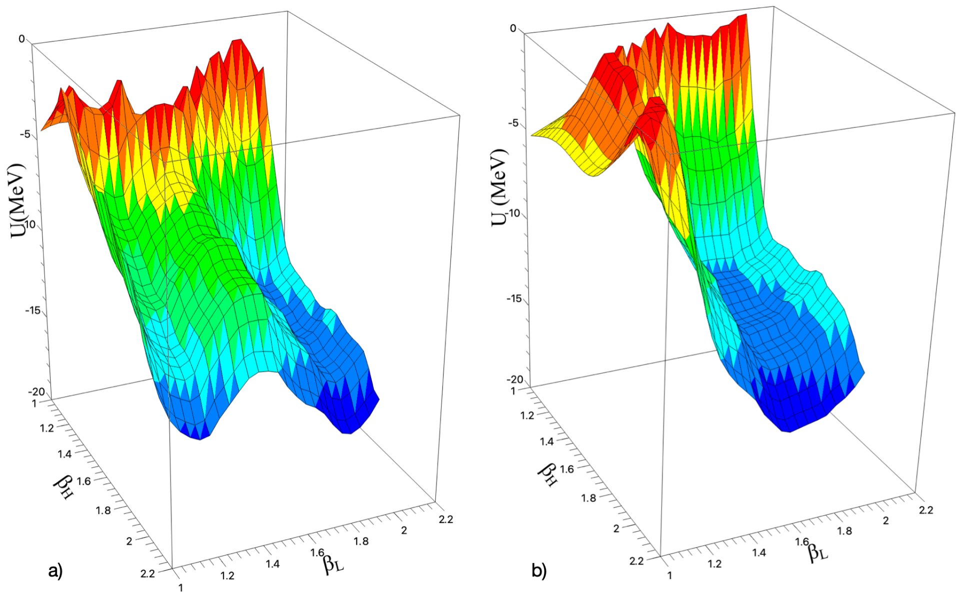

^{148}Ce + ^{104}Zr $\qquad \epsilon^{*}_{Ce} = E^{*}_{Ce} + U^{def}_{Ce} = 24.1$ MeV

	ΔV (MeV)	Q (MeV)	ε^{**}_H (MeV)	TKE (MeV)
(^{144}Ba+α)+^{104}Zr	8.3	1.1	31.3	162.0
(^{138}Xe+^{10}Be)+^{104}Zr	13.9	2.9	35.1	140.5
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(^{122}Pd+^{24}Ne)+^{106}Mo	44.8	-5.6	78.5	158.0

Large variations in ΔV, especially for heavy third nuclei.

Large negative Q-values enhance ε^{**}, especially for heavy third nuclei.

Extremely large excitation energy for the heavy fragment after heavy cluster's fusion.

Focus: ^{252}Cf

Competing mechanisms?

The probability of emitting exactly ν neutrons, taking into account binary and tripartition contribution, can be written as:

$$P(\nu) = \lambda_d P_\nu(A_i, Z_i, \beta_i, \varepsilon^*) + \lambda_t P_\nu(A_i, Z_i, \beta_i, \varepsilon^{**})$$

$$P_\nu(A_i, Z_i, \beta_i, \varepsilon) = \sum_{\nu_L=0}^{\nu} \int_0^{\varepsilon - U_H^{\mathrm{def}} - U_L^{\mathrm{def}}} dE P_C(E) P_{\nu_L}(U_L^{\mathrm{def}} + E) P_{\nu-\nu_L}(\varepsilon - U_L^{\mathrm{def}} - E)$$

The probability of emitting the third cluster is the product of the probabilities for formation of ternary system and three body decay.

- ↳ λ_t can be estimated using the experimental values.
- ↳ our estimates: $< 10^{-2}$ compared to binary decay.

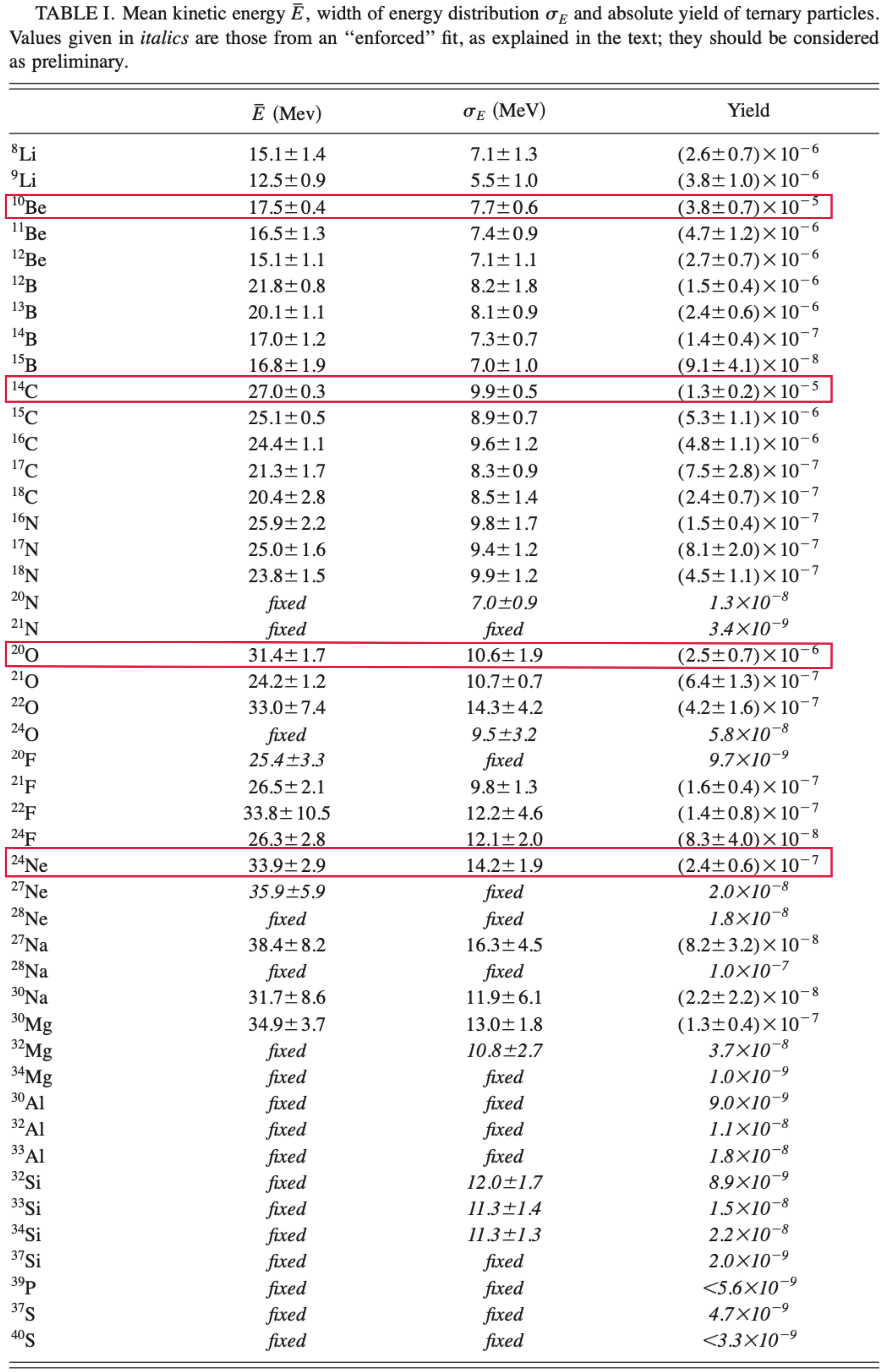

TABLE I. Mean kinetic energy $\bar{E}$, width of energy distribution σ_E and absolute yield of ternary particles. Values given in *italics* are those from an "enforced" fit, as explained in the text; they should be considered as preliminary.

	$\bar{E}$ (Mev)	σ_E (MeV)	Yield
^{8}Li	15.1±1.4	7.1±1.3	$(2.6\pm0.7)\times10^{-6}$
^{9}Li	12.5±0.9	5.5±1.0	$(3.8\pm1.0)\times10^{-6}$
^{10}Be	17.5±0.4	7.7±0.6	$(3.8\pm0.7)\times10^{-5}$
^{11}Be	16.5±1.3	7.4±0.9	$(4.7\pm1.2)\times10^{-6}$
^{12}Be	15.1±1.1	7.1±1.1	$(2.7\pm0.7)\times10^{-6}$
^{12}B	21.8±0.8	8.2±1.8	$(1.5\pm0.4)\times10^{-6}$
^{13}B	20.1±1.1	8.1±0.9	$(2.4\pm0.6)\times10^{-6}$
^{14}B	17.0±1.2	7.3±0.7	$(1.4\pm0.4)\times10^{-7}$
^{15}B	16.8±1.9	7.0±1.0	$(9.1\pm4.1)\times10^{-8}$
^{14}C	27.0±0.3	9.9±0.5	$(1.3\pm0.2)\times10^{-5}$
^{15}C	25.1±0.5	8.9±0.7	$(5.3\pm1.1)\times10^{-6}$
^{16}C	24.4±1.1	9.6±1.2	$(4.8\pm1.1)\times10^{-6}$
^{17}C	21.3±1.7	8.3±0.9	$(7.5\pm2.8)\times10^{-7}$
^{18}C	20.4±2.8	8.5±1.4	$(2.4\pm0.7)\times10^{-7}$
^{16}N	25.9±2.2	9.8±1.7	$(1.5\pm0.4)\times10^{-7}$
^{17}N	25.0±1.6	9.4±1.2	$(8.1\pm2.0)\times10^{-7}$
^{18}N	23.8±1.5	9.9±1.2	$(4.5\pm1.1)\times10^{-7}$
^{20}N	*fixed*	*7.0±0.9*	*1.3×10^{-8}*
^{21}N	*fixed*	*fixed*	*3.4×10^{-9}*
^{20}O	31.4±1.7	10.6±1.9	$(2.5\pm0.7)\times10^{-6}$
^{21}O	24.2±1.2	10.7±0.7	$(6.4\pm1.3)\times10^{-7}$
^{22}O	33.0±7.4	14.3±4.2	$(4.2\pm1.6)\times10^{-7}$
^{24}O	*fixed*	*9.5±3.2*	*5.8×10^{-8}*
^{20}F	*25.4±3.3*	*fixed*	*9.7×10^{-9}*
^{21}F	26.5±2.1	9.8±1.3	$(1.6\pm0.4)\times10^{-7}$
^{22}F	33.8±10.5	12.2±4.6	$(1.4\pm0.8)\times10^{-7}$
^{24}F	26.3±2.8	12.1±2.0	$(8.3\pm4.0)\times10^{-8}$
^{24}Ne	33.9±2.9	14.2±1.9	$(2.4\pm0.6)\times10^{-7}$
^{27}Ne	*35.9±5.9*	*fixed*	*2.0×10^{-8}*
^{28}Ne	*fixed*	*fixed*	*1.8×10^{-8}*
^{27}Na	38.4±8.2	16.3±4.5	$(8.2\pm3.2)\times10^{-8}$
^{28}Na	*fixed*	*fixed*	*1.0×10^{-7}*
^{30}Na	31.7±8.6	11.9±6.1	$(2.2\pm2.2)\times10^{-8}$
^{30}Mg	34.9±3.7	13.0±1.8	$(1.3\pm0.4)\times10^{-7}$
^{32}Mg	*fixed*	*10.8±2.7*	*3.7×10^{-8}*
^{34}Mg	*fixed*	*fixed*	*1.0×10^{-9}*
^{30}Al	*fixed*	*fixed*	*9.0×10^{-9}*
^{32}Al	*fixed*	*fixed*	*1.1×10^{-8}*
^{33}Al	*fixed*	*fixed*	*1.8×10^{-8}*
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^{39}P	*fixed*	*fixed*	*$<5.6\times10^{-9}$*
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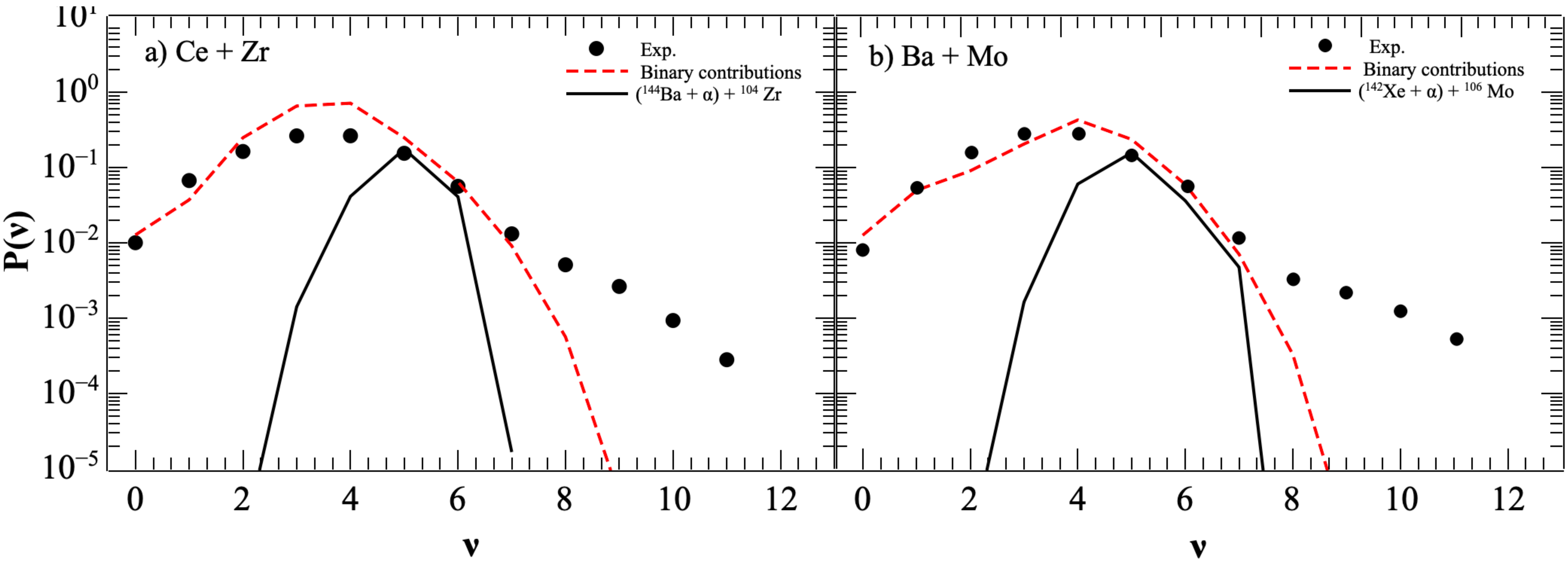
Focus: ^{252}Cf

Competing mechanisms? - Neutron multiplicity



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^{146}Ba + ^{106}Mo $\epsilon^*_{Ba} = E^*_{Ba} + U^{def}_{Ba} = 28.1$ MeV

	ΔV (MeV)	Q (MeV)	ε^{**}_H (MeV)	TKE (MeV)
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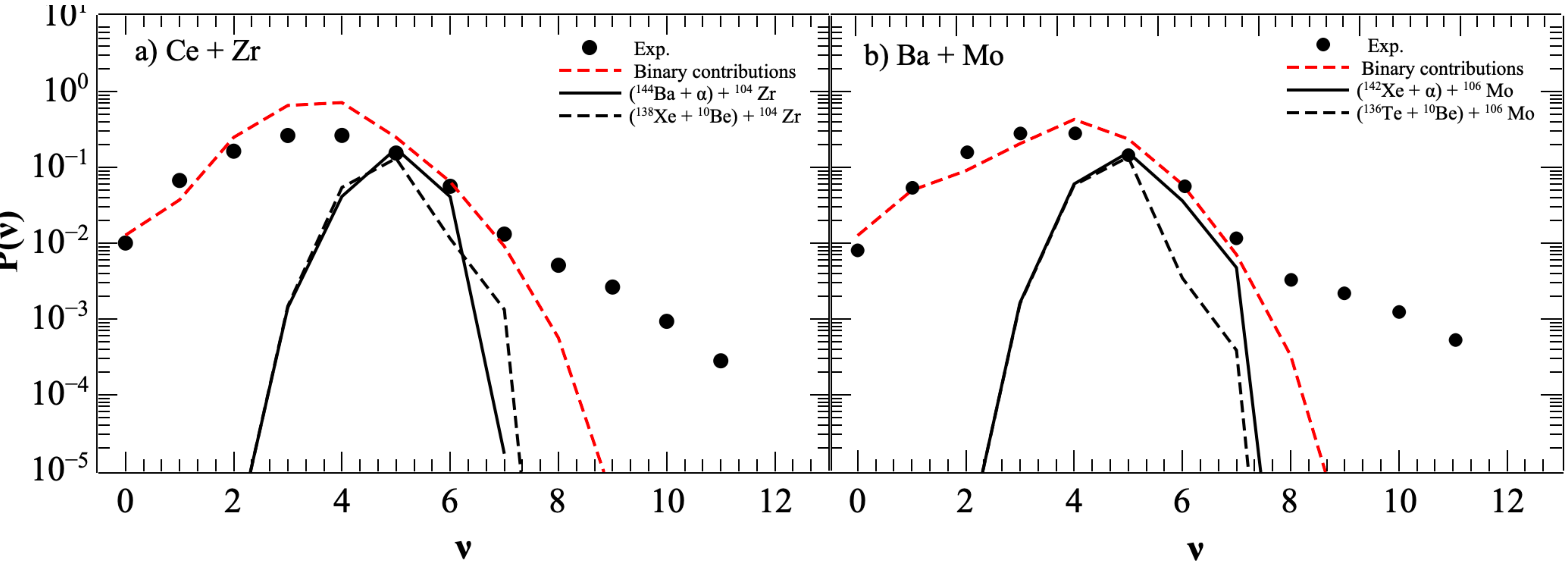
Competing mechanisms? - Neutron multiplicity



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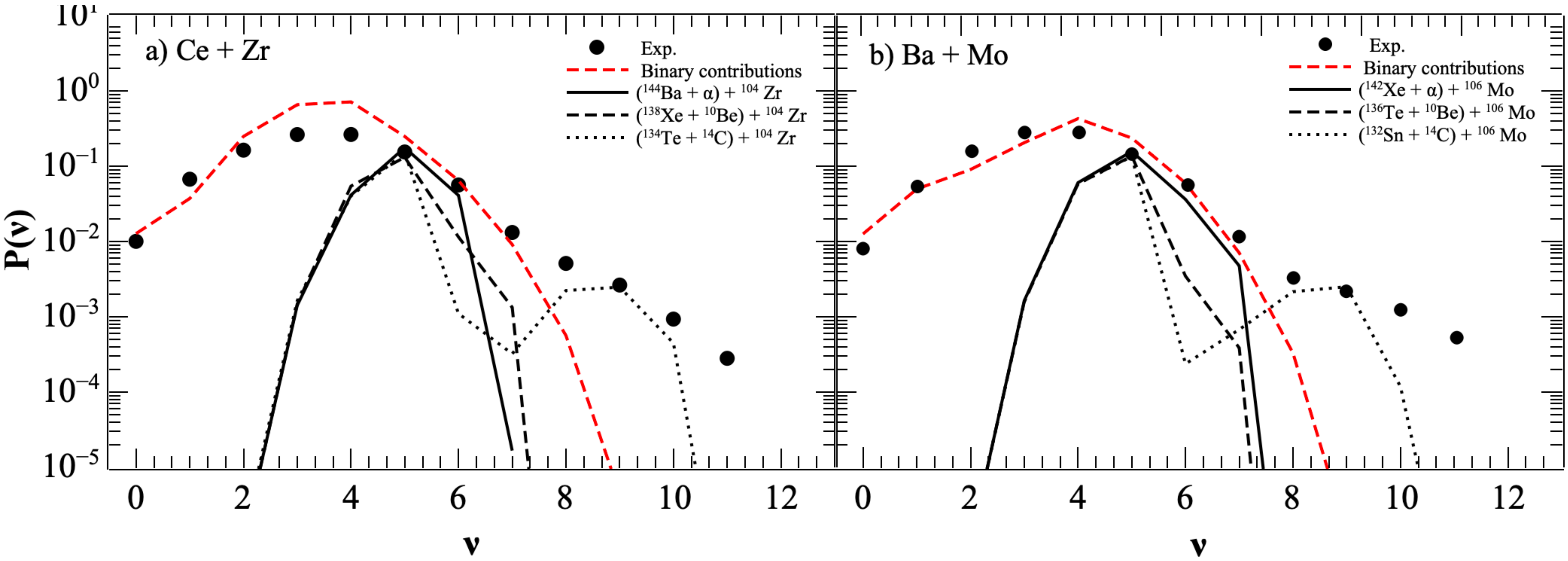
Competing mechanisms? - Neutron multiplicity



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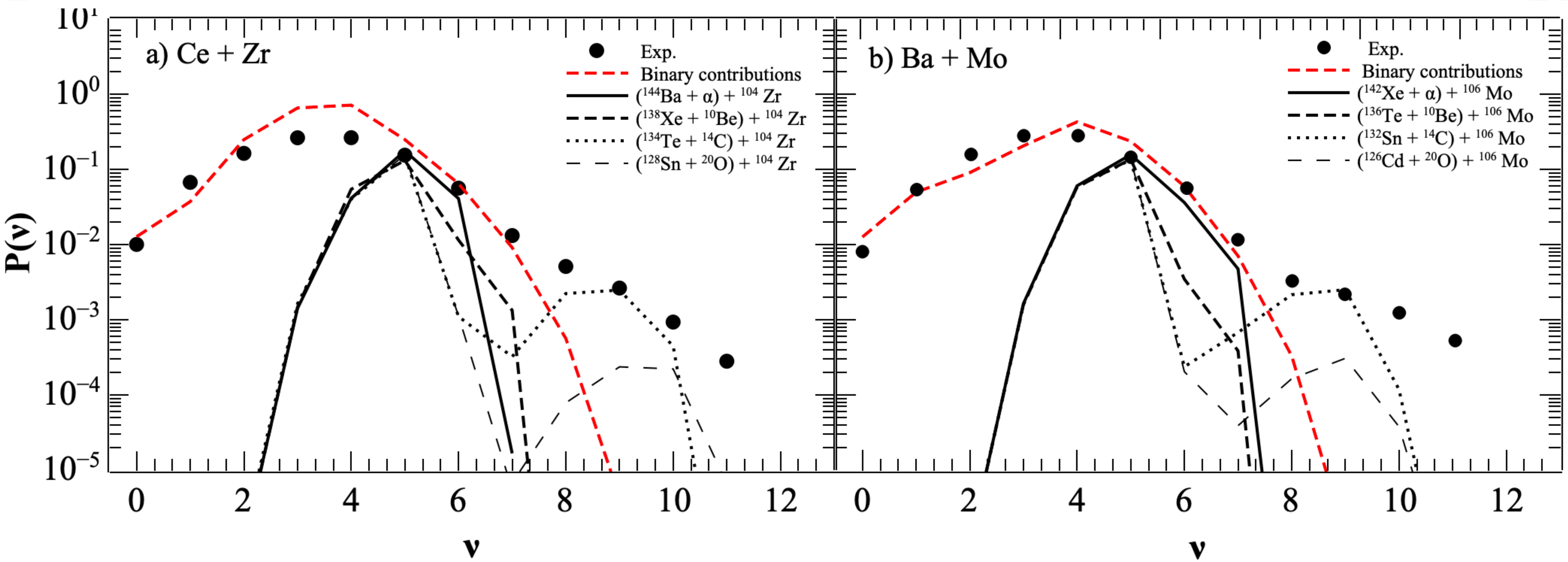
(^{136}Te+^{10}Be)+^{106}Mo	13.7	3.2	38.6	144.4
(^{132}Sn+^{14}C)+^{106}Mo	30.5	-8.5	67.1	155.9
(^{126}Cd+^{20}O)+^{106}Mo	39.0	-3.5	70.6	160.6
(^{120}Pd+^{26}Ne)+^{106}Mo	45.0	-4.7	77.8	157.1
(^{122}Pd+^{24}Ne)+^{106}Mo	44.8	-5.6	78.5	158.0

Focus: ^{252}Cf

Competing mechanisms? - Neutron multiplicity



^{148}Ce + ^{104}Zr $\epsilon^*_{Ce} = E^*_{Ce} + U^{def}_{Ce} = 24.1$ MeV

	ΔV (MeV)	Q (MeV)	ε^{**}_H (MeV)	TKE (MeV)
$(^{144}\mathrm{Ba}+\alpha)+{}^{104}\mathrm{Zr}$	8.3	1.1	31.3	162.0
$(^{138}\mathrm{Xe}+{}^{10}\mathrm{Be})+{}^{104}\mathrm{Zr}$	13.9	2.9	35.1	140.5
$(^{134}\mathrm{Te}+{}^{14}\mathrm{C})+{}^{104}\mathrm{Zr}$	30.8	-9.2	64.0	150.3
$(^{128}\mathrm{Sn}+{}^{20}\mathrm{O})+{}^{104}\mathrm{Zr}$	39.6	-9.2	72.7	153.6
$(^{122}\mathrm{Cd}+{}^{26}\mathrm{Ne})+{}^{104}\mathrm{Zr}$	47.4	-9.9	81.4	144.5
$(^{124}\mathrm{Cd}+{}^{24}\mathrm{Ne})+{}^{104}\mathrm{Zr}$	45.8	-11.0	80.9	144.2

^{146}Ba + ^{106}Mo $\epsilon^*_{Ba} = E^*_{Ba} + U^{def}_{Ba} = 28.1$ MeV

	ΔV (MeV)	Q (MeV)	ε^{**}_H (MeV)	TKE (MeV)
$(^{142}\mathrm{Xe}+\alpha)+{}^{106}\mathrm{Mo}$	12.7	2.0	38.8	166.6
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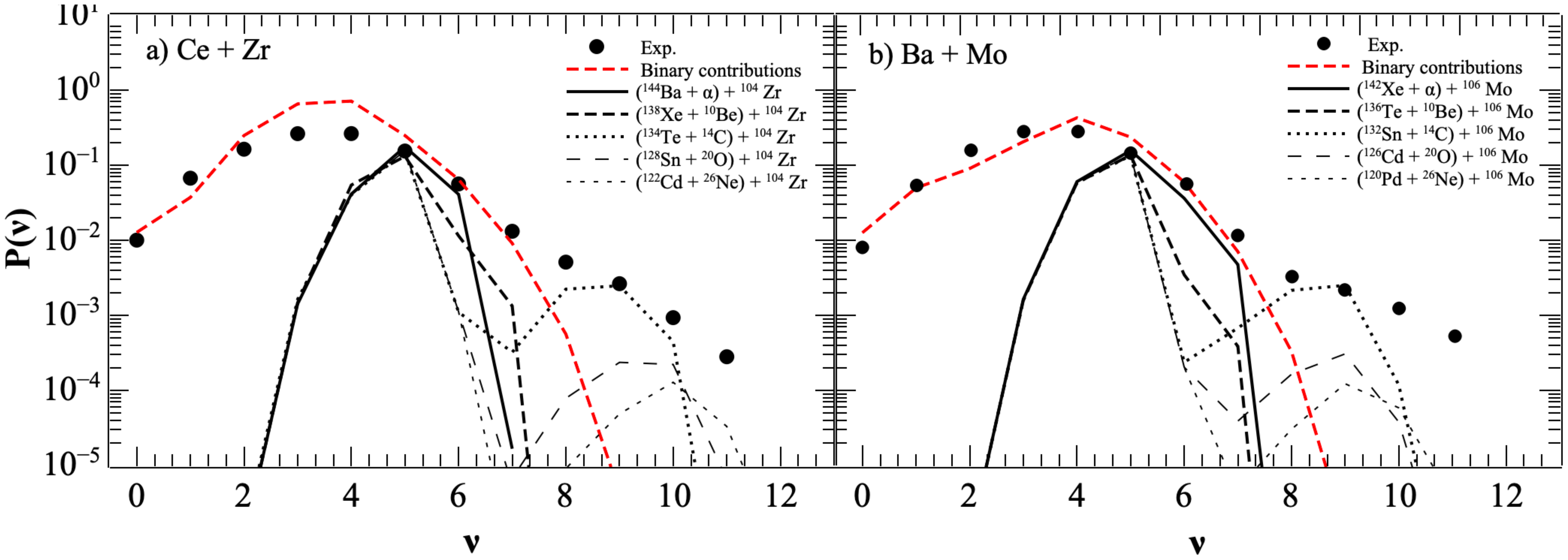
Focus: ^{252}Cf

Competing mechanisms? - Neutron multiplicity



^{148}Ce + ^{104}Zr $\qquad \epsilon^*_{Ce} = E^*_{Ce} + U^{def}_{Ce} = 24.1$ MeV

	ΔV (MeV)	Q (MeV)	ε^{**}_H (MeV)	TKE (MeV)
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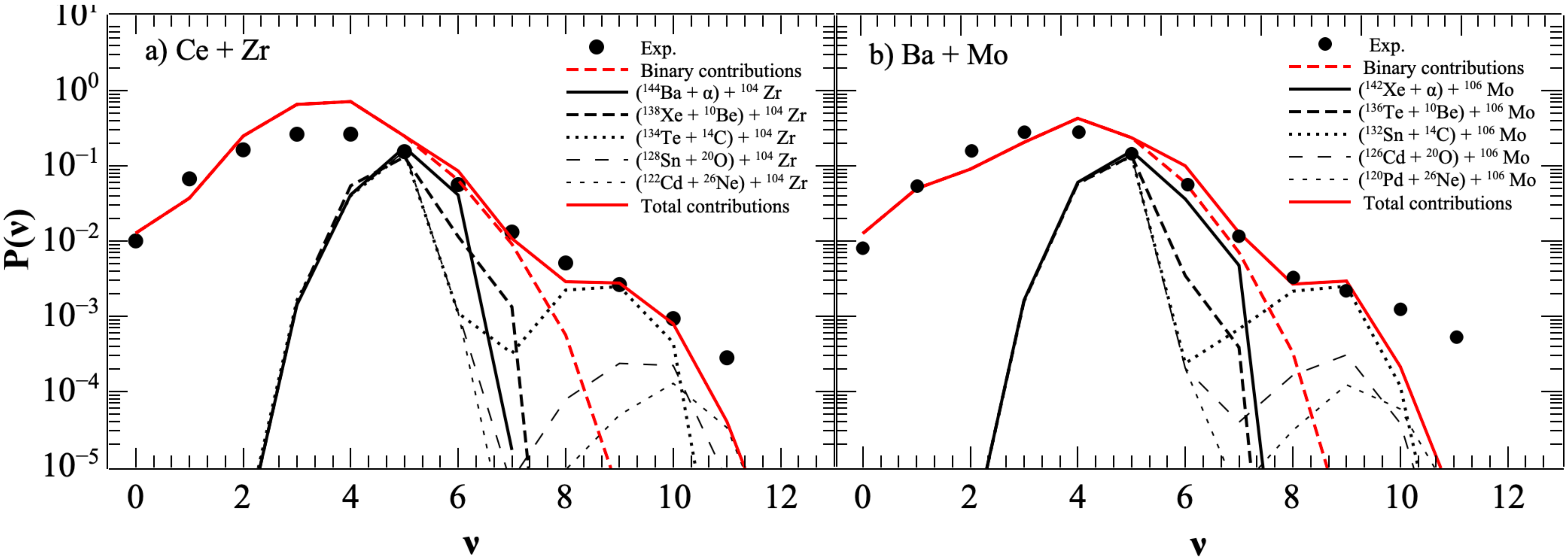
Focus: ^{252}Cf

Competing mechanisms? - Neutron multiplicity



^{148}Ce + ^{104}Zr $\epsilon^*_{Ce} = E^*_{Ce} + U^{def}_{Ce} = 24.1$ MeV

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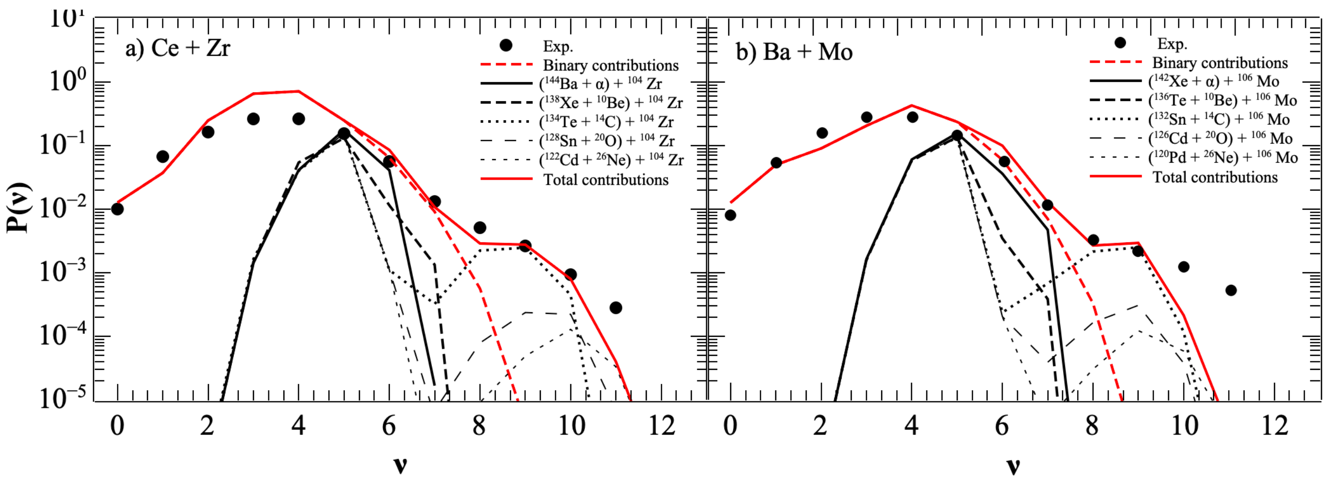
Focus: ^{252}Cf

Competing mechanisms? - Neutron multiplicity



Other observables in the 2nd mode for Ba-Mo:

Total kinetic energy:

$$< TKE >_{exp} = 153 \pm 3 \text{ MeV}$$
$$< TKE >_{th} = 155{,}9 \text{ MeV}$$

Neutron multiplicity:

$$< \nu >_{exp} = 8$$
$$< \nu >_{th} \simeq 9$$

Excitation energy:

G.M. Ter-Akopian et.al., PRL**77**, 32 (1996)

$$\left(\frac{E^*_{Ba,mode1}}{E^*_{Ba,mode2}} \right)_{exp} = 2.6$$

$$\left(\frac{E^*_{Ba,mode1}}{E^*_{Ba,mode2}} \right)_{th} = 2.4$$

$^{148}\text{Ce} + {}^{104}\text{Zr}$ $\qquad \epsilon^*_{Ce} = E^*_{Ce} + U^{def}_{Ce} = 24.1$ MeV

	ΔV (MeV)	Q (MeV)	ε^{**}_H (MeV)	TKE (MeV)
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Focus: ^{252}Cf

Other fragmentations - is the second mode present?

Nd+Sr fragmentation:

→ Binary decay contribution much narrower than experimental data;

↳ PES minimum is much narrower than previous cases.

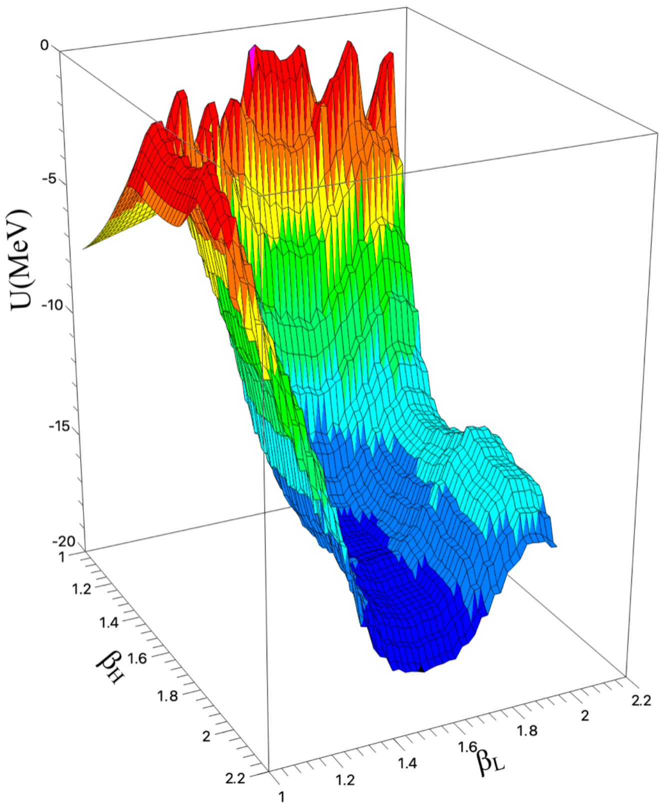
↳ example $P(\nu = 7)$ is at least two orders of magnitude less than previous cases.

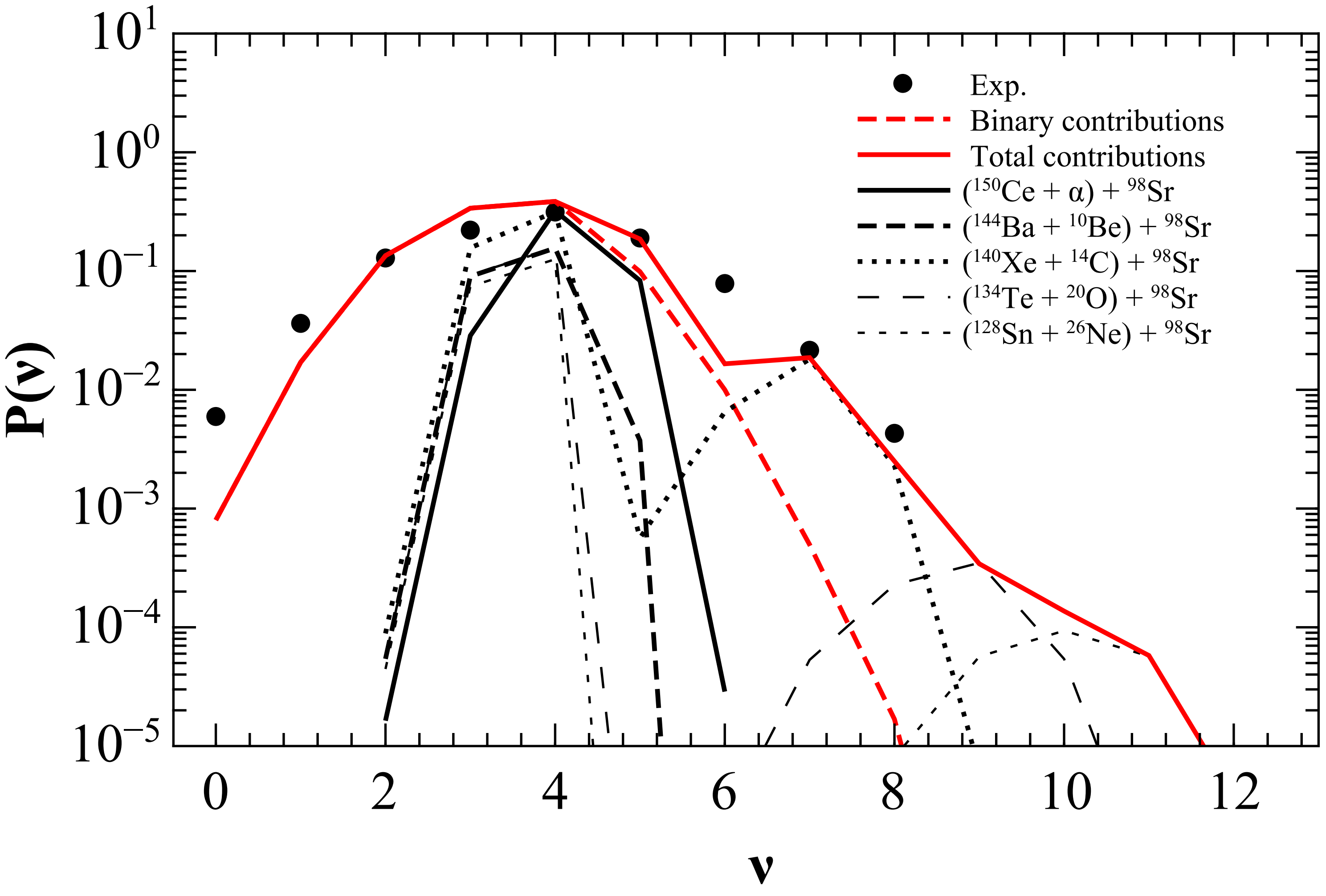
→ Most probable cluster is $Nd \rightarrow Xe + C$.

→ 2nd mode overlaps significantly with 1st mode.

→ O, Ne clusters offer just a “tail” due to low probabilities.

Configuration	ΔV	Q	ϵ^{**}
$(^{150}Ce + \alpha) +^{98} Sr$	9,7	4,12	29,4
$(^{144}Ba +^{10} Be) +^{98} Sr$	14,7	6,53	31,9
$(^{140}Xe +^{14} C) +^{98} Sr$	28,75	-4,3	50,09
$(^{134}Te +^{20} O) +^{98} Sr$	41,8	-13,1	78,6
$(^{128}Sn +^{26} Ne) +^{98} Sr$	56,04	-17,2	97





Conclusions

- The mass, charge, TKE and neutron distributions can be calculated within the same model.
- Clusterisation of the heavy fragment can lead to a highly excited fission fragment.
- Competing mechanisms are possible, and they provide key signatures in $< n >$ and TKE values.
- Evidence for cluster effects for can be "hidden" within existing experimental data.
- Question : Is this mechanism more common than previously thought ?

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Thank you!