Isotopic trends in the production of superheavy nuclei

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Experimental data on structure of SHE (Z=112-118):

The found experimental trend of the nuclear properties [Q(alpha)-values and half-lives] of the SHE indicates

the importance of* N=184 *shell
but
***a small influence of the proton shell at* Z=114.**

No discontinuity is observed when the proton number 114 is crossed at N=172 - 176!

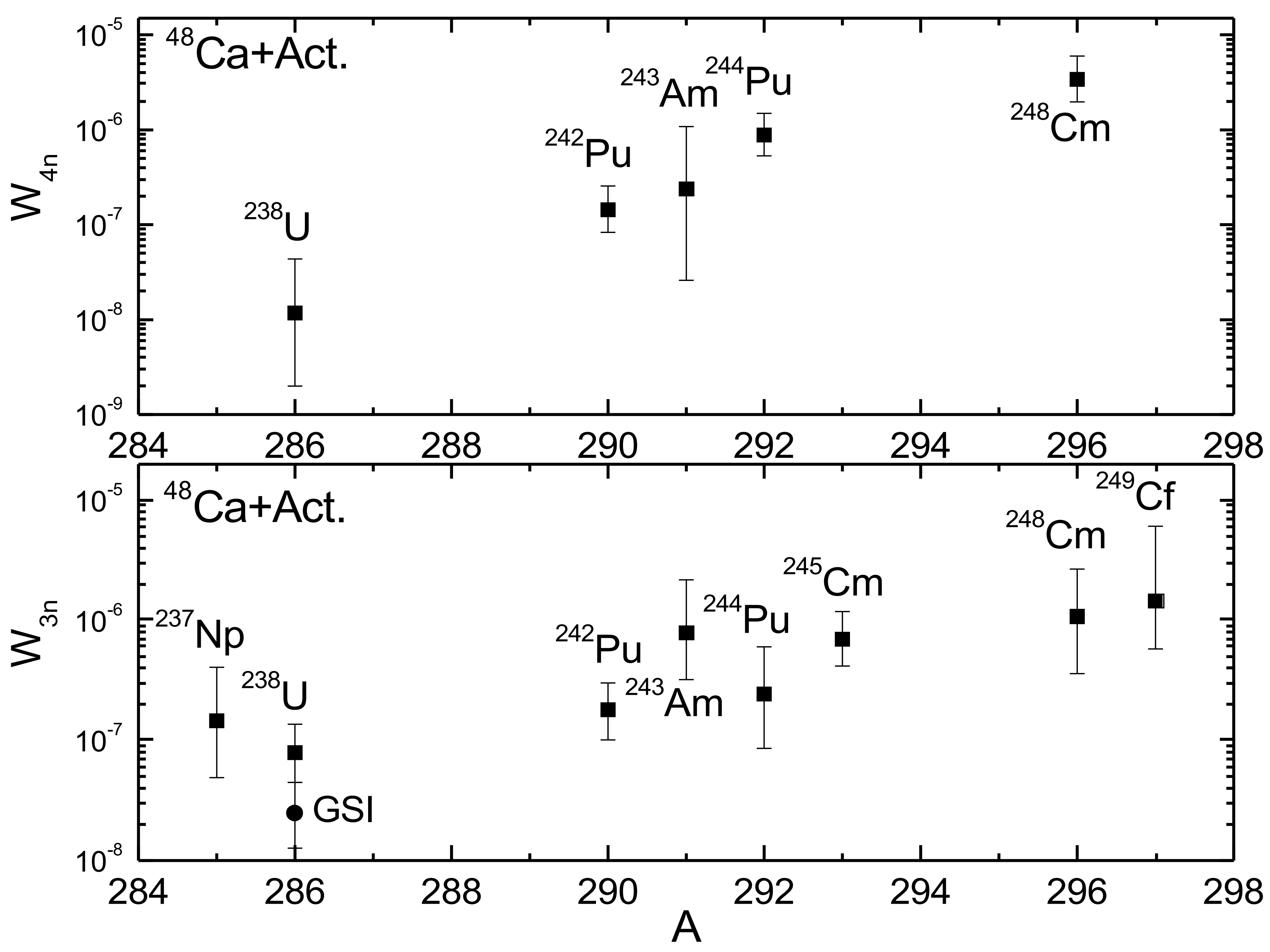
Magic numbers Z=114 & N=184 were predicted with microscopic-macroscopic models.

Experimental data on SHE production cross sections:

The measured production cross sections in reactions ^{48}Ca+Actinide do not depend strongly on atomic number Z of SHE and are on the picobarn level.

The fusion cross section strongly decreases with increasing $Z_1 x Z_2$!

Production cross section=
=(Fusion cross section) x (Survival probability)



48Ca+Act.
238U
242Pu
243Am
244Pu
248Cm
W4n
10-5
10-6
10-7
10-8
10-9
284
286
288
290
292
294
296
298
48Ca+Act.
237Np
238U
GSI
242Pu
243Am
244Pu
245Cm
248Cm
249Cf
W3n
10-5
10-6
10-7
10-8
284
286
288
290
292
294
296
298
A

Thus, the present experimental data point out that magic proton shell is located at Z >118 !

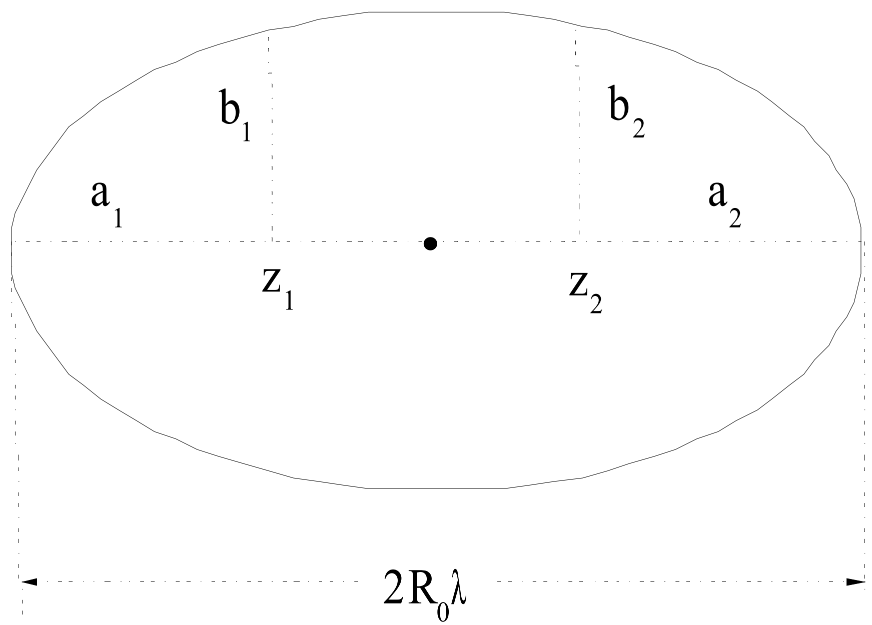
This observation is an accordance with predictions of mean field models where island of stability is near nucleus with Z=120 – 126 and N=184.

All microscopic-macroscopic approaches based on various shape parametrizations provide the closed proton shell Z=114 ?

Microscopic-macroscopic approach based on the two-center shell model (TCSM) [J.Maruhn and W.Greiner] was used.

Parameters were set so to describe spins & parities of g.-s. of known heavy nuclei.

$\beta_i = a_i / b_i$



$\beta_1 = \beta_2$, even multipolarities; $\beta_1 \neq \beta_2$, odd and even multipolarities

R_0 is the radius of spherical nucleus

Parametrisation of nuclear shape with TCSM

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

Potential energy

$$U(Z,A,\lambda,\beta)=U_{LDM}(Z,A,\lambda,\beta)+\delta U_{mic}(Z,A,\lambda,\beta)$$

Binding energy

$$B(Z,A)=U(Z,A,\lambda_{gs},\beta_{gs})-a_v\left(1-1.78\left(\frac{N-Z}{A}\right)^2\right)A+\ldots$$

$$a_v=15.83\,MeV$$

Q_α energy

$$Q_\alpha(Z,A)=B(Z,A)+28.296-B(Z-2,A-4)$$

Alpha decay half-lives T_α (A. Sobiczewski et al.)

$$\log_{10}T_\alpha(Z,A)=1.5372\,ZQ_\alpha^{-1/2}-0.1607\,Z-36.573$$

Comparison with other calculations

^{270}Hs gs.:

λ=1.14, β=1.06 -> β_2=0.25, β_4=-0.03

P.Möller et al.: β_2=0.231, β_4=-0.086

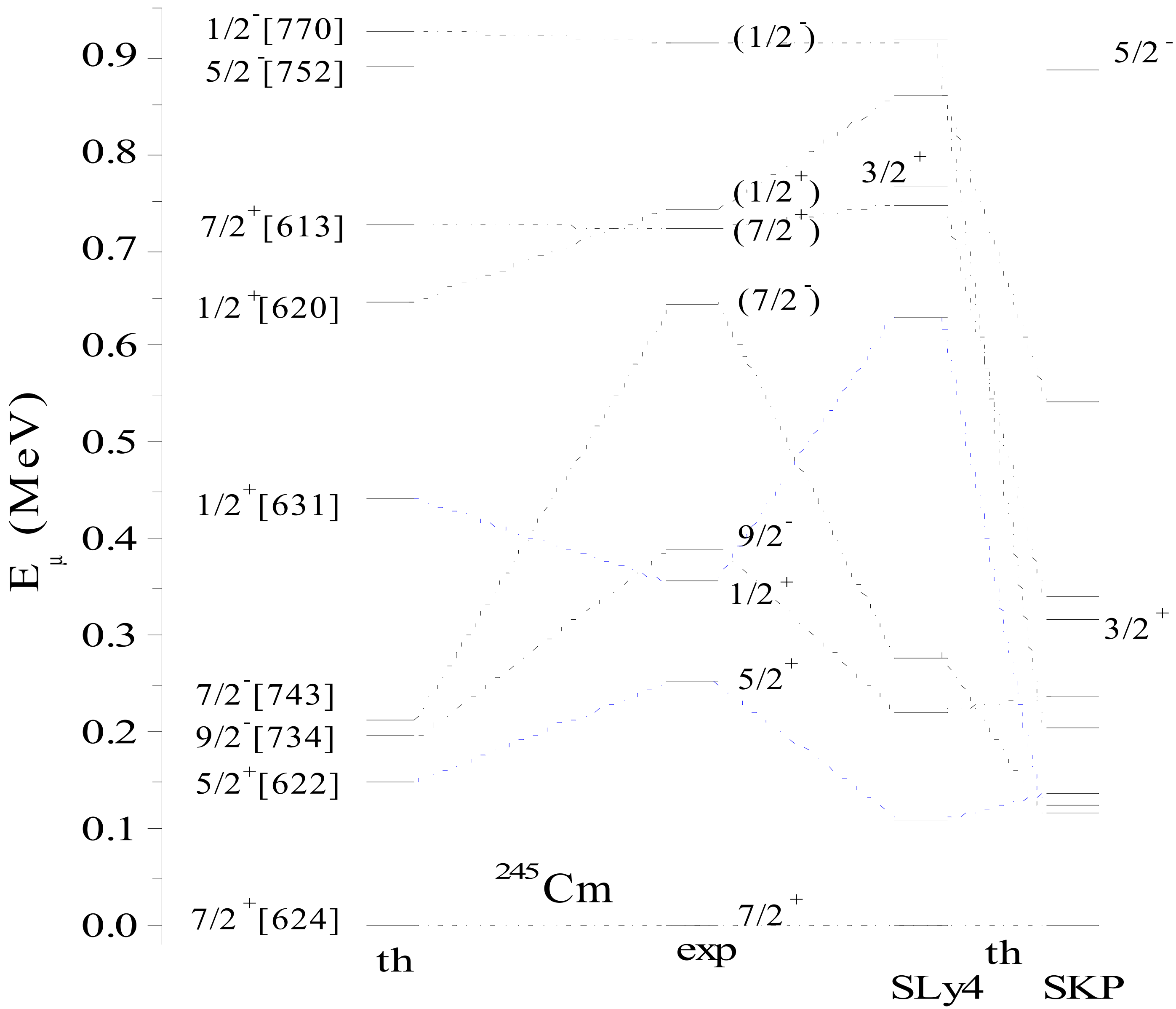
For ^{268,269,270,271}Hs, the microscopic corrections are

-5.95, -6.38, -6.54, -6.64 MeV

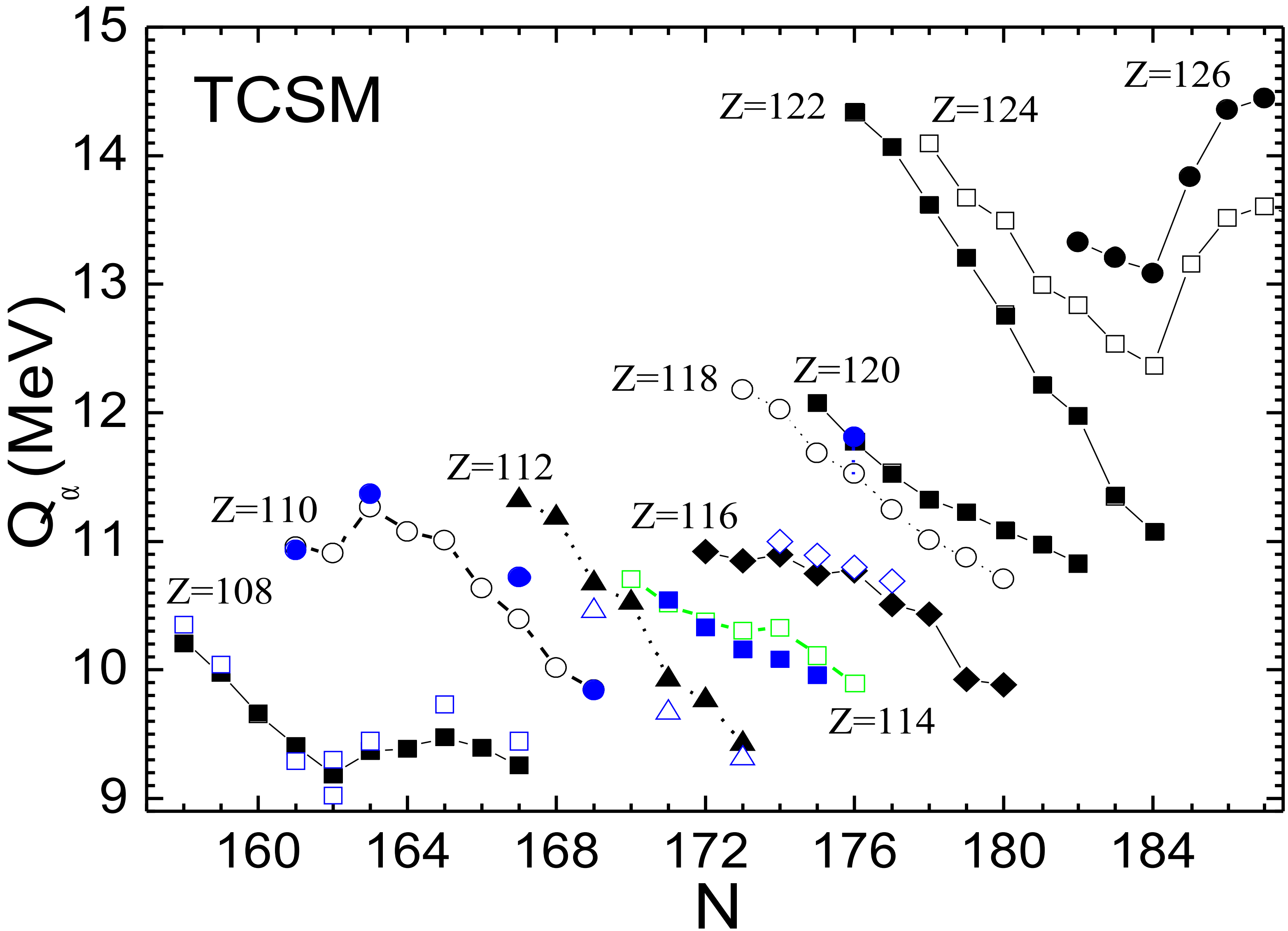
P.Möller et al.: -5.94, -6.37, -5.95, -5.86 MeV

A.Kuzmina et al., Eur. Phys. J. A 47 (2011) 145

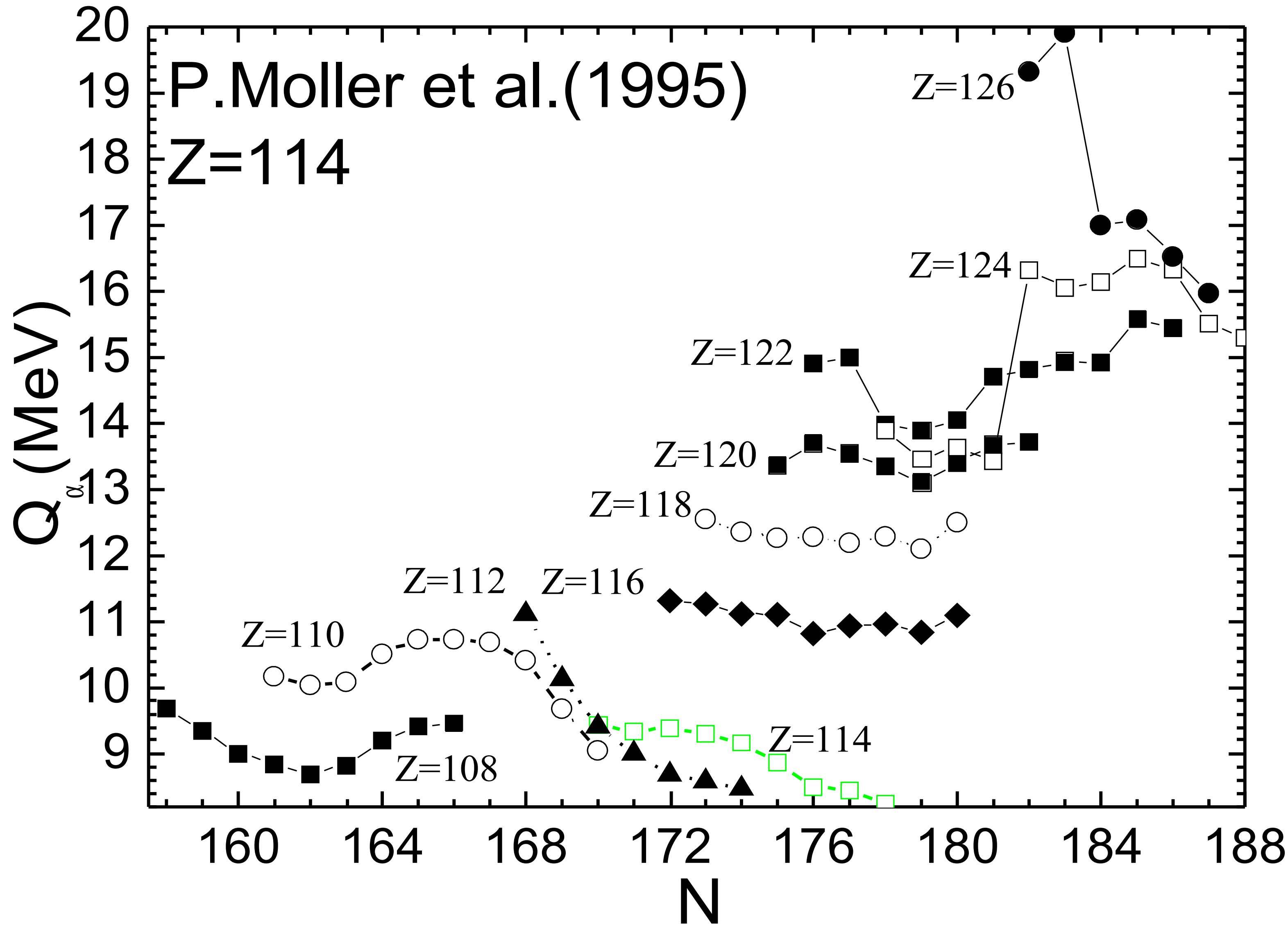
Phys. Rev. C 85 (2012) 014319; 017302



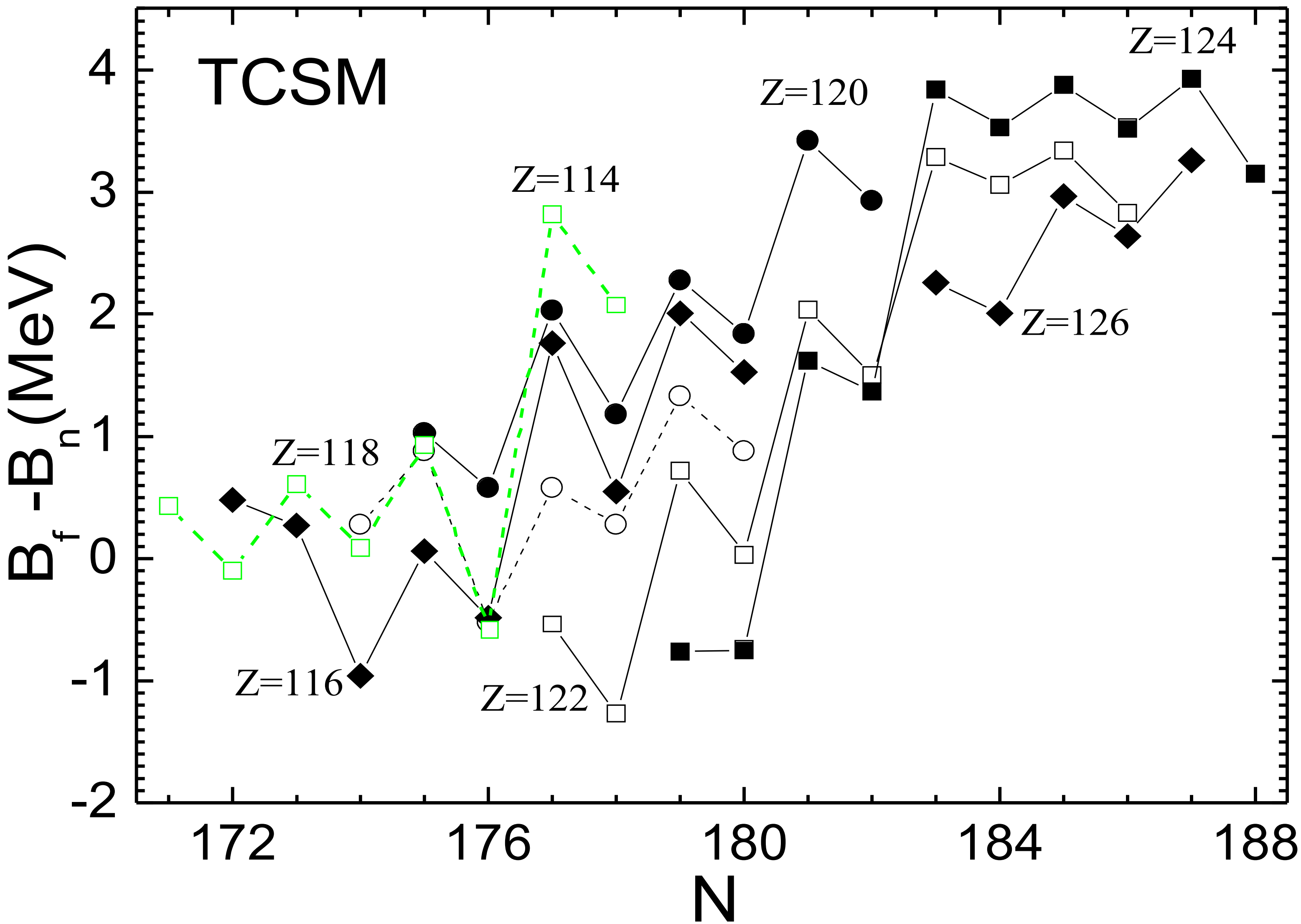
E_μ (MeV)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1/2⁻[770]
5/2⁻[752]
7/2⁺[613]
1/2⁺[620]
1/2⁺[631]
7/2⁻[743]
9/2⁻[734]
5/2⁺[622]
7/2⁺[624]
(1/2⁻)
(1/2⁺)
(7/2⁺)
(7/2⁻)
9/2⁻
1/2⁺
5/2⁺
7/2⁺
3/2⁺
5/2⁻
3/2⁺
245Cm
th
exp
th
SLy4
SKP



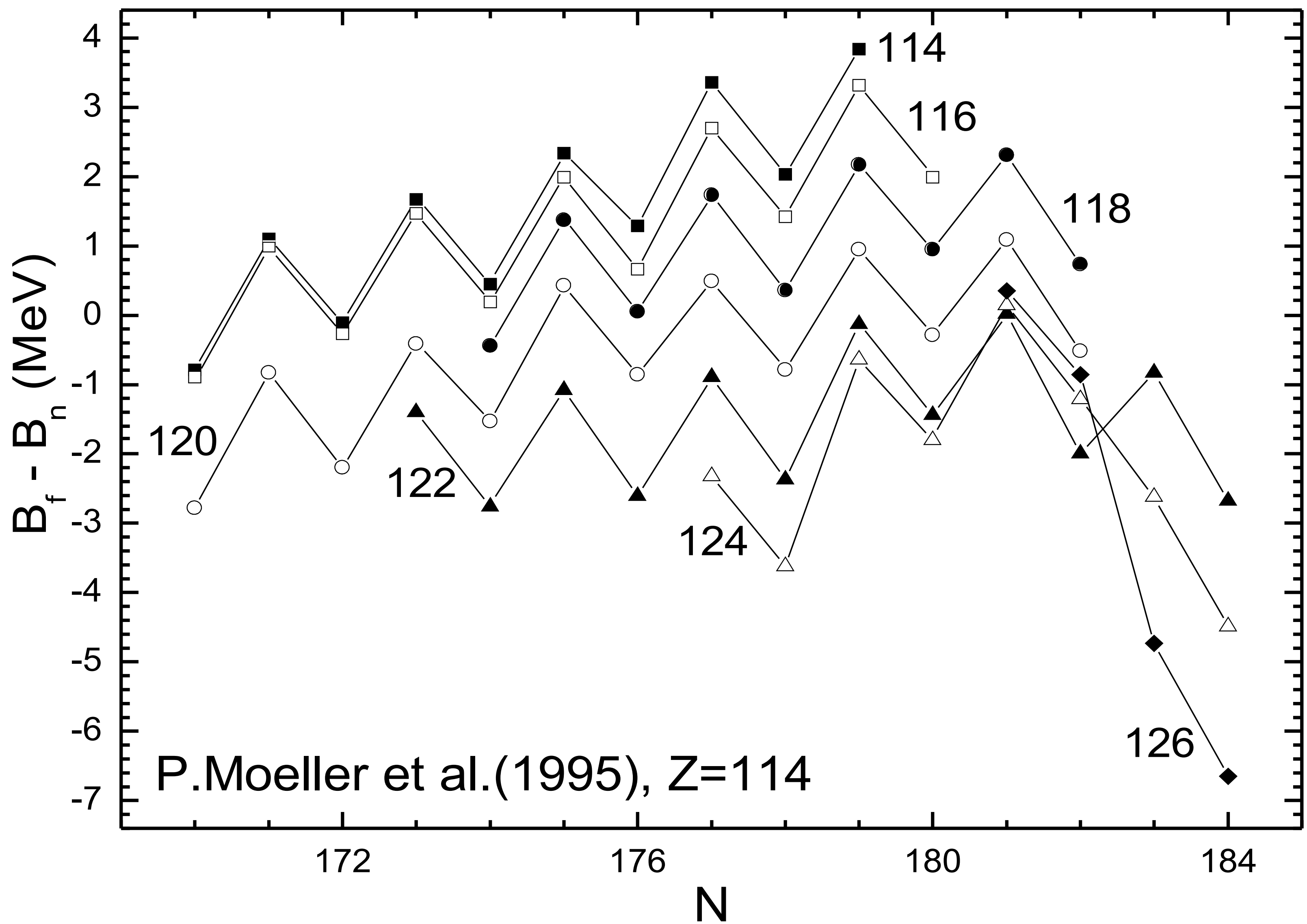
TCSM
Z=108
Z=110
Z=112
Z=114
Z=116
Z=118
Z=120
Z=122
Z=124
Z=126
Q_α (MeV)
N
15
14
13
12
11
10
9
160
164
168
172
176
180
184



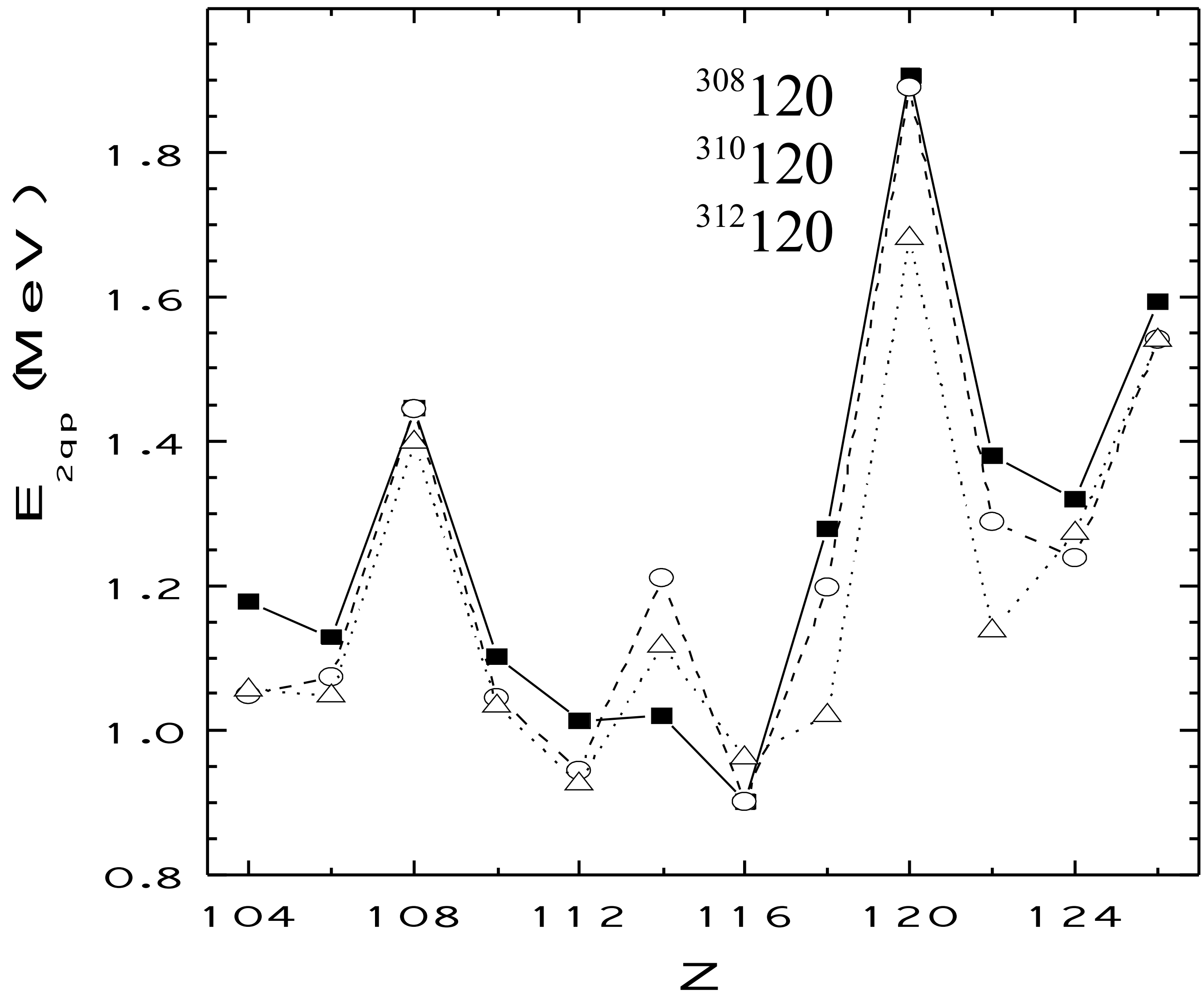
P.Moller et al.(1995)
Z=114
Z=126
Z=124
Z=122
Z=120
Z=118
Z=116
Z=112
Z=110
Z=108
Z=114
Q_α (MeV)
N
20
19
18
17
16
15
14
13
12
11
10
9
160
164
168
172
176
180
184
188



TCSM
Z=124
Z=120
Z=114
Z=126
Z=118
Z=116
Z=122
$B_f - B_n$(MeV)
N
4
3
2
1
0
-1
-2
172
176
180
184
188

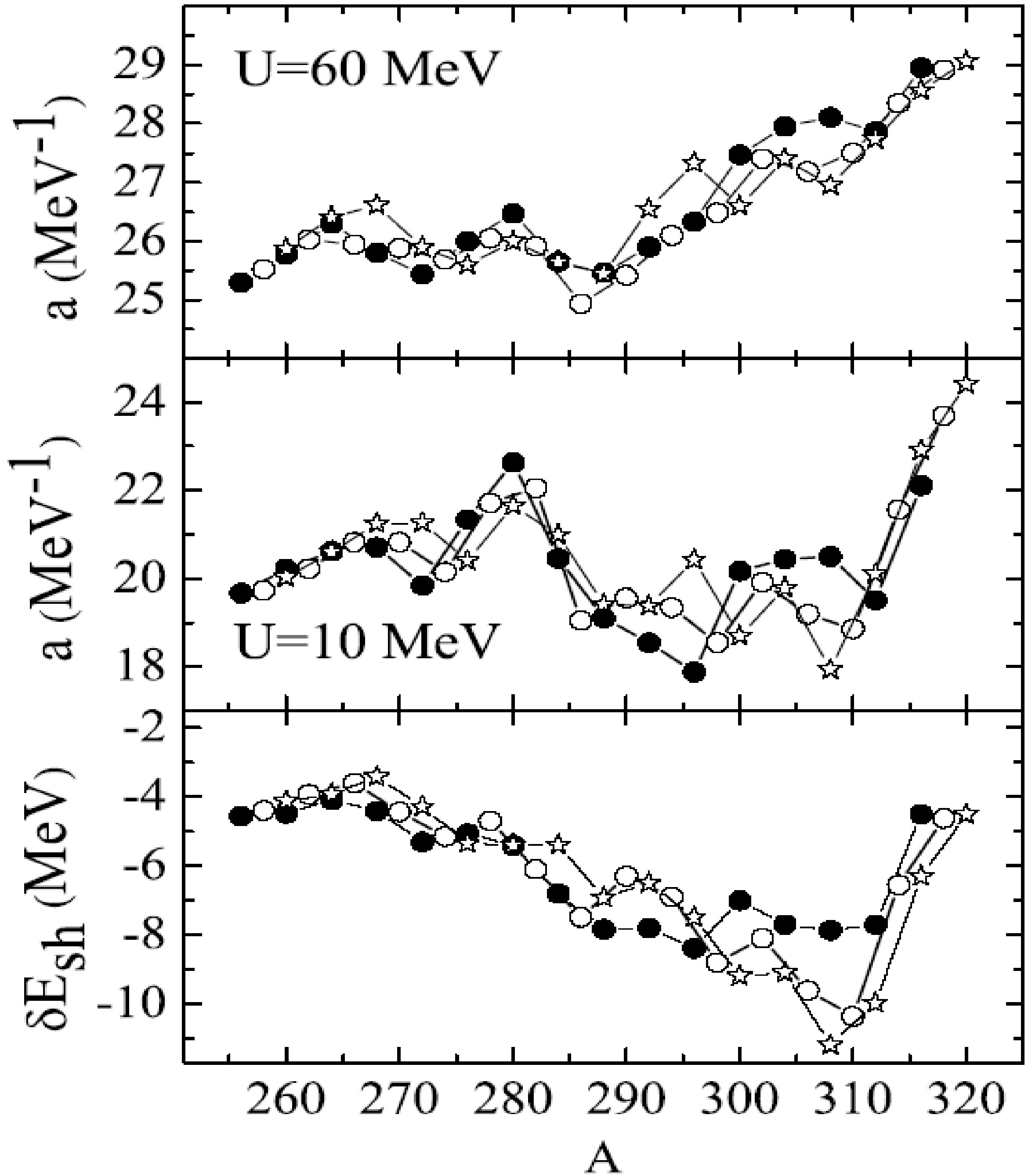


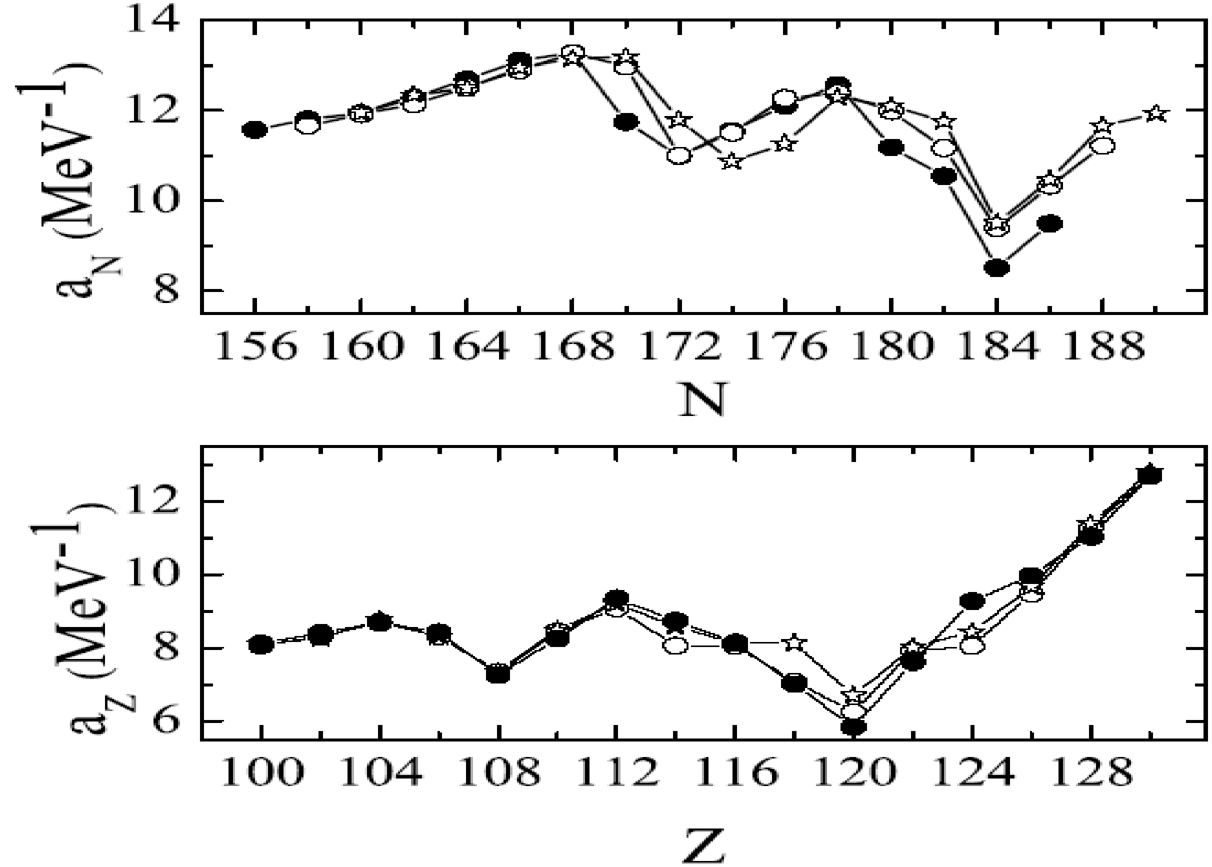
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
B_f - B_n (MeV)
172
176
180
184
N
114
116
118
120
122
124
126
P.Moeller et al.(1995), Z=114



Energies of two-quasi-proton states in alpha-decay chains containing indicated nuclei with Z=120

$^{296,298,300}120$





$^{296,298,300}120$

$$a(A,U) = \tilde{a}(A)\left[1 + \frac{1-\exp\{-E^*/E'_D\}}{E^*}\delta E_{sh}\right]$$

$$\tilde{a}(A) = \alpha A + \beta A^2$$

$E'_D = 27\,\mathrm{MeV}$

$\alpha = 0.118\,\mathrm{MeV}^{-1}$ $\beta = -0.53 \times\ 10^{-4}\,\mathrm{MeV}^{-1}$

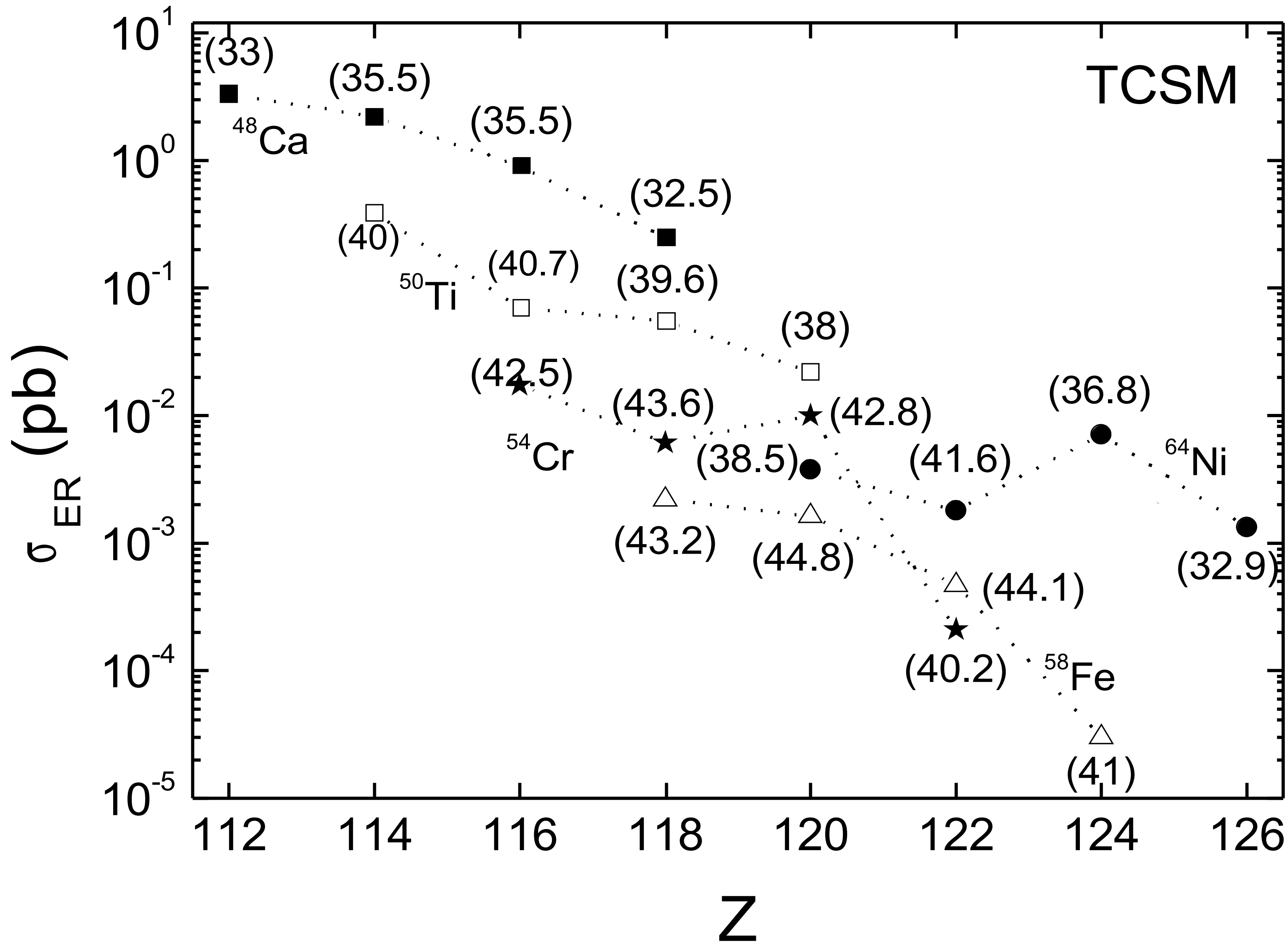
Dependence of the calculated evaporation residue cross sections on the predicted shell structure and magic numbers of SHE

Within the dinuclear system model we analysed the production of SHE in various actinide-based complete fusion reactions with projectiles heavier than ^{48}Ca.

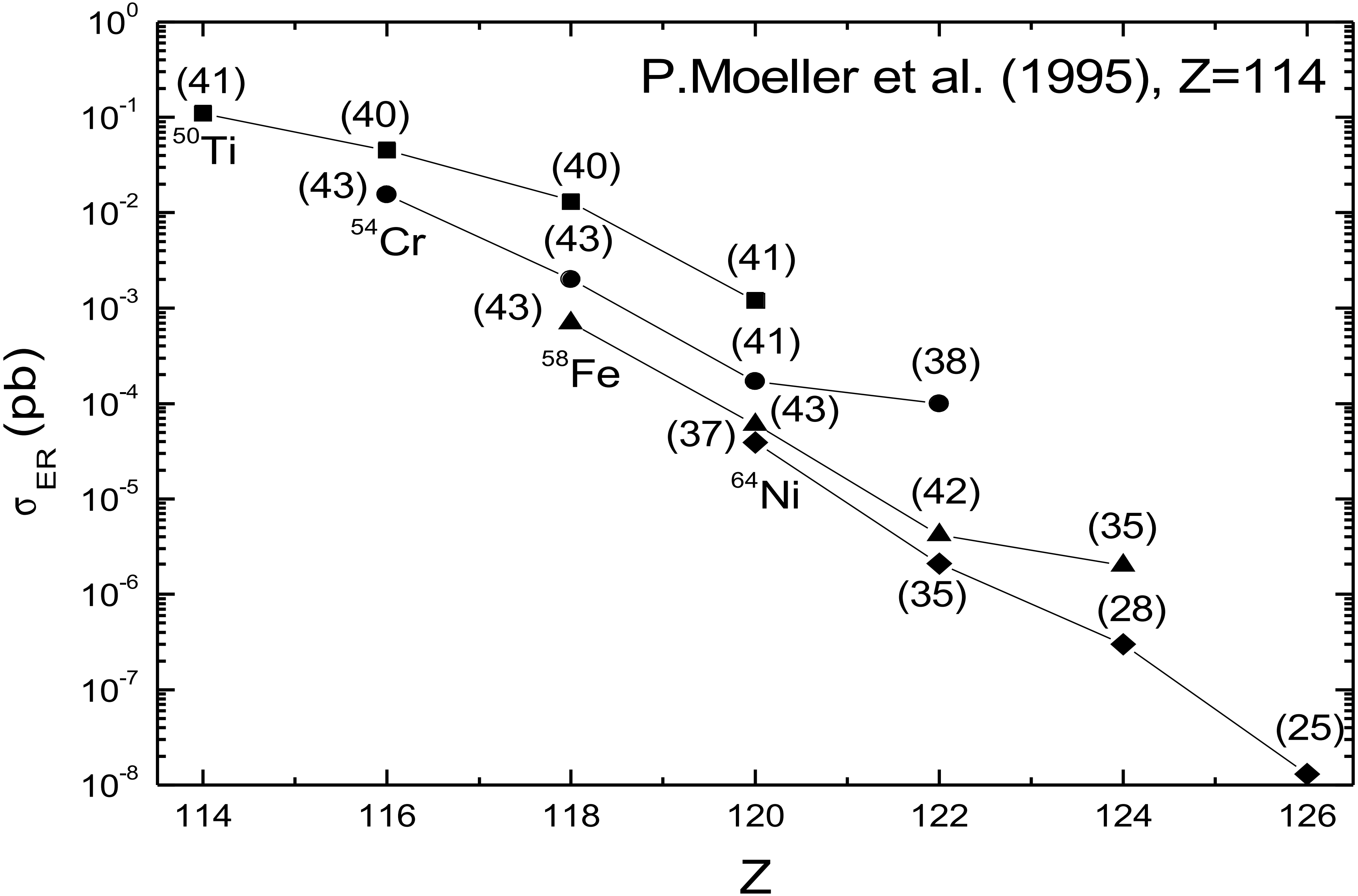
Different predictions of the properties of heaviest nuclei were used:

1) mass table from TCSM (2011), Z=120-126;

2) mass table by P. Moeller et al.(1995), Z=114;



TCSM
σ_{ER} (pb)
Z
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
112
114
116
118
120
122
124
126
^{48}Ca
^{50}Ti
^{54}Cr
^{58}Fe
^{64}Ni
(33)
(35.5)
(35.5)
(32.5)
(40)
(40.7)
(39.6)
(38)
(42.5)
(43.6)
(42.8)
(38.5)
(41.6)
(36.8)
(32.9)
(43.2)
(44.8)
(44.1)
(40.2)
(41)



P.Moeller et al. (1995), Z=114
(41)
^{50}Ti
(40)
(43)
^{54}Cr
(40)
(43)
(41)
(43)
^{58}Fe
(41)
(38)
(43)
(37)
^{64}Ni
(42)
(35)
(35)
(28)
(25)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
σ_{ER} (pb)
114
116
118
120
122
124
126
Z

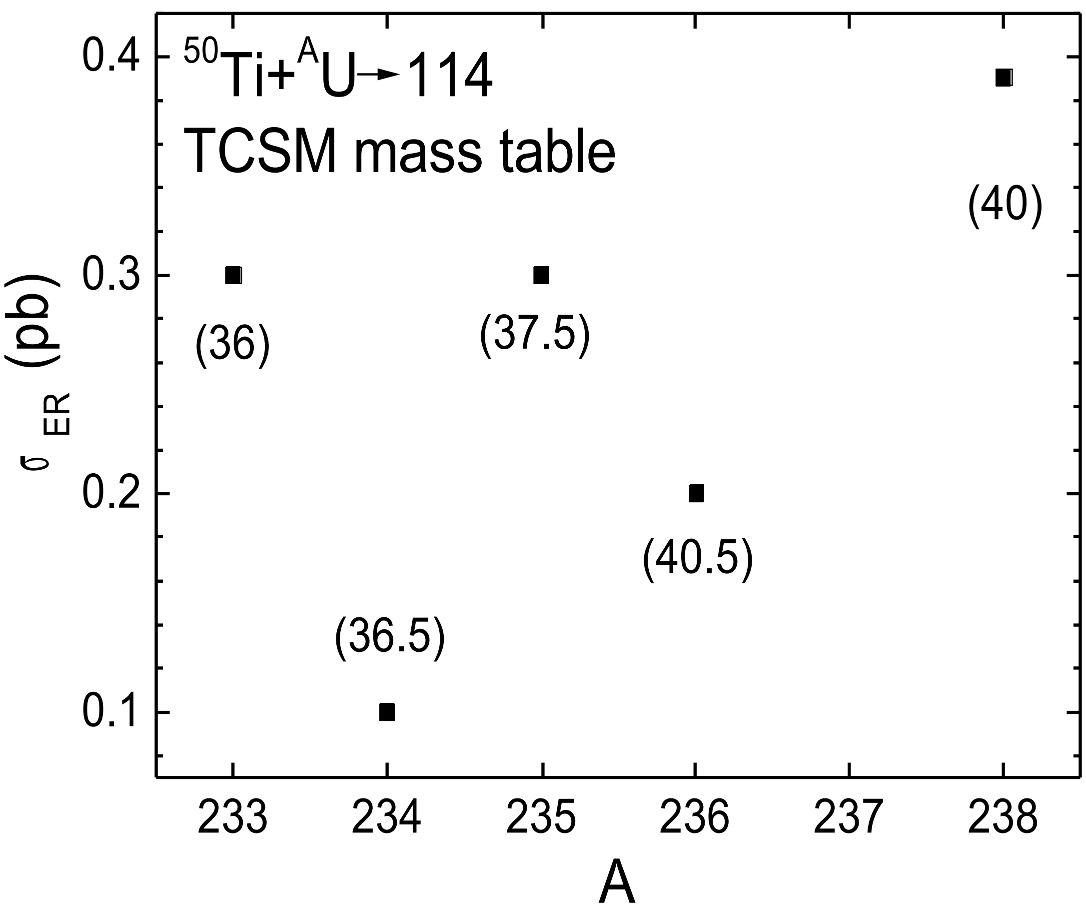
Summary

The calculations performed with the modified **TCSM** reveal quite strong shell effects at **Z=120-126** & **N=184** as in the self-consistent mean-field treatments.

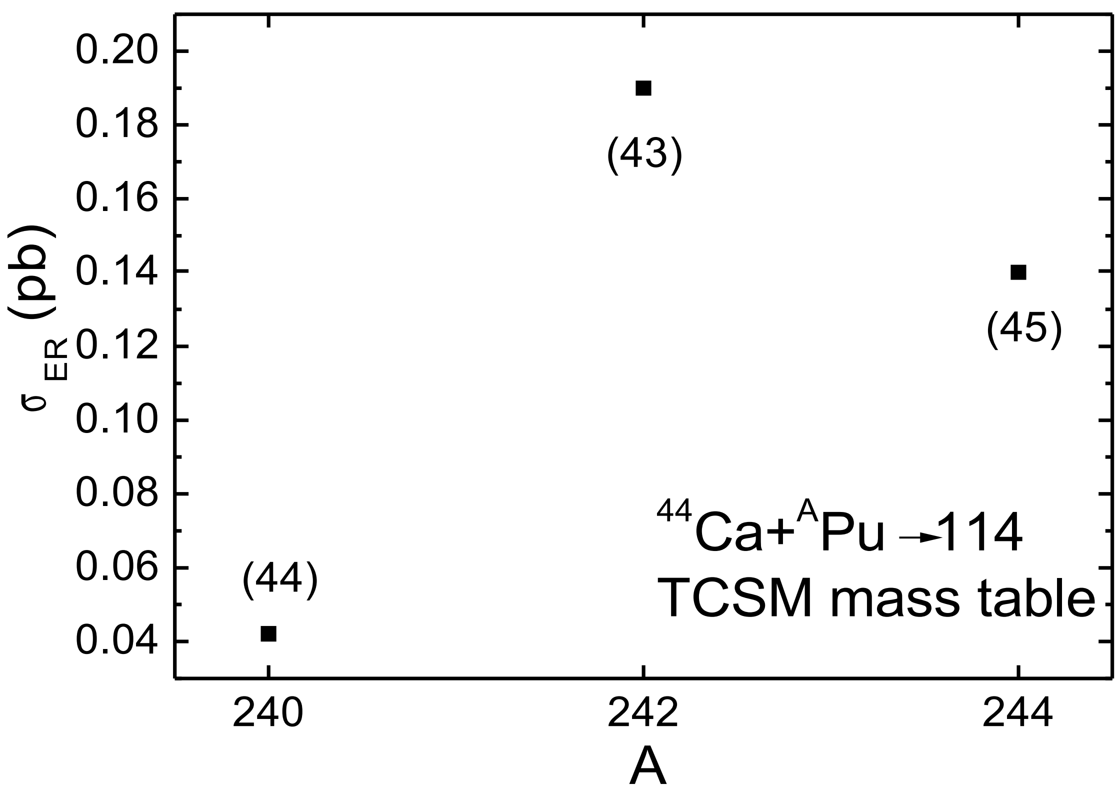
If our prediction of the structure of heaviest nuclei is correct, than one can expect the production of **Z=120** in the reactions **$^{50}Ti+^{249}Cf$** and **$^{54}Cr+^{248}Cm$** with the cross sections **23** and **10 fb**, respectively.

Z=120 nuclei with **N=175-179** are expected to have **Q_α** about **12.1 - 11.2 MeV** and lifetimes **1.7 ms - 0.16 s** in accordance with our predictions. These **Q_α** are in fair agreement with **S.Liran et al.(2000)** and about **2 MeV** smaller than those from **P.Möller et al.(1995)** **& A.Sobiczewski et al.(2003)**.

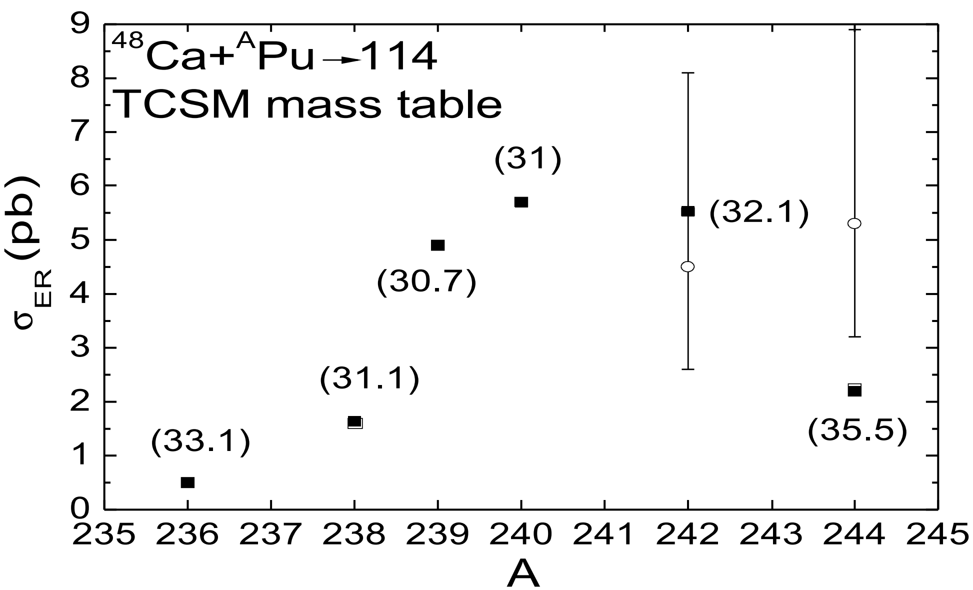
Experimental measurement of **Q_α** for at least one isotope of **Z=120** nucleus would help us to set proper shell model for the **SHE** with **Z>118**.

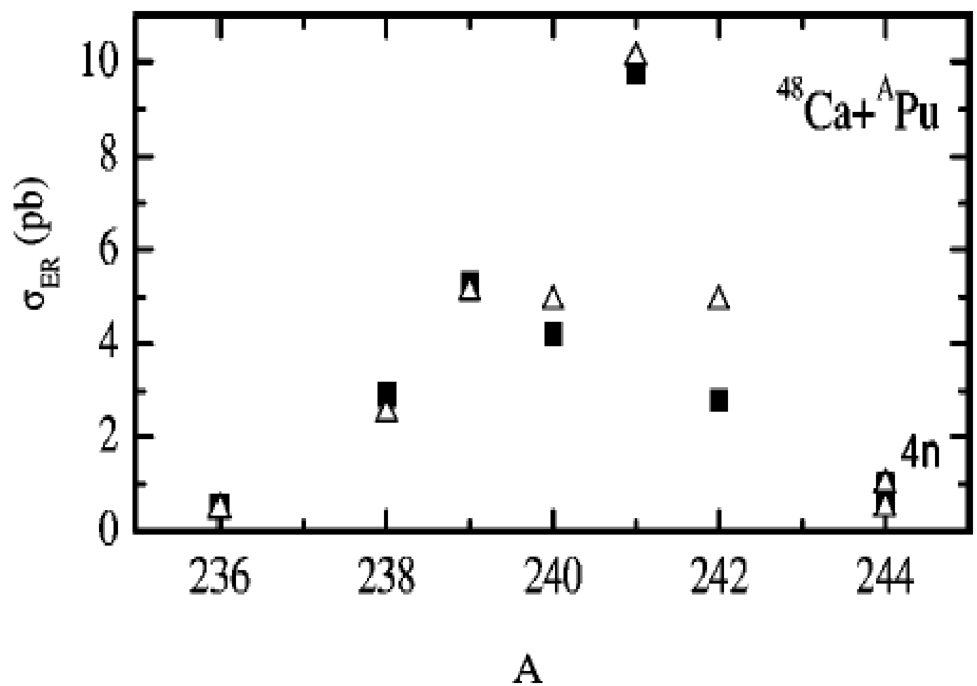


^{50}Ti+^{A}U→114
TCSM mass table
σ_{ER} (pb)
0.4
0.3
0.2
0.1
(36)
(36.5)
(37.5)
(40.5)
(40)
233
234
235
236
237
238
A



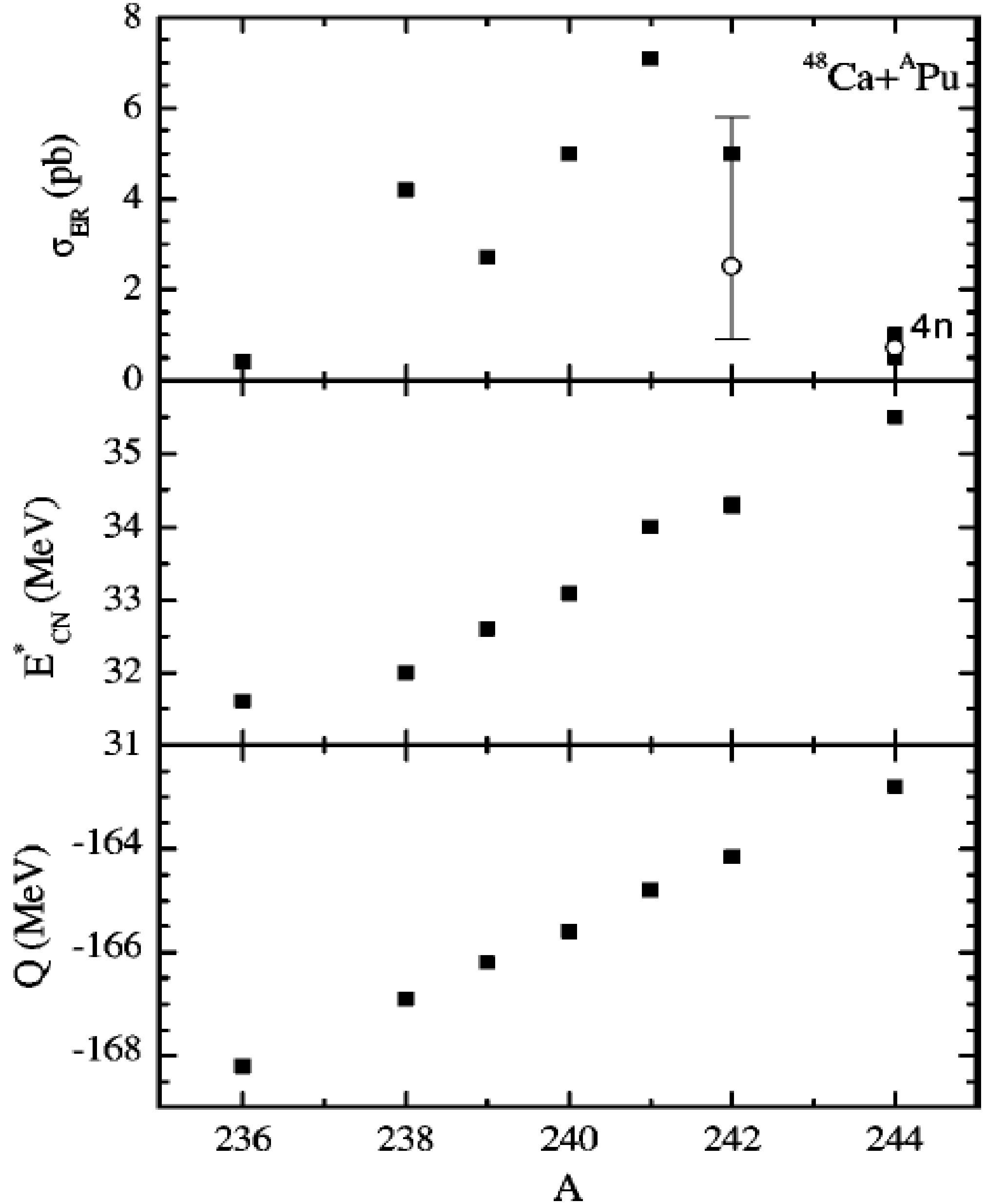
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
σ ER (pb)
240
242
244
A
(43)
(45)
(44)
44Ca+APu →114
TCSM mass table



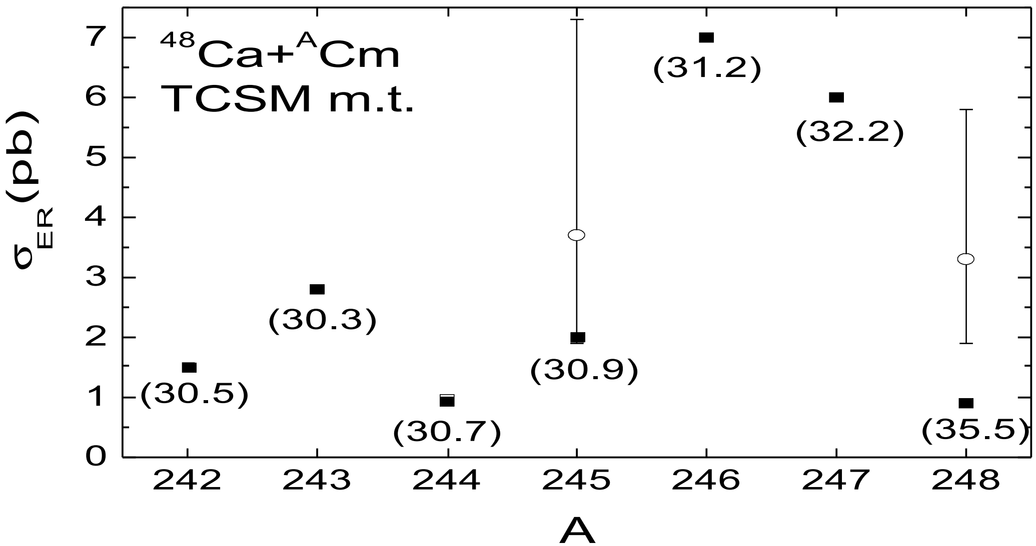


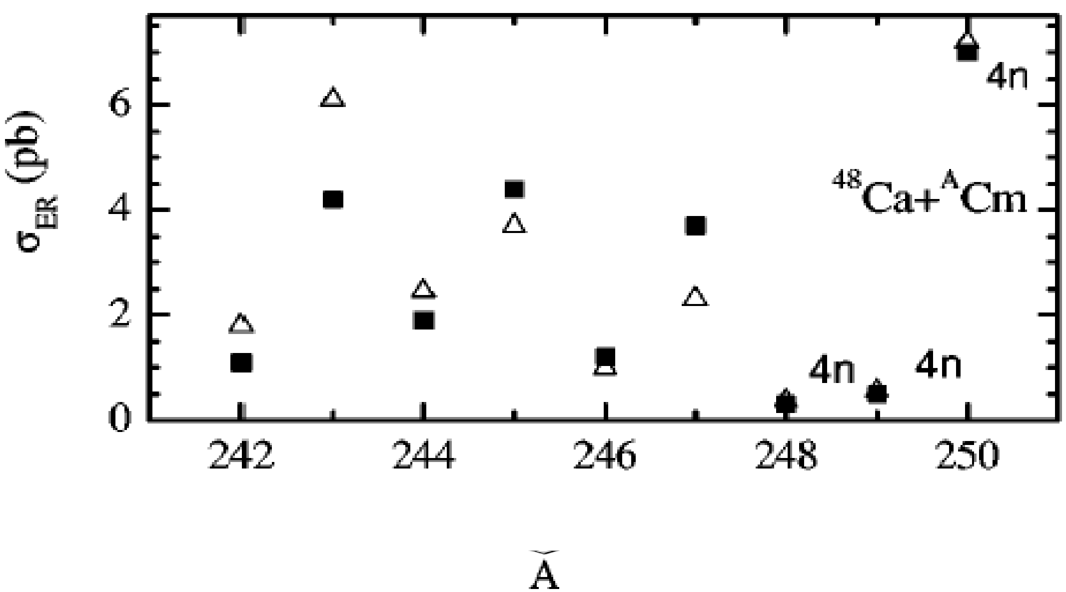
P.Möller et al.

W.D. Myers,
W.J. Swiatecki



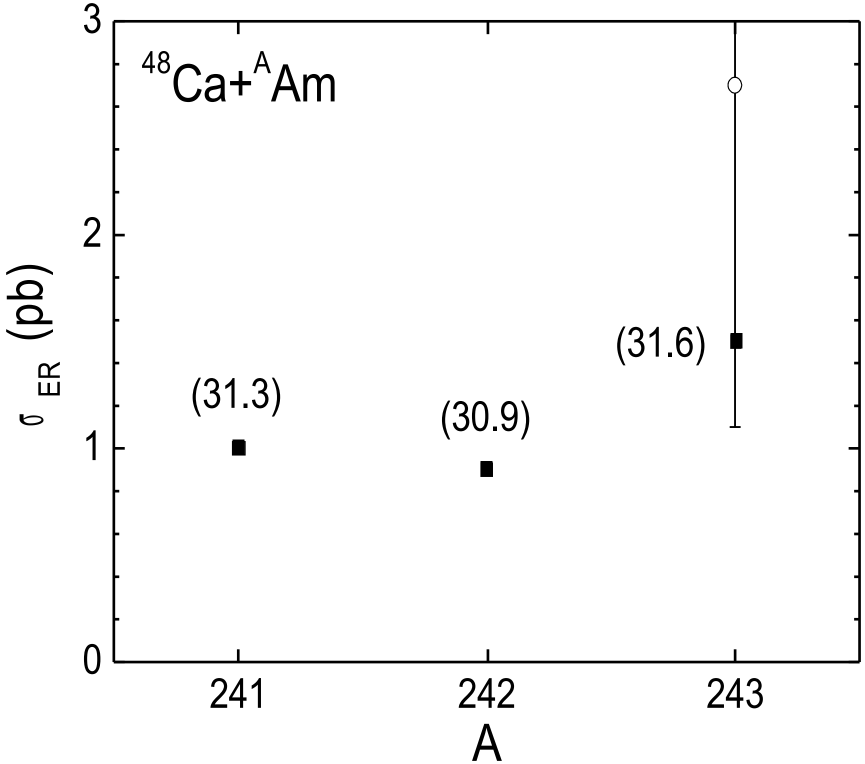
P.Möller et al.





P.Möller et al.

W.D. Myers,
W.J. Swiatecki



$^{48}Ca+^{A}Am$
(31.3)
(30.9)
(31.6)
σ_{ER} (pb)
0
1
2
3
241
242
243
A

Cross sections calculated with different mass tables are comparable because:

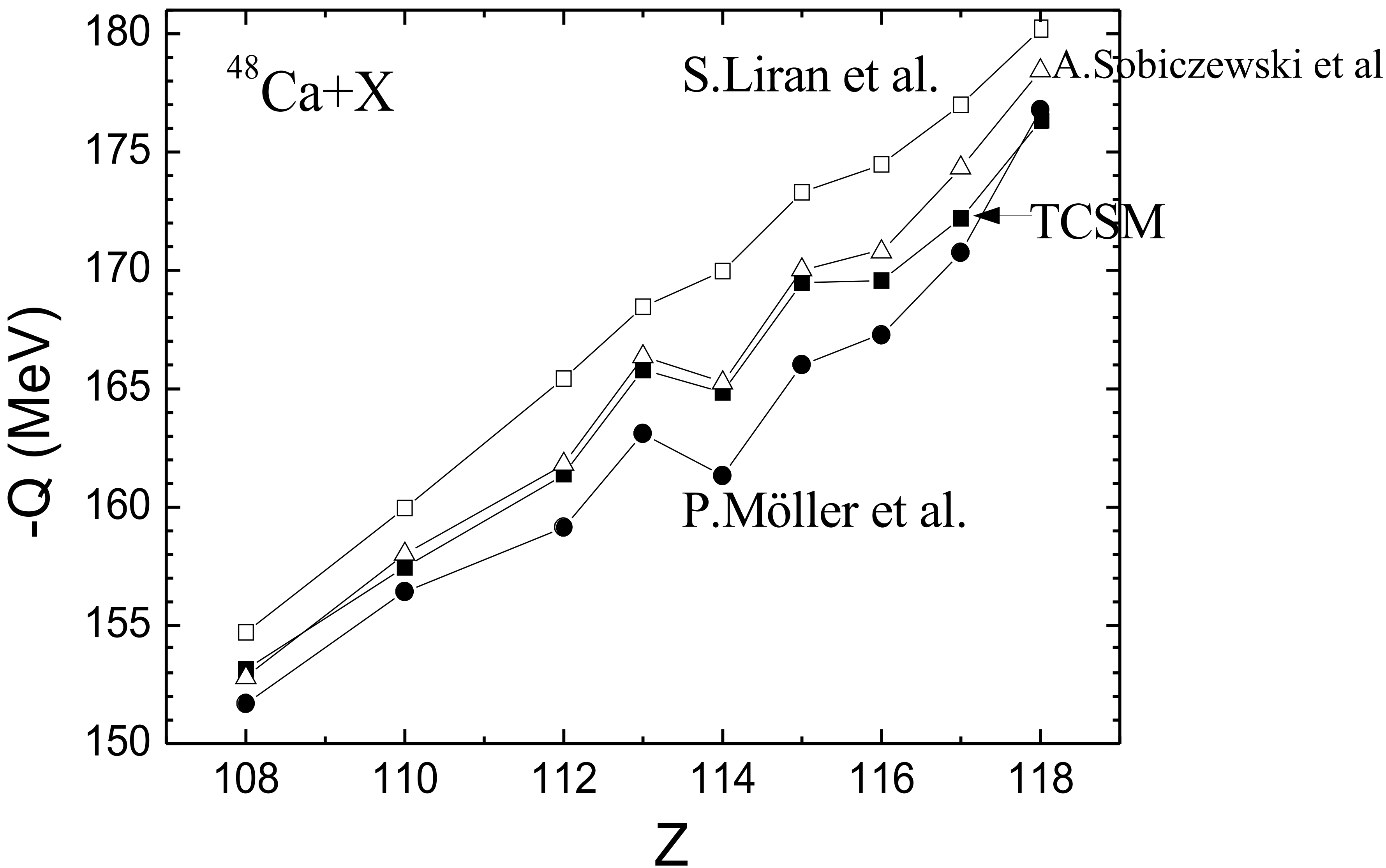
1. **Fusion probability depends on the predicted mass of nuclei.**
2. **Smaller barrier requires smaller a_f/a_n**

Summary

In ^{48}Ca-induced reactions the actinide targets with smaller neutron excess (within certain intervals of mass) are even more favorable than those with larger neutron excess.

This result is almost independent of mass table!

Thank you.



^{48}Ca+X
S.Liran et al.
A.Sobiczewski et al.
TCSM
P.Möller et al.
-Q (MeV)
Z
180
175
170
165
160
155
150
108
110
112
114
116
118

Parameter of level density

$$\rho = \frac{\exp[S(\beta, \lambda_Z, \lambda_N)]}{(2\pi)^{3/2}\sqrt{D}},$$

where S is the entropy, $\beta = T^{-1}$ is the inverse temperature, λ_Z and λ_N are the chemical potentials for protons and neutrons, respectively, and D is the determinant of the matrix comprised of the second derivatives of the entropy

$$D = \begin{vmatrix} \frac{\partial^2 S}{\partial \beta^2} & \frac{\partial^2 S}{\partial \beta \partial \mu_Z} & \frac{\partial^2 S}{\partial \beta \partial \mu_N} \\ \frac{\partial^2 S}{\partial \beta \partial \mu_Z} & \frac{\partial^2 S}{\partial \mu_Z^2} & 0 \\ \frac{\partial^2 S}{\partial \beta \partial \mu_N} & 0 & \frac{\partial^2 S}{\partial \mu_N^2} \end{vmatrix},$$

where $\mu_k = \beta\lambda_k$, $(k = N, Z)$.

$$S = 2\sum_{k=Z,N}\sum_{\nu}\left\{\ln[1+\exp(-\beta E_{\nu k})] + \frac{\beta E_{\nu k}}{1+\exp(\beta E_{\nu k})}\right\},$$

$$E_{\nu k} = \sqrt{(\varepsilon_{\nu k} - \lambda_k)^2 + \Delta_k^2}$$

$$Z = \sum_{\nu}\left(1 - \frac{\varepsilon_{\nu Z} - \lambda_Z}{E_{\nu Z}}\tanh[\frac{1}{2}\beta E_{\nu Z}]\right),$$

$$N = \sum_{\nu}\left(1 - \frac{\varepsilon_{\nu N} - \lambda_N}{E_{\nu N}}\tanh[\frac{1}{2}\beta E_{\nu N}]\right),$$

$$\frac{2}{G_Z} = \sum_{\nu}\frac{\tanh[\beta E_{\nu Z}/2]}{E_{\nu Z}},$$

$$\frac{2}{G_N} = \sum_{\nu}\frac{\tanh[\beta E_{\nu N}/2]}{E_{\nu N}},$$

where G_Z and G_N are the constants of pairing interaction.

The total E and excitation U energies of the nucleus at temperature T are calculated as

$$E(T) = \sum_{k=Z,N} \left\{ \sum_{\nu} \varepsilon_{\nu k} \left(1 - \frac{\varepsilon_{\nu k} - \lambda_k}{E_{\nu k}} \tanh \frac{1}{2} \beta E_{\nu k} \right) - \frac{\Delta_k^2}{G_k} \right\},$$

$$U = E(T) - E(0).$$

Level-density parameter

$$\rho_{FG}(U) = \frac{\sqrt{\pi}}{12 a^{1/4} E^{*5/4}} \exp 2\sqrt{a E^*},$$

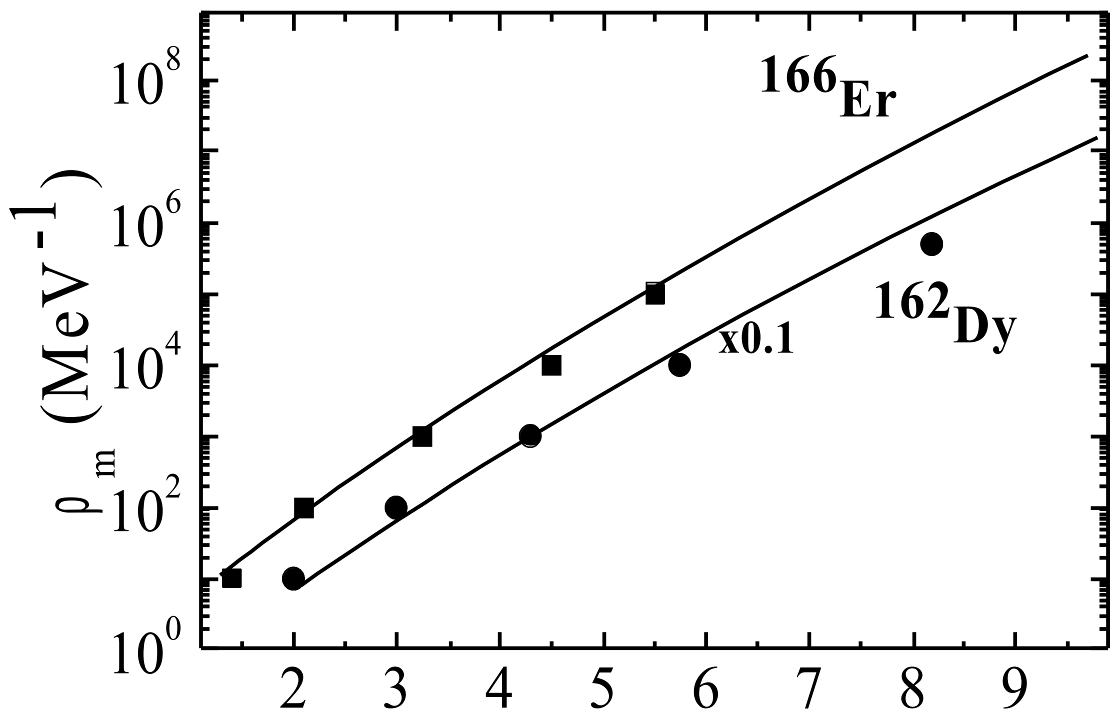
where $E^* = U - \Delta_Z - \Delta_N$ is the excitation energy back-shifted

$$a = U / T^2$$

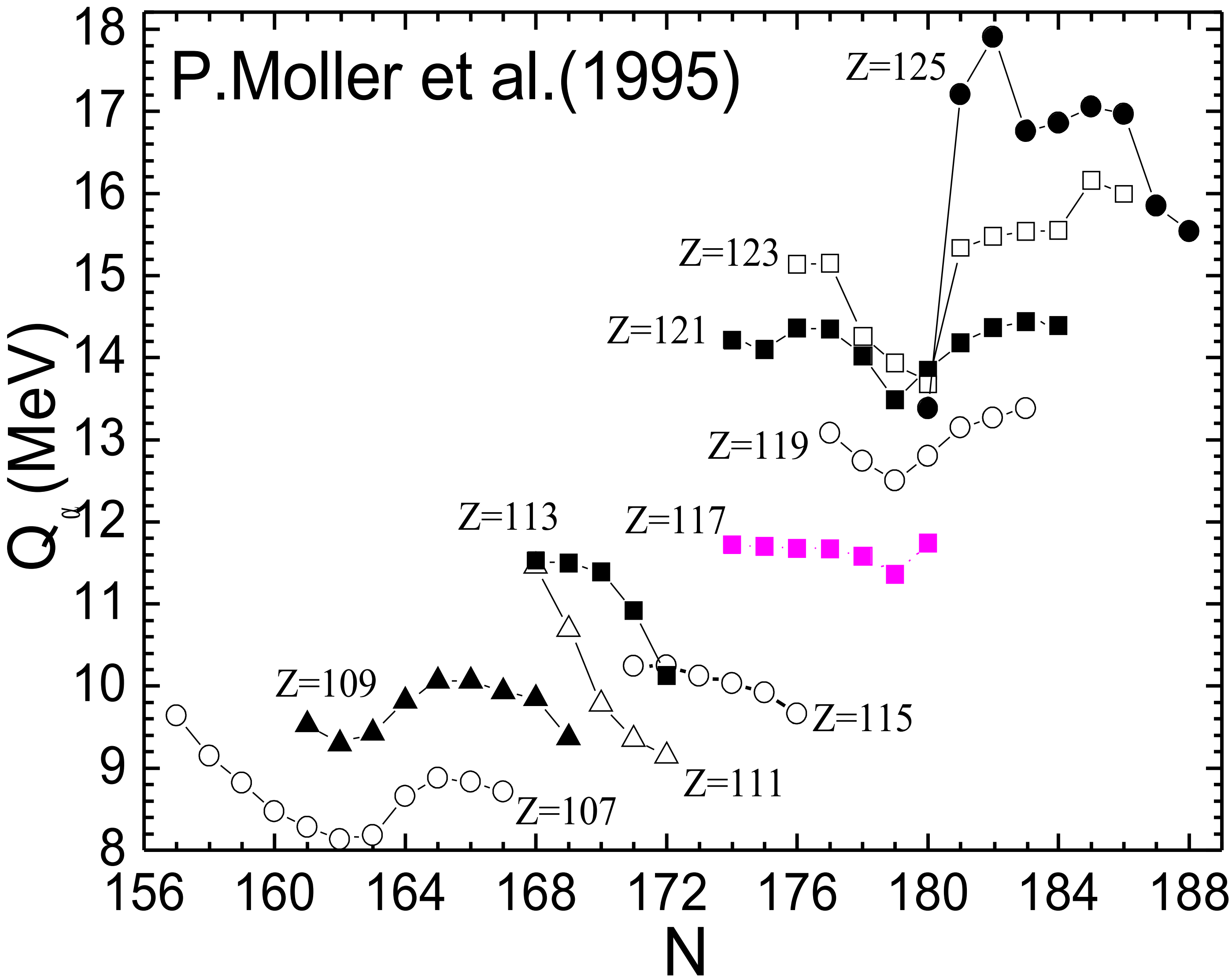
or

$$a = \frac{\pi^2}{6T} \sum_{k=Z,N} \sum_{\nu} \overline{n}_{k\nu} (1 - \overline{n}_{k\nu})$$

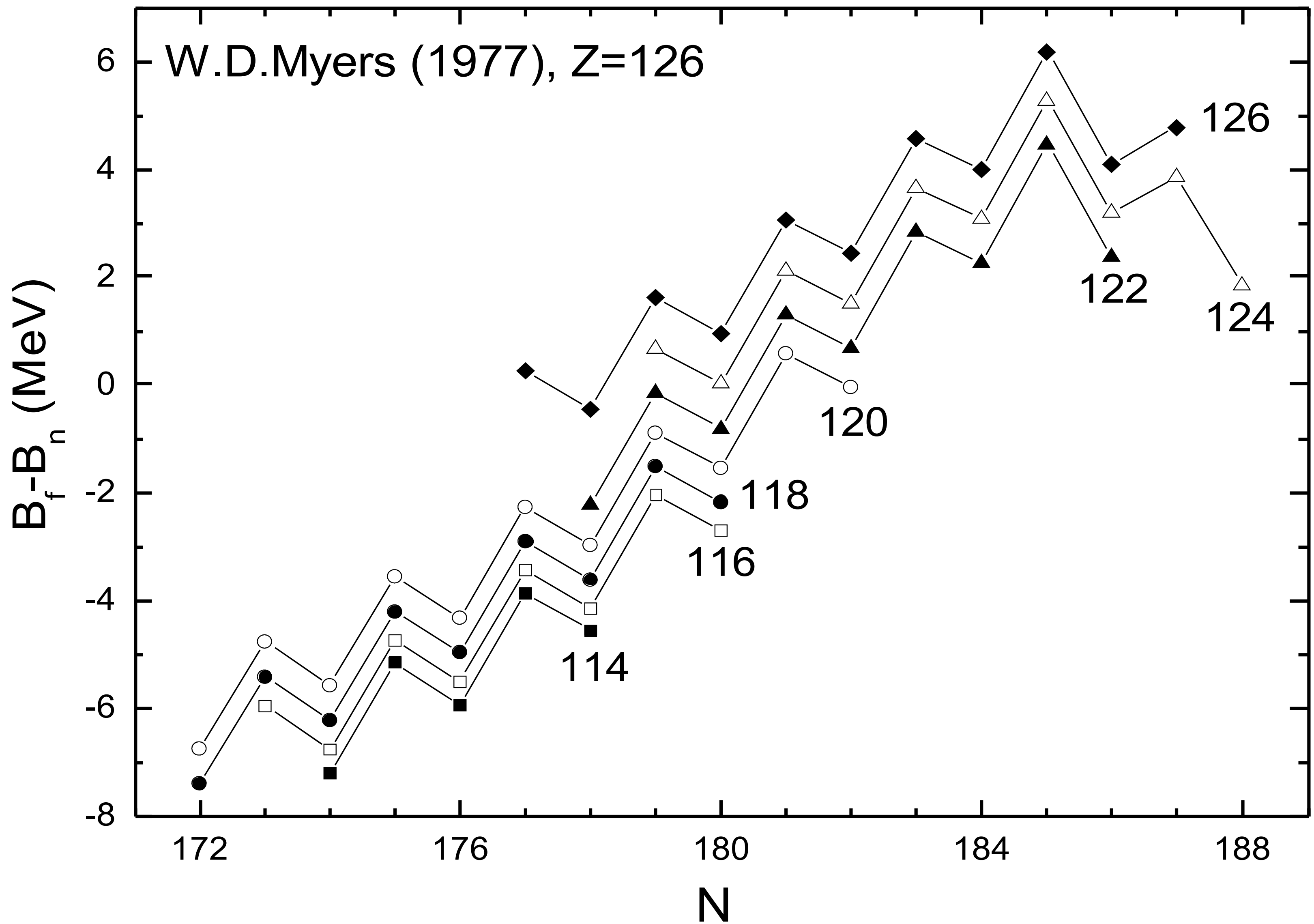
$$\overline{n}_{k\nu} = \left[1 + \exp\left(\beta E_{k\nu} \right) \right]^{-1}$$

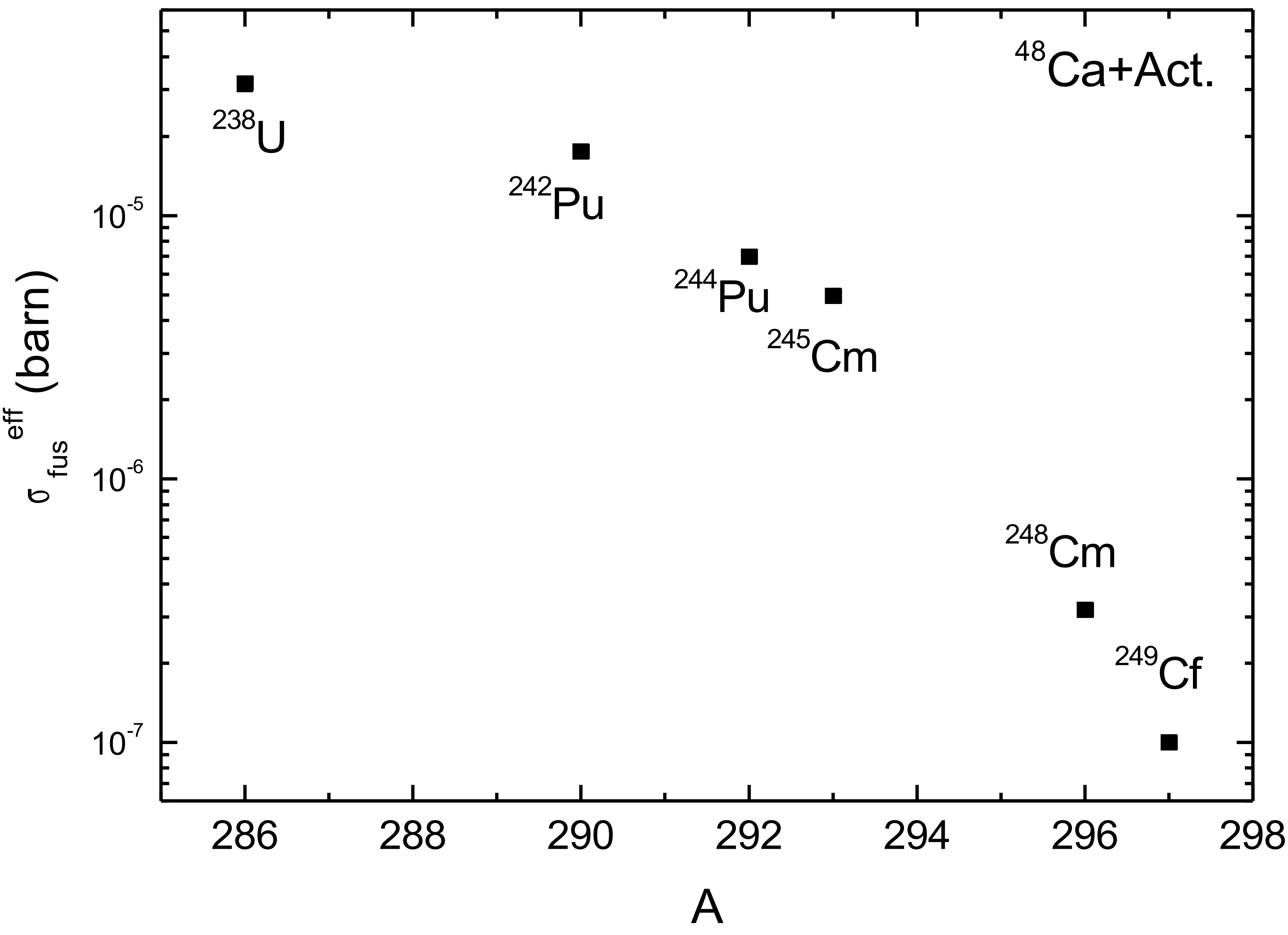


E. Melby, M. Guttormsen, J. Rekstad, A. Schiller, and S. Siem, Phys. Rev. C **63**, 044309 (2001).

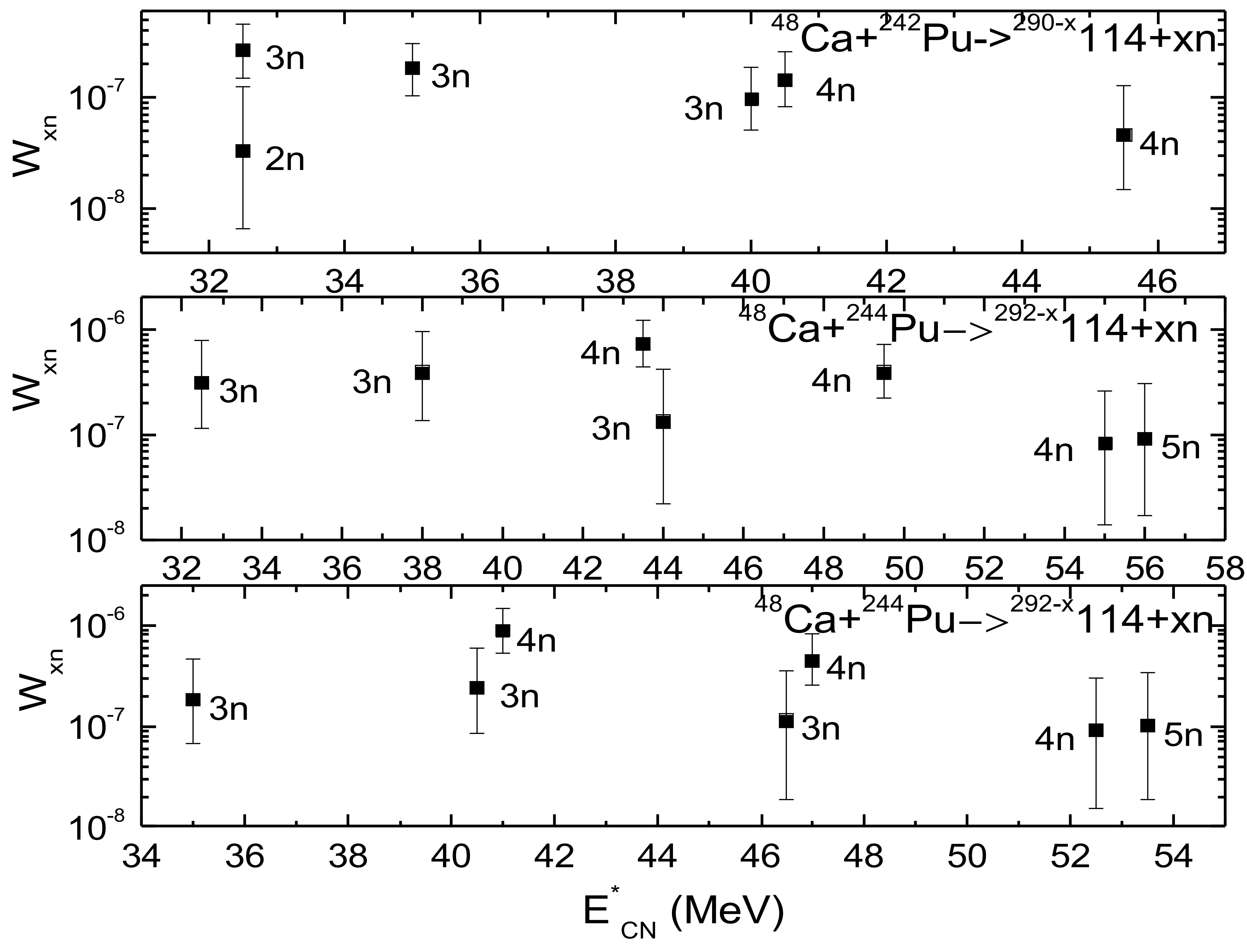


P.Moller et al.(1995)
Z=125
Z=123
Z=121
Z=119
Z=117
Z=113
Z=115
Z=111
Z=109
Z=107
Q_α (MeV)
N
18
17
16
15
14
13
12
11
10
9
8
156
160
164
168
172
176
180
184
188

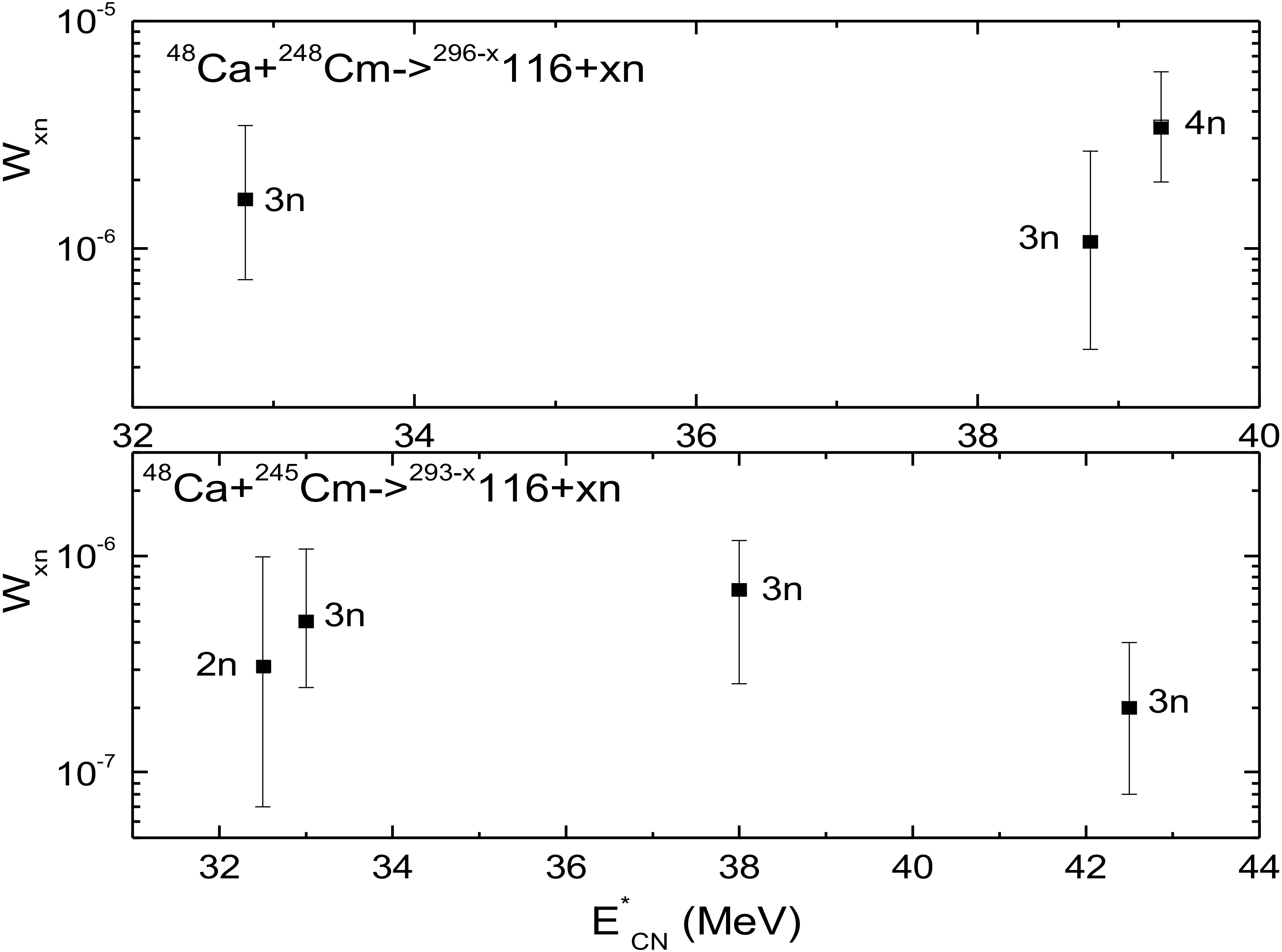

W.D.Myers (1977), Z=126
126
122
124
120
118
116
114
B_f-B_n (MeV)
N
6
4
2
0
-2
-4
-6
-8
172
176
180
184
188



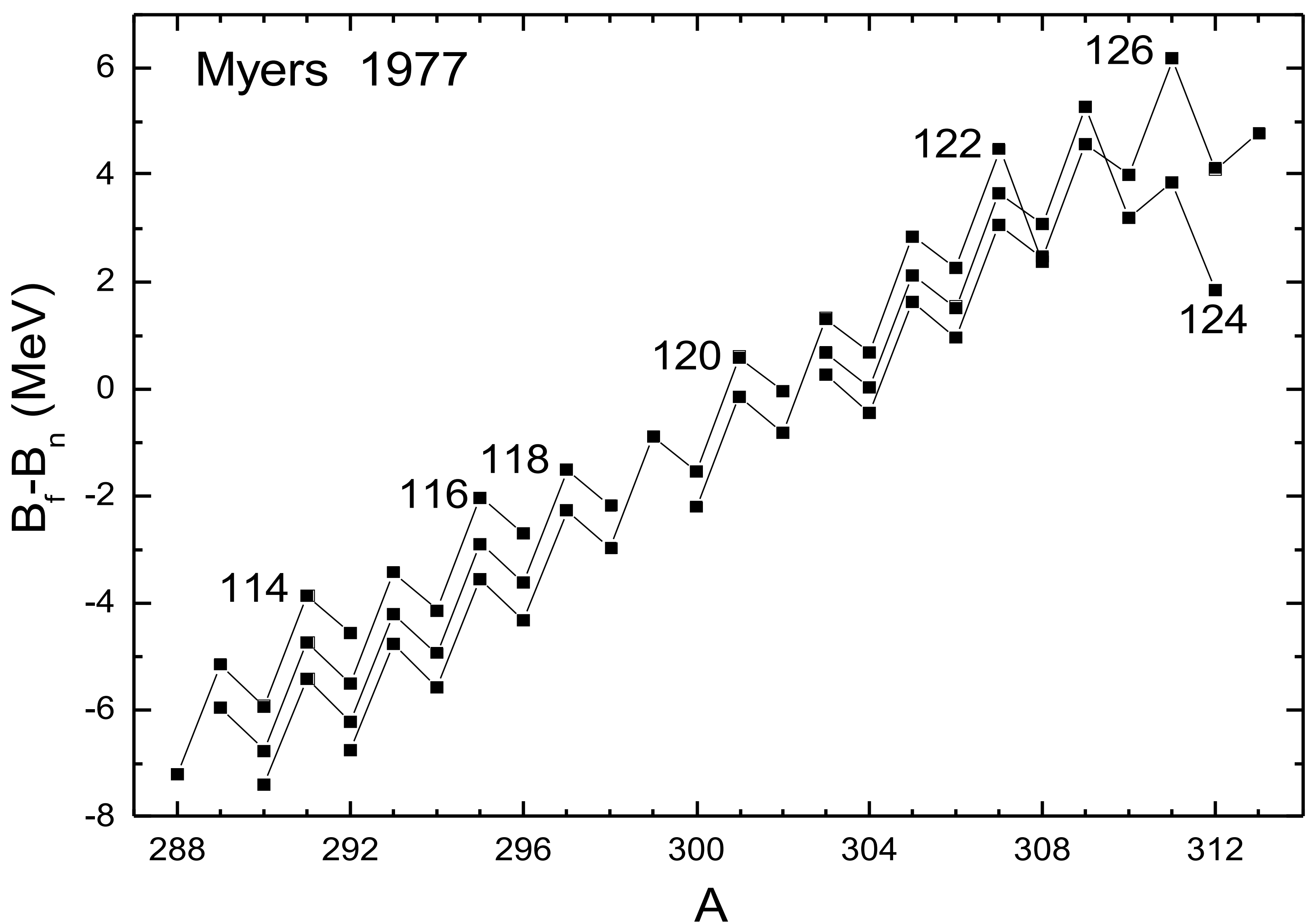
48Ca+Act.
238U
242Pu
244Pu
245Cm
248Cm
249Cf
10-5
10-6
10-7
σfus eff (barn)
286
288
290
292
294
296
298
A



$^{48}Ca+^{242}Pu\rightarrow^{290-x}114+xn$
$^{48}Ca+^{244}Pu\rightarrow^{292-x}114+xn$
$^{48}Ca+^{244}Pu\rightarrow^{292-x}114+xn$
W_{xn}
E^*_{CN} (MeV)
2n
3n
4n
5n



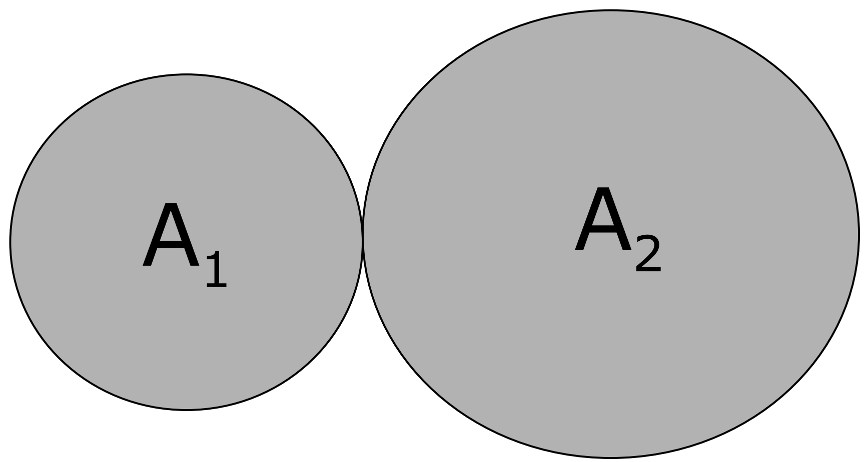
$^{48}Ca+^{248}Cm \rightarrow ^{296-x}116+xn$
W_{xn}
10^{-5}
10^{-6}
3n
3n
4n
32
34
36
38
40
$^{48}Ca+^{245}Cm \rightarrow ^{293-x}116+xn$
W_{xn}
10^{-6}
10^{-7}
2n
3n
3n
3n
32
34
36
38
40
42
44
E^{*}_{CN} (MeV)



Myers 1977
126
122
124
120
118
116
114
B_f-B_n (MeV)
A
6
4
2
0
-2
-4
-6
-8
288
292
296
300
304
308
312

Mass asymmetry coordinate

$$\eta = \frac{A_1 - A_2}{A_1 + A_2}$$



$\eta = 0$ for $A_1 = A_2$, $\eta = \pm 1$ for A_1 or $A_2 = 0$

Potential energy

$$U(Z,A,\lambda,\beta)=U_{LDM}(Z,A,\lambda,\beta)+\delta U_{mic}(Z,A,\lambda,\beta)$$

Binding energy

$$B(Z,A)=U(Z,A,\lambda_{gs},\beta_{gs})-a_v(1-a_s(\frac{N-Z}{A})^2)A$$

$$+W|\frac{N-Z}{A}|+\delta+c[(N-Z)-58]$$

$$a_s=1.778, W=30\,MeV, c=0.25\,MeV,$$

$$\delta=4.8/N^{1/3}\delta_{N,odd}+4.8/Z^{1/3}\delta_{Z,odd},$$

$$a_v=15.703\,MeV\ at\ N-Z<52;15.715\,MeV\ at\ 54\leqslant N-Z\leqslant 61,$$

Potential energy

$$U(Z,A,\lambda,\beta) = U_{LDM}(Z,A,\lambda,\beta) + \delta U_{mic}(Z,A,\lambda,\beta)$$

Binding energy

$$B(Z,A) = U(Z,A,\lambda_{gs},\beta_{gs}) - a_v\left(1 - 1.78\left(\frac{N-Z}{A}\right)^2\right)A + \ldots$$

$$a_v = 15.83\, MeV$$

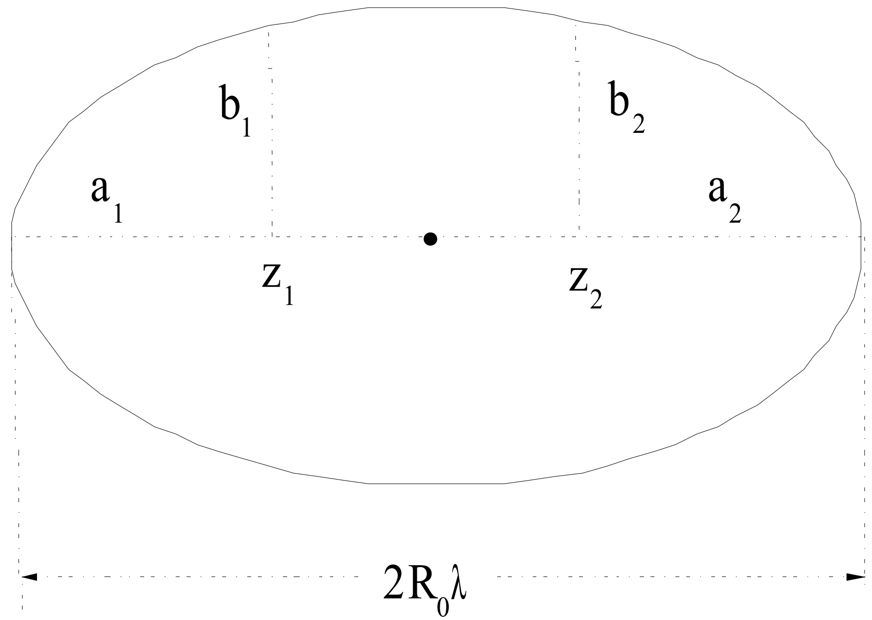
Q_α energy

$$Q_\alpha(Z,A) = B(Z,A) + 28.296 - B(Z-2, A-4)$$

Alpha decay half-lives T_α (A. Sobiczewski et al.)

$$\log_{10} T_\alpha(Z,A) = 1.5372\, Z Q_\alpha^{-1/2} - 0.1607\, Z - 36.573$$

$\beta_i = a_i / b_i$



$\beta_1 = \beta_2$, even multipolarities; $\beta_1 \neq \beta_2$, odd and even multipolarities

R_0 is the radius of spherical nucleus

Parametrisation of nuclear shape with TCSM

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

Strength parameters of paring interaction

$$G_{\substack{n\\p}} = \left(19.2 \mp 7.4 \frac{N-Z}{A}\right) A^{-1}\, MeV$$

$$A \approx 250 \rightarrow G_n \approx 0.075\, MeV, G_p \approx 0.085\, MeV$$

One-quasiparticle excitations

$$E_\mu = \sqrt{\left(e_\mu - e_F\right)^2 + \Delta^2} - \sqrt{\left(e_\mu{}' - e_F\right)^2 + \Delta^2}$$

Two-quasiparticle excitations

$$E_\mu = \sqrt{\left(e_\mu - e_F\right)^2 + \Delta^2} + \sqrt{\left(e_\mu{}' - e_F\right)^2 + \Delta^2}$$

Parameters

$$35 \leq N - Z \leq 56$$

forneutrons

$$\kappa_n = -0.076 + 0.0058(N-Z) - 6.53\times10^{-5}(N-Z)^2 + 0.002\,A^{1/3},$$

$$\mu_n = 1.598 - 0.0295(N-Z) + 3.036\times10^{-4}(N-Z)^2 - 0.095\,A^{1/3},$$

forprotons

$$\kappa_p = 0.0383 + 0.00137(N-Z) - 1.22\times10^{-5}(N-Z)^2 - 0.003\,A^{1/3},$$

$$\mu_p = 0.335 + 0.01(N-Z) - 9.367\times10^{-5}(N-Z)^2 + 0.003\,A^{1/3},$$

The parts in front of the terms with $A^{1/3}$ vary: (0.05-0.053) for κ_n , (0.075-0.0768) for κ_p , (0.88-0.92) for μ_n , (0.58-0.61) for μ_p

Dynamics of fusion in the dinuclear system model

Evaporation residue cross section for the production of superheavy nuclei:

$$\sigma^{s}_{ER}(E_{c.m.}) = \sum_{J=0} \sigma_c(E_{c.m.}, J) P_{CN}(E_{c.m.}, J) W^{s}_{sur}(E_{c.m.}, J)$$

$$\sigma_c(E_{c.m.}, J) = \pi \lambda\!\!\!^{-2} (2J+1) T(E_{c.m.}, J)$$

$$\sigma^{s}_{ER}(E_{c.m.}) \approx P_{CN}(E_{c.m.}, J=0) \sum_{J} \sigma_c(E_{c.m.}, J) W^{s}_{sur}(E_{c.m.}, J)$$

$$\approx \sigma_c(E_{c.m.}) P_{CN}(E_{c.m.}) W^{s}_{sur}(E_{c.m.})$$

The stronger shell effects revealed for nuclei with Z>118 result larger survival probabilities and lager values of the cross section.