Production and properties of superheavy elements

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Ukrainian-German Conference:

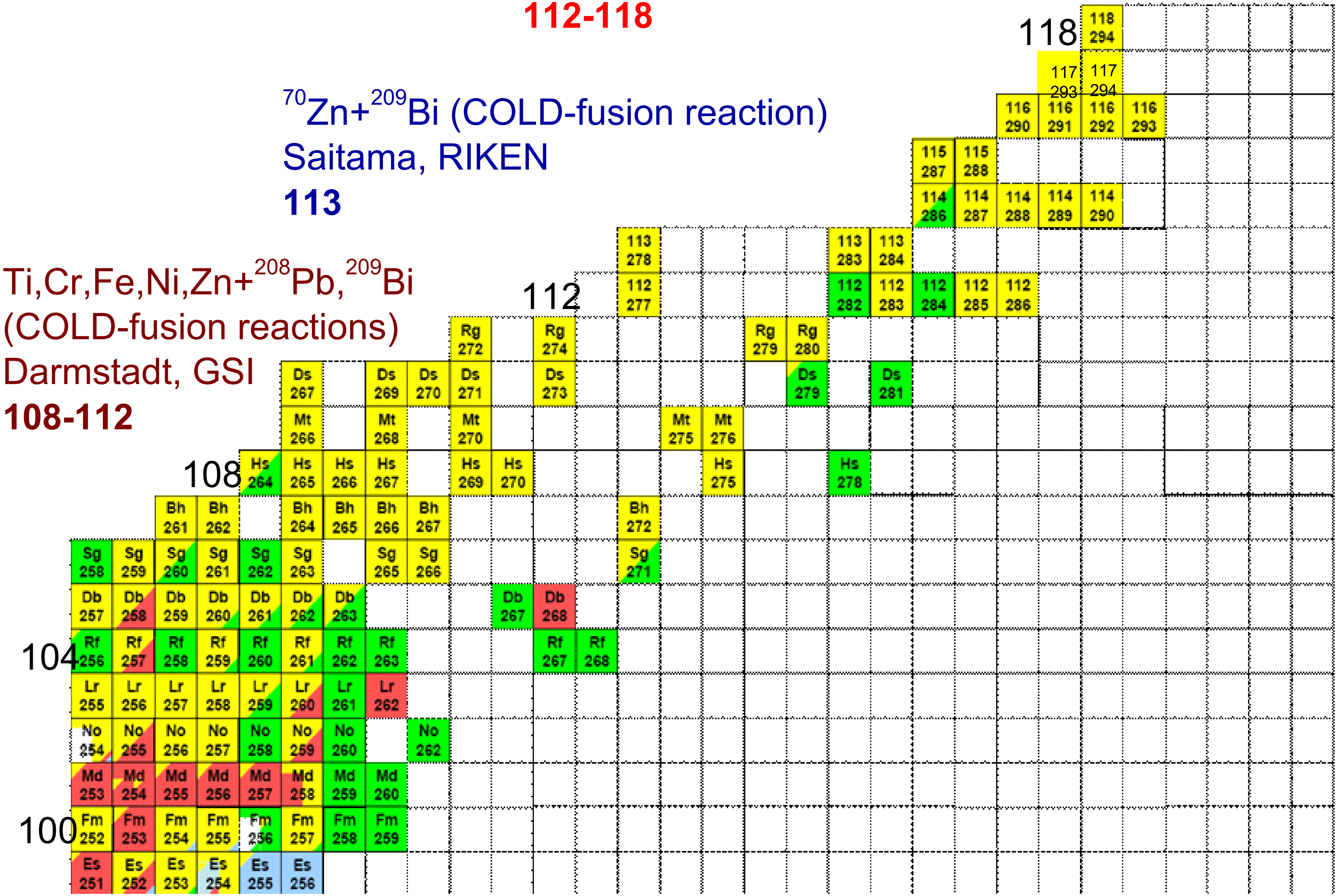
Possibilities of cooperation in the framework of the international project FAIR

September 26, 2014

^{48}Ca+U,Pu,Am,Cm,Bk,Cf (HOT-fusion reactions)
Dubna, JINR
112-118

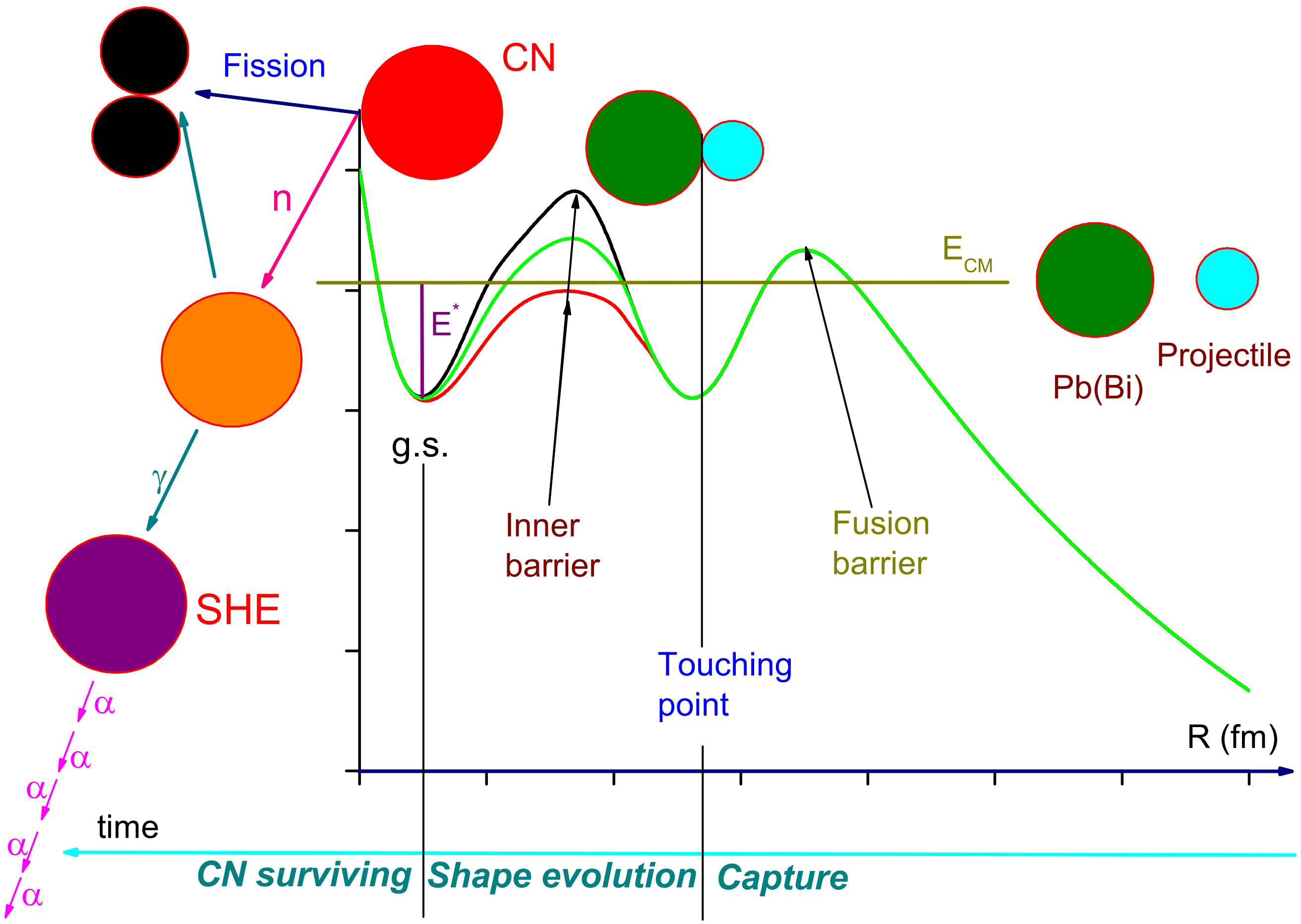
$^{70}Zn + ^{209}Bi$ (COLD-fusion reaction)
Saitama, RIKEN
113

Ti,Cr,Fe,Ni,Zn+^{208}Pb,^{209}Bi
(COLD-fusion reactions)
Darmstadt, GSI
108-112



Main feature of the model

$$\sigma_{\mathrm{SHE}}(E) = \frac{\pi\hbar^2}{2\mu E}\sum_{\ell}(2\ell+1)\cdot \mathcal{W}_{\mathrm{surv}}(E,\ell)\cdot T_{\mathrm{CN}}(E,B_{\mathrm{inner}},\ell)\cdot T_{\mathrm{capture}}(E,B_{\mathrm{fusion}},\ell).$$



Capture

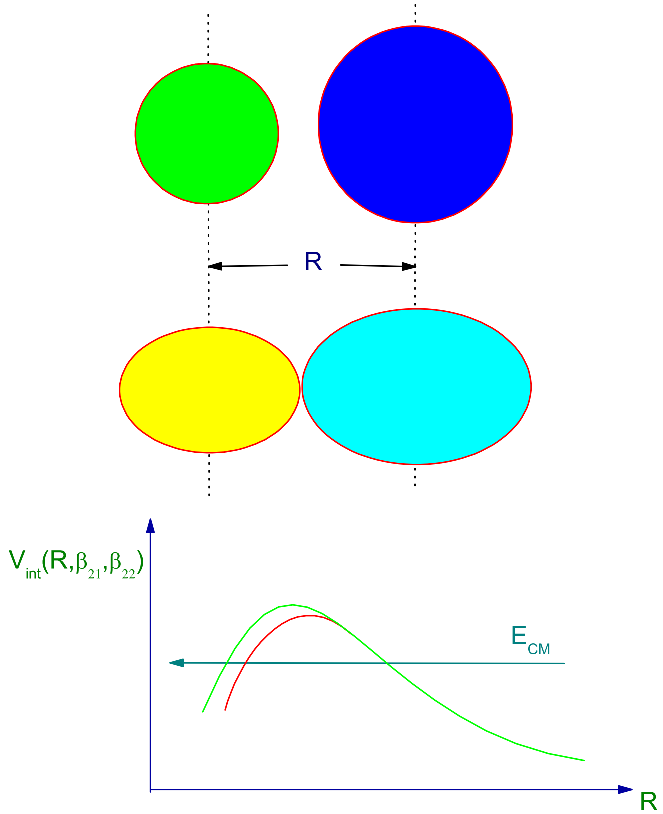
Interaction potential: $V_{\text{Nucleus-Nucleus}}(R,\ell) = V_{\text{nuclear}}(R) + V_{\text{Coulomb}}(R) + \frac{\hbar^2 \ell(\ell+1)}{2\mathcal{M}R^2}$

Penetration through barrier: WKB approximation

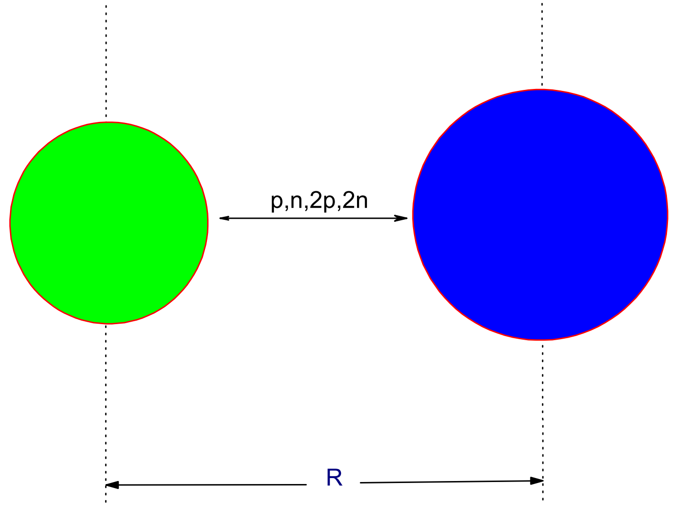
Enhancement of the penetrability due to: - low-energy surface 2^+, 3^- vibrations

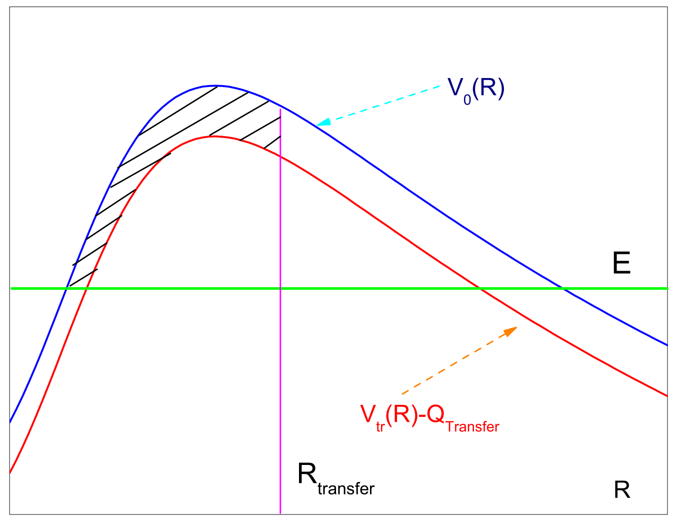
- nucleon transfer with positive Q-value

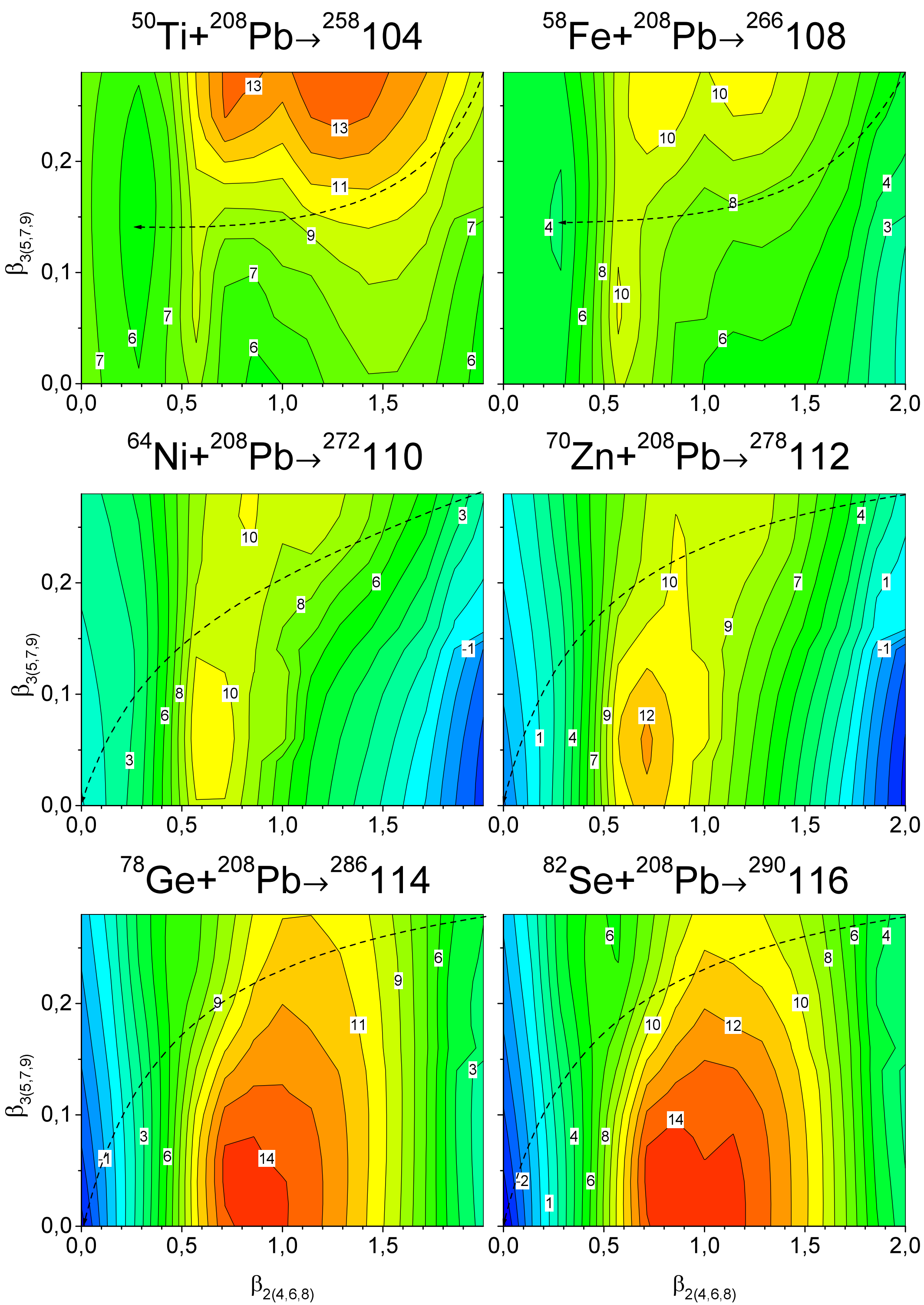
$V_{int}(R,\beta_{21},\beta_{22})=V_{Nucl}(R,\beta_{21},\beta_{22})+V_{Coul}(R,\beta_{21},\beta_{22})$



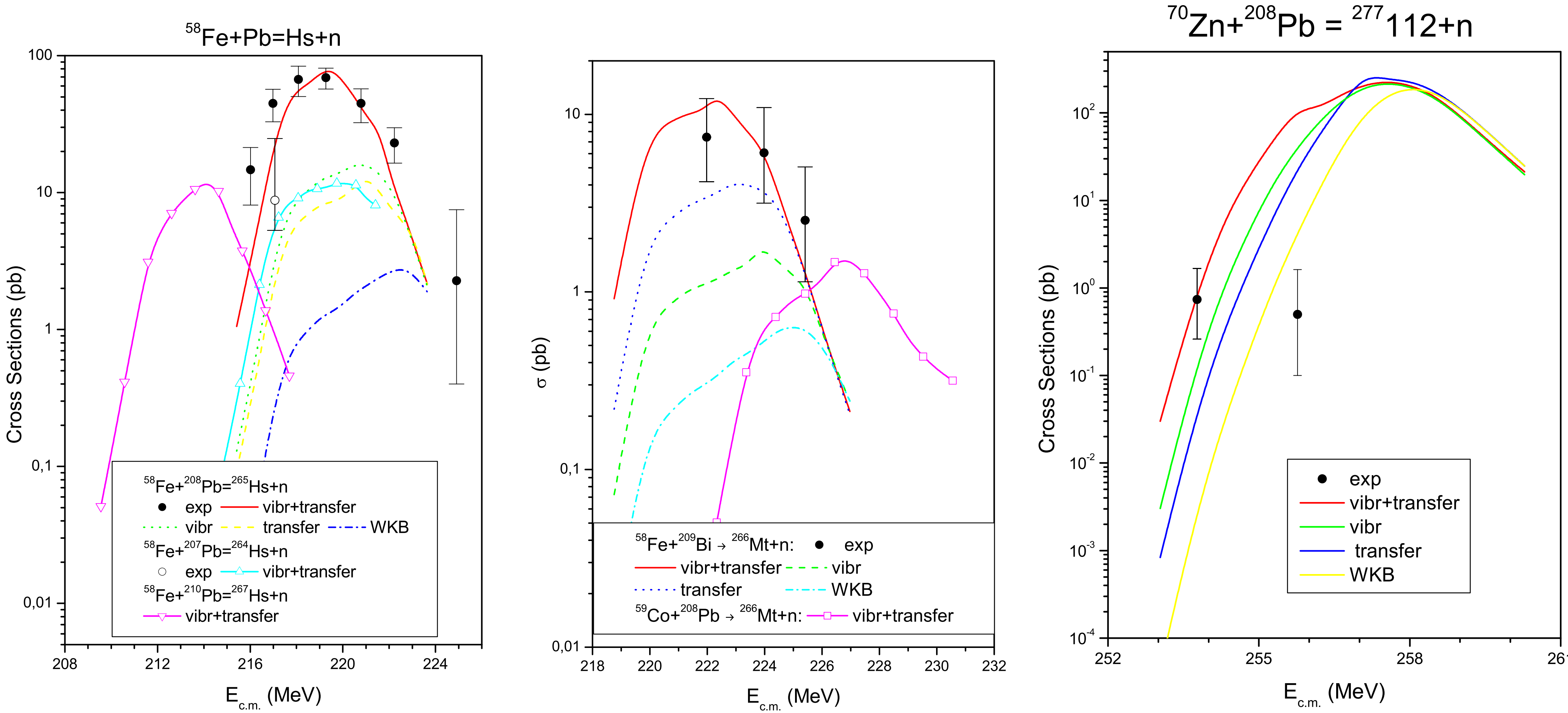
$V_{int}(R,\beta_{21},\beta_{22})=V_{int}(R,\beta_{21},\beta_{22})-Q_{Transfer}$







$^{50}Ti+^{208}Pb\rightarrow^{258}104$
$^{58}Fe+^{208}Pb\rightarrow^{266}108$
$^{64}Ni+^{208}Pb\rightarrow^{272}110$
$^{70}Zn+^{208}Pb\rightarrow^{278}112$
$^{78}Ge+^{208}Pb\rightarrow^{286}114$
$^{82}Se+^{208}Pb\rightarrow^{290}116$
$\beta_{3(5,7,9)}$
$\beta_{2(4,6,8)}$


58Fe+Pb=Hs+n
Cross Sections (pb)
E c.m. (MeV)
58Fe+208Pb=265Hs+n
exp
vibr+transfer
vibr
transfer
WKB
58Fe+207Pb=264Hs+n
exp
vibr+transfer
58Fe+210Pb=267Hs+n
vibr+transfer
σ (pb)
E c.m. (MeV)
58Fe+209Bi → 266Mt+n: exp
vibr+transfer
vibr
transfer
WKB
59Co+208Pb → 266Mt+n: vibr+transfer
70Zn+208Pb = 277112+n
Cross Sections (pb)
E c.m. (MeV)
exp
vibr+transfer
vibr
transfer
WKB

Semi-Microscopic Potential (SMP) between heavy nuclei

The interaction energy between spherical and axial-symmetric nuclei in the frozen density approximation is

$$V(R,\vartheta) = E_{12}(R,\vartheta) - E_1 - E_2,$$

R is the distance between mass centers of colliding nuclei,

ϑ is the angle between the axial-symmetry axis of deformed nuclei and the line connected the mass centers of nuclei,

binding energies are

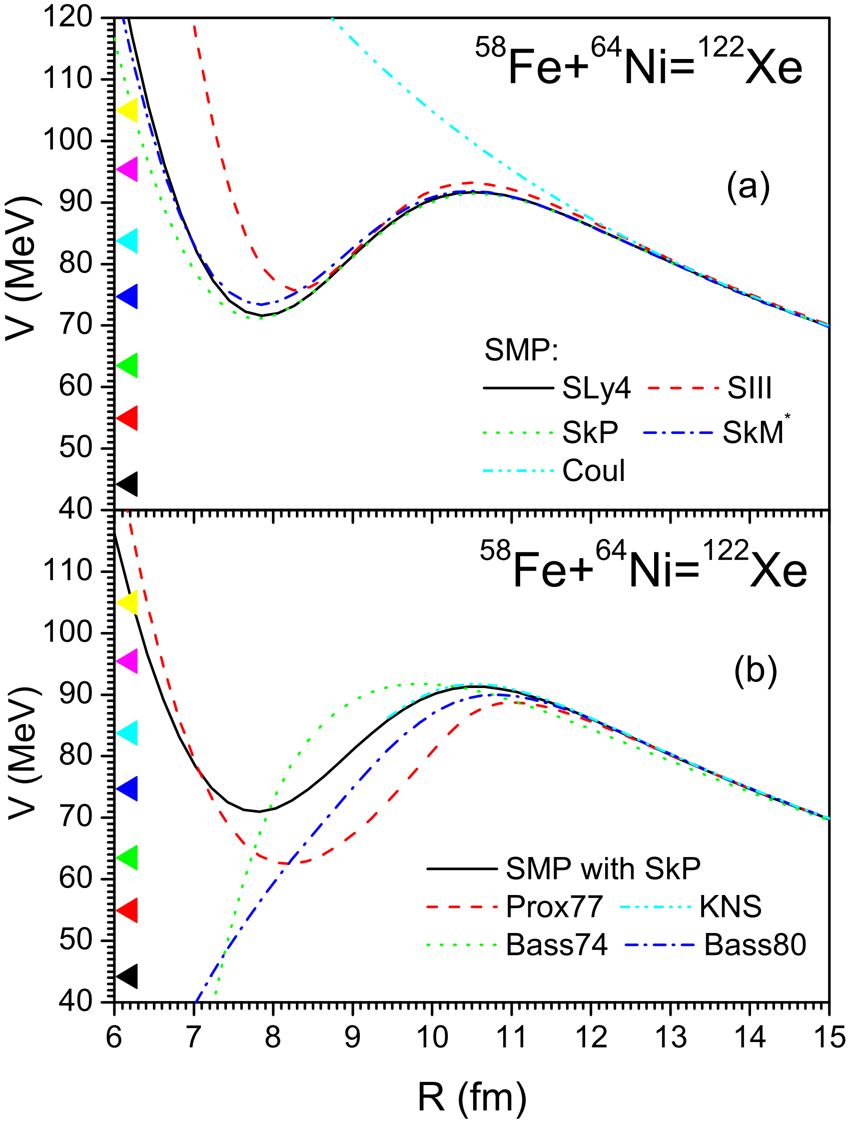
$$E_{12}(R,\vartheta) = \int \mathcal{E}[\rho_{1p}(\mathbf{r}) + \rho_{2p}(R,\vartheta,\mathbf{r}), \rho_{1n}(\mathbf{r}) + \rho_{2n}(R,\vartheta,\mathbf{r})]\, d\mathbf{r},$$
$$E_1 = \int \mathcal{E}[\rho_{1p}(\mathbf{r}), \rho_{1n}(\mathbf{r})]\, d\mathbf{r}, \quad E_2 = \int \mathcal{E}[\rho_{2p}(\mathbf{r}), \rho_{2n}(\mathbf{r})]\, d\mathbf{r}.$$

The energy density functional

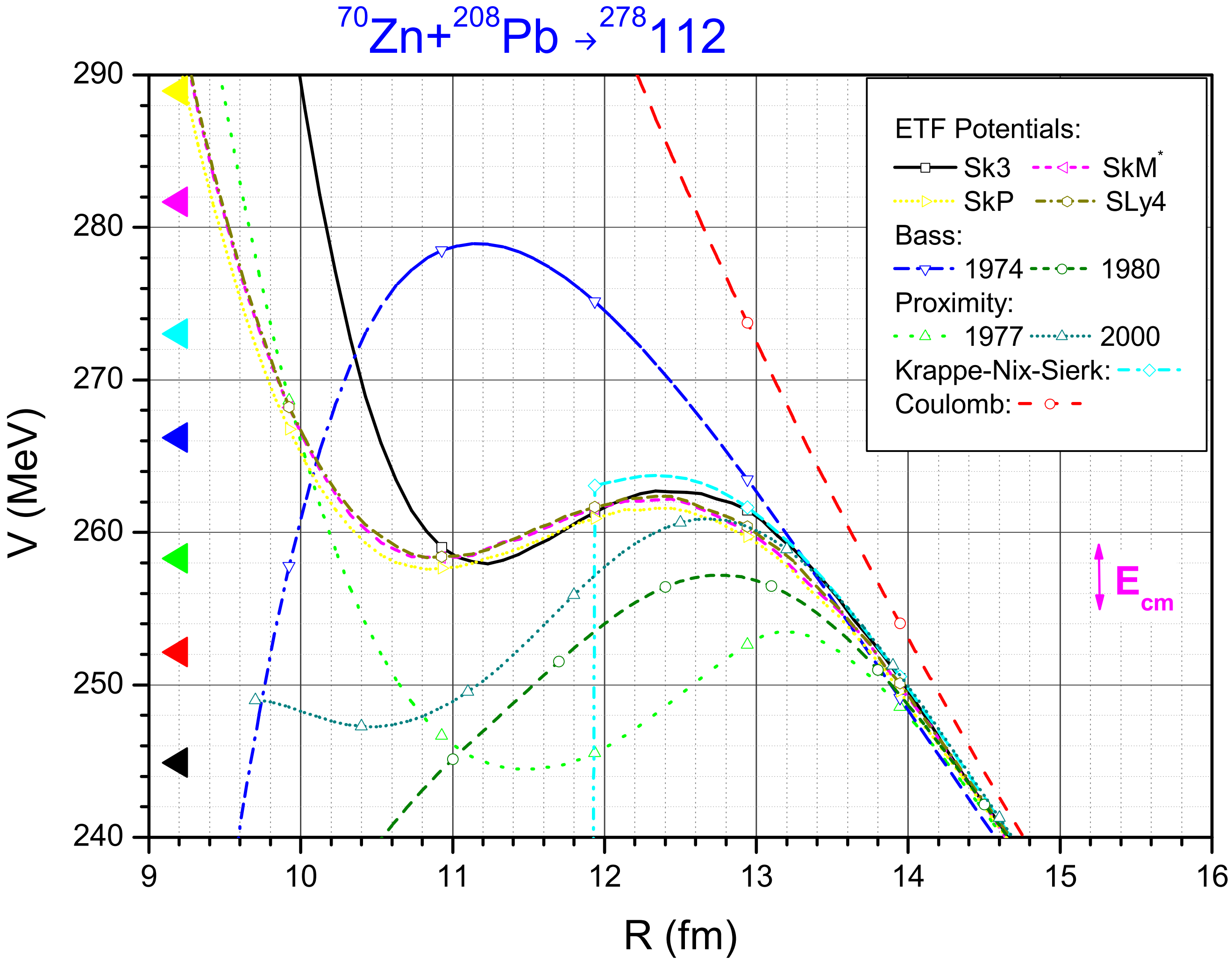
$$\mathcal{E}[\rho_p(\mathbf{r}), \rho_n(\mathbf{r})] = \frac{\hbar^2}{2m}[\tau_p(\mathbf{r}) + \tau_n(\mathbf{r})] + \mathcal{V}(\mathbf{r}),$$

where m is the nucleon mass. The expressions for proton τ_p and neutron τ_n kinetic energy density functionals are taken into account $\hbar^2$ corrections. The potential energy density functional splits into Skyrme and Coulomb (direct and exchange) parts

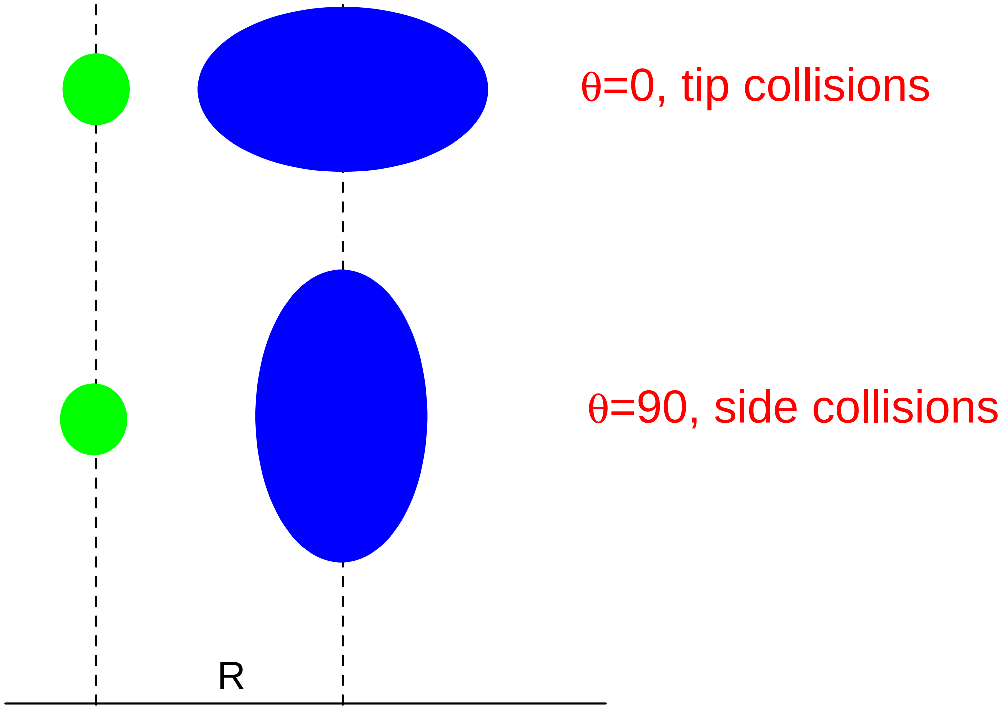
$$\mathcal{V}(\mathbf{r}) = \mathcal{V}_{\text{Skyrme}}(\mathbf{r}) + \mathcal{V}_{\text{Coul}}(\mathbf{r}).$$

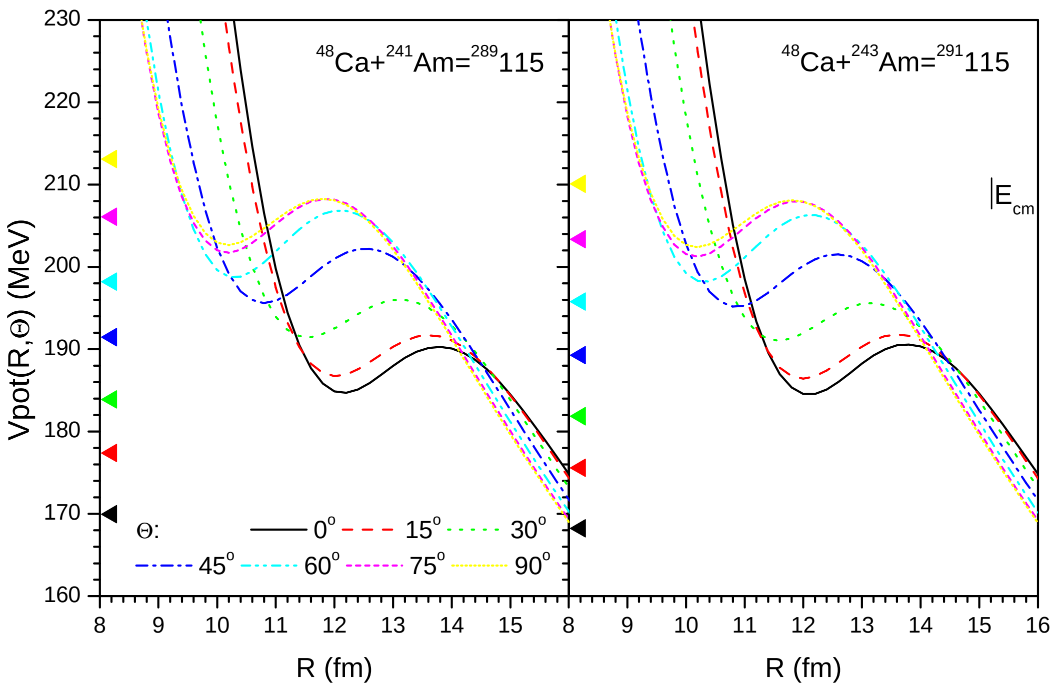


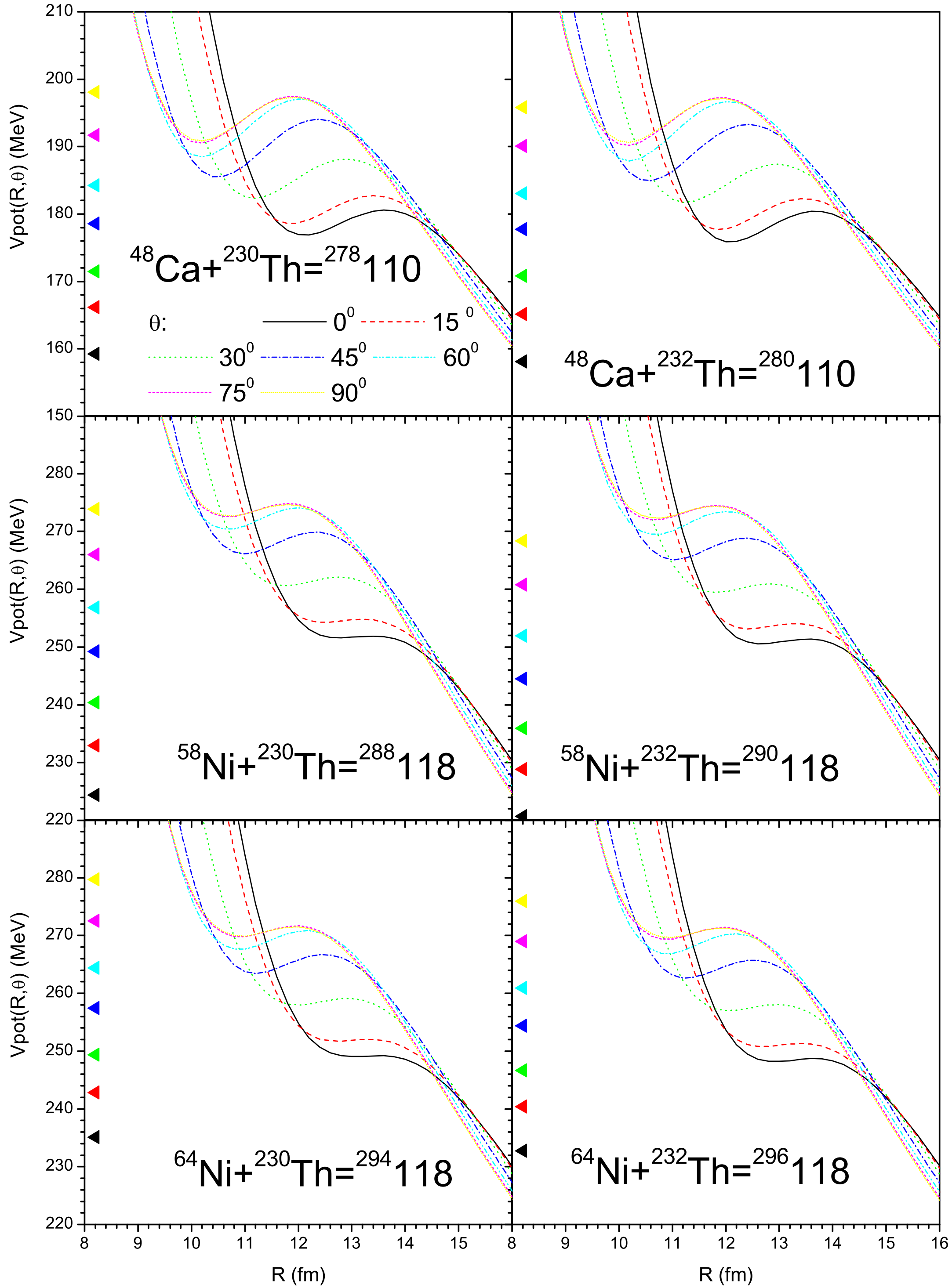
$^{58}Fe+^{64}Ni=^{122}Xe$
(a)
SMP:
SLy4
SIII
SkP
SkM*
Coul
$^{58}Fe+^{64}Ni=^{122}Xe$
(b)
SMP with SkP
Prox77
KNS
Bass74
Bass80
V (MeV)
R (fm)



$^{70}Zn+^{208}Pb \rightarrow ^{278}112$
ETF Potentials:
Sk3
SkM*
SkP
SLy4
Bass:
1974
1980
Proximity:
1977
2000
Krappe-Nix-Sierk:
Coulomb:
E cm
V (MeV)
R (fm)


θ=0, tip collisions
θ=90, side collisions
R


48Ca+241Am=289115
48Ca+243Am=291115
Ecm
Vpot(R,Θ) (MeV)
R (fm)
R (fm)
Θ:
0°
15°
30°
45°
60°
75°
90°
230
220
210
200
190
180
170
160
8
9
10
11
12
13
14
15
16



Vpot(R,θ) (MeV)
R (fm)
^{48}Ca+^{230}Th=^{278}110
θ: 0^0 15^0 30^0 45^0 60^0 75^0 90^0
^{48}Ca+^{232}Th=^{280}110
^{58}Ni+^{230}Th=^{288}118
^{58}Ni+^{232}Th=^{290}118
^{64}Ni+^{230}Th=^{294}118
^{64}Ni+^{232}Th=^{296}118

The Coulomb interaction of two axial-symmetric nuclei

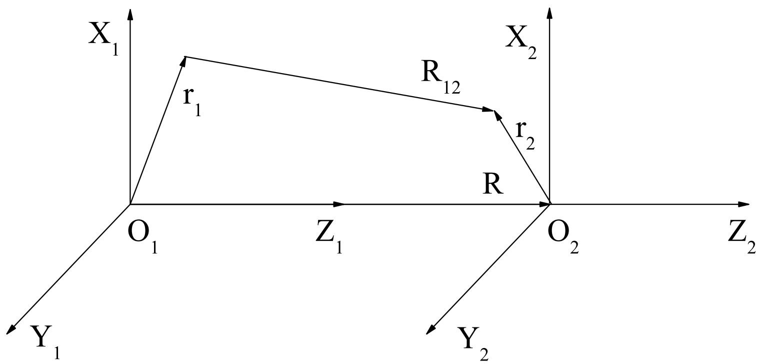
The Coulomb interaction of two nuclei at distances between their mass centers R is

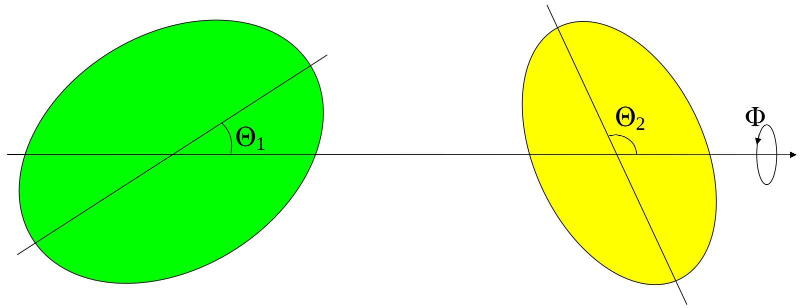
$$V_{\rm C}(R) = e^2 \int \frac{\rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2)}{|\mathbf{R}+\mathbf{r}_2-\mathbf{r}_1|} d\mathbf{r}_1 d\mathbf{r}_2.$$

where the denominator in can be presented as

$$\frac{1}{|\mathbf{R}+\mathbf{r}_2-\mathbf{r}_1|} = \sum_{\ell_1,\ell_2=0}^{\infty} \frac{r_1^{\ell_1} r_2^{\ell_2}}{R^{\ell_1+\ell_2+1}} \frac{4\pi(-1)^{\ell_2}(\ell_1+\ell_2)!}{\sqrt{(2\ell_1+1)(2\ell_2+1)}} \times \sum_m \frac{Y_{\ell_1 m}(\vartheta_1,\varphi_1) Y_{\ell_2 -m}(\vartheta_2,\varphi_2)}{\sqrt{(\ell_1+m)!(\ell_1-m)!(\ell_2+m)!(\ell_2-m)!}},$$

where $Y_{\ell m}(\vartheta,\varphi)$ is the spherical harmonic functions, $r_i, \vartheta_i, \varphi_i$ are the spherical coordinates in the laboratory coordinate system O_i. Note that $Y_{\ell m}(\vartheta,\varphi)$ vanish whenever $|m| > \ell$.





The Coulomb interaction of two axial-symmetric arbitrary-oriented nuclei in the form

$$V_{\rm C}(R,\Theta_1,\Theta_2,\Phi) = \frac{Z_1 Z_2 e^2}{R}\{1 + \sum_{\ell\geq 2}[f_{1\ell}(R,\Theta_1,R_{10})\beta_{1\ell} + f_{1\ell}(R,\Theta_2,R_{20})\beta_{2\ell}]$$

$$+f_2(R,\Theta_1,R_{10})\beta_{12}^2 + f_2(R,\Theta_2,R_{20})\beta_{22}^2 + f_3(R,\Theta_1,\Theta_2,R_{10},R_{20})\beta_{12}\beta_{22} + f_4(R,\Theta_1,\Theta_2,\Phi,R_{10},R_{20})\beta_{12}\beta_{22}\}\,.$$

We approximate the nuclear part of the potential between deformed nuclei as

$$V_{\rm n}(R,\Theta_1,\Theta_2,\Phi)\approx\frac{C_{10}+C_{20}}{C_{\rm def}}V_{\rm n}^0(d^0(R_{\rm sph},R_{10},R_{20})),$$

where

$$C_{\rm def}=\left[(C_1^{\parallel}+C_2^{\parallel})(C_1^{\perp}+C_2^{\perp})\right]^{1/2}$$

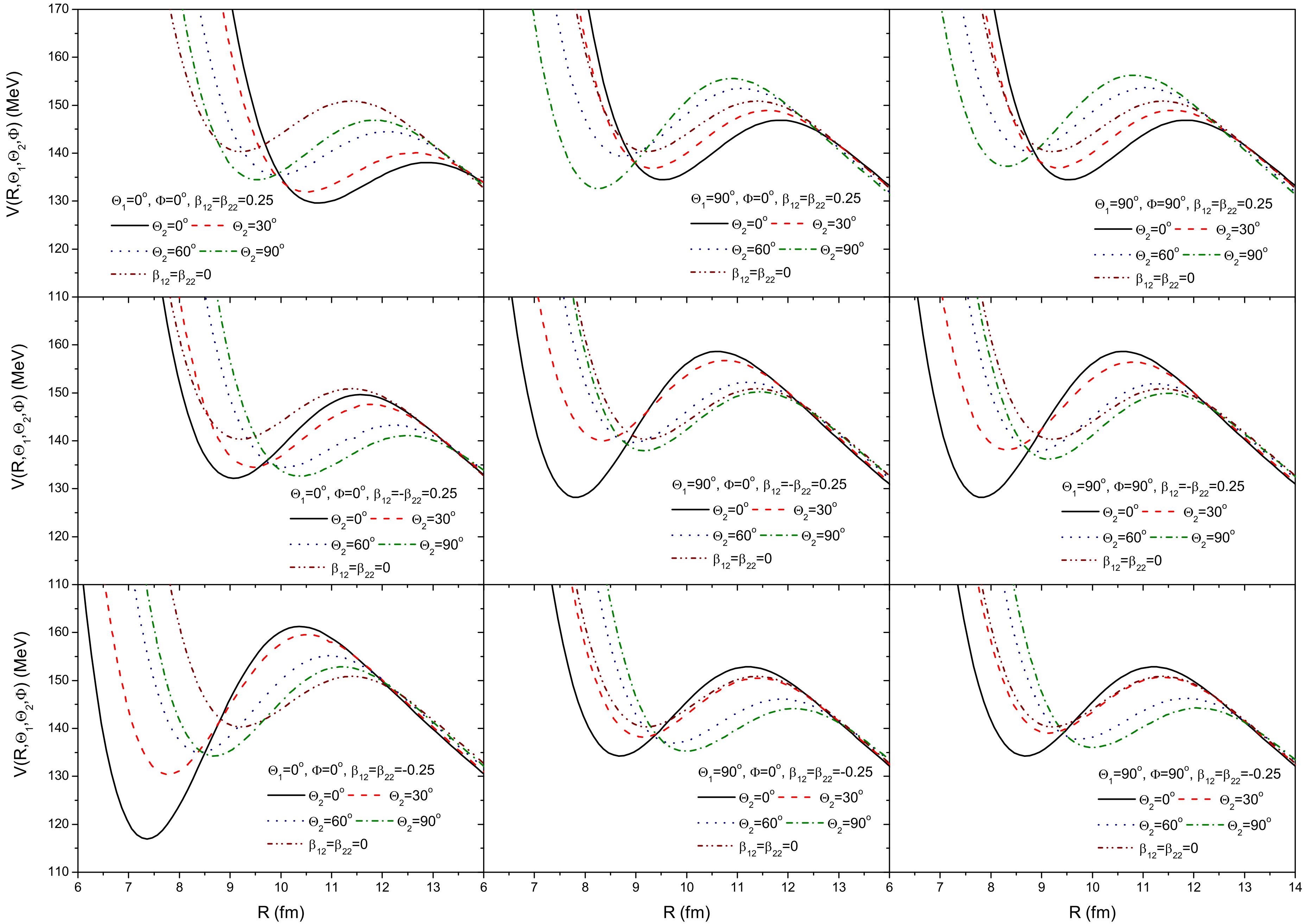
is the generalized reciprocal curvature and

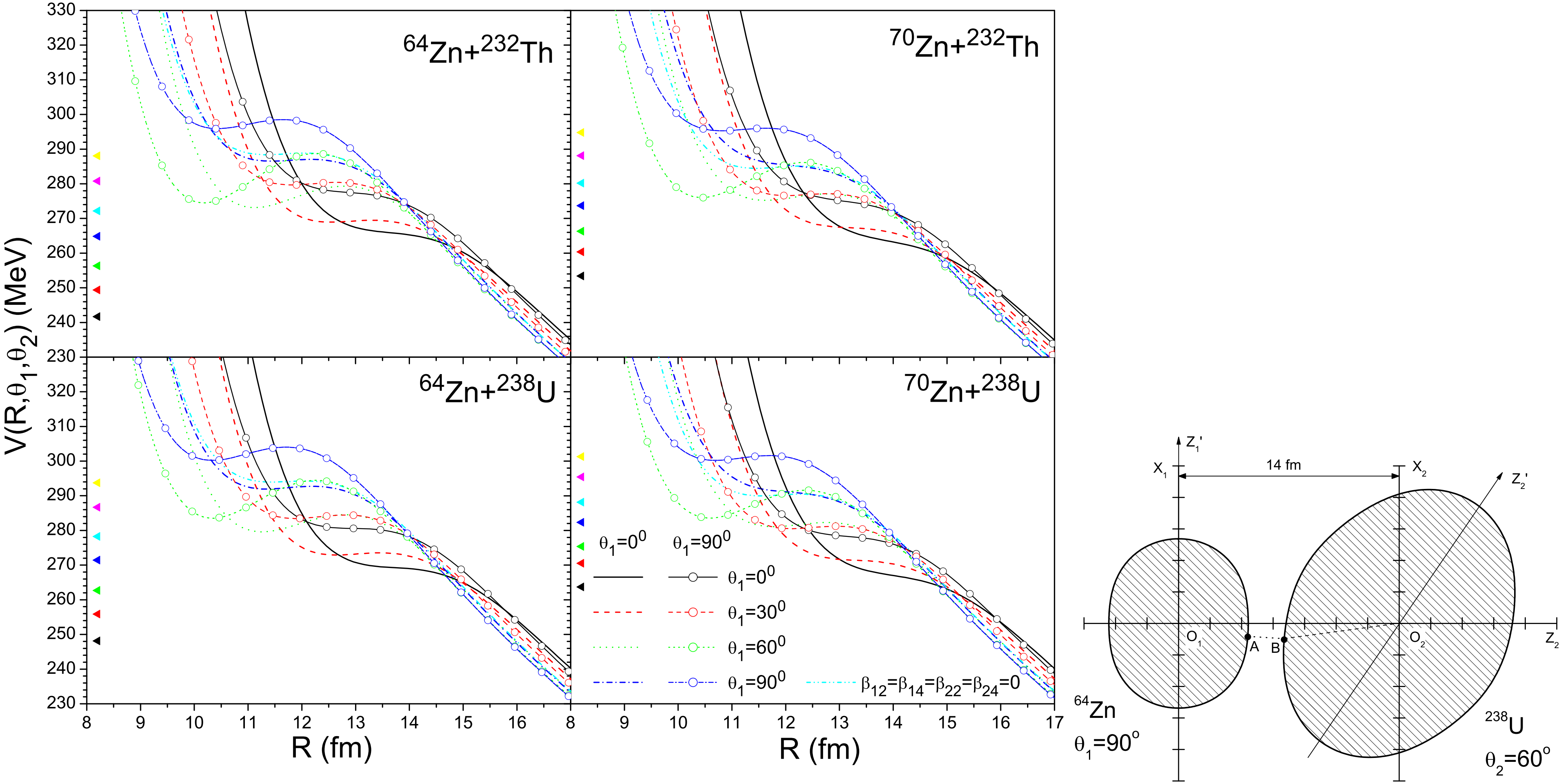
$$d^0(R_{\rm sph},R_{10},R_{20})=d(R,\Theta_1,\Theta_2,\Phi,R_{10},R_{20},\beta_1,\beta_2).$$

The nucleus-nucleus interaction potential of axial-symmetric nuclei at various relative orientations for zero value of orbital momentum is given as

$$V(R,\Theta_1,\Theta_2,\Phi)=V_{\rm C}(R,\Theta_1,\Theta_2,\Phi)+V_{\rm n}(R,\Theta_1,\Theta_2,\Phi).$$

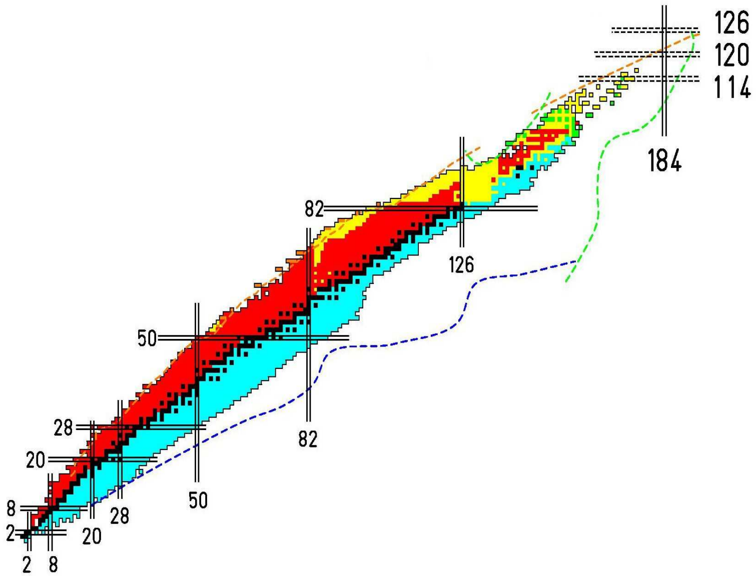
Potentials ^{86}Kr($\beta_{12} = \pm 0.25$)+^{86}Kr($\beta_{22} = \pm 0.25$)





$^{64}Zn+^{232}Th$
$^{70}Zn+^{232}Th$
$^{64}Zn+^{238}U$
$^{70}Zn+^{238}U$
$V(R,\theta_1,\theta_2)$ (MeV)
R (fm)
$\theta_1=0^0$
$\theta_1=90^0$
$\theta_1=0^0$
$\theta_1=30^0$
$\theta_1=60^0$
$\theta_1=90^0$
$\beta_{12}=\beta_{14}=\beta_{22}=\beta_{24}=0$
14 fm
^{64}Zn
$\theta_1=90^o$
^{238}U
$\theta_2=60^o$

Magic numbers for ultraheavy region. Alpha-decay half-life and fission barriers for double-magic ultraheavy nuclei



Magic Numbers **Z = 8, 20, 28, 50, 82, N = 8, 20, 28, 50, 82, 126** are related to filling of the nucleonic shells.

Nuclei with magic number(s) of nucleons have:

- $\Longrightarrow$ higher stability
- $\Longrightarrow$ higher stiffness to perturbation of different nature
- $\Longrightarrow$ higher abundance in the nature

then neighboring nuclei.

The N or Z dependencies of nucleon(s) separation energy have jump at crossing magic numbers.

The largest magic numbers "experimentally known" up to now are: $Z = 114$, $N = 184$.

The P or N shell corrections have deep local minimum at magic numbers.

TASKs: 1. determinate magic numbers for heavy systems with $A = 300 - 1200$ by studying deep local minimum of shell corrections.

2. evaluate $T_{1/2}(\alpha)$ and fission barrier for magic ultraheavy.

Ultra-heavy nuclei can exist in star (neutron stars, magnetars, and etc)

Green's β-stability line:

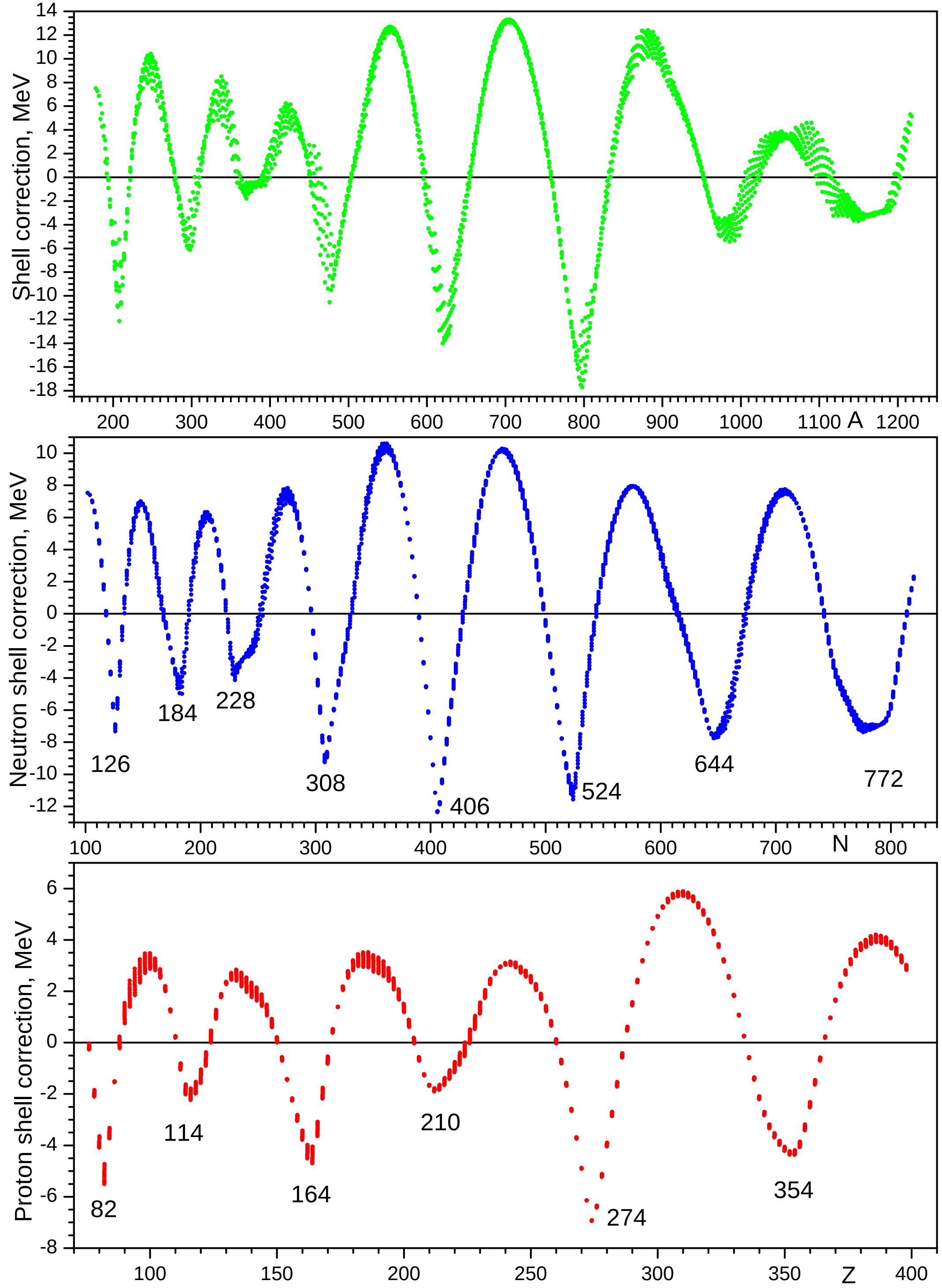
$$N_{Green} = \frac{2}{3}Z + \frac{5}{3}(10000 + 40Z + Z^2)^{1/2} - \frac{500}{3}. \quad (1)$$

We evaluate Proton δ_P and Neutron δ_N shell corrections for even-even nuclei along Green's β-stability line for $Z = 76 - 400$, $N = 102 - 820$, $A = 178 - 1218$.

$$Z = 76, 78, 80, ...400.$$

$$N = N_{Green} - 10, N_{Green} - 8, N_{Green} - 6, ...N_{Green} + 10$$

Mean field potential: Woods-Saxon + spin-orbit interaction + Lipkin-Nogami pairing + Coulomb (protons). Parametrization : "universal" - S.Cwiok, et al, CPC **46** 379 (1987).



Shell correction, MeV
A
Neutron shell correction, MeV
126
184
228
308
406
524
644
772
N
Proton shell correction, MeV
82
114
164
210
274
354
Z

WE OBTAINE: Proton Magic Numbers: Z= 82, 114, 164, 210, 274, 354

Neutron Magic Numbers: N= 126, 184, 228, 308, 406, 524, 644, 772

Comparison with other calculations:

Z=82, 114, 164 and N=126, 184, 228 $\Leftrightarrow$ Shell model.

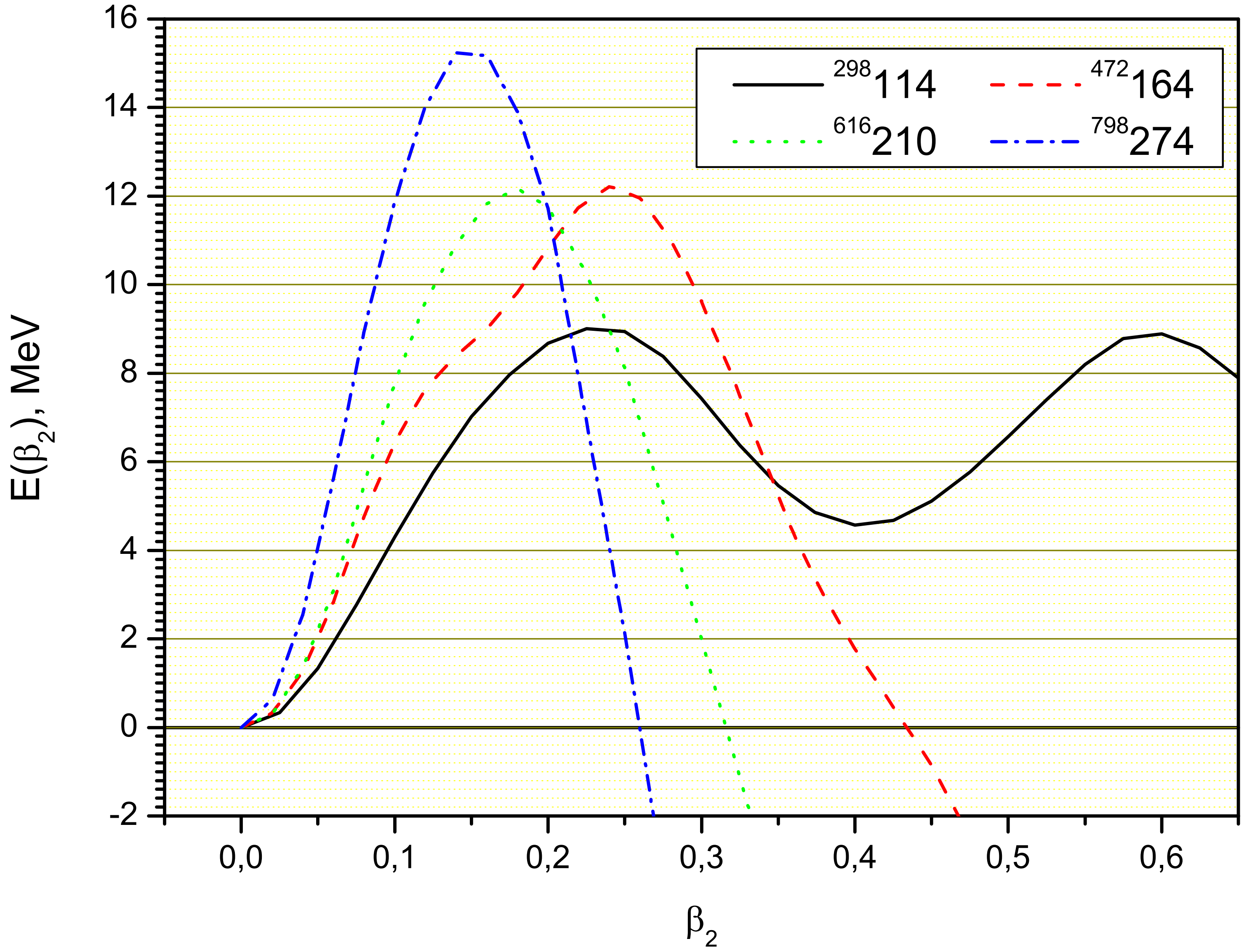
S.G. Nilsson, I. Ragnarsson I., Shapes and shells in nuclear structure (Cambridge Univ. Press, Cambridge, 1995).

Z≈114-126, Z≈164, N≈172-184, N≈228, N≈308, N≈406 $\Leftrightarrow$ HFB+Skyrme or RMF

There is strong dependence on the both model and force set.

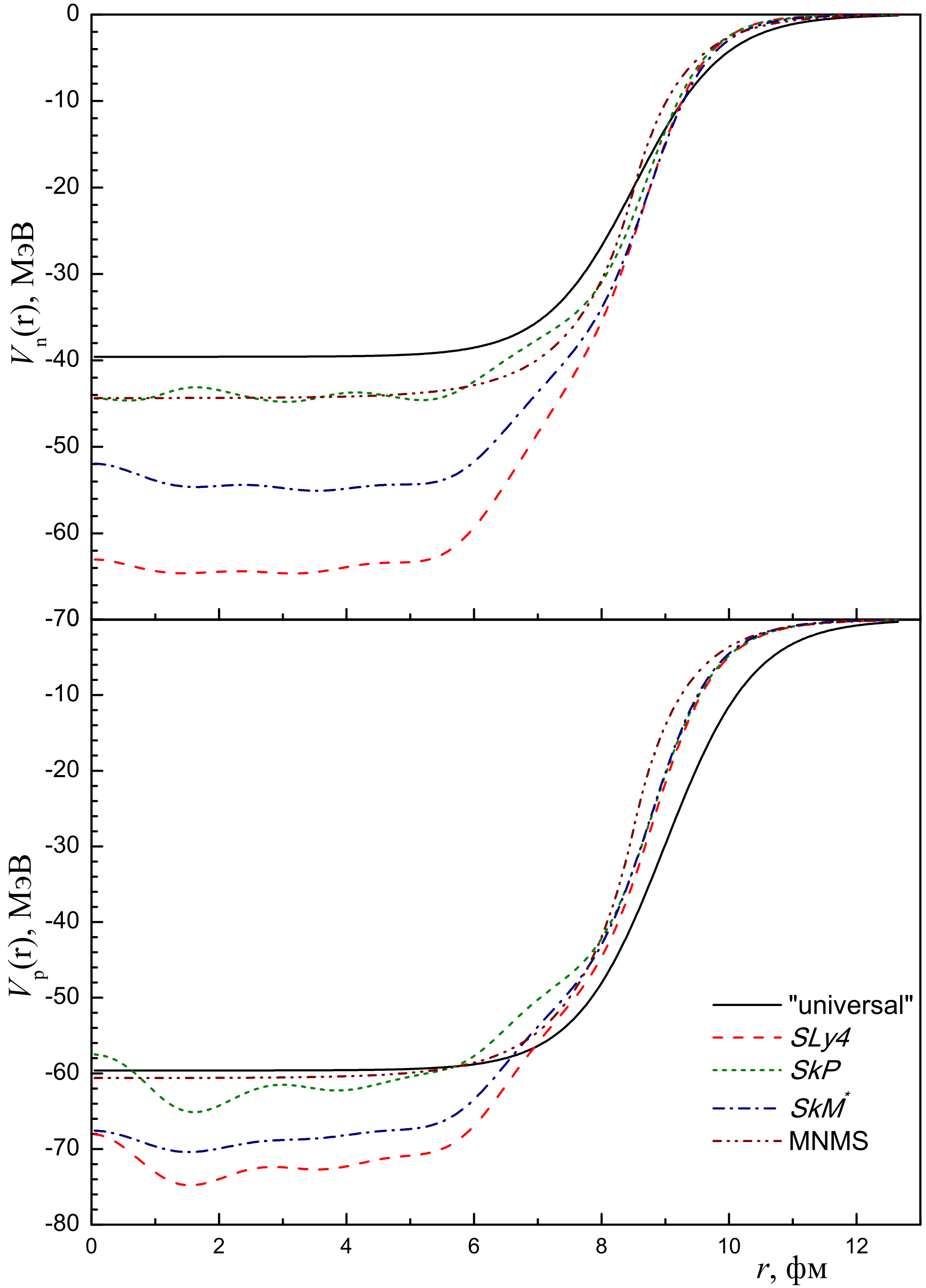
M. Bender, W. Nazarewicz, P.-G. Reinhard, Phys. Lett. **B515**, 42 (2001).

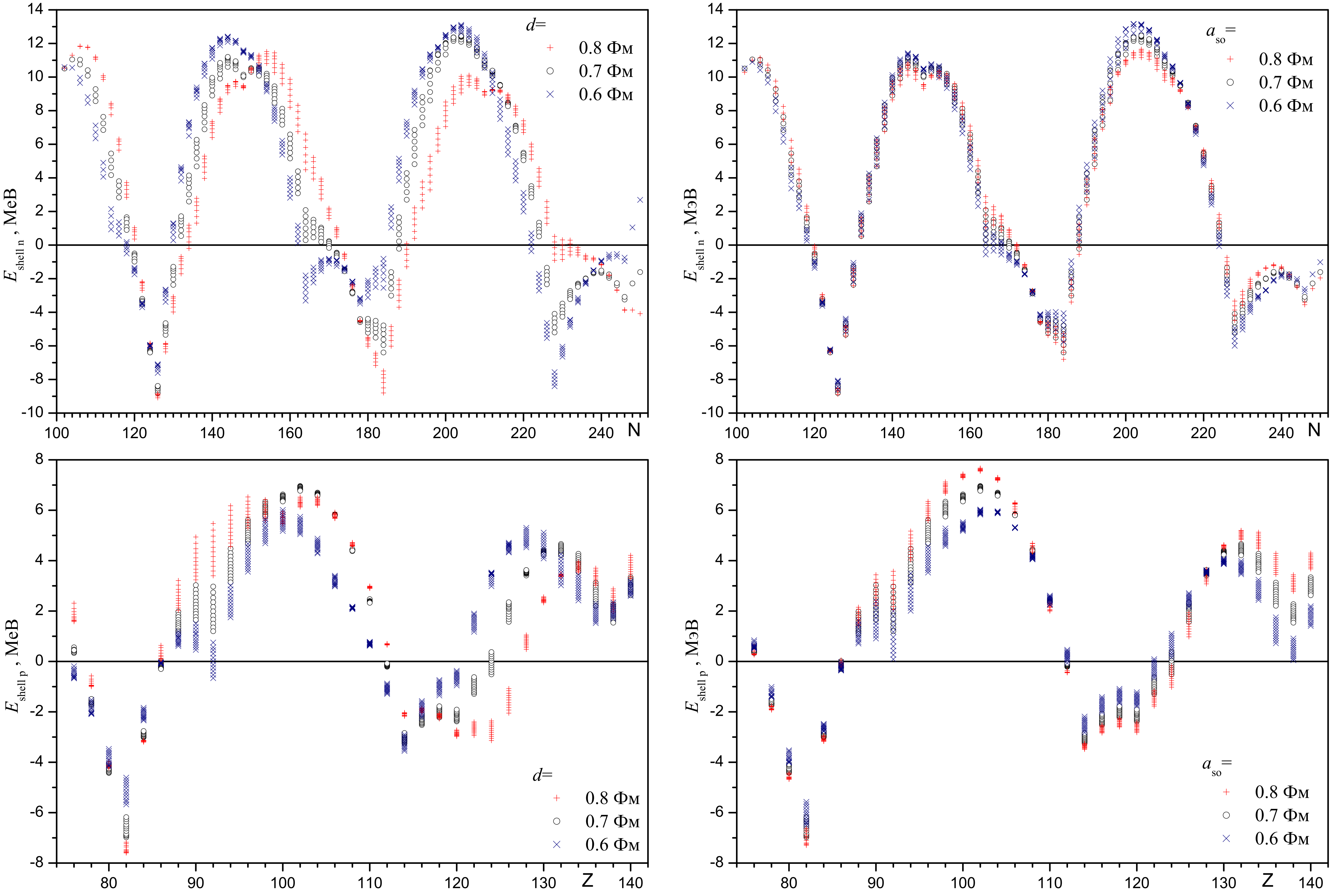
Fission barriers of ultraheavy double-magic nuclei.

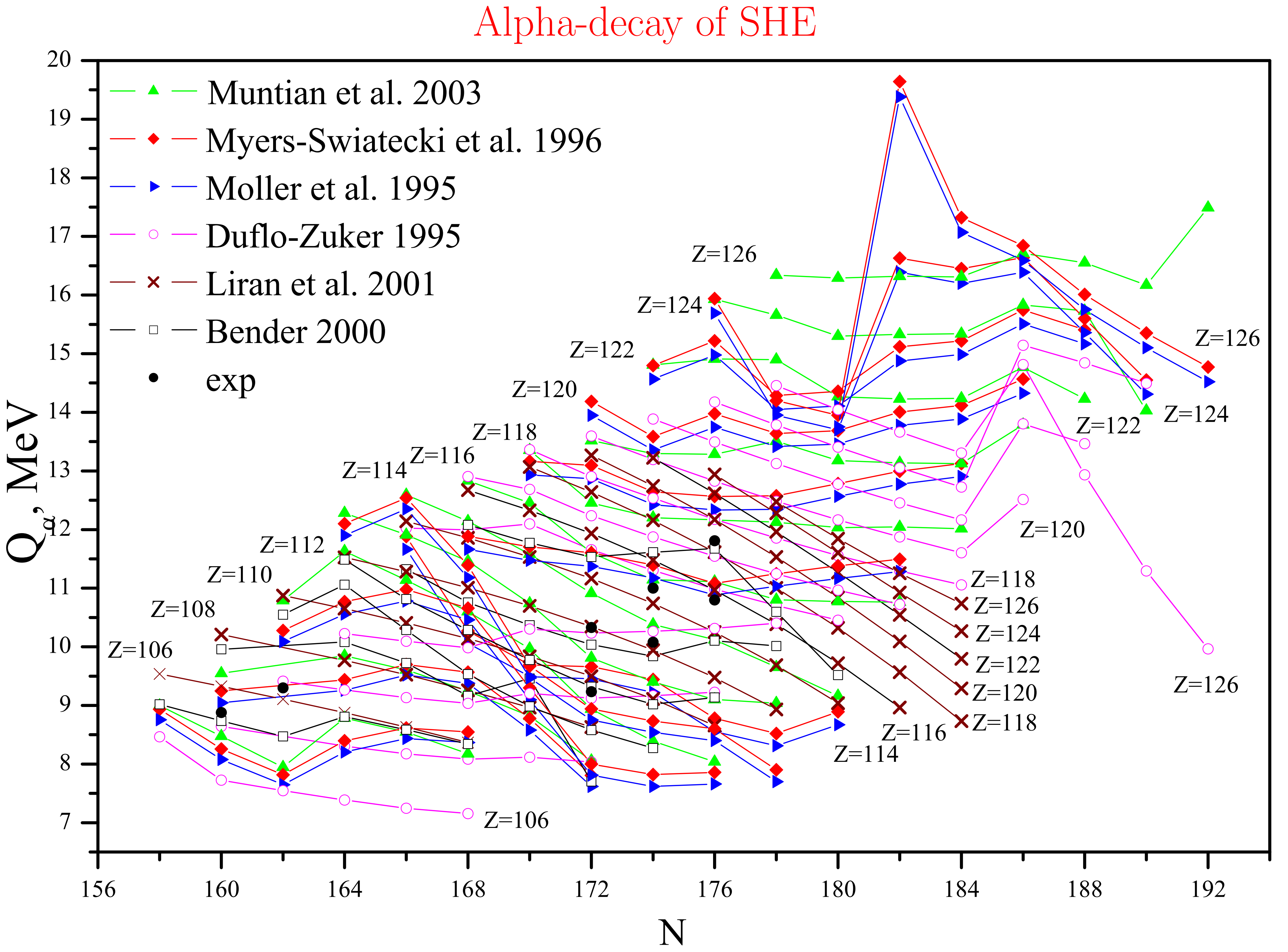


Deformation energy ⇔ Droplet Model (Yukawa+exp) + shell correction

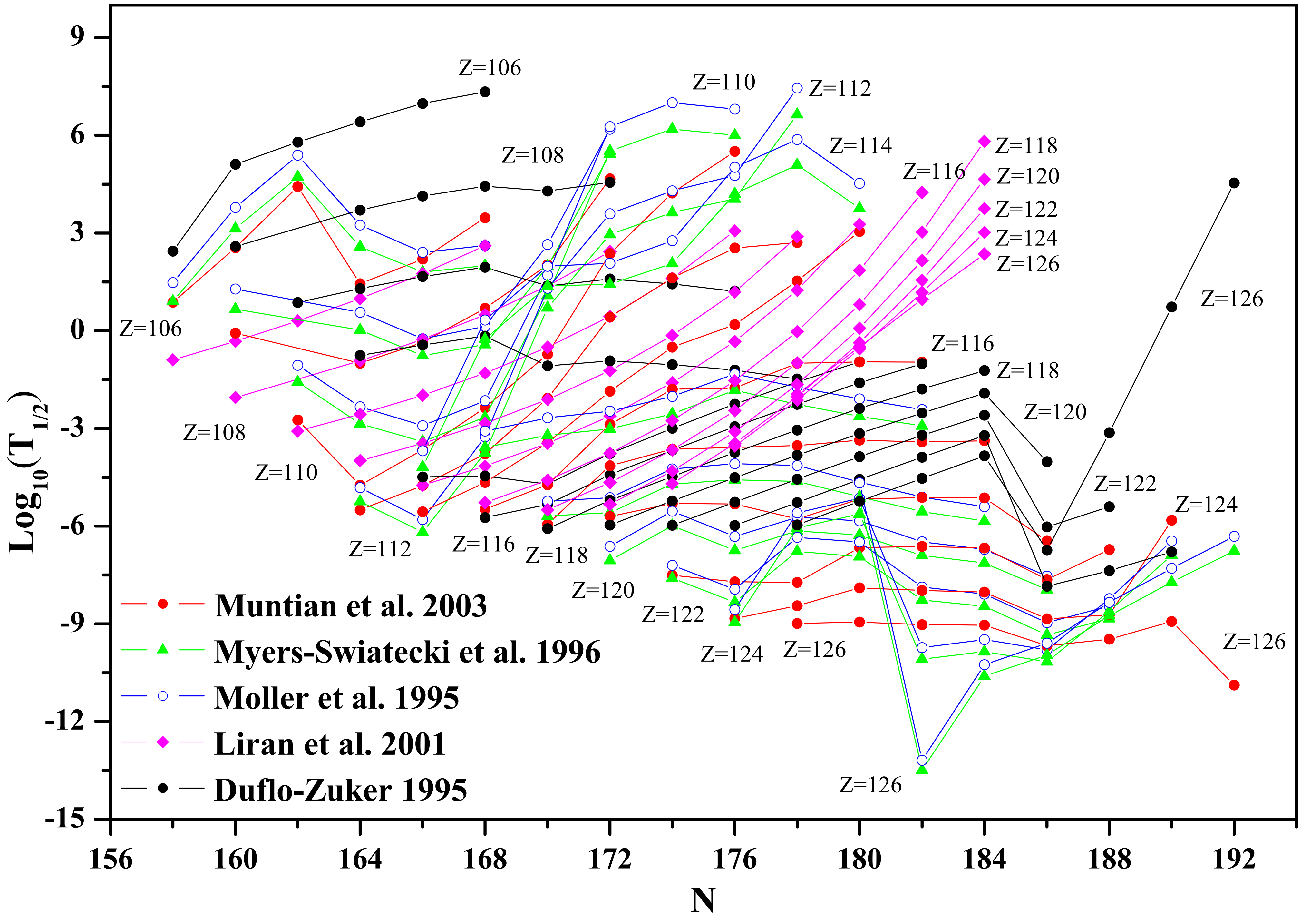
Dependence of magic number in SHE region on mean-field approximation




d=
0.8 Фм
0.7 Фм
0.6 Фм
E shell n , МеВ
N
a so =
0.8 Фм
0.7 Фм
0.6 Фм
E shell n , МэВ
N
d=
0.8 Фм
0.7 Фм
0.6 Фм
E shell p , МеВ
Z
a so =
0.8 Фм
0.7 Фм
0.6 Фм
E shell p , МэВ
Z



Alpha-decay of SHE
Muntian et al. 2003
Myers-Swiatecki et al. 1996
Moller et al. 1995
Duflo-Zuker 1995
Liran et al. 2001
Bender 2000
exp
Q_α, MeV
N
Z=106
Z=108
Z=110
Z=112
Z=114
Z=116
Z=118
Z=120
Z=122
Z=124
Z=126



Log10(T1/2)
N
Muntian et al. 2003
Myers-Swiatecki et al. 1996
Moller et al. 1995
Liran et al. 2001
Duflo-Zuker 1995
Z=106
Z=108
Z=110
Z=112
Z=114
Z=116
Z=118
Z=120
Z=122
Z=124
Z=126

Thanks for your attention!