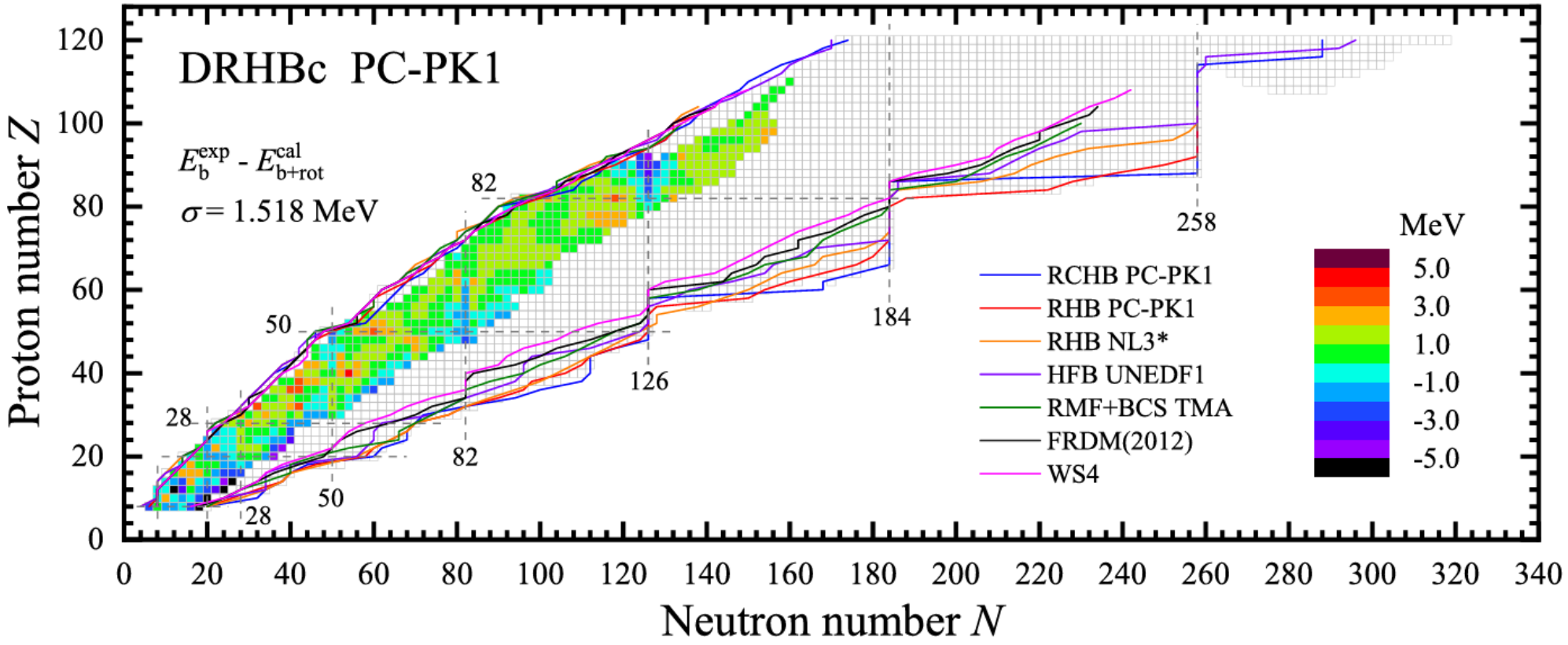
Symmetry energy and the properties of super-heavy elements

Hana Gil

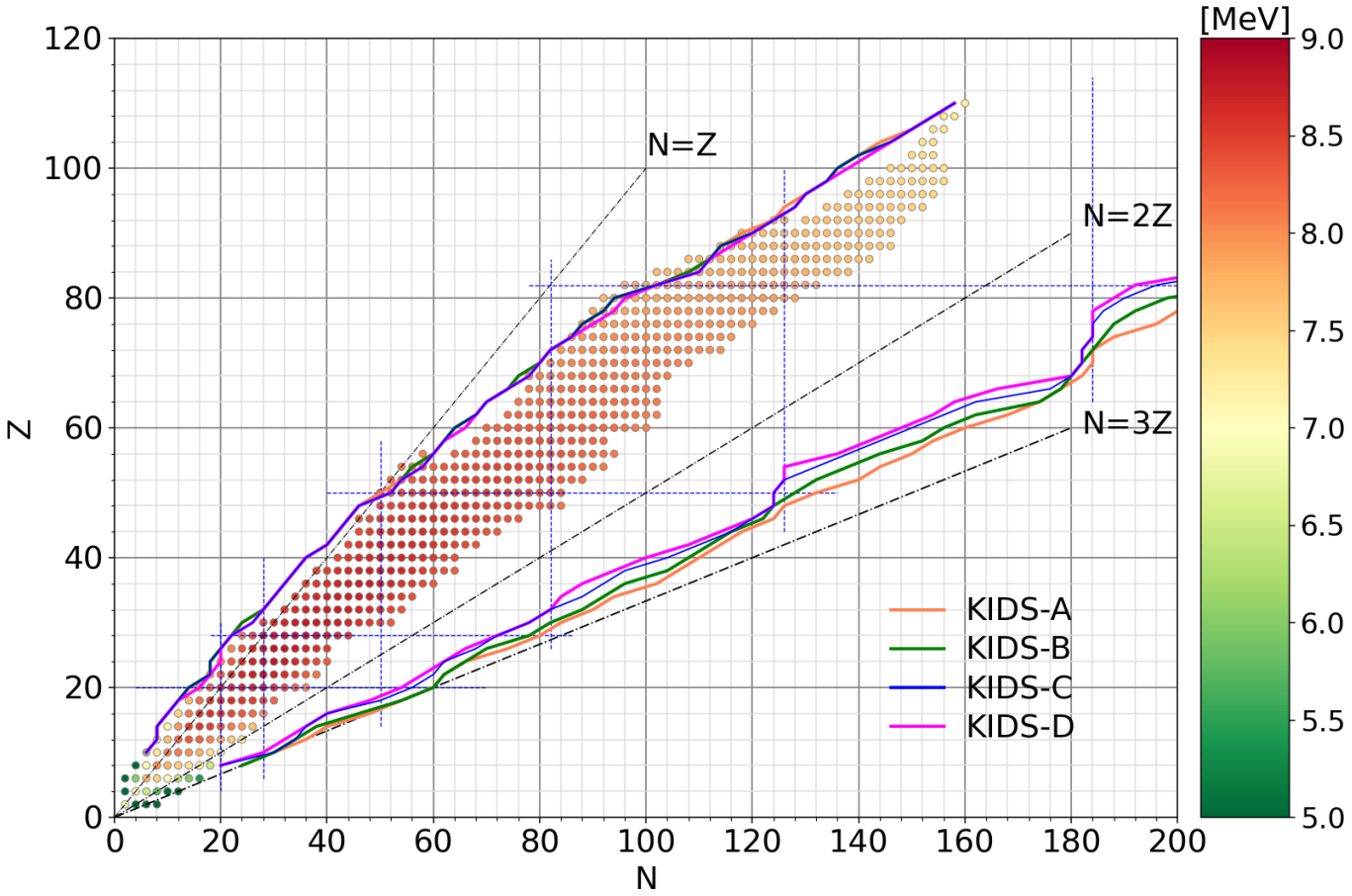
Daegu University & CENuM, Korea University

Motivation

K. Zhang et al., At. Data Nucl. Data Tables 144, 101488 (2022)



Motivation



H. Gil et al., Phys. Rev. C 108, 044316 (2023)

	K_0	J	L	K_τ
KIDS-A	230	33	66	−420
KIDS-B	240	32	58	−420
KIDS-C	250	31	58	−360
KIDS-D	260	30	47	−360
SLy4	229.9	32.0	45.9	−322.8

- HFBTHO (v2) code

Comput. Phys. Commun. 184, 1592 (2013).

Motivation

H. Gil et al., Phys. Rev. C 108, 044316 (2023)

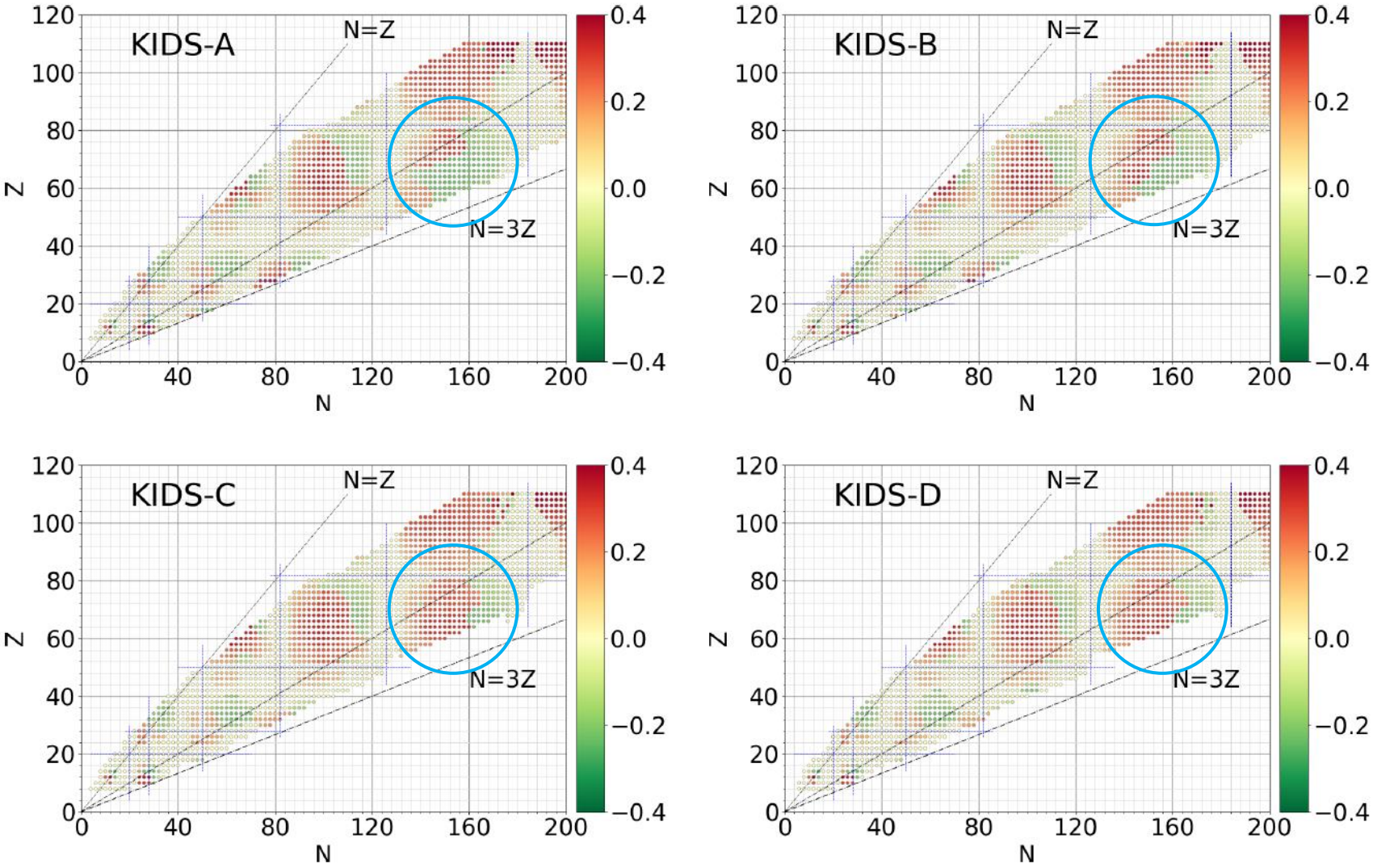
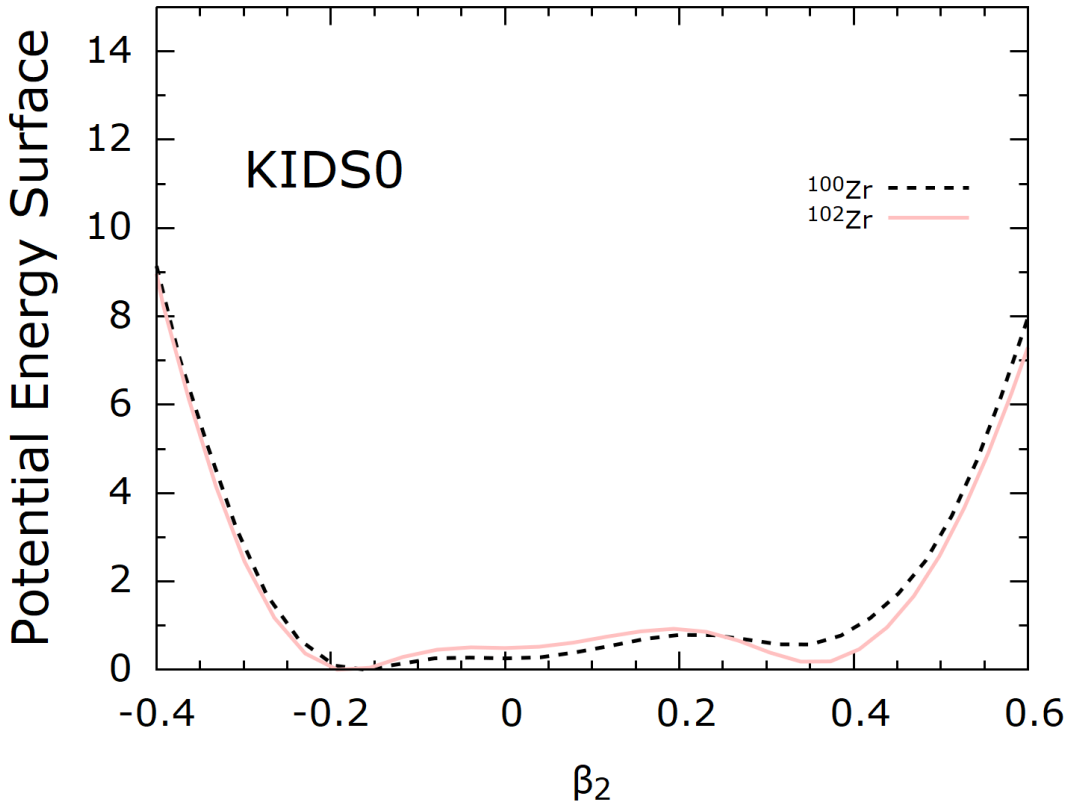
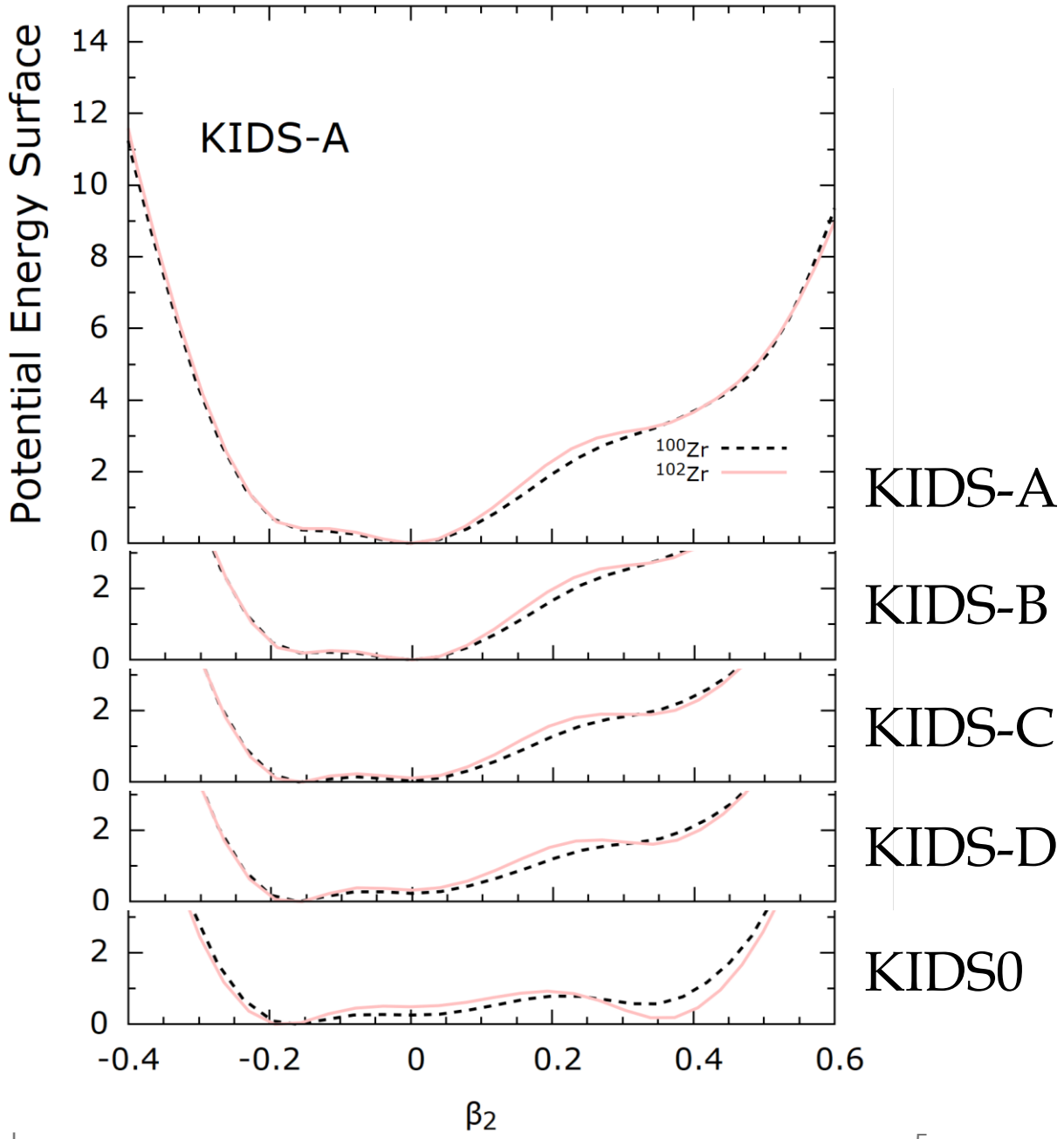


FIG. 3. Calculated quadrupole deformation $\beta_{2,p}$ for bound nuclei obtained by employing the KIDS-A–D models.

Potential surface energy





KIDS(Korea-IBS-Daegu-SSKU) Energy Density Functional

KIDS EDF : $\mathcal{E}(\rho,\delta) = \mathcal{T}(\rho,\delta) + \sum_{j=0}^{3} c_j(\delta)\rho^{1+j/3}$

$$\delta = (\rho_n - \rho_p)/\rho$$

P. Papakonstantinou et al., Phys. Rev. C 97, 014312 (2018)

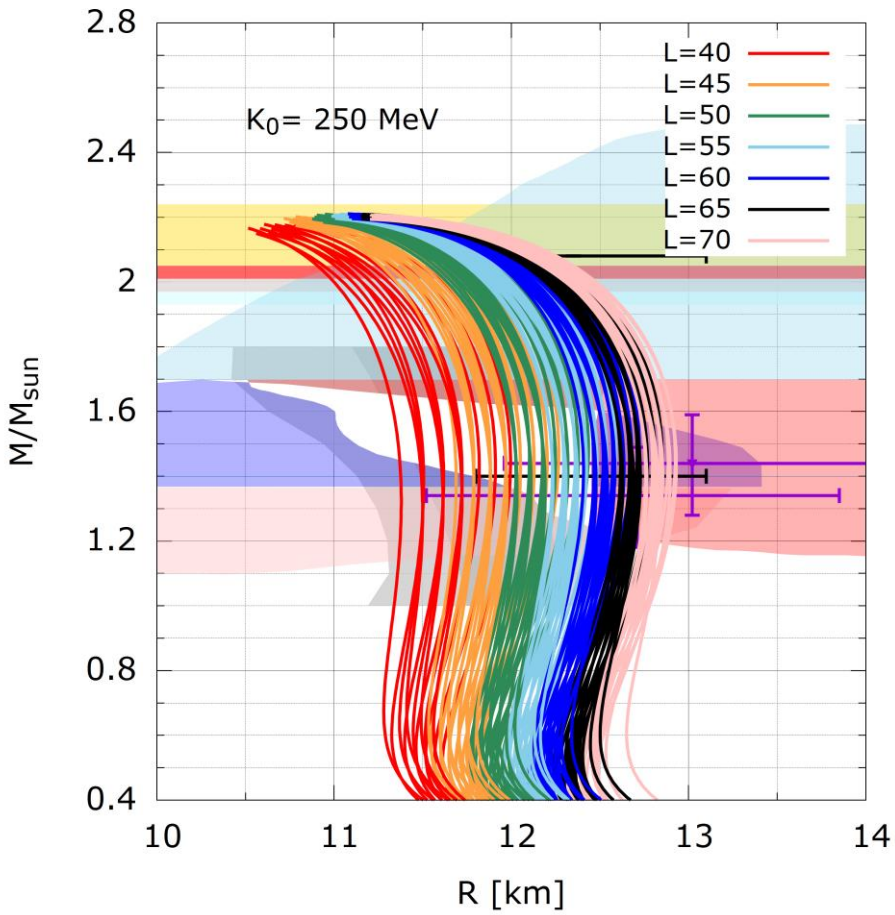
Nuclear EoS :

$$\mathcal{E}(\rho,\delta) = E(\rho) + S(\rho)\delta^2 + O(\delta^4),$$

$$E(\rho) = E_0 + \frac{1}{2}K_0 x^2 + \frac{1}{6}Q_0 x^3 + \cdots,$$

$$S(\rho) = J + Lx + \frac{1}{2}K_{\rm sym}x^2 + \frac{1}{6}Q_{\rm sym}x^3 + \cdots.$$

$$x = (\rho - \rho_0)/3\rho_0$$



KIDS(Korea-IBS-Daegu-SSKU) Energy Density Functional

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k & W_0

E/A of ^{16}O, ^{40,48}Ca, ^{90}Zr, ^{132}Sn, ^{208}Pb, ^{218}U

R_c of ^{16}O, ^{40,48}Ca, ^{90}Zr, ^{132}Sn, ^{208}Pb

Skyrme functional

$$\mathcal{H}(r) = \frac{\hbar^2}{2m_p}\tau_p + \frac{\hbar^2}{2m_n}\tau_n + C_0\rho^2 + C_3\rho^{\alpha+2} + C_{\text{eff}}\rho\tau + D_0\rho_3^2 + D_3\rho^{\alpha}\rho_3^2 + D_{\text{eff}}\rho_3\tau_3 + C_{12}\rho\nabla^2\rho + D_{12}\rho_3\nabla^2\rho_3 - \frac{W_0}{4}[3\rho\vec{\nabla}\cdot\vec{J} + \rho_3\vec{\nabla}\cdot\vec{J}_3],$$

$$C_0 = \tfrac{3}{8}t_0, \quad C_3 = \tfrac{1}{16}t_3,$$
$$C_{\text{eff}} = \tfrac{1}{16}[3t_1 + t_2(4x_2+5)],$$
$$D_0 = -\tfrac{1}{8}t_0(2x_0+1), \quad D_3 = -\tfrac{1}{48}t_3(2x_3+1),$$
$$D_{\text{eff}} = \tfrac{1}{16}[-t_1(2x_1+1) + t_2(2x_2+1)],$$
$$C_{12} = \tfrac{1}{64}[-9t_1 + t_2(5+4x_2)],$$
$$D_{12} = \tfrac{1}{32}[3t_1(\tfrac{1}{2}+x_1) + t_2(\tfrac{1}{2}+x_2)],$$

KIDS(Korea-IBS-Daegu-SSKU) Energy Density Functional

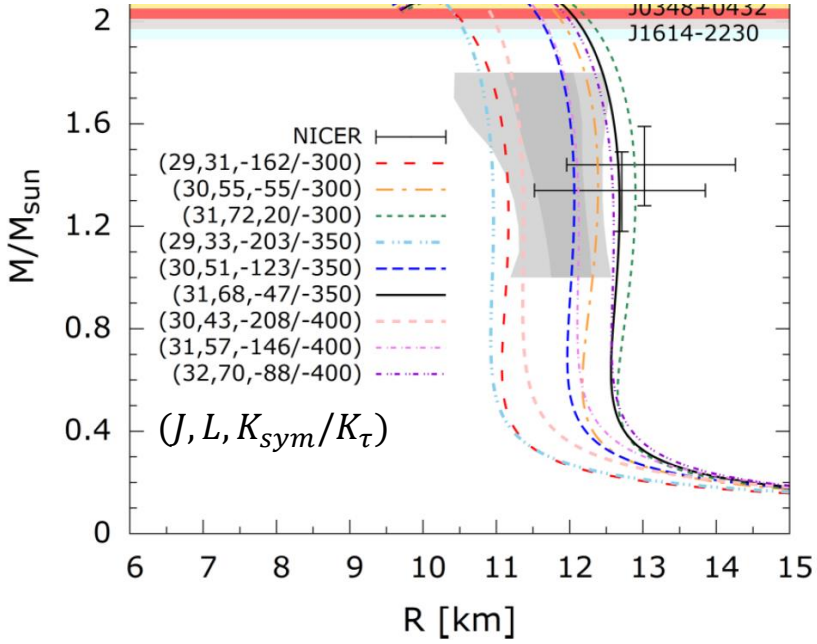
Keep the symmetric matter part :

$\rho_0 = 0.16\ fm^{-3}$

$E_0 = -16$ MeV

$K_0 = 240$ MeV

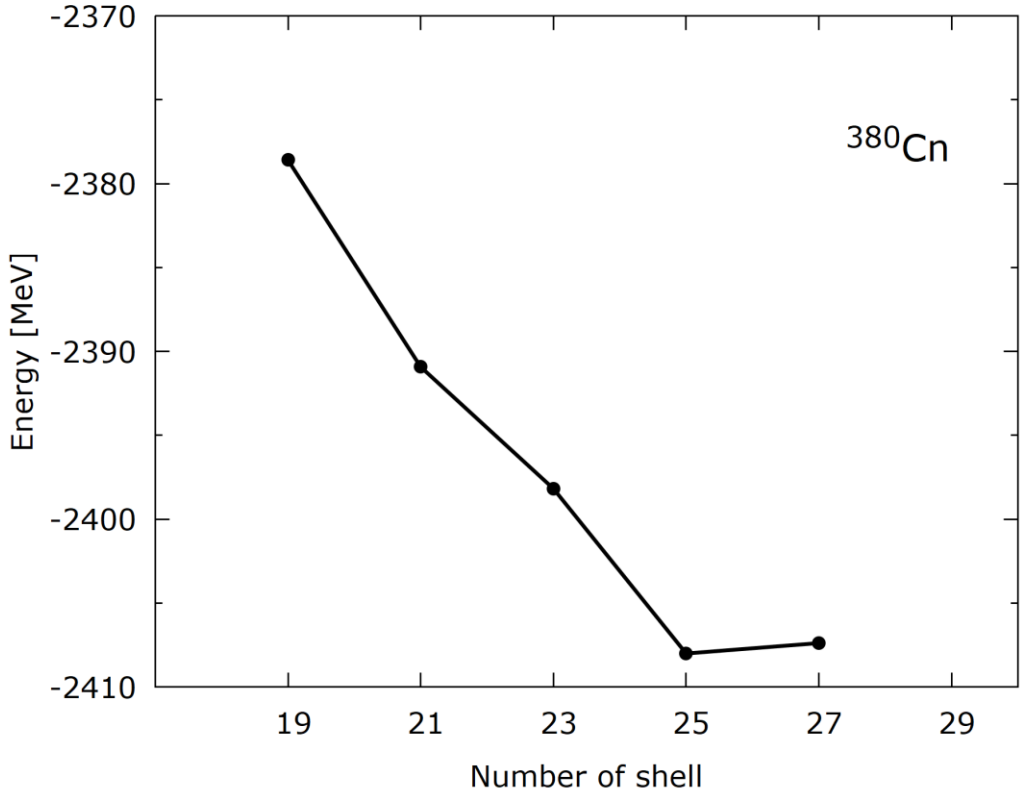
H. Gil et al., Phys. Rev. C 103, 034330 (2021)



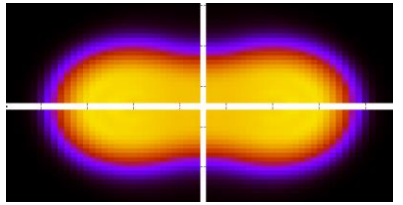
K_τ (MeV)	−300			−350			−400		
(J, L) (MeV)	(29, 31)	(30, 55)	(31, 72)	(29, 33)	(30, 51)	(31, 68)	(30, 43)	(31, 57)	(32, 70)
K_{sym} (MeV)	−162	−55	20	−203	−123	−47	−208	−146	−88
Mass ($M_\odot$)	1.40	1.41	1.40	1.40	1.39	1.40	1.40	1.39	1.41
Λ	234.7	455.0	604.9	209.2	402.3	535.3	256.9	401.7	485.8
R (km)	11.2	12.4	12.9	11.0	12.1	12.7	11.4	12.1	12.6
ρ_{cen} (fm^{-3})	0.58	0.43	0.39	0.60	0.46	0.41	0.54	0.46	0.43
	EoS #1			**EoS #5**			**EoS #9**		

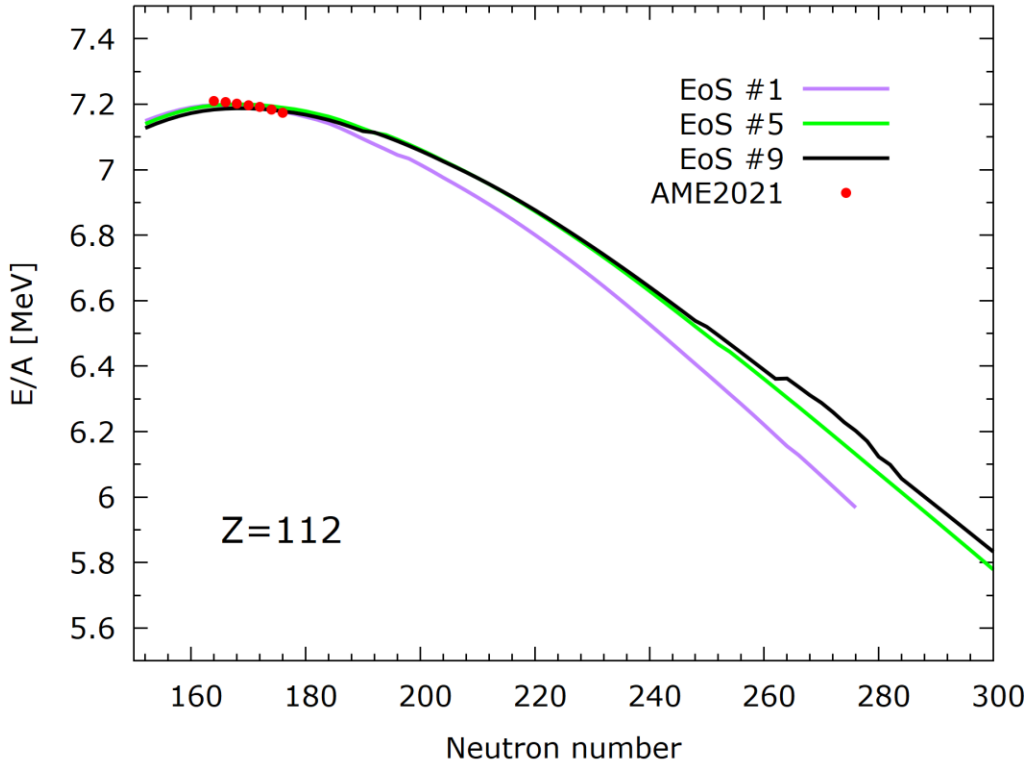
HFBTHO open code

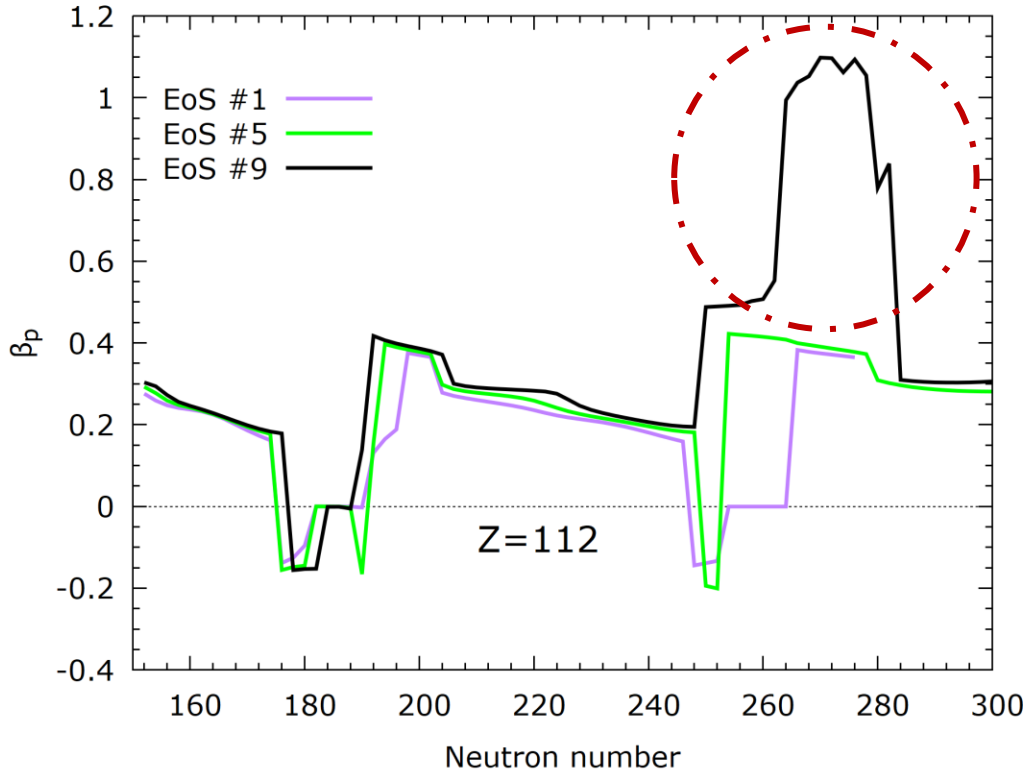
- HFBTHO (v3) code, Comput. Phys. Commun. 220, 363 (2017).
- Convergence test within KIDS framework



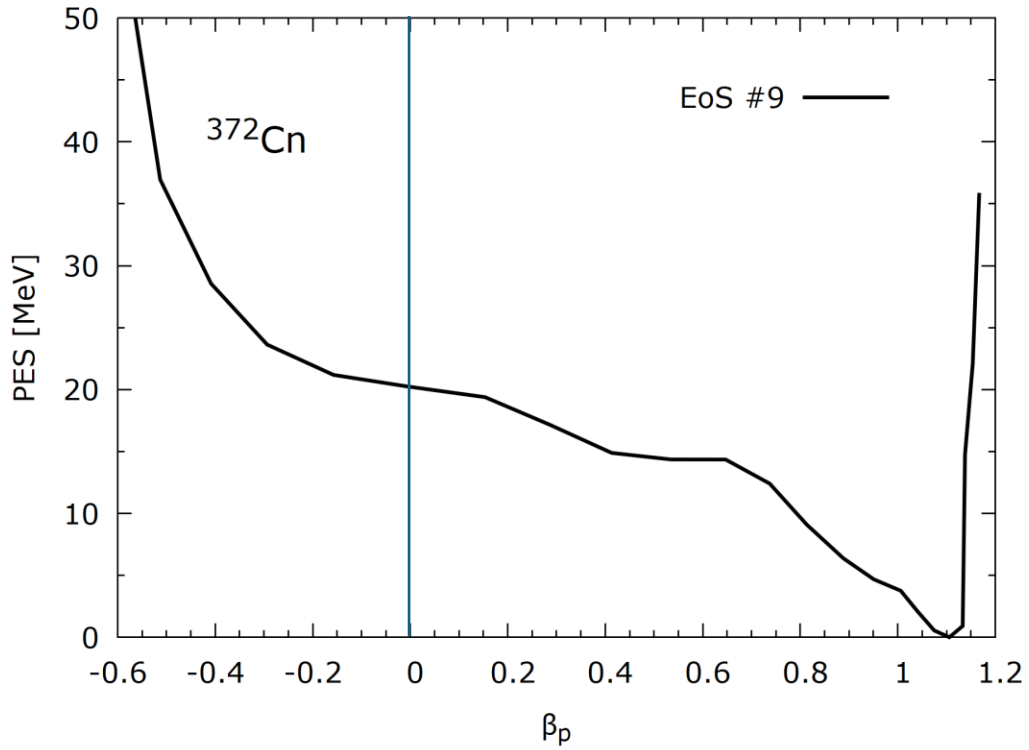
Results : beyond superdeformation in Z=112



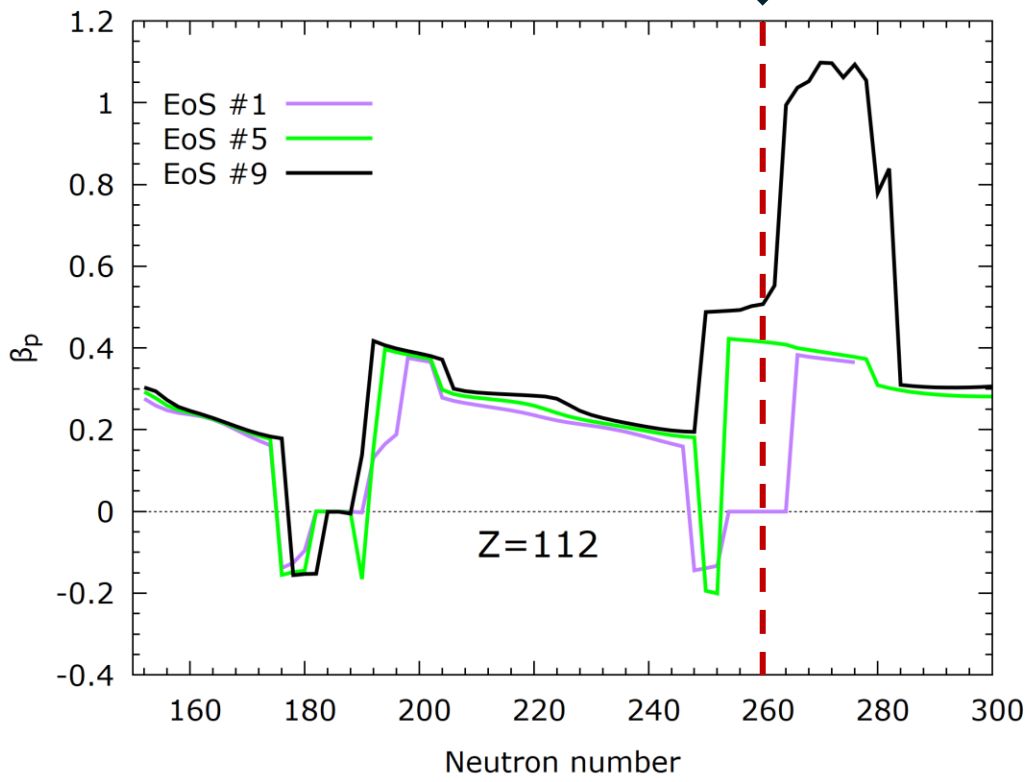




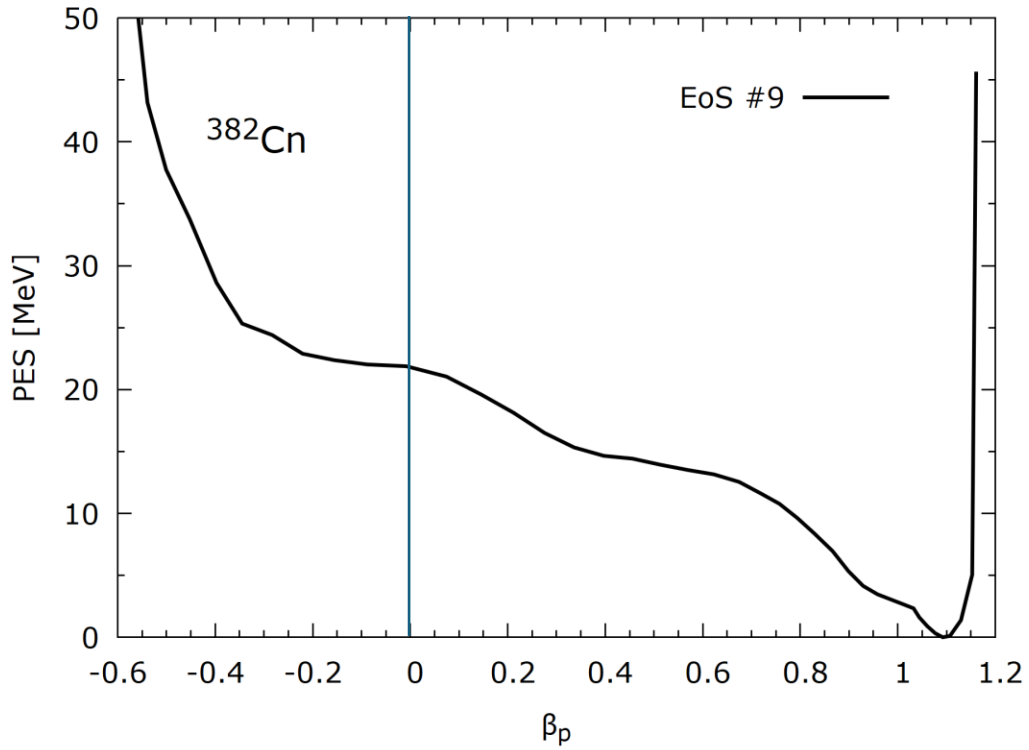
Results : beyond superdeformation in Z=112



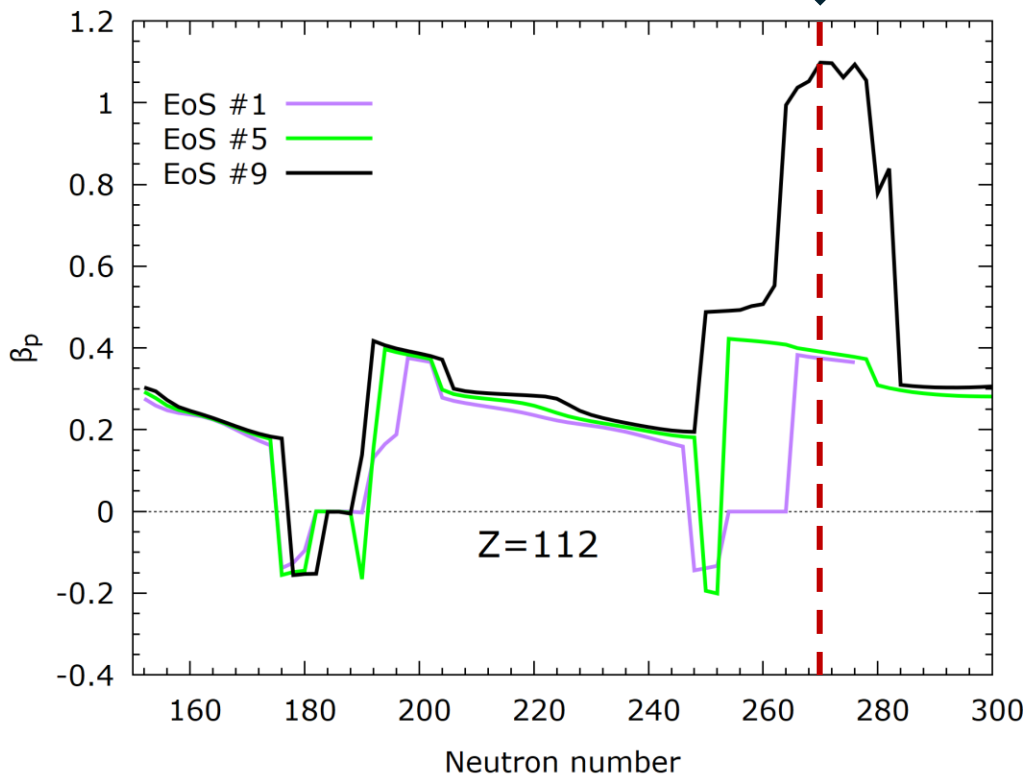
$N = 260$



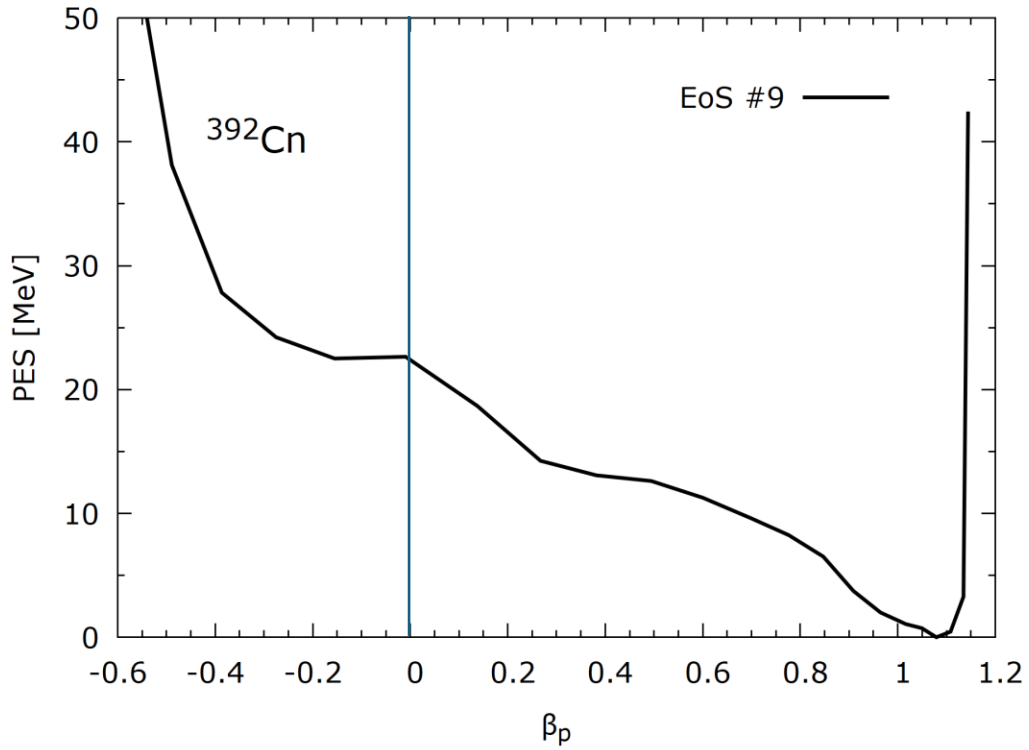
Results : beyond superdeformation in Z=112



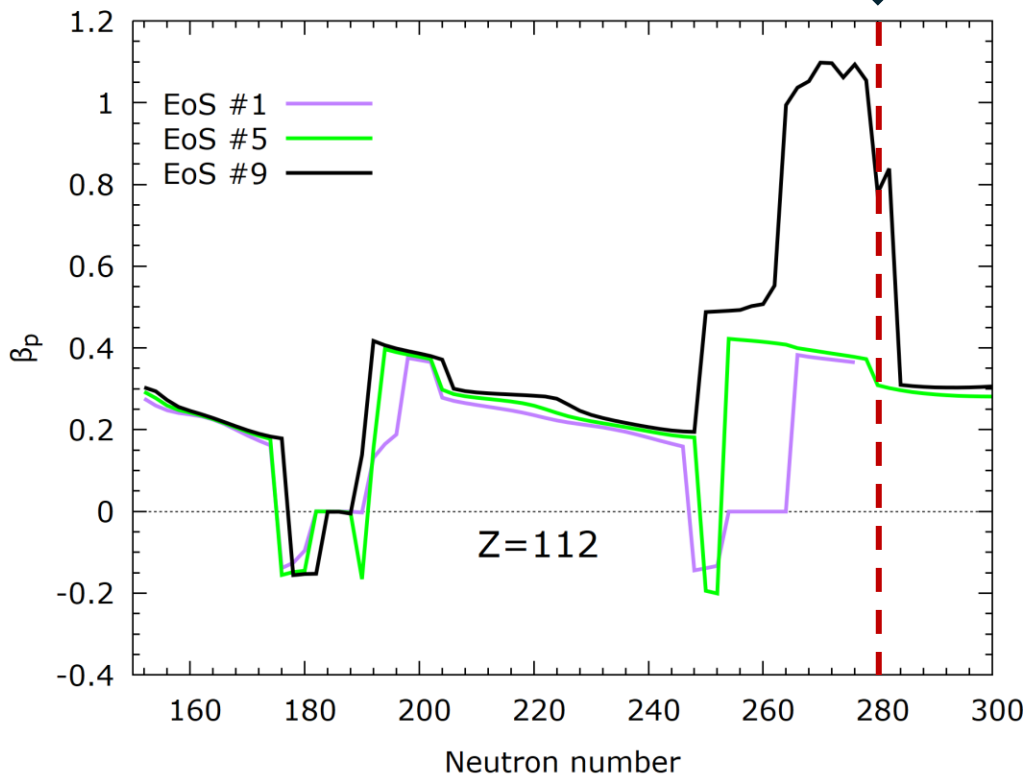
$N = 270$



Results : beyond superdeformation in Z=112

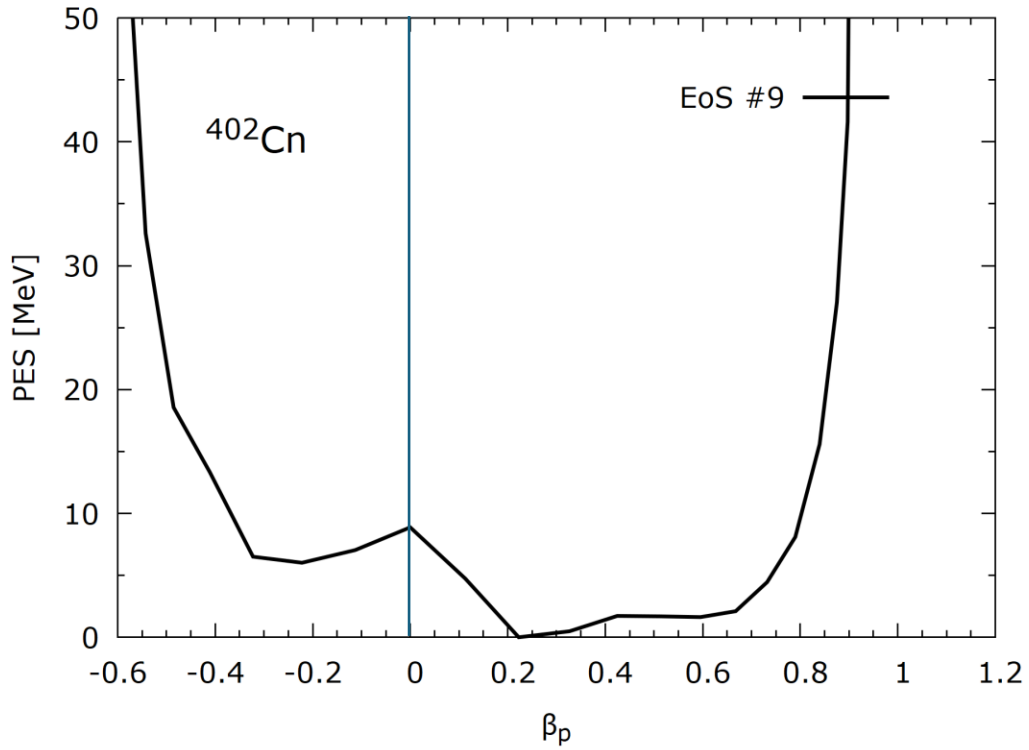


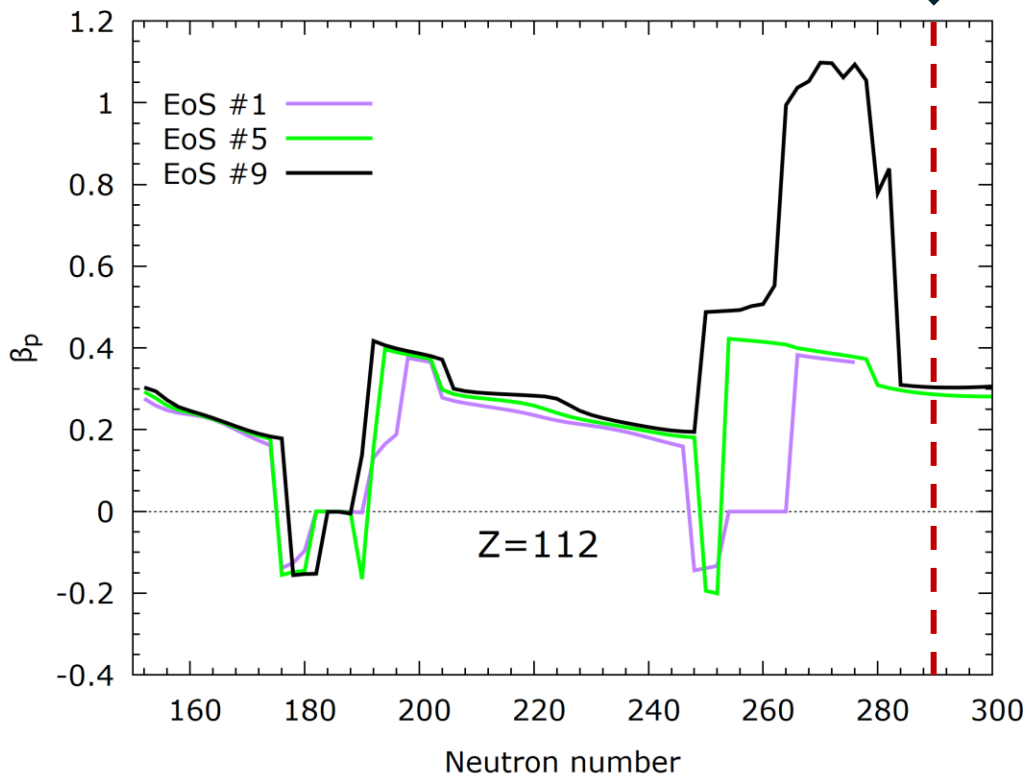
$N = 280$



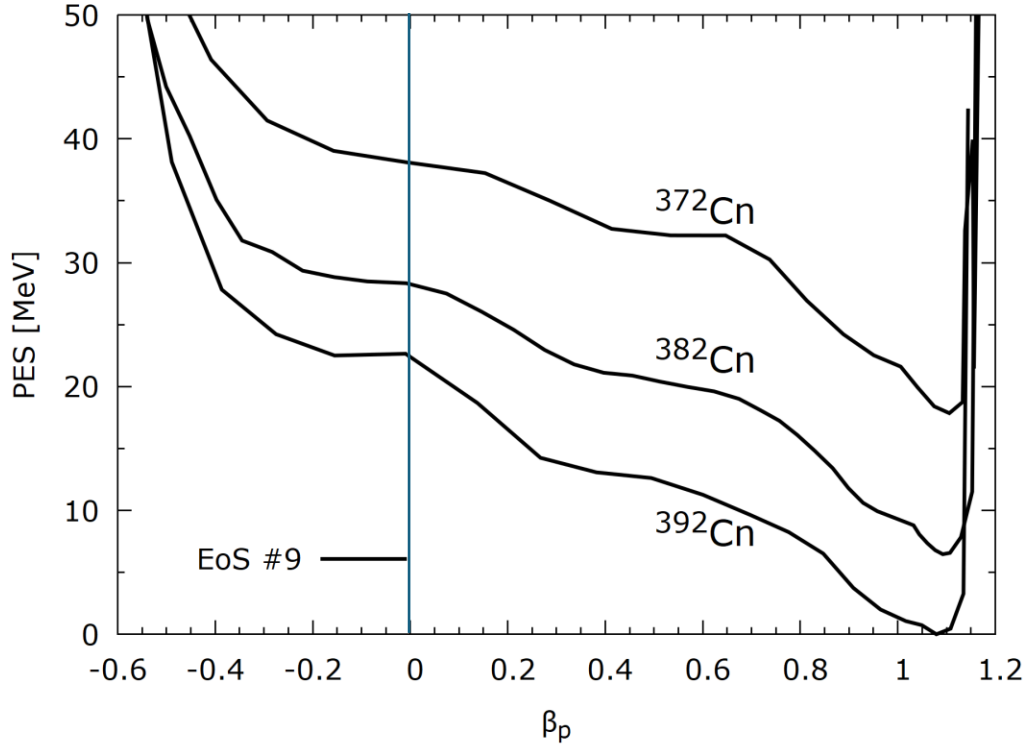
Results : beyond superdeformation in Z=112

$N = 290$

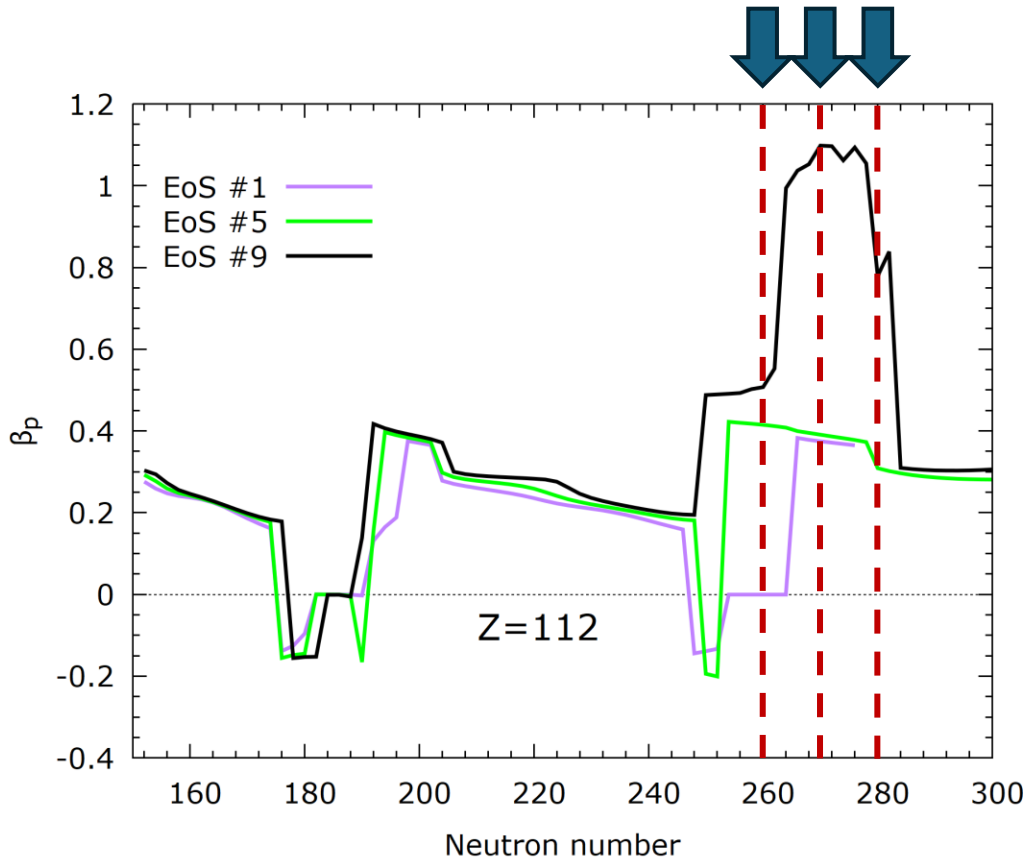




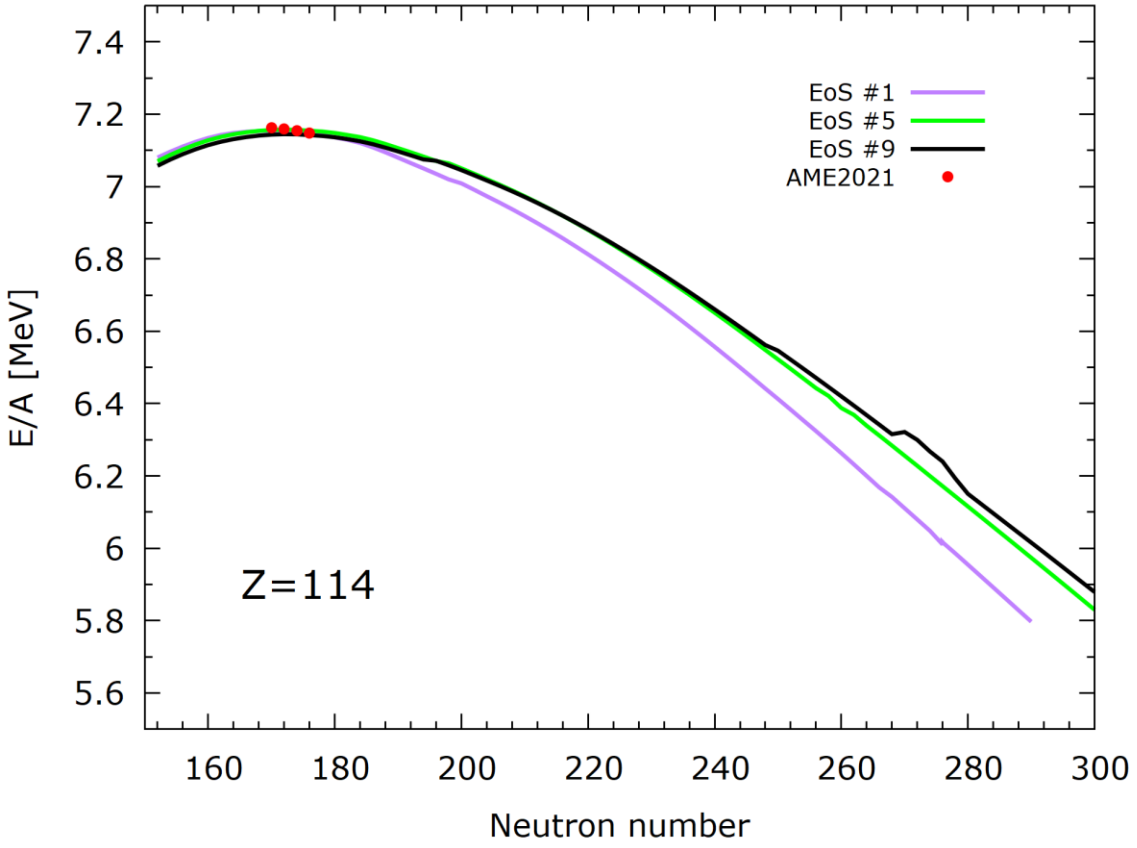
Results : beyond superdeformation in Z=112

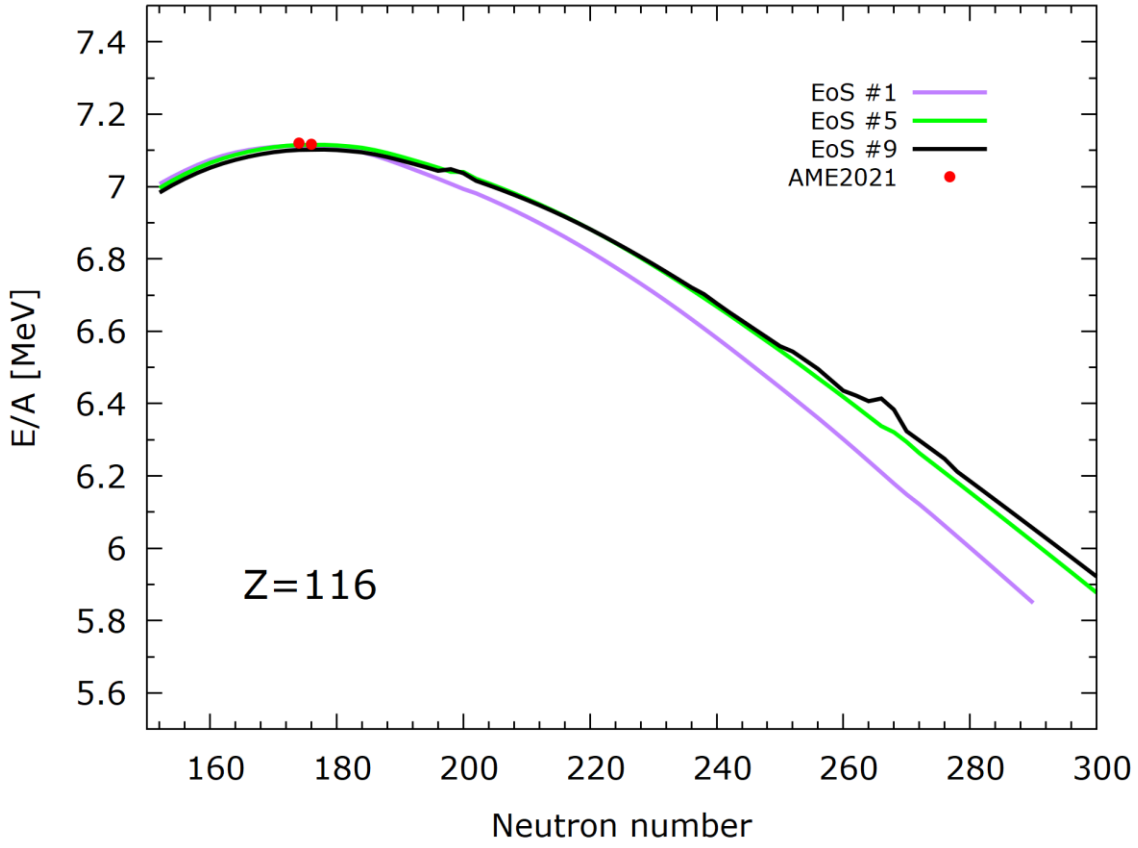


^{372,382,392}Cn

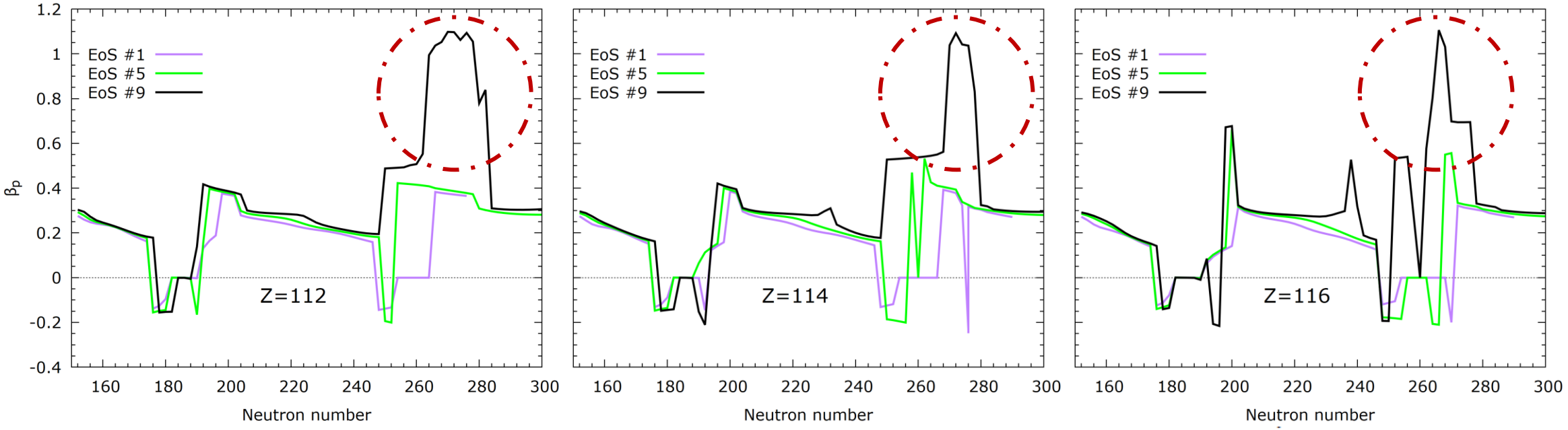


Results : Energy per particle in Z=114 and 116





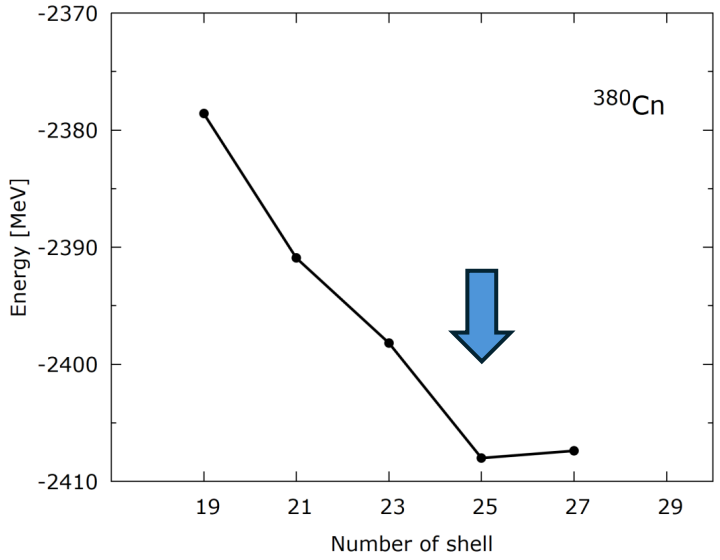
Results : Shape evolution and drip-line in Z= 112, 114 and 116



K_τ (MeV)	−300			−350			−400		
(J, L) (MeV)	(29, 31)	(30, 55)	(31, 72)	(29, 33)	(30, 51)	(31, 68)	(30, 43)	(31, 57)	(32, 70)
K_{sym} (MeV)	−162	−55	20	−203	−123	−47	−208	−146	−88
Cn ($Z = 112$)	268			290	302	292	296	276	
Fl ($Z = 114$)	296			296	306		302	306	
Lv ($Z = 116$)	280			300	310	302	306	308	

Next Step

- HFB calculation within Number of Shell = 25



- 9 EoSs ➔ 3 EoSs

EoS	#1	#2	#3	#4	#5	#6	#7	#8	#9
K_τ	-300			-350			-400		
(J, L)	(29,31)	(30,55)	(31,72)	(29,33)	(30,51)	(31,68)	(30,43)	(31,57)	(32,70)
K_{sym}	-162	-55	20	-203	-123	-47	-208	-146	-88

EoS	#1	#5	#9
K_τ	-300	-350	-400
(J, L)	(29,31)	(30,51)	(32,70)
K_{sym}	-162	-123	-88

Summary

- Super-heavy nuclei, different symmetry energies
- Comparing with AME2021 data, dependence is weak
- For more extreme neutron rich nuclei dependence becomes more apparent
- With stiff symmetry energy, super and large deformation appears
- Origin of dependence on the symmetry energy is in progress.

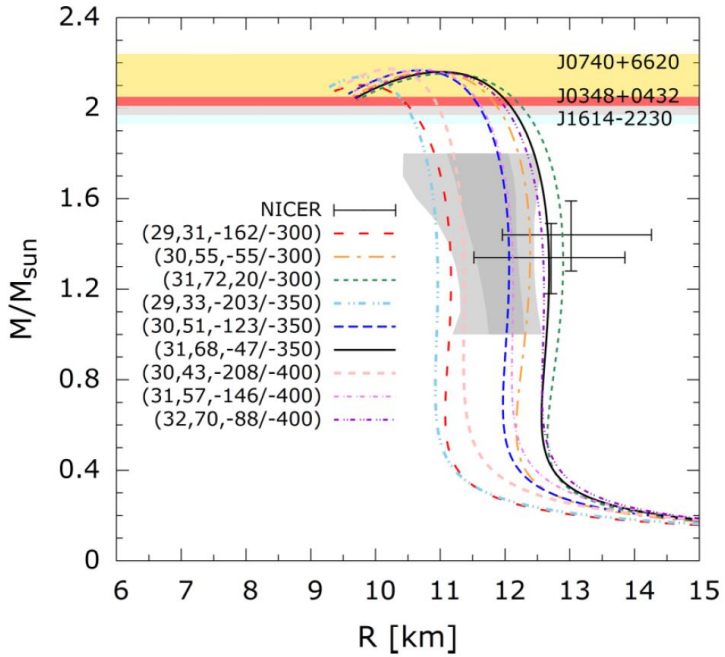
Back-up

TABLE IV. The predicted saturation properties for nuclear matter by PC-PK1 in comparison with those by DD-PC1, PC-F1, PC-LA, NL3*, and PK1.

	PC-PK1	DD-PC1	PC-F1	PC-LA	NL3*	PK1
ρ_0 (fm^{-3})	0.154	0.152	0.151	0.148	0.150	0.148
E/A (MeV)	−16.12	−16.06	−16.17	−16.13	−16.31	−16.27
M_D^*/M	0.59	0.58	0.61	0.58	0.59	0.60
M_L^*/M	0.65	0.64	0.67	0.64	0.65	0.66
K_0 (MeV)	238	230	255	264	258	283
E_{sym} (MeV)	35.6	33	37.8	37.2	38.7	37.6
L (MeV)	113	70	117	108	123	116
K_{asy} (MeV)	−583	−528	−627	−709	−630	−641

Back-up

H. Gil et al., Phys. Rev. C 103, 034330 (2021)



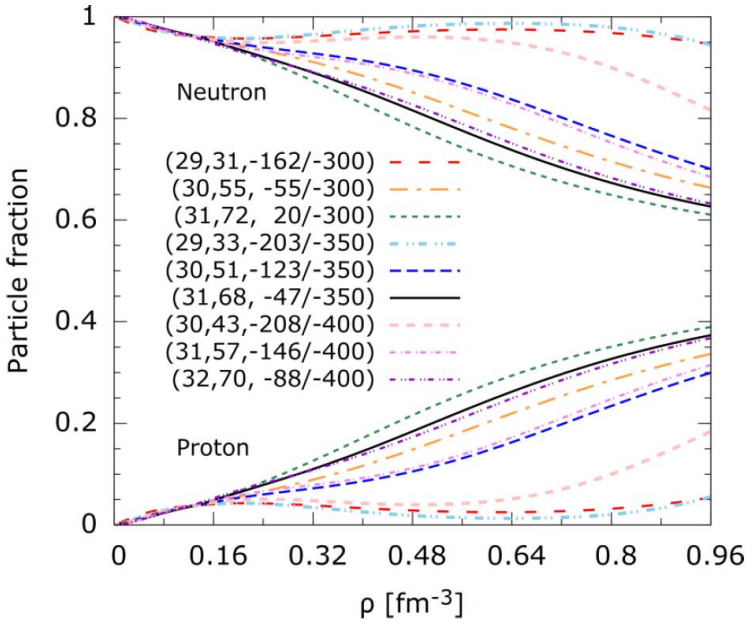


TABLE II. Tidal deformability Λ, radius R, and density at the center $\rho_{\rm cen}$ of the $1.4M_\odot$ neutron star with the $(J, L, K_{\rm sym}$ or $K_\tau)_{\rm CS+NS}$ values.

K_τ (MeV)	−300			−350			−400		
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Λ	234.7	455.0	604.9	209.2	402.3	535.3	256.9	401.7	485.8
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$\rho_{\rm cen}$ (fm^{-3})	0.58	0.43	0.39	0.60	0.46	0.41	0.54	0.46	0.43