Odd-even mass staggering, shell effects, and pairing correlation in neutron-rich nuclei

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Motivation

- Pairing correlation plays an important role in many nuclear phenomena and is the dominant many-body correlation beyond the nuclear mean field. Yet, many features are not well understood.
- An especially interesting problem concerns the weakly bound neutron systems close to the neutron drip line for instance ^{11}Li and the theoretical challenges on the halo structure
- How the density dependence of the zero range pairing interaction affects the pairing correlation and two neutron clustering

My Subject

Pairing correlation in nuclei on the very edge of particle stability
What have we done?

- Study various odd-even mass staggering formulae
- Comprehensive study of Hartree-Fock-Bogoliubov and seniority model
- Systematic calculations for all semi-magic even-even isotopes in coordinate-space
- Systematic calculations for all even-even isotopes harmonic oscillator basis
- Global assessment of the effect of the density dependence of the zero-range pairing interaction
- Two-neutron clustering for different pairing interactions
- The effect of pairing interaction on weakly bound $s1/2$

Papers

Odd-even mass staggering, shell effects, and pairing correlation in neutron-rich nuclei

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Abstract

The empirical pairing gaps derived from four different odd-even mass staggering formulae are compared. By performing single-j shell and multi-shell seniority model calculations as well as by using the standard HFB approach with Skryme force we show that the three-point formula $\Delta_C^{(3)}(N) = \frac{1}{2}[B(N,Z) + B(N-2,Z) - 2B(N-1,Z)]$ provides a good measure of the neutron pairing gap in even-N nuclei. It removes to the largest extent the contribution from the nuclear mean field as well as contributions from shell structure details. It is also free from the Wigner effect for nuclei around $N = Z$. We also show that the strength of $\Delta_C^{(3)}(N)$ can serve as a good indication of the two-particle correlation in the nucleus of concern and that the weakening of $\Delta_C^{(3)}(N)$ in some neutron-rich nuclei indicates that the di-neutron correlation itself is weak in these nuclei.

Density dependence of the pairing interaction and pairing correlation in unstable nuclei

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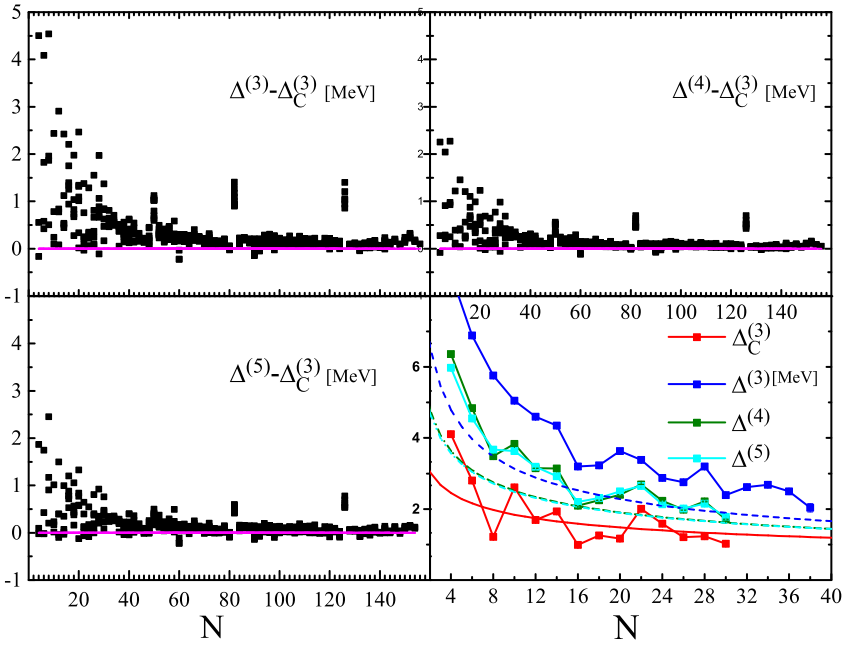
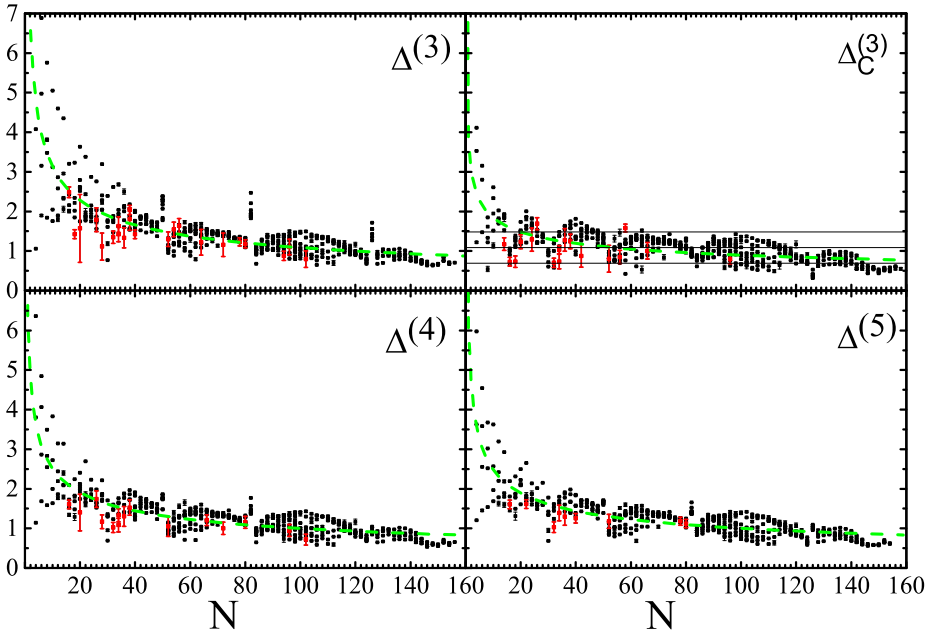
This work aims at the global assessment of the effect of the density dependence of the zero-range pairing interaction. Systematic Skryme-Hartree-Fock-Bogoliubov calculations with the volume, surface and mixed pairing forces are done to study the pairing gaps in even-even nuclei over the whole nuclear chart. For comparison calculations are also done in coordinate representation for unstable semi-magic even-even nuclei. The calculated pairing gaps are compared with empirical values from 4 different OES formulae. Calculations with the three pairing interactions are comparable for most nuclei close to β-stability line. However, the surface interaction calculation predict pairing gap that is significantly stronger than those given by the mixed and volume pairing, which can even overcome the shell effect. On the other hand, calculations with volume and mixed pairing forces show noticeable reduction of pairing gap in nuclei far from the stability.

3-point formula - Bohr and Mottelson

$$\Delta_C^{(3)} = \frac{1}{2}\left[E_b(N) + E_b(N-2) - 2E_b(N-1)\right] = \Delta^{(3)}(N-1)$$
$$\Delta^{(3)} = -\frac{1}{2}\left[E_b(N-1) + E_b(N+1) - 2E_b(N)\right]$$





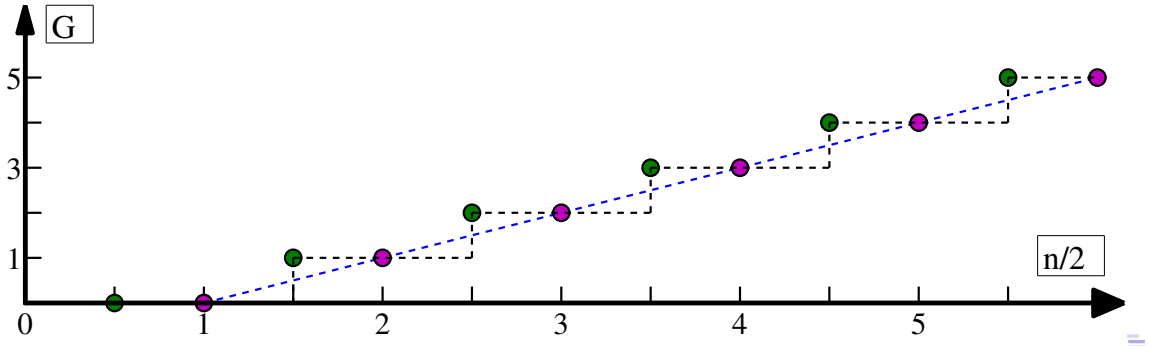
The origin of the OES and different formulae

The energy of the state with seniority v:

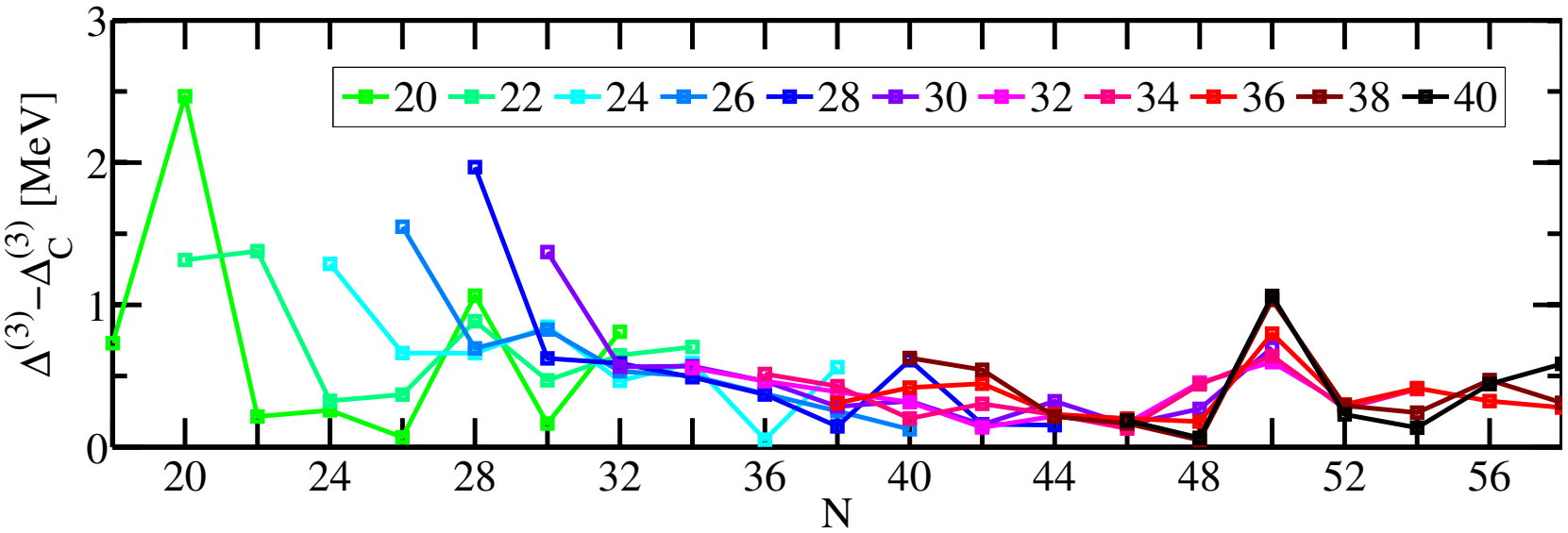
$$E(n,v) = -G\frac{n-v}{4}(2j+3-n-v) \tag{1}$$
$$= \frac{n(n-1)}{4}G - \frac{v(v-1)}{4}G - \frac{1}{2}(n-v)(j+1)G$$

If one assumes $v=0$ for the ground state of even-even system and $v=1$ for that of the odd system, the expression above can be simplified as

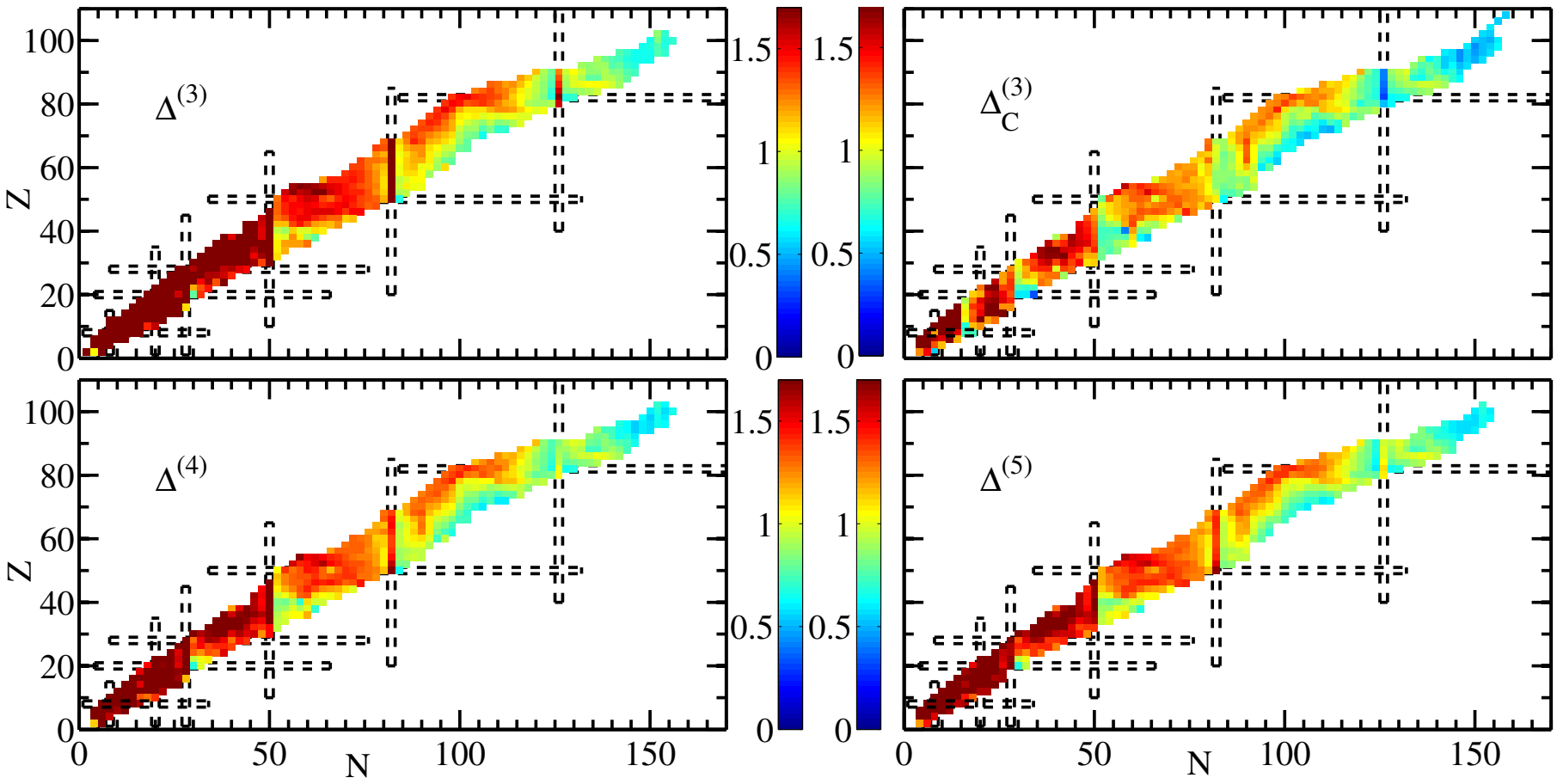
$$E(n) = \frac{n(n-1)}{4}G - \left[\frac{n}{2}\right](j+1)G, \tag{2}$$
$$= \left[\frac{n}{2}\right]\left(\left[\frac{n}{2}\right]-1\right)G + \delta_{v,1}\left[\frac{n}{2}\right]G + \left[\frac{n}{2}\right]E_2$$



$$\Delta_C^{(3)} = -\frac{1}{2}E_2 = \frac{1}{2}(j+\frac{1}{2})G$$
$$\Delta^{(3)} = -\frac{1}{2}E_2 + \frac{1}{2}G$$



Experimental values of Δ_n for even-even



METHODOLOGIES

Skyrme functional SLy4 in the particle-hole channel. For pairing channel two-body density-dependent contact interaction between particles. v_0,ρ_c and are constant.

$$V_{pair}(\mathbf{r},\mathbf{r}') = V_0\left(1-\eta\frac{\rho(\mathbf{r})}{\rho_c}\right)\delta(\mathbf{r}-\mathbf{r}') \tag{3}$$

Δ_{LCS}

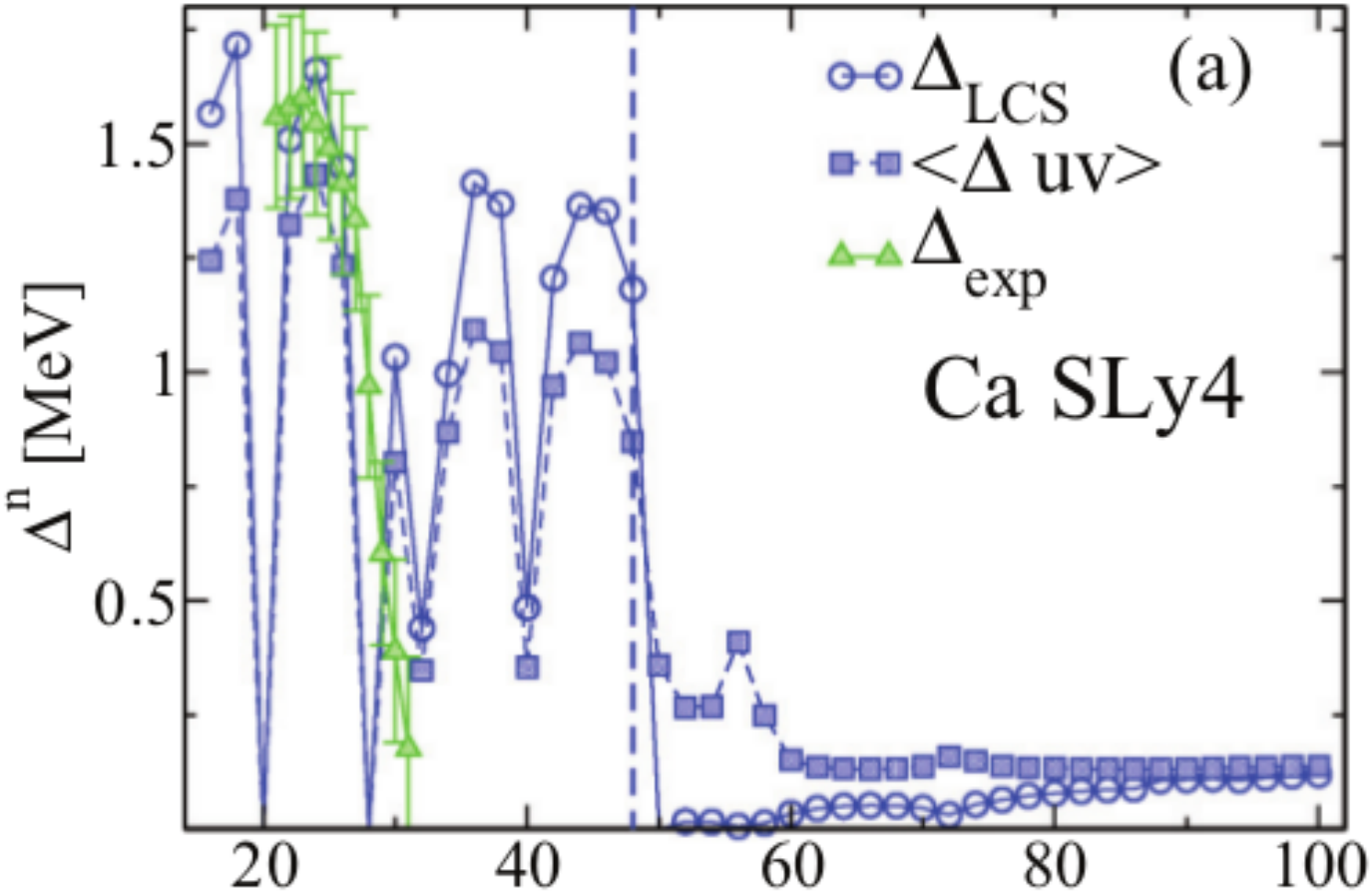
The diagonal pairing matrix elements corresponding to the canonical single-particle state

Δ_{mean}

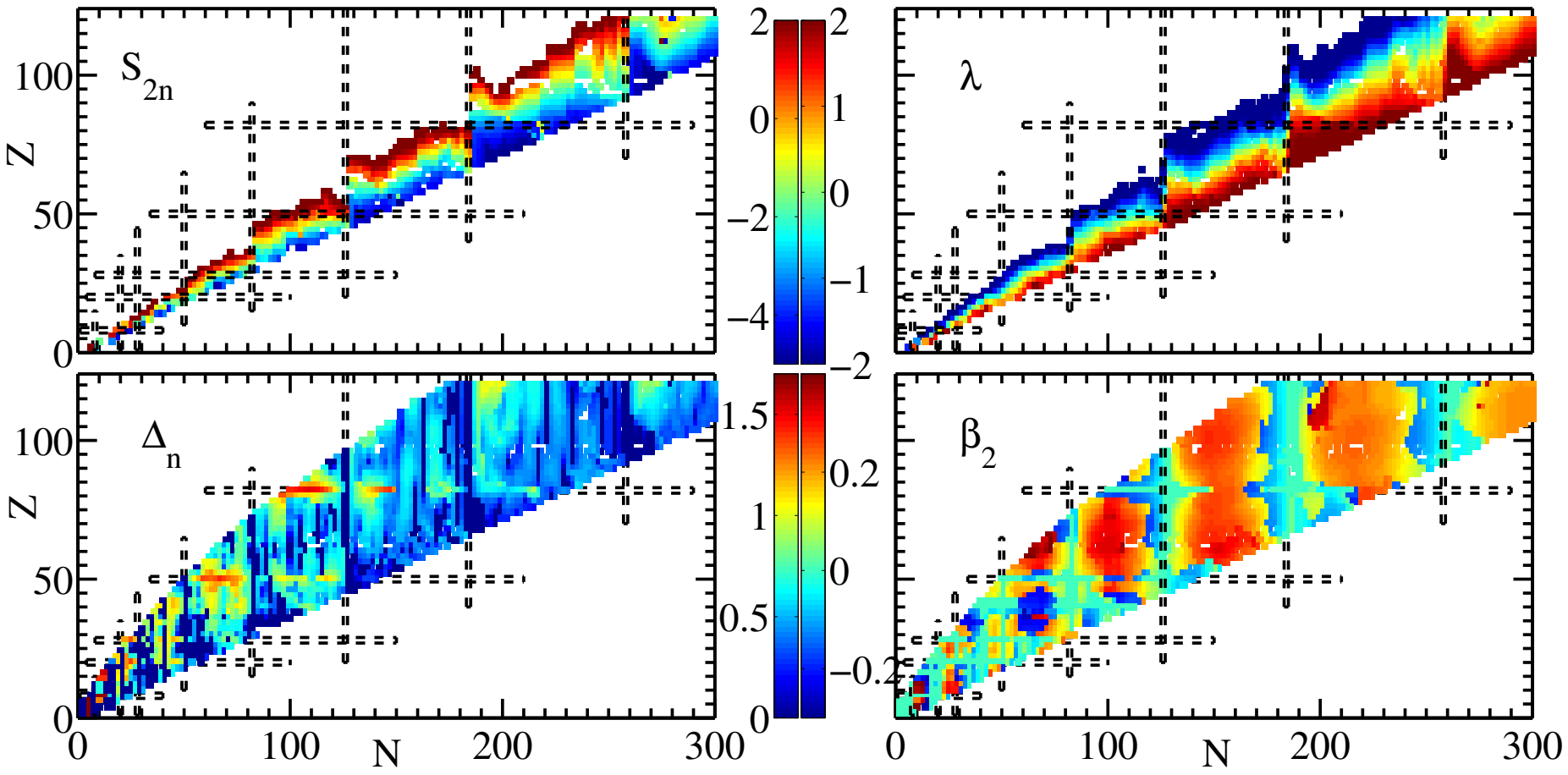
Average value of the pairing fields

Calcium - Pastore et al. Physical Review C 88, 034314 (2013)

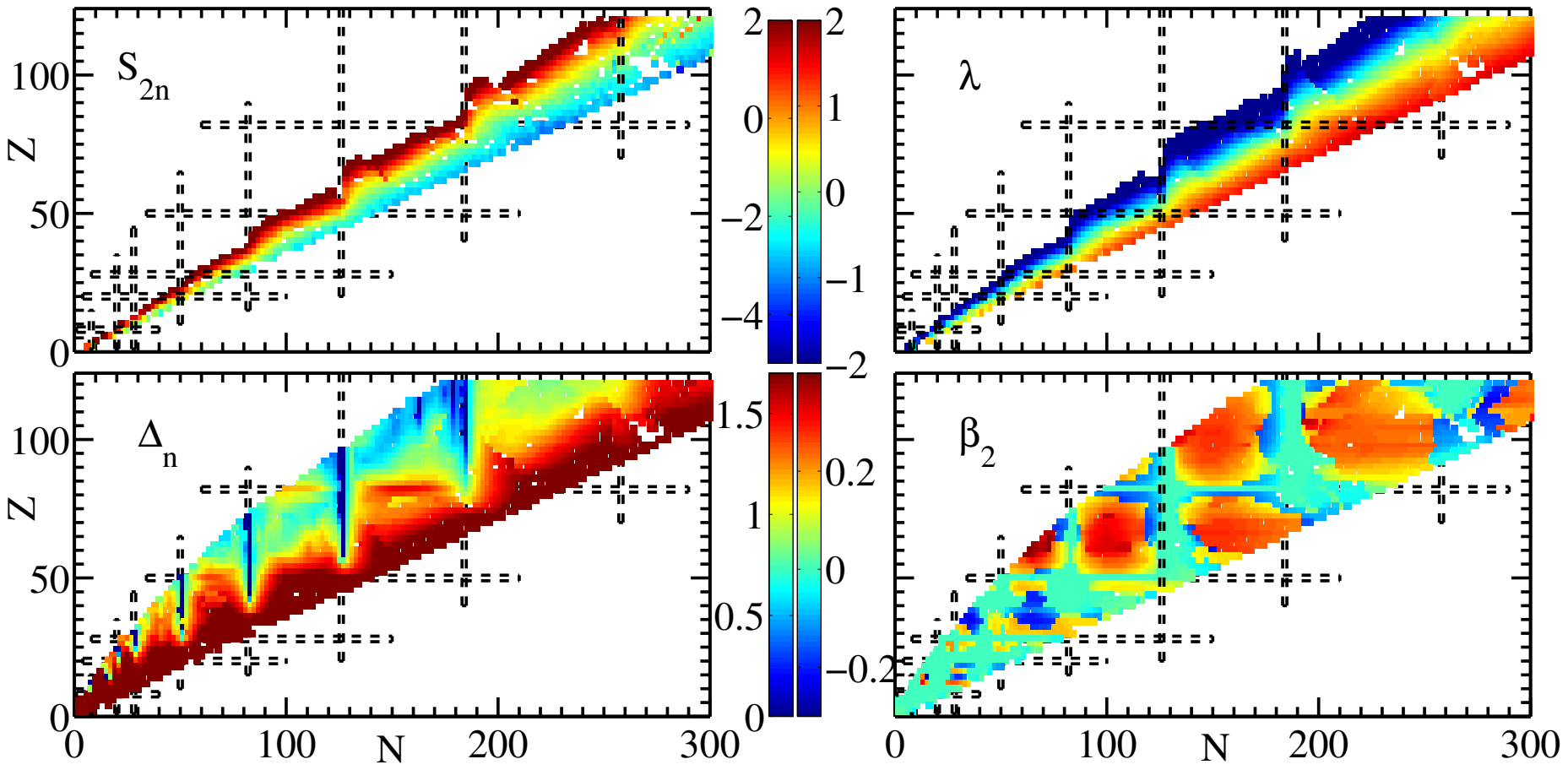
Skyrme with SLy4 and Separable Finite-Range interaction in particle-particle channel



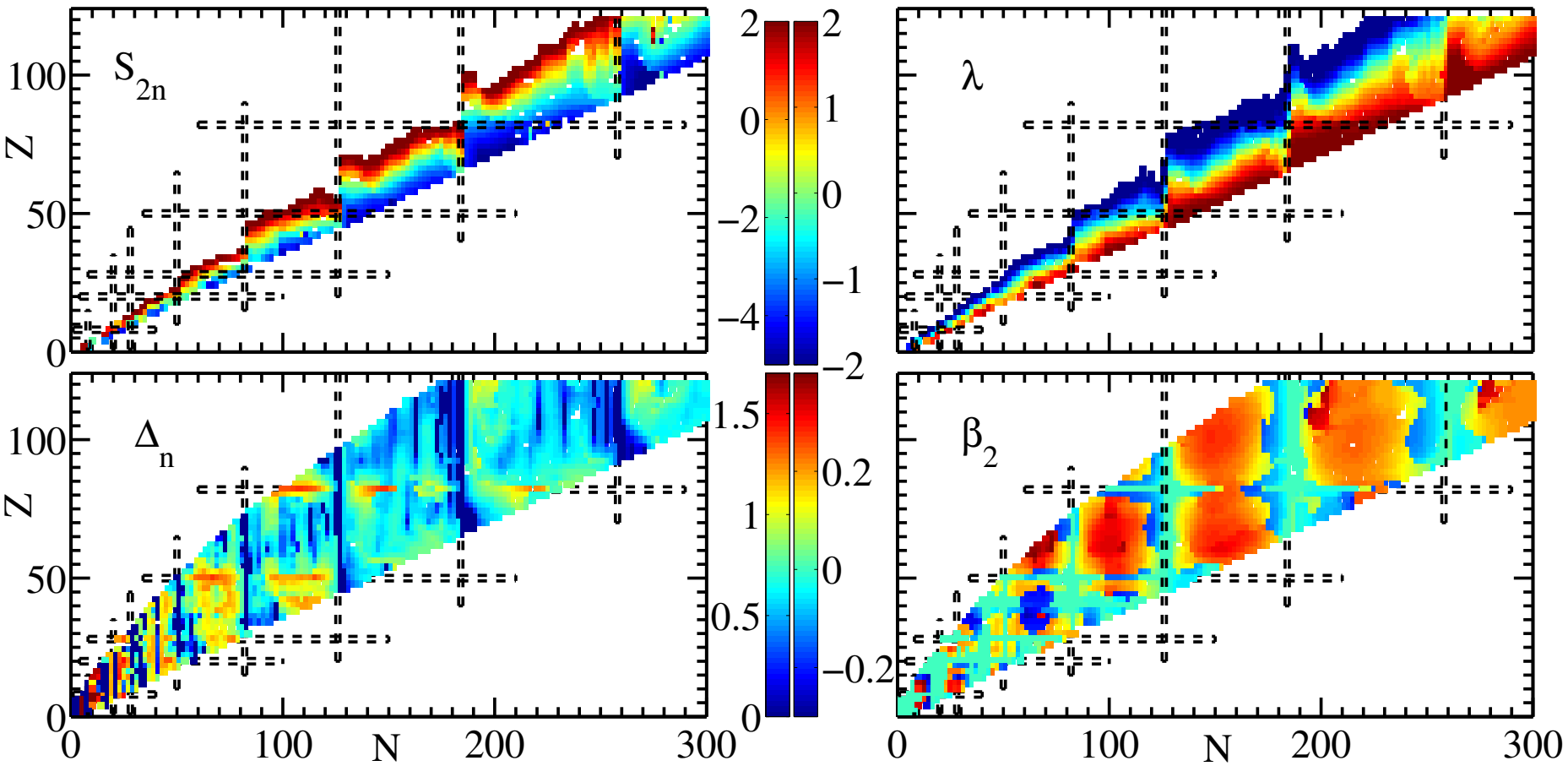
Global calculation for even-even nuclei - volume pairing



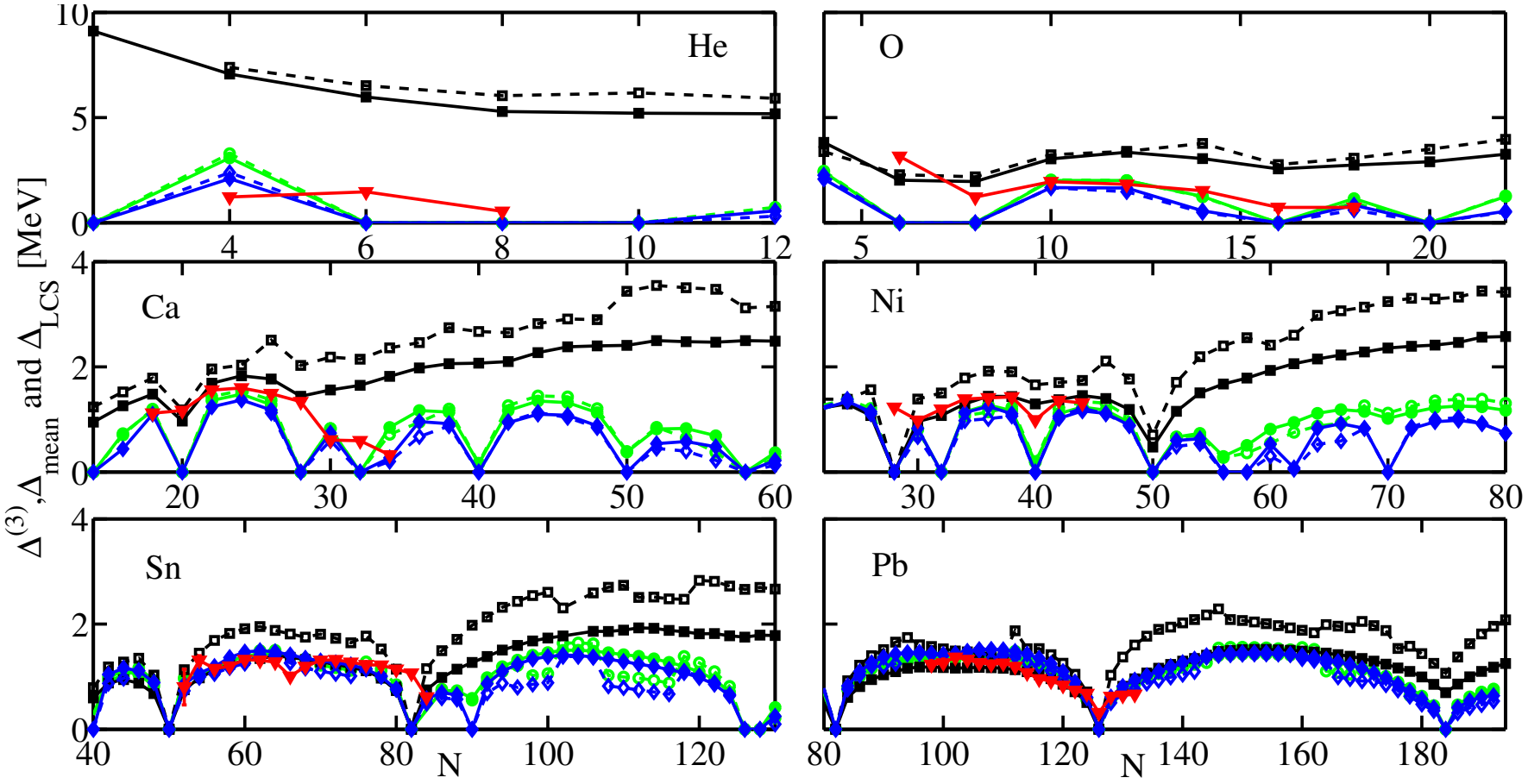
Global calculation for even-even nuclei - surface pairing



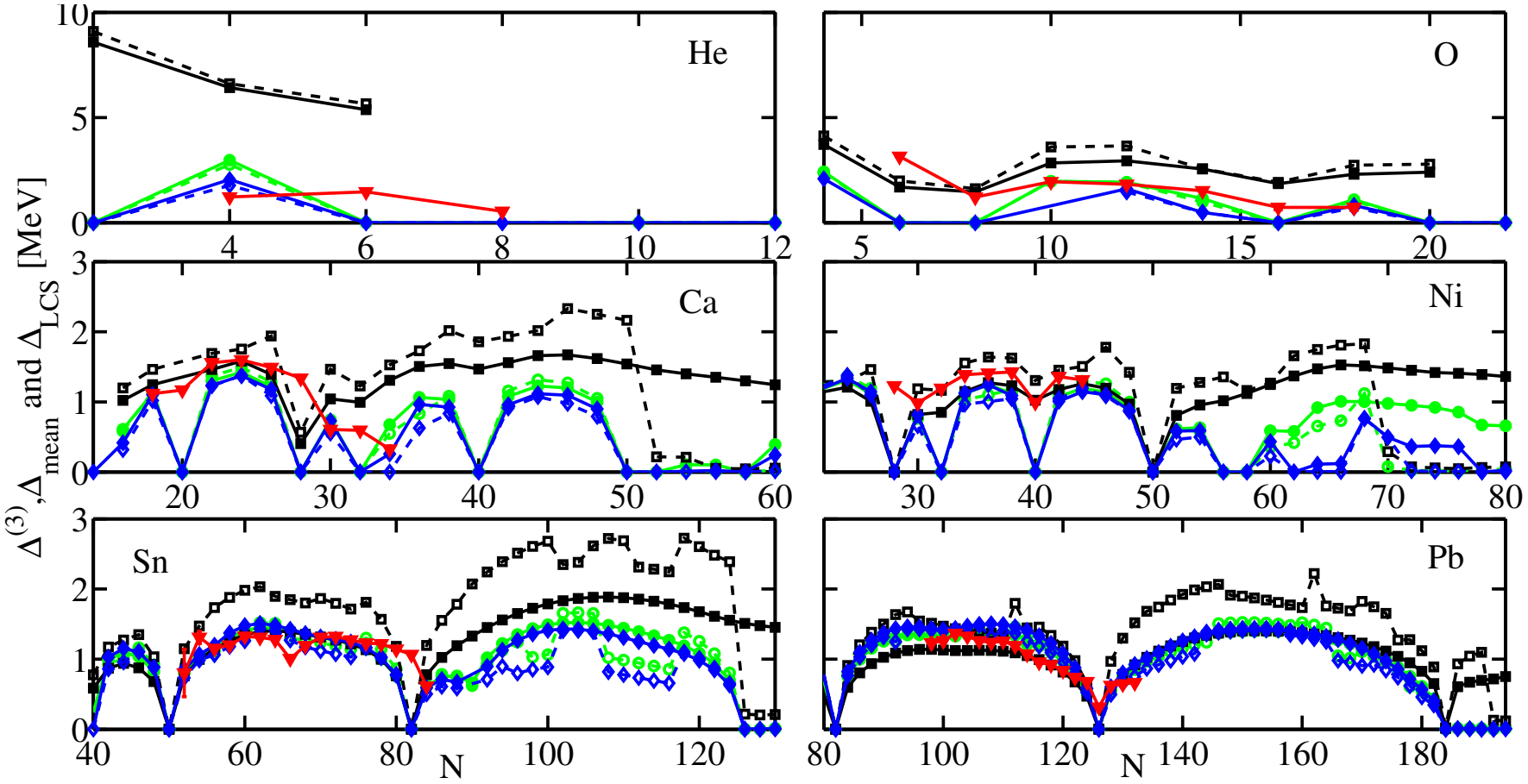
Global calculation for even-even nuclei - mix pairing



HFBTHO for all semi-magic nuclei



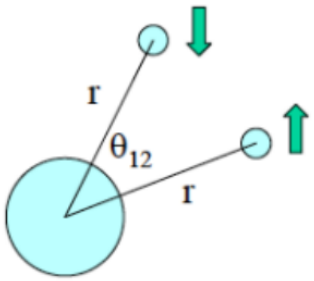
HFBRAD for all semi-magic nuclei



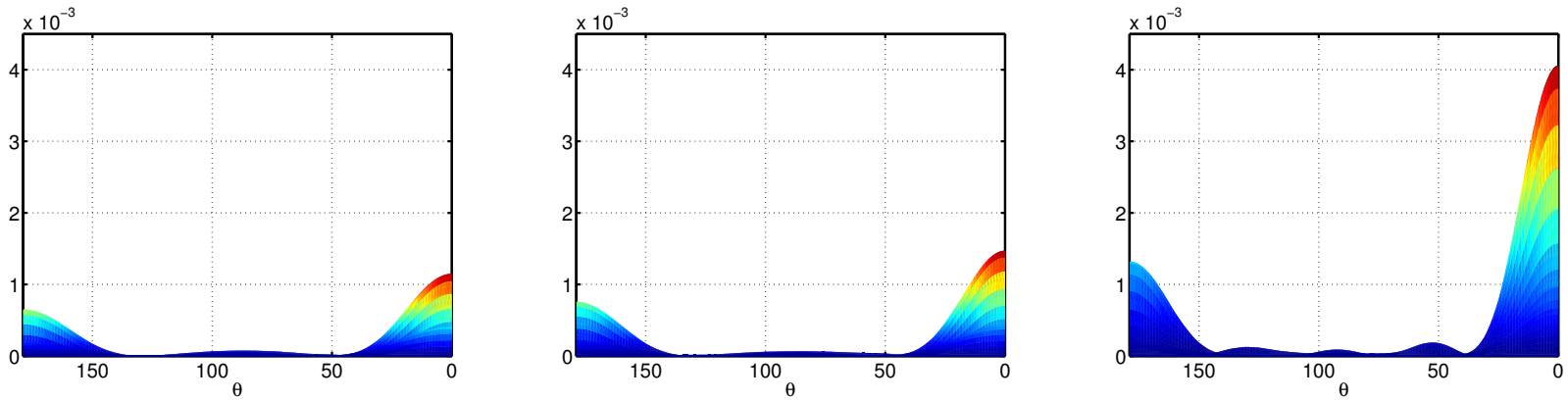
Two-particle wave function

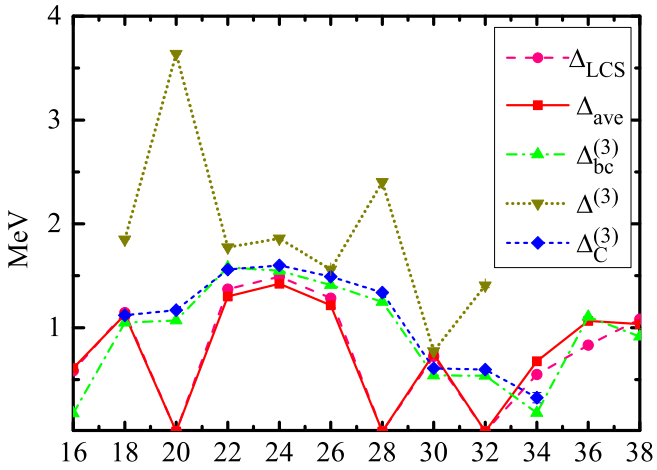
Clustering feature of two neutrons at the nuclear surface, the spin-singlet component of two-particle wave function (Chong et al. Phys. Rev. C 81, 064319):

$$\Psi^{(2)}(r_1, r_2, \theta_{12}) = \frac{1}{4\pi} \sum_{pq} \sqrt{\frac{2j_p + 1}{2}} \delta_{l_p l_q} \delta_{j_p j_q} X_{pq} \phi_p(r_1) \phi_p(r_2) P_{l_p}(\cos\theta_{12})$$

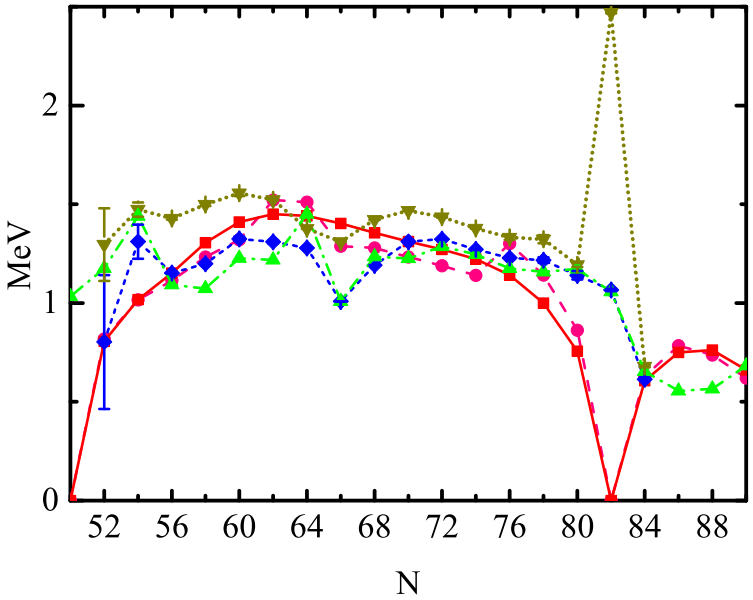


Two-particle wave function $\Psi^{(2)}$ for ^{82}Ni. Calculations with the volume, mixed and surface

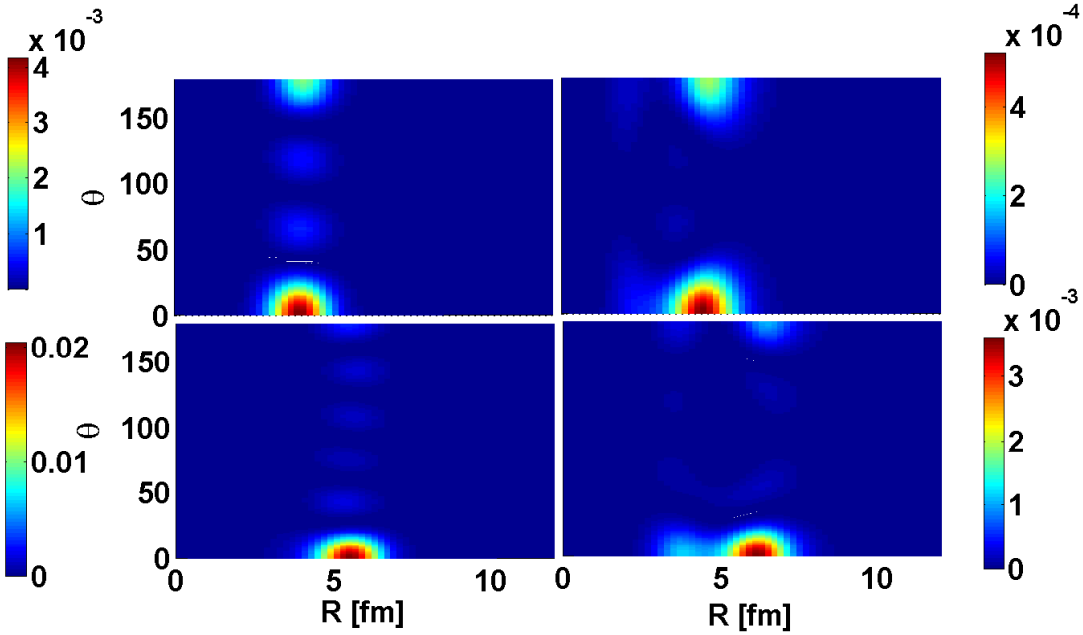




^{46}Ca and ^{54}Ca



^{128}Sn and ^{136}Sn



PHYSICAL REVIEW C **69**, 064302 (2004)

Weakly bound $s_{1/2}$ neutrons in the many-body pair correlation of neutron drip line nuclei

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(Received 15 December 2003; published 2 June 2004)

With a simplified model in the Hartree-Fock-Bogoliubov (HFB) approximation, the behavior of weakly bound $s_{1/2}$ neutrons in the many-body pair correlation is studied by solving the HFB equation in coordinate

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Pair correlation in neutron drip line nuclei

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(Received 6 June 2003; published 17 September 2003)

The Hartree-Fock-Bogoliubov (HFB) equation in a simplified model is solved in coordinate space with the correct asymptotic boundary conditions, in order to study the pair correlation in nuclei close to the neutron drip line. The occupation probability obtained in the HFB approach for lower-ℓ orbits decreases considerably

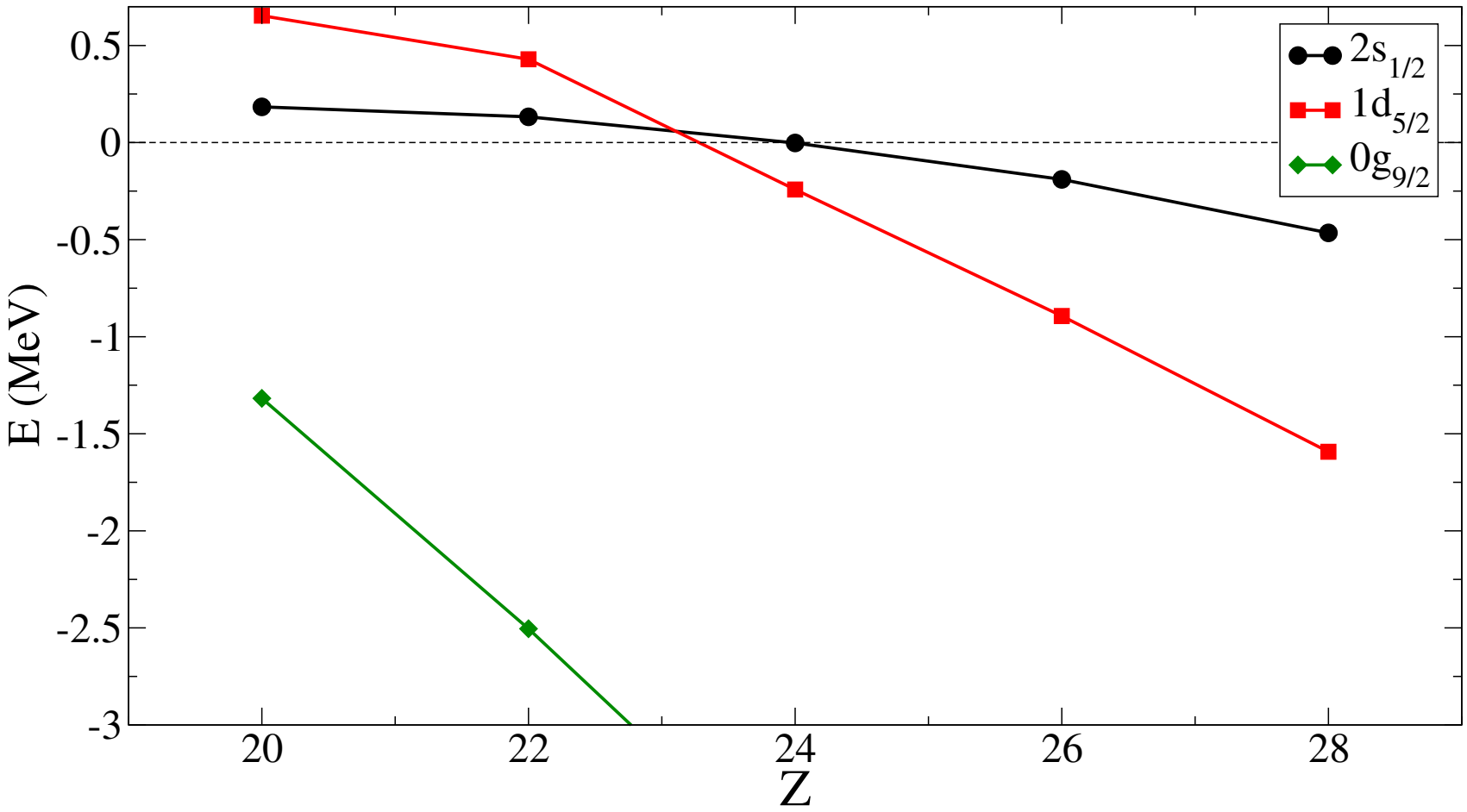

Figure : HF calculations with the Sly4 force on the evolution of the single-particle energies in the neutron-rich $N = 52$ isotones.

Conclusion

- We compared the pairing gaps derived from four different OES formulae. We showed that $\Delta_C^{(3)}$ gauge very well the nuclear pairing gap since it removes, to the largest extent, the contribution from the nuclear mean field and the shell effect.
- The strength of $\Delta_C^{(3)}$ is a good measure of the two-particle correlation.
- We have performed a systematic study of pairing properties of nuclei around the neutron drip line.
- Surface pairing interaction shows more pairing collectivity at the neutron drip line.
- Three pairing interactions are comparable for isotope close to β-stability line, however, close to drip line, volume and mix pairing show significantly reduction of pairing gap for nuclei far from the stability. The difference between Δ_{mean} and Δ_{LCS} close to neutron drip line and beyond is model dependent and the outcome results differs significantly.

Thank you for your attention