Near-threshold clustering

Jacek Okołowicz, IFJ PAN

Collaborators: Witek Nazarewicz (MSU/UW)
Marek Płoszajczak (GANIL)

Catania 27 April 2016

Near-threshold clustering

Phenomenological observation:

α-cluster states can be found in the proximity of α-particle decay threshold

K. Ikeda, N. Takigawa, H. Horiuchi (1968)

Theoretical modelling:

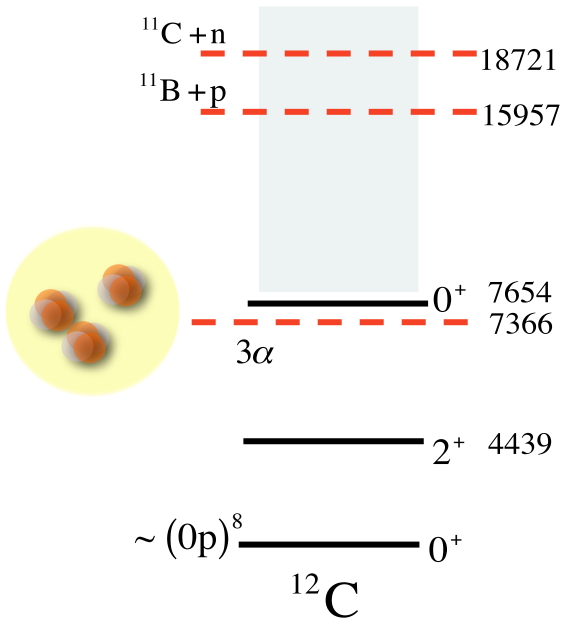
- *a posteriori* approaches: different cluster models
- *a priori* approaches: shell model do not provide an understanding of this phenomenon

Conjecture (J. Okolowicz, M. Ploszajczak, W. Nazarewicz (2012)) **:**

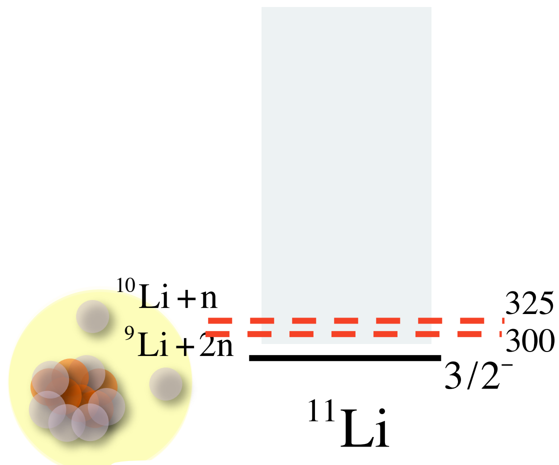
- The clustering is the generic near-threshold phenomenon in many body open quantum systems, which does not originate from any particular property of the nuclear forces or any dynamical symmetry of the nuclear many-body problem, and holds for all kinds of clustering, including unstable clusters

* The coupling to a nearby decay channel induces correlations in the shell model wave functions which are the imprint of this channel

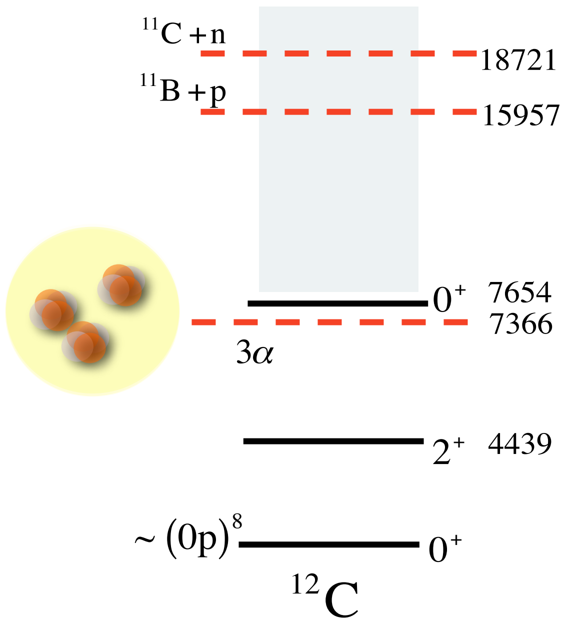
Borromean
α - cluster state



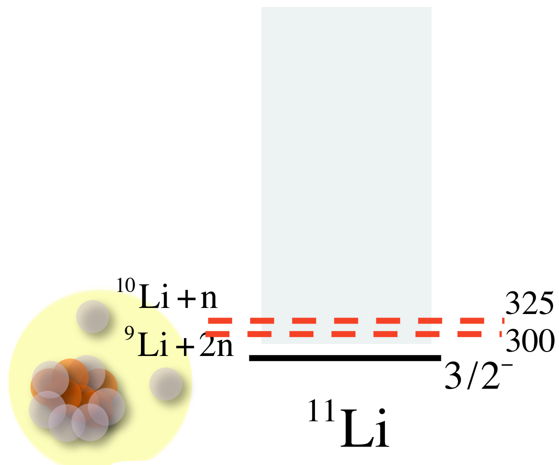
Borromean
halo state



Borrowmean
α - cluster state



Borrowmean
halo state



What is ‘specific’ and what is ‘generic’ in properties of the near-threshold states?

Specific

Energetic order of emission thresholds and absence of stable cluster entirely composed of like nucleons

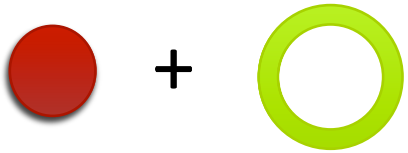
Generic

Correlations in the near-threshold states depend always on the nature of the nearby decay threshold

Shell Model Embedded in the Continuum (SMEC)

Hilbert space is divided into two subspaces

Localized nucleus with *A* nucleons



Environment of scattering states: nucleon and localized *A* – 1 nucleons

New effective Hamiltonian:

$$\mathcal{H}(E) = H_0 + H_1(E) \cong H^{SM} + V_0^2 * h(E)$$

SMEC solution is a mixture of SM states:

$$\psi_i = \sum_j b_{ij}\varphi_j$$

The correction to Shell Model energy of state:

$$E_i^{corr} = \left\langle \psi_i \middle| \mathcal{H} - H_0 \middle| \psi_i \right\rangle \cong V_0^2 \left\langle \psi_i \middle| h(E) \middle| \psi_i \right\rangle$$

Threads of Exceptional Points

Exceptional point:

coalescence of two eigenvalues of complex extended Hamiltonian results in double poles of scattering matrix V_0 - complex

$$E < 0$$

Hamiltonian is Hermitian
EP cannot cross real axis of V_0

$$E > 0$$

Hamiltonian is complex symmetric
some EP can appear as real state

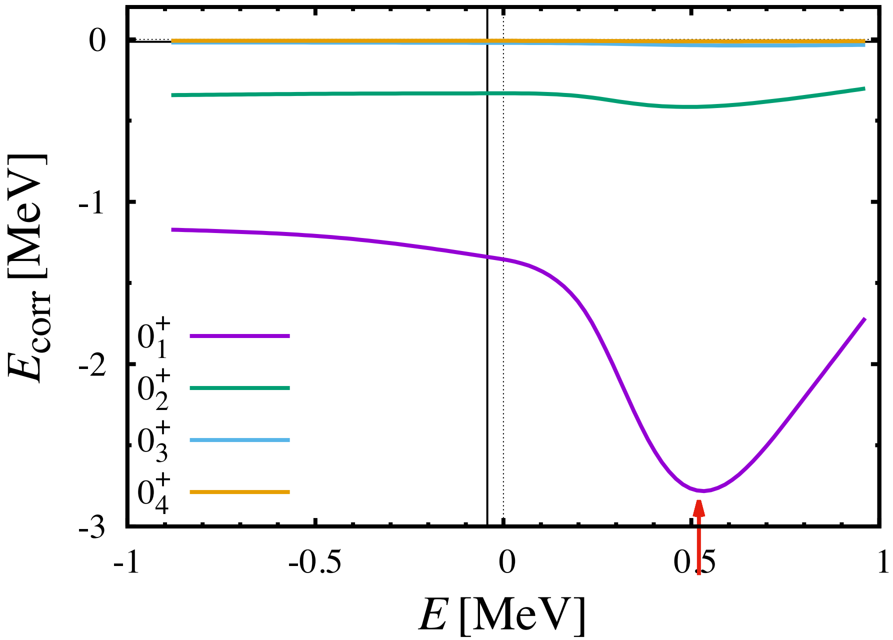
Mathematical condition for exceptional point

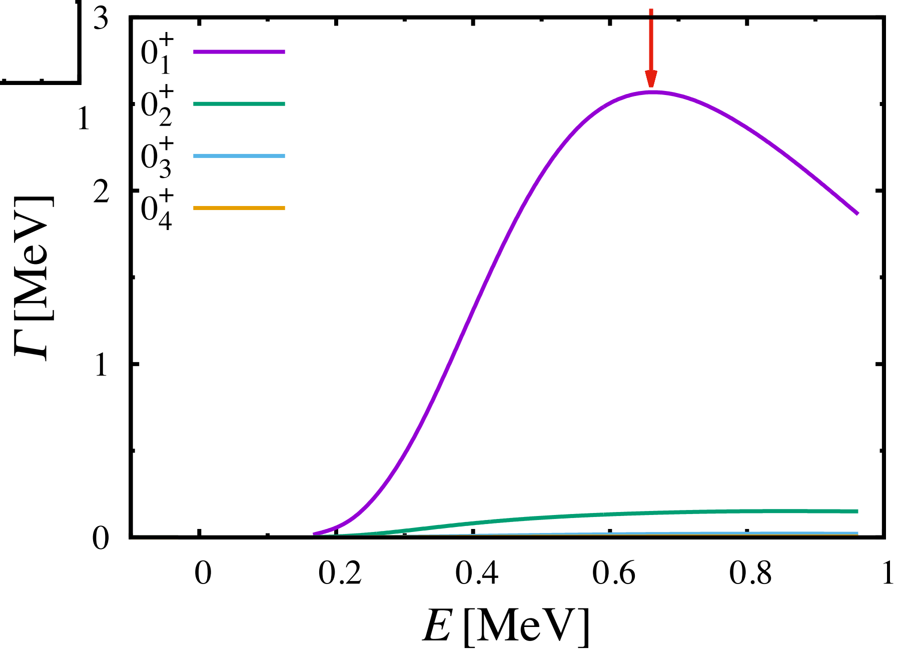
$$\frac{\partial^{(\nu)}}{\partial \omega} \left\| \mathcal{H}\left(E;V_0\right) - \omega \mathcal{I} \right\| = 0, \nu = 0,1$$

Therefore each exceptional point is a function of energy and forms a **thread**

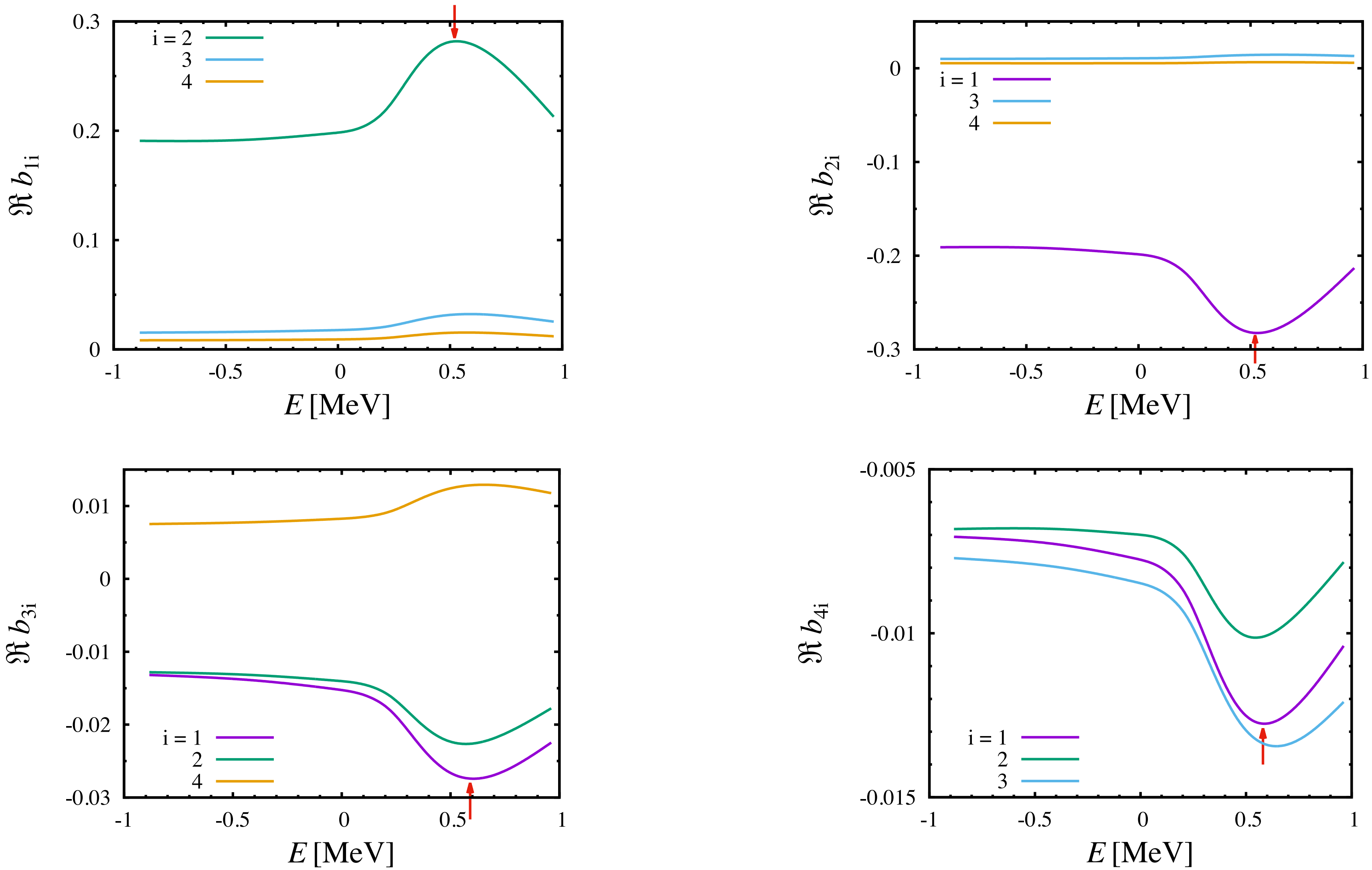
Number of threads: $N_{\max} = 2n(n-1)$

Aligned state: energy corrections



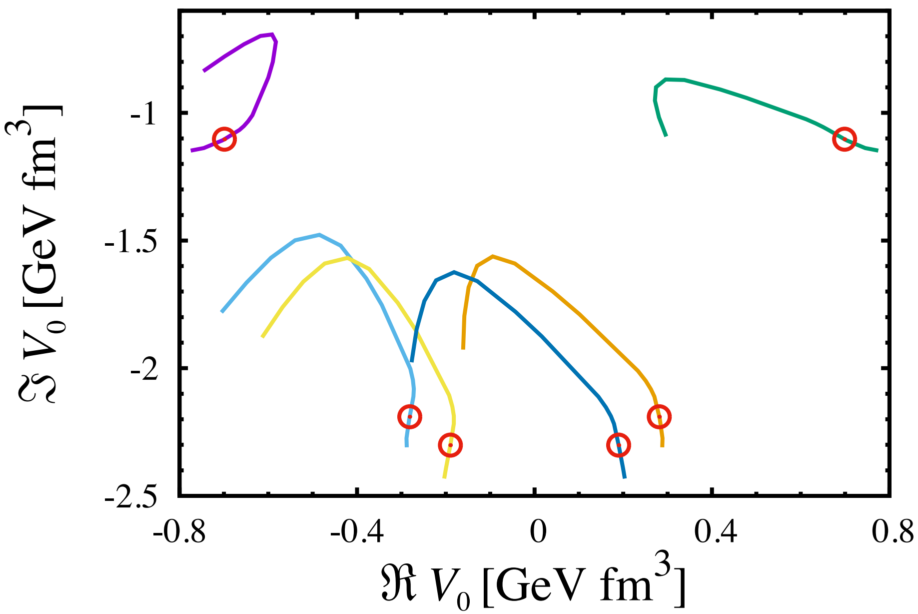


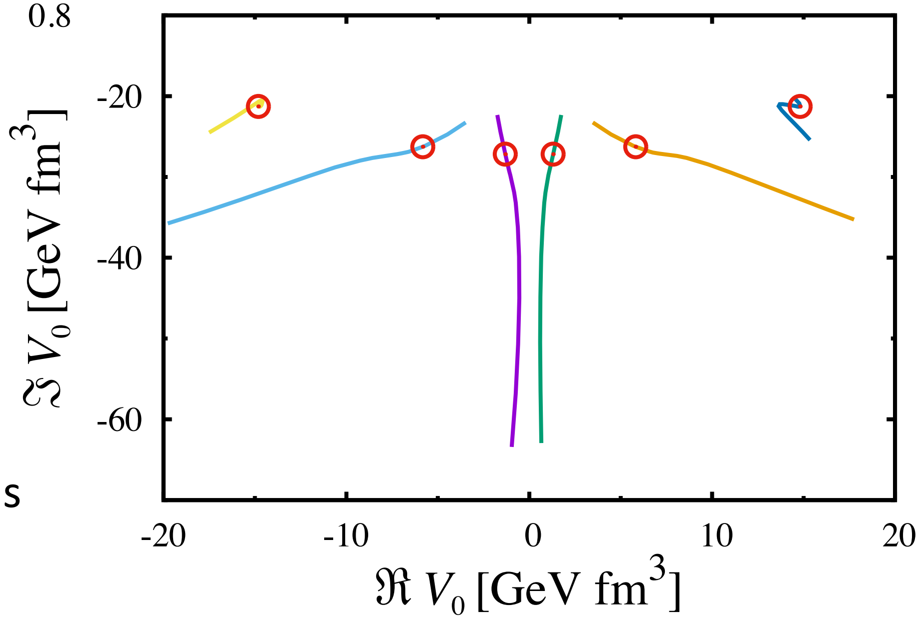
Aligned state: mixing



Aligned state

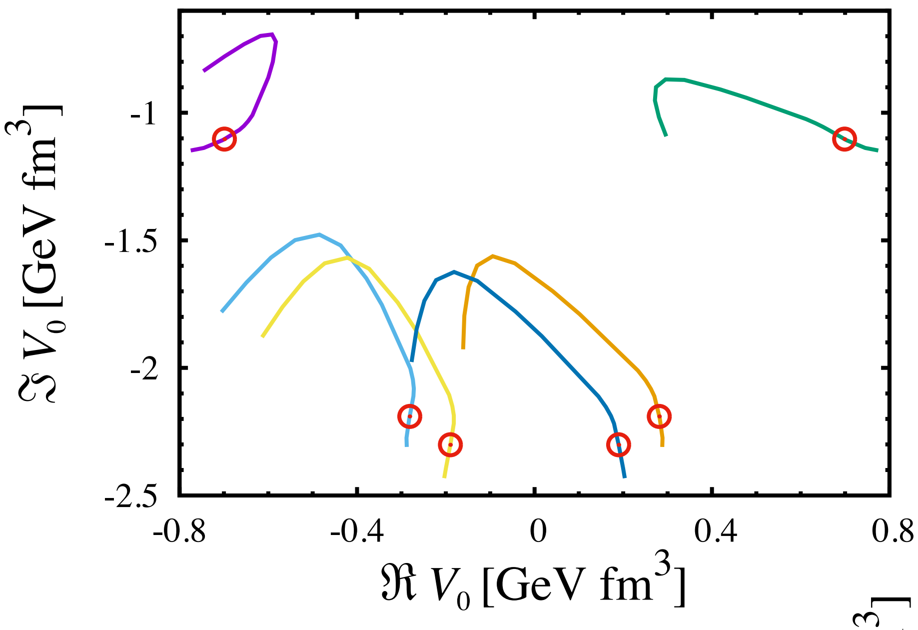
Exceptional point threads involving aligned state



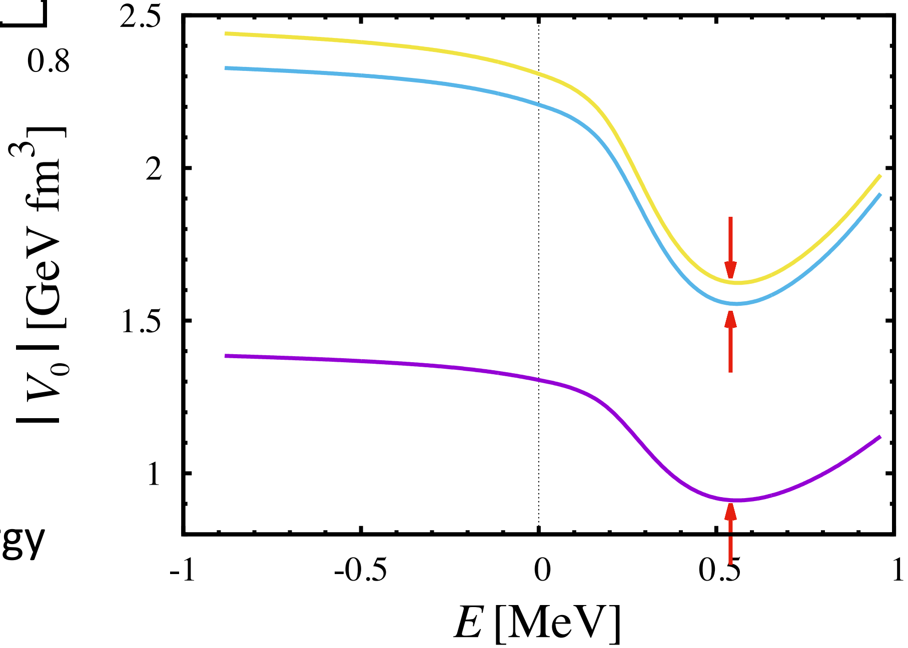


Remaining exceptional point threads

Aligned state

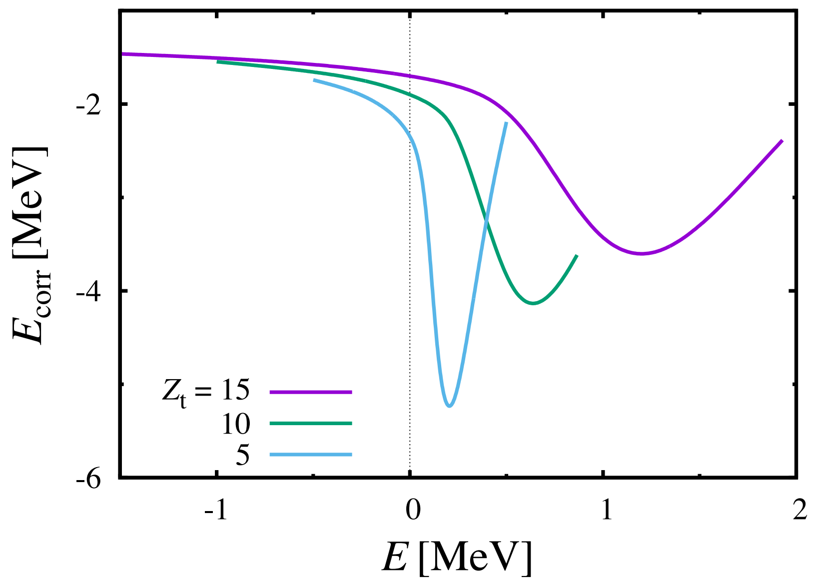


Exceptional point threads involving aligned state



All minima appear at the same energy

Opportunity window

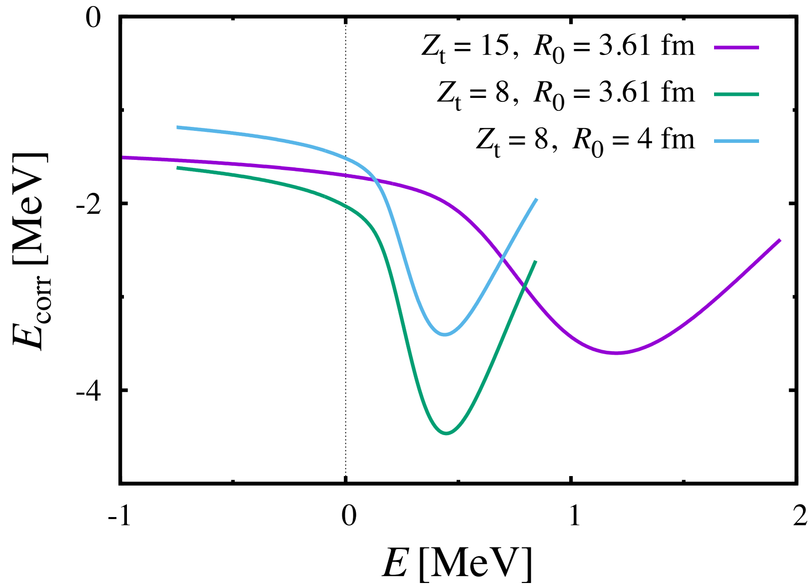


Coulomb potential strength: $Z_t = Z_1 Z_2$

number of protons in the system: $Z = Z_1 + Z_2$

proton: $Z_1 = 1$, $Z_2 = 15$ -> $Z = 16$ (S)

α-particle: $Z_1 = 2$, $Z_2 = 4$ -> $Z = 6$ (C)

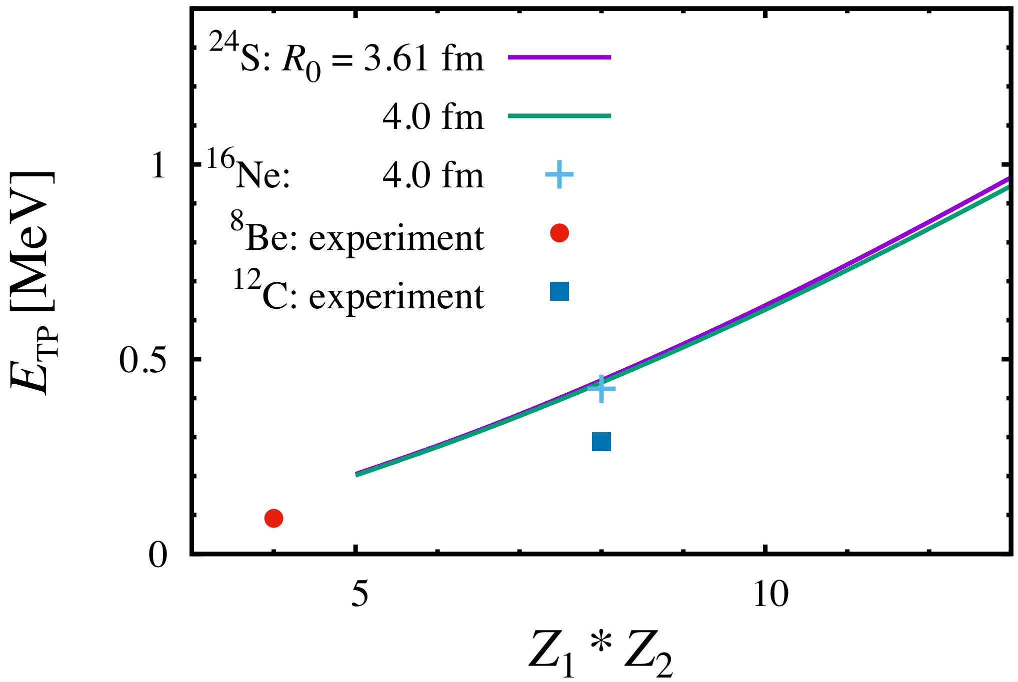


Coulomb radius (uniformly charged sphere)

proton: $R_0 = 1.27\ (A-1)^{1/3}$ fm

α-particle: $R_0 = 1.35\ (A-4)^{1/3} + 1.3$ fm

Opportunity window



$$S_\alpha\left[{}^{12}\mathrm{C}\left(0_2^+\right)\right] \cong -290\mathrm{keV}$$

$$S_\alpha\left[{}^{8}\mathrm{Be}\left(0_1^+\right)\right] = -97\mathrm{keV}$$

For a given Z_1Z_2 , the centroid of the 'opportunity window' at E_{TP} depends weakly on the charged particle decay channel and parameters of the potential

Conclusions:

- The mixing of SM eigenstates via the continuum has universal features which explain:
  (i) the nature of near-threshold clustering/correlations and optimal energies for its appearance,
  and
  (ii) a gradual disappearance of charged-particle clustering in heavier nuclei

* Experimental verification of the predicted 'exotic' near-threshold clustering(s)/correlation(s) far from the valley of stability is needed!

J. Okolowicz, M. Ploszajczak, W. Nazarewicz, PTP Suppl 196, 230 (2012);
Fortschr. Phys. 61, 66 (2013)

What about multineutron clustering?

- Correlated four neutrons reported
  in the disintegration of ^{14}Be F.M. Marques et al, PRC 65, 044006 (2002)
  in ^{4}He(^{8}He,^{8}Be) reaction K. Kisamori et al, PRL 6115 052501 (2016)

- Standard isospin structure of the nuclear force prevents that: $S_{4n} < S_{2n}/S_{1n}$

- Bound tetraneutron incompatible with our understanding of nuclear forces
  but possible tetraneutron resonance with $T = 3/2$ isospin 3-neutron force

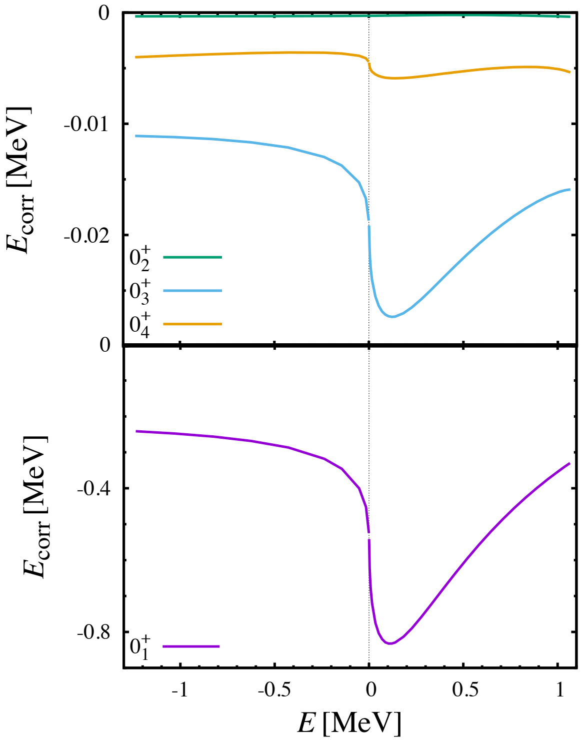
  E. Hiyama et al, arXiv:1604.04363 (2016)

but

- The nature of nuclear forces does not preclude the manifestation of tetraneutron correlations in the vicinity of the 4n-emission threshold

- The tetraneutron clustering may arise as a consequence of the collective coupling of many-body resonances via the 4n-emission channel

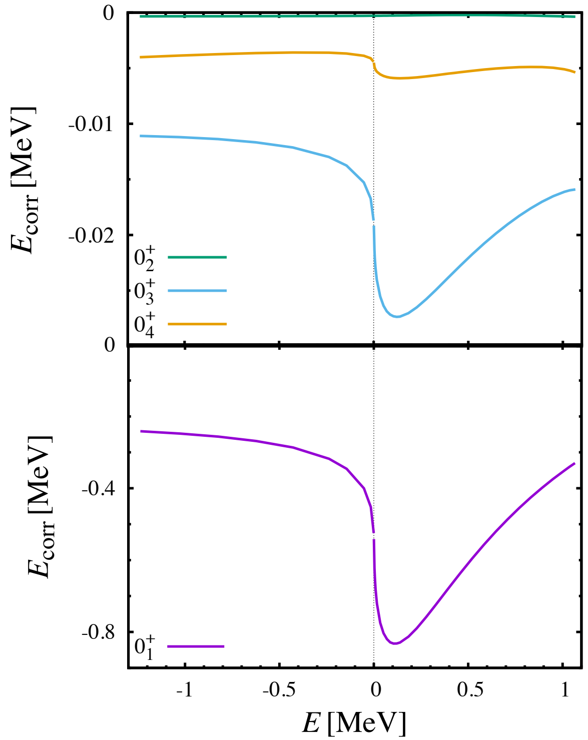
$\ell = 2$

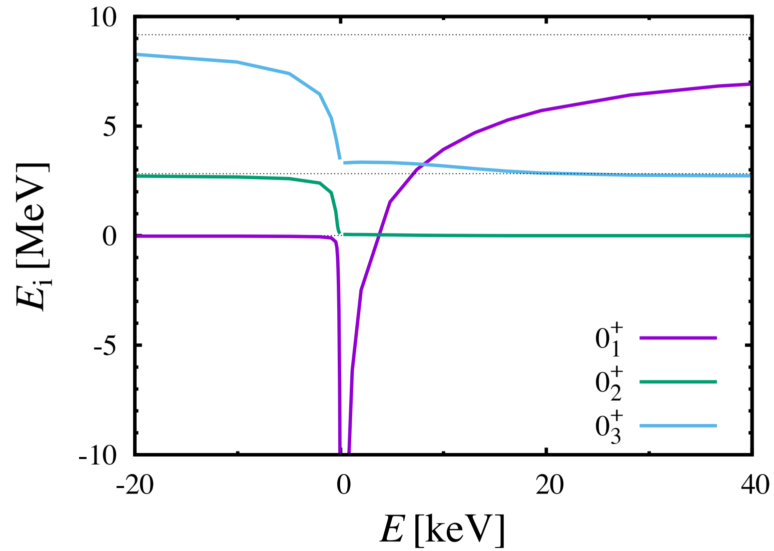


Similarity between $\ell \geq 2$ neutral particle clustering and $\ell = 0$ charged particle clustering

$\ell = 2$

$\ell = 1$





Similarity between $\ell \geq 2$ neutral particle clustering and $\ell = 0$ charged particle clustering

Collectivity of the aligned state manifests itself in the appearance of large energy gap between the aligned state and higher lying states with the same quantum numbers

Conclusions:

- Strong multi-neutron correlations in a very narrow energy range around the threshold

- The closest approximation to a genuine multi-neutron cluster states are 2n-halos. However, S_{2n} in all known cases are too large to speak about the dineutron cluster configurations

- Contrary to the charged-particle clustering, the multi-neutron correlations around the $\ell = 0, 1$ multi-neutron decay threshold are expected to appear along the whole nuclear landscape

J. Okolowicz, M. Ploszajczak, W. Nazarewicz, Acta Physica Polonica B 45, 331 (2014)