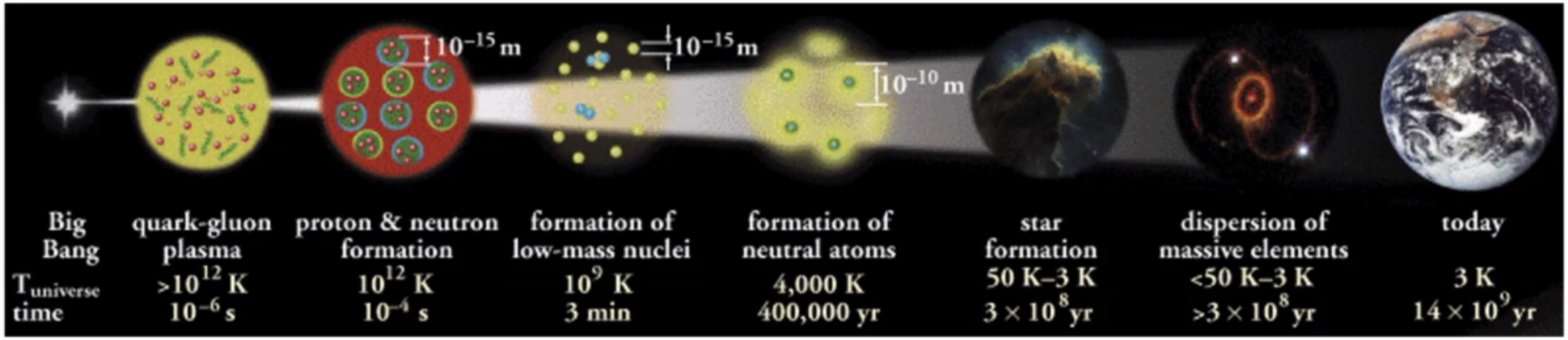
Clustering phenomenon from nuclear physics perspective

Marek Płoszajczak (GANIL)

1. Clustering and fragment production
2. Statistical mechanism of clusterization
   - Clustering in heavy ion collisions
3. Near-threshold states and the origin of clustering
   - Near-threshold effects in nuclei, hadronic molecules and multiquark systems
   - Shell model for open quantum systems
   - Puzzle of 0^+ resonance of the α particle
   - Astrophysical relevance for α- and proton-capture reactions of nucleosynthesis
4. Mimicry mechanism of clusterization
   - 'Chameleon' nature of resonances
   - Rise and fall of α-clustering in ^{8}Be
5. Message to take

Clustering and fragment production

Clustering is *ubiquitous* in Nature and clearly one of the most *mysterious* processes in Physics. It happens at all scales in time, distances and energies: from the microscopic scales of hadrons and nuclei to the macroscopic scales of living organisms and clusters of galaxies, from the high excitation energies to cold systems



There are many specific reasons for the cluster production but there are only very few *generic mechanisms* of the clusterization, independent of individual features of the studied system:

- *statistical mechanisms* rooted in the Central Limit Theorem

- mimicry mechanisms related due to the interaction between closed subsystem and its environment

Statistical mechanism of clusterization

Basic ingredients of the statistical mechanism of clusterization

Central Limit Theorem (CLT)

$\{X_i\} \rightarrow \{M_N\}$

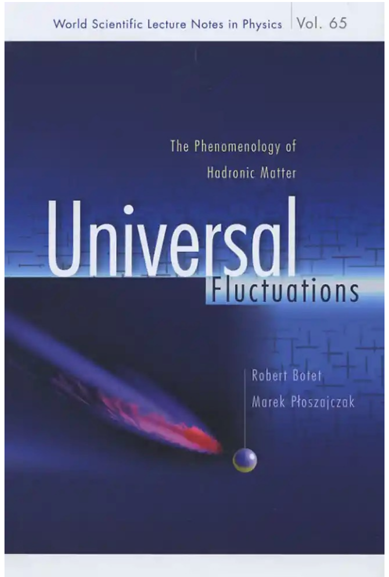
microscopic random variable → $\{X_i\}$

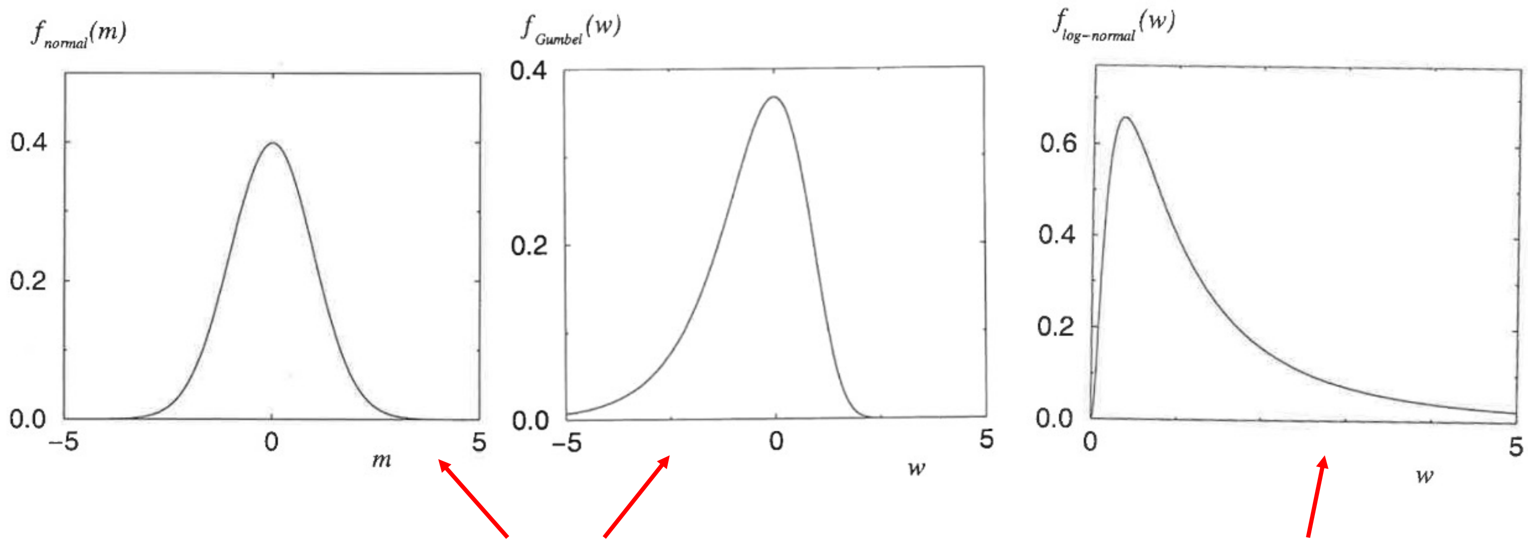
macroscopic random variable → $\{M_N\}$

How should we choose the shift and normalization factors A_N and B_N in order that the random variable:

$$M_N = \sum_{J=1}^{N} (X_j - A_N)/B_N$$

has a smooth positive probability distribution when N goes to ∞?





R. Botet, M. Ploszajczak
Universal Fluctuations – The Phenomenology of Hadronic Matter
World Scientific Lecture Notes in Physics, Vol. 65 (2002)

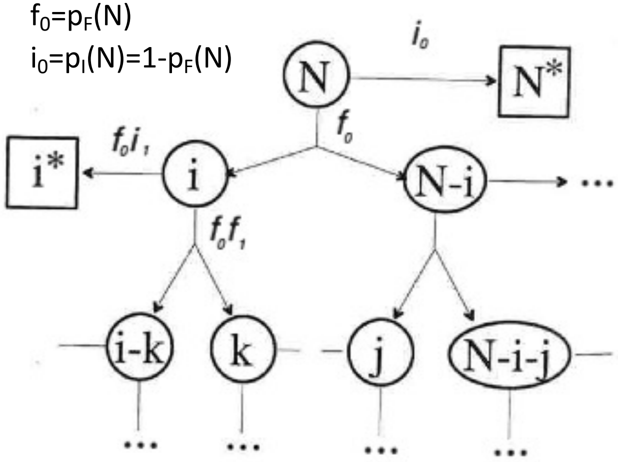
Clustering in heavy ion collisions

Statistical cluster formation mechanisms

Fragmentation scenario

Various hybrids of the Fragmentation–Inactivation model

$f_0=p_F(N)$
$i_0=p_I(N)=1-p_F(N)$



$\boldsymbol{F}_{j,k-j}$: fragmentation kernel
$\boldsymbol{I}_k$: inactivation kernel

R. Botet, M. Ploszajczak
Universal Fluctuations – The Phenomenology of Hadronic Matter
World Scientific Lecture Notes in Physics, Vol. 65 (2002)

Clustering in heavy ion collisions

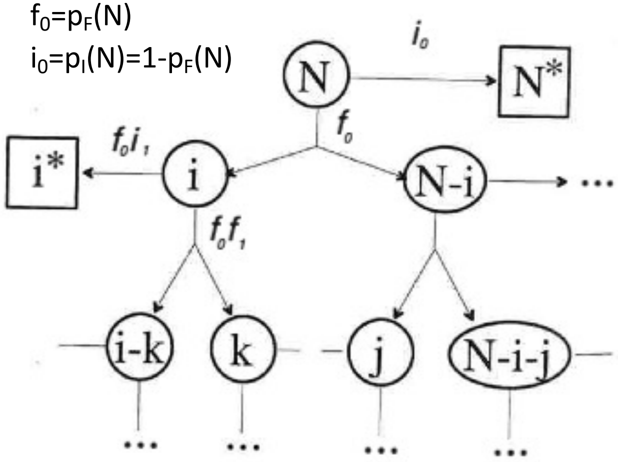
Statistical cluster formation mechanisms

Fragmentation scenario

Various hybrids of the Fragmentation–Inactivation model

$f_0 = p_F(N)$

$i_0 = p_I(N) = 1 - p_F(N)$



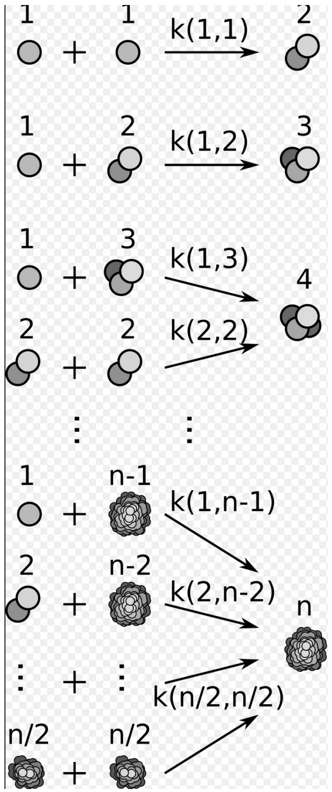
$\boldsymbol{F}_{j,k-j}$: fragmentation kernel

$\boldsymbol{I}_k$: inactivation kernel

R. Botet, M. Ploszajczak
Universal Fluctuations – The Phenomenology of Hadronic Matter
World Scientific Lecture Notes in Physics, Vol. 65 (2002)

Aggregation scenario

Equilibrium models: Fisher droplet model, Ising model, percolation model
Off-equilibrium models: Smoluchowski model of gelation



Smoluchowski equation

$$\frac{dc_s}{dt} = \frac{1}{2}\sum_{i+j=s} \boldsymbol{A}_{i,j} c_i\, c_j - \sum_{j} \boldsymbol{A}_{s,j} c_s\, c_j$$

$\boldsymbol{A}_{i,j}$: aggregation kernel

Exp.: $\boldsymbol{A}_{\omega l,\omega j} = \omega^{\alpha} \boldsymbol{A}_{i,j}$

S. Simons (1986)

Clustering in heavy ion collisions

Observables: cluster size and multiplicity of clusters

Δ - scaling of the normalized probability distribution $P_{<m>}[m]$ of the variable m for different 'system sizes' $<m>$

$$<m>^{\Delta} P_{<m>}[m] = \Phi(z_{(\Delta)}) \qquad 0 < \Delta \leq 1$$

$$z_{(\Delta)} = (m-m^*)/<m>^{\Delta}$$

most probable value   average value

If the scaling holds then the scaling relation holds independently of any phenomenological reasons to change <m>

Tail of the scaling function for large $z_{(\Delta)}$

If the infinite system experiences a second-order phase transition and m is the extensive order parameter then at the critical point Δ = 1 and the tail of scaling function for large $z_{(\Delta)}$ is:

$$\Phi(z_{(\Delta)}) \sim \exp(-z_{(\Delta)}^{\tilde{\nu}}) \qquad \tilde{\nu} = 1/(1-g) > 2 \qquad \text{at the critical point}$$

anomalous dimension

The finite system exhibits the 'second scaling law' (Δ=1/2) in the *ordered phase* and the 'first scaling law' (Δ=1) in the *disordered phase*. In both cases: $\tilde{\nu} = 2$

The crossover close to the critical point with the continuous Δ - scaling and $\tilde{\nu} = 2$

Clustering in heavy ion collisions

Order parameter fluctuations

Aggregation scenario

Order parameter : average size of the largest cluster $<s_{max}>$

Cluster-size distribution : $n(s) \sim s^{-\omega}$, $\omega > 2$

Anomalous dimension : $g = 1/(\omega-1)$

Fragmentation scenario

Order parameter : average cluster multiplicity $<n>$

Cluster-size distribution : $n(s) \sim s^{-\omega}$, $\omega < 2$

Anomalous dimension : $g = \omega-1$

Clustering in heavy ion collisions

Order parameter fluctuations

Aggregation scenario

Order parameter : average size of the largest cluster <s_{max}>

Cluster-size distribution : $n(s) \sim s^{-\underline{\omega}}$, $\underline{\omega} > 2$

Anomalous dimension : $g = 1/(\underline{\omega}-1)$

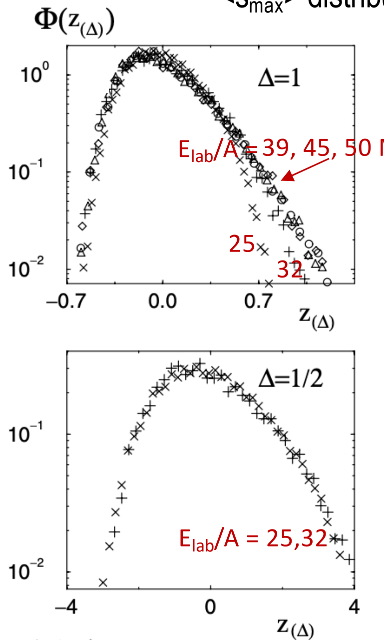
Fragmentation scenario

Order parameter : average cluster multiplicity <n>

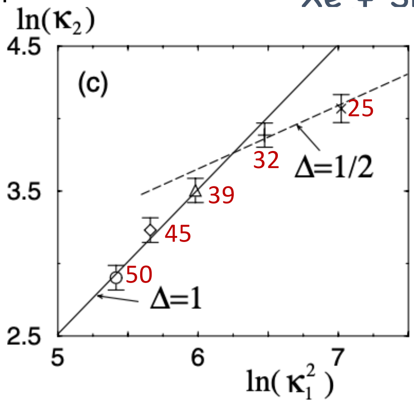
Cluster-size distribution : $n(s) \sim s^{-\underline{\omega}}$, $\underline{\omega} < 2$

Anomalous dimension : $g = \underline{\omega}-1$

<s_{max}> distribution



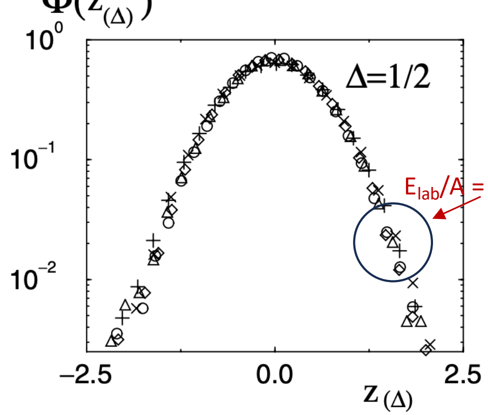
Xe + Sn central collisions



$\kappa_1 = \langle m \rangle, \ \kappa_2 = \langle m^2 \rangle - \langle m \rangle^2$

$\kappa_1 = \langle s_{max} \rangle$

<n> distribution



Exp.: INDRA Coll., R. Bougault et al., in Proc. of the XXXIV Int. Winter Meeting on Nuclear Physics, Bormio, Italy, (1997)
INDRA Coll., N. Marie et al., Phys. Lett. B 391, 15 (1997).

Clustering in central heavy-ion collisions is a generic aggregation process

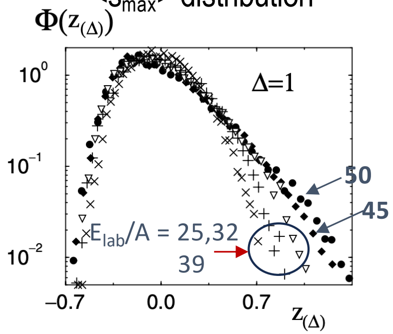
R. Botet, M. Ploszajczak and INDRA Coll., Phys. Rev. Lett. 86, 3514 (2001)

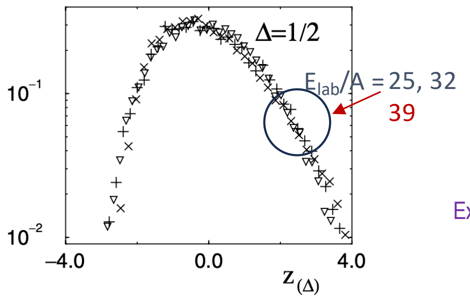
Clustering in heavy ion collisions

Order parameter fluctuations

Aggregation scenario	Fragmentation scenario
Order parameter : average size of the largest cluster $<s_{max}>$	Order parameter : average cluster multiplicity $<n>$
Cluster-size distribution : $n(s) \sim s^{-\underline{\omega}}$, $\underline{\omega} > 2$	Cluster-size distribution : $n(s) \sim s^{-\underline{\omega}}$, $\underline{\omega} < 2$
Anomalous dimension : $g = 1/(\underline{\omega}-1)$	Anomalous dimension : $g = \underline{\omega}-1$

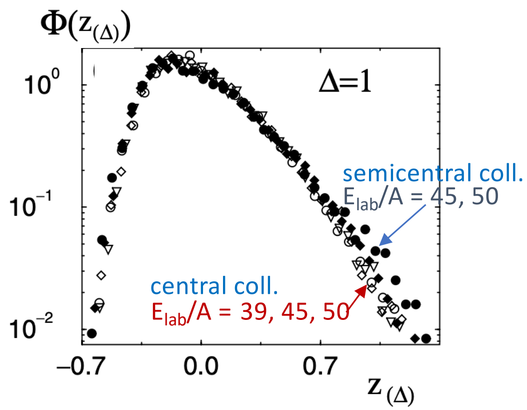
$<s_{max}>$ distribution





Xe + Sn central and semicentral collisions

$<s_{max}>$ distribution (central & semicentral)



Exp.: INDRA Coll., R. Bougault et al., in Proc. of the XXXIV Int. Winter Meeting on Nuclear Physics, Bormio, Italy, (1997)
INDRA Coll., N. Marie et al., Phys. Lett. B 391, 15 (1997).

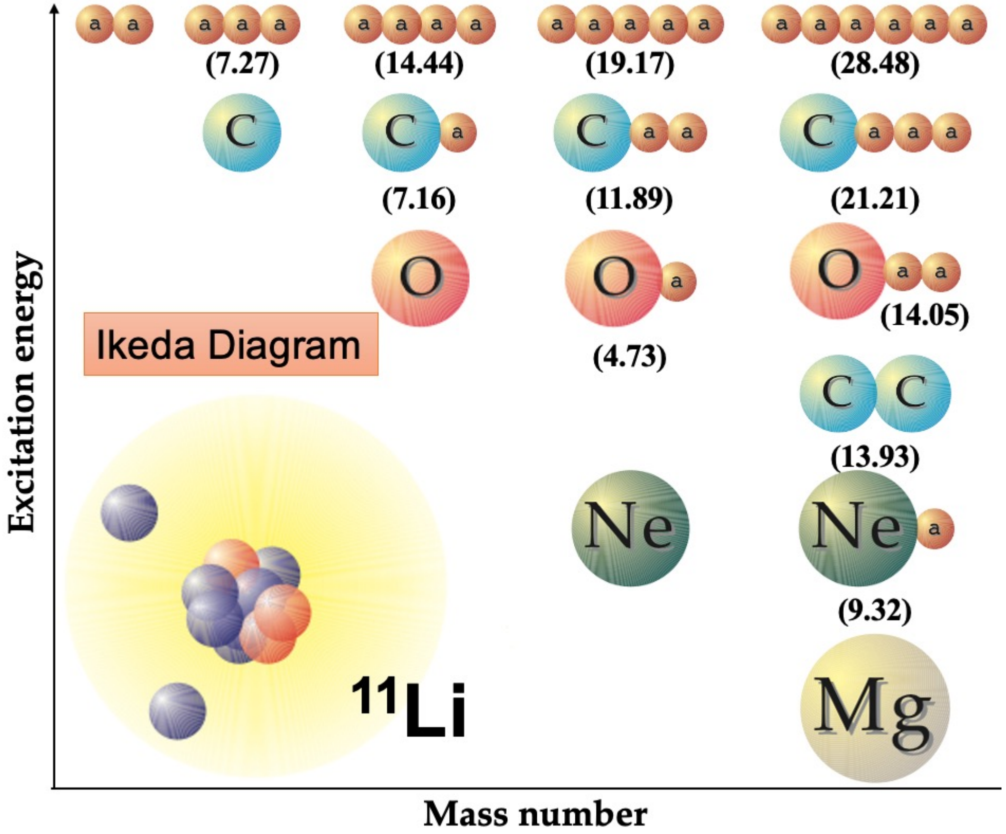
- Fragment production in central HI collisions is governed by the aggregation scenario with $<s_{max}>$ as an order parameter
- Tail of the scaling function in the critical region: $\tilde{\nu} = 1/(1-g) > 2$ is incompatible with the experimental finding $\tilde{\nu} = 1.6 +/- 0.4$
  ➡ transition from ordered to disordered phase avoids the critical point of the aggregation process
- Bombarding energy for the transition from Δ=1/2 (ordered phase) to Δ=1 (disordered phase) depends on the centrality of the collision

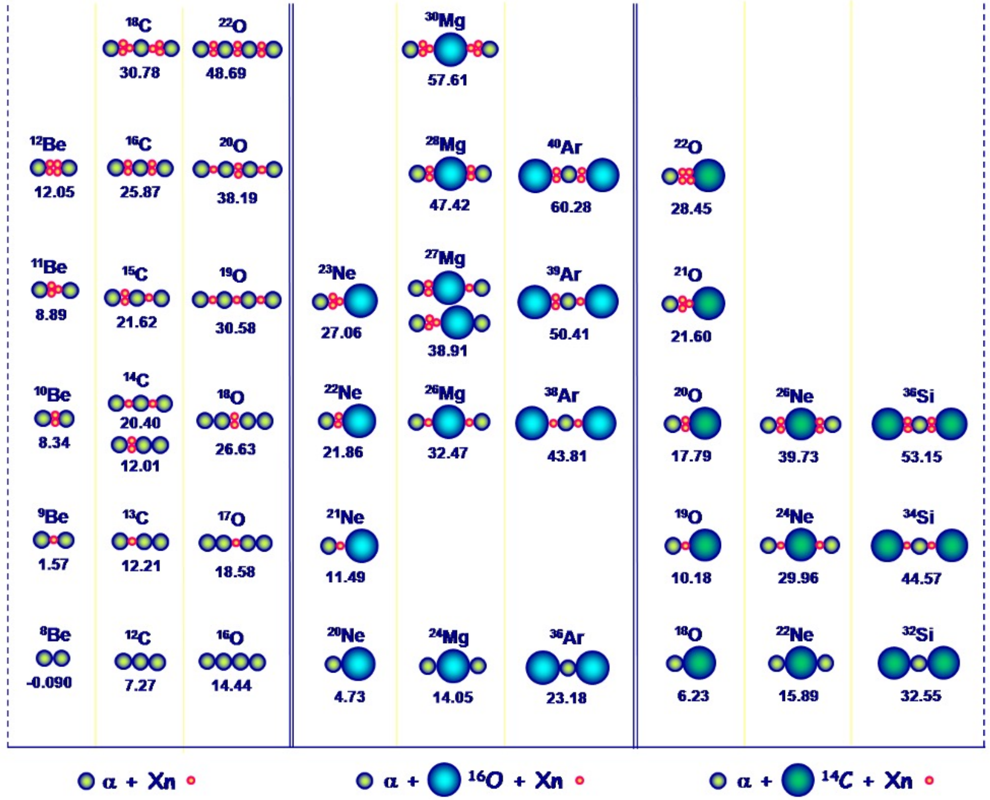
R. Botet, M. Ploszajczak and INDRA Coll., Phys. Rev. Lett. 86, 3514 (2001)

Near-threshold states and the origin of clustering

α-clustering “…α-cluster states can be found in the proximity of α-particle decay threshold…”

K. Ikeda, N. Takigawa, H. Horiuchi (1968)
W. von Oertzen et al., Eur. Phys. J. A 46, 345 (2010)

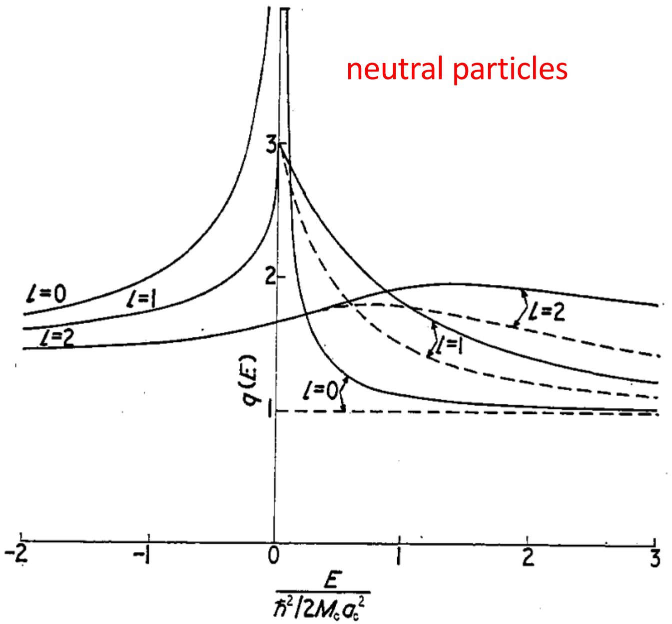


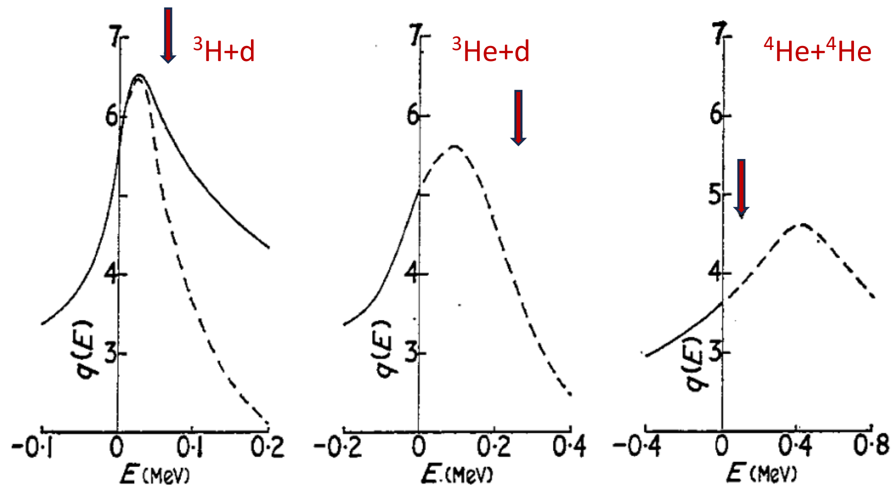


But this is only the tip of the iceberg!

R-matrix perspective

F. Barker, Proc. Phys. Soc. 84, 681 (1964)





Large enhancement factor for the probability of finding the eigenenergy around the threshold

- The threshold is a *branching point* (hence, nonanalytic behavior)
- The threshold effects are rooted in the *unitarity of scattering matrix* and the resulting flux conservation

  - Wigner threshold law for elastic and total cross-sections:

    $\sigma(i \rightarrow j) \sim (k_j)^{2\ell_j+1} \sim (E_j)^{\ell_j+1/2}$ for endoergic reactions

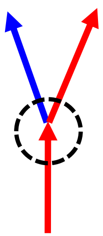
    E.P. Wigner, Phys. Rev. 73, 1002 (1948)

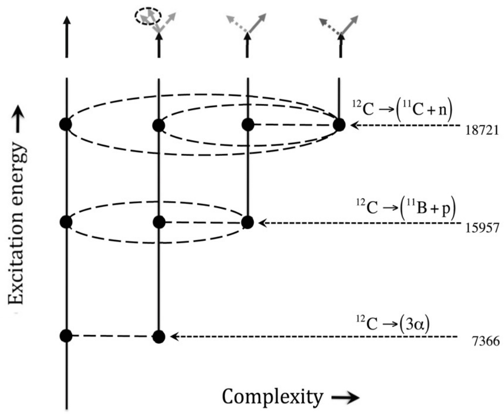
    $\sigma(i \rightarrow j) \sim (k_i)^{2\ell_i-1} \sim (E_i)^{\ell_i-1/2}$ for exoergic reactions

  - Analogous law for spectroscopic factors

    N. Michel et al., Phys. Rev. C(R) 75, 031301 (2007)

- If a new channel opens, a redistribution of the flux in other open channels appears, i.e., a modification of their reaction cross-sections





The multichannel representation of ^{12}C

With the increasing excitation energy, subsequent decay channels open at threshold energies Q_n, leading to a complex multichannel network of couplings. When a new channel opens up at the threshold Q_i, the unitarity imposes the appearance of new channel couplings; hence, a modification of all eigenfunctions.

Threshold effects in nuclei

Coupling of the analogous channels in a (d,p) and (d,n) reaction

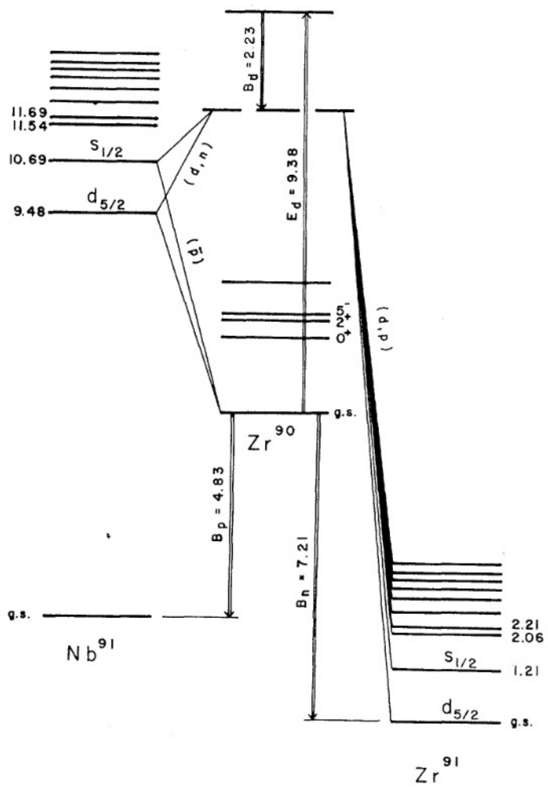


FIG. 1. Level diagram showing the low-lying states in ^{90}Zr, the parent analog states in ^{91}Zr, and the known analog states in ^{91}Nb.

C.F. Moore et al., PRL 17, 926 (1966)

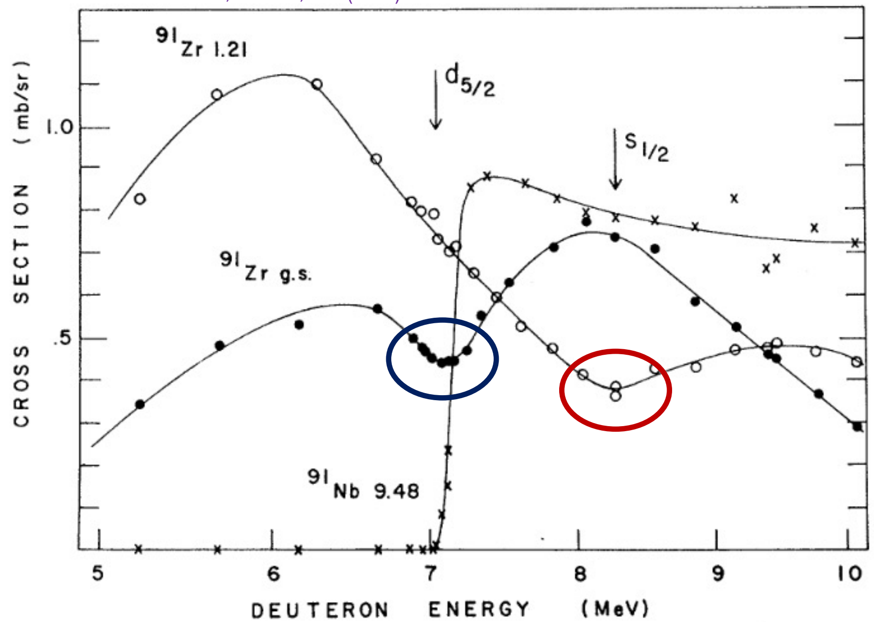
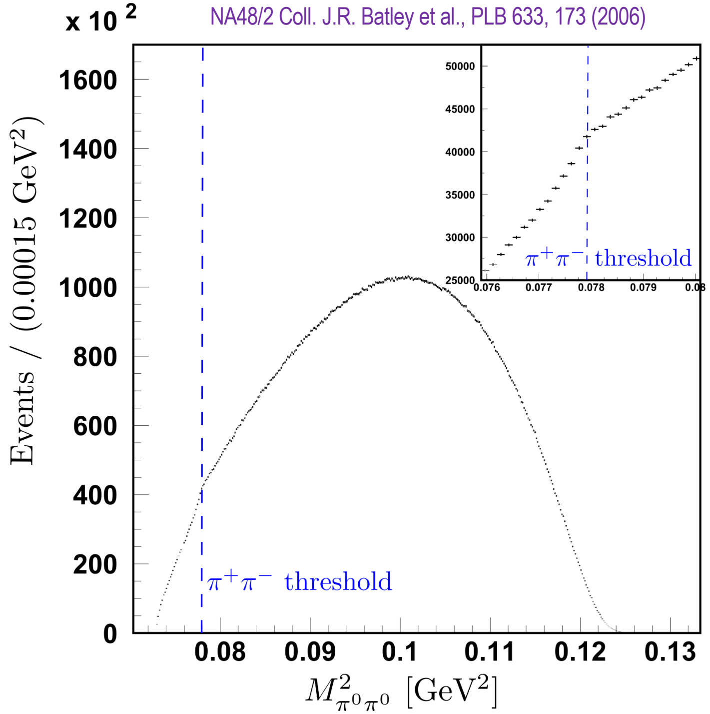


FIG. 3. Excitation curves in ^{90}Zr$(d,p)^{91}$Zr ($d_{5/2}$, g.s.), ^{90}Zr$(d,p)^{91}$Zr ($s_{1/2}$, 1.21 MeV), and ^{90}Zr$(d,np)^{91}$Nb ($d_{5/2}$, 9.48 MeV) at 170 deg. The arrows show the thresholds for the reactions ^{90}Zr$(d,np)^{91}$Nb ($d_{5/2}$, 9.48 MeV), and ^{90}Zr$(d,np)^{91}$Nb ($s_{1/2}$, 10.69 MeV).

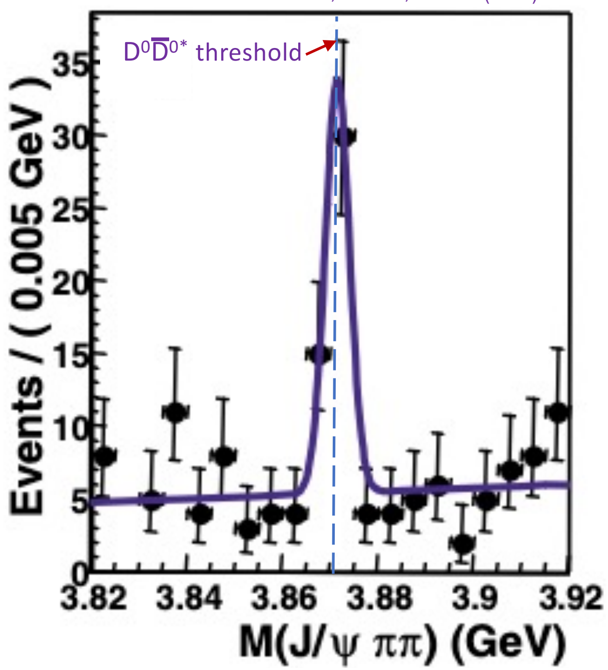
Near-threshold effects in hadrons, hadronic molecules, multiquark systems

NA48/2 Coll. J.R. Batley et al., PLB 633, 173 (2006)



$K^+ \to \pi^+\pi^0\pi^0$

Belle Coll. J.-K. Choi et al., PRL 91, 262001 (2003)



$B^\pm \to K^\pm \pi^+\pi^- J/\psi$

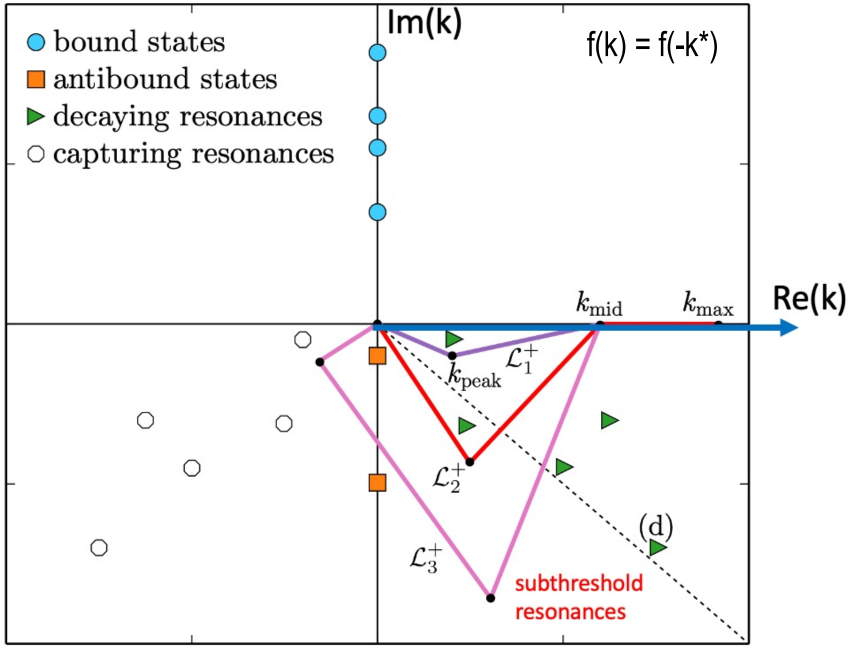
M_X = 3872 +/- 0.6 (stat) +/- 0.5 (syst) MeV

$(M_{D^0} + M_{D^{*0}})$ = 3871.1 +/- 1 MeV

Threshold effects can also result in some resonance-like structures in the pertinent invariant mass spectrum that can be confounded with a genuine resonance states, like molecular states, multiquark states, or hybrid.

Atomic nucleus: the open quantum system

Threshold Gamow poles: Quasi-stationary extension in the complex k-plane



$$\sum_n |u_n\rangle\langle\tilde{u}_n| + \int_{L_+} |u_k\rangle\langle\tilde{u}_k|dk = 1 \ ; \ \langle u_i|\tilde{u}_j\rangle = \delta_{ij}$$

T. Berggren, Nucl. Phys. A109, 265 (1968)
T. Lind, Phys. Rev. C47, 1903 (1993)

$$i\hbar\frac{\partial}{\partial t}\Phi(r,t) = \hat{H}\Phi(r,t) \ ; \quad \Phi(r,t) = \tau(t)\Psi(r)$$

$$\hat{H}\Psi = \left(e - i\frac{\Gamma}{2}\right)\Psi \quad \Rightarrow \quad \tau(t) = \exp\left(-i\left(e - i\frac{\Gamma}{2}\right)\right)$$

$$\Psi(0,k) = 0 \ , \quad \begin{cases} \Psi(\vec{r},k) \underset{r\to\infty}{\to} O_l(kr) \\ \Psi(\vec{r},k) \underset{r\to\infty}{\to} I_l(kr) + O_l(kr) \end{cases}$$

Only bound states are integrable!

Euclidean inner product

$$\langle u_n|u_n\rangle = \int_0^\infty dr u_n^*(r)u_n(r)$$

Rigged Hilbert Space inner product

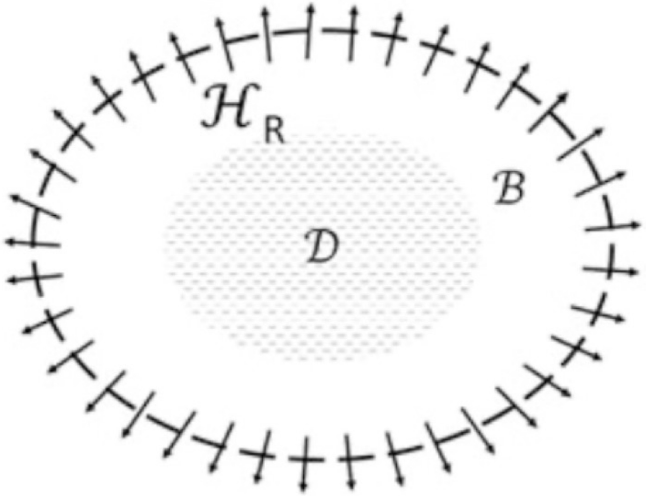
$$\langle\tilde{u}_n|u_n\rangle = \int_0^\infty dr\tilde{u}_n^*(r)u_n(r)$$

Rigged Hilbert Space (RHS) is the natural setting of Quantum Mechanics in which resonance spectrum, Dirac bra-ket formalism (and Heisenberg uncertainty relations) have place

I.M. Gel'fand and N. J. Vilenkin. Generalized Functions, vol. 4: *Some Applications of Harmonic Analysis. Rigged Hilbert Spaces*, Academic Press, New York, 1964
G. Ludwig, *Foundation of Quantum Mechanics*, Vol. I and II, Springer-Verlag, New York, 1983

Shell model for open quantum systems

Hermitian QM in rigged Hilbert space



N. Michel et al, Phys. Rev. Lett. 89 (2002) 042502
R. Id Betan et al, Phys. Rev. Lett. 89 (2002) 042501

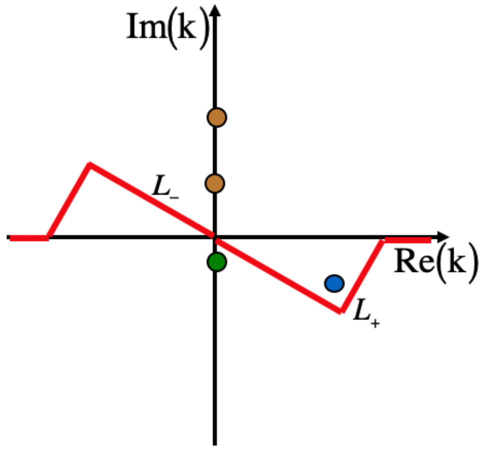
N. Michel, et al, J. Phys. G37 (2010) 064042

N. Michel, M. Płoszajczak,
«*Gamow Shell Model: The Unified Theory of Nuclear Structure and Reactions* »
Lecture Notes in Physics, Vol. 983, (Springer Verlag, 2021)

Gamow shell model (GSM)

$$\sum_n |u_n\rangle\langle\tilde{u}_n| + \int_{L_+} |u_k\rangle\langle\tilde{u}_k| dk = 1 \; ; \; \langle u_i|\tilde{u}_j\rangle = \delta_{ij}$$

$$|SD_i\rangle = |u_{i_1} \dots u_{i_A}\rangle \Rightarrow \sum_k |SD_k\rangle\langle SD_k| \cong 1$$

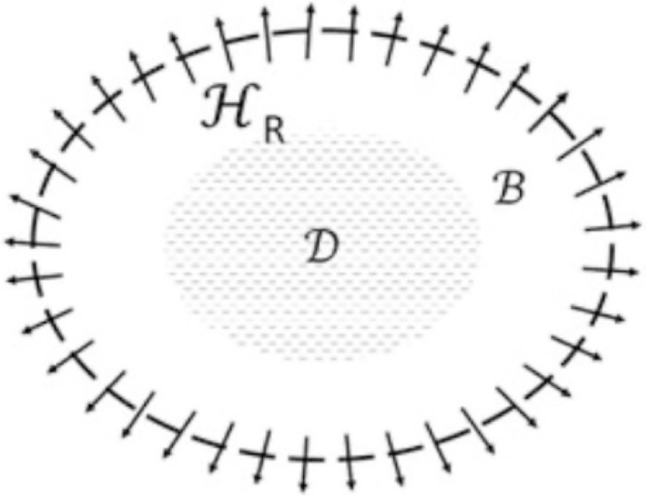


$$H \rightarrow [H]_{ij} = [H]_{ji}$$

- Unitary formulation of the nuclear Shell Model
- No identification of reaction channels

Shell model for open quantum systems

Hermitian QM in rigged Hilbert space



GSM – Coupled-channel representation

$$|\Psi_M^J\rangle = \sum_c \int_0^{+\infty} |(c,r)_M^J\rangle \, \frac{u_c^{JM}(r)}{r} r^2 \, dr$$

$$|(c,r)\rangle = \hat{\mathcal{A}}[|\Psi_T^{J_T}; N_T, Z_T\rangle \otimes |r \; L_{CM} \; J_{int} \; J_P; n, z\rangle]_M^J$$

$$H\,|\Psi_M^J\rangle = E\,|\Psi_M^J\rangle \Rightarrow \sum_c \int_0^{\infty} r^2 \left(H_{cc'}(r,r') - E N_{cc'}(r,r')\right) \frac{u_c(r)}{r} = 0$$

$$H_{cc'}(r,r') = \langle (c,r)|\,\hat{H}\,|(c',r')\rangle$$

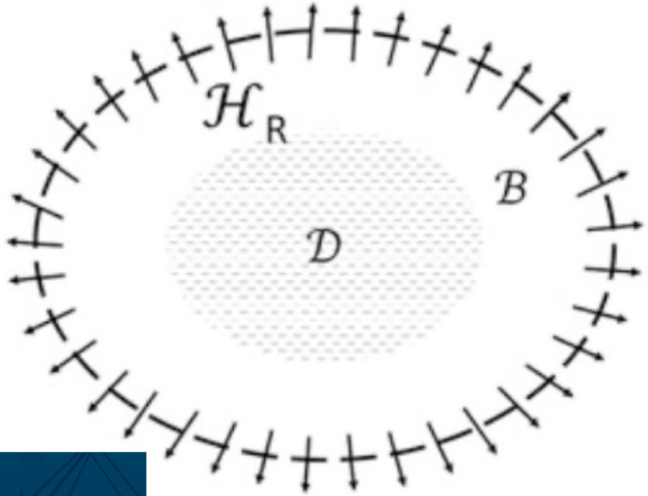
$$N_{cc'}(r,r') = \langle (c,r)|(c',r')\rangle$$

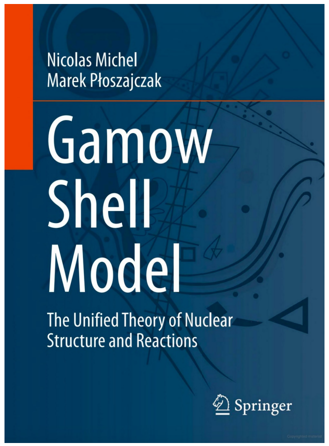
Y. Jaganathen et al, Phys. Rev. C 88, 044318 (2014)
K. Fossez et al., Phys. Rev. C 91, 034609 (2015)
A. Mercenne et al., Phys. Rev. C 99, 044606 (2019)

N. Michel, M.Płoszajczak,
«*Gamow Shell Model: The Unified Theory of Nuclear Structure and Reactions* »
Lecture Notes in Physics, Vol. 983, (Springer Verlag, 2021)

Shell model for open quantum systems

Hermitian QM in rigged Hilbert space





Y. Jaganathen et al, Phys. Rev. C 88, 044318 (2014)
K. Fossez et al., Phys. Rev. C 91, 034609 (2015)
A. Mercenne et al., Phys. Rev. C 99, 044606 (2019)

N. Michel, M.Płoszajczak,
«*Gamow Shell Model: The Unified Theory of Nuclear Structure and Reactions* »
Lecture Notes in Physics, Vol. 983, (Springer Verlag, 2021)

GSM – Coupled-channel representation

$$|\Psi_M^J\rangle = \sum_{\mathrm{c}} \int_0^{+\infty} |(\mathrm{c},r)_M^J\rangle \, \frac{u_{\mathrm{c}}^{JM}(r)}{r} r^2 \, dr$$

$$|(\mathrm{c},r)\rangle = \hat{\mathcal{A}}[|\Psi_{\mathrm{T}}^{J_{\mathrm{T}}}; N_T, Z_T\rangle \otimes |r \; L_{\mathrm{CM}} \; J_{\mathrm{int}} \; J_{\mathrm{P}}; n, z\rangle]_M^J$$

$$H\,|\Psi_M^J\rangle = E\,|\Psi_M^J\rangle \;\Rightarrow\; \sum_{\mathrm{c}} \int_0^{\infty} r^2 \left(H_{\mathrm{cc'}}(r,r') - E N_{\mathrm{cc'}}(r,r')\right) \frac{u_{\mathrm{c}}(r)}{r} = 0$$

$$H_{\mathrm{cc'}}(r,r') = \langle(\mathrm{c},r)|\,\hat{H}\,|(\mathrm{c}',r')\rangle$$

$$N_{\mathrm{cc'}}(r,r') = \langle(\mathrm{c},r)|(\mathrm{c}',r')\rangle$$

- Entrance and exit reaction channels defined
  ➡ Unification of nuclear structure and reactions
- Calculation in relative coordinates of core cluster orbital shell model coordinates. Center-of-mass handled by recoil term in the Hamiltonian
- Scattering wave functions are the many-body states
- Antisymmetry handled

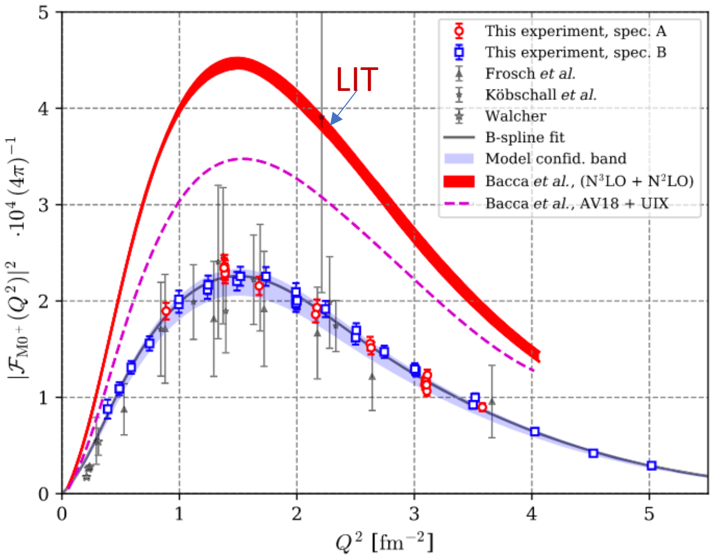
- Reaction channels with different (binary) mass partitions
- Core arbitrary

Puzzle of 0^+ resonance of the α particle

PHYSICAL REVIEW LETTERS **130,** 152502 (2023)

Editors' Suggestion | Featured in Physics

Measurement of the α-Particle Monopole Transition Form Factor Challenges Theory: A Low-Energy Puzzle for Nuclear Forces?



… we observe that modern nuclear forces, including those derived within chiral effective field theory that are well tested on a variety of observables, fail to reproduce the excitation of the **α** particle…

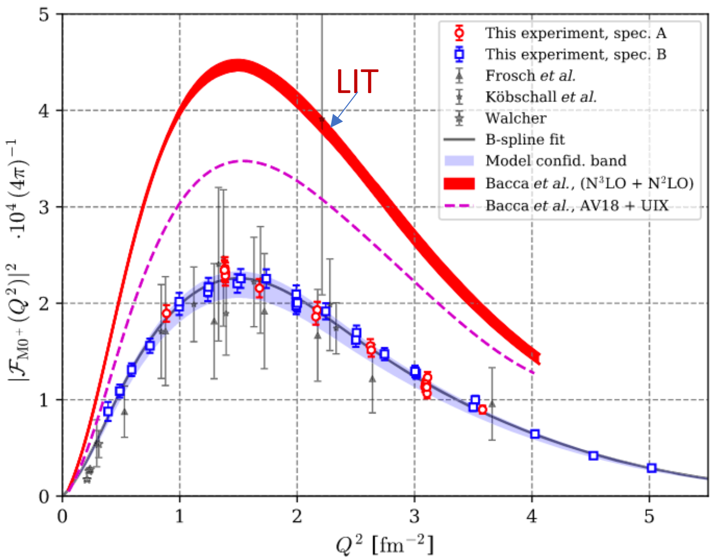
S. Kegel et al., PRL 130, 152502 (2023)

Puzzle of 0^+ resonance of the α particle

PHYSICAL REVIEW LETTERS **130**, 152502 (2023)

Editors' Suggestion | Featured in Physics

Measurement of the α-Particle Monopole Transition Form Factor Challenges Theory: A Low-Energy Puzzle for Nuclear Forces?



… we observe that modern nuclear forces, including those derived within chiral effective field theory that are well tested on a variety of observables, fail to reproduce the excitation of the α particle…

S. Kegel et al., PRL 130, 152502 (2023)

PHYSICS TODAY

Volume 76, Issue 6

1 June 2023

Theory and experiment disagree on alpha particles

Electron-scattering experiments on excited helium nuclei open questions about the accuracy and sensitivity of state-of-the-art nuclear models.

Heather M. Hill

LIVESCIENCE

Scientists tried to solve the mystery of the helium nucleus — and ended up more confused than ever

News By Anna Demming published June 27, 2023

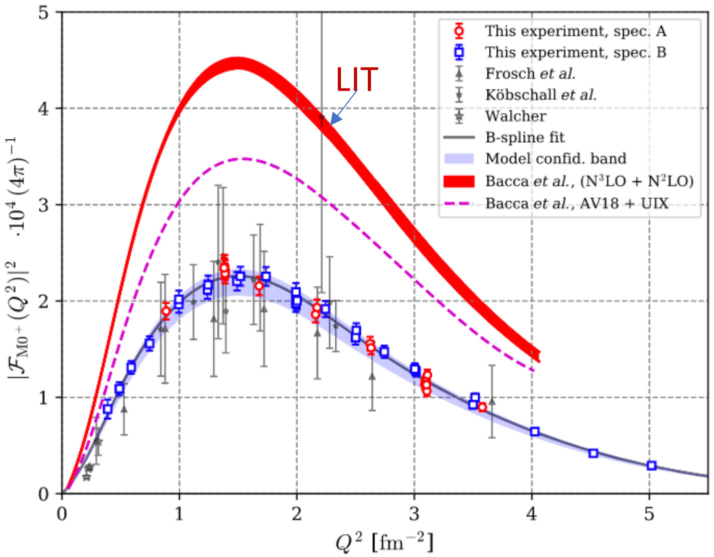
Helium is the simplest element in the periodic table with more than one particle in its nucleus, yet state of the art theory and experiments on it don't add up.

Puzzle of 0+ resonance of the α particle

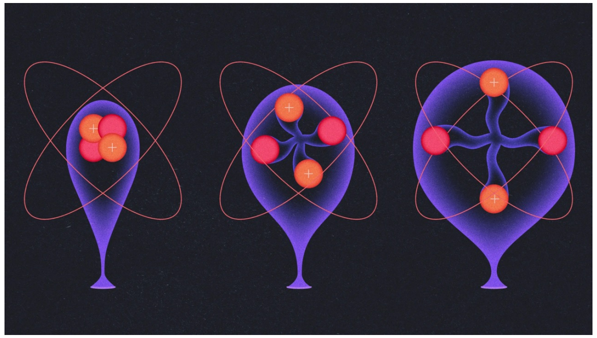
PHYSICAL REVIEW LETTERS **130**, 152502 (2023)

Editors' Suggestion Featured in Physics

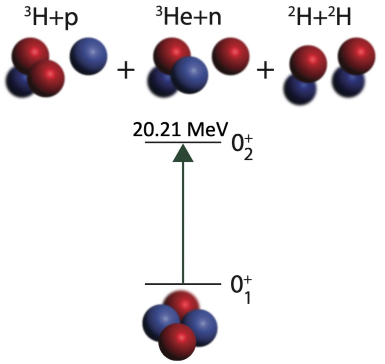
Measurement of the α-Particle Monopole Transition Form Factor Challenges Theory: A Low-Energy Puzzle for Nuclear Forces?



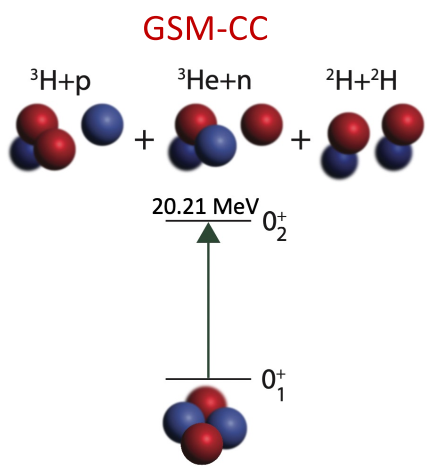
Is the first excited state of ^{4}He really inflating like a balloon?



or it is the cluster state?



Puzzle of 0^+ resonance of the α particle

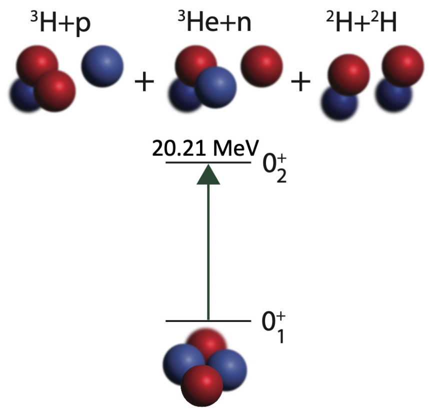


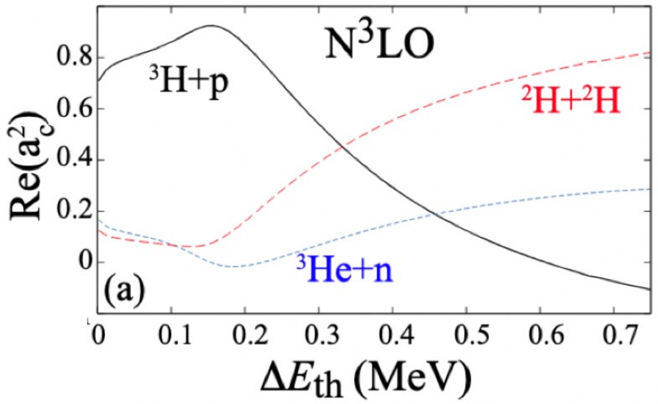
- • χ-EFT N^3LO interaction
- • No-core GSM-CC - full treatment of continuum couplings
- • Since 0+ resonance is proton unbound, its wave function should contain open ^3H+ p component
- • As the neutron and deuteron thresholds lie above, a ^3He+n and $^2H+^2H$ closed channels should also be present
- • Correct threshold energies
- • Correct binding energy of the 0+ resonance

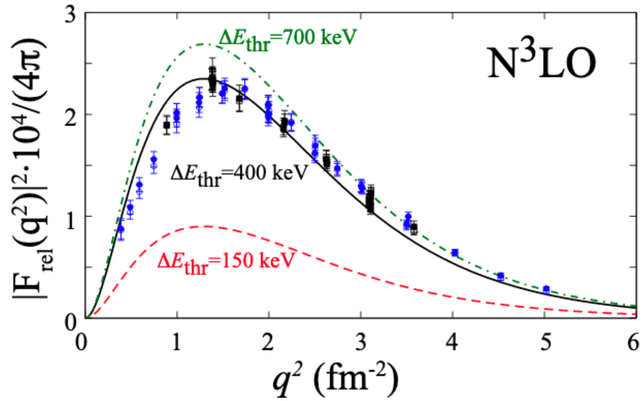
N. Michel, W. Nazarewicz, M. Ploszajczak, Phys. Rev. Lett. 131, 242502 (2023)

Puzzle of 0^+ resonance of the α particle

GSM-CC







- ✚ • χ-EFT N³LO interaction
- ✚ • No-core GSM-CC - full treatment of continuum couplings
- ✚ • Since 0+ resonance is proton unbound, its wave function should contain open ^{3}H+ p component
- ✚ • As the neutron and deuteron thresholds lie above, a ^{3}He+n and ^{2}H+^{2}H closed channels should also be present
- ✚ • Correct threshold energies
- ✚ • Correct binding energy of the 0+ resonance

N. Michel, W. Nazarewicz, M. Ploszajczak, Phys. Rev. Lett. 131, 242502 (2023)

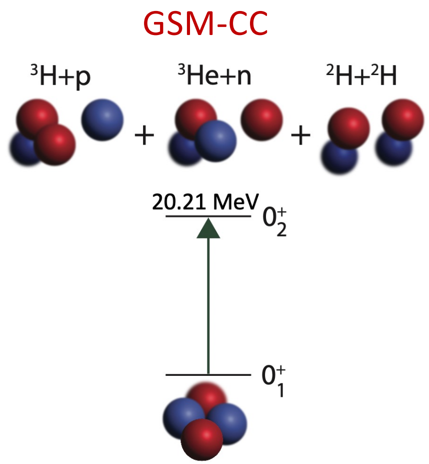
- Strong dependence of normalized channel probabilities on the energy separation from the proton threshold
- At the resonance energy, both ^{3}H+ p and ^{2}H+^{2}H channels are important
- Monopole transition form factor is reproduced using χ-EFT N³LO interaction

  D.R. Entem, R. Machleidt, Phys. Rev. C 68, 041001(R) (2003)

  if the 0^+ resonance is at the experimental energy with respect to the proton threshold

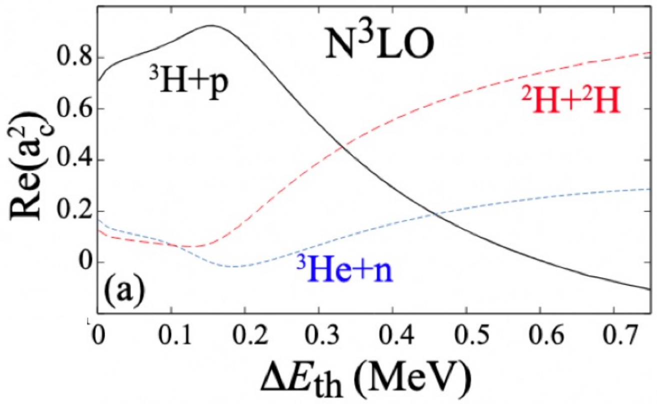
First excited state of ^{4}He is NOT a breathing mode but a mixture of ^{3}H+p and ^{2}H+^{2}H clusters

Puzzle of 0+ resonance of the α particle



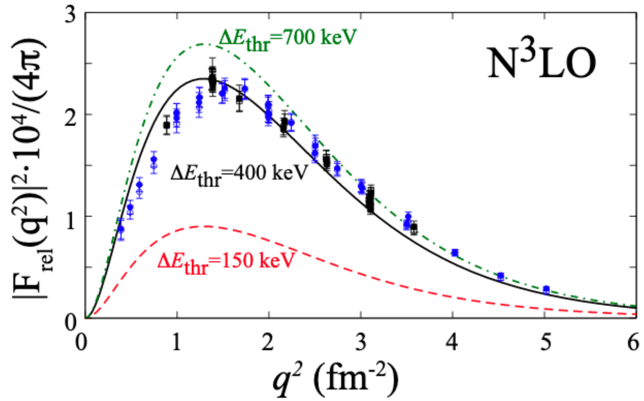
- ✚ • χ-EFT N³LO interaction
- ✚ • No-core GSM-CC - full treatment of continuum couplings
- ✚ • Since 0+ resonance is proton unbound, its wave function should contain open ^{3}H+ p component
- ✚ • As the neutron and deuteron thresholds lie above, a ^{3}He+n and ^{2}H+^{2}H closed channels should also be present
- ✚ • Correct threshold energies
- ✚ • Correct binding energy of the 0+ resonance

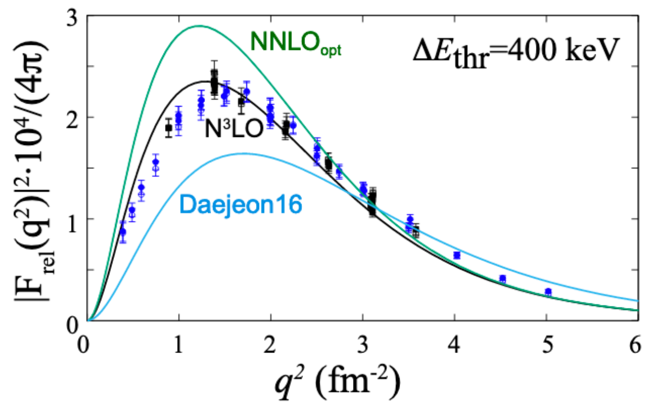
N. Michel, W. Nazarewicz, M. Ploszajczak, Phys. Rev. Lett. 131, 242502 (2023)



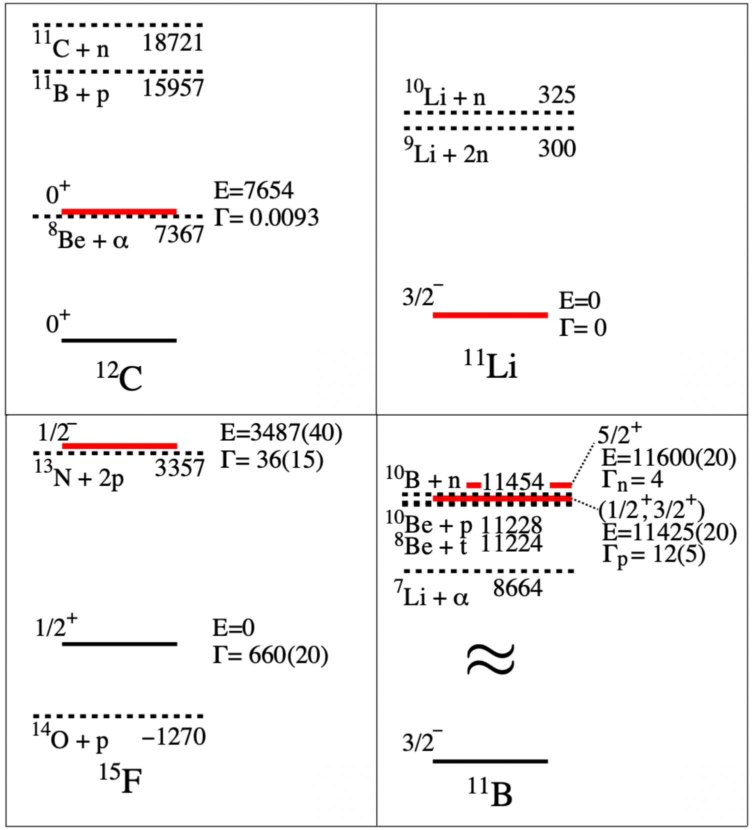
- Strong dependence of normalized channel probabilities on the energy separation from the proton threshold
- At the resonance energy, both ^{3}H+ p and ^{2}H+^{2}H channels are important
- Monopole transition form factor is reproduced using χ-EFT N³LO interaction
  D.R. Entem, R. Machleidt, Phys. Rev. C 68, 041001(R) (2003)
  if the 0+ resonance is at the experimental energy with respect to the proton threshold
- Strong dependence on the variant of the EFT interaction

First excited state of ^{4}He is NOT a breathing mode but a mixture of ^{3}H+p and ^{2}H+^{2}H clusters



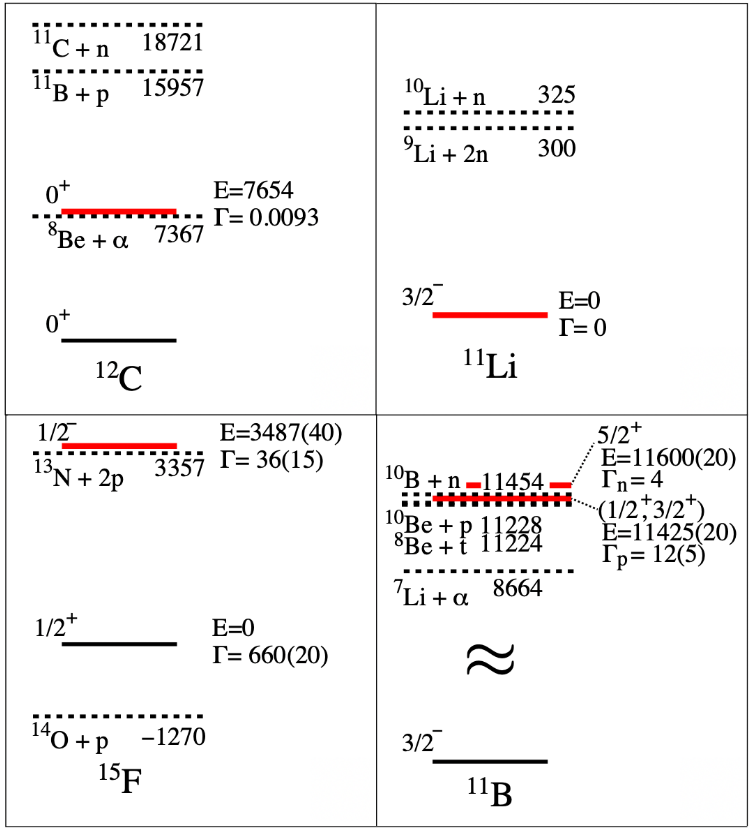


Near-threshold states and origin of clustering



- Other cases: ^{5}He, ^{5}Li, ^{6}He, ^{6}Li, ^{7}Be, ^{7}Li, ^{11}O, ^{11}C, ^{17}O, ^{20}Ne, ^{26}O, …
- Various clusterings: ^{2}H, ^{3}He, ^{3}H, 2p, 2n
- *Astrophysical relevance* of near-threshold resonances for α- and proton-capture reactions of nucleosynthesis

Near-threshold states and origin of clustering



Is the appearance of correlated states close to open channels 'fortuitous' ?

➡ They cannot result from any particular feature of the NN interaction or any dynamical symmetry of the nuclear many-body problem

Open quantum system perspective

The correlated (cluster) states in a vicinity of reaction channel thresholds are the generic manifestations of *quantum openness* of a many-body system related to the *collective rearrangement* of (shell model) wave functions due to their mutual coupling via the continuum

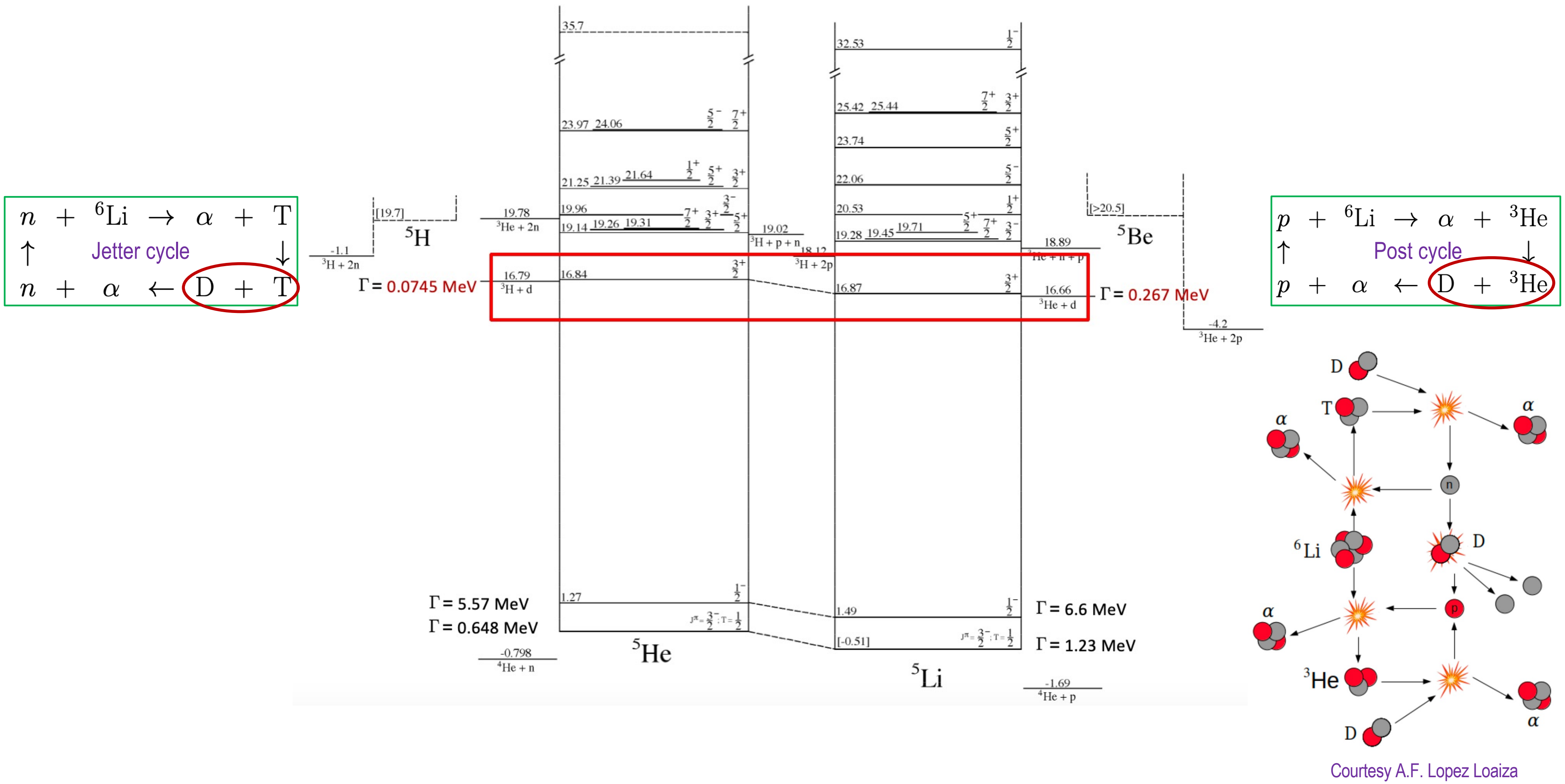
Specific aspects of clusterization

- Energetic order of particle emission thresholds which depends on nuclear Hamiltonian
- Absence of stable cluster entirely composed of like nucleons

J. Okołowicz, M. Płoszajczak, W. Nazarewicz, Prog. Theor. Phys. Suppl. 196, 230 (2012); Fortschr. Phys. 61, 66 (2013)

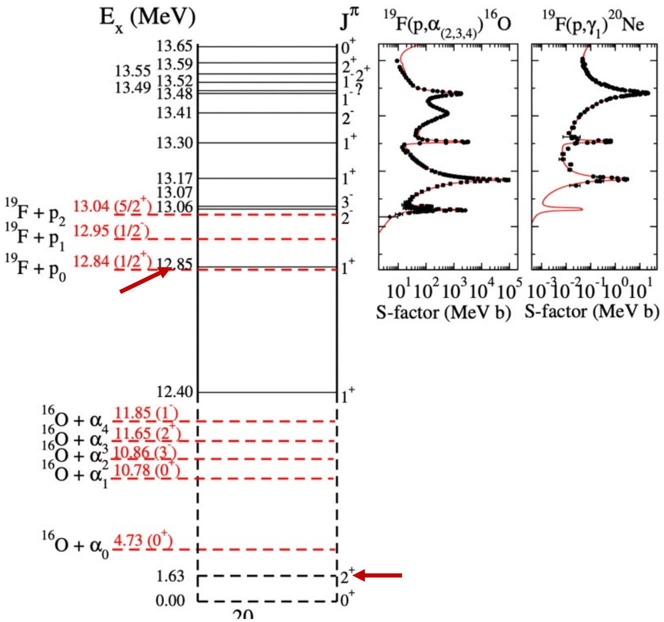
- Other cases: ^{5}He, ^{5}Li, ^{6}He, ^{6}Li, ^{7}Be, ^{7}Li, ^{11}O, ^{11}C, ^{17}O, ^{20}Ne, ^{26}O, …
- Various clusterings: ^{2}H, ^{3}He, ^{3}H, 2p, 2n
- *Astrophysical relevance* of near-threshold resonances for α- and proton-capture reactions of nucleosynthesis

^{5}He, ^{5}Li and fusion

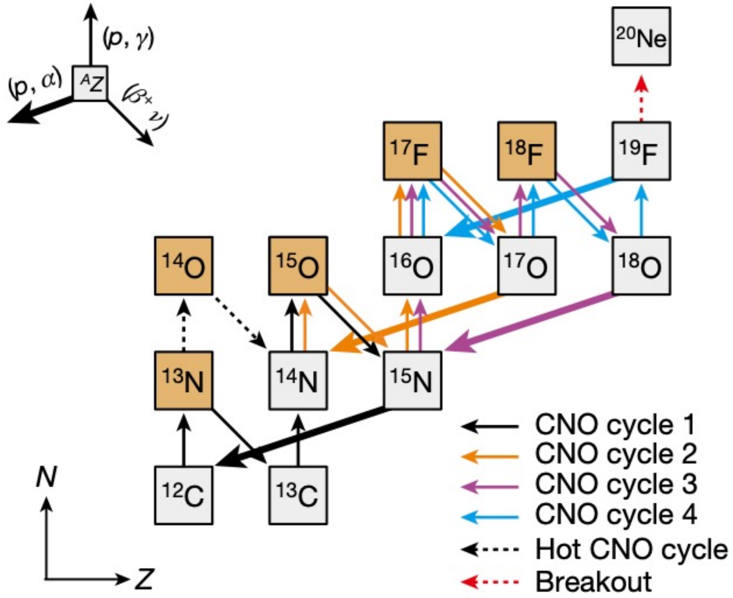


Near-threshold resonances in ^{20}Ne and their role for ^{19}F(p,γ)^{20}Ne and ^{19}F(p,α)^{16}O reaction rates

R.J. DeBoer et al, Nature 610, 656 (2022)



What is the effect of 1⁺ resonance at ~10 keV above the proton emission threshold on the S-factor?

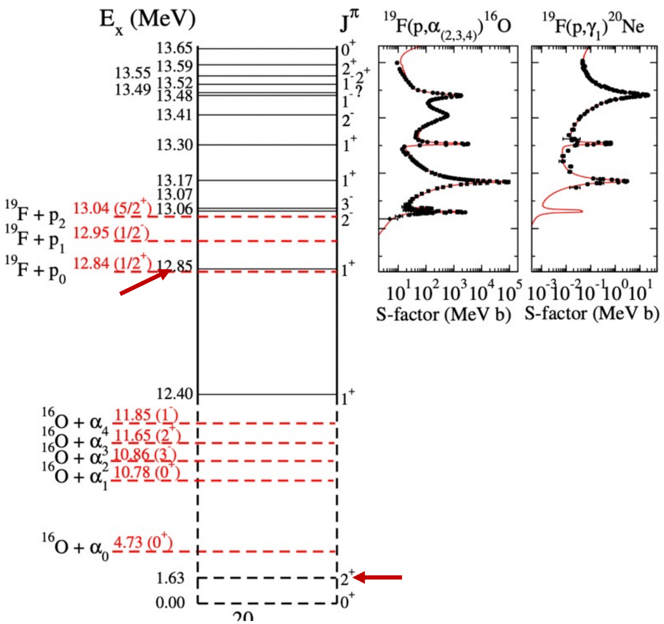


Liyong Zhang et al., Nature 610, 656 (2022)

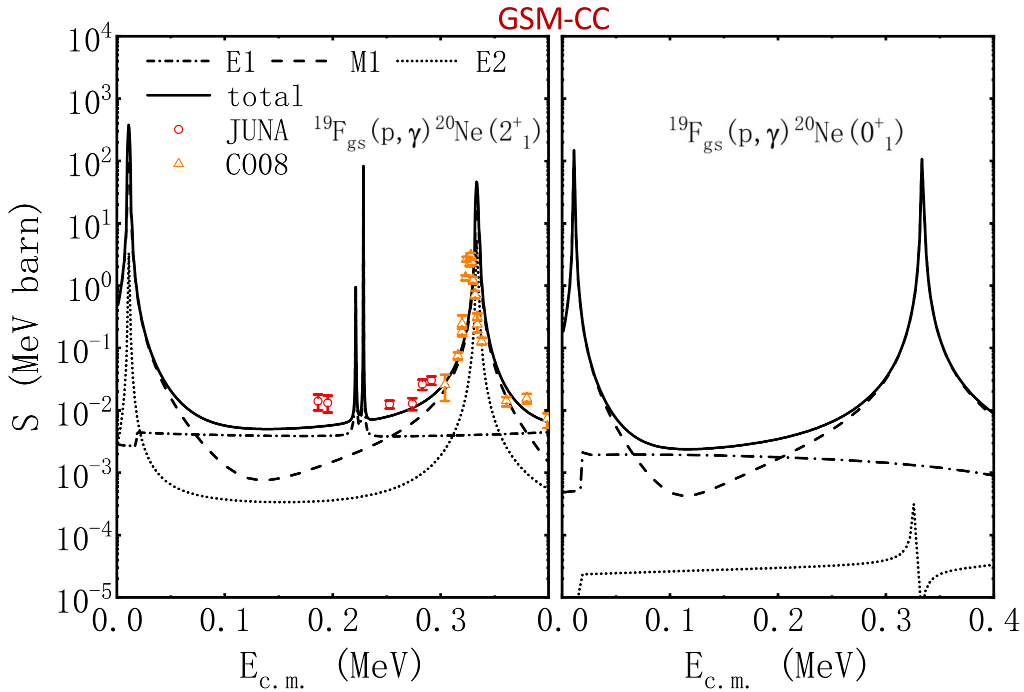
Can Ca be produced in hot-CNO cycle?

Near-threshold resonances in ^{20}Ne and their role for $^{19}F(p,\gamma)^{20}Ne$ and $^{19}F(p,\alpha)^{16}O$ reaction rates

R.J. DeBoer et al, Nature 610, 656 (2022)



What is the effect of 1⁺ resonance at ~10 keV above the proton emission threshold on the S-factor?



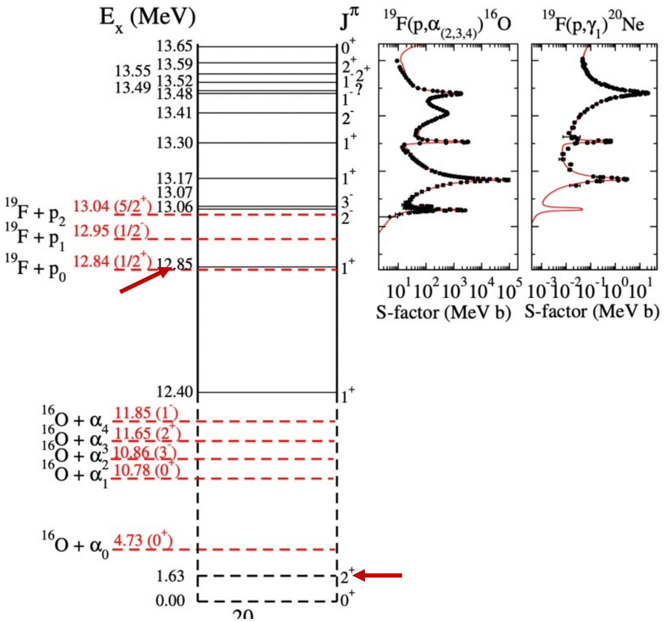
Exp: Liyong Zhang et al., Nature 610, 656 (2022)

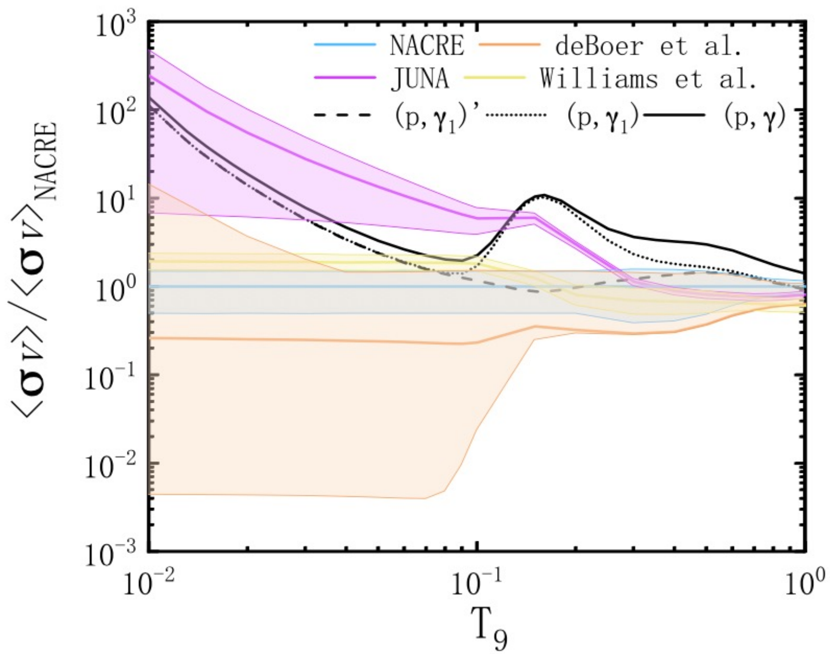
- S(0) astrophysical factor increases by more than 2 orders of magnitude!
- The decay to the 2+ first excited state in ^{20}Ne dominates

X.B. Wang, G.X. Dong, N. Michel, M. Płoszajczak (2024)

Near-threshold resonances in ^{20}Ne and their role for $^{19}F(p,\gamma)^{20}Ne$ and $^{19}F(p,\alpha)^{16}O$ reaction rates

R.J. DeBoer et al, Nature 610, 656 (2022)





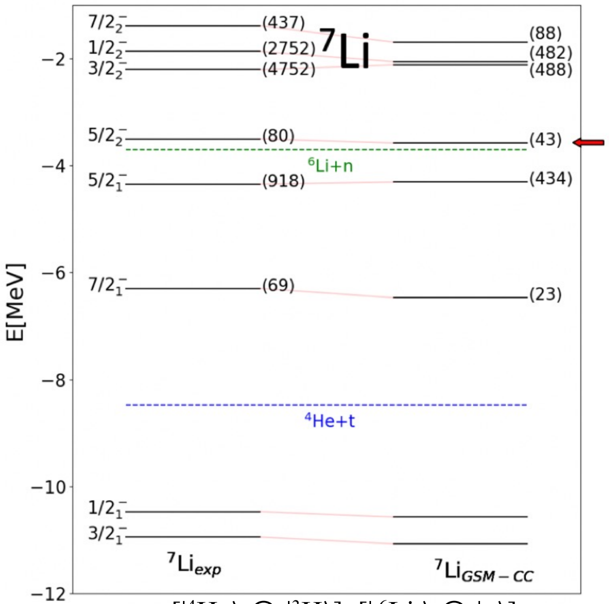
What is the effect of 1^+ resonance at ~10 keV above the proton emission threshold on the S-factor?

GSM-CC reaction rates significantly larger than in NACRE and comparable with JUNA data so it can overcome $^{19}F(p,\alpha)^{16}O$ back-process reaction cross-section

→ $^{19}F(p,\gamma)^{20}Ne$ breakout reaction from the CNO cycle could become a source of the calcium abundance in the first generation stars

Mimicry mechanism of clusterization

Chameleon nature of resonances

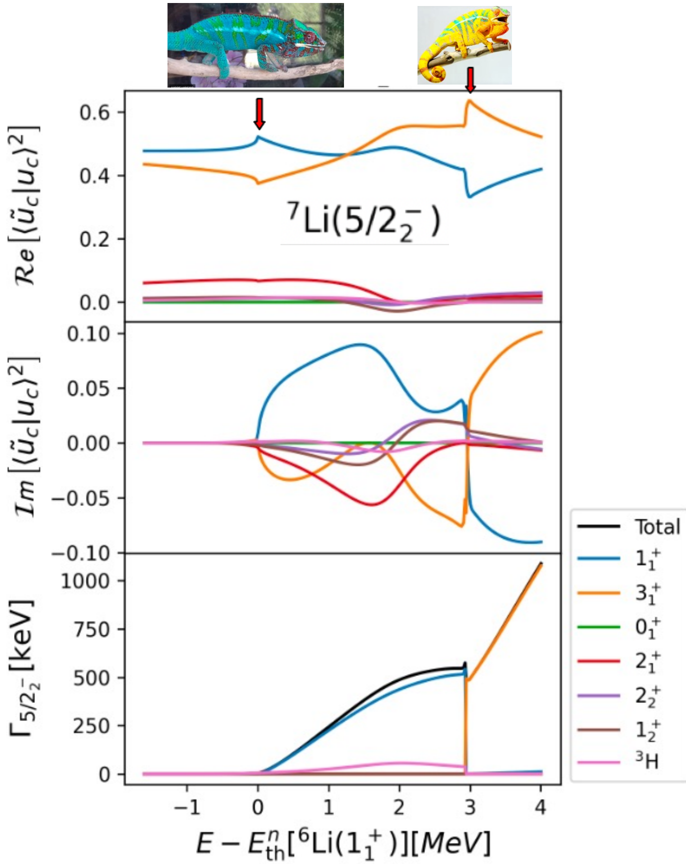


$[|^4\mathrm{He}\rangle \otimes |^3\mathrm{H}\rangle]$, $[|^6\mathrm{Li}\rangle \otimes |n\rangle]$

- Hamiltonian: 1-body potential, 2-body FHT interaction
  ^{3}H wave functions calculated using N^{3}LO$_{(2\text{-body})}$ interaction

H. Furutani et al, Prog. Theor. Phys. 62, 981 (1979)

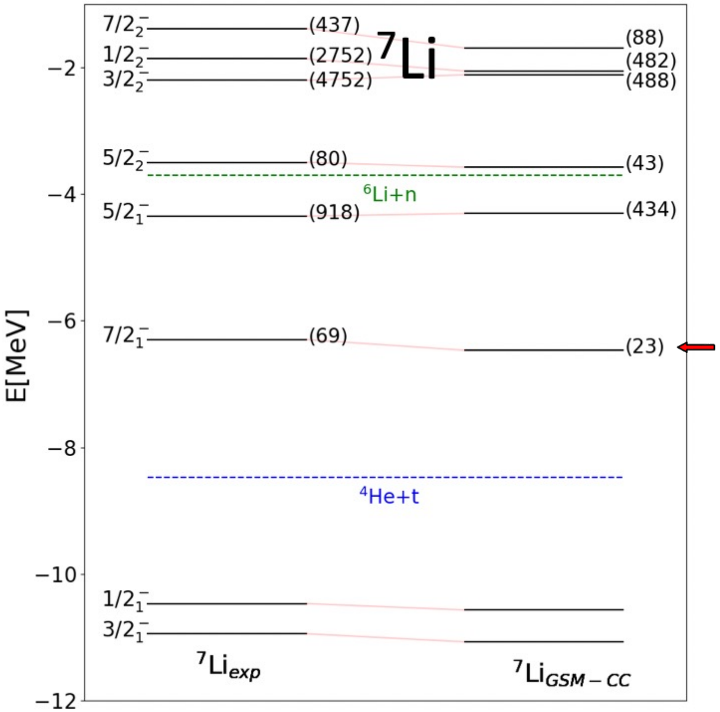
- Channels: ^{6}Li(K^π): $K^\pi = 1_1^+, 1_2^+, 3_1^+, 0_1^+, 2_1^+, 2_2^+$
  n: ℓ_j = $s_{1/2}$, $p_{1/2}$, $p_{3/2}$, $d_{3/2}$, $d_{5/2}$, $f_{5/2}$, $f_{7/2}$
  ^{3}H(L): L ≡ $^{2\mathrm{Jint}+1}[L_{CM}]_{JP}$ = $^2S_{1/2}$, $^2P_{1/2}$, $^2P_{3/2}$, $^2D_{3/2}$, $^2D_{5/2}$, $^2F_{5/2}$, $^2F_{7/2}$



- The *'chameleon'* resonance changes its structure/property as a result of the alignment (*mimicry*) with the nearby new reaction channel (*changing environment*)

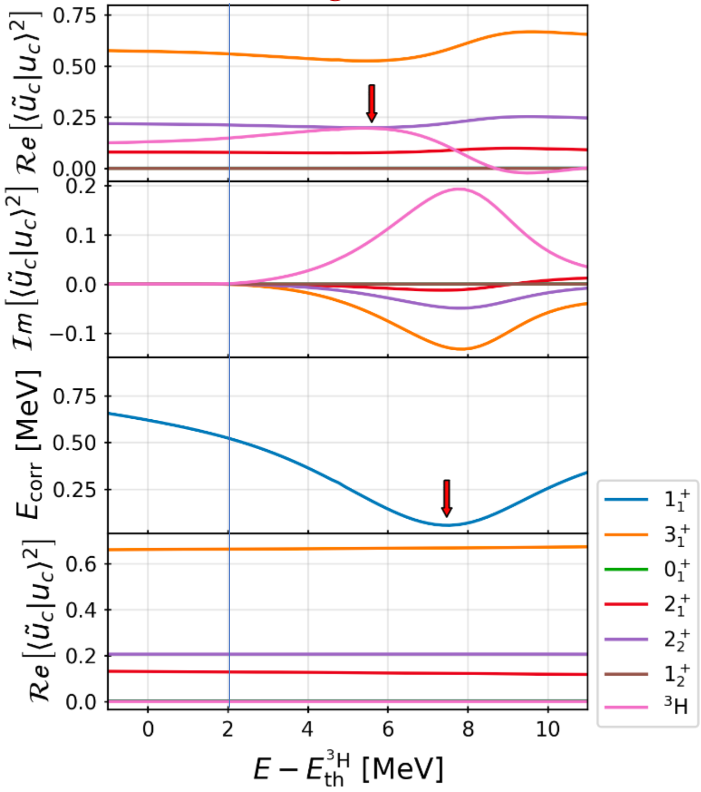
J.P. Linares Fernandez, et al, Phys. Rev. C 108, 044616 (2023)

Rise and fall of triton-clustering in ^{7}Li



$[|^4\mathrm{He}\rangle \otimes |^3\mathrm{H}\rangle], [|^6\mathrm{Li}\rangle \otimes |\mathrm{n}\rangle]$

Near-threshold *alignment* of ^{7}Li($7/2_1^-$)



- Strong influence of the *centrifugal barrier (ℓ=3)* on alignment and ^{3}H-clusterization
- Weak ^{3}H-clusterization in $7/2_1^-$ state

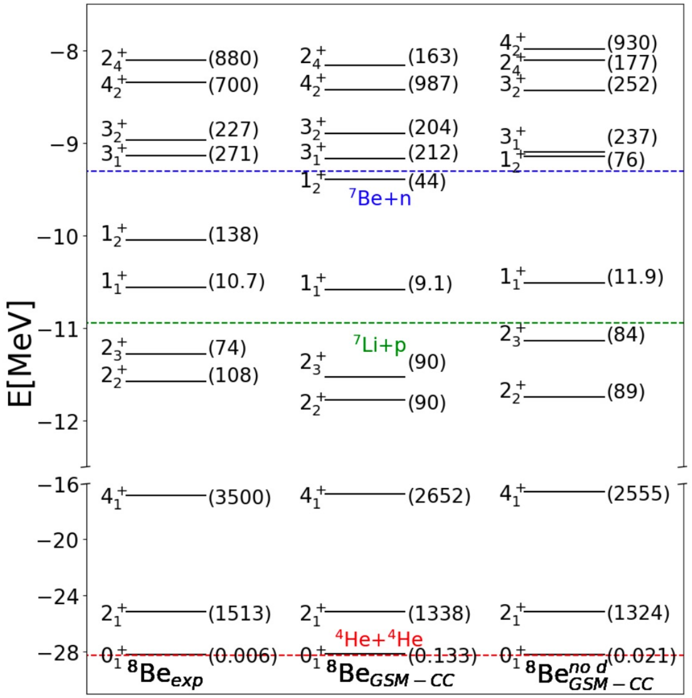
J.P. Linares Fernandez, et al, Phys. Rev. C 108, 044616 (2023)

Near-threshold clustering in ^{8}Be

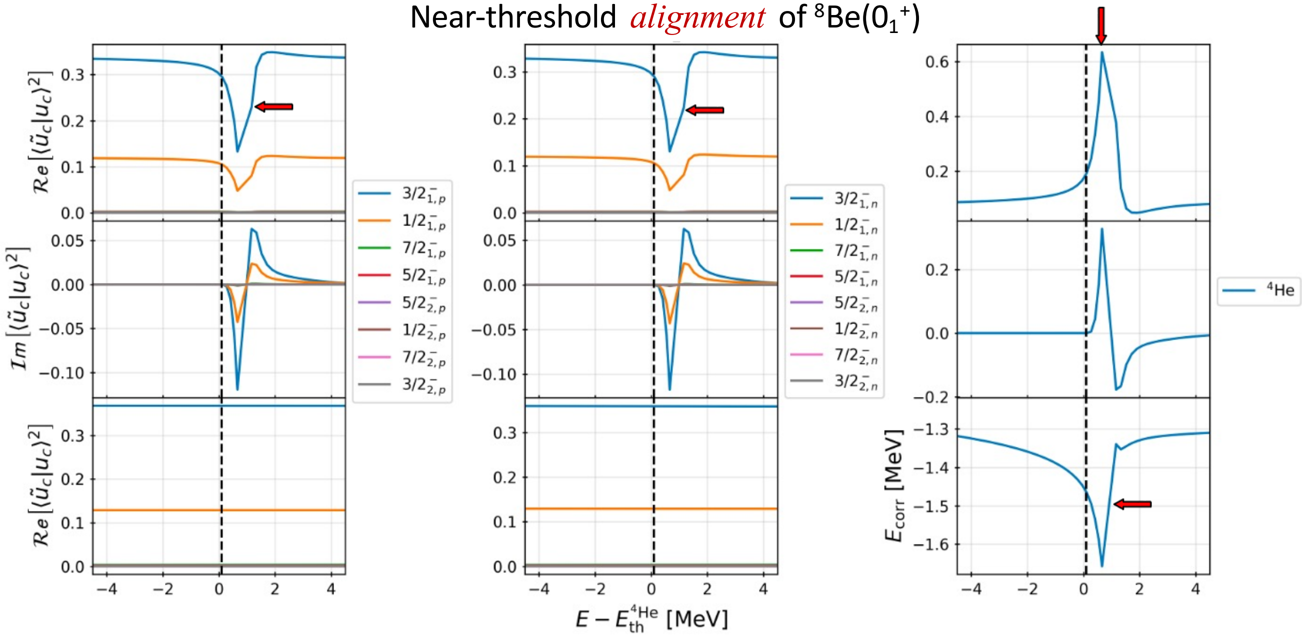
Continuum coupling correlation energy ➡ $E^{(\text{corr})}_{J^\pi,M} = \langle \tilde{\Psi}^J_M | H | \Psi^J_M \rangle - \langle \tilde{\Phi}^{J;(\alpha)}_M | H | \Phi^{J;(\alpha)}_M \rangle \equiv \mathcal{E}_{J^\pi,M} - \mathcal{E}^{(\alpha)}_{J^\pi,M}$

$$|\Phi^{J;(\alpha)}_M\rangle = \sum_{c;c\neq\alpha} \int_0^{+\infty} |(c,r)^J_M\rangle \frac{\bar{u}^{JM}_c(r)}{r} r^2\, dr$$

^{8}Be



Near-threshold *alignment* of ^{8}Be(0_1^+)

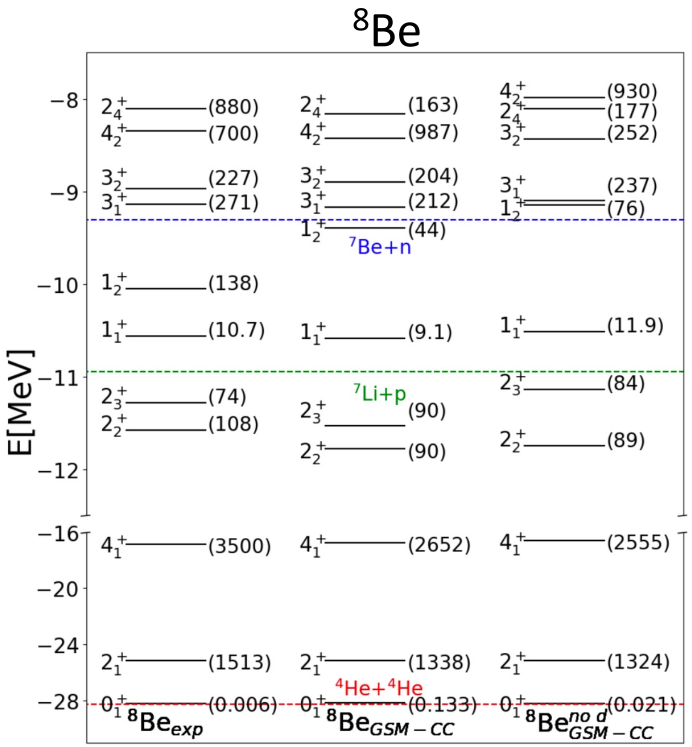


Mass partitions:
$[|^4\text{He}\rangle \otimes |^4\text{He}\rangle]$, $[|^7\text{Li}\rangle \otimes |p\rangle]$, $[|^7\text{Be}\rangle \otimes |n\rangle]$, $[|^6\text{Li}\rangle \otimes |d\rangle]$

Near-threshold clustering is the *emergent phenomenon* in SM for open quantum systems

J.P. Linares Fernandez, et al, Phys. Rev. C 108, 044616 (2023)

Near-threshold clustering in ^{8}Be



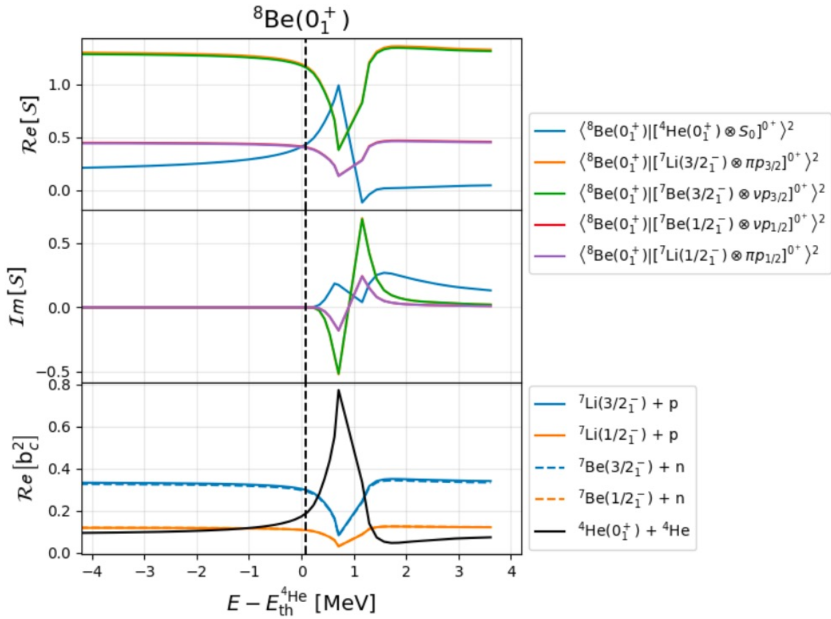
Mass partitions:

$[|^4\mathrm{He}\rangle \otimes |^4\mathrm{He}\rangle]$, $[|^7\mathrm{Li}\rangle \otimes |\mathrm{p}\rangle]$, $[|^7\mathrm{Be}\rangle \otimes |\mathrm{n}\rangle]$, $[|^6\mathrm{Li}\rangle \otimes |\mathrm{d}\rangle]$

Spectroscopic factor (GSM-CC)

$$S^2_{L_{CM}J_P} = \int_0^{+\infty} u_c(r)^2\,dr + \left[\sum_{N_{CM}} \mathcal{A}^2_{L_{CM}J_P}(N_{CM}) - \int_0^{+\infty} u_c(r)^2\,dr\right]^{(HO)}$$

$$\mathcal{A}_{L_{CM}J_P}(N_{CM}) = \frac{\langle \Psi_A || A^\dagger_{N_{CM}L_{CM}J_P} || \Psi_{A-k}\rangle}{\sqrt{2J_A+1}}$$



Near-threshold clustering is the *emergent phenomenon* in SM for open quantum systems

J.P. Linares Fernandez, et al, Phys. Rev. C 108, 044616 (2023)

Message to take

- Two generic clusterization mechanisms have been identified in atomic nucleus:
  - the statistical mechanism of clusterization rooted in the CLT
  - the quantum mimicry mechanism of near-threshold clusterization

- Two generic clusterization mechanisms have been identified in atomic nucleus:
  - the statistical mechanism of clusterization rooted in the CLT
  - the quantum mimicry mechanism of near-threshold clusterization

Is the heavy-cluster radioactivity governed by the quantum mimicry mechanism?

Emitter	Cluster	Q(MeV)	Detection System	$B = \lambda_{cl}/\lambda_\alpha$	$\lg_{10} T(s)$
^{231}Pa	^{24}Ne	60.42	BP1	$(1.34 \pm 0.17)10^{-11}$	22.88
^{230}U	^{22}Ne	61.40	BP1	$(4.8 \pm 2.0)10^{-14}$	19.57
^{232}U	^{24}Ne	62.31	PET	$(2.0 \pm 0.5)10^{-12}$	21.08
^{232}U	^{24}Ne	62.31	PSK50	$(8.68 \pm 0.93)10^{-12}$	20.42
^{232}U	^{24}Ne	62.31	PSK50	$(9.16 \pm 1.10)10^{-12}$	20.40
^{233}U	^{24,25}Ne	60.50,60.75	PET	$(7.5 \pm 2.5)10^{-13}$	24.83
^{233}U	^{24,25}Ne	60.50,60.75	PSK50	$(7.2 \pm 0.9)10^{-13}$	24.84
^{234}U	^{24,26}Ne	58.84,59.47	PSK50	$(9.06 \pm 6.60)10^{-14}$	25.92
^{234}U	^{24,26}Ne	58.84,59.47	PET	$(9.90 \pm 9.90)10^{-14}$	25.88
^{235}U	^{24,25}Ne	57.36,57.83	PET	$(8.06 \pm 4.32)10^{-12}$	27.42
^{236}U	^{24,26}Ne	55.96,56.75	PET	$< 9.2 \cdot 10^{-12}$	>25.90
^{232}U	^{28}Mg	74.32	PSK50	$< 1.18 \cdot 10^{-13}$	>22.26
^{233}U	^{28}Mg	74.24	PSK50	$< 1.30 \cdot 10^{-15}$	>27.59
^{234}U	^{28}Mg	74.13	PET	$(2.3^{+0.8}_{-0.6}$	27.54
^{234}U	^{28}Mg	74.13	PSK50	$(1.38 \pm 0.25)10^{-13}$	25.14
^{235}U	^{28,29}Mg	72.20,72.61	PET	$< 1.8 \cdot 10^{-12}$	>28.09
^{236}U	^{28,30}Mg	71.69,72.51	PET	$2.0 \cdot 10^{-13}$	27.58
^{237}Np	^{30}Mg	75.02	PET	$< 8.0 \pm 10^{-14}$	>26.93
^{237}Np	^{30}Mg	75.02	PSK50	$< 1.8 \cdot 10^{-14}$	>27.57
^{236}Pu	^{28}Mg	79.67	PET	$2.0 \cdot 10^{-14}$	21.67
^{236}Pu	^{28}Mg	79.67	PHOSP. GLASS	$(2.7 \pm 0.7)10^{-14}$	21.52
^{238}Pu	^{28,30}Mg	75.93,77.03	LG750	$(5.62 \pm 3.97)10^{-17}$	25.70
^{238}Pu	^{32}Si	91.21	LG750	$(1.38 \pm 0.50)10^{-16}$	25.27
^{240}Pu	^{34}Si	90.95	PET	$< 6 \cdot 10^{-15}$	>25.52
^{241}Am	^{34}Si	93.84	POLY	$< 2.6 \cdot 10^{-13}$	>22.71
^{241}Am	^{34}Si	93.84	PET	$< 5.4 \cdot 10^{-15}$	>24.41
^{241}Am	^{34}Si	93.84	LG750	$< 7.4 \cdot 10^{-16}$	>25.26
^{242}Cm	^{34}Si	96.53	LG750, GOI-104	10^{-16}	23.15

Emitter	Cluster	Q(MeV)	Detection System	$B = \lambda_{cl}/\lambda_\alpha$	$\lg_{10} T(s)$
^{114}Ba	^{12}C	18.3-20.5	POLY	$< 10^{-4}$	> 3.63
^{114}Ba	^{12}C	18.3-20.5	BP1	$< 3.4 \cdot 10^{-5}$	> 4.10
^{221}Fr	^{14}C	31.28	BP1	$(8.14 \pm 1.14)10^{-13}$	14.52
^{221}Ra	^{14}C	32.39	BP1	$(1.15 \pm 0.91)10^{-12}$	13.39
^{222}Ra	^{14}C	33.05	POLY	$(3.7 \pm 0.6)10^{-10}$	11.01
^{222}Ra	^{14}C	33.05	SOLENO	$(3.1 \pm 1.0)10^{-10}$	11.09
^{222}Ra	^{14}C	33.05	SOLENO	$(2.3 \pm 0.3)10^{-10}$	11.22
^{223}Ra	^{14}C	31.85	$E \times \Delta E$	$(8.5 \pm 2.5)10^{-10}$	15.06
^{223}Ra	^{14}C	31.85	SOLENO	$(5.5 \pm 2.0)10^{-10}$	15.25
^{223}Ra	^{14}C	31.85	$E \times \Delta E$	$(7.6 \pm 3.0)10^{-10}$	15.11
^{223}Ra	^{14}C	31.85	POLY	$(6.1 \pm 1.0)10^{-10}$	15.20
^{223}Ra	^{14}C	31.85	SPLIT-POLE	$(4.7 \pm 1.3)10^{-10}$	15.32
^{223}Ra	^{14}C	31.85	SOLENO	$(6.4 \pm 0.4)10^{-10}$	15.19
^{223}Ra	^{14}C	31.85	SOLENO	$(7.0 \pm 0.4)10^{-10}$	15.14
^{223}Ra	^{14}C	31.85	SOLENO	$(8.9 \pm 0.4)10^{-10}$	15.04
^{224}Ra	^{14}C	30.54	POLY	$(4.3 \pm 1.2)10^{-11}$	15.86
^{224}Ra	^{14}C	30.54	SOLENO	$(6.5 \pm 1.0)10^{-11}$	15.68
^{225}Ac	^{14}C	30.48	BP1	$(6.0 \pm 1.3)10^{-12}$	17.16
^{225}Ac	^{14}C	30.48	BP1	$(4.5 \pm 1.4)10^{-12}$	17.28
^{226}Ra	^{14}C	28.21	SOLENO	$(3.2 \pm 1.6)10^{-11}$	21.19
^{226}Ra	^{14}C	28.21	POLY	$(2.9 \pm 1.0)10^{-11}$	21.24
^{226}Ra	^{14}C	28.21	POLY	$(2.3 \pm 0.8)10^{-11}$	21.34
^{228}Th	^{20}O	44.72	BP1	$(1.13 \pm 0.22)10^{-13}$	20.72
^{231}Pa	^{23}F	51.84	BP1	$(9.97^{+22.9}_{-8.28}$	26.02
^{230}Th	^{24}Ne	57.78	PET	$(5.6 \pm 1.0)10^{-13}$	24.61
^{232}Th	^{24,26}Ne	55.62,55.97	PET	$< 2.82 \cdot 10^{-12}$	>29.20
^{231}Pa	^{24}Ne	60.42	PET	$6 \cdot 10^{-12}$	23.23

- Two generic clusterization mechanisms have been identified in atomic nucleus:
  - the statistical mechanism of clusterization rooted in the CLT
  - the quantum mimicry mechanism of near-threshold clusterization

- Quantum systems in the vicinity of a particle emission threshold belong to the category of *open quantum systems* having unique properties which distinguish them from well-bound *closed quantum systems*

- Proximity of the threshold (branching point) induces the collective mixing of eigenstates resulting in a single aligned eigenstate of the open quantum system Hamiltonian (→ *chameleon resonance*)

- Chameleon resonances are important astrophysically

- The correlated (cluster) states in a vicinity of reaction channel thresholds are the generic manifestations of *quantum openness* of a many-body system related to the *collective rearrangement* of wave functions due to their mutual coupling via the continuum. Clustering is the *emergent phenomenon* associated with the **branch point singularity** at the particle emission threshold
  ➡ Essential role of the *unitarity*!

- The richness of nuclear interaction and the existence of nucleons in four distinct states (proton/neutron, spin-up/spin-down) make studies on the near-threshold phenomena in atomic nucleus unique

In collaboration with:

Robert Botet		CNRS/UNIV. Paris-Sud
Witek Nazarewicz		MSU/FRIB East Lansing, USA
Nicolas Michel		IMP/CAS Lanzhou/Beijin, China
Jose Pablo Linares		LSU Baton Rouge, USA
Jacek Okołowicz		INP Kraków, Poland
Alexis Mercenne		LSU Baton Rouge, USA
Xiaobao Wang		Huzhou University
Guoxiang Dong		Huzhou University

Thank You