Discussion session on:

Nuclear structure, short-range correlations, and clustering from direct reactions

- Possibility to examine the transportation model by charge-changing reactions at intermediate energies
  Baohua Sun

- Nuclear structure inputs to constrain the symmetry energy – The complex pattern of the pygmy resonance
  Marine Vandebrouck

- Implications of PREX-II and CREX experiments for relativistic nuclear energy density functionals
  Esra Yuksel

- Intertwined quantum phase transitions in even-even and odd-mass nuclei
  Noam Gavrielov

- Investigations on the Pygmy Dipole Resonance and implications on the EOS symmetry energy
  Nunzia Simona Martorana

- Microscopic determination of the isospin symmetry breaking energy density functional
  Tomoya Naito

- The Mainz Radius EXperiment (MREX): setup optimization and uncertainty prediction
  Nikita Kozyrev

- PREX and CREX: Evidence for Strong Isovector Spin-Orbit Interaction
  Zhen Zhang

Pygmy dipole resonance

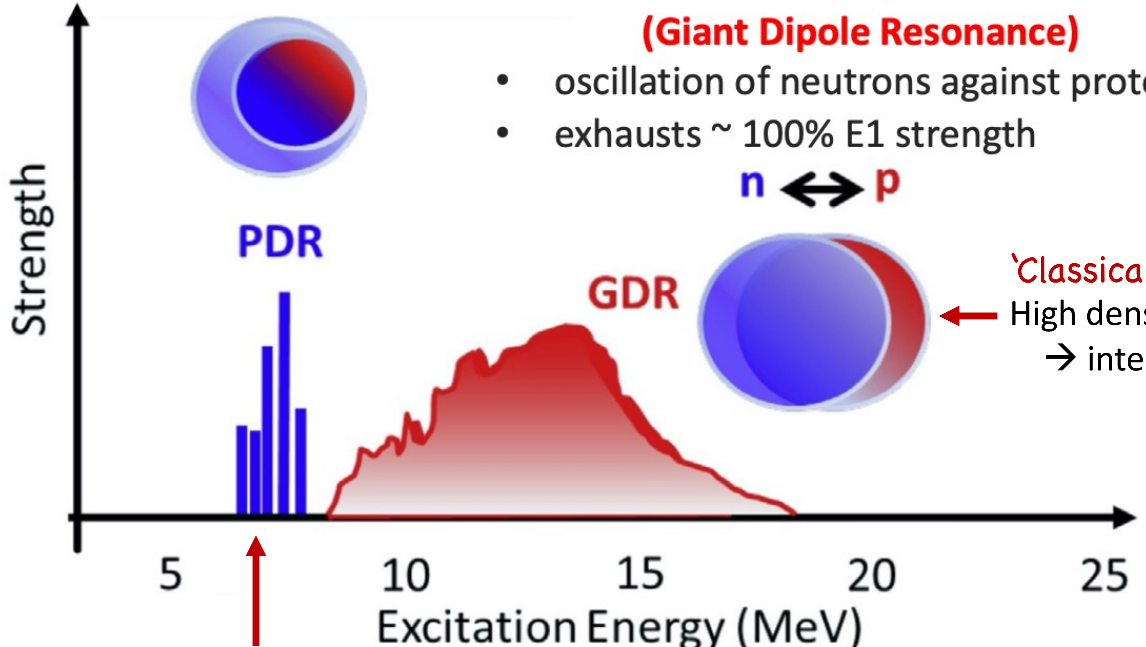
PDR
(Pygmy Dipole Resonance)

- oscillation of a neutron skin against a symmetric proton/neutron core ?
- additionnal E1 strength at lower energy

Marine Vandebrouck
Nunzia Simona Martorani

GDR
(Giant Dipole Resonance)

- oscillation of neutrons against protons
- exhausts ~ 100% E1 strength



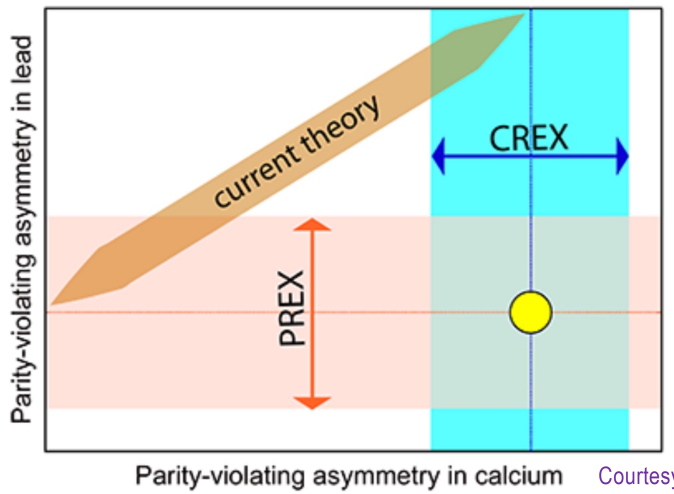
'Classical' regime
High density of states and reaction channels
→ interpretation as a vibrational mode

Courtesy of M. Vandebrouck

Quantal regime

- Important role of continuum coupling
- Interplay of two collectivities: conventional coherent p-h (SM) induced collectivity and collectivity due to the interaction through decay channels V. Zelevinsky
- New probes are necessary to resolve the complexity of PDR
  → Systematic studies of the competition between particle and EM decays

Tension between PREX and CREX



Courtesy of Zhen Zhang

Zhen Zhang et al.
Nikita Kozyrev, et al.
Esra Yüksel et al

R_n-R_p = 0.283 +/- 0.71 fm in ^{208}Pb

R_n-R_p = 0.121 +/- 0.026 +/- 0.024 fm in ^{48}Ca

https://frib.msu.edu/news/2022/prl-paper.html

- Tension between the results of CREX and PREX measurements and the predictions of current global models.

Is the strong isovector spin-orbit coupling (> 240 MeV fm^5) a solution to the tension between CREX and PREX?

- **Such a strong isovector spin-orbit interaction is expected to have significant impacts on essentially all properties of neutron-rich nuclei: The location of neutron-drip line, shell evolution in exotic nuclei, the new magic number, the properties of superheavy nuclei, …** Zhen Zhang et al.

... but Esra Yüksel affirms that the new RNEDFs cannot provide a description for ^{48}Ca and ^{208}Pb simultaneously!

Answer at the next NUSYM workshop?

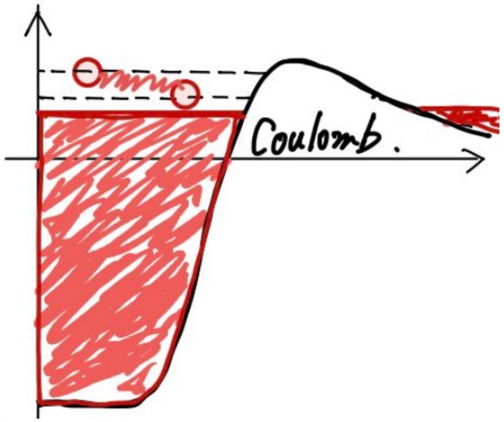
Phenomenon of nuclear clusterization

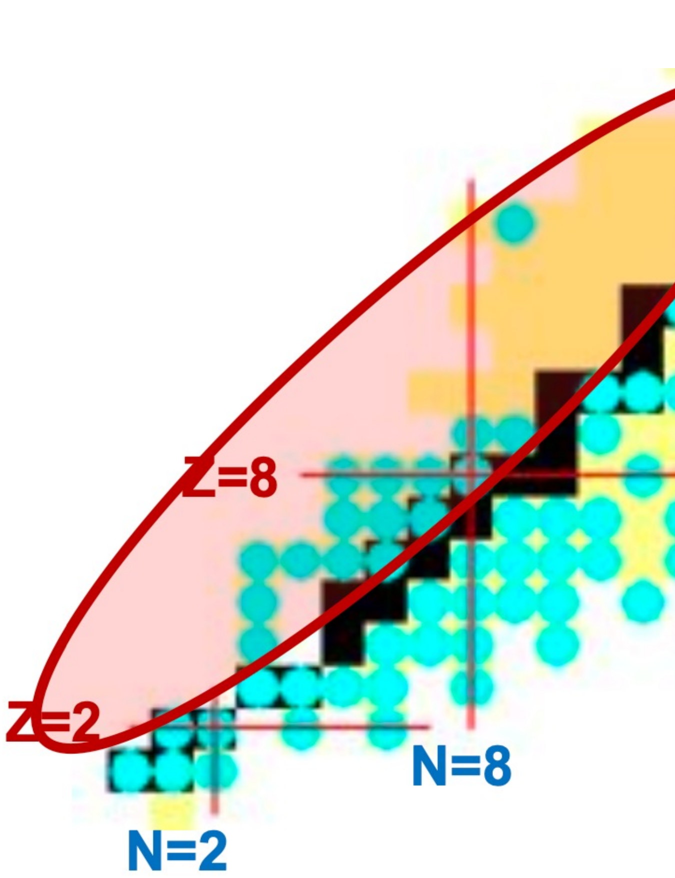
Near-told states and origin of clustering

Beyond proton dripline

Correlation > Mean-field

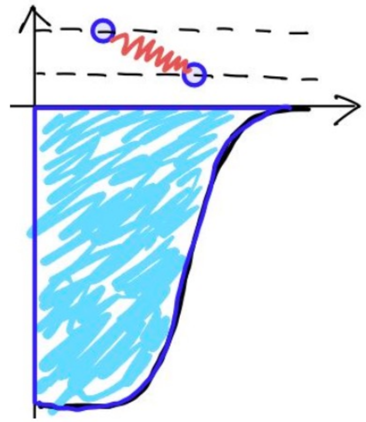
Coulomb ≃ Nuclear





Beyond neutron dripline

Correlation > Mean-field

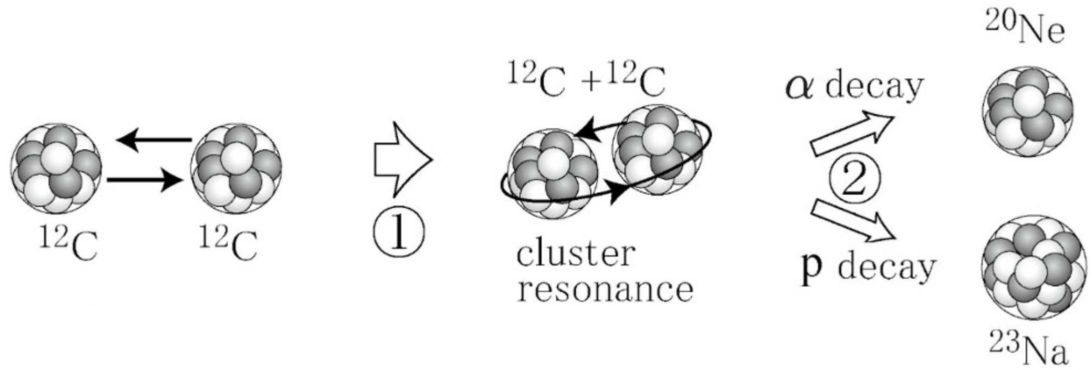


“Coulomb barrier” + “dominance of correlation” creates long-lived and strongly correlated states

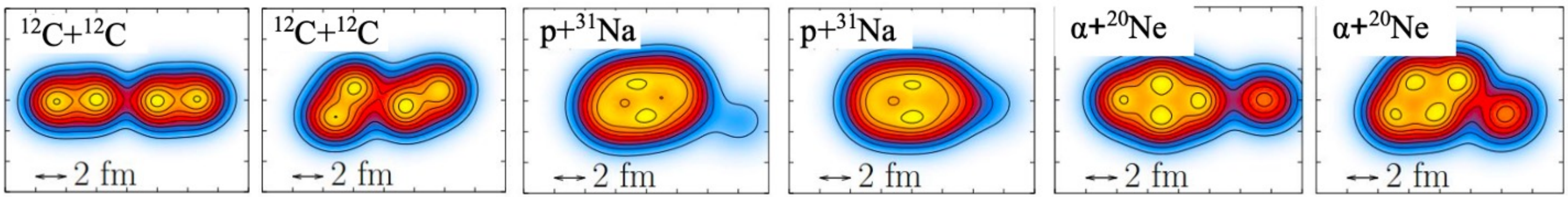
Courtesy M. Kimura

Nuclear clustering and fusion reactions

$$
\begin{aligned}
{}^{12}\mathrm{C} + {}^{12}\mathrm{C} &\to p + {}^{23}\mathrm{Na} + 2.2\mathrm{MeV} \\
&\to \alpha + {}^{20}\mathrm{Ne} + 4.6\mathrm{MeV}
\end{aligned}
$$



Numerical simulation of the stellar fusion reaction

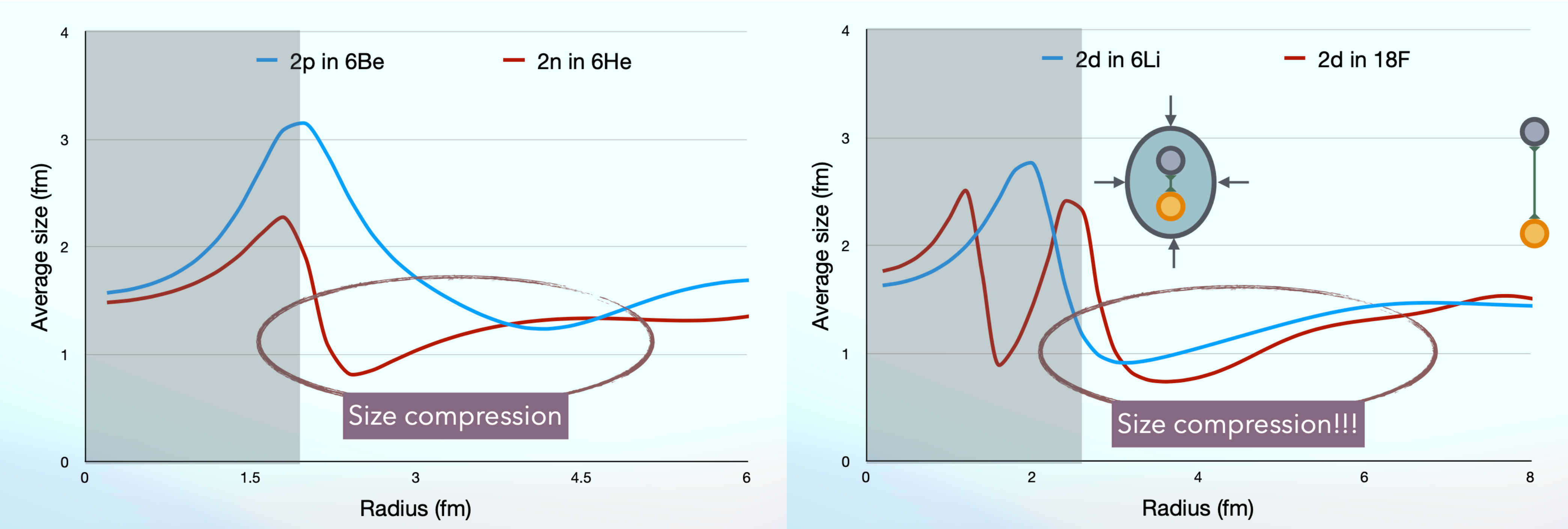


- The first full-microscopic calculation for the ^{12}C+^{12}C fusion
- Proposed isoscalar monopole as a probe for clusters

Y. Taniguchi et al. (2021,2023)

Generator coordinate + core studies of average size of a di-nucleon system during the emission process

Qing Zhao et al.

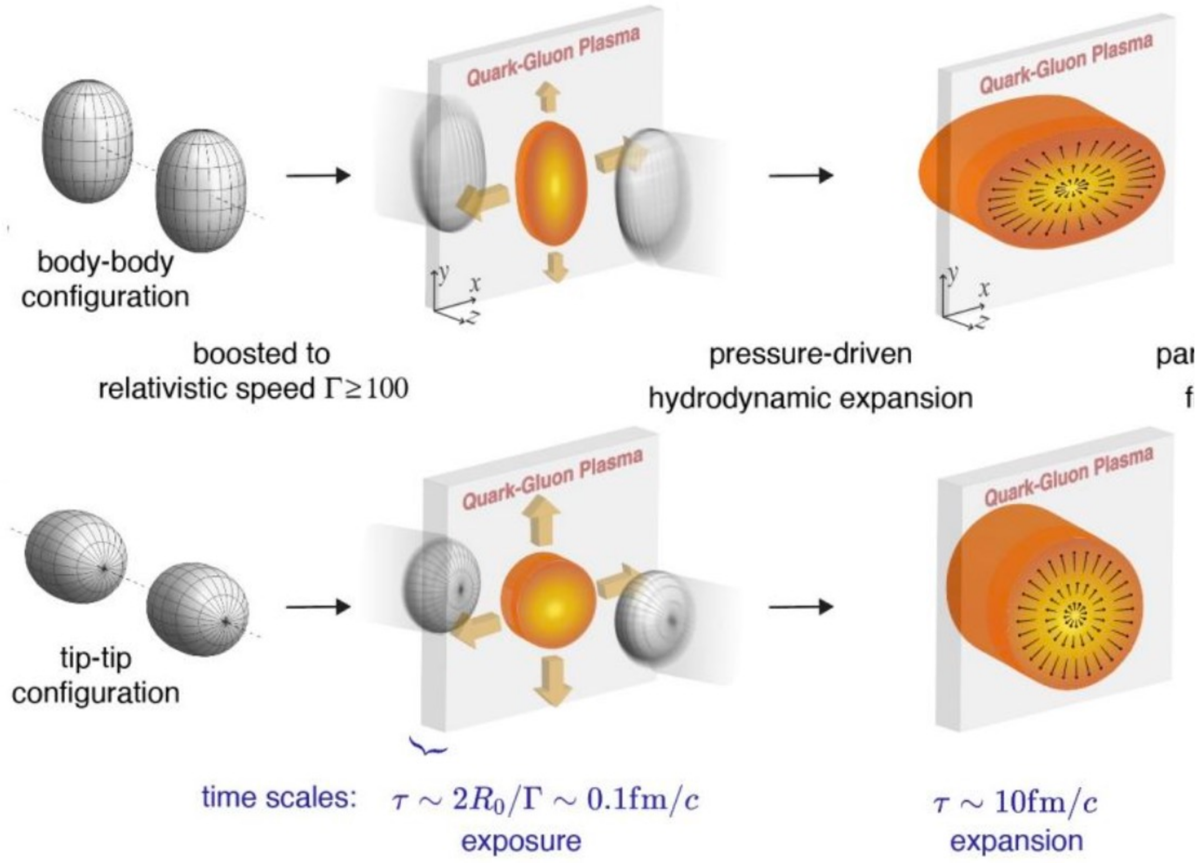


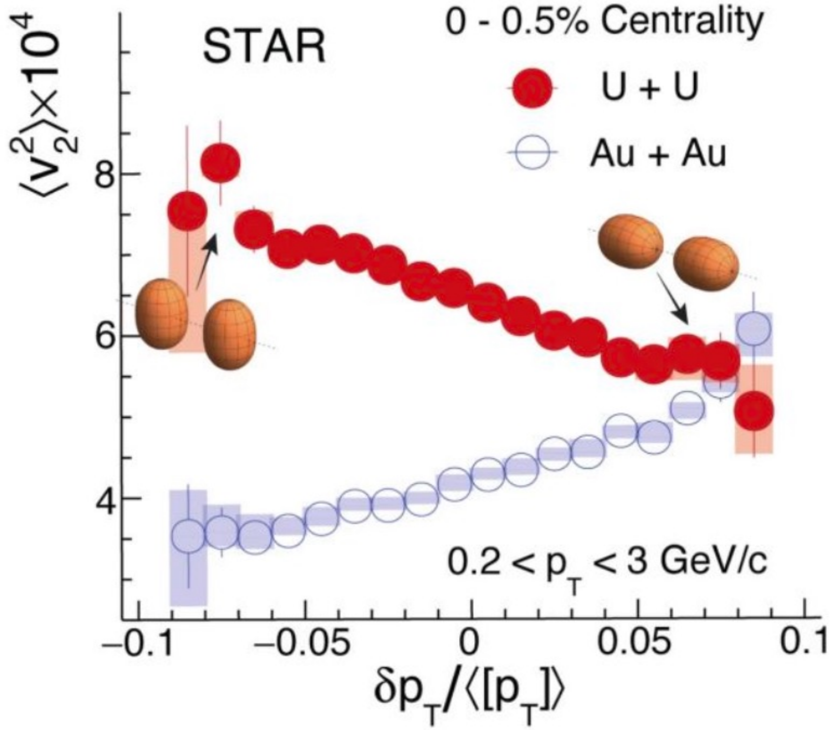
Courtesy Qing Zhao

Are these phenomenon seen in the time-dependent GSM-CC calculation?

Impact of low-energy physics in relativistic HI collisions

Quadrupole deformation seen directly by comparing $^{238}U+^{238}U$ with almost spherical $^{197}Au+^{197}Au$





People have started to discuss clusters from data of RHIC and LHC

G. Giacalone et al. (2024)

Nucleon-nucleon interaction in different regimes of binding

NN interaction in different regimes of binding

★ B(ja,jb)=-10 MeV
★ B(ja,jb)= -1 MeV
★ B(ja,jb)=+1 MeV

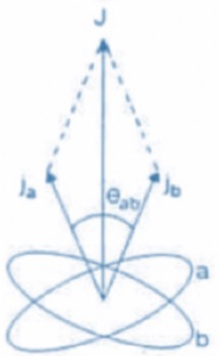
ℓ=p,d,f,g,h
Minnesota interaction

$\Re(V_{12})=E_n/\langle E_n \rangle$; $E_n=E-e_a-e_b$

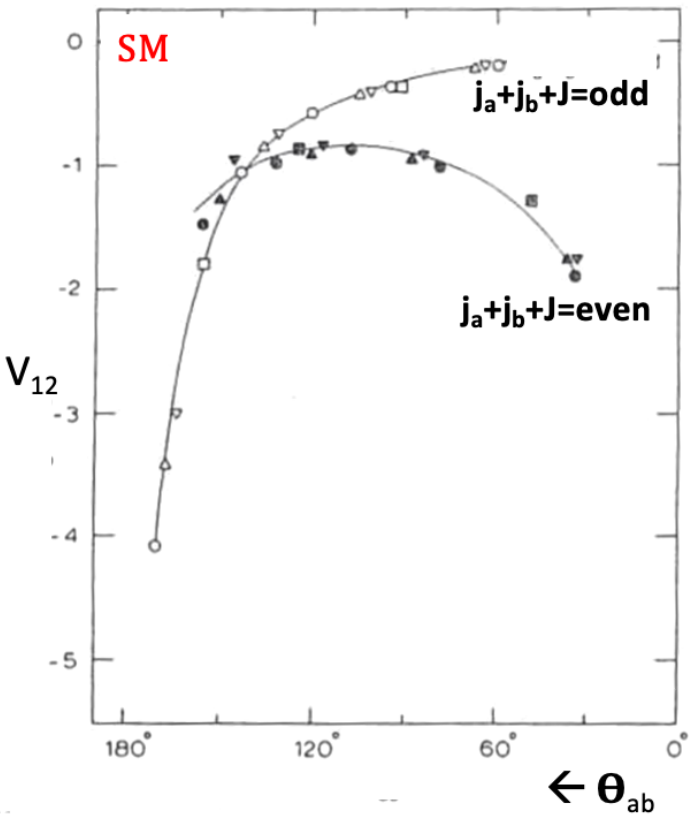
$\langle E_n \rangle = | \Sigma_J (2J+1)(E-e_a-e_b)/\Sigma_J(2J+1) |$

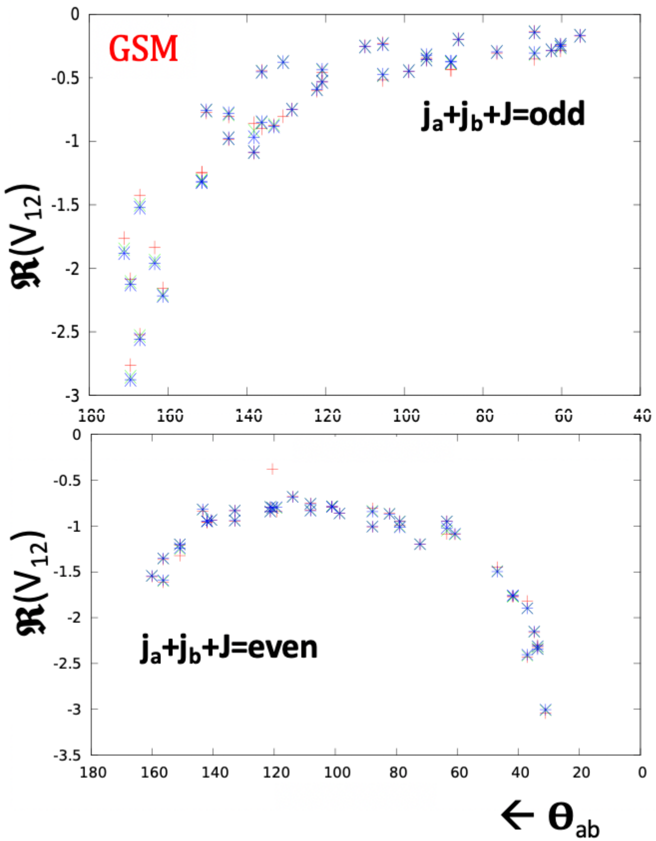
$\Im(V_{12})=\Gamma_n/\langle \Gamma_n \rangle$; $\Gamma_n=\Gamma-\gamma_a-\gamma_b$

$\langle \Gamma_n \rangle = | \Sigma_J (2J+1)(\Gamma-\gamma_a-\gamma_b)/\Sigma_J(2J+1) |$



$$\cos(\theta) = \frac{J(J+1) - j_a(j_a+1) - j_b(j_b+1)}{2\sqrt{j_a(j_a+1)j_b(j_b+1)}}$$

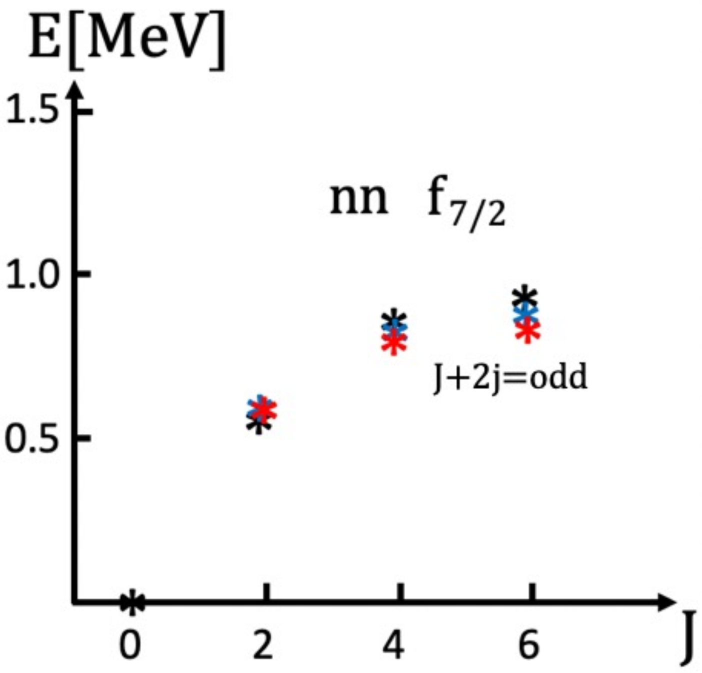


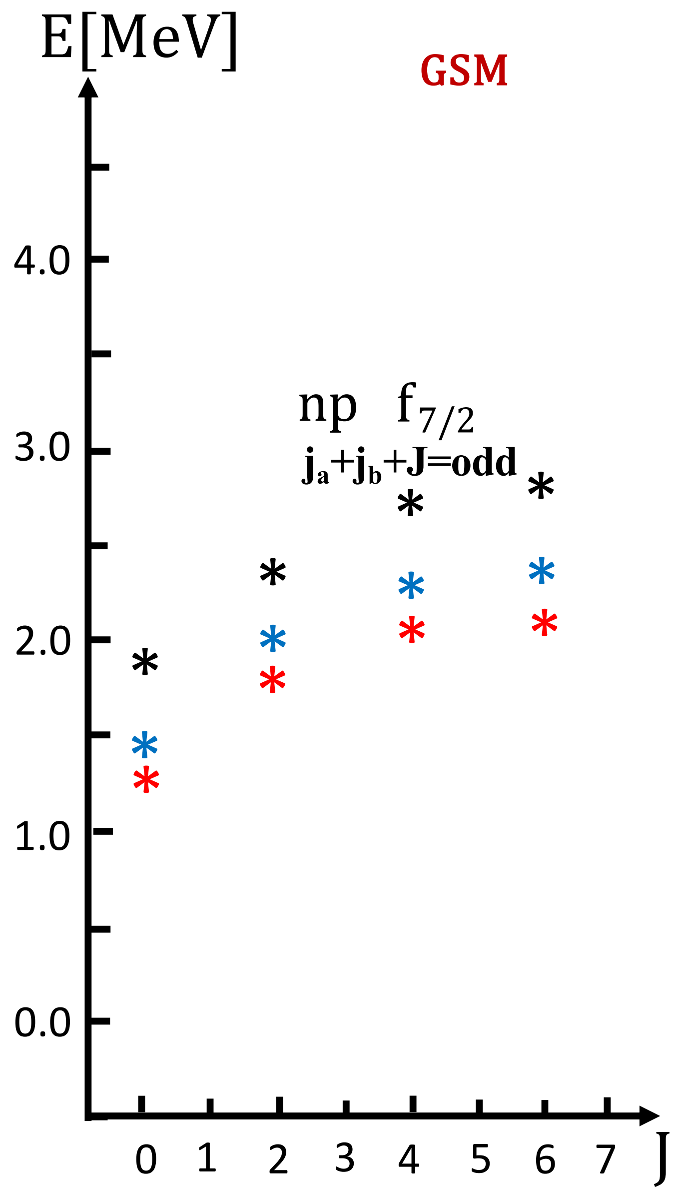


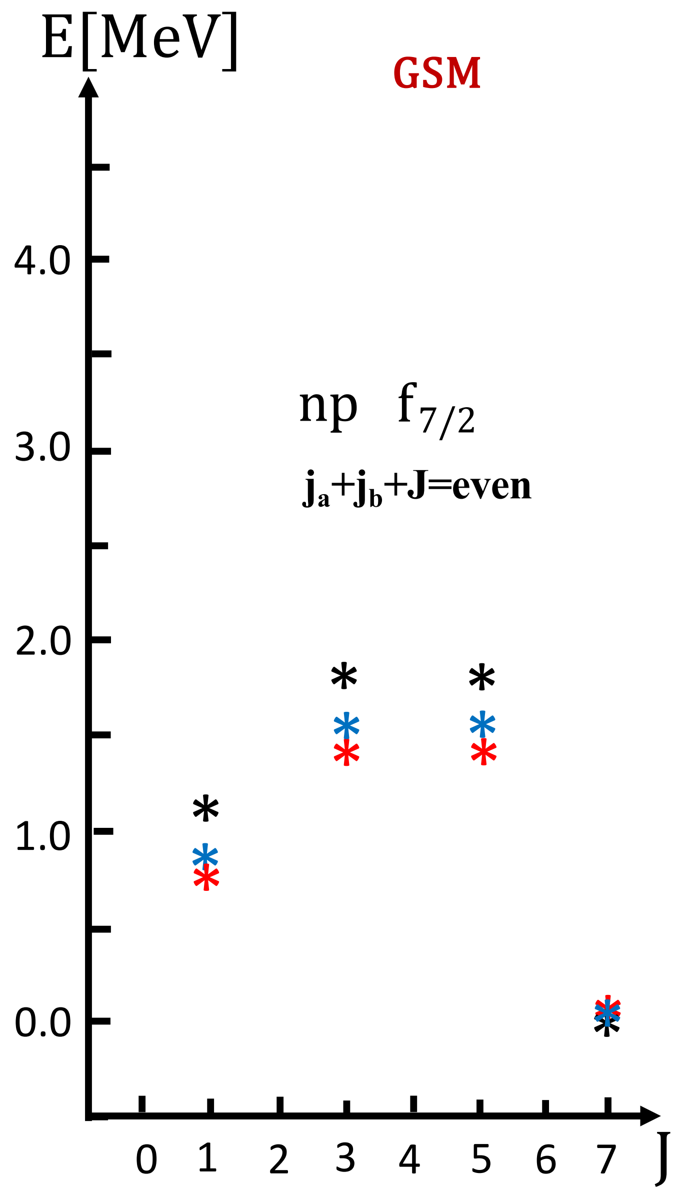
N. Michel, M. Płoszajczak,
«*Gamow Shell Model: The Unified Theory of Nuclear Structure and Reactions* »
Lecture Notes in Physics, Vol. 983, (Springer Verlag, 2021)

- Similar qualitative dependence of the TBMEs on angle θ_{ab} in SM and GSM
- *TBMEs are complex* in weakly bound/unbound nuclei

* $(S_n, S_p) = (10, 10)$ [MeV]
* $(S_n, S_p) = (1, 10)$ [MeV]
* $(S_n, S_p) = (-1, 10)$ [MeV]







Strong reduction of np interaction V_{np} for weakly bound or unbound nuclei, in particular for low-angular momenta shells, e.g. ~50% for p-shell

$\mathbf{p_{3/2}}$: $\dfrac{V_{np}(10,10)}{V_{np}(\text{-}1,10)} \simeq 2$ $\mathbf{d_{5/2}}$: $\dfrac{V_{np}(10,10)}{V_{np}(\text{-}1,10)} \simeq 1.45$ $\mathbf{f_{7/2}}$: $\dfrac{V_{np}(10,10)}{V_{np}(\text{-}1,10)} \simeq 1.30$

NN interactions between unlike particles (V_{np}) becomes weaker in weakly bound (unbound) states

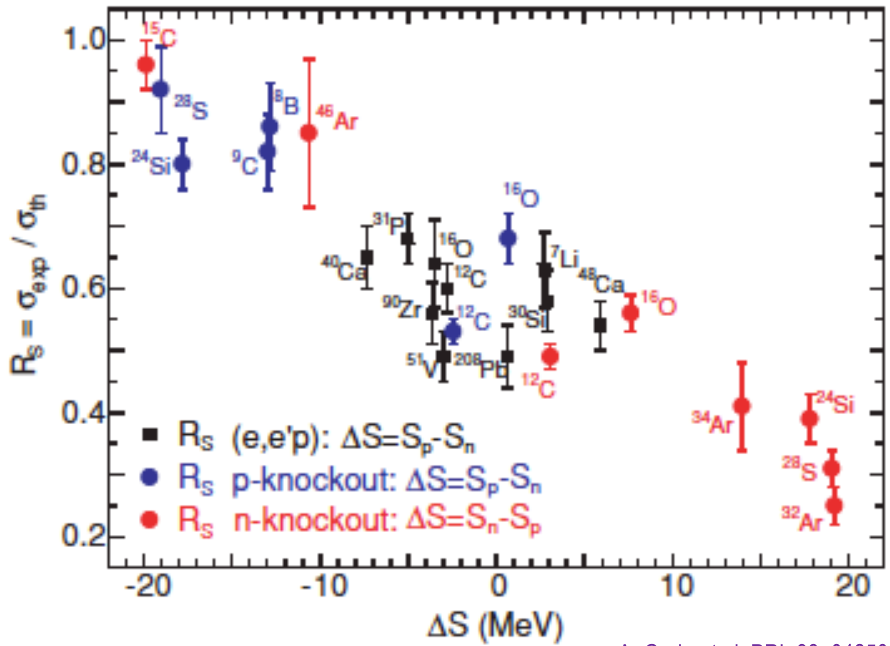
Similar conclusion from the binding-energy systematics Yan-an Luo et al, nucl-th/0201073; N. Michel et al., Acta Physica Polonica B35, 1249 (2004)

How the ratio V_{nn}/V_{np}, V_{pp}/V_{np} depends on $S_n - S_p$ asymmetry?

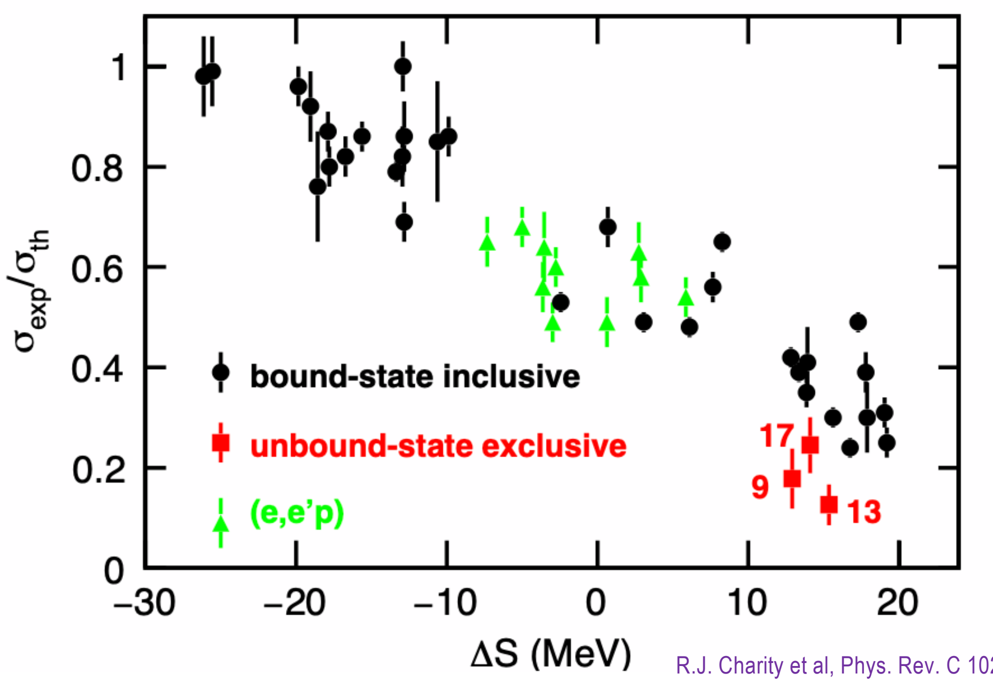
ℓ_j	J^π	$S_p = 10$ MeV; $S_n = -1$ MeV
$p_{1/2}$	2^+	$V_{nn}/V_{np} = 0.2$ $V_{pp}/V_{np} = 0.52$
$d_{5/2}$	2^+	$V_{nn}/V_{np} = 0.27$ $V_{pp}/V_{np} = 0.33$
	4^+	$V_{nn}/V_{np} = 0.31$ $V_{pp}/V_{np} = 0.41$
$f_{7/2}$	2^+	$V_{nn}/V_{np} = 0.325$ $V_{pp}/V_{np} = 0.32$
	4^+	$V_{nn}/V_{np} = 0.38$ $V_{pp}/V_{np} = 0.425$
	6^+	$V_{nn}/V_{np} = 0.4$ $V_{pp}/V_{np} = 0.445$

- Strong asymmetry of V_{nn}/V_{np} and V_{pp}/V_{np} for large $|S_n - S_p|$
- If $S_n \ll S_p$, then $V_{pp}/V_{np} > V_{nn}/V_{np}$, i.e. protons in the neutron-rich environment interact stronger than neutrons
  → Proton SF is reduced with respect to neutron SF, and *vice versa* if $S_p \ll S_n$
- The asymmetry of V_{nn}/V_{np} and V_{pp}/V_{np} decreases gradually with increasing angular momentum of the shell.

Are these findings relevant for understanding the behavior of σ_{exp}/σ_{th} as a function of asymmetry between S_n and S_p?



A. Gade et al, PRL 93, 04250



R.J. Charity et al, Phys. Rev. C 102, 044614

Model	N_{cont}	$^9C\to{}^8C$	$^9Li\to{}^8He$	$^9C\to{}^8B$	$^9Li\to{}^8Li$
	S_n	14.22	4.06	14.22	4.06
	S_p	1.3	13.94	1.3	13.94
HO-SM	0	0.86	0.85	0.95	0.96
GSM-*ps*	3	0.67	0.67	0.95	0.96
GSM-*psd*	3	0.60	0.61	0.89	0.87
GSM-*psd*	4	0.48	0.57	0.88	0.87

.J. Wylie, J. Okołowicz et al, (2022)

Paradoxical result?

Reduction of spectroscopic factor depends strongly on continuum coupling for the removal of a well bound nucleon!

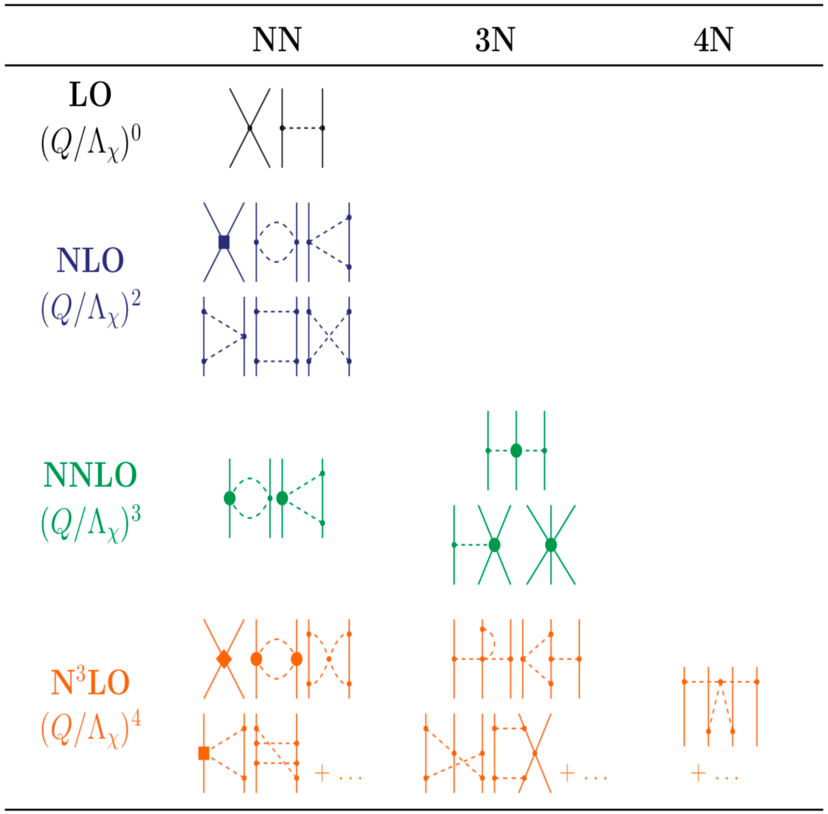
EOS and in medium nucleon-nucleon interaction

- First principles for nuclear physics: QCD
  - non-perturbative at low energies
  - lattice QCD in the future; first applications to spectrum, magnetic moments, polarizabilities (A<5) and np→dγ, β-decay of ^{3}H, … for unphysical quark masses: m_π~450 MeV, m_N~1200 MeV

- For now inter-nucleon forces from chiral effective field theory (χEFT)
  - based on the symmetries of QCD; χ-symmetry of QCD ($m_u \approx m_d \approx 0$) broken with pion as a Goldstone boson
  - degrees of freedom: nucleons and pions

but

> - χEFT is not regularizable; dependence on artificial cutoffs
>
> - Systematic low-momentum expansion to a given order (Q/Λ_χ) is still debated
>
>   ⟹ the hierarchy of many-body interactions and consistency of the χEFT framework is not yet proven



Christian Drischler

Challenge:

- The determination of EFT scheme which allows for a reliable and systematic low-momentum expansion and defines the hierarchy of many-body interactions
- At present, the determination of EOS going from low-density end is uncertain

Waiting for the next edition of NUSYM workshop

- Many new results have been presented at this workshop, new challenges appeared

- Crucial advances in low-energy nuclear theory have been made in this century:
  - In medium nucleon-nucleon interaction from basic principles (EFT)
  - *Ab initio* structure and reactions (GFMC, NCSM(C), NCGSM, CCM,...)
  - Continuum Shell Model (GSM, SMEC); structure and reactions in the low-energy continuum

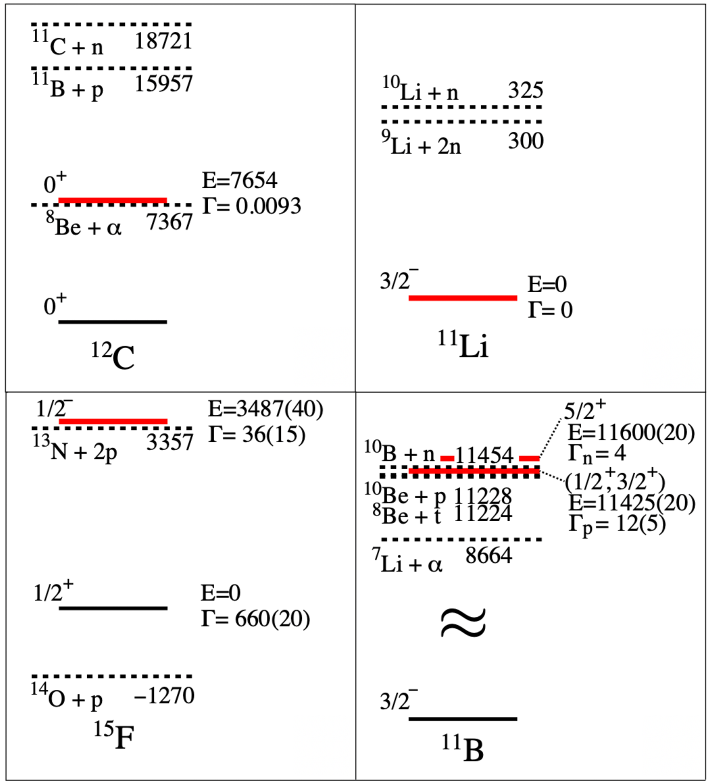
    → Tremendous efforts are needed before these conceptual advances will bring a real progress in the quantitative description of atomic nuclei

- Interaction with other communities, discoveries and technological progress change paradigms and methodology in nuclear studies

"No man is an island entire of itself; every man is a piece of the continent, a part of the main..."

John Donne (1572-1631), MEDITATION XVII, *Devotions upon Emergent Occasions*

Near-told states and origin of clustering



Mimicry mechanism of clusterization

- The appearance of correlated (cluster) states close to open channels is the generic *open quantum system phenomenon* related to the collective rearrangement of SM wave functions due to the coupling via the continuum
- Specific aspects:
  - Energetic order of particle emission thresholds depends on (nuclear) Hamiltonian
  - Absence of stable cluster entirely composed of like nucleons

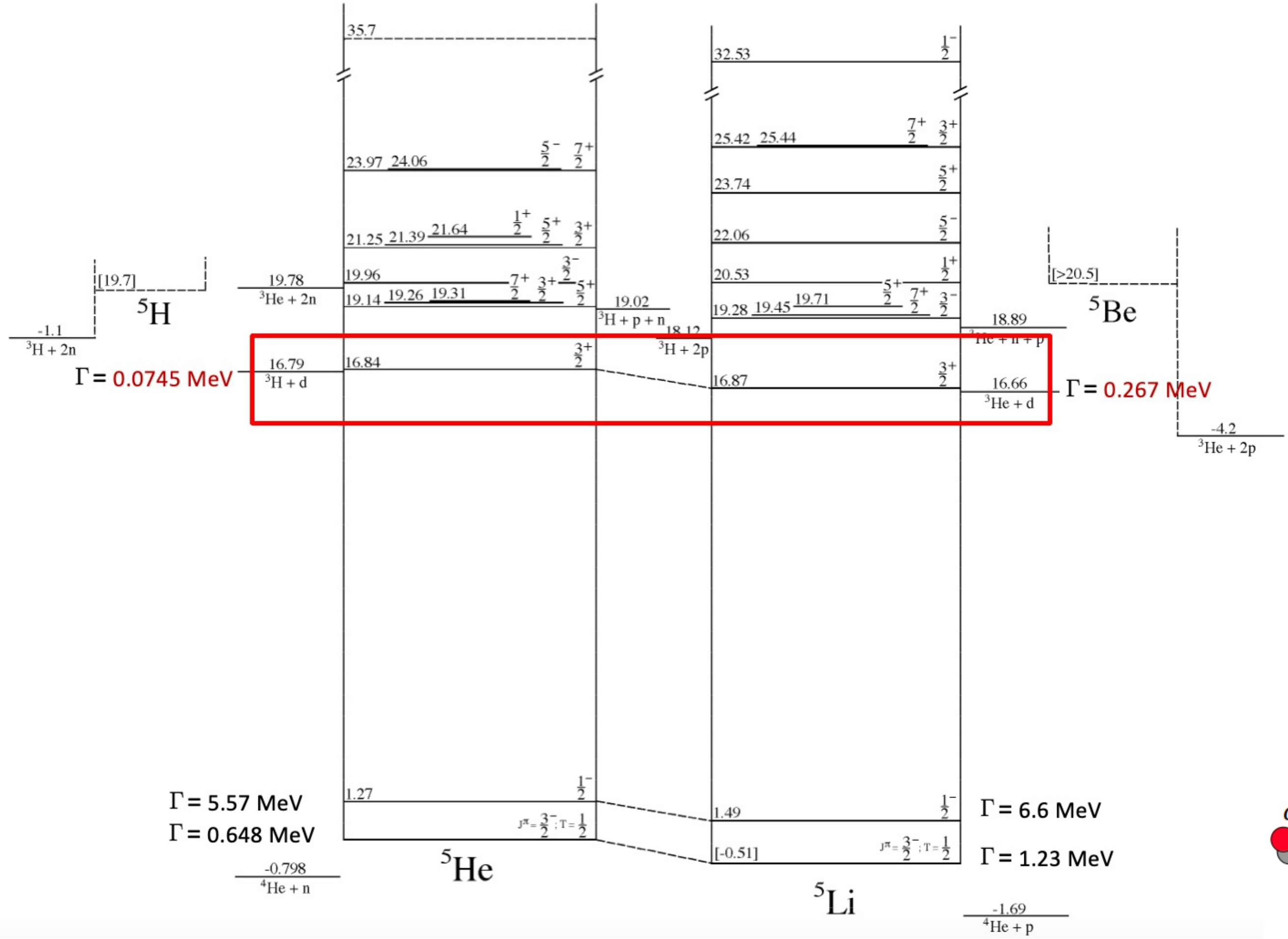
Challenge:
Identification of various clusters and their decays in hot matter produced in HI collisions

- Other cases: ^{6}He, ^{6}Li, ^{7}Be, ^{7}Li, ^{11}O, ^{11}C, ^{17}O, ^{20}Ne, ^{26}O, ^{24}Mg,...
- *Various clusterings*: ^{2}H, ^{3}He, ^{3}H, 2p, 2n
- *Astrophysical relevance* of near-threshold resonances for α- and proton-capture reactions of nucleosynthesis

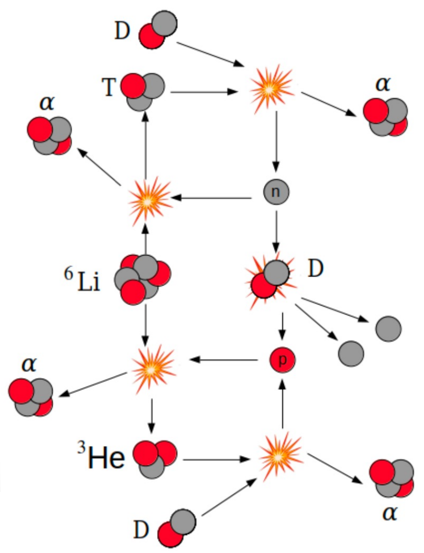
Nuclear clustering and fusion reactions

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

$$\begin{array}{ccccccccc} n & + & ^6\mathrm{Li} & \rightarrow & \alpha & + & \mathrm{T} \\ \uparrow & & \text{Jetter cycle} & & & & \downarrow \\ n & + & \alpha & \leftarrow & \mathrm{D} & + & \mathrm{T} \end{array}$$



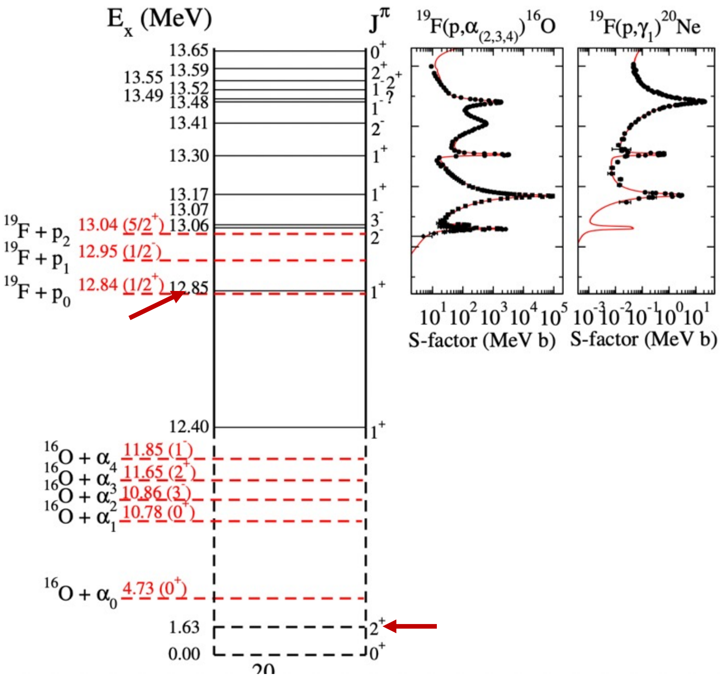
$$\begin{array}{ccccccccc} p & + & ^6\mathrm{Li} & \rightarrow & \alpha & + & ^3\mathrm{He} \\ \uparrow & & \text{Post cycle} & & & & \downarrow \\ p & + & \alpha & \leftarrow & \mathrm{D} & + & ^3\mathrm{He} \end{array}$$



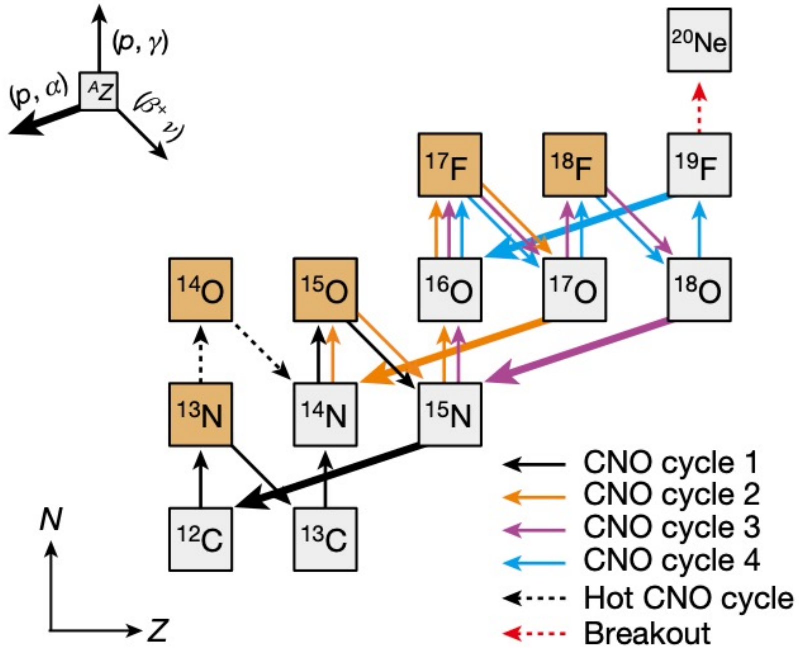
Astrophysical relevance of near-threshold resonances for α- and p-capture reactions of nucleosynthesis

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

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



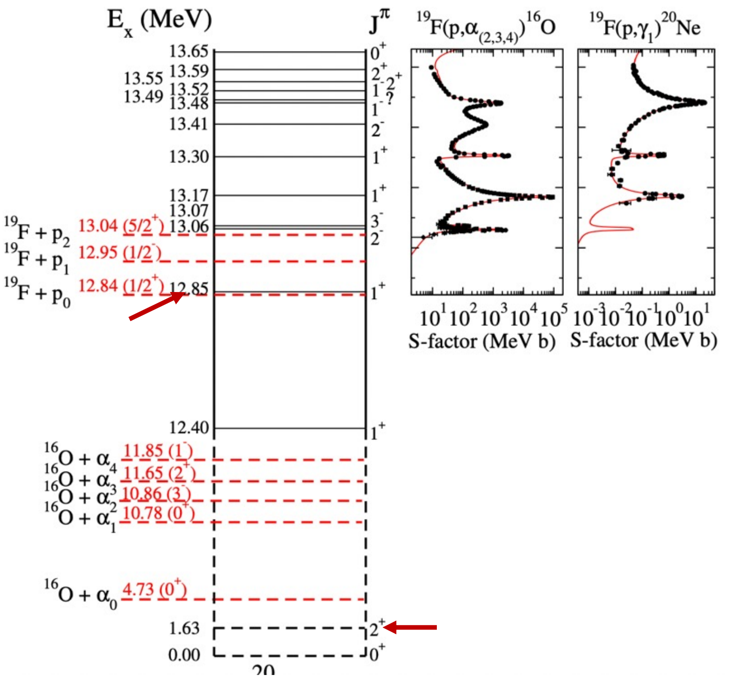
What is the effect of 1⁺ resonance at ~10 keV above the proton emission threshold on the S-factor?



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

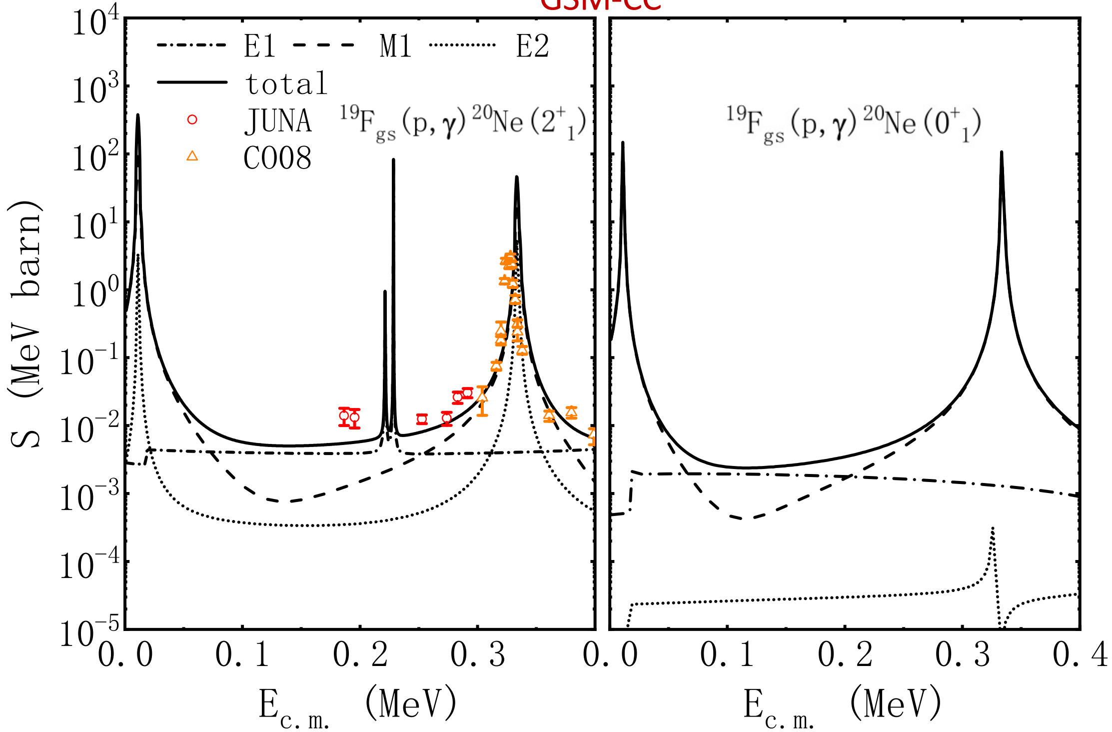
Can Ca be produced in hot-CNO cycle?

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



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, et al (2024)