Selected examples on mirror symmetries and nuclear clustering

O. Sorlin (GANIL)

Breaking of mirror symmetry due to the influence of the continuum ^{16}N - ^{16}F (I. Stefan)

Massive breaking of mirror symmetry in ^{36}Ca - ^{36}S du to shape coexistence (L. Lalanne)

Study of mirror symmetries at both edges of the valley of stability ^{8}C - ^{8}He (S. Koyama)

Search for ^{3}He clustering in N=2 isotones (S. Koyama)

Conclusions and perspectives

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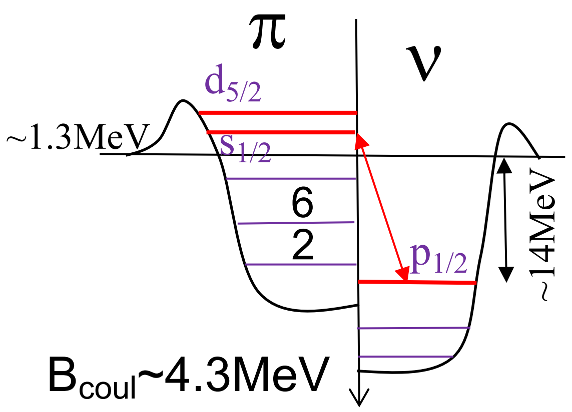
Study of the mirror nuclei ^{16}F and ^{16}N : effect of drip line



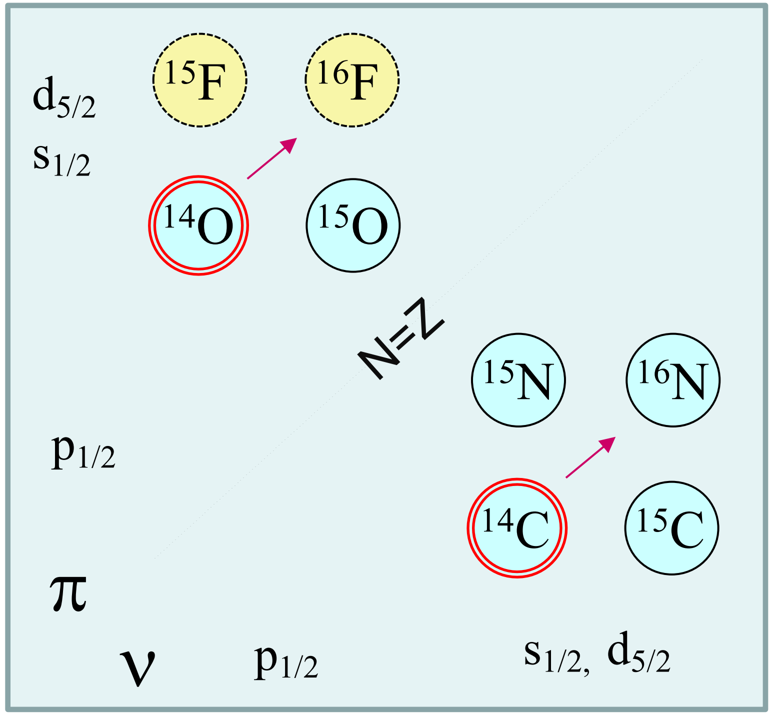
^{16}F

S_p= -536(8) MeV

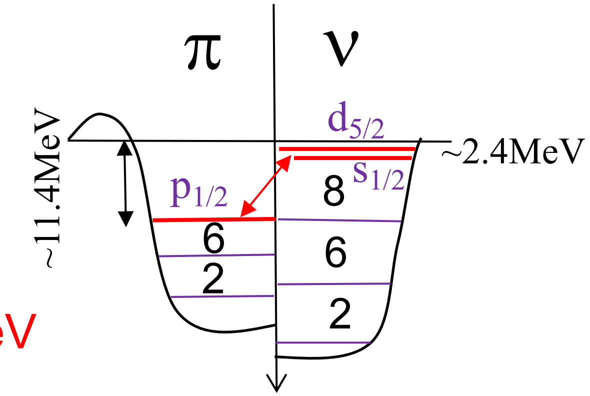
Coupling of a proton and a neutron above the ^{14}O and ^{14}C cores

$(s_{1/2} \times p_{1/2}) \rightarrow J = 0^-, 1^-$

$(d_{5/2} \times p_{1/2}) \rightarrow J = 2^-, 3^-$



E*(^{14}O) = 5.173 MeV , E*(^{14}C)= 6.093 MeV



^{16}N

S_n= +2.489 MeV

Study of unbound states in ^{16}F using resonant elastic scattering

- Rutherford elastic scattering :

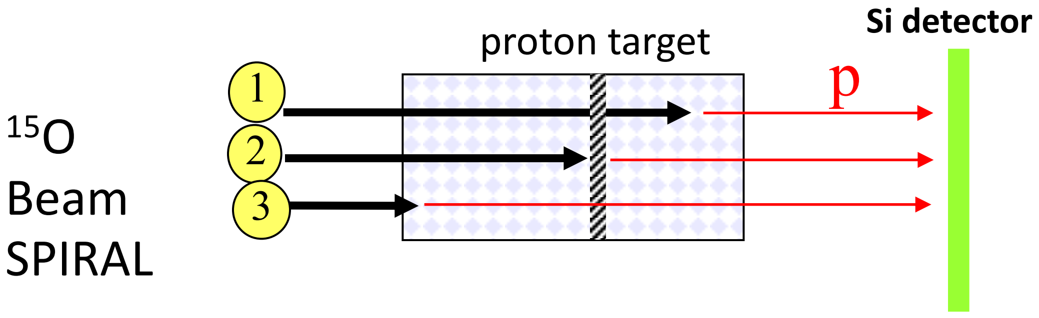
  $p + {}^{15}O \rightarrow p + {}^{15}O$

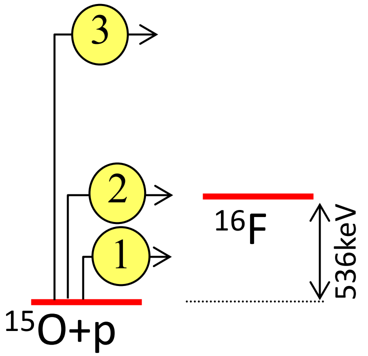
$$\frac{d\sigma}{d\Omega} = \left[\frac{Z\,Z'\,e^2}{4\,E\,\sin(\theta/2)^2}\right]^2$$

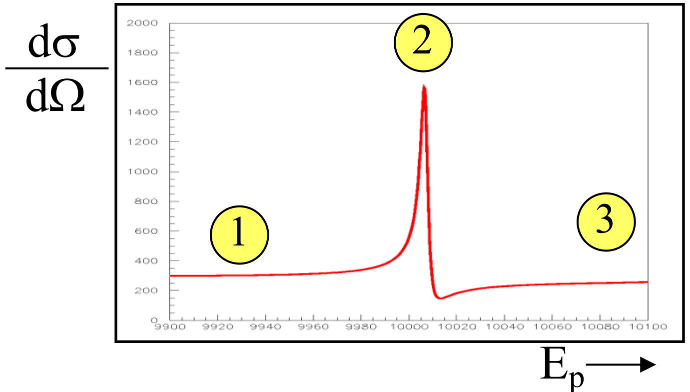
- Elastic scattering through a resonant state:

  $p + {}^{15}O \rightarrow {}^{16}F^{*} \rightarrow p + {}^{15}O$

- Use of inverse kinematics since ^{15}O is radioactive
- Thick 'proton' target in which the beam is eventually stopped



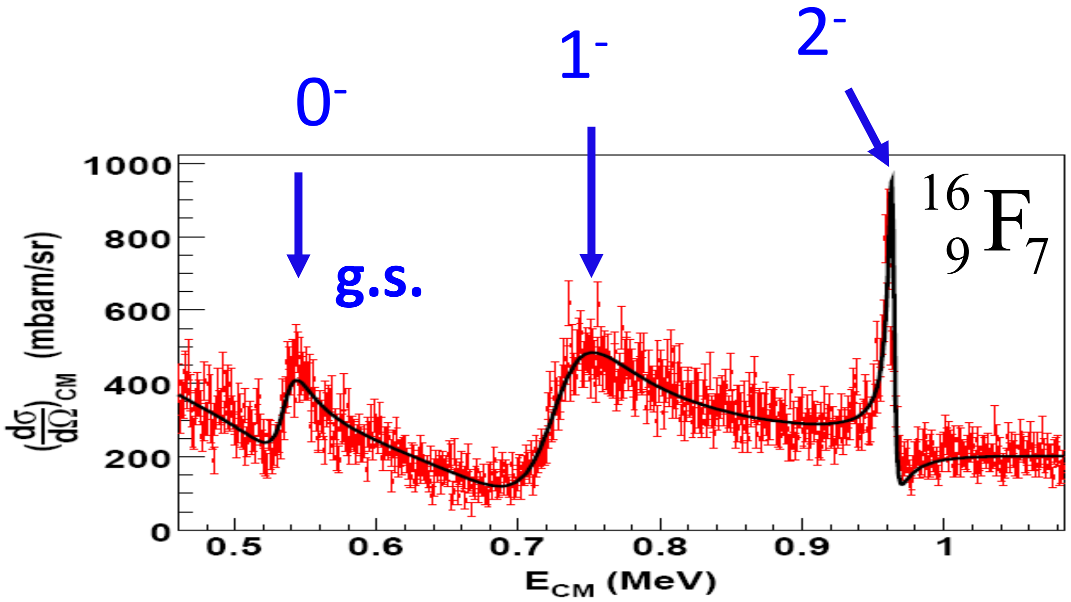




Search for unbound states in ^{16}F

$^{16}_{9}F_{7}$

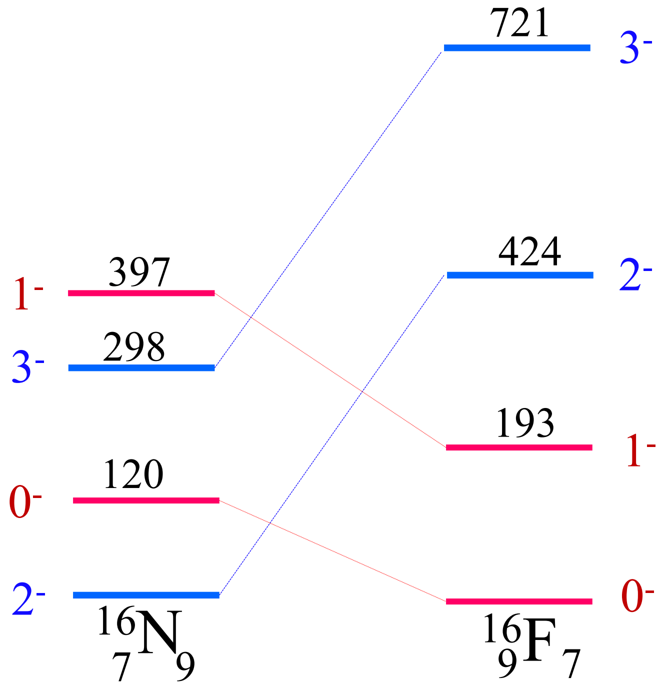
$H(^{15}O,p)^{15}O$ Resonant elastic scattering
(SPIRAL/GANIL)



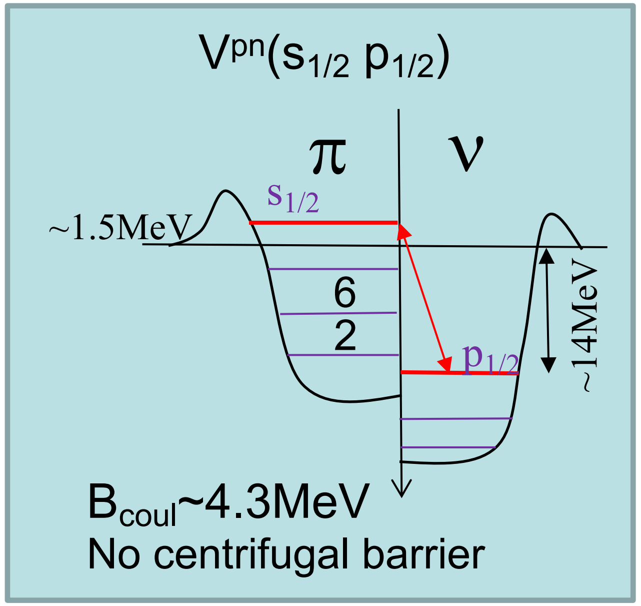
I. Stefan et al. *PRC 90 (2014) 014307*

E_x(keV)	Γ_p (keV)	J^π
0	25 ± 10	0^-
193 (10)	70 ± 5	1^-
424 (2)	6 ± 3	2^-
721 (4)	(15± 5)	3^-

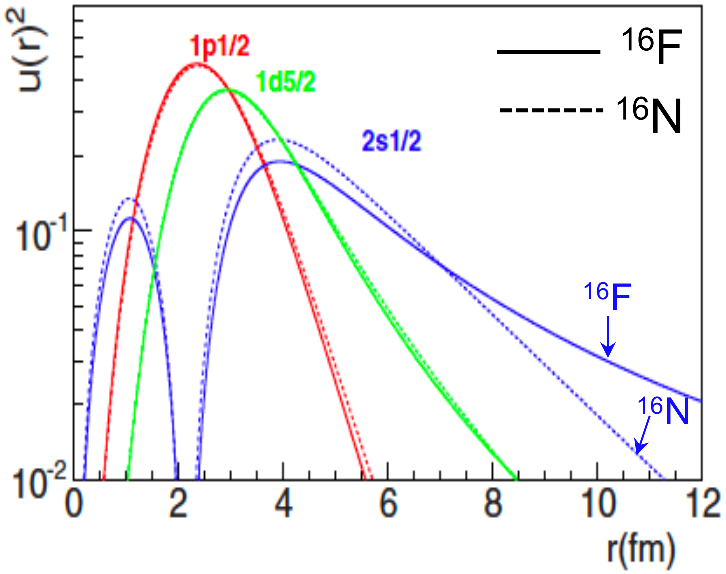
Breaking of mirror symmetry is so large that it induces an inversion between g.s. & excited states



Proton-neutron interaction and influence of continuum



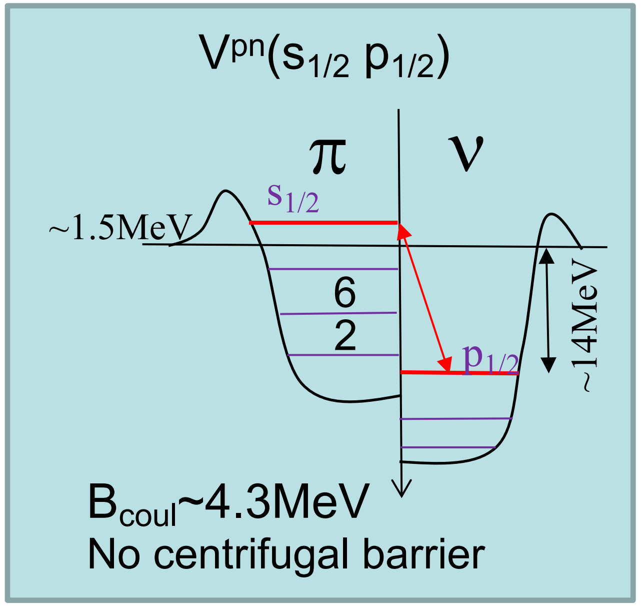
	^{16}F	^{16}N	Diff
J = $0^-,1^-$	$V^{pn}(s_{1/2}\ p_{1/2}) = -0.62$	$V^{pn}(p_{1/2}\ s_{1/2}) = -0.94$	40%

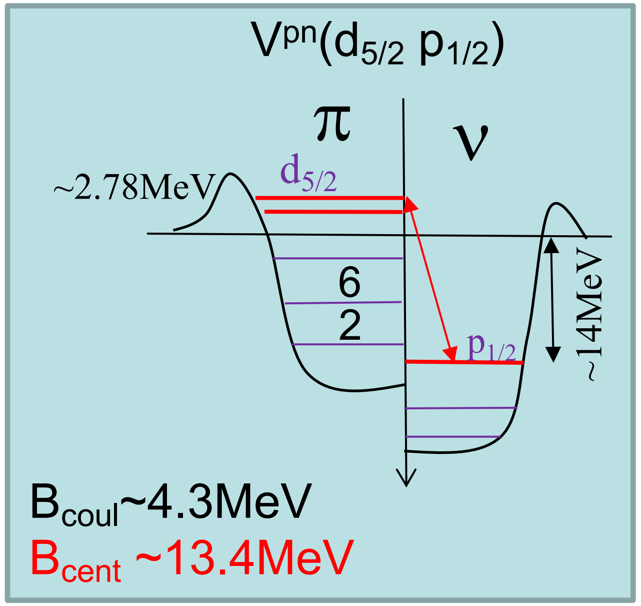


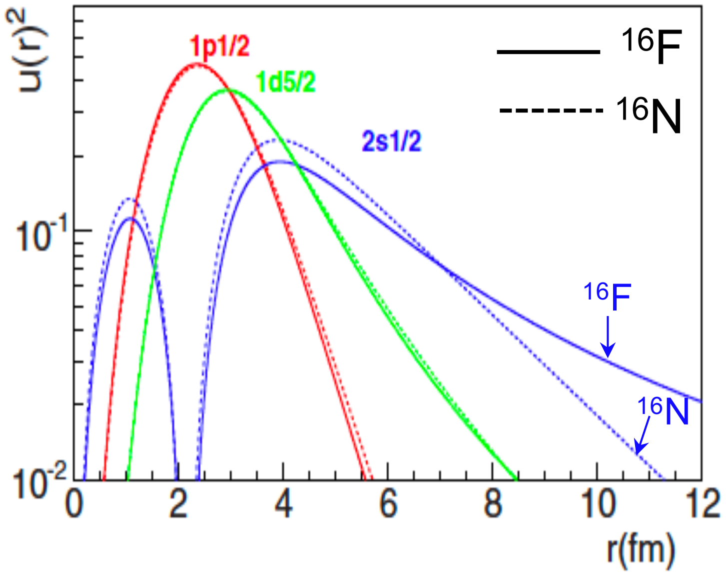
Significant reduction of the effective pn forces between mirror systems for $V^{pn}(s_{1/2}\ p_{1/2})$

-> Effect of continuum and spatial extension of s-wave

Proton-neutron interaction and influence of continuum







	^{16}F	^{16}N	Diff
J = 0⁻,1⁻	$V^{pn}(s_{1/2}\ p_{1/2}) = -0.62$	$V^{pn}(p_{1/2}\ s_{1/2}) = -0.94$	40%
J = 2⁻,3⁻	$V^{pn}(d_{5/2}\ p_{1/2}) = -1.66$	$V^{pn}(p_{1/2}\ d_{5/2}) = -1.83$	10%

Significant reduction of the effective pn forces between mirror systems for $V^{pn}(s_{1/2}\ p_{1/2})$
-> Effect of continuum and spatial extension of s-wave

Smaller change for $V^{pn}(d_{5/2}\ p_{1/2})$ owing to effect of high centrifugal barrier
-> These combined effect account for the complete reordering of the orbitals.

Breaking of mirror symmetry due to the influence of the continuum ^{16}N - ^{16}F (I. Stefan)

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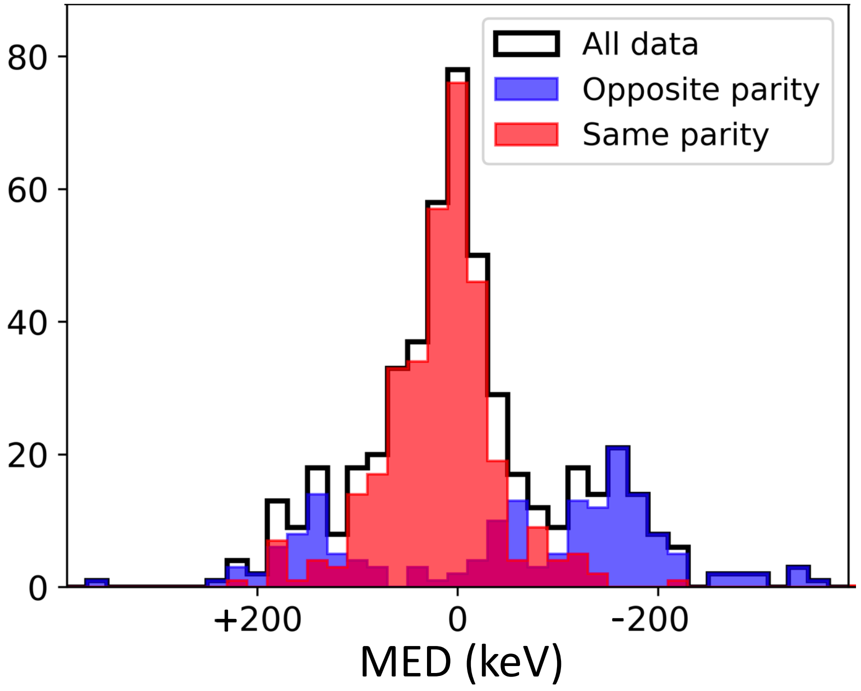
Conclusions and perspectives

Mirror symmetry and shape coexistence

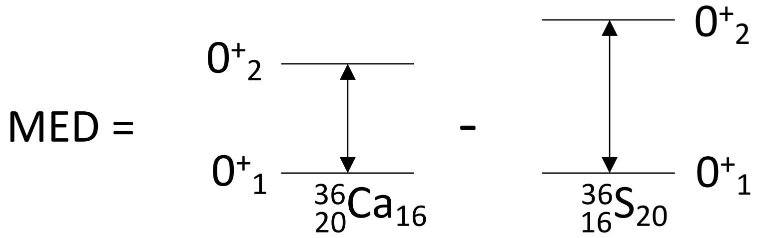
Nuclear spectra between mirror nuclei usually very similar -> Mirror Energy difference very small (MED)

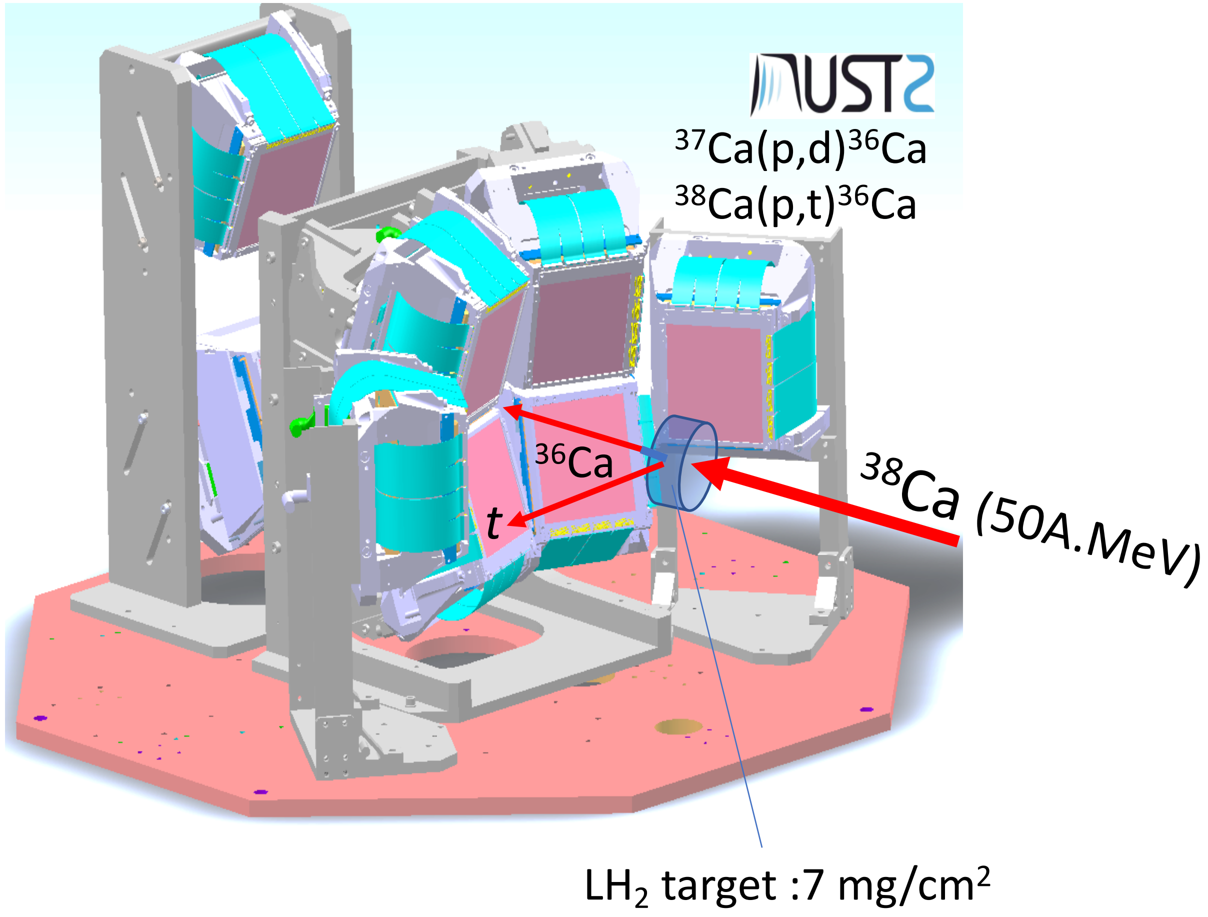
Few exceptions at the dripline (up to 700 keV), e.g. ^{16}F - ^{16}N *I. Stefan et al. PRC 90 (2014).*

'Colossal MED (-700 keV) predicted between the 0^+_1 and 0^+_2 states in ^{36}S - ^{36}Ca, *Valiente-Dobon et al., PRC 98 (2018).*

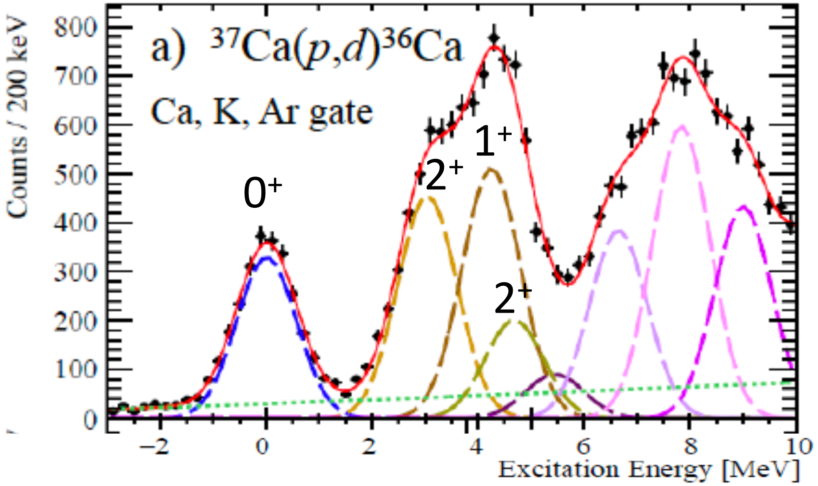


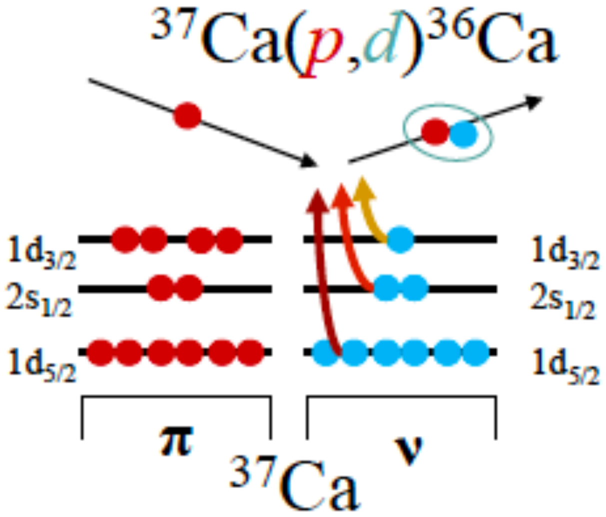
Henderson and Stroberg, PRC 102 (2020) 031303(R)

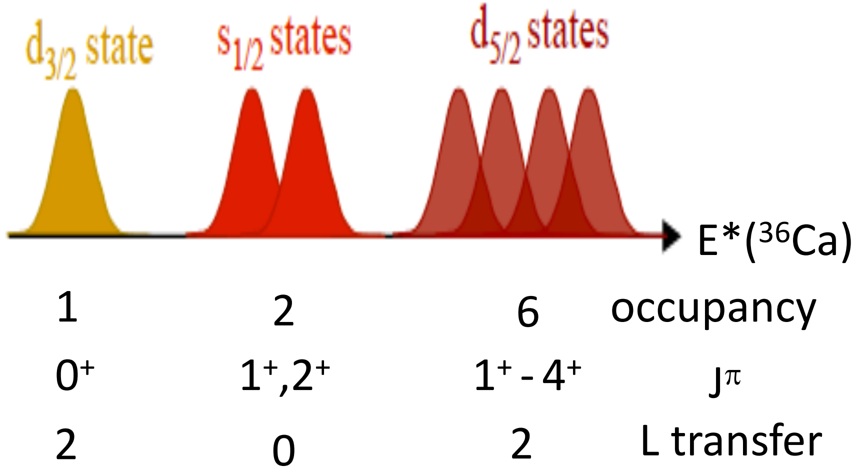


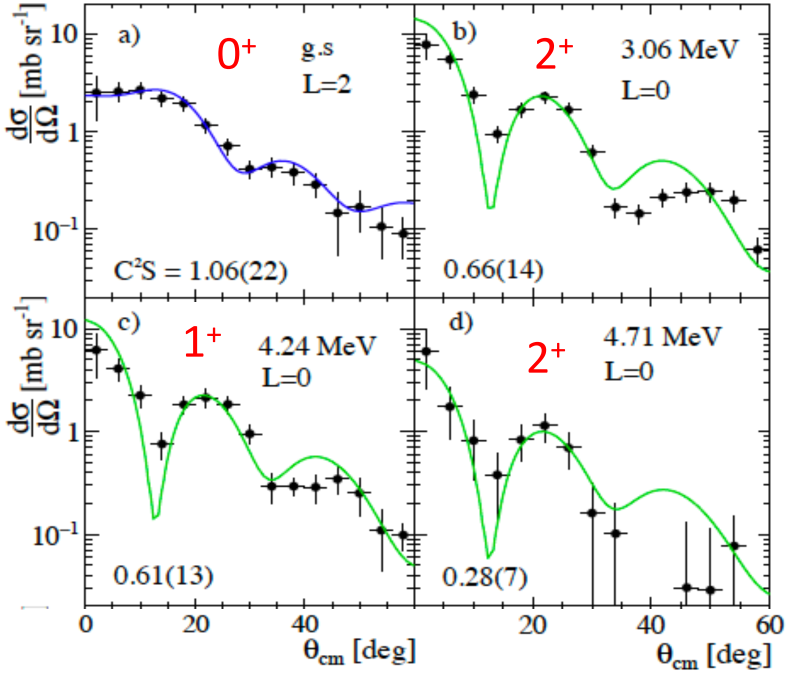


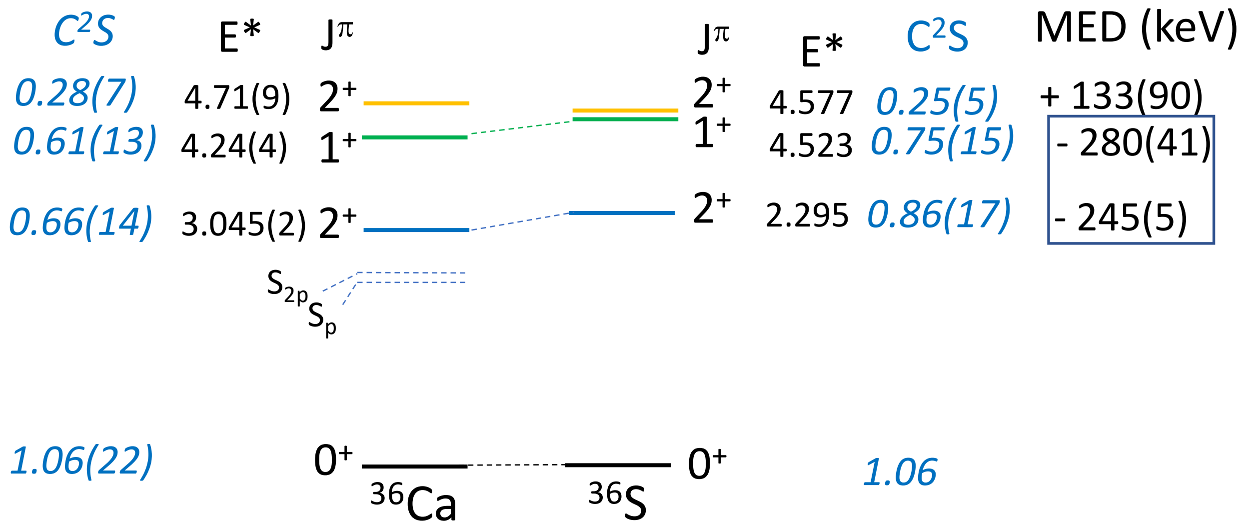
$^{37}Ca(p,d)^{36}Ca$ reaction to probe neutron-hole states







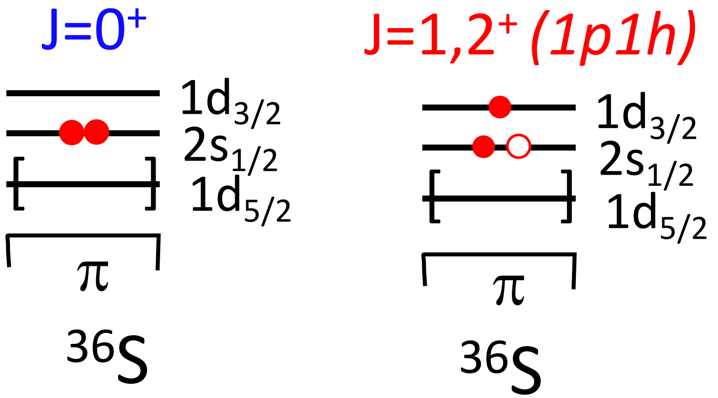


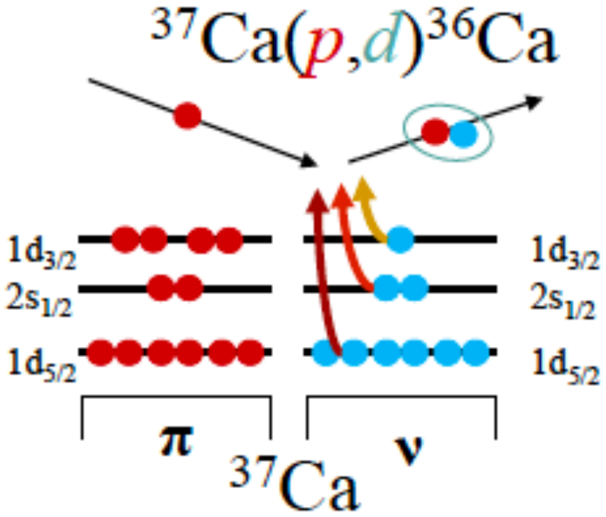


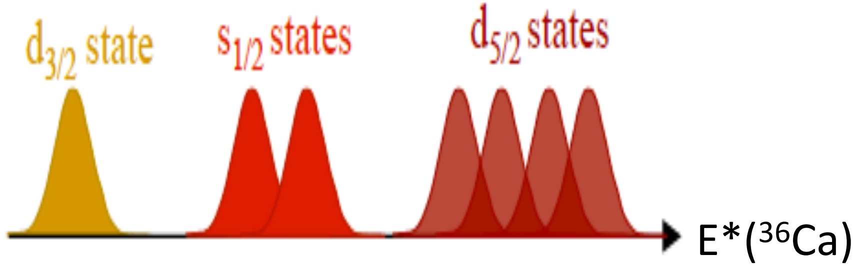
Compatible C^2S values for the two mirror nuclei despite large MED

-> Their configuration is likely unchanged

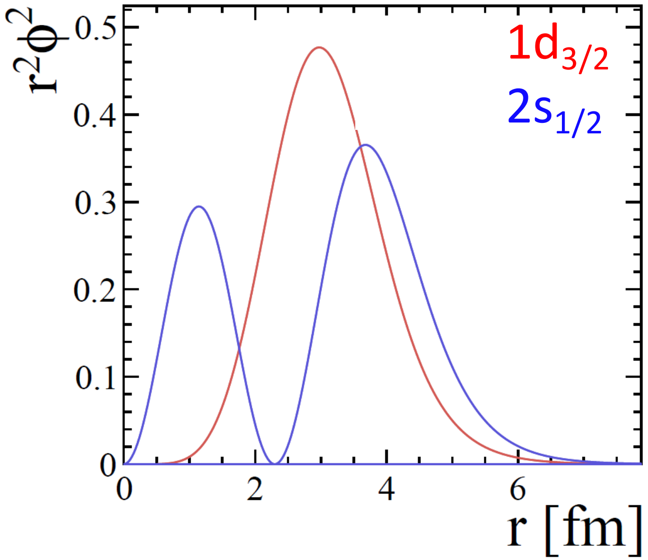
MED of 1^+ & 2^+ between ^{36}Ca and ^{36}S

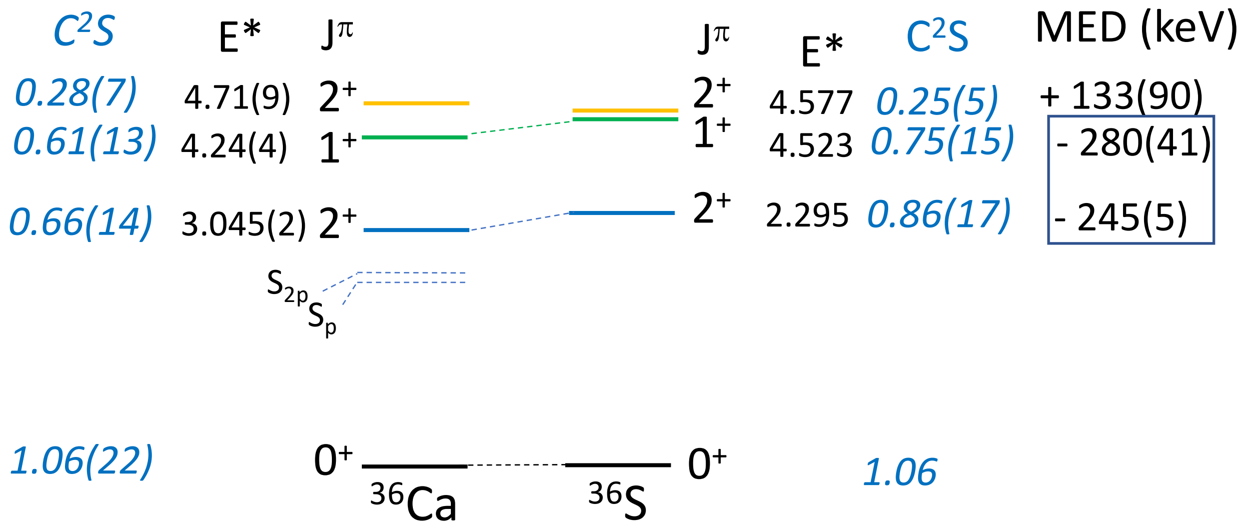






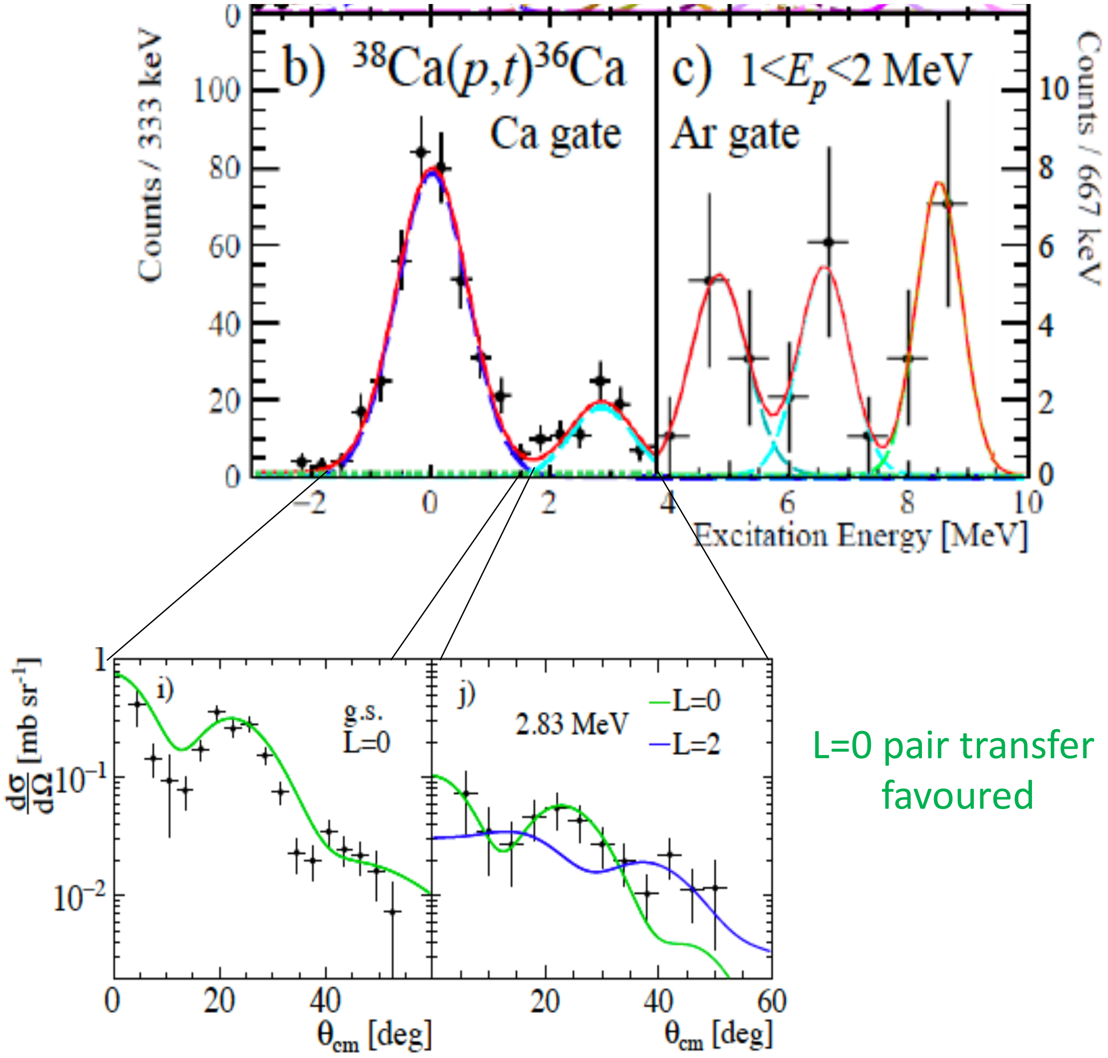
1	2	6	occupancy
0^+	$1^+,2^+$	1^+ - 4^+	J^π
2	0	2	L transfer



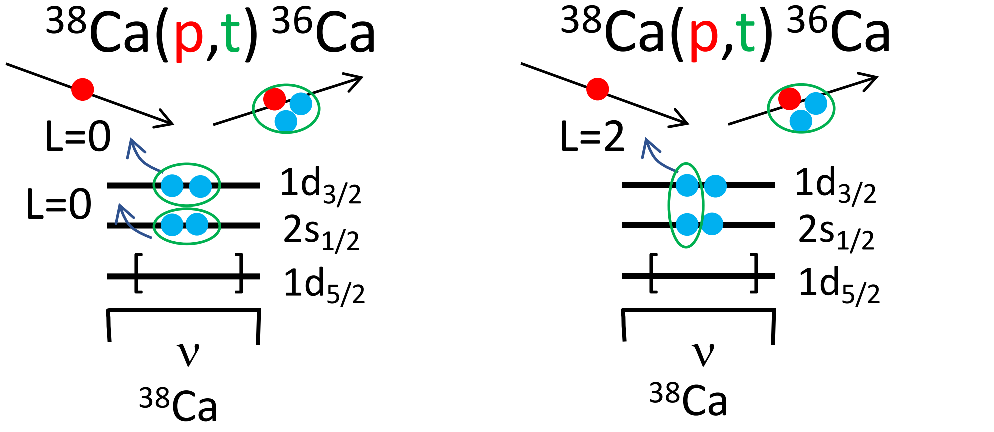


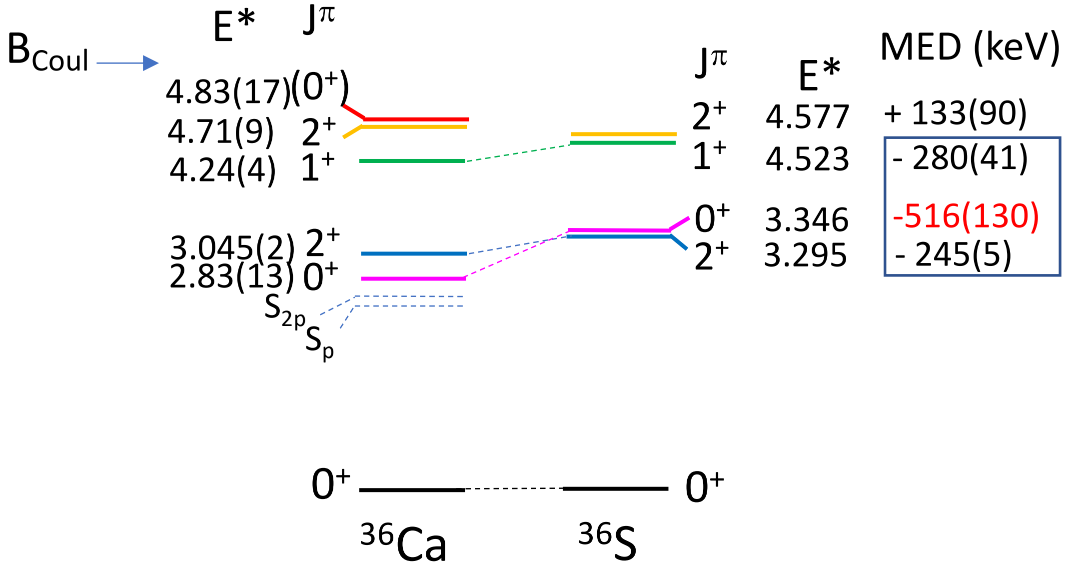
$(1,2)^+$ states in ^{36}S have more repulsive Coulomb force than the g.s. due to their proton *(ph)* structure from $2s_{1/2}$ (large r) to $1d_{3/2}$ orbits (smaller r)

^{38}Ca(p,t)^{36}Ca reaction to probe 0$^+$ states



L=0 pair transfer favoured

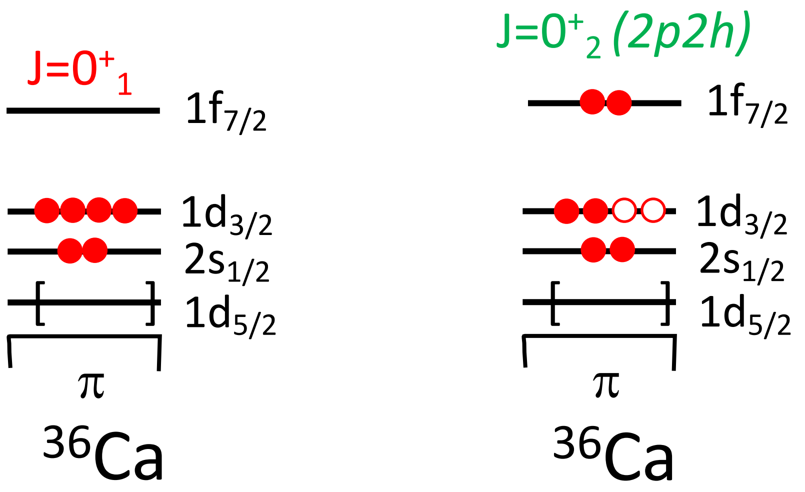


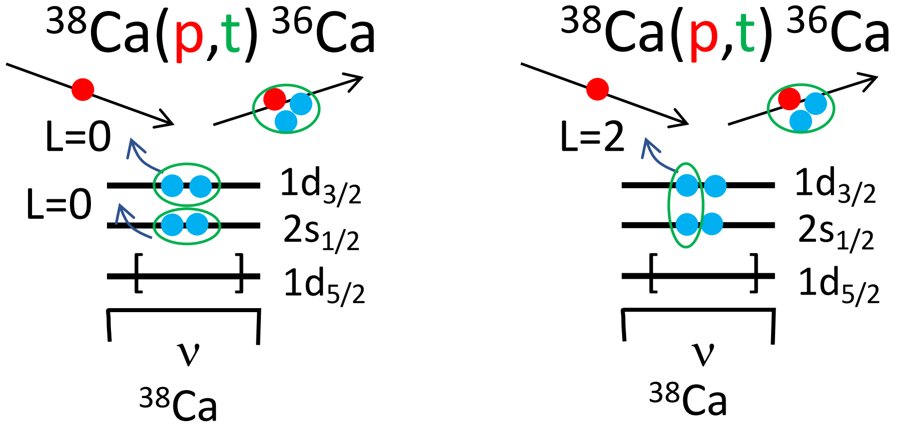


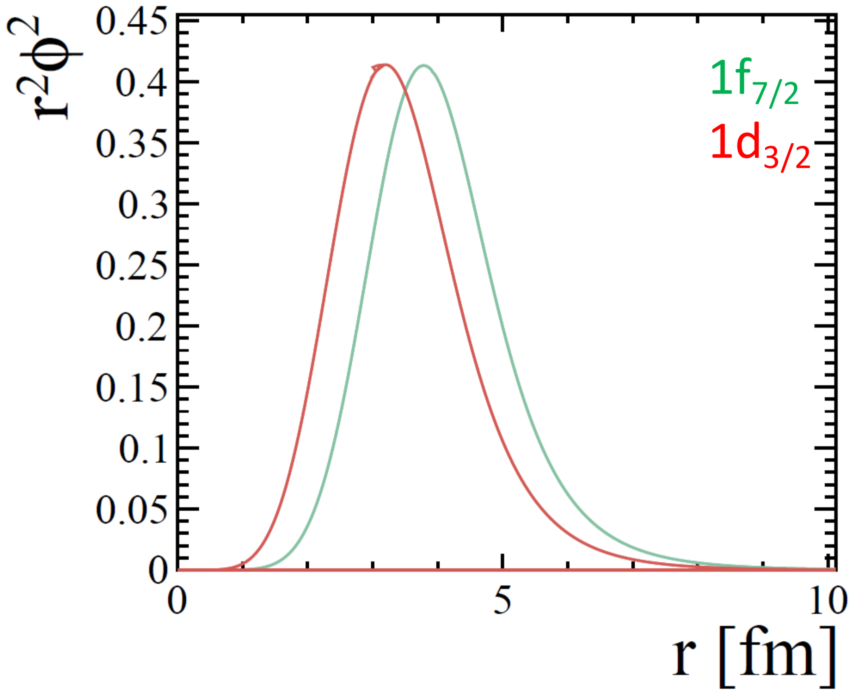
Very large MED between the 0$^+_2$ states -> first excited state in ^{36}Ca

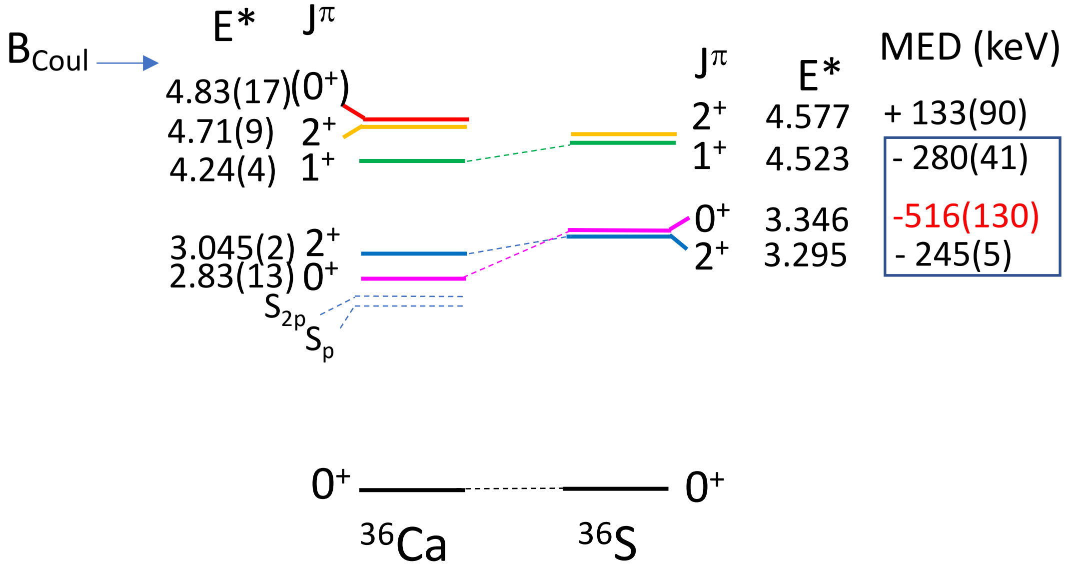
L. Lalanne, O. Sorlin, A. Poves et al., PRL 103 (2021) 055809

Colossal shift between 0^+_2 states due to shape coexistence









Very large MED between the 0^+_2 states -> first excited state in ^{36}Ca

Closed-shell for 0^+_1 and deformed ν(1p1h) & π(2p2h) &) for 0^+_2 in ^{36}Ca

+250 (^{36}S) & -250 (^{36}Ca) & = -500 keV

L. Lalanne, O. Sorlin, A. Poves et al., PRL 103 (2021) 055809

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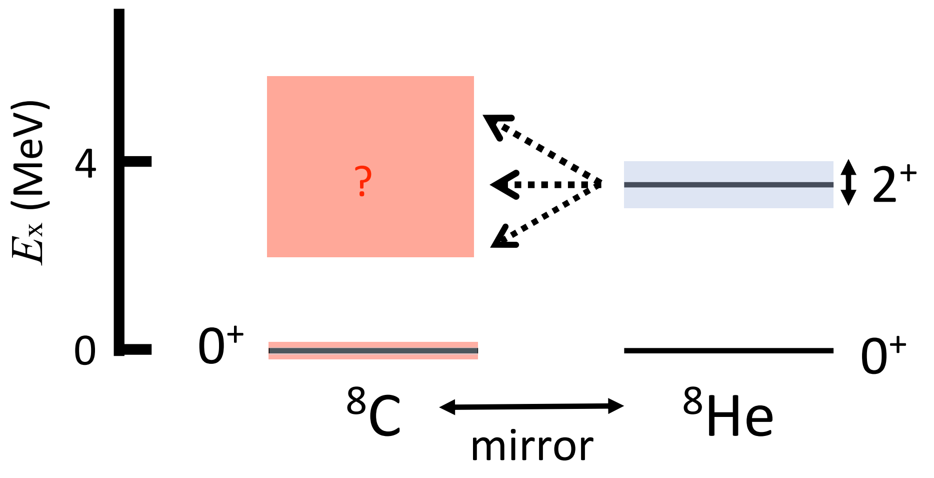
Conclusions and perspectives

Study of mirror symmetries at both edges of the valley of stability ^{8}C - ^{8}He

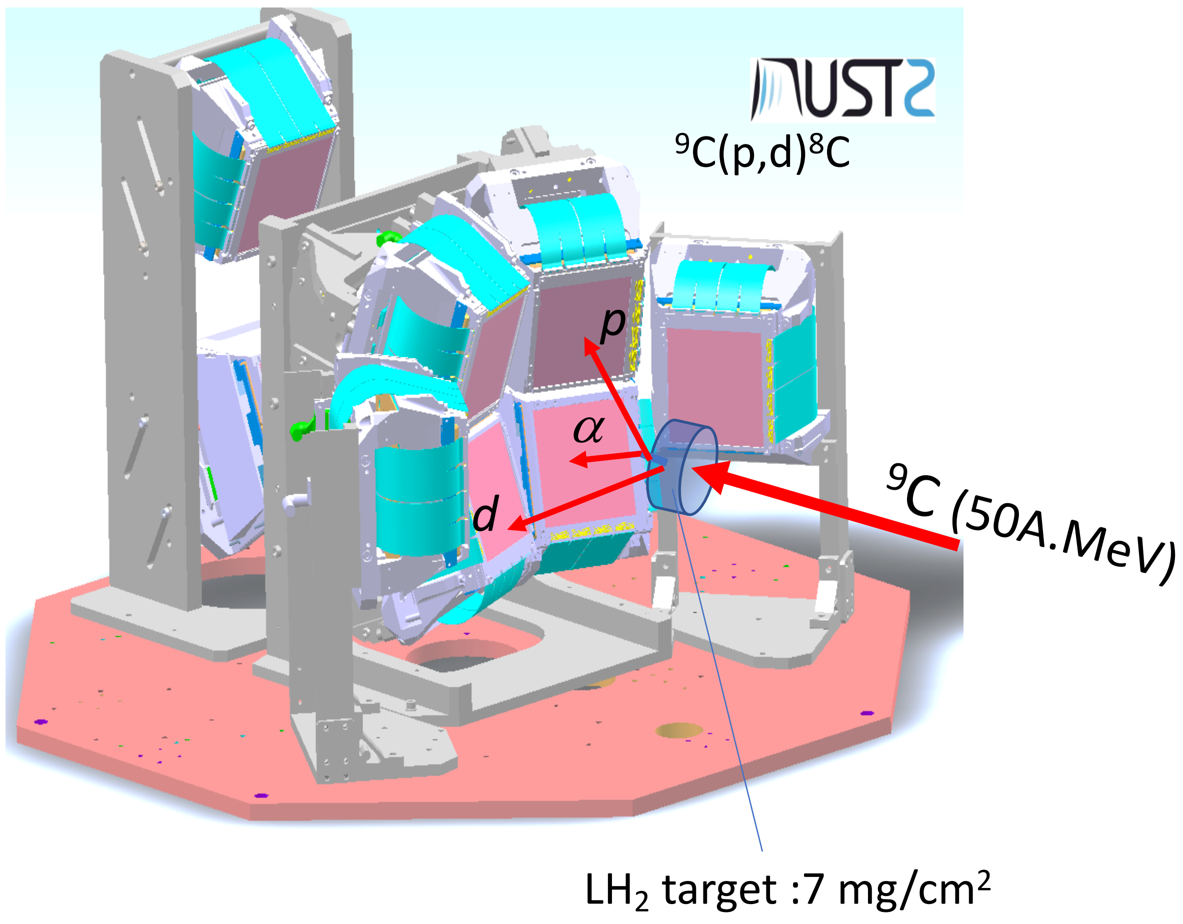


^{8}He : S_n= 2.13 MeV,
2^{+}_{1} resonance unbound by 1.4 MeV
2*n* emission, $\Gamma \sim$ 0.8 MeV

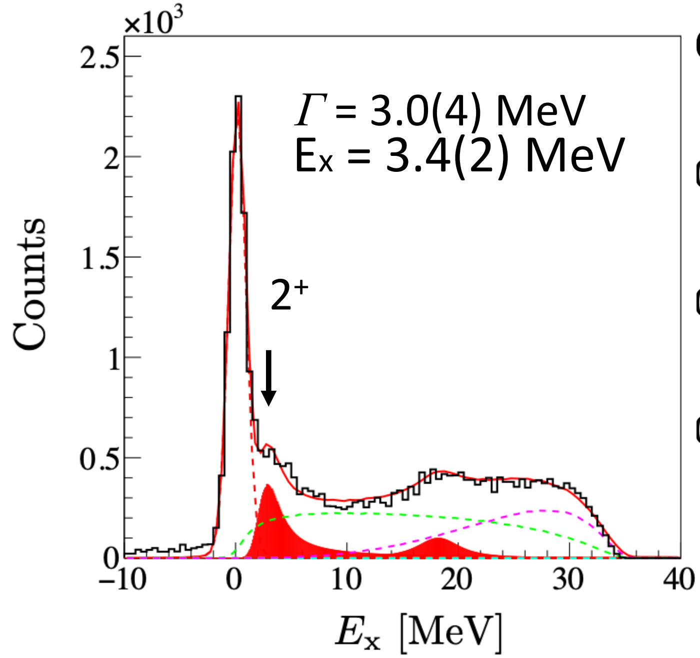
^{8}C : S_p = - 3.48 MeV
only g.s. is known α+4*p* emission, Γ = 130(50) keV
R. J. Charity et al., PRC 84 014320

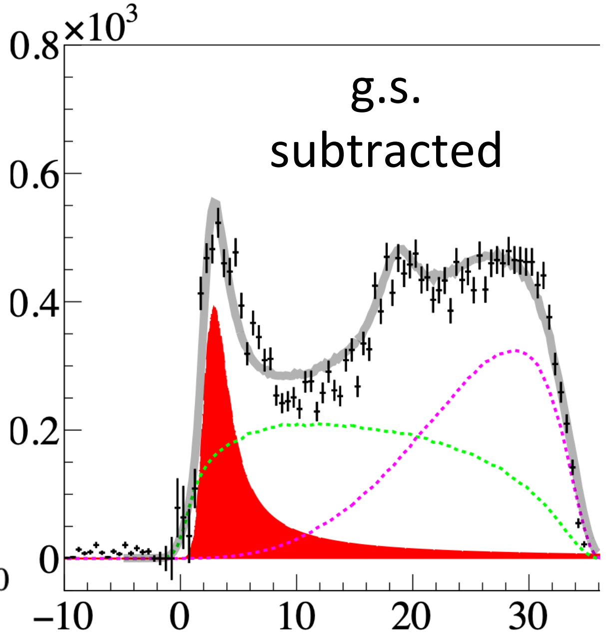
↓

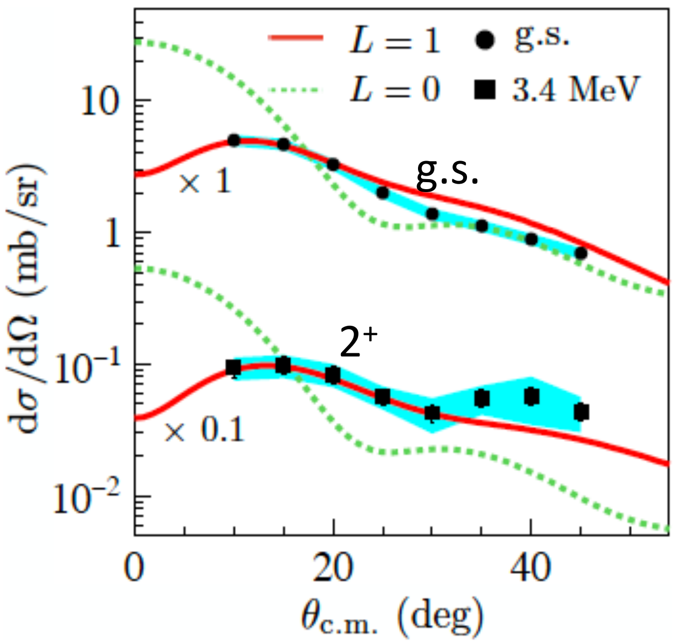
Determine the 2^{+}_{1} energy of ^{8}C (large Γ expected)
-> What is the mirror energy difference?



Transfer $^{9}C(p,d)^{8}C$ reaction (50A.MeV) to populate unbound states in ^{8}C

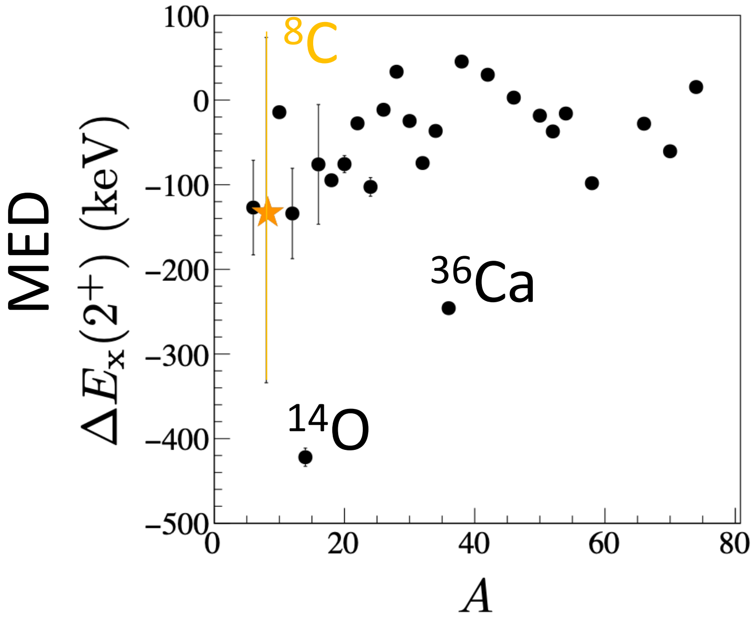






Mirror energy compatible between A=8 2+ states, both unbound

^{8}He by 1.4 MeV, ^{8}C by about 6.9 MeV



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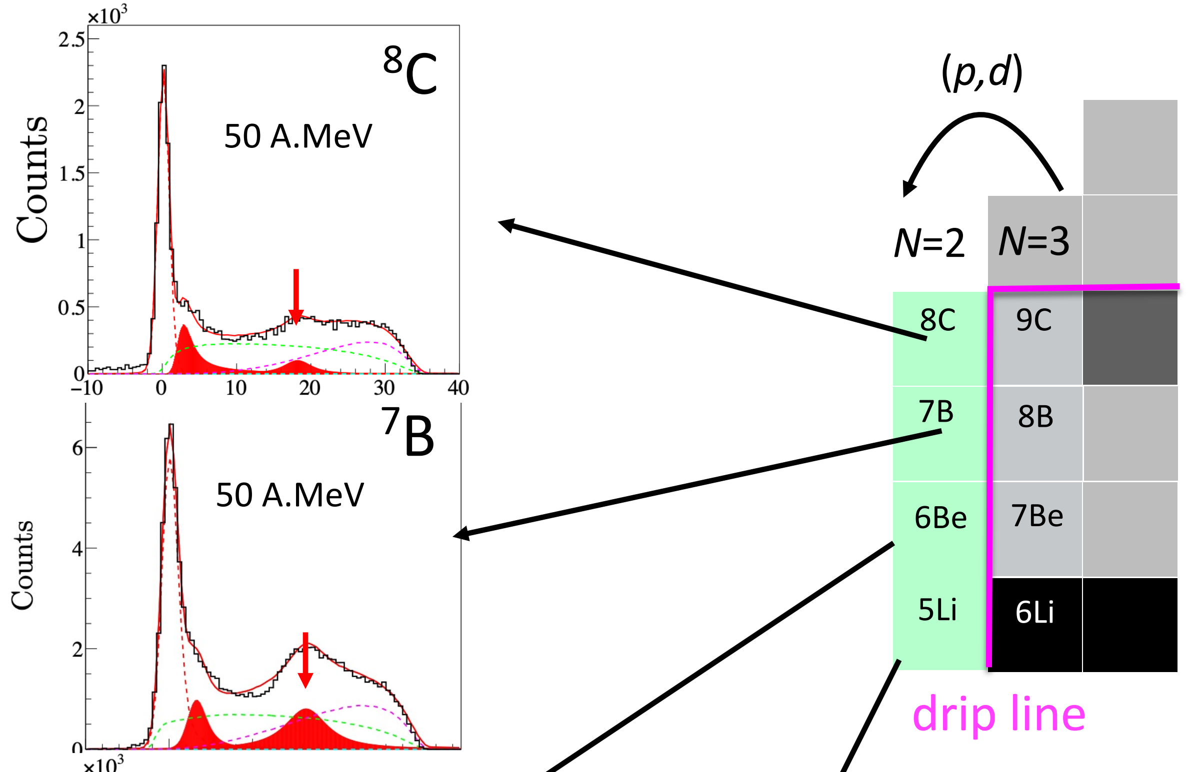
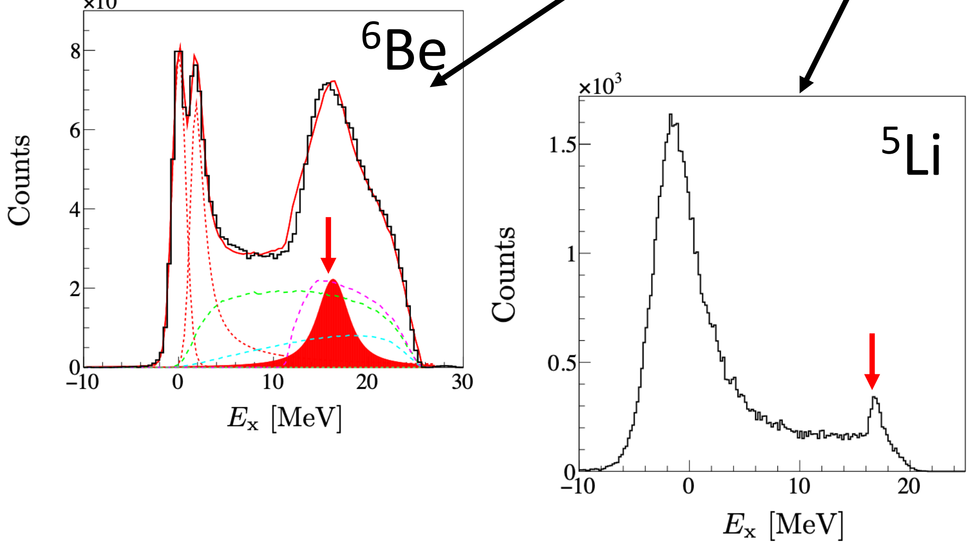
Conclusions and perspectives

Study of high-lying resonant states populated through (p,d) reaction





(p,d) reactions performed from all N=3 isotones

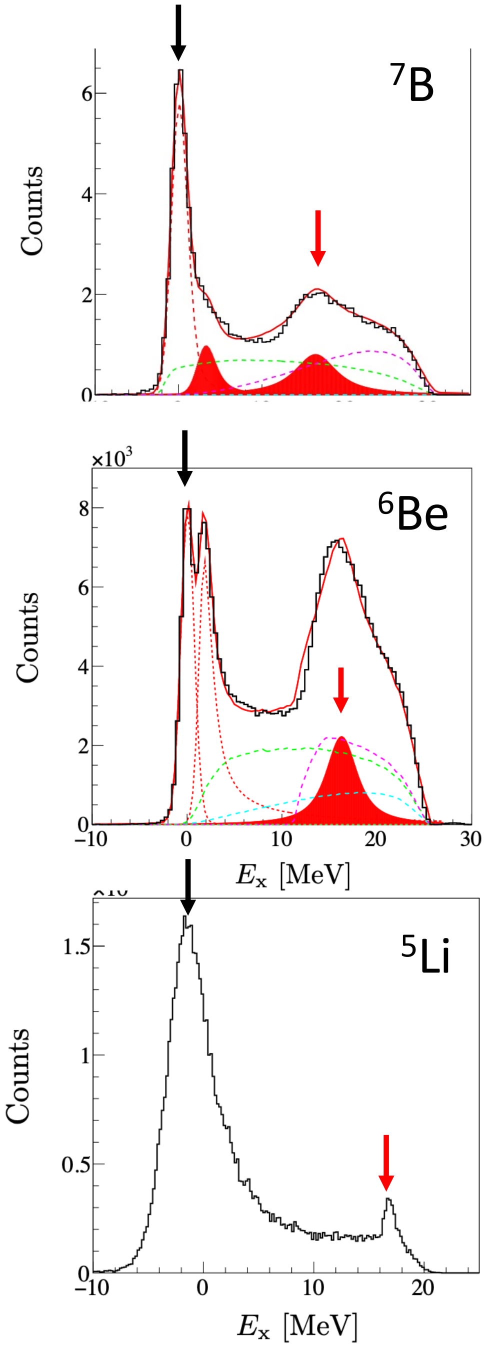
Spectra obtained using kinematics of the deuteron

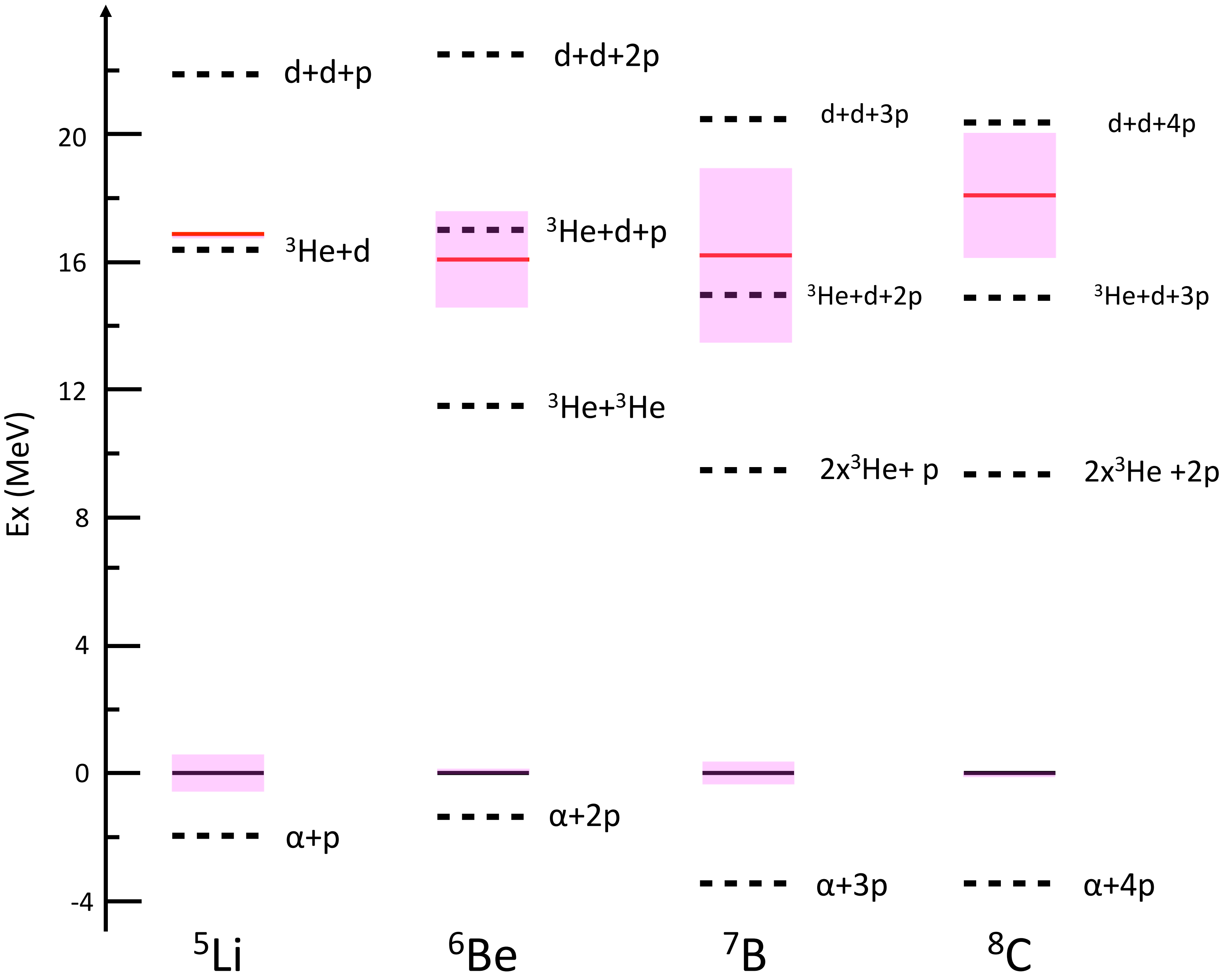
Resonances systematically observed around 17 MeV

What is their origin ?

Narrow resonance at 16.87 MeV
Ground state of ^{5}Li already unbound

Position of the resonances as compared to particle-emission thresholds



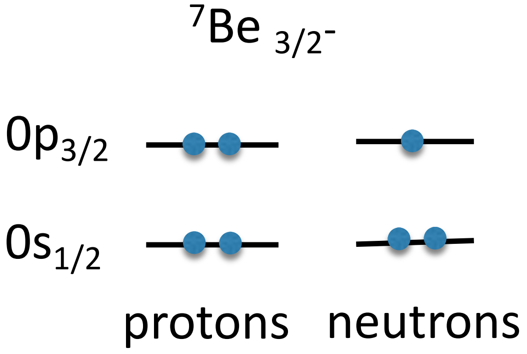


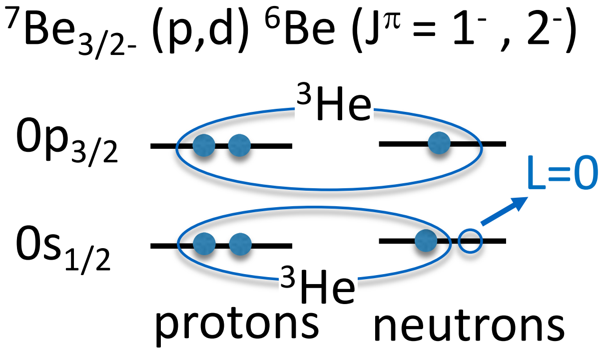
Study of ^{3}He cluster states in ^{6}Be produced by 7Be (p,d) reaction

Removal of an L=0 neutron favors the population of ^{3}He

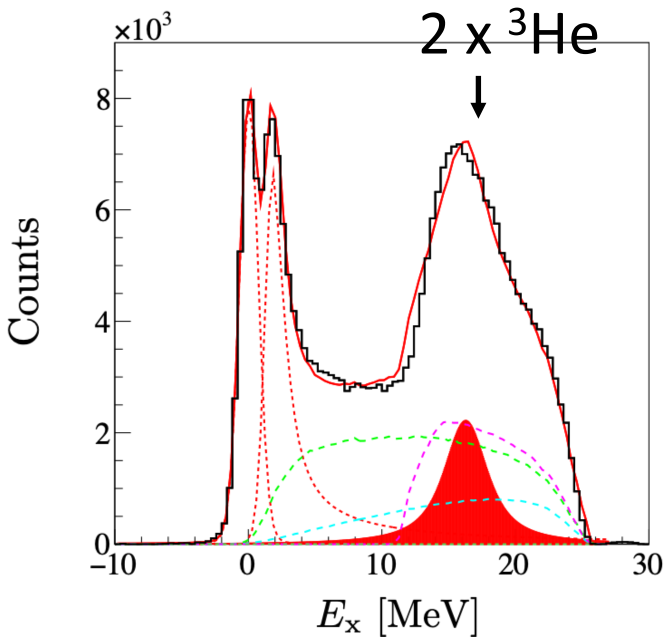
Two resonant states are likely produced with $J^{\pi} = 1^{-}, 2^{-}$

Resonances exclusively decay by ^{3}He + ^{3}He
despite unbound by about 16 MeV w.r.t α + 2p threshold
-> strong clustering

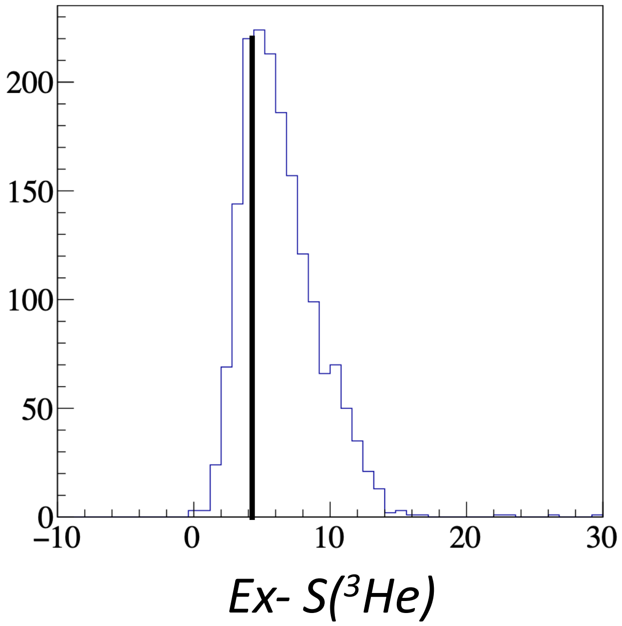




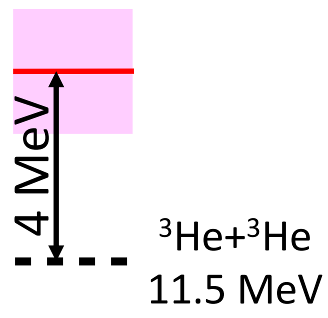
Resonances relatively high above threshold w.r.t ^{4}He + ^{4}He in ^{8}Be
-> Fermions vs bosons ?
-> Angular momenta between the two ^{3}He ?



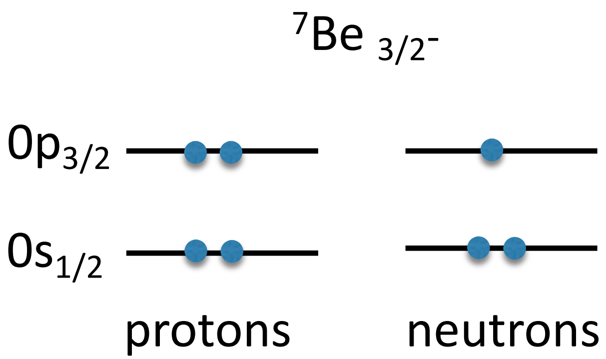
Using d kinematics

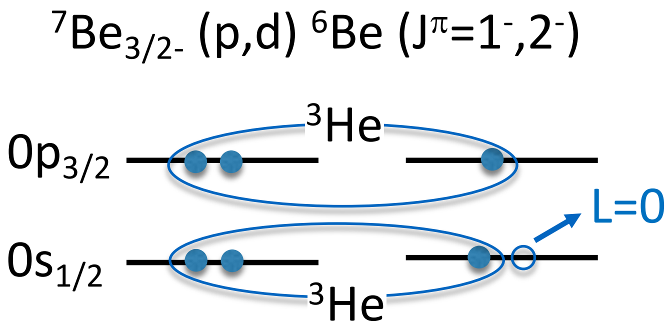


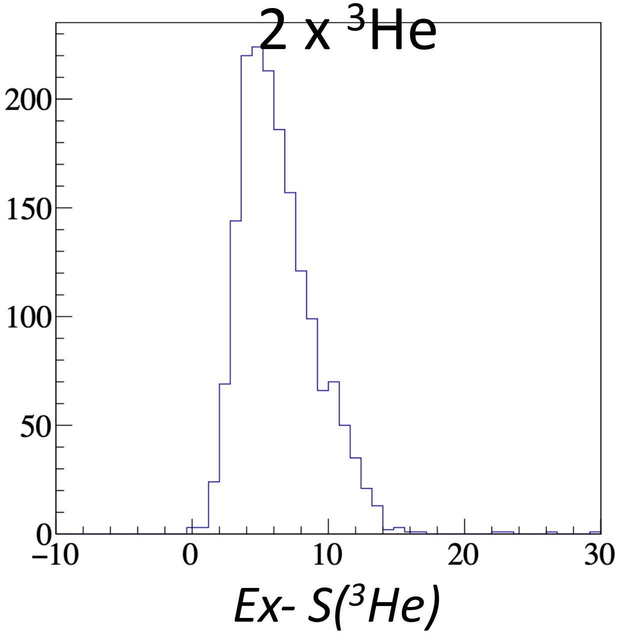
Using ^{3}He + ^{3}He kinematics

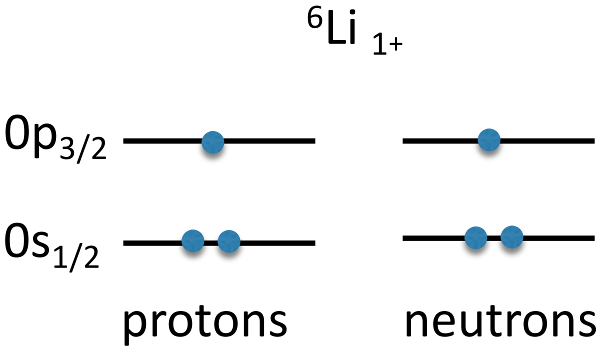


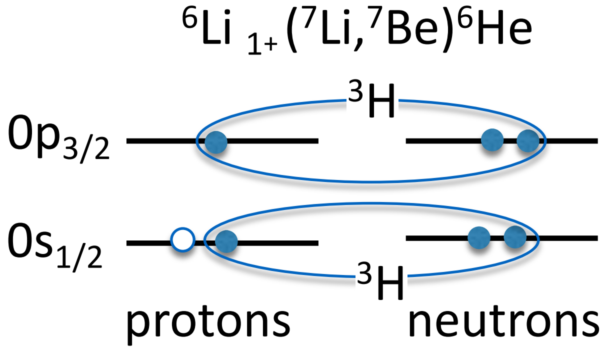
Signatures of 3He and 3H clustering in ^{6}Be and ^{6}He

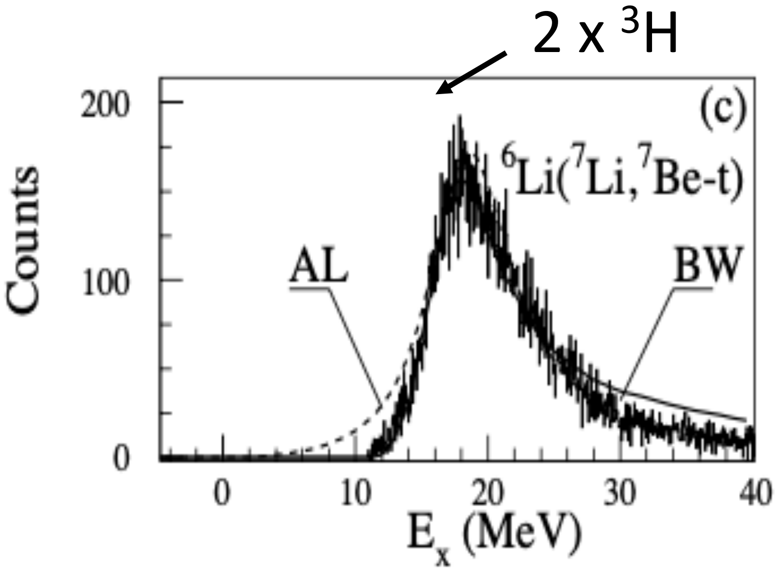












H. Akimune et al., PRC 67 (2003) 051302

Breaking of mirror symmetry due to the influence of the continuum ^{16}N - ^{16}F (I. Stefan)

Massive breaking of mirror symmetry in ^{36}Ca - ^{36}S du to shape coexistence (L. Lalanne)

Study of mirror symmetries at both edges of the valley of stability ^{8}C - ^{8}He (S. Koyama)

Search for ^{3}He clustering in N=2 isotones (S. Koyama)

Conclusions (and perspectives)

Conclusions

MED studied using RES in the ^{16}F (unbound) – ^{16}N (bound) system

-> large effect due to the continuum and extension of radial wave function for s orbit

-> change of g.s. config. between mirror nuclei observed for the first time

I. Stefan et al. PRC 90 (2014) 014307

MED studied by (p,d) reaction for 2^+ state in the ^{8}C (unbound) – ^{8}He (unbound) system

-> Compatible with zero, despite ^{8}C being much strongly unbound

-> Good test for no-core SM models

S. Koyama et al. , submitted to Phys. Rev. Lett.

MED studied by (p,d) and (p,t) reactions for 1^+, 2^+ and 0^+ states in the ^{36}Ca- ^{36}S system

-> Large MED of about 250 for the J=1,2

-> Same C^2S values between mirror reactions – astrophysical implications

-> 'Colossal' MED of about 500 keV for the 0+2 state – shape coexistence

The Coulomb force acts a magnifying glass to reveal the structure of the states, without changing their structure

L. Lalanne et al., PRL 103 (2021) 055809

Presence (and persistence) of ^{3}He clustering in the N=2 isotones studied by (p,d) reaction

-> Well populated resonances around E* = 18 MeV in ^{5}Li, ^{6}Be, ^{7}B and ^{8}C.

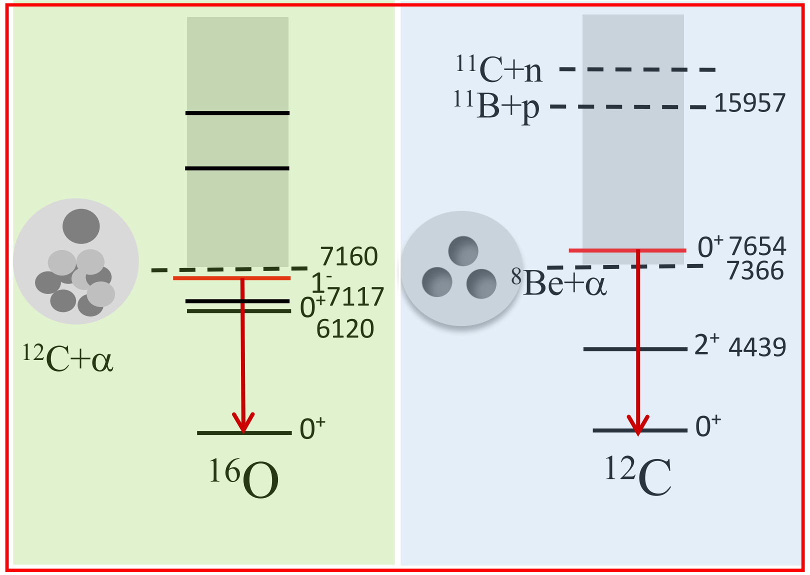
-> That of ^{6}Be decays exclusively through 2 x ^{3}He despite the a + 2p threshold is largely open

-> Adding 1 and 2p to the (2 x ^{3}He) system seems to preserve the clustering

S. Koyama et al. , to be submitted

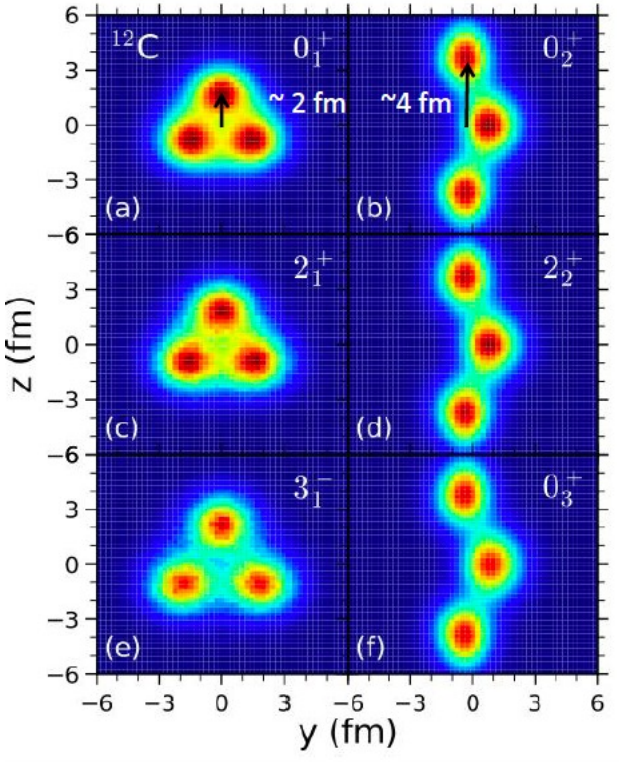
The Ikeda conjecture and its role in nuclear astrophysics

α cluster states



Ikeda conjecture:

Systematic identification of narrow resonances close to the corresponding emission thresholds



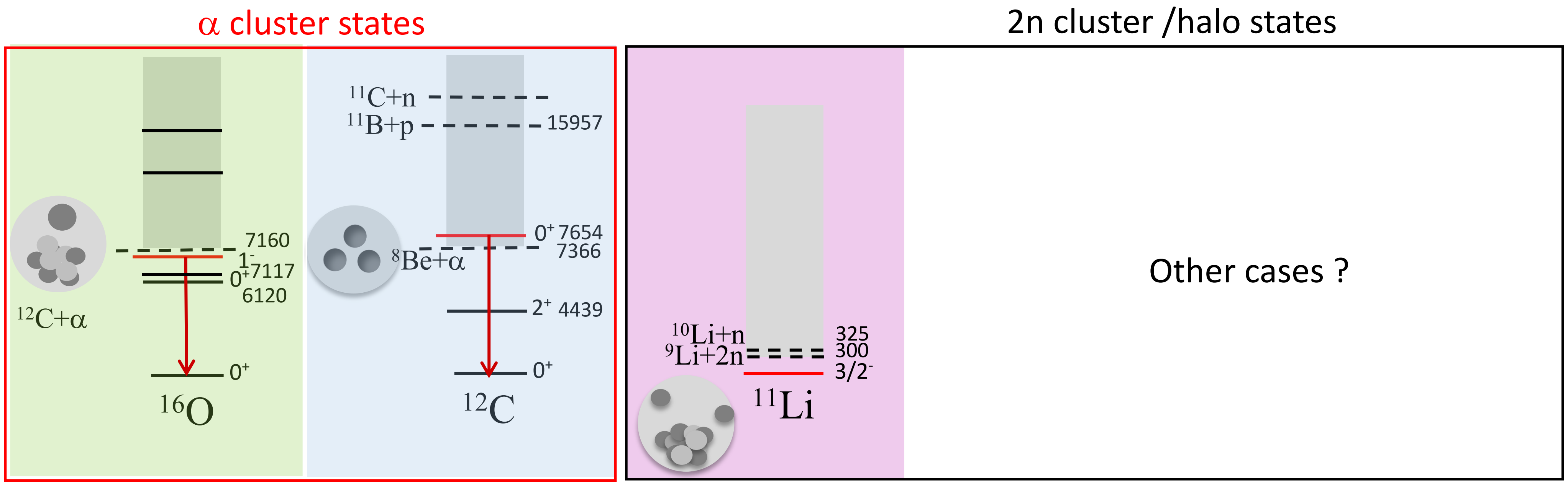
The (3α) Hoyle state in ^{12}C and the (^{12}C+ α) subthreshold resonance in ^{16}O play crucial roles in regulating the ^{12}C/^{16}O ratio in the universe

The γ-decay branch of the Hoyle state allows the ^{12}C to be synthesized

II. Can the ikeda conjecture be generalized to 2n-4n clusters ?

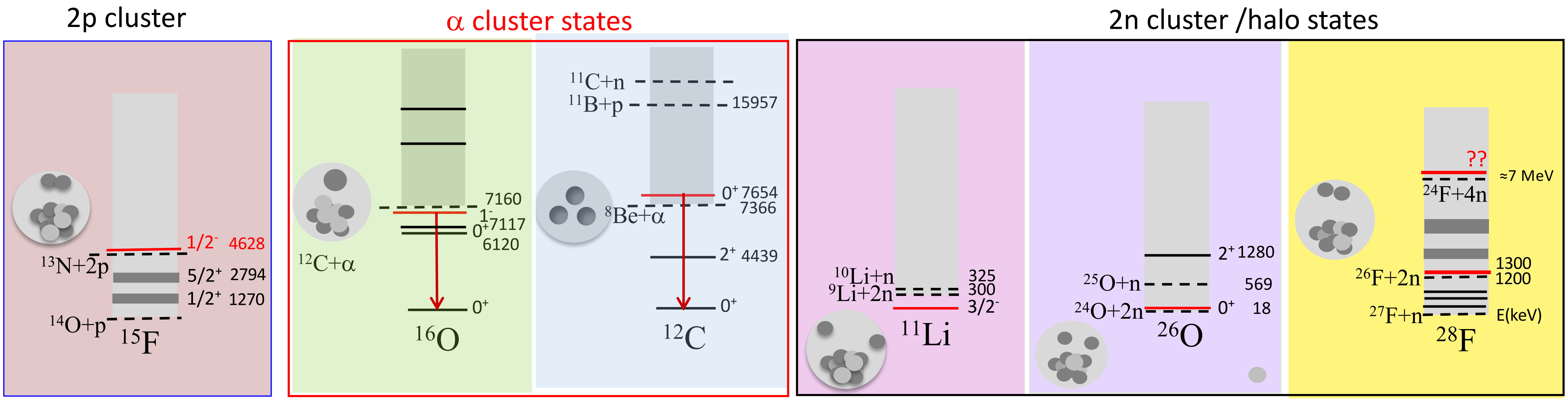
J. Okolowicz, et al. Prog. Th. Phys. Supp. 196 (2012)

See also J. Okolowicz; M. Ploszajczak and W. Nazarewicz PRL 124 (2020) 042502



The 2n-halo ^{11}Li nucleus (bound by 300 keV) was the only remarkable case that fell into a generalized conjecture ...

Generalized Ikeda conjecture to 2n, 2p clusters ?

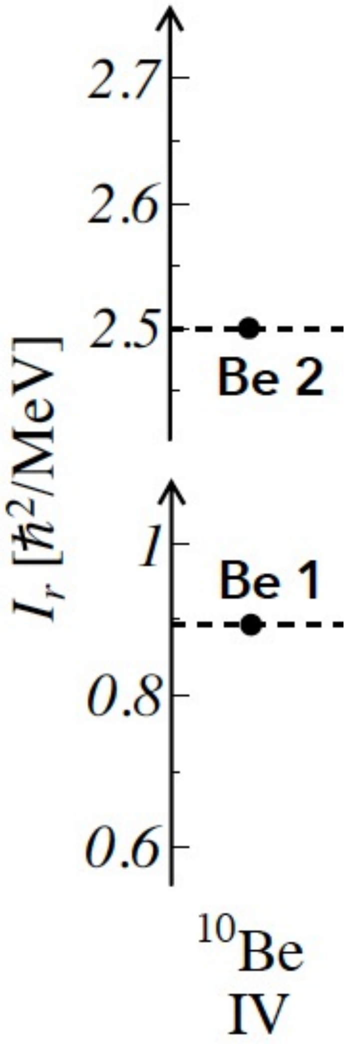


Occurrence for such clusters -> presence of nearby orbits ?
-> Such resonances woulc considerably speed up neutron captures in the r process nucleosythesis
-> Look at the competition with gamma decay

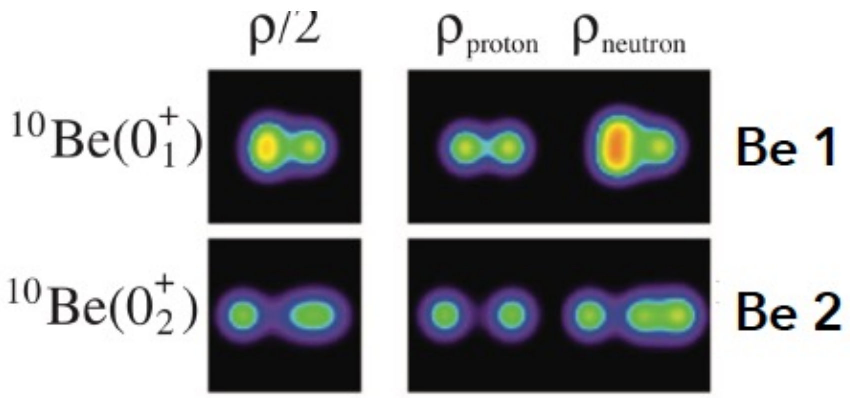
Do they form a compact di-neutron or a dilute one ?
-> Find experimental probes to determine their distances and correlations (transfer, knockout...)

Alpha clustering in the A=10 systems: dependence with isospin

$^{10}Be = \alpha + \alpha + 2n$, $^{10}B = \alpha + \alpha + n + p$, $^{10}C = \alpha + \alpha + 2p$



Explore the isospin dependance of rotational bands



Y. Kanada-En'yo, M. Kimura, A. Ono, PTEP, 01A202 (2012)

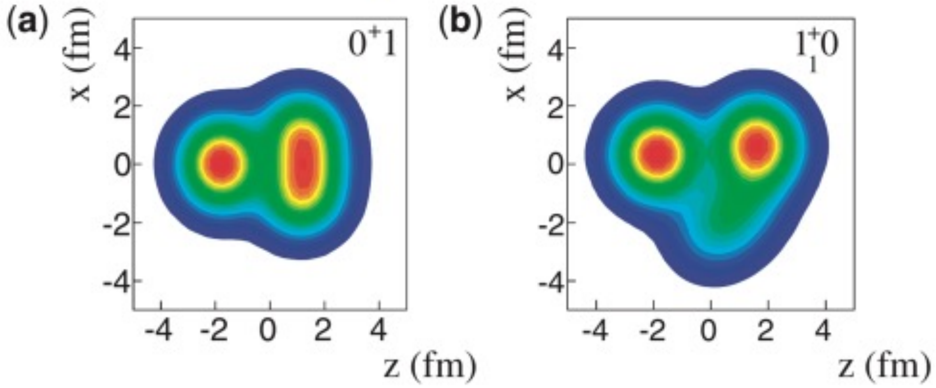
From B. Mauss

Alpha clustering in the A=10 systems: dependence with isospin

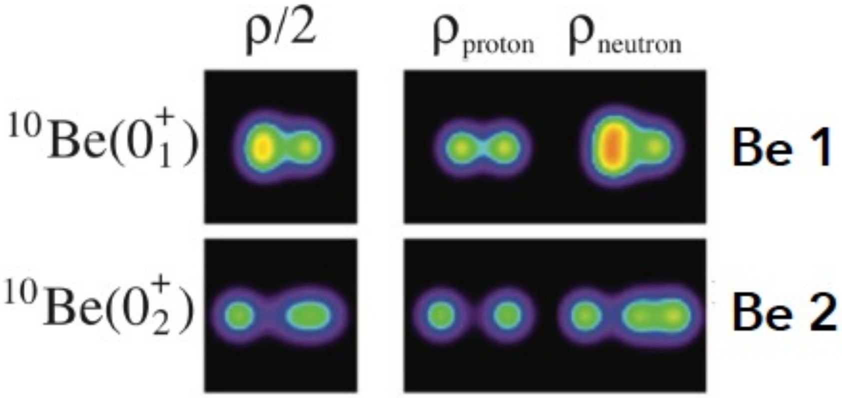
^{10}Be = $\alpha + \alpha$ + 2n, ^{10}B = $\alpha + \alpha$ + n +p, ^{10}C= $\alpha + \alpha$ + 2p

^{10}B

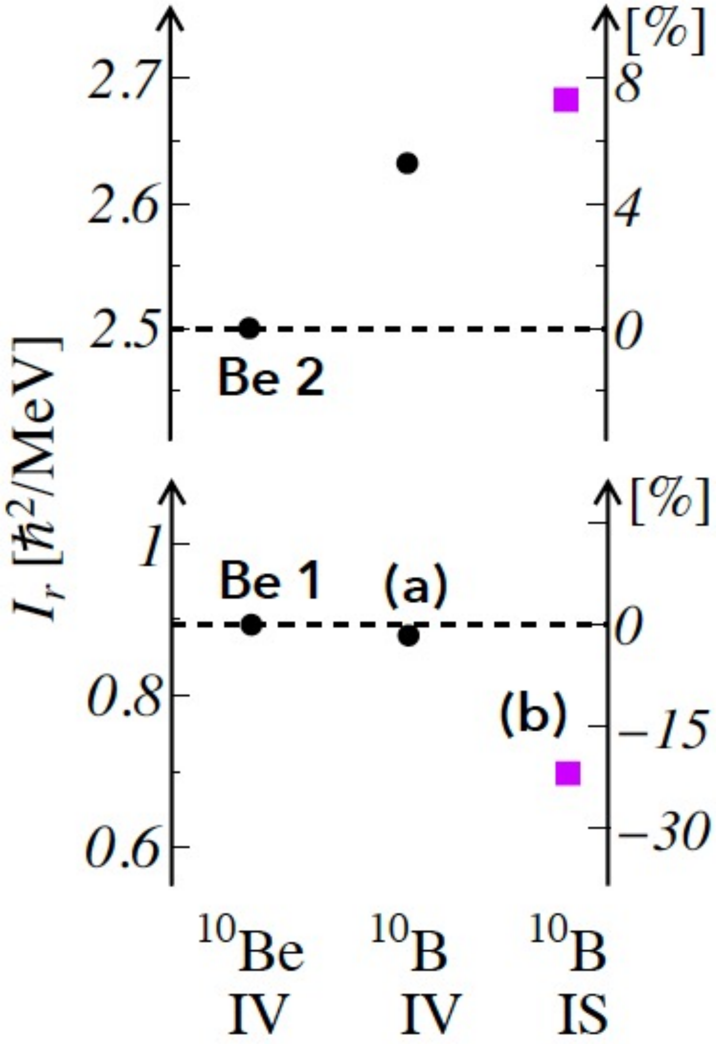
Density distributions



H. Morita and Y. Kanada-En'yo, PTEP 103D02 (2016)



Y. Kanada-En'yo, M. Kimura, A. Ono, PTEP, 01A202 (2012)

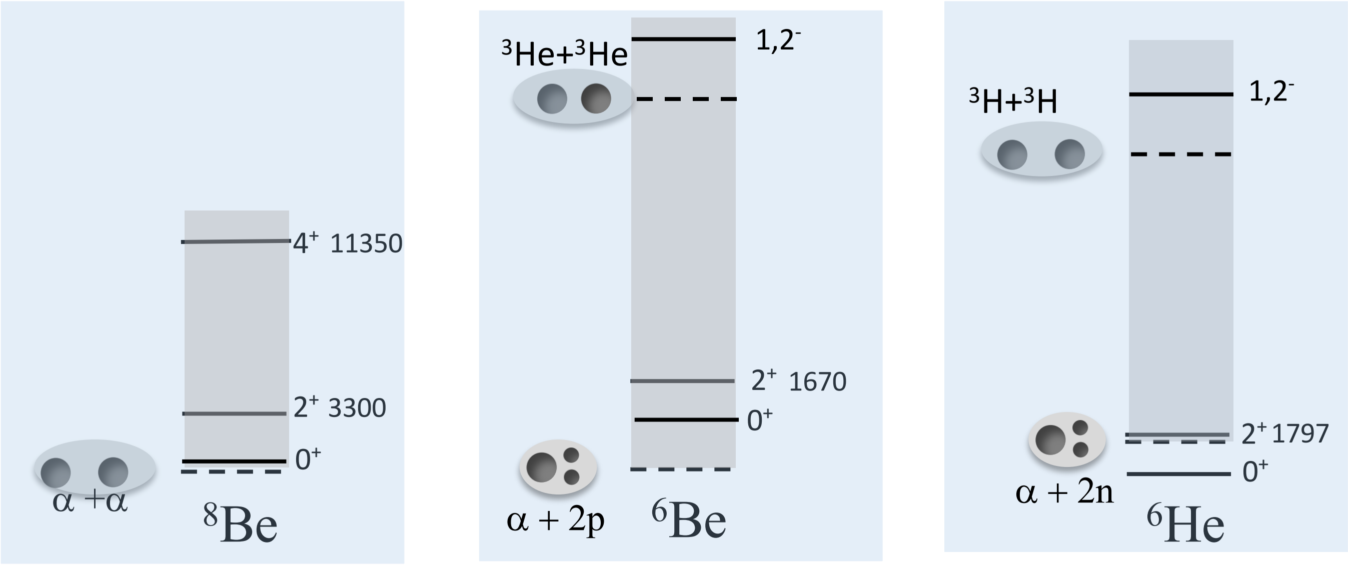


Explore the isospin dependance of rotational bands

-> missing link is ^{10}C
Role of Coulomb repulsion

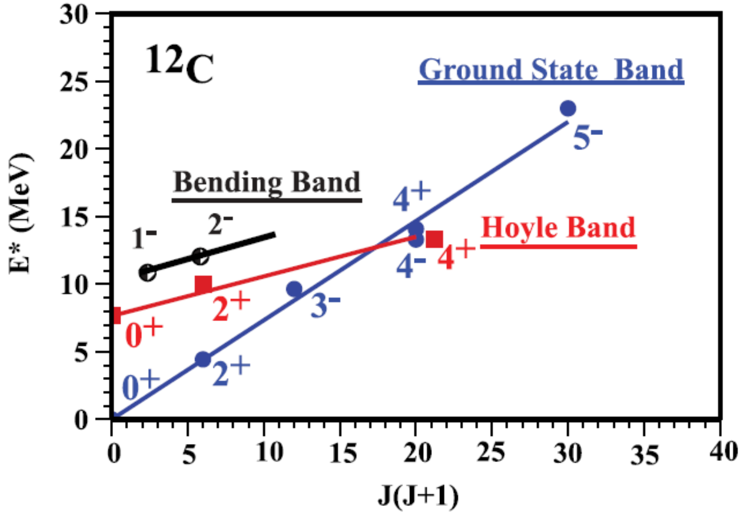
From B. Mauss

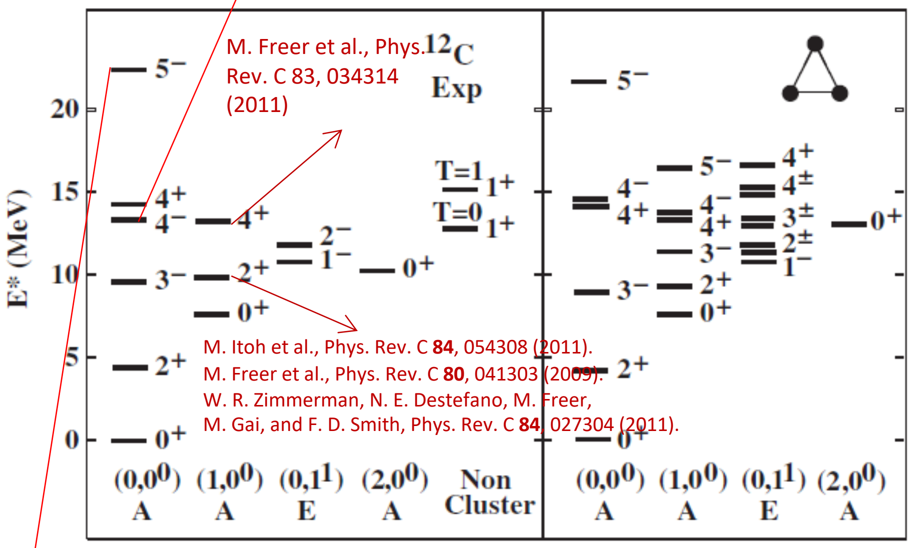
Generalized Ikeda conjecture to ^{3}He, t clusters ?



Experimental study of ^{3}He and ^{3}H clustering
-> Analogies and differences with clusters of bosons ^{4}He
-> Is there a Hoyle-like state existing ?

M. Freer, et al., Phys. Rev. C 76 (2007) 034320.
O.S. Kirsebom, et al., Phys. Rev. C 81 (2010) 064313.



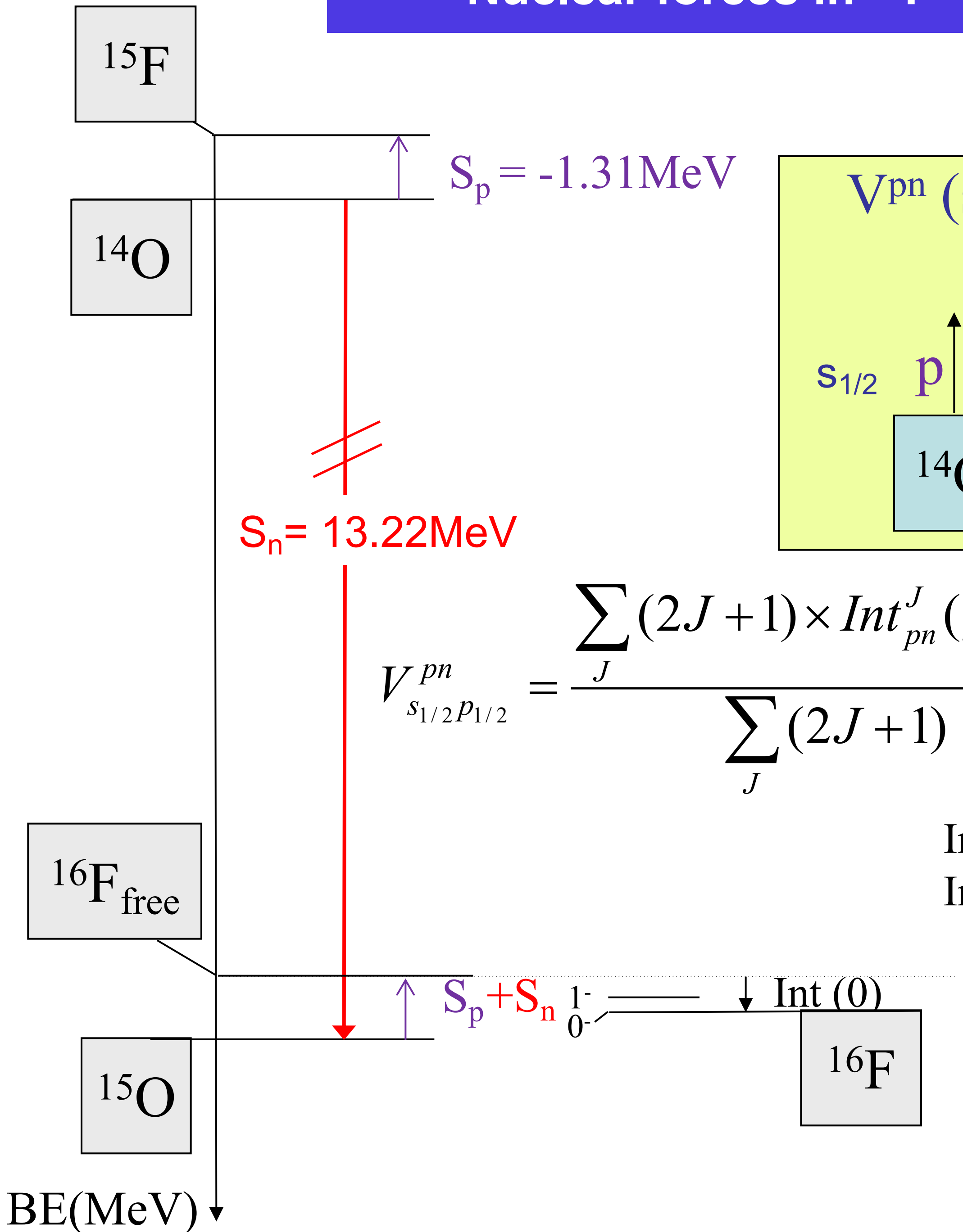


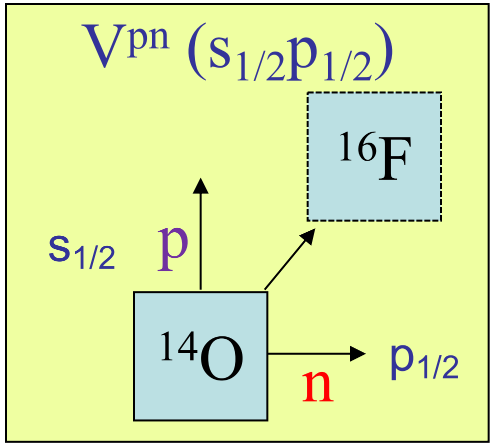
M. Freer et al., Phys. Rev. C 83, 034314 (2011)

M. Itoh et al., Phys. Rev. C **84**, 054308 (2011).
M. Freer et al., Phys. Rev. C **80**, 041303 (2009).
W. R. Zimmerman, N. E. Destefano, M. Freer, M. Gai, and F. D. Smith, Phys. Rev. C **84**, 027304 (2011).

D.J. Marín-Lámbarri et al., Phys. Rev. Lett. 113 (2014) 012502.

Nuclear forces in ^{16}F



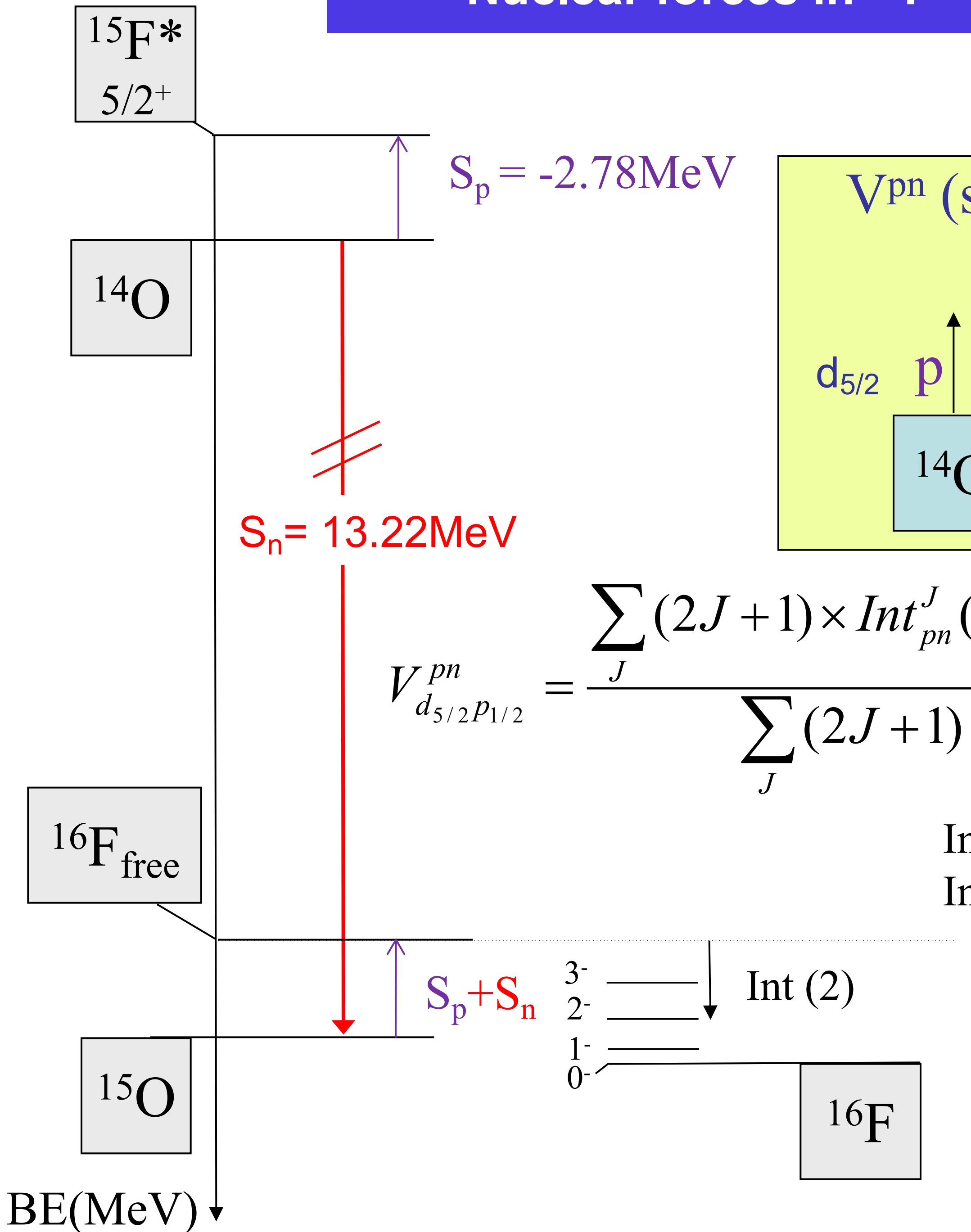


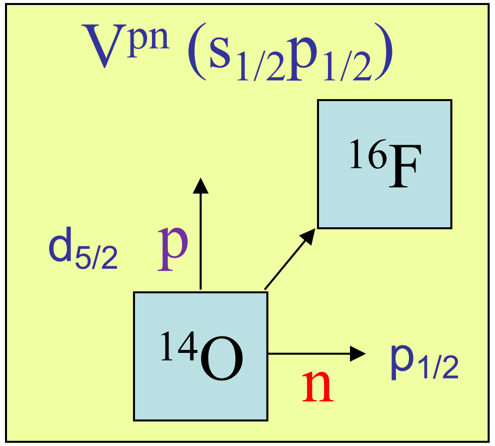
$$V^{pn}_{s_{1/2}p_{1/2}} = \frac{\sum_J (2J+1)\times Int^J_{pn}(j_p, j_n)}{\sum_J (2J+1)} = -0.621 MeV$$

Int (0) = -0.775MeV

Int (1) = -0.577MeV

Nuclear forces in ^{16}F





$$V^{pn}_{d_{5/2}p_{1/2}} = \frac{\sum_J (2J+1)\times Int^J_{pn}(j_p, j_n)}{\sum_J (2J+1)} = -1.66 MeV$$

Int (2) = -1.834MeV

Int (3) = -1.537MeV