Clustering aspects in neutron-rich nuclei studied by AMD

M. Kimura

Introduction: Island of Inversion

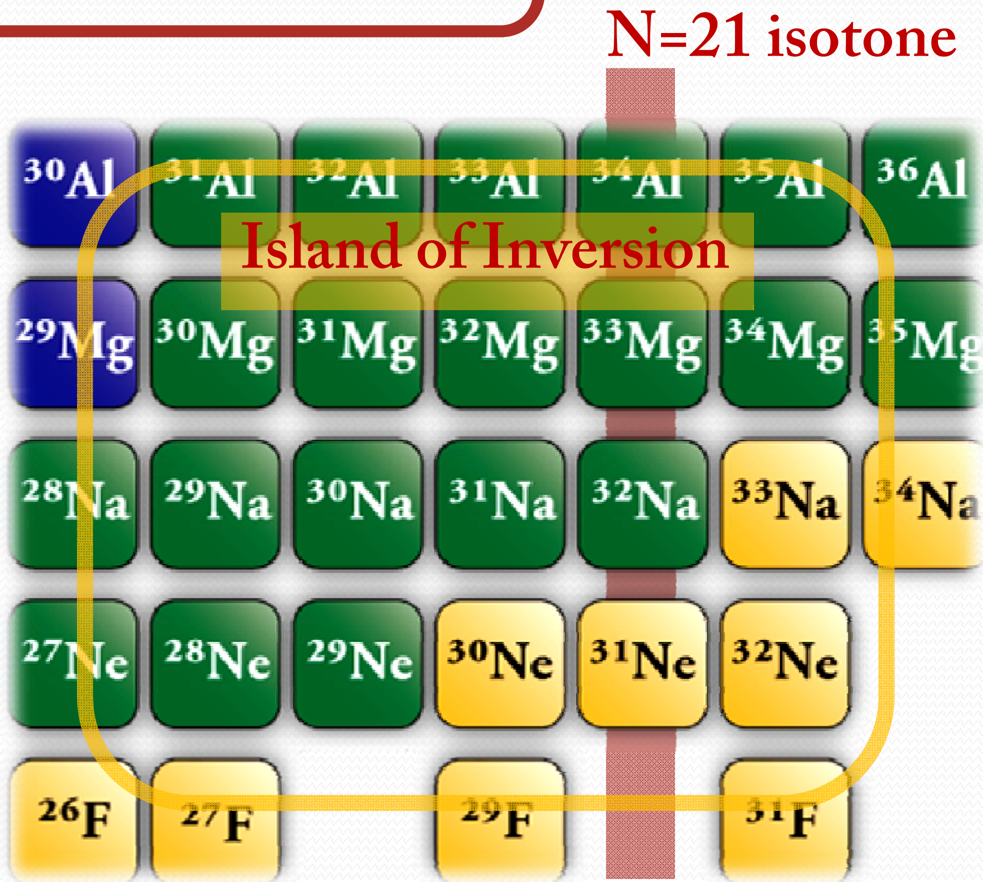
Island of Inversion: N～20 Ne, Na, Mg isotopes

Topics: large deformation, mpmh config., shell gap quench

N=21 isotone: ^{31}Ne(binding limit), ^{33}Mg

Topics: spin-parity, p-wave halo, neutron orbital

- Odd-mass(neutron) system reveals neutron-orbital, shape coexistence in the Island
- The last neutron particle (hole) orbital has strong influence on nuclear properties
- In N=21 isotone, $0f_{7/2}$ and $0d_{3/2}$ orbials take part in the game



Theoretical Framework: AMD

A-body Hamiltonian

$$\hat{H} = \sum_{i=1}^{A} \hat{t}_i - \hat{t}_{c.m.} + \sum_{i<j} \hat{v}_{ij}^{NN} + \sum_{i<j\in P} \hat{v}_{ij}^{Coulomb}, \quad \hat{v}^{NN} : \text{Gogny D1S}$$

Parity projected Slater determinant

$$\Psi_{\text{int}}^{\pm} = \frac{1 \pm \hat{P}_x}{2} \mathcal{A}\{\varphi_1, \varphi_2, ..., \varphi_A\},$$

Single particle wave packets

$$\varphi_i = \phi(\boldsymbol{r})\chi_i\eta_i, \qquad \phi(\boldsymbol{r}) = \exp\{-(\boldsymbol{r} - \boldsymbol{Z}_i)M(\boldsymbol{r} - \boldsymbol{Z}_i)\},$$

$$\chi_i = \alpha_i\chi_\uparrow + \beta_i\chi_\downarrow,$$

Variational parameters

$\boldsymbol{Z}_i$: centroid of wave packet

M : deformation of wave packet

α_i, β_i : spin dirction

Theoretical Framework: AMD

Angular momentum projection

$$\Psi^{J\pm}_{MK} = \int d\Omega D^{J*}_{MK}(\Omega)\hat{R}(\Omega)\Psi^{\pm}_{\text{int}},$$

GCM $\Psi^{J\pm}_{MK}(\beta_1), \Psi^{J\pm}_{MK}(\beta_2), ..., \Psi^{J\pm}_{MK}(\beta_N)$

Generator Coordinate: quadrupole deformation β

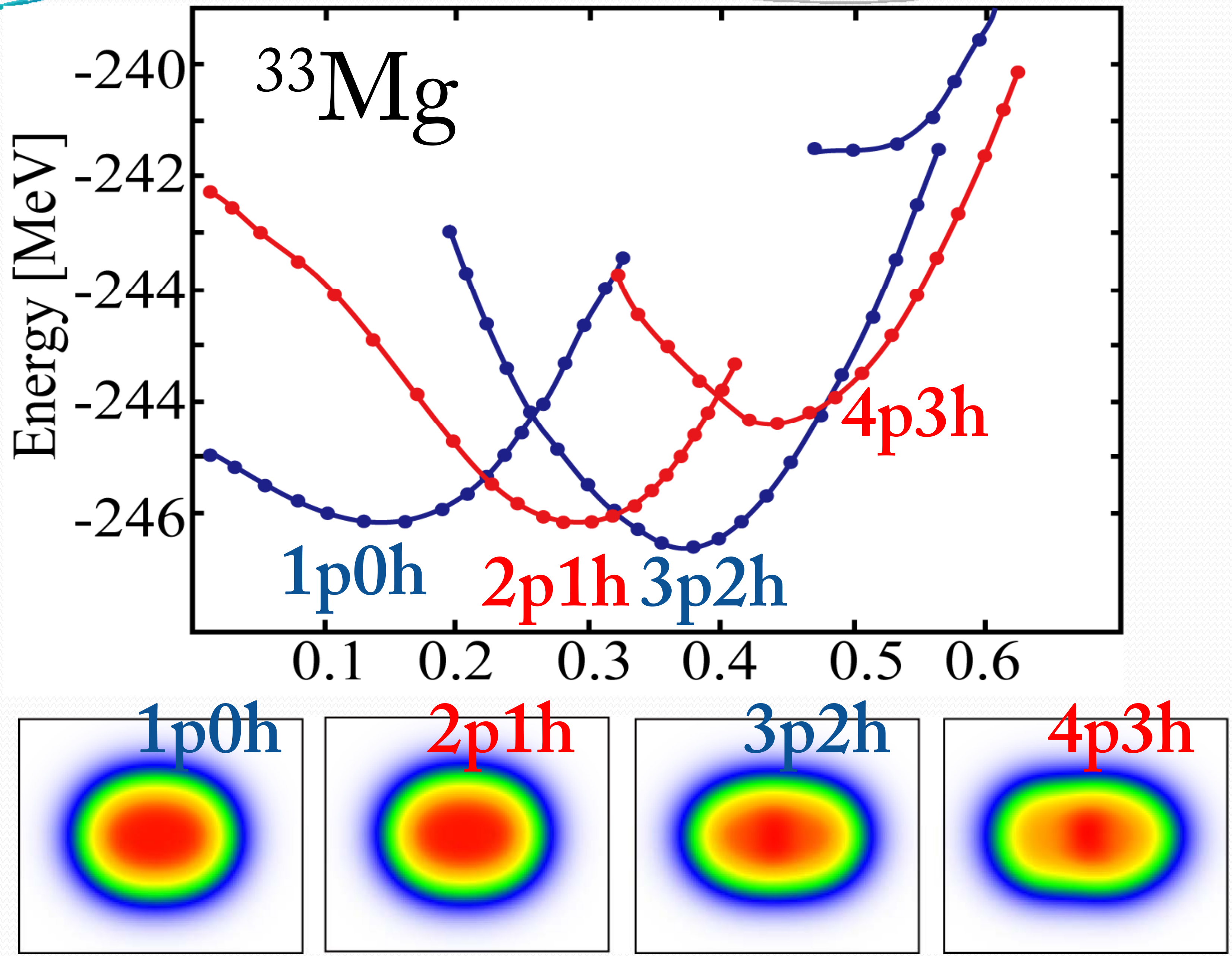
$$\Psi^{J\pm}_{\alpha} = \sum_{iK} c_{ik}\Psi^{J\pm}_{MK}(\beta_i),$$

Hill-Wheeler eq.

$$\sum_{jK'} H_{iKjK'}c_{jK',\alpha} = E_\alpha \sum_{jK'} N_{iKjK'}c_{jK',\alpha},$$

$$H_{iKjK'} = \langle\Psi^{J\pm}_{MK}(\beta_i)|\hat{H}|\Psi^{J\pm}_{MK'}(\beta_j)\rangle, \quad N_{iKjK'} = \langle\Psi^{J\pm}_{MK}(\beta_i)|\Psi^{J\pm}_{MK'}(\beta_j)\rangle$$

Results: Energy Curve and PH Config. of ^{33}Mg

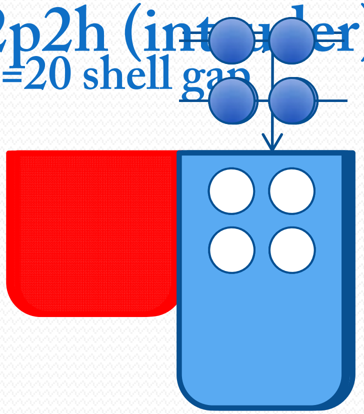


Consideration on the curves

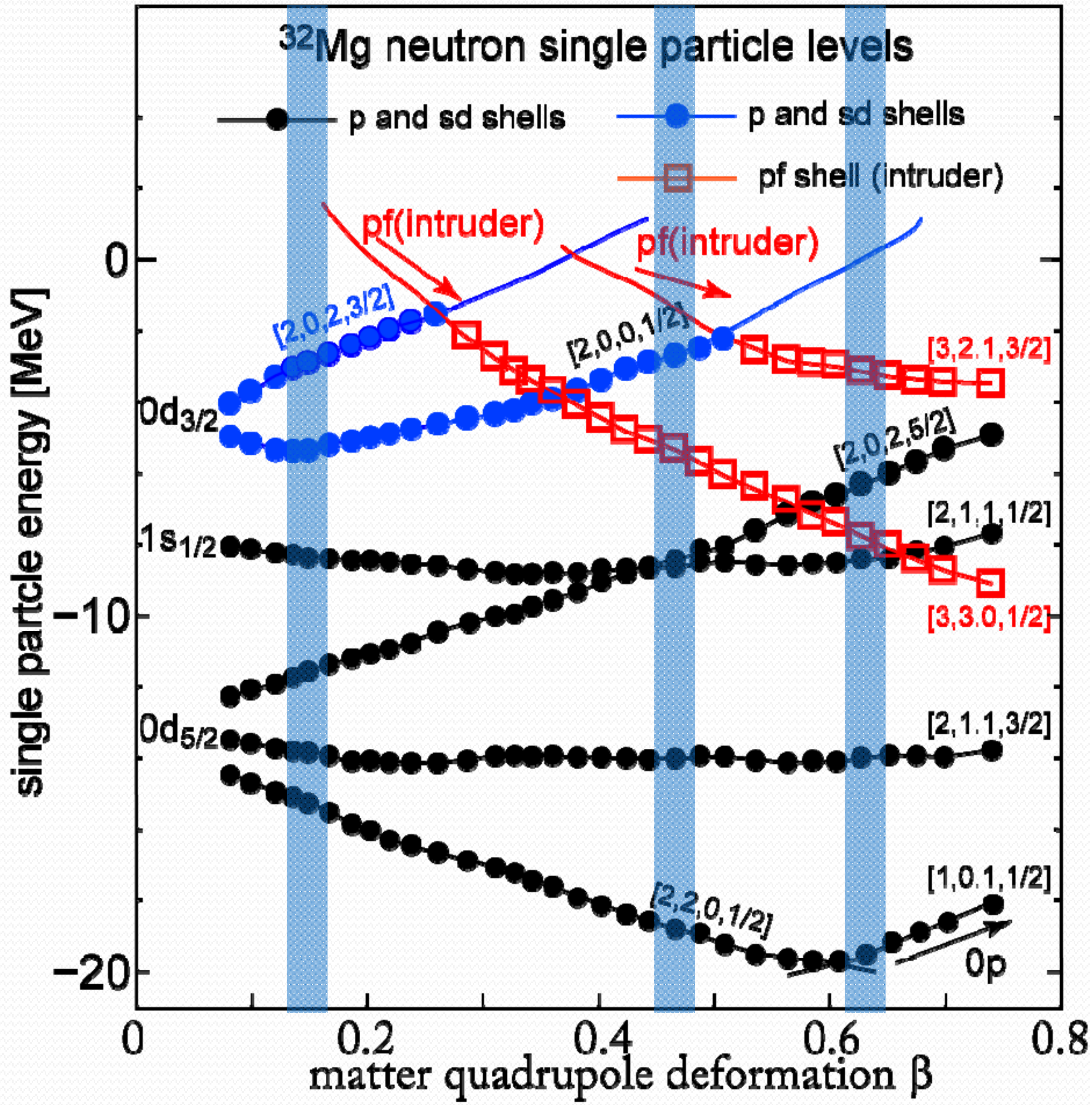
0p0h (normal config.)

4p4h (intruder)

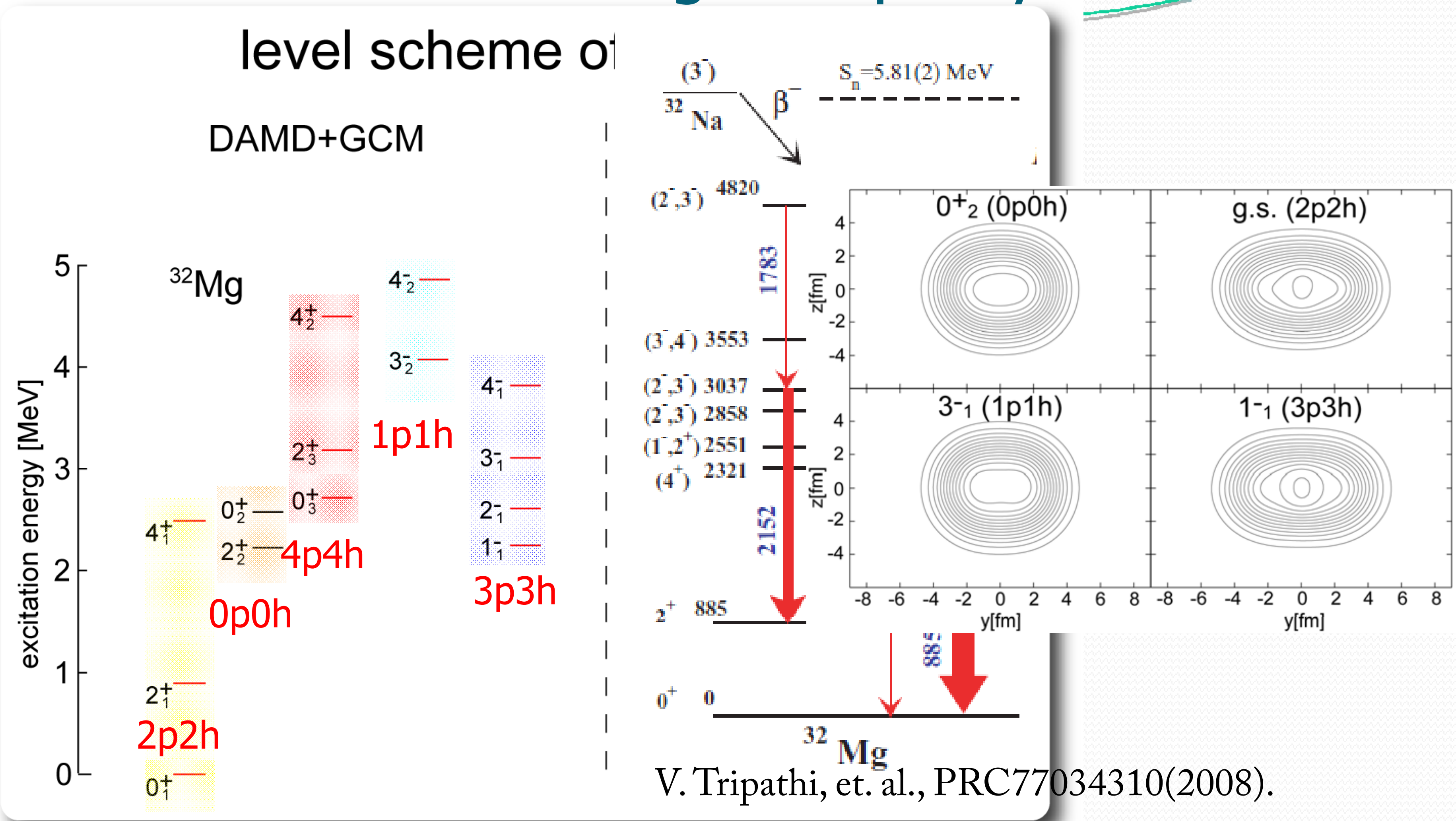
2p2h (intruder)



- 2 orbits of sd and 2 of pf shell participate in this game
- From this one can deduce a naive rule for ph configurations



Results: Behavior of negative parity states



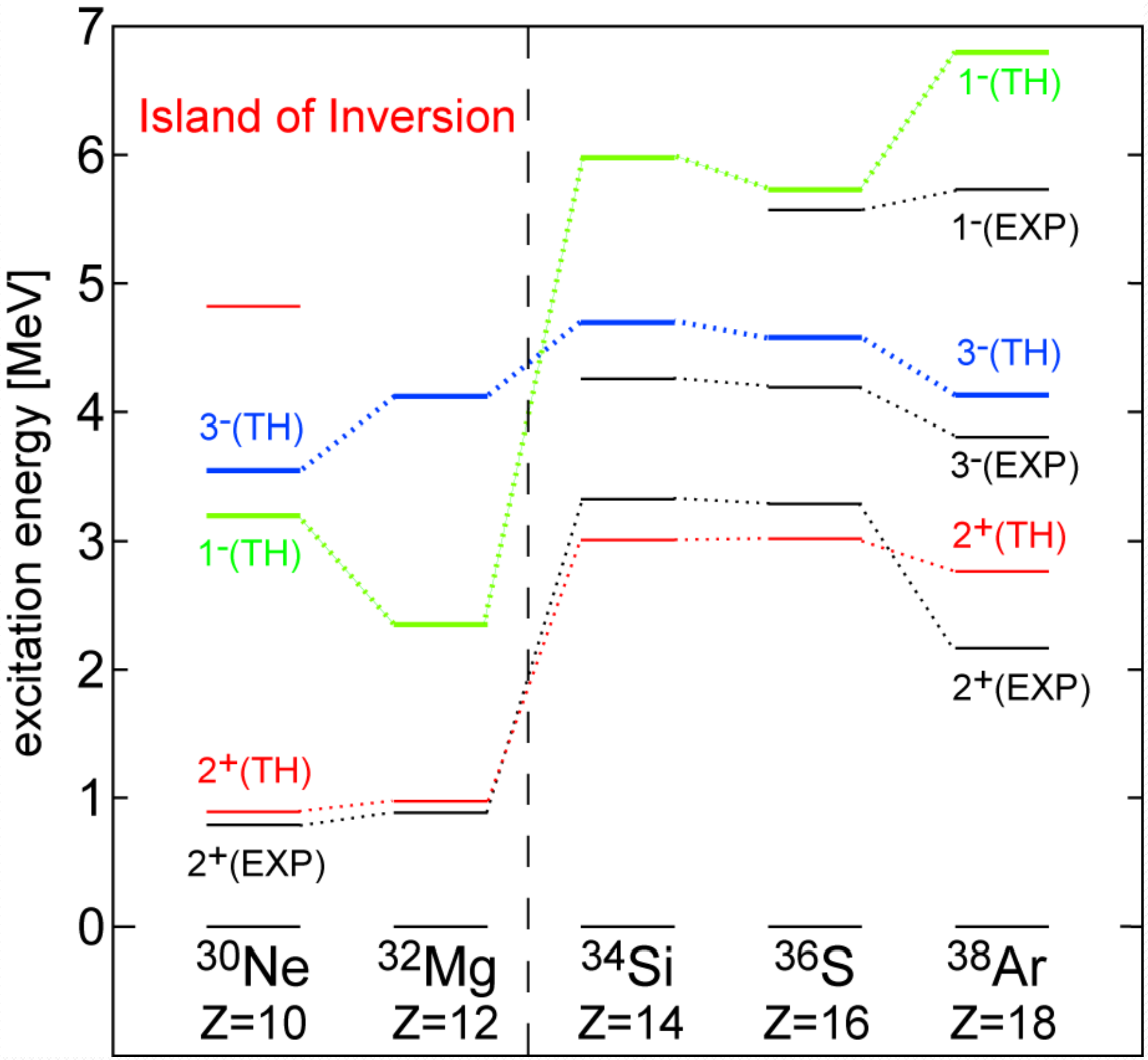
V. Tripathi, et. al., PRC77034310(2008).

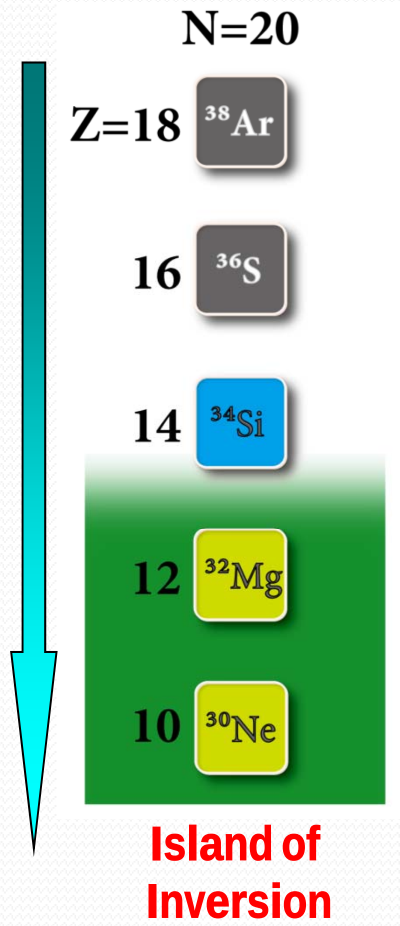
- 1^-(3p3h) state is built on the deformed g.s. (1p1h from 2p2h)
- 3^-(1p1h) state is built on the spherical 0^+ state (1p1h from 0p0h)

Low lying 1^- state is a good signal of the inversion.

Results: Behavior of negative parity states

Case of the N=20 isotone



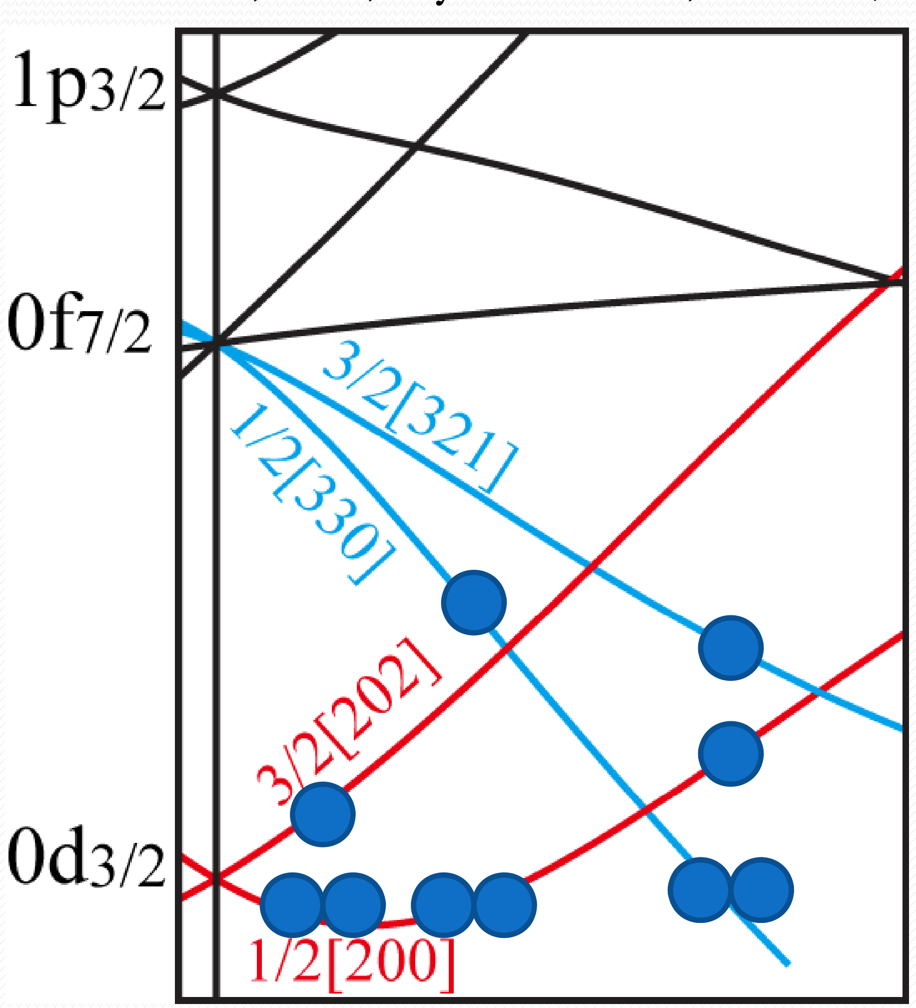


Introduction: Particle Hole Config. (N=19 System)

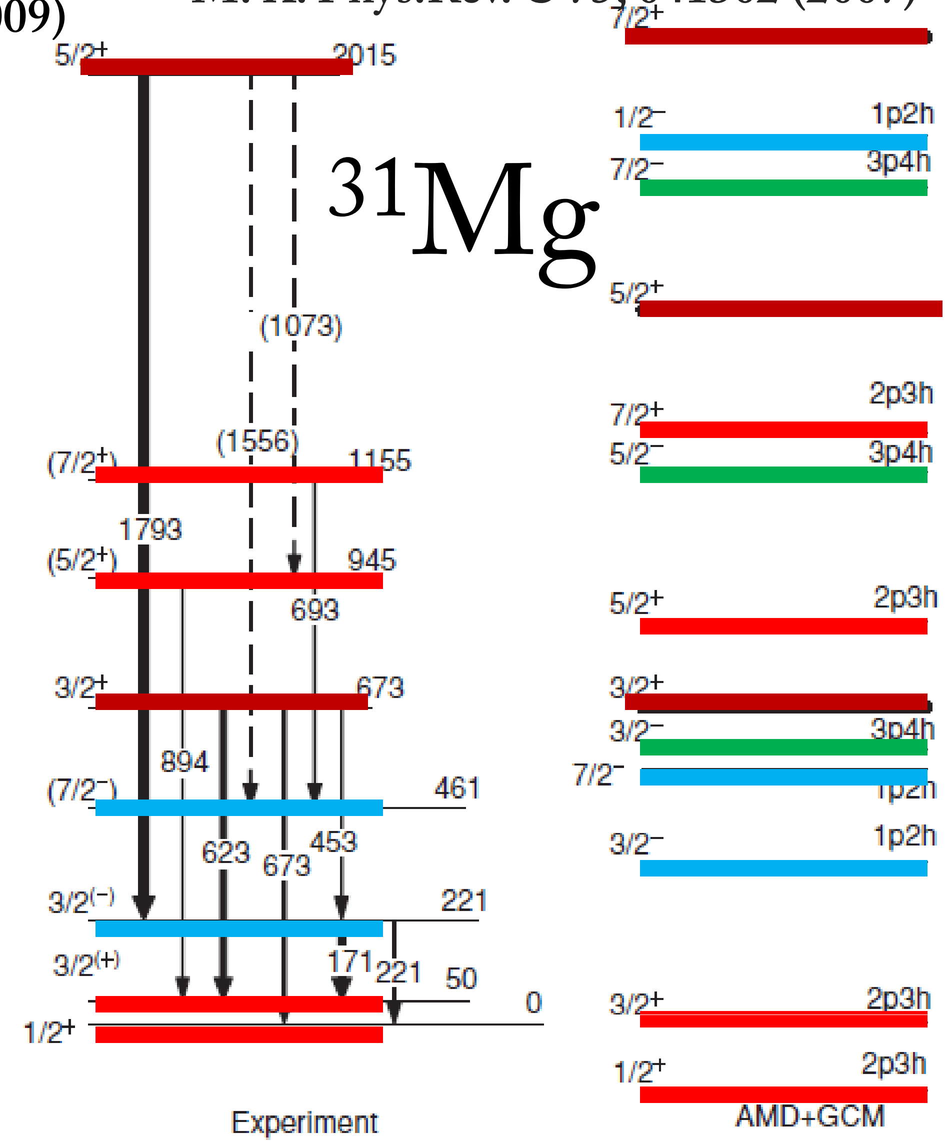
1p-removal from ^{32}Al

D. Miller, et.al.,Phys. Rev. C 79, 054306 (2009)

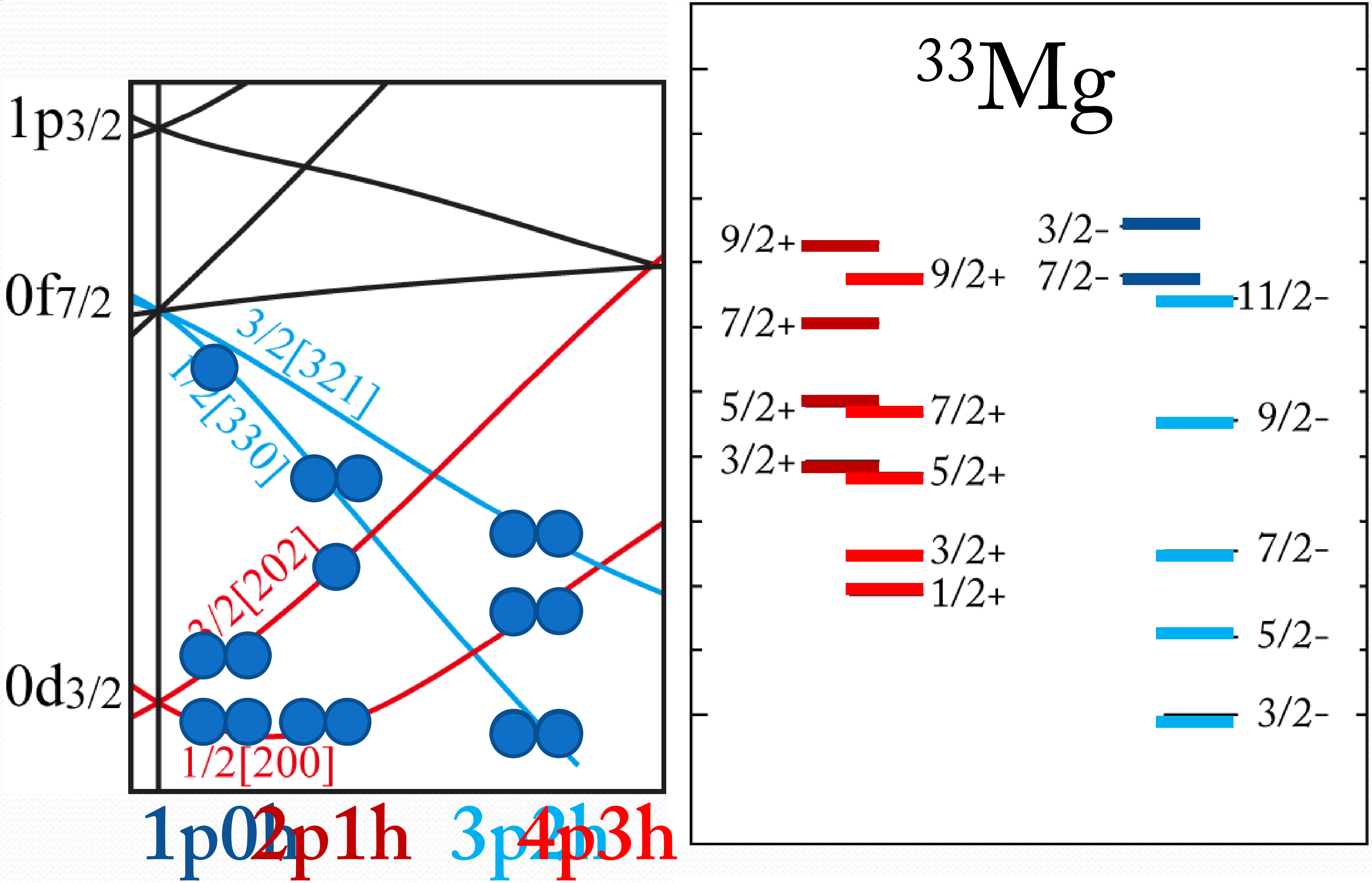
M. K. Phys.Rev. C 75, 041302 (2007)



0p1h 1p2h 2p3h 3p4h



Introduction: Particle Hole Config. (N=21 System)



Introduction: Spin-parity of ^{33}Mg(N=21)

- $J^{\pi} = (3/2, 5/2)^{+}$

  β-decays

  ^{33}Na(N=22,g.s.) → ^{33}Mg(g.s.)

  S. Nummela, et. al., PRC64, 054313 (2001)

  ^{33}Mg(g.s.) → ^{33}Al(N=20, g.s.)

  V. Tripathi, et. al., PRL101,142504 (2008)

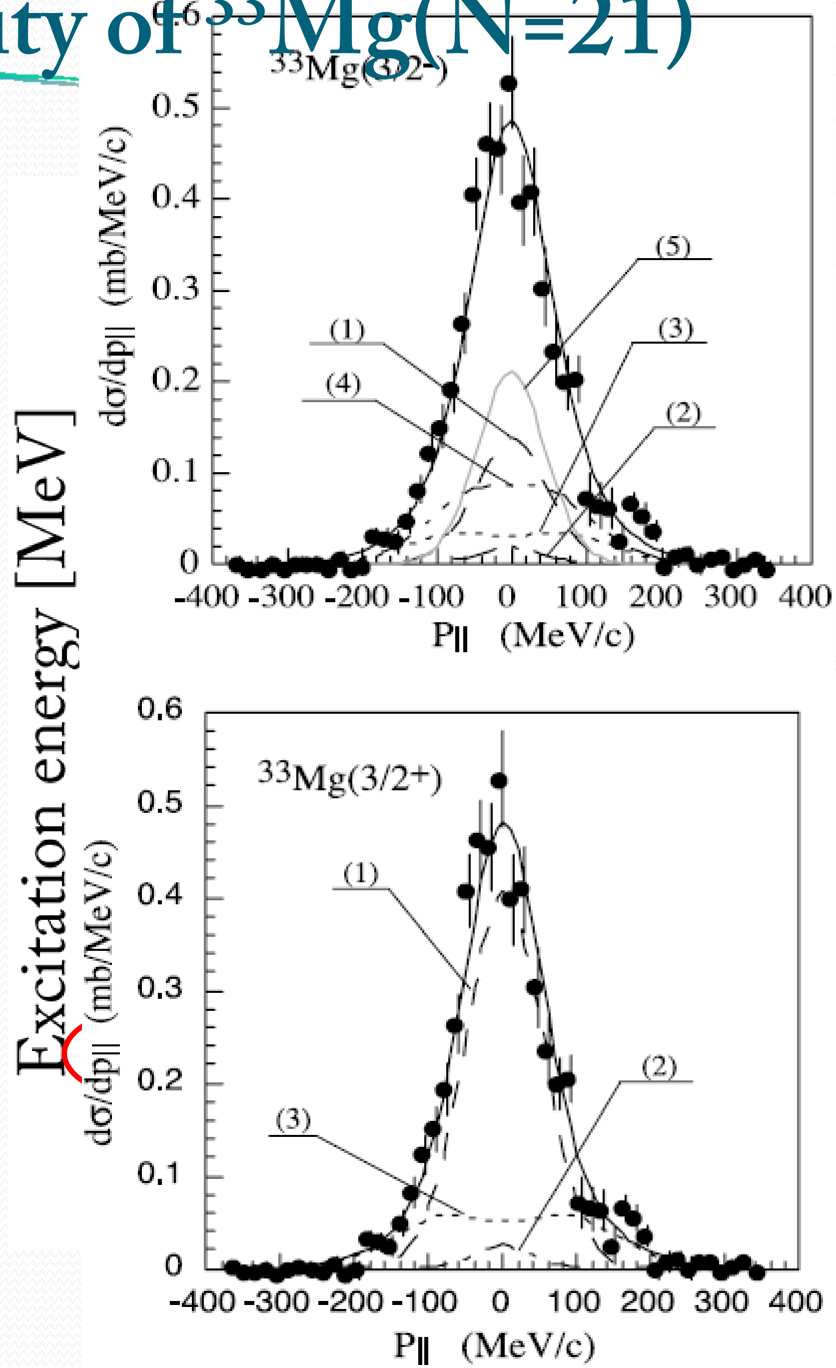
- $J^{\pi} = 3/2^{-}$

  magnetic-moment: $\mu = -0.7456\mu_N$

  D. T. Yordarov, et. al., PRL99, 212501 (2007)

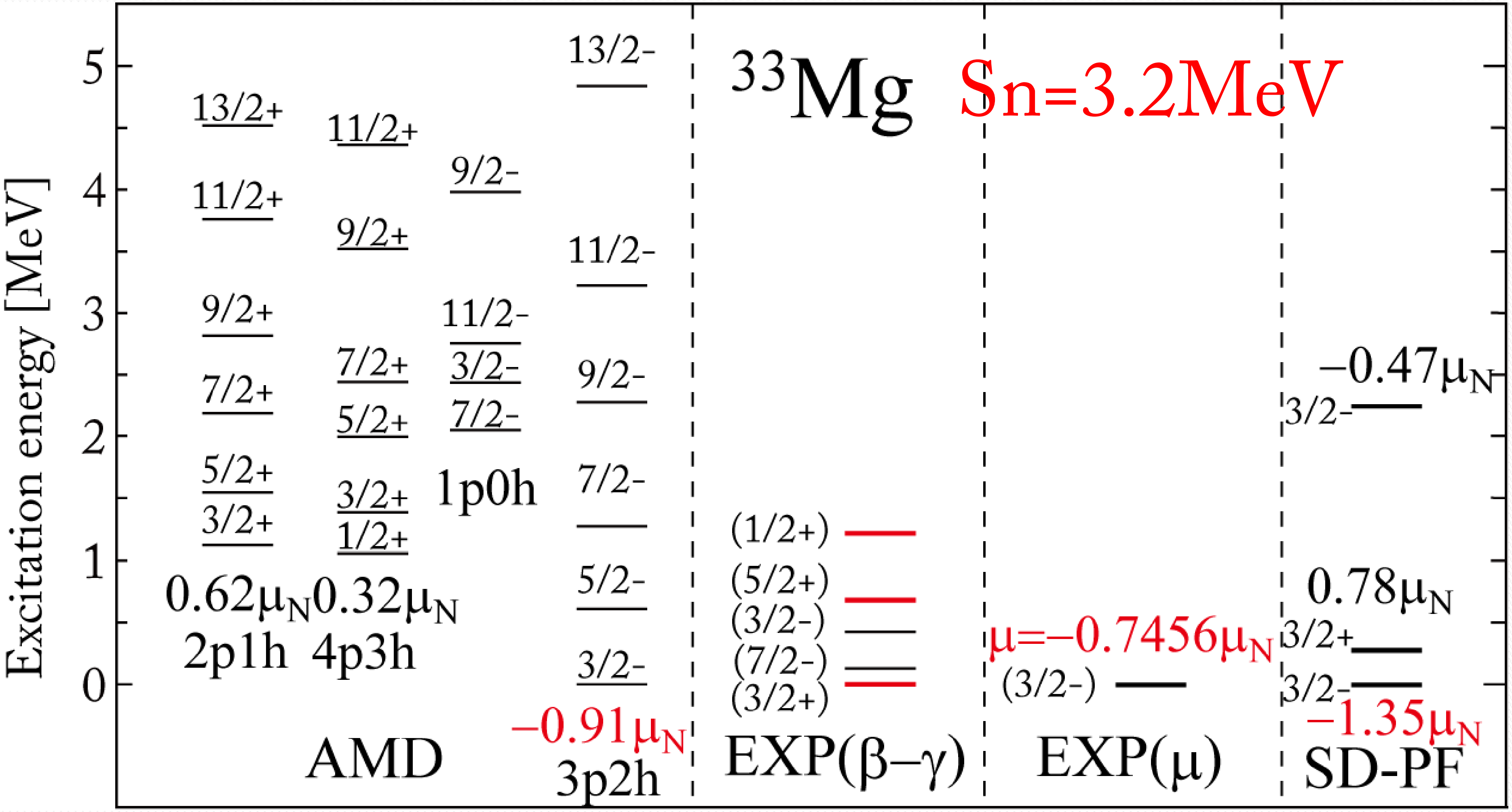
  1n-removal: $p_{3/2}$

  R. Kanungo, et. Al., PLB685, 253 (2010)



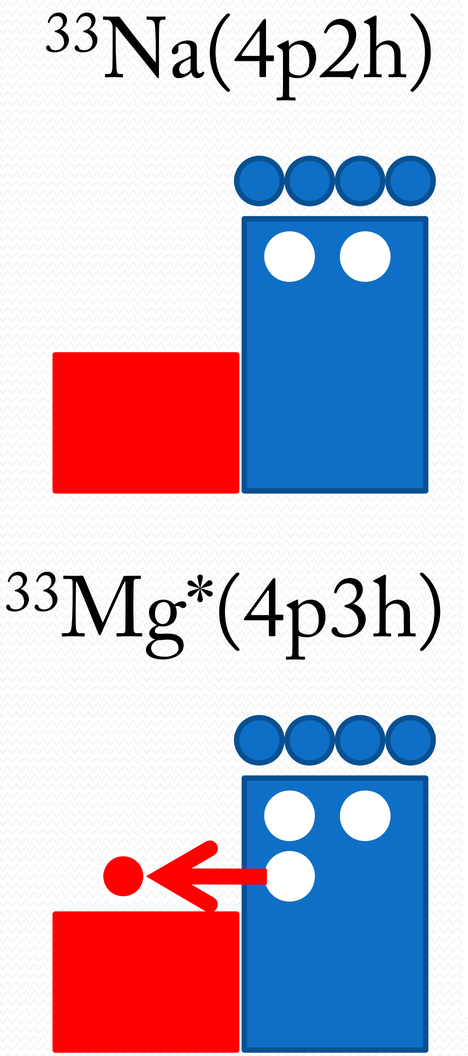
Results: Spectrum of ^{33}Mg

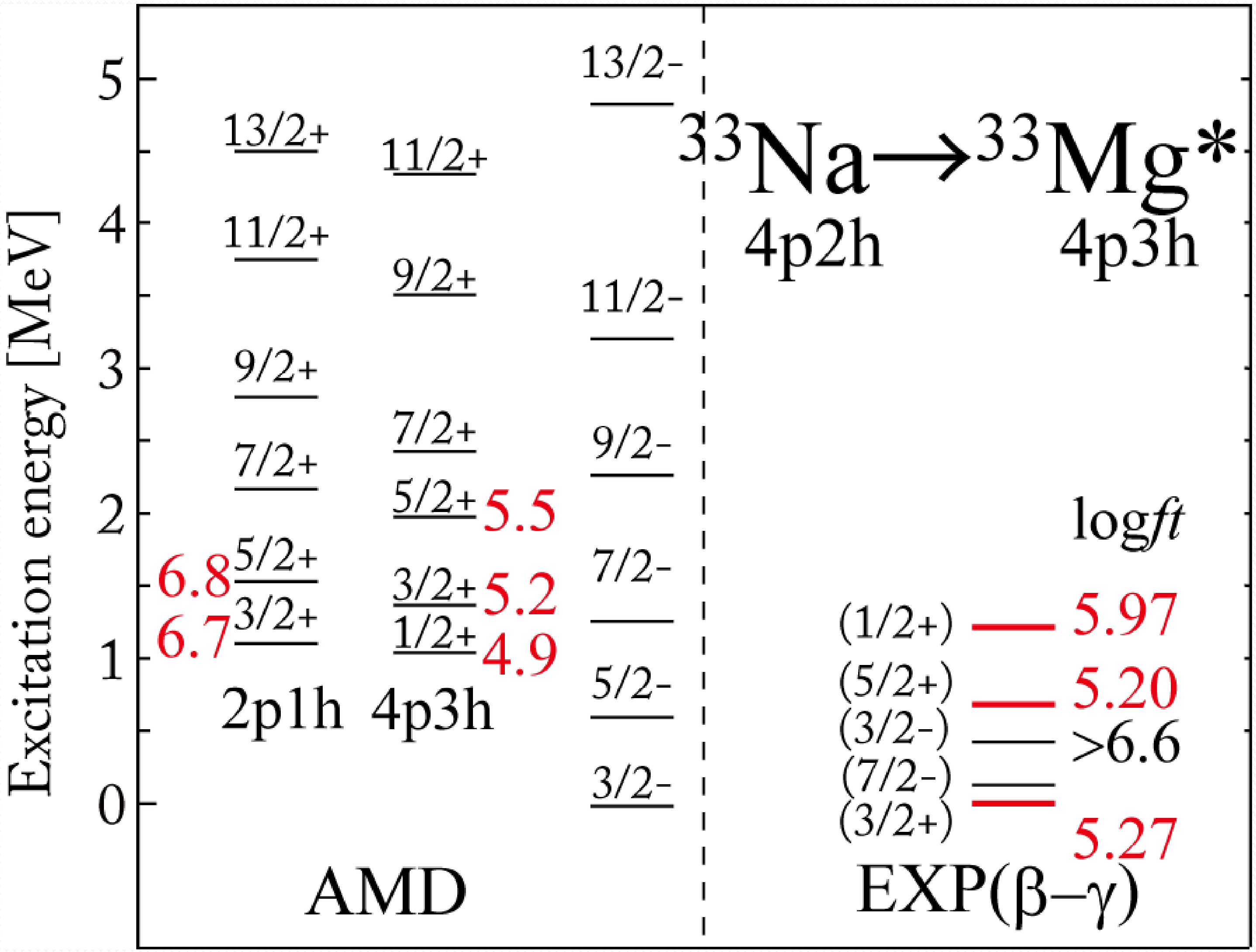
- Consistent with magnetic moment exp.
- AMD underestimates number of very low-lying states



Results: β-decay and Jπ assignment

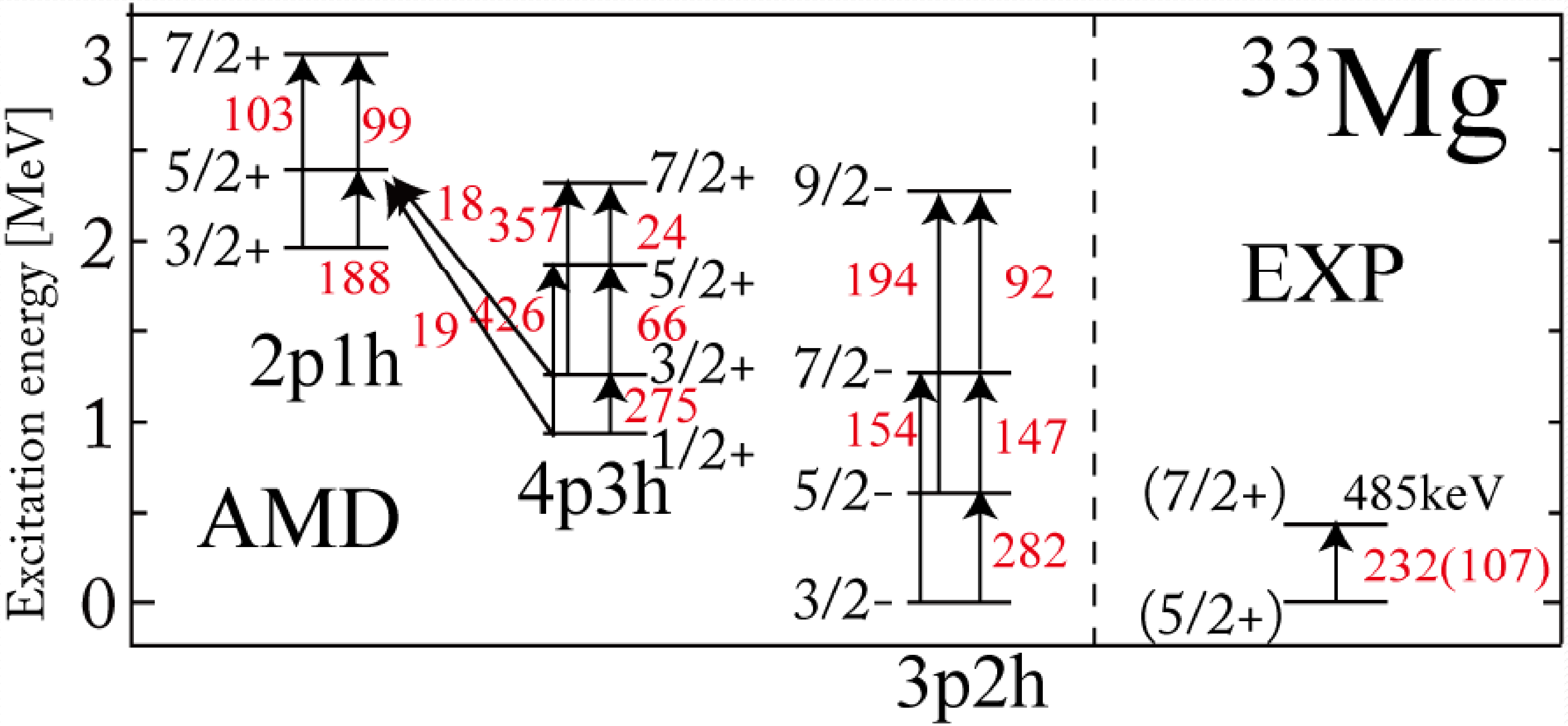
- ^{33}Na(4p2h) feeds 4p3h config.





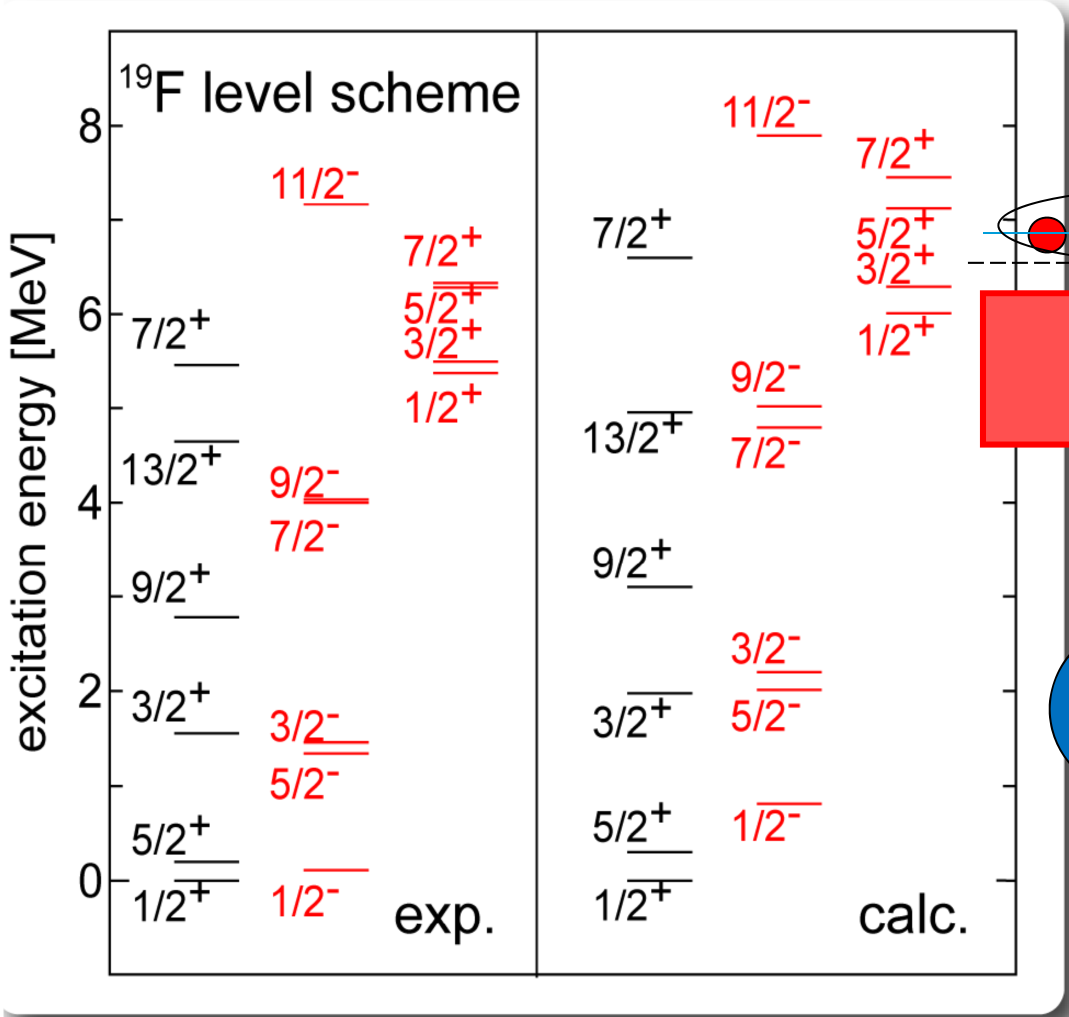
Results: B(E2) of ^{33}Mg

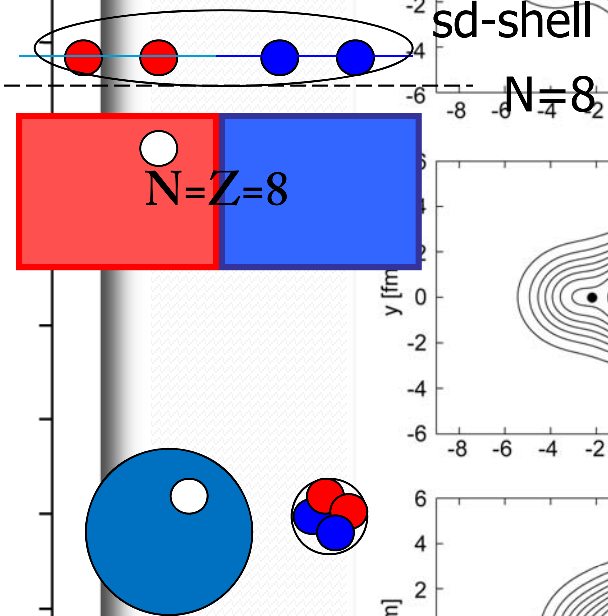
- **Coulomb Excitation Exp. :** B.V. Pritychenko, et. al., PRC65, 061304(R) (2002).
  Large cross section for 485keV state
- Authors assumed Jπ=5/2+ for the ground state (no information was available at that time except for β-decay data that suggested positive parity)
- Large cross section does not contradict to AMD (Further exp. is required.)

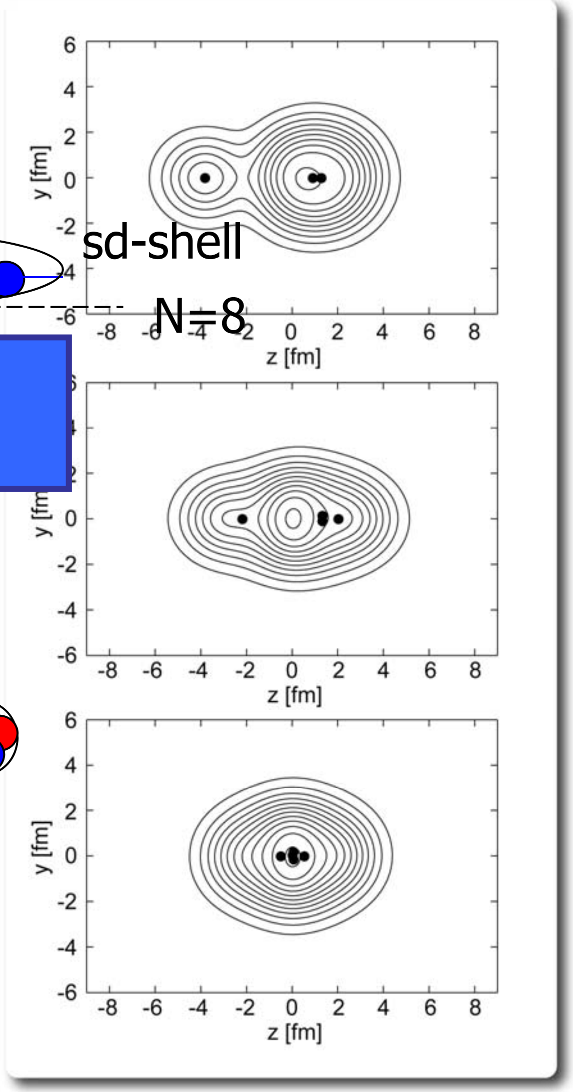


Results: alpha cluster structure in ^{19}F

Key point: Alpha cluster states of ^{19}F has a proton hole in 0p orbital.

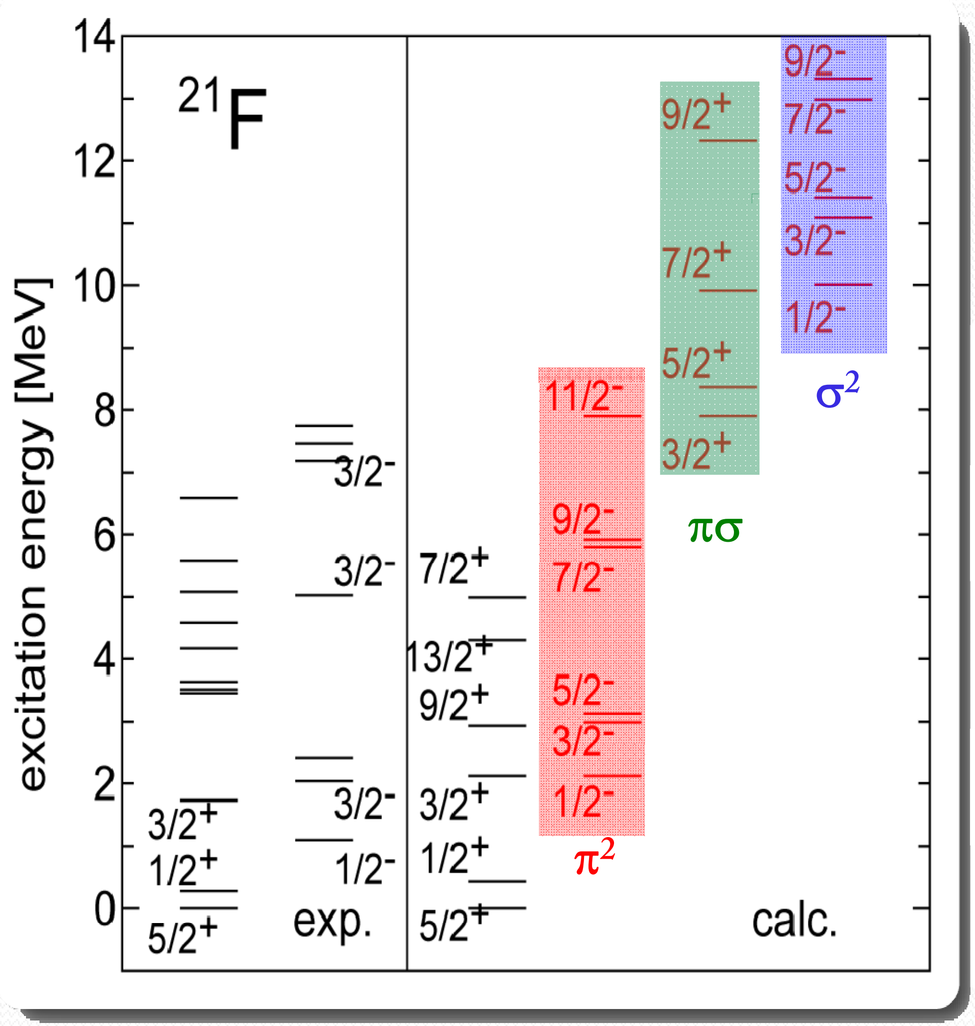






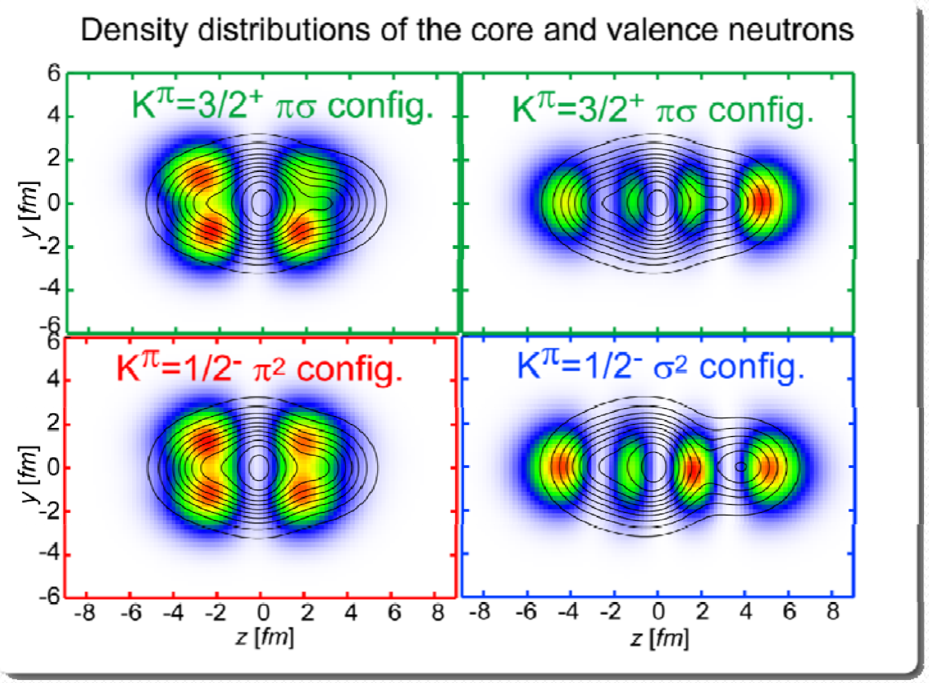
Results: Molecular-orbitals in ^{21}F

M. Kimura, submitted to PRC.

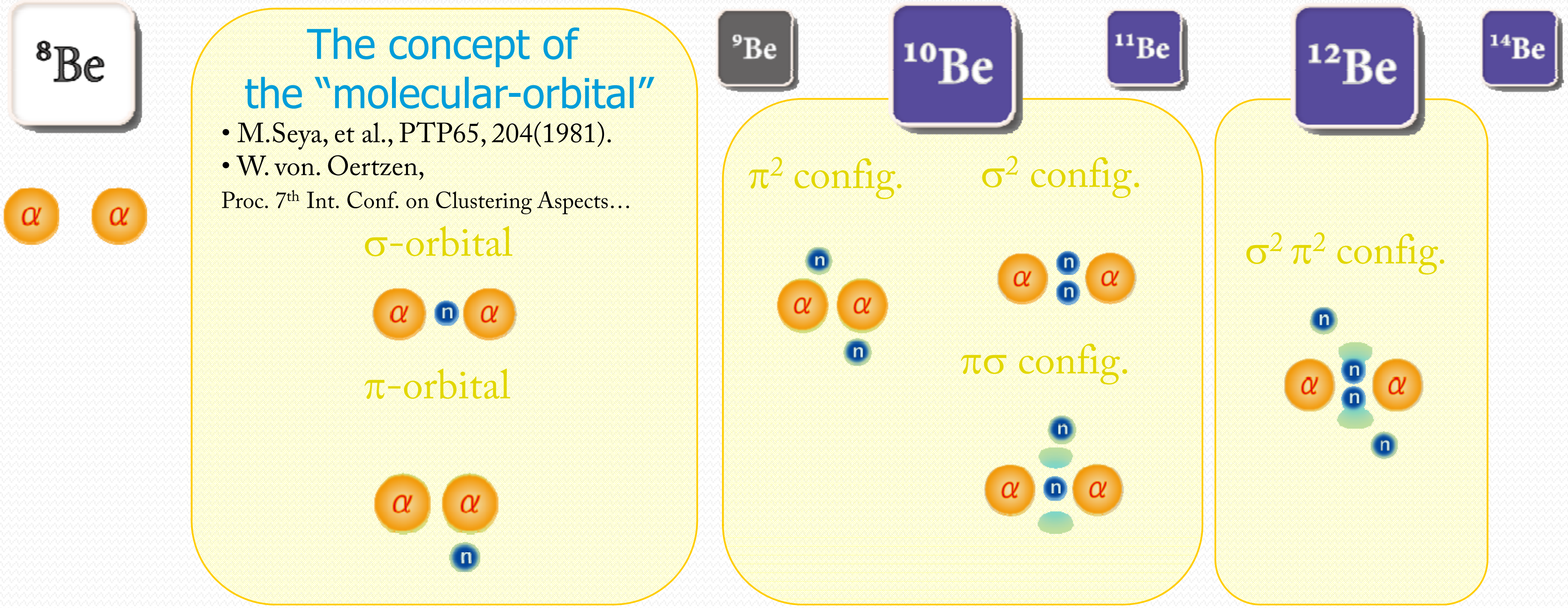


- proton hole states has the α cluster structure
- π^2, ps and σ^2 configurations appear as

$K^\pi=1/2^-$, $3/2^+$ and $1/2^-$ bands



Results: Analogue to molecular-orbitals of Be



• M. Seya, et al., PTP65, 204 (1981).
• Y. Kanada-En'yo, et al., PRC60, 064304(1999).
• N. Itagaki, et al., PRC62 034301, (2000). …

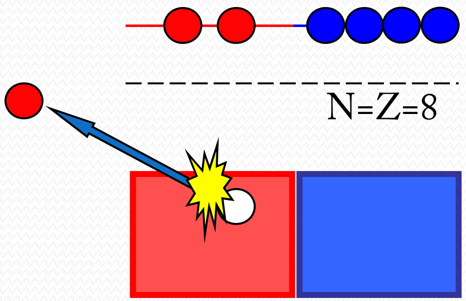
Molecular Structure in Be isotopes suggests us new aspects specific to N≠Z nuclei.

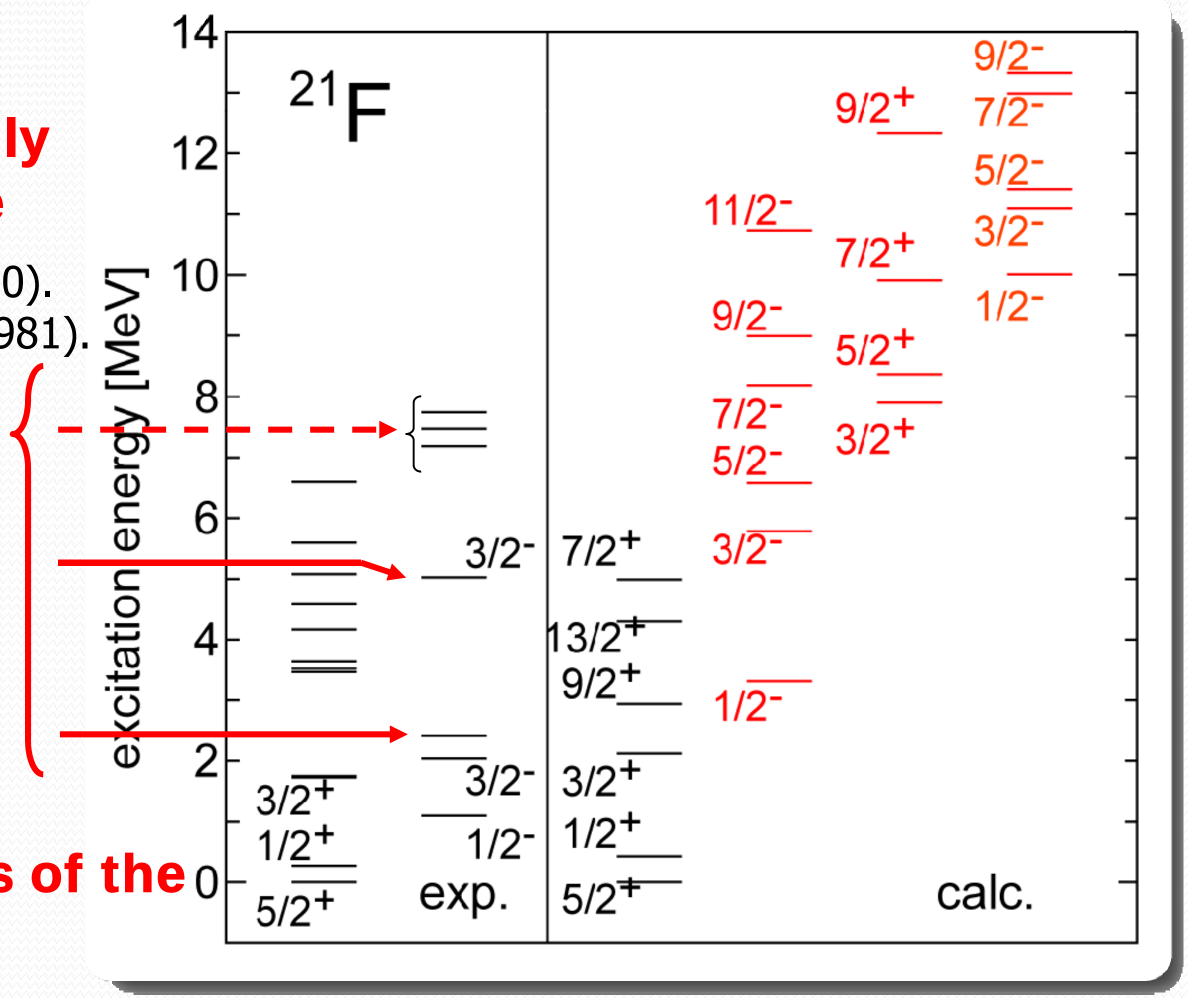
- A new binding mechanism.
- A new type of cluster structure.

Results: Molecular-orbitals in ^{21}F

Populated directly by only 1p knockout from ^{22}Ne

- G. Th. Kaschl, NPA155, 417 (1970).
- G. Mairle, et al., NPA363, 413 (1981).

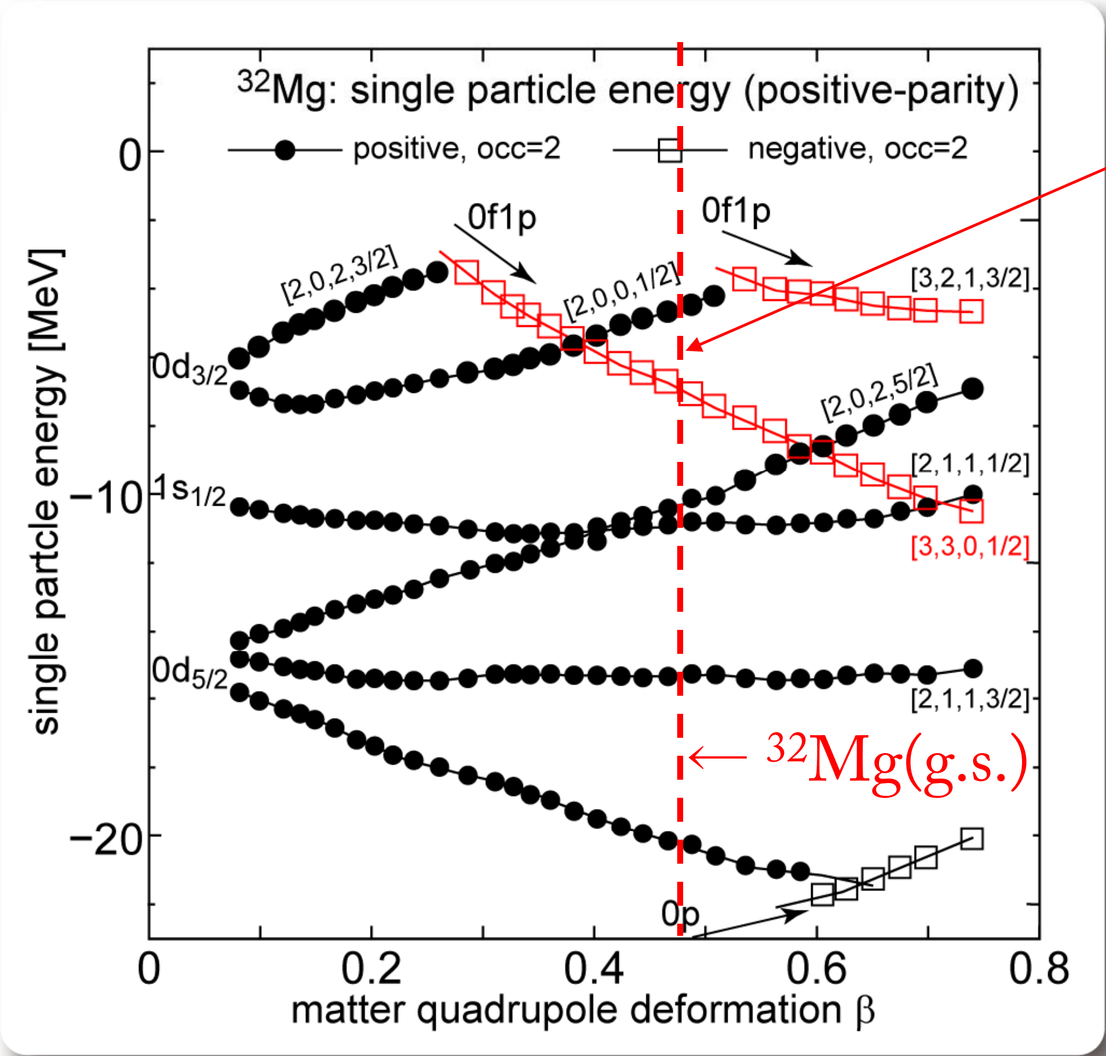




They are the candidates of the molecular states

Results: Evolution toward drip-line

Behavior of the a cluster states in F isotopes



Intruder orbital from pf-shell has large overlap with σ-orbital

The origin of the reduction of ex. energy

1. proton excitation from *p* to *sd* shell does not cost much energy due to strong a correlation.
2. It induces the strong deformation of system.
3. Strong deformation lowers σ-orbital

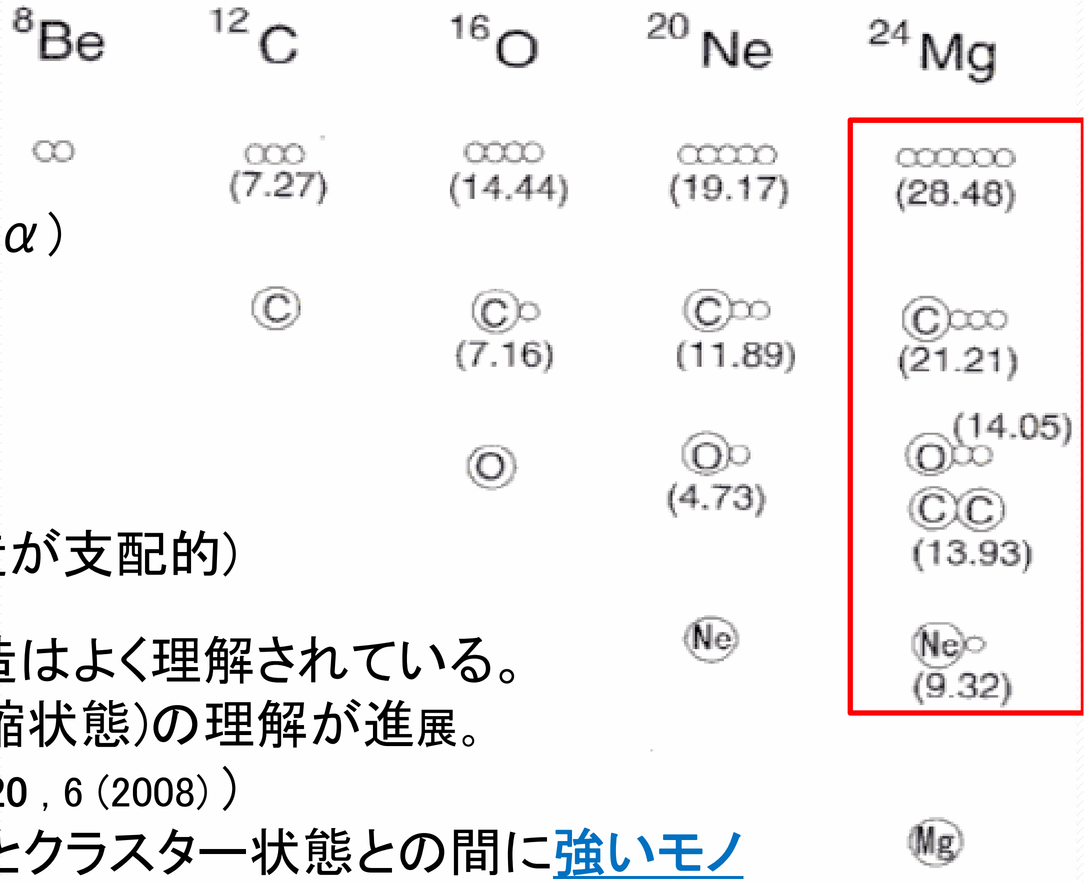
Molecular states with valence neutron in σ-orbital comes down.

- α cluster states with neutron 0hw configuration monotonously go up.

Ⅰ. Introduction : ^{24}Mgの多様なクラスター構造

池田図:

^{24}Mgの高励起状態に多様なクラスター構造が存在することを示唆
(α+^{20}Ne,^{12}C+^{12}C,^{16}O+2α,^{12}C+3α,6α)



高励起状態のクラスター構造:

- ^{24}Mgのクラスター状態は十分に明らかにはされていない。
(^{24}Mgの低励起状態では平均場構造が支配的)

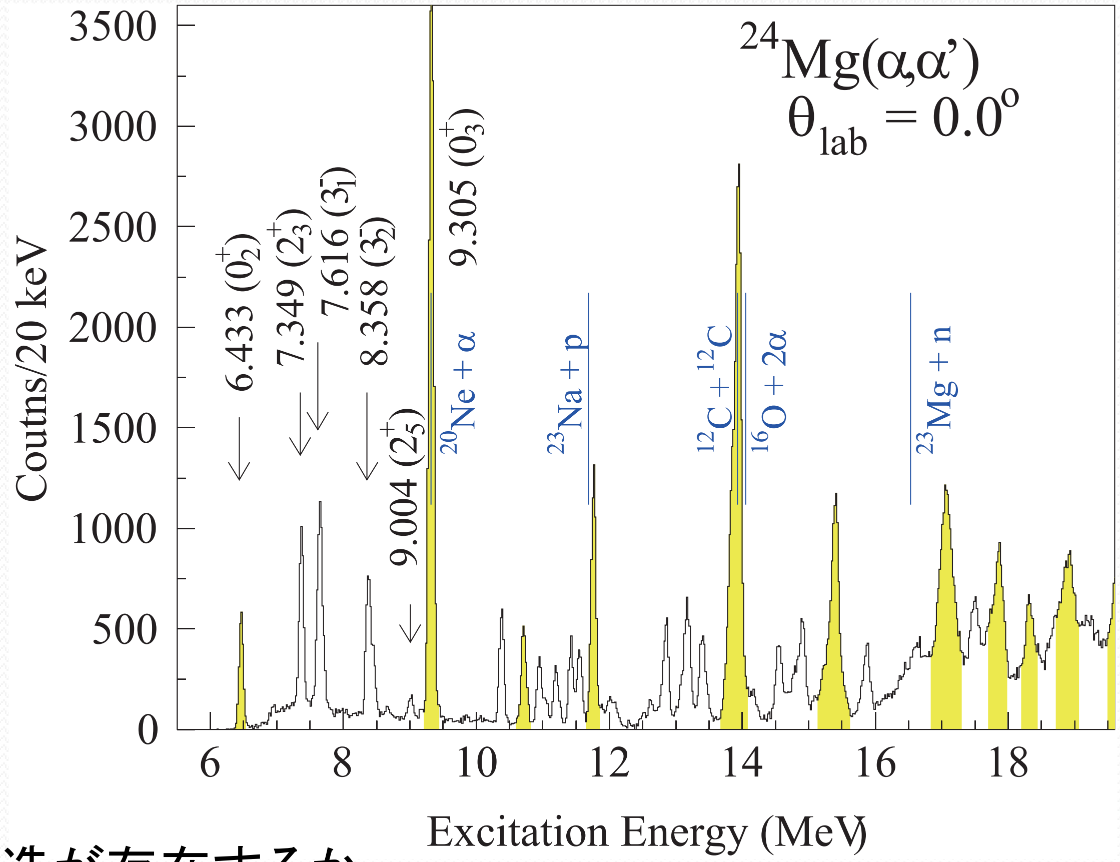
- ^{24}Mgよりも軽い核のクラスター構造はよく理解されている。
近年、3α ,4αクラスター状態(α凝縮状態)の理解が進展。
(Taiichi Yamada,Yasuro Funaki, et al PTP **120** , 6 (2008))

- α凝縮状態の研究では基底状態とクラスター状態との間に<u>強いモノポール遷移があることがしめされた。</u>
(Taiichi Yamada, Yasuro Funaki ,et al PTP **120** , 6 (2008))

^{24}Mgのクラスター状態を理解するための鍵となりうる。

• ^{24}Mg(α,α')散乱のデータ

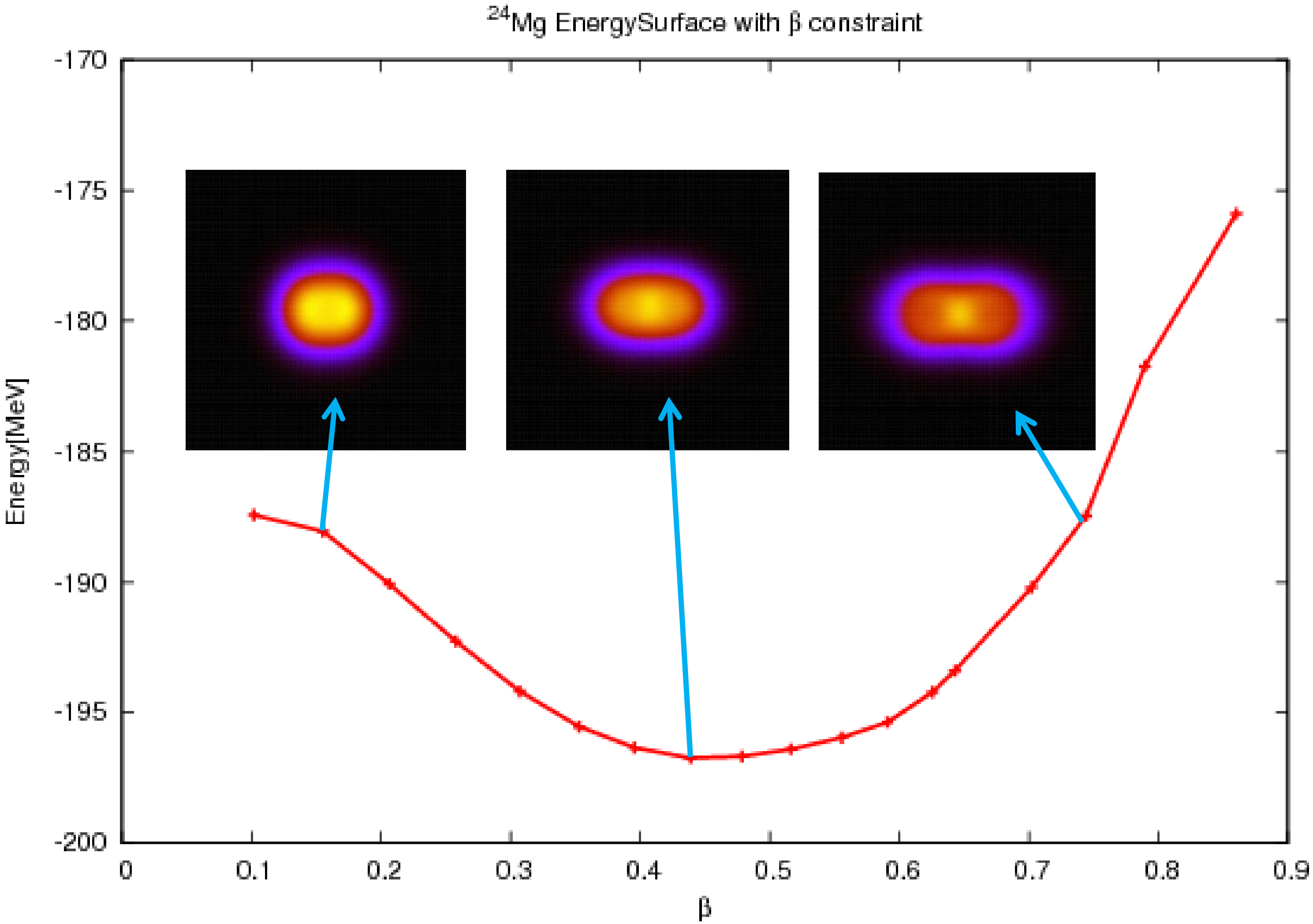
- 超前方のα非弾性散乱(0+を選択的に励起)
- 10～20MeVの領域に強く励起される状態が多数見つかった。
- これらのピークは敷居値エネルギー近傍にあり、大きなモノポール遷移確率をもつ可能性が指摘されている。
- 観測されたこれらの状態は池田図に現れる多様なクラスター構造に対応しているのではないか。



[目的]
^{24}Mgの高励起状態にクラスター構造が存在するかどうか。どのようなクラスター構造が存在するか。
[方法]
平均場構造とクラスター構造を両方記述するためAMD模型を用い、^{24}Mgの高励起状態を調べる。

Takahiro Kawabata : ppt
Alpha Inelastic Scattering and
Cluster Structures in ^{13}C and ^{24}Mgより

• β拘束でのエネルギー曲線



β 拘束での計算では平均場構造がえられ、クラスター構造が現れない。

^{24}Mgの低励起状態では平均場構造が支配的となっている。

- # 主量子数Nの拘束

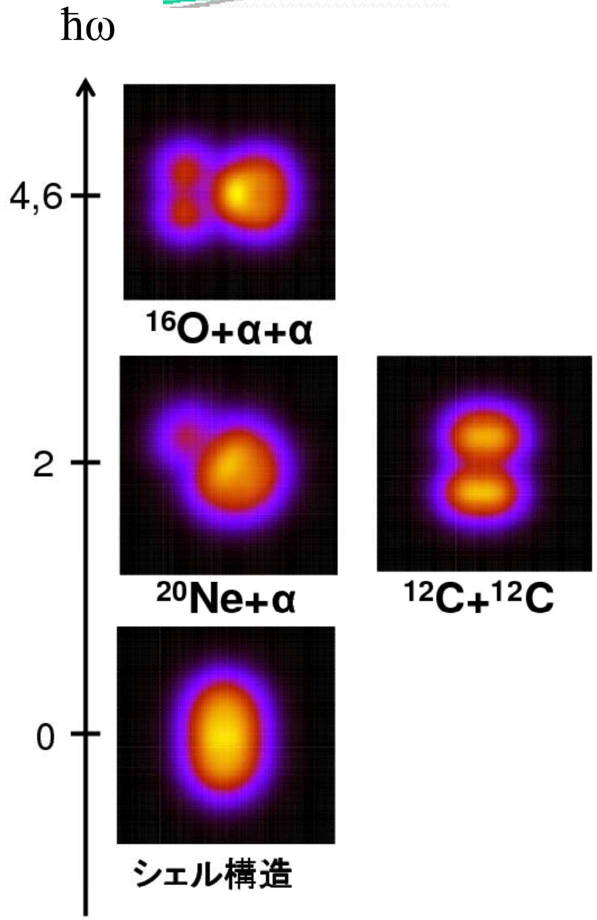
^{24}Mgの高励起状態は多粒子多空孔配位をもつと考えられる。
そこで、主量子数を拘束する。

$$\hat{N} = \hat{\mathbf{a}}^{\dagger}\hat{\mathbf{a}} \qquad \hat{\mathbf{a}}^{\dagger} = \sqrt{\nu}\hat{\mathbf{r}} - \frac{i}{2\hbar\sqrt{\nu}}\hat{\mathbf{p}}$$

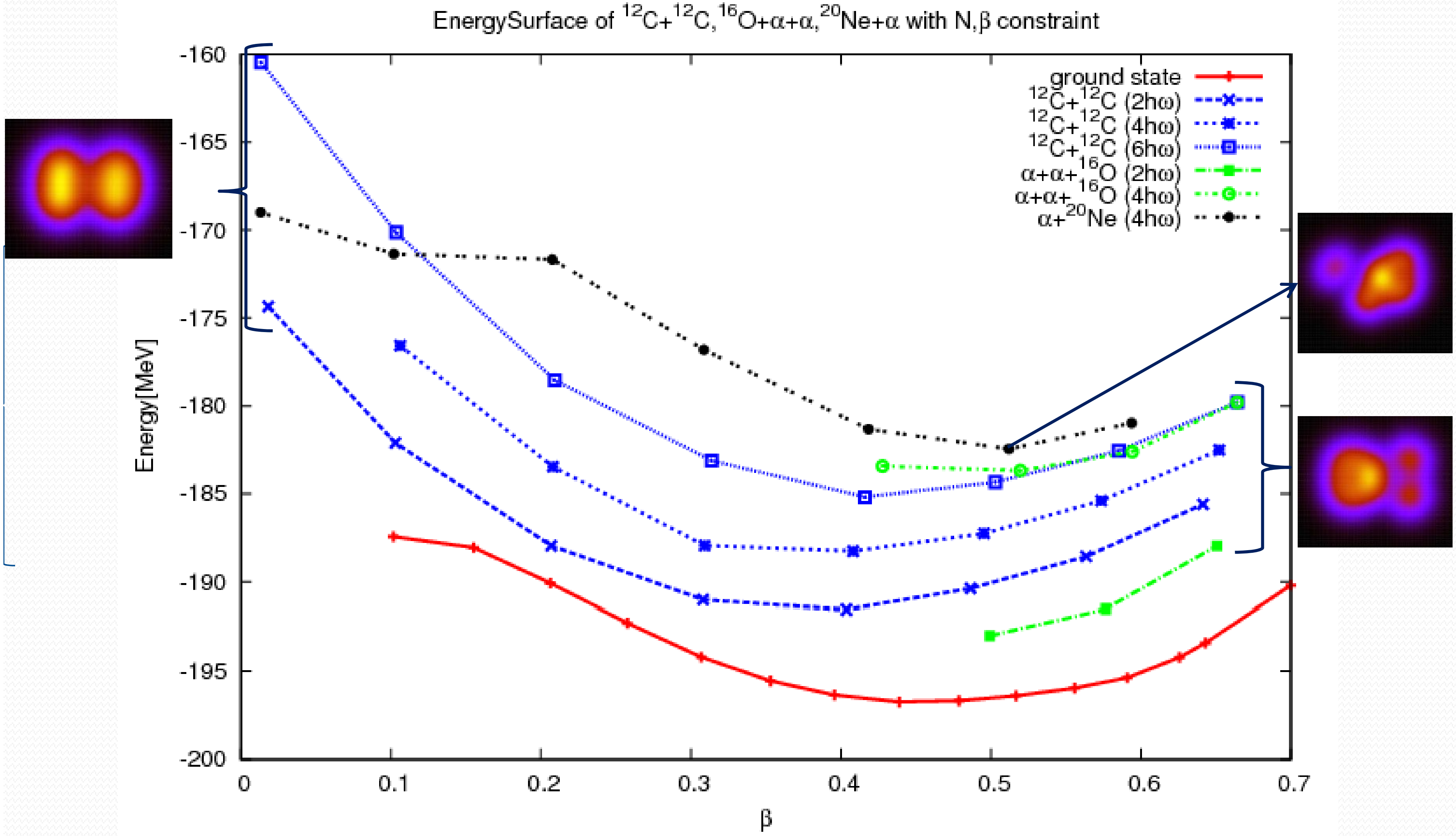
主量子数を拘束すると、高励起状態に多様なクラスター構造をもつ解が現れた。（β 拘束とは対照的）

高励起状態では低励起状態とは逆にクラスター構造が支配的になっている可能性

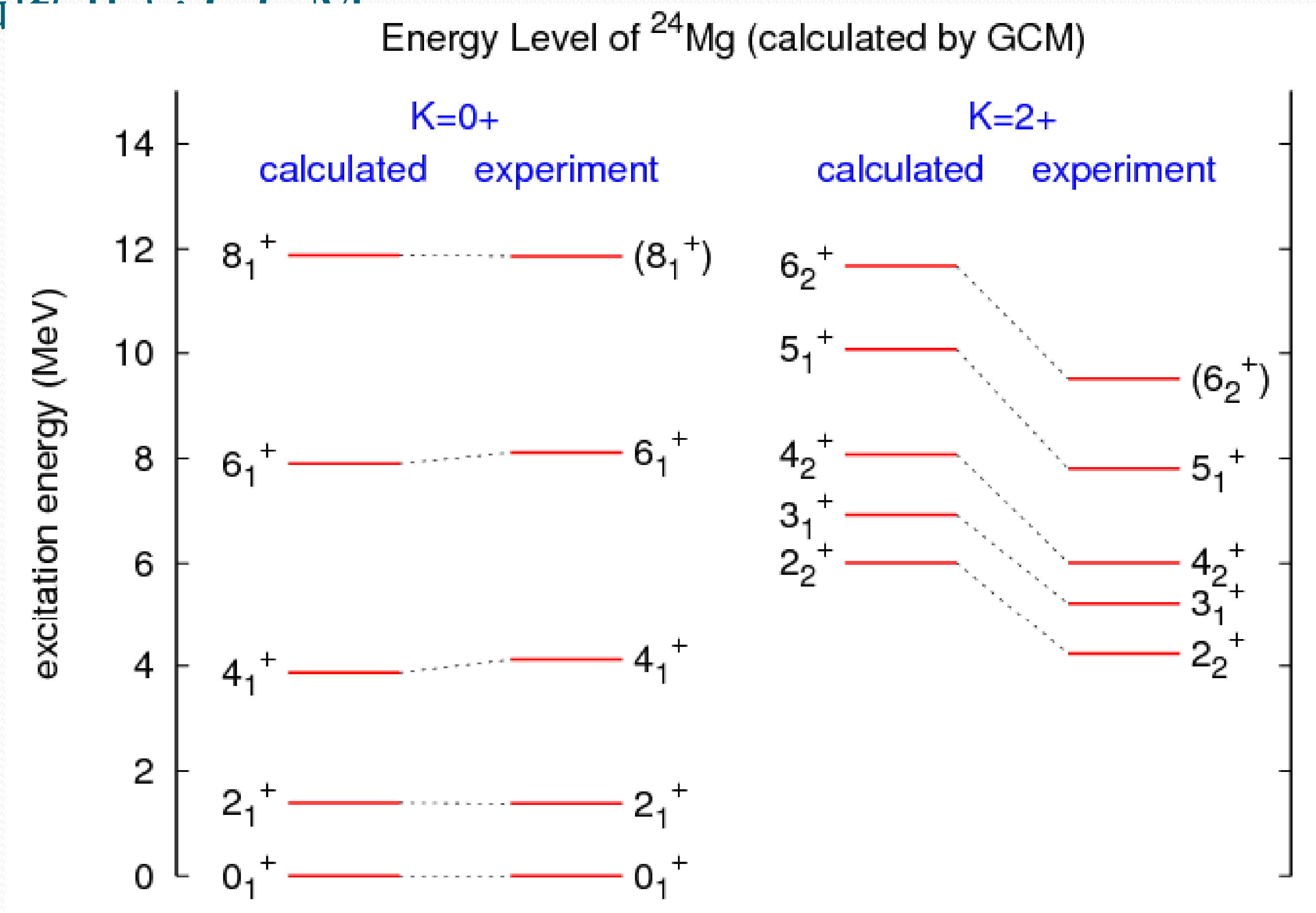
そこで主量子数と四重極変形度 β を同時に拘束した系統的な計算を行い、^{24}Mgの低−高励起状態を調べる。



Ⅲ.Result(Ⅰ) : Energy Surface ($^{12}C+^{12}C,^{16}O+\alpha+\alpha,^{20}Ne+\alpha$)

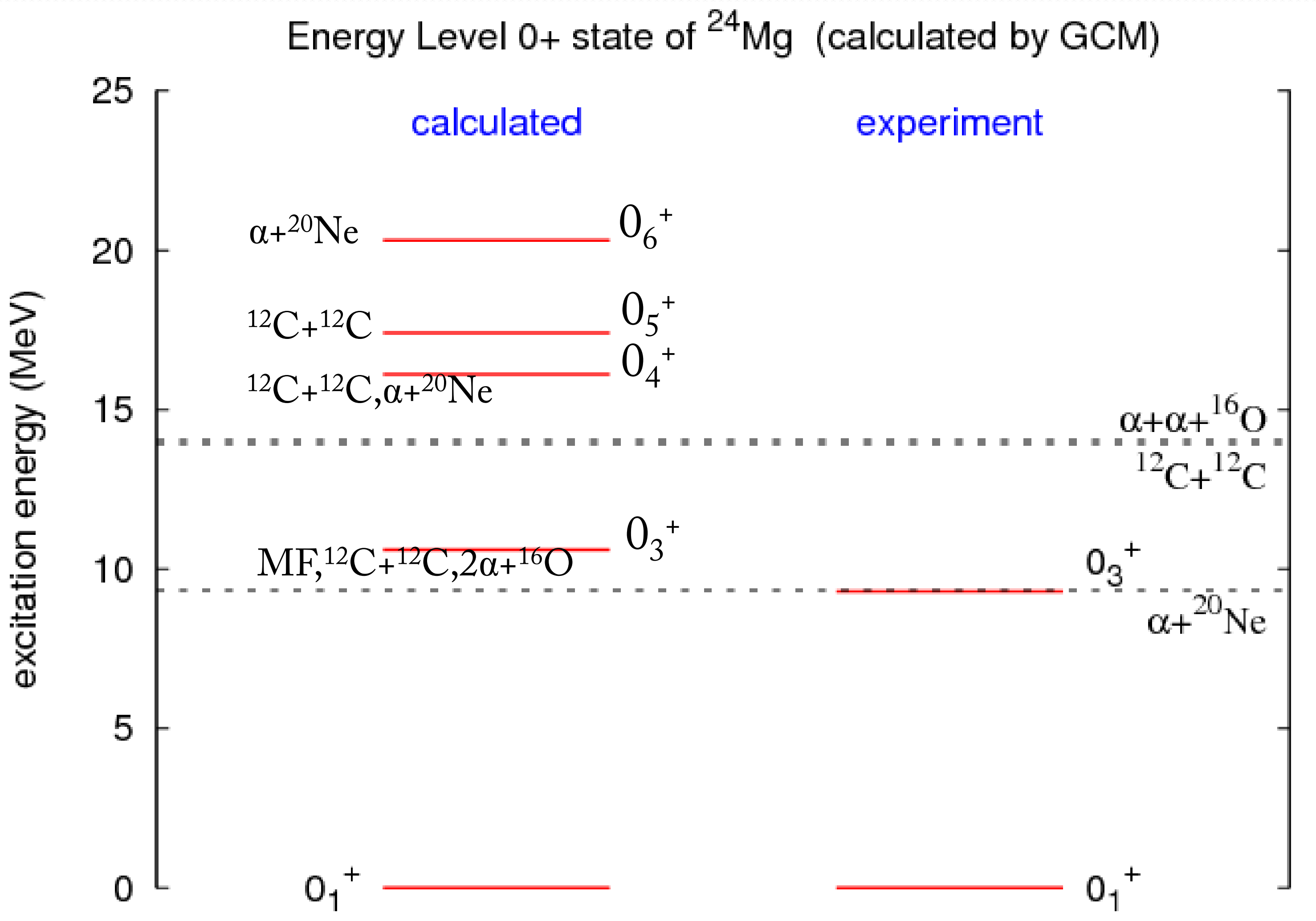


- Result(II) : GCM



0^+: 198.6MeV（実験値：198.26MeV） K=0+状態は実験とほぼ一致している。

• Result(Ⅲ) : GCM



実験データでみられたような10MeV～20MeV付近に多数の0+状態が現れた。これらの状態がクラスター状態をつくっていると予想される。