Spectroscopy of N=21 isotones in the Island of Inversion with AMD

- Coexistence of mpmh configurations -

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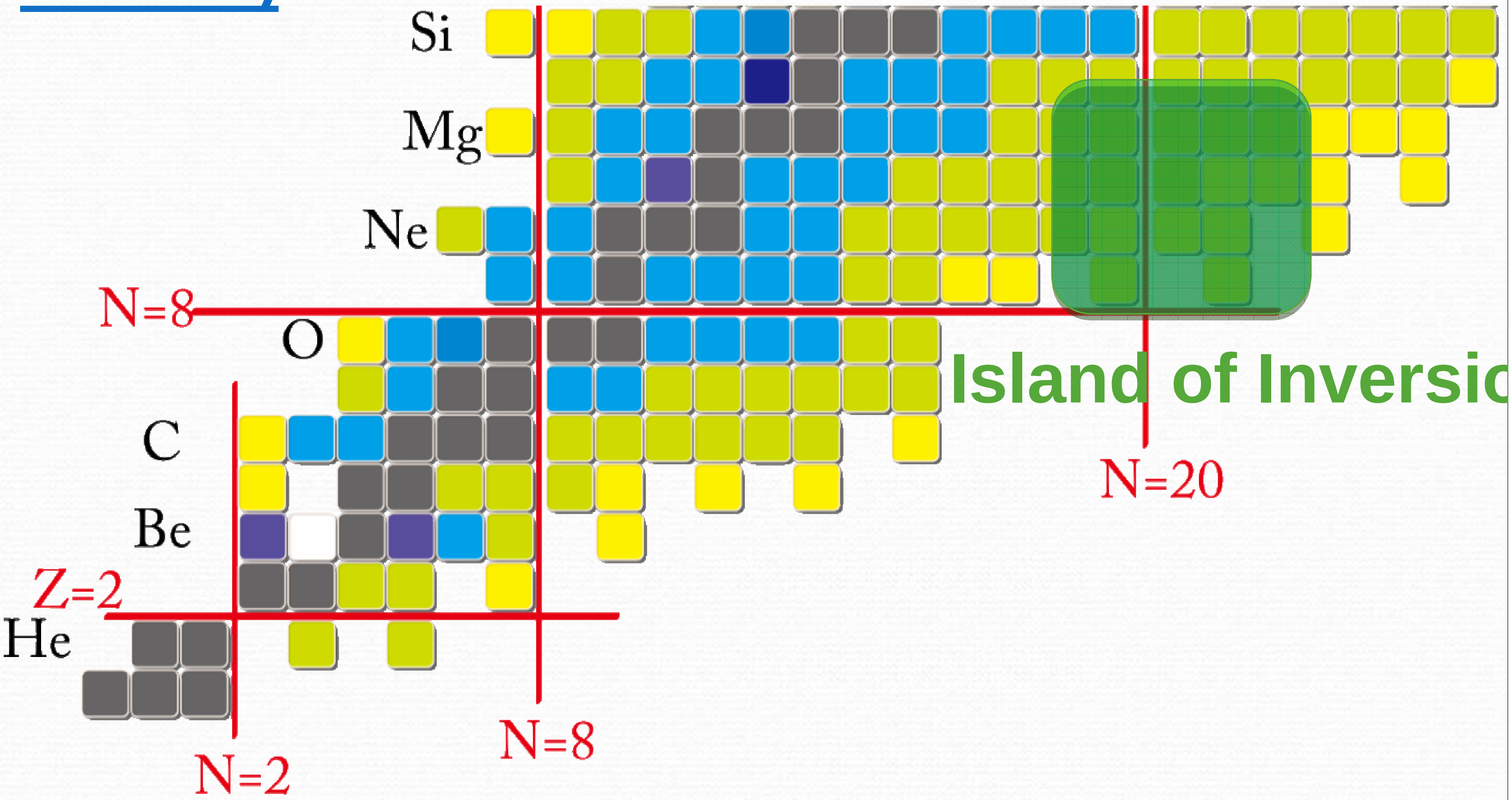
The Island in the Nuclear Chart

Neutron-rich F, Ne, Na, Mg isotopes (Z=9-12, N=18-22)

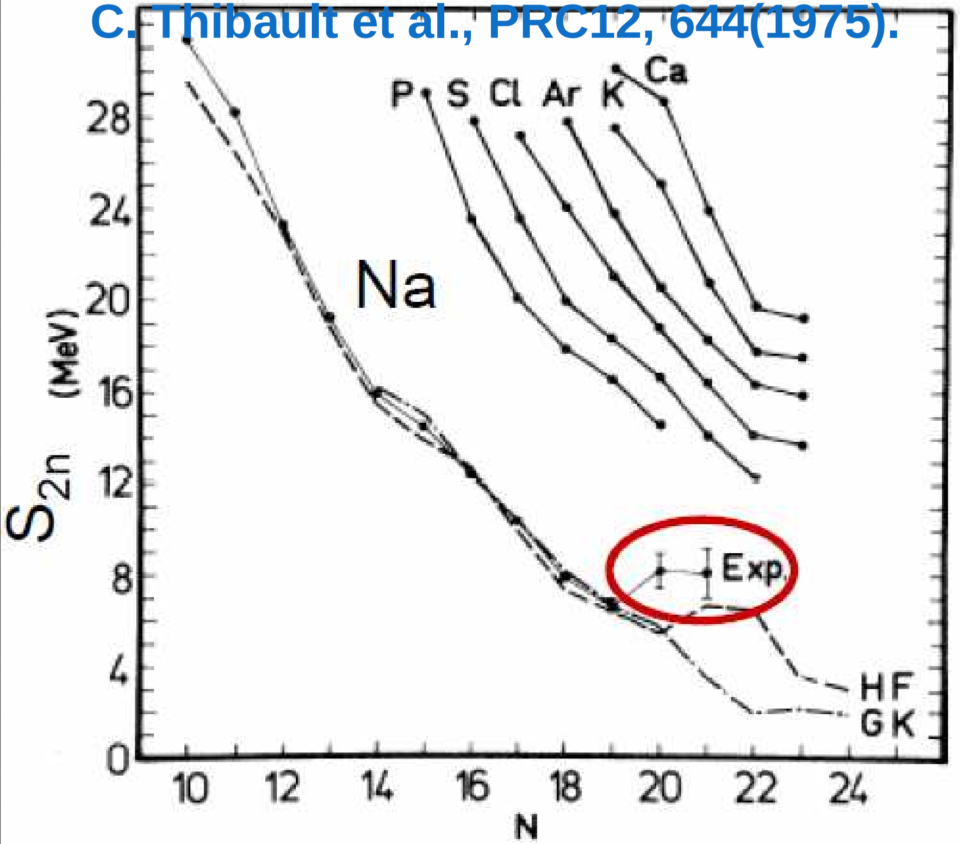


Its Discovery

Experiment

Anomalous masses and spin

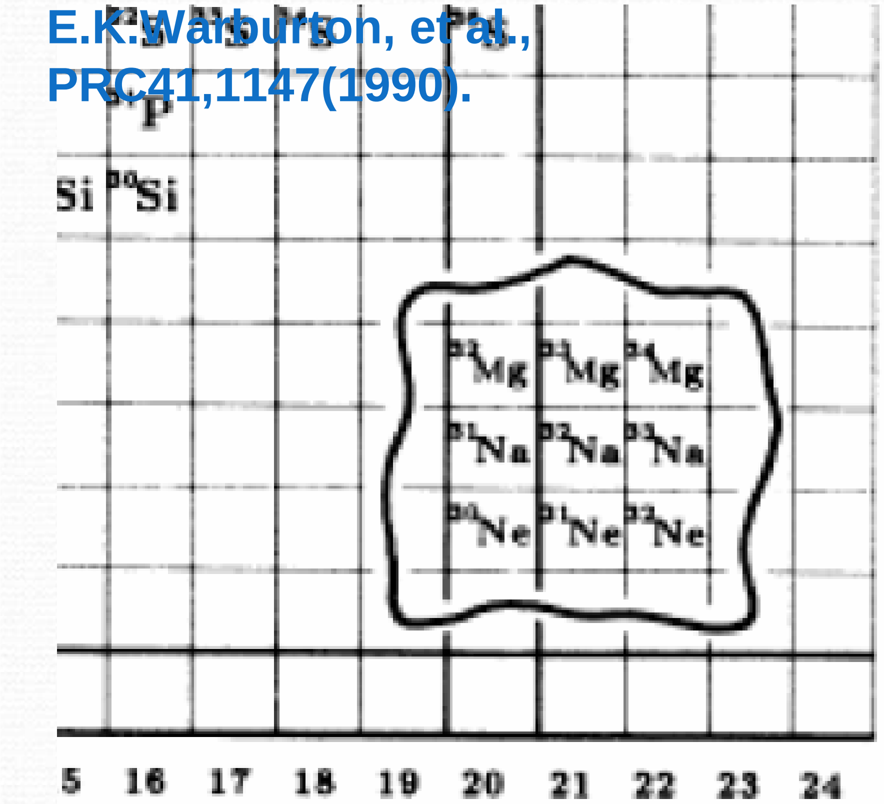
C. Thibault et al., PRC12, 644(1975).



Theory

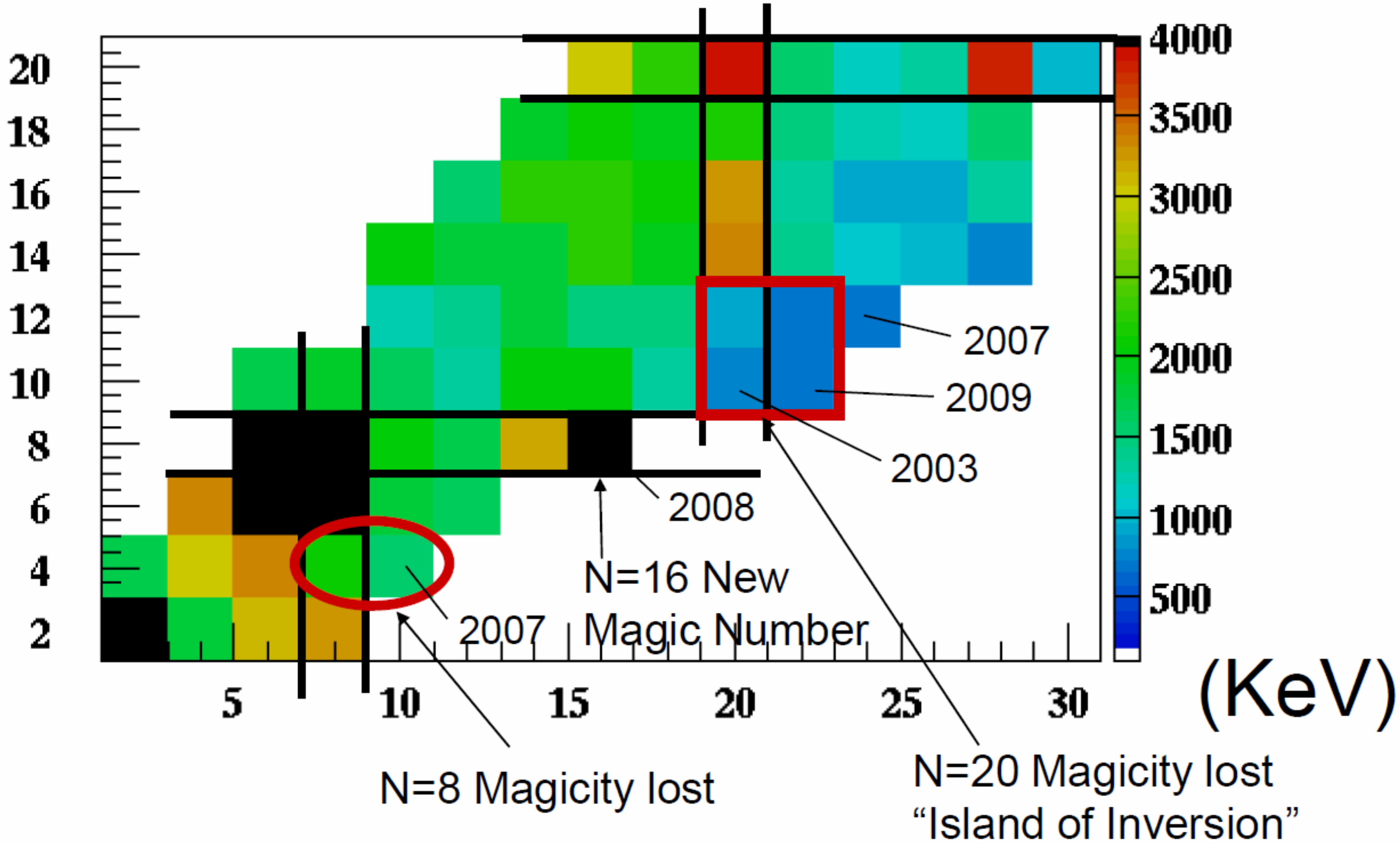
Dominance of intruder config.

E.K. Warburton, et al., PRC41,1147(1990).



Visualize the Island

Small Ex(2+) and Large B(E2)

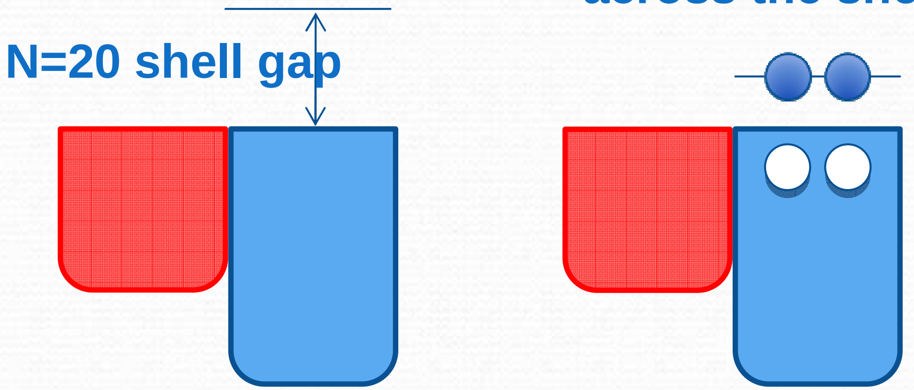


Its Mechanism

Dominance of the Intruder Configurations and Deformation

Normal Config. **Intruder Config.**

Neutron excitation across the shell gap



- Several neutrons are promoted into pf-shell
- Those neutrons bring about strong deformation to the system
- Strong deformation reduces Ex(2+) and enhances B(E2)

Many Particle-Many Hole States

Coexistence of MPMH Configurations and Deformations

Argument:

Island of Inversion is more dynamical region. There is always a competition between mpmh configurations and between spherical and deformed states.

It leads to

A)Coexistence of mpmh configurations

B)Precursor of the inversion around the island

Theoretical Framework of AMD

A-body Hamiltonian

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

Parity projected Slater determinant

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

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

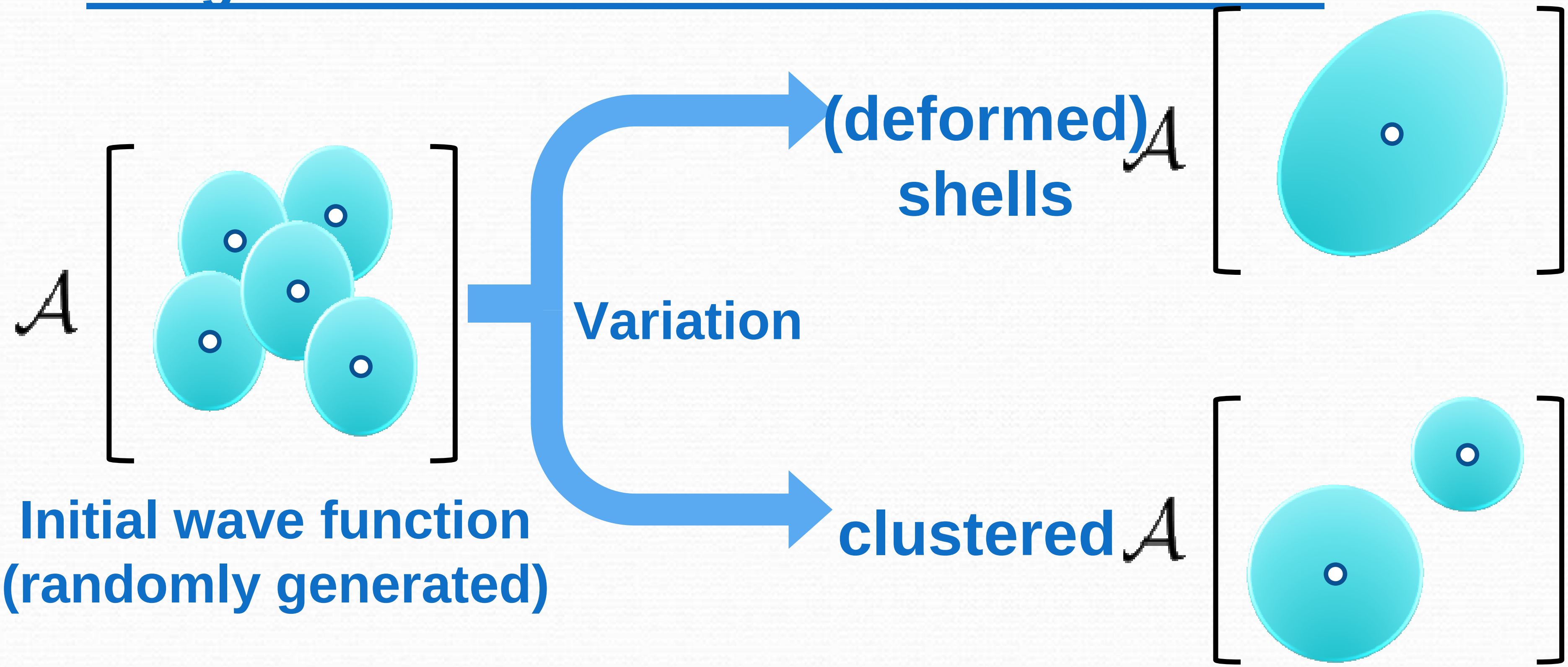
α_i, β_i : spin direction

Theoretical Framework of AMD

Energy variation (frictional cooling)

$$\frac{d}{d\tau}X_i = -\mu\frac{\partial}{\partial X_i^*} \quad (X_i = \boldsymbol{Z}_i, M, \alpha_i, \beta_i), \quad E = \frac{\langle\Psi_{\rm int}^{\pm}|\hat{H}|\Psi_{\rm int}^{\pm}\rangle}{\langle\Psi_{\rm int}^{\pm}|\Psi_{\rm int}^{\pm}\rangle}.$$

Rough sketch of wave function and variation



Theoretical Framework of 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

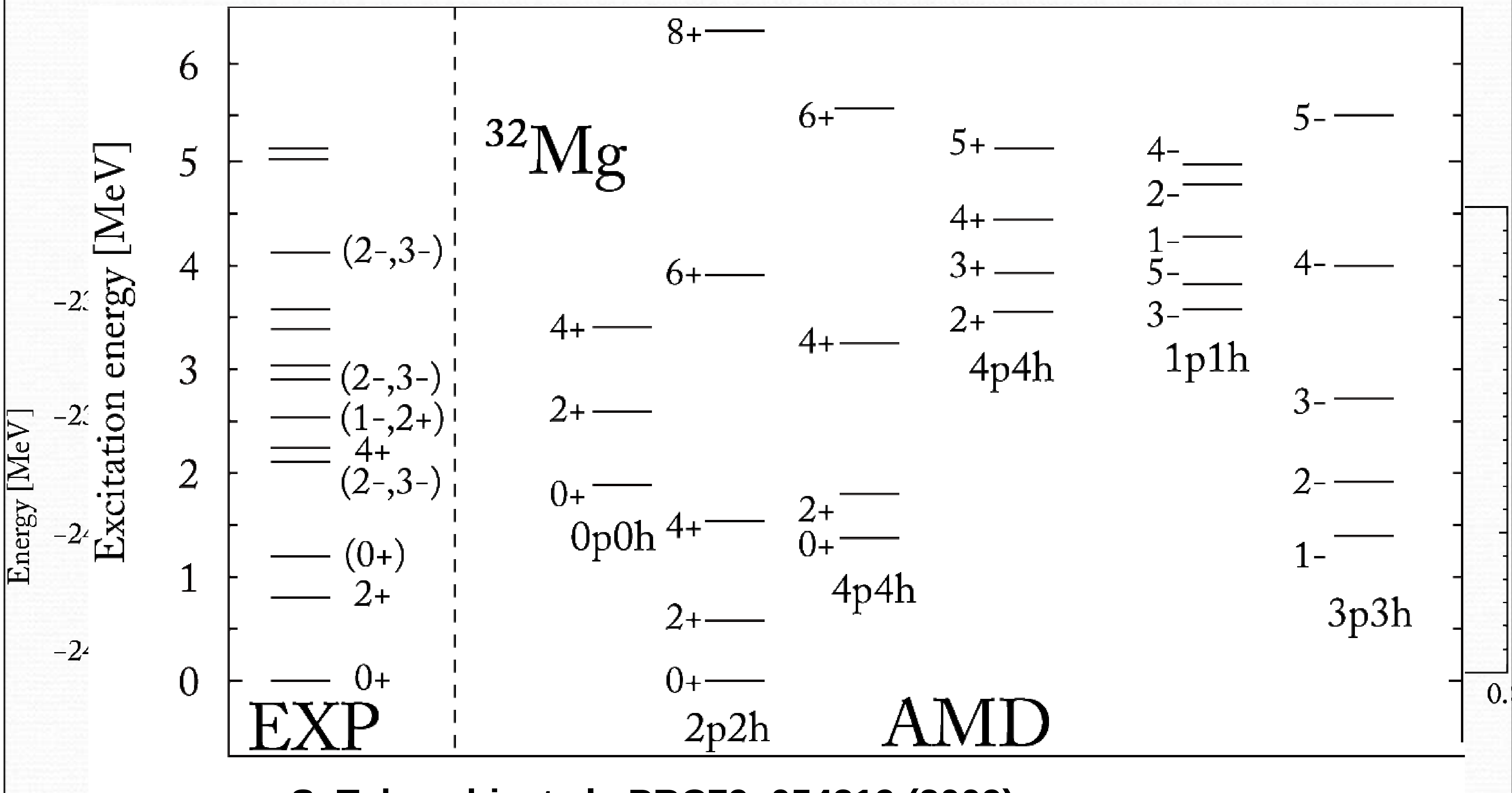
$$\Psi^{J\pm}_{\alpha} = \sum_{iK} c_{ik}\Psi^{J\pm}_{MK}(\beta_i),$$

Hill-Wheeler eq.

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

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

Actual Calculation (^{32}Mg)



S. Takeuchi, et al., PRC79, 054319 (2009).

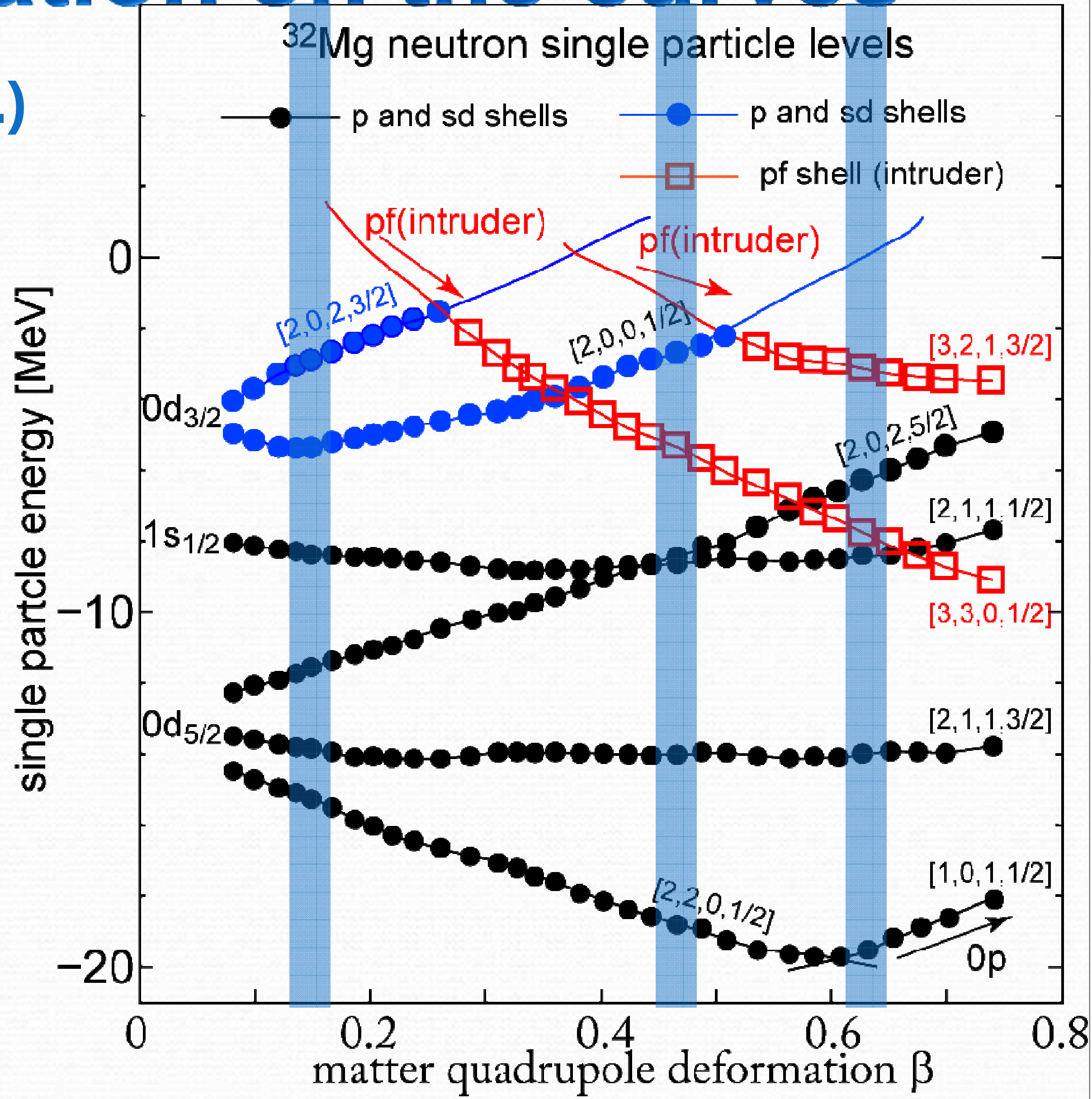
Consideration on the curves

0p0h (normal config.)

4p4h (intruder)

2p2h (intruder)

N=20 shell gap



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

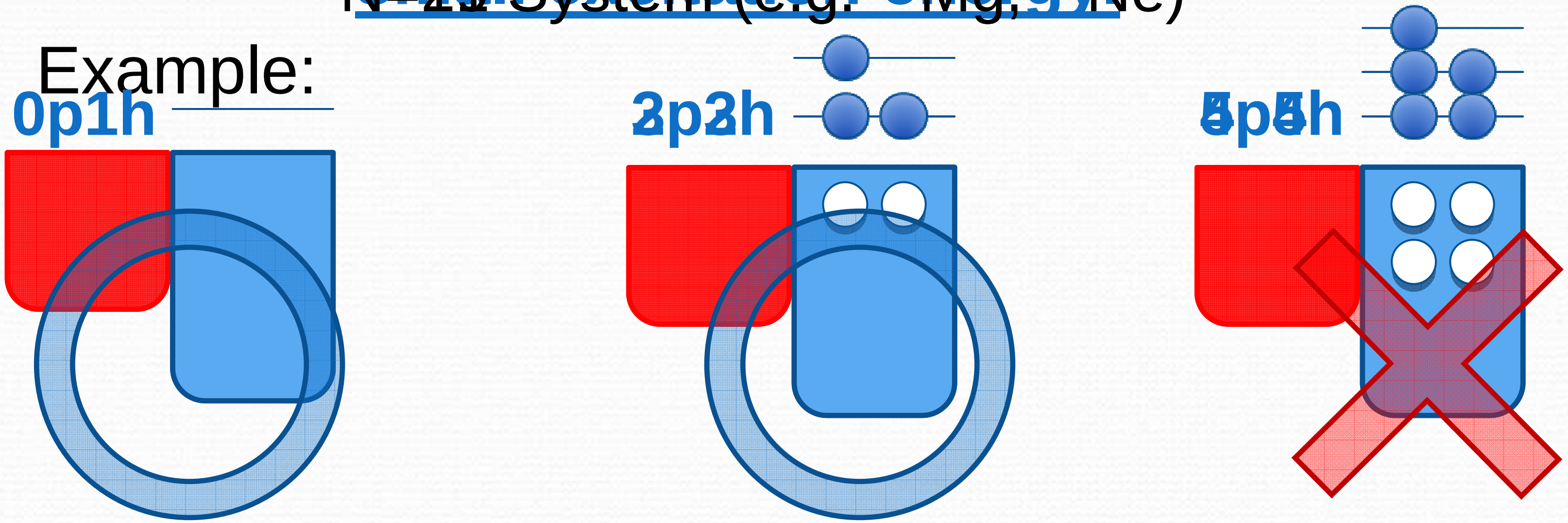
Rule for ph configurations

Rule #1: <u>Up to 4p and up to 4h configurations appear in small excitation energy.</u>

N=19 System (e.g. ^{31}Mg, ^{29}Ne)

N=21 System (e.g. ^{33}Mg, ^{31}Ne)

Example:



Note that this rule also explains magic number N=16

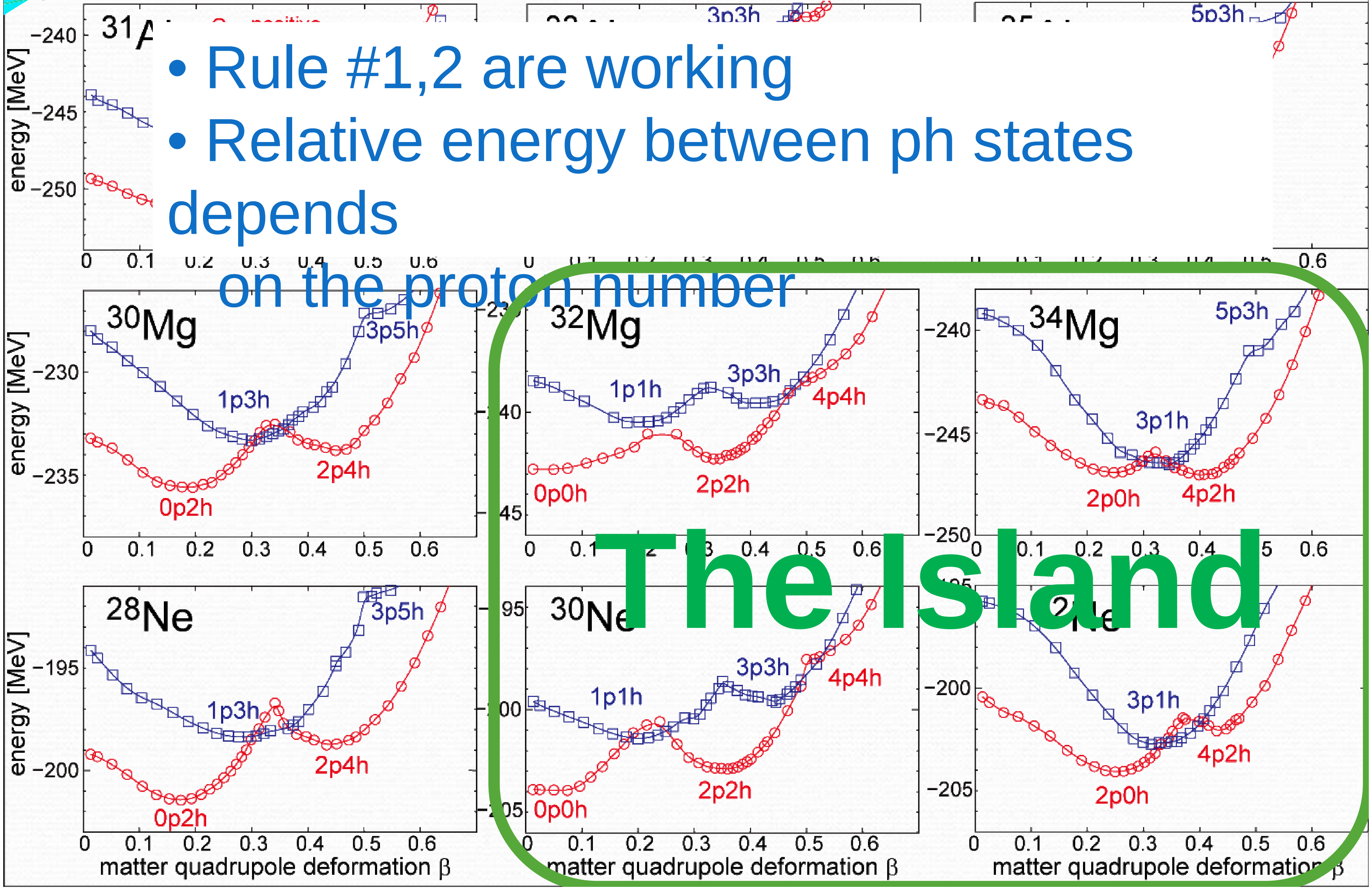
Rule #2: <u>As the number of particles (neutrons in pf</u>

Too simple,

but it works,
and it makes things interesting

Energy curves in and around the Island

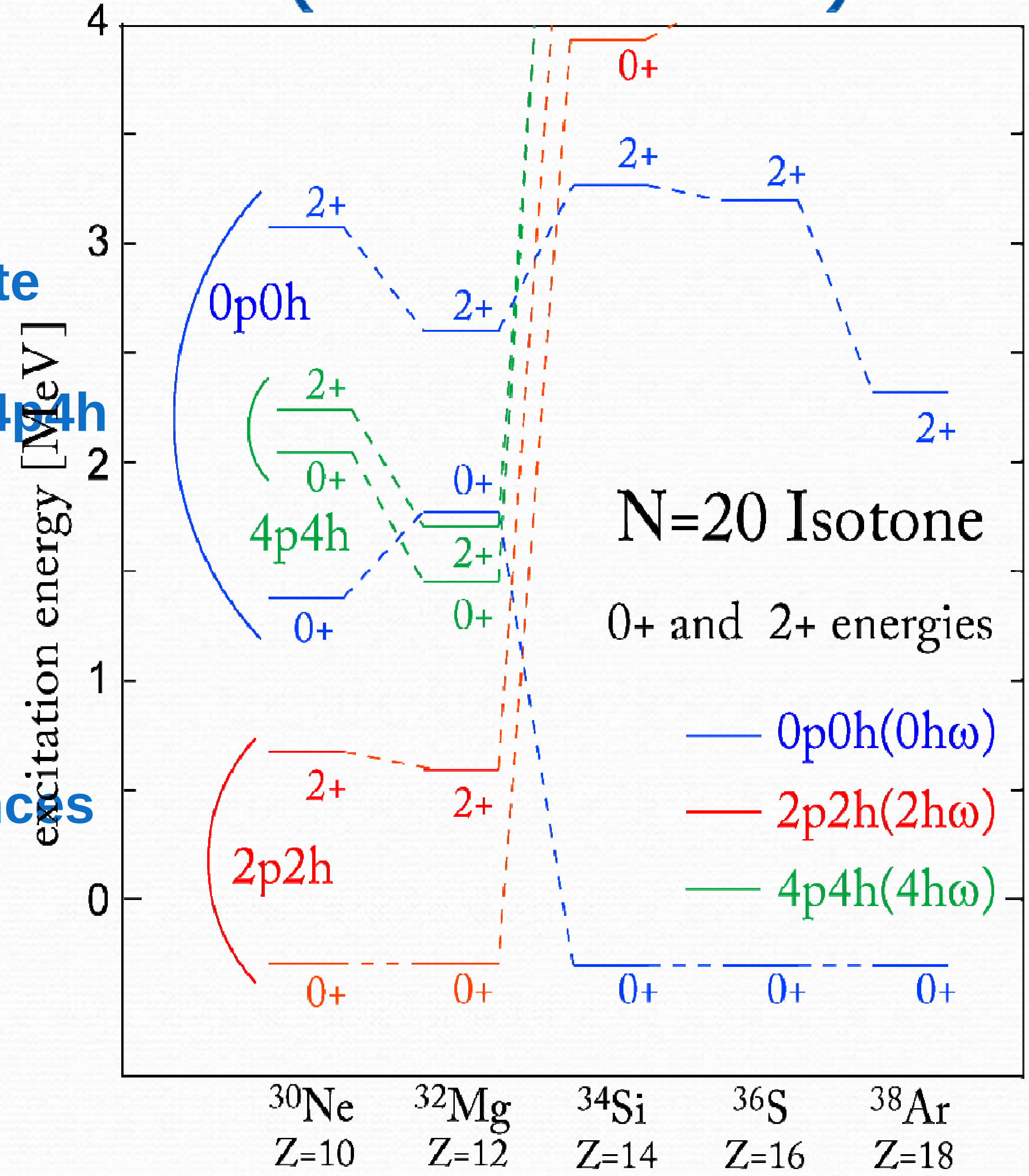
- Rule #1,2 are working
- Relative energy between ph states depends on the proton number



The Island

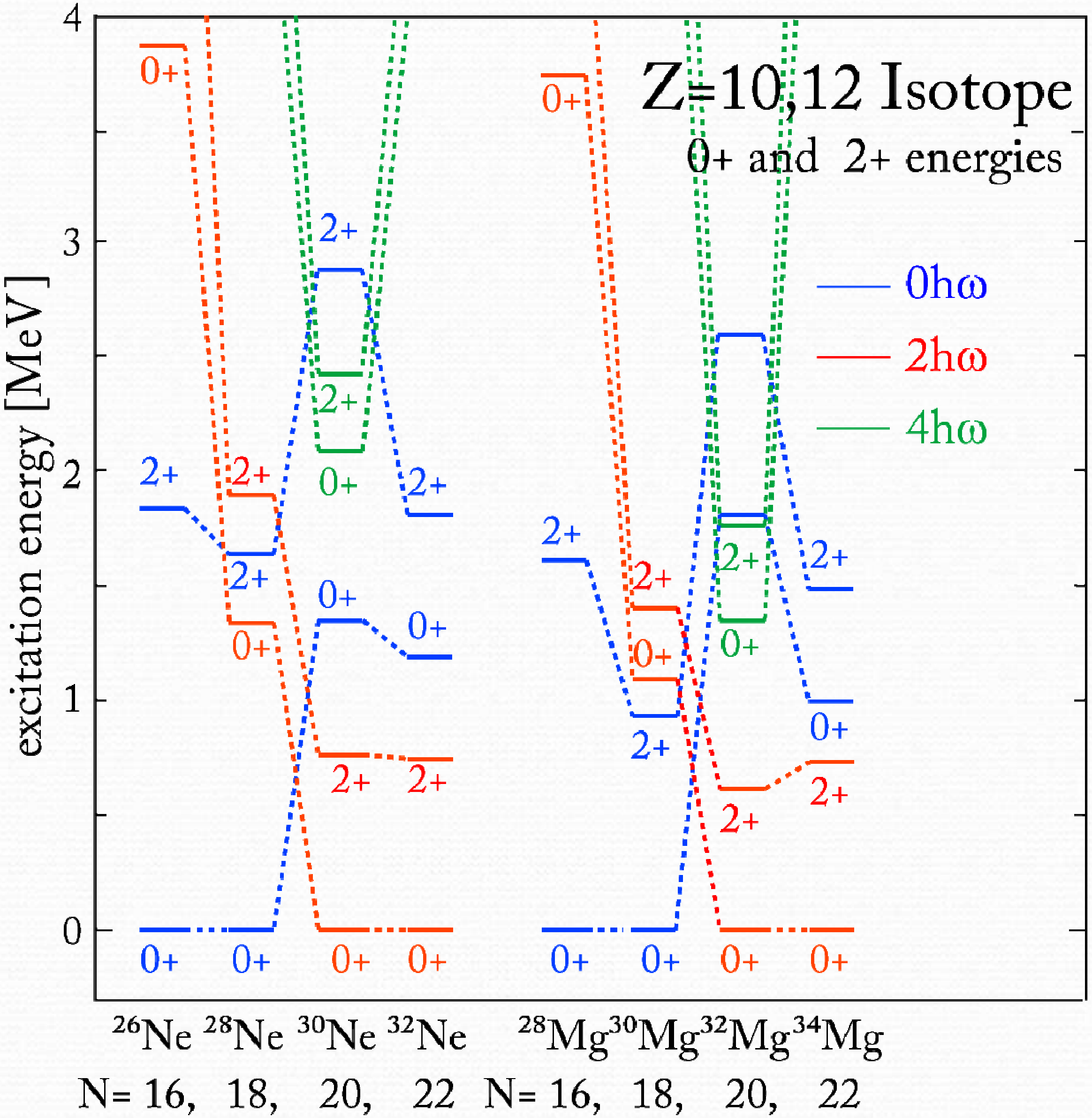
Results: 0^+ and 2^+ states (N=20 isotones)

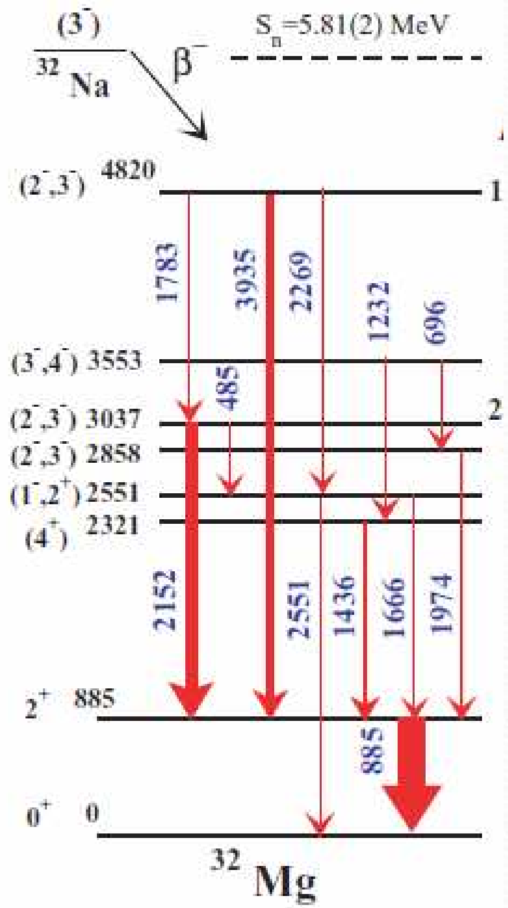
- Strongly deformed 2p2h takes over the ground state
- Note that 0p0h, 2p2h and 4p4h appear in the Island
- 4p4h (more deformed) also participates in.
- Some experimental evidences

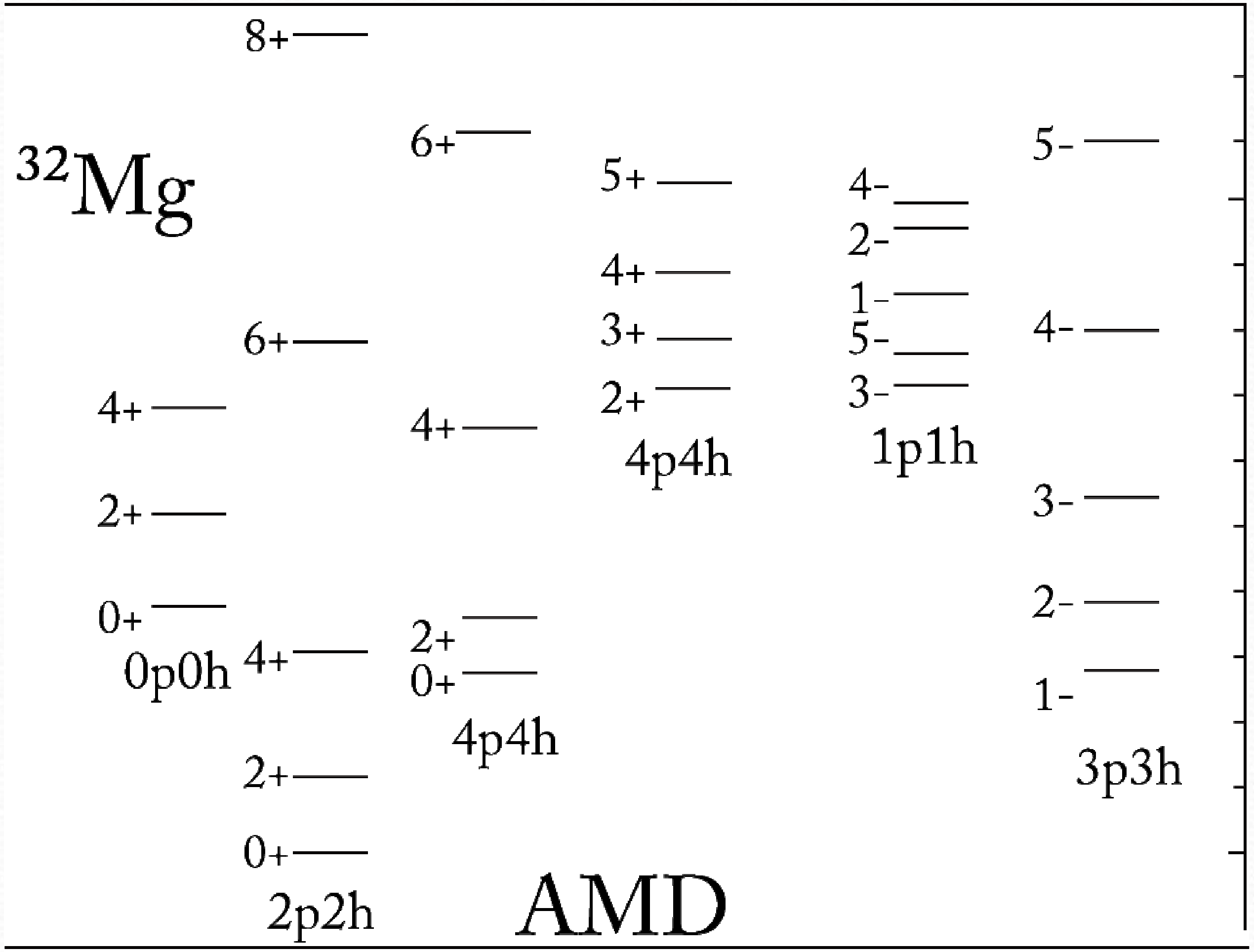


Results: 0^+ and 2^+ states (Z=10,12 isotopes)

- **2p2h dominates in N=20, 22 system**
- **4p4h (4hω)appears only in N=20 isotopes**
- **Intermediate character of N=18 isotopes**
- Precursor in N=18 system



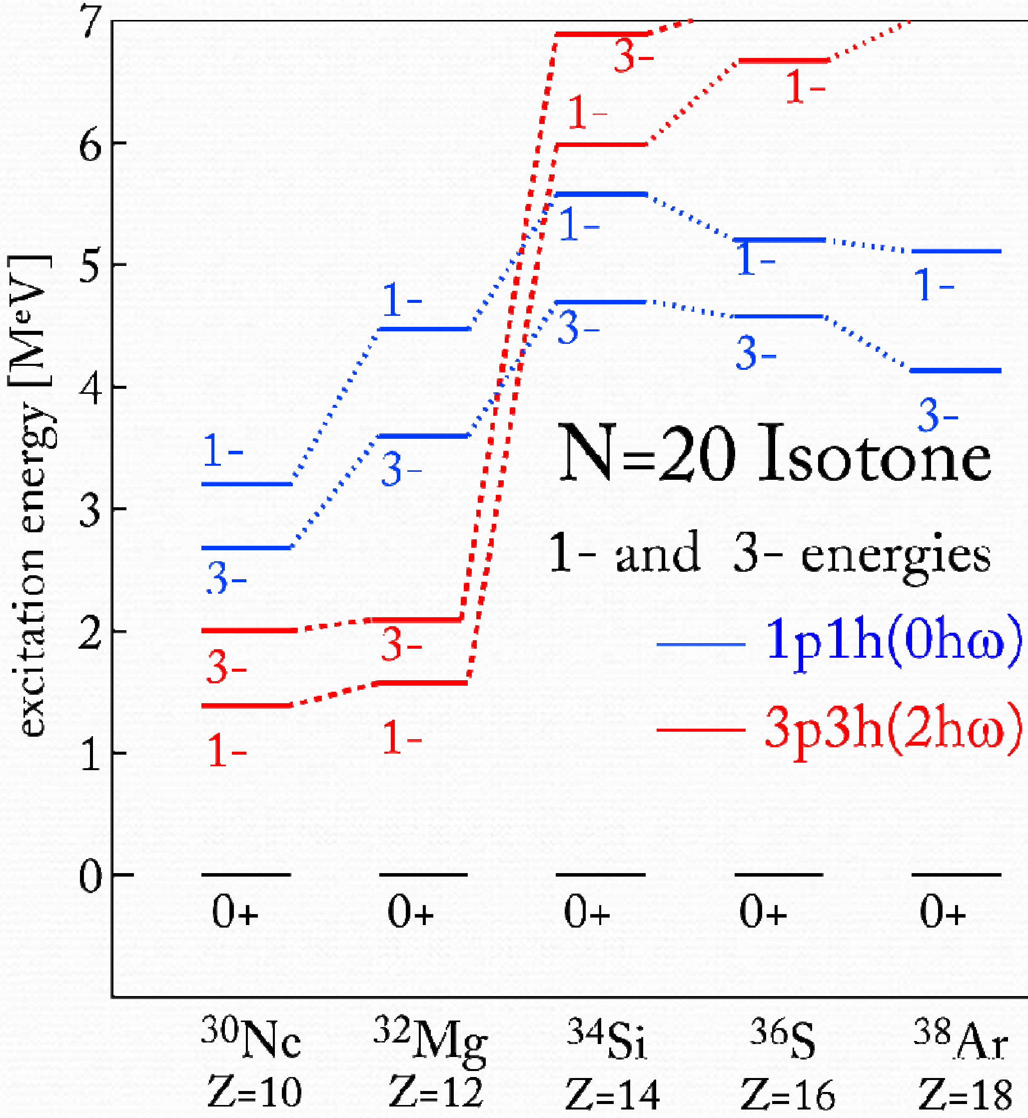




V. Tripathi, et. al., PRC77

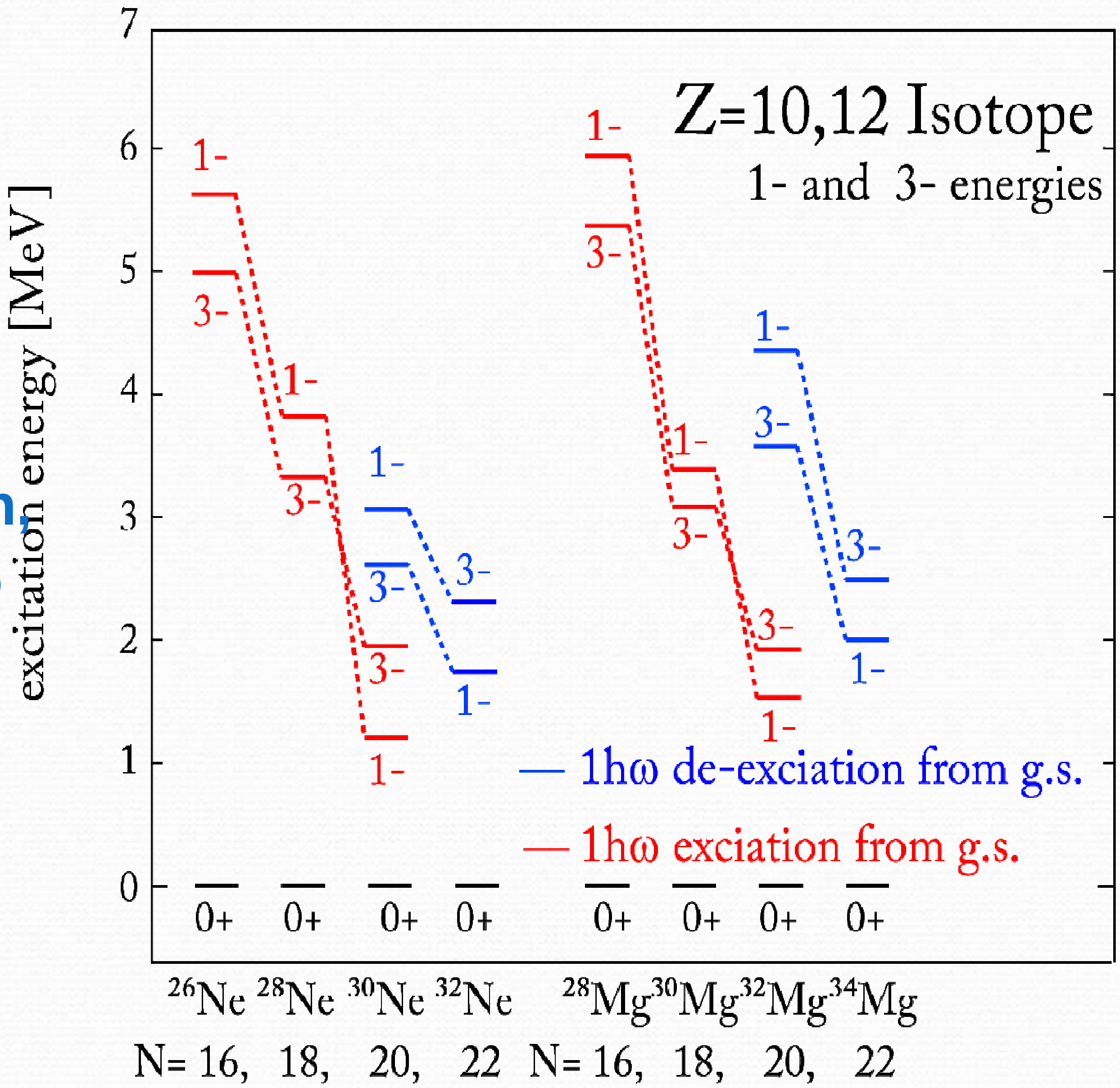
Results: 1^- and 3^- states (N=20 isotones)

- **Great reduction of 3p3h energy**
- **1p1h is not so sensitive to the proton number**



Results: 1^- and 3^- states (Z=10,12 isotopes)

- **Great reduction of 1hω excitation energy**
- **Due to the reduction, de-excitation is also possible in the island**
- **Precursor in N=18 system**



N=21 sysmtem (^{31}Ne)

Spin parity of the ground state: Jπ= 7/2-, 1/2+, 3/2- , 3/2+?

PRL **103**, 262501 (2009)

Halo Structure of the Island of Inversion Nucleus ^{31}Ne

T. Nakamura,[1] N. Kobayashi,[1] Y. Kondo,[1] Y. Satou,[1] N. Aoi,[2] H. Baba,[2] S. Deguchi,[1] N. Fukuda,[2] J. Gibelin,[3] N. Inabe,[2] M. Ishihara,[2] D. Kameda,[2] Y. Kawada,[1] T. Kubo,[2] K. Kusaka,[2] A. Mengoni,[4] T. Motobayashi,[2] T. Ohnishi,[2] M. Ohtake,[2] N. A. Orr,[3] H. Otsu,[2] T. Otsuka,[5] A. Saito,[5] H. Sakurai,[2] S. Shimoura,[5] T. Sumikama,[6] H. Takeda,[2] E. Takeshita,[2] M. Takechi,[2] S. Takeuchi,[2] K. Tanaka,[2] K. N. Tanaka,[1] N. Tanaka,[1] Y. Togano,[2] Y. Utsuno,[7] K. Yoneda,[2] A. Yoshida,[2] and K. Yoshida[2]

PHYSICAL REVIEW C **81**, 024606 (2010)

Probing the weakly-bound neutron orbit of ^{31}Ne with total reaction and one-neutron removal cross sections

W. Horiuchi,[1,*] Y. Suzuki,[2,†] P. Capel,[3,4,‡] and D. Baye[3,§]

N=21 sysmtem (^{33}Mg)

Spin parity of the ground state: Jπ= 3/2- , 3/2+?

PRL101,142504(2008).

Spin and Magnetic Moment of ^{33}Mg: Evidence for a Negative-Parity Intruder Ground State

D. T. Yordanov,[1] M. Kowalska,[2,3] K. Blaum,[2] M. De Rydt,[1] K. T. Flanagan,[1,3] P. Lievens,[4]
R. Neugart,[2] G. Neyens,[1] and H. H. Stroke[5]

PRL103,262501(2009).

Intruder Configurations in the $A = 33$ Isobars: ^{33}Mg and ^{33}Al

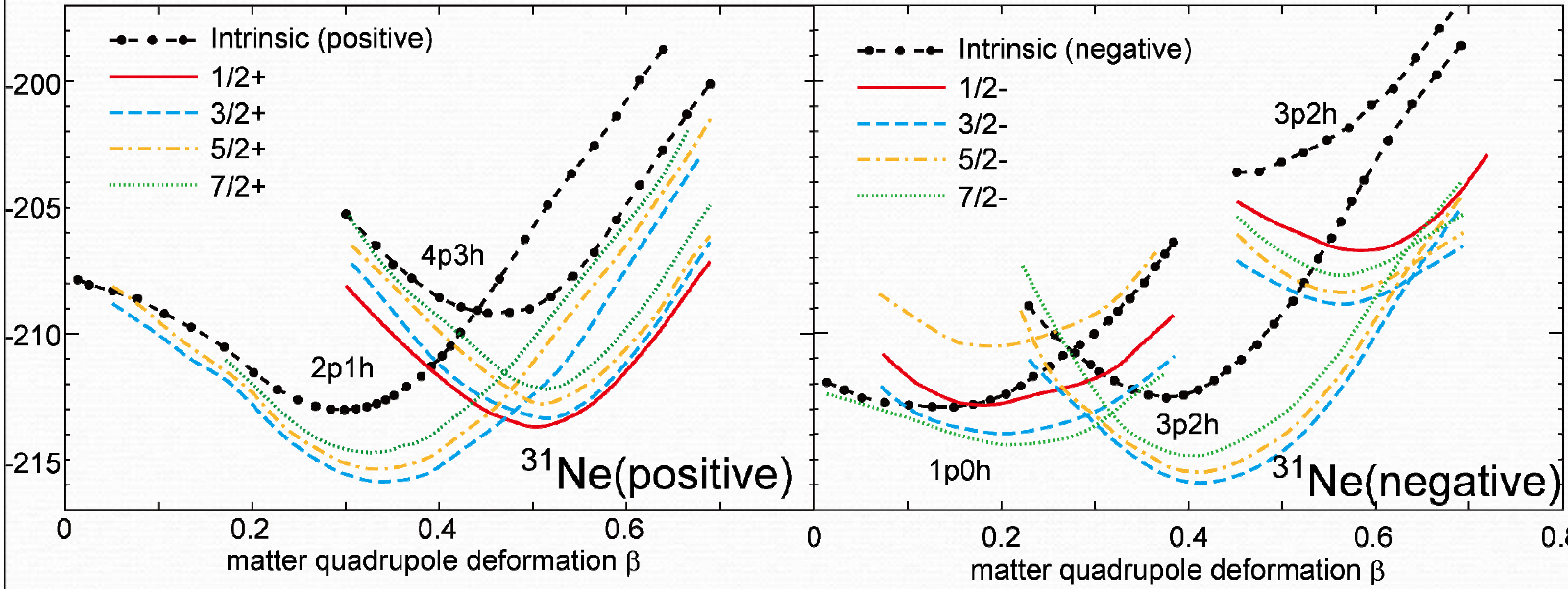
Vandana Tripathi,[1] S. L. Tabor,[1] P. F. Mantica,[2,3] Y. Utsuno,[4] P. Bender,[1] J. Cook,[2] C. R. Hoffman,[1] Sangjin Lee,[1]
T. Otsuka,[5,6] J. Pereira,[2] M. Perry,[1] K. Pepper,[1] J. S. Pinter,[3] J. Stoker,[3] A. Volya,[1] and D. Weisshaar[2]

PLB685, 253 (2010).

Structure of ^{33}Mg sheds new light on the $N = 20$ island of inversion

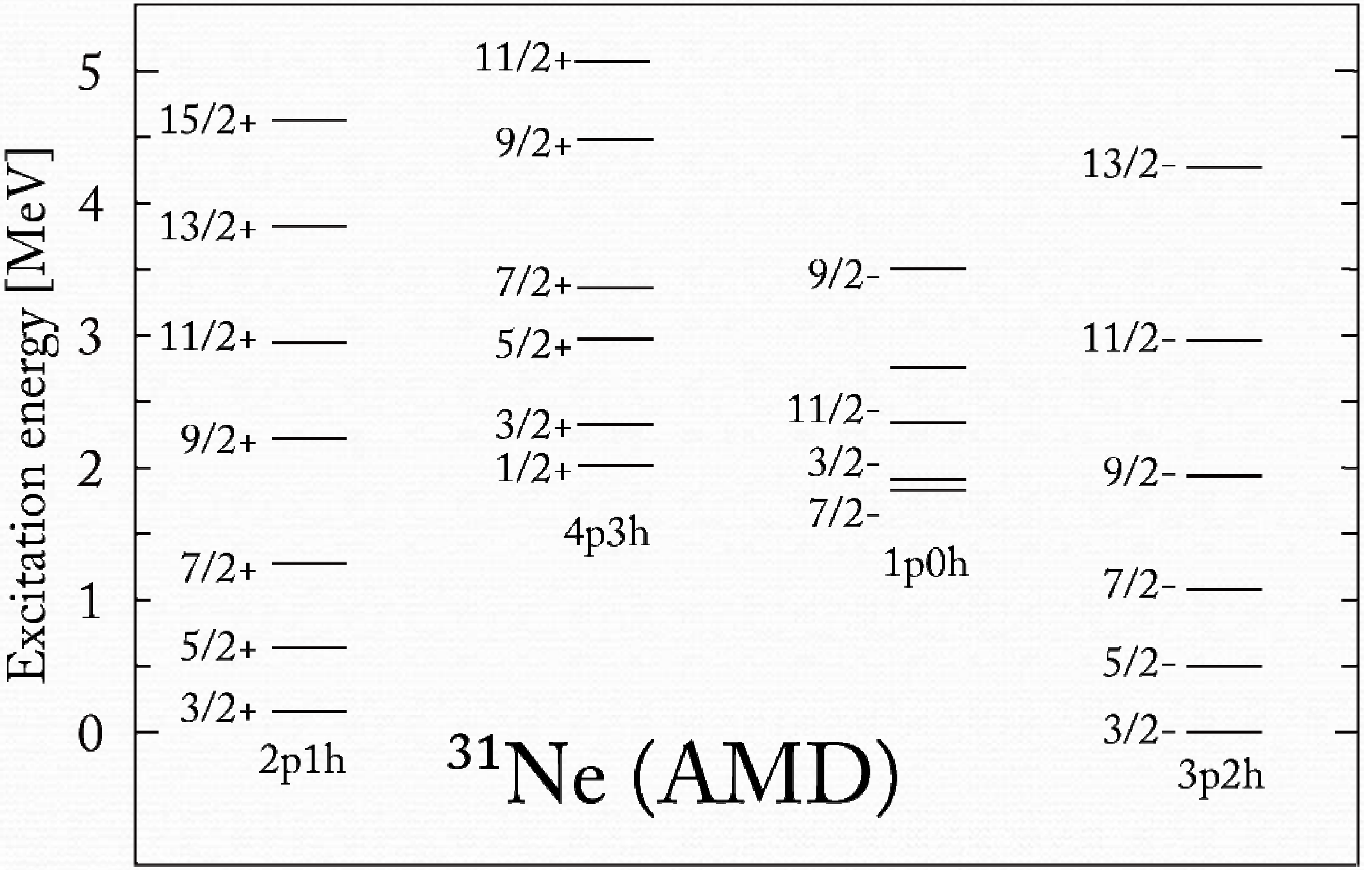
R. Kanungo[a,*], C. Nociforo[b], A. Prochazka[b,c], Y. Utsuno[d], T. Aumann[b], D. Boutin[c], D. Cortina-Gil[e],
B. Davids[f], M. Diakaki[g], F. Farinon[b,c], H. Geissel[b], R. Gernhäuser[h], J. Gerl[b], R. Janik[i], B. Jonson[j],
B. Kindler[b], R. Knöbel[b,c], R. Krücken[h], M. Lantz[j], H. Lenske[c], Y. Litvinov[b,k], K. Mahata[b], P. Maierbeck[h],
A. Musumarra[l,m], T. Nilsson[j], T. Otsuka[n], C. Perro[a], C. Scheidenberger[b], B. Sitar[i], P. Strmen[i], B. Sun[b],
I. Szarka[i], I. Tanihata[o], H. Weick[b], M. Winkler[b]

^{31}Ne: Energy curves



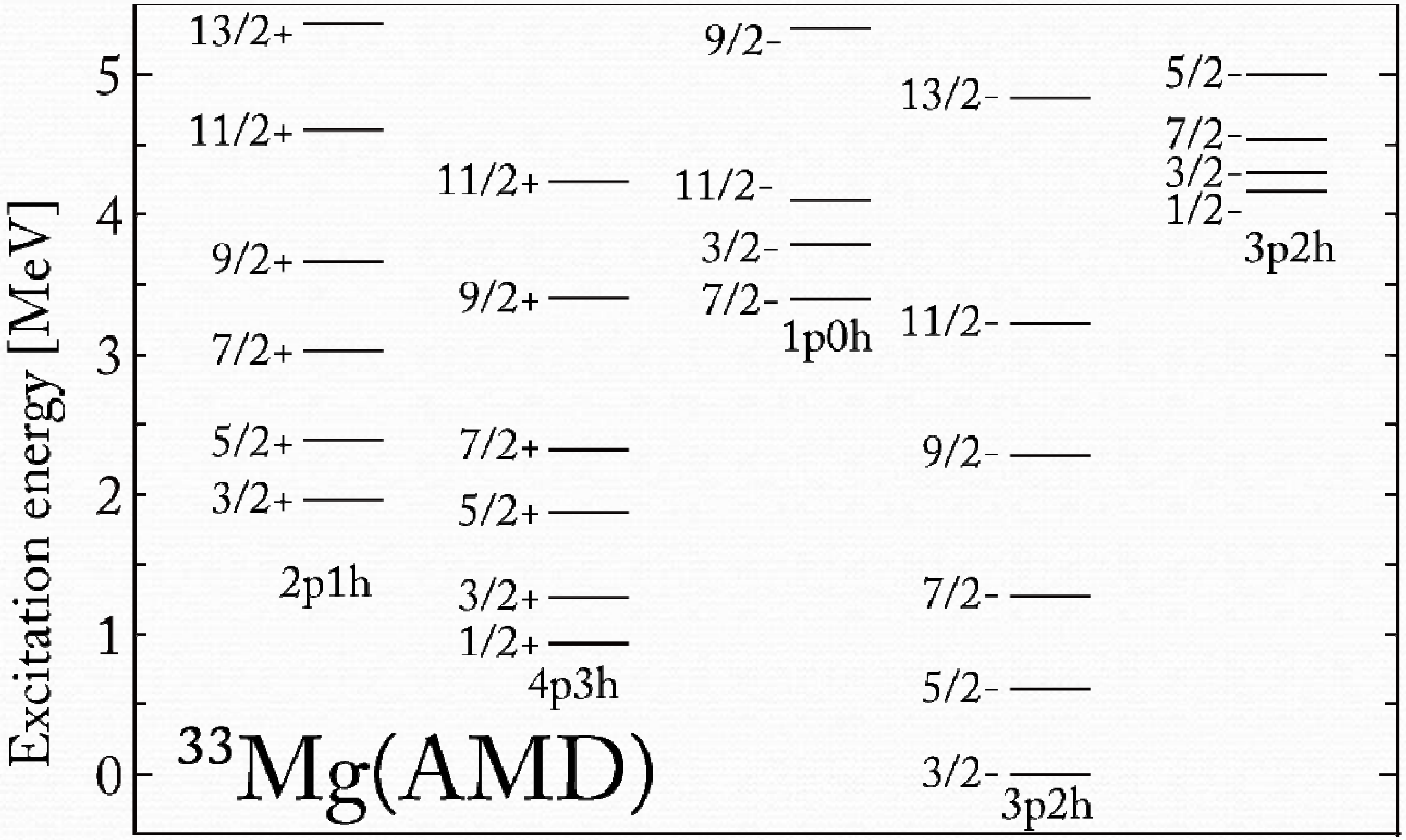
- Competition between 2p1h (3/2+) and 3p2h (3/2-) config.
- No chance for 1p0h (7/2-, normal config)

^{31}Ne: Levels



- Almost degenerated 3/2+, 3/2- states

^{33}Mg



- 3/2- is the ground state, consistent with one-neutron removal experiment

Summary

- A simple rule

  Rule #1: Up to 4p and up to 4h configurations appear in

  small excitation energy.

  Rule #2: As the number of particles (neutrons in pf shell)

  increases, deformation becomes large.

- Coexistence and competition between mpmh states
  - Behavior of 0,2+ and 1-,2- states as function of proton and neutron numbers
  - Precursor of the inversion in N=18 system
- Ground states of N=21 system
  - Competition between mpmh states, normal config is excluded