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What locates neutron driplines ?

Takaharu Otsuka

N. Tsunoda, T. Takayanagi, N. Shimizu, T. Suzuki, Y. Utsuno, H. Ueno
U. Tokyo, CNS, Sophia U., JAEA, RIKEN, Nihon U.

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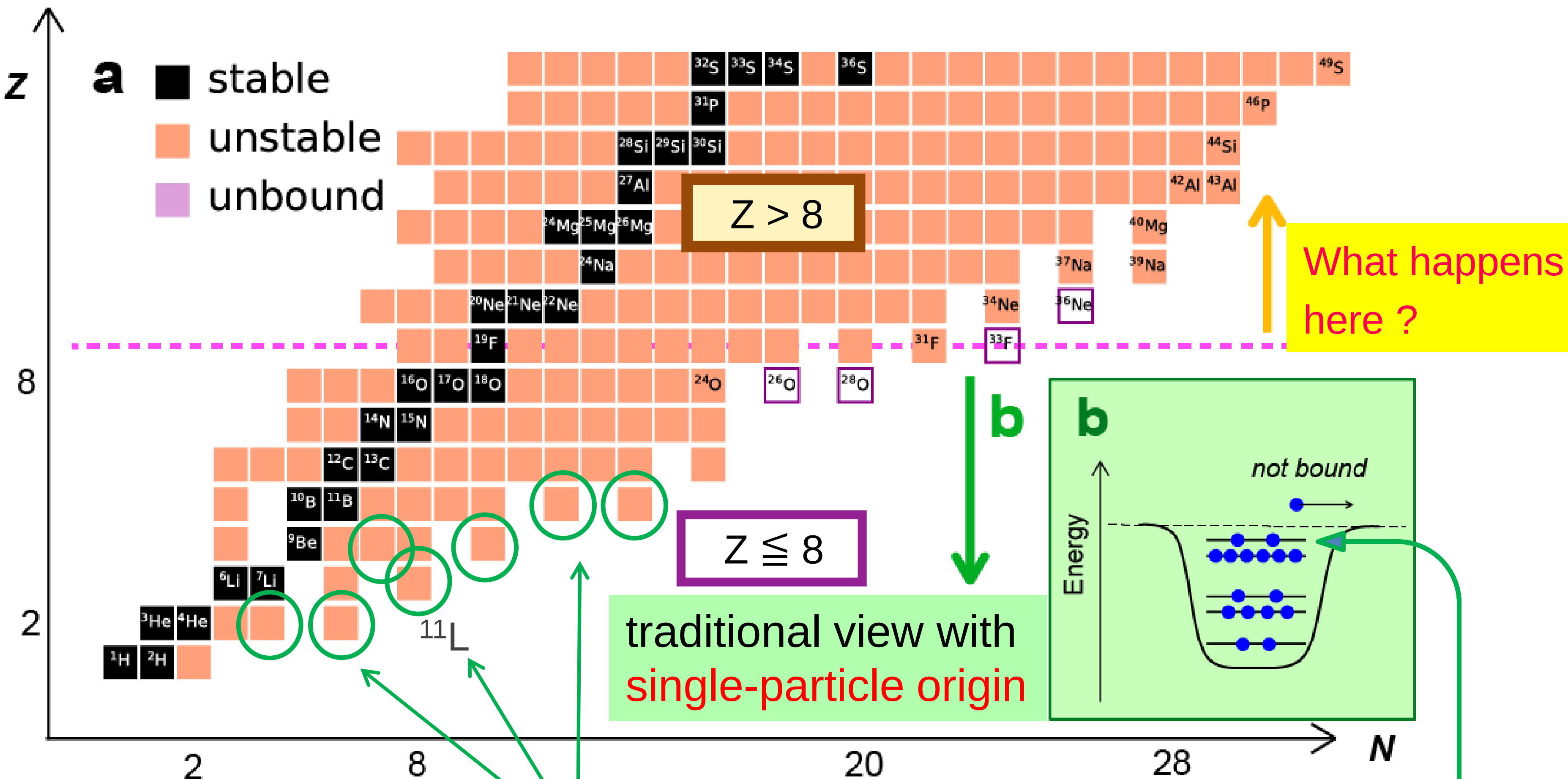
Neutron driplines : traditional and new(?) views

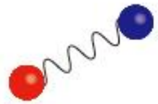


Neutron halo appears, if last neutrons are extremely loosely bound.
^{11}Li: Tanihata *et al*. PRL 55 (1985)

QCD

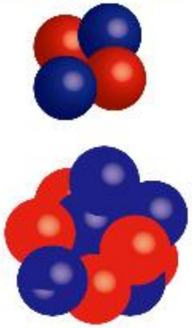
Lattice QCD
Effective Field Theory

Nuclear force



Few body techniques
No core shell model
and many others…

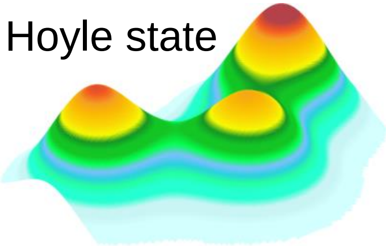
Light nuclei ~A≒10-20



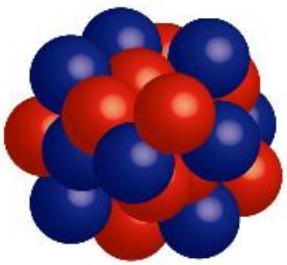
Example: ^{12}C

TO *et al*. Nature Com. **13**, 2234 (2022)

Hoyle state



Medium mass nuclei~A≒20-100



shell model with core
via the **effective interaction**
derived from **nuclear force**

Courtesy from N. Tsunoda

Chiral EFT *NN* int. + Fujita-Miyazawa 3*N* int. with averaging

(to be replaced by EFT N2LO 3*N* int.)

$V_{\text{low k}}$: treatment of high-momentum components

EKK : in-medium correction (core polarization)
(*conventional MBPT may diverge in two major shells*)

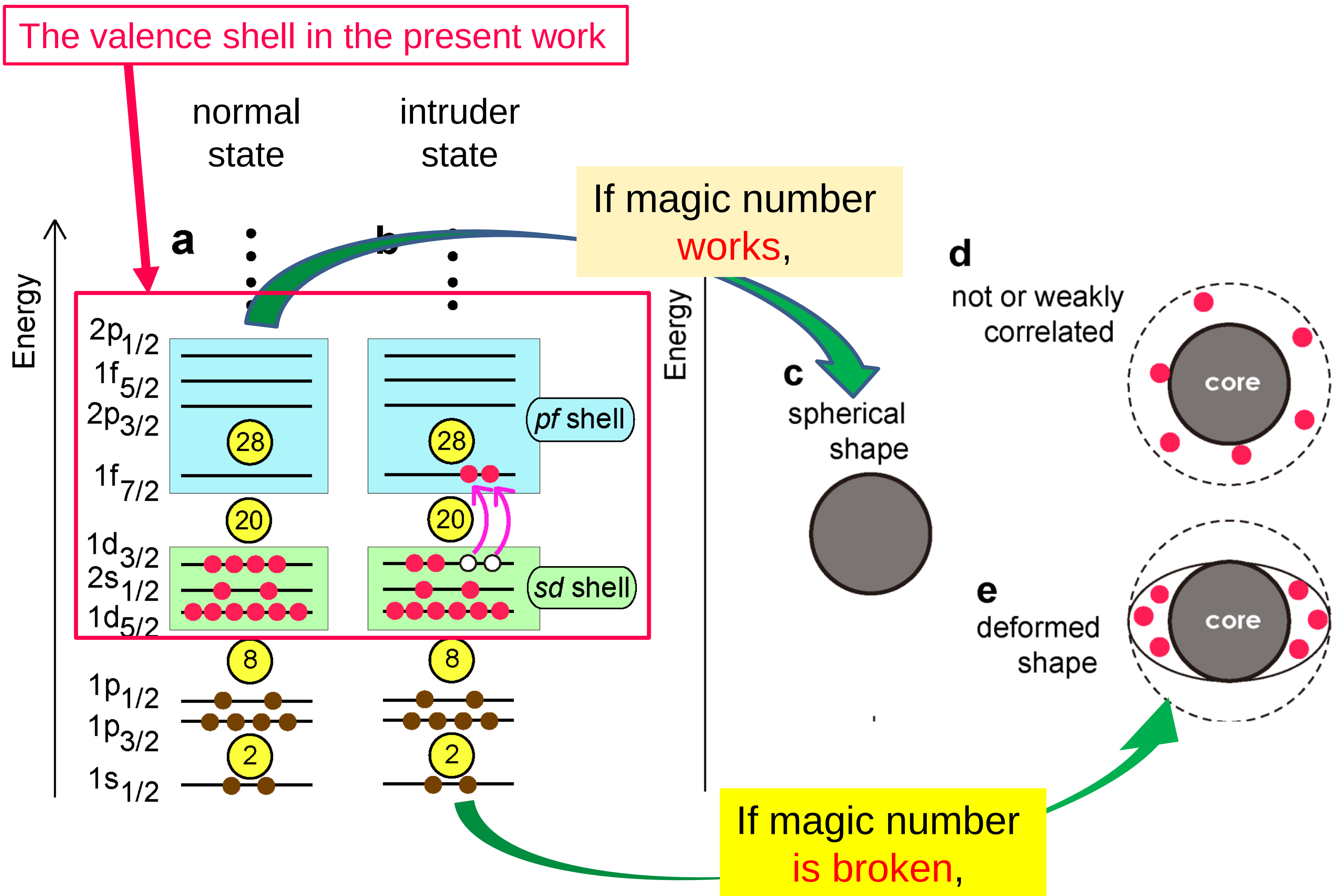
Krenciglwa and Kuo (1971) -> Extended KK (by Takayanagi)

ab initio effective interaction : EEdf1

Shell model (or Configuration Interaction; CI) calculation
by the conventional matrix diagonalization
or by the Monte Carlo Shell Model

Energy levels, electromagnetic matrix elements
(diagonalization of Hamiltonian matrix)

Relation to the magic number N=20 and the present valence shell



Anomaly in energy levels : not expected from the N=20 magicity

β-DECAY SCHEMES OF VERY NEUTRON-RICH SODIUM ISOTOPES AND THEIR DESCENDANTS

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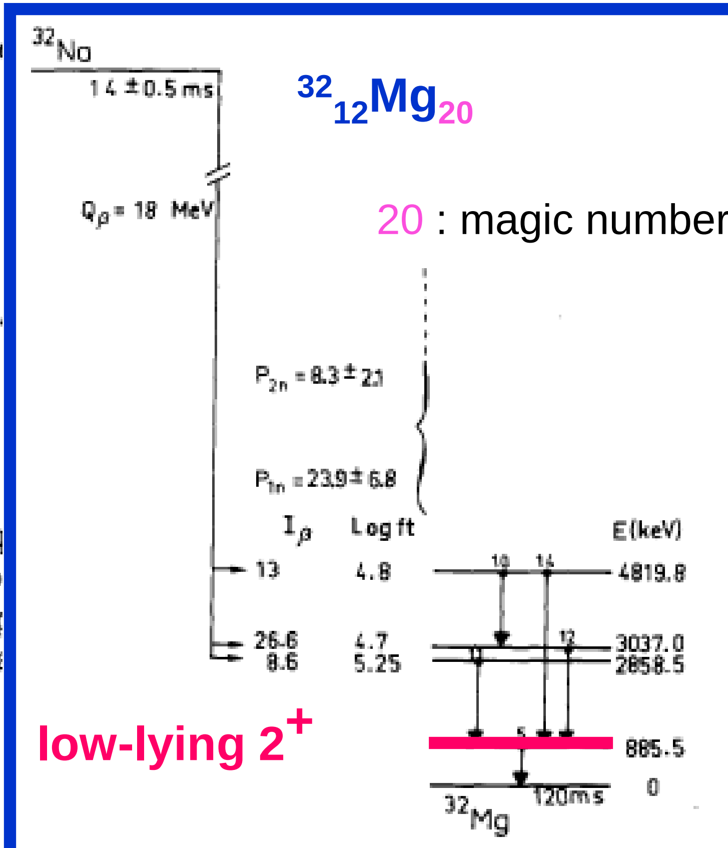
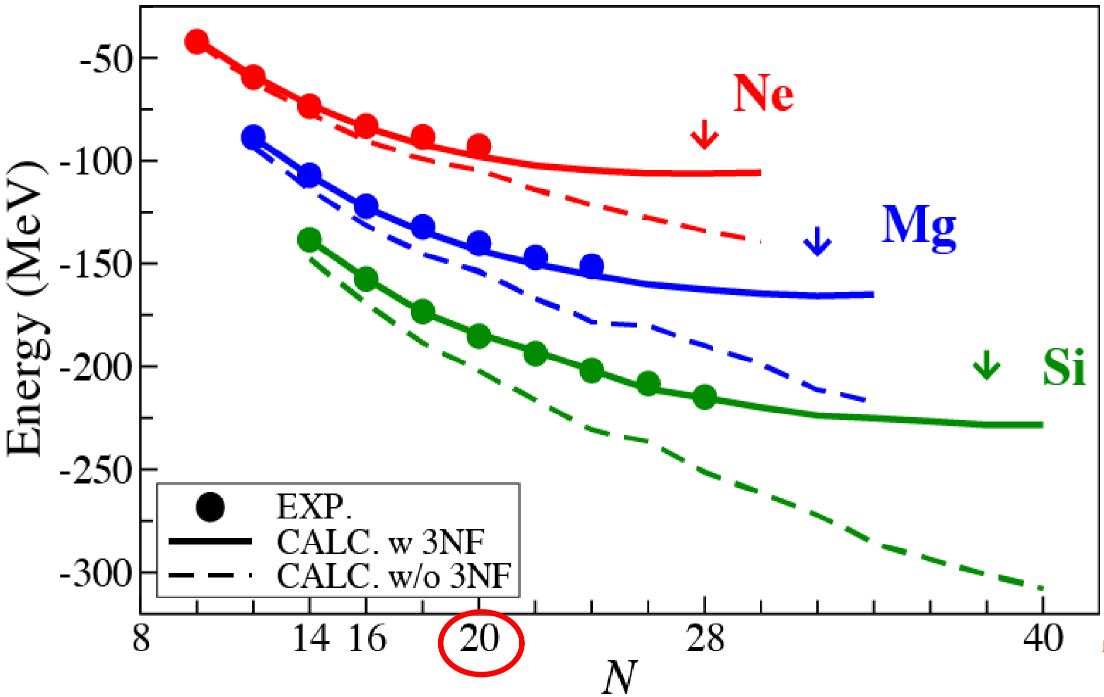
Received 6 February 1984

Abstract: The γ-activities from the β-decay of Na isotopes up
fragmentation and analysed through mass-spectrometry techniq
from their Mg descendants. The I_γ intensities, the β-delayed o
and the I_β intensities are measured. Decay schemes are prop
location of the first 2^+ level of ^{32}Mg, the occurrence of a nucle

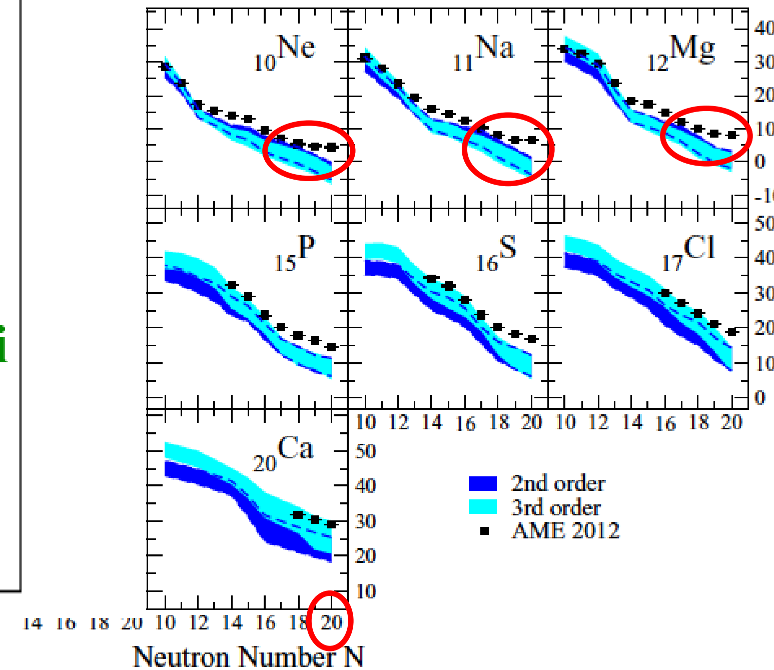


ground-state energies

Earlier (2017 PRC) work by EEdf1



Earlier work



Calculations with full sd + pf shell

Simonis et al.
PRC 93, 011302(R) (2016)

PHYSICAL REVIEW C 95, 021304(R) (2017)

Exotic neutron-rich medium-mass nuclei with realistic nuclear forces

Naofumi Tsunoda,[1] Takaharu Otsuka,[1,2,3,4] Noritaka Shimizu,[1] Morten Hjorth-Jensen,[5,6] Kazuo Takayanagi,[7] and Toshio Suzuki[8]

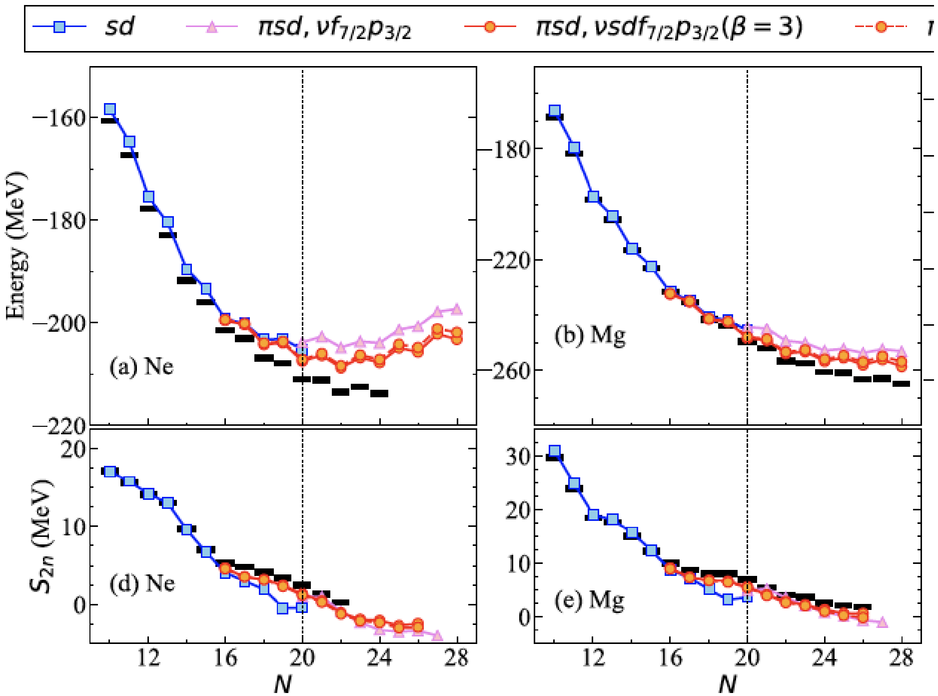
Recent *ab initio* calculation (IM-SRG)

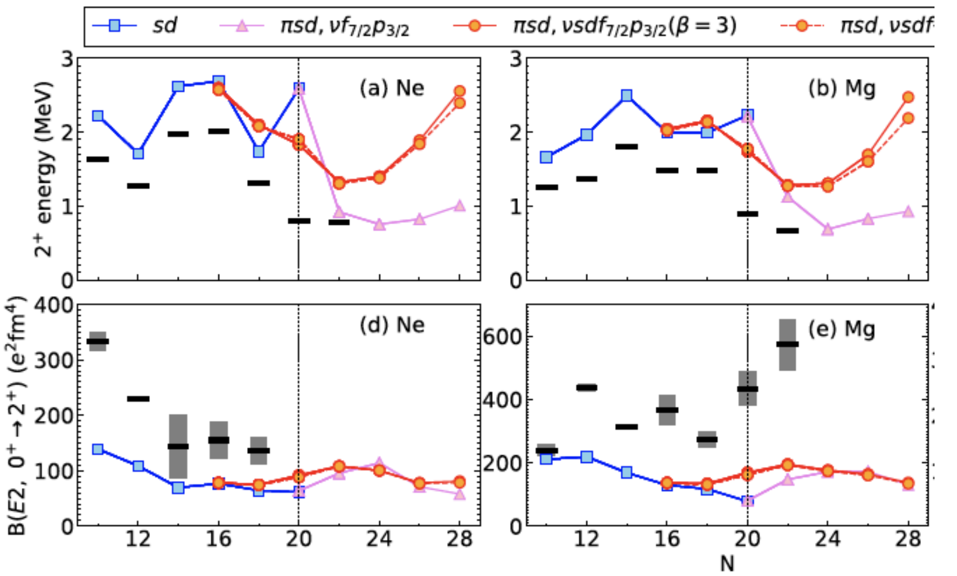
PHYSICAL REVIEW C **102**, 034320 (2020)

Editors' Suggestion

Ab initio multishell valence-space Hamiltonians and the island of inversion

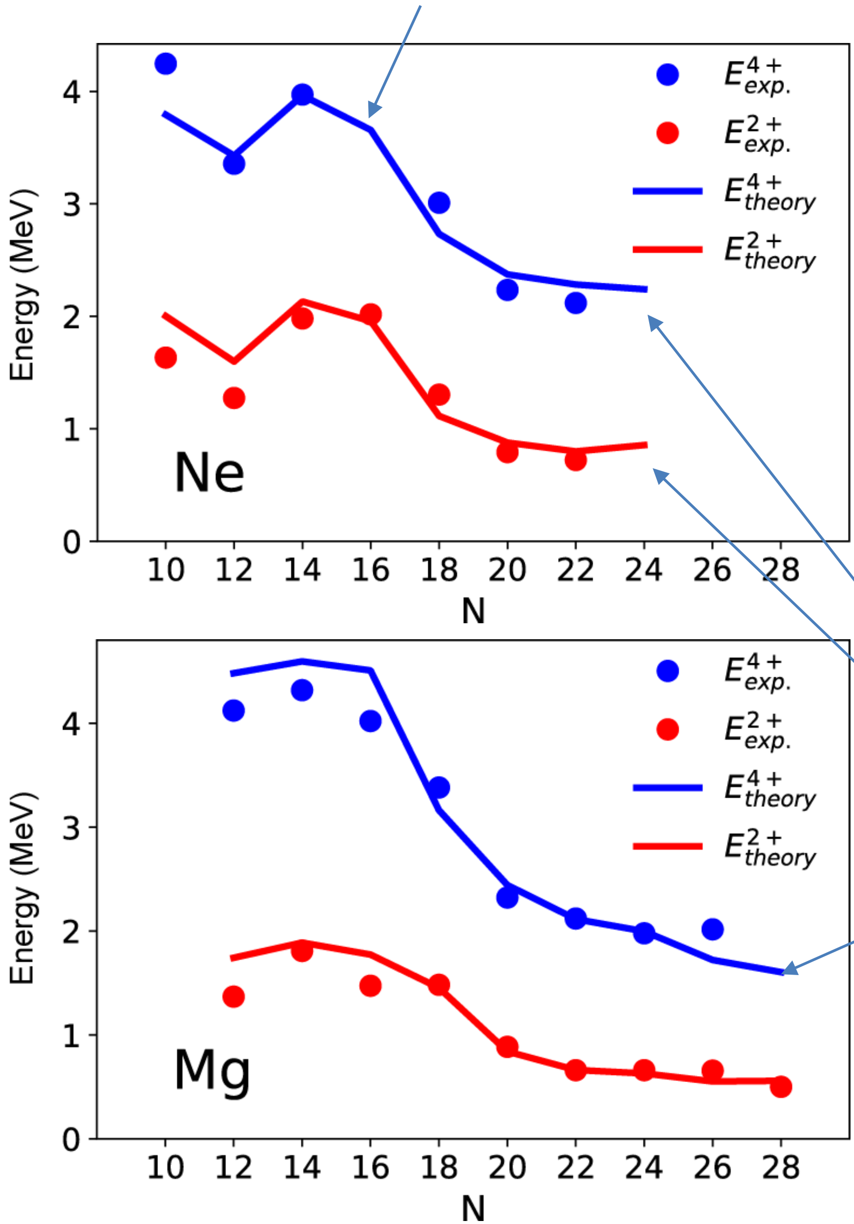
T. Miyagi,[1] S. R. Stroberg,[2] J. D. Holt,[1,3] and N. Shimizu[4]





Large deformation seems to be a challenge.

Ne and Mg systematics



The EEdf1 Hamiltonian appears to be reasonable up to N~28 for Z=9-12.

Levels may not exist as bound states, because their energies are above the threshold of neutron emission.

Dripline mechanism

Driplines known for F and Ne, and most likely for Na.

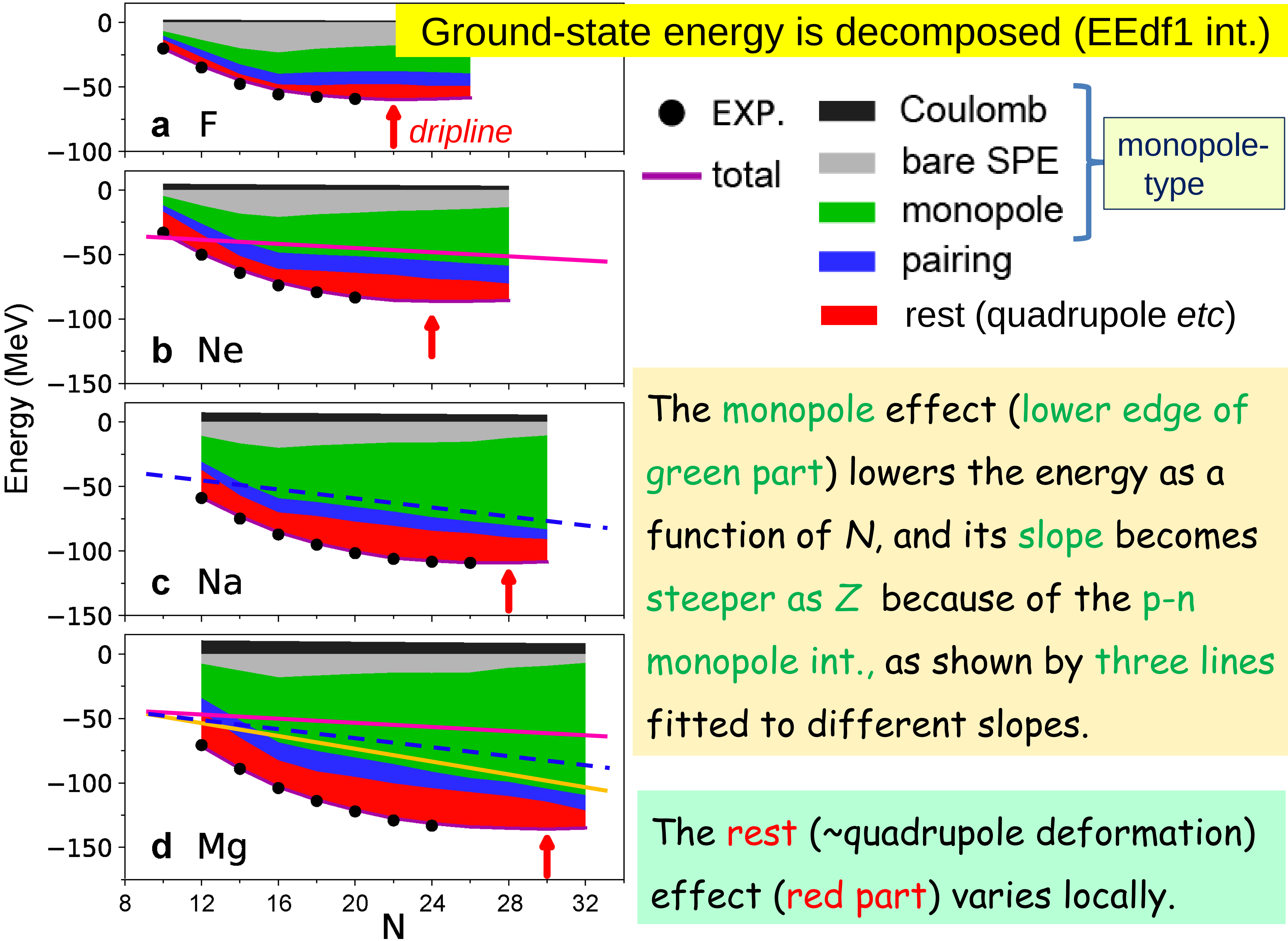
PHYSICAL REVIEW LETTERS **123**, 212501 (2019)

Editors' Suggestion   Featured in Physics

Location of the Neutron Dripline at Fluorine and Neon

D. S. Ahn,[1] N. Fukuda,[1] H. Geissel,[5] N. Inabe,[1] N. Iwasa,[4] T. Kubo,[1,*,†] K. Kusaka,[1] D. J. Morrissey,[6] D. Murai,[3] T. Nakamura,[2] M. Ohtake,[1] H. Otsu,[1] H. Sato,[1] B. M. Sherrill,[6] Y. Shimizu,[1] H. Suzuki,[1] H. Takeda,[1] O. B. Tarasov,[6] H. Ueno,[1] Y. Yanagisawa,[1] and K. Yoshida[1]

Ground-state energy is decomposed (EEdf1 int.)



The monopole effect (lower edge of green part) lowers the energy as a function of *N*, and its slope becomes steeper as *Z* because of the p-n monopole int., as shown by three lines fitted to different slopes.

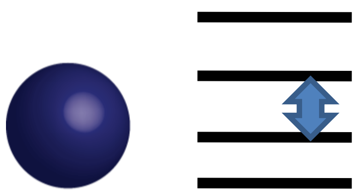
The rest (~quadrupole deformation) effect (red part) varies locally.

Decomposition of the Hamiltonian

monopole part

bare SPE $\sum \epsilon_i a_i^+ a_i$

monopole $\sum_{i,j} V^{ab}_{\rm mono} a_i^+ a_j^+ a_j a_i$ $\quad V^{ab}_{\rm mono} = \sum_J \frac{(2J+1)\langle ab|V|ab\rangle_J}{2J+1}$



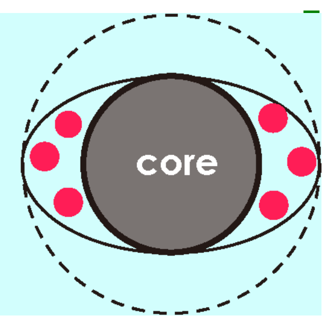
monopole: shift of SPE

multipole part

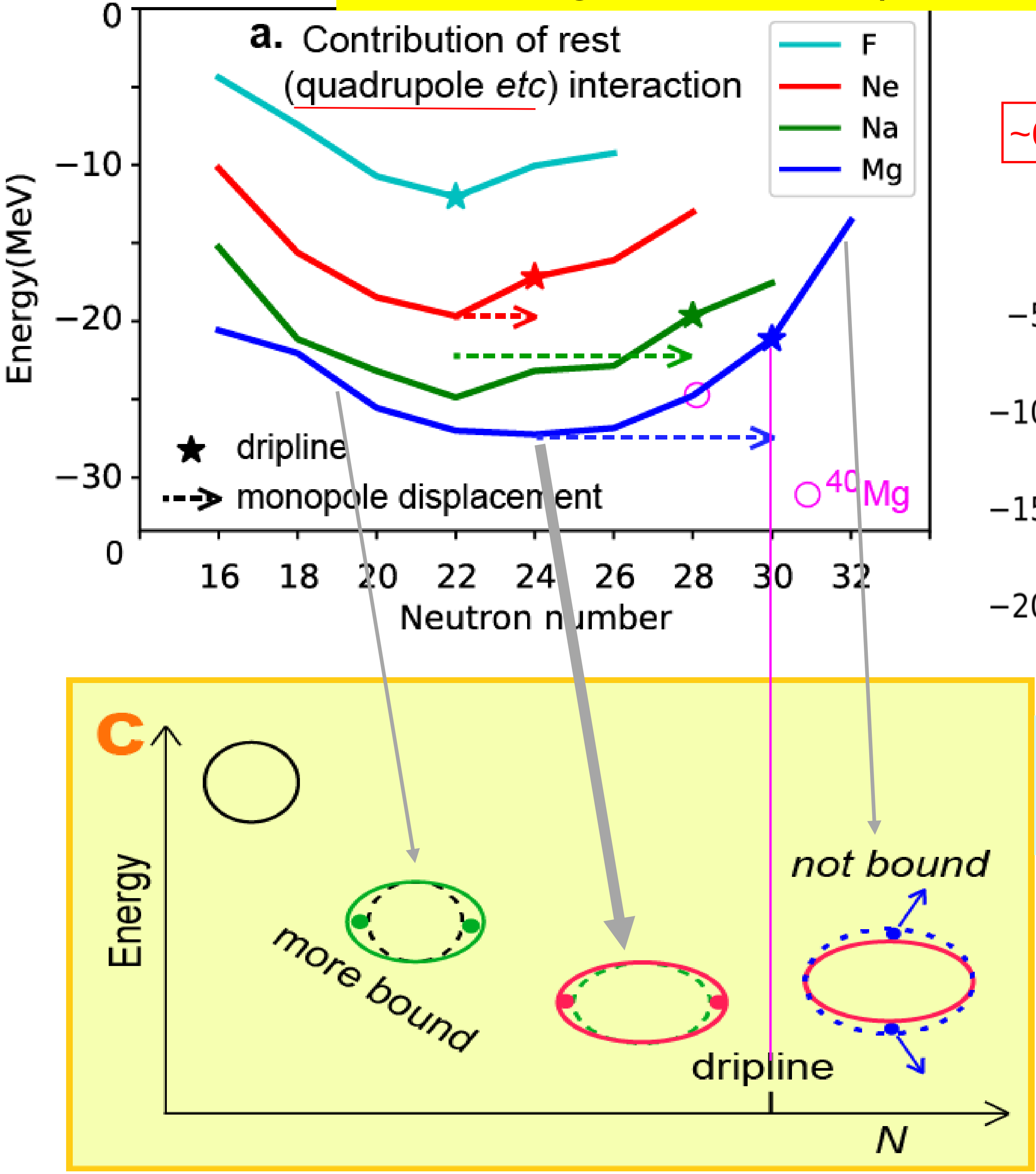
pairing J=0 nn + pp pairing correlations

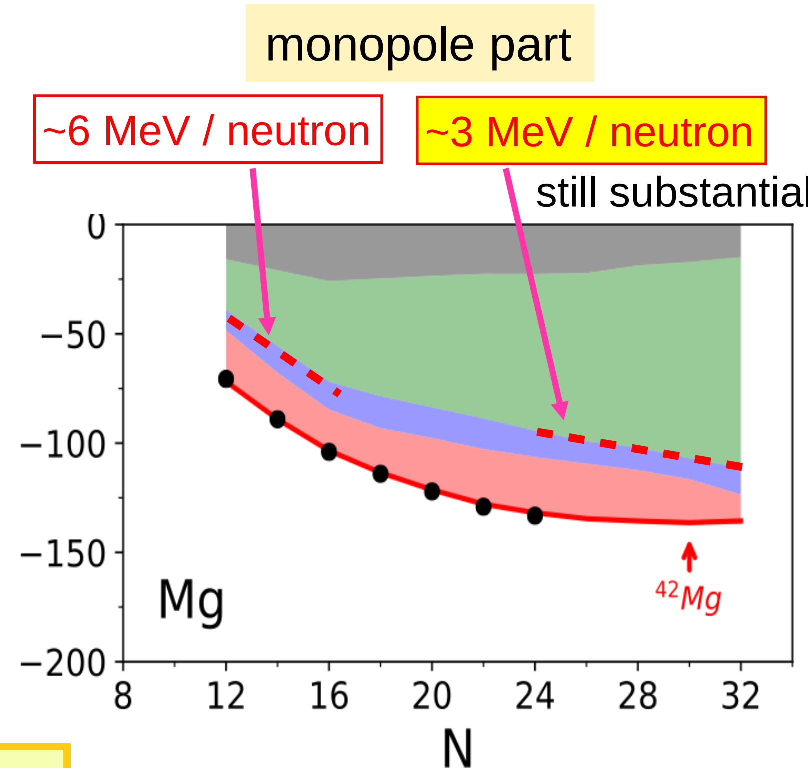
rest quadrupole deformation, *etc*

deformed shape



Two driving forces: example from Mg isotopes

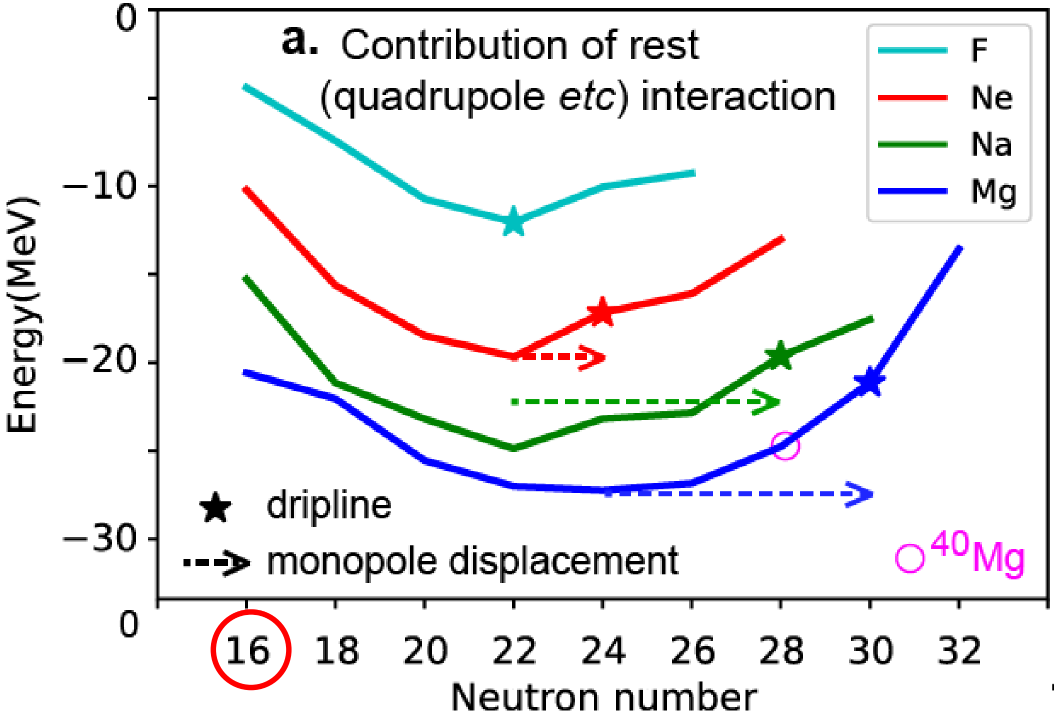


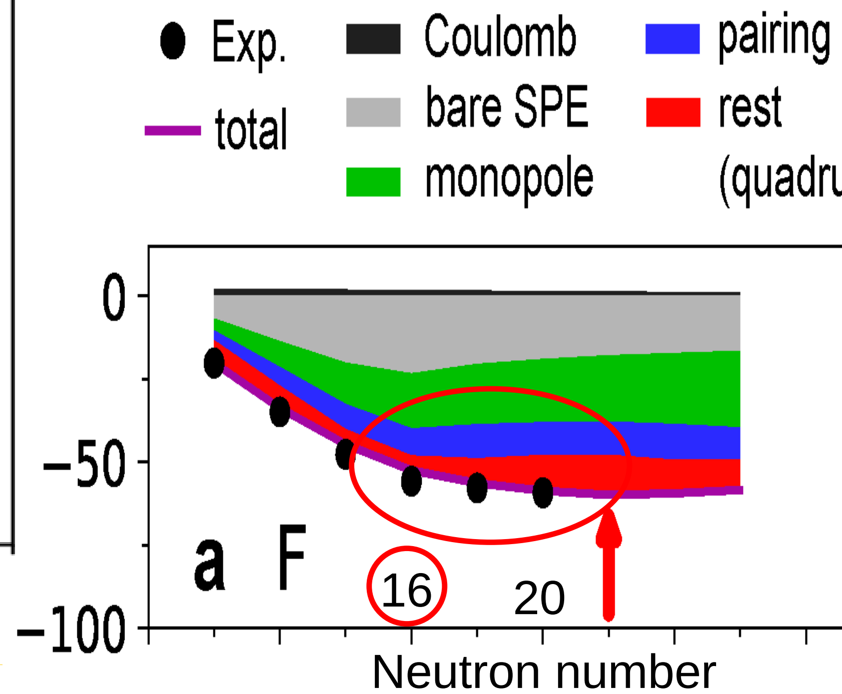


The rest (mainly deformation energy) part is saturated at N=24.

The monopole effects compensate it, and pushes the dripline away (dashed arrows).

Dripline of F isotopes





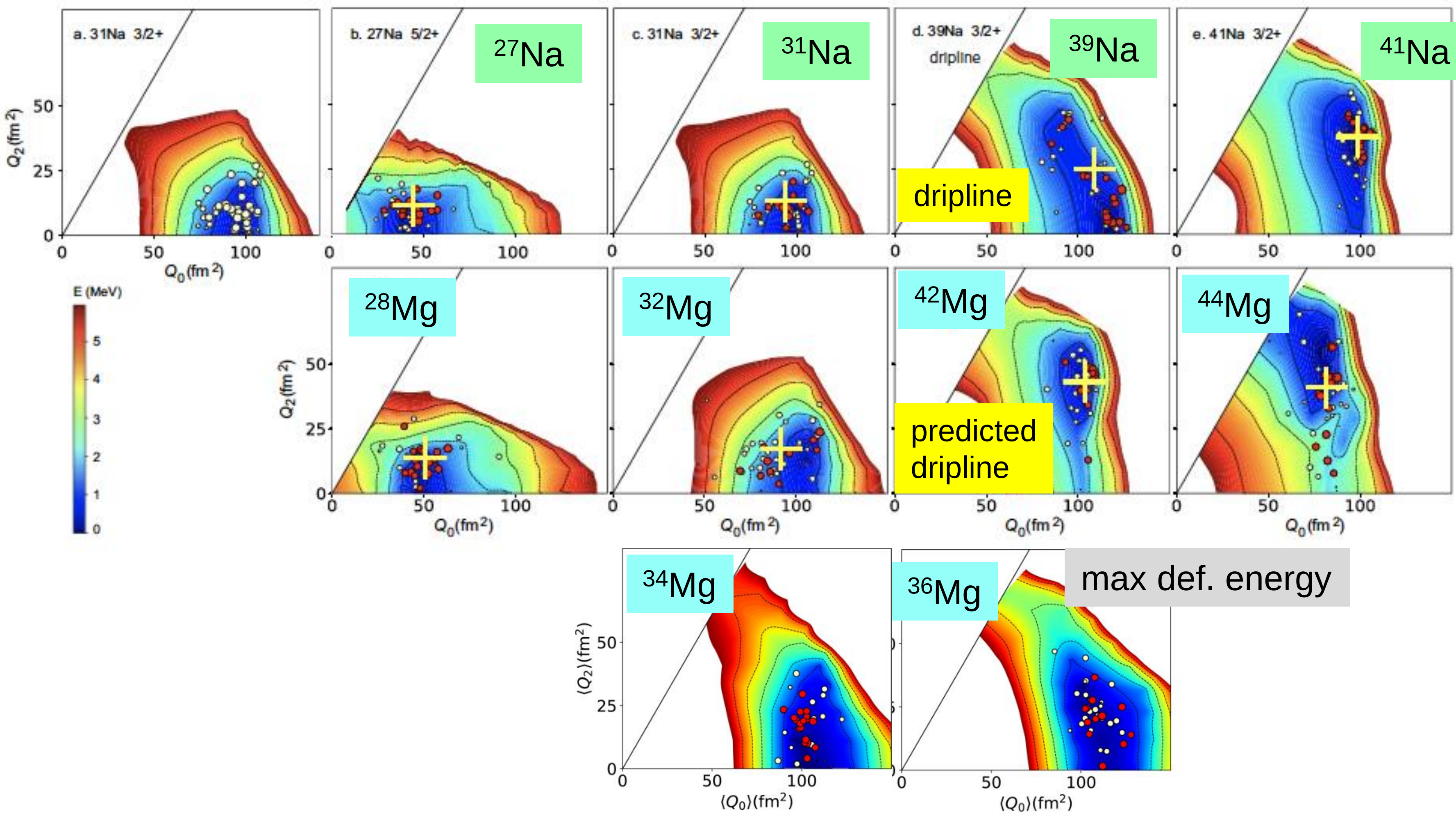
Monopole effect (edge of green part) becomes weaker for N > 16 in F isotopes. It even decreases (see gray edge).

If there were no "rest" (~ quadrupole deformation) effect (red part), the dripline would be at N = 16, which is the same as oxygen isotopes.

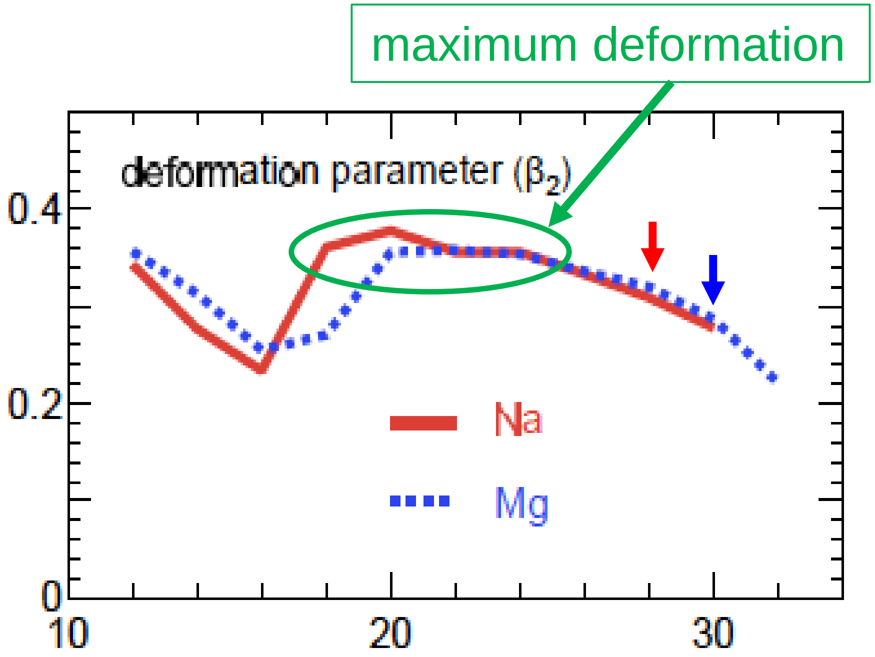
Loose binding phenomena may be seen, in contrast to Ne, Na or Mg.

Prevailing triaxiality in nuclei near driplines

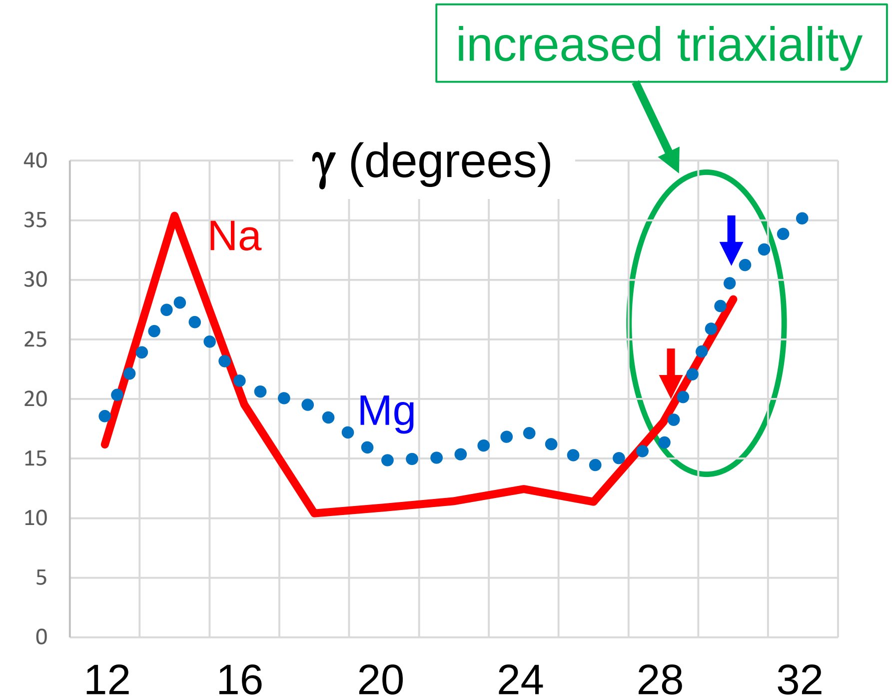
T-plots on the PES



Deformation parameters extracted from T-plot



Neutron number (N)



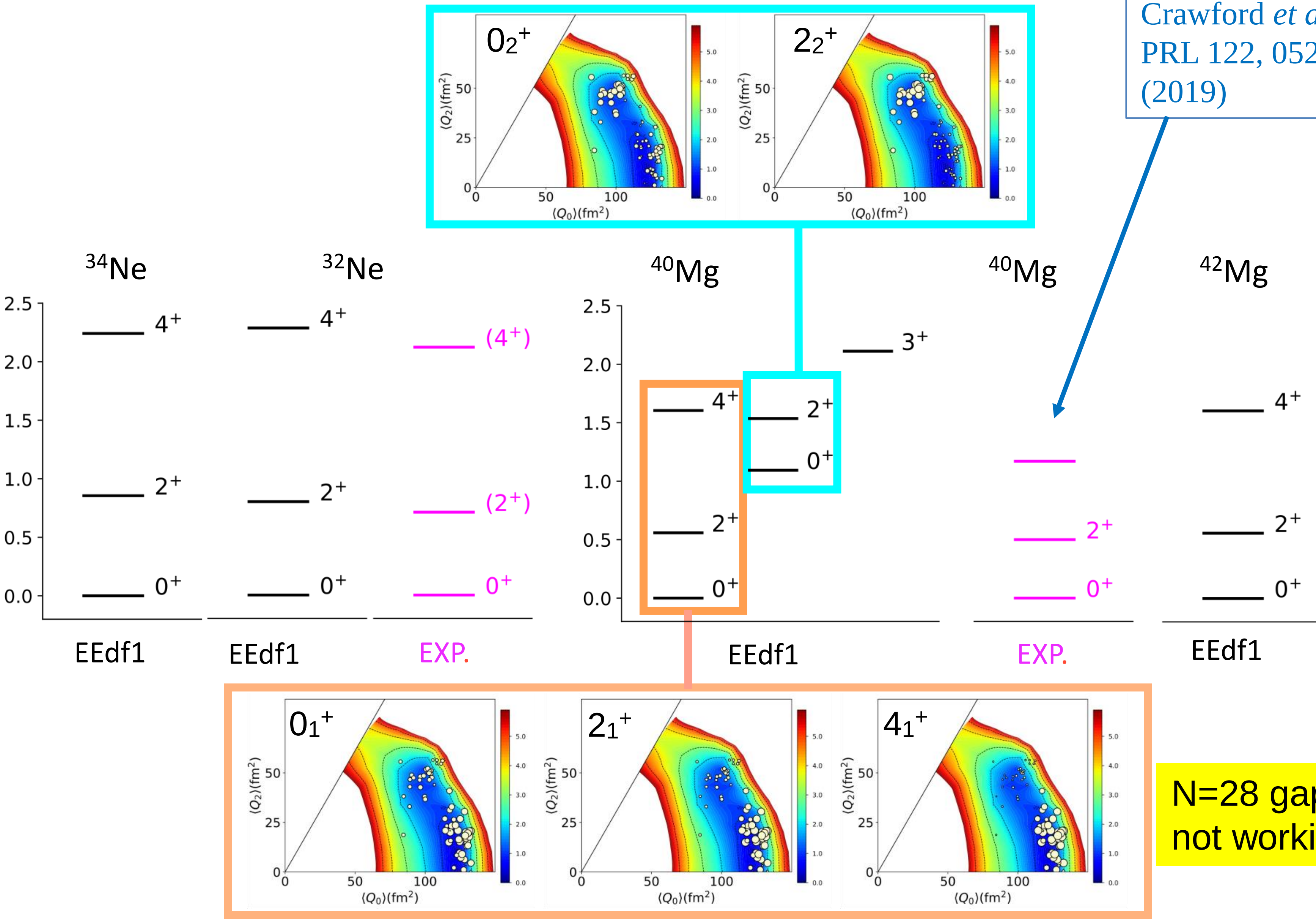
Neutron number (N)

Na
Mg
driplines

$$\beta_2 = \sqrt{5/16\pi}\,\{(e+e'_p+e'_n)/e\}\,(4\pi/3R_0^2A^{5/3})\sqrt{(Q_0)^2+2(Q_2)^2}$$

$$\gamma = \arctan\{\sqrt{2}\,Q_2/Q_0\}$$

Shape coexistence near dripline



Crawford *et al.*, PRL 122, 052501 (2019)

N=28 gap is not working

Summary

0. Correlation energies can be crucial to driplines.

1. There are, at least, two dripline mechanisms:
   one with a single-particle origin, while the other due to the interplay between the monopole and quadrupole (deformation) effects.

2. The driplines of F, Ne, Na and Mg isotopes follow the new mechanism.
   Two mechanisms may appear alternatively as Z increases further.

3. Those isotopes are described well by the EEdf1 interaction derived in an *ab initio* way.

4. These isotopes remain deformed up to dripline.
   Neutrons are still well bound as single particles (except for F isotopes).

   The magnitude of the deformation energy decreases around driplines.
   Monopole compensation per ΔN depends on # of valence protons:
   ~ 0 MeV for F, …, -3 MeV for Mg, near driplines.
   It is stressed that this variation is a fully *ab initio* consequence.

5. Prevailing and developing triaxial shapes in nuclei towards driplines.

This talk is mainly based on

nature

Article | Published: 04 November 2020

The impact of nuclear shape on the emergence of the neutron dripline

Naofumi Tsunoda, Takaharu Otsuka, Kazuo Takayanagi, Noritaka Shimizu, Toshio Suzuki, Yutaka Utsuno, Sota Yoshida & Hideki Ueno

Nature **587**, 66–71(2020) | Cite this article

"Moments and radii of exotic Na and Mg isotopes"
TO, N. Shimizu and Y. Tsunoda
Phys. Rev. C, 105, 014319 (2022)

From a global view point, this mechanism can be interpreted :

physics

Physics 2022, 4, 258–285.
https://doi.org/10.3390/physics4010018

MDPI

Review

Emerging Concepts in Nuclear Structure Based on the Shell Model

Takaharu Otsuka [1,2,3]

THANK YOU

A development starting from chiral EFT

EKK method* to handle consistently
two (or more) major shells
-> Effective shell-model interaction
(i) without fit of two-body m. e.,
(ii) applicable to broken magicity, or
merging two shells,
both are crucial for exotic nuclei.

*) Extended Krenciglwa-Kuo method is a magic by Takayanagi

K. Takayanagi, Nucl. Phys. A 852, 61 (2011).

N. Tsunoda, **K. Takayanagi**, M. Hjorth-Jensen, and T. Otsuka, Phys. Rev. C 89, 024313 (2014).

K. Takayanagi, Annals of Physics 350, 501 (2014).

Extended KK method and conventional KK method

EKK method

New parameter E (arbitrary parameter)

$$H = H_0' + V'$$
$$= \begin{pmatrix} E & 0 \\ 0 & QH_0Q \end{pmatrix} + \begin{pmatrix} P\tilde{H}P & PVQ \\ QVP & QVQ \end{pmatrix},$$

$$H_{\rm BH}(E) = PHP + PVQ\frac{1}{E - QHQ}QVP.$$

$$\tilde{H}_{\rm eff}^{(n)} = \tilde{H}_{\rm BH}(E) + \sum_{k=1}^{\infty} \hat{Q}_k(E)\{\tilde{H}_{\rm eff}^{(n-1)}\}^k,$$

KK method (conventional)

Krenciglwa and Kuo (1971)

Divergence problem in multi-shell

$$H = H_0 + V$$
$$= \begin{pmatrix} PH_0P & 0 \\ 0 & QH_0Q \end{pmatrix} + \begin{pmatrix} PVP & PVQ \\ QVP & QVQ \end{pmatrix}$$

$$\hat{Q}(E) = PVP + PVQ\frac{1}{E - QHQ}QVP$$

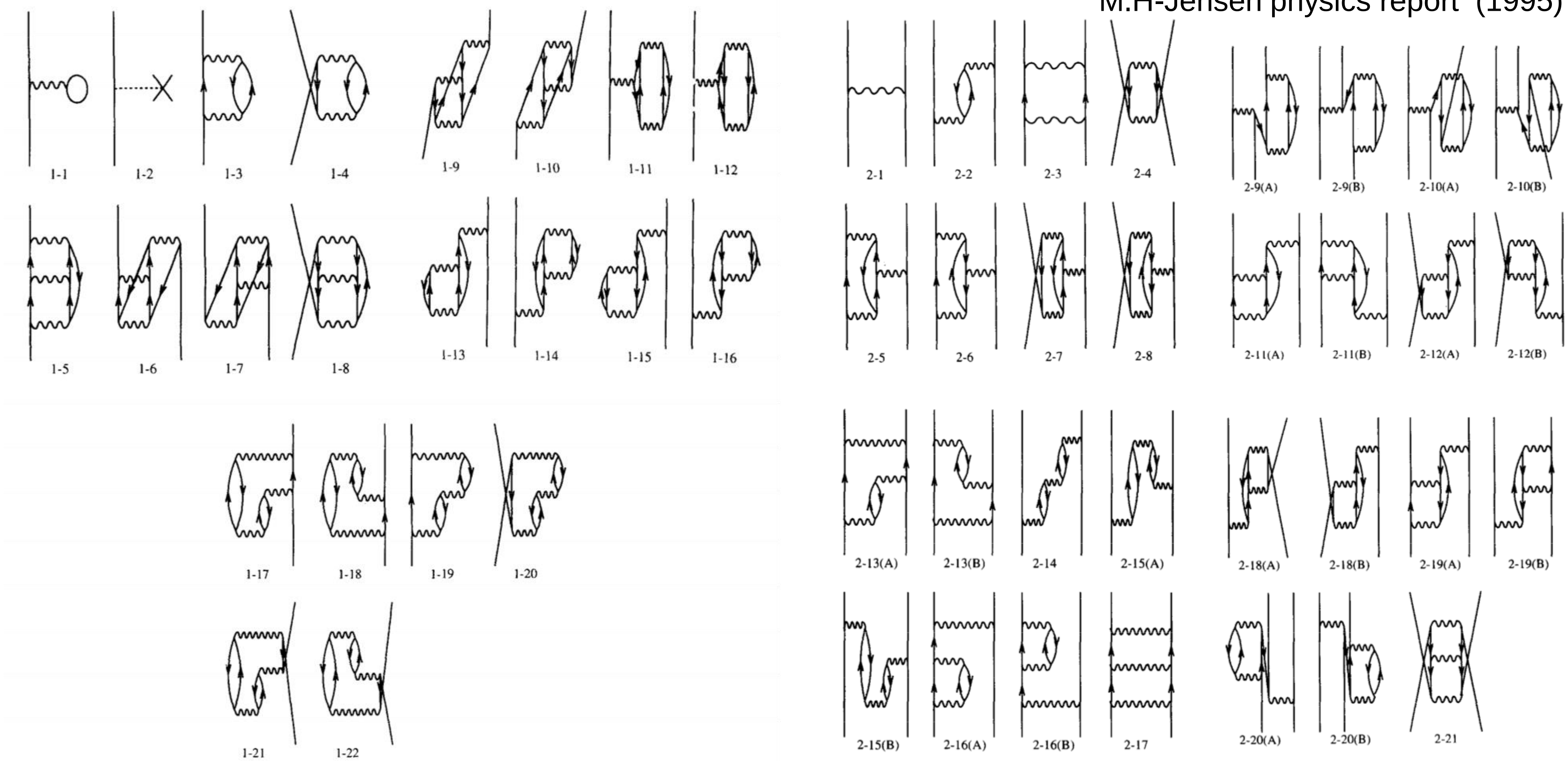
$$V_{\rm eff}^{(n)} = \hat{Q}(\epsilon_0) + \sum_{k=1}^{\infty} \hat{Q}_k(\epsilon_0)\{V_{\rm eff}^{(n-1)}\}^k.$$

- EKK method enables us to construct effective interaction for multi-major shell

N. Tsunoda, K. Takayanagi, M. Hjorth-Jensen, and T. Otsuka, Phys. Rev. C 89, 024313 (2014).
K. Takayanagi, Annals of Physics 350, 501 (2014).
K. Takayanagi, Nucl. Phys. A 852, 61 (2011).

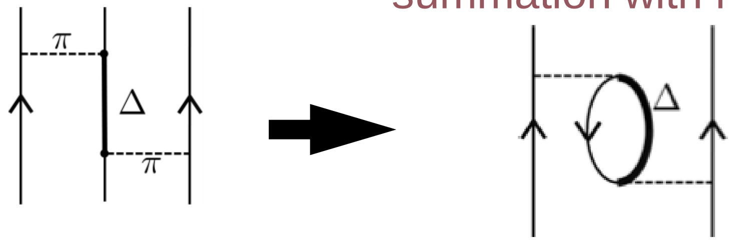
Many-body perturbation theory

M.H-Jensen physics report (1995)



Fujita-Miyazawa type
3N interaction

summation with hole state



Effective
2N interaction

T-plot : visualization of MCSM eigenvector on Potential Energy Surface

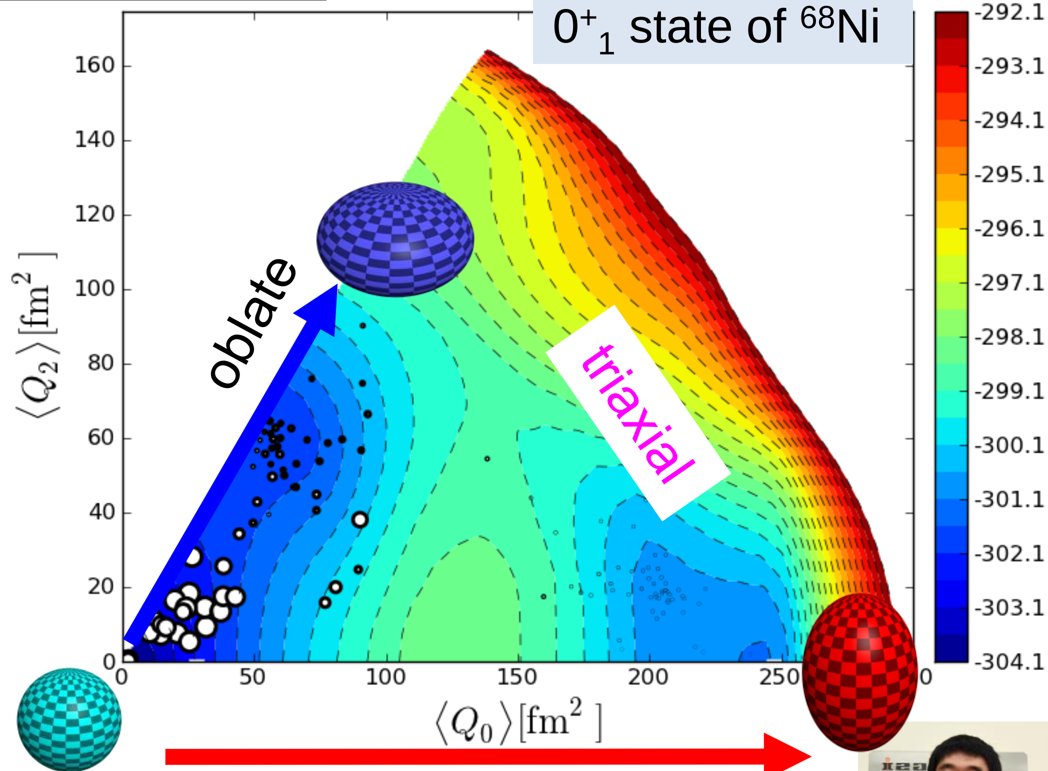
eigenstate $\Psi = \sum_i c_i P[J^\pi] \Phi_i$

stochastically deformed Slater determinant
→ intrinsic shape

amplitude

projection onto J^π

- PES is calculated by CHF for the shell-model Hamiltonian
- Location of circle : quadrupole deformation of unprojected MCSM basis vectors
- Area of circle : overlap probability between each projected basis and eigen wave function



Y. Tsunoda, *et al.*
PRC 89, 031301 (R) (2014)