MCD2022 – 5th week
Yukawa Institute
June 7 (6-10), 2022

Structure evolutions towards neutron driplines

Takaharu Otsuka

N. Tsunoda, T. Takayanagi, N. Shimizu, T. Suzuki, Y. Utsuno, H. Ueno
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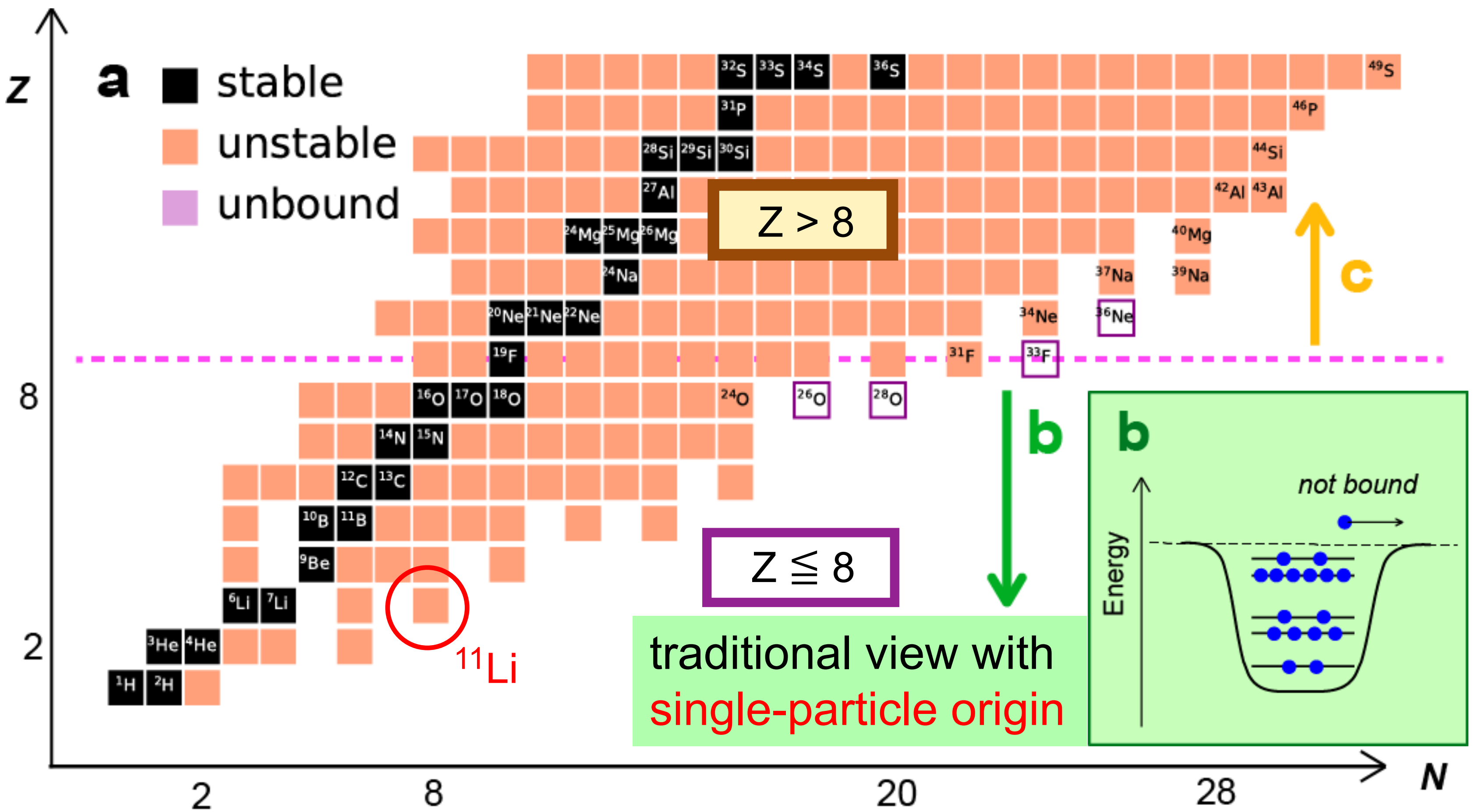
JICFuS　東京大学 THE UNIVERSITY OF TOKYO　RIKEN NiSHiNA CENTER　JAEA

This work was supported also by MEXT as "Program for Promoting Researches on the Supercomputer Fugaku" (Simulation for basic science: from fundamental laws of particles to creation of nuclei) and "Priority Issue on post-K computer" (Elucidation of the Fundamental Laws and Evolution of the Universe), and by JICFuS.

Neutron driplines : traditional view (somewhat vague)



Neutron halo appears in some cases.

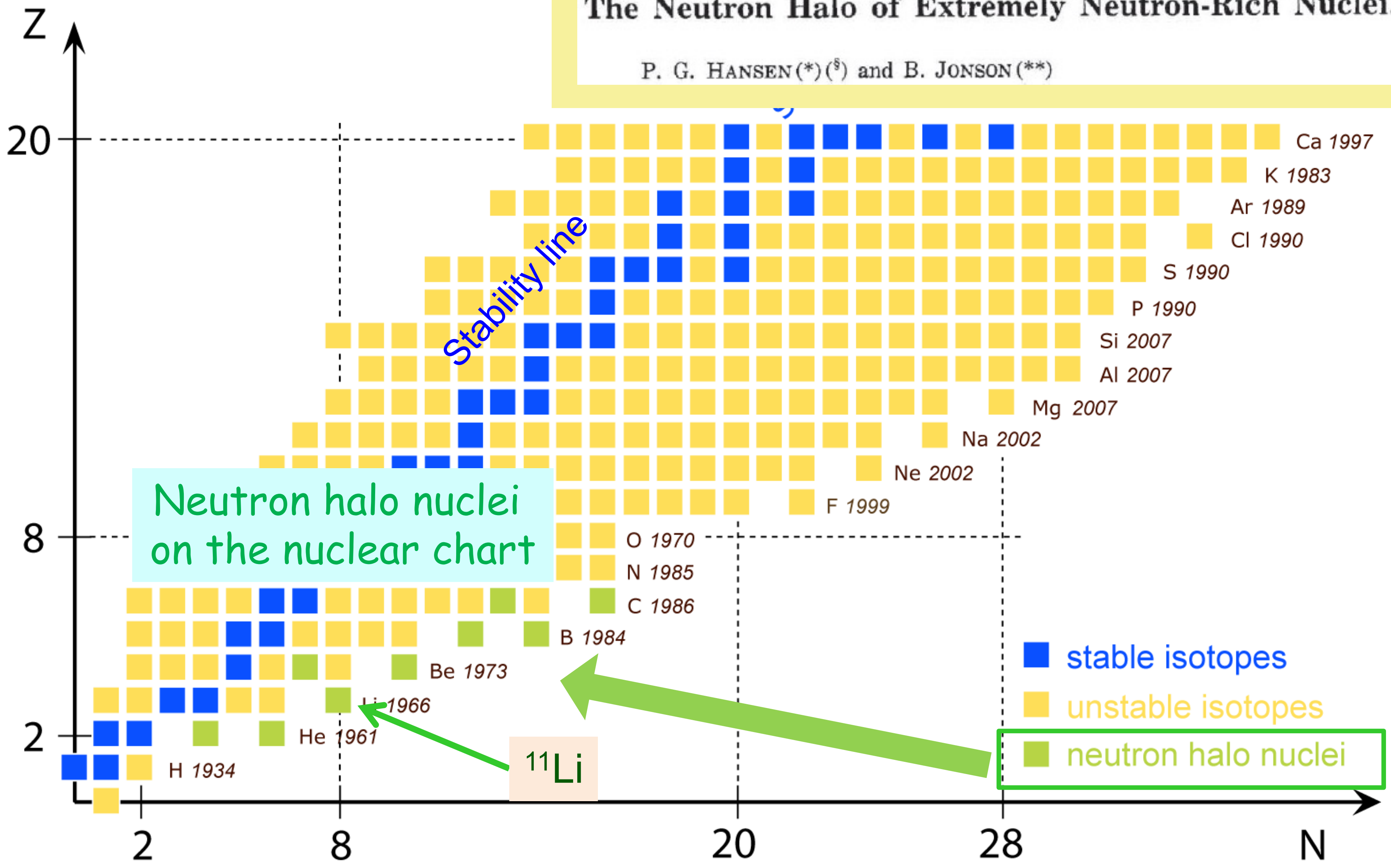
The large radius is due to neutron halo, a tunneling of loosely bound neutrons.

EUROPHYSICS LETTERS

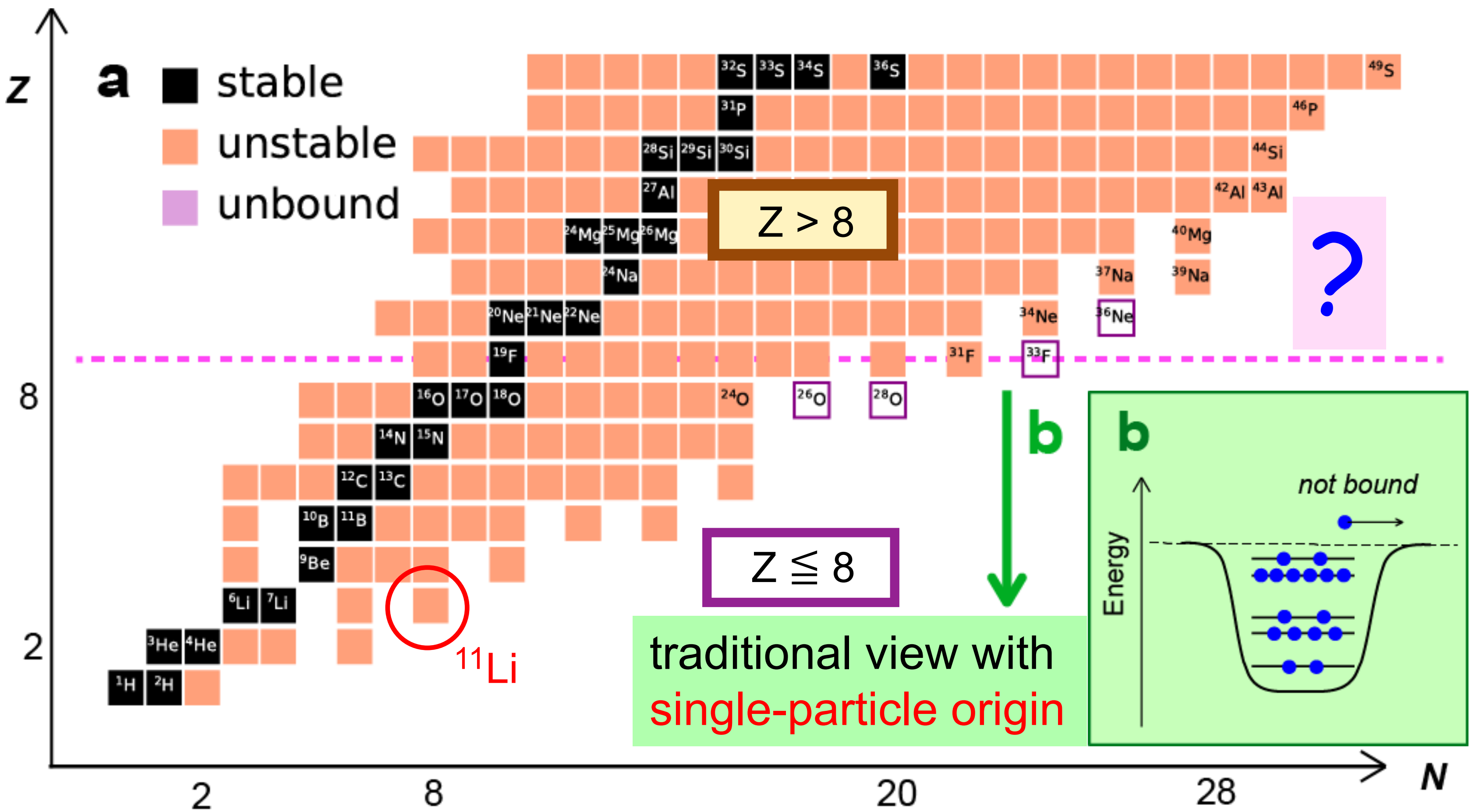
Europhys. Lett., 4 (4), pp. 409-414 (1987)

The Neutron Halo of Extremely Neutron-Rich Nuclei.

P. G. HANSEN (*) (§) and B. JONSON (**)



Neutron driplines in heavier elements and the nuclear structure there



Neutron halo appears in some cases.

This talk is mainly based on

nature

Article | Published: 04 November 2020

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

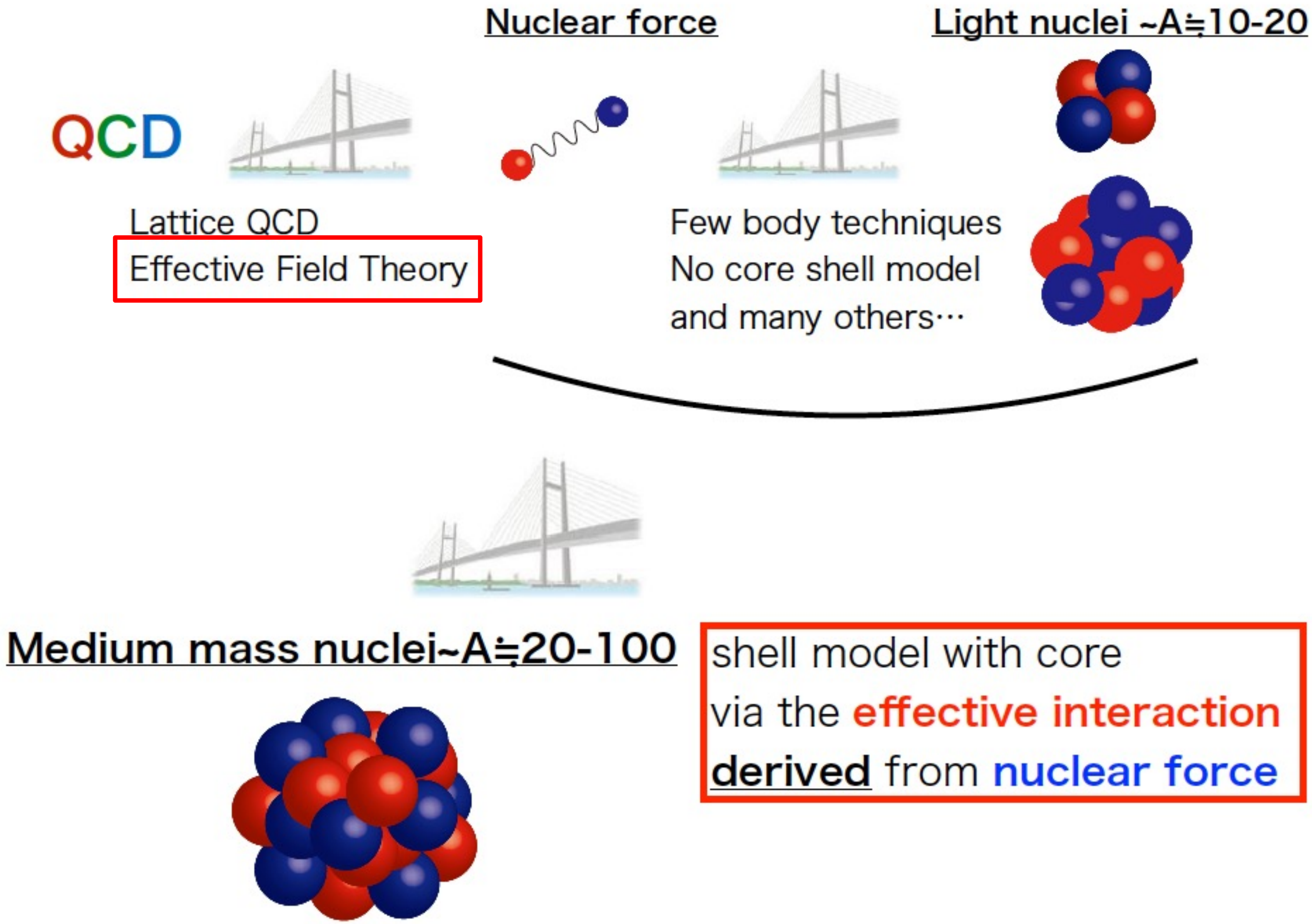
Naofumi Tsunoda, Takaharu Otsuka, Kazuo Takayanagi, Noritaka Shimizu, Toshio Suzuki, Yutaka Utsuno, Sota Yoshida & Hideki Ueno

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

PHYSICAL REVIEW C **105**, 014319 (2022)

Moments and radii of exotic Na and Mg isotopes

Takaharu Otsuka,[1,2,3,*] Noritaka Shimizu,[4] and Yusuke Tsunoda[4]

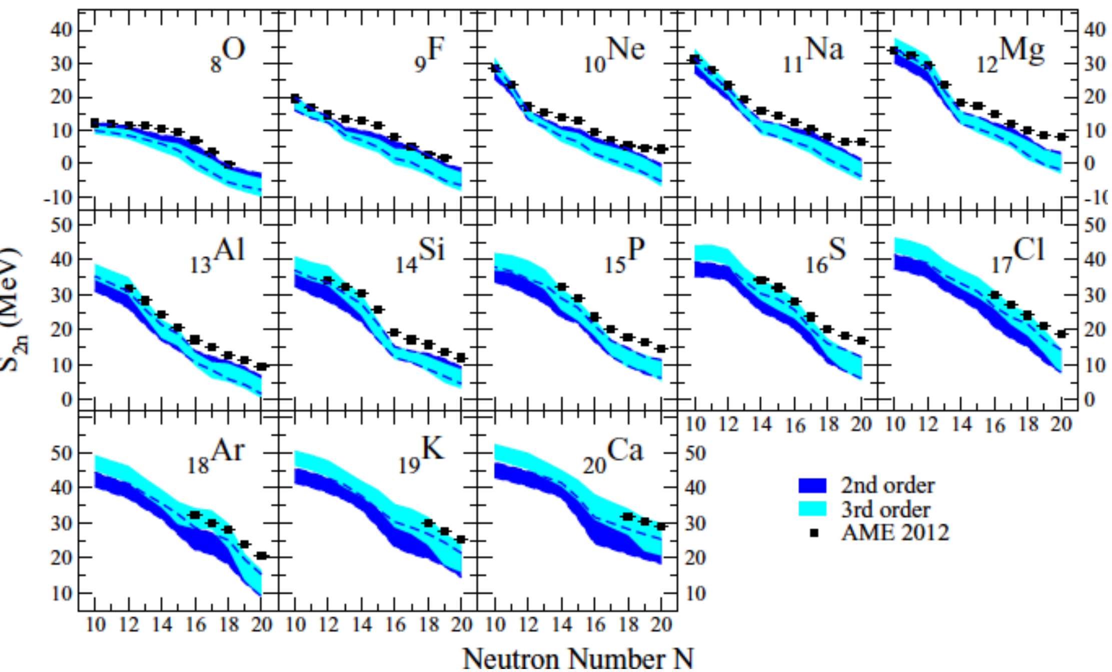


Courtesy from N. Tsunoda

Examples of structure calculations starting from chiral EFT forces

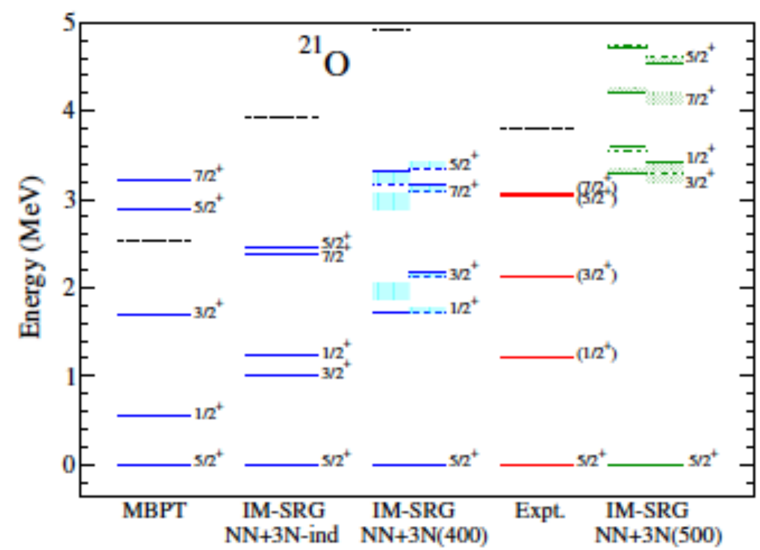
NN force: N3LO + 3N force: N2LO
-> valence shell interaction

MBPT
(Many-body Perturbation Theory)
applicable to one major shell



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

IM-SRG
(In-Medium Similarity Renormalization Group)



Bogner et al. PRL 113, 142501 (2014)

+ Coupled Cluster calculation + N2LOsat potential + ….

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)

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

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

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

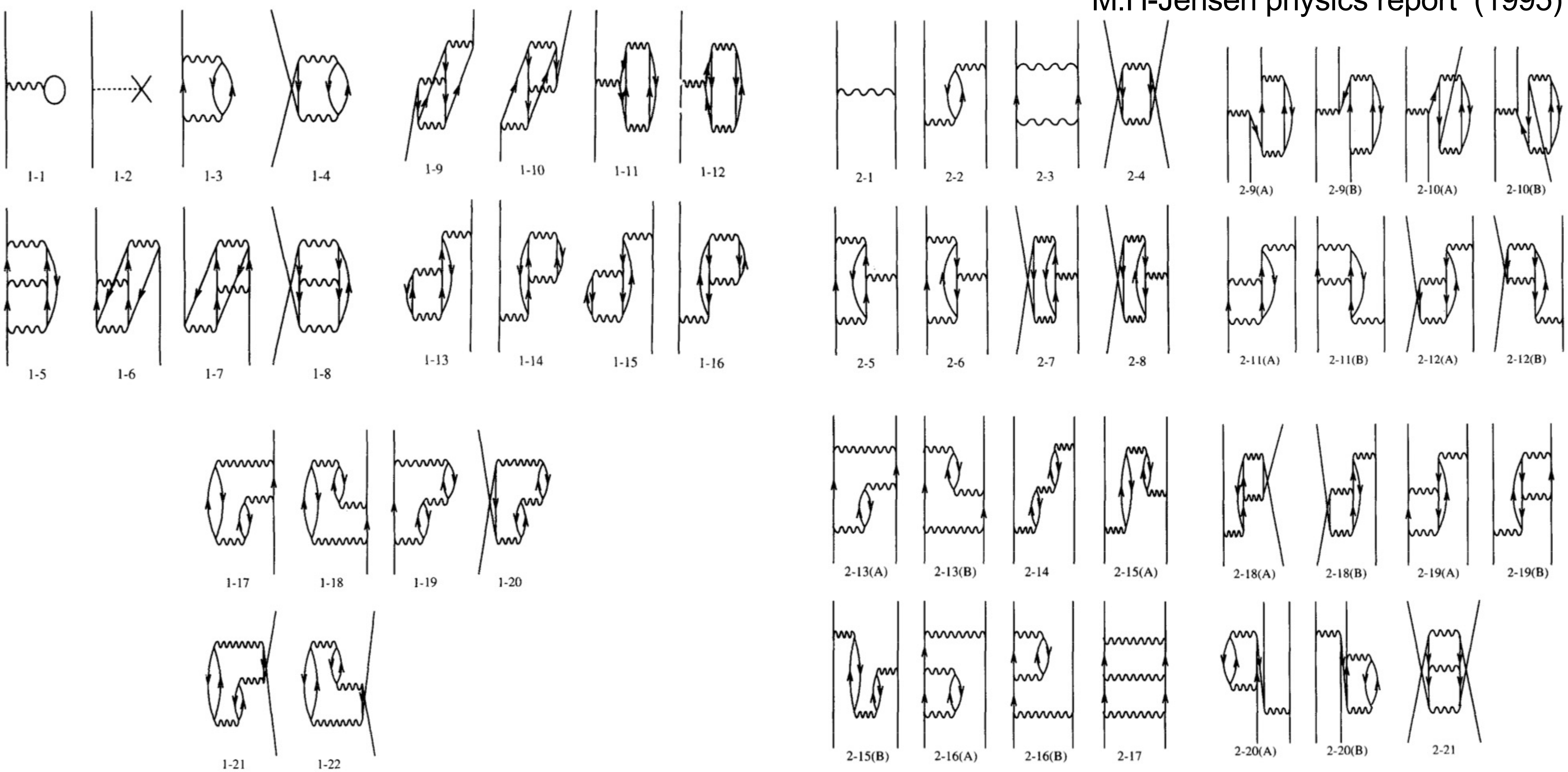
$$V_{\rm eff}^{(n)} = \hat{Q}(\epsilon_0) + \sum_{k=1}^{\infty} \hat{Q}_k(\epsilon_0)\{V_{\rm eff}^{(n-1)}\}^k.$$

- **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).

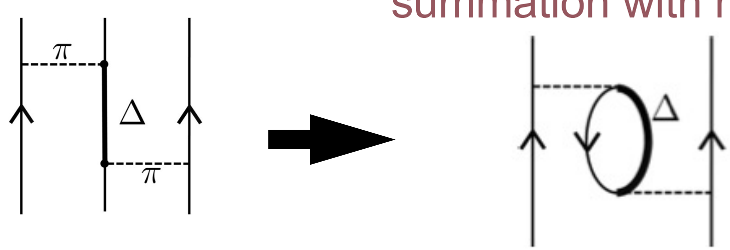
Many-body perturbation theory

M.H-Jensen physics report (1995)



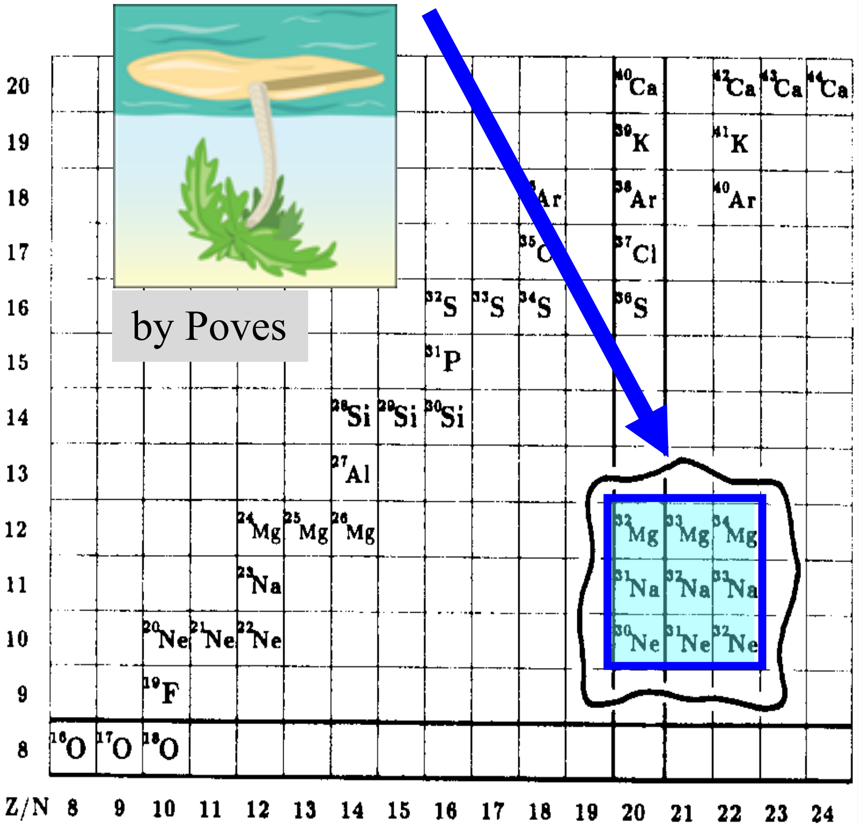
Fujita-Miyazawa type
3N interaction

summation with hole state



Effective
2N interaction

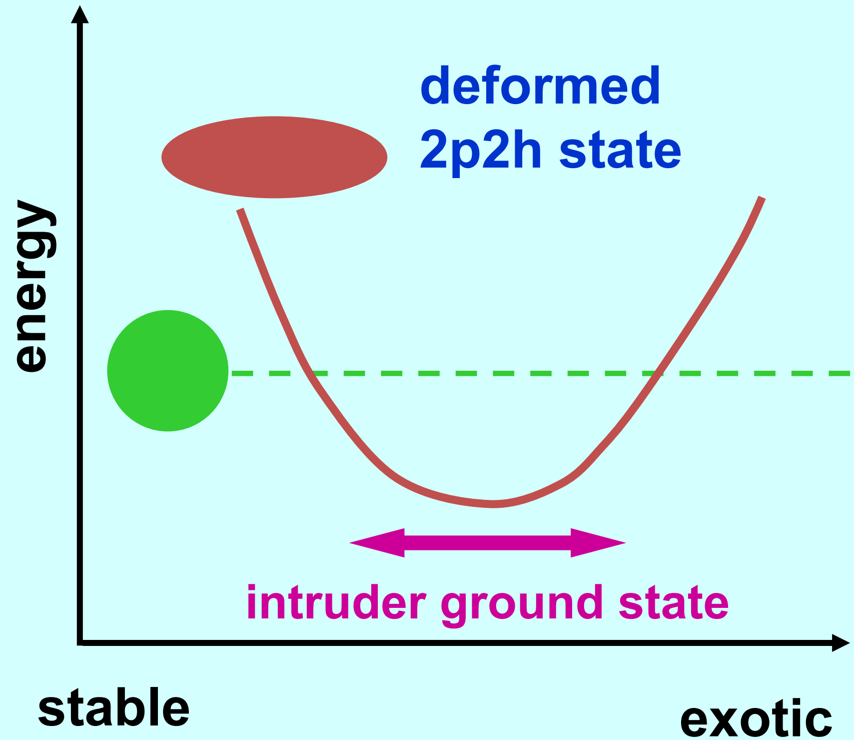
Island of Inversion

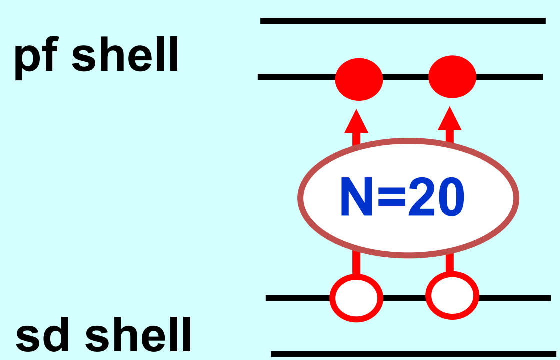


9 nuclei:
Ne, Na, Mg with N=20-22

Phys. Rev. C 41, 1147 (1990), Warburton, Becker and Brown

Traditional picture





gap ~ constant

Anomaly in energy levels : not expected from a magicity

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

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M. DE SAINT-SIMON, C. THIBAULT and F. TOUCHARD

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BP 1, F-91406 Orsay, France

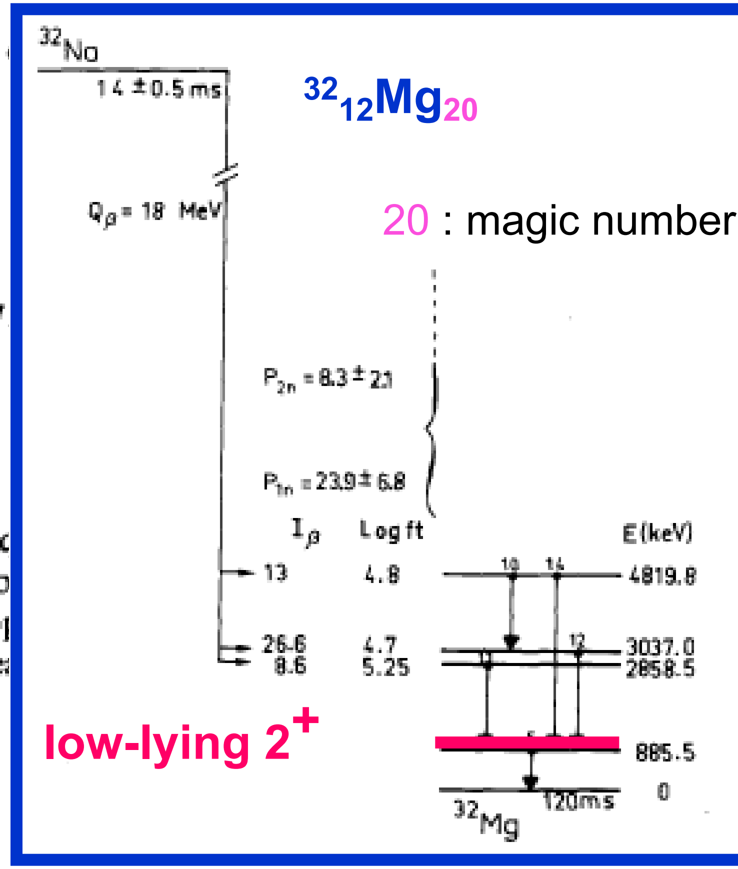
and

M. EPHERRE

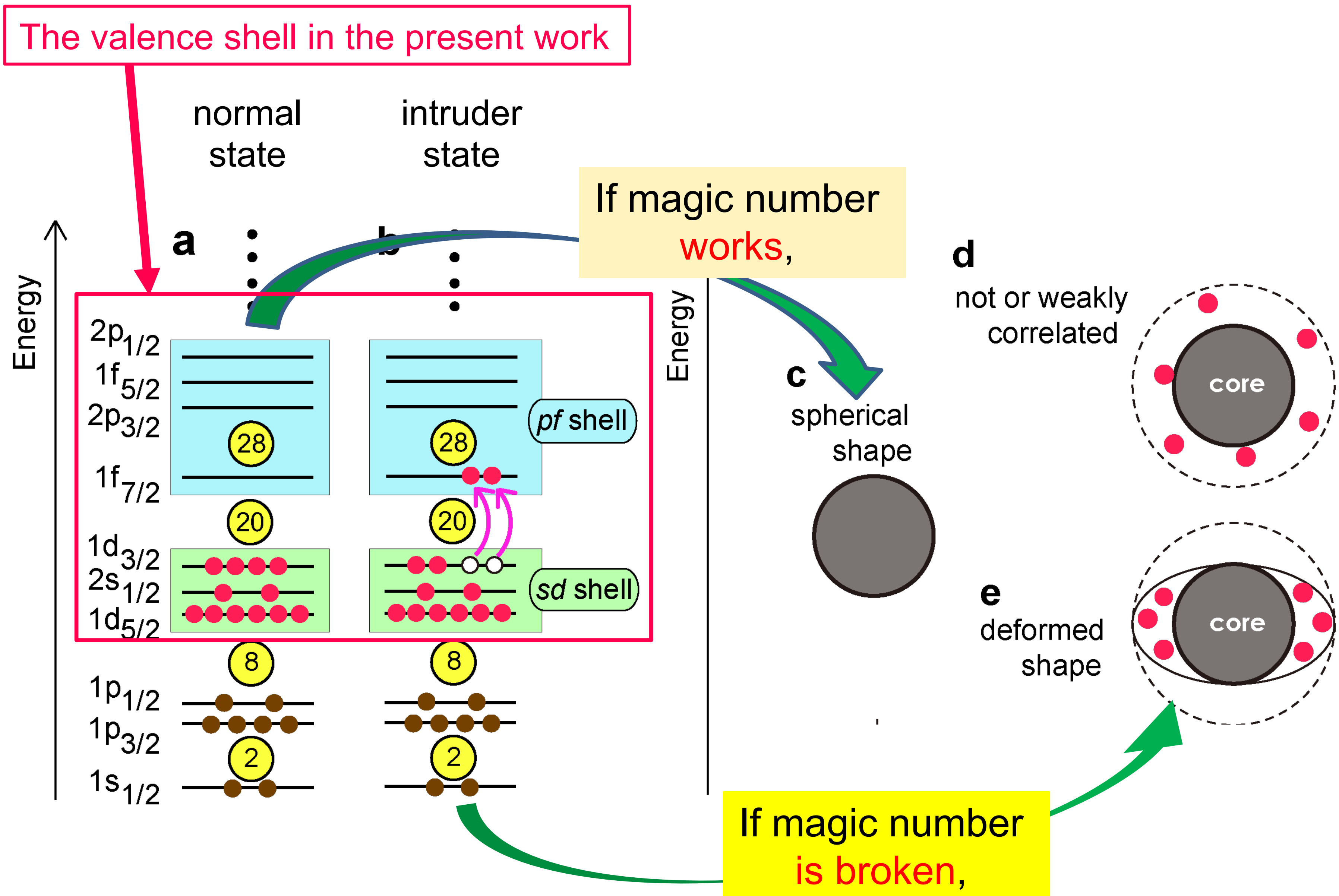
Laboratoire René Bernas and CERN, Division EP, CH-121

Received 6 February 1984

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

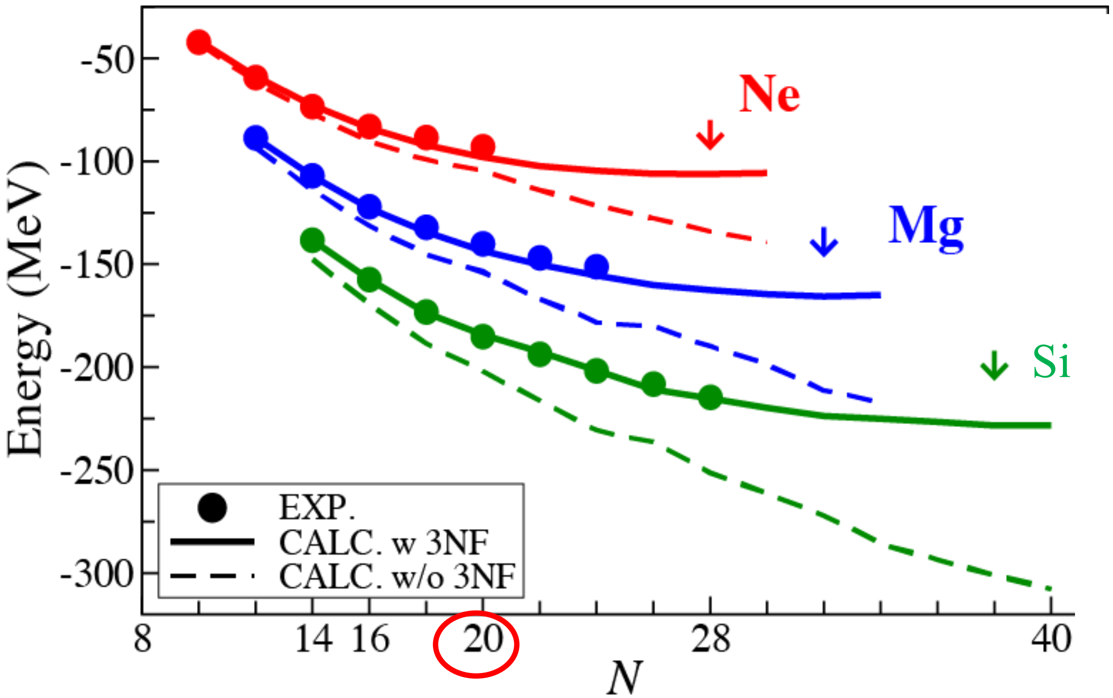


Relation to the magic number N=20 and the present valence shell



ground-state energies

Earlier (2017 PRC) work by EEdf1



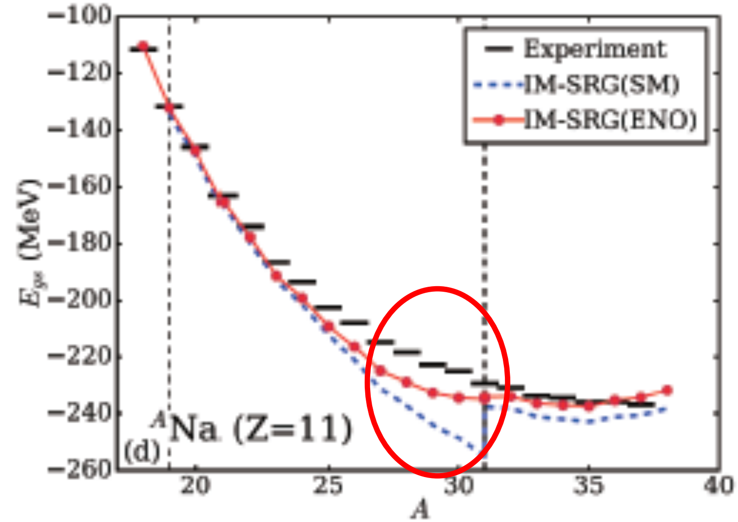
Calculations with full sd + pf shell

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

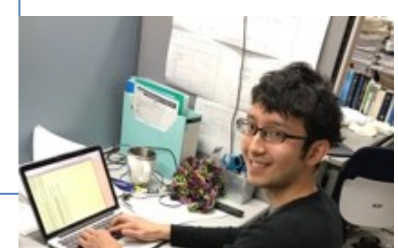
Exotic neutron-rich medium-mass nuclei with realistic nuclear forces

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

Earlier *ab initio* work on Na isotopes



IM-SRG (SM) : core reference
IM-SRG (ENO) : ensemble reference
Stroberg et al. PRL 118, 032502 (2017)



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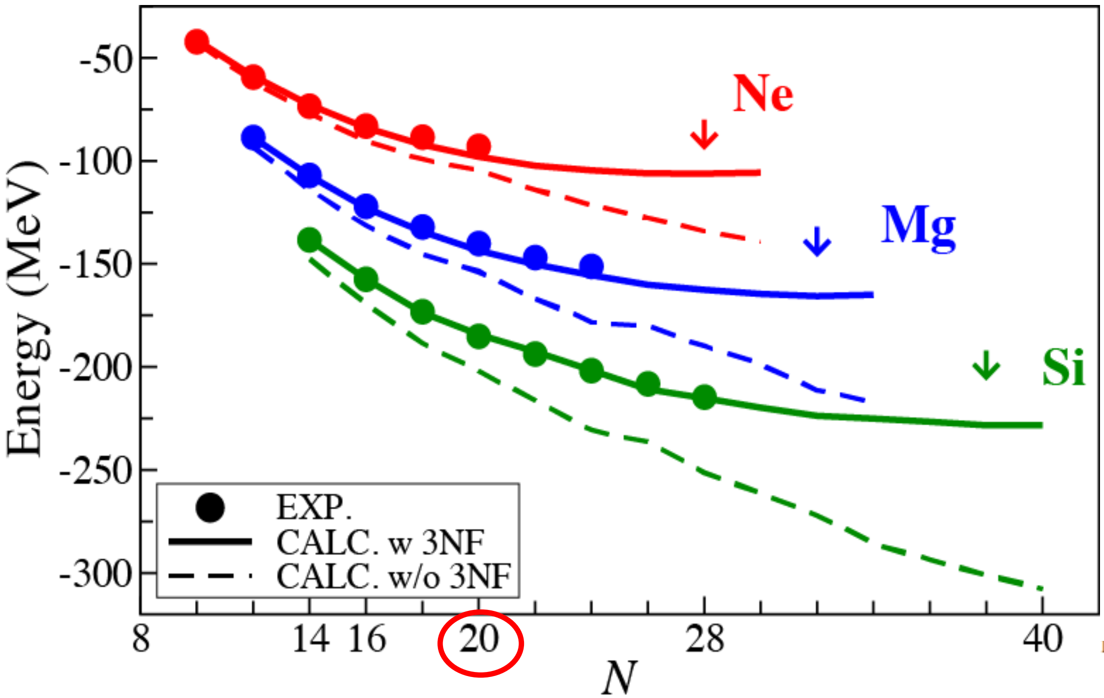
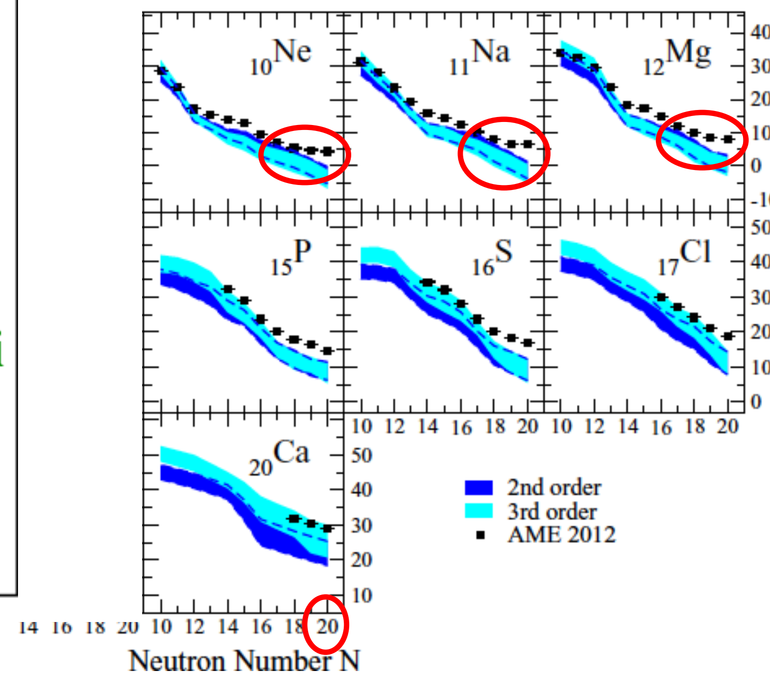
Earlier (2017 PRC) work by EEdf1



Earlier work



Calculations with full sd + pf shell

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

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

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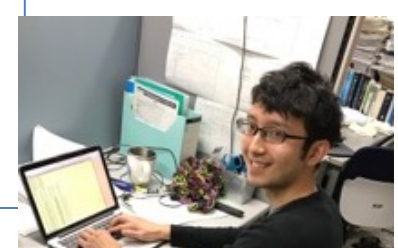
Kazuo Takayanagi,[7] and Toshio Suzuki[8]

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



Earlier (2017 PRC) work by EEdf1

Ne-Mg-Si

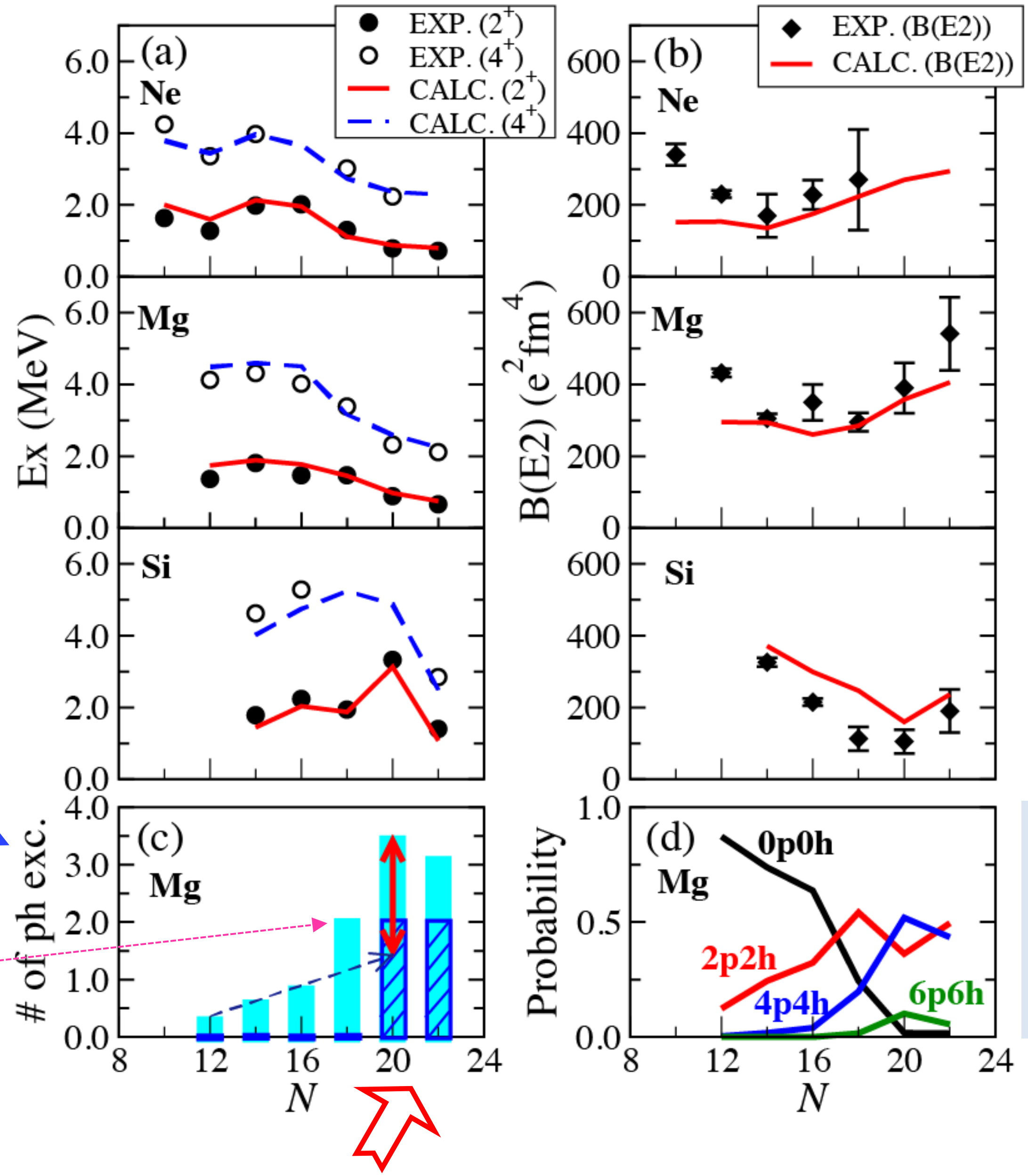
2^+ & 4^+ levels and B(E2) values

# of particle-hole excitations across N=20 gap :

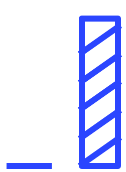
(modest) steady increase

\+

abrupt increase after N=18



ground states of Mg isotopes



Early idea of the Island of Inversion (WBB)

0p-0h or 2p-2h (discrete)

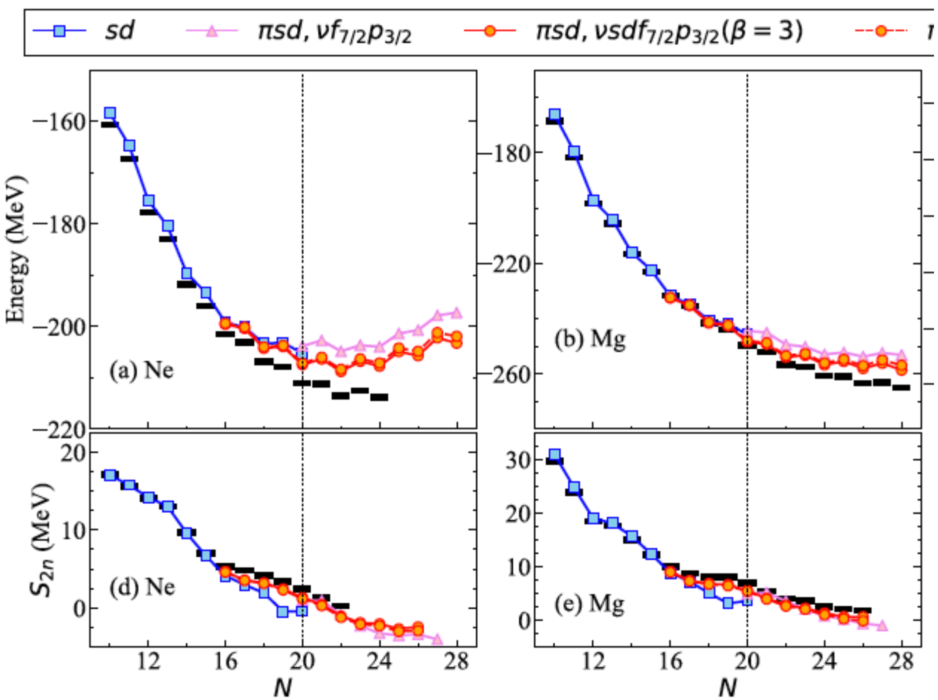
Recent *ab initio* calculation (IM-SRG)

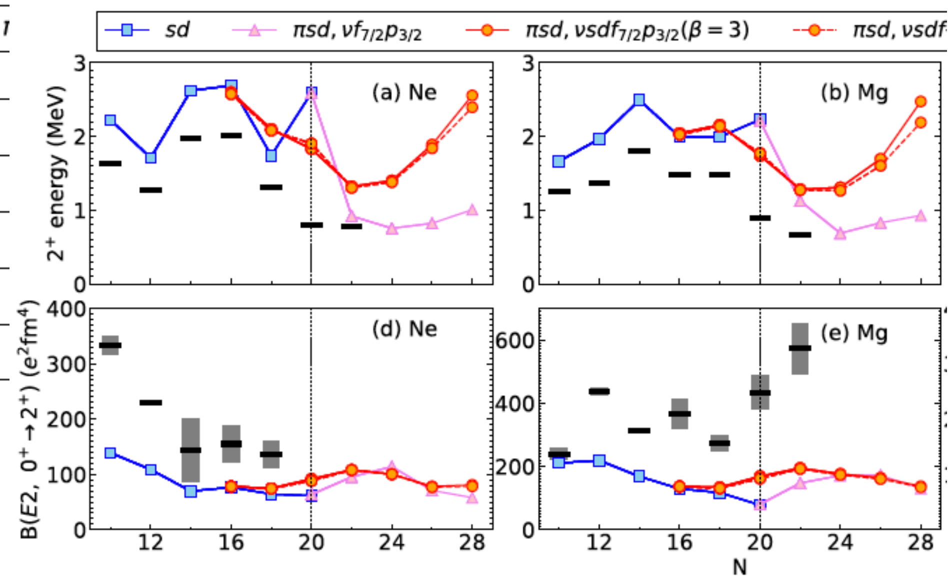
PHYSICAL REVIEW C **102**, 034320 (2020)

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]

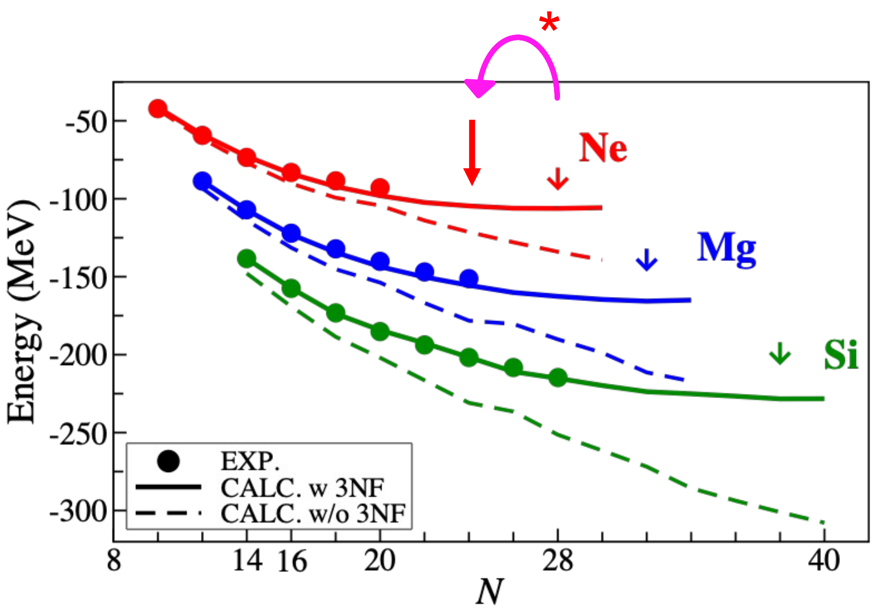




Large deformation seems to be a challenge.

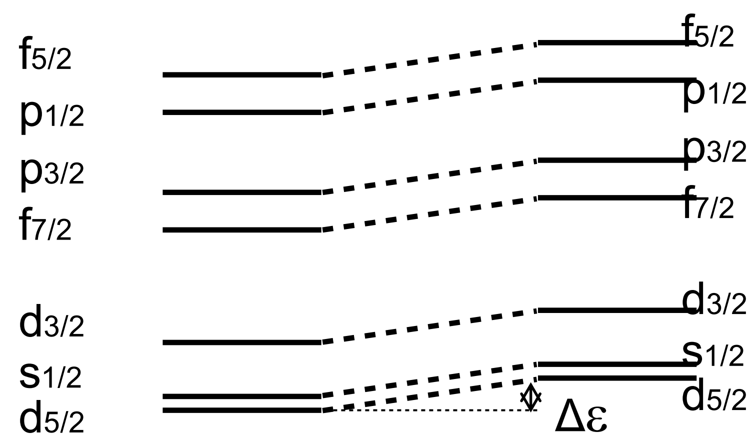
Dripline mechanism

Our earlier (2017) calculation was not perfect; fine-tuning of SPEs for EEdf1 is done



Tsunoda, *et al*. Phys. Rev. C 95, 021304 (2017).

- We fine-tuned the SPEs to reproduce recent experimental findings*.



$0.82 < \Delta\varepsilon < 0.87$ is needed

*

PHYSICAL REVIEW LETTERS 123, 212501 (2019)

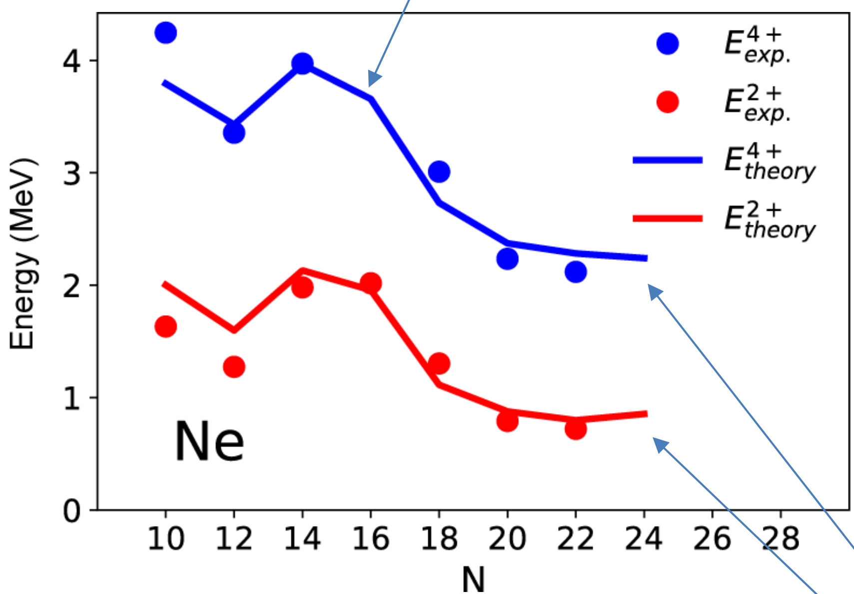
Editors' Suggestion | Featured in Physics

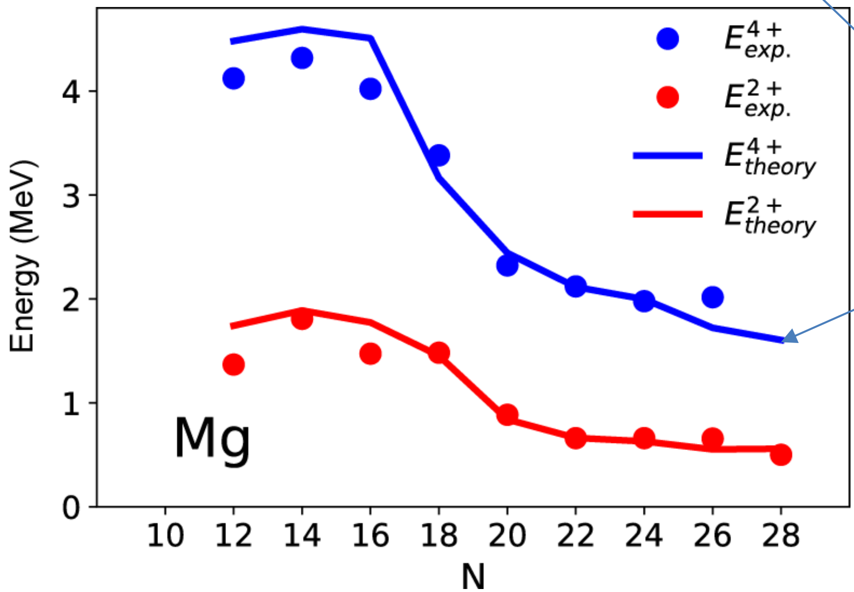
Location of the Neutron Dripline at Fluorine and Neon

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]

^{31}F and ^{34}Ne are dripline nuclei,
+
1 event of ^{39}Na

Ne and Mg systematics





Δε changes neither excitation energies nor wave functions.

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

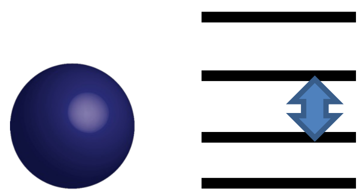
Levels do not exist as bound states, because their energies are above the threshold of neutron emission.

Decomposition of the Hamiltonian

monopole part

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

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



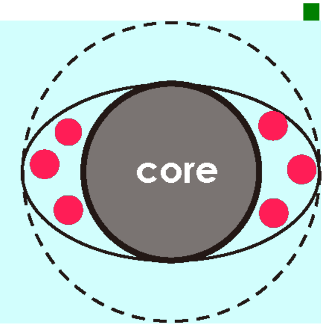
monopole: shift of SPE

multipole part

pairing J=0 nn + pp pairing correlations

rest quadrupole deformation, *etc*

deformed shape



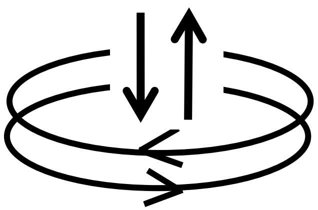
Pairing interaction

*Pairing interaction

$<j_1^2\ J=0|V|j_2^2\ J=0>$ $\quad j_1^2 = j_1 \times j_1$

in T=1 channel

(identical particles)

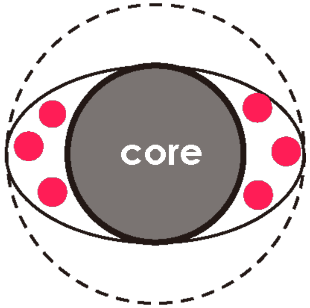


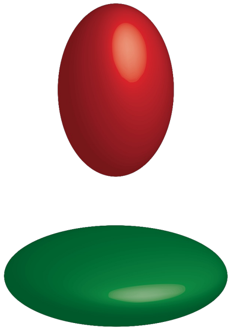
time reversal states
-> strong attraction

Rest of the interaction

major effect ~ quadrupole shape deformation

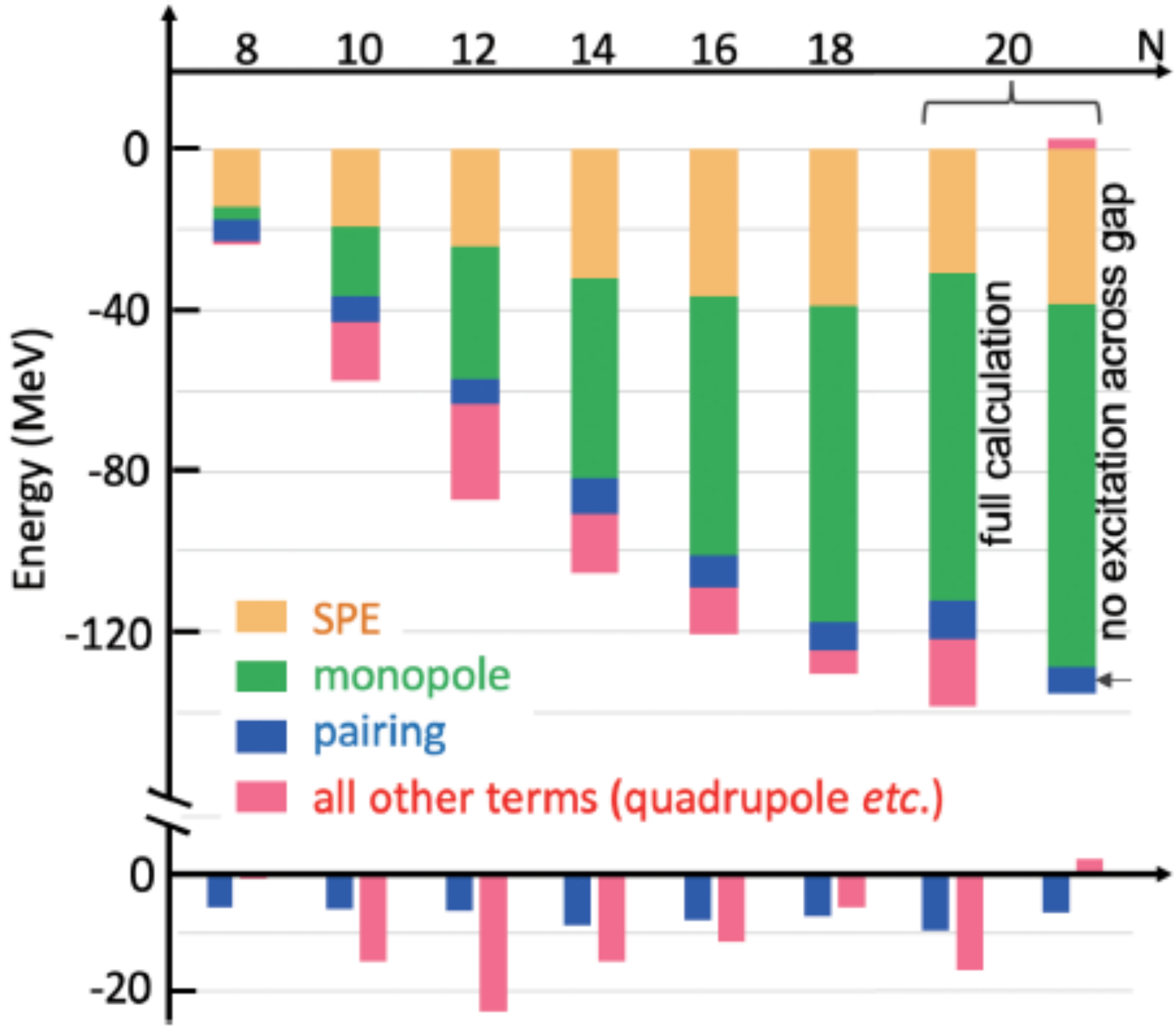
deformed shape





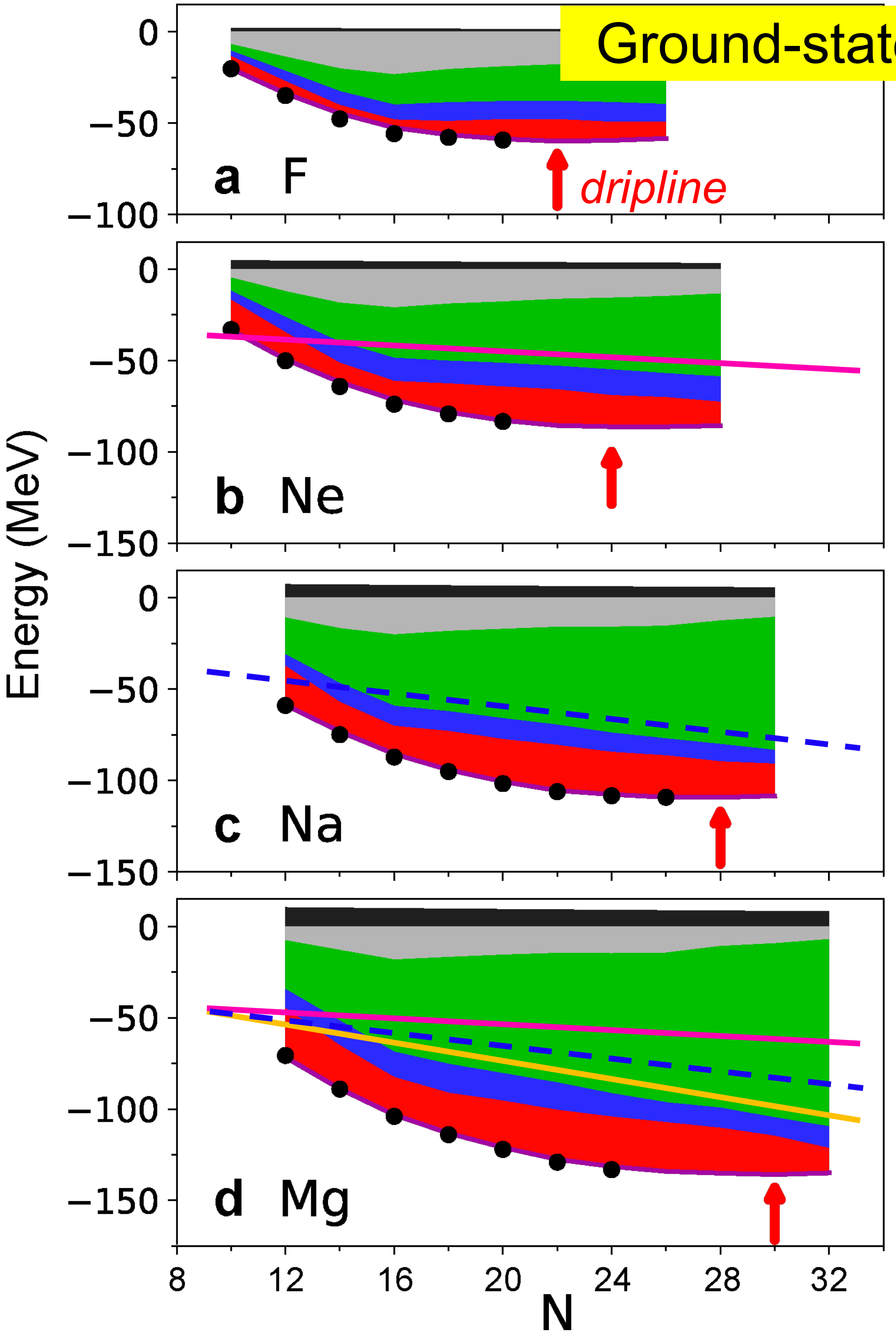
Ground-state energies of Mg isotopes up to N=20 (USD int. up to N=18)

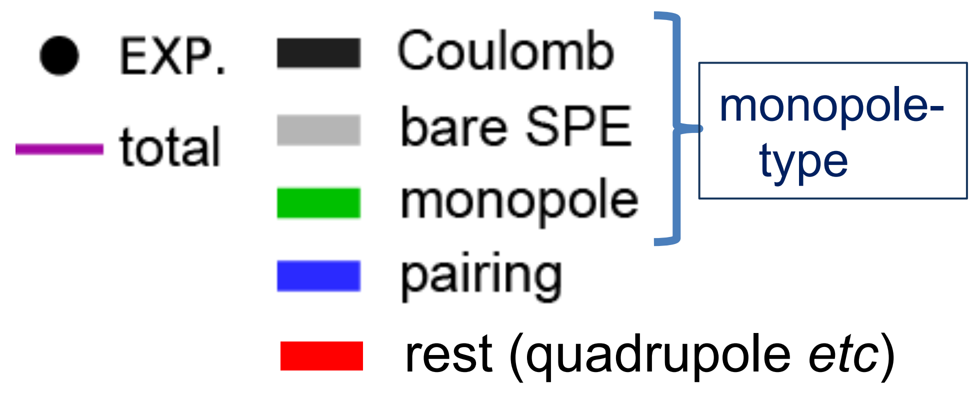
Otsuka *et al.*: RMP 92, 015002 (2020)



sdpf-m int.
for N=20

Ground-state energy is decomposed (EEdf1 int.)



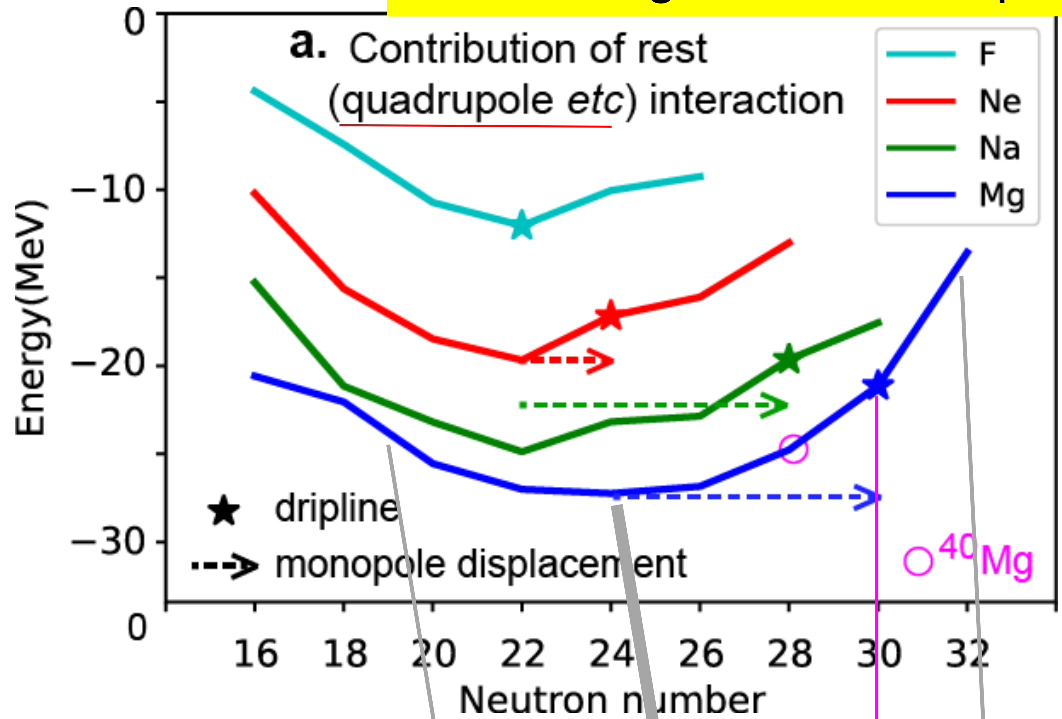


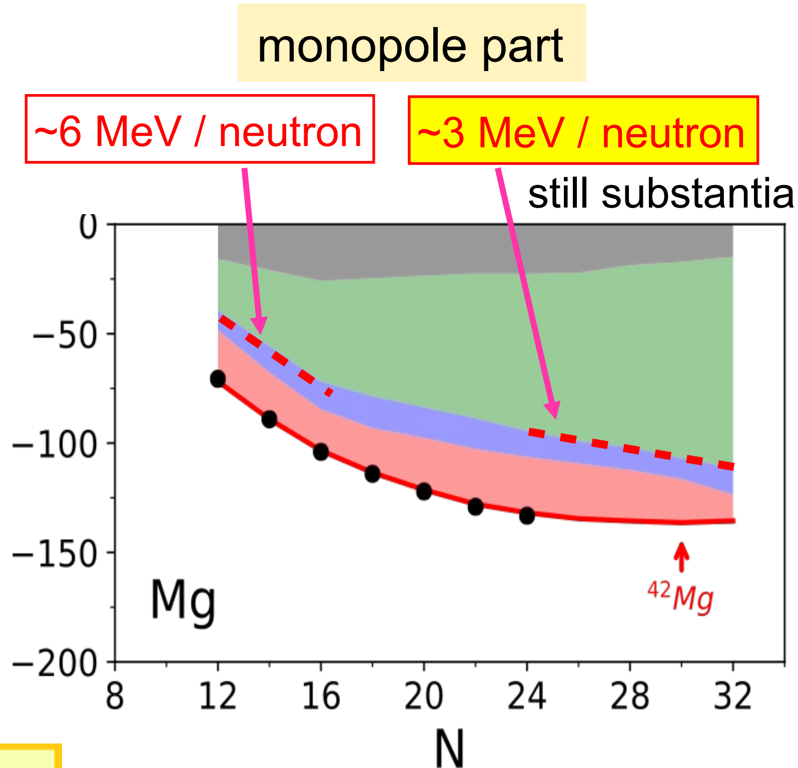
The monopole effect (lower edge of green part) lowers the energy as a function of *N*, and its slope becomes steeper as *Z* because of the p-n monopole int., as shown by three lines fitted to different slopes.

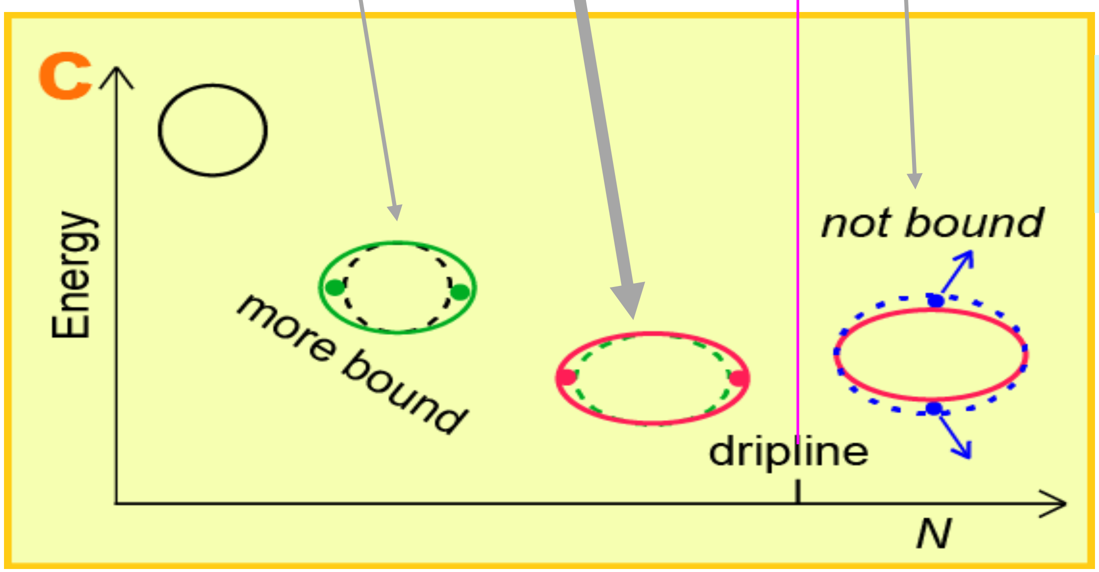
The rest (~quadrupole deformation) effect (red part) varies locally.

… see next page

Two driving forces: example from Mg isotopes



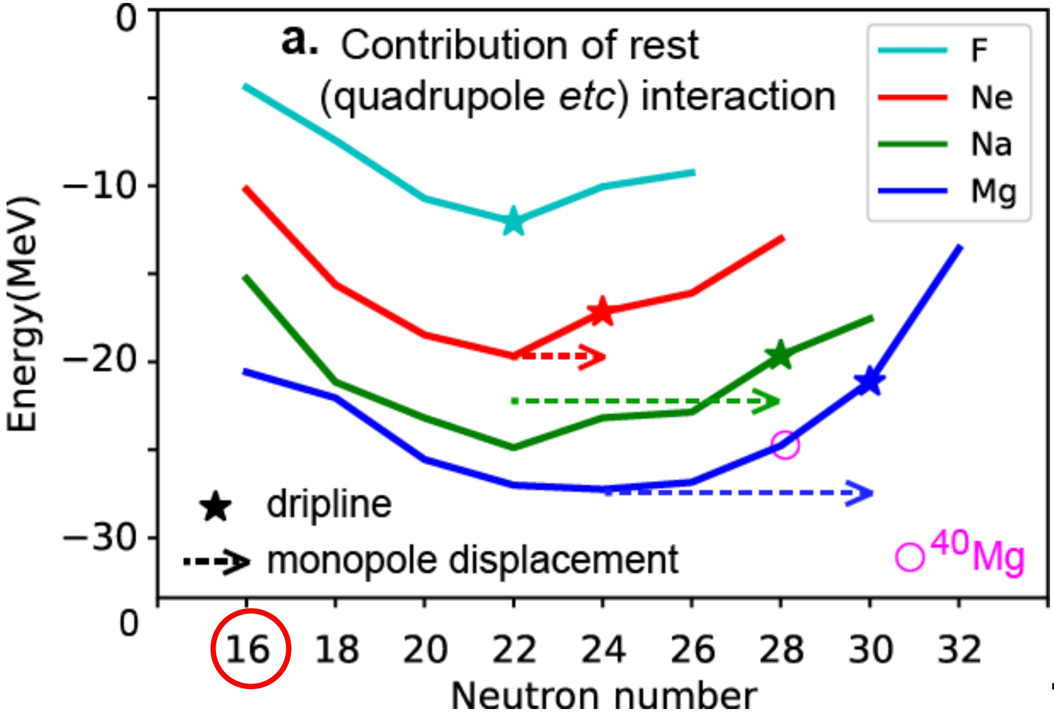


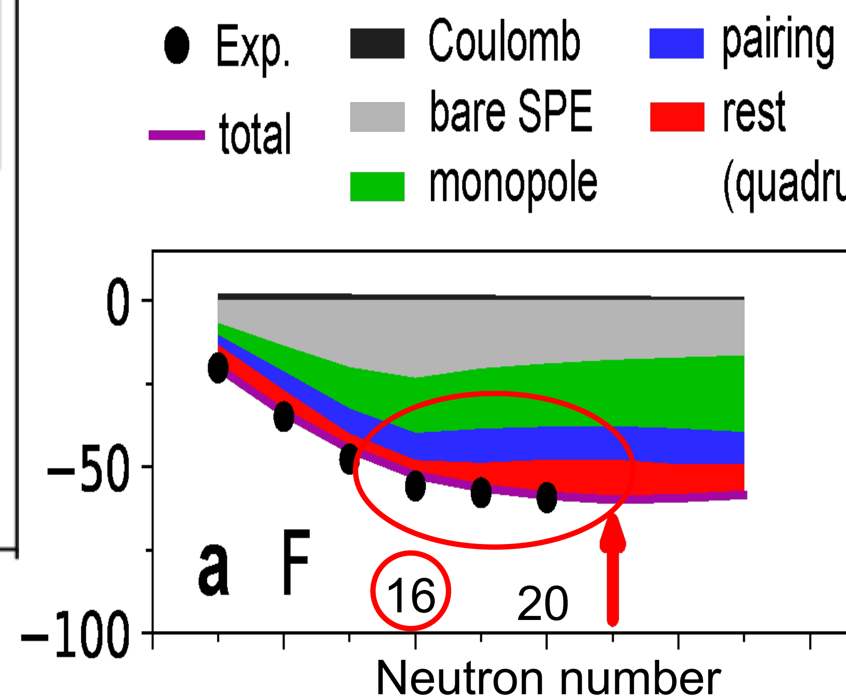


The rest (mainly deformation energy) part is saturated at N=24.

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

Dripline of F isotopes



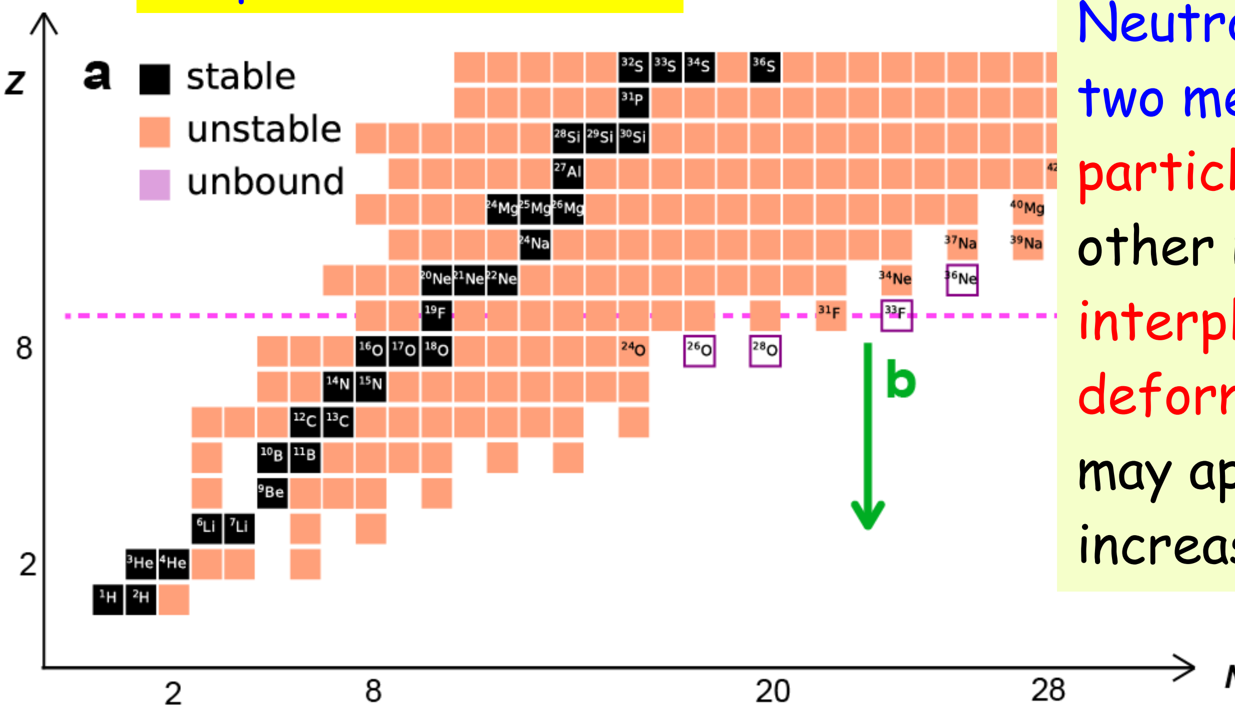


Monopole effect (edge of green part) becomes weaker for N > 16 in F isotopes. It even decreases because of high-lying d3/2 (see gray edge).

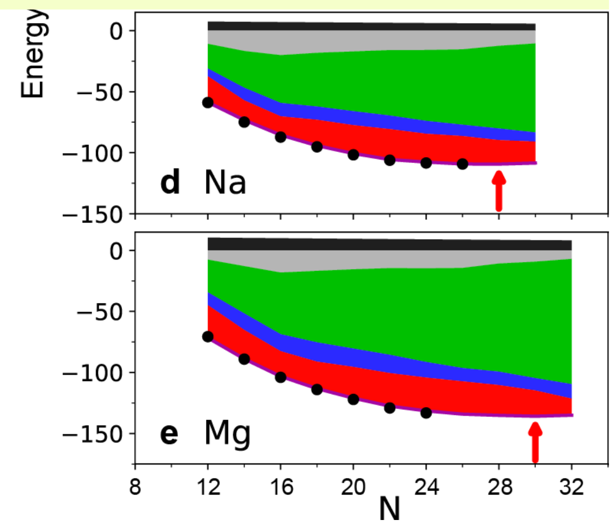
If there were no "rest" (~ quadrupole deformation) effect (red part), the dripline would be at N = 16, which is the same as oxygen isotopes.

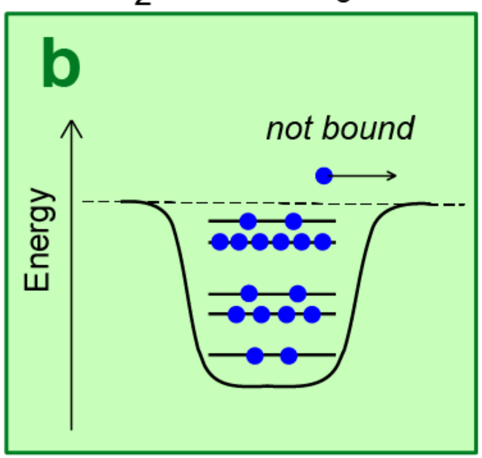
Loose binding phenomena may be seen (?), in contrast to Ne, Na or Mg.

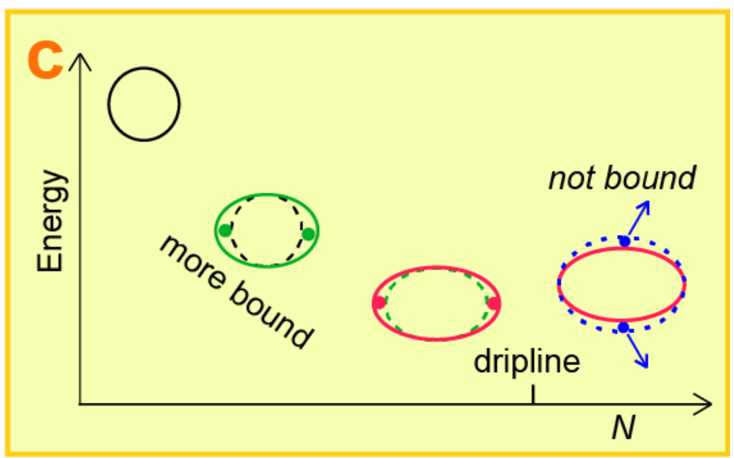
Dripline mechanisms



Neutron driplines are due to two mechanisms: one has single-particle origin (b), while the other new one (c) is due to the interplay of monopole and deformation energies. They may appear alternatively as Z increases.







Traditional (vague) view
-> extreme: neutron halo

New view

Intermedaite case: ^{22}C

Suzuki, O, Yuan & Alahari, PLB 753, 199 (2016).

A probe of this mechanism : magnetic moment of Na isotopes

PHYSICAL REVIEW C **105**, 014319 (2022)

Moments and radii of exotic Na and Mg isotopes

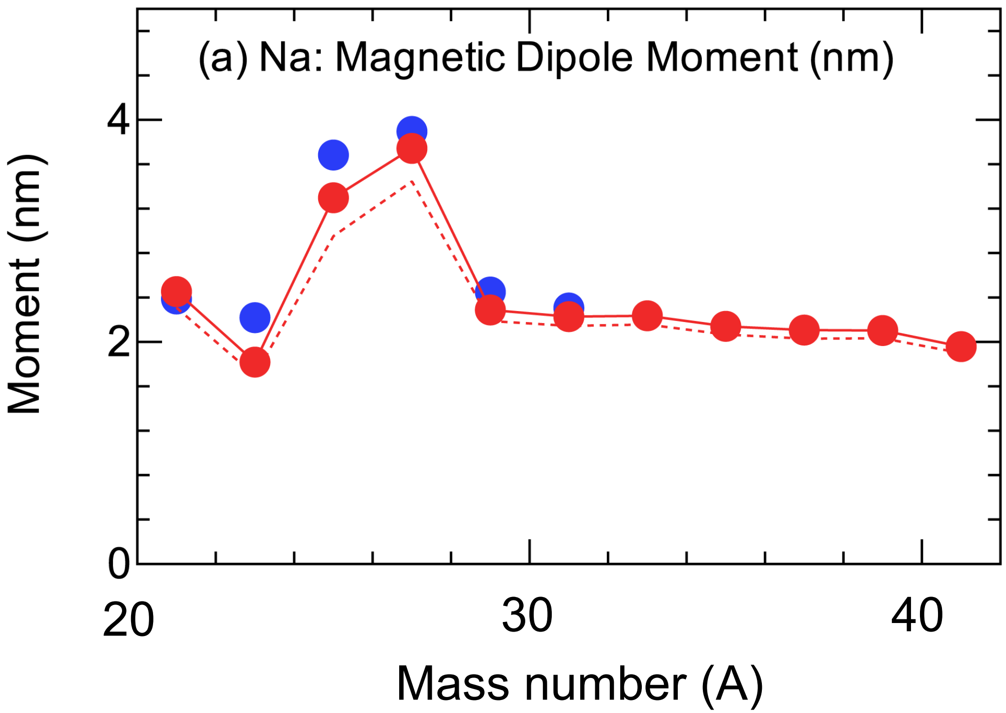
Takaharu Otsuka,[1,2,3,*] Noritaka Shimizu,[4] and Yusuke Tsunoda[4]

● exp

● —— present calc. (g_l shifted: 1.2 for proton and -0.2 for neutron)

------ present calc. (free g factors)

A pionic effect on the M1 operator.



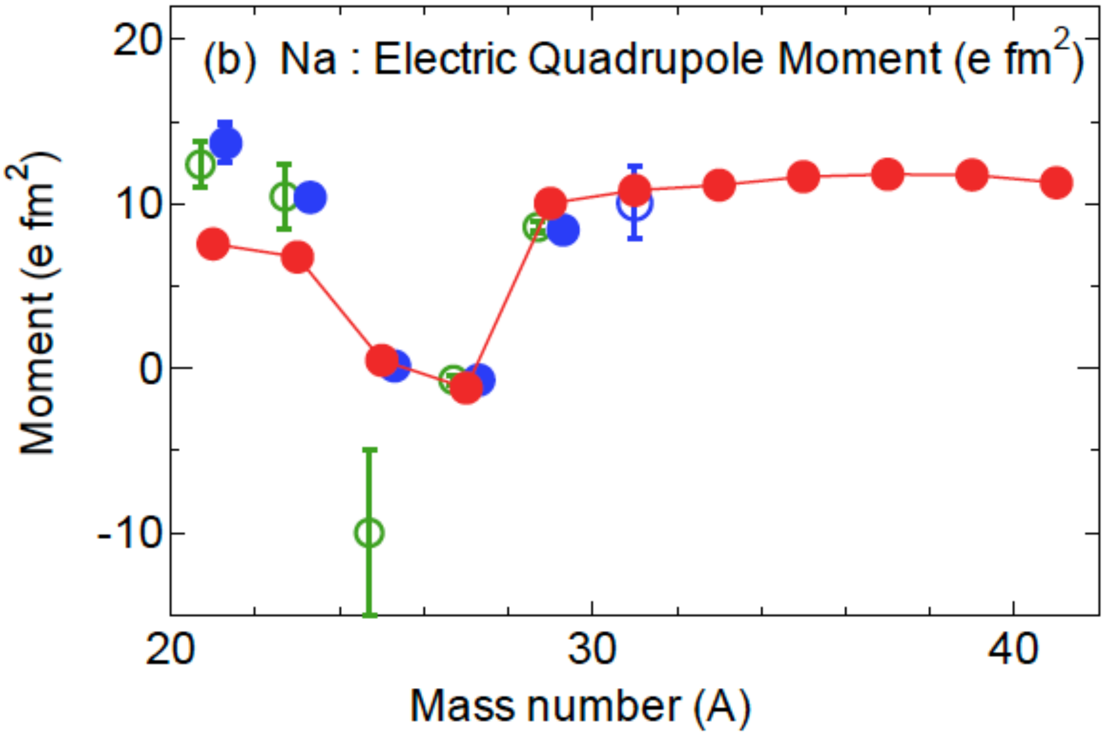
The quenching of spin g-factor (g_s) is needed to incorporate 2p2h cross shell excitations.

Most of such excitations are treated explicitly in this work, and the mixing occurs due to the *ab initio* interaction EEdf1. It looks natural that free spin g-factors work well around ^{31}Na. But, how far ?

exp

National Nuclear Data Center. Evaluated Nuclear Structure Data File, https://www.nndc.bnl.gov/ensdf/.

Electric quadrupole moments of Na isotopes



○ National Nuclear Data Center. Evaluated Nuclear Structure Data File, https://www.nndc.bnl.gov/ensdf/.

● M. De Rydt, M. Depuydt and G. Neyens, At. Data Nucl. Data Tab. **99**, 391 (2013).

○ M. Keim, in *Proc. of the Int. Conf. on Exotic Nuclei and Atomic Masses (ENAM98)*, edited by B. M. Sherrill, D. J. Morrissey, and C. N. Davis, AIP Conf. Proc. No. **455** (AIP, New York, 1998), p. 50.

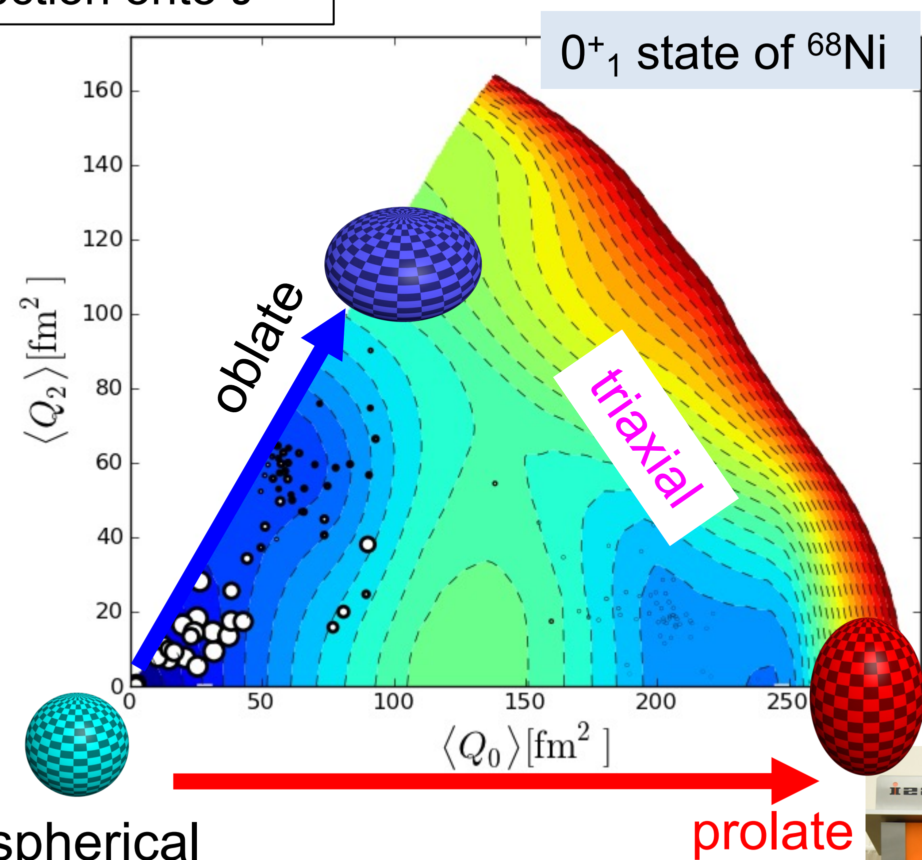
Can we obtain deformation parameters β_2 and γ?

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

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

- amplitude: c_i
- projection onto J^π: $P[J^\pi]$
- Φ_i: stochastically deformed Slater determinant → intrinsic shape

- 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



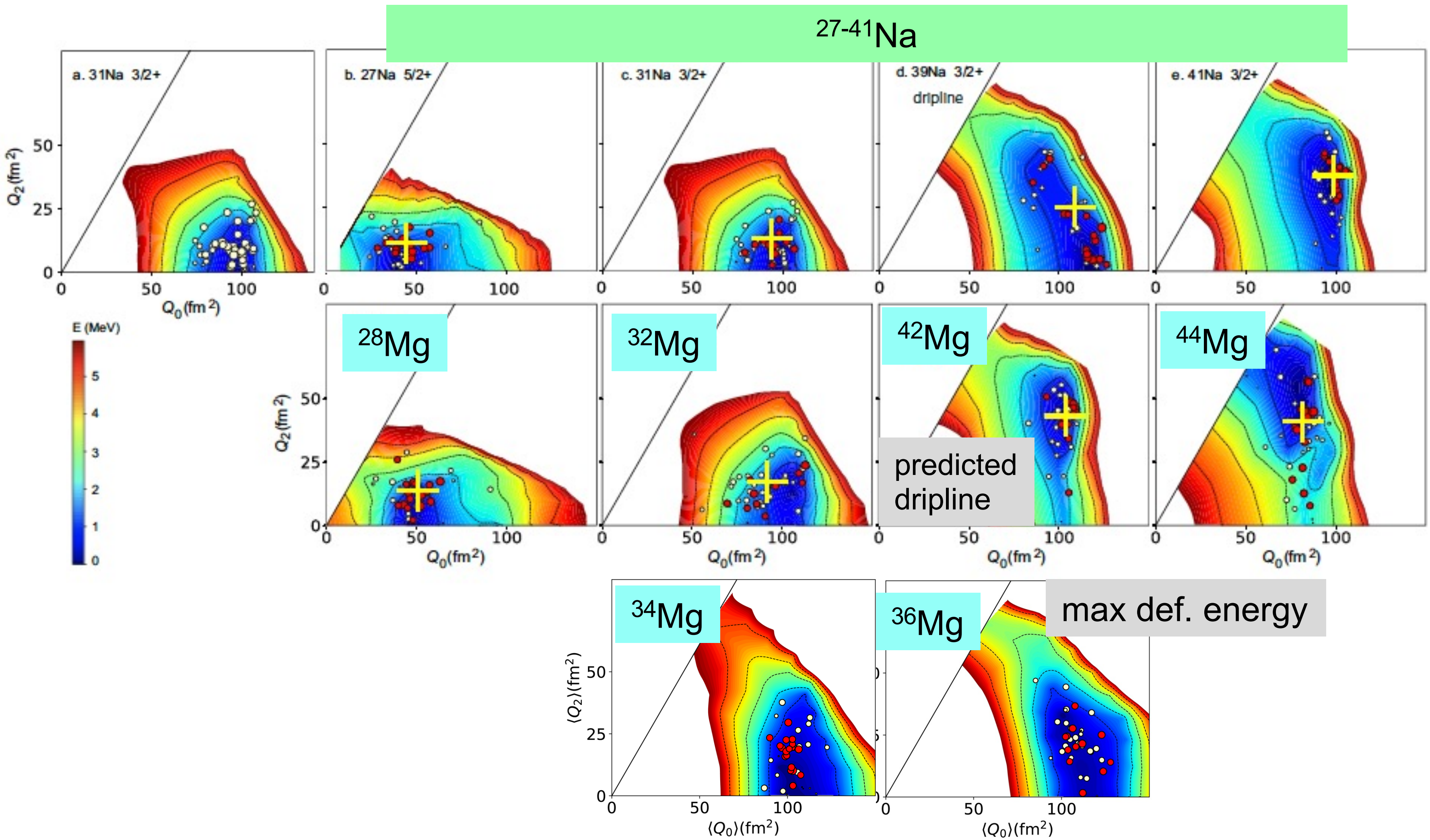
Y. Tsunoda, *et al.*
PRC 89, 031301 (R) (2014)

T plots for the ground states of Na and Mg isotopes

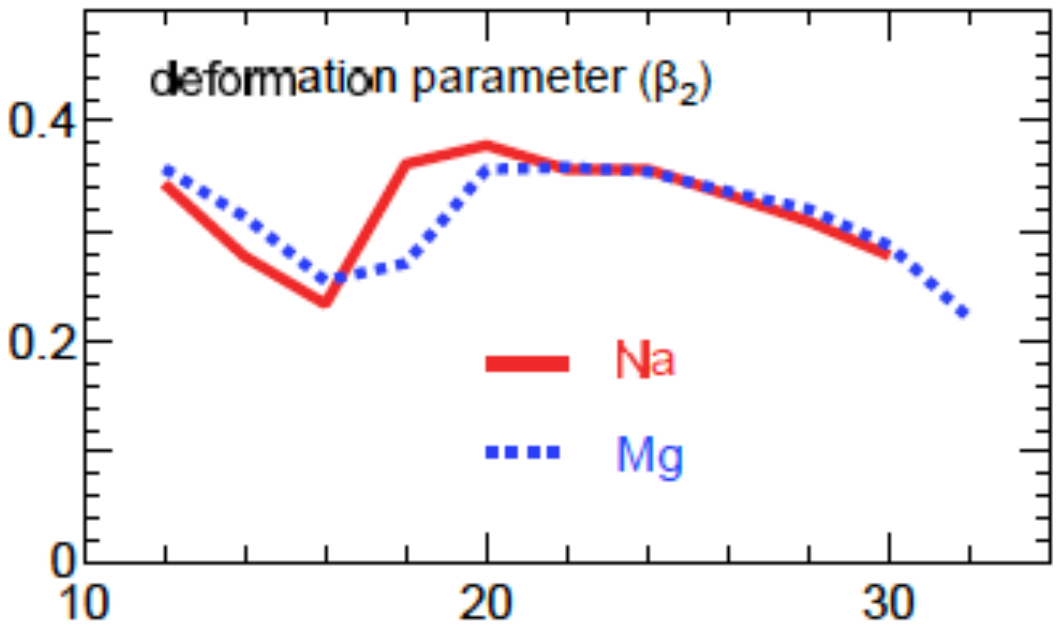
Crosses indicate representative values of Q_0 and Q_2

Deformation parameter β_2 is obtained from (Utsuno et al. PRL 114, 032501 (2015))

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



Deformation parameters extracted from T-plot



Neutron number (N)

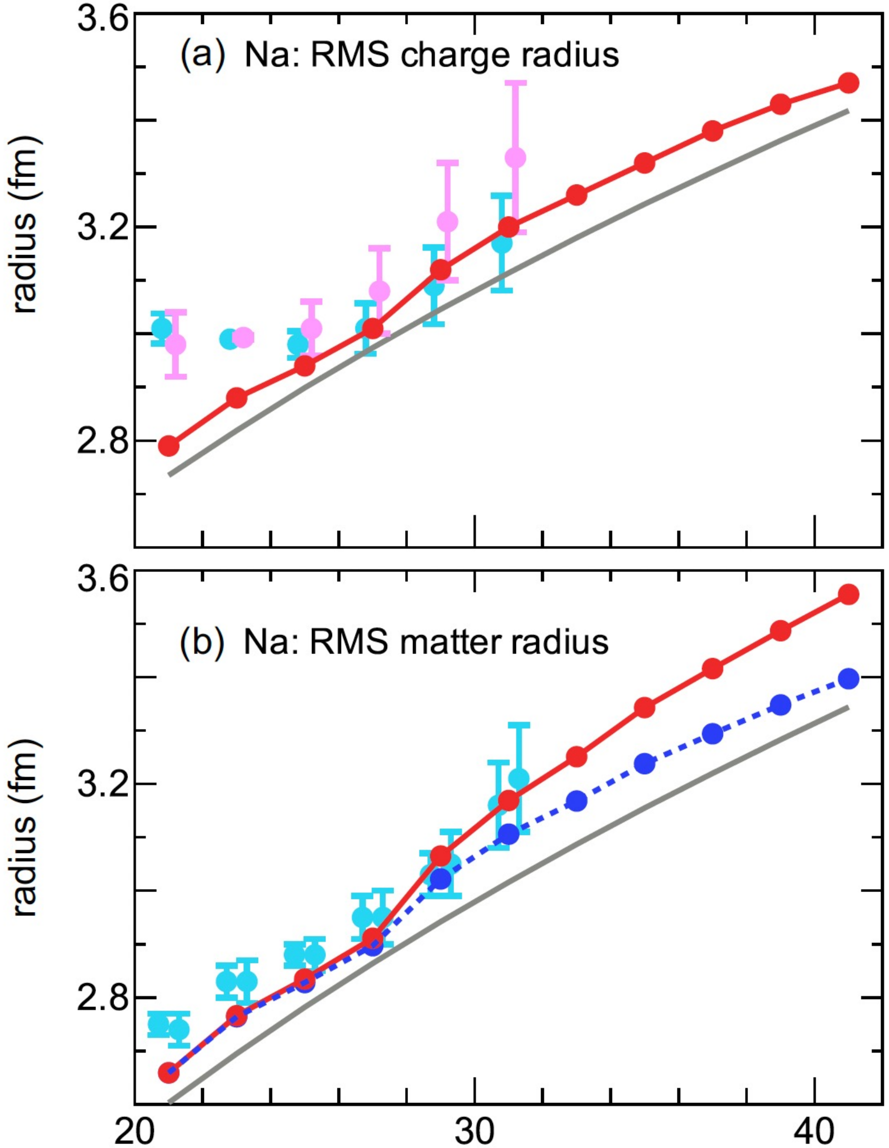
Charge radius is calculated from the usual relation

$$\langle r^2\rangle_{ch} = \langle r^2\rangle_{\rm DM}\{1 + (5/4\pi)\beta_2^2\}$$

with a droplet model term,

$$\langle r^2\rangle_{\rm DM} = (3/5)\,(R_0A^{1/3})^2 \qquad R_0 = 1.28(\mathrm{fm})$$

charge and matter radii (fm)



exp

I. Angelo and K. P. Marinova, At. Data Nucl. Data Tab. **99**, 69 (2013).
B. Ohayon, R. F. Garcia Ruiz, Z. H. Sun, G. Hagen, T. Papenbrock,4 and B. K. Sahoo, arXiv:2019.10539v1.

present calc.

Droplet model

exp

from the interaction cross section

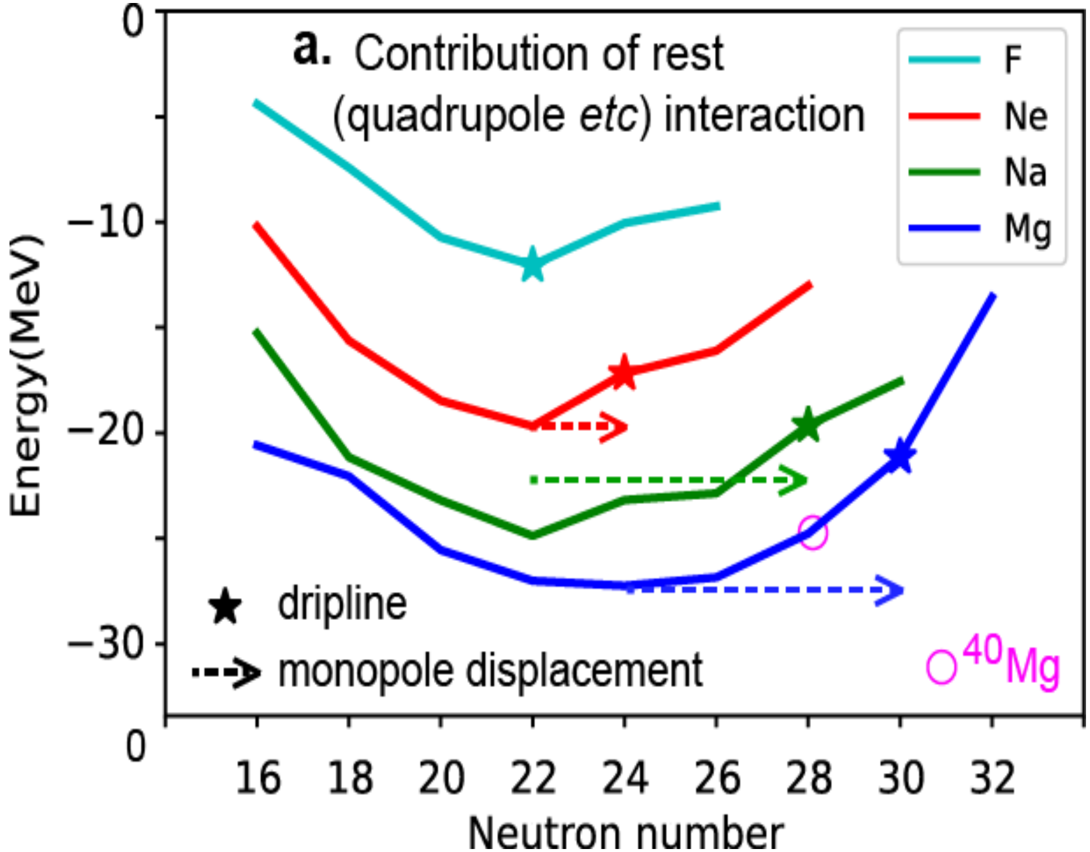
T. Suzuki *et al.*, Nucl. Phys. A **630**, 661 (1998).

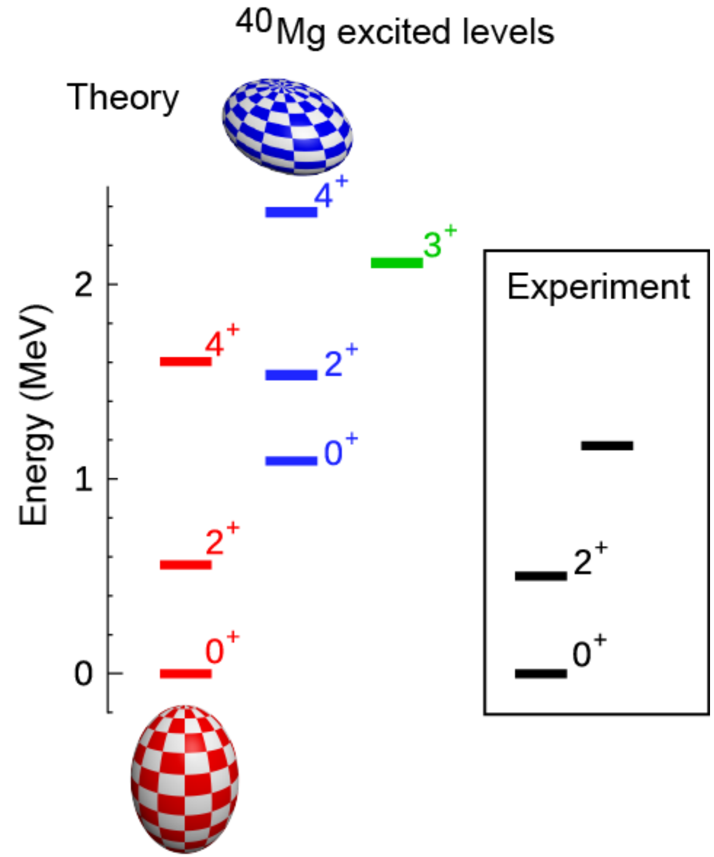
calc. (full)

calc.

Droplet model

Validity of the EEdf1 interaction : still “yes” at ^{40}Mg





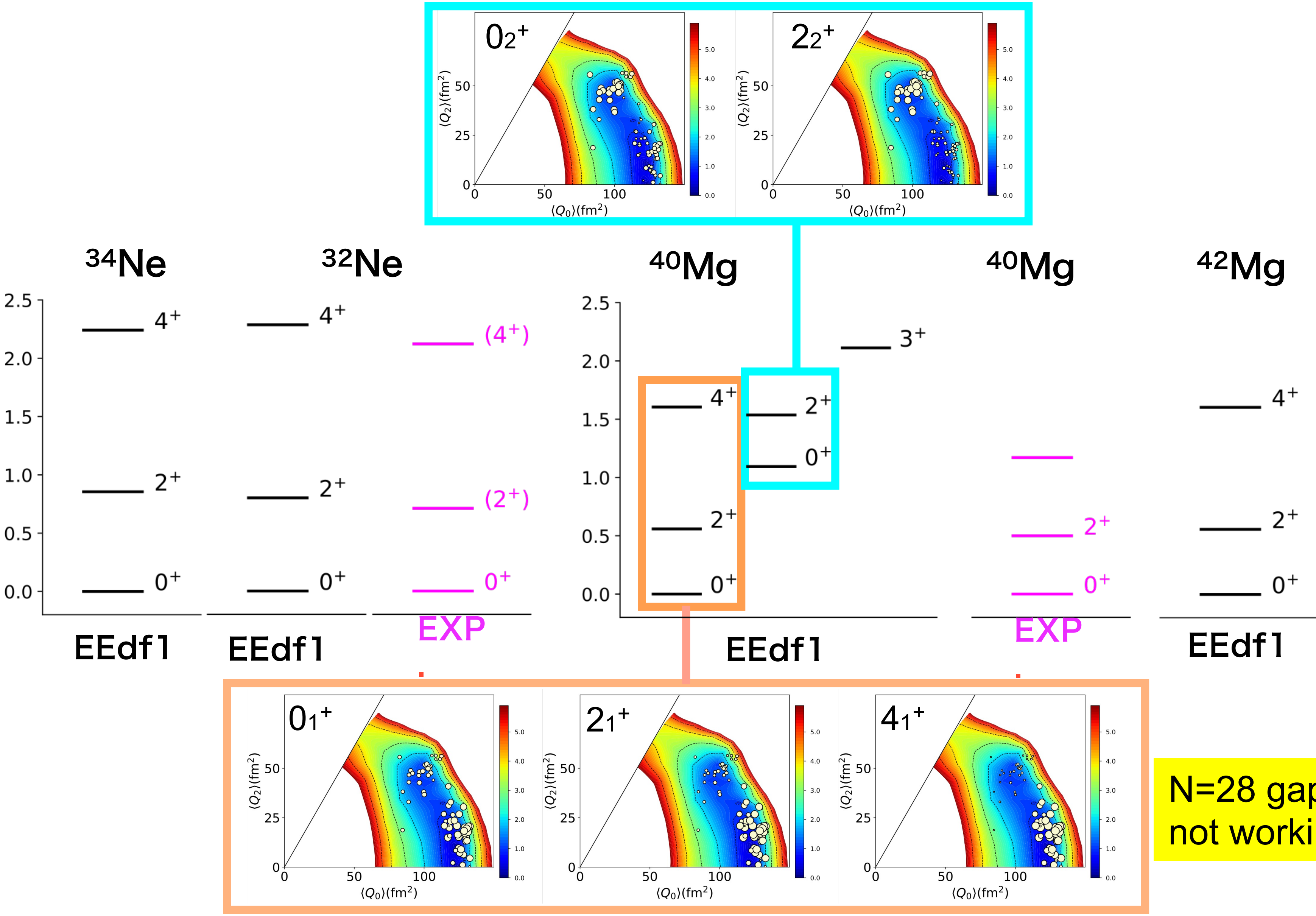
PHYSICAL REVIEW LETTERS 122, 052501 (2019)

Editors' Suggestion

First Spectroscopy of the Near Drip-line Nucleus ^{40}Mg

H. L. Crawford,[1,*] P. Fallon,[1] A. O. Macchiavelli,[1] P. Doornenbal,[2] N. Aoi,[3] F. Browne,[2] C. M. Campbell,[1] S. Chen,[2] R. M. Clark,[1] M. L. Cortés,[2] M. Cromaz,[1] E. Ideguchi,[3] M. D. Jones,[1,†] R. Kanungo,[4,5] M. MacCormick,[6] S. Momiyama,[7] I. Murray,[6] M. Niikura,[7] S. Paschalis,[8] M. Petri,[8] H. Sakurai,[2,7] M. Salathe,[1] P. Schrock,[9] D. Steppenbeck,[9] S. Takeuchi,[2,10] Y. K. Tanaka,[11] R. Taniuchi,[7] H. Wang,[2] and K. Wimmer[7]

Shape coexistence near dripline



N=28 gap is not working

Summary

0. Correlation energies are crucial to driplines. Perhaps unexpected from the viewpoint of mass formulas.
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 for Z larger.
3. Those isotopes are described well by the EEdf1 interaction derived by the EKK method from the chiral EFT interaction.
4. Monopole effects per ΔN depends on # of valence protons:
   in exotic region, ~none for F, …, -3 MeV for Mg. → makes F unique.
   Without the monopole effect, F, Ne and Na would have the same dripline. Virtually all these nuclei show large triaxial shapes.
5. These isotopes remain deformed up to dripline, and have intruder ground states with $d_{3/2}$ half occupied; not an "*island*".
6. Magnetic moments of the ground states of Na isotopes are described well without the quenching of the spin g factor (g_s).
   Deformation parameters are deduced, and charge radius is estimated.

THANK YOU

ご清聴ありがとうございました