Island of Inversion by microscopically derived shell-model Hamiltonian

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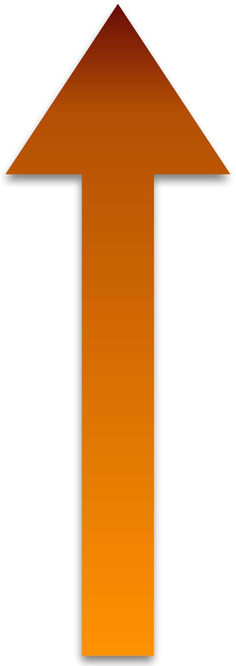
2016/07/12, DREB2016, Halifax

Neutron-rich nuclei~ island of inversion

large shell gap



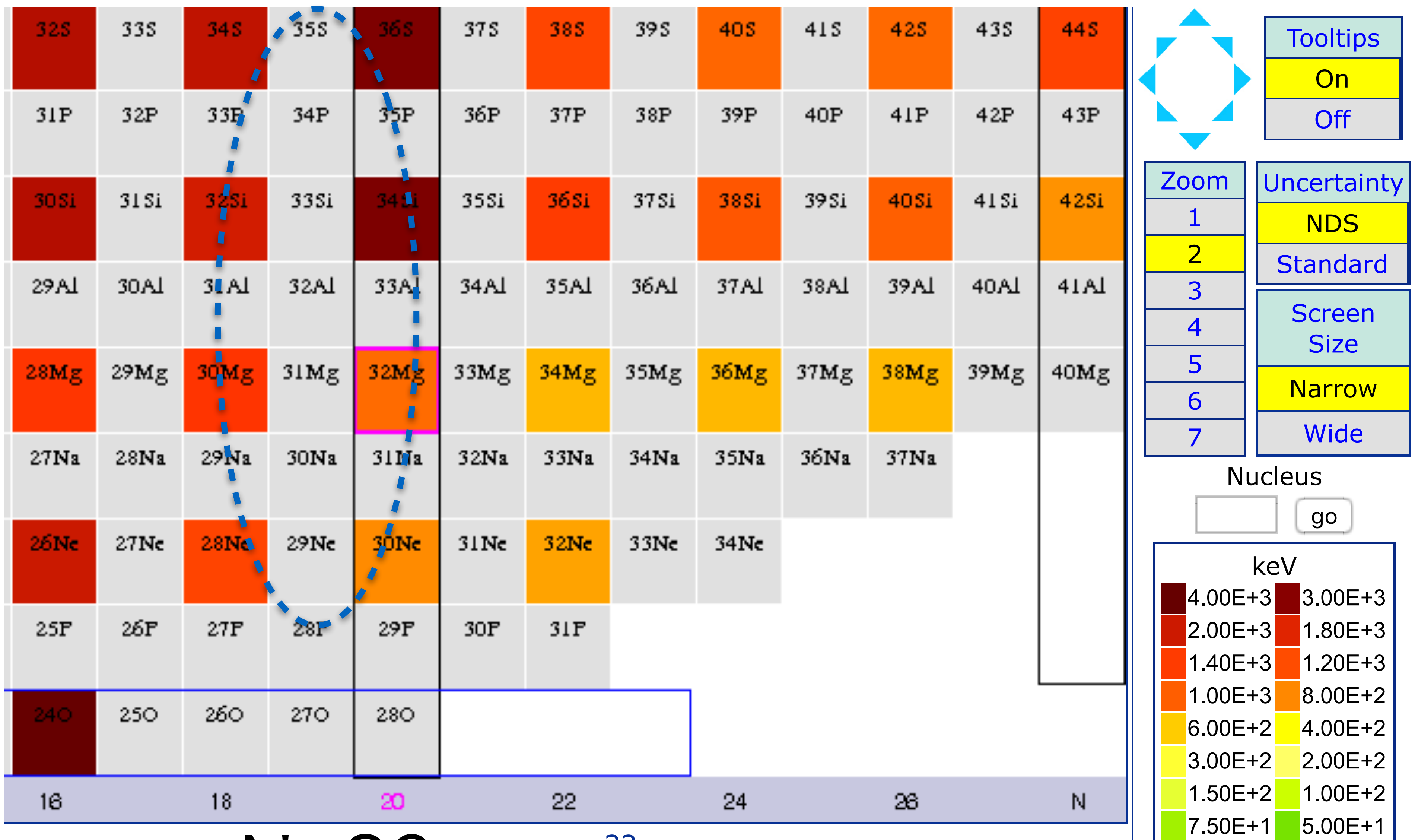
Si

Mg

Ne

breaking of

shell gap

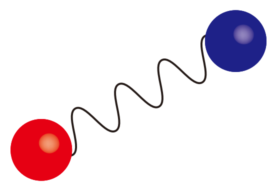


N=20

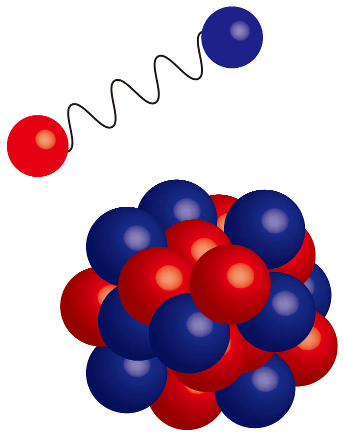
- E(2+)~1 MeV on N=20 indicate **breaking** of major shell gap
- Unified treatment beyond and below the N=20 gap is necessary
- Two-major shell degrees of freedom is essential

Microscopically derived Hamiltonian

Nuclear force in free space



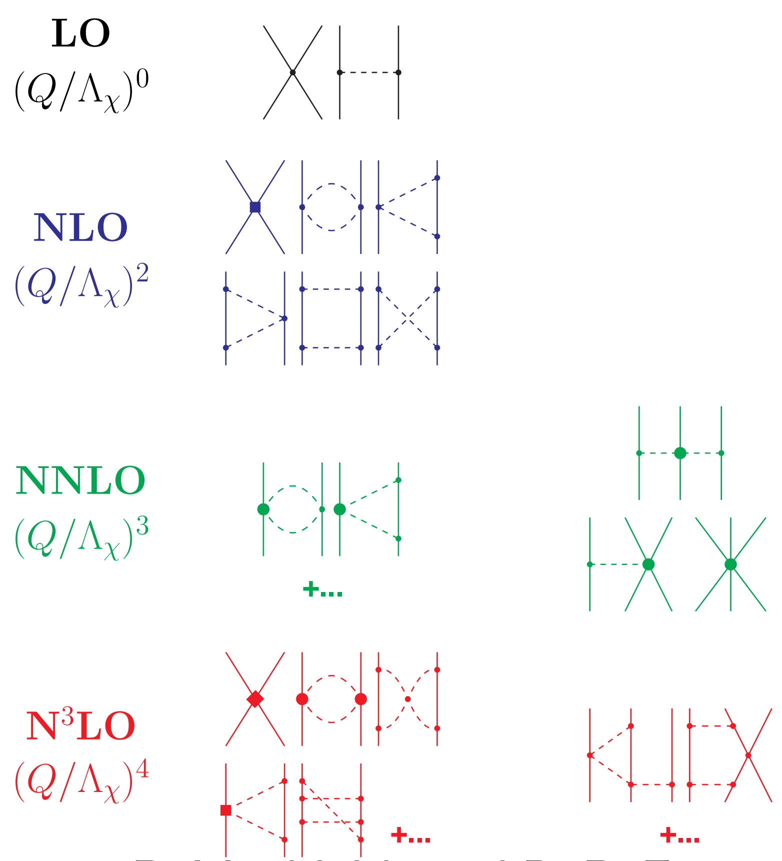
Effective nuclear force for model space



derive →

Many body perturbation theory

χN3LO int. by χEFT



R. Machleidt and D. R. Entem, arXiv nucl-th, (2011).

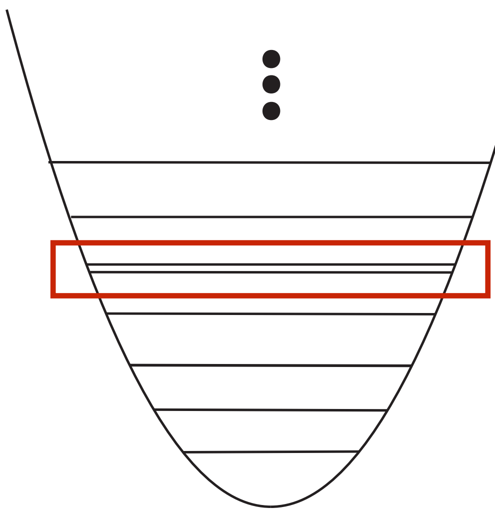
Shell model Hamiltonian

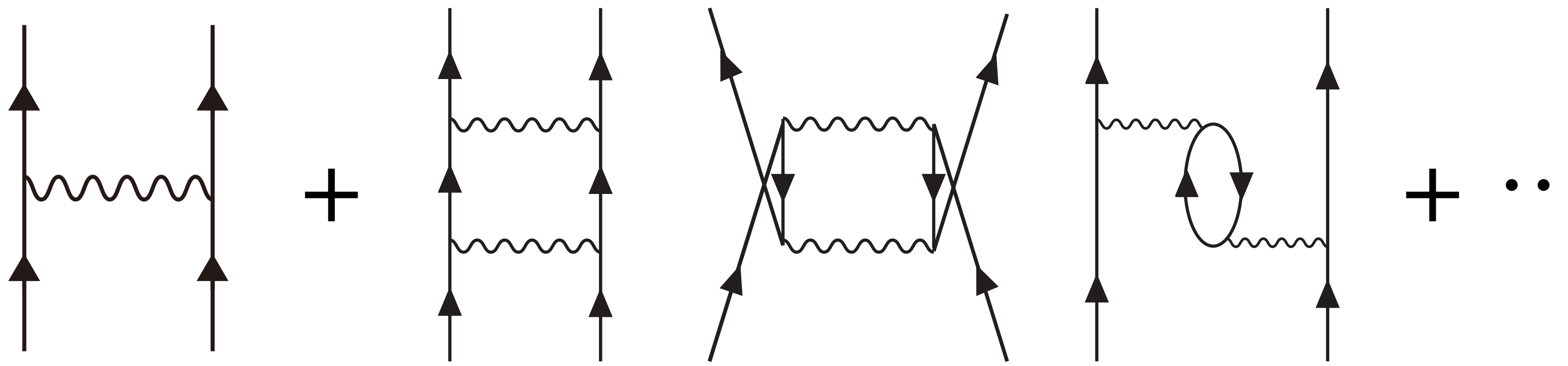
$$H = \sum_i \epsilon_i a_i^\dagger a_i + \sum_{ijkl} V_{ij,kl} a_i^\dagger a_j^\dagger a_l a_k.$$

- Single particle energies
- Two-body matrix elements
- in many cases empirically constructed

Many-body perturbation theory

P: model space

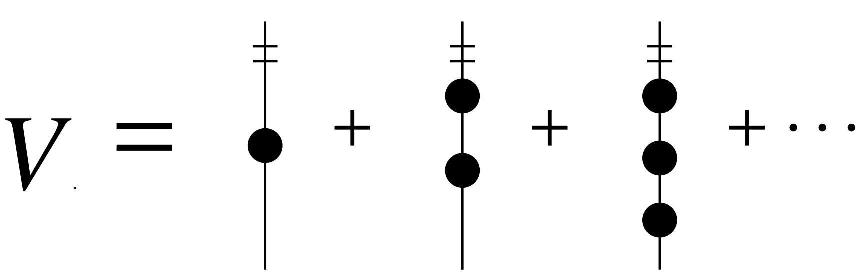




$$\hat{Q}(E) = PVP + PVQ\frac{1}{E - QHQ}QVP$$

Q-box

As non-perturbative correction, we further include infinite repetition of Q-box

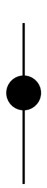


some algebra⋯

non-perturbative correction

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

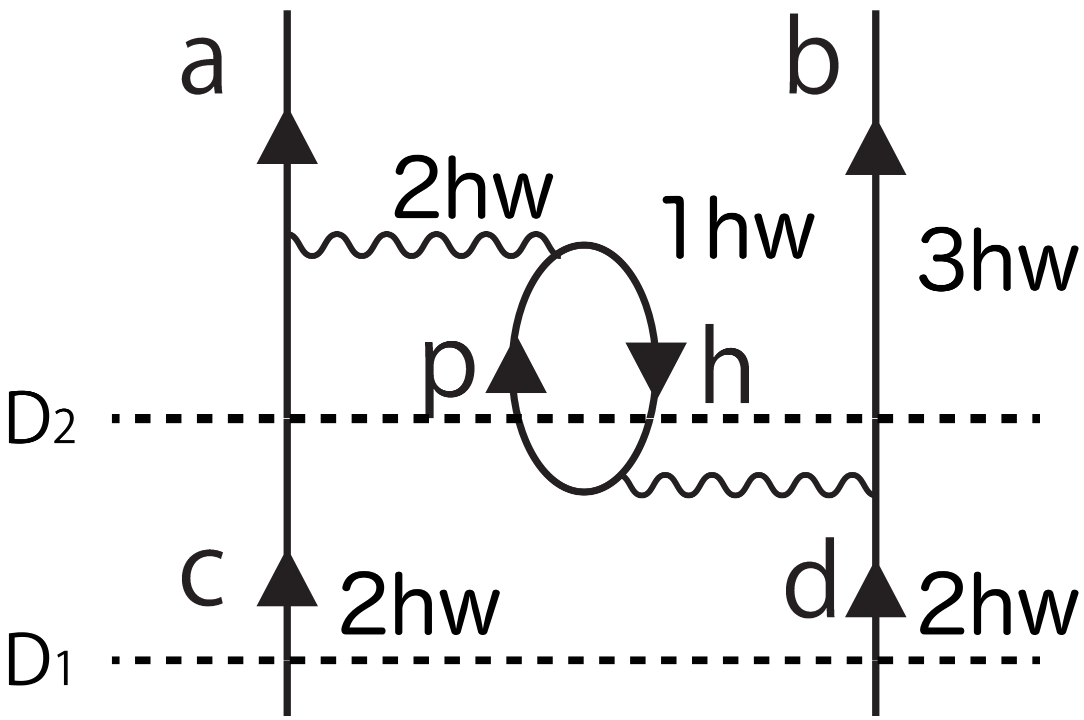
$$\hat{Q}_k(E) = \frac{1}{k!}\frac{\mathrm{d}^k \hat{Q}(E)}{\mathrm{d}E^k}.$$


:Q-box

Kuo-Krenciglowa method

Divergent problem and EKK method

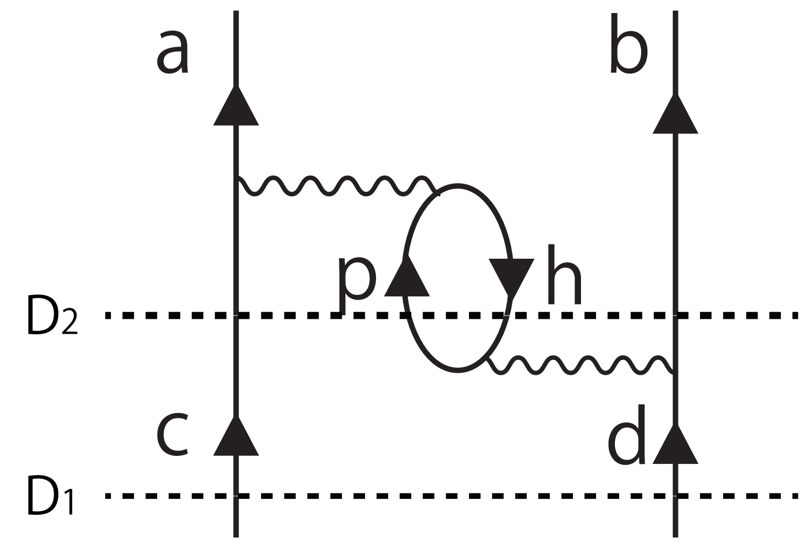
Ex: core-polarization diagram



(D1-D2) = (2+2)hw-(2-1+3)hw = 0hw

-> diverges with naive petrubation theory

then, we introduce **EKK method** to avoid unwanted divergence with re-summation



$$\frac{V_{ah,cp}V_{pb,hd}}{E - \epsilon_c - \epsilon_b - \epsilon_p + \epsilon_h}$$

KK method

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

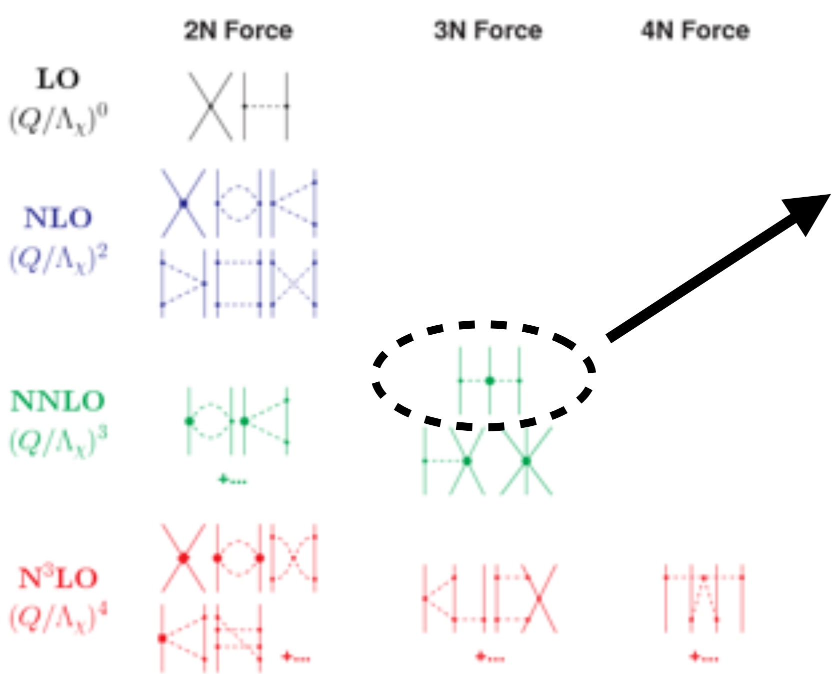
EKK method

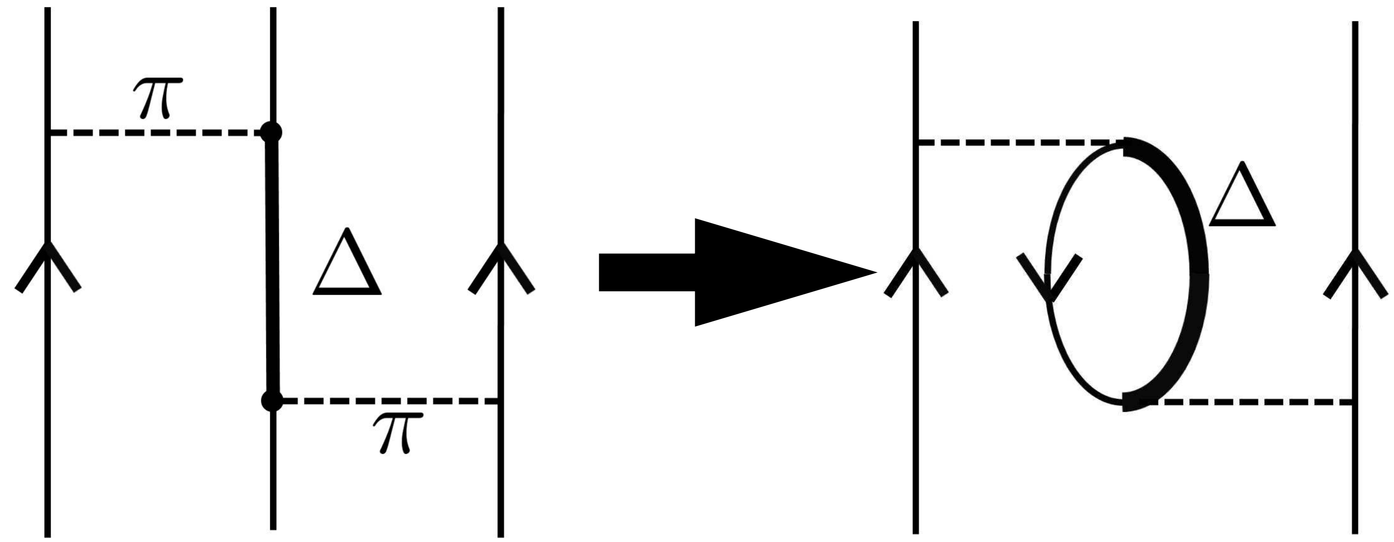
$$\tilde{H}_{\rm eff}^{(n)} = \tilde{H}_{\rm BH}(E) + \sum_{k=1}^{\infty} \hat{Q}_k(E)\{\tilde{H}_{\rm eff}^{(n-1)}\}^k$$

3N interaction (Δ-hole interaction)

summation with hole state

main contribution of 3N





Fujita-Miyazawa type
3N interaction

Effective
2N interaction

- Adding up effective 2N interaction derived from 3N interaction to EKK 2N effective interaction [1]
- This is one of the lowest order interaction from 3N force and for higher order we are working on…

[1] T. Otsuka, T. Suzuki, J. D. Holt, A. Schwenk, and Y. Akaishi, Phys. Rev. Lett. 105, 032501 (2010).

Microscopically derived Hamiltonian vs empirical Hamiltonian

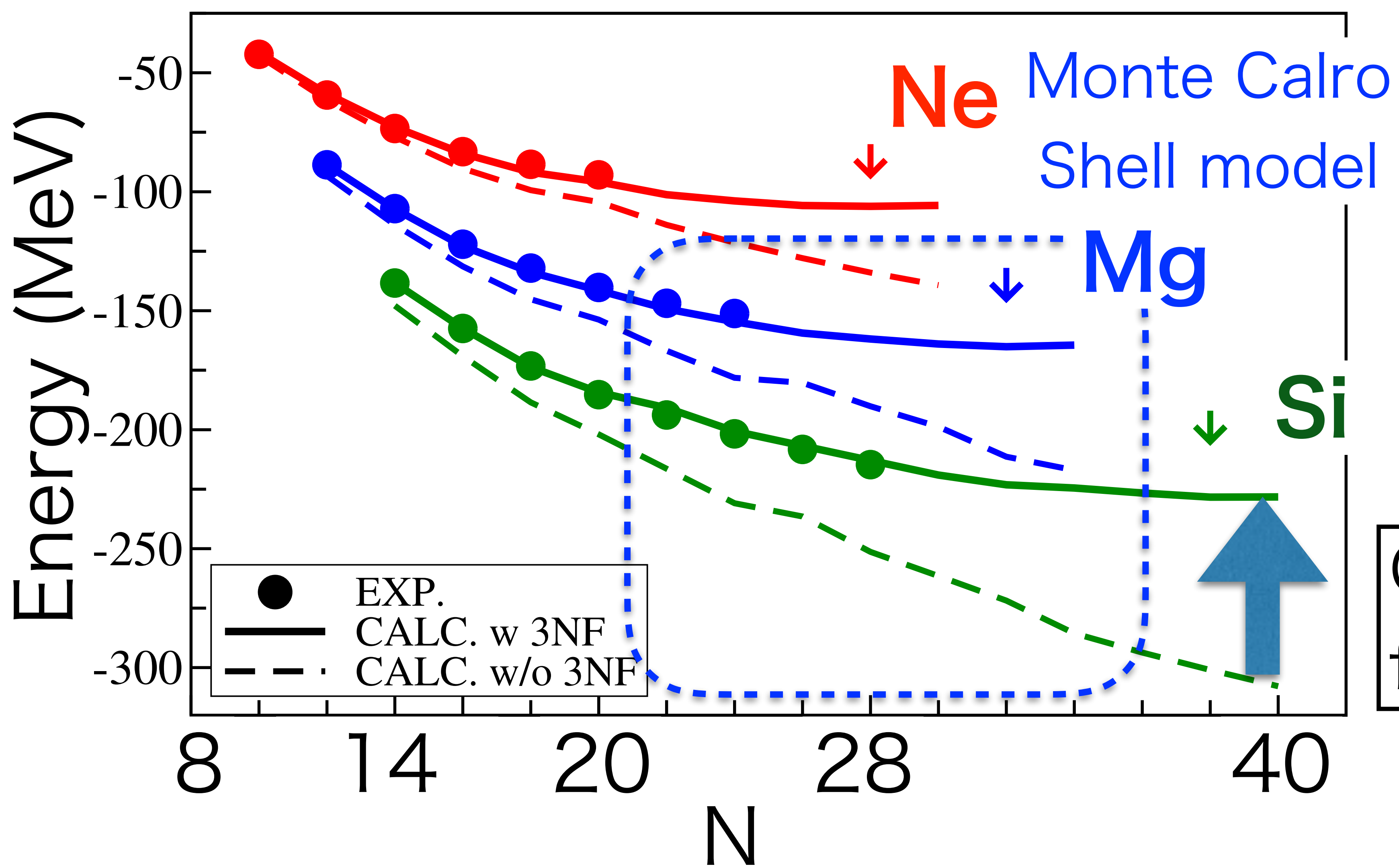
	Microscopic	Empirical
Example	EKK+3N(multi-shell), In-medium SRG(single-shell)	USD, GXPF1, KB3, sdpf-MU, sdpf-U-mix, etc.
Reproducetion of the known data	Good	Very good
Theoretical meaning	Clear	Sometimes not clear
# of parameters	Only a few practical parameters	Basically the same as number of matrix

# of matrix elements in sdpf-shell: 2116

It is generally difficult to fit the matrix elements empirically by hand !

Island of inversion by microscopically derived Hamiltonian

Ground state energies and dripline



Resource:

~10^6 node*hour

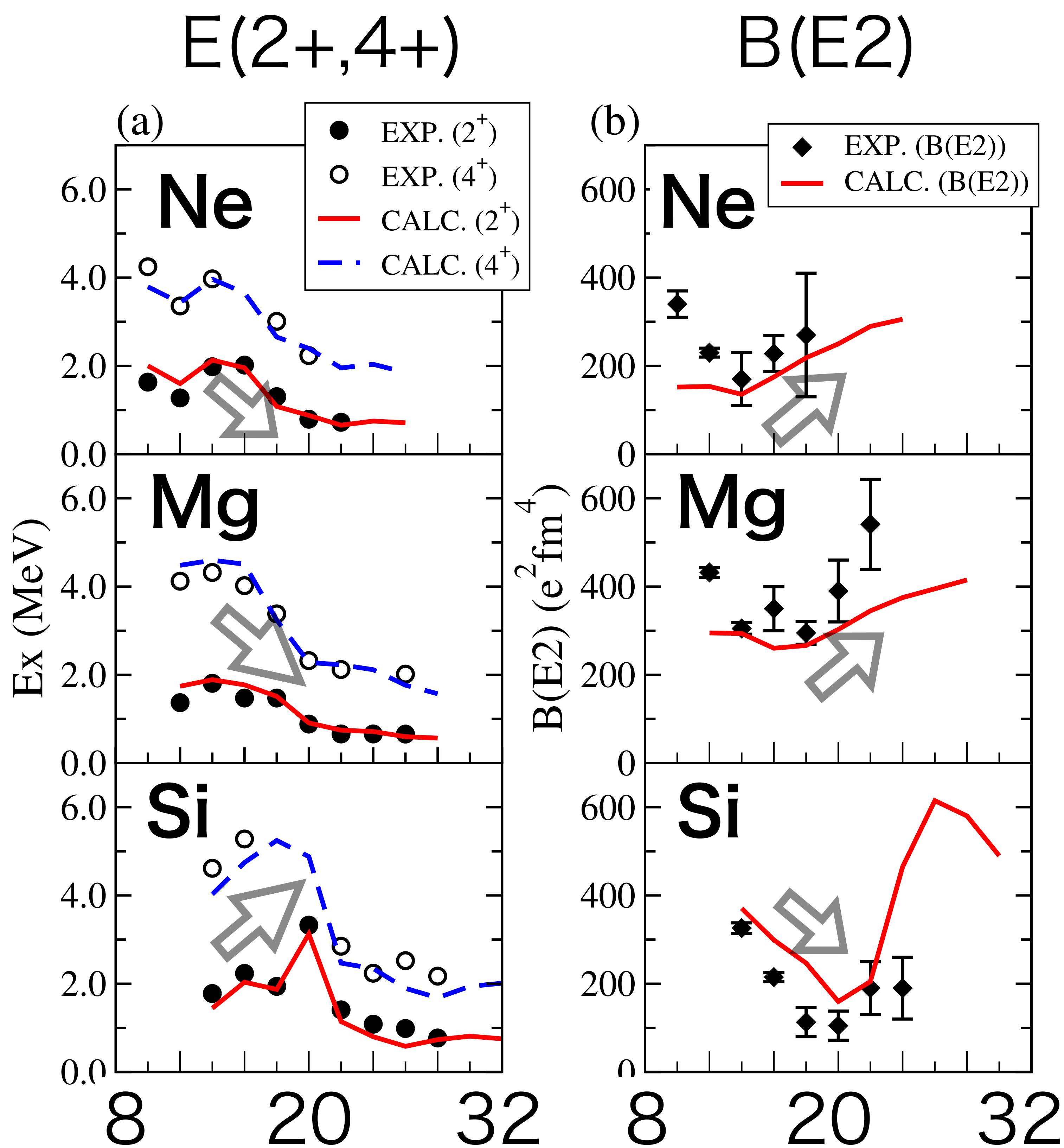
in K-computer for

around **100 states**

Contribution from 3N force

- Experimental ground state energies are well reproduced
- Contribution of 3N force is significant in neutron-rich nuclei
- Combination of **Microscopic theory** and **Large scale calc.**

E(2+,4+) and B(E2)

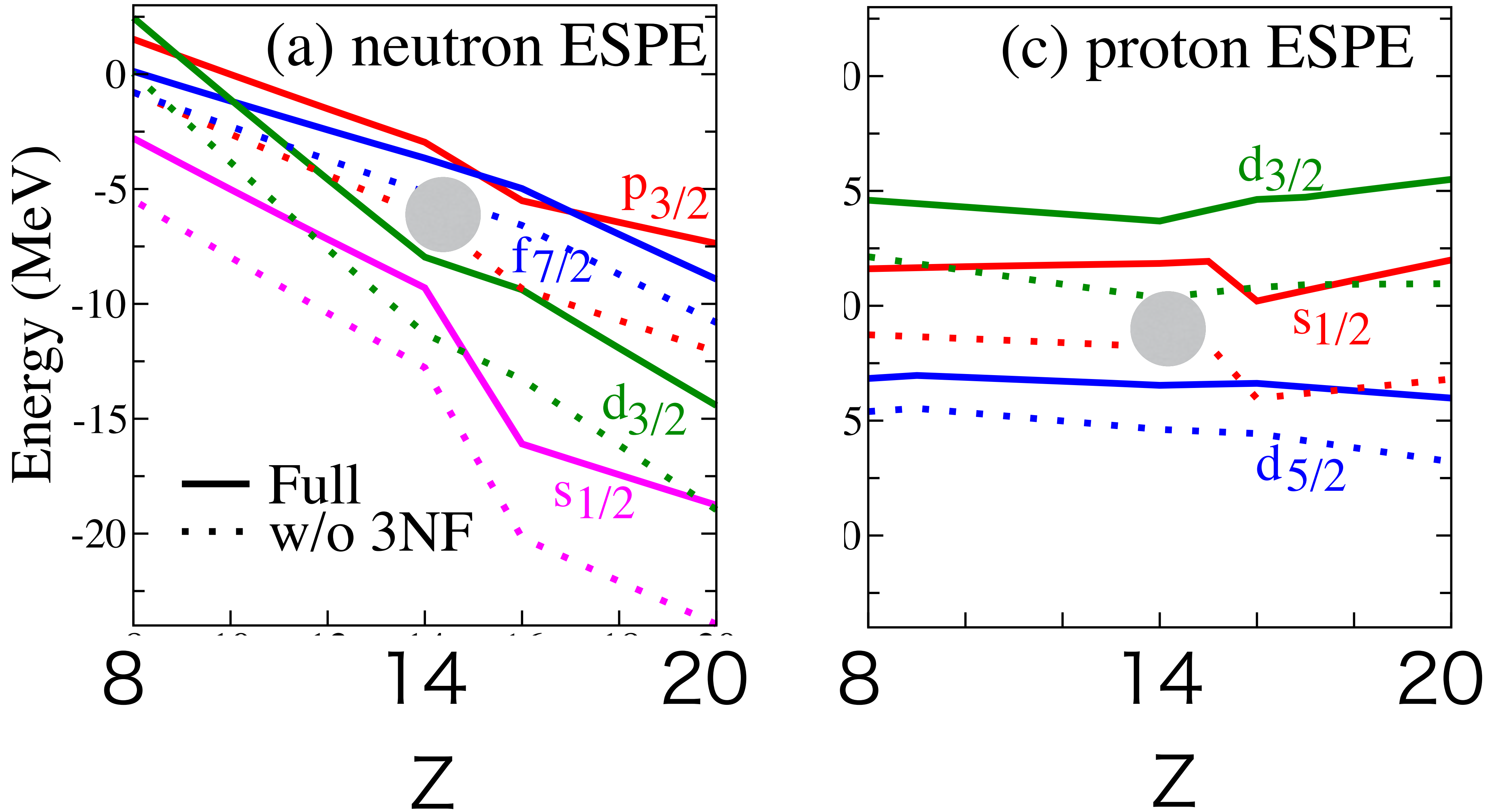


Effective charges
(ep,en)=(1.25, 0.25)

Clear indication of breaking of N=20 gap for Ne and Mg.

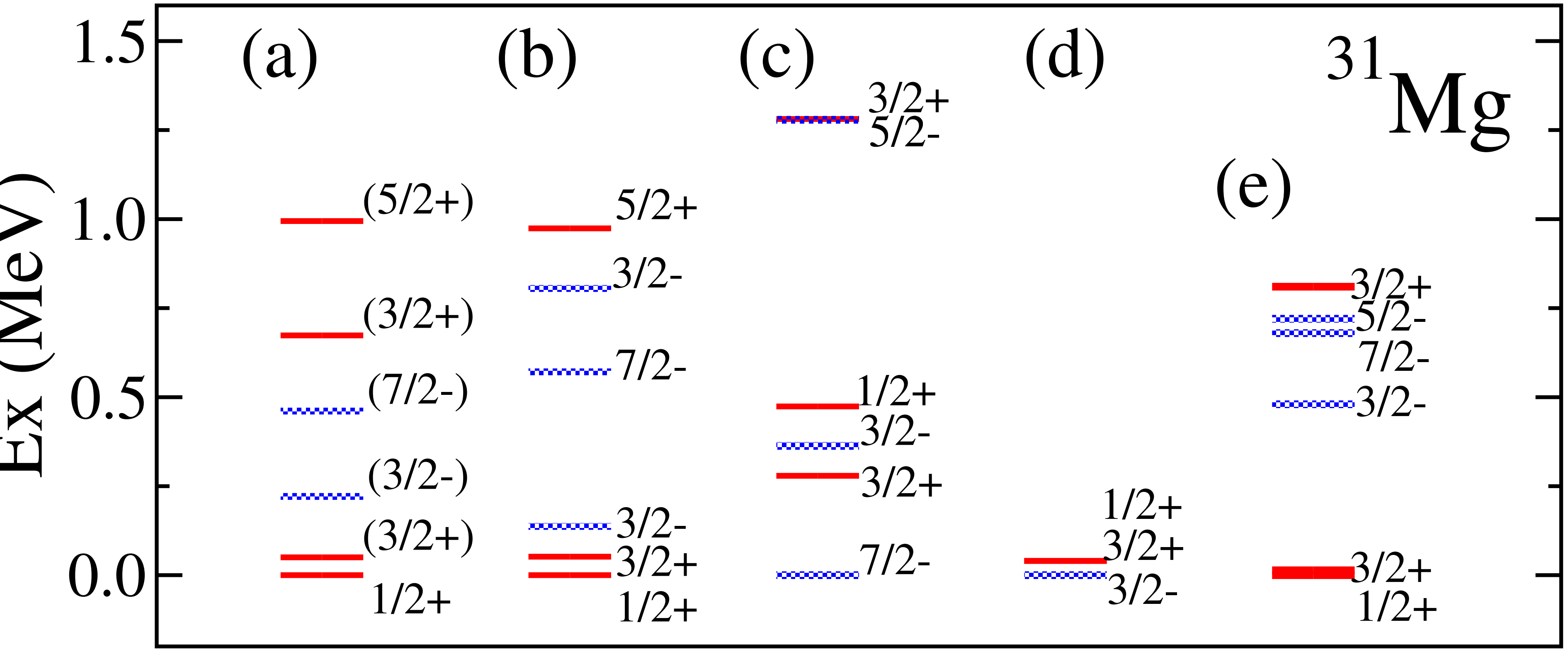
N=20 gap remains in Si case.

ESPEs



- Both neutron and proton gap is appearing when Z=14
- Proton-neutron force drive the N=20 gap at Z=14
- at Z=20, f7/2 and p3/2 levels are consistent with empirical pf-shell interactions (gxpf1a, KB3 etc.)

31Mg



(a) EXP.
(b) EKK+3N
(c) sdpf-m
(d) sdpf-U-mix
(e) AMD+GCM

<u>points</u>

- onset of island of inversion
- ordering of levels reproduced
- mixing of different np-nh contribution

ex) 1/2+ 0hw: 2% 2hw: 66% 4hw: 30% 6hw: 2%
3/2- 1hw: 33% 3hw: 56% 5hw: 11%

Summary and conclusion

- The physics in island of inversion is well described by microscopically derived effective Hamiltonian
  - Ground state energies, E(2+,4+), B(E2) of even-even nuclei, positive and negative party states of 31Mg
- MBPT is the theory to construct the effective Hamiltonian starting from nuclear force.
- EKK method is introduced to derive the effective interaction for the shell model which is applicable to **multi-shell** system.
- **EKK** and **3N** combination is the powerful tool to explore the wide area of the nuclear chart

Collaborators

- Takaharu Otsuka (Univ. Tokyo)
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- Toshio Suzuki (Nihon Univ.)
- Morten Hjorth-Jensen (Oslo Univ.)