Physics in island of inversion starting from nuclear force

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Tsukuba-CCS workshop on “microscopic theories of nuclear structure and dynamics”
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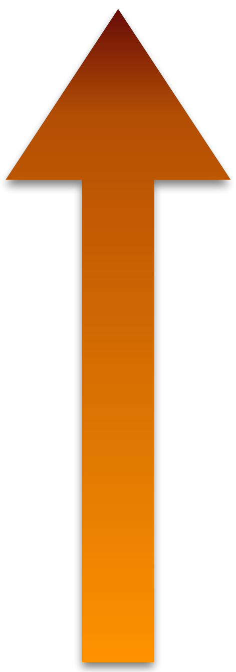
This work has been supported by MEXT and JICFuS as a priority issue (Elucidation of the fundamental laws and evolution of the universe) to be tackled by using Post “K” Computer.

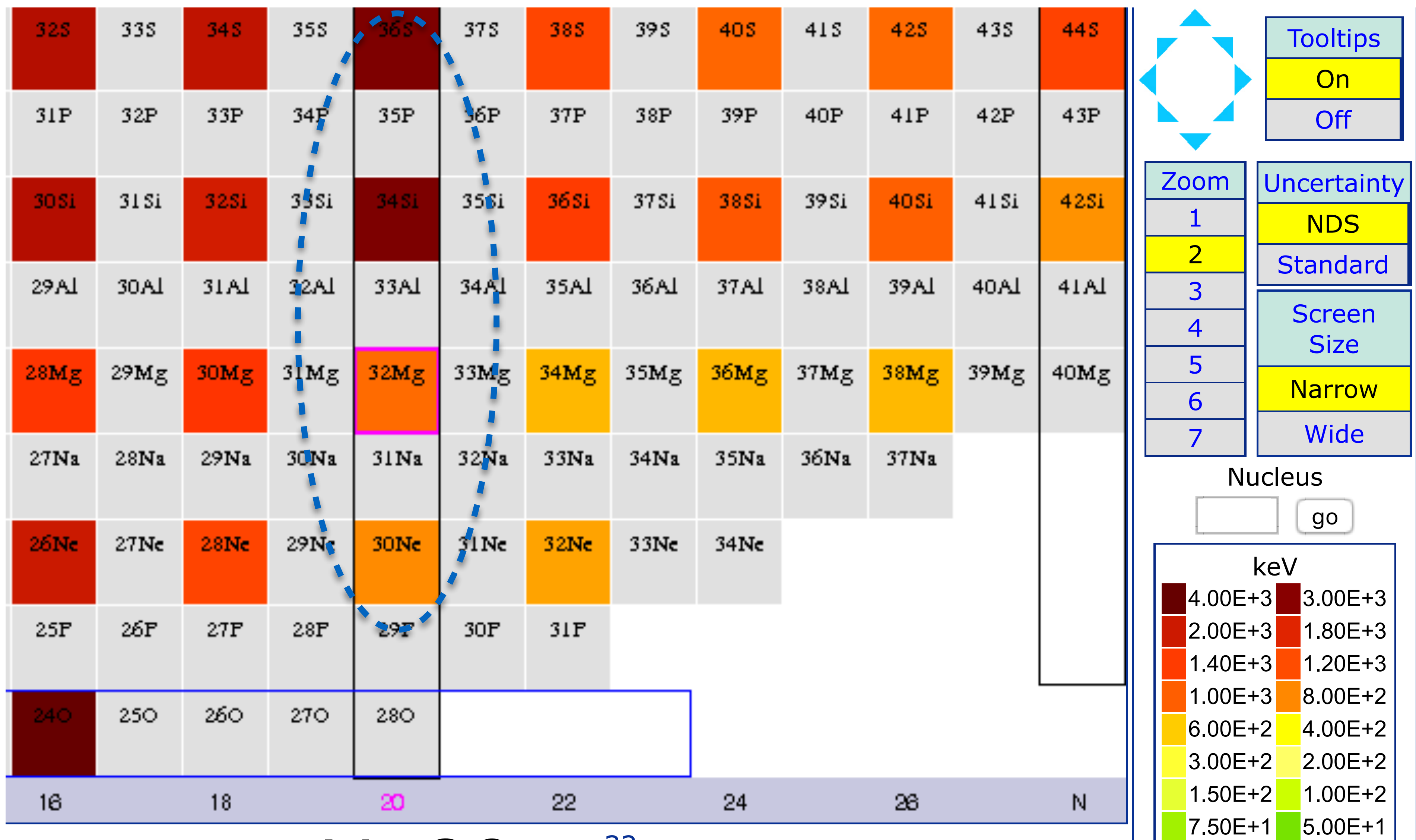
Neutron-rich nuclei~ island of inversion

http://www.nndc.bnl.gov/nudat2/reCenter.jsp?z=12&n=20

shell gap



breaking of shell gap



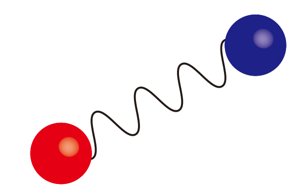
N=20

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

Many body problem

Original Hamiltonian

$$H = T + \sum_{i,j=1}^{N} V_{NN} + \sum_{i,j,k}^{N} V_{NNN}$$



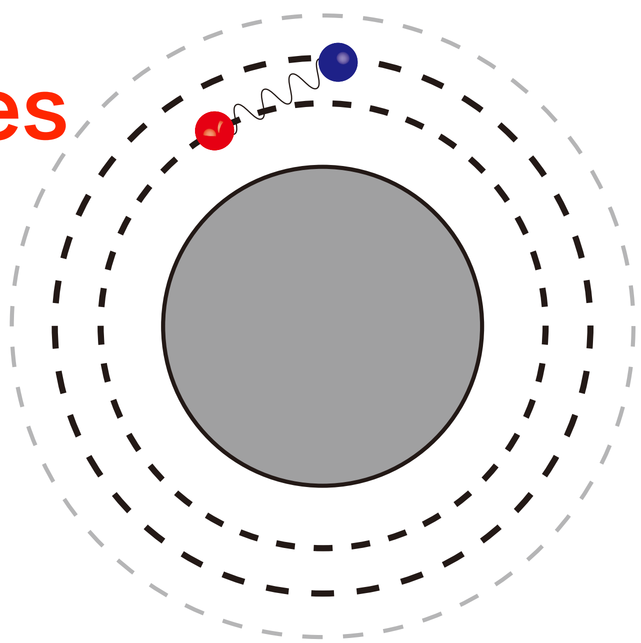
Shell model Hamiltonian

Single particle energies

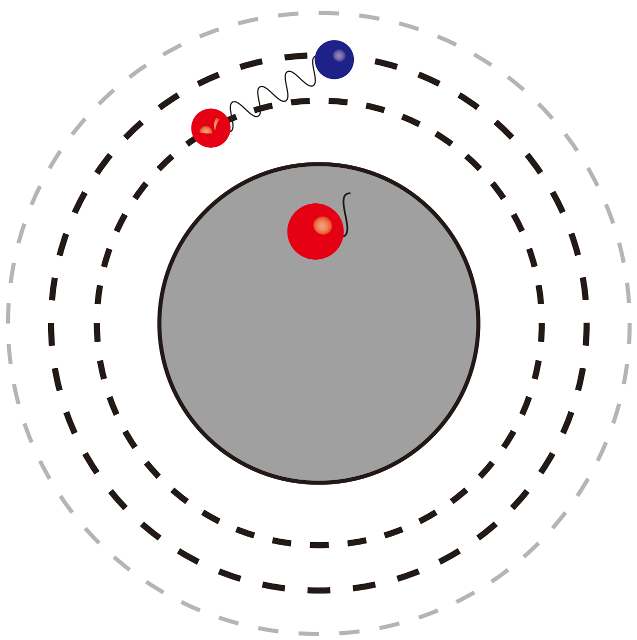
$$H = \sum_i \epsilon_i a_i^\dagger a_i + \sum_{ijkl} V_{ij,kl}\, a_i^\dagger a_j^\dagger a_l a_k .$$

Two-body matrix elemetns

NN force

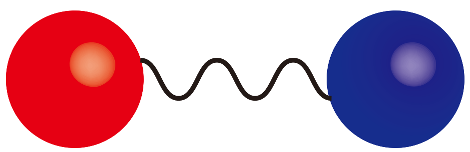


effective NN from 3N

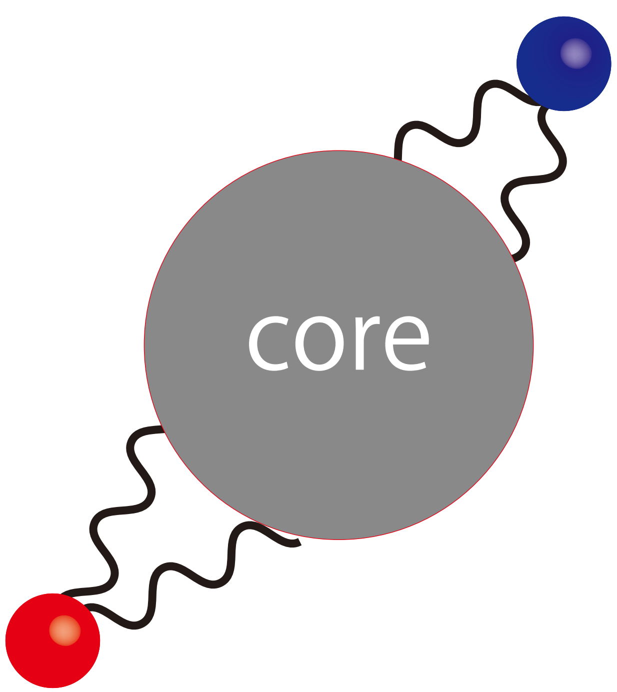


Effective interaction

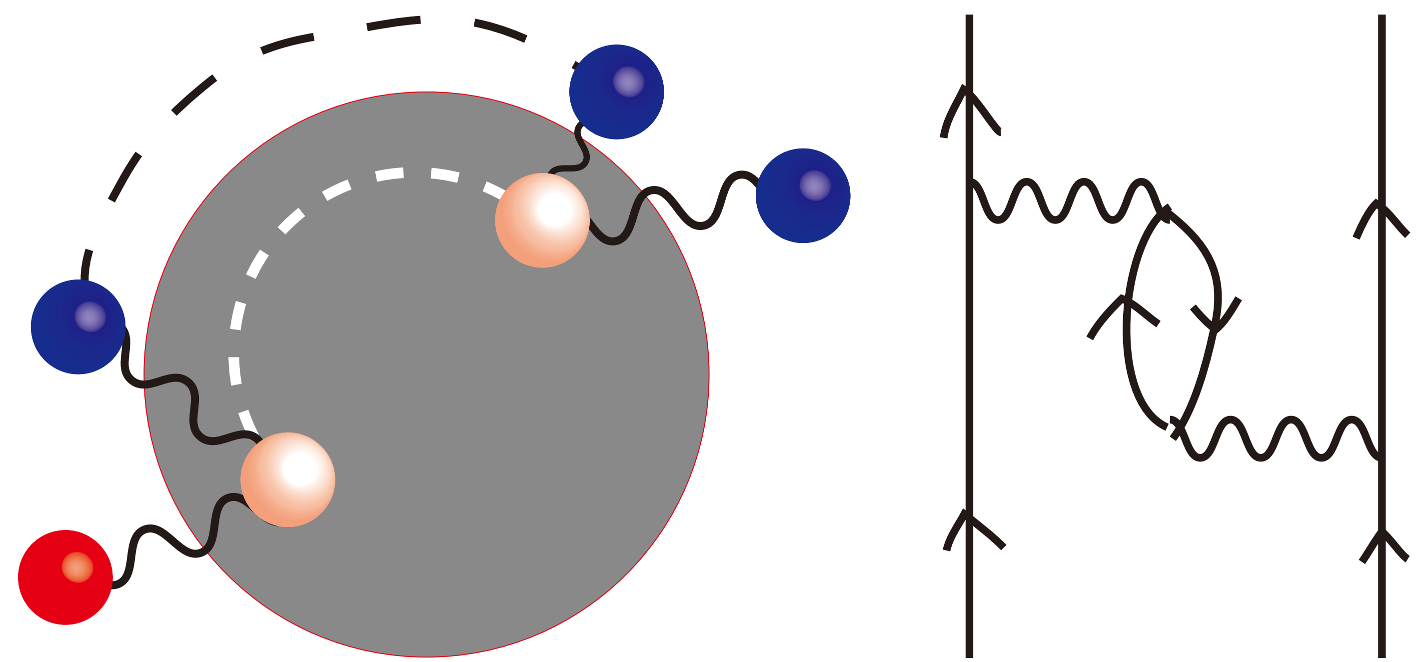
Nuclear force in vacuum



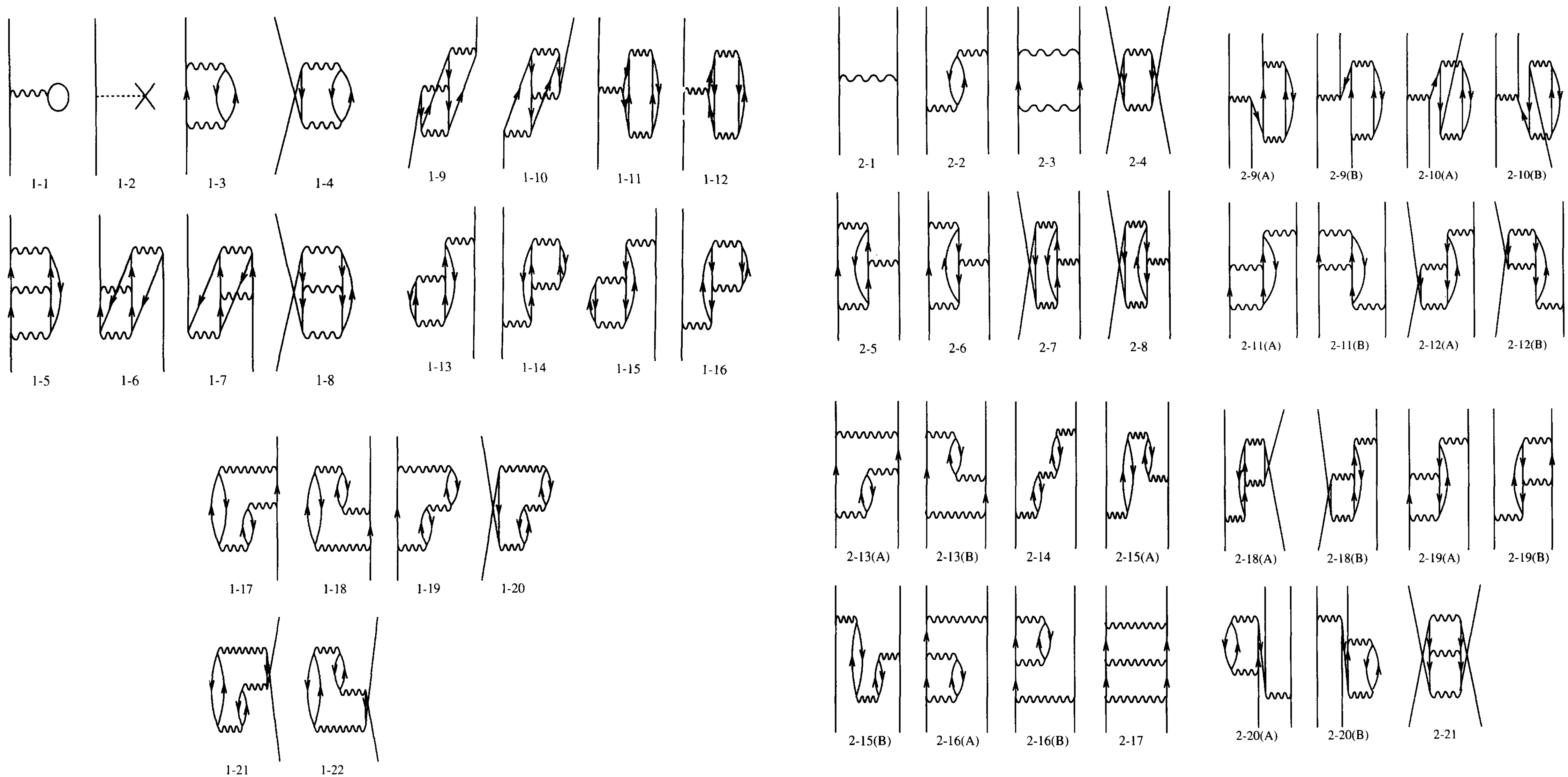
Medium effect



Core polarization (3p1h)



Many-body perturbation theory



Extended KK method and conventional KK method

EKK method

New parameter E (arbitrary parameter)

$$H = H'_0 + V' = \begin{pmatrix} E & 0 \\ 0 & QH_0Q \end{pmatrix} + \begin{pmatrix} P\tilde{H}P & PVQ \\ QVP & QVQ \end{pmatrix},$$

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

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

KK method (conventional)

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

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

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

- **EKK method enable 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).

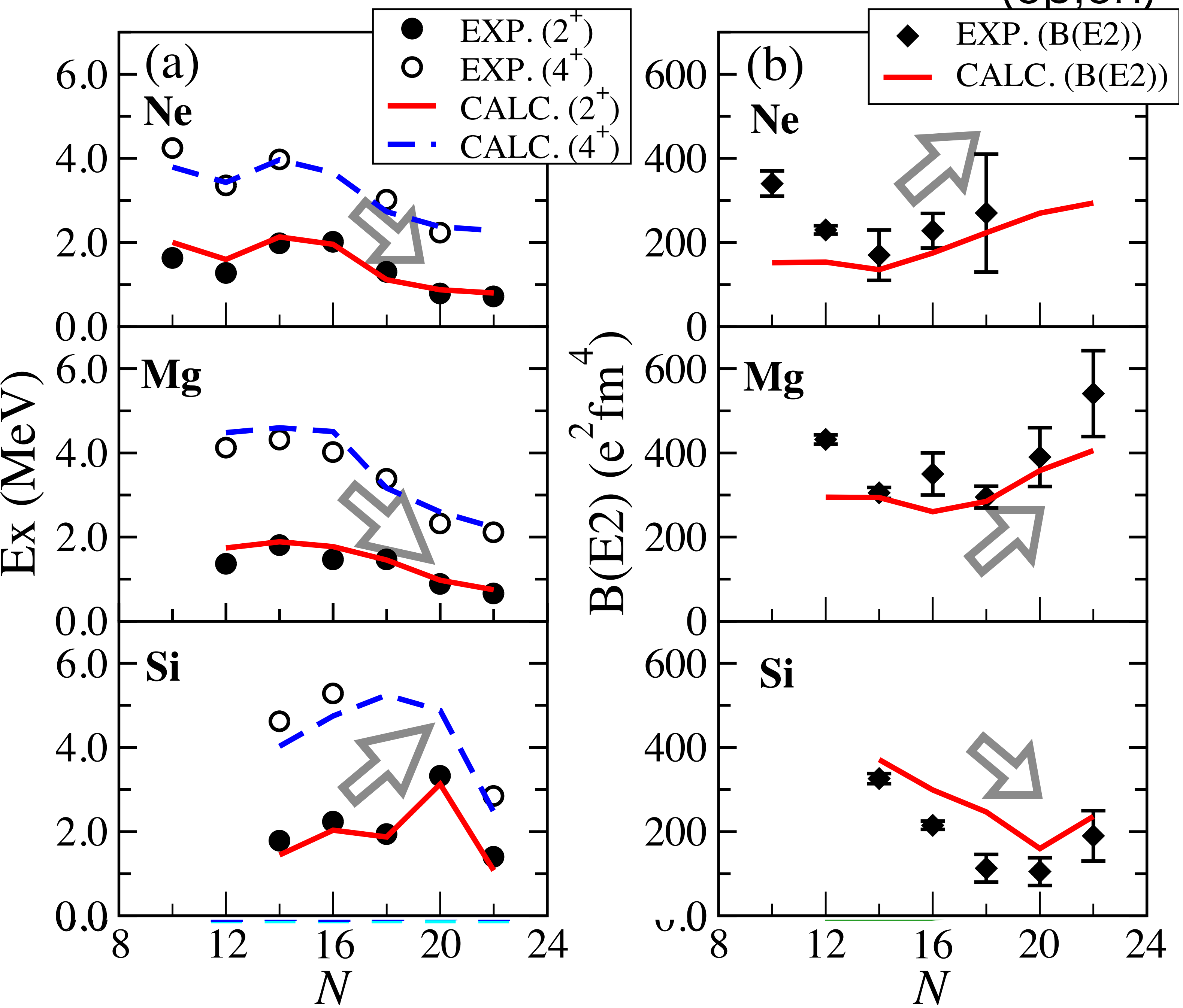
EEdf1 interaction

- Effective interaction for **island of inversion**
- Effective interaction designed for **sd+pf** shell
- TBMEs are determined by **EKK method**
- Effective 2NF from **3NF**(Fujita-Miyazawa type) force is added
- SPEs are fitted to experimental data

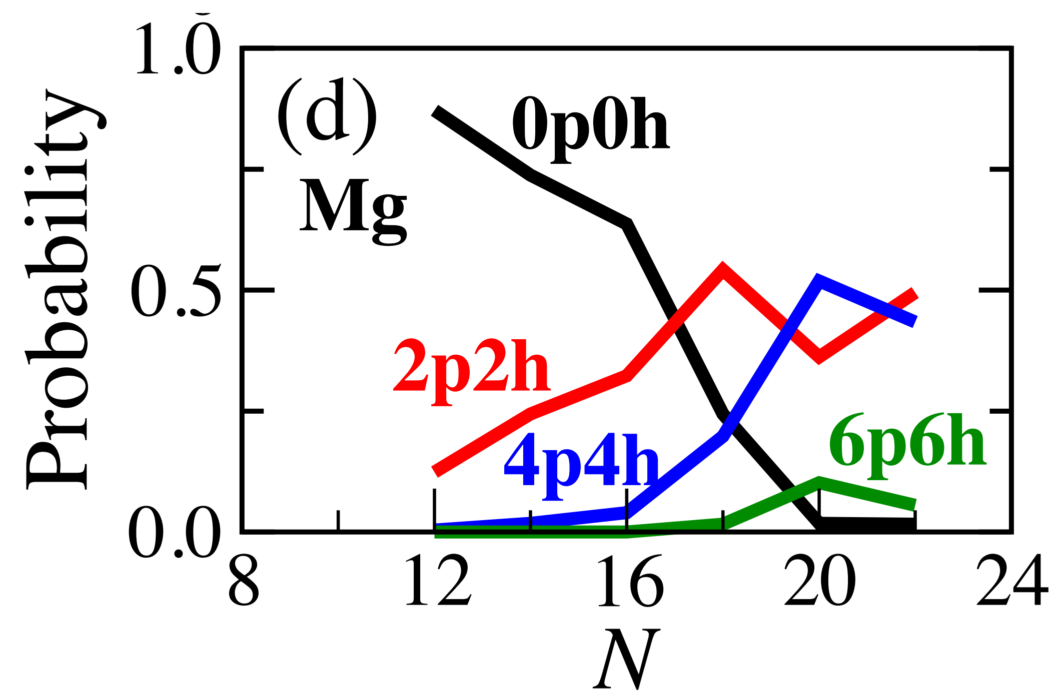
Shell structure in "island of inversion"

EEdf1

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



N.T, et al. Phys. Rev. C 95, 021304 (20



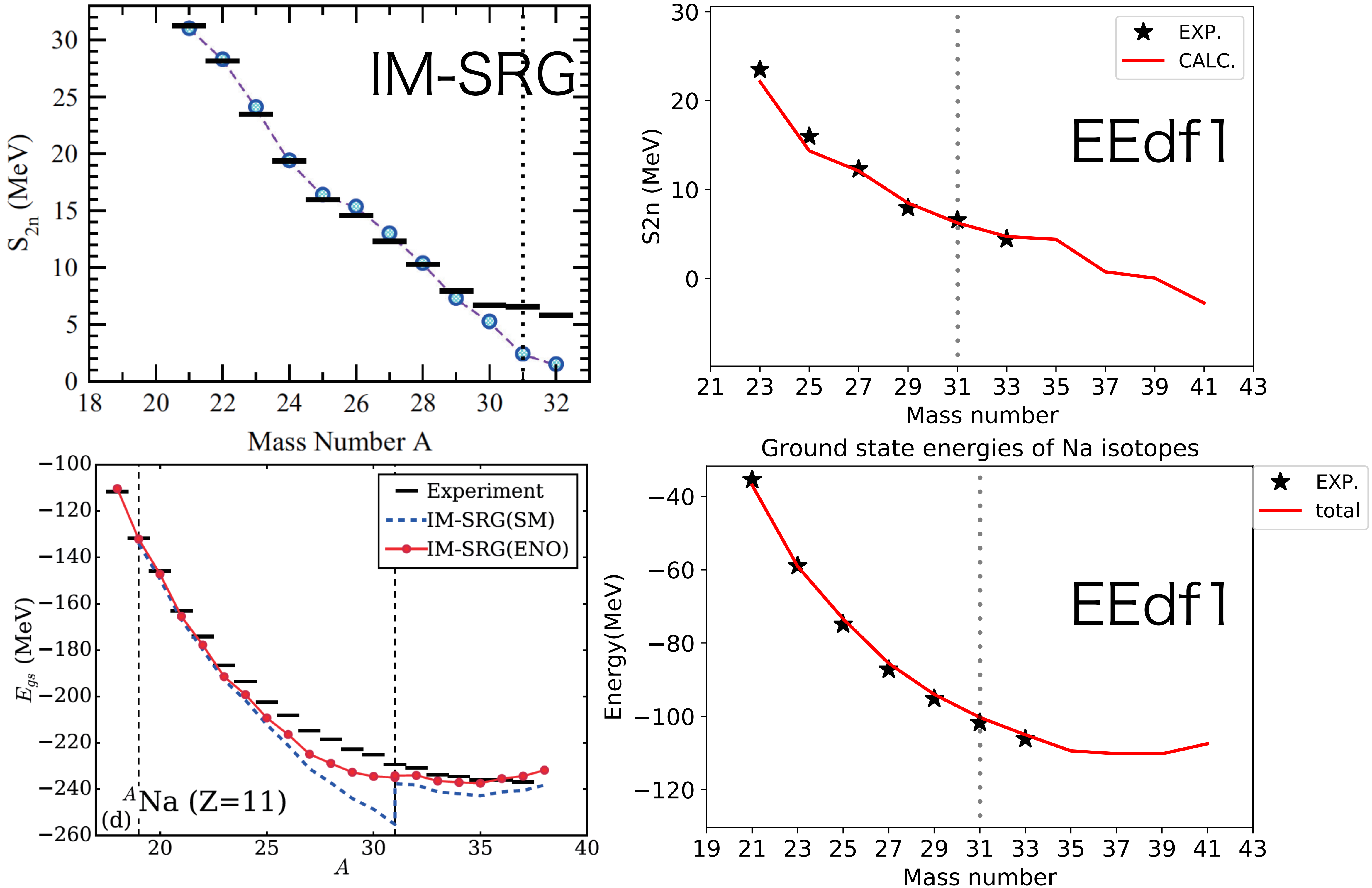
Similar ph excitation pattern to:

A. O. Macchiavelli, et al., Phys. Rev. C 94, 051303 (2016).

For larger N, we are now working on…

(e.g. 40Mg 2+ by Crawford's talk)

Comparison to ab initio calculations



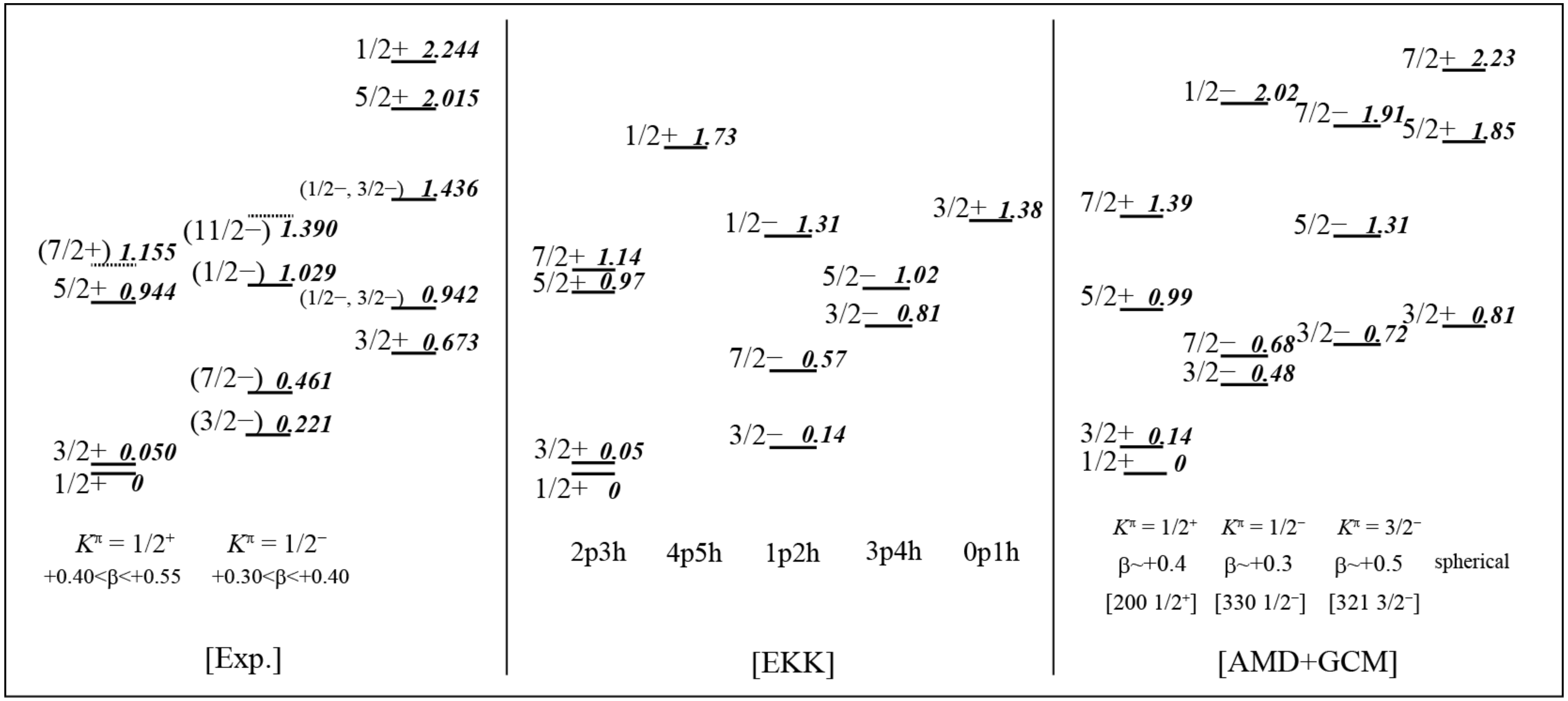
S. R. Stroberg, et al., Phys. Rev. Lett. 118, 032502 (2017).

J. Simonis, et al., Phys. Rev. C 96, 014303 (2017).

Experiment of 32Ne @RIBF (preliminary)

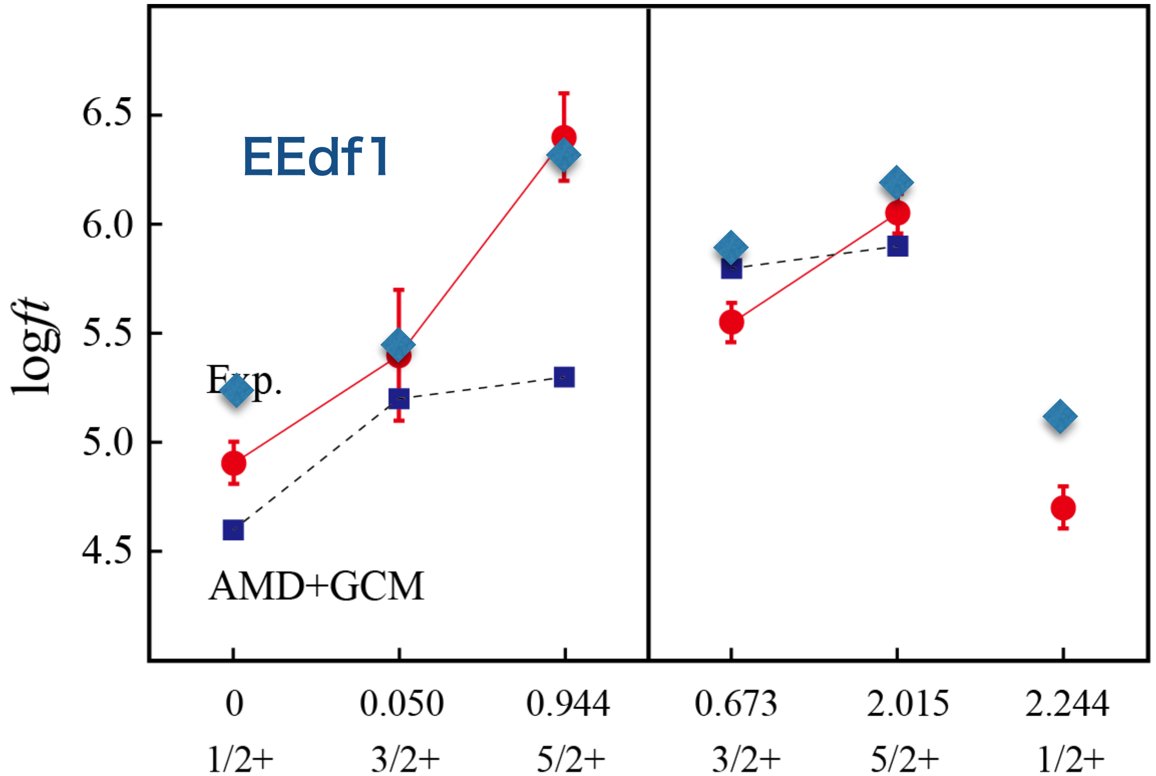
Ian Murray et al. (in preparation)

Experiment of 31Mg @Triumf



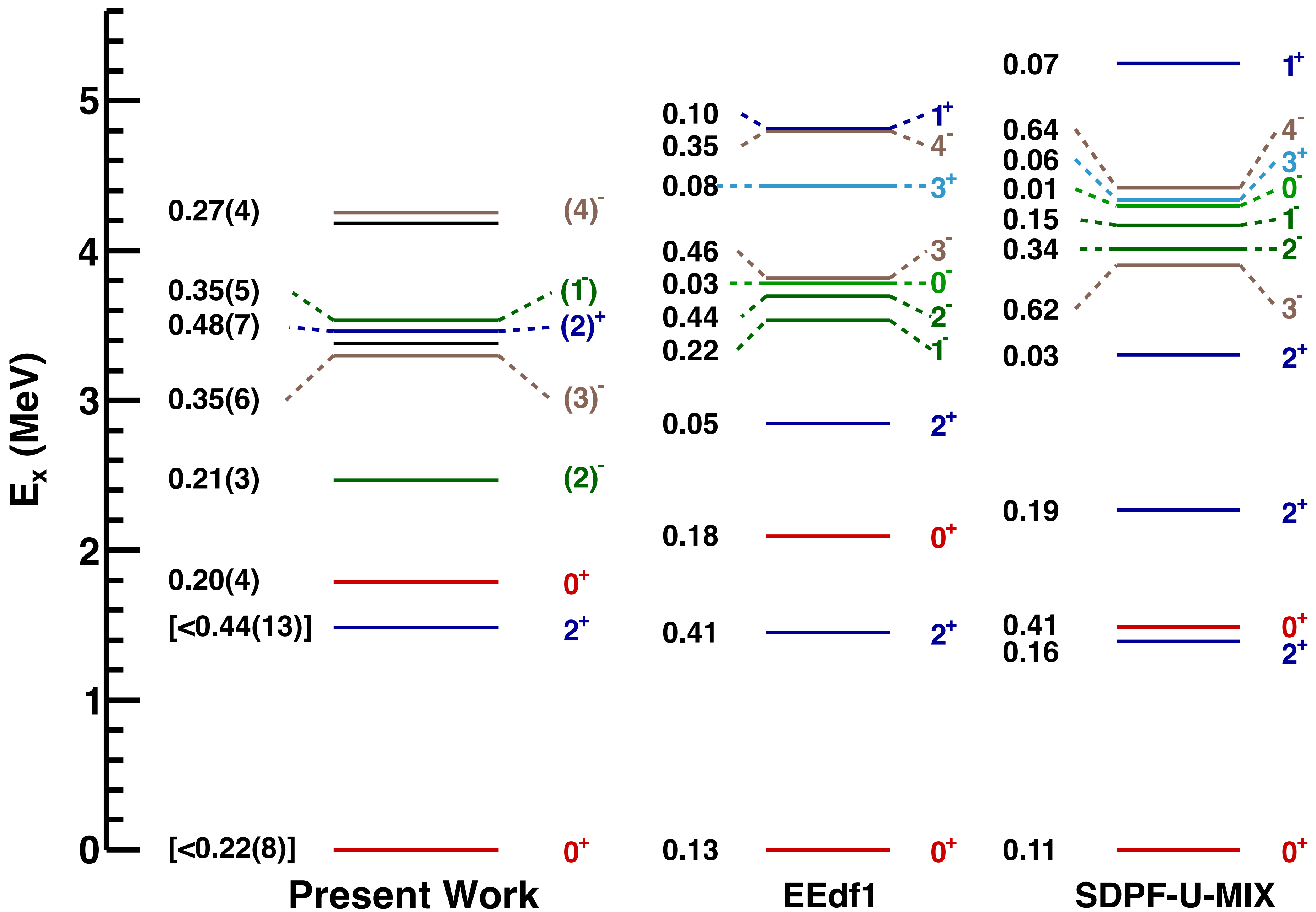
Good agreement to experimental data

talk by Dr. Nishibata



Spectroscopic factors and levels of 30Mg @GANIL

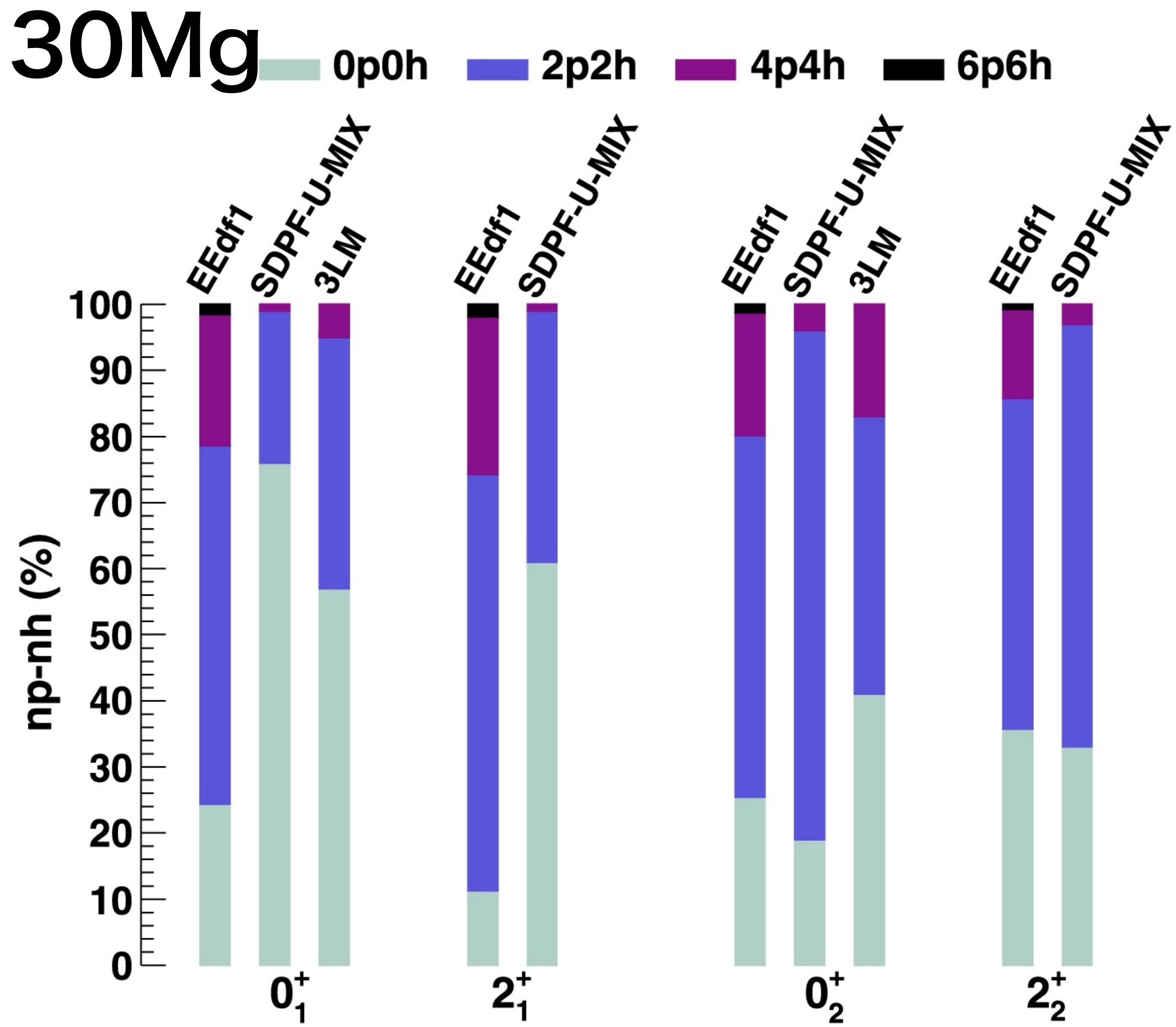
Single neutron removal from 31Mg to 30Mg



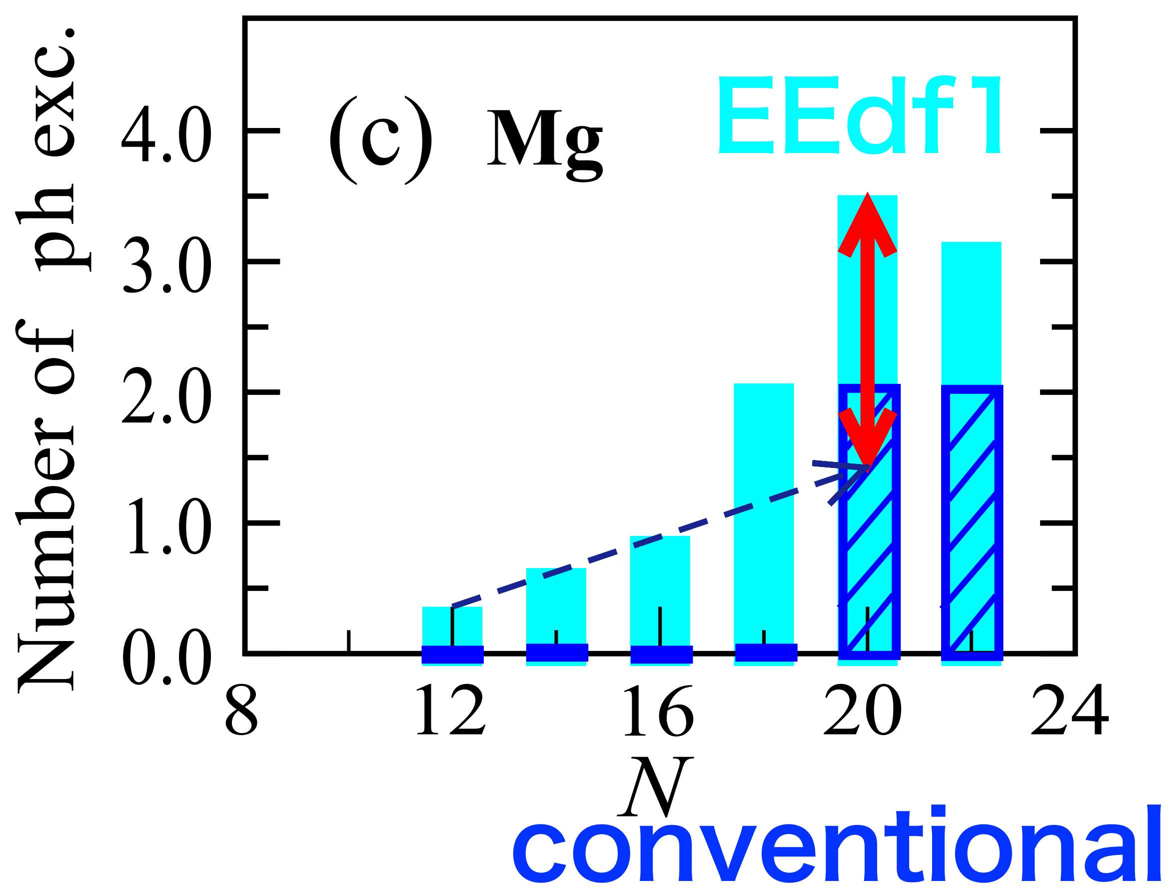
Low-lying levels and spectroscopic factors are reproduced.

B. Fernández-Domínguez, …. T. Otsuka, N.T. ….et al., Phys. Lett. B 779, 124 (2018).

What is essential in EEdf1?



Ground states



More ph excitation beyond N=20 occurring in EEdf1

==> More correlation, more deformation

B. Fernández-Domínguez, …. T. Otsuka, N.T. ….et al., Phys. Lett. B 779, 124 (2018).

Dripline physics @ RIBF

[redacted]

DeukSoon Ahn et al. in preparation

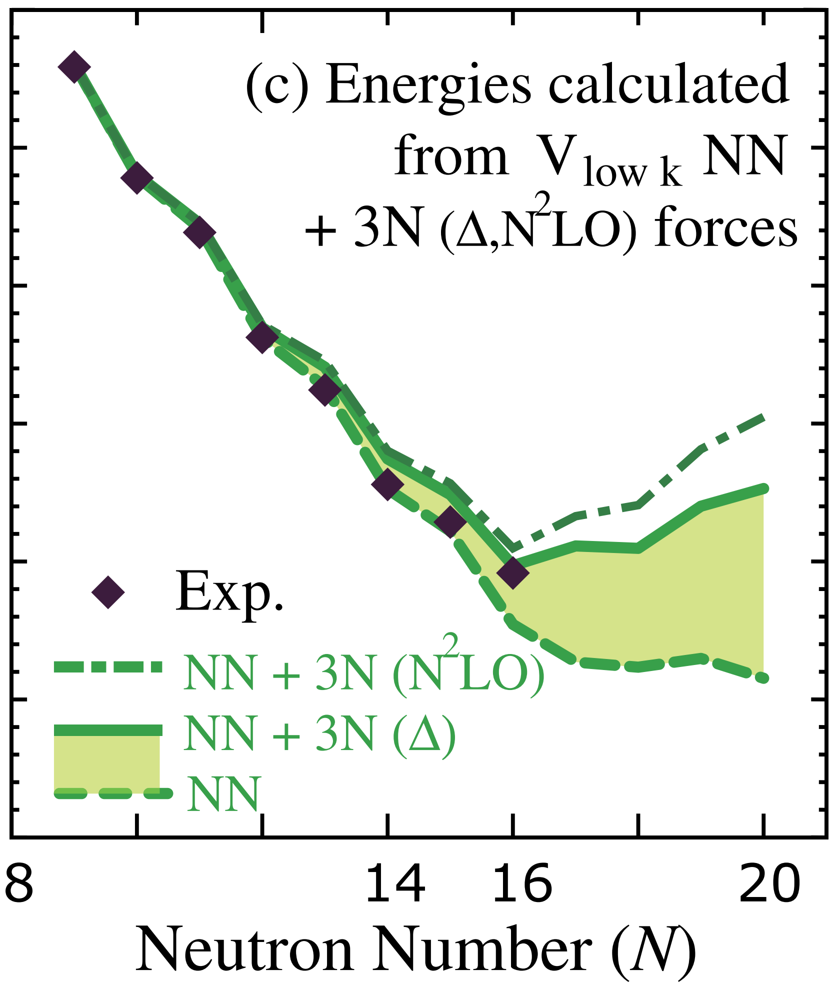
==> 36Ne does **NOT** exist and 39Na **EXISTS**.

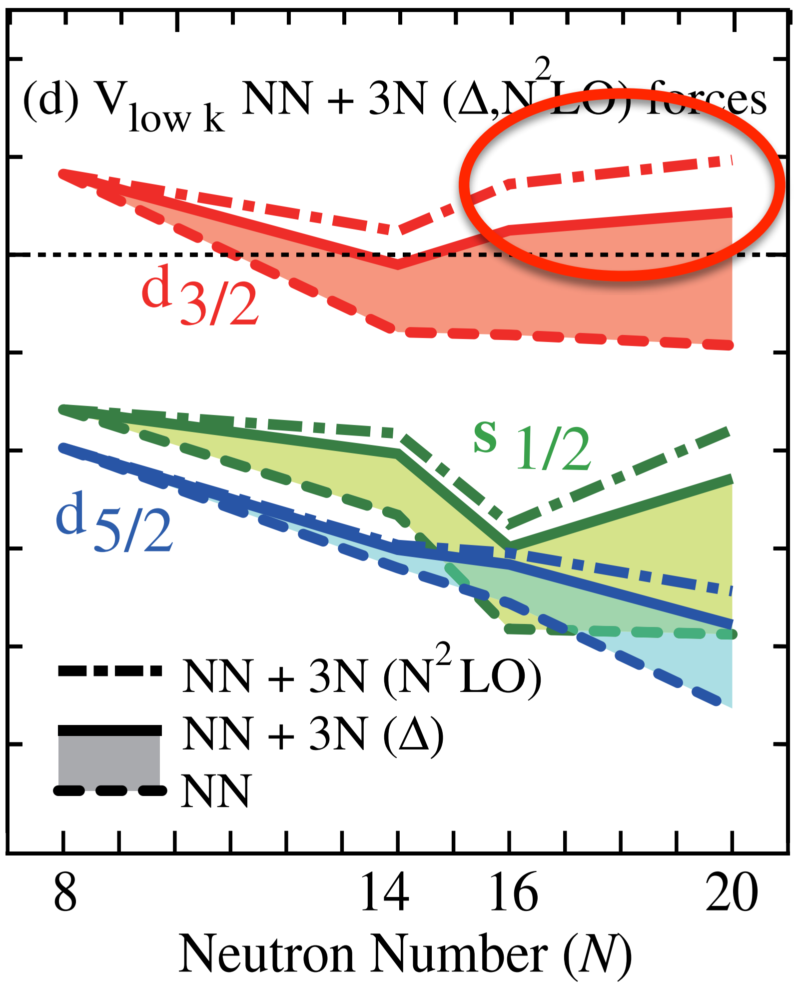
What is the mechanism of this dripline?
Relation to large mixing beyond N=20 gap?

Dripline in Oxygen case

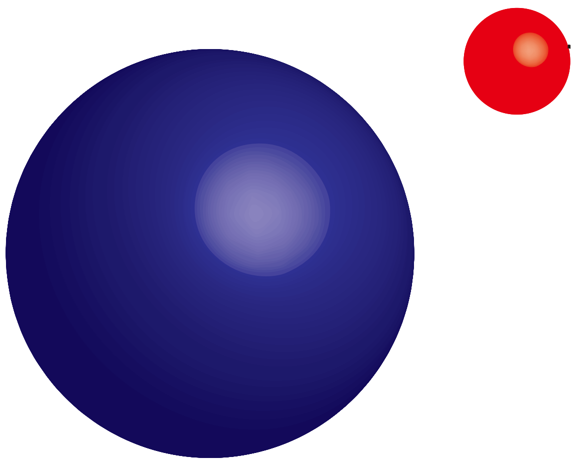
Oxygen case

T. Otsuka et al., Phys. Rev. Lett. 105, 032501 (2010).





positive ESPE



ESPE mostly determines drip line

Anatomy of interaction

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

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

pairing J=0 (monopole removed)

multipole other (QQ etc.)

Anatomy of interaction

bare and effective SPE

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

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

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Anatomy of interaction

bare and effective SPE

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

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correlation

pairing J=0 (monopole removed)

multipole other (QQ etc.)

Anatomy of interaction

bare and effective SPE

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

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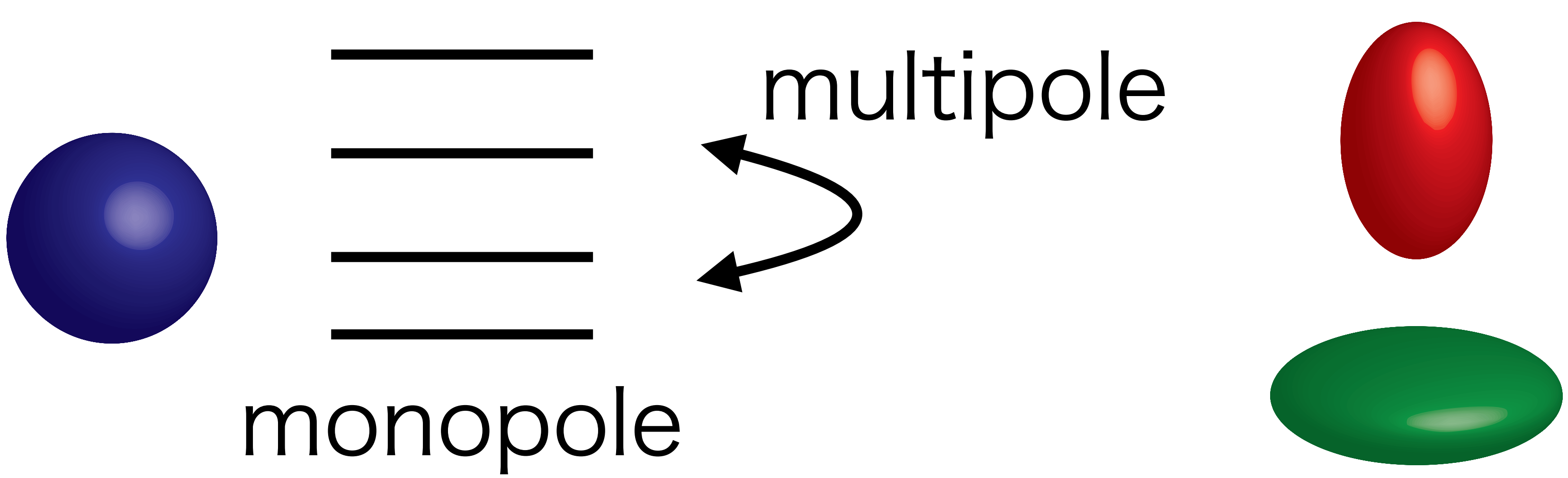
correlation

pairing J=0 (monopole removed)

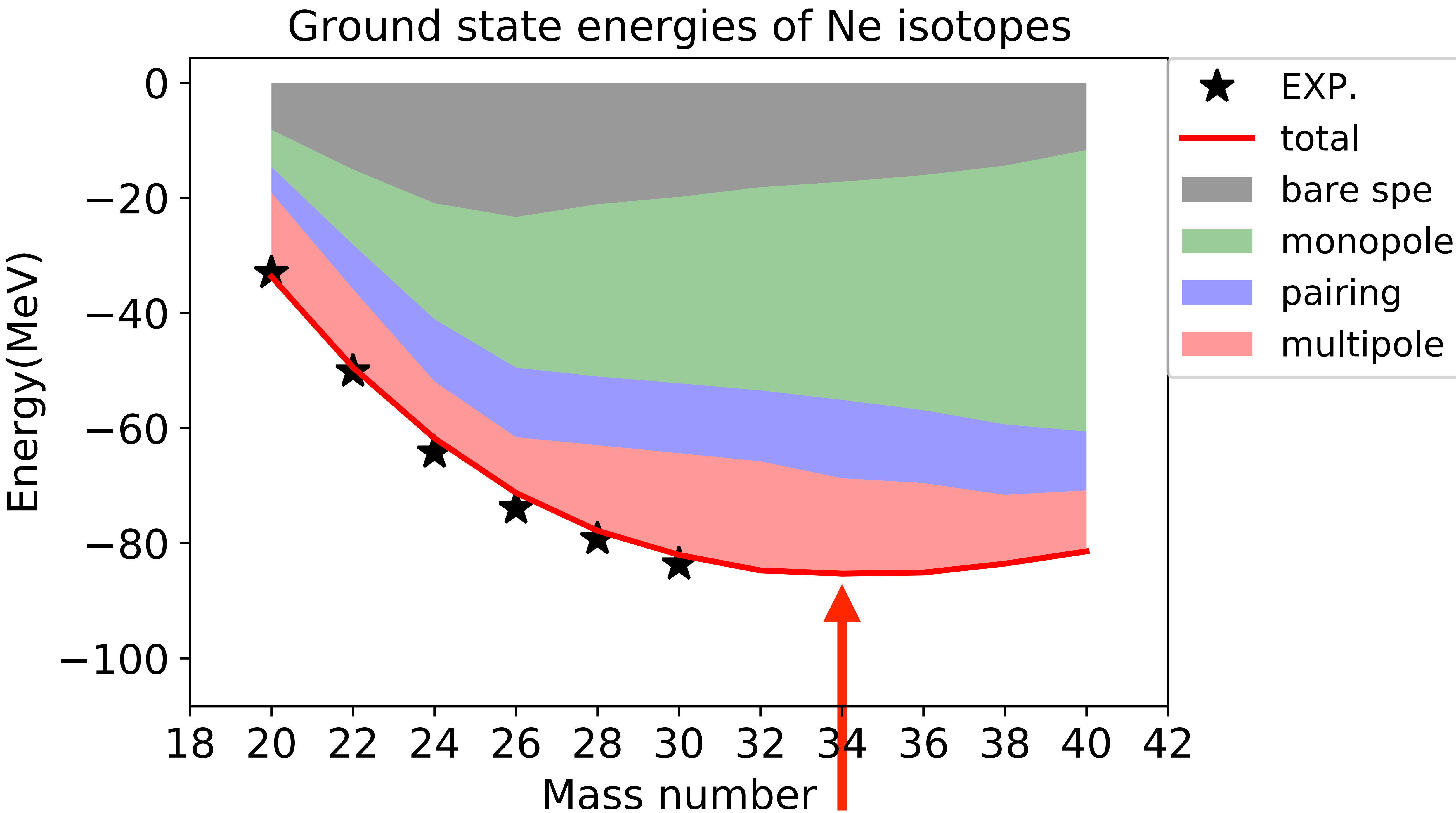
deformation

multipole other (QQ etc.)



Ne isotope

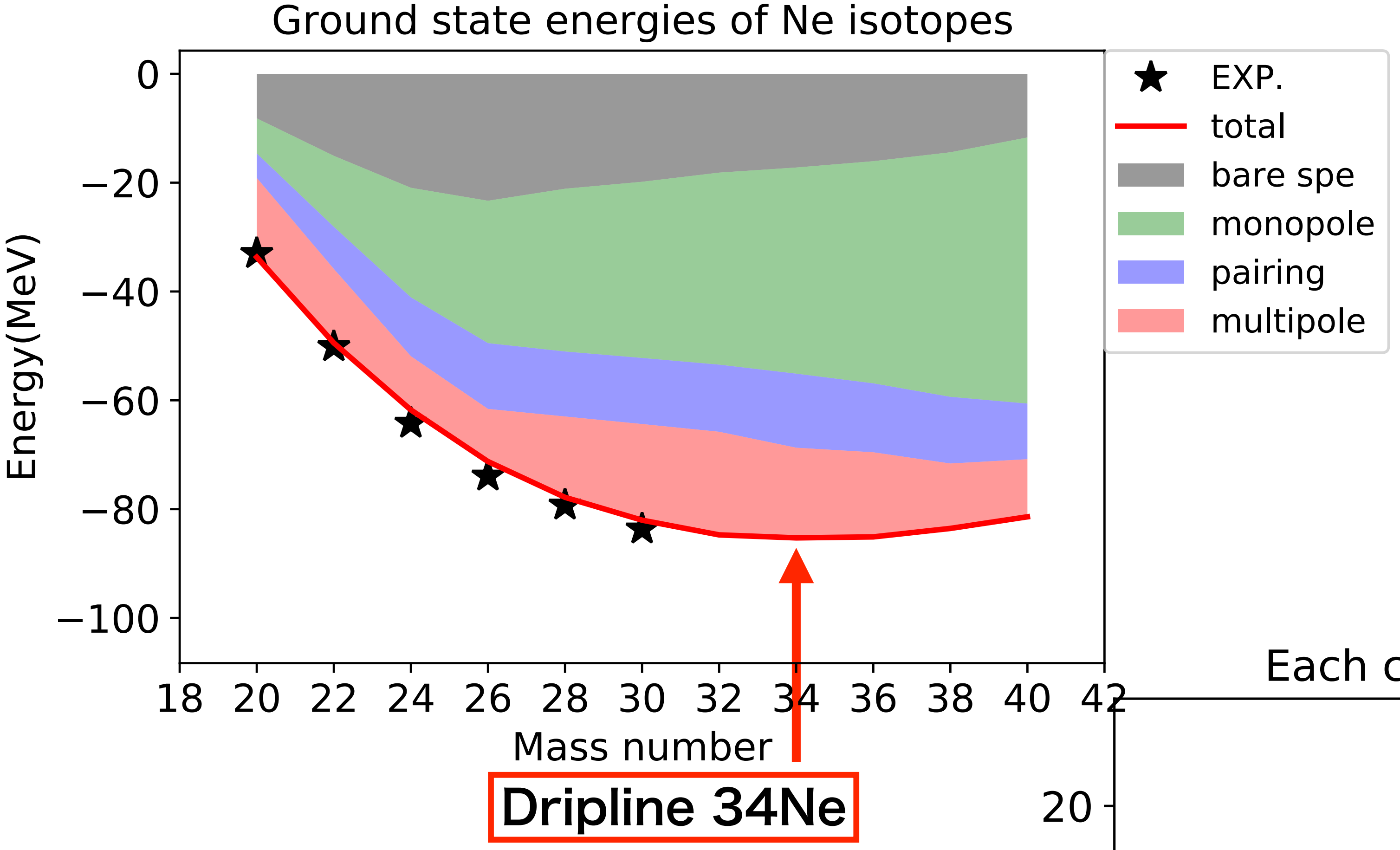
(all the SPEs shifted by 0.9 MeV)

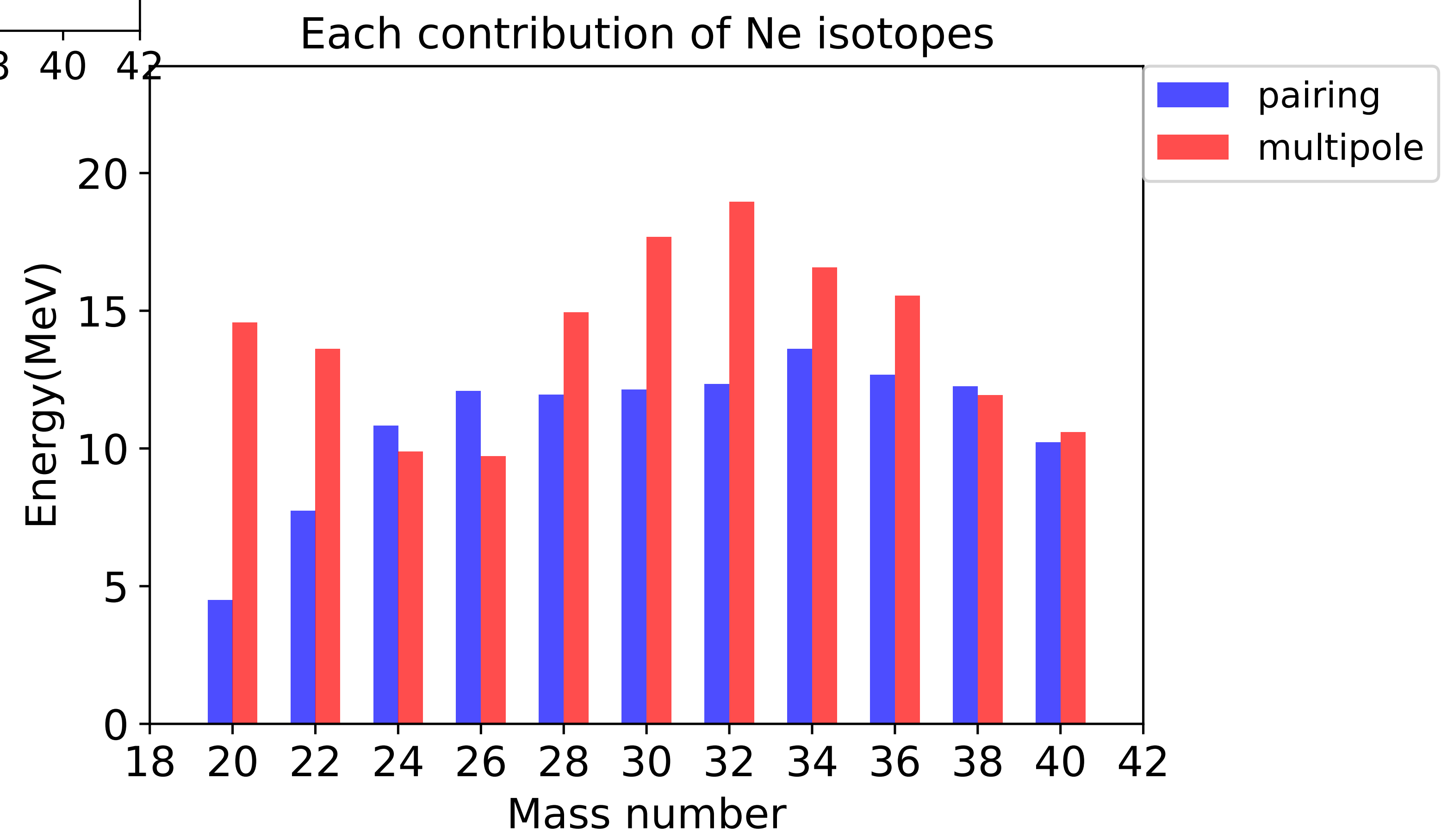


Dripline 34Ne

Ne isotope

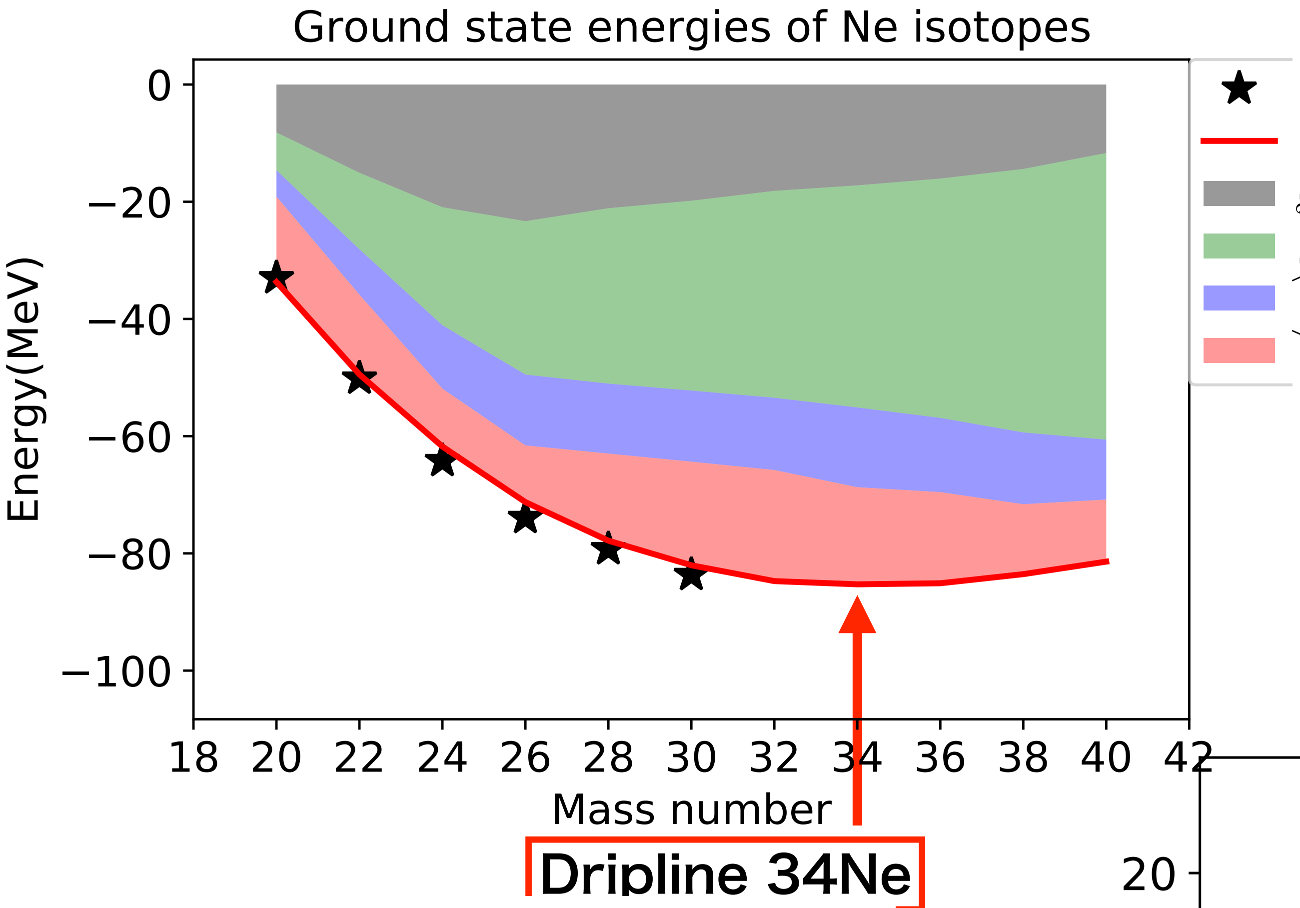
(all the SPEs shifted by 0.9 MeV)

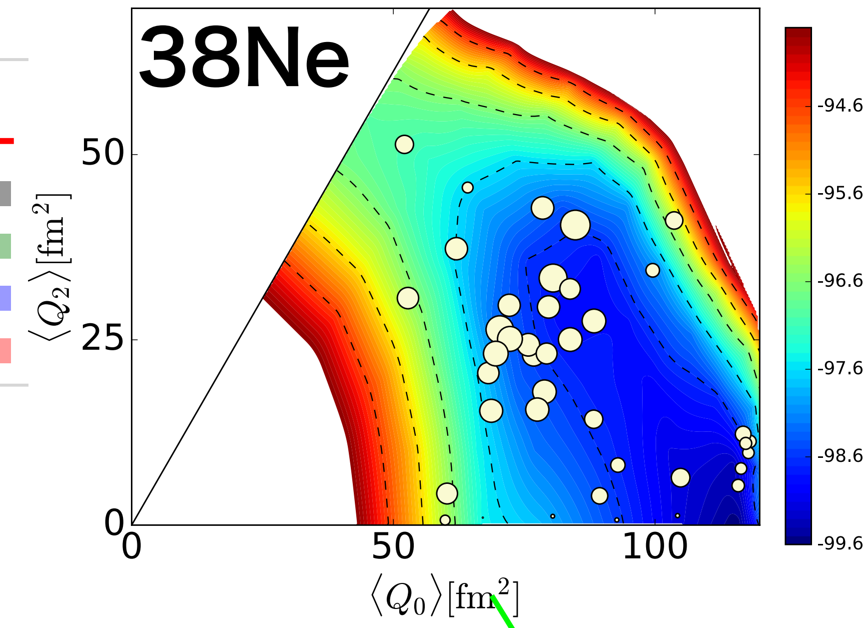


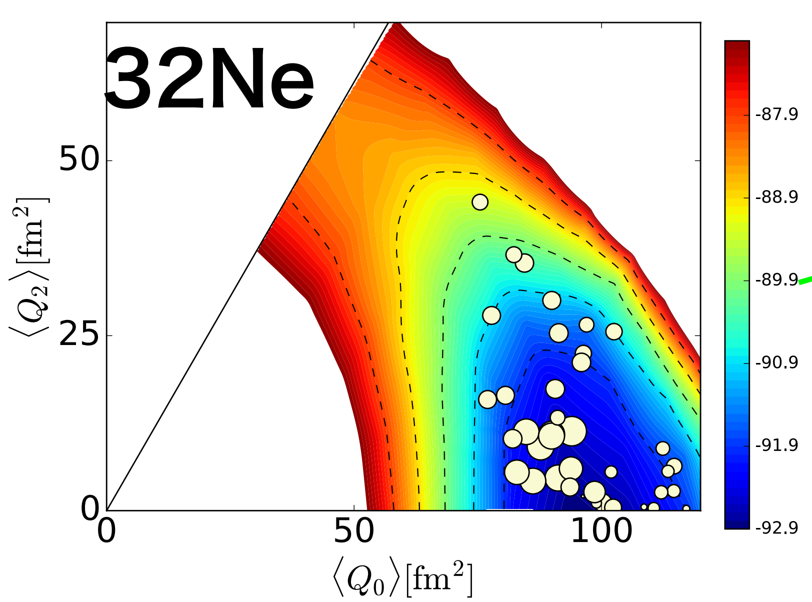


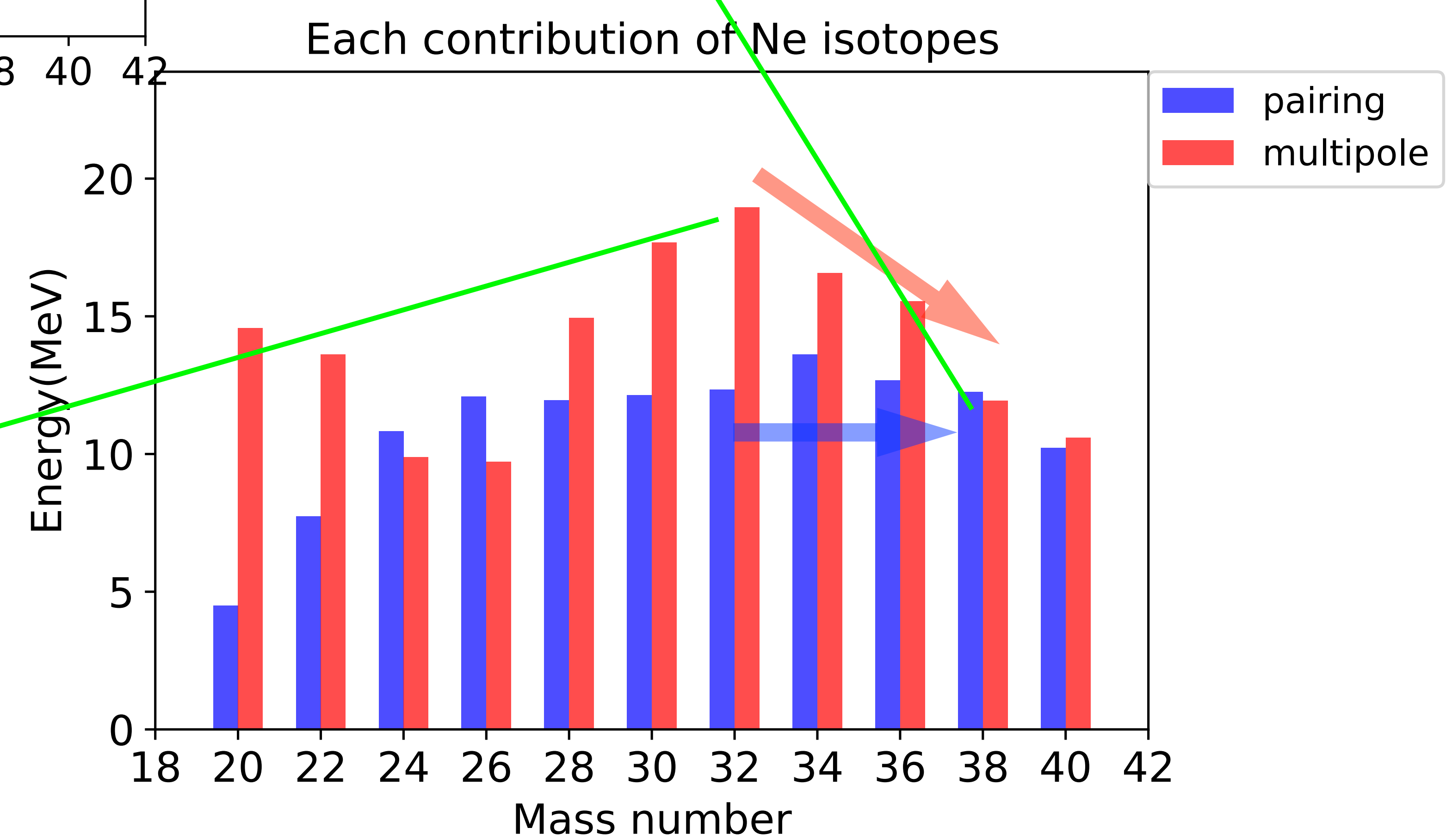
Ne isotope

(all the SPEs shifted by 0.9 MeV)

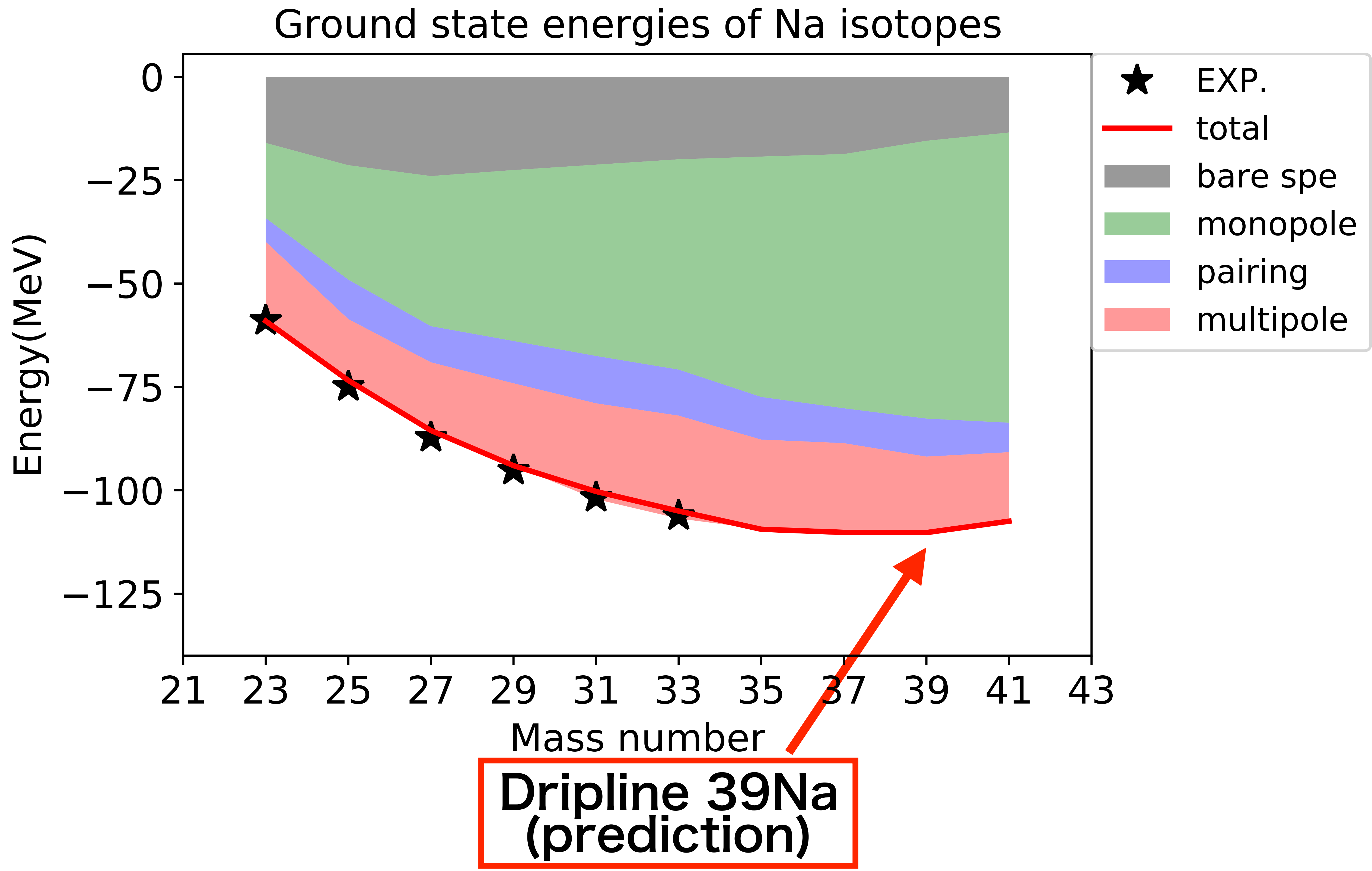






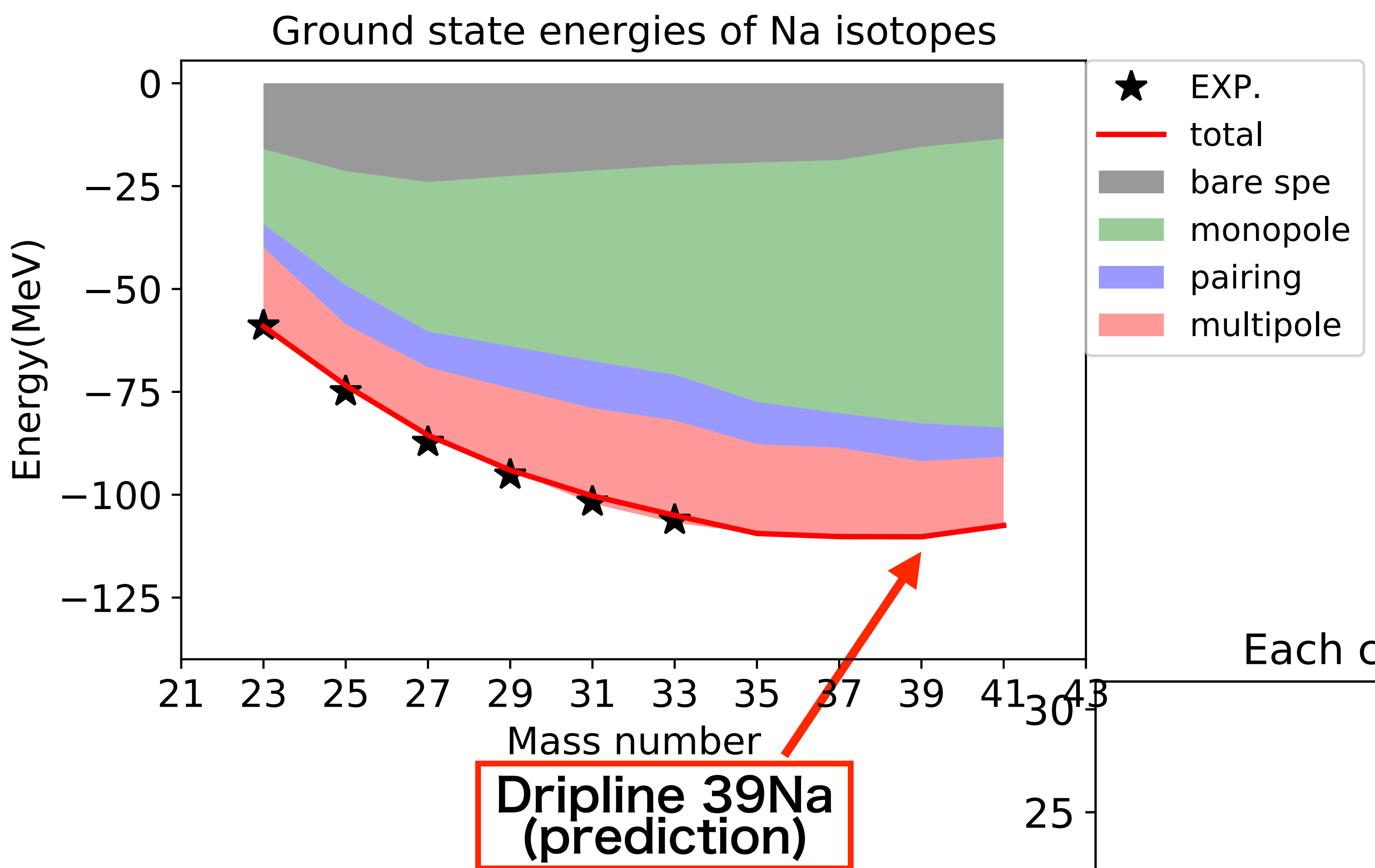


Na isotope

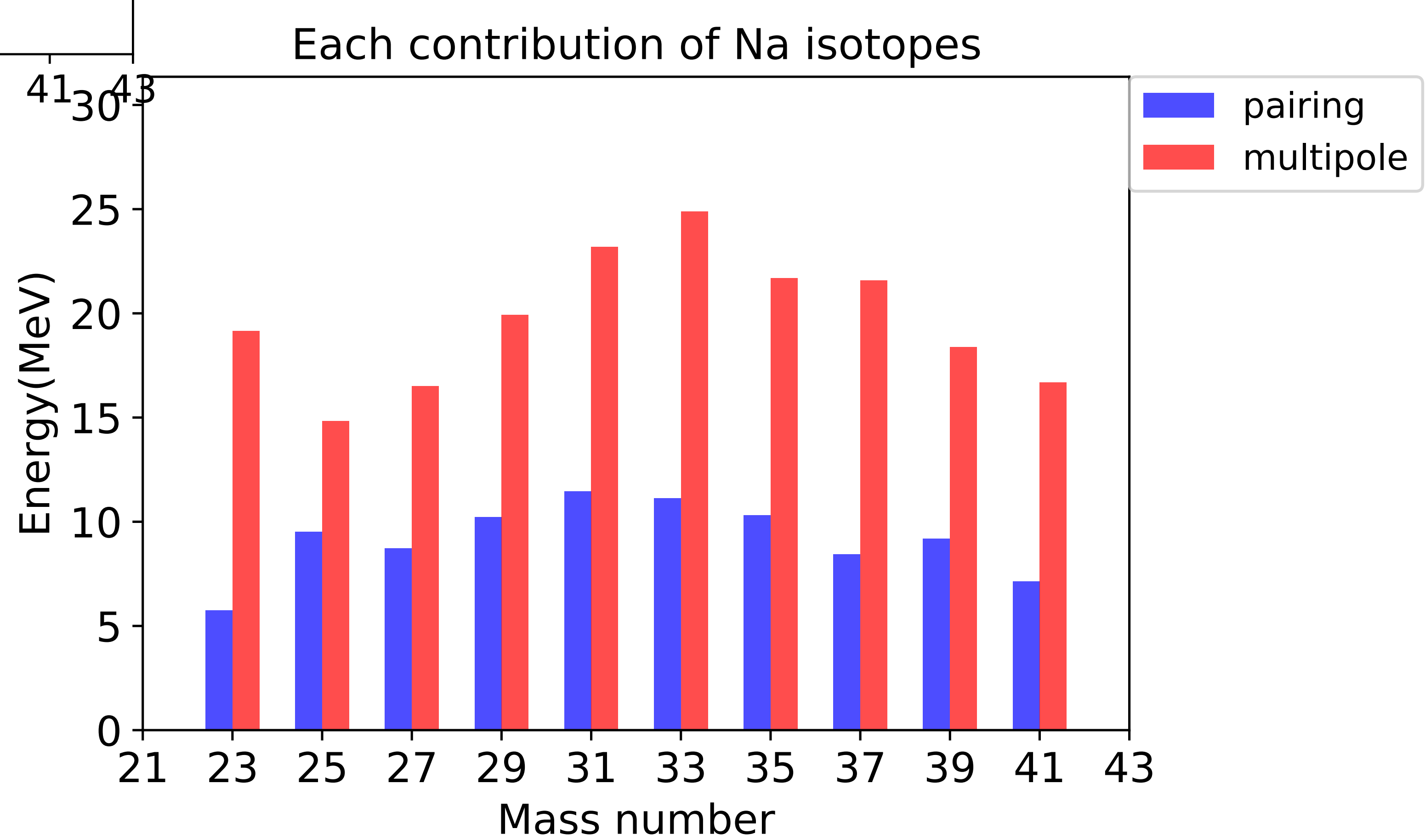


Ground state energies of Na isotopes
Energy(MeV)
0
−25
−50
−75
−100
−125
21 23 25 27 29 31 33 35 37 39 41 43
Mass number
EXP.
total
bare spe
monopole
pairing
multipole
Dripline 39Na
(prediction)

Na isotope

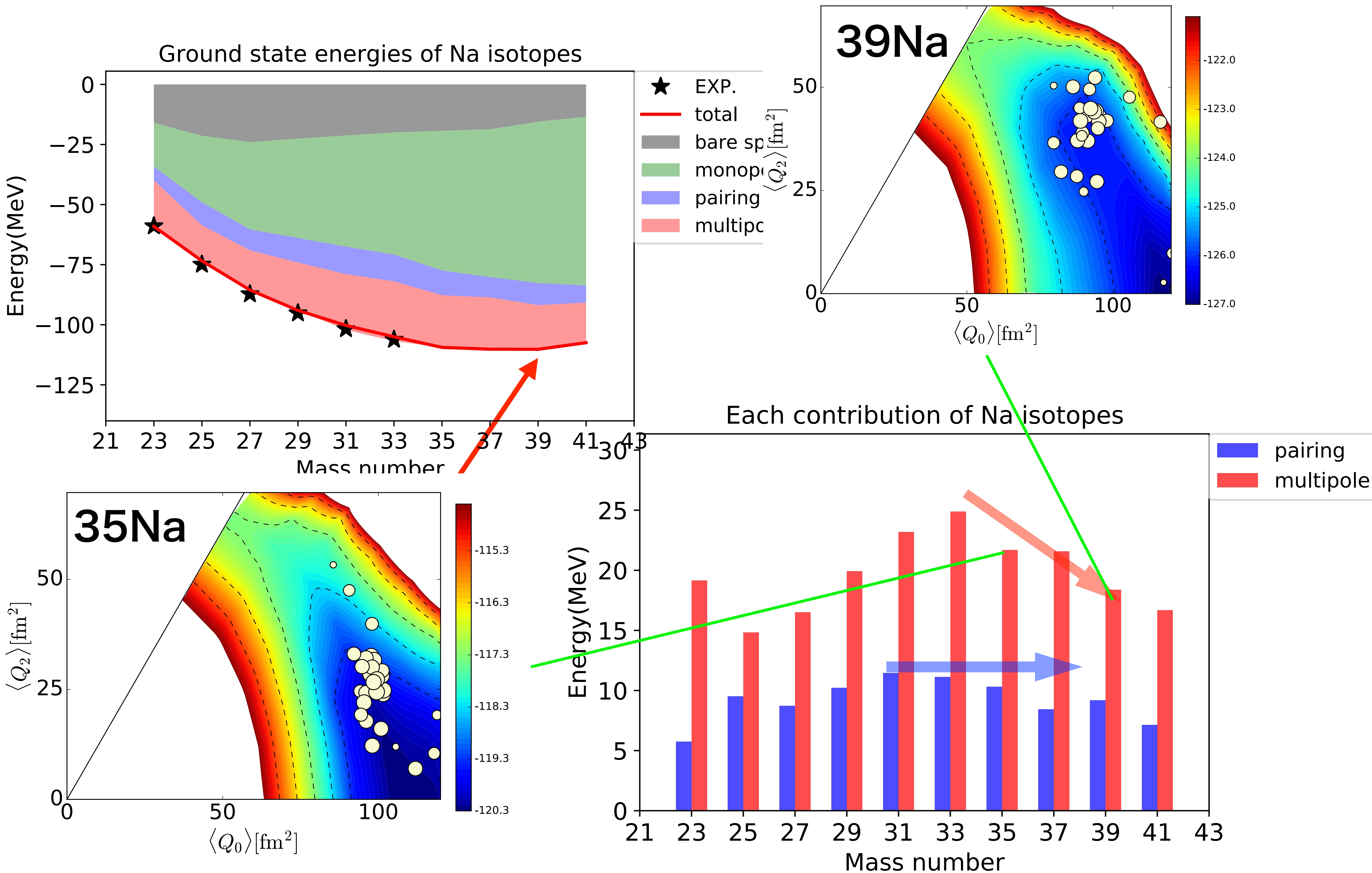


Ground state energies of Na isotopes
Energy(MeV)
Mass number
EXP.
total
bare spe
monopole
pairing
multipole
Dripline 39Na (prediction)

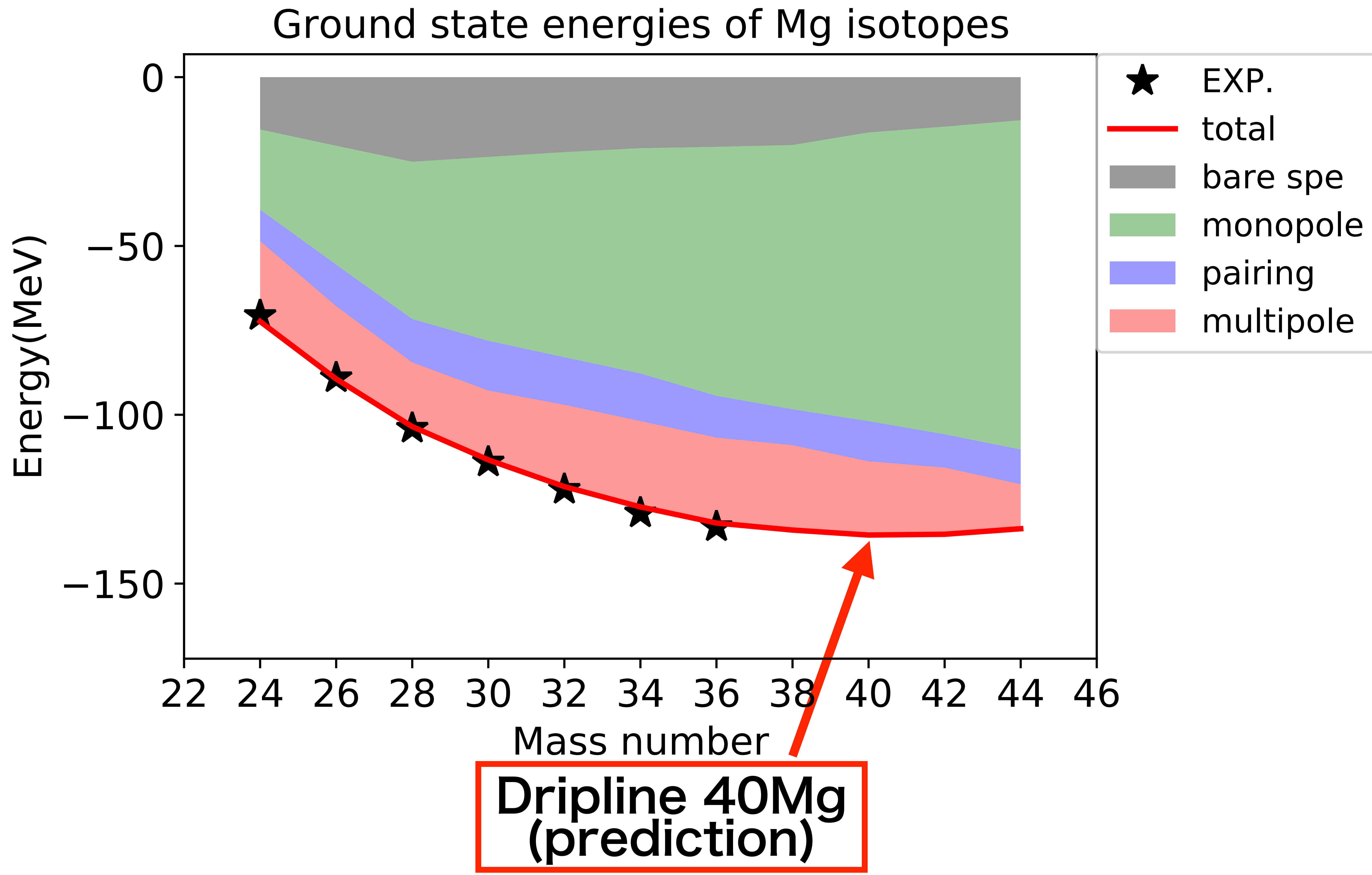


Each contribution of Na isotopes
Energy(MeV)
Mass number
pairing
multipole

Na isotope

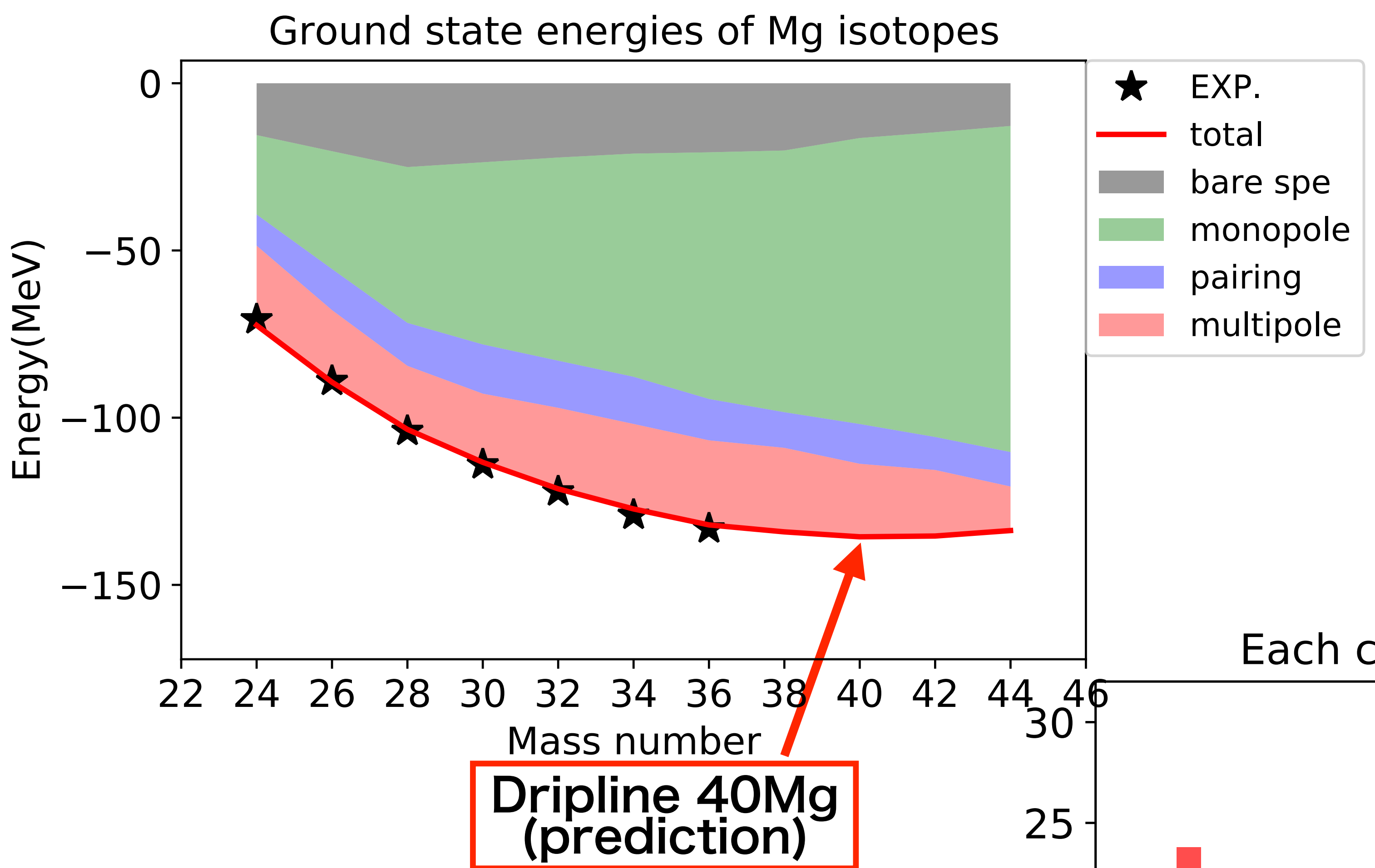

Ground state energies of Na isotopes
Energy(MeV)
Mass number
EXP.
total
bare sp
monop
pairing
multipo
39Na
35Na
$\langle Q_0 \rangle [\mathrm{fm}^2]$
$\langle Q_2 \rangle [\mathrm{fm}^2]$
Each contribution of Na isotopes
pairing
multipole

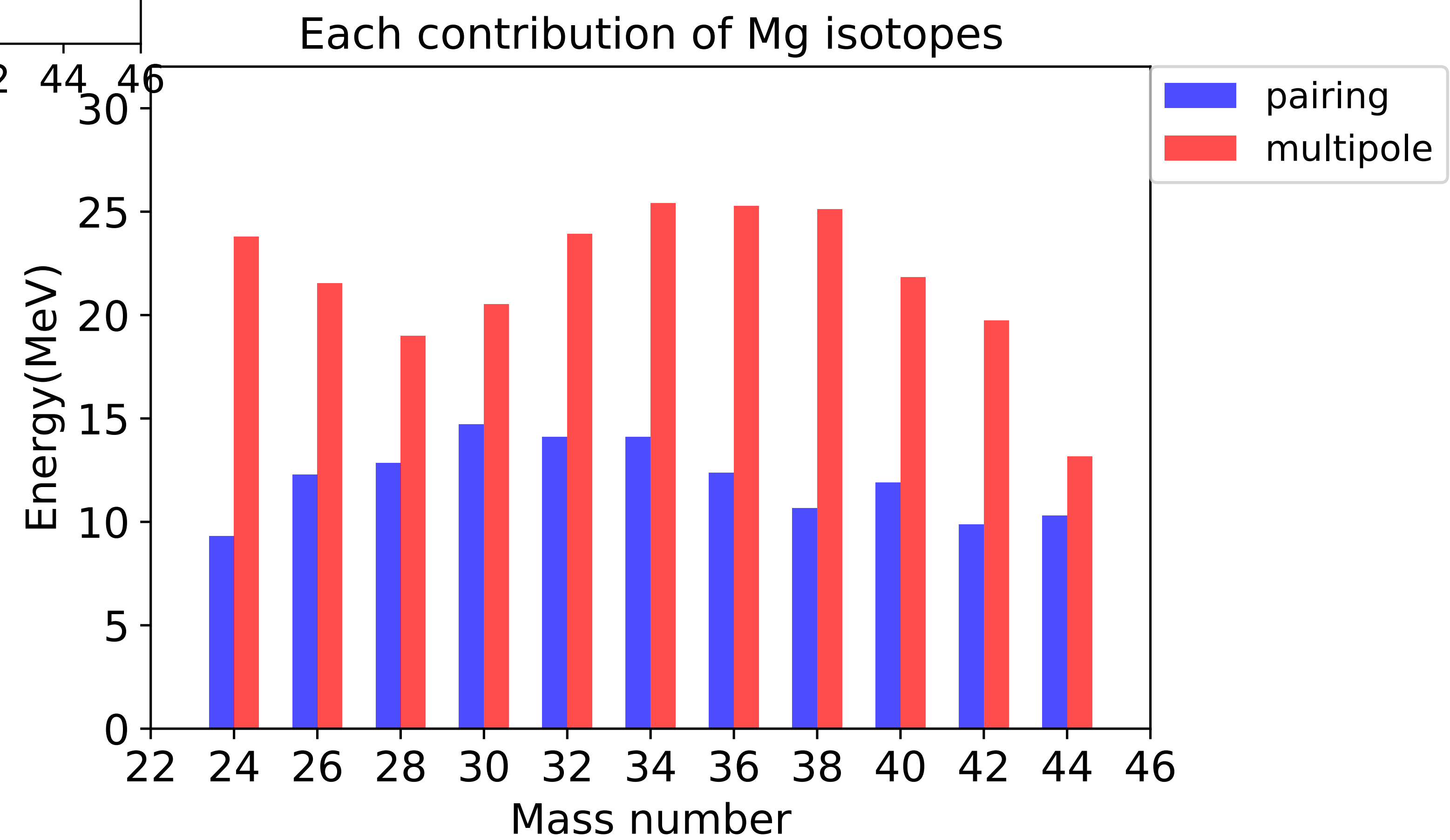
Mg isotope



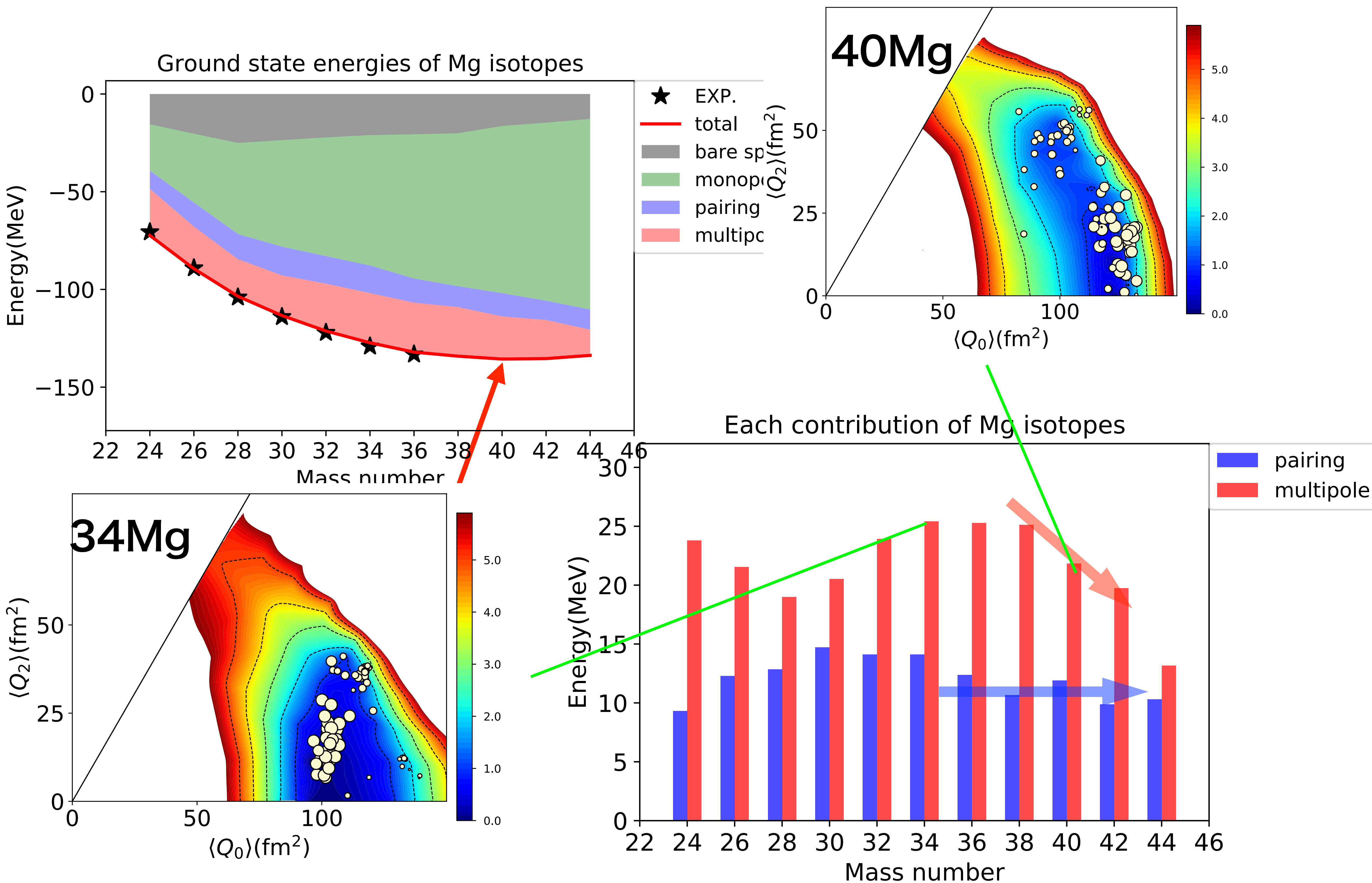
Ground state energies of Mg isotopes
0
−50
−100
−150
Energy(MeV)
22
24
26
28
30
32
34
36
38
40
42
44
46
Mass number
EXP.
total
bare spe
monopole
pairing
multipole
Dripline 40Mg
(prediction)

Mg isotope


Ground state energies of Mg isotopes
0
−50
−100
−150
Energy(MeV)
22 24 26 28 30 32 34 36 38 40 42 44 46
Mass number
EXP.
total
bare spe
monopole
pairing
multipole
Dripline 40Mg
(prediction)

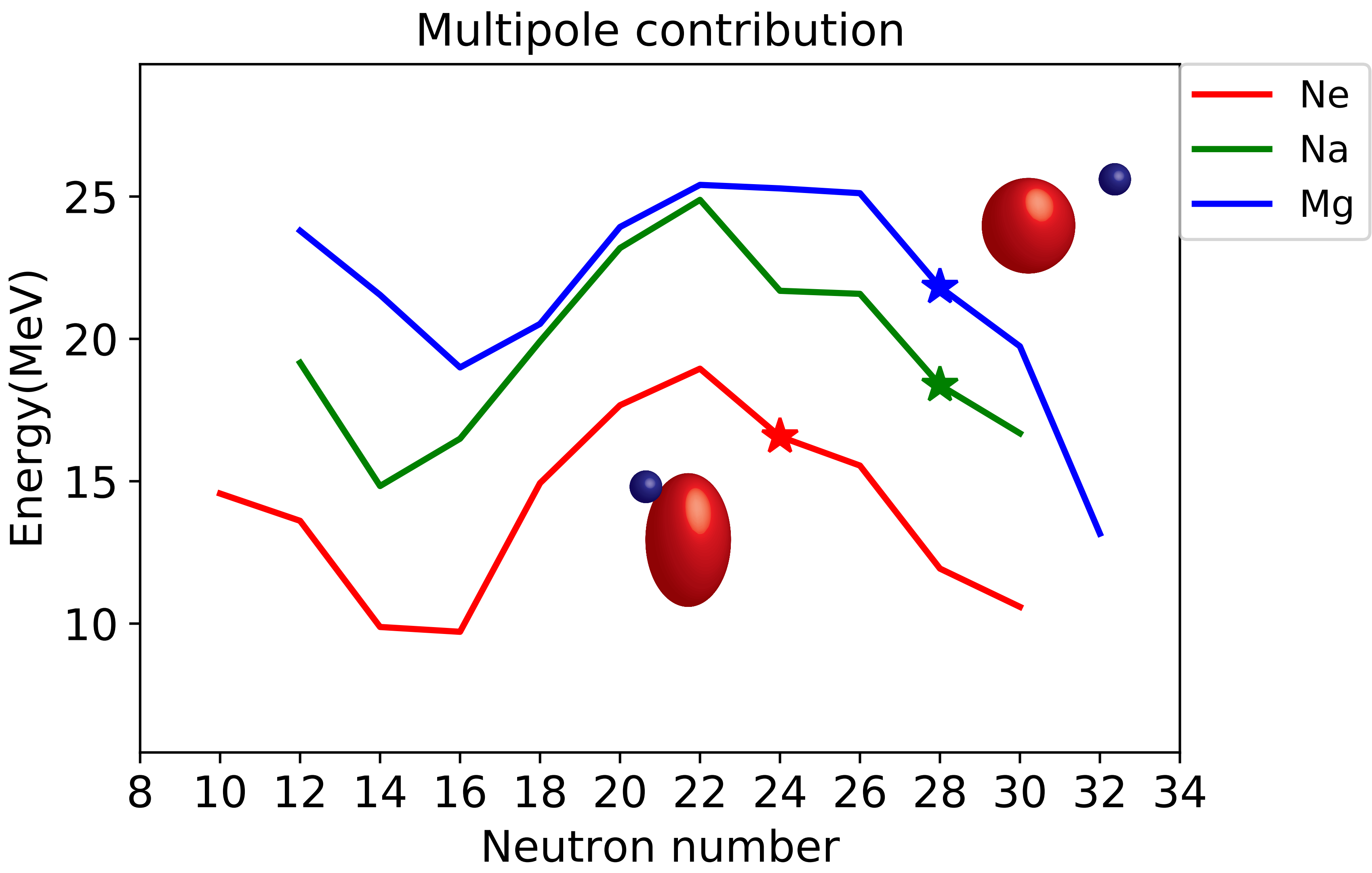

Each contribution of Mg isotopes
0
5
10
15
20
25
30
Energy(MeV)
22 24 26 28 30 32 34 36 38 40 42 44 46
Mass number
pairing
multipole

Mg isotope



Ground state energies of Mg isotopes
EXP.
total
bare sp
monop
pairing
multipo
Energy(MeV)
Mass number
40Mg
34Mg
$\langle Q_2 \rangle (\mathrm{fm}^2)$
$\langle Q_0 \rangle (\mathrm{fm}^2)$
Each contribution of Mg isotopes
pairing
multipole
Energy(MeV)
Mass number

Multipole contribution



The mechanism of dripline

==> **competition** between EPSE and Deformation

negative ESPE but **less deformation energy**

Conclusion

- Neutron-rich nuclei are studied by nuclear force and microscopic theory
- Comparisons to experimental data are successful
- Driplines of Ne, Na and Mg are determined by the competitions of **single particle nature** and **multipole contribution**

collaborators

- Takaharu Otsuka
- Noritaka Shimizu
- Kazuo Takayanagi
- Morten Hjorth-Jensen
- Toshio Suzuki
- DeukSoon Ahn (and her collaborators)
- Hiroki Nishibata (and his collaborators)
- B. Fernández-Domínguez (and her collaborators)
- Ian Murray (and his colloborators)