Ab initio resonance and continuum Gamow shell model: applied to calcium isotopes up to beyond dripline

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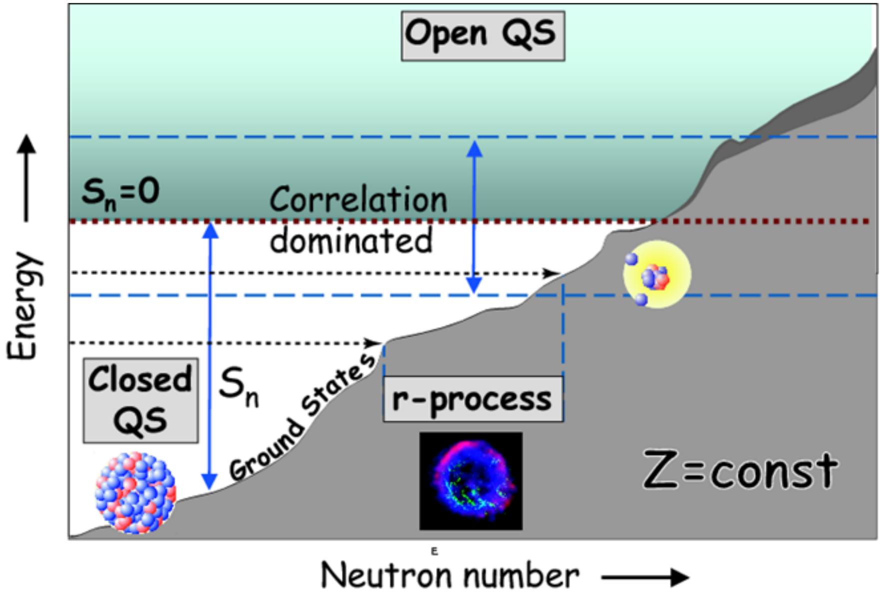
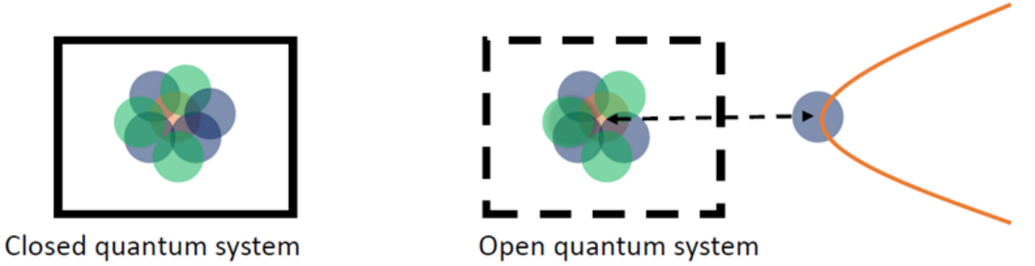
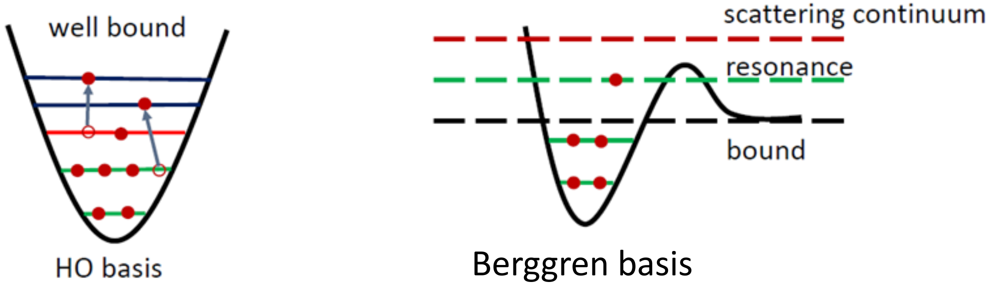
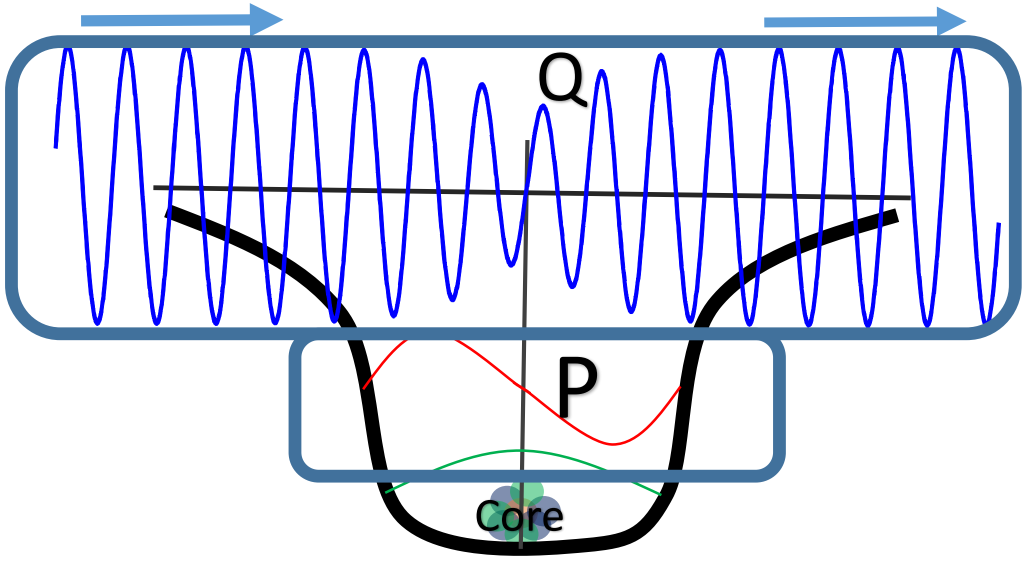
Peking University

Weakly bound and unbound nuclei



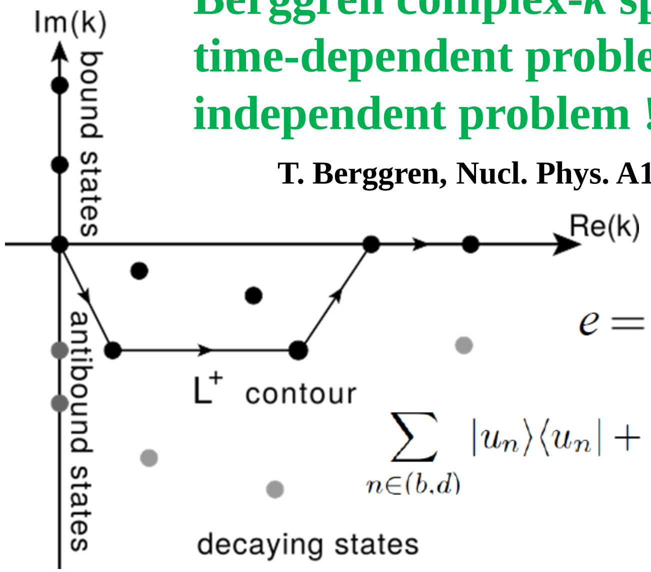






Berggren complex-*k* space transfers a time-dependent problem to a time-independent problem !

T. Berggren, Nucl. Phys. A109 (1968) 265



$$e=\frac{\hbar^2k^2}{2m}=e_n-i\frac{\gamma_n}{2}$$

$$\sum_{n\in(b,d)}|u_n\rangle\langle u_n|+\int_{L^+}|u(k)\rangle\langle u(k)|dk=1$$

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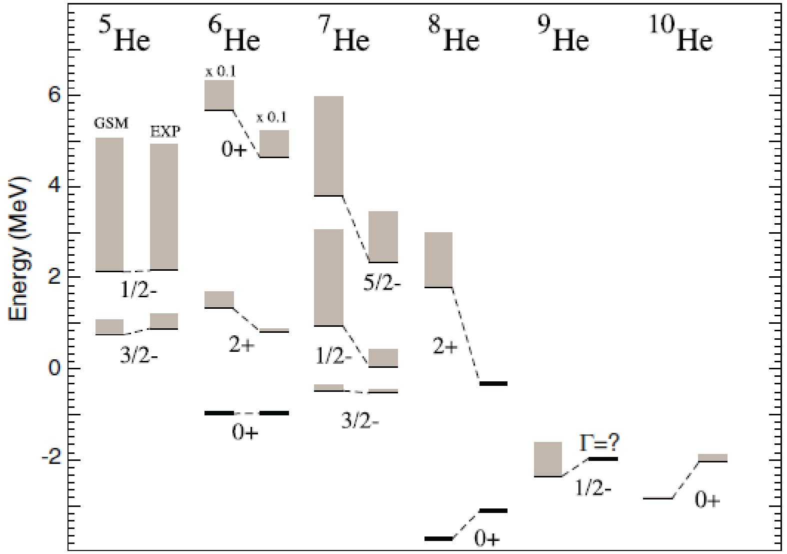
Gamow shell model for weakly bound or unbound nuclei

$$H = H_{onebody}(WS) + V_{J,T}(\vec{r}_1, \vec{r}_2)$$

Phenomenological nuclear force

$$V_{J,T}(\mathbf{r}_1,\mathbf{r}_2) =$$
$$V_0(J,T)\cdot\exp\left[-\left(\frac{\mathbf{r}_1-\mathbf{r}_2}{\mu}\right)^2\right]\cdot\delta(|\mathbf{r}_1|+|\mathbf{r}_2|-2\cdot R_0)$$



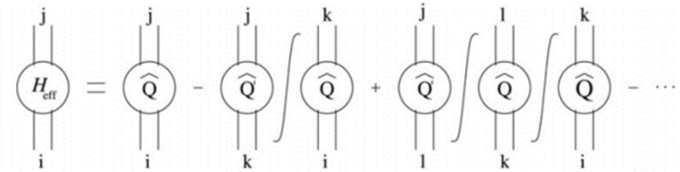
N.Michel, Nazarewicz, Płoszajczak, Vertse,

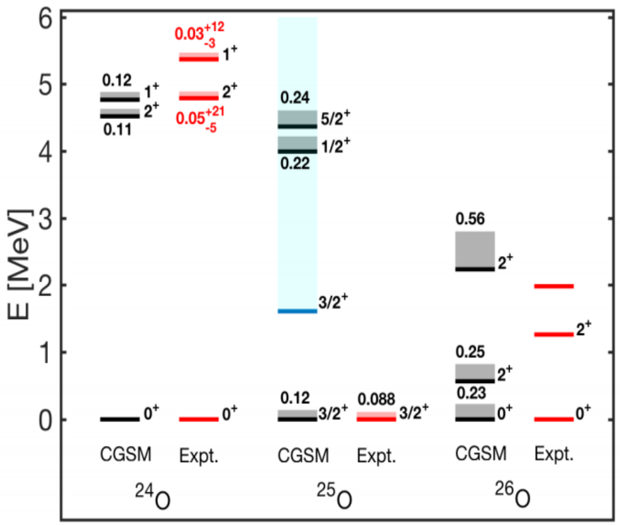
Phys. G: Nucl. Part. Phys. 36 (2009) 013101

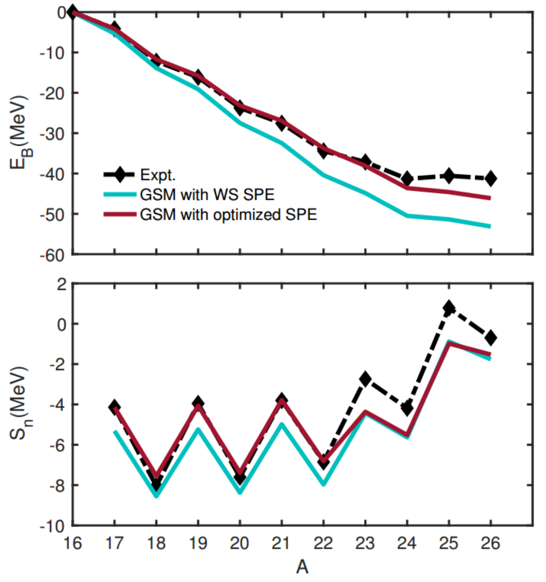
See Nicolas Michel's talk

$$H = \sum_{i=1}^{A}\frac{p_i^2}{2m} + \sum_{i<j=1}^{A} v_{ij}^{NN} - \frac{\mathbf{P}^2}{2Am}$$

Realistic nuclear force (CD-Bonn)







Z.H.Sun, Q.Wu, Z.H.Zhao, B.S.Hu, S.J,Dai, F.R.Xu

Phys. Lett. B 769 (2017) 227-232

Gamow shell model based on realistic nuclear force

Realistic nuclear force → Gamow shell model calculations（GSM）

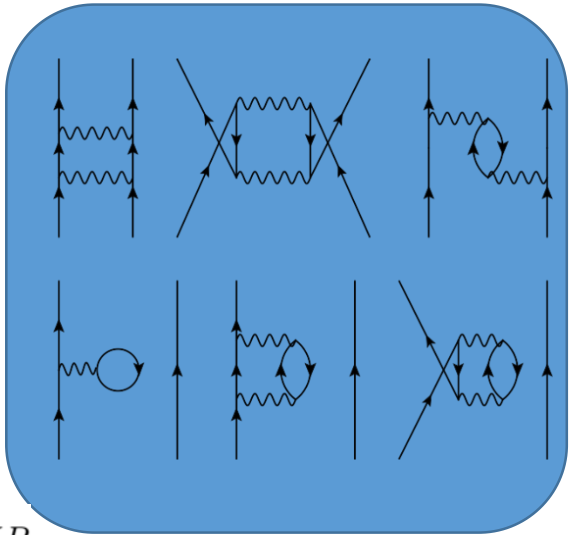
Bare forces: Strong repulsion, slow convergence

CD-Bonn

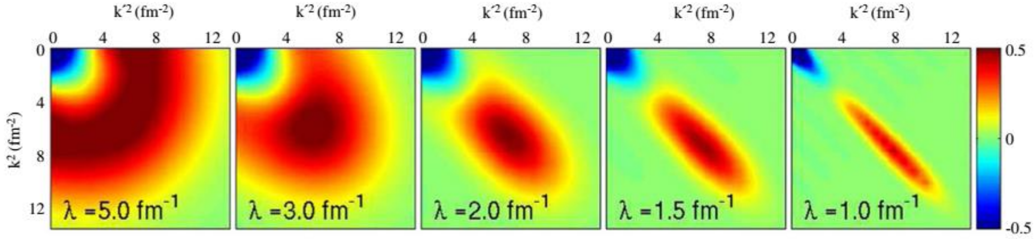
$V_{low\ k}$ or SRG

To remove hard core, but still keep good descriptions of NN scattering phase shifts

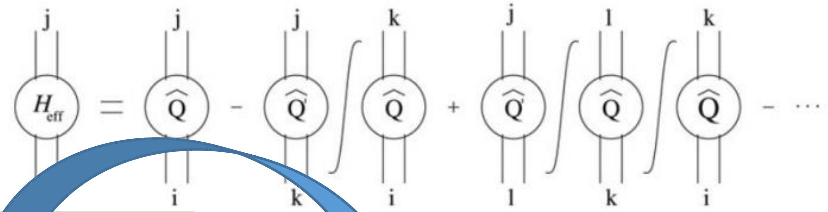
MBPT



$$\langle \alpha_P | \bar{H}_{\text{eff}} | \alpha_{P'} \rangle = \sum_{\alpha_{P''}} \sum_{\alpha_{P'''}} \sum_{kk'k'' \in \mathcal{K}} \langle \alpha_P | \tilde{k}'' \rangle \langle \tilde{k}'' | \alpha_{P''} \rangle \langle \alpha_{P''} | \tilde{k} \rangle E_k \langle \tilde{k} | \alpha_{P'''} \rangle \langle \alpha_{P'''} | \tilde{k}' \rangle \langle \tilde{k}' | \alpha_{P'} \rangle$$



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



$$H = \sum_{i=1}^{A} \frac{p_i^2}{2m} + \sum_{i<j=1}^{A} v_{ij}^{NN} - \frac{\boldsymbol{P}^2}{2Am}$$

$$\begin{pmatrix} PHP & PHQ \\ QHP & QHQ \end{pmatrix} \xrightarrow[\mathcal{Q}\mathcal{H}P = 0]{\mathcal{H} = X^{-1}HX} \begin{pmatrix} P\mathcal{H}P & P\mathcal{H}Q \\ 0 & \mathcal{Q}\mathcal{H}Q \end{pmatrix}$$

$$H_{\text{eff}} = P\mathcal{H}P$$

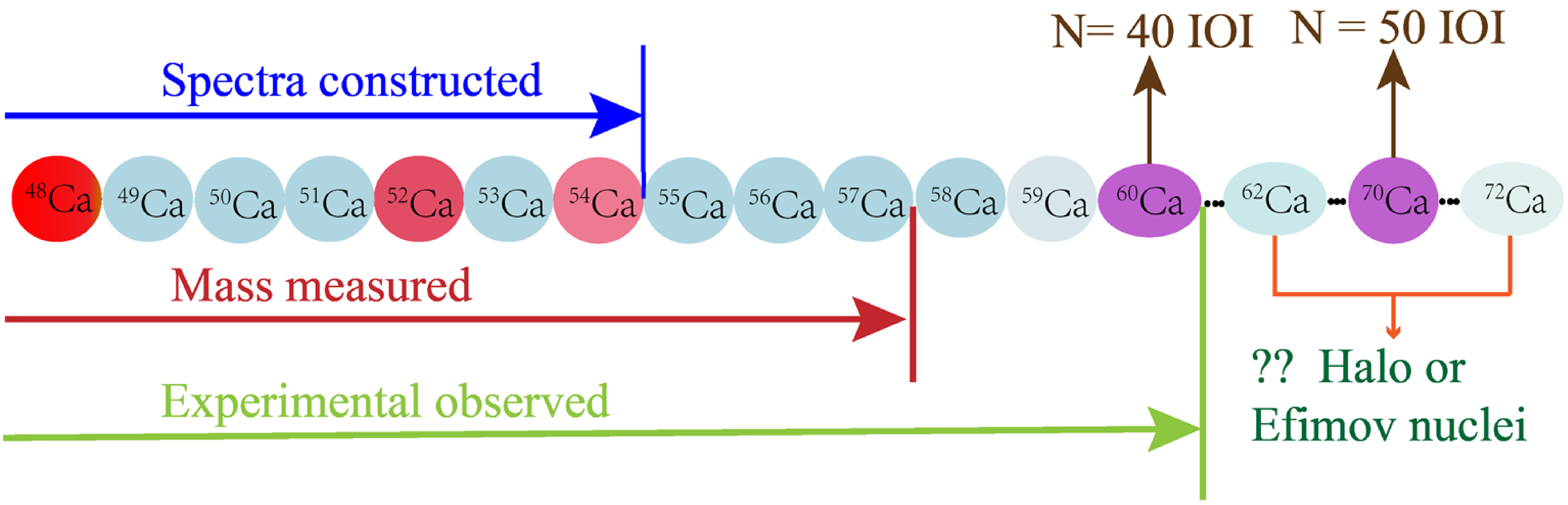
Shell model calculations

GSM calculations

The frontier : calcium isotopes

PRL.110.242701(2013)
PRL.110.242701(2018)

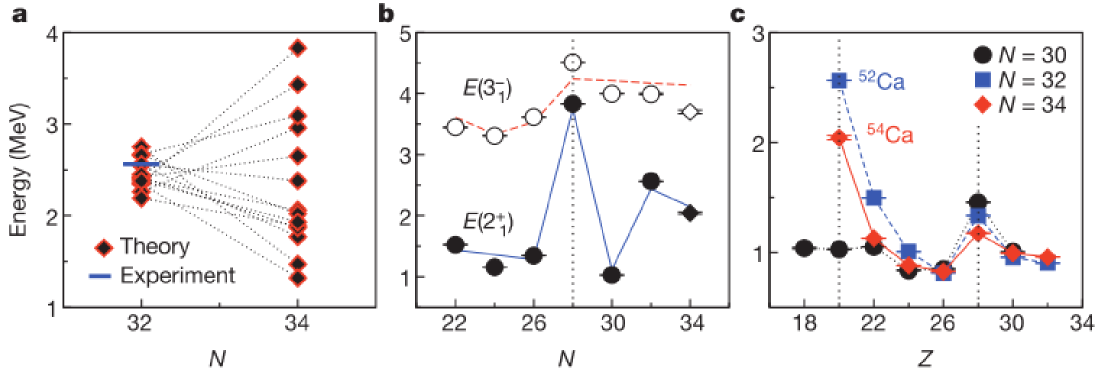
PRL 117, 272501 (2016)



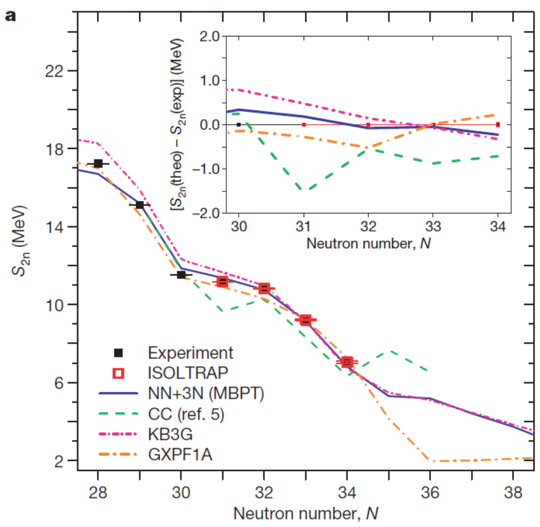
Steppenbeck *et al.*,Nature 502,207 (2013) S. Michimasa *et al*. PRL. 121, 022506 (2018) O. B. Tarasov *et al*. PRL. 121, 022501(2018)

PRL.120.052502(2018)

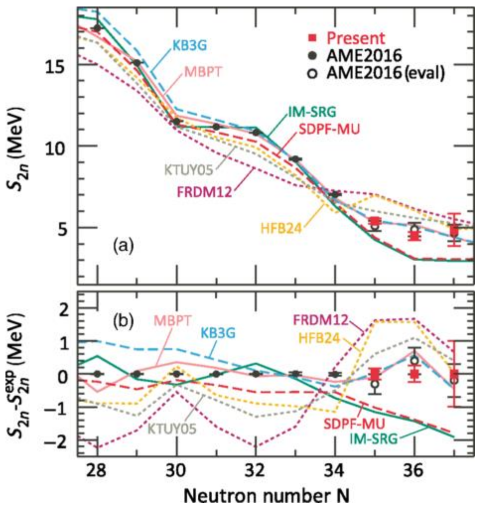
The frontier : calcium isotopes



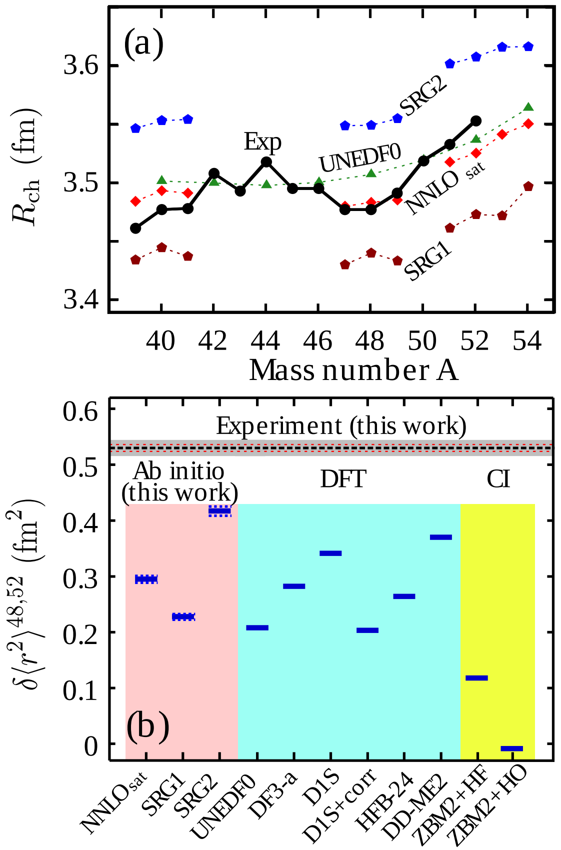
Steppenbeck *et al.*,Nature 502,207 (2013)



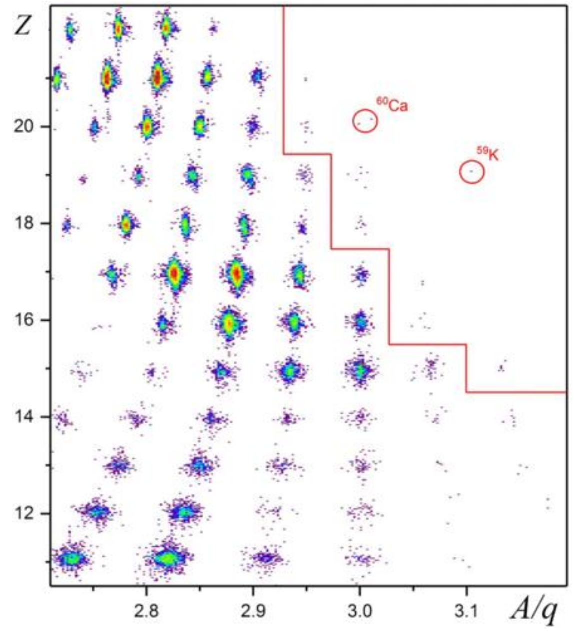
F.Wienholtz *et al.*, Nature 498,346 (2013)



S. Michimasa *et al*. PRL. 121, 022506 (2018)



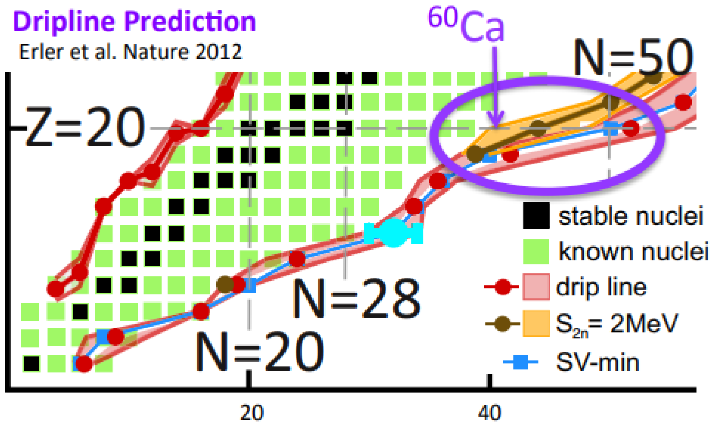
R. F. Garcia Ruiz *et al*. Nat.Phys 12, 594 (2016)

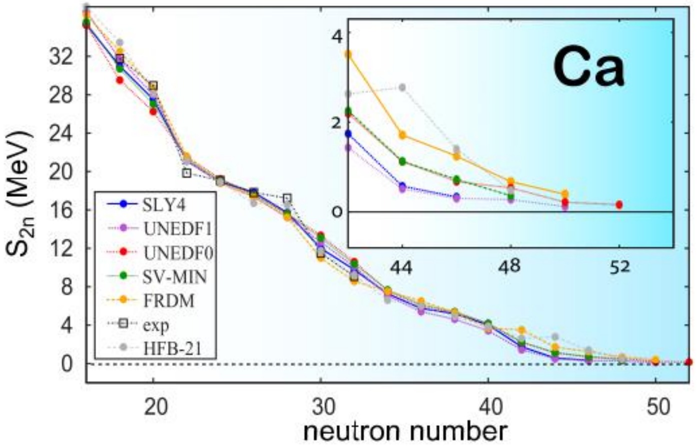


O. B. Tarasov *et al*. PRL. 121, 022501(2018)

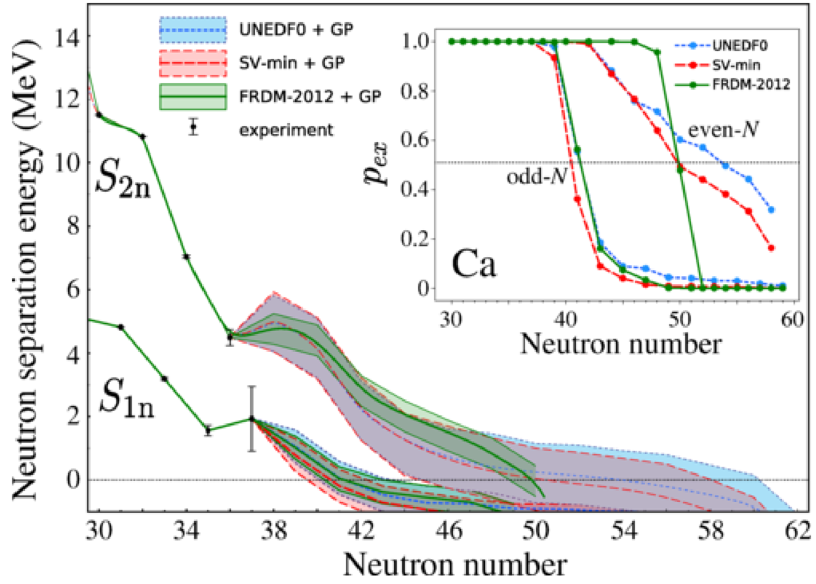
See Prof. X.F Yang and Prof. M Wang’s talks

Mean-field calculations of calcium isotopes

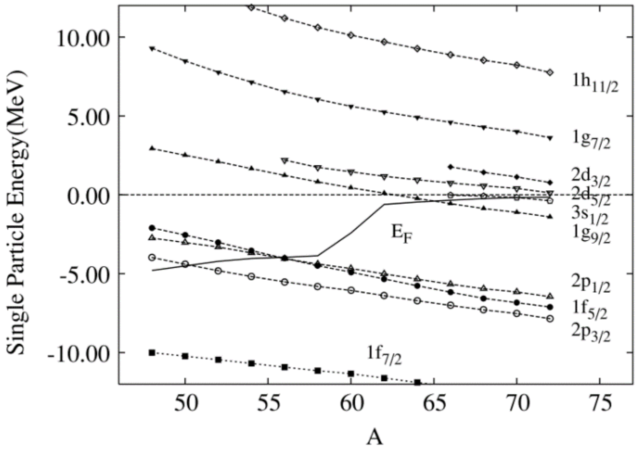


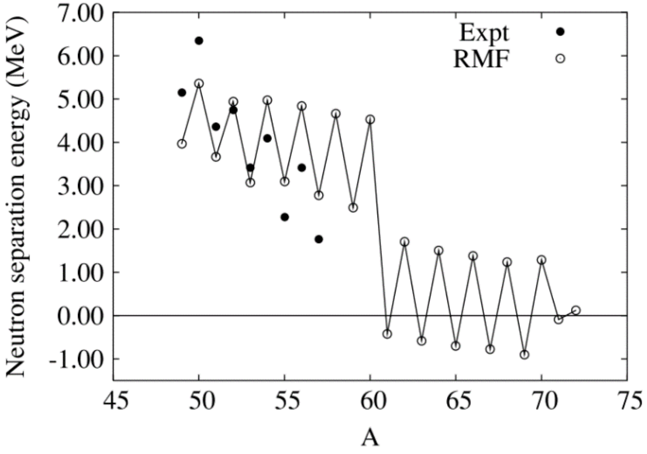


Jochen Erler *et al.* Nature 486.509 (2012)



Léo Neufcourt, Yuchen Cao,Witold Nazarewicz, Erik Olsen, and Frederi Viens PRL. **122**, 062502 (2019)





Madhubrata Bhattacharya *et al.* PRC.72.044318(2005)

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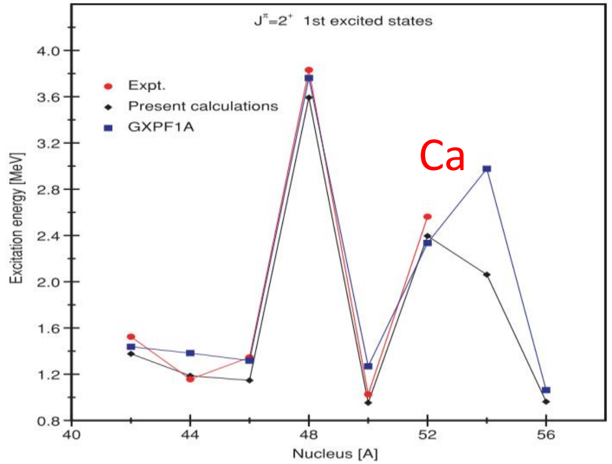
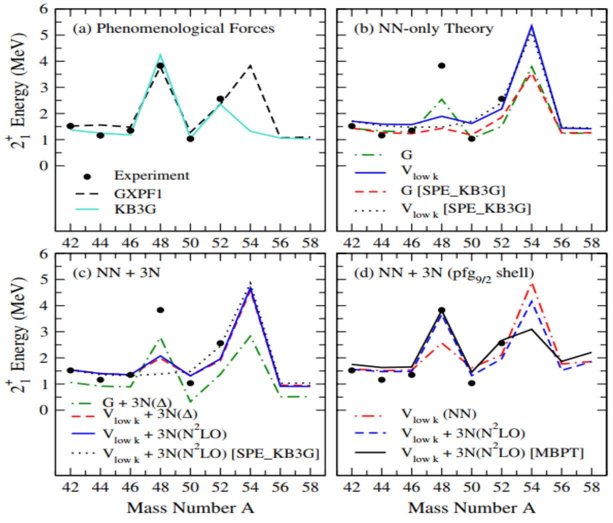
Ab-initio calculations of calcium isotopes

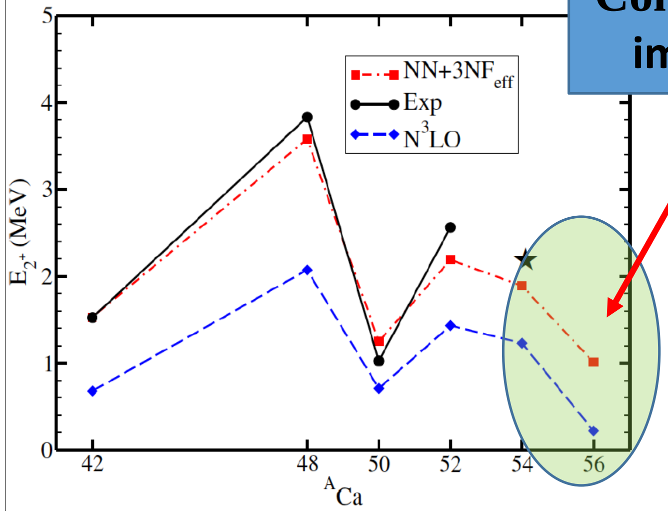


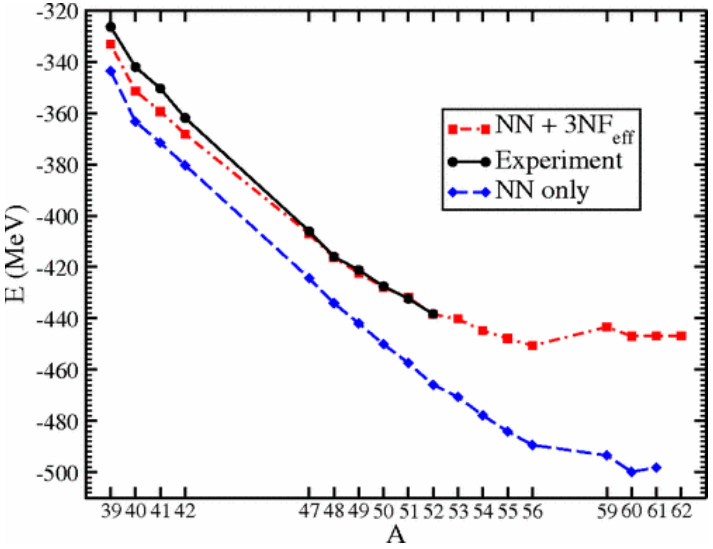
L.Caroggio *et al.*,PRC.80.044311(2009)
Q_box(Ca40,pf,HO,third order CDbonn)



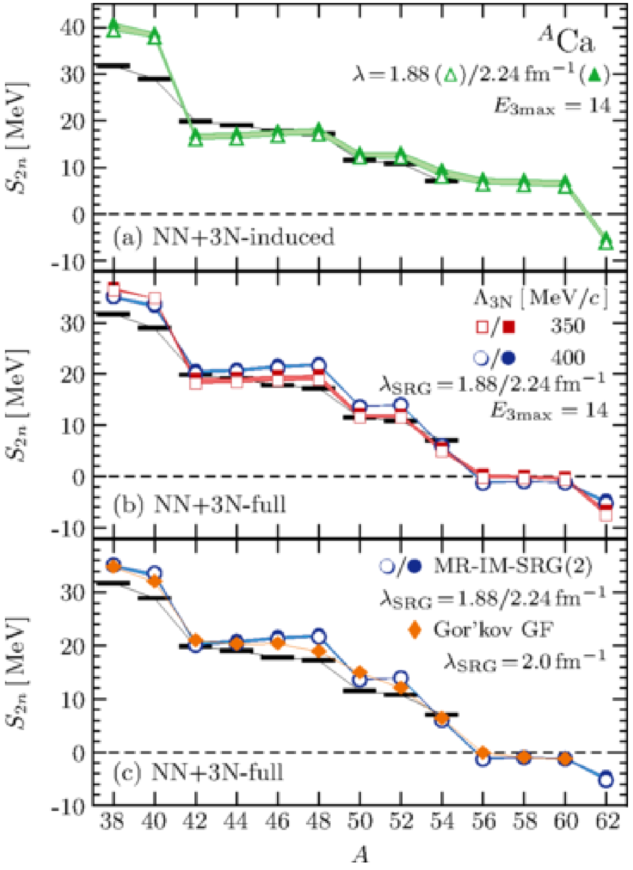
J.D.Holt *et al.*, JPG.39.085111(2013)
Q_box(Ca40,pfg,HO,3rd order NN+3N)

Continuum is important



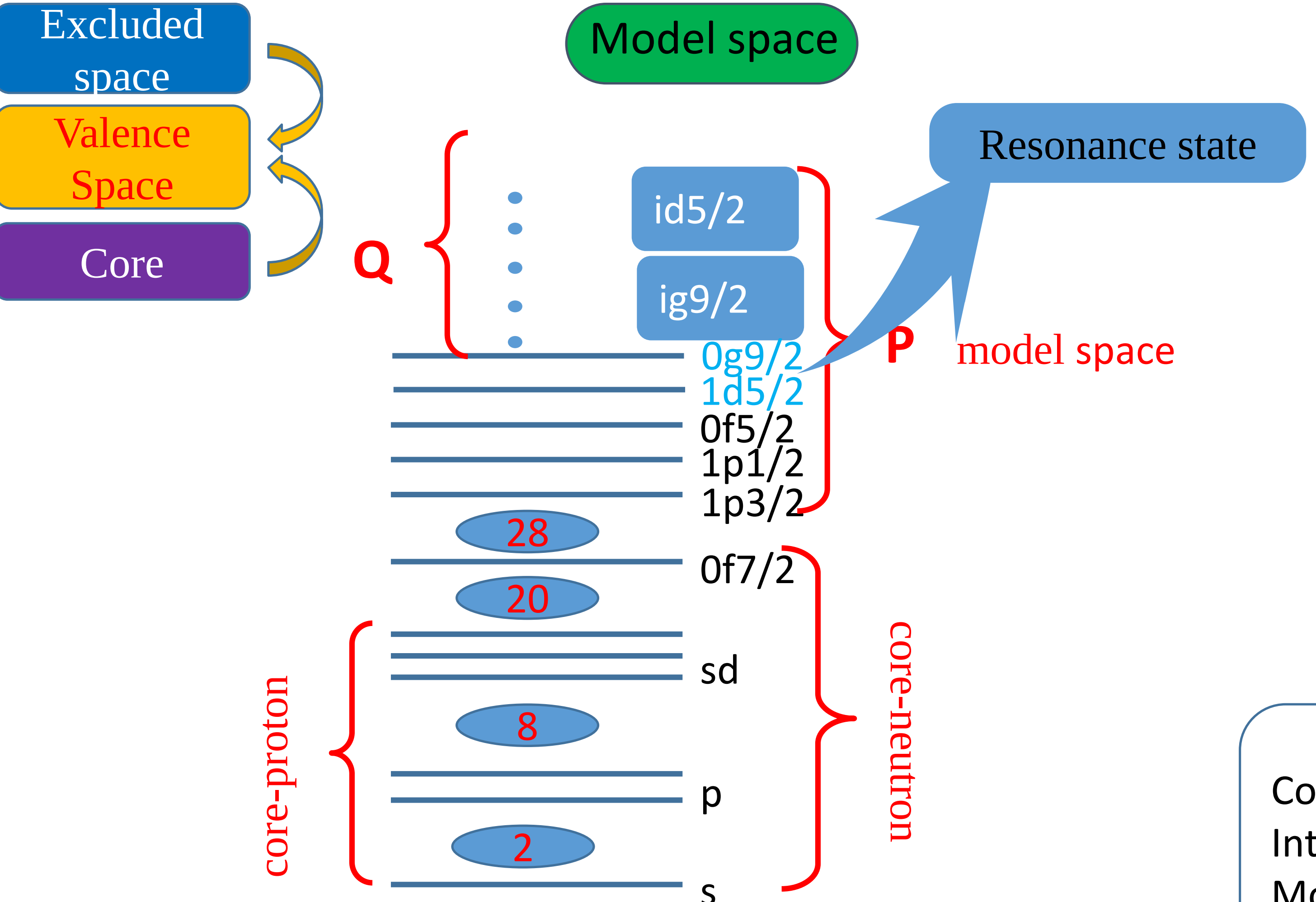


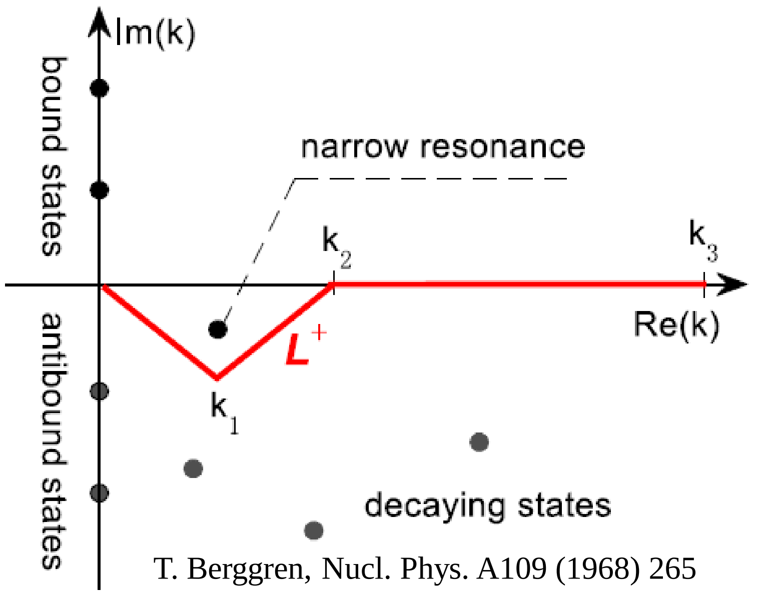
Hagen *et al.*, PRL. 109.032502(2012)
Couple-Cluster(continuum)



H. Hergert *et al.* PRC.90.041302(2014)

GSM calculations of calcium isotopes

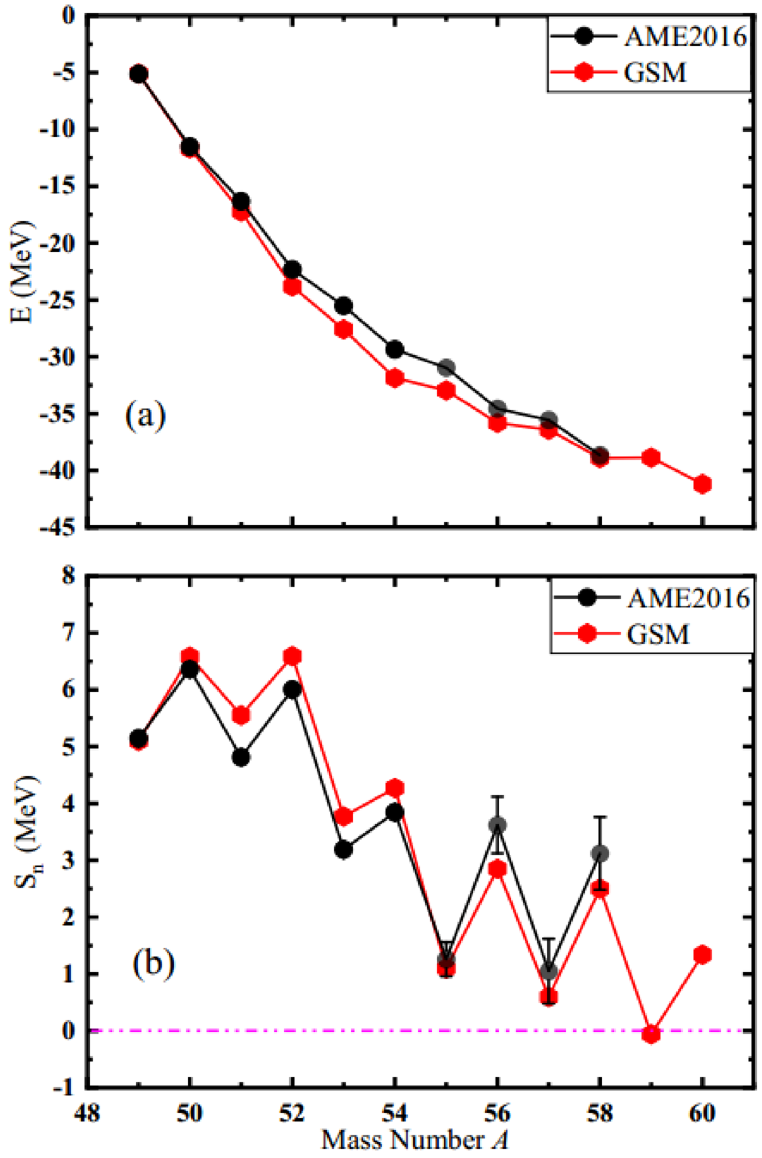




T. Berggren, Nucl. Phys. A109 (1968) 265

Core : ^{48}Ca
Interactions : CD-Bonn $V_{low\text{-}k}$ $\Lambda = 2.6\ fm^{-1}$
Model space : $\{1p_{3/2}, 1p_{1/2}, 0f_{5/2}, 0g_{9/2}+ig_{9/2}+1d_{5/2}+id_{5/2}\}$

Binding energies and single-neutron separation energies



Core : ^{48}Ca
Interactions : CD-Bonn $V_{low\text{-}k}$ $\Lambda = 2.6\ \mathrm{fm}^{-1}$
Model space : $\{1p_{3/2}, 1p_{1/2}, 0f_{5/2}, 0g_{9/2}+ig_{9/2}+1d_{5/2}+id_{5/2}\}$
Calcium isotopes : $^{49\text{-}60}$Ca (produced up to ^{60}Ca, mass ^{57}Ca)

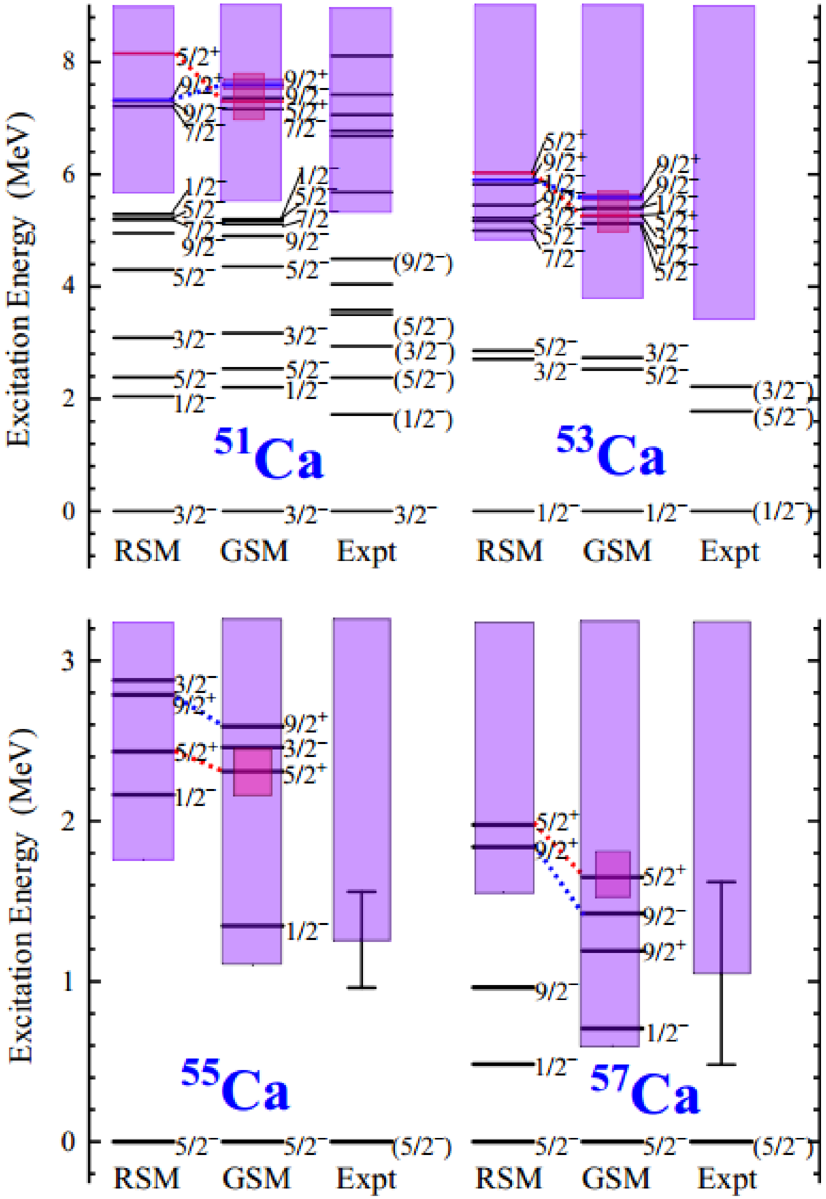
- Our GSM calculations provide good agreement with data.
- The last odd nucleus against neutron emission is predicted as ^{57}Ca in our GSM calculations.

Last odd nucleus against neutron emission	method	reference
^{57}Ca	GSM	Our work
^{59}Ca	RMF	PRC 72, 044318 (2005)
$^{\sim 61}$Ca	MF	PRL 122, 062502(2019)
^{53}Ca	IM-SRG	PRL 118.032502(2017)

- The ^{60}Ca is a bound nucleus in our calculations, consistent with experiment.

MF and RMF : ^{60}Ca is bound. IM-SRG and CC : ^{60}Ca is unbound

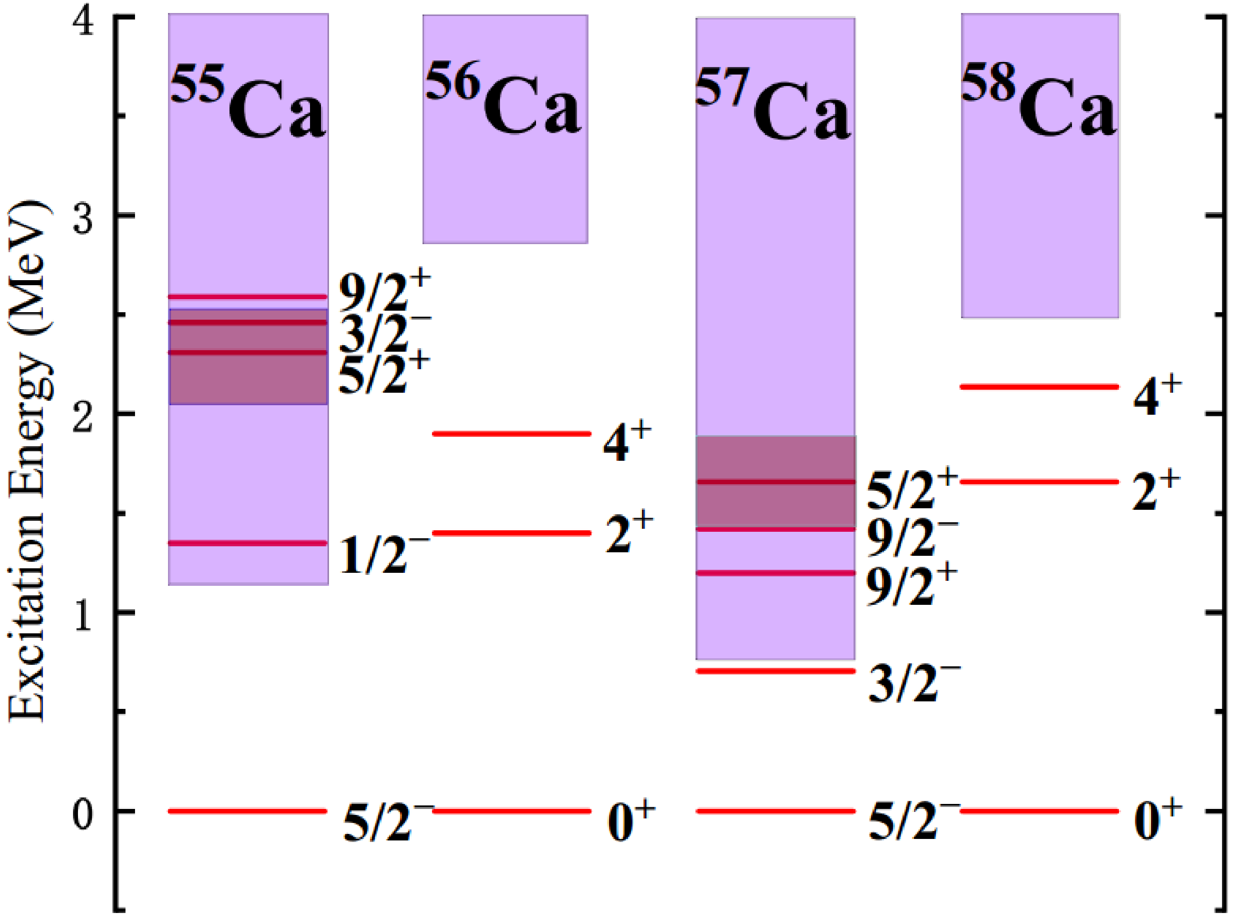
Excited states in ^{51,53,55,57}Ca and continuum effect



- For the low-lying bound states in ^{51,53}Ca, RSM and GSM provide very close results.
- For the higher excited states in ^{51,53}Ca, the calculations shows that the order of $5/2^+$ and $9/2^+$ level inverts. And the excitation energies of $5/2^+$ and $9/2^+$ level in GSM is smaller than RSM calculations. (continuum effects)

J^π	$E(^{51}\mathrm{Ca})$	$\Gamma(^{51}\mathrm{Ca})$	$E(^{53}\mathrm{Ca})$	$\Gamma(^{53}\mathrm{Ca})$	$E(^{55}\mathrm{Ca})$	$\Gamma(^{55}\mathrm{Ca})$	$E(^{57}\mathrm{Ca})$	$\Gamma(^{57}\mathrm{Ca})$
$5/2_1^+$	7.304	1.226	5.27	0.996	2.316	0.580	1.62	0.484
$9/2_1^+$	7.592	0.041	5.59	0.008	2.601	0.00	1.18	0.00

Predictions of the low-lying states of $^{55\text{-}58}$Ca

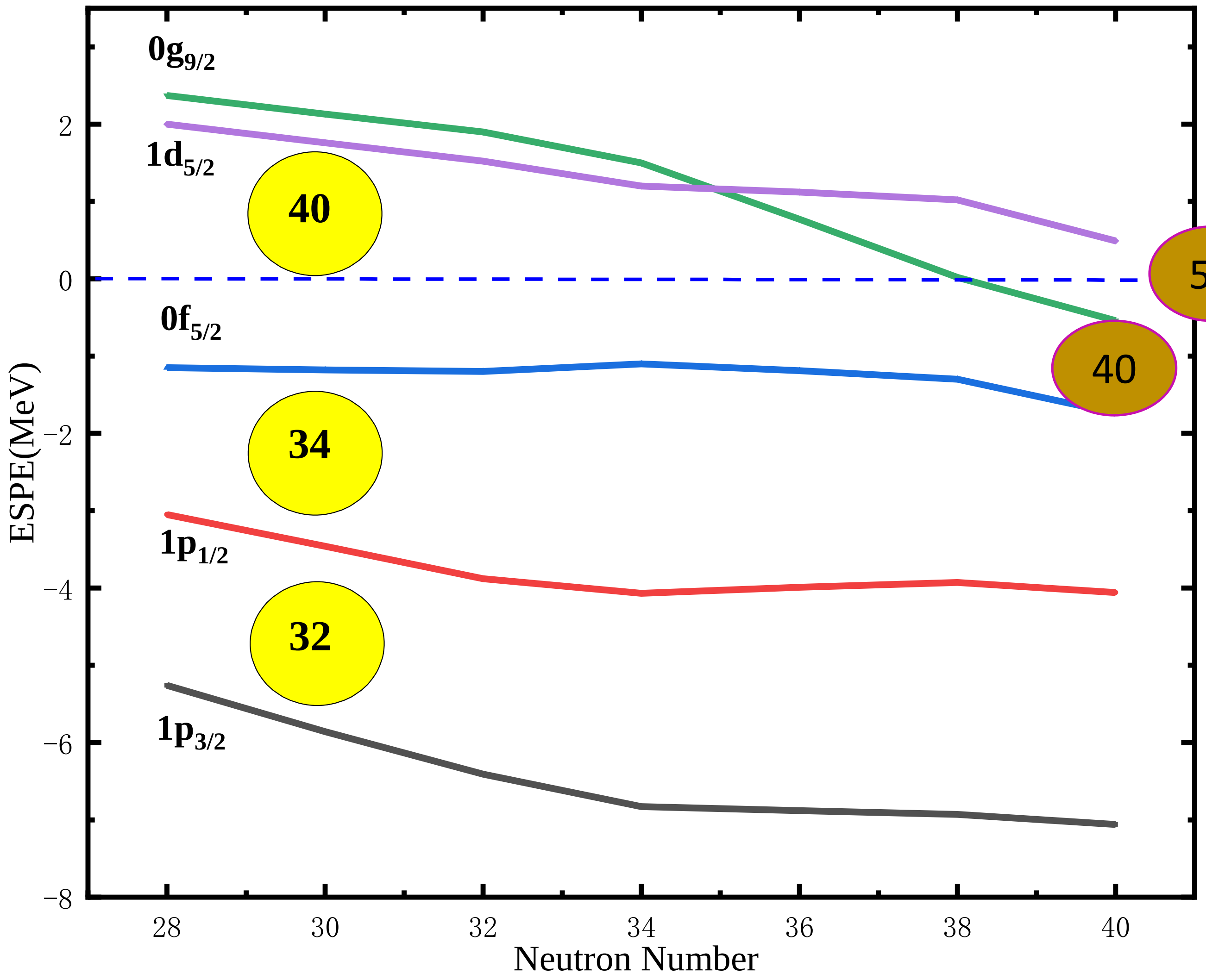


- Predictions of the spectra of $^{55\text{-}58}$Ca.
- The intruder configurations in the low-lying states of ^{58}Ca.
- the disappearance of the N = 40 subshell in the calcium chain.

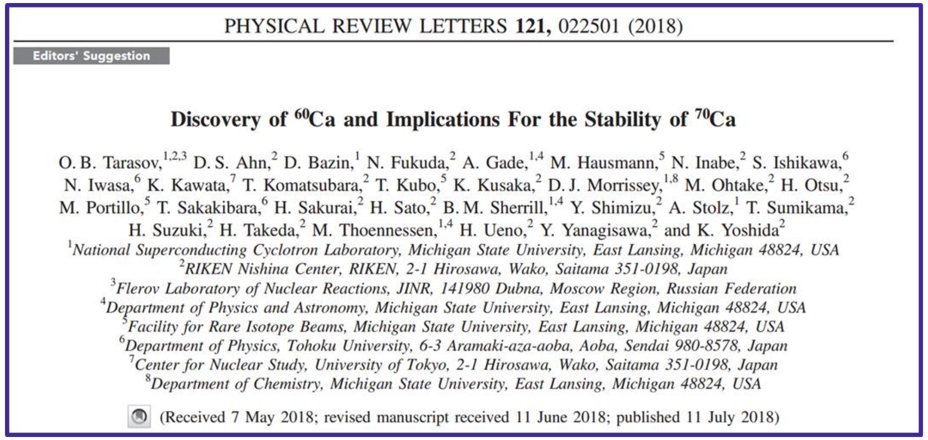
Configurations of the ground states in ^{58}Ca	contributions
$(1p_{3/2})^4(1p_{1/2})^2(0f_{5/2})$^4	77.09%
$(1p_{3/2})^4(1p_{1/2})^2(0f_{5/2})^2(0g_{9/2})$^2	14.6%
$(1p_{3/2})^4(1p_{1/2})^2(0f_{5/2})^2(1d_{5/2})$^2	2.29%

Neutron shell evolution in the calcium chain 1/2

effective single particle energies(ESPE)



^{60}Ca is bound, and calculations also suggest that ^{70}Ca is also bound.



PHYSICAL REVIEW LETTERS **121**, 022501 (2018)

Editors' Suggestion

Discovery of ^{60}Ca and Implications For the Stability of ^{70}Ca

O. B. Tarasov,[1,2,3] D. S. Ahn,[2] D. Bazin,[1] N. Fukuda,[2] A. Gade,[1,4] M. Hausmann,[5] N. Inabe,[2] S. Ishikawa,[6] N. Iwasa,[6] K. Kawata,[7] T. Komatsubara,[2] T. Kubo,[5] K. Kusaka,[2] D. J. Morrissey,[1,8] M. Ohtake,[2] H. Otsu,[2] M. Portillo,[5] T. Sakakibara,[6] H. Sakurai,[2] H. Sato,[2] B. M. Sherrill,[1,4] Y. Shimizu,[2] A. Stolz,[1] T. Sumikama,[2] H. Suzuki,[2] H. Takeda,[2] M. Thoennessen,[1,4] H. Ueno,[2] Y. Yanagisawa,[2] and K. Yoshida[2]

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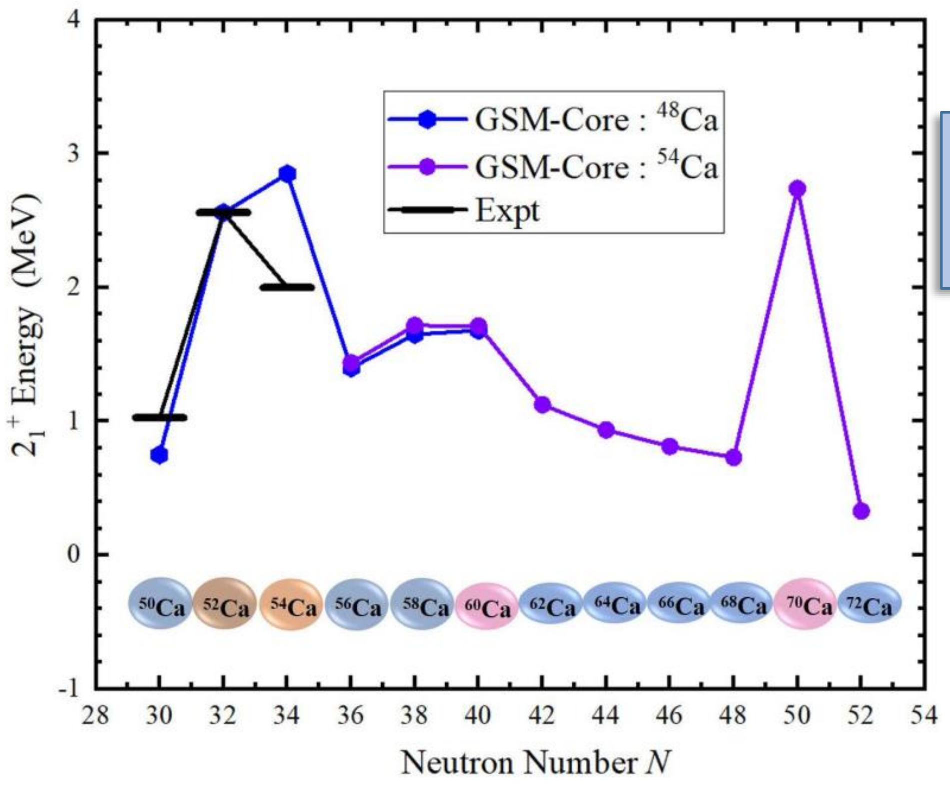
The N = 32,34 is shown in our GSM calculations, which consistent with experimental data.

Prediction of the $N = 40$ subshell disappears in the Ca chain.

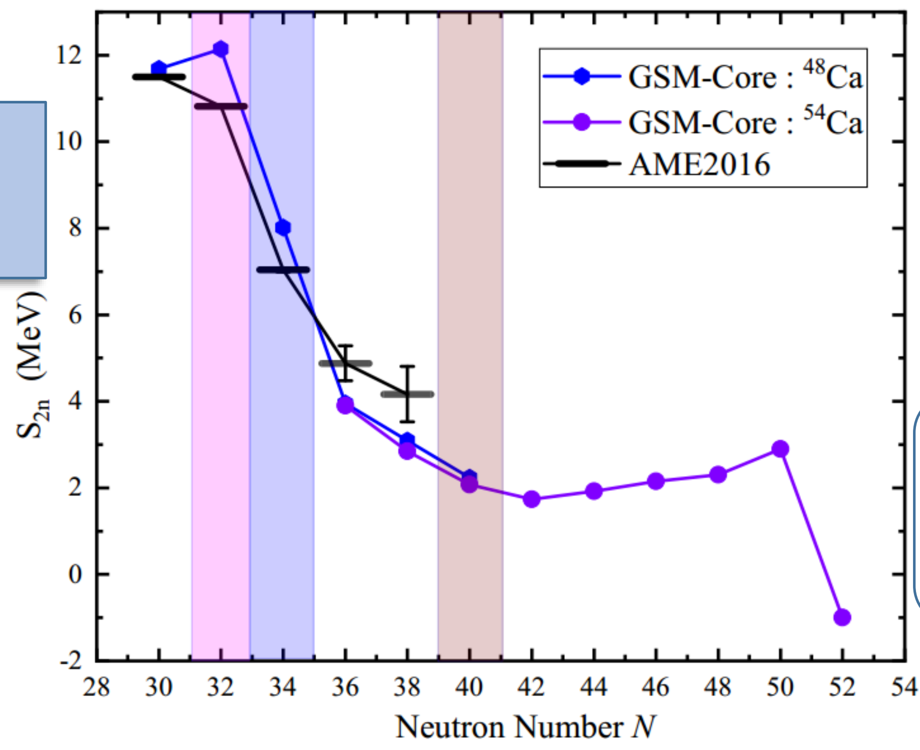
Neutron shell evolution in the calcium chain 2/2

The energies of the first 2_1^+ states

The two-neutron separation energies



no fitting in Ab-intio calculations



two-neutron dripline is located at ^{70}Ca

The existence of the N = 32 and 34 sub-shell and the disappearance of the N = 40 sub-shell in the calcium chain.
The calculations of the nuclei near N = 32,34 is agree with experiment data. Nature 502,207 (2013),Nature 498,346 (2013) PRL. 121 022506 (2018)
The disappearance of the N = 40 sub-shell also happens in the Ti, Cr and Fe isotopes. PRL.110.242701(2013) PRL.110.242701(2018)
See Prof. X.F Yang and Prof. M Wang’s talks about the N =32 shell evolution in K and Sc isotopes, respectively.

summary

1. Calculations of binding energies of the calcium isotopes.

   Calculations provide the stability of the ^{60}Ca.

   Results predict that the one- and two-neutron dripline locate ^{58}Ca and ^{70}Ca, respectively.

2. Excited states in $^{51,53,55,57}Ca$ is calculated.

   Continuum effects are indicated in the high excited states of $9/2^+$ and $5/2^+$.

3. Low-lying states of $^{55\text{-}58}Ca$ are predicted.

   The intruder configurations are shown in the ground state of ^{58}Ca.

4. Shell evolution of the N = 32,34,40 are discussed via the calculations of ESPEs, $E(2_1^+)$ and S_{2n}.

   The calculations of around the N = 32,34 are in line with experimental data.

   Results also suggest the disappearance of the N = 40 sub-shell in the calcium chain.

Thanks for your attention

Collaborators :

Furong Xu, Baishan Hu, Qiang Wu, Sijie Dai,Yuan Gao

Zhonghao Sun

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Siming Wang

Chong Qi

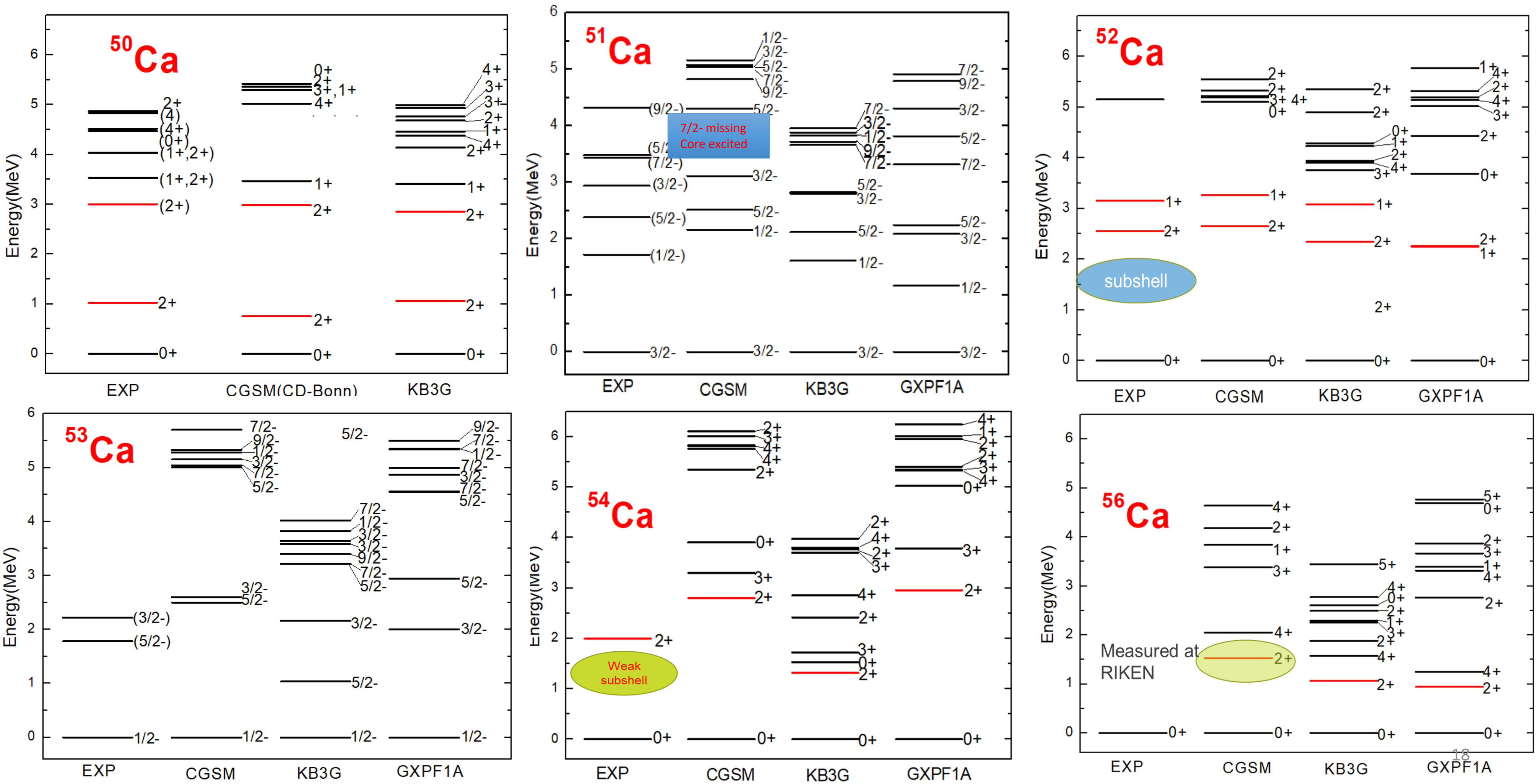
Cenxi Yuan

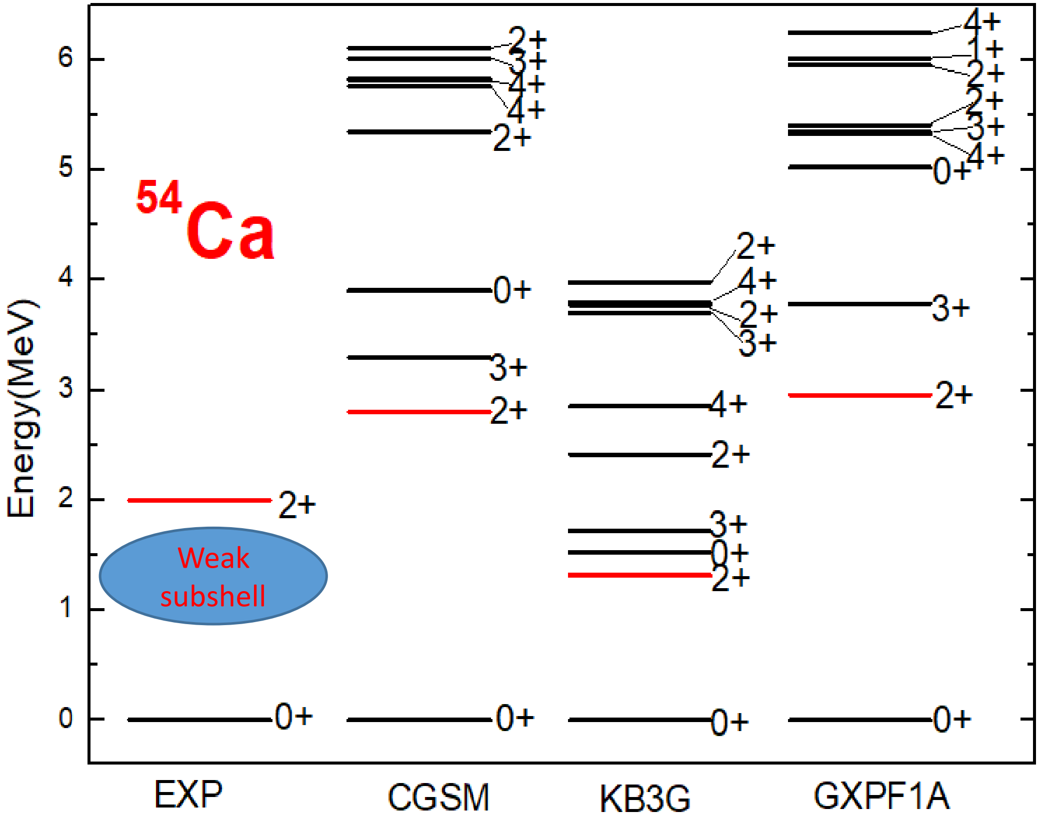
Nicolas Michel
Wei Zuo

backup slides

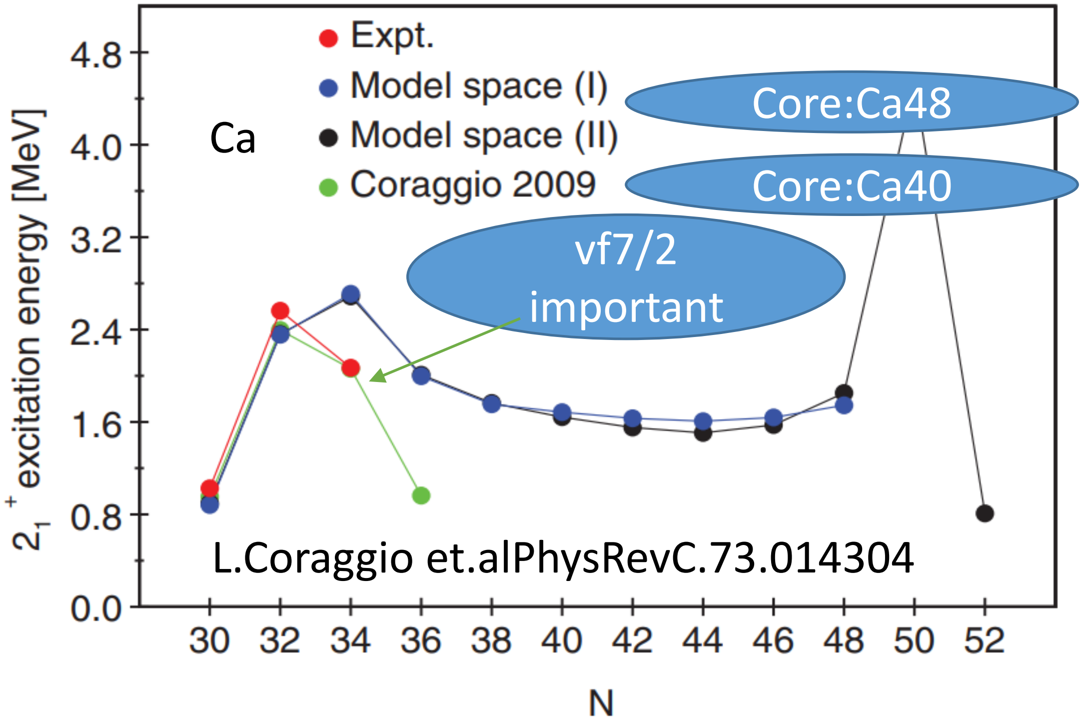
GSM results

CD-Bonn
Λ=2.6fm-1





Energy(MeV)
54Ca
Weak subshell
EXP
CGSM
KB3G
GXPF1A



Expt.
Model space (I)
Model space (II)
Coraggio 2009
Ca
Core:Ca48
Core:Ca40
vf7/2 important
2+1 excitation energy [MeV]
N
L.Coraggio et.alPhysRevC.73.014304