Workshop on Strongly Interacting Matter
January 20, 2026, ITP/CAS

Dipole response of deformed halo nuclei ^{31}Ne and ^{37}Mg

Xiao Lu (陆晓)

Institute of Theoretical Physics, Chinese Academy of Sciences

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Collaborators: Hiroyuki Sagawa, Shan-Gui Zhou (周善贵)

Contents

- Background
- Theoretical framework
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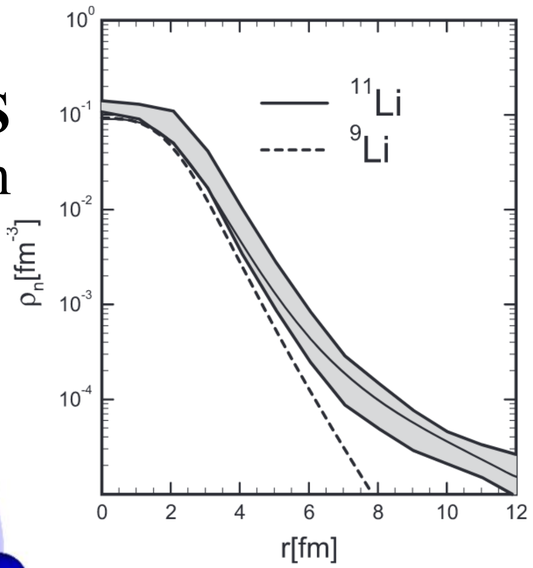
- Summary and perspective

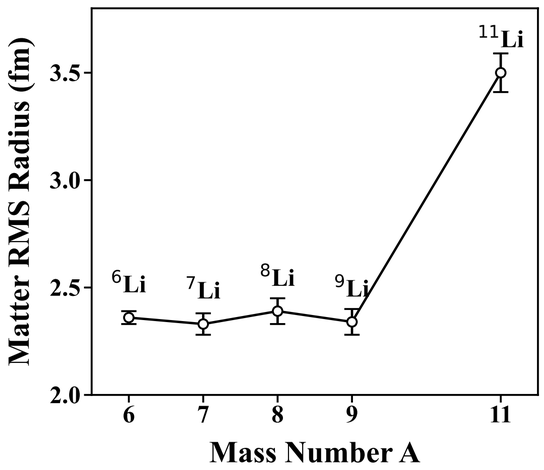
Exotic halo phenomena

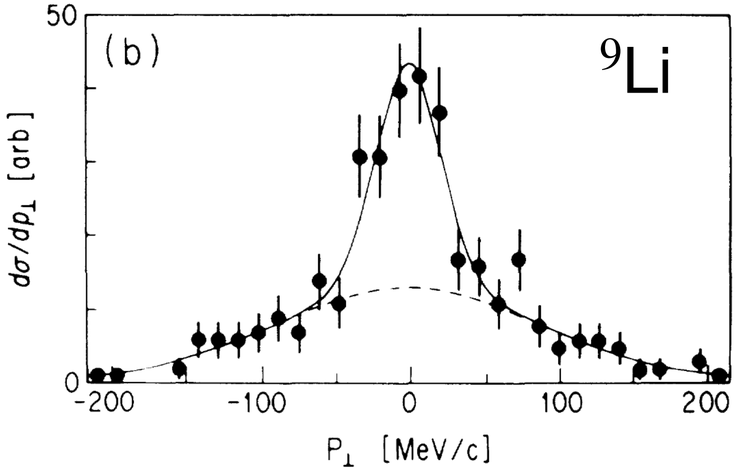
- A halo structure appears as an extended density distribution, which is one of the characteristic features of weakly bound neutron-rich and proton-rich nuclei.
  - In 1985, Tanihata et al. first observed **an anomalously large matter RMS radius** in the neutron-rich nucleus ^{11}Li, indicating significant deformation or an extended matter tail.

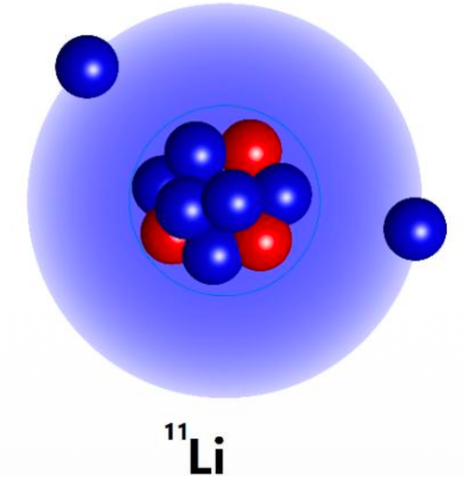
I. Tanihata, et al., Phys. Rev. Lett. 55 (1985) 2676.



J. Meng, et al., J. Phys. G: Nucl. Part. Phys. 42 (2015) 093101.







From X.H. Wu

- In 1988, Kobayashi et al. revealed **an extremely narrow momentum component** in ^{11}Li fragmen--tation, providing direct evidence for a two-neutron halo structure.

T. Kobayashi, et al., Phys. Rev. Lett. 60 (1988) 2599.

Features for halo nuclei

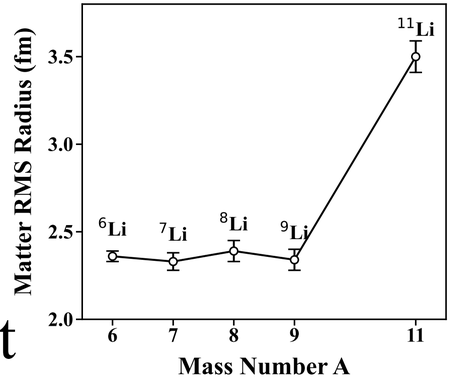
J. Meng, et al., Prog. Part. Nucl. Phys. 57 (2006) 470-563.
J. Meng, et al., J. Phys. G: Nucl. Part. Phys. 42 (2015) 093101.
I. Tanihata, et al., Prog. Part. Nucl. Phys. 68 (2013) 215-313.
T. Nakamura, et al., Phys. Rev. Lett. 112 (2014) 142501.
K. J. Cook, et al., Phys. Rev. Lett. 124 (2020) 212503.
Y. L. Ye, et al., Nature Rev. 7 (2025) 21-37.

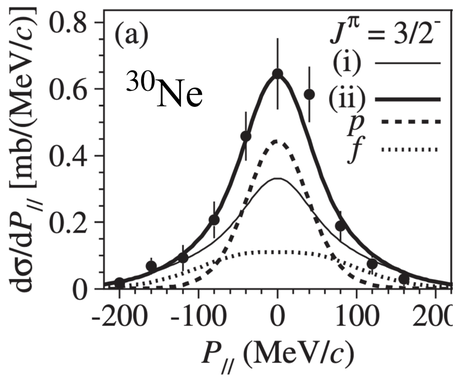
Prerequisite

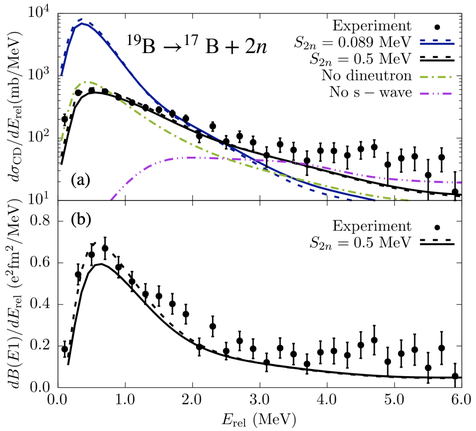
- ☑ Low binding energy ($S_n, S_{2n} \lesssim 1$ MeV)
- ☑ Low angular momentum ($l = 0,\ 1$)

Typical phenomena

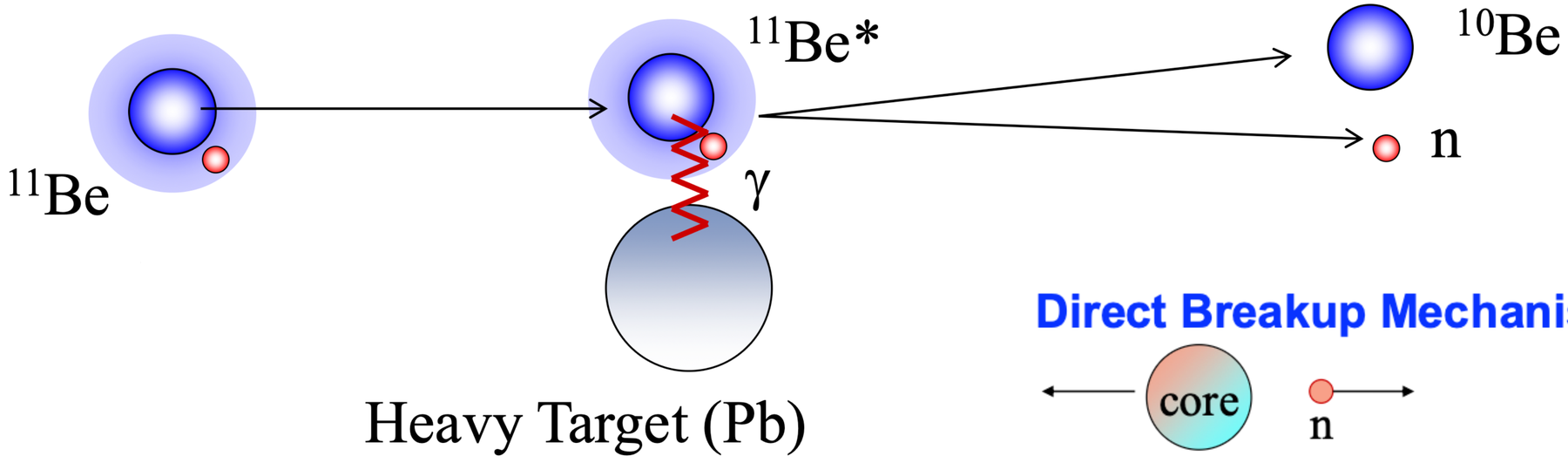
- ☑ The large spatial extend of the dilute nuclear surface
- ☑ The narrow momentum distribution of the core fragment
- ☑ The substantial increase in the electromagnetic dissociation cross section
- ☑ The **soft electric dipole ($E1$) response (excitation)** or the possible formation of the soft dipole resonance







Coulomb breakup — soft $E1$ response



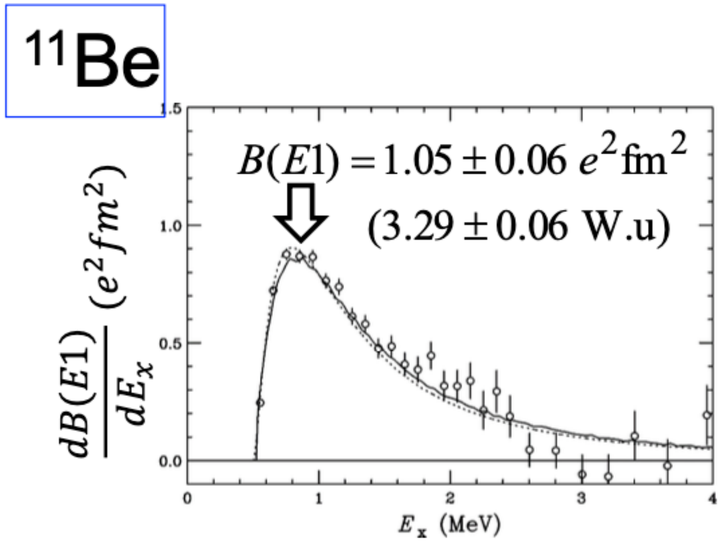
Direct Breakup Mechanism (Not Resonance!)

Equivalent Photon Method

$$\frac{d\sigma_{CB}}{dE_x} = \frac{16\pi^3}{9\hbar c} n_{E1}(E_x) \frac{dB(E1)}{dE_x}$$

Cross section = (Photon Number)×(Transition Probability)

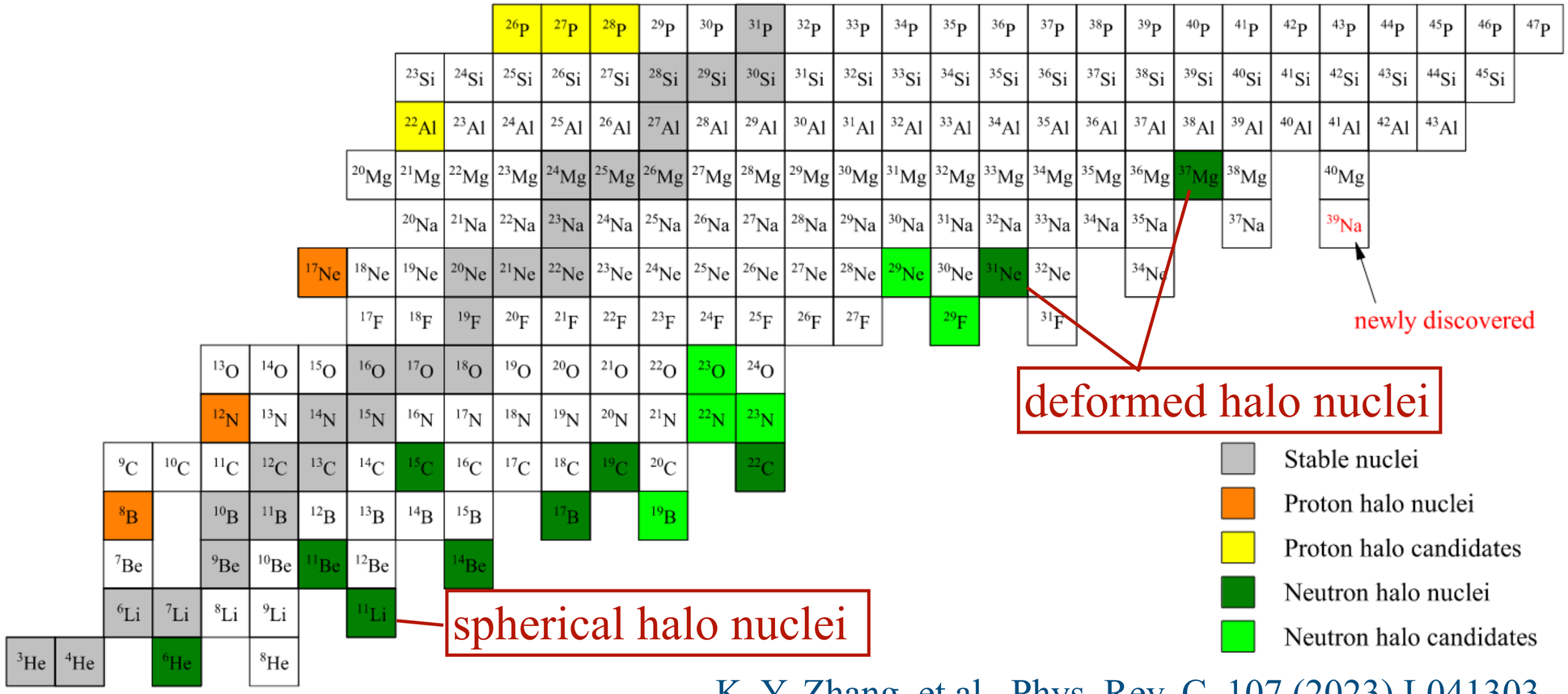
C.A. Bertulani, G. Baur, Phys. Rep. **163**, 299(1988).
T. Aumann, T. Nakamura, Phys. Scr. T**152**, 014142(2013).
T. Nakamura, Handbook of Nuclear Physics, pp1-37 (2023).



From Takashi Nakamura's talk

Exotic halo phenomena near the drip line

- ☑ To date, about 20 halo nuclei or candidates have been suggested in experiments.



K. Y. Zhang, et al., Phys. Rev. C. 107 (2023) L041303.

Most known nuclei are deformed. S.G. Zhou, Phys. Scr. 91 (2016) 063008.

- What kind of new features can **deformation effects** bring to **halo nuclei**?

Dipole mode

- ☑ The ground state deformation of nuclei can be reflected by the shape of the giant dipole resonance (GDR) strength distributions

  - Spherical nuclei

    GDR appears as a single broad peak

  - Deformed nuclei

    GDR splits into two or three peaks

J. H. Bai, et al., Phys. Lett. B 815 (2021) 136147.
J. A. Maruhn, et al., Phys. Rev. C 71 (2005) 064328.
W. D. Myers, et al., Phys. Rev. C 15 (1977) 2032–2043.
S. Goriely, et al., Eur. Phys. J. A 55 (2019) 10.

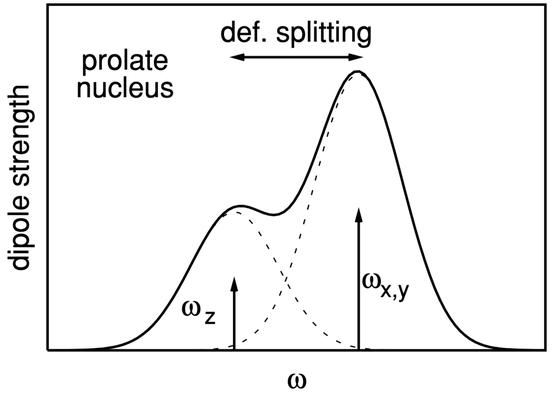


FIG. 1. Schematic view of collective dipole strengths in a prolate deformed nucleus. The dashed lines show the strength for the *x*-*y* and *z* modes separately.

- ☐ Deformed halo nuclei

Deformation + weakly bound → What's the shape of the soft dipole response strength distributions?

Deformed halo nucleus ^{31}Ne

Experimentally

- ☑ Larger Coulomb breakup cross section

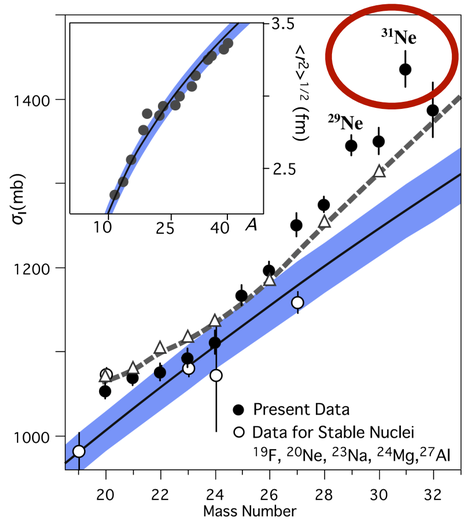
  T. Nakamura, et al., Phys. Rev. Lett. 103 (2009) 262501.

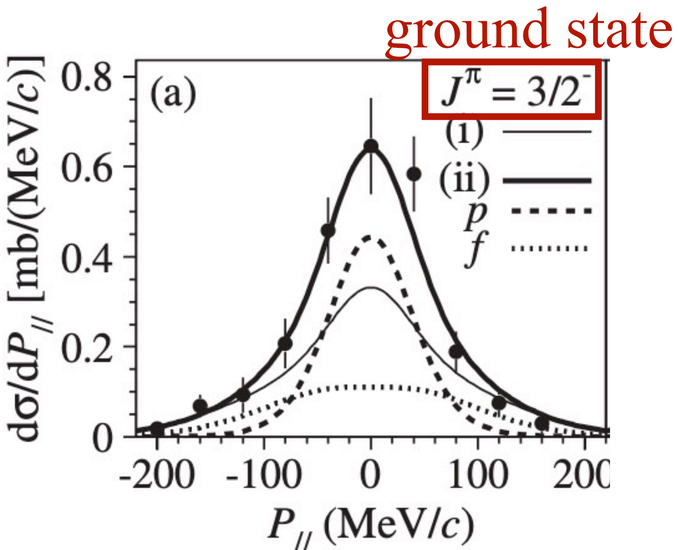
- ☑ Larger reaction cross sections

  M. Takechi, et al., Phys. Lett. B 707 (2012) 357–361.

- ☑ Small neutron separation energy ($0.15^{+0.16}_{-0.10}$ MeV)

  T. Nakamura, et al., Phys. Rev. Lett. 112 (2014) 142501.





Theoretically

- ☑ Deformed Woods-Saxon potential

  I. Hamamoto, Phys. Rev. C 81 (2010) 021304(R).

- ☑ DRHBc + Glauber model

  S. Y. Zhong, et al., Sci. China Phys. Mech. Astron. 65 (2022) 262011.

- ☑ Particle-rotor model

  Kouichi Hagino, et al., Halo 40, October 14th, 2025

- ☑ …

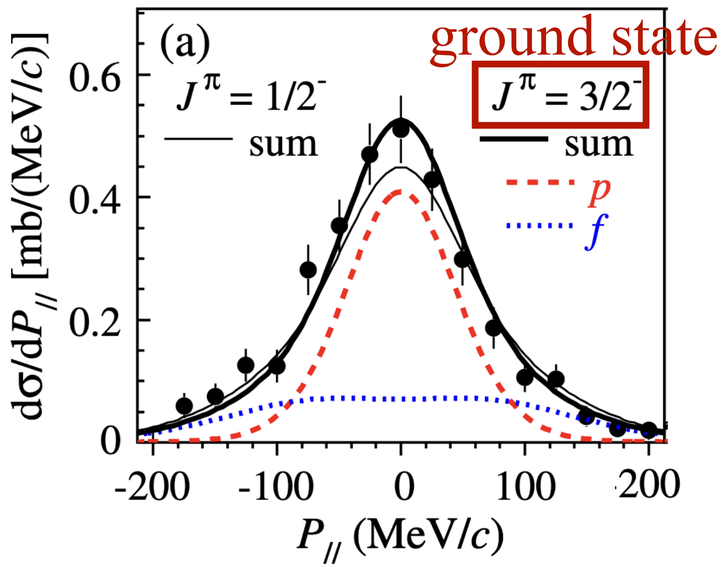
  - *p*-wave neutron halo together with the deformed core ^{30}Ne

Deformed halo nucleus ^{37}Mg

Experimentally

- ☑ Larger Coulomb breakup cross section
- ☑ Small neutron separation energy ($0.22^{+0.12}_{-0.09}$ MeV)

T. Nakamura, et al., Phys. Rev. Lett. 112 (2014) 242501.



- ☑ Larger reaction cross sections

M. Takechi, et al., Phys. Rev. C 90 (2014) 061305(R).

Theoretically

- ☑ Hartree–Fock–Bogoliubov

X. Y. Xiong, et al., Chin. Phys. C 40 (2016) 024101.
H. Nakada, et al., Phys. Rev. C 98 (2018) 011301(R).
H. Kasuya, et al., Prog. Theor. Exp. Phys. 2021 (2020) 013D01.

- ☑ DRHBc / DRHBc + Glauber model

K. Y. Zhang, et al., Phys. Lett. B. 844 (2023) 138112.
J. L. An, et al., Phys. Lett. B. 849 (2024) 138422.

- ☑ …

▶ deformed *p*-wave halo in ^{37}Mg

Theoretical framework

A. Bohr and B. R. Mottelson, Nuclear Struture, Vol. I (World Scientific, Singapore, 1975).

I. Hamamoto, Phys. Rev. C 81 (2010) 021304(R).

Y. Urata, et al., Phys. Rev. C 83 (2011) 041303(R).

XL, et al., Phys. Rev. C 111 (2025) 064320.

- Deformed Woods-Saxon potential

$$H = -\frac{\hbar^2}{2\mu}\nabla^2 + V(\boldsymbol{r}),$$

$$V(\boldsymbol{r}) = -V_{\mathrm{WS}}\left(1 - F_{ls}r_0^2(\boldsymbol{l}\cdot\boldsymbol{s})\frac{1}{r}\frac{d}{dr}\right)f(r) + V_{\mathrm{WS}}R_0\beta_2\frac{df(r)}{dr}Y_{20}\left(\hat{\boldsymbol{r}}\right)(\boldsymbol{r}) \equiv V_0(r) + V_{\mathrm{def}}(\boldsymbol{r})$$

- The single-particle wave function in the deformed Woods-Saxon potential is obtained as

$$H|\phi_\Omega\rangle = \varepsilon_\Omega|\phi_\Omega\rangle$$

- The single particle wave function in continuum ($\varepsilon > 0$): plane wave approximation

$$\left|\Phi_\varepsilon^{(c)} : \ell jm\right\rangle = \frac{1}{r}R_{\ell j}^{(c)}(\varepsilon, r)\left[Y_\ell \otimes \chi_{1/2}\right]_{jm} = \sqrt{\frac{2\mu}{\hbar^2\pi k}}\left[\cos\left(\delta_{\ell j}\right)kj_\ell(kr) - \sin\left(\delta_{\ell j}\right)kn_\ell(kr)\right] \times \left[Y_\ell \otimes \chi_{1/2}\right]_{jm}$$

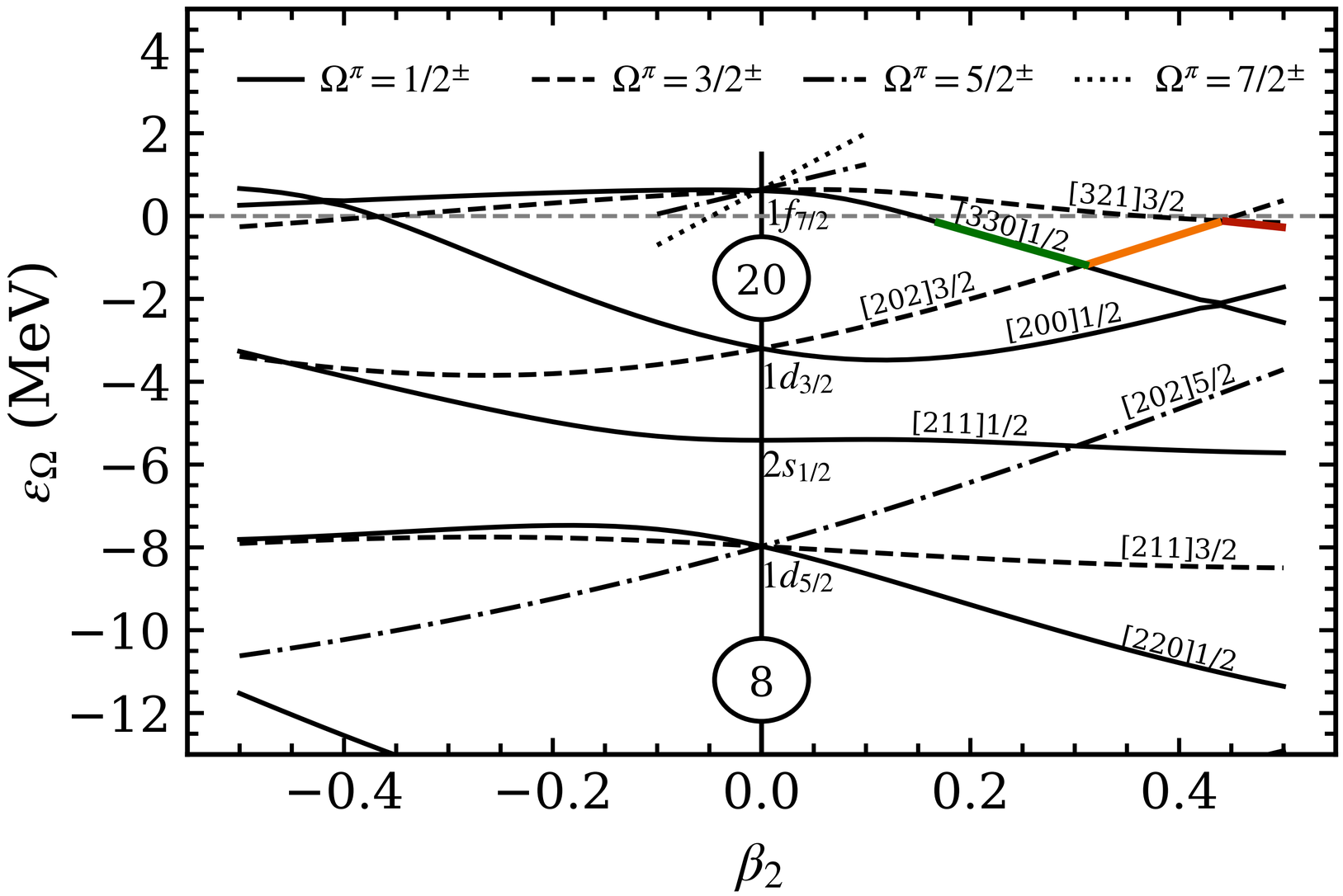
- The dipole transition strength at the excitation energy ω in the continuum

$$\frac{\mathrm{d}B(E1)}{\mathrm{d}\omega} = \int \mathrm{d}\varepsilon\delta\left(\omega - (\varepsilon + S)\right) \times B\left(E1(\varepsilon); I_i^\pi, K_i^\pi \to I_f^\pi, K_f^\pi\right)$$

$l \leq 4$ are taken into account in the $B(E1)$ calculation.

Nilsson diagram of ^{31}Ne

- Single neutron levels



- $S_n = 0.15$ MeV
- Ground Sate: $3/2^-$

T. Nakamura, et al., Phys. Rev. Lett. 112 (2014) 142501.

Last neutron occupy:

- $0.15 < \beta_2 < 0.3$: [330]1/2
- $0.3 < \beta_2 < 0.4$: [202]3/2
- $\beta_2 > 0.4$: [321]3/2

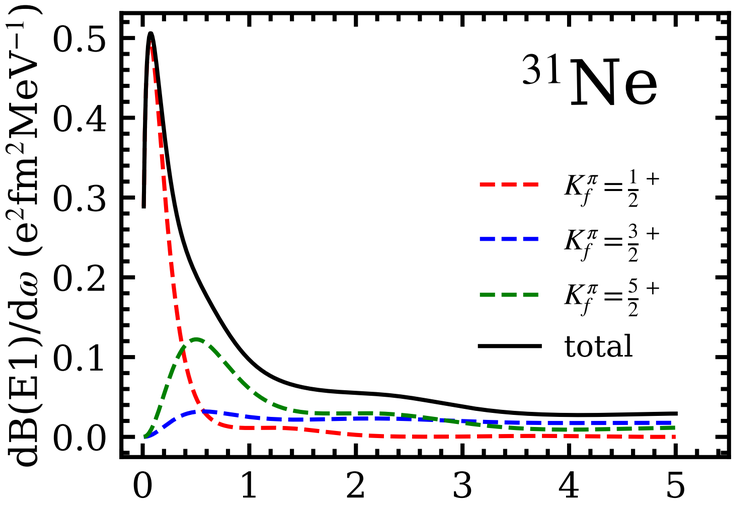
Soft electric dipole response in ^{31}Ne

32% p-wave (T. Nakamura, et al., Phys. Rev. Lett. 112 (2014) 142501.)

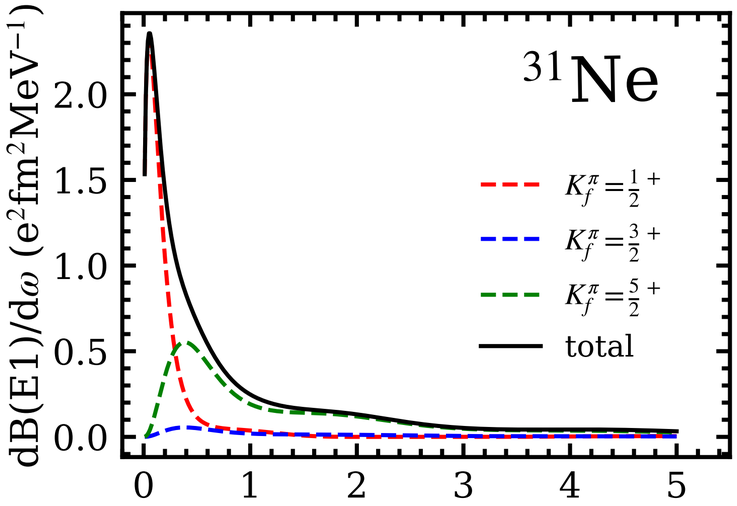
[321]3/2: $0.327p_{3/2}+0.022f_{5/2}+0.650f_{7/2}$

$I^\pi = \frac{3}{2}^-$, $K^\pi = \frac{3}{2}^-$

$\beta_2 = 0.5$



$p_{3/2}$: 100 %

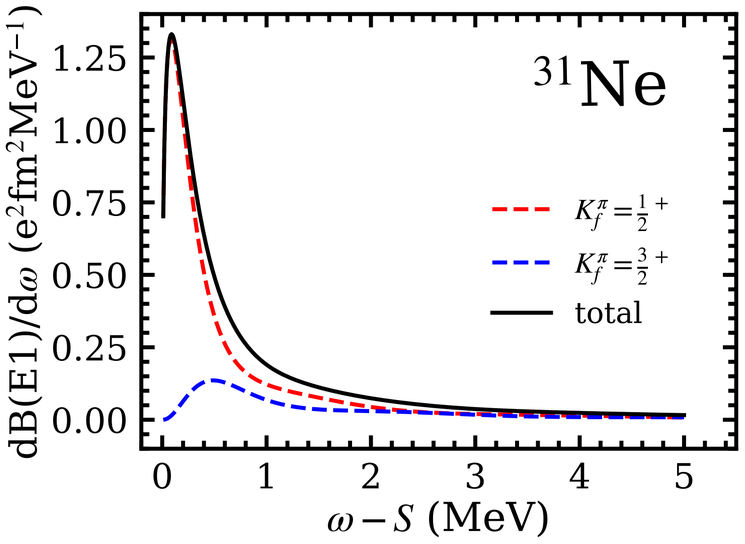


$I^\pi = \frac{3}{2}^-$, $K^\pi = \frac{3}{2}^-$

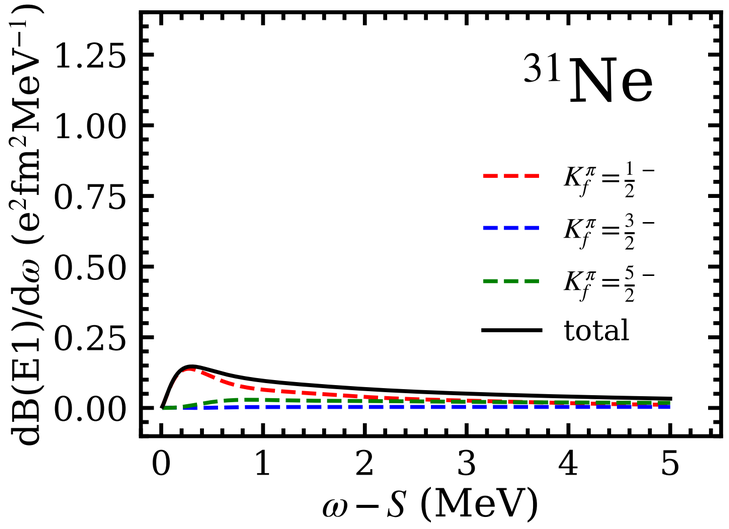
[330]1/2: $0.063p_{1/2}+0.59p_{3/2}+0.004f_{5/2}+0.342f_{7/2}$

$I^\pi = \frac{3}{2}^-$, $K^\pi = \frac{1}{2}^-$

$\beta_2 = 0.24$



[202]3/2: $0.965d_{3/2}+0.034d_{5/2}$

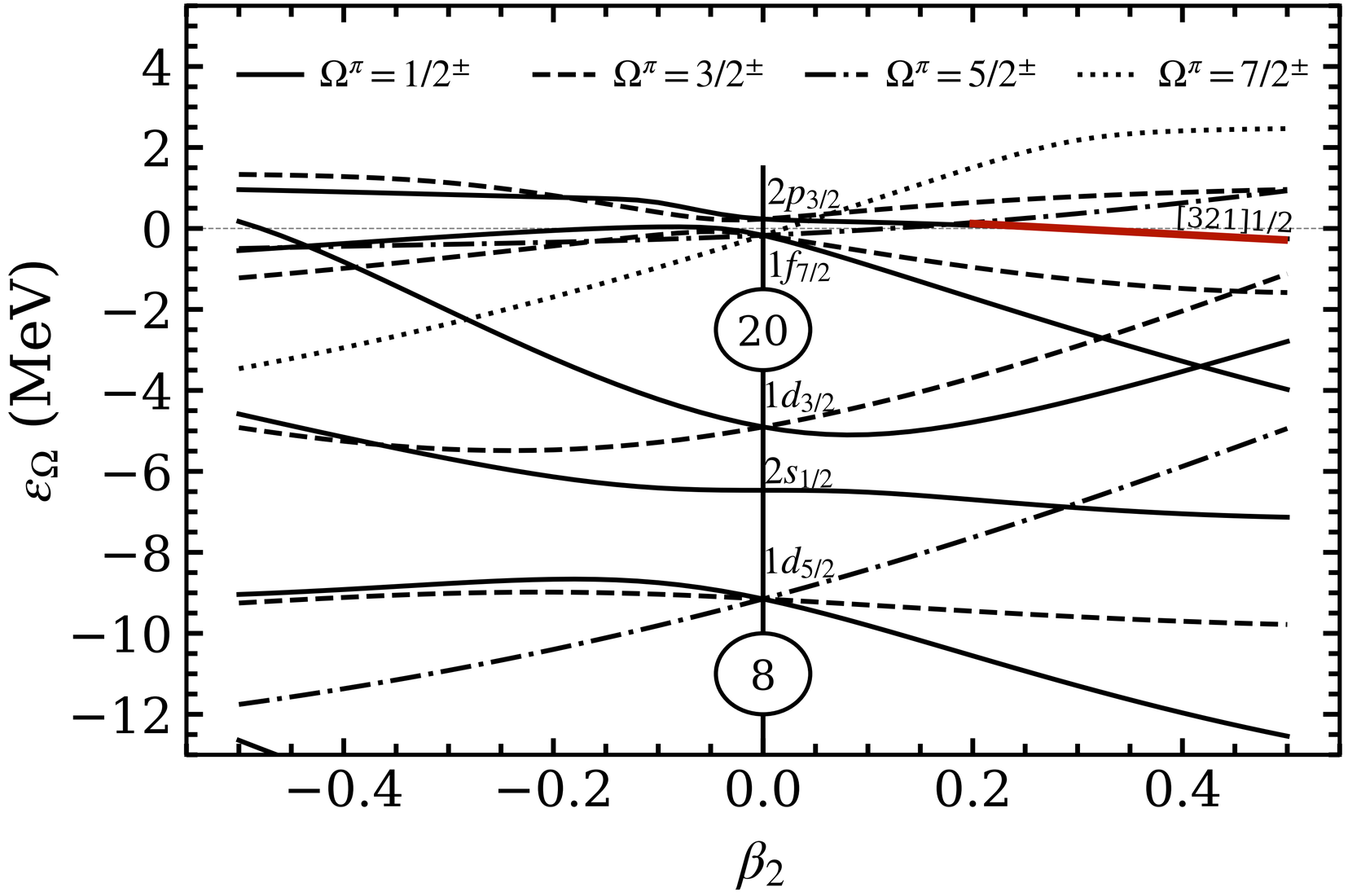


$I^\pi = \frac{3}{2}^+$, $K^\pi = \frac{3}{2}^+$

$\beta_2 = 0.3$

Nilsson diagram of ^{37}Mg

- Single neutron levels



- $S_n = 0.22$ MeV
- Ground Sate: $3/2^-$

T. Nakamura, et al., Phys. Rev. Lett. 112 (2014) 242501.

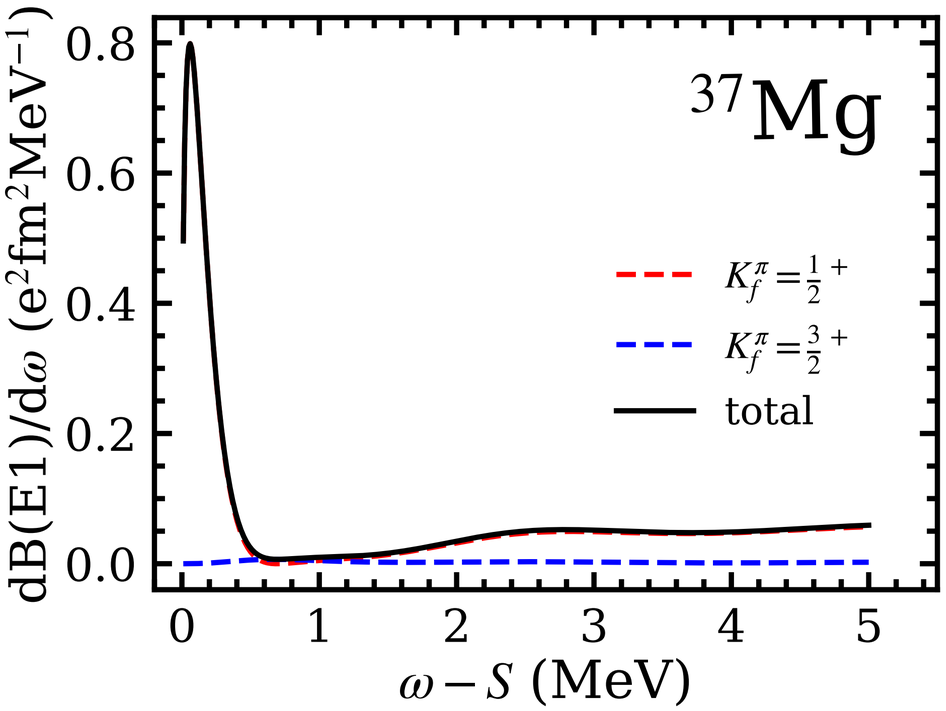
Last neutron occupy:

- $\beta_2 > 0.2$: [321]1/2

Soft electric dipole response in ^{37}Mg

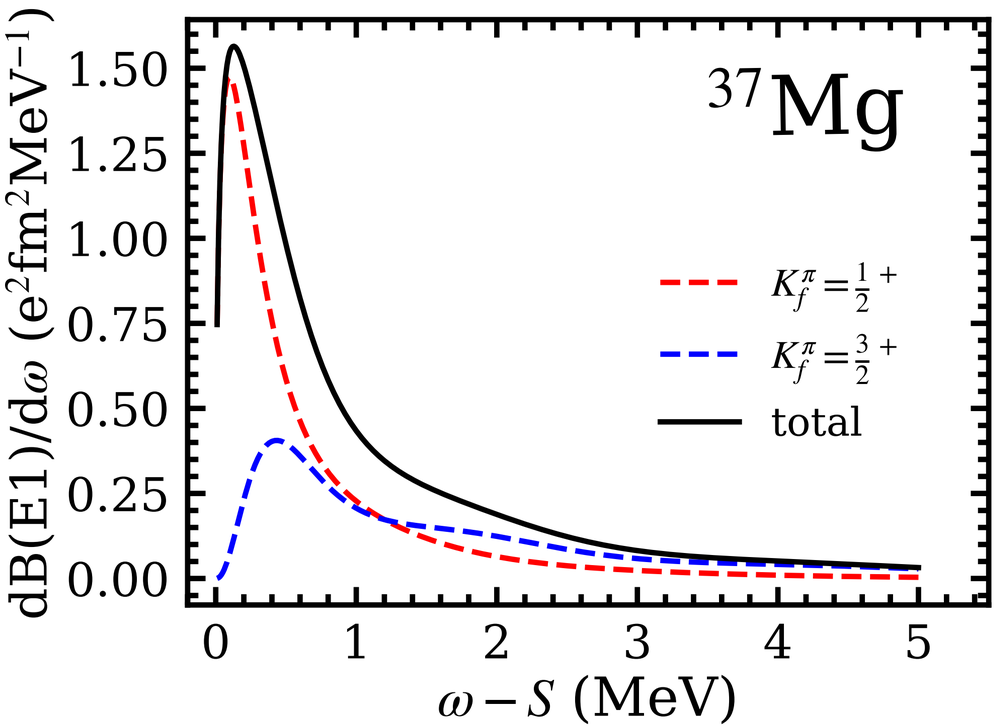
[321]1/2: $0.428p_{1/2} + 0.149p_{3/2} + 0.077f_{5/2} + 0.345f_{7/2}$

$p_{3/2}$: 100 %



$I^\pi = \frac{3}{2}^-$, $K^\pi = \frac{1}{2}^-$

$\beta_2 = 0.46$



$I^\pi = \frac{3}{2}^-$, $K^\pi = \frac{1}{2}^-$

Summary

- The soft electric dipole ($E1$) response of deformed $1n$ halo nuclei ^{31}Ne and ^{37}Mg is studied using a deformed Woods-Saxon potential.
  - The $E1$ response shows a strong soft dipole excitations for

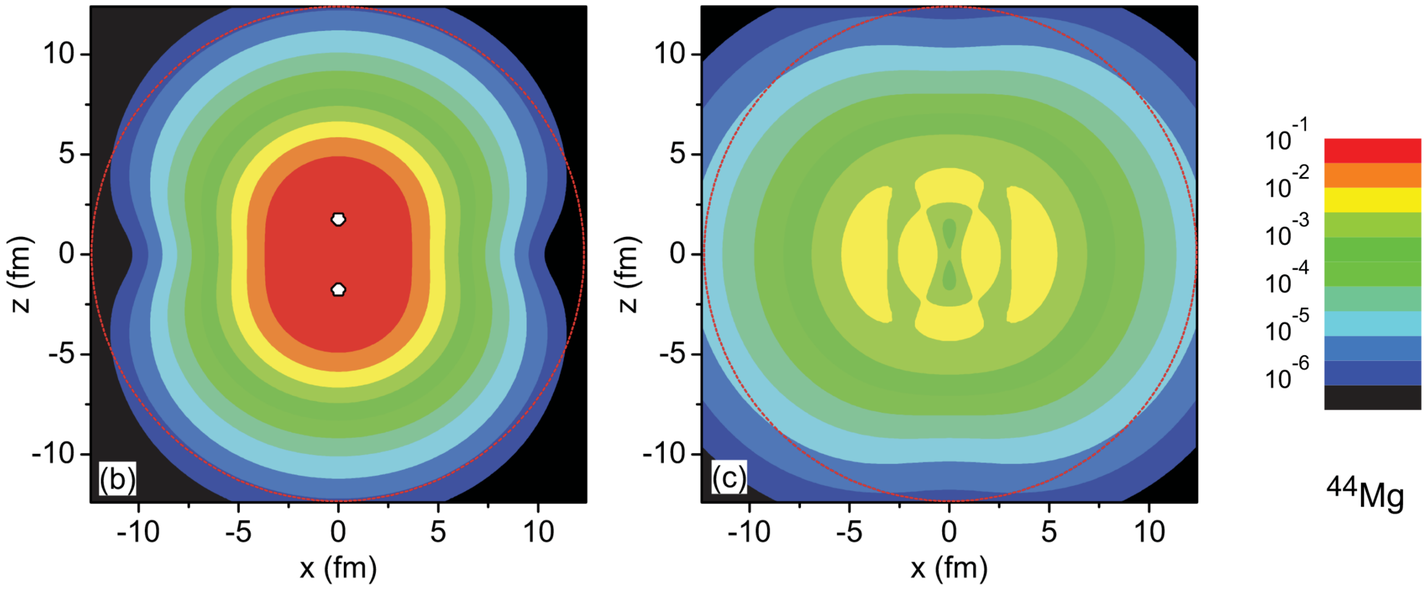
^{31}Ne	[321]3/2	[330]1/2	~~[202]3/2~~
	$\beta_2 = 0.5$	$\beta_2 = 0.24$	$\beta_2 = 0.37$
^{37}Mg	[321]1/2		
	$\beta_2 = 0.46$		

  - The different peak hight and width indicate the dipole response distribution is configuration dependence.

Perspective

- ☑ It has been predicted with the deformed relativistic Hartree-Bogoliubov theory in continuum (DRHBc) that there are **shape decoupling in deformed halo nuclei**, i.e., shapes of the core and the halo are drastically different

The density of the neutron core The density of the neutron halo



What are the signatures of shape decoupling?

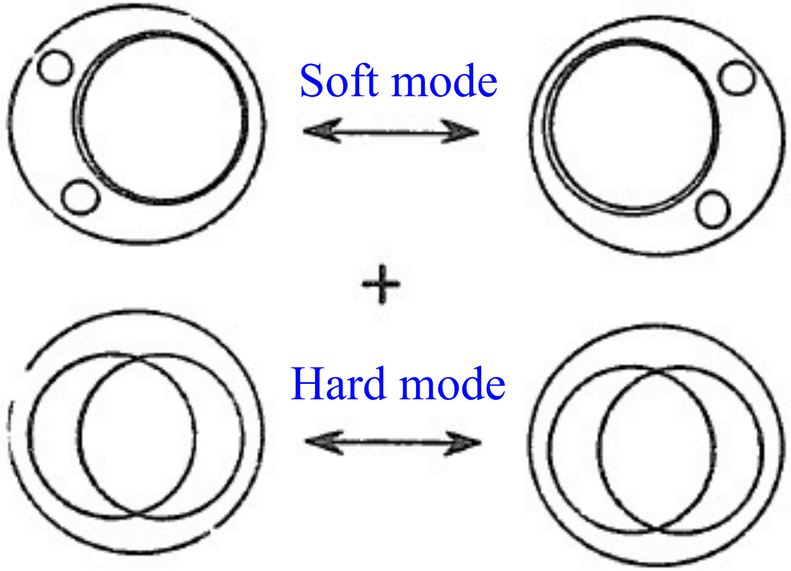
- ☐ Investigate the dipole response for shape decoupling in deformed halo nuclei.

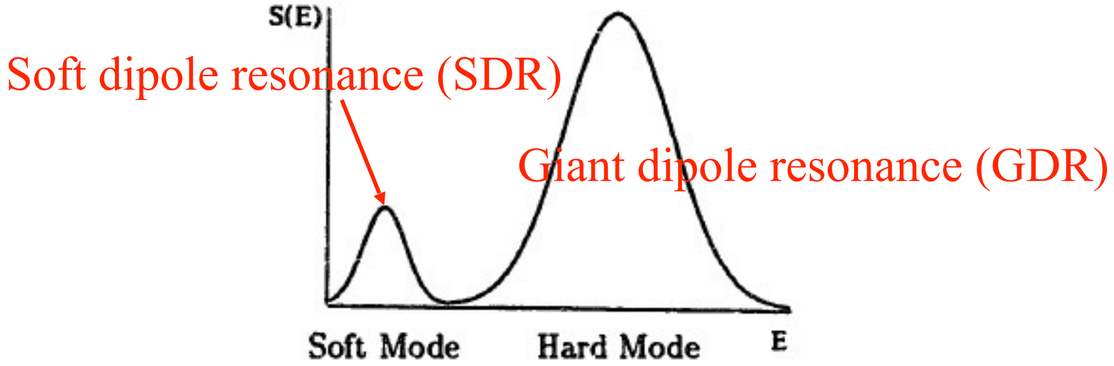
Thank you!

Appendix: Dipole mode

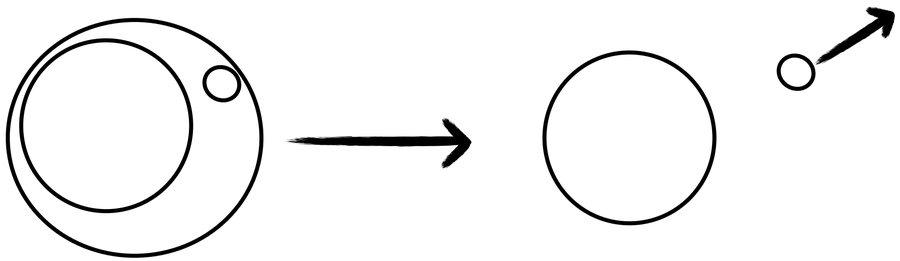
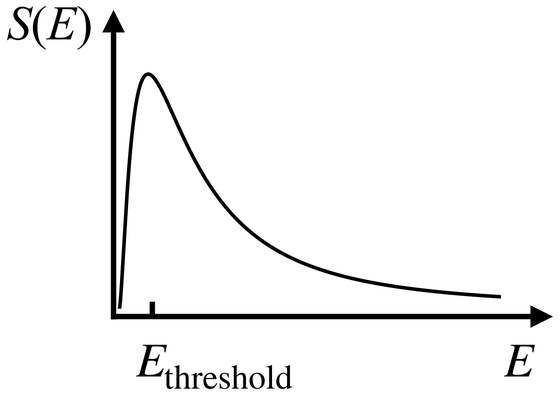
- Soft dipole resonance

  The motion of the unsaturated neutron part against the saturated nuclear core part





K. Ikeda, Nucl. Phys. A 538 (1992) 355c-366c.

- Soft dipole response

  Direct breakup of the halo neutron from the core induced by Coulomb excitation