International Symposium Commemorating the 40th Anniversary of the Halo Nuclei
Oct 12 - 18, 2025, Beijing

Prediction of deformed halo nuclei in neutron-rich silicon isotopes

Cong Pan (潘琮)

School of Physics and Electronic Information,

Anhui Normal University, China

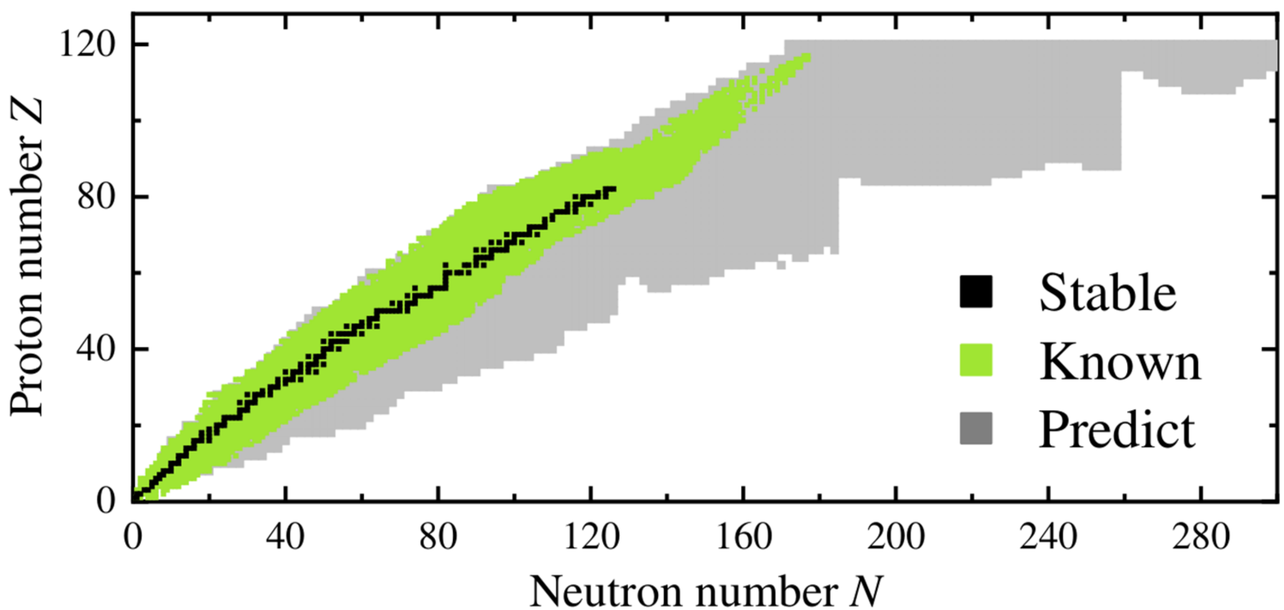
Collaborators: K.Y. Zhang (CAEP)

Outline

- **Introduction**
- Theoretical framework
- Results and discussions
- Summary and perspectives

Exotic nuclei

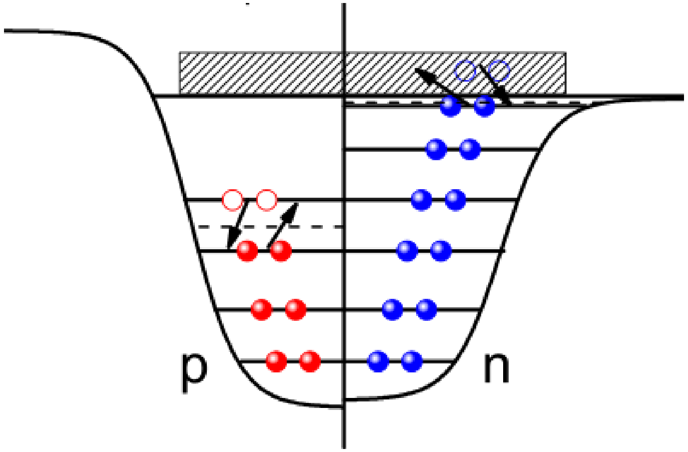
- The study of exotic nuclei far away from β-stability line is one of the most important frontiers in nuclear physics.
  - **Neutron/proton halo** Tanihata *et al*., PRL 55, 2676 (1985)
  - Change in magic number Ozawa *et al*., PRL 84, 5493 (2000)
  - Pygmy resonance Adrich *et al*., PRL 95, 132501 (2005)
  - ……



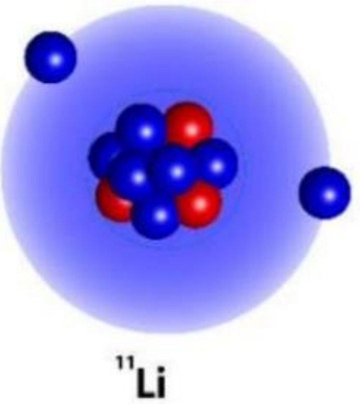
National Nuclear Data Center (NNDC)
DRHBc Mass Table Collaboration, ADNDT 106, 014316 (2022)

Continuum effect

- In halo nuclei, the system is weakly bound, and the Fermi energy is close to the continuum threshold:



Meng *et al*., PPNP 57, 470 (2006)



From X.H. Wu

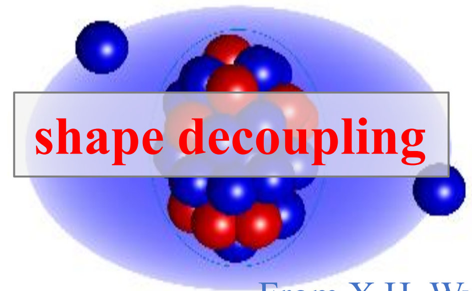
➢ The pairing interaction can scatter nucleons from bound states to the resonant states in the continuum.
—— Effects of pairing correlations and continuum

➢ The density could become more diffuse.
—— Asymptotic behaviors of nuclear density far away from the center.

DRHBc theory

- For exotic nuclei, Zhou *et al* developed the deformed relativistic Hartree-Bogoliubov theory in continuum (DRHBc) by taking into account the effects of deformation, pairing correlations and continuum simultaneously.

Zhou *et al*., PRC 82, 011301(R) (2010)
Li *et al*., PRC 85, 024312 (2012)



From X.H. Wu

- Applications of DRHBc:
  - Prediction of new halos: ^{42,44}Mg, ^{39}Na, …

    PRC 82, 011301(R) (2010); PRC 85, 024312 (2012); PRC 107, L041303 (2023) … …
  - Interpretation of observed halos: ^{17,19}B, ^{15,19,22}C, ^{31}Ne, ^{37}Mg, …

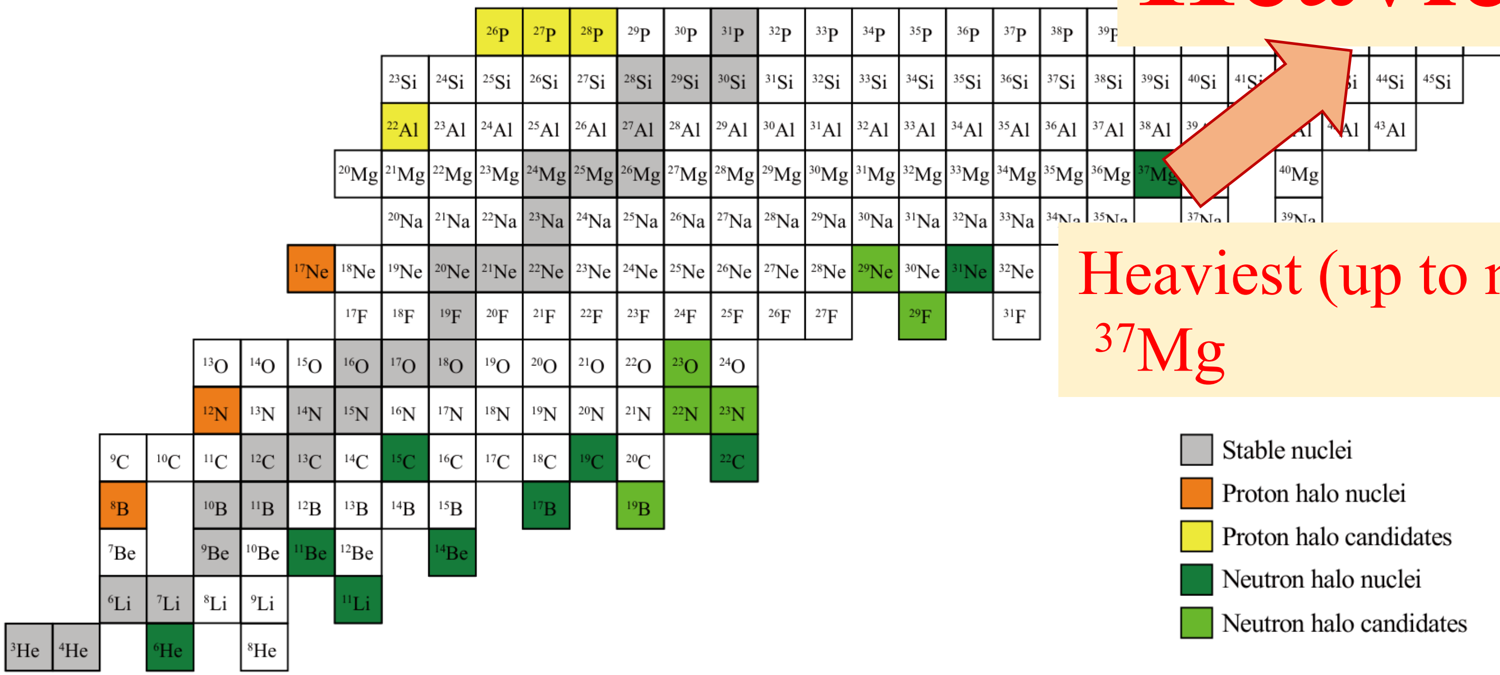
    PRL 126, 082501 (2021); PLB 844, 138112 (2023); PLB 855, 138792 (2024) … …
  - Nuclear mass, stability, shape, size, and extensions

    AAPPS Bulletin, 35, 13 (2025)

See the talks of:
- Prof. P. Ring
- Prof. K.Y. Zhang, Dr. Y.B. Choi, X.F. Jiang, C. Zhou ……

Heavier halo nuclei?

Heavier?



Heaviest (up to now): ^{37}Mg

Figure from: PRC 107, L041303 (2024)

- For light halo nuclei, the theoretical descriptions are well under control.
- For heavier ones, existing theoretical tools are often too qualitative and the associated observables are incomplete.

Meng and Zhou, JPG 42, 093101 (2015)

In this talk

- ✓ Possible **halos in silicon isotopes** are explored based on the DRHBc theory.
- ✓ Different criteria for the halo phenomenon are analyzed.

Outline

- Introduction
- **Theoretical framework**
- Results and discussions
- Summary and perspectives

Theoretical framework

- The mean fields and pairing correlations are self-consistently treated by the relativistic Hartree-Bogoliubov (RHB) equations:

$$\begin{pmatrix} \hat{h}_D - \lambda_\tau & \hat{\Delta} \\ -\hat{\Delta}^* & -\hat{h}_D^* + \lambda_\tau \end{pmatrix} \begin{pmatrix} U_k \\ V_k \end{pmatrix} = E_k \begin{pmatrix} U_k \\ V_k \end{pmatrix}$$

Kucharek and Ring, ZPA 339, 23 (1991)

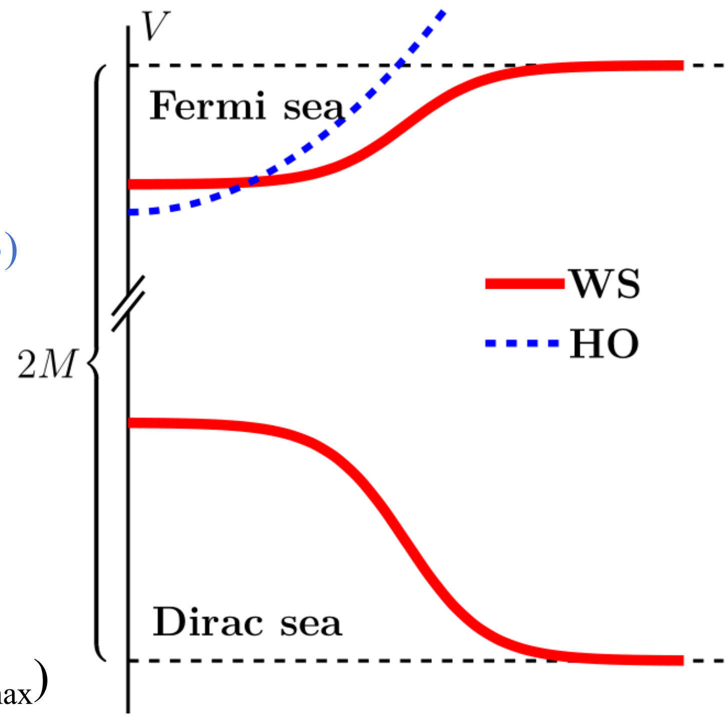
- To properly consider continuum effect, the RHB equations are solved in a spherical Dirac Woods-Saxon (DWS) basis.

Zhou *et al*., PRC, 68, 034323 (2003)

- For the nuclei with axial deformation and spatial reflection symmetry, the densities and potentials are expanded with Legendre polynomials:

$$f(\boldsymbol{r}) = \sum_\lambda f_\lambda(r) P_\lambda(\cos\theta), \quad (\lambda = 0, 2, 4, \ldots, \lambda_{\max})$$

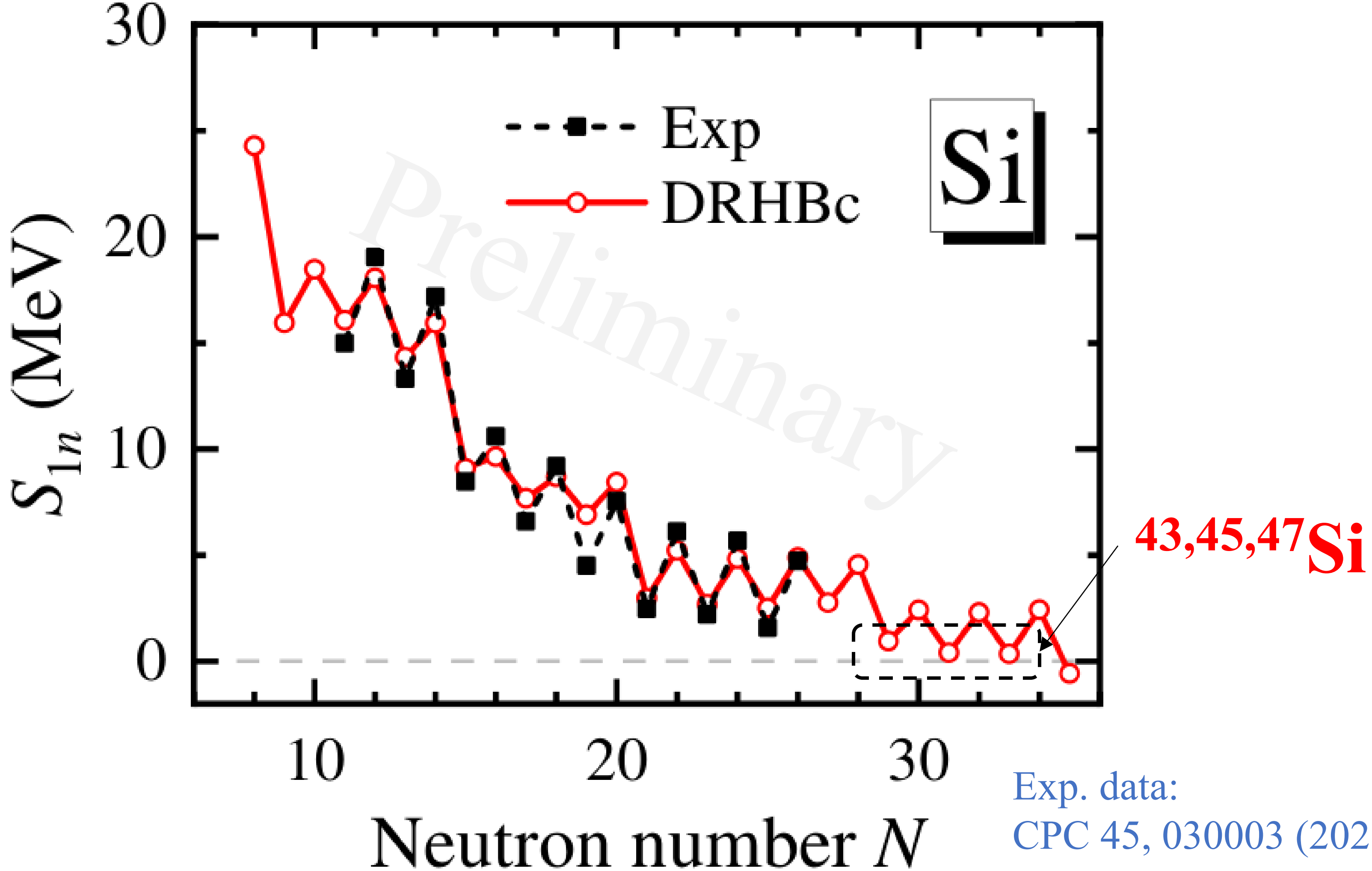
Zhou *et al*., PRC 82, 011301 (2010)



Outline

- Introduction
- Theoretical framework
- **Results and discussions**
  - **Global halo criteria: Si isotopes**
  - Microscopic criteria
- Summary and perspectives

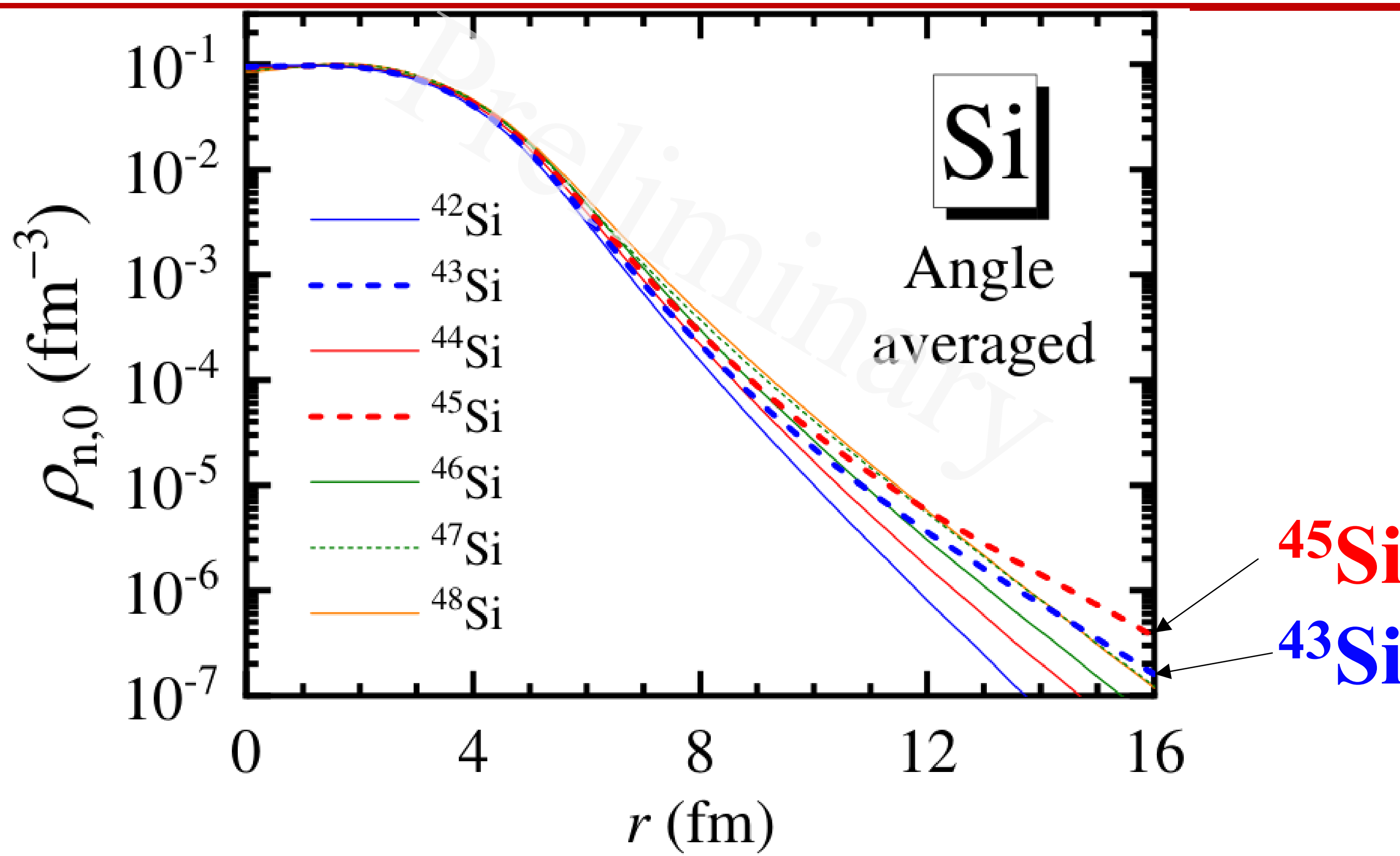
Separation energy



Exp. data:
CPC 45, 030003 (2021)

- Available data are well reproduced. (σ = 1.03 MeV)
- S_{1n} < 1 MeV in ^{43,45,47}**Si**.

Neutron density profile



- ^{43,45}Si: Larger spatial extensions.
- We calculated several quantities to characterize halos, and results also support possible halos in ^{43,45}Si.

Zhang *et al*., PRC 108, L041301 (2023)
Rotival *et al*., PRC 79, 054308 (2009)

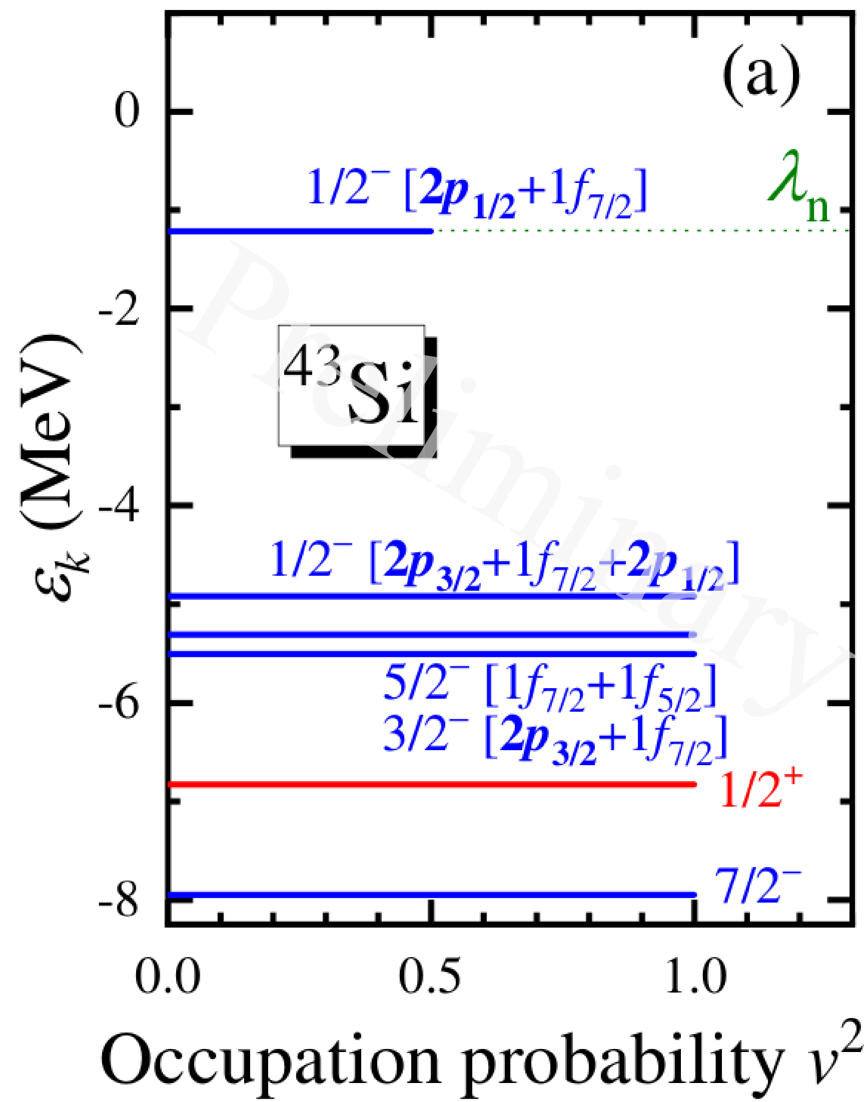
Outline

- Introduction
- Theoretical framework
- **Results and discussions**
  - Global halo criteria: Si isotopes
  - **Microscopic criteria: ^{43,45}Si**
- Summary and perspectives

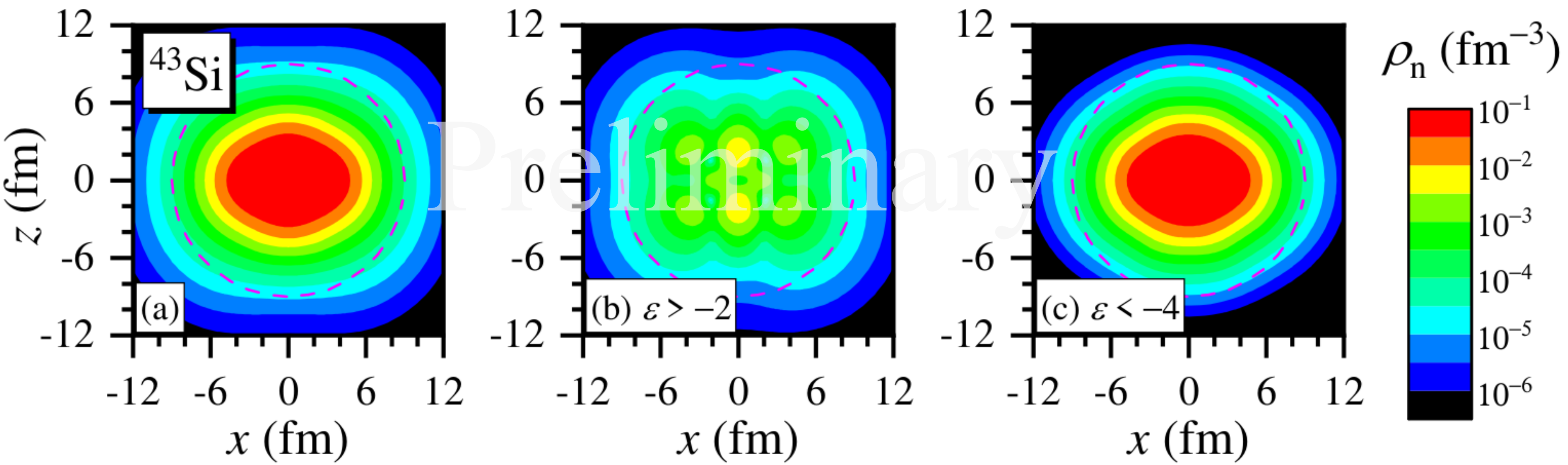
^{43}Si: Single-neutron levels

- In ^{43}Si:
  - Weakly bound $1/2^-$: significant *p*-wave component.
  - A significant gap from –1.2 to –4.9 MeV.

  → in favor of a halo.



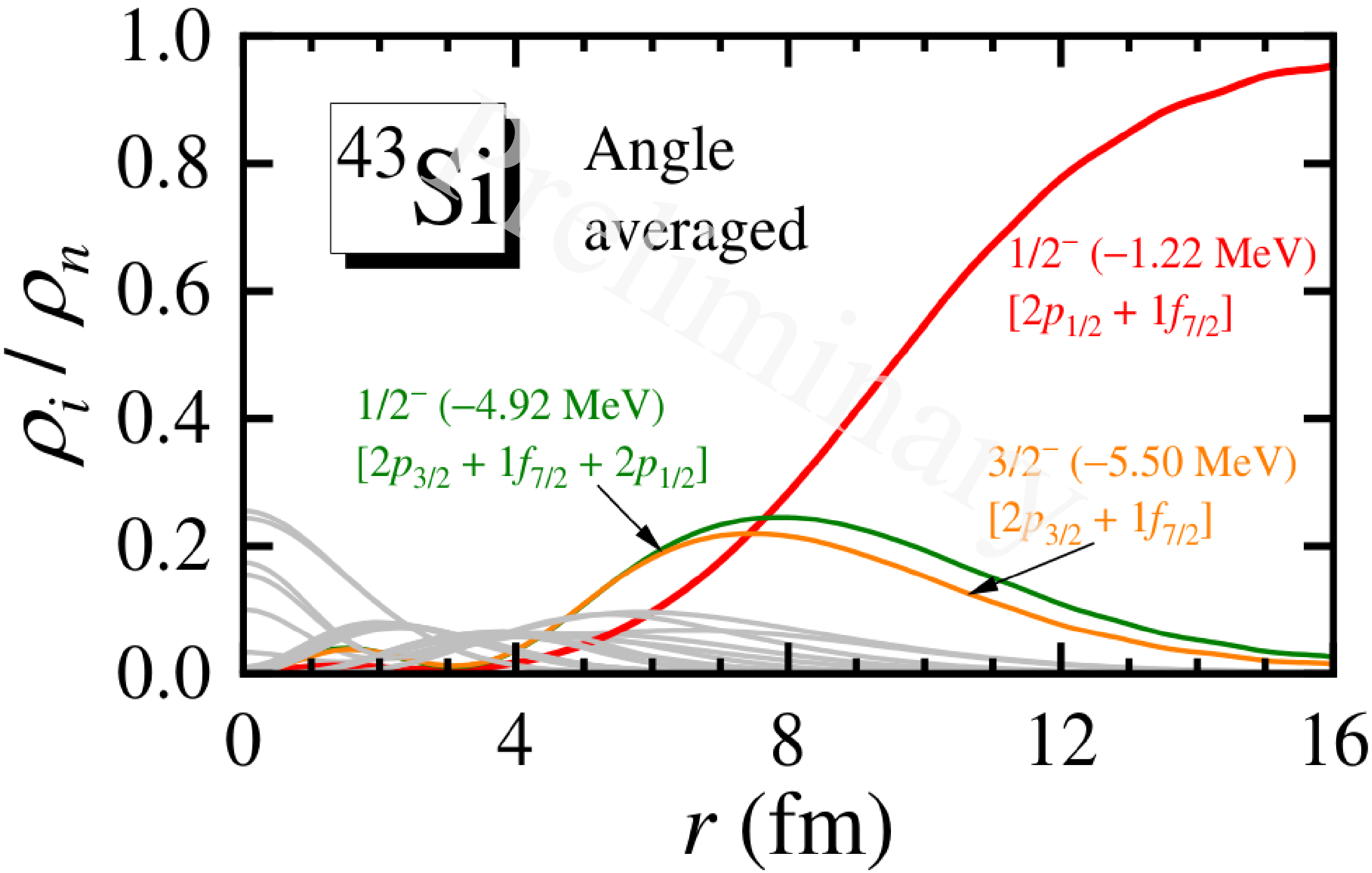
^{43}Si: Densities of halo and core



- ^{43}Si:
  - $\varepsilon > -2$ MeV: $R_n = 5.56$ fm , $\beta_2 = -0.01$.
  - $\varepsilon < -4$ MeV: $R_n = 3.83$ fm , $\beta_2 = -0.37$.

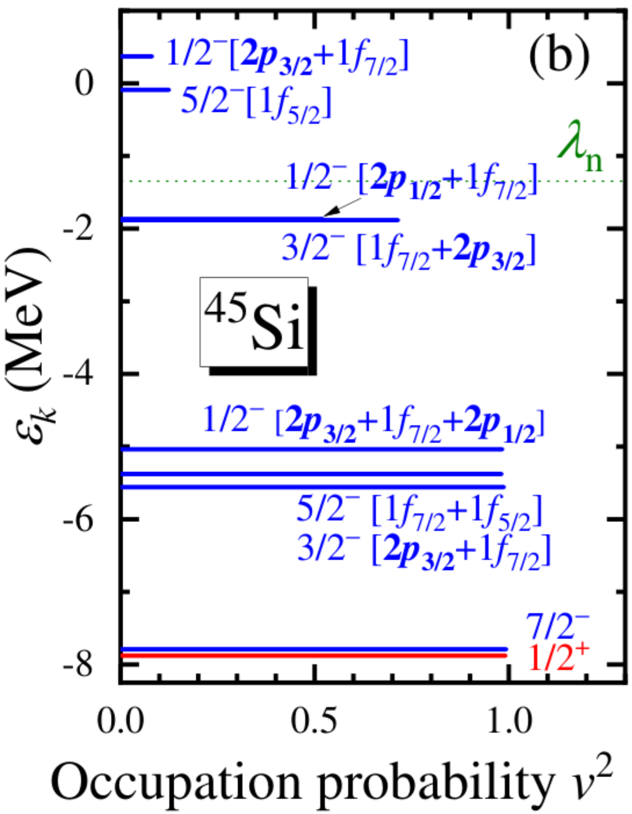
$\rightarrow$ Neutron halo with shape decoupling in ^{43}Si.

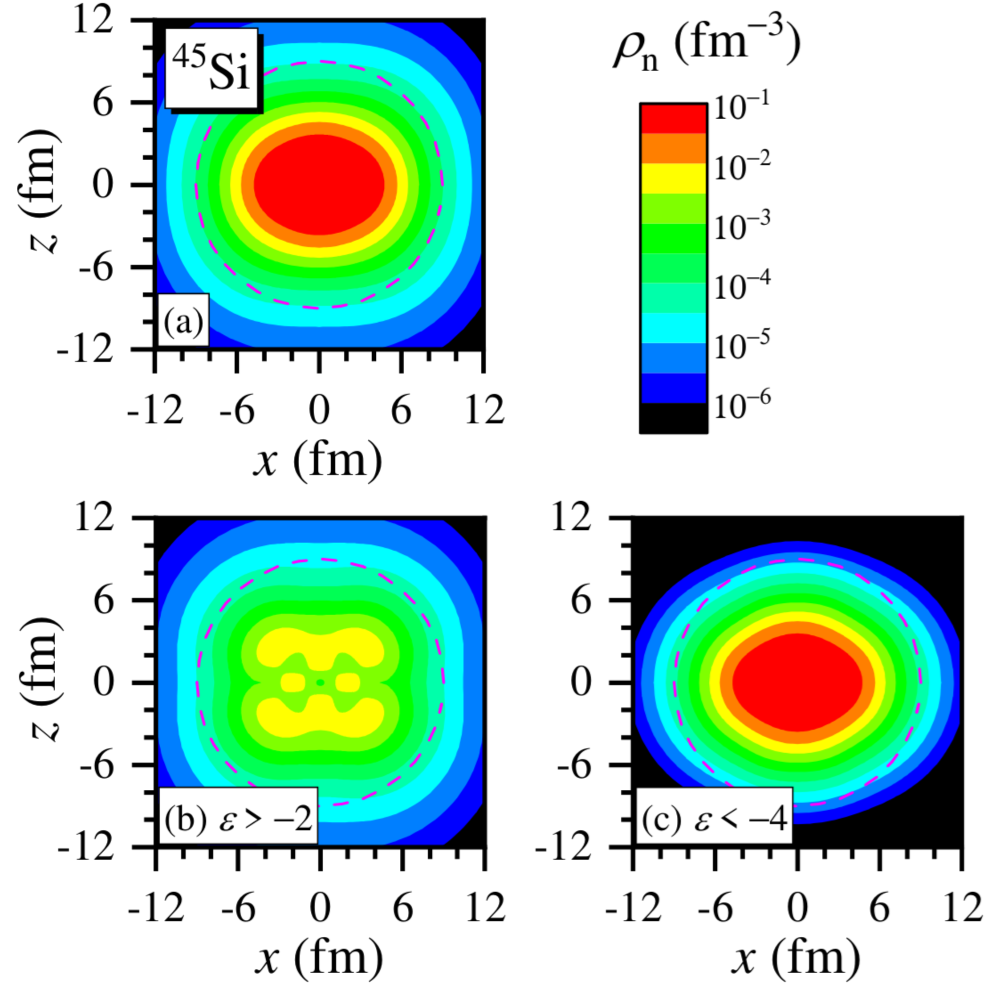
^{43}Si: Decomposition of neutron density



- The *p*-wave component plays a dominant role in the neutron density at large *r*, supporting the halo.

^{45}Si





- $\varepsilon > -2$ MeV: $R_n = 5.21$ fm , $\beta_2 = +0.01$.
- $\varepsilon < -4$ MeV: $R_n = 3.83$ fm , $\beta_2 = -0.31$.

→ Neutron halo with shape decoupling in ^{45}Si.

Outline

- Introduction
- Theoretical framework
- Results and discussions
- **Summary and perspectives**

Summary and perspectives

- Possible **deformed halo nuclei ^{43,45}Si** with shape decoupling are predicted from different halo criteria based on the DRHBc theory.
- In progress:
  - ➢ Potential **lightest giant halo nuclei ^{47,48}Si**.
  - ➢ Reaction observables of these halo nuclei.

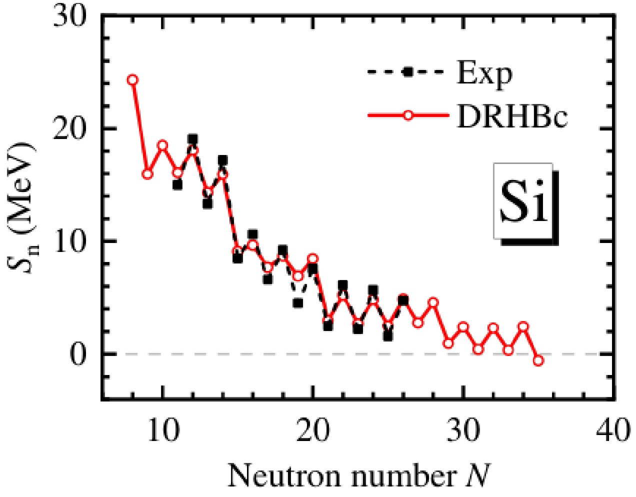
Collaborators: S.S. Zhang (BUAA)

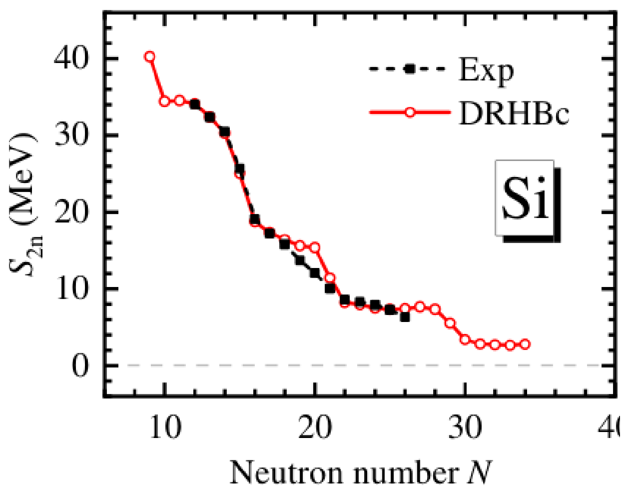
- Future experiments are welcome!

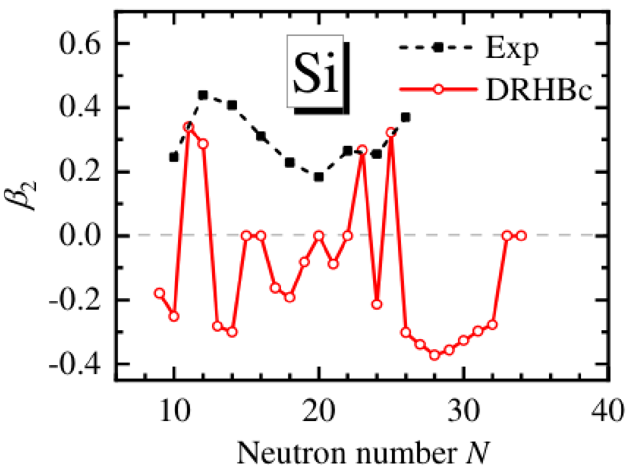
Thank you for your attention!

Appendix

Si: bulk properties







Characterizing possible halos

a) Halo scale

Zhang *et al.*, PRC 108, L041301 (2023)

$$S_{\text{halo-1n}} = \frac{\Delta \tilde{R}_n}{\Delta R_n^{\text{emp}}} = \frac{\tilde{R}_n(N) - \tilde{R}_n(N-1)}{R_n^{\text{emp}}(N) - R_n^{\text{emp}}(N-1)}$$

- $\tilde{R}$: "spherical" reduced radius
- R_n^{emp}: empirical radius

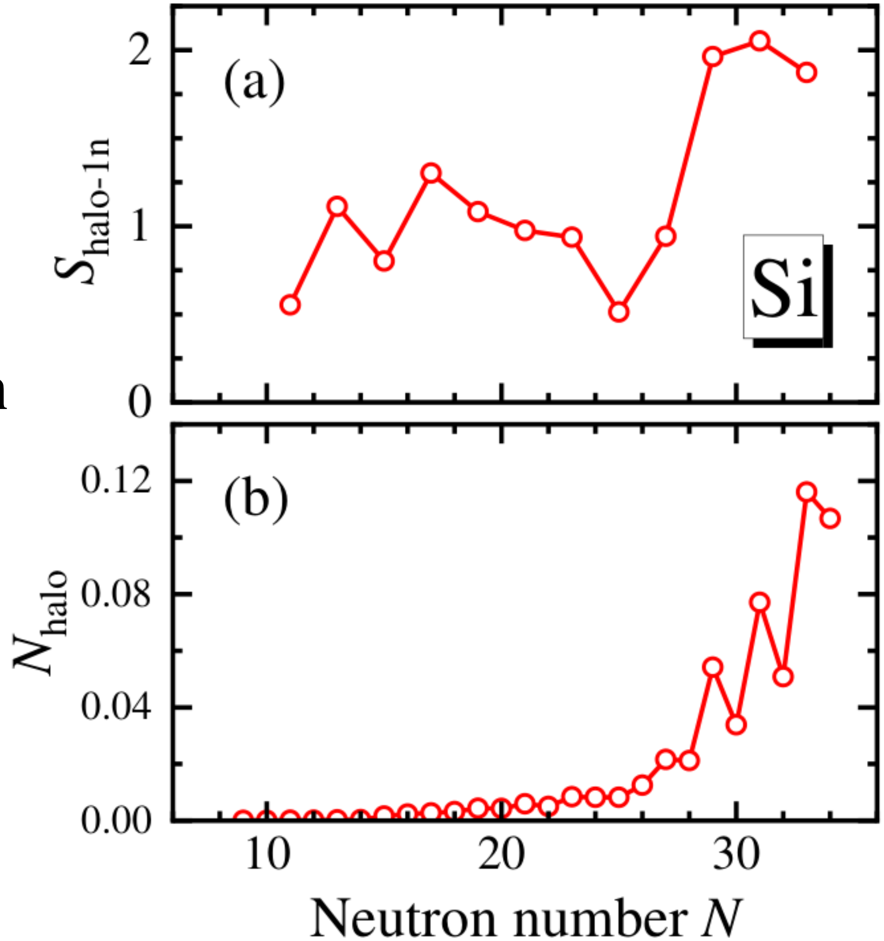
b) Neutron number in halo region

$$N_{\text{halo}} = 4\pi \int_{r_0}^{\infty} \rho_{n,0}(r)\mathrm{d}r$$

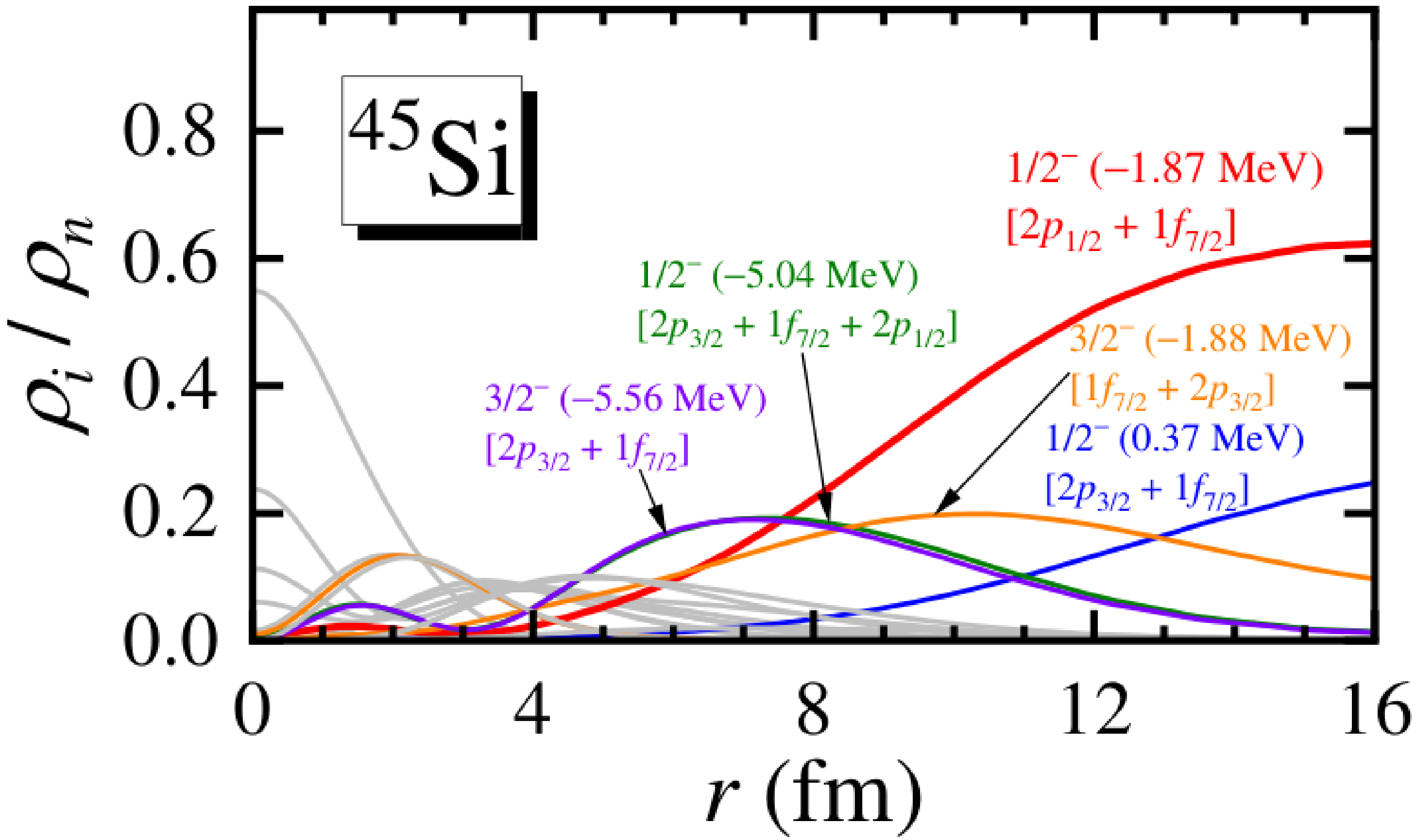
Rotival *et al.*, PRC 79, 054308 (2009)

- Significant enhancements of $S_{\text{halo-1n}}$ and N_{halo} correspond to potential halos:
  $N =$ **29, 31**, 33 (**^{43}Si, ^{45}Si**, ^{47}Si).

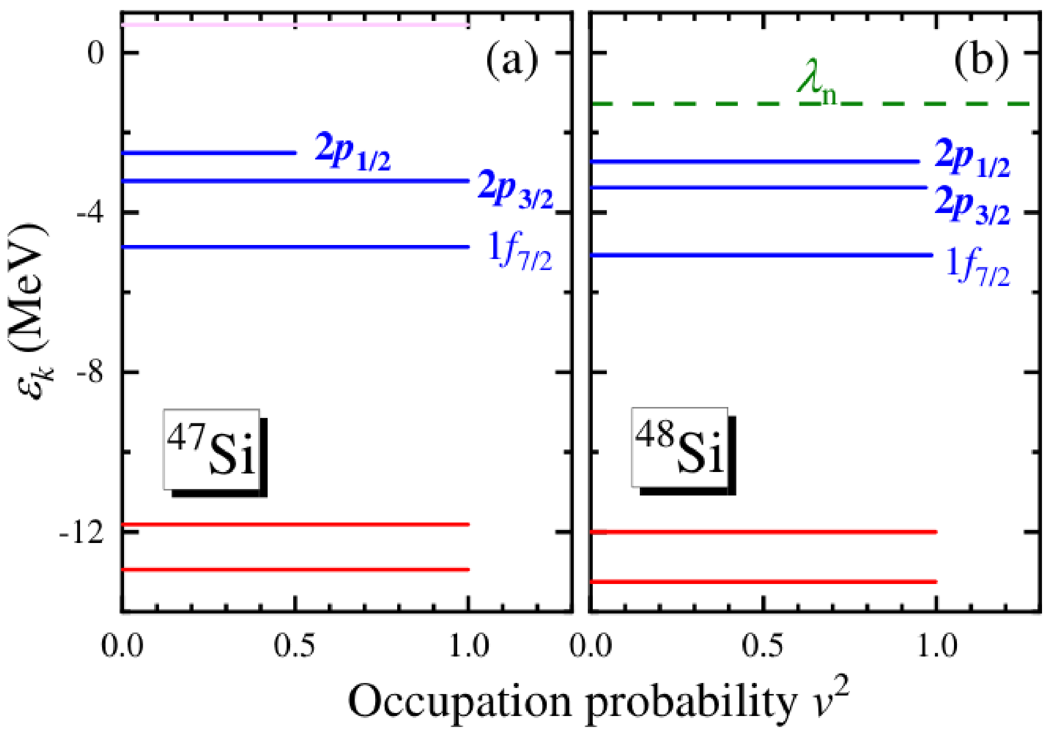
(future work)

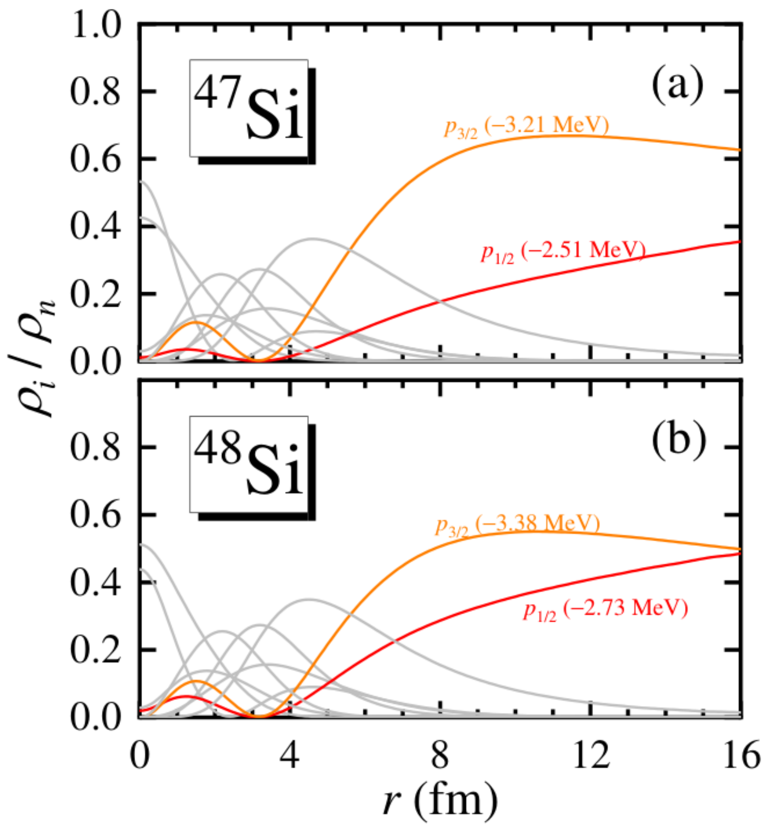


Density decomposition of ^{45}Si

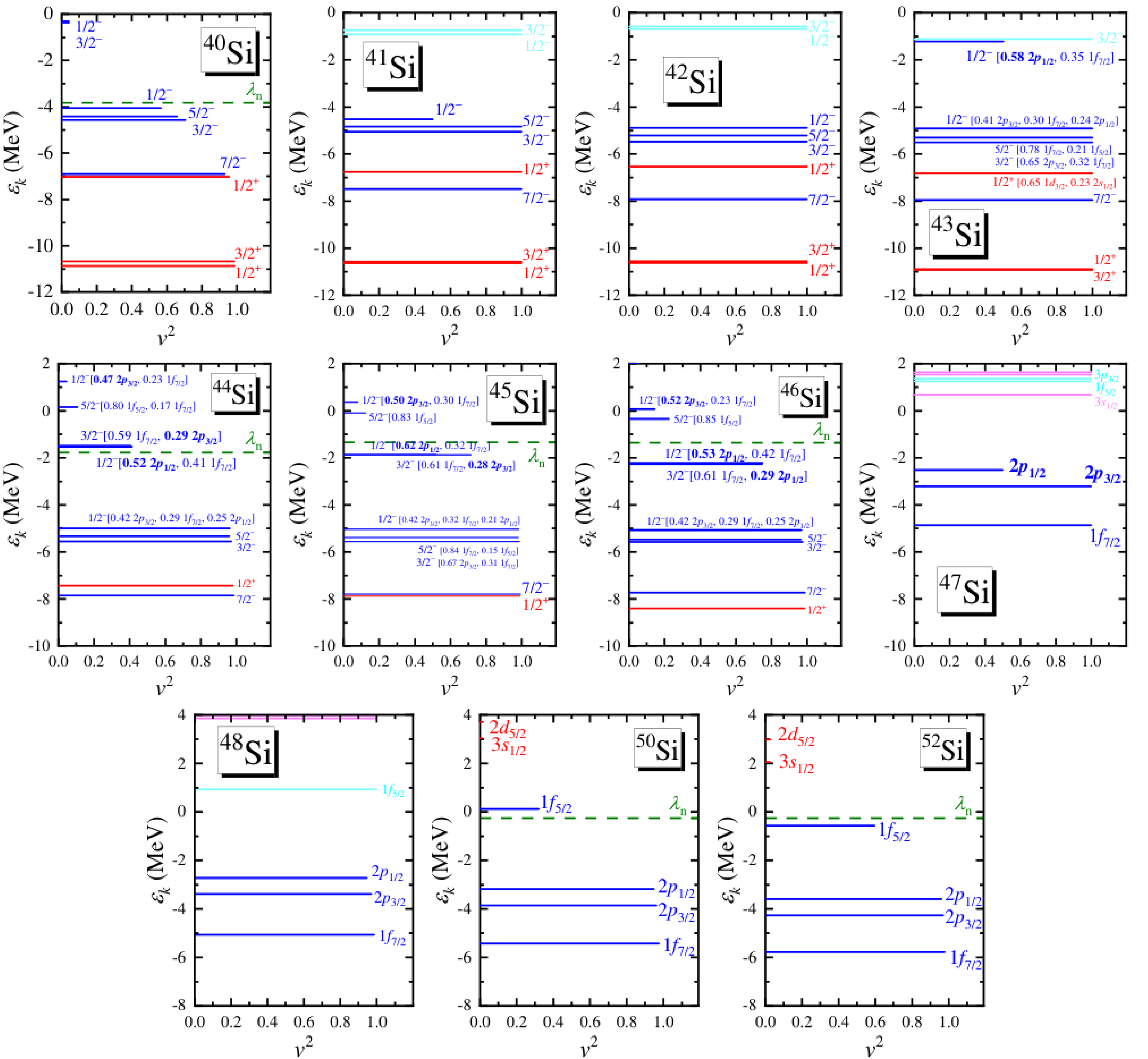


Possible giant halos in ^{47,48}Si



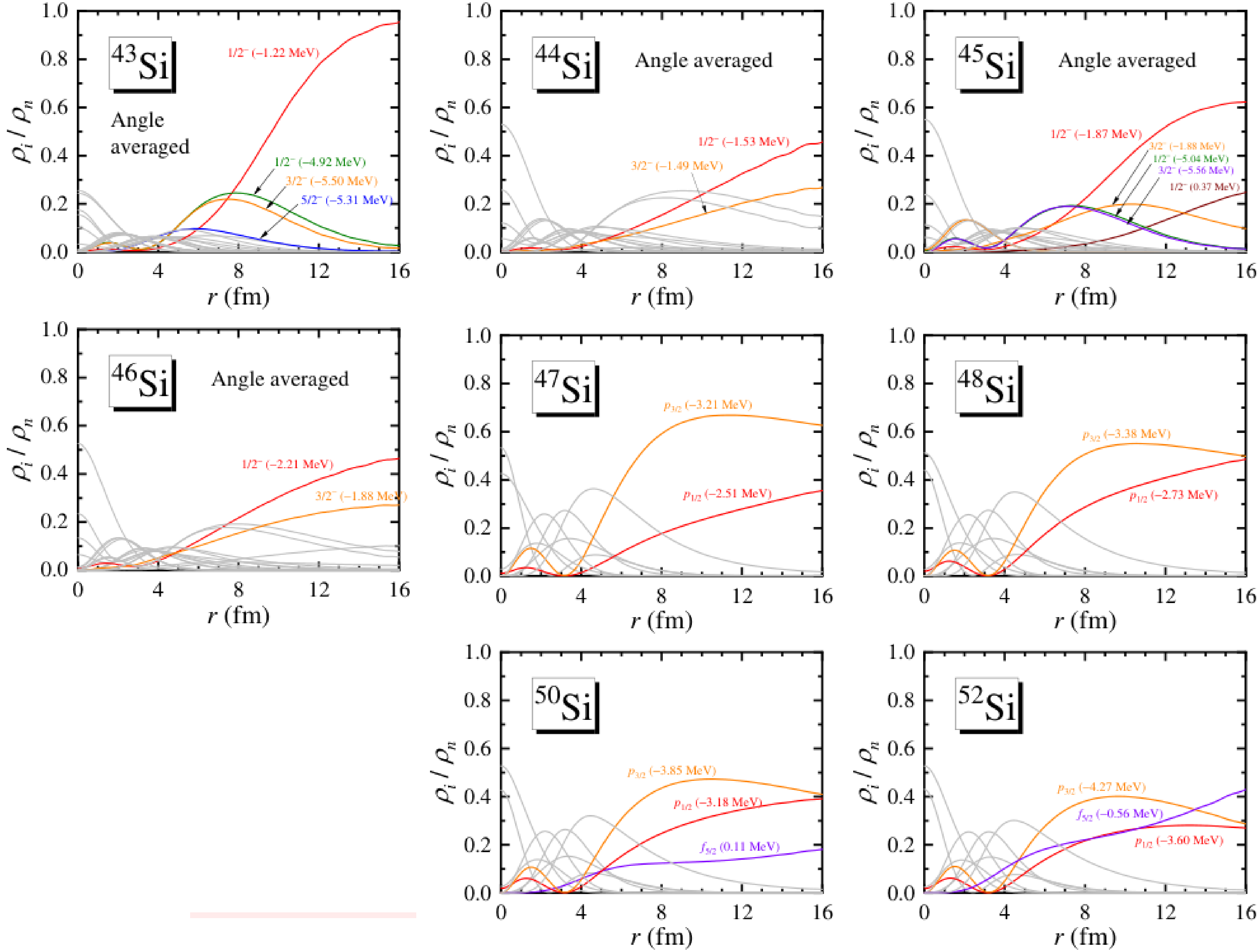


Si: SPL



^{40}Si
^{41}Si
^{42}Si
^{43}Si
^{44}Si
^{45}Si
^{46}Si
^{47}Si
^{48}Si
^{50}Si
^{52}Si
ε_k (MeV)
v^2
λ_n
1/2$^-$ [0.58 $2p_{1/2}$, 0.35 $1f_{7/2}$]
1/2$^-$ [0.41 $2p_{3/2}$, 0.30 $1f_{7/2}$, 0.24 $2p_{1/2}$]
5/2$^-$ [0.78 $1f_{5/2}$, 0.21 $1f_{5/2}$]
3/2$^-$ [0.65 $2p_{3/2}$, 0.32 $1f_{7/2}$]
1/2$^+$ [0.65 $1d_{3/2}$, 0.23 $2s_{1/2}$]
1/2$^-$[0.47 $2p_{3/2}$, 0.23 $1f_{7/2}$]
5/2$^-$[0.80 $1f_{5/2}$, 0.17 $1f_{7/2}$]
3/2$^-$[0.59 $1f_{7/2}$, 0.29 $2p_{3/2}$]
1/2$^-$[0.52 $2p_{1/2}$, 0.41 $1f_{7/2}$]
1/2$^-$[0.42 $2p_{3/2}$, 0.29 $1f_{7/2}$, 0.25 $2p_{1/2}$]
1/2$^-$[0.50 $2p_{3/2}$, 0.30 $1f_{7/2}$]
5/2$^-$[0.83 $1f_{5/2}$]
1/2$^-$[0.62 $2p_{1/2}$, 0.32 $1f_{7/2}$]
3/2$^-$ [0.61 $1f_{7/2}$, 0.28 $2p_{3/2}$]
1/2$^-$ [0.42 $2p_{3/2}$, 0.32 $1f_{7/2}$, 0.21 $2p_{1/2}$]
5/2$^-$ [0.84 $1f_{5/2}$, 0.15 $1f_{5/2}$]
3/2$^-$ [0.67 $2p_{3/2}$, 0.31 $1f_{7/2}$]
1/2$^-$[0.52 $2p_{3/2}$, 0.23 $1f_{7/2}$]
5/2$^-$[0.85 $1f_{5/2}$]
1/2$^-$[0.53 $2p_{1/2}$, 0.42 $1f_{7/2}$]
3/2$^-$[0.61 $1f_{7/2}$, 0.29 $2p_{1/2}$]
1/2$^-$[0.42 $2p_{3/2}$, 0.29 $1f_{7/2}$, 0.25 $2p_{1/2}$]
$3p_{3/2}$
$1f_{5/2}$
$3s_{1/2}$
$2p_{1/2}$
$2p_{3/2}$
$1f_{7/2}$
$2d_{5/2}$

Si: decomposition of neutron density



Si: neutron densities