# Electric-dipole transitions in $^{6}$Li with a fully microscopic six-body calculation

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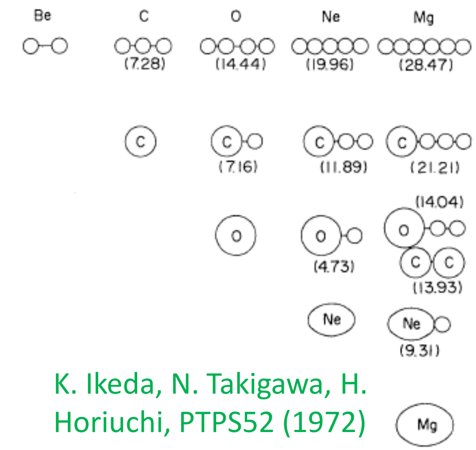
S. Satsuka and WH, Phys. Rev. C 100, 024334 (2019), published on 29 August

# Nuclear clustering and E1 transition




K. Ikeda, N. Takigawa, H. Horiuchi, PTPS52 (1972)

- Nuclear clustering play an important role in light N=Z nuclei
  (e.g. Ikeda diagram, Hoyle state in $^{12}$C)

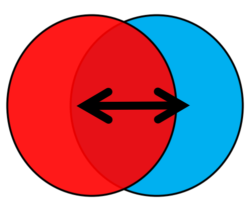
- Electric-dipole (E1) transition
  - Leading order of electric-multipoles
  - Giant dipole resonance (GDR) phenomena for all nuclei
  - *A probe of the structure information*
  - Exploring new exotic excitation mode

    E.g. neutron rich unstable nuclei

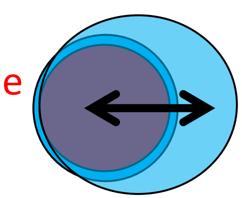
    Vibration of valence nucleons against the core

    A variant of the macroscopic picture of giant dipole resonance (GDR)
    - Goldhaber-Teller, Steinwedel-Jensen models

GDR



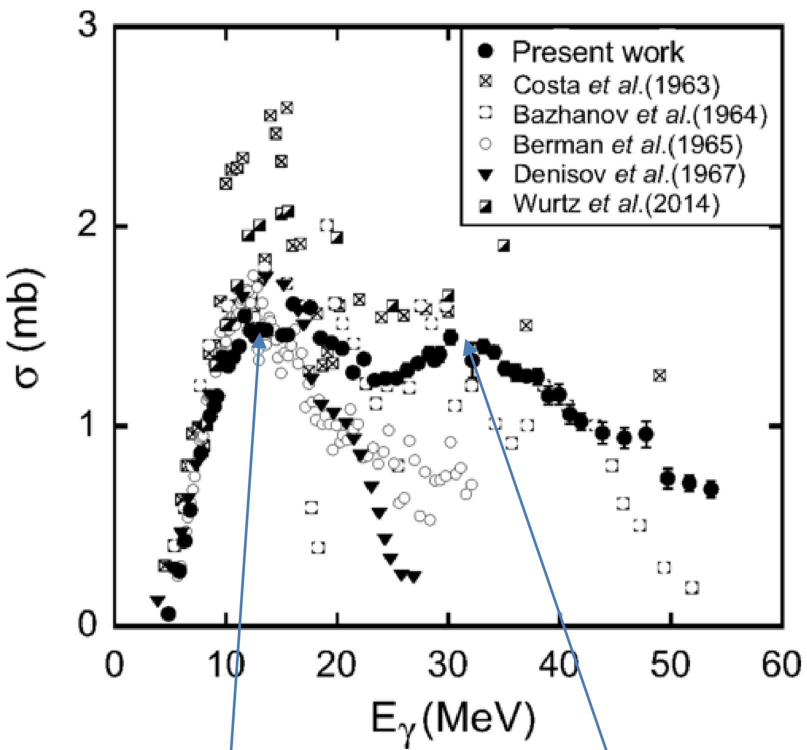
Soft dipole mode



T. Yamazaki et al., JHP Report (1986)
P.G. Hansen and B. Jonson, Europhys. Lett. 4, 409 (1987)
K. Ikeda, INS Report No. (1988)

# Recent photoabsorption measurement of $^6$Li

T. Yamagata, S. Nakayama, H. Akimune, S. Miyamoto, Phys. Rev. C 95, 044307 (2017)




First peak: GDR of $^6$Li?
Second peak: GDR of alpha cluster in $^6$Li?

- Low-lying photoabsorption mainly occurs through E1 transition
- A two peak structure is found

  Their interpretation
  - First peak: GDR of $^6$Li?
  - Second peak: GDR of alpha cluster in $^6$Li?

- Is the interpretation is correct?
- What is the role of the nuclear clustering in $^6$Li

  → possible to find new modes in other nuclei

Microscopic six-body calculation

# Variational calculation for many-body quantum system

- Many-body wave function $\Psi$ has all information of the nucleon dynamics
- Solve many-body Schoedinger equation
  ⇔ Eigenvalue problem with Hamiltonian matrix
  $$H\Psi = E\Psi$$
- Variational principle $<\Psi|H|\Psi> = E \geqq E_0$ ("Exact" energy)
  (Equal holds if $\Psi$ is the "exact" solution)

- Expand the wave function with the explicitly correlated Gaussian functions
  $$\Psi = \Sigma_k c_k \exp\{- \Sigma_{i,j} \beta^k_{ij}(r_i-r_j)^2\}$$
  - Optimal parameters $\beta^k_{ij}$ are selected stochastically

    **Stochastic Variational Method** K. Varga and Y. Suzuki, PRC52, 2885 (1995).

    1. Randomly generate candidates
    2. Calculate energy for each candidate
    3. Select the basis which gives the lowest energy among them
    4. Increase the basis size
    5. Return to 1. and repeat the procedure until energy is converged

    → accurate solution can be obtained with a small basis size

# Ground-state properties of $^6$Li

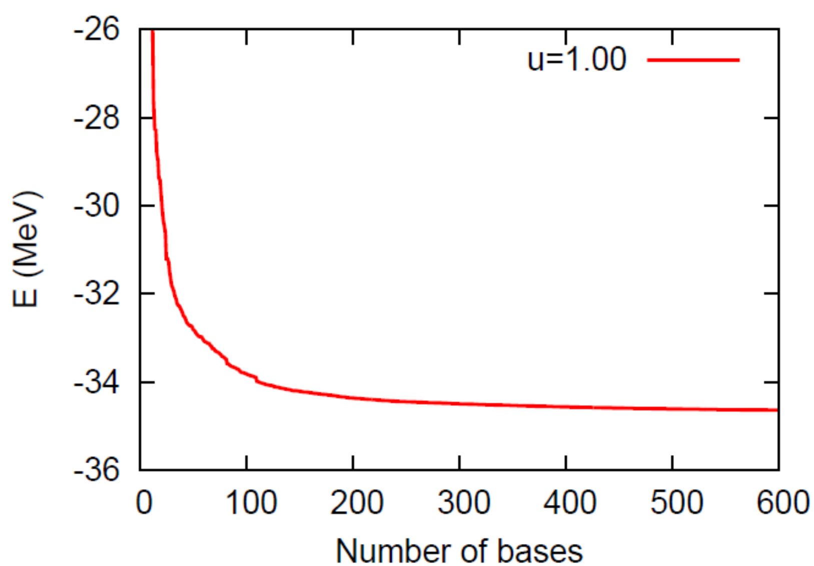
$$H = \sum_{i=1}^{N} T_i - T_{\rm cm} + \sum_{i<j} v_{ij}$$

Free of spurious c.m. motion

$v_{ij}$: Minnesota potential

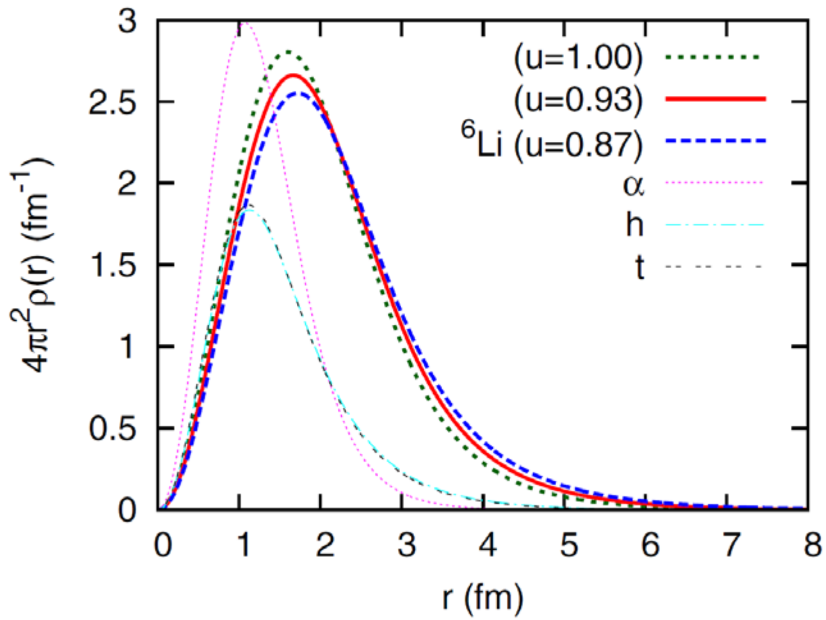
Reasonable descriptions of s-shell nuclei

"u" ⇔ odd-wave strength




Converged only with 600 basis states

Note: 15 parameters for each basis




| $u$ | $E_0(^6\text{Li})$ | $E_0(\alpha)$ | $S_{pn}$ | $r_m$ | $r_p$ | $r_n$ | $r_{pp}$ | $S^2_{\alpha d}$ |
|---|---|---|---|---|---|---|---|---|
| 1.00 | −34.63 | −29.94 | 4.7 | 2.20 | 2.20 | 2.20 | 3.62 | 0.856 |
| 0.93 | −33.63 | −29.90 | 3.7 | 2.33 | 2.34 | 2.33 | 3.86 | 0.869 |
| 0.87 | −32.94 | −29.87 | 3.1 | 2.45 | 2.46 | 2.45 | 4.07 | 0.882 |
| Expt. | −31.99 | −28.30 | 3.70 | | 2.452 | | | |

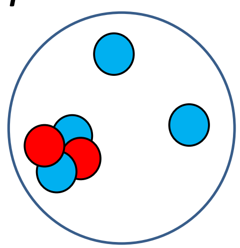
# Cluster degrees of freedom

Six-body calculation for $^6$He

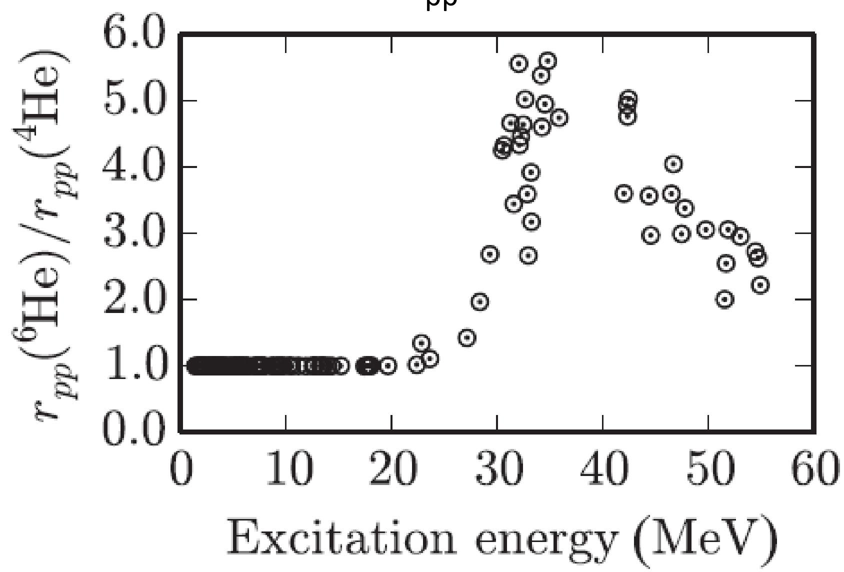
D. Mikami, WH, Y. Suzuki, Phys. Rev. C 89, 046303 (2014)

Distance between two protons

*A measure of alpha clustering*



Ratio of $r_{pp}$ of $^6$He and $^4$He



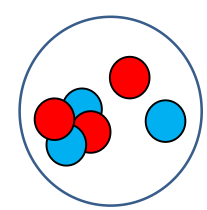

- The ratio is unity up to 20 MeV

  Three-body model for the excited state is valid up to 20 MeV
- Large core distortion in the GDR region >30 MeV

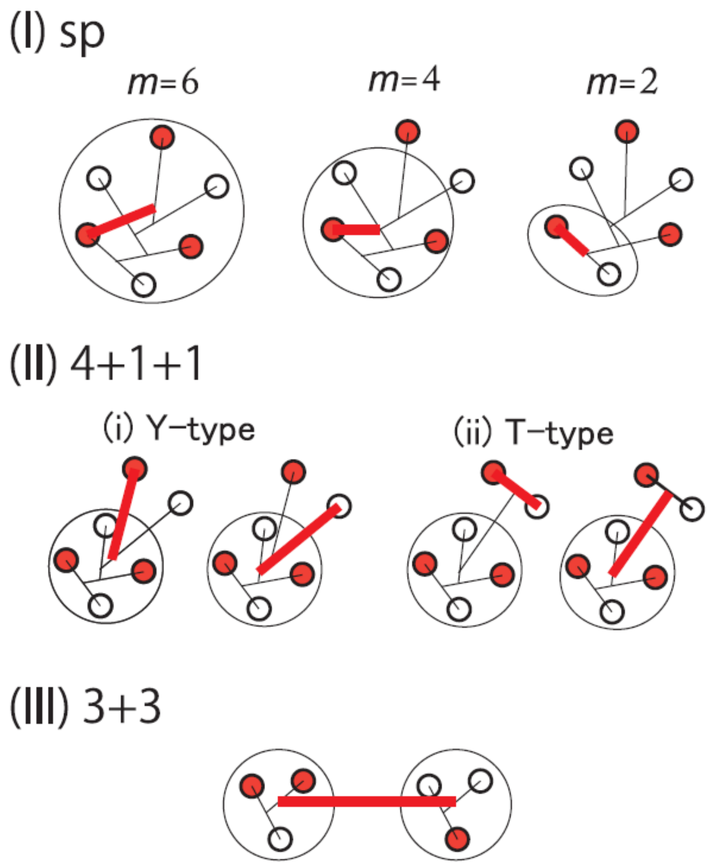
Extension to $^6$Li case

- Proton in valence or cluster cannot be distinguished
- Spectroscopic factors $S_{ab}^2 = \left|\langle \Psi^{(a)}\Psi^{(b)} \middle| \Psi_{JM_J}^{(6)}(E)\rangle\right|^2,$

  A more direct measure of the nuclear clustering



# Configurations for the final state




Basis functions for all subsystems are obtained by SVM

**Correlated Gaussian + global vector**

$$F_{LM_L}(v, A, \boldsymbol{x}) = \exp\left(-\tfrac{1}{2}\tilde{\boldsymbol{x}} A \boldsymbol{x}\right) \mathcal{Y}_{LM_L}(\tilde{v}\boldsymbol{x})$$

$$\tilde{\boldsymbol{x}} A \boldsymbol{x} = \sum_{i,j=1}^{N-1} A_{ij} \boldsymbol{x}_i \cdot \boldsymbol{x}_j \quad \tilde{v}\boldsymbol{x} \left(= \sum_{i=1}^{N-1} v_i \boldsymbol{x}_i\right).$$

**E1 operator**

$$\mathcal{M}_{1\mu} = e \sum_{i \in p} (\boldsymbol{r}_i - \boldsymbol{x}_6)_\mu = \sqrt{\frac{4\pi}{3}} e \sum_{i \in p} \mathcal{Y}_{1\mu}(\boldsymbol{r}_i - \boldsymbol{x}_6)$$

**(i)Single particle excitations**

$M_{1\mu}(E1)\Psi_i(^6\mathrm{Li})$

"Coherent E1 state"

Well account for the E1 sumrule

3 × 600 basis states

**(ii)α+n+n disintegration**

$\Psi_i(^4\mathrm{He})\chi(R, r)$

valence nucleon excitation

2 × 8100 basis states

**(iii)h+t disintegration**

$\Psi_i(^3\mathrm{He})\Psi_j(^3\mathrm{H})\chi(R)$

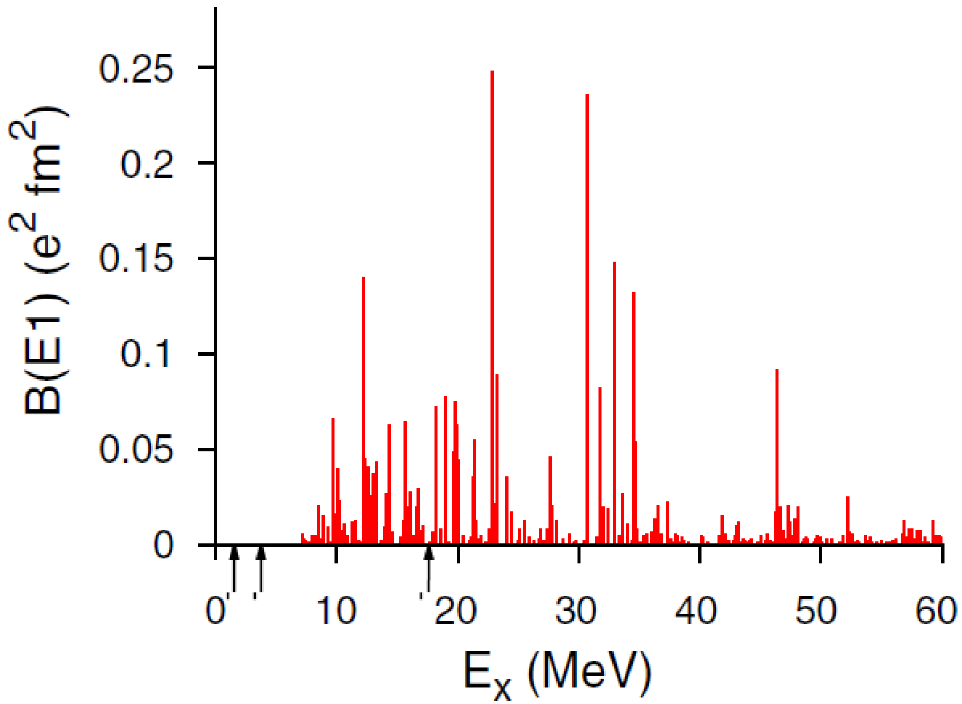
GDR configuration

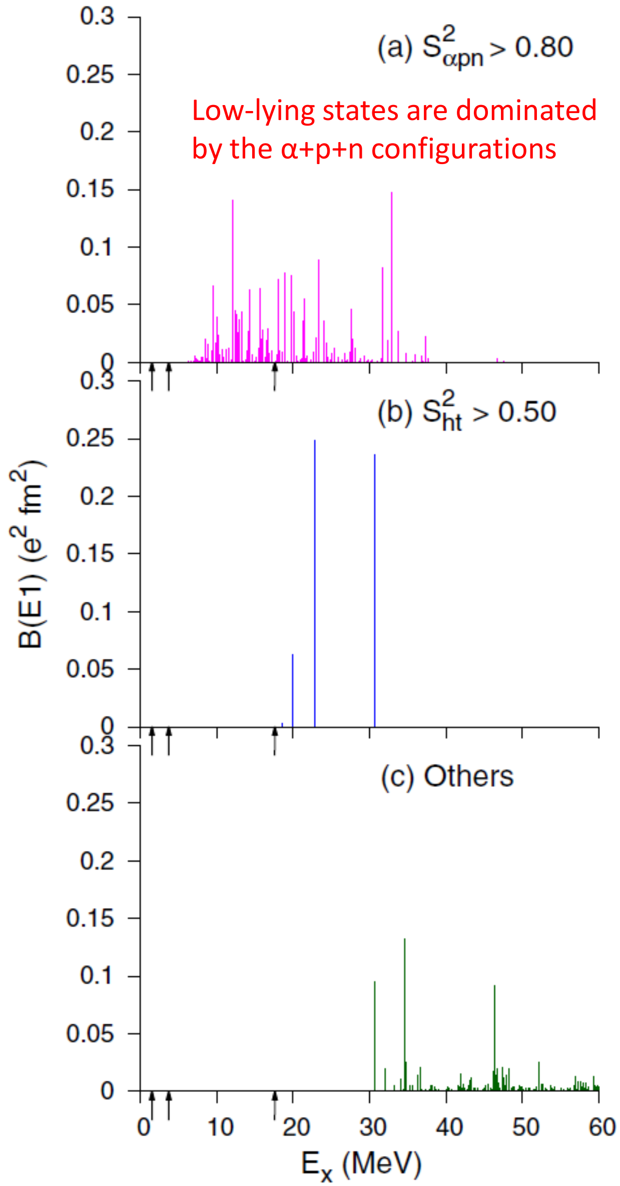
490 basis states

Diagonalization with 18490 bases

- Distortion of the clusters are taken into account through their pseudo states
- ～2000 states found below 100 MeV

# E1 transition strengths



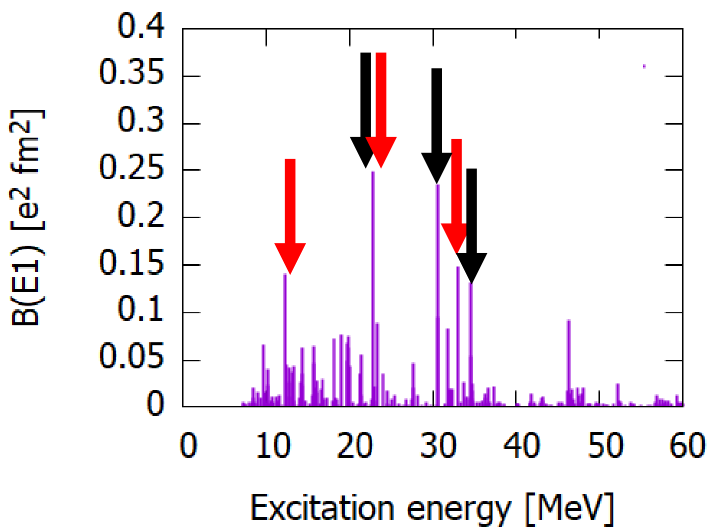




- E1 strength distribution
  - Some prominent strengths around 12, 23, 33 MeV
- Categoize them with respect to the spectroscopic factors: α+p+n, h+t, and the others
- Various excitations appear after opening the h+t threshold

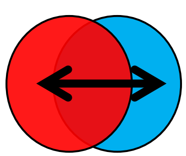
# E1 transition densities

$$\rho^{\rm tr}_{p/n}(r) = \sum_{i\in p/n} \langle \Psi^{(6)}_{J_f} \| \mathcal{Y}_1(\boldsymbol{r}_i - \boldsymbol{x}_6)\delta(|\boldsymbol{r}_i - \boldsymbol{x}_6| - r) \| \Psi^{(6)}_{J_0}\rangle,$$

$$\langle \Psi^{(6)}_{J_f} \| \mathcal{M}(E1) \| \Psi^{(6)}_{J_0}\rangle = e\sqrt{\frac{4\pi}{3}} \int_0^\infty dr\, \rho^{\rm tr}_p(r).$$

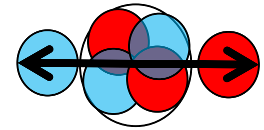



Goldhaber-Teller (GT) mode: out-of-phase transition between protons and neutrons



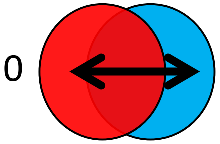
**Soft GT mode (GT mode of valence nucleon)**

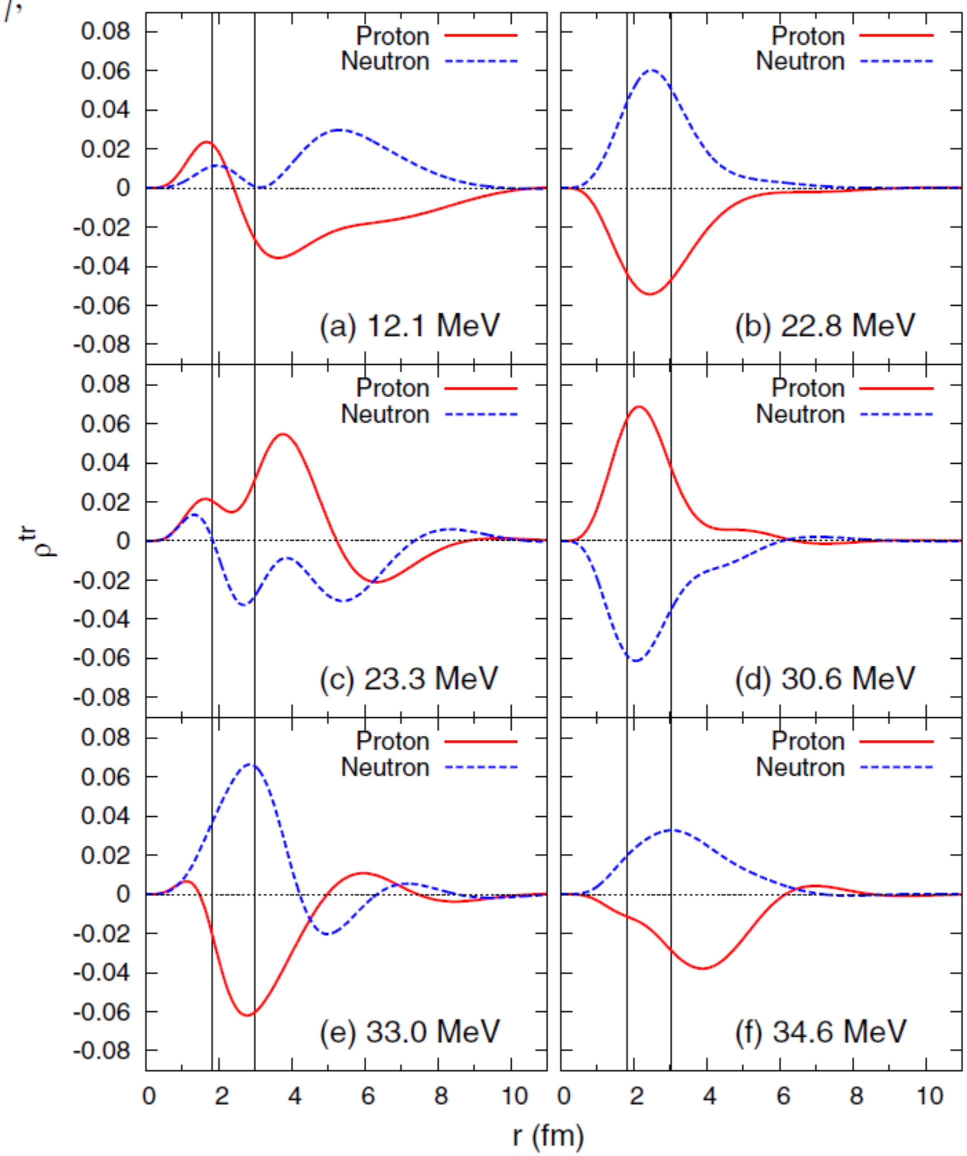
$S_{\alpha pn}{}^2 \sim 1$



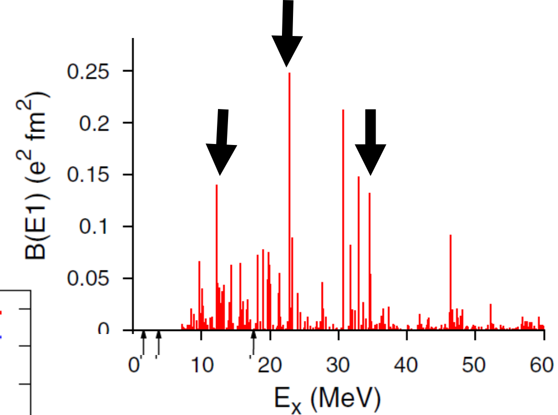
Typical GT mode

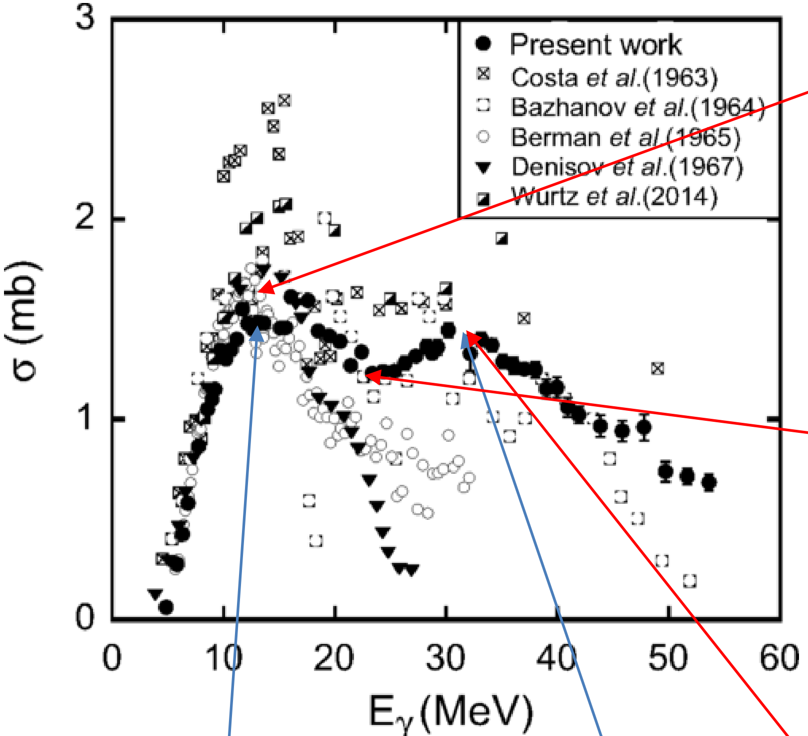
$S_{\alpha pn}{}^2 \sim 0$

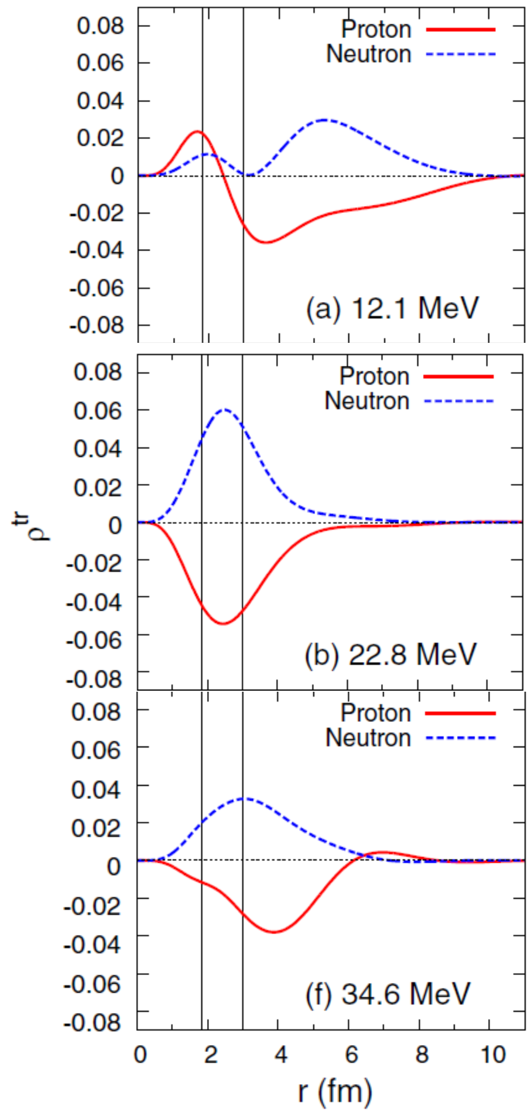




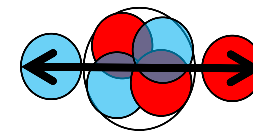
# Photoabsorption of $^6$Li



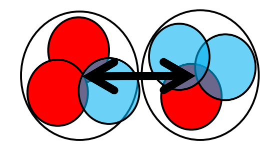




Soft GT excitation



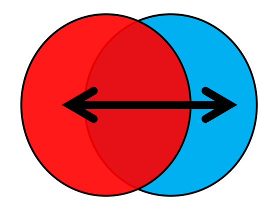
$S_{\alpha pn}^2 \sim 1$

Cluster ($^3$He+$^3$H) exc.



$S_{ht}^2 \sim 0.85$

Typical GT excitation



$S_{\alpha pn}^2 \sim 0.2$

$S_{ht}^2 \sim 0$

First peak: GDR of $^6$Li?

Second peak: GDR of alpha cluster in $^6$Li?

T. Yamagata, S. Nakayama, H. Akimune, S. Miyamoto, Phys. Rev. C 95, 044307 (2017)

Note: Only a one-peak structure is found in S. Bacca et al., PRL89, 052502 (2002)

# E1 excitations of $^6$He

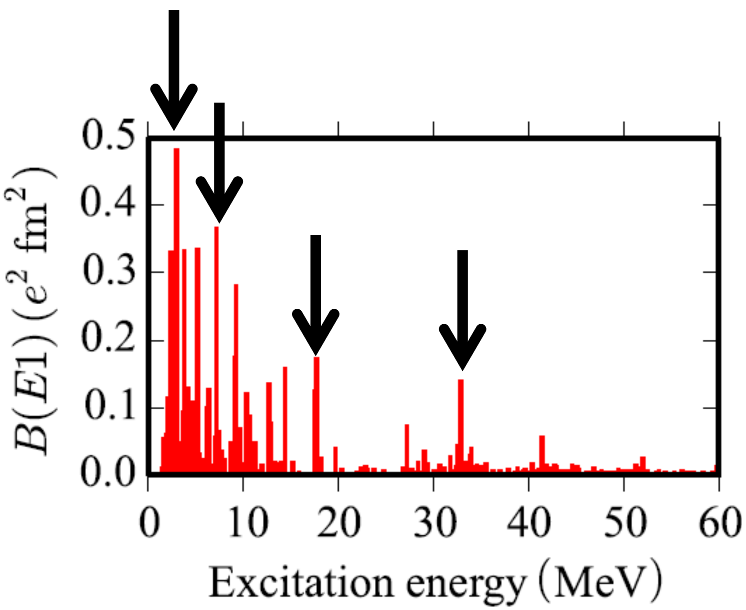
D. Mikami, WH, Y. Suzuki, Phys. Rev. C 89, 046303 (2014)

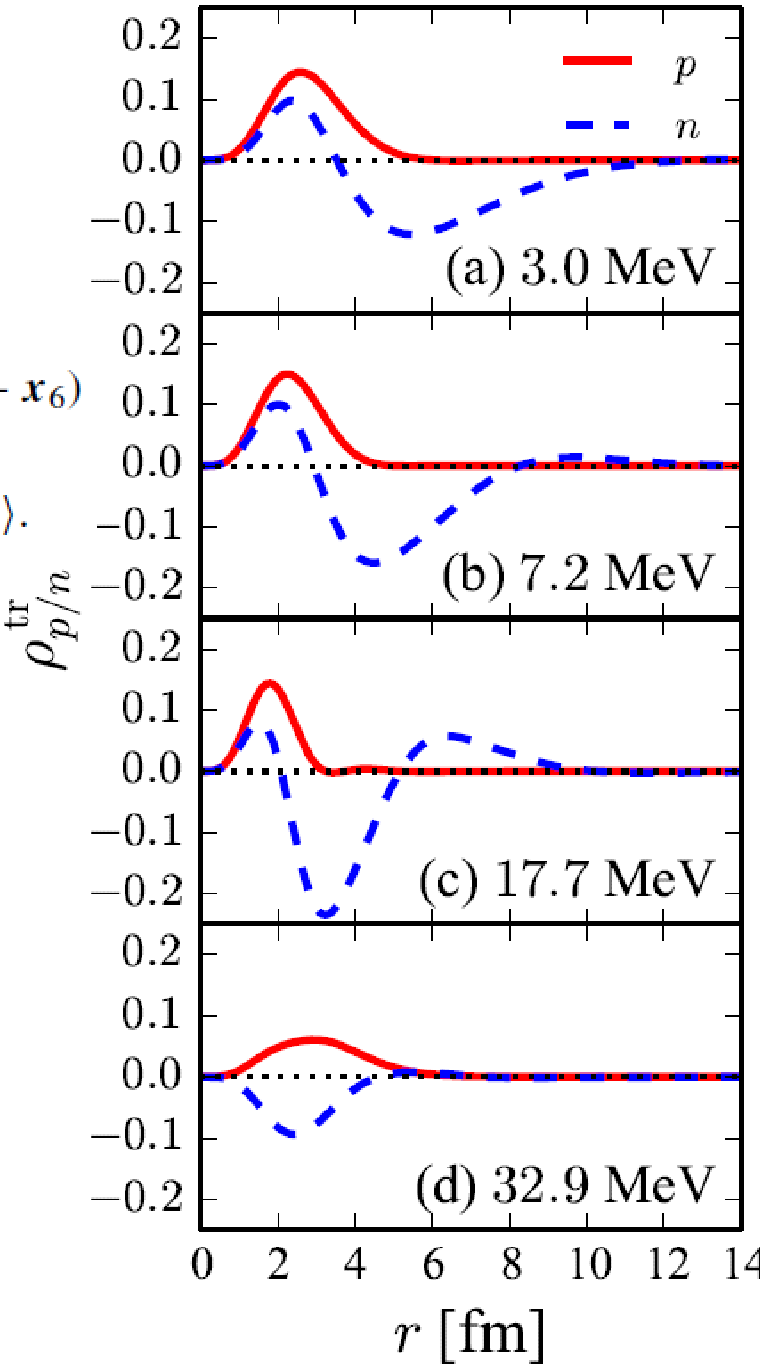
**Transition density ($x_6$: c.m of $^6$He)**

$$\rho^{\rm tr}_{p/n}(E_\nu, r) = \langle \Psi_1(E_\nu) \| \sum_{i\in p/n} \mathcal{Y}_1(\boldsymbol{r}_i - \boldsymbol{x}_6) \times \delta(|\boldsymbol{r}_i - \boldsymbol{x}_6| - r) \| \Psi_0 \rangle .$$

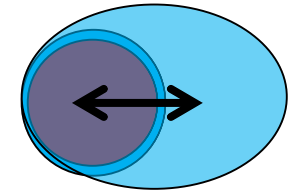
**E1 matrix element**

$$\langle \Psi_1(E_\nu) \| \mathcal{M}_1 \| \Psi_0 \rangle = e\sqrt{\frac{4\pi}{3}} \int_0^\infty \rho^{\rm tr}_p(E_\nu, r) dr .$$

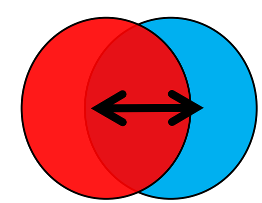



“Soft” dipole mode



Giant dipole mode



# Summary

- Electric-dipole transitions in $^{6}$Li with a fully microscopic six-body calculations
  - Explicitly correlated basis approach
    - Distortion of clusters are taken into account
    - Emergence of nuclear clustering
- Nuclear clustering plays an important role in the excitation of light nuclei
  - Various excitation modes appear with increasing the excitation energy following the threshold rule
    - Soft GT dipole mode (4+1+1 cluster), 3+3 cluster, giant dipole excitation modes
    - Exploring soft GT dipole and other cluster excitations (e.g. $^{7}$Li, $^{9}$Be, $^{18}$F, $^{20}$Ne) are interesting

S. Satsuka and WH, Phys. Rev. C 100, 024334 (2019)