Six-body calculation for electric-dipole response of $^{6}\mathrm{Li}$

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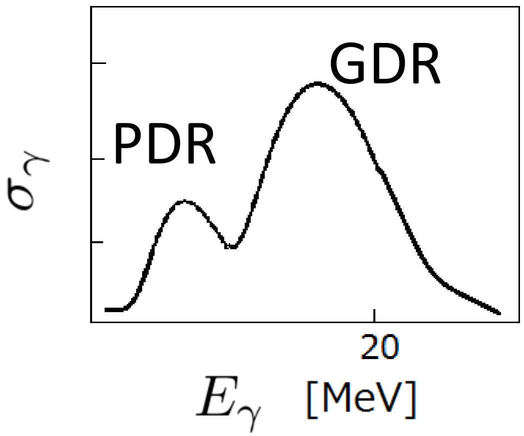
Introduction

Electric-dipole (E1) response reflects the nuclear structure

✓The peak energy region

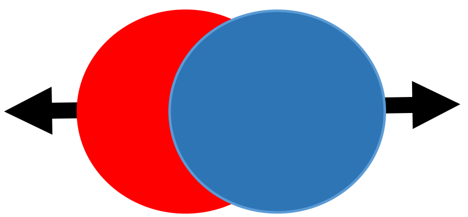
✓The shape of peak

⋮



Giant-dipole-resonance (GDR)

- large and broad peak
- occurring at high energy region
- out-of-phase oscillation of all protons and neutrons

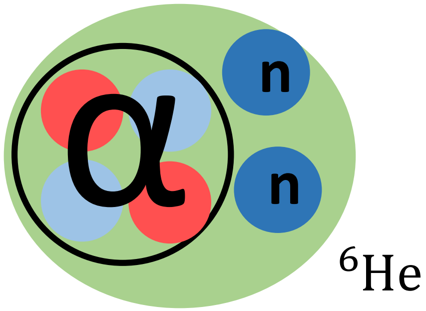


Pygmy-dipole-resonance (PDR)

- Occurring at low energy region in neutron-proton unbalanced nuclei
- Mechanism is still controversial

The mode is collective, one-particle excitation or …

Introduction



$\alpha(^4\mathrm{He})$ cluster structure appears in light nuclei (e.g. $^6\mathrm{He}$, $^6\mathrm{Li}$, …)

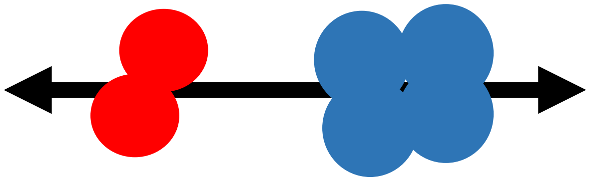
In the case of $^6\mathrm{He}$, there are two modes of GDR

D. Mikami, W. Horiuchi, and Y. Suzuki, Phys. Rev. C89, 064303 (2014)

Two valence neutrons is bound weakly

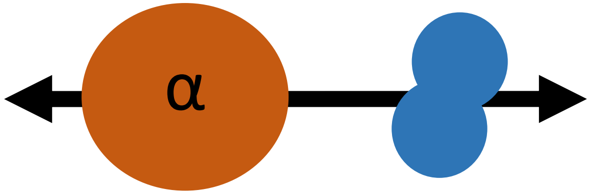
GDR

- occurring at high energy region (∼ 30MeV)



Soft-dipole mode (SDM)

- out-of-phase oscillation of α and two valence neutron
- occurring at low energy region (∼ 3MeV)



Introduction

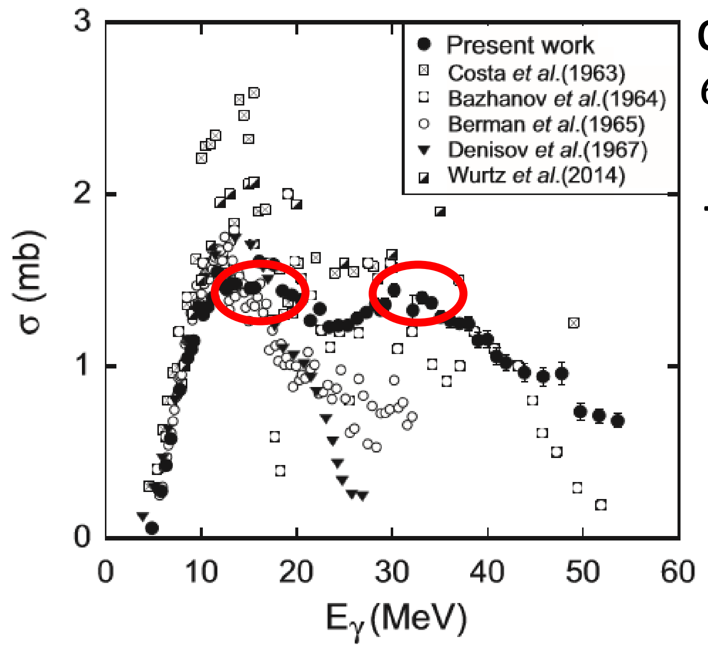


FIG. 9. Comparison of the present data with the ^{6}Li(γ,n) reaction data reported by Costa *et al.* [1], Bazhnov *et al.* [2], Denisov *et al.* [3], Berman *et al.* [4], and Wurtz *et al.* [5]. For simplicity, error bars in the previous data are not shown.

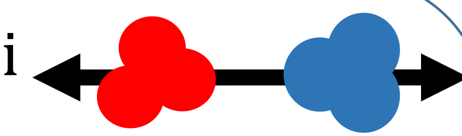
T. Yamagata *et al.* Phys. Rev. C 95, 044307, (2017)

The photoabsorption reaction cross section was measured for ^{6}Li recently

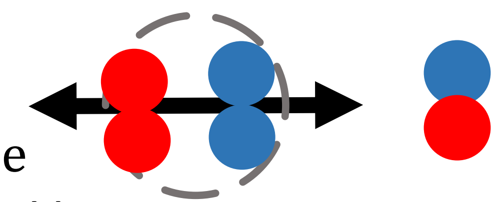
Two peak structure was shown

They conjectured ...

$E_\gamma \sim 12$ MeV GDR of ^{6}Li



$E_\gamma \sim 33$ MeV GDR of ^{4}He in ^{6}Li



However the GDR of free ^{4}He was shown to occur at 26 MeV

W. Horiuchi, Y. Suzuki, K. Arai, Phys. Rev. C 85 (2012) 054002

^{4}He is distorted
by interaction with other particles

Introduction

Its conjecture are not confirmed by
fully microscopic (six-body) calculation

The distortion of α cluster is taken into account naturally

Purpose

- Perform fully microscopic calculation for ground and E1 excited states of $^{6}\mathrm{Li}$
- Understand the E1 excitation mechanism of $^{6}\mathrm{Li}$

Problem

□ Difficulty to calculate many-body system

✓ describe the full variety of correlations between particles

→ Correlated Gaussian (CG) basis expansion

- Correlations are described explicitly

✓ High calculation cost : the number of bases increases , the cost becomes higher

→ Stochastic variational method (SVM)

- More important bases are selected

K.Varga and Y.Suzuki Phys. Rev .C52 (1995), 6

Method: Wave function

Schrödinger equation

$$\hat{H}\Psi = E\Psi$$

Hamiltonian

$$H = \sum_{i=1}^{N} T_i - T_{c.m.} + \sum_{j>i=1}^{N} \left(V_{ij}^{NN} + V_{ij}^{coul}\right)$$

Wave function $\rightarrow$ Basis expansion

$$\Psi = \sum_i c_i \varphi_i$$

Variational method + Basis expansion

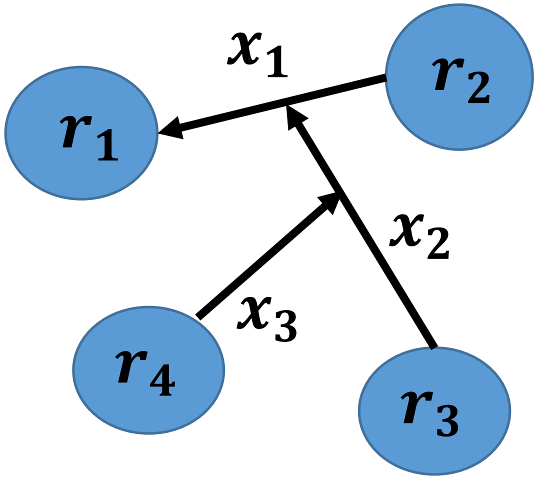
Generalized eigenvalue problem

$$\boldsymbol{H c} = \boldsymbol{E B c}$$

$$B_{jk} = \langle \varphi_j | \varphi_k \rangle$$

$$H_{jk} = \langle \varphi_j | \hat{H} | \varphi_k \rangle$$

Method: Basis function



$$\varphi_i = \mathcal{A}[\underbrace{\exp(-\tfrac{1}{2}\tilde{\boldsymbol{x}}A_i\boldsymbol{x})}_{\text{Correlated Gaussian}}\chi_S^{(i)}\eta]$$:basis function

$$\chi_S^{(i)} = [[\chi^1\chi^2]_{S_{12}^{(i)}}\chi^3]_{S_{123}^{(i)}}\cdots\chi^6]_{S=1}$$

$$\eta = |\mathrm{pppnnn}>$$

$$\boldsymbol{x} = (\boldsymbol{x}_1, \cdots \boldsymbol{x}_{A-1})$$

:Jacobi coordinates

A_i :positive-definite matrix

$$\tilde{\boldsymbol{x}}A\boldsymbol{x} = \sum_{j,k=1}^{N} A_{jk}\boldsymbol{x}_j \cdot \boldsymbol{x}_k$$

Off diagonal elements describe correlations among particles

Variational parameters A_i, $\chi_S^{(i)}$

Method: Selection of bases

Stochastic variational method (SVM)

K.Varga and Y.Suzuki Phys. Rev .C52 (1995), 6

①Candidates of variational parameter set $\{A^1, A^2, \ldots, A^K\}$ are generated randomly

②Energies $\{E^1, E^2, \ldots, E^K\}$ for each set are calculated

③Set A^i giving lowest energy is selected and added in bases

④ ①~③ are repeated until the energy reaches convergence

Results: ground state

$$V_{ij}^{NN} = (V_1 + \frac{1}{2}(1+P_{ij}^{\sigma})V_2 + \frac{1}{2}(1-P_{ij}^{\sigma})V_3)(\frac{1}{2}u + \frac{1}{2}(2-u)P_{ij}^{r})$$:Minnesota potential

$$V_l = V_{0l}\exp(-\mu_l|\boldsymbol{r}_i - \boldsymbol{r}_j|^2)$$

D. R. Thompson *et al*. Nucl. Phys. A286 (1977) ,53

	r_m[fm]	r_p[fm]	r_n[fm]	$E_{g.s.}$ [MeV]
^{6}He	2.40	1.83	2.64	-30.95
^{6}He(*)	2.41	1.83	2.65	-30.98

Experimental S_{2N} is reproduced by adjusting the u value

(*)D. Mikami, W. Horiuchi, and Y. Suzuki, Phys. Rev. C89, 064303 (2014)

	r_m[fm]	r_p[fm]	r_n[fm]	$E_{g.s.}$ [MeV]	S_{2N} [MeV]
^{6}Li	2.29	2.29	2.29	-33.90	4.0
^{6}Li(Exp.)		2.45		-31.99	3.7

F. Ajzenberg-Selove, Nucl. Phys. A413, 1 (1984)

Different u values to reproduce the experimental data of rms radius can be considered

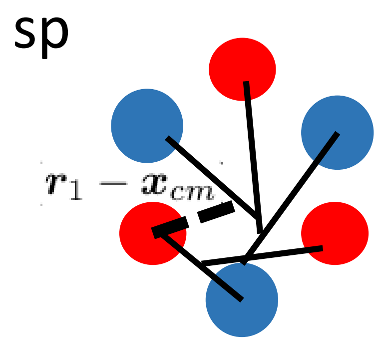
E1 excited state

E1 strength

$$B(E1,E_\nu)=\frac{1}{2J_{g.s.}+1}\sum_{M,m}|<\Phi_M^{(ex)}(E_\nu)|M(E1,\mu)|\Phi_m^{(g.s.)}>|^2$$

E1 operator

$$M(E1,\mu)=\sqrt{\frac{4\pi}{3}}e\sum_{i\in\mathrm{proton}}\mathcal{Y}_{1\mu}(\boldsymbol{r}_i-\boldsymbol{x}_{cm})$$

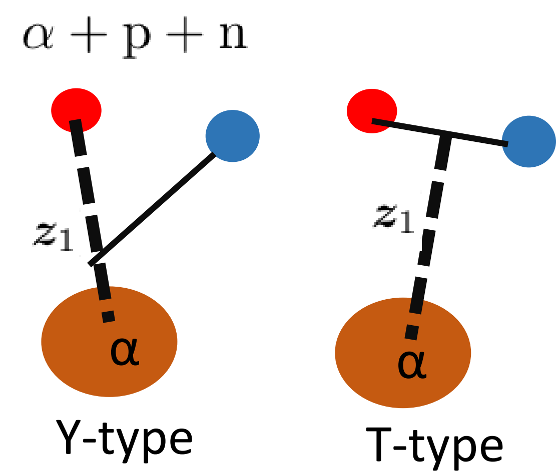


Model space

W. Horiuchi, Y. Suzuki, K. Arai, Phys. Rev. C 85 (2012) 054002

single-particle (sp) excitation

$$\phi_i^{(sp)}=\mathcal{A}[\phi_i^{(^6\mathrm{Li})}\mathcal{Y}_{1\mu}(\boldsymbol{r}_1-\boldsymbol{x}_{cm})]_J$$

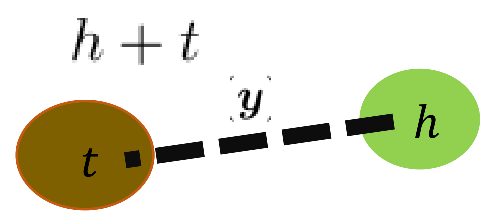


$\alpha+\mathrm{p}+\mathrm{n}$ decay channel

$$\phi_i^{(\alpha pn)}=\mathcal{A}[\phi_i^{(\alpha)}\exp(-\frac{1}{2}\tilde{\boldsymbol{z}}B_i\boldsymbol{z})[[\chi^{(5)}\chi^{(6)}]_{s_1}]\mathcal{Y}_{1\mu}(\boldsymbol{z}_1)]_{J_1}]_J$$

$h(^3\mathrm{He})+t(^3\mathrm{H})$ decay channel (Not included in this work)

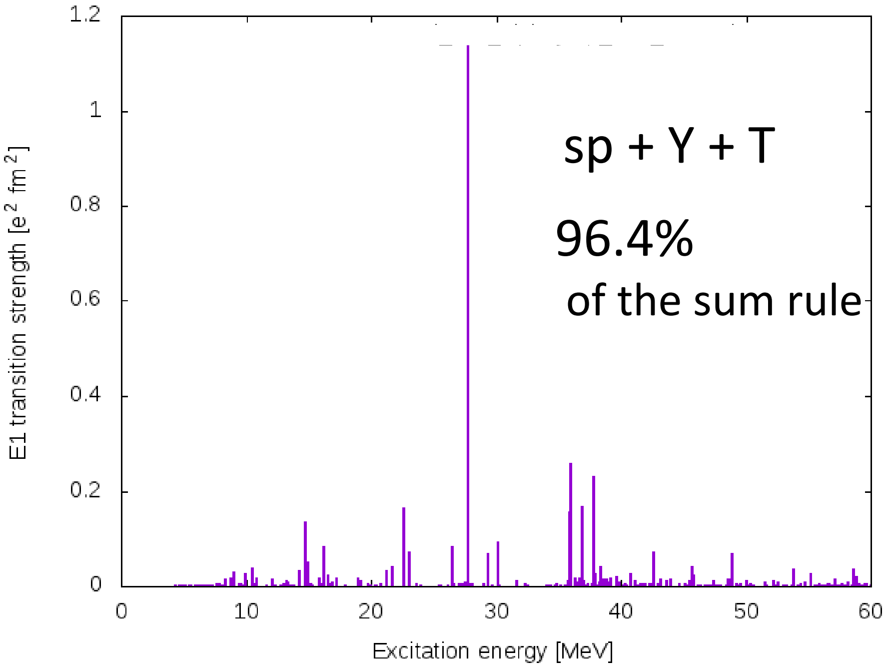
$$\phi_i^{(ht)}=\mathcal{A}[[\phi_i^{(h)}\phi_i^{(t)}]_{J_1}\exp(-\frac{1}{2}a\boldsymbol{y}^2)\mathcal{Y}_{1\mu}(\boldsymbol{y})]_{J_2}]_J$$

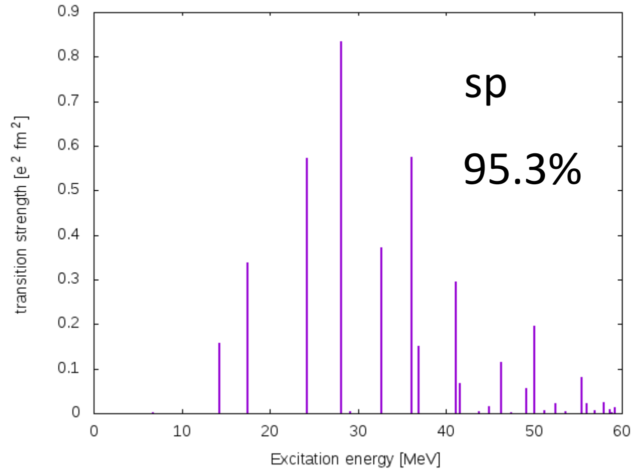


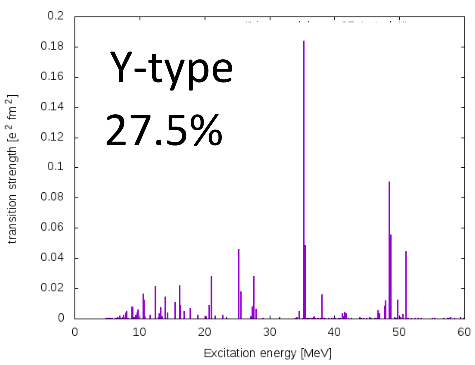
Results: E1 strength

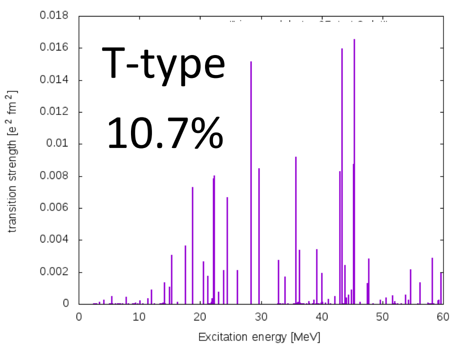
E1 sum rule

$$\sum_{\nu} B(E1, E_{\nu}) = e^2(Z^2 < r_p^2 > -\frac{Z(Z-1)}{2} < r_{pp}^2 >)$$



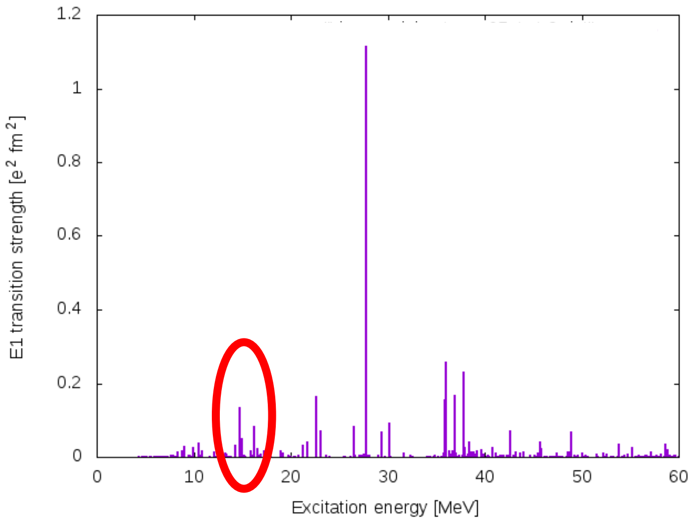


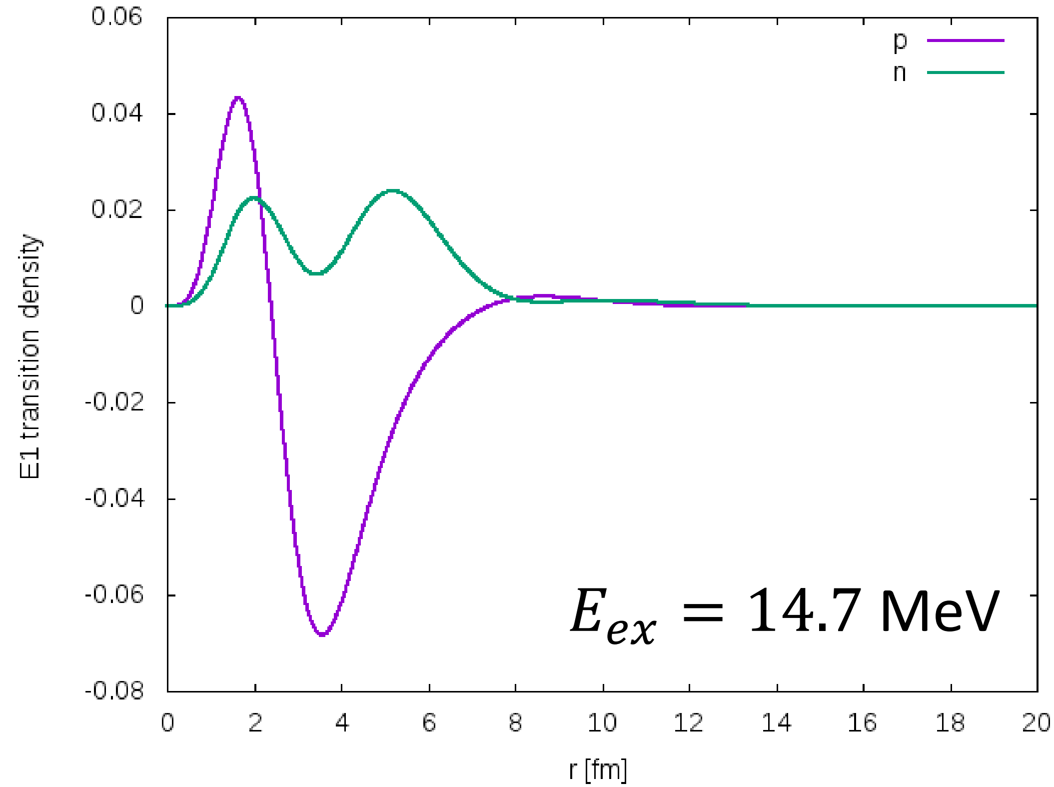




Results: Transition density

$$\rho^{tr}_{p/n}(E_\nu, r) =< \Phi^{(ex)}(E_\nu)|| \sum_{i\in p/n} \mathcal{Y}_1(\boldsymbol{r}_i - \boldsymbol{x}_{cm})\delta(|\boldsymbol{r}_i - \boldsymbol{x}_{cm}| - r)||\Phi^{(g.s.)} >$$





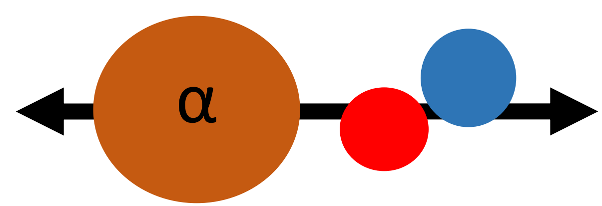
interior region $r < 2.5$ fm

: in-phase

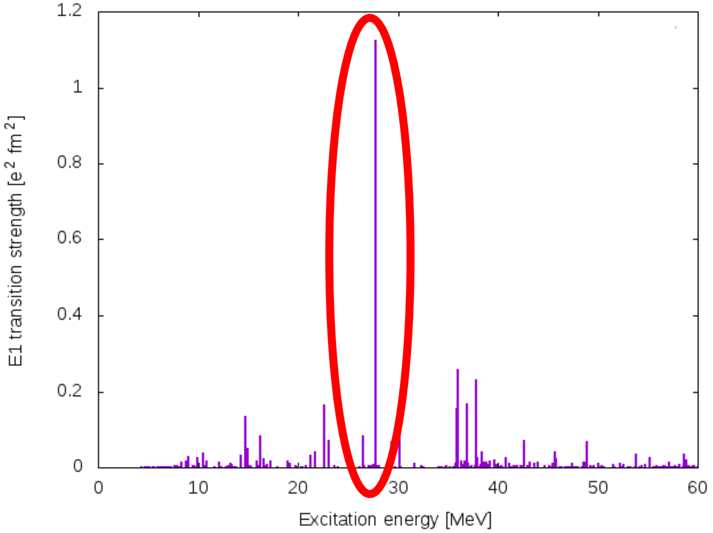
external region $r > 2.5$ fm

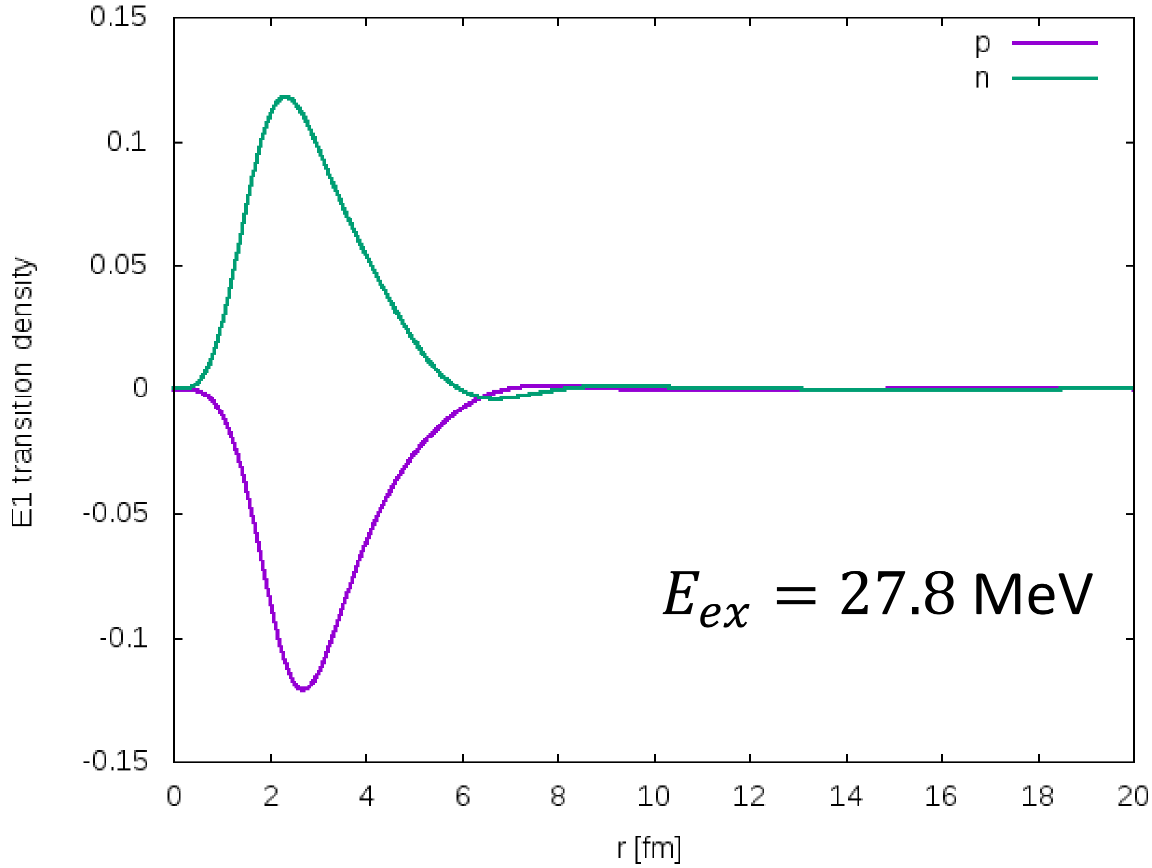
: out-of-phase

Like soft-dipole mode



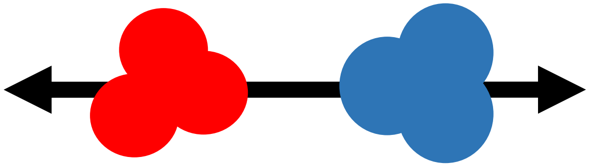
Results: Transition density





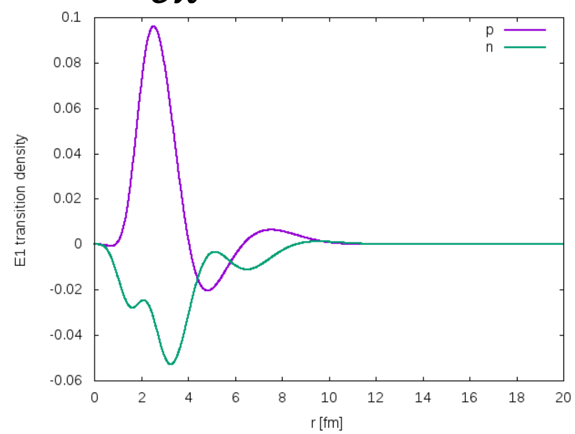
whole region
: out-of-phase

GDR of ^{6}Li

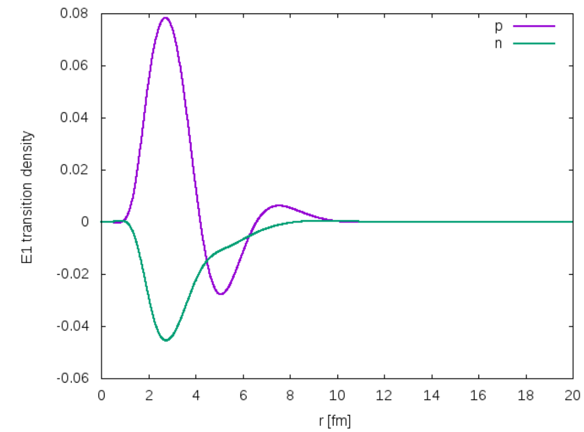


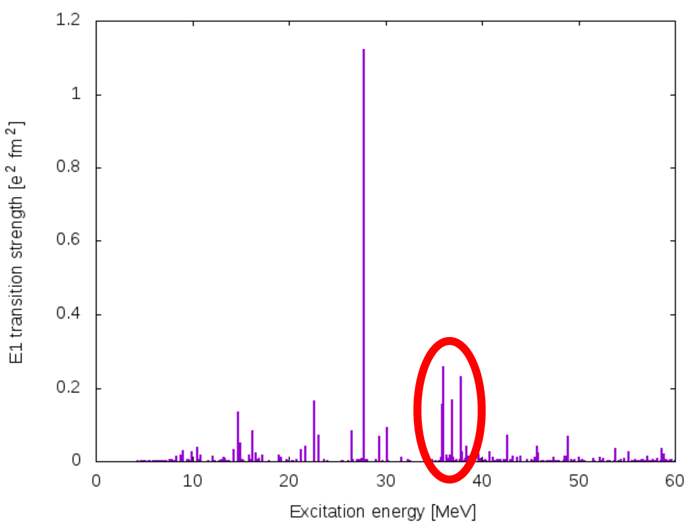
Results: Transition density

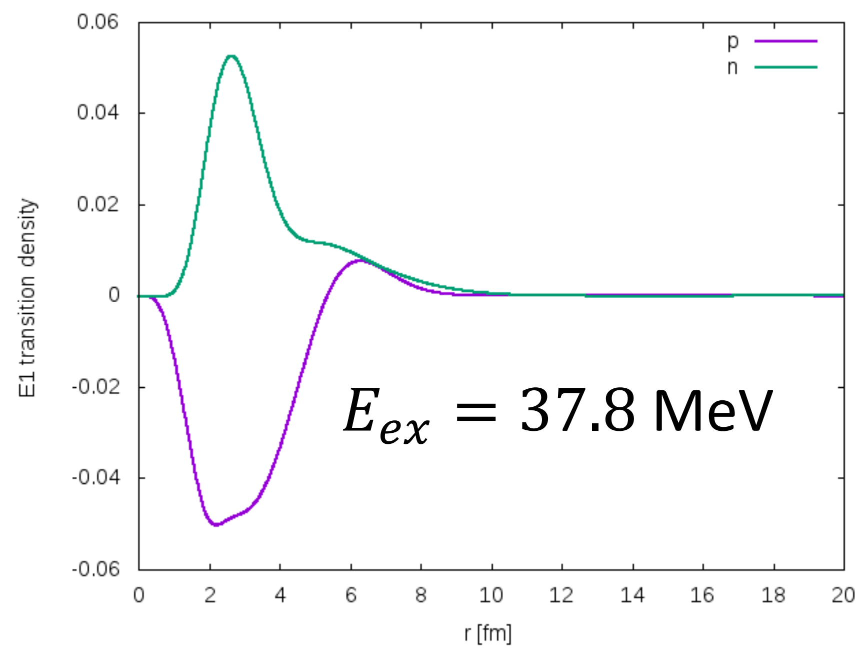
$E_{ex} = 36.0$ MeV



$E_{ex} = 36.9$ MeV



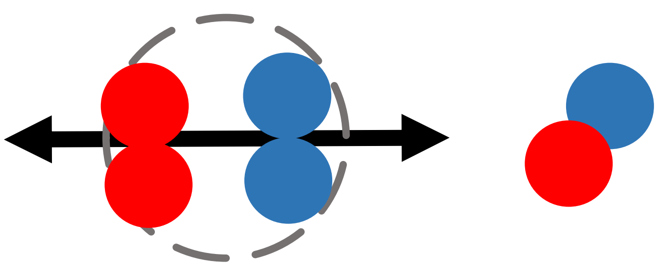




interior region $r < 4$ fm

: out-of-phase

GDR of ^{4}He (α) in ^{6}Li ?



Summary

- ✓Six-body calculation for ground and E1 excited state of $^{6}\mathrm{Li}$ is performed
- ✓The u parameter of Minnesota potential is adjusted to reproduce the experimental data of two nucleon separation energy for the ground state
- ✓The E1 strength and transition density show the possibility of three modes of GDR, SDM, GDR of $^{6}\mathrm{Li}$ and GDR of $^{4}\mathrm{He}$ in $^{6}\mathrm{Li}$

Future work

- ➢ Add h + t decay channel to the model space
- ➢ Detail analyses of the modes of GDR