Pair and quartet correlations in the shell model

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Two-nucleon correlation functions

Alpha-particle correlation functions

Deuteron and alpha clustering

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Two-nucleon correlators

Two-nucleon correlation operators are defined as

$$\sum_{i<j} \delta(r - \hat{r}_{ij}), \qquad \sum_{i<j} \delta(R - \hat{R}_{ij})\delta(r - \hat{r}_{ij})$$

with

$$\hat{R}_{ij} = \frac{1}{2}|\hat{\vec{r}}_i + \hat{\vec{r}}_j|, \qquad \hat{r}_{ij} = |\hat{\vec{r}}_i - \hat{\vec{r}}_j|$$

Expectation value defines a probability density:

times dr $\rightarrow$ *probability of two nucleons separated by r;*

times drdR $\rightarrow$ *probability of two nucleons separated by* *r* and at a distance *R* from their centre of mass.

Two-nucleon correlation functions

Expectation values for a two-nucleon state

$$\langle abLST|\delta(r-\hat{r}_{12})|cdLST\rangle = \frac{1}{\sqrt{8}}r^2 \sum_{\mathcal{N}\mathcal{L}nn'l} \tilde{a}^{n_a l_a n_b l_b}_{\mathcal{N}\mathcal{L}nl,LST} \tilde{a}^{n_c l_c n_d l_d}_{\mathcal{N}\mathcal{L}n'l,LST} R_{nl}\left(\frac{r}{\sqrt{2}}\right) R_{n'l}\left(\frac{r}{\sqrt{2}}\right)$$

and

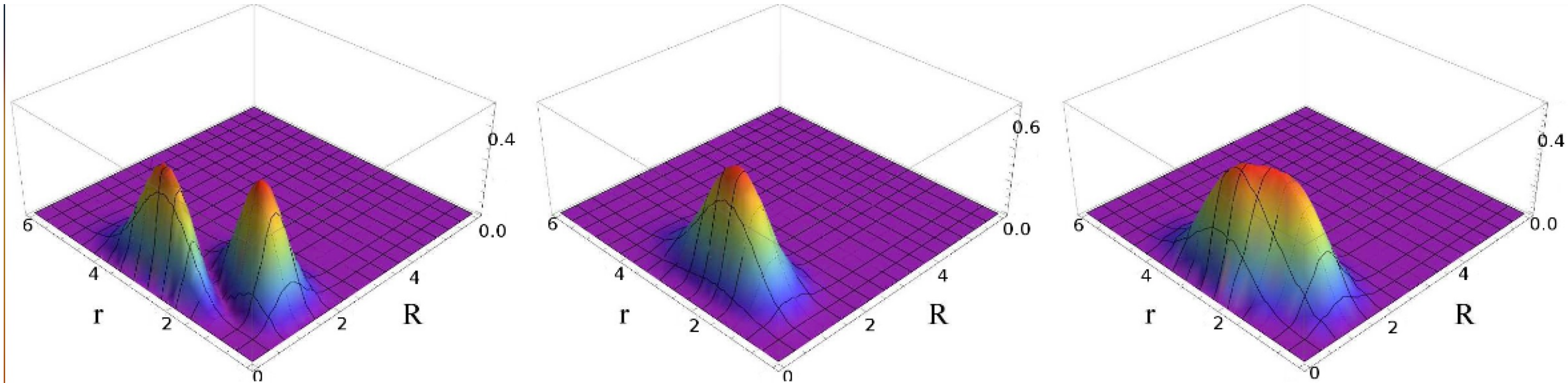
$$\begin{aligned}&\langle abLST|\delta(R-\hat{R}_{12})\delta(r-\hat{r}_{12})|cdLST\rangle \\ &\quad = R^2 r^2 \sum_{\mathcal{N}\mathcal{N}'\mathcal{L}} \sum_{nn'l} \tilde{a}^{n_a l_a n_b l_b}_{\mathcal{N}\mathcal{L}nl,LST} \tilde{a}^{n_c l_c n_d l_d}_{\mathcal{N}'\mathcal{L}n'l,LST} R_{\mathcal{N}\mathcal{L}}\left(\sqrt{2}R\right) R_{\mathcal{N}'\mathcal{L}}\left(\sqrt{2}R\right) R_{nl}\left(\frac{r}{\sqrt{2}}\right) R_{n'l}\left(\frac{r}{\sqrt{2}}\right)\end{aligned}$$

in terms of modified Talmi-Moshinsky brackets

$$\tilde{a}^{n_a l_a n_b l_b}_{\mathcal{N}\mathcal{L}nl,LST} \equiv \frac{1-(-)^{l+S+T}}{\sqrt{2(1+\delta_{n_a n_b}\delta_{l_a l_b})}} a^{n_a l_a n_b l_b}_{\mathcal{N}\mathcal{L}nl,L}$$

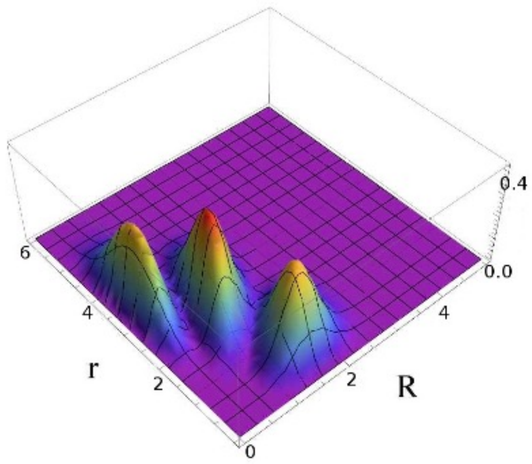
P. Mei & P. Van Isacker, Ann. Phys. (NY) **327** (2012) 1162

Two identical nucleons in $0p$ orbital

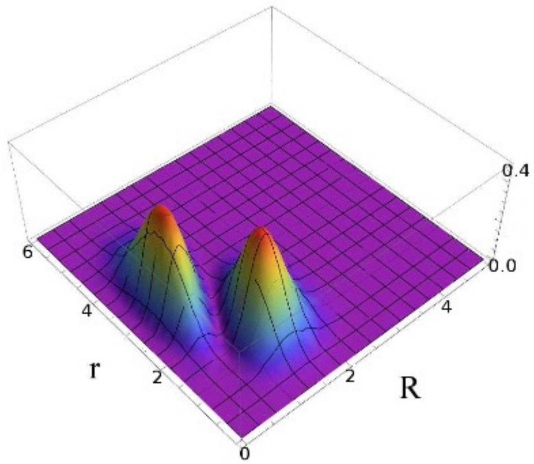


(a) $|(0p)^2;00\rangle$ (b) $|(0p)^2;11\rangle$ (c) $|(0p)^2;20\rangle$

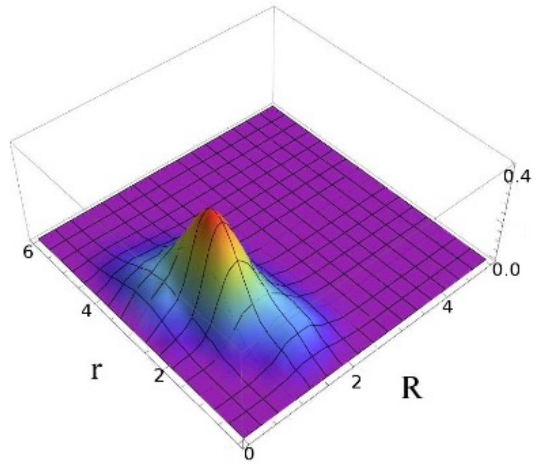
Two identical nucleons in 0*d* orbital



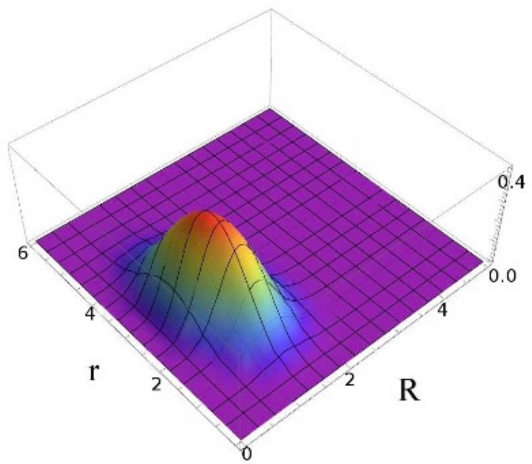
(a) $|(0d)^2; 00\rangle$



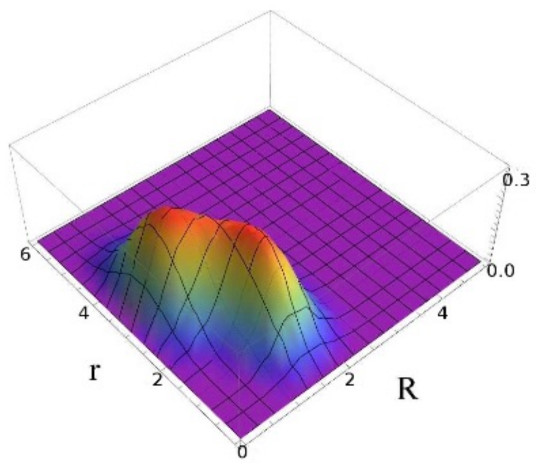
(b) $|(0d)^2; 11\rangle$



(c) $|(0d)^2; 20\rangle$



(d) $|(0d)^2; 31\rangle$



(e) $|(0d)^2; 40\rangle$

Four identical nucleons in $0p$

A $J=0$ state has $(LS)=(00)$ or $(LS)=(11)$ with probability densities given by

$$\mathcal{P}_{p^4;00} = \frac{9}{1024\pi^4} \sum_{(ij)\neq(kl)} \sin^2\theta_{ij} \sin^2\theta_{kl} \cos^2\theta_{ij,kl},$$

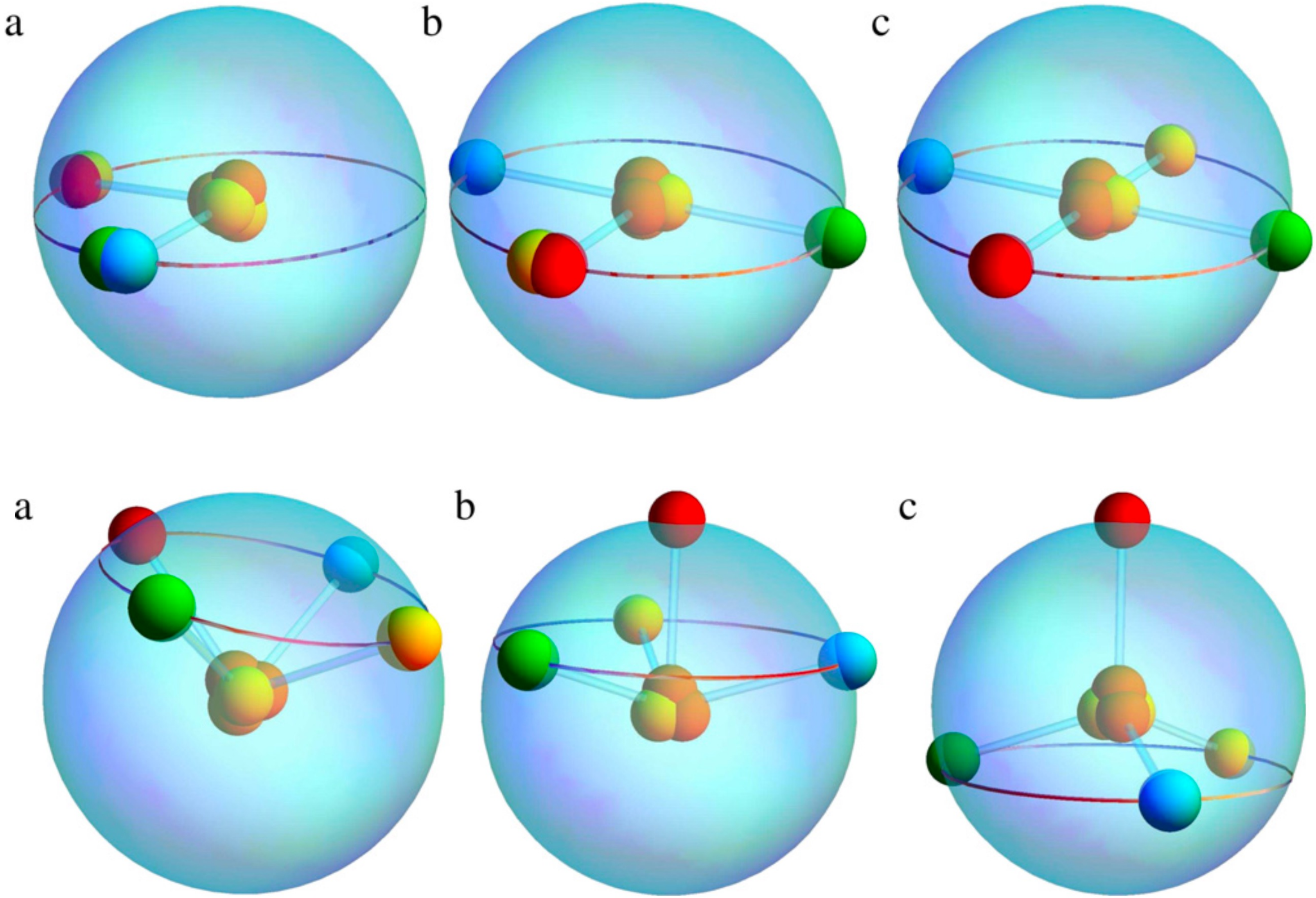
and

$$\mathcal{P}_{p^4;11} = \frac{9}{2048\pi^4} \sum_{(ij)\neq(kl)} \sin^2\theta_{ij} \sin^2\theta_{kl} \sin^2\theta_{ij,kl}.$$

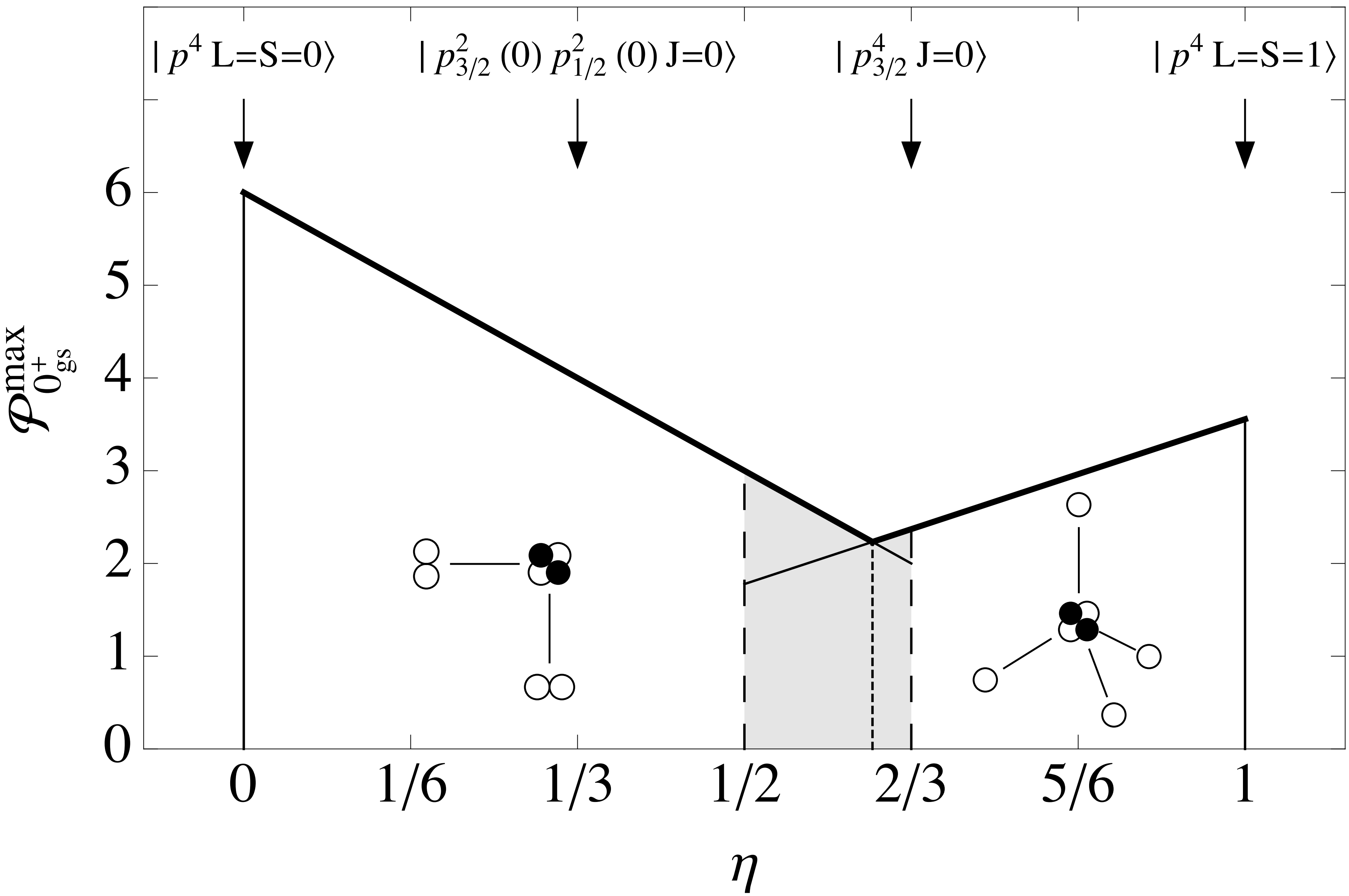
where θ_{ij} is the angle between $\bar{r}_i$ and $\bar{r}_j$, and $\theta_{ij,kl}$ is the angle between $\bar{r}_{ij}$ and $\bar{r}_{kl}$.

P. Mei & P. Van Isacker, Ann. Phys. (NY) **327** (2012) 1182

Four identical nucleons in $0p_{3/2}$



Example: ^{8}He



| p^4 L=S=0⟩
| $p^2_{3/2}$ (0) $p^2_{1/2}$ (0) J=0⟩
| $p^4_{3/2}$ J=0⟩
| p^4 L=S=1⟩
6
5
4
3
2
1
0
$\mathcal{P}^{\max}_{0^+_{\rm gs}}$
0
1/6
1/3
1/2
2/3
5/6
1
η

Four-nucleon $(2\nu, 2\pi)$ correlators

Four-nucleon correlation operators are defined as

$$\hat{\Delta}_{ijkl}(R_{\nu\pi}, r_{\nu\nu}, r_{\pi\pi}) \equiv \delta(R_{\nu\pi} - \hat{R}_{ij\cdot kl})\delta(r_{\nu\nu} - \hat{r}_{ij})\delta(r_{\pi\pi} - \hat{r}_{kl})$$

with ($ij \in \nu, kl \in \pi$) where

- $r_{\nu\nu}$ *is the distance between the neutrons,*
- $r_{\pi\pi}$ *is the distance between the protons,*
- $R_{\nu\pi}$ *is the distance between the centres of mass of the neutrons and of the protons,*
- $r_{\nu\pi}$ *is the distance between a neutron and a proton.*

One has the relation, valid for a tetrahedron,

$$4R_{\nu\pi}^2 = 4r_{\nu\pi}^2 - r_{\nu\nu}^2 - r_{\pi\pi}^2$$

Four-nucleon correlation function

$$\langle ab(L_\nu S_\nu), cd(L_\pi S_\pi); LS|\hat{\Delta}_{1234}(R_{\nu\pi}, r_{\nu\nu}, r_{\pi\pi})|a'b'(L'_\nu S'_\nu), c'd'(L'_\pi S'_\pi); LS\rangle$$

$$= \frac{1}{8} R_{\nu\pi}^2 r_{\nu\nu}^2 r_{\pi\pi}^2 \delta_{S_\nu S'_\nu} \delta_{S_\pi S'_\pi} \sum_{\mathcal{L}_\nu \mathcal{L}_\pi} \sum_{\mathcal{L}'_\nu \mathcal{L}'_\pi} \sum_{l_\nu l_\pi} \sum_{\mathcal{L}_\rho l_\rho} \begin{bmatrix} \mathcal{L}_\nu & l_\nu & L_\nu \\ \mathcal{L}_\pi & l_\pi & L_\pi \\ \mathcal{L}_\rho & l_\rho & L \end{bmatrix} \begin{bmatrix} \mathcal{L}'_\nu & l_\nu & L'_\nu \\ \mathcal{L}'_\pi & l_\pi & L'_\pi \\ \mathcal{L}_\rho & l_\rho & L \end{bmatrix}$$

$$\times \sum_{\mathcal{N}_\nu \mathcal{N}_\pi} \left[\sum_{n_\nu} \tilde{a}^{n_a l_a n_b l_b}_{\mathcal{N}_\nu \mathcal{L}_\nu n_\nu l_\nu, L_\nu S_\nu} R_{n_\nu l_\nu}\left(\frac{r_{\nu\nu}}{\sqrt{2}}\right) \right] \left[\sum_{n_\pi} \tilde{a}^{n_c l_c n_d l_d}_{\mathcal{N}_\pi \mathcal{L}_\pi n_\pi l_\pi, L_\pi S_\pi} R_{n_\pi l_\pi}\left(\frac{r_{\pi\pi}}{\sqrt{2}}\right) \right]$$

$$\times \sum_{\mathcal{N}'_\nu \mathcal{N}'_\pi} \left[\sum_{n'_\nu} \tilde{a}^{n'_a l'_a n'_b l'_b}_{\mathcal{N}'_\nu \mathcal{L}'_\nu n'_\nu l_\nu, L'_\nu S'_\nu} R_{n'_\nu l_\nu}\left(\frac{r_{\nu\nu}}{\sqrt{2}}\right) \right] \left[\sum_{n'_\pi} \tilde{a}^{n'_c l'_c n'_d l'_d}_{\mathcal{N}'_\pi \mathcal{L}'_\pi n'_\pi l_\pi, L'_\pi S'_\pi} R_{n'_\pi l_\pi}\left(\frac{r_{\pi\pi}}{\sqrt{2}}\right) \right]$$

$$\times \sum_{\mathcal{N}\mathcal{L}l} \left[\sum_{n} a^{\mathcal{N}_\nu \mathcal{L}_\nu \mathcal{N}_\pi \mathcal{L}_\pi}_{\mathcal{N}\mathcal{L}nl, \mathcal{L}_\rho} R_{nl}(R_{\nu\pi}) \right] \left[\sum_{n'} a^{\mathcal{N}'_\nu \mathcal{L}'_\nu \mathcal{N}'_\pi \mathcal{L}'_\pi}_{\mathcal{N}\mathcal{L}n'l, \mathcal{L}_\rho} R_{n'l}(R_{\nu\pi}) \right],$$

The α particle: $0\hbar\omega$

If all nucleons are in the 0s orbital, $(LST) = (000)$, the probability density is

$$P_{000}^{(0)}(R_{\nu\pi}, r_{\nu\nu}, r_{\pi\pi}) = \frac{8}{\pi^{3/2}} R_{\nu\pi}^2 r_{\nu\nu}^2 r_{\pi\pi}^2 e^{-R_{\nu\pi}^2 - \frac{1}{2} r_{\nu\nu}^2 - \frac{1}{2} r_{\pi\pi}^2}$$

The probability peaks at $r_{\nu\nu} = r_{\pi\pi} = \sqrt{2}$ and $R_{\nu\pi} = 1$ or $r_{\nu\pi} = r_{\nu\nu} = r_{\pi\pi} = \sqrt{2}$.

$\rightarrow$ *The most probable geometry of an α particle is a Platonic tetrahedron.*

The α particle: $1\hbar\omega$

The isoscalar 1^- state $(LST) = (100)$ is spurious and has the probability density

$$P_{100}^{(1)}(R_{\nu\pi}, r_{\nu\nu}, r_{\pi\pi}) = \frac{8}{\pi^{3/2}} R_{\nu\pi}^2 r_{\nu\nu}^2 r_{\pi\pi}^2 e^{-R_{\nu\pi}^2 - \frac{1}{2} r_{\nu\nu}^2 - \frac{1}{2} r_{\pi\pi}^2}$$

The probability peaks at $r_{\nu\nu} = r_{\pi\pi} = \sqrt{2}$ and $R_{\nu\pi} = 1$ or $r_{\nu\pi} = r_{\nu\nu} = r_{\pi\pi} = \sqrt{2}$.

$\rightarrow$ *The spurious state has the same density distribution as the $0\hbar\omega$ ground state since it has the same intrinsic structure.*

The α particle: $1\hbar\omega$

The isovector 1^- state $(LST) = (101)$ has the probability density

$$P_{101}^{(1)}(R_{\nu\pi}, r_{\nu\nu}, r_{\pi\pi}) = \frac{16}{3\pi^{3/2}} R_{\nu\pi}^4 r_{\nu\nu}^2 r_{\pi\pi}^2 e^{-R_{\nu\pi}^2 - \frac{1}{2} r_{\nu\nu}^2 - \frac{1}{2} r_{\pi\pi}^2}$$

The probability peaks at $r_{\nu\nu} = r_{\pi\pi} = \sqrt{2}$ and $R_{\nu\pi} = \sqrt{2}$ or $r_{\nu\pi} = \sqrt{3}$.

The α particle: $1\hbar\omega$

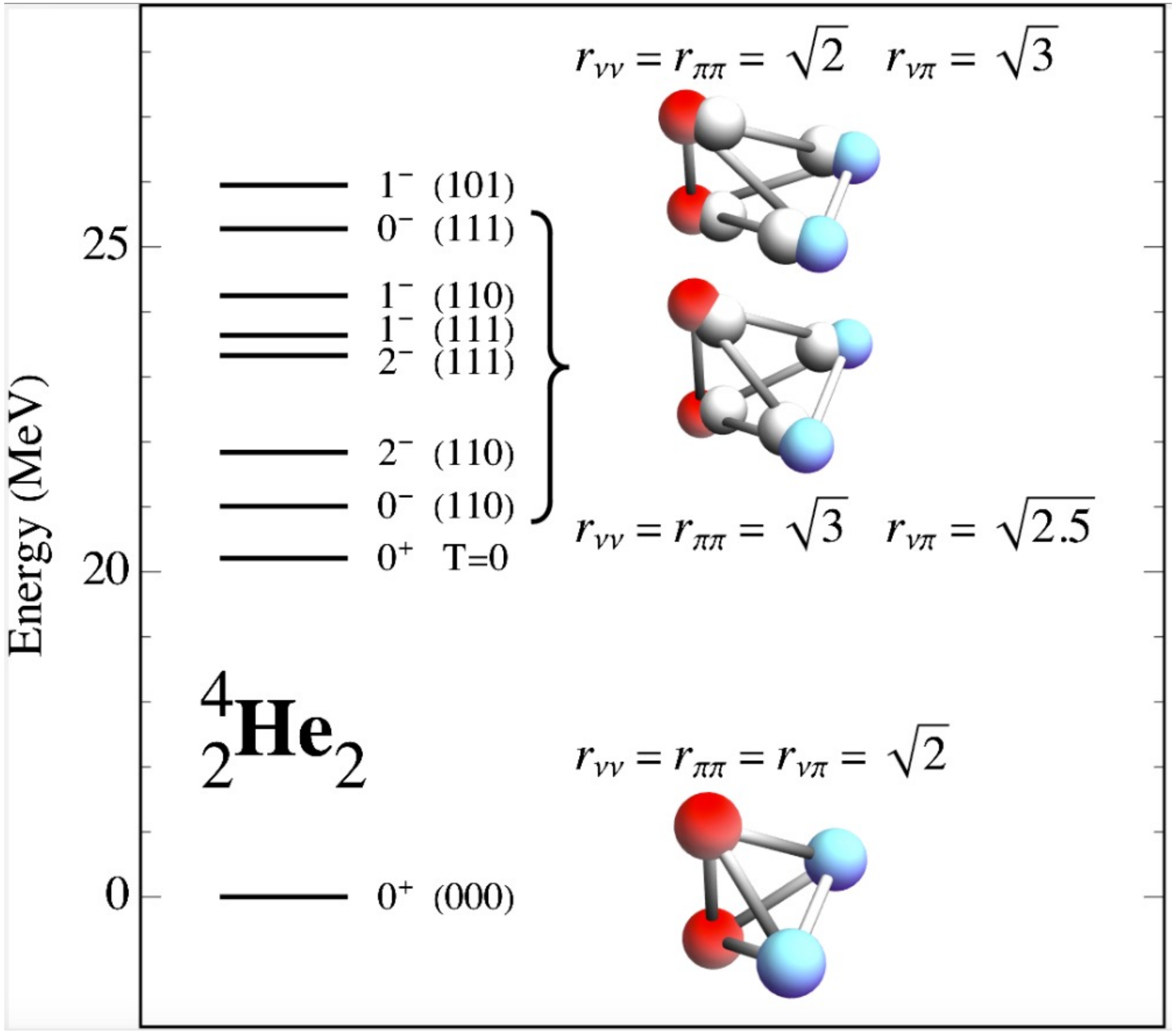
The isoscalar and isovector states with $(LS) = (11)$ have the probability density

$$P^{(1)}_{110}(R_{\nu\pi}, r_{\nu\nu}, r_{\pi\pi}) = \frac{4}{3\pi^{3/2}} R^2_{\nu\pi} r^2_{\nu\nu} r^2_{\pi\pi} (r^2_{\nu\nu} + r^2_{\pi\pi}) e^{-R^2_{\nu\pi} - \frac{1}{2} r^2_{\nu\nu} - \frac{1}{2} r^2_{\pi\pi}}$$

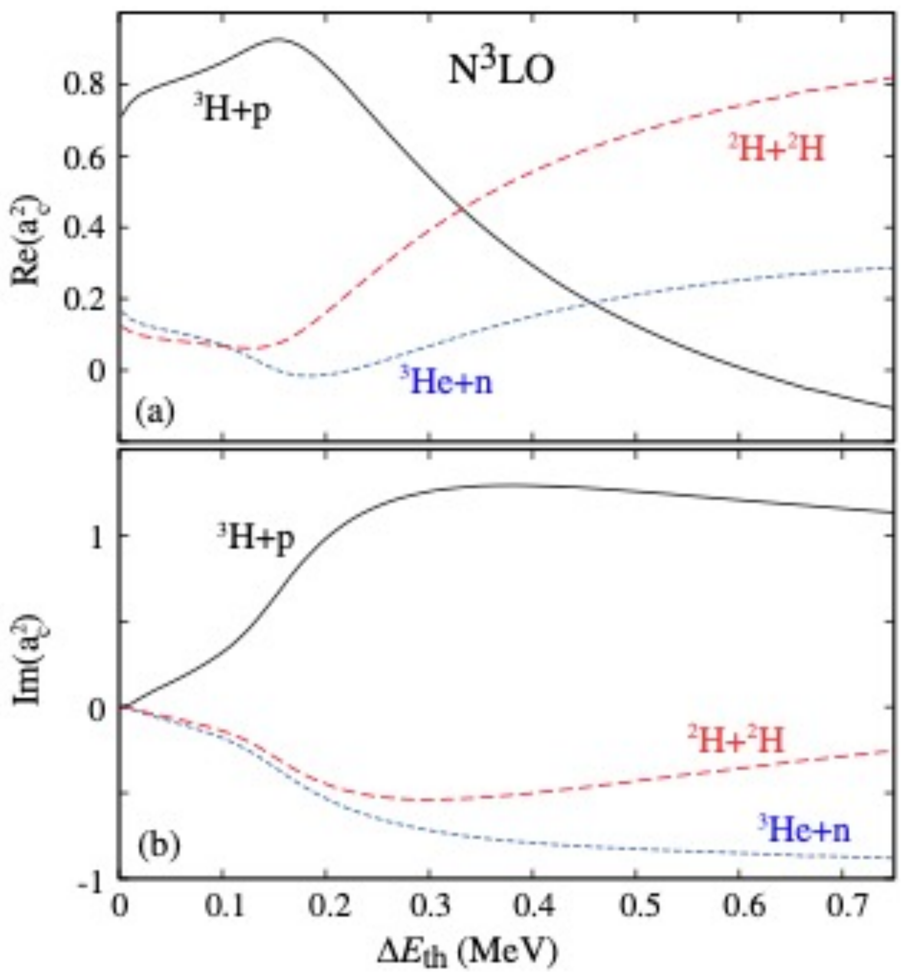
$$P^{(1)}_{111}(R_{\nu\pi}, r_{\nu\nu}, r_{\pi\pi}) = \frac{4}{3\pi^{3/2}} R^2_{\nu\pi} r^2_{\nu\nu} r^2_{\pi\pi} (r^2_{\nu\nu} + r^2_{\pi\pi}) e^{-R^2_{\nu\pi} - \frac{1}{2} r^2_{\nu\nu} - \frac{1}{2} r^2_{\pi\pi}}$$

The probability peaks at $r_{\nu\nu} = r_{\pi\pi} = \sqrt{3}$ and $R_{\nu\pi} = 1$ or $r_{\nu\pi} = \sqrt{2.5}$.

The α particle: $0\hbar\omega + 1\hbar\omega$



Unbound nuclear states



First-excited 0^+ state in ^{4}He is close to the ^{3}H+p threshold and adopts its shape.

Nuclear chameleonic mimicry.

N. Michel *et al.*, Phys. Rev. Lett. **131** (2023) 242502

The α particle: $0\hbar\omega + 2\hbar\omega$

The tensor force mixes the $(LS) = (00)$ ground state with $(LS) = (22)$, with probability density

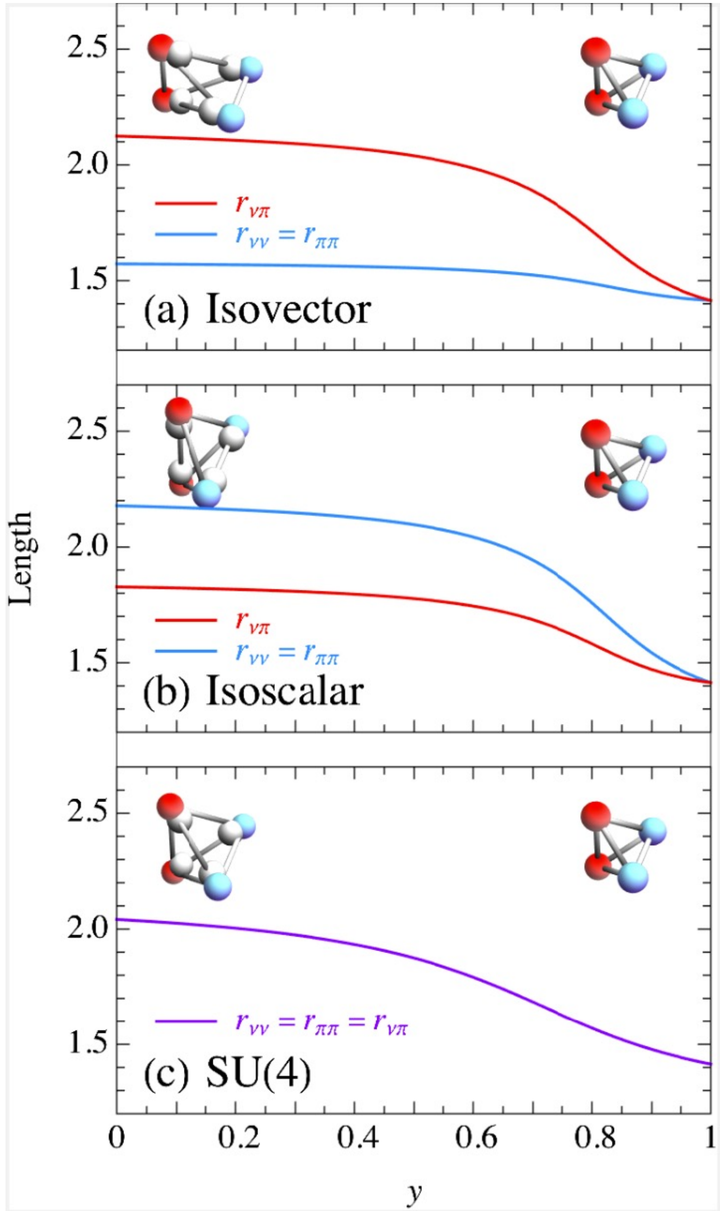
$$P_{220}^{(2)}(R_{\nu\pi}, r_{\nu\nu}, r_{\pi\pi}) = \frac{8}{9\pi^{3/2}} R_{\nu\pi}^2 r_{\nu\nu}^4 r_{\pi\pi}^4 e^{-R_{\nu\pi}^2 - \frac{1}{2} r_{\nu\nu}^2 - \frac{1}{2} r_{\pi\pi}^2}$$

The probability peaks at $r_{\nu\nu} = r_{\pi\pi} = 2$ and $R_{\nu\pi} = 1$ or $r_{\nu\pi} = \sqrt{3}$.

The α particle: $0\hbar\omega + 2\hbar\omega$

If $y = 0$, orbitals are degenerate, $\hbar\omega = 0$.

If $y = 1$, $\hbar\omega \gg a_T$ and we recover s^4 solution.



Deuteron and alpha clustering

How to quantify the probability of formation of a deuteron or an α particle in an arbitrary shell-model state with n_ν neutrons and n_π protons?

This probability is obtained by summing over all np pairs or 2n2p quartets with the *intrinsic* structure of a deuteron or an α particle.

Put all quanta of the pair/quartet in the centre-of-mass coordinate and none in the other degrees of freedom.

Discussions with Augusto Macchiavelli since 2021

Deuteron cluster probability

Expansion of an eigenstate in an isospin basis

$$|\Phi\Gamma_n\rangle = \sum_{\bar{n}\alpha_n} b^{\Gamma_n}_{\bar{n}\alpha_n} |\Omega^{1\ldots n}\bar{n}\alpha_n\Gamma_n\rangle$$

In isospin formalism $[\hat{P}_d = \sum_{i<j} \hat{P}_d(i,j)]$

$$\langle\Phi\Gamma_n|\hat{P}_{\mathrm{d}}|\Phi\Gamma_n\rangle = \frac{n(n-1)}{2} \sum_{\bar{n}\alpha_n} \sum_{\bar{n}'\alpha'_n} b^{\Gamma_n}_{\bar{n}\alpha_n} b^{\Gamma_n}_{\bar{n}'\alpha'_n} \langle\Omega^{1\ldots n}\bar{n}\alpha_n\Gamma_n|\hat{P}_{\mathrm{d}}(1,2)|\Omega^{1\ldots n}\bar{n}'\alpha'_n\Gamma_n\rangle$$

with

$$\begin{aligned}\langle\Omega^{1\ldots n}\bar{n}\alpha_n\Gamma_n|\hat{P}_{\mathrm{d}}(1,2)|\Omega^{1\ldots n}\bar{n}'\alpha'_n\Gamma_n\rangle \\ = \sum_{\bar{r}\alpha_r\Gamma_r} [\bar{2}\Gamma_{\mathrm{d}}, \bar{r}\alpha_r\Gamma_r|\}\bar{n}\alpha_n\Gamma_n]\,[\bar{2}'\Gamma_{\mathrm{d}}, \bar{r}\alpha_r\Gamma_r|\}\bar{n}'\alpha'_n\Gamma_n]\,\tilde{a}^{n_a l n_b l}_{\mathcal{N}000,\Gamma_{\mathrm{d}}}\,\tilde{a}^{n'_a l' n'_b l'}_{\mathcal{N}'000,\Gamma_{\mathrm{d}}}\end{aligned}$$

Deuteron cluster probability

Expansion of an eigenstate in an np basis

$$|\Phi\Gamma_n\rangle = \sum_{\Lambda_{n\nu}\Lambda_{n\pi}} b^{\Gamma_n}_{\Lambda_{n\nu}\Lambda_{n\pi}} |\Omega_\nu^{1_\nu\ldots n_\nu}\Lambda_{n\nu}, \Omega_\pi^{1_\pi\ldots n_\pi}\Lambda_{n\pi};\Gamma_n\rangle$$

In neutron-proton formalism $[\hat{P}_d = \sum_{i_\nu i_\pi} \hat{P}_d(i_\nu, i_\pi)]$

$$\langle\Phi\Gamma_n|\hat{P}_\mathrm{d}|\Phi\Gamma_n\rangle = n_\nu n_\pi \sum_{\Lambda_{n\nu}\Lambda_{n\pi}} \sum_{\Lambda'_{n\nu}\Lambda'_{n\pi}} b^{\Gamma_n}_{\Lambda_{n\nu}\Lambda_{n\pi}} b^{\Gamma_n}_{\Lambda'_{n\nu}\Lambda'_{n\pi}}$$
$$\times \langle\Omega_\nu^{1_\nu\ldots n_\nu}\Lambda_{n\nu}, \Omega_\pi^{1_\pi\ldots n_\pi}\Lambda_{n\pi};\Gamma_n|\hat{P}_\mathrm{d}(1_\nu, 1_\pi)|\Omega_\nu^{1_\nu\ldots n_\nu}\Lambda'_{n\nu}, \Omega_\pi^{1_\pi\ldots n_\pi}\Lambda'_{n\pi};\Gamma_n\rangle$$

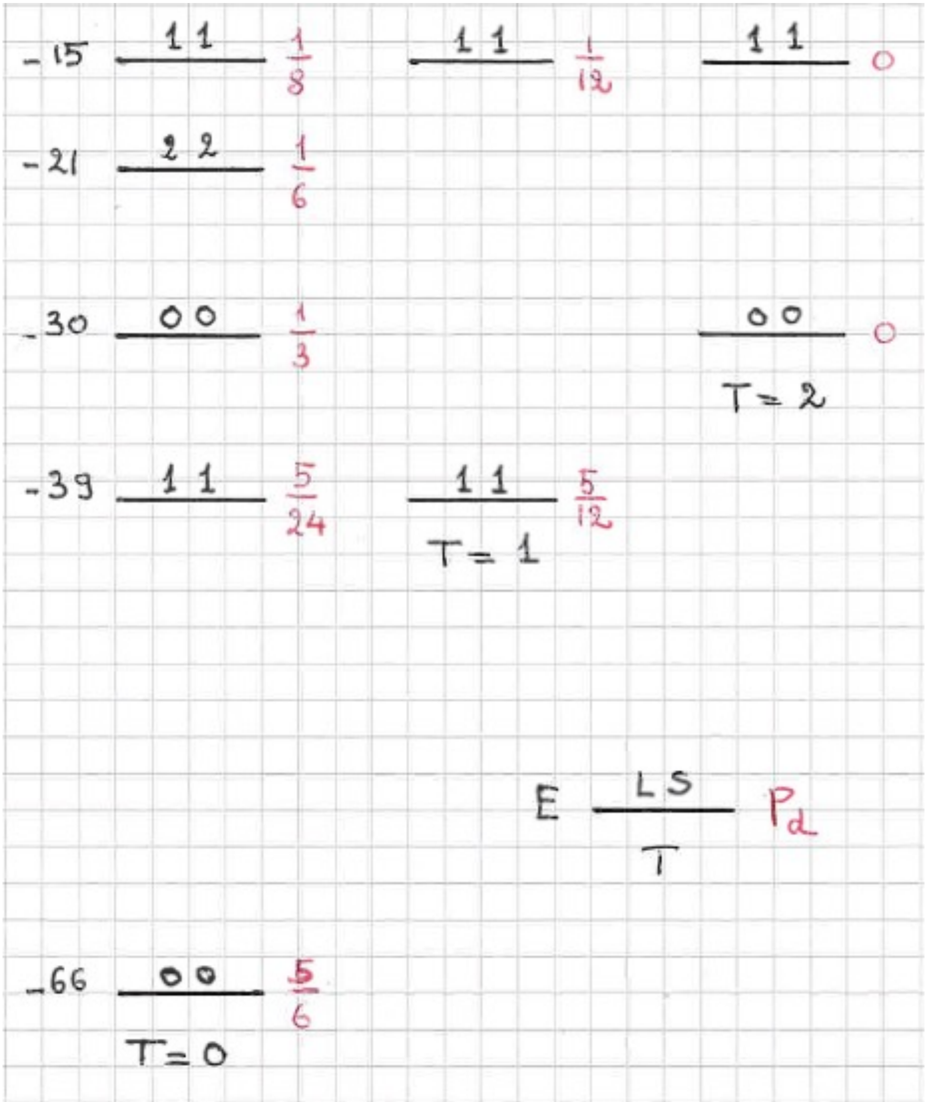
with

$$\langle\Omega_\nu^{1_\nu\ldots n_\nu}\Lambda_{n\nu}, \Omega_\pi^{1_\pi\ldots n_\pi}\Lambda_{n\pi};\Gamma_n|\hat{P}_\mathrm{d}(1_\nu, 1_\pi)|\Omega_\nu^{1_\nu\ldots n_\nu}\Lambda'_{n\nu}, \Omega_\pi^{1_\pi\ldots n_\pi}\Lambda'_{n\pi};\Gamma_n\rangle.$$
$$= \sum_{\Lambda_{r\nu}\Lambda_{r\pi}} [\bar{1}_\nu\Gamma_{1\nu}, \Lambda_{r\nu}|\}\Lambda_{n\nu}]\,[\bar{1}_\pi\Gamma_{1\pi}, \Lambda_{r\pi}|\}\Lambda_{n\pi}]\,[\bar{1}'_\nu\Gamma'_{1\nu}, \Lambda_{r\nu}|\}\Lambda'_{n\nu}]\,[\bar{1}'_\pi\Gamma'_{1\pi}, \Lambda_{r\pi}|\}\Lambda'_{n\pi}]$$
$$\times \sum_{\Gamma_r} \begin{bmatrix} \Gamma_{1\nu} & \Gamma_{r\nu} & \Gamma_{n\nu} \\ \Gamma_{1\pi} & \Gamma_{r\pi} & \Gamma_{n\pi} \\ \Gamma_\mathrm{d} & \Gamma_r & \Gamma_n \end{bmatrix} \begin{bmatrix} \Gamma'_{1\nu} & \Gamma_{r\nu} & \Gamma'_{n\nu} \\ \Gamma'_{1\pi} & \Gamma_{r\pi} & \Gamma'_{n\pi} \\ \Gamma_\mathrm{d} & \Gamma_r & \Gamma_n \end{bmatrix} a^{n_\nu l n_\pi l}_{\mathcal{N}000,0}\, a^{n'_\nu l' n'_\pi l'}_{\mathcal{N}'000,0},$$

Example: $(0p)^4$ 0^+ states

SDI with isoscalar and isovector strengths a_0 and a_1 and spin-orbit term with strength g.

For $g = 0 \to LS$-coupled eigenstates.



α cluster probability

The α-particle probability of the state

$$|\Phi\Gamma_n\rangle = \sum_{\Lambda_{n\nu}\Lambda_{n\pi}} b_{\Lambda_{n\nu}\Lambda_{n\pi}\Gamma_n} |\Lambda_{n\nu}, \Lambda_{n\pi}; \Gamma_n\rangle$$

is

$$p_\alpha \equiv \langle\Phi\Gamma_n|\hat{P}_\alpha|\Phi\Gamma_n\rangle^2 = \sum_{\Lambda_{r\nu}\Lambda_{r\pi}} \sum_{\mathcal{S}=0,1} \left(\sum_{\Lambda_{n\nu}\Lambda_{n\pi}} b_{\Lambda_{n\nu}\Lambda_{n\pi}\Gamma_n} d^{\mathcal{S}\Lambda_{r\nu}\Lambda_{r\pi}}_{\Lambda_{n\nu}\Lambda_{n\pi}\Gamma_n} \right)^2$$

$$d^{\mathcal{S}\Lambda_{r\nu}\Lambda_{r\pi}}_{\Lambda_{n\nu}\Lambda_{n\pi}\Gamma_n} = \sum_{\Gamma_2} [\Lambda_{2\nu}, \Lambda_{r\nu}|\}\Lambda_{n\nu}][\Lambda_{2\pi}, \Lambda_{r\pi}|\}\Lambda_{n\pi}] \begin{bmatrix} \Gamma_2 & \Gamma_{r\nu} & \Gamma_{n\nu} \\ \Gamma_2 & \Gamma_{r\pi} & \Gamma_{n\pi} \\ 00 & \Gamma_n & \Gamma_n \end{bmatrix} c^{\mathcal{S}00}_{\Lambda_{2\nu}\Lambda_{2\pi}}$$

$$c^{\mathcal{S}00}_{\Lambda_{2\nu}\Lambda_{2\pi}} = -\tilde{a}^{n_{a\nu}l_{a\nu}n_{b\nu}l_{b\nu}}_{\mathcal{N}_\nu L_2 00, L_2 S_2} \tilde{a}^{n_{a\pi}l_{a\pi}n_{b\pi}l_{b\pi}}_{\mathcal{N}_\pi L_2 00, L_2 S_2} \begin{bmatrix} 1/2 & 1/2 & S_2 \\ 1/2 & 1/2 & S_2 \\ \mathcal{S} & \mathcal{S} & 0 \end{bmatrix} a^{\mathcal{N}_\nu L_2 \mathcal{N}_\pi L_2}_{\mathcal{N}000,0}$$

Example: the *sd* shell

How does the α cluster probability p_α change with neutron and proton numbers?

Consider the ground state of even-even nuclei in the *sd* shell.

Three choices of interaction:

- *only isoscalar*
- *only isovector*
- *isoscalar=isovector [SU(4)]*

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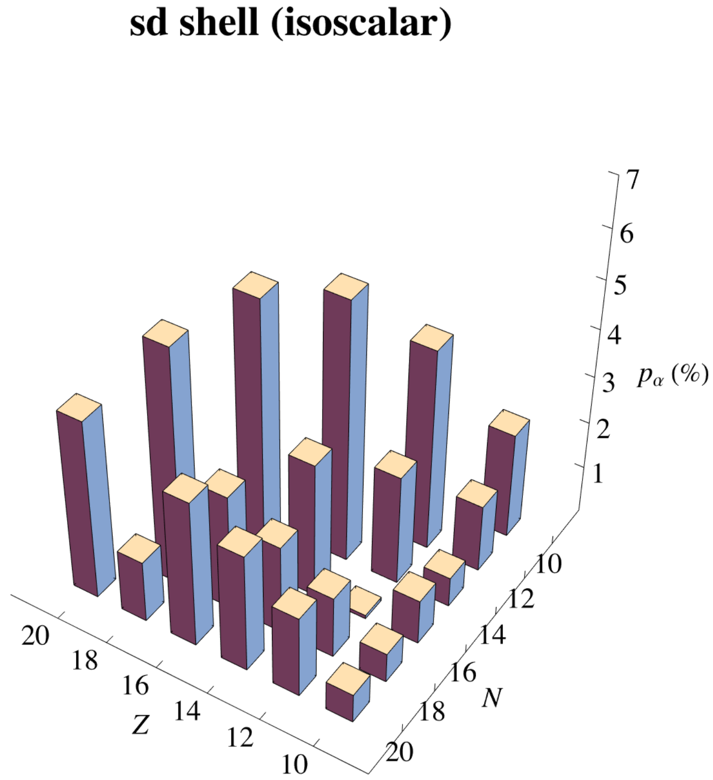

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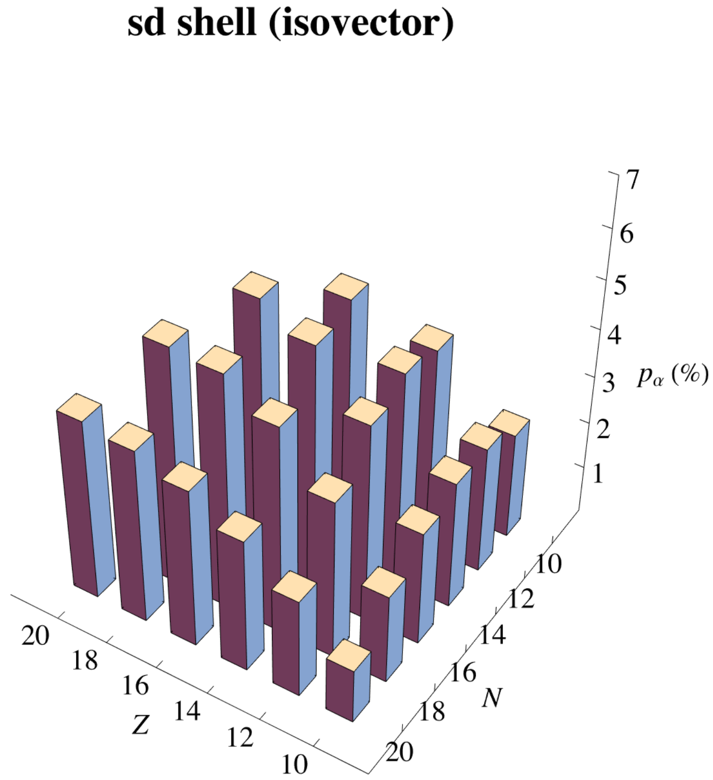

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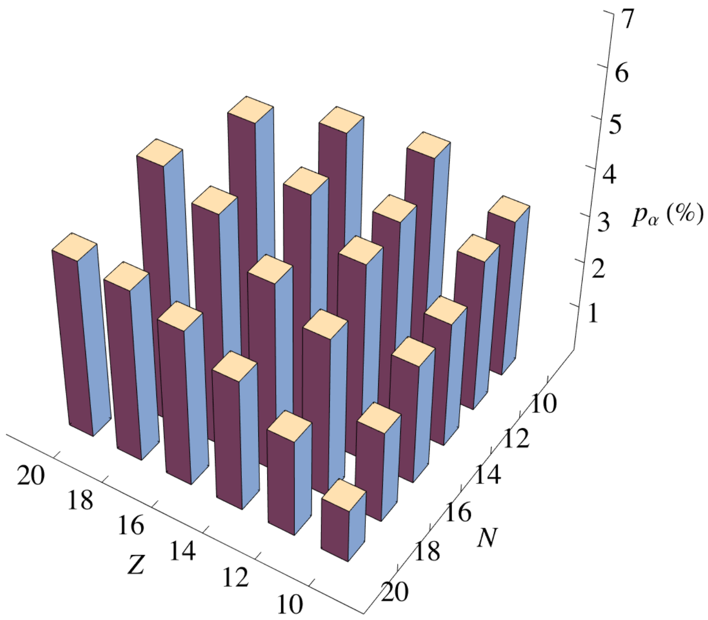
sd shell [SU(4)]



Closing remarks

Probability of deuteron clustering: Apply to np transfer reactions.

Experimental program on $f_{7/2}$ nuclei (M. Assié)

Probability of α clustering: What is the effect of cross-shell excitations?

Example: ^{20}Ne (Stu Pittel)

Thank you