Weakly bound nuclei:

A unified description of intrinsic and relative degrees of freedom

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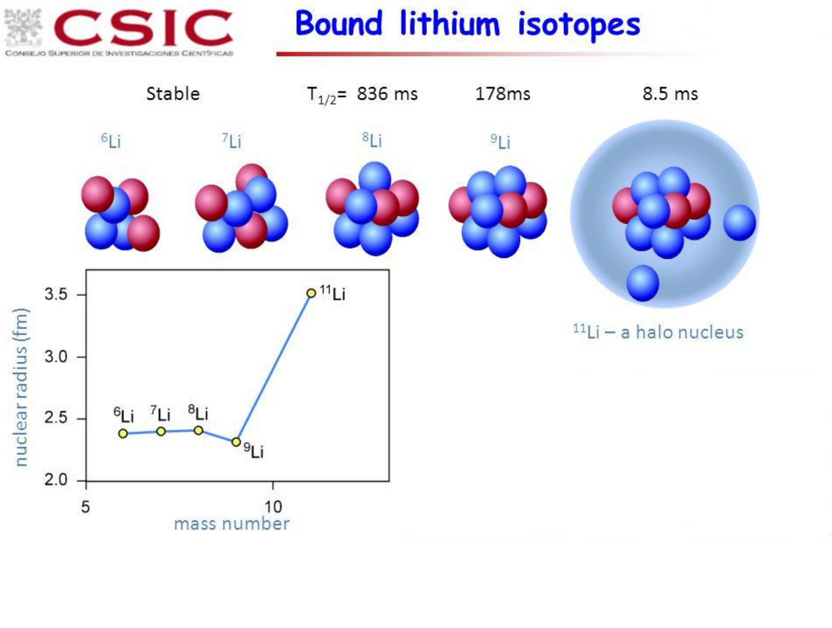

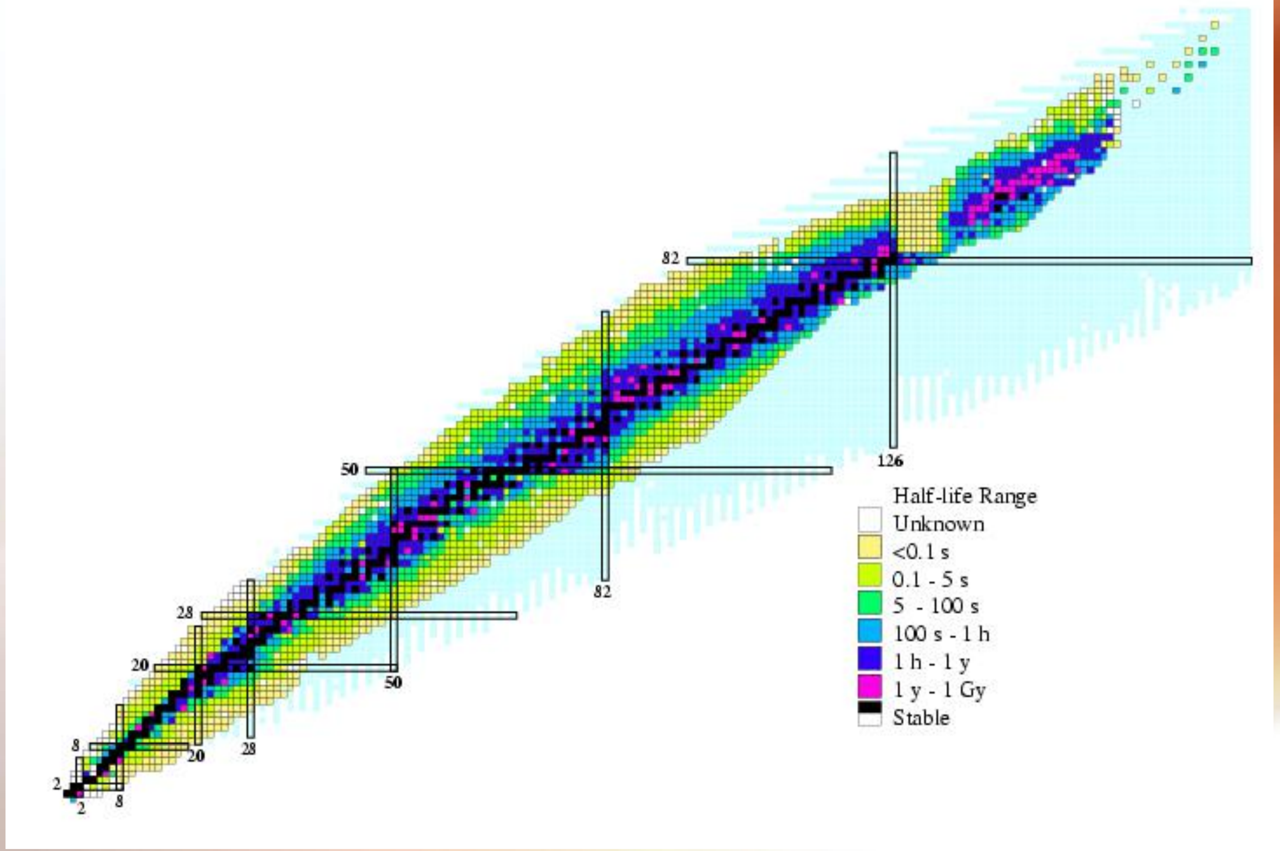

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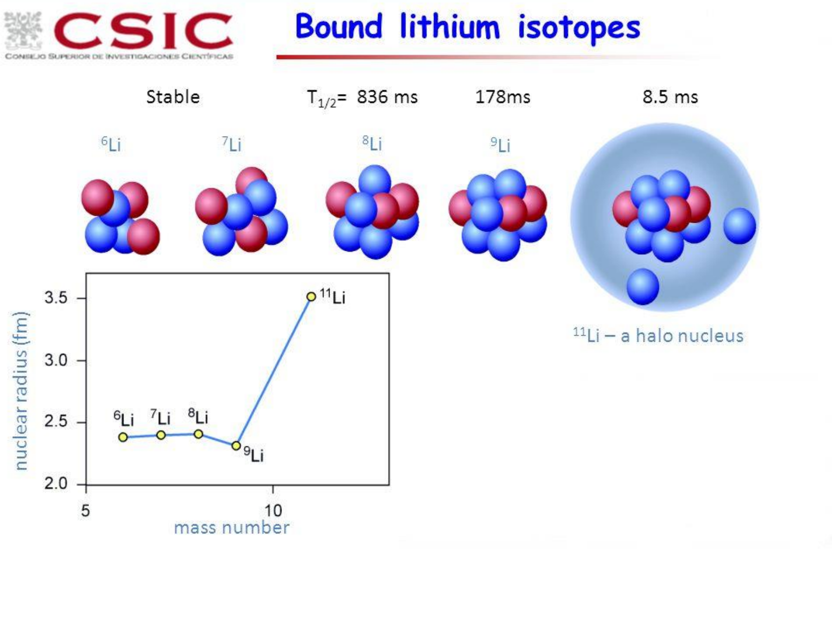

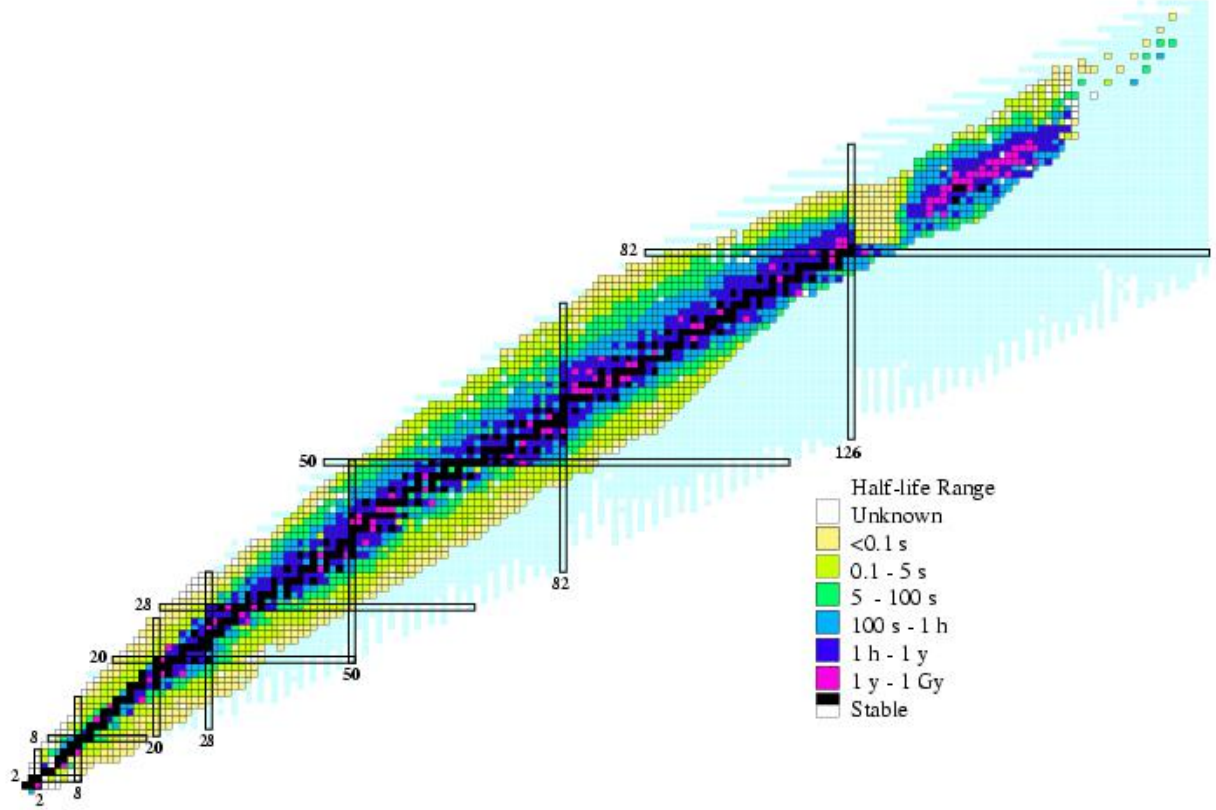

$$[T_x + T_y + V_{12}(r_{12}) + V_{13}(r_{13}) + V_{23}(r_{23})]\,\Psi = E\Psi$$

- ✓ The core is assumed to be an inert particle.
- ✓ What to do when experimental information is not available.

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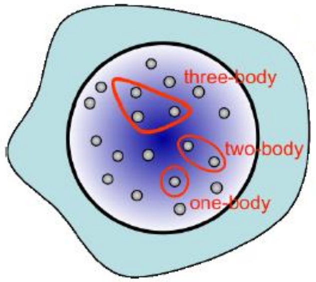

$$H = \sum_i T(i) + \sum_{i<j} V^{(2)}(i,j) + \sum_{i<j<k} V^{(3)}(i,j,k)$$

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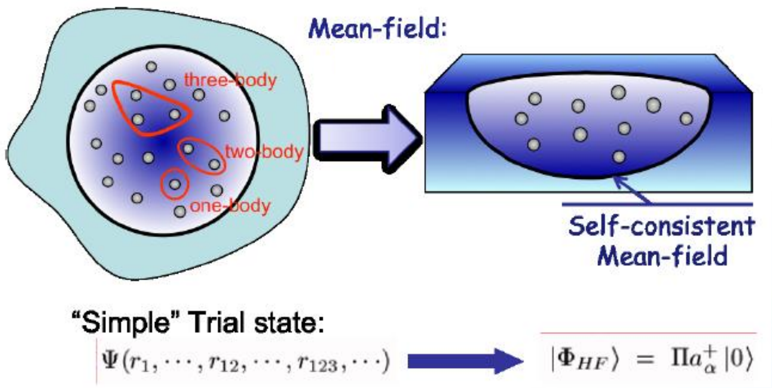

$$H = \sum_{i} T(i) + \sum_{i<j} V^{(2)}(i,j) + \sum_{i<j<k} V^{(3)}(i,j,k)$$

- ✓ The particles do not interact with each other, but through an average mean-field.
- ✓ The complex N-body wave function is replaced by a Slater determinant.

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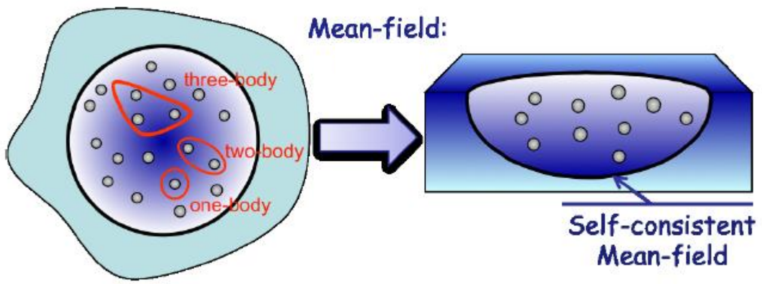

"Simple" Trial state:

$\Psi(r_1, \cdots, r_{12}, \cdots, r_{123}, \cdots) \rightarrow |\Phi_{HF}\rangle = \Pi a_\alpha^+ |0\rangle$

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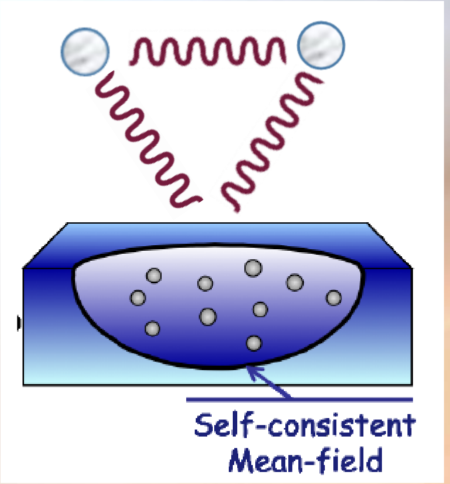

- ✓ The mean-field determines the interaction with the loosely bound nucleons.

Three-body problem

Weakly bound nuclei:

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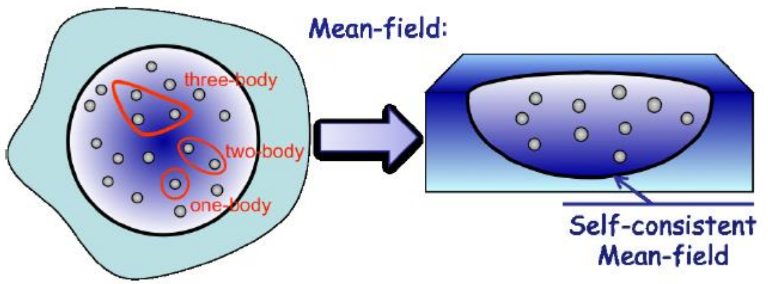

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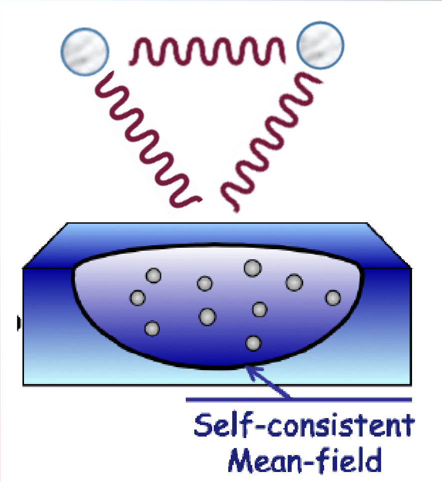

- ✓ The mean-field determines the interaction with the loosely bound nucleons.

Three-body problem

- ✓ The presence of the loosely bound nucleons distorts the mean-field.

- ✓ The distorted mean-field modifies the core-nucleon interaction and the wave function of the valence nucleons.

Self-consistent calculation

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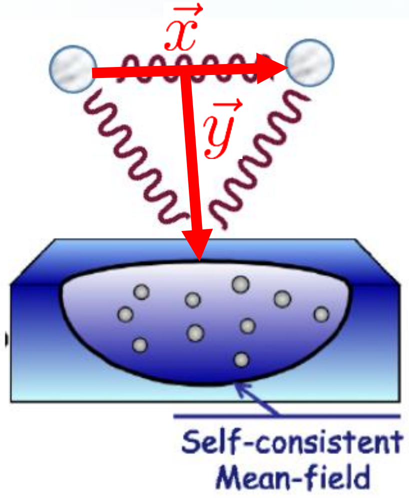
- ✓ Some formal hints about the formalism
- ✓ The case of ^{26}O
- ✓ Proton dripline: ^{70}Kr
- ✓ Approaching the dripline: Ca isotopes
- ✓ Summary and possible extensions

Formalism:



$$H = \underbrace{\frac{1}{4mA}\sum_{i=1}^{A}\sum_{j=1}^{A}(\vec{p}_i - \vec{p}_j)^2 + \sum_{i<j}^{A} V_{ij}}_{H_c} + \underbrace{\frac{p_x^2}{2\mu_x} + \frac{p_y^2}{2\mu_y} + V_{v_1 v_2}}_{H_3} + \underbrace{\sum_{i=1}^{A}(V_{iv_1} + V_{iv_2})}_{H_{coup}}$$

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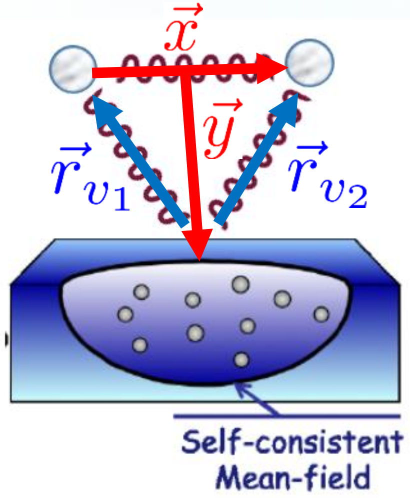

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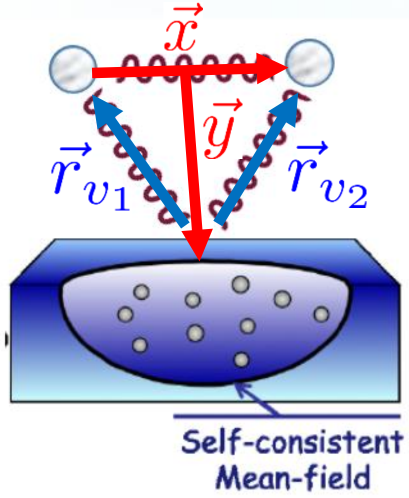
$$\begin{aligned}
\Psi &= \mathcal{A}\{\Phi_c(\{\vec{r}_A\})\psi_3(\vec{r}_{v_1}, \vec{r}_{v_2})\} \\
&= \Phi_c(\{\vec{r}_A\})\psi_3(\vec{r}_{v_1}, \vec{r}_{v_2}) - \sum_{i=1}^{A} \Phi_c(\vec{r}_{v_1}, \{\vec{r}_{A-1}\})\psi_3(\vec{r}_i, \vec{r}_{v_2}) \\
&- \sum_{i=1}^{A} \Phi_c(\vec{r}_{v_2}, \{\vec{r}_{A-1}\})\psi_3(\vec{r}_{v_1}, \vec{r}_i) + \sum_{i<j}^{A} \Phi_c(\vec{r}_{v_1}, \vec{r}_{v_2}, \{\vec{r}_{A-2}\})\psi_3(\vec{r}_i, \vec{r}_j)
\end{aligned}$$

Formalism:



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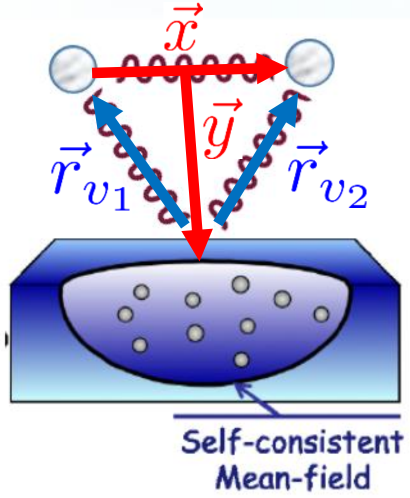
$$\Psi = \mathcal{A}\{\Phi_c(\{\vec{r}_A\})\psi_3(\vec{r}_{v_1}, \vec{r}_{v_2})\}$$

$$E = \langle\Psi|H|\Psi\rangle = \langle\Phi_c|H_c|\Phi_c\rangle + \langle\psi_3|H_3|\psi_3\rangle + \langle\Psi|H_{coup}|\Psi\rangle$$

Formalism:



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$$\Psi = \mathcal{A}\{\Phi_c(\{\vec{r}_A\})\psi_3(\vec{r}_{v_1}, \vec{r}_{v_2})\}$$

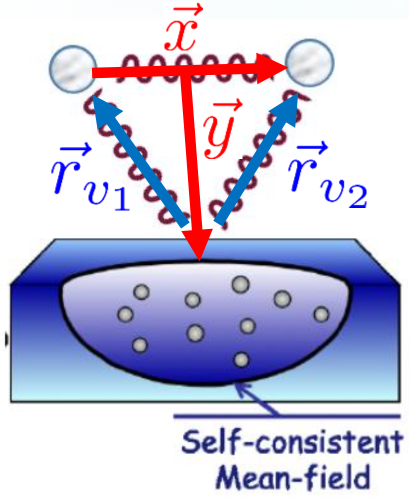
$$\langle\Psi|H'|\Psi\rangle = \langle\Psi|H|\Psi\rangle - E_c \int |\Phi_c(\{\vec{r}_A\})|^2 d\vec{r}_1 \cdots d\vec{r}_A - E_3 \int |\psi_3(\vec{r}_{v_1}, \vec{r}_{v_2})|^2 d\vec{r}_{v_1} d\vec{r}_{v_2}$$

$$0 = \frac{\delta}{\delta\Phi_c^*}\langle\Psi|H'|\Psi\rangle$$

$$0 = \frac{\delta}{\delta\psi_3^*}\langle\Psi|H'|\Psi\rangle$$

$$\Phi_c(\{\vec{r}_A\}) = \det(\{\phi_i^{q_i}(\vec{r}_i)\})$$

Formalism:



$$\epsilon_i \phi_i^{q_i}(\vec{r}) = -\frac{\hbar^2}{2mA}\sum_{k=1}^{A}\int \phi_k^{q_k *}(\vec{r'})\left(\vec{\nabla}_r - \vec{\nabla}_{r'}\right)^2\left(\phi_k^{q_k}(\vec{r'})\phi_i^{q_i}(\vec{r}) - \phi_k^{q_k}(\vec{r})\phi_i^{q_i}(\vec{r'})\delta_{q_i q_k}\right) d\vec{r'}$$
$$+\sum_{k=1}^{A}\int \phi_k^{q_k *}(\vec{r'})V_{ik}(\vec{r},\vec{r'})\left(\phi_k^{q_k}(\vec{r'})\phi_i^{q_i}(\vec{r}) - \phi_k^{q_k}(\vec{r})\phi_i^{q_i}(\vec{r'})\delta_{q_i q_k}\right) d\vec{r'}$$
$$+\int \psi_3^*(\vec{r}_{v_1},\vec{r}_{v_2})V_{v_1 i}(\vec{r}_{v_1},\vec{r})\left(\psi_3(\vec{r}_{v_1},\vec{r}_{v_2})\phi_i^{q_i}(\vec{r}) - \psi_3(\vec{r},\vec{r}_{v_2})\phi_i^{q_i}(\vec{r}_{v_1})\delta_{q_i q_{v_1}}\right) d\vec{r}_{v_1} d\vec{r}_{v_2}$$
$$+\int \psi_3^*(\vec{r}_{v_1},\vec{r}_{v_2})V_{v_2 i}(\vec{r}_{v_2},\vec{r})\left(\psi_3(\vec{r}_{v_1},\vec{r}_{v_2})\phi_i^{q_i}(\vec{r}) - \psi_3(\vec{r}_{v_1},\vec{r})\phi_i^{q_i}(\vec{r}_{v_2})\delta_{q_i q_{v_2}}\right) d\vec{r}_{v_1} d\vec{r}_{v_2}$$

$$E_3\psi_3(\vec{r}_{v_1},\vec{r_{v_2}}) = \left(\frac{p_x^2}{2\mu_x} + \frac{p_y^2}{2\mu_y} + V_{v_1 v_2}\right)\psi_3(\vec{r}_{v_1},\vec{r_{v_2}})$$
$$+\sum_{i=1}^{A}\int \phi_i^{q_i *}(\vec{r})V_{v_1 i}(\vec{r}_{v_1},\vec{r})\left(\psi_3(\vec{r}_{v_1},\vec{r}_{v_2})\phi_i^{q_i}(\vec{r}) - \psi_3(\vec{r},\vec{r}_{v_2})\phi_i^{q_i}(\vec{r}_{v_1})\delta_{q_{v_1} q_i}\right) d\vec{r}$$
$$+\sum_{i=1}^{A}\int \phi_i^{q_i *}(\vec{r})V_{v_2 i}(\vec{r}_{v_2},\vec{r})\left(\psi_3(\vec{r}_{v_1},\vec{r}_{v_2})\phi_i^{q_i}(\vec{r}) - \psi_3(\vec{r}_{v_1},\vec{r})\phi_i^{q_i}(\vec{r}_{v_2})\delta_{q_{v_2} q_i}\right) d\vec{r}$$

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$$\epsilon_i \phi_i^{q_i}(\vec{r}) = \Big[-\vec{\nabla} \cdot \frac{\hbar^2}{2m^*_{q_i}(\vec{r})} \vec{\nabla} + U_{q_i}(\vec{r}) - i\vec{W}_{q_i}(\vec{r}) \cdot (\vec{\nabla} \times \vec{\sigma}) - \vec{\nabla} \cdot \frac{1}{m'^*_{q_i}(\vec{r})} \vec{\nabla} + U'_{q_i}(\vec{r}) - i\vec{W}'_{q_i}(\vec{r}) \cdot (\vec{\nabla} \times \vec{\sigma}) \Big] \phi_i^{q_i}(\vec{r})$$

$$E_3 \psi_3(\vec{r}_1, \vec{r}_2) = \left[\frac{p_x^2}{2\mu_x} + \frac{p_y^2}{2\mu_y} + V_{v_1 v_2} + V_{cv_1}(\vec{r}_{cv_1}) + V_{cv_2}(\vec{r}_{cv_2}) \right] \psi_3(\vec{r}_1, \vec{r}_2)$$

concludes that the single-particle wave functions ϕ_i have to satisfy the following set of equations (see Appendix C):

$$\left[-\vec{\nabla} \cdot \frac{\hbar^2}{2m^*_q(\vec{r})} \vec{\nabla} + U_q(\vec{r}) + \vec{W}_q(\vec{r}) \cdot (-i)(\vec{\nabla} \times \vec{\sigma}) \right] \phi_i = e_i \phi_i , \tag{20}$$

where q stands for the charge of the single-particle state i. Equation (20) has the form of a local Schrödinger equation with an effective mass $m^*(\vec{r})$ which depends on the density only,

$$\frac{\hbar^2}{2m^*_q(\vec{r})} = \frac{\hbar^2}{2m} + \tfrac{1}{4}(t_1 + t_2)\rho + \tfrac{1}{8}(t_2 - t_1)\rho_q ; \tag{21}$$

whereas, the potential $U(\vec{r})$ also depends on the kinetic energy density,

$$U_q(\vec{r}) = t_0[(1 + \tfrac{1}{2}x_0)\rho - (x_0 + \tfrac{1}{2})\rho_q] + \tfrac{1}{4}t_3(\rho^2 - \rho_q^2) - \tfrac{1}{8}(3t_1 - t_2)\nabla^2\rho + \tfrac{1}{16}(3t_1 + t_2)\nabla^2\rho_q + \tfrac{1}{4}(t_1 + t_2)\tau + \tfrac{1}{8}(t_2 - t_1)\tau_q - \tfrac{1}{2}W_0(\vec{\nabla} \cdot \vec{J} + \vec{\nabla} \cdot \vec{J}_q) + \delta_{q,+\frac{1}{2}} V_C(\vec{r}) . \tag{22a}$$

The form factor $\vec{W}$ of the one-body spin-orbit potential is

$$\vec{W}_q(\vec{r}) = \tfrac{1}{2}W_0(\vec{\nabla}\rho + \vec{\nabla}\rho_q) + \tfrac{1}{8}(t_1 - t_2)\vec{J}_q(\vec{r}) . \tag{22b}$$

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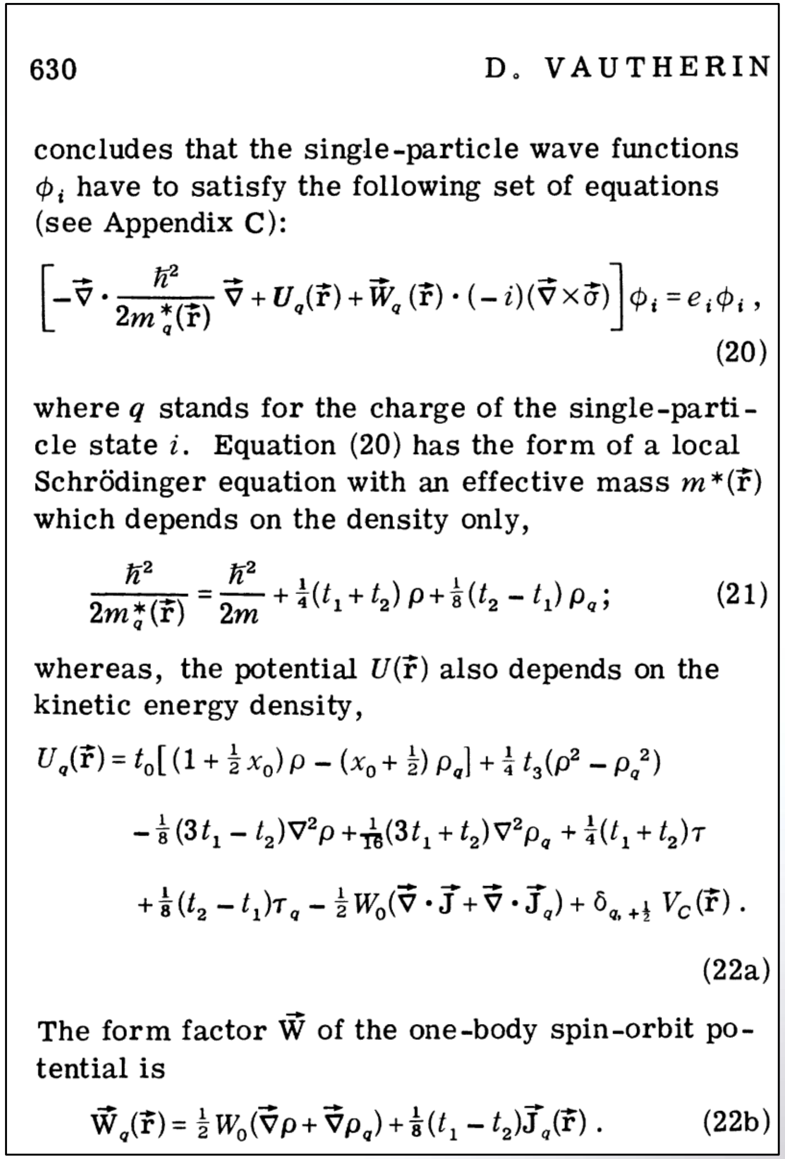

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$$-\tfrac{1}{8}(3t_1-t_2)\nabla^2\rho+\tfrac{1}{16}(3t_1+t_2)\nabla^2\rho_q+\tfrac{1}{4}(t_1+t_2)\tau$$
$$+\tfrac{1}{8}(t_2-t_1)\tau_q-\tfrac{1}{2}W_0(\vec{\nabla}\cdot\vec{J}+\vec{\nabla}\cdot\vec{J}_q)+\delta_{q,+\frac{1}{2}}V_C(\vec{r})\,. \quad (22a)$$

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Adiabatic Expansion Method

$$\psi_3(\vec{r}_{v_1},\vec{r}_{v_2})=\frac{1}{\rho^{5/2}}\sum_n f_n(\rho)\Phi_n(\rho,\Omega)$$

$$\rho^2=x^2+y^2 \qquad \tan\alpha=\frac{x}{y}$$
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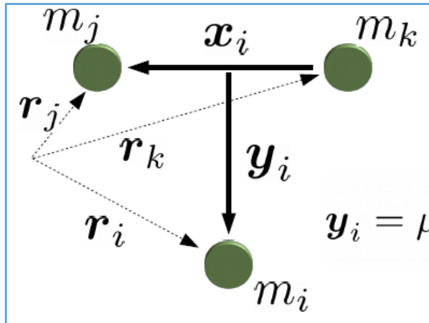

$$\boldsymbol{x}_i=\mu_{jk}(\boldsymbol{r}_j-\boldsymbol{r}_k)$$
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$$E_3\psi_3(\vec{r}_1,\vec{r}_2)=\left[\frac{p_x^2}{2\mu_x}+\frac{p_y^2}{2\mu_y}+V_{v_1v_2}+V_{cv_1}(\vec{r}_{cv_1})+V_{cv_2}(\vec{r}_{cv_2})\right]\psi_3(\vec{r}_1,\vec{r}_2)$$

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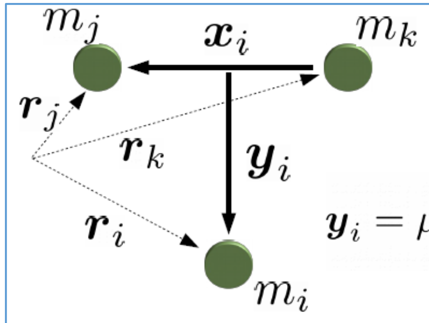

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$$\boldsymbol{y}_i=\mu_{i,jk}\left(\boldsymbol{r}_i-\frac{m_j\boldsymbol{r}_j+m_k\boldsymbol{r}_k}{m_j+m_k}\right)$$

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial\rho^2}+V_{eff}(\rho)-E_3\right]f_n-\frac{\hbar^2}{2m}\sum_m\left(2P_{nm}(\rho)\frac{\partial}{\partial\rho}+Q_{nm}(\rho)\right)f_m=0$$

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$$\left[-\vec{\nabla}\cdot\frac{\hbar^2}{2m_q^*(\vec{r})}\vec{\nabla}+U_q(\vec{r})+\vec{W}_q(\vec{r})\cdot(-i)(\vec{\nabla}\times\vec{\sigma})\right]\phi_i=e_i\phi_i\,, \quad (20)$$

where q stands for the charge of the single-particle state i. Equation (20) has the form of a local Schrödinger equation with an effective mass $m^*(\vec{r})$ which depends on the density only,

$$\frac{\hbar^2}{2m_q^*(\vec{r})}=\frac{\hbar^2}{2m}+\tfrac{1}{4}(t_1+t_2)\rho+\tfrac{1}{8}(t_2-t_1)\rho_q\,; \quad (21)$$

whereas, the potential $U(\vec{r})$ also depends on the kinetic energy density,

$$U_q(\vec{r})=t_0[(1+\tfrac{1}{2}x_0)\rho-(x_0+\tfrac{1}{2})\rho_q]+\tfrac{1}{4}t_3(\rho^2-\rho_q^{\,2})$$
$$-\tfrac{1}{8}(3t_1-t_2)\nabla^2\rho+\tfrac{1}{16}(3t_1+t_2)\nabla^2\rho_q+\tfrac{1}{4}(t_1+t_2)\tau$$
$$+\tfrac{1}{8}(t_2-t_1)\tau_q-\tfrac{1}{2}W_0(\vec{\nabla}\cdot\vec{J}+\vec{\nabla}\cdot\vec{J}_q)+\delta_{q,+\frac{1}{2}}V_C(\vec{r})\,. \quad (22a)$$

The form factor $\vec{W}$ of the one-body spin-orbit potential is

$$\vec{W}_q(\vec{r})=\tfrac{1}{2}W_0(\vec{\nabla}\rho+\vec{\nabla}\rho_q)+\tfrac{1}{8}(t_1-t_2)\vec{J}_q(\vec{r})\,. \quad (22b)$$

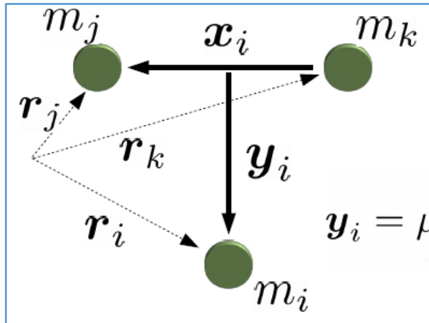
$$\epsilon_i\phi_i^{q_i}(\vec{r}) = \left[-\vec{\nabla}\cdot\frac{\hbar^2}{2m^*_{q_i}(\vec{r})}\vec{\nabla}+U_{q_i}(\vec{r})-i\vec{W}_{q_i}(\vec{r})\cdot(\vec{\nabla}\times\vec{\sigma}) -\vec{\nabla}\cdot\frac{1}{m'^*_{q_i}(\vec{r})}\vec{\nabla}+U'_{q_i}(\vec{r})-i\vec{W'}_{q_i}(\vec{r})\cdot(\vec{\nabla}\times\vec{\sigma})\right]\phi_i^{q_i}(\vec{r})$$

$$E_3\psi_3(\vec{r}_1,\vec{r}_2)=\left[\frac{p_x^2}{2\mu_x}+\frac{p_y^2}{2\mu_y}+V_{v_1v_2}+V_{cv_1}(\vec{r}_{cv_1})+V_{cv_2}(\vec{r}_{cv_2})\right]\psi_3(\vec{r}_1,\vec{r}_2)$$

Adiabatic Expansion Method

$$\psi_3(\vec{r}_{v_1},\vec{r}_{v_2})=\frac{1}{\rho^{5/2}}\sum_n f_n(\rho)\Phi_n(\rho,\Omega)$$

$$\rho^2=x^2+y^2 \qquad \tan\alpha=\frac{x}{y}$$
$$\Omega\equiv\{\alpha,\Omega_x,\Omega_y\}$$



$$\boldsymbol{x}_i=\mu_{jk}(\boldsymbol{r}_j-\boldsymbol{r}_k)$$
$$\boldsymbol{y}_i=\mu_{i,jk}\left(\boldsymbol{r}_i-\frac{m_j\boldsymbol{r}_j+m_k\boldsymbol{r}_k}{m_j+m_k}\right)$$

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial\rho^2}+V_{eff}(\rho)-E_3\right]f_n$$
$$-\frac{\hbar^2}{2m}\sum_m\left(2(P_{nm}(\rho)+P'_{nm}(\rho))\frac{\partial}{\partial\rho}+Q_{nm}(\rho)+Q'_{nm}(\rho)\right)f_m=0$$

D. Hove et al., JPG 45, 073001 (2018)

The case of ^{26}O:

PRL 109, 022501 (2012) PHYSICAL REVIEW LETTERS week ending 13 JULY 2012

$N = 16$ Spherical Shell Closure in ^{24}O

K. Tshoo,[1,*] Y. Satou,[1] H. Bhang,[1] S. Choi,[1] T. Nakamura,[2] Y. Kondo,[2] S. Deguchi,[2] Y. Kawada,[2] N. Kobayashi,[2] Y. Nakayama,[2] K. N. Tanaka,[2] N. Tanaka,[2] N. Aoi,[3] M. Ishihara,[3] T. Motobayashi,[3] H. Otsu,[3] H. Sakurai,[3] S. Takeuchi,[3] Y. Togano,[3] K. Yoneda,[3] Z. H. Li,[3] F. Delaunay,[4] J. Gibelin,[4] F. M. Marqués,[4] N. A. Orr,[4] T. Honda,[5] M. Matsushita,[5] T. Kobayashi,[6] Y. Miyashita,[7] T. Sumikama,[7] K. Yoshinaga,[7] S. Shimoura,[8] D. Sohler,[9] T. Zheng,[10] and Z. X. Cao[10]

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The unbound excited states of the neutron drip-line isotope ^{24}O have been investigated via the ^{24}O$(p, p')^{23}$O $+ n$ reaction in inverse kinematics at a beam energy of 62 MeV/nucleon. The decay energy spectrum of ^{24}O* was reconstructed from the momenta of ^{23}O and the neutron. The spin parity of the first excited state, observed at $E_x = 4.65 \pm 0.14$ MeV, was determined to be $J^\pi = 2^+$ from the angular distribution of the cross section. Higher-lying states were also observed. The quadrupole transition parameter β_2 of the 2_1^+ state was deduced, for the first time, to be 0.15 ± 0.04. The relatively high excitation energy and small β_2 value are indicative of the $N = 16$ shell closure in ^{24}O.

Physics Letters B 672 (2009) 17–21

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Evidence for a doubly magic ^{24}O

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ABSTRACT

The decay energy spectrum for neutron unbound states in ^{24}O ($Z = 8$, $N = 16$) has been observed for the first time. The resonance energy of the lowest lying state, interpreted as the 2^+ level, has been observed at a decay energy above 600 keV. The resulting excitation energy of the 2^+ level above 4.7 MeV, supplies strong evidence that ^{24}O is a doubly magic nucleus. The data is also consistent with the presence of a second excited state around 5.33 MeV which can be interpreted as the 1^+ level.

^{24}O is, to a large extent, a spherical nucleus

The case of ^{26}O:

PRL 116, 102503 (2016) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2016

Nucleus ^{26}O: A Barely Unbound System beyond the Drip Line

Y. Kondo,[1] T. Nakamura,[1] R. Tanaka,[1] R. Minakata,[1] S. Ogoshi,[1] N. A. Orr,[2] N. L. Achouri,[2] T. Aumann,[3,4] H. Baba,[5] F. Delaunay,[2] P. Doornenbal,[5] N. Fukuda,[5] J. Gibelin,[2] J. W. Hwang,[6] N. Inabe,[5] T. Isobe,[5] D. Kameda,[5] D. Kanno,[1] S. Kim,[6] N. Kobayashi,[1] T. Kobayashi,[7] T. Kubo,[5] S. Leblond,[2] J. Lee,[5] F. M. Marqués,[2] T. Motobayashi,[5] D. Murai,[8] T. Murakami,[9] K. Muto,[7] T. Nakashima,[1] N. Nakatsuka,[9] A. Navin,[10] S. Nishi,[1] H. Otsu,[5] H. Sato,[5] Y. Satou,[6] Y. Shimizu,[5] H. Suzuki,[5] K. Takahashi,[7] H. Takeda,[5] S. Takeuchi,[5] Y. Togano,[4,1] A. G. Tuff,[11] M. Vandebrouck,[12] and K. Yoneda[5]

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The unbound nucleus ^{26}O has been investigated using invariant-mass spectroscopy following one-proton removal reaction from a ^{27}F beam at 201 MeV/nucleon. The decay products, ^{24}O and two neutrons, were detected in coincidence using the newly commissioned SAMURAI spectrometer at the RIKEN Radioactive Isotope Beam Factory. The ^{26}O ground-state resonance was found to lie only $18 \pm 3(\text{stat}) \pm 4(\text{syst})$ keV above threshold. In addition, a higher lying level, which is most likely the first 2^+ state, was observed for the first time at $1.28^{+0.11}_{-0.08}$ MeV above threshold. Comparison with theoretical predictions suggests that three-nucleon forces, pf-shell intruder configurations, and the continuum are key elements to understanding the structure of the most neutron-rich oxygen isotopes beyond the drip line.

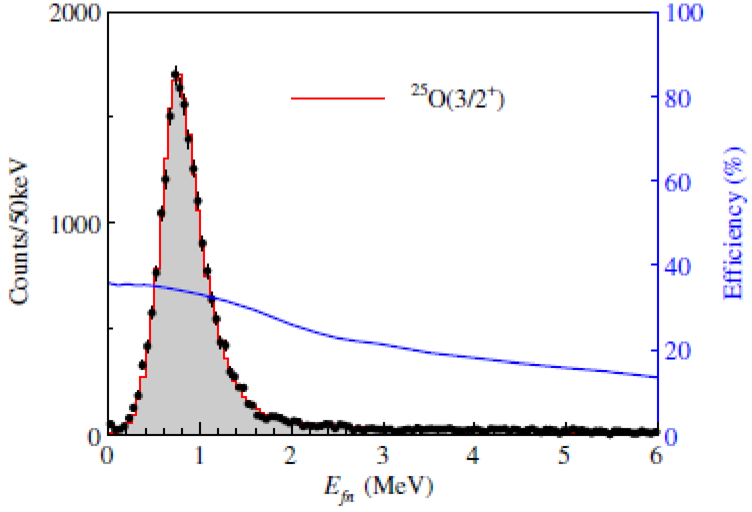
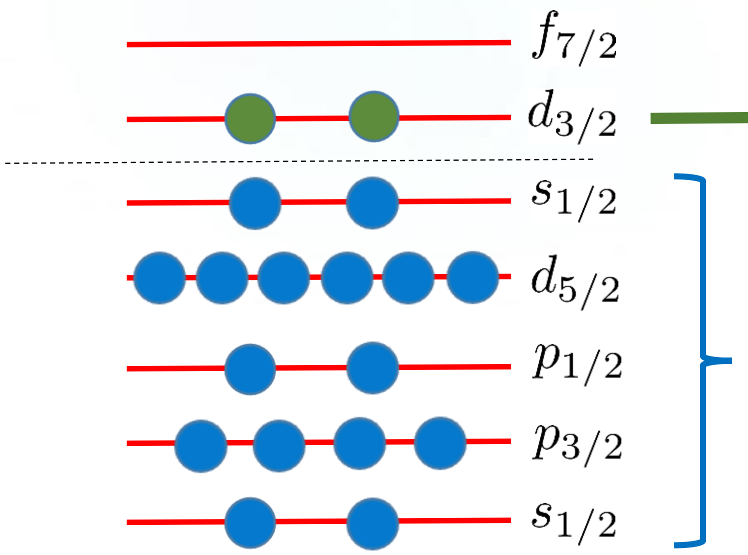


FIG. 1. Decay-energy spectrum of ^{24}O + n observed in one-proton removal from ^{26}F. The red-shaded histogram shows the fit, after accounting for the experimental response of the setup, assuming population of the ground state of ^{25}O. The blue curve represents the overall detection efficiency.

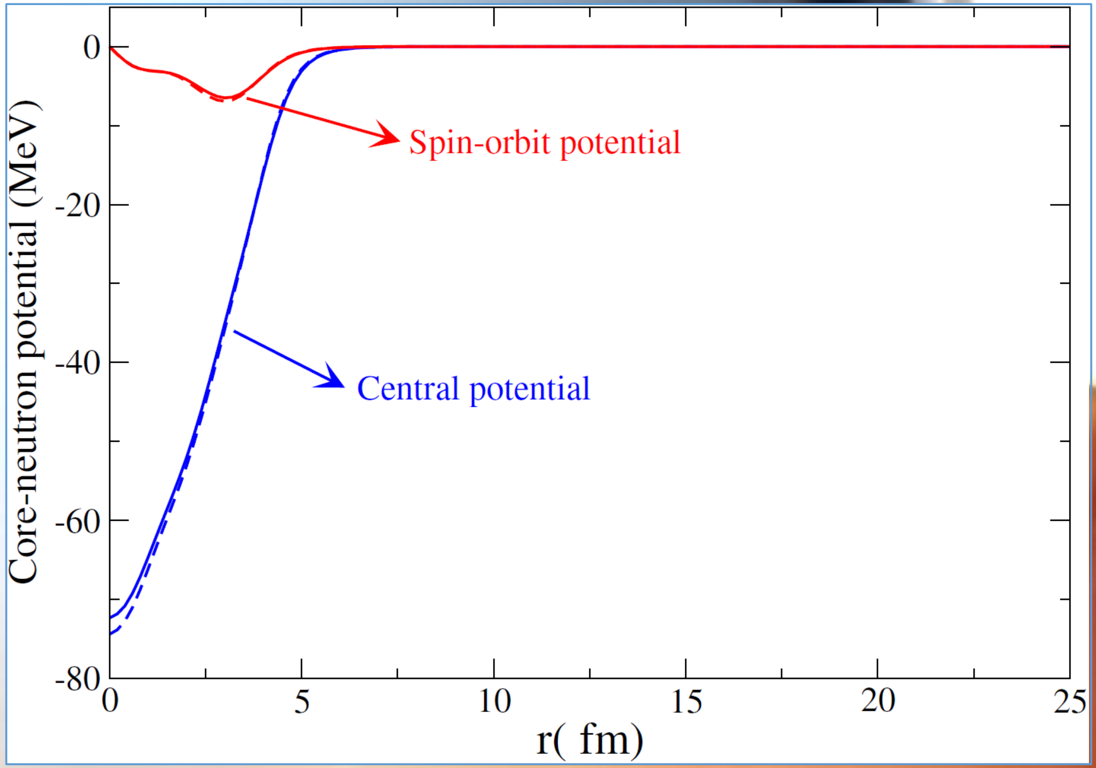
Experimental information about ^{26}O is available

The case of ^{26}O:



Valence neutrons

16 neutron states occupied by the neutrons in the ^{24}O core.



Adiabatic Expansion Method

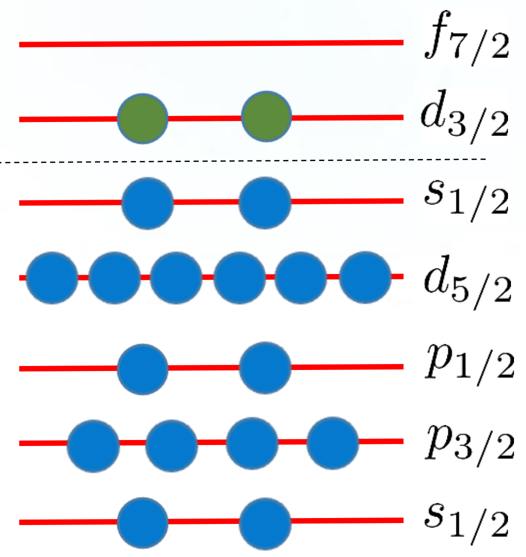
$$\psi_3(\vec{r}_{v_1},\vec{r}_{v_2}) = \frac{1}{\rho^{5/2}} \sum_n f_n(\rho)\Phi_n(\rho,\Omega)$$

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial\rho^2} + V_{eff}(\rho) - E_3\right] f_n - \frac{\hbar^2}{2m}\sum_m \left(2P_{nm}(\rho)\frac{\partial}{\partial\rho} + Q_{nm}(\rho)\right) f_m = 0$$

	SLy4	SkM*	Sk3
$E_{d_{3/2}}$	0.85	0.83	1.23
$E_{d_{3/2}}$(HF)	-0.96	-1.15	-0.53

s, p, d, and f waves are included in the calculation

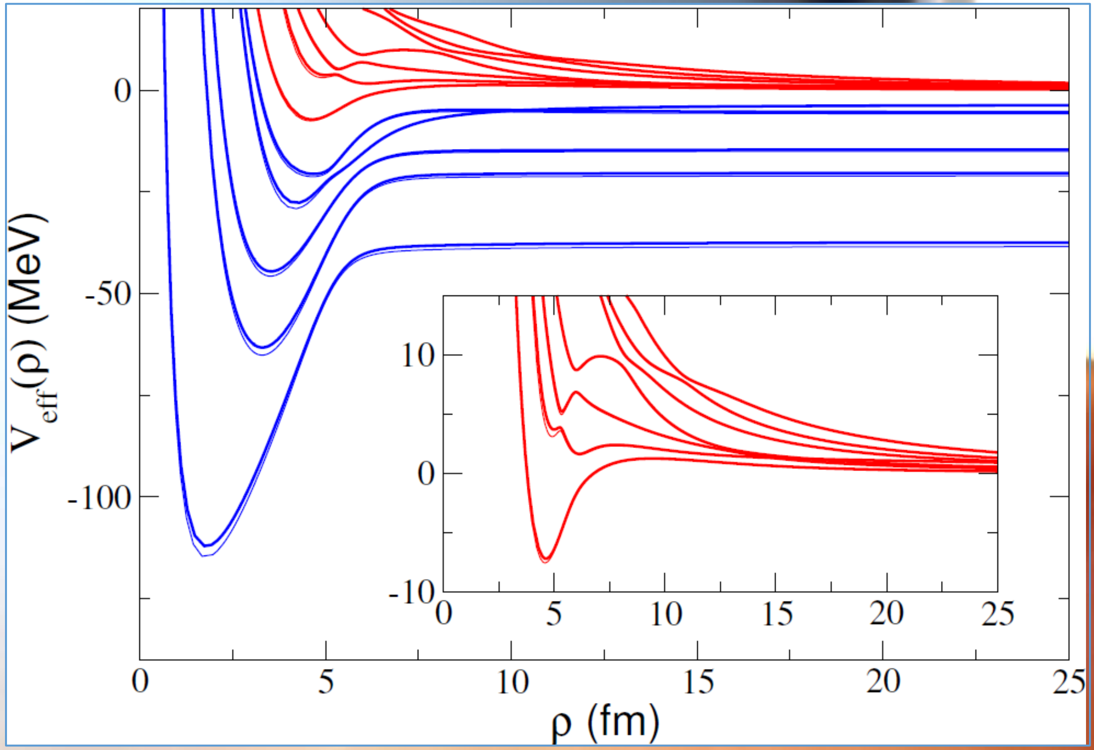
The case of ^{26}O:



Valence neutrons

16 neutron states occupied by the neutrons in the ^{24}O core.

Pauli forbidden to the valence neutrons !!!



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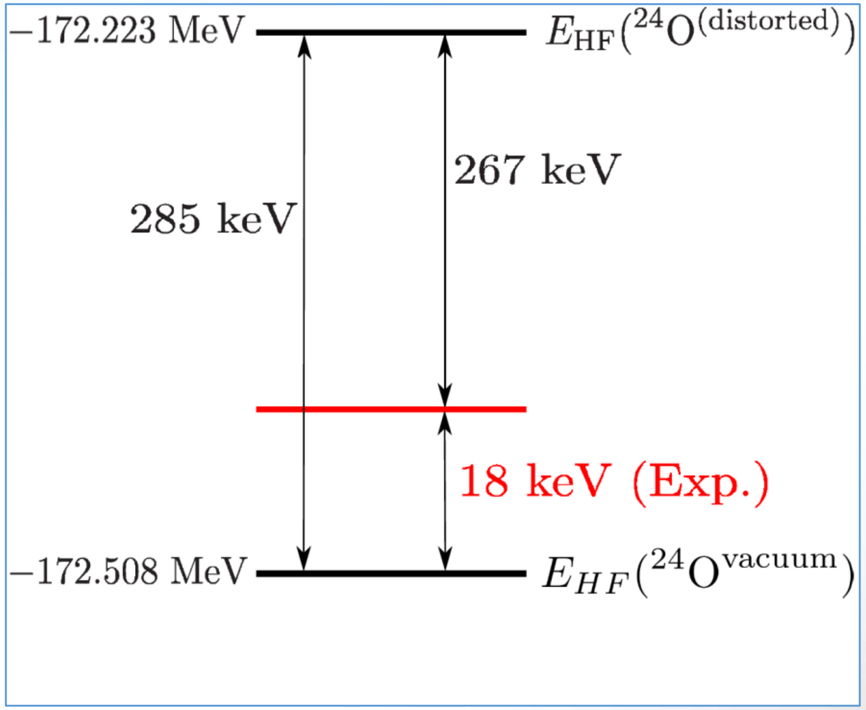
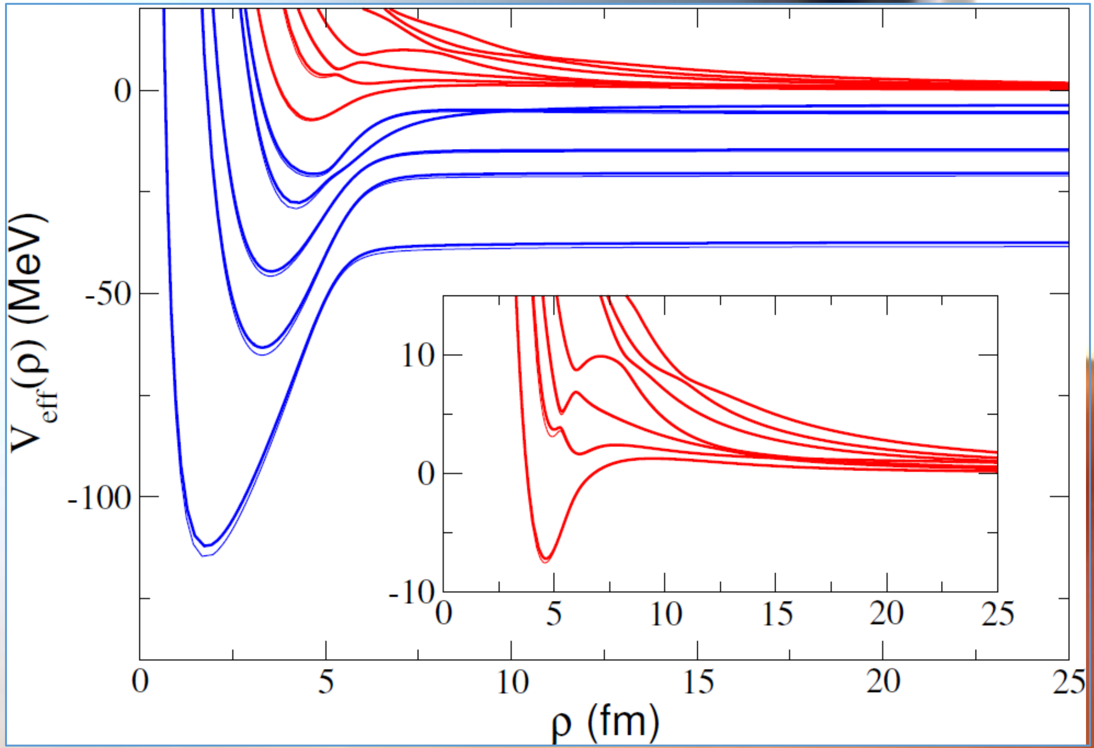
The adiabatic channels associated to Pauli forbidden states are removed from the calculation

s, p, d, and f waves are included in the calculation

The case of ^{26}O:





$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial\rho^2} + V_{eff}(\rho) + V_{3b}(\rho) - E_3\right] f_n$$
$$-\frac{\hbar^2}{2m}\sum_m \left(2P_{nm}(\rho)\frac{\partial}{\partial\rho} + Q_{nm}(\rho) + \right) f_m = 0$$

The adiabatic channels associated to Pauli forbidden states are removed from the calculation

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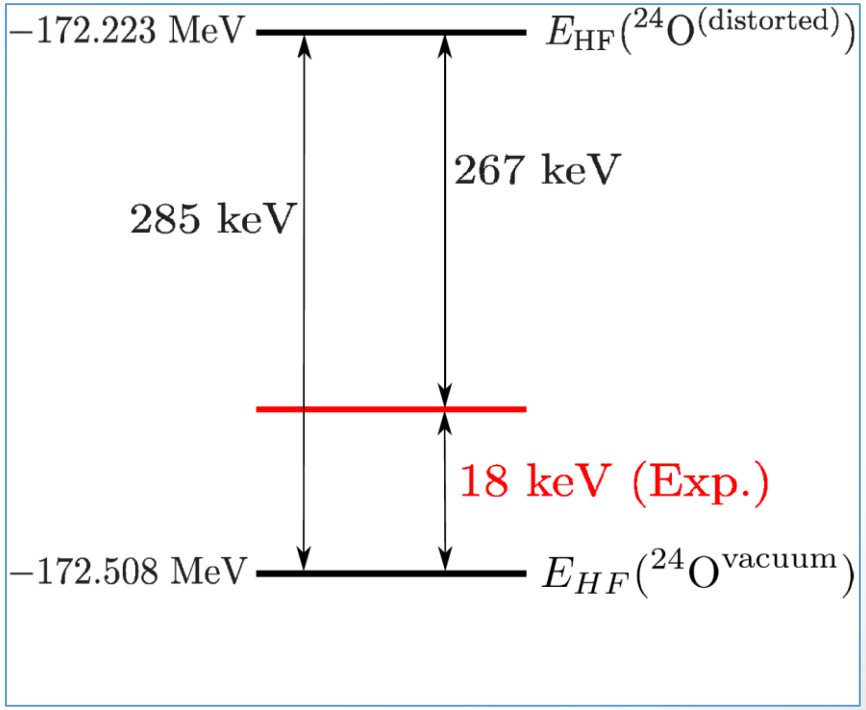
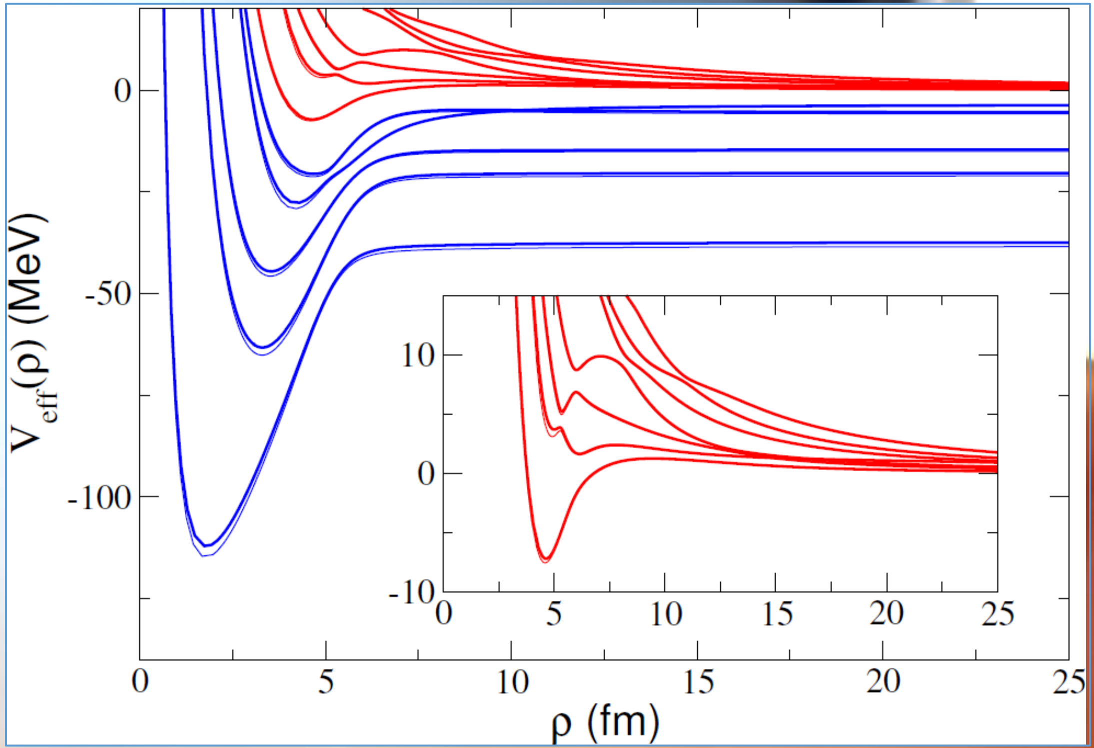
The case of ^{26}O:





	$(d_{3/2},d_{3/2})$	$(f_{7/2},f_{7/2})$	$(p_{3/2},p_{3/2})$
% of the norm	90.1	3.7	2.1

$$1 = \sum_{\ell_x} \int_0^{\infty} \left(|f_{\ell_x=0}(\rho)|^2 + |f_{\ell_x=1}(\rho)|^2 + |f_{\ell_x=2}(\rho)|^2 + \cdots \right)$$

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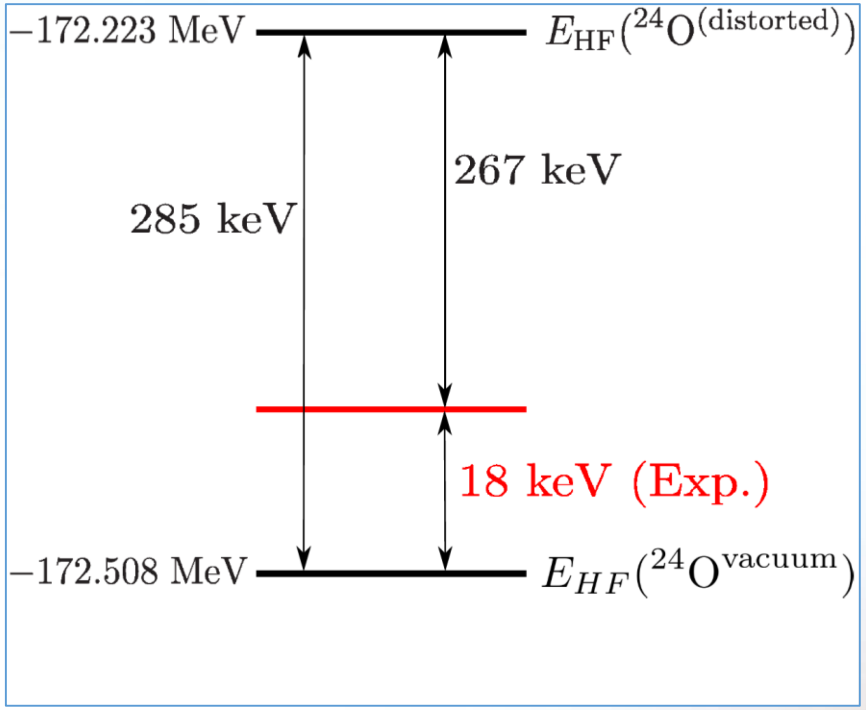

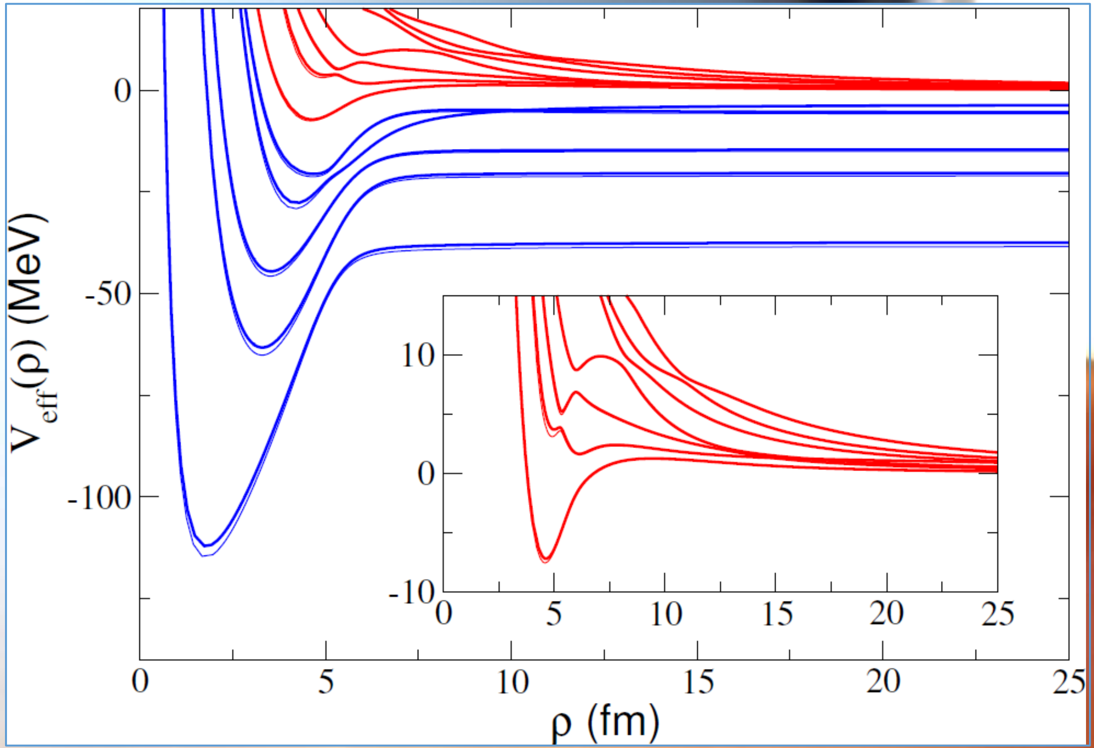

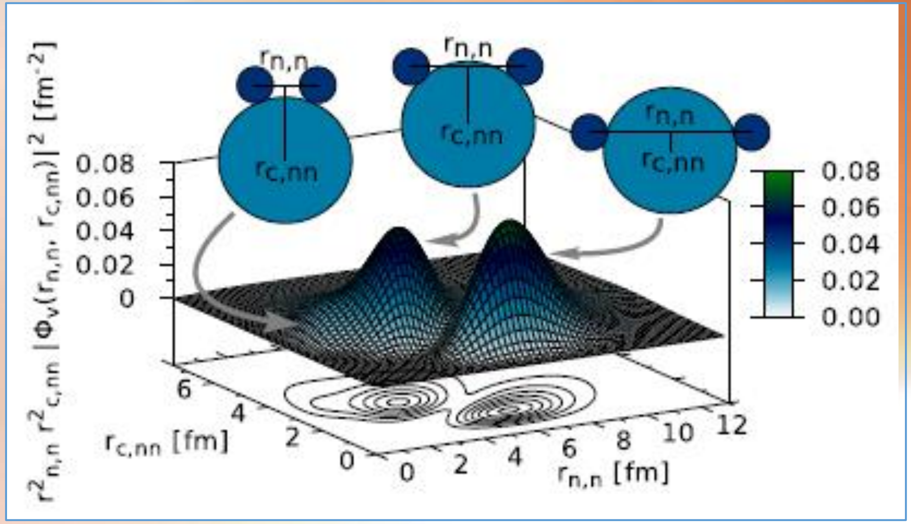

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% of the norm	90.1	3.7	2.1

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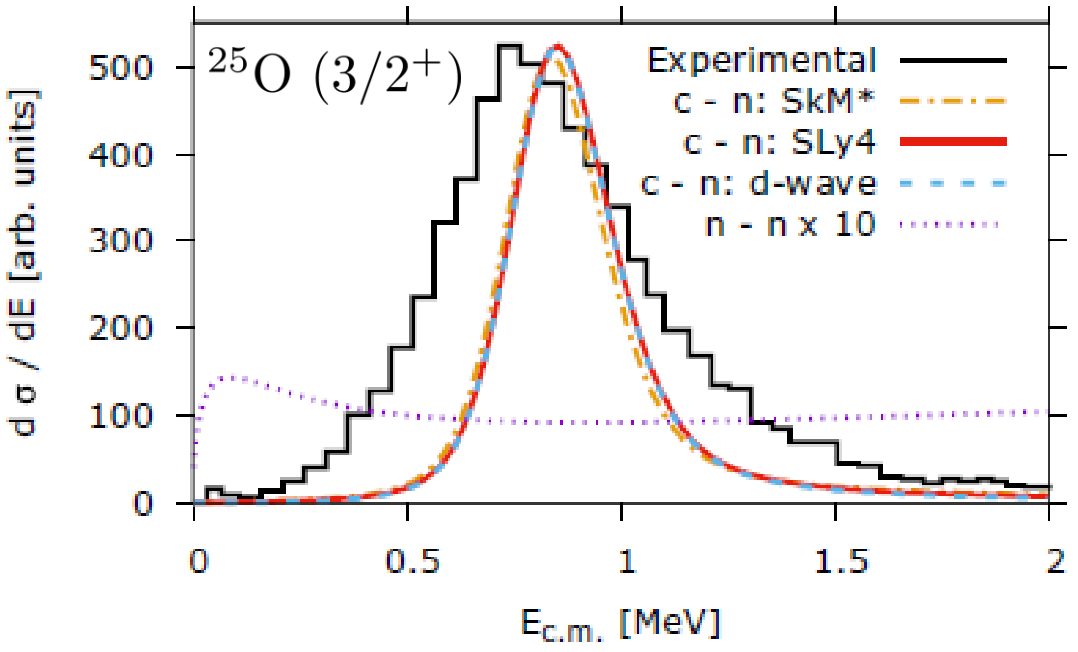
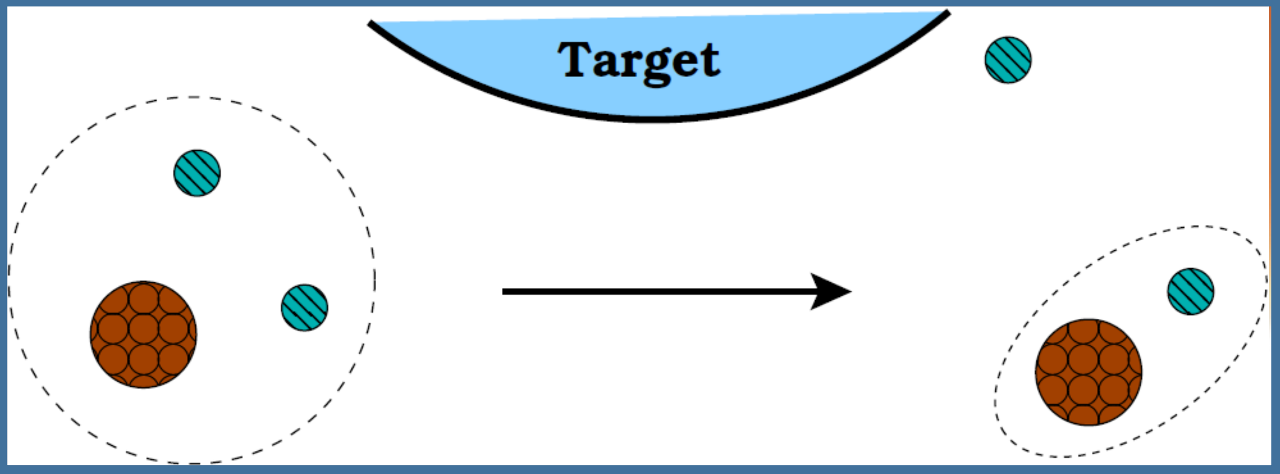


FIG. 4. The invariant mass spectra of core neutron for the SkM* (dash-dotted, orange) and SLy4 (solid, red) Skyrme parameters. The SLy4 core-neutron *d*-wave contribution (dashed, blue) and neutron-neutron (dotted, purple) invariant mass spectrum is also included. The black step curve is the measurements from Ref. [26].

Sudden approximation

$$\frac{d^6\sigma}{d\boldsymbol{k}_x\boldsymbol{k}_y} \propto \sum_M \sum_{s_x\sigma_x\sigma_y} \left|\langle e^{i\boldsymbol{k}_x\cdot\boldsymbol{k}_y}\chi_{s_y}^{\sigma_y} w_{s_x}^{\sigma_x}(\boldsymbol{k}_x, x)|\Psi^{JM}(\boldsymbol{x},\boldsymbol{y})\rangle\right|^2$$

$$\frac{d\sigma}{dE_{nc}} = \frac{E_cE_n}{E_c+E_n}\frac{m(M_c+M_n)}{M_cM_n}\frac{1}{k_x}\frac{d\sigma}{dk_x}$$



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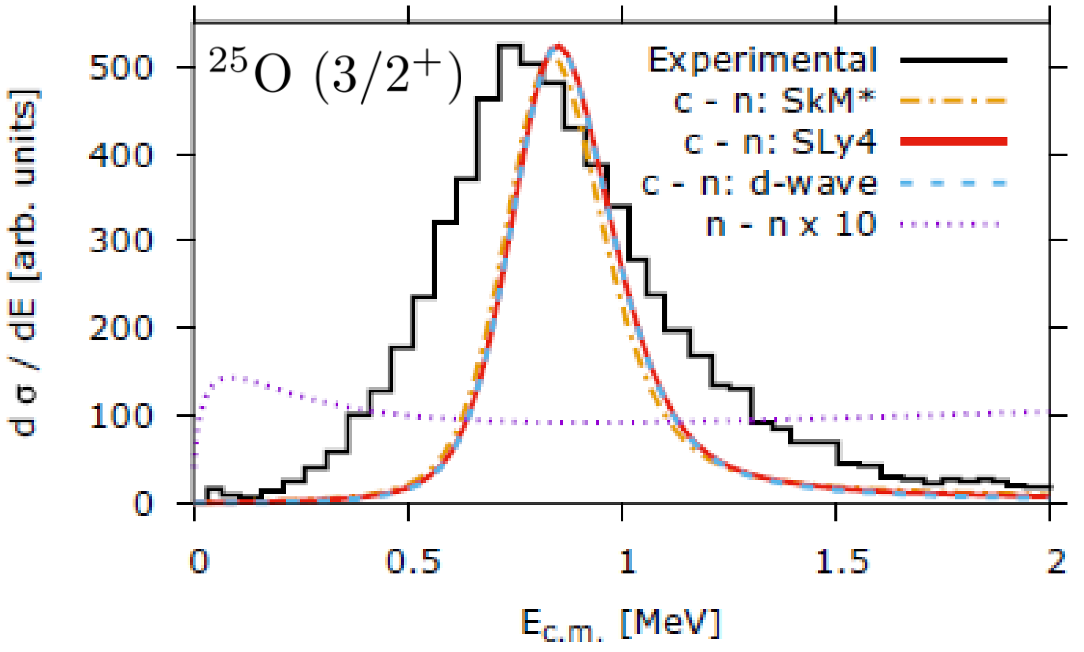

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$$\frac{d^6\sigma}{d\boldsymbol{k}_x \boldsymbol{k}_y} \propto \sum_M \sum_{s_x \sigma_x \sigma_y} \left| \langle e^{i\boldsymbol{k}_x \cdot \boldsymbol{k}_y} \chi_{s_y}^{\sigma_y} w_{s_x}^{\sigma_x}(\boldsymbol{k}_x, x) | \Psi^{JM}(\boldsymbol{x}, \boldsymbol{y}) \rangle \right|^2$$

$$\frac{d\sigma}{dE_{nc}} = \frac{E_c E_n}{E_c + E_n} \frac{m(M_c + M_n)}{M_c M_n} \frac{1}{k_x} \frac{d\sigma}{dk_x}$$

Once the NN interaction has been chosen, the invariant mass spectrum is fully determined.

Two-proton capture: ^{70}Kr

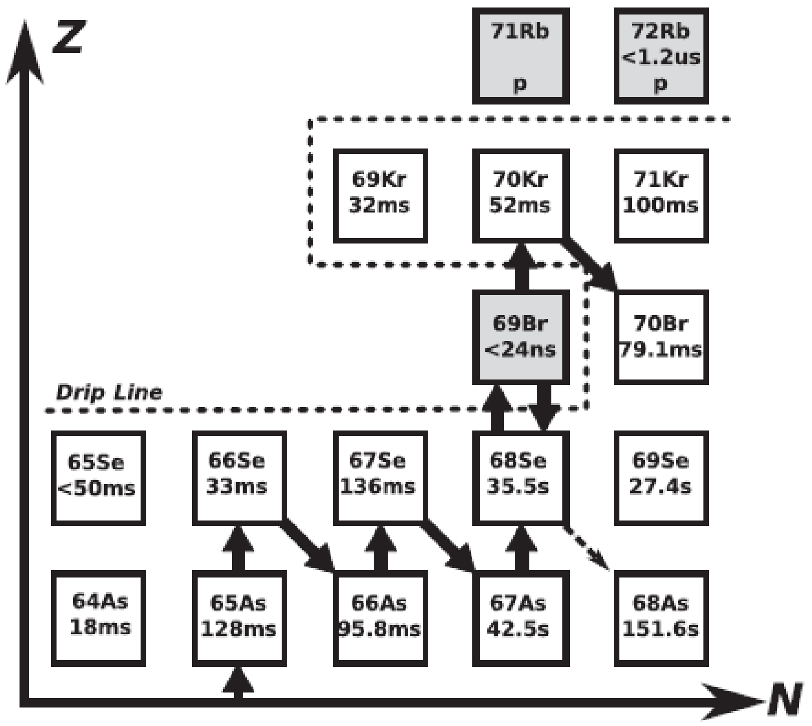
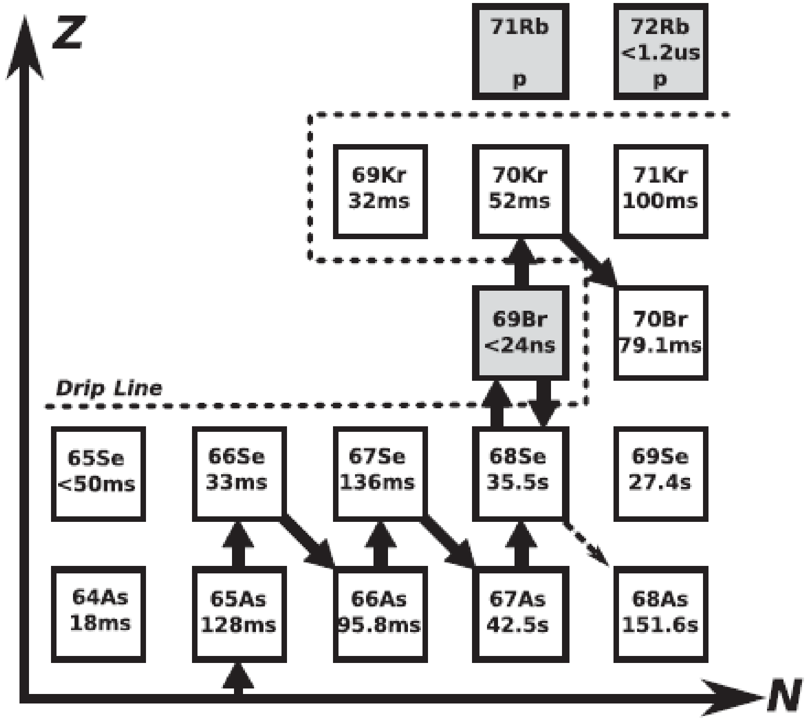


FIG. 1. Illustration of 2p-capture reactions through ^{69}Br bypassing the ^{68}Se waiting point. The slow β decay of ^{68}Se restricts the rp-process reaction flow in type I x-ray bursts.

A.M. Rogers et al., PRL 106, 252503 (2011)

$$^{68}\mathrm{Se} + p + p \rightarrow {}^{70}\mathrm{Kr} + \gamma$$

Two-proton capture: ^{70}Kr



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A.M. Rogers et al., PRL 106, 252503 (2011)

$$^{68}\mathrm{Se} + p + p \to {}^{70}\mathrm{Kr} + \gamma$$

$$R_{ppc}(E) = \frac{8\pi}{(\mu_{cp}\mu_{cp,p})^{3/2}} \frac{\hbar^3}{c^2} \left(\frac{E_\gamma}{E}\right)^2 \sigma_\gamma^\lambda(E_\gamma)$$

$$\sigma_\gamma^\lambda(E_\gamma) = \frac{(2\pi)^3(\lambda+1)}{\lambda((2\lambda+1)!!)^2} \left(\frac{E_\gamma}{\hbar c}\right)^{2\lambda-1} \frac{d}{dE}\mathcal{B}(E\lambda, 0^+ \to \lambda^\pi)$$

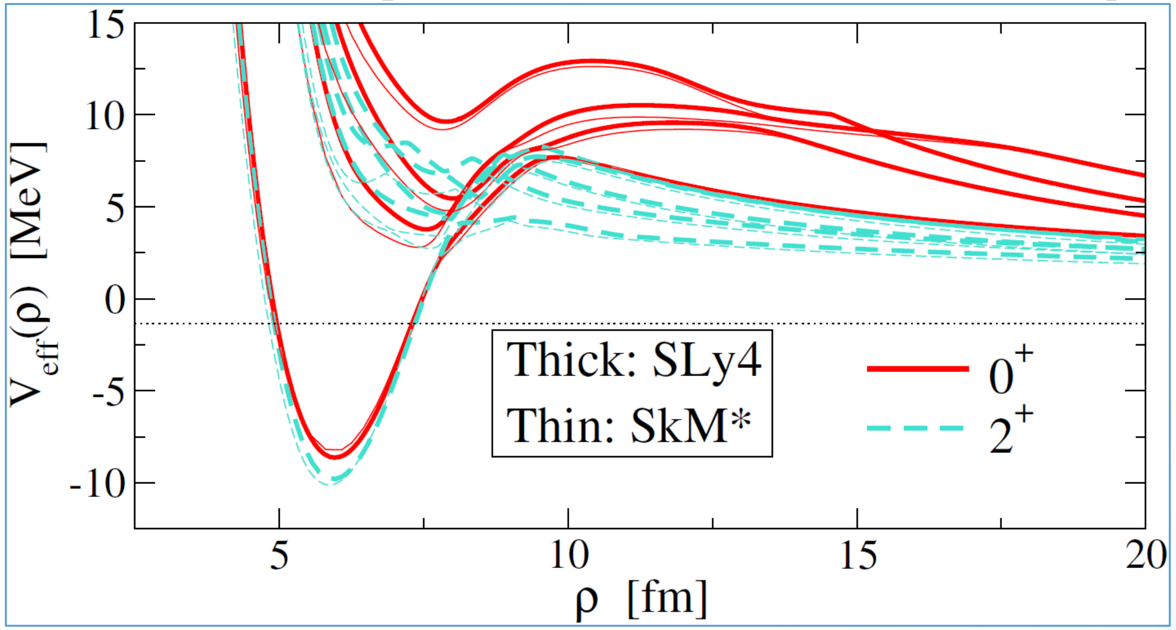
$$E_\gamma = E + |E_{g.s}|$$

$$\frac{d}{dE}\mathcal{B}(E\lambda, 0^+ \to \lambda^\pi) = \sum_i \left|\langle \psi_{\lambda^\pi}^{(i)} \parallel \hat{\mathcal{O}}_\lambda \parallel \Psi_{0^+}\rangle\right|^2 \delta(E - E_i)$$

$$\langle R_{ppc}(E)\rangle = \frac{1}{2(KT)^3} \int E^2 R_{ppc}(E) e^{-E/KT} dE$$

✓ Dominated by the E2 transition $2^+ \to 0^+$

Two-proton capture: ^{70}Kr



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$$E_\gamma = E + |E_{g.s}|$$

$$\frac{d}{dE}\mathcal{B}(E\lambda, 0^+ \rightarrow \lambda^\pi) = \sum_i \left| \langle \psi_{\lambda^\pi}^{(i)} \parallel \hat{\mathcal{O}}_\lambda \parallel \Psi_{0^+} \rangle \right|^2 \delta(E - E_i)$$

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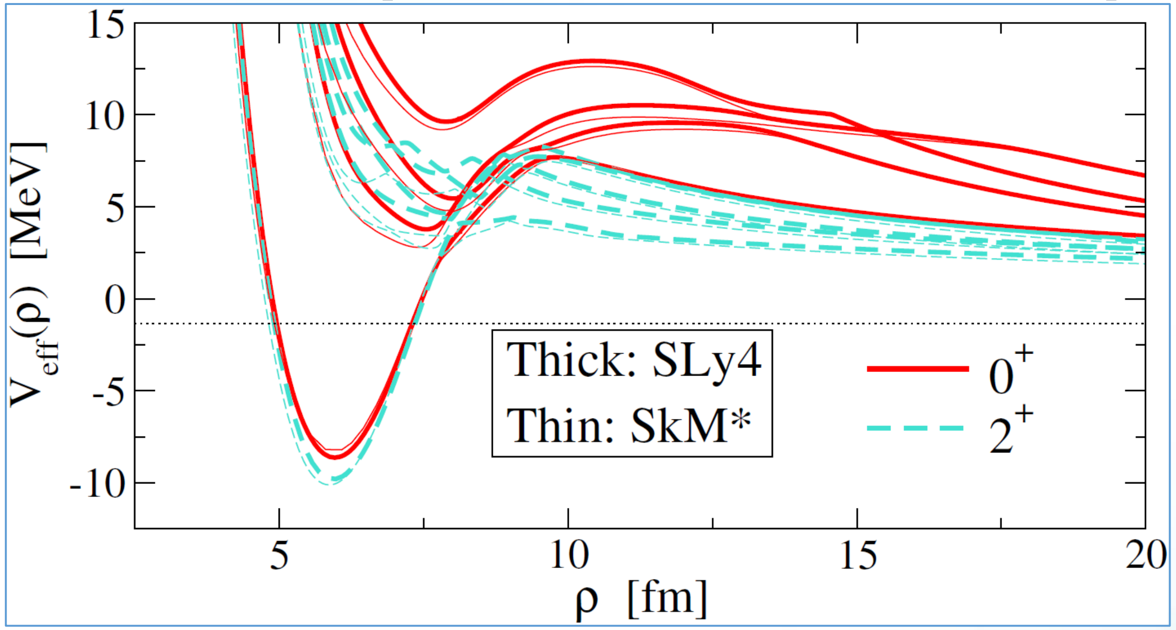
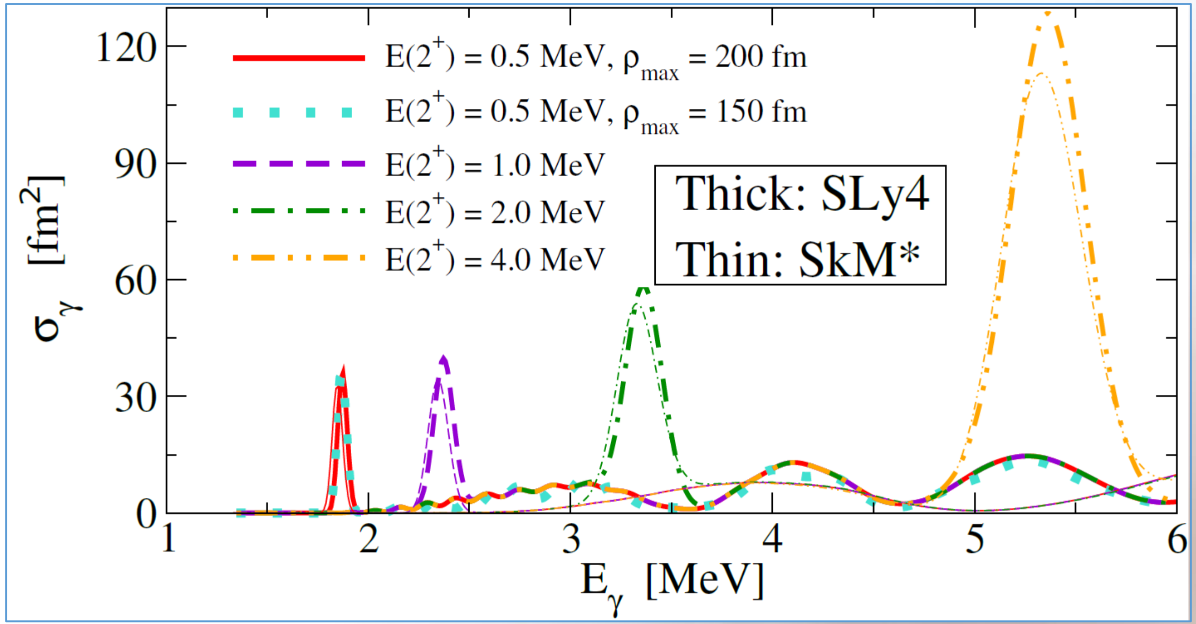
✓ Dominated by the E2 transition $2^+ \rightarrow 0^+$

Two-proton capture: ^{70}Kr





$$^{68}\mathrm{Se} + p + p \to {}^{70}\mathrm{Kr} + \gamma$$

$$R_{ppc}(E) = \frac{8\pi}{(\mu_{cp}\mu_{cp,p})^{3/2}} \frac{\hbar^3}{c^2} \left(\frac{E_\gamma}{E}\right)^2 \sigma_\gamma^\lambda(E_\gamma)$$

$$\sigma_\gamma^\lambda(E_\gamma) = \frac{(2\pi)^3(\lambda+1)}{\lambda((2\lambda+1)!!)^2} \left(\frac{E_\gamma}{\hbar c}\right)^{2\lambda-1} \frac{d}{dE}\mathcal{B}(E\lambda, 0^+ \to \lambda^\pi)$$

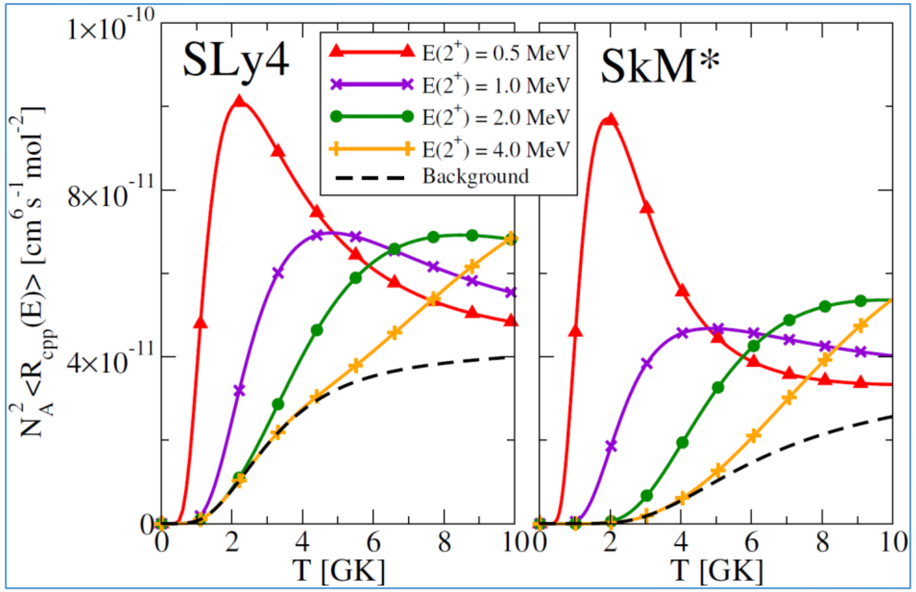
$$E_\gamma = E + |E_{g.s}|$$

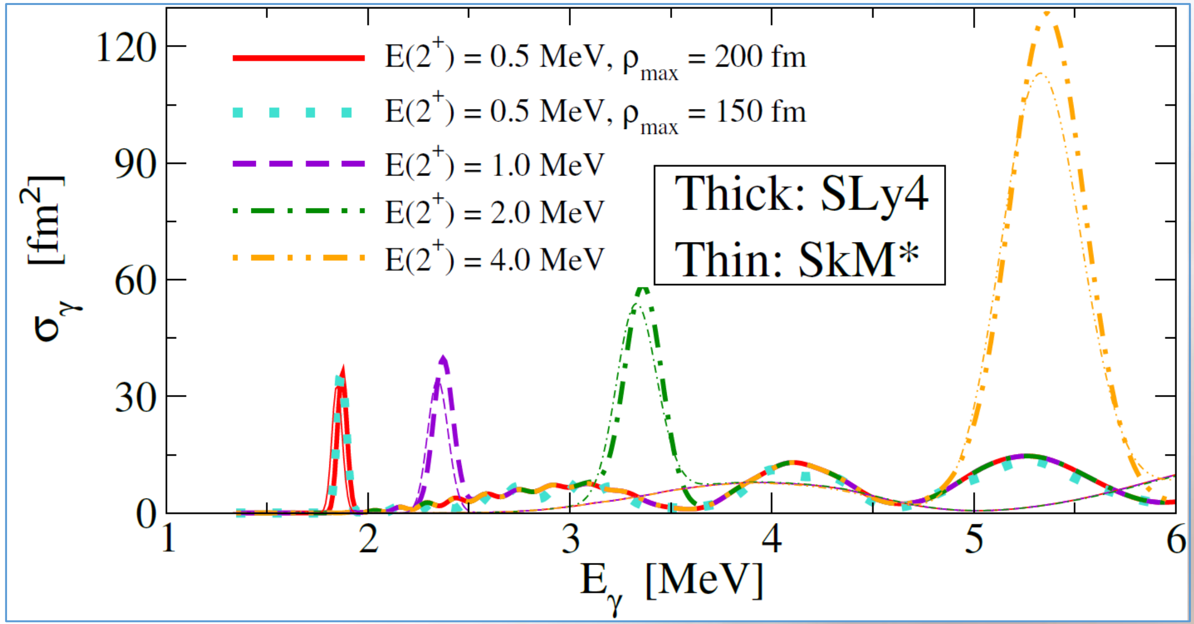
$$\frac{d}{dE}\mathcal{B}(E\lambda, 0^+ \to \lambda^\pi) = \sum_i \left|\langle \psi_{\lambda^\pi}^{(i)} \parallel \hat{\mathcal{O}}_\lambda \parallel \Psi_{0^+}\rangle\right|^2 \delta(E - E_i)$$

$$\langle R_{ppc}(E)\rangle = \frac{1}{2(KT)^3} \int E^2 R_{ppc}(E) e^{-E/KT} dE$$

✓ Dominated by the E2 transition $2^+ \to 0^+$

Two-proton capture: ^{70}Kr





$$^{68}\mathrm{Se} + p + p \rightarrow {}^{70}\mathrm{Kr} + \gamma$$

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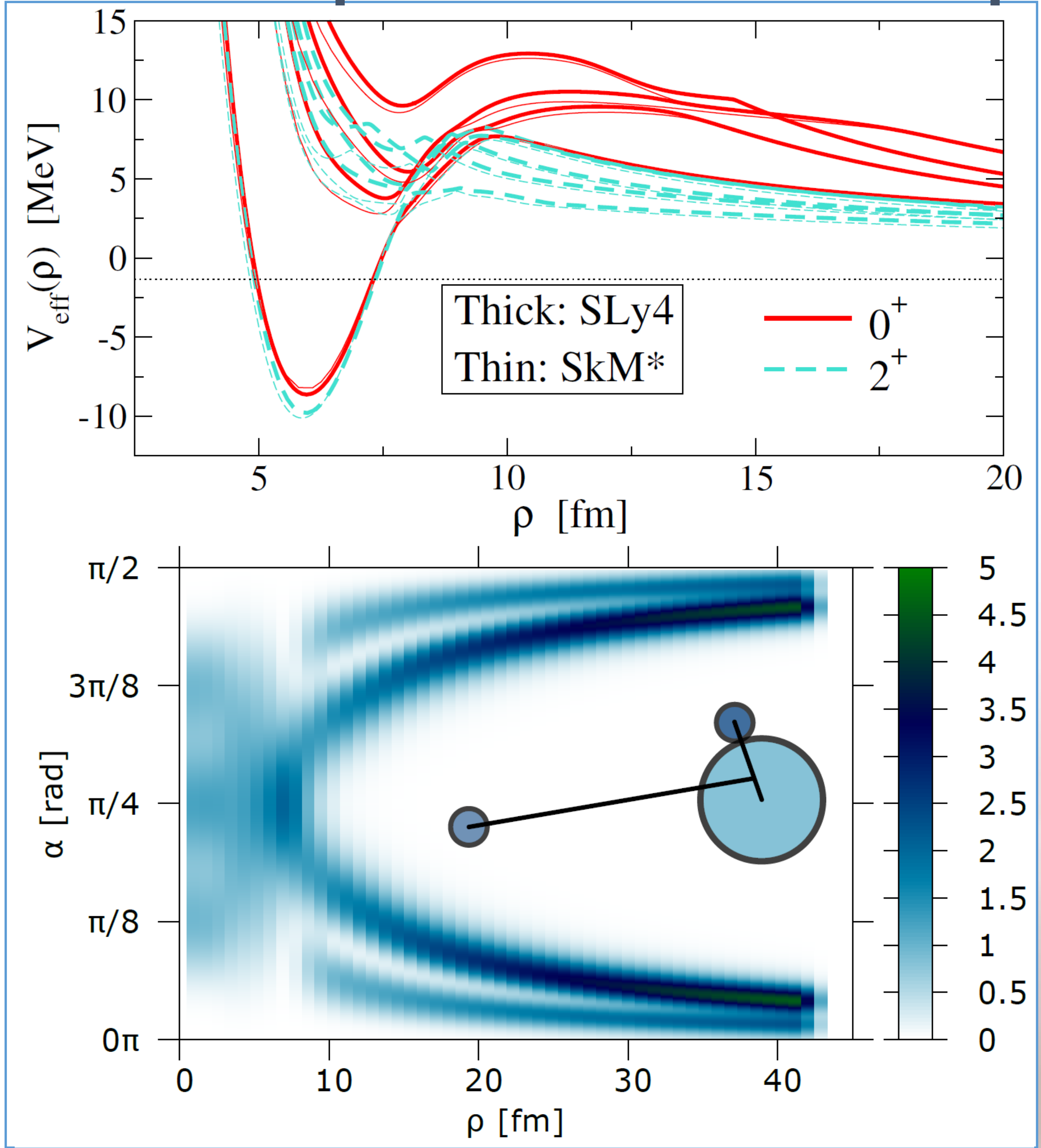
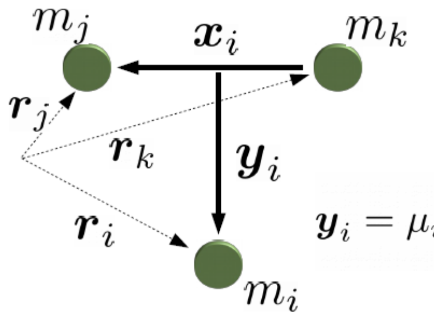
Two-proton capture: ^{70}Kr



Capture mechanism

$$P(\alpha,\rho) = \sin^2\alpha\cos^2\alpha \int |\Phi(\rho,\alpha,\Omega_x,\Omega_y)|^2 d\Omega_x d\Omega_y$$



$$\boldsymbol{x}_i = \mu_{jk}(\boldsymbol{r}_j - \boldsymbol{r}_k)$$

$$\boldsymbol{y}_i = \mu_{i,jk}\left(\boldsymbol{r}_i - \frac{m_j\boldsymbol{r}_j + m_k\boldsymbol{r}_k}{m_j + m_k}\right)$$

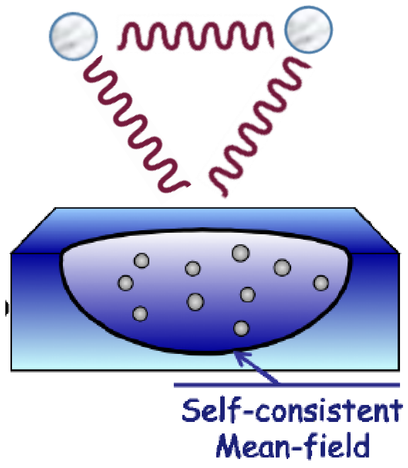
$$x_i = \rho\sin\alpha_i$$
$$y_i = \rho\cos\alpha_i$$

- ✓ Sequential capture through the $f_{5/2}$ resonance in ^{69}Br at 0.6 MeV.

D. Hove et al., PLB 782, 42 (2018)

Summary:

The model presented here treats the many-body core and the two valence particles self-consistently:



- ✓ The mean-field determines the interaction with the loosely bound nucleons.

Three-body problem

- ✓ The presence of the loosely bound nucleons distorts the mean-field.
- ✓ The distorted mean-field modifies the core-nucleon interaction and the wave function of the valence nucleons.

Self-consistent calculation

Core: Spherical Skyrme Hartree-Fock

- ✓ Core deformation?
- ✓ Finite range NN interactions?
- ✓ odd-odd nuclei?

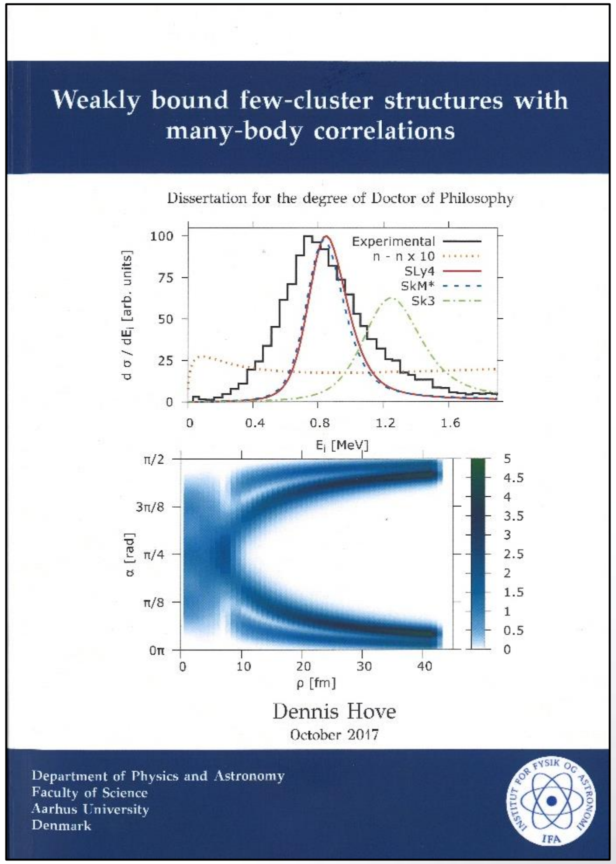
Three-body calculation: Adiabatic expansion

- ✓ Three-body force from the mean field?

- ✓ Generalization to more than one cluster and more than two valence nucleons

Weakly bound nuclei:

A unified description of intrinsic and relative degrees of freedom


Weakly bound few-cluster structures with many-body correlations

Dissertation for the degree of Doctor of Philosophy

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