

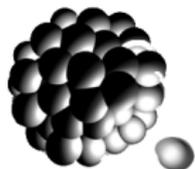
# Long-range versus short range correlations in two neutron transfer reactions

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A better understanding of the nuclear structure and reactions will help to improve the model calculation of nuclear reactions.

The knowledge of the internal degrees of freedom is crucial to understand nuclear structure features like:

- Collectivity states
- Single particle states
- Pairing properties
- Clustering
- ...

**by means of:**

- Pick up reactions
- Stripping reactions
- Single and Two nucleon transfer reactions
- ...

Two nucleons transfer can be used as a test of pairing correlations in nuclei.

Therefore one has to identify:

- If the two-neutron transfer occurs in one step (**direct**), under strong influence of pairing correlations or in two steps (**sequentially**).
- If the ground state of the residual nucleus is feed from the ground state of the target

In previous works has been noticed that direct two neutron transfer are important like in  $^{12}\text{C}(^{18}\text{O}, ^{16}\text{O})^{14}\text{C}$   
F. Cappuzzello et al, Nature Communications 6, 6743 (2015)



Therefore we want study the collectivity properties of the nuclei

# The two neutron transfer $^{64}\text{Ni}$ ( $^{18}\text{O}, ^{16}\text{O}$ ) $^{66}\text{Ni}$

So, how we can do that?



- The experimentalists performed the two-neutron transfer of  $^{18}\text{O} + ^{64}\text{Ni}$  at 84 MeV incident energy, to the ground and first excited state of the residual  $^{66}\text{Ni}$  nucleus.
- Therefore to study this reaction we require compute the **spectroscopic factors** and **cross sections** for two neutron transfer.



- All the experimental data were measured by the large acceptance MAGNEX spectrometer at the INFN- Laboratori Nazionali del Sud (Italy)

- The coupled channel Born approximation (CCBA) has been used for the the **sequential** two neutron transfer..
- The Coupled reaction channel (CRC) has been used for **direct** two neutron transfer.
- The FRESCO code (program for direct reactions) has been selected to perform the cross sections calculations.
- The Sao Paolo double folding potential has been used.
- The Wood Saxon potential has been used to generate the single particle energies.

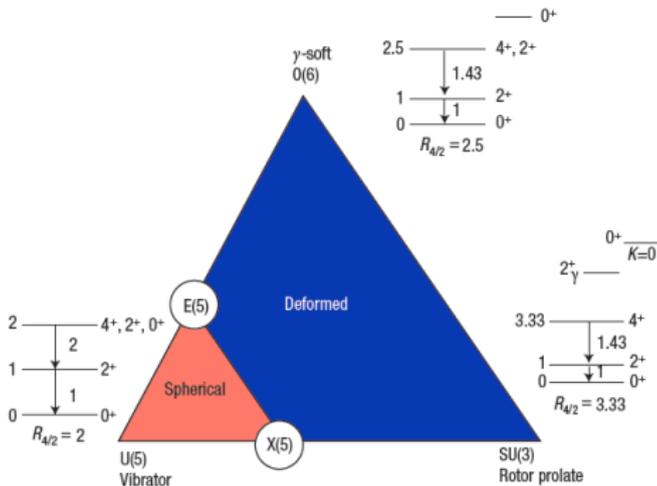


# What about the nuclear wave functions?

It has been chosen the Interacting Boson Model 2 (IBM). In this model pairs of valence nucleons are described in terms of bosons. The model is constructed in terms of the Casimirs operators with three dynamical symmetries.

- $U(5)$  for vibrational symmetry
- $SU(3)$  for rotational symmetry
- $O(6)$   $\gamma$  -unstable nuclei

R. F. Casten. Nature Physics 2, 811 - 820 (2006)



# Interacting Boson Model (IBM)



The even-even nuclei can be described by IBM. The building blocks are bosons with angular momentum  $L = 0$  and  $L = 2$  (bosons s and d)

## Creation and annihilation operators for bosons

$$b_i^\dagger, b_i \quad i = l, m \quad (l = 0, 2 \quad -l \leq m \leq l)$$

$$[b_i, b_j^\dagger] = \delta_{ij}, \quad [b_i^\dagger, b_j^\dagger] = [b_i, b_j] = 0$$

## Generators of $U(6)$

$$G_i^j = b_i^\dagger b_j \quad i, j = 1, \dots, 6$$

there are 36 bilinear products

$$[G_i^j, G_l^k] = G_i^j \delta_{j,k} - G_l^k \delta_{i,l}$$

where  $i, j, k, l = 1, \dots, 6$

A. Arima y F. Iachello Phys. Rev. Lett. 35 1069 (1975)

# Dynamical Symmetries

In IBM the Hamiltonian is written in terms of the elements of the algebra  $A$

$$H = f(G_k), \quad G_k \in A$$
$$H_B = E_0 + \sum_{\alpha\beta} \varepsilon_{\alpha\beta} G^B + \frac{1}{2} \sum_{\alpha\beta\gamma\delta} G_{\alpha\beta}^B G_{\gamma\delta}^B + \dots$$

if we build the Hamiltonian in terms of invariant Casimir operators

$$[C_k, G_k^k] = 0$$

from a chain of the 'algebra  $A \subset A' \subset A'' \subset \dots$

$$H = f(C_k)$$

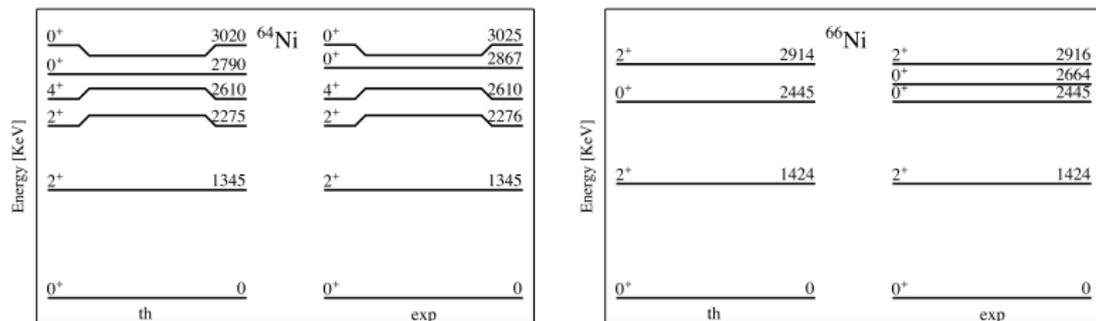
(called Dynamical Symmetries) F. Iachello and A. Arima, The interacting boson model, Cambridge University Press (1987).

# The even-even nuclei $^{64}\text{Ni}$ and $^{66}\text{Ni}$

For the  $^{64}\text{Ni}$  and  $^{66}\text{Ni}$  it is required consider the basic features of the effective nucleon-nucleon interaction, that emerge from pairing, quadrupole and symmetry energy. (IBM2)

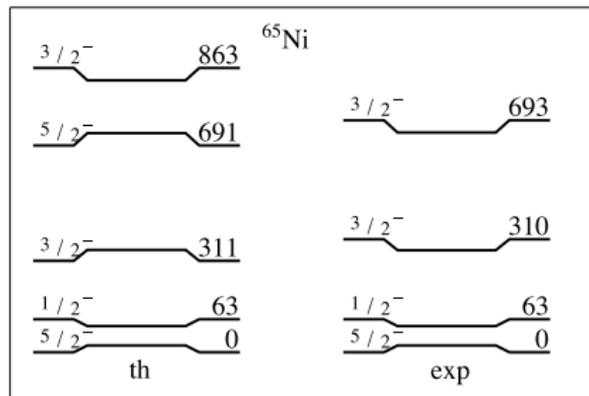
$$H_B = E_0 + \epsilon_\pi \hat{n}_{d_\pi} + \epsilon_\nu \hat{n}_{d_\nu} + \kappa \hat{Q}_\pi^X \cdot \hat{Q}_\nu^X + \lambda' \hat{M}_{\pi\nu} + V_{\pi\pi} + V_{\nu\nu}$$

We have calculated the theoretical spectrum of the  $^{64,66}\text{Ni}$  nuclei coming from IBM2 and it is in accordance with the experimental data.



We will use the eigenstates to calculate the matrix elements of the two nucleon transfer operator.

# The odd-even $^{65}\text{Ni}$ nucleus



We have calculated the theoretical spectrum of the fthe  $^{65}\text{Ni}$  nucleus using the interacting boson fermion model (IBFM)  $H_B + H_{BF} + H_F$

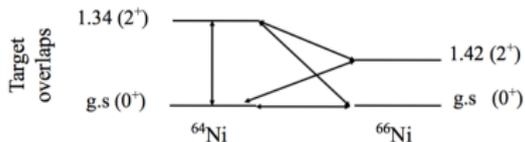
$$\begin{aligned}
 H_F &= E_0 + \sum_{j\pi} \epsilon_{j\pi} \hat{n}_{j\pi} + \sum_{j\nu} \epsilon_{j\nu} \hat{n}_{j\nu} \\
 V_{BF} &= \sum_{j\pi} A_{j\pi} (\hat{n}_{d\pi} \hat{n}_{j\pi}) + \sum_{j\nu} A_{j\nu} (\hat{n}_{d\nu} \hat{n}_{j\nu}) \\
 &\quad + \Gamma_{\pi\nu} \hat{Q}_\nu^X \cdot \hat{q}_\pi + \Gamma_{\nu\pi} \hat{Q}_\pi^X \cdot \hat{q}_\nu + \Gamma_{\nu\nu} \hat{Q}_\nu^X \cdot \hat{q}_\nu + \Gamma_{\pi\pi} \hat{Q}_\pi^X \cdot \hat{q}_\pi \\
 &\quad + \Lambda_{\nu\pi} F_{\pi\nu} + \Lambda_{\pi\nu} F_{\nu\pi}
 \end{aligned}$$

F. Iachello and P. V. Isacker, *The interacting Boson-Fermion Model* Cambridge University Press (1991).

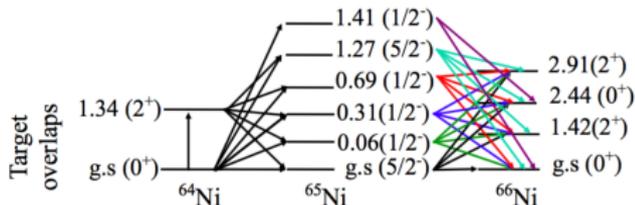
# Coupling scheme

In order to proceed with the calculation, we propose a coupling scheme:

For the **direct two-neutron** transfer reaction (or one step mechanism) we use microscopic IBM-2



For **sequential transfer** (or two-step mechanism) we use IBFM



But is needed a transfer operator!

# Transfer operator - Direct Operator

The calculation of the spectroscopic amplitudes for the two nucleon transfer reactions in the scheme of IBM2 requires the two body matrix elements in the scheme the Generalized Seniority Scheme

P. O. Lipas, M. Koskinen, H. Harter, R. Nojarov, and A. Faessler, Nucl. Phys. A508, 509 (1990).

$$S_+ = \sum_j \alpha_j S_+(j)$$
$$D_+ = \sum_{j \leq j'} \beta_{j,j'} D_+(j)$$

with

$$S_+(j) = \sqrt{\frac{\Omega_j}{2}} [c_j^\dagger \times c_j^\dagger]^0$$
$$D_+(j, j') = \sqrt{\frac{1}{1 + \delta_{jj'}}} [c_j^\dagger \times c_{j'}^\dagger]^2$$

where  $\alpha_i$  and  $\beta_{ij}$  are structure constants that depends on the shell selected,  $S_+$  and  $D_+$  create the energetically the lowest  $0_+$  and  $2_+$  paired fermion states.

# Transfer operator - Direct operator

Taking into account the Otsuka- Arima -Iachello (OAI) expansion to the next to leading order (NLO)

$$\begin{aligned}(c_j^\dagger \times c_{j'}^\dagger)^{(0)} &\rightarrow A_\rho(j) s_\rho^\dagger \\(c_j^\dagger \times c_{j'}^\dagger)_M^{(2)} &\rightarrow B_\rho(j, j')(d_\rho^\dagger)_M + C_\rho(j, j') s_\rho^\dagger (s^\dagger \tilde{d}_\rho)^{(2)} \\ &\quad + D_\rho(j, j') s_\rho^\dagger (d_\rho^\dagger \tilde{d}_\rho)^{(2)}\end{aligned}$$

Therefore we introduce the **two nucleon transfer** in **microscopic IBM-2** considering the structure of the shells given by the mapping coefficients.

$$\begin{aligned}T_{+\rho}^{(0)} &\rightarrow \sqrt{\frac{1}{2}} A_\rho(j) s_\rho^\dagger \\T_{+\rho}^{(2)} &\rightarrow \sqrt{\frac{1}{1+\delta_{j,j'}}} [B_\rho(j, j') d_\rho^\dagger \\ &\quad + C_\rho(j, j') s_\rho^\dagger (s^\dagger \tilde{d}_\rho)^{(2)} \\ &\quad + D_\rho(j, j') s_\rho^\dagger (d_\rho^\dagger \tilde{d}_\rho)^{(2)}]\end{aligned}$$

The advantage of this operator is that the effects of the pairing interaction are in terms of the occupation of different single-particle orbitals and the two body matrix elements take into account the non-degenerate orbits of the GS states.

P. D. Duval and B. R. Barrett, Phys. Rev. C 24, 1272(1981)

## Structure Constants

The mapping coefficients  $A_\rho, B_\rho, D_\rho, C_\rho$  with  $(\rho = \nu, \pi)$  depends on the structure coefficients  $\alpha_{\rho j}, \beta_{\rho j, j'}$  and can be estimated by diagonalizing a surface delta pairing interaction, which is given by

$$H_{jj'} = \epsilon_{0j} + \epsilon_{0j'} - V_{SDI},$$

$$V_{SDI} = \frac{1}{2} A_t (-1)^{n_a + n_b + n_c + n_d} \sqrt{\frac{(2j_a + 1)(2j_b + 1)(2j_c + 1)(2j_d + 1)}{(2J + 1)^2 (\delta(j_a j_b) + 1)(\delta(j_c j_d) + 1)}} \\ (1 - (-1)^{J + l_a + l_b + T}) (-1)^{j_b + j_d + l_b + l_d} \\ \langle j_b, -\frac{1}{2}, j_a, \frac{1}{2}, J, 0 \rangle \langle j_d, -\frac{1}{2}, j_c, \frac{1}{2}, J, 0 \rangle - ((-1)^T + 1) \\ \langle j_b, \frac{1}{2}, j_a, \frac{1}{2}, J, 1 \rangle \langle j_d, \frac{1}{2}, j_c, \frac{1}{2}, J, 1 \rangle,$$

Pittel Duval and Barret, Ann. Phys, 144, 168-199 (1982) F. Iachello, J. Barea, and J. Kotila AIP Conf. Proc. 1572, 69 (2013)

## Transfer operator - Sequential

The calculation of the spectroscopic amplitudes for single nucleon transfer reactions has been performed in the IBFM scheme.

The creation operators  $P_{j\rho}$  for a neutron and a proton are in the orbitals  $j_\nu$  and  $j_\pi$ , respectively.

$$P_{j\rho}^+ = \xi_{j\rho} a_{j\rho}^\dagger + \sum_{j'_\rho} \xi_{j\rho j'_\rho} [[s^\dagger \times \tilde{d}_{j\rho}]^{(2)} \times a_{j'_\rho}]^{(j\rho)}$$

where the  $a_{j\rho}^\dagger$  is the fermion creation operator,  $s^\dagger$  is the  $s$ -boson operator, and  $\tilde{d}$  is related to the  $d$ -boson annihilation operator by  $\tilde{d}_\mu = (-1)^\mu d_\mu$ . where  $u_j$  and  $v_j$  are the Bardeen-Cooper-Schrieffer (BCS) unoccupation and occupation amplitudes.

O. Scholten, PhD thesis, University of Groningen, The Netherlands, (1980).

# Preliminary Results for $^{64}\text{Ni}(^{18}\text{O},^{16}\text{O})^{66}\text{Ni}$

- For the transfer reaction to the ground state  $^{66}\text{Ni}$ , both two reaction mechanisms are important.
- For the transfer to the ground state of  $^{66}\text{Ni}$ , the pairing correlation seems to be relevant, specially at the bell shape maximum region.
- For the two-neutron transfer to the first excited state of the  $^{66}\text{Ni}$ , there is a dominance of the two step processes.

## Summary and Conclusions

- It is interesting to observe that for the same nucleus different states prefer different transfer mechanism.
- Therefore we conclude that for the two neutron transfer to the ground to the ground state of  $^{66}\text{Ni}$  the direct transfer is the dominant whereas for the transfer to the first excited state of  $^{66}\text{Ni}$  , the sequential process.

Thank you for your attention

