# Effects of pairing through the intermediary continuum in a 2n transfer process

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## Background

- **Direct transfer reactions:** convenient tools to study exotic nuclei because of *simple mechanisms* that probe internal structure of participating nuclei with sufficient accuracy.
- Two-neutron or $2n$ transfer reactions enable an understanding of halo phenomenon in two neutron halos.
- Also provide information about correlations between valence neutrons.
- $2n$ transfers involving $^{6}$**He** also vital nuclear astrophysics and stellar nucleosynthesis.

## Motivation

- For any $2n$ transfer process, couplings between energy states of intermediate nucleus strongly enhance transfer.
- Pairing enhancement could originate from ***coherent interferences*** of different paths through states in the $(A+1)$ intermediate nuclei.
- Taking $^{4}$He as our nucleus $A$ and adding two neutron to it via $^{18}$O($^{4}$He,$^{6}$He)$^{16}$O reaction, we try and study effect of pairing through the continuum of $^{5}$He.
- Ground state of intermediate $^{17}$O taken to be made up entirely of $1d_{5/2}$ at -4.14 MeV.
- Actual case of $^{5}$He being unbound (resonance at 0.79 MeV) compared with hypothetically bound cases with $S_n = 1$ MeV and $S_n = 0.1$ MeV to see the role of pairing in the continuum.
- Spectra of $^{5}$He generated and discretized using Transformed Harmonic Oscillator (THO) wave functions.

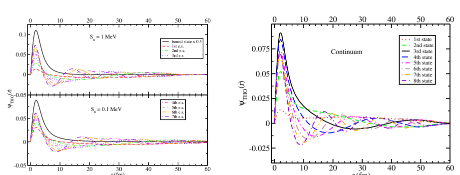
## Objective

- To study the effect of pairing enhancement due to the continuum of an intermediate nucleus in a $2n$ transfer.
- To investigate the effect of couplings between intermediate continuum states during such a process.
- To compare any such effects with the presence of a bound state in the intermediate system, if any.

## Transformed Harmonic Oscillator basis

Why THO?!

- Good substitution for continuum wave functions that oscillate asymptotically.
- Can *discretize the continuum*; easy to control the *density of pseudostates* near the threshold; convert the *Gaussian nature of harmonic oscillator functions to exponential* mode.
- **The transformation parameters**, $\gamma$ and $b$ were adjusted for the three cases to values 1.8, 2.0 and 2.0, and 1.0, 1.0 and 1.2, respectively.




- The THO wave functions generated for the spectra of $^{5}$He for the three cases under consideration.
- As expected, the wave functions in the cases when $^{5}$He is supposedly bound die out quicker than in the natural, unbound case.

J.-A. Lay, A. M. Moro, J. M. Arias, and J. Gómez-Camacho, Phys. Rev C **82**, 024605 (2010); G. Singh, Jagjit Singh, J. Casal, and L. Fortunato Phys Rev C **105**, 014328 (2022).

## The theory

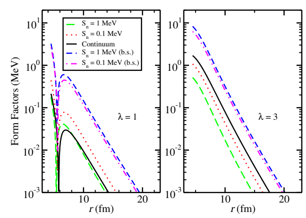
For an $A(a, a-2)A+2$ reaction, we have the probability amplitude for a pair transfer from an initial state $\alpha$ to a final state $\beta_2$ given at the lowest order by:

$$\mathcal{A}^{(2)}(b) = g\sum_{\beta} B_i(a)B_j(A) \times \int_{-\infty}^{\infty} dt' f_{\beta_2\beta}(r)\exp\left(\frac{i}{\hbar}[(Q_{\beta_2\beta}t' + \gamma_{\beta_2\beta}(t')) + i\mu\phi(t')]\right) \times \int_{-\infty}^{t'} dt f_{\beta\alpha}(r)\exp\left(\frac{i}{\hbar}[(Q_{\beta\alpha}t + \gamma_{\beta\alpha}(t)) - i\mu\phi(t)]\right),$$

where $\beta$'s are 1 particle transfer channels, $B_i(a)$ and $B_j(A)$ are 2 particle Spectroscopic amplitudes (in projectile and target states). $f_{\beta\alpha}(r)$ and $f_{\beta_2\beta}(r)$ are single particle transfer *form factors* for the first and second steps, $Q$'s are the $Q$-values, while $\gamma_{\beta\alpha}(t)$ and $\gamma_{\beta_2\beta}(t)$ are the time-dependent phases evaluated in parabolic approximation. $g$ is the geometrical factors containing details of angular momenta, angular integrations in wave functions and dimensional factors [R. A. Broglia and A. Winther, *Heavy Ion Reactions*, Addison-Wesley Publishing Co., 1991].

## Form Factors

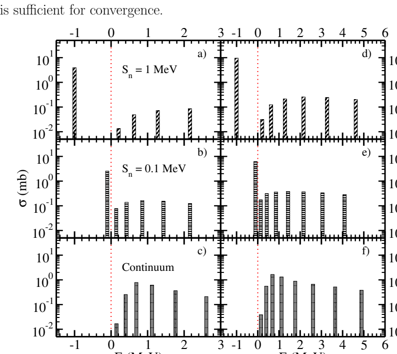
- One particle transfer **Form factors**, computed in the *prior form* using the Transformed Form Factors (TFF) code, show expected behaviour. L. Fortunato, I. Inci, J.-A. Lay and A. Vitturi, Computation **5**(3) (2017).



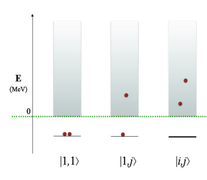

- The form factors for the resonance state of $^{5}$He obviously are larger than other states, but smaller than bound cases.

## One-neutron transfer cross-sections

- $\sigma_{1n}$ (in mb) for each basis state of each case plotted.
- Computations at beam energy 100 MeV enabled population of higher lying energy states and *neglect any effects of Q-value that may play a role.*
- Higher lying states contribute lesser and lesser. A small basis up to $\sim 6$ MeV is sufficient for convergence.

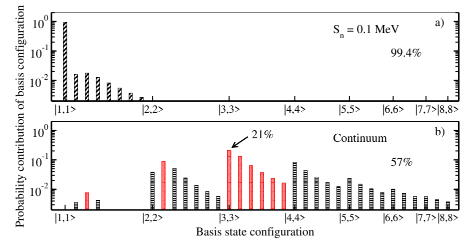



## Possibilities for two-neutron transfers




- **Three possibilities**:
  → Both particles in ground state ($|1,1\rangle$).
  → One particle in ground state, the other in any of the continuum states ($|1,j\rangle; j \neq 1$).
  → Both particles in any of the continuum states ($|i,j\rangle; i,j \neq 1$).

## Probability contribution




- Probability contribution of each of the configurations through their respective bases.
- Evidently, the continuum contributes more in the unbound case and the couplings amongst the neutrons enhance that contribution.
- States closest to the resonance clearly contribute more, both in $|i,i\rangle$ and $|i,j\rangle$ configurations.
- The zero spins of our $A, (A+2)$ nuclei ensured there were no contributions from the non-orthogonality and simultaneous transfer terms.

## Two-neutron transfer cross-sections

- A contact Delta interaction $-g\delta(\vec{r}_1 - \vec{r}_2)$ used in modified TFF code for *attractive pairing* between transferred neutrons. ∴, neglect bound $^{5}$He with $S_n = 1$ MeV case.

**Parameters:**

- (a) Coupling constant, $g$ (for $S_n$ = 0.1 MeV case)= -1037 @ $E_l$=21 MeV, -992 @ $E_l$=100 MeV, respectively.
- (b) Coupling constant, $g$ (for unbound $^{5}$He)= -10430 @ $E_l$=21 MeV, -7827 @ $E_l$=100 MeV, respectively.

- Pairing interaction, $\Delta$ was adjusted so as to reproduce the ground state energy of $^{6}$He at -0.975 MeV.

Variation of the $2n$ transfer cross-section (in mb) for different cases at the two different beam energies considered in the study. The ratio of the perturbed $\sigma_{2n}$ to unperturbed cross-sections $\sigma_{2n}$ (u) is especially important.

| Case | $\Delta$ | $E_l$=21 MeV | | | $E_l$=100 MeV | | |
|---|---|---|---|---|---|---|---|
| | (MeV) | $\sigma_{2n}$ | $\sigma_{2n}$ (u) | $\sigma_{2n}/\sigma_{2n}$(u) | $\sigma_{2n}$ | $\sigma_{2n}$ (u) | $\sigma_{2n}/\sigma_{2n}$(u) |
| $S_n = 0.1$ MeV | 0.775 | 6.95 | 6.89 | 1.01 | 147 | 125 | 1.18 |
| Continuum | 2.356 | 0.94 | 0.51 | 1.84 | 44 | 8.6 | 5.12 |

► **Pairing enhances the transfer probability in the continuum much more than for the bound states.** G. Singh, L. Fortunato, and A. Vitturi *arXiv:2204.11739v1 [nucl-th].*

## Conclusions

- For a weakly bound $(A+2)$ system near the drip lines, the inclusion of continuum states of the intermediate nucleus is vital for a $2n$ transfer process.
- The highly correlated case (unbound $^{5}$He) offers many paths where $2n$ transfer can occur via constructive interference.
- Such pairing correlations, present more in the ***unbound*** intermediate system, enhance $2n$ transfer cross-sections considerably.

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- We, the authors, acknowledge José Antonio Lay Valera for taking this poster to DREB 2022 on our behalf since we could not make it in person.
- As we are not present to answer your questions, please feel free to direct any queries to any of the email id's provided for the same. It would be our pleasure to try and answer them.
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