Outline

Introduction

Like Particle Pairing
n-p pairing near the N=Z line

Generalized Pairing Hamiltonian

T=1 and T=0 n-p pairing

Variational Wavefunctions

Unblocked Orbitals

T=0 Pair Number Symmetry- Q quantum Number
Q-degeneracy in odd-odd nuclei

Blocked Orbitals - odd number parity
Blocked Orbitals - Ω-blocking
Configuration Interaction

0+ and 1+ Ladders in o-o Nuclei

Applications

Spectra of Odd- Odd Nuclei with neutron excess
Wigner Energy
Splitting of Q=1 and Q=2 states in N=Z Nuclei
n-p Pair Transfer Spectroscopic Factors
Motivation

Data

Large Wigner Energy Anomaly in $N=Z$
Even Even Nuclei

$\sim 6\text{MeV} \text{ near } A=30$

Large Excitation Energy of $T=1$ States
in $E-E \ N=Z$ Nuclei

$> 7 \text{ MeV} \text{ near } A=30$

$\forall$ Odd-Odd $N=Z$ Nuclei

$<< 1 \text{ MeV}$

Theory

N-P Pairing Problem is Bridge from
Simple Pairing to
Full Many-Body Problem
Wigner Energy

Start with $E(2N, 2Z) = E_0 ; \ N=Z$

$E_{2n} = 2 \epsilon_{n+1} - \Delta_{2n} - E_0$

$E_{2p} = 2 \epsilon_{p+1} - \Delta_{2p} - E_0$

$E_\alpha = 2 (\epsilon_{N+1} + \epsilon_{P+1}) - \Delta_\alpha - E_0$

$-E_{\text{wigner}} = 1/4(E_\alpha - E_{2n} - E_{2p} + E_0)$

$E_{\text{wigner}} = 1/4(\Delta_\alpha - \Delta_{2n} - \Delta_{2p})$

Symmetry Energy

Start with $E(2N, 2Z) ; \ N=Z$

$E_{\text{g.s.}} = 0^+ \ T = 0$

$E^* = 1^+ \ T = 1$

$E_{\text{symmetry}} = E(T = 1) - E(T = 0)$
References

References

PLB 524 (2002) 81
PLB 553 (2003) 581
PLB 577 (2003) 47
Fig. 10a. Nilsson diagram for protons or neutrons, Z=50
Nilsson Levels

Cylindrical Symmetry
J is not Conserved

\[ \Omega^\pi \]

- 3/2^-
- 5/2^-
- 3/2^+
$K=0$ Pairs

- Two Neutrons
- Two Protons
- Neutron Proton
- Proton Neutron
\[ H = \sum_{k>0} \epsilon_k [a_k^\dagger a_k + a_{-k}^\dagger a_{-k} + b_k^\dagger b_k + b_{-k}^\dagger b_{-k}] \]

\[- \sum_{i,j} G_{i,j}^{T=1} [A_i^\dagger A_j + B_i^\dagger B_j + C_i^\dagger C_j] \]

\[- \sum_{i,j} G_{i,j}^{T=0} [D_i^\dagger D_j + (M_i^\dagger M_j + N_i^\dagger N_j) \delta(\Omega_{i,j})] \]

\[ a_k^\dagger (b_k^\dagger) \text{ is neutron (proton) creation operator} \]

\[ A_i^\dagger = (a_i^\dagger a_{-i}^\dagger); \ B_i^\dagger = (b_i^\dagger b_{-i}^\dagger) \]

\[ M_i^\dagger = (a_i^\dagger b_i^\dagger); \ N_i^\dagger = (a_{-i}^\dagger b_{-i}^\dagger) \]

\[ T=1 \ n-p \ pair \ creation \ operator \]

\[ C_i^\dagger = \frac{1}{\sqrt{2}} \left[ a_i^\dagger b_{-i}^\dagger + a_{-i}^\dagger b_i^\dagger \right] \]

\[ T=0 \ n-p \ pair \ creation \ operator \]

\[ D_i^\dagger = \frac{i}{\sqrt{2}} \left[ a_i^\dagger b_{-i}^\dagger - a_{-i}^\dagger b_i^\dagger \right] \]

\[ \text{Phase convention: } b_i^\dagger = -a_i^\dagger \]
Pairing and Two-Body Interaction

Although the Pairing problem is formally a two-body interaction, the two-body interaction depends on only two indices $a_i^\dagger a_{-i} a_{-j} a_j$ rather than four indices $a_i^\dagger a_j^\dagger a_k a_l$.

Each orbital has a unique partner.

**Pairing is 1.5 body problem.**

In the case of N-P Pairing, each orbital has two orbitals as partners. There are terms $a_i^\dagger a_{-i}^\dagger a_{-j} a_j$ and the new terms $a_i^\dagger b_{-i}^\dagger a_{-j} b_j$ in the two-body interaction.

N-P pairing is 1.75 body problem.
Variational Wavefunction

$$\Theta = \prod^k \Psi_k \prod^m \Phi_m \prod^n \Xi_n$$

$k$ unblocked orbitals

$m$ blocked

$n$ $\Omega$-blocked

$$\Psi_k = [1 + U(1, k)A^\dagger_k + U(2, k)B^\dagger_k + U(3, k)C^\dagger_k + U(4, k)D^\dagger_k + U(5, k)W^\dagger_k ]|0\rangle$$

$$W^\dagger_k = A^\dagger_k B^\dagger_k = C^\dagger_k C^\dagger_k = D^\dagger_k D^\dagger_k$$

$$\Phi_m = [V(1, m)a^\dagger_m + V(2, m)b^\dagger_m + V(3, m)A^\dagger_m b^\dagger_m + V(4, m)a^\dagger_m B^\dagger_m ]|0\rangle$$

$$\Xi_n = [a^\dagger_n b^\dagger_n] |0\rangle$$
Q Quantum Number
Q counts the Number Parity of $D^\dagger$ Pairs in Each Term of the Wavefunction

$Q = 1$
number parity of $D^\dagger$ pairs is even

$Q = 2$
number parity of $D^\dagger$ pairs is odd

In E-E nucleus, the ground state is $Q=1$ - even number of $D^\dagger$ pairs and $C^\dagger$ pairs in each configuration

In O-O N=Z nucleus, there are two low-lying states

$I = 0^+$ State
$Q=1$ - even number of $D^\dagger$ pairs and odd number of $C^\dagger$ pairs in each configuration

$I = 1^+$ State
$Q=2$ - odd number of $D^\dagger$ pairs and even number of $C^\dagger$ pairs in each configuration

For states in which all orbitals are unblocked, or $\Omega$-blocked, there is no interaction between configurations with $Q=1$ and configurations with $Q=2$
Number Parity and Parity Projection

assume $A^\dagger$, $B^\dagger$, $C^\dagger$ positive parity

assume $D^\dagger$ negative parity

Projection would be Parity Projection
Triple Projection - Two Levels

Two Protons and Two Neutrons

Excluded Configurations

$W_1^\dagger \ast W_2^\dagger$ and $A_1^\dagger \ast A_2^\dagger$ ....

$Q=1$ Configurations

$W_1^\dagger$ and $W_2^\dagger$

$A_1^\dagger \ast B_2^\dagger$ and $A_2^\dagger \ast B_1^\dagger$

$C_1^\dagger \ast C_2^\dagger$ and $D_1^\dagger \ast D_2^\dagger$

$Q=2$ Configurations

$C_1^\dagger \ast D_2^\dagger$ and $D_1^\dagger \ast C_2^\dagger$
\[ G_{i,i}^{T=1} = G_{i,i}^{T=0} = G \]
\[ G_{i,i}^{T=1} = G_{i,i}^{T=0} = 1.9 * G \quad \text{\(\delta\)-interaction} \]
\[ G_{i,i}^{T=1} = G_{i,i}^{T=0} = 1.94 * G \quad \text{surface-\(\delta\)} \]
\[ G_{i,i}^{T=1} = G_{i,i}^{T=0} = 2.4 * G \quad \text{Gogny} \]
\[ G_{i,i}^{\Omega-\text{blocked}} = G_{i,i}^{T=0} \]
\[ E(A_k^\dagger) = E(B_k^\dagger) = E(C_k^\dagger) = 2 * \epsilon_k - G_{i,i}^{T=1} \]
\[ E(D_k^\dagger) = E(M_k^\dagger) = E(N_k^\dagger) = 2 * \epsilon_k - G_{i,i}^{T=0} \]
\[ E(W_k^\dagger) = 4 * \epsilon_k - 3 * G_{i,i}^{T=1} - 3 * G_{i,i}^{T=0} \]
Variational Wavefunction

Determine amplitudes $U(i, k)$ and $V(i, m)$ by solving the coupled algebraic equations iteratively.

$$\partial \langle \Theta | \text{PHP} | \Theta \rangle / \partial U(i, k) = 0$$

$$\partial \langle \Theta | \text{PHP} | \Theta \rangle / \partial V(i, m) = 0$$

where $|\text{PHP}\rangle$ is a triple projection carried out before variation when no blocked levels.

Project Proton Number, Neutron Number and $Q$

and $|\Theta\rangle$ is a double projection when there are blocked levels.

Project Proton Number, Neutron Number
Parameters $A = 60$

$G_{i,j} = 0.316 \text{ MeV}$

Single Particle Spacing = 0.85 MeV
Why Configuration Interaction?

In a shell model calculation one constructs a finite valence space and determines an amplitude for each configuration.

In our many-body wavefunction, there are $1.74492 \times 10^{22}$ $Q=1$ distinct configuration.

for 30 levels and $N=Z=30$

There are just 150 independent amplitudes in our product wavefunction.

There is room for a few more amplitudes.
Generator Coordinates
Pairing Strengths

\[ H_0 = H[Q^{nn}, Q^{pp}, G^{npT=1}, G^{npT=0}] \]

\[ H_0 = H[R_0, S_0, T_0, U_0] \]

\[ H_0 \Psi_0 = E_0 \Psi_0 \]

\[ H_1 = H[R_1, S_0, T_0, U_0] \]

\[ H_1 \Psi_1 = E_1 \Psi_1 \]

\[ H_{i,j} = \langle \Psi_i | H_0 | \Psi_j \rangle \]

\[ \langle \Psi_i | \Psi_j \rangle \neq 0 \]
Amplitude Interchange

\[ 1 + U(1,1)A_1^† + U(2,1)B_1^† + U(3,1)C_1^† + U(4,1)D_1^† + U(5,1)W_1^† \]

Row Interchange

Old Wavefunction

\[
\begin{align*}
U(1,1) & \quad U(2,1) & \quad U(3,1) & \quad U(4,1) & \quad U(5,1) \\
U(1,2) & \quad U(2,2) & \quad U(3,2) & \quad U(4,2) & \quad U(5,2)
\end{align*}
\]

New Wavefunction

\[
\begin{align*}
U(1,2) & \quad U(2,2) & \quad U(3,2) & \quad U(4,2) & \quad U(5,2) \\
U(1,1) & \quad U(2,1) & \quad U(3,1) & \quad U(4,1) & \quad U(5,1)
\end{align*}
\]

Column Interchange

\[
\begin{align*}
U(1,1) & \quad U(2,1) & \quad U(3,1) & \quad U(4,1) & \quad U(5,1) \\
U(1,2) & \quad U(2,2) & \quad U(3,2) & \quad U(4,2) & \quad U(5,2)
\end{align*}
\]
N = 30  Z = 30

Single Particle Spacing = 0.85 MeV
G_{i,j} = 0.316 MeV

Q=1 Spectrum (MeV)

Ground State Variational Calculation
+ Diag with 8 Gen. Coord W.F.'s
+ Interchange Rows 15 & 16 in G.S.

Additional Row and Column Interchanges

C^+(15) C^+(16)
A^+(16) B^+(15)
A^+(15) B^+(16)
W^+(16)
W^+(15)
Diagonal Pairing Energy

$$\sum_i \langle A_i^\dagger A_i \rangle$$

The diagonal pairing energy is just a number operator and insensitive to the details of the wavefunction. It is large for a single Slater determinant wavefunction.

$W^\dagger$ 'α-like' terms in the wavefunction are enhanced by the diagonal pairing energy.

Off Diagonal Pairing Energy

$$\sum_{i \neq j} \langle A_i^\dagger A_j \rangle$$ is a sensitive measure of the collectivity of the wavefunction.

The off-diagonal pairing correlation energy is usually (much) smaller than the diagonal correlation energy.
$Z=30$

Off-Diagonal Correlation Energy (MeV) vs. Neutron Excess

- $G_{T=1}^{-1} <A^+A>$
- $G_{T=0}^{-1} <D^+D>$
Fig. 1. Experimental values of $W$ (filled circles) and $d$ [Eq. (6), open circles] in $N = Z$ nuclei extracted from measured binding energies [24]. The values of $W$ were obtained using the indicators given by Eqs. (4) and (5). The triangles mark the values of $d$ calculated with Eq. (6) using experimental binding energies of the lowest $T = 0$ states in odd-odd nuclei. The solid line represents
Wigner Energy

$$-4 \times E_{W\text{ig}} = [E(N, Z) - E(N - 2, Z)$$
$$-E(N, Z - 2) + E(N - 2, Z - 2)]$$

empirical smoothed value \(47/A\)

W. Satula et al., PLB 407 (1997) 103

$$E(N1, Z1) = E_0(N1, Z1) + [E_{\text{Corr}}(N1, Z1) - E_0(N1, Z1)]$$

\(E_0(N1, Z1)\) is the Slater determinant energy

For E-E nuclei and equally spaced levels

$$[E_{\text{Corr}}(N1, Z1) - E_0(N1, Z1)]$$

is independent of \(N1\) and \(Z1\)

setting \(E_0(N - 2, Z - 2) = E_0^0\)

$$[E_0(N, Z) - E_0^0] = 4 \times \epsilon - 3 \times [G_{T=1}^T + G_{T=0}^T]$$

$$[E_0(N, Z - 2) - E_0^0] = 2 \times \epsilon - G_{T=1}^T$$

$$[E_0(N - 2, Z) - E_0^0] = 2 \times \epsilon - G_{T=1}^T$$

$$[E_0(N - 2, Z - 2) - E_0^0] = 0$$

\(E(Wigner) \sim 0.25 \times [G_{i,i}^{T=1} + 3 \times G_{i,i}^{T=0}]\)

\(E(Wigner) \sim 46/A\)
\[ E_0 (N-1, z-1) = 2 \varepsilon - G_{l, l}^{T=0} \]  
\[ E_0^* (N-1, z-1) = 2 \varepsilon - G_{l, l}^{T=0} \]  
\[ -4 E_{WJ} = \left[ E(N, z) - 2 E(N-1, z-1) + E(N-2, z-2) \right] \]  
\[ \sim 0.25 \left[ G_{l, l}^{T=1} + 3 G_{l, l}^{T=0} \right] \]  
\[ -4 E_{WS} = \left[ E(N, z) - 2 E^*(N-1, z-1) + E(N-2, z-2) \right] \]  
\[ \sim 0.25 \left[ 3 G_{l, l}^{T=1} + G_{l, l}^{T=0} \right] \]
0.90–0.95 with \(\Theta_{\text{et}}, \Theta_2\). We repeat this procedure for \(G^+0, G^+1, G^+2, T^01\), and \(G^+0, T^30\). This gives eight wavefunctions in addition to \(\Theta_{\text{et}}\). We then do a diagonalization of these nine wavefunctions, using the physical values of the pairing interaction strengths. The non-orthogonality of the basis states is fully taken into account. This gives a better estimate of the correlation energy. When there are nearly degenerate states with the same value of \(Q\), the diagonalization involves 9\(n\) basis states, where \(n\) is the number of degenerate states. The correlation energies given in this Letter are obtained from configuration interaction calculations.

The Wigner energy [24] is defined in terms of the BE of various combinations of nuclei in the quantity, \(\delta V(N, Z)\), where

\[
\delta V(N, Z) = \frac{1}{4} \left[ \text{BE}(N, Z) - \text{BE}(N - 2, Z) - \text{BE}(N, Z - 2) + \text{BE}(N - 2, Z - 2) \right].
\]  

(11)

For \(N\) and \(Z\) even, the Slater energy approximation to \(\delta V(N, Z)\) is

\[
\delta V(N, Z) = \frac{1}{4} \left( G_{L,1}^{T=1} + 3 G_{L,1}^{T=0} \right) \quad \text{for} \quad N = Z
\]

(12)

and

\[
\delta V(N, Z) = 0 \quad \text{for} \quad N \neq Z.
\]

(13)

Within the accuracy of our calculations, there is no change in \(\delta V(N, Z)\) arising from the correlation energy corrections, for the values of \(N\) and \(Z\) that concern us. Specifically, the configuration interaction results give a correlation energy varying between 6.49 and 6.56 MeV for the ground states of interest. Although the correlation energy is fairly large, it is essentially constant.

For \(N\) and \(Z\) odd, the relevant Slater energy approximations to \(\delta V(N, Z)\) are

\[
\delta V(N, Z) = \frac{1}{2} G_{L,1}^{T=1} \quad \text{for} \quad N = Z
\]

(14)

and

\[
\delta V(N = Z + 2, Z) = \frac{1}{8} G_{L,1}^{T=1} + \frac{3}{8} G_{L,1}^{T=0} - \frac{1}{4} G_{L,1}^{T=0}
\]

for \(N = Z + 2\),

(15)

where \(G_{L,1}^{T}\) denotes the larger of the two diagonal pairing matrix elements. In the \(A = 60\) region we have taken the \(T = 0\) and \(T = 1\) pairing strengths to be the same. In this case, we get \(\delta V(N = Z + 2, Z) = (1/4) G_{L,1}^{T=0}\).

For even–even nuclei [24], the Wigner energy is

\[
W(A) = \delta V\left(\frac{A}{2}, \frac{A}{2}\right)
- \frac{1}{2} \left[ \delta V\left(\frac{A}{2} + 1, \frac{A}{2} + 1\right) + \delta V\left(\frac{A}{2} + 2, \frac{A}{2} + 2\right) \right].
\]

(16)

For odd–odd nuclei, the Wigner energy is

\[
W(A) = \frac{1}{2} \left[ \delta V\left(\frac{A}{2} - 1, \frac{A}{2} - 1\right) + \delta V\left(\frac{A}{2} + 1, \frac{A}{2} + 1\right) \right] - \delta V\left(\frac{A}{2} + 1, \frac{A}{2} - 1\right).
\]

(17)

Note that \(W(A)\) for odd–odd nuclei involves only even–even nuclei, and there are no changes in \(W(A)\) from correlation energies, as the correlation energies are essentially the same.

There is a second combination of \(\delta V(N, Z)\) terms that contributes to the Wigner energy in odd–odd nuclei.

\[
d(A) = 2 \left[ \delta V\left(\frac{A}{2} + 1, \frac{A}{2} + 1\right) + \delta V\left(\frac{A}{2} + 2, \frac{A}{2} + 2\right) \right] - 4 \delta V\left(\frac{A}{2} + 1, \frac{A}{2} - 1\right).
\]

(18)

The first two terms in \(d(A)\) involve binding energies in odd–odd nuclides. The values of \(d(A)\) extracted from experimental data are quite irregular [24] in behavior. For \(^{62}\text{O}\), we get a value of \(-0.32\) MeV for the correlation energy contribution to \(d(A)\).

Plugging in the energies of the relevant configurations, we immediately get the Slater energy approximations to \(W(A)\) and \(d(A)\) as

\[
W(A)^{T=0} = \frac{1}{4} \left( 3 G_{L,1}^{T=0} + G_{L,1}^{T=1} \right),
\]

(19)

\[
W(A)^{T=1} = \frac{1}{4} \left( 3 G_{L,1}^{T=0} + G_{L,1}^{T=1} \right),
\]

(20)

\[
d(A) = \frac{1}{2} \left( G_{L,1}^{T=0} + G_{L,1}^{T=1} \right) + (G_{L,1}^{T=0} - G_{L,1}^{T=1}).
\]

(21)

The fact that the \(T = 0\) matrix elements dominate the expression for \(W(A)\) does not mean that \(T = 0\) pairing
Octupole Deformation

Even - Even    Odd Mass    Even - Even    Odd - Odd

1+

1- = = 5/2- = 0+ = 1+
0+ = = 5/2+ = 0+
$Z=31 \quad N=31$

$Q=1$ and $Q=2$ States

4 Nucleons $E_i = 4e_i - 6G_{i,i}$
3 Nucleons $E_i = 3e_i - 3G_{i,i}$
2 Nucleons $E_i = 2e_i - G_{i,i}$

$E^* = G_{i,i}^{T=1} - G_{i,i}^{T=0}$

- Level 15: $5/2^+$
- Level 16: $7/2^-$
- Level 17: $1/2^+$

Excitation Energy (MeV)

$1/2^+$

$7/2^-$ (PN) - $C^+$

$5/2^+$ (PPNN)

$1/2^+$

$7/2^-$ (PN) - $D^+$

$5/2^+$ (PPNN)

Level Occupation

$Q=1$

Level Occupation

$Q=2$
\[ Z=30 \quad N=30 \]

\[ Q=1 \quad \text{and} \quad Q=2 \quad \text{States} \]

4 Nucleons \[ E_i = 4e_i - 6G_{i,i} \]

3 Nucleons \[ E_i = 3e_i - 3G_{i,i} \]

2 Nucleons \[ E_i = 2e_i - G_{i,i} \]

\[ E^* = 2(e_{7/2} - e_{5/2}) + 4G_{i,i} \]

Level 15: \( 5/2^+ \)

Level 16: \( 7/2^- \)

Level 17: \( 1/2^+ \)

Excitation Energy (MeV)

Level Occupation

Q=1

Q=2

Q=2
Q-splitting in \( N=Z \) Nuclei

\[ G^{T=1} = 0.316 \text{ MeV} \]

For \( N=Z=31 \) and \( N=Z=30 \), the graph shows the energy difference between the states with different \( Q \) values.

- **PN (D\(^+\))**: Q=1, \( E = 4e_{15} - 6G_{i,i} \)
- **PN (C\(^+\))**: Q=2, \( E = 2e_{15} + 2e_{16} - 2G_{i,i} \)

The graph plots the energy difference \( E(Q=2) - E(Q=1) \) (MeV) versus \( G^{T=0} \) (MeV) for different values of \( G^{T=0} \).
Excitation Of $1^+$ States in $E-E$ $N=Z$ Nuclei

Systematics

$E(T=1) - E(T=0) = 150/A + 24/A^{1/2}$

$\sim 5.6\,\text{MeV}$ at $A = 60$

A.O. Macchiavelli et al.

Diagonal Pairing Effects

empirical W. Satula and R. Wyss, N.P. A676(2000)120

\[ G_{i,j} = 19/A \]

Gogny Interaction

M.E. from J.L. Egido and L.M. Robledo

\[ G_{i,j} = 19/A; \quad G_{i,i} = 45.6/A \]

\[ \Delta \epsilon = 0.85 \text{MeV for } A \sim 60 \]

Even - Even Nuclei

\[ E(Q = 2) - E(Q = 1) \sim 2 \times \Delta \epsilon + 2 \times [G_{i,i}^{T=1} + G_{i,i}^{T=0}] \]

\[ E(Q = 2) - E(Q = 1) \sim 182/A + 2 \times \Delta \epsilon \]

Odd - Odd Nuclei

\[ E(Q = 2) - E(Q = 1) = G_{i,i}^{T=1} - G_{i,i}^{T=0} \]

Wigner Energy

\[ E(\text{Wigner}) \sim 0.25 \times [G_{i,i}^{T=1} + 3 \times G_{i,i}^{T=0}] \]

\[ E(\text{Wigner}) \sim 46/A \]
Conclusion

Both Wigner Energy
and Symmetry Energy
are relatively insensitive to Many Body Correlations in $\Psi$
They depend primarily on diagonal matrix elements
'The Smoking Gun'
Pair Transfer Spectroscopic Factor

\[
\langle Z + 1, N + 1 | \Sigma_k C_k^\dagger | Z, N \rangle^2
\]

\[
\langle Z + 1, N + 1 | \Sigma_k D_k^\dagger | Z, N \rangle^2
\]

In the no correlation limit
the spectroscopic factor is 1.0
n-p Pair Transfer Probability

$G^{T=1} = 0.316$ MeV

Transition Probability

$G^{T=0}$ (MeV)

Initial State $|^{60}EE>$

Final State $|^{62}OO Q=1$

Final State $|^{62}OO Q=2$
The astrophysical reaction rates are shown in Fig. 4 as a function of the temperature $T_\gamma$. Since the proton widths are much smaller than the $\gamma$ widths, the yield from the first two ($\frac{5}{2}^-$ and $\frac{1}{2}^-\gamma$) resonances is proportional to these widths and not sensitive to the precise values of the $\gamma$ widths. In the temperature region $T_\gamma < 1$, the $\frac{1}{2}^-\gamma$ state completely dominates (see dot-dashed line in Fig. 4). Higher-lying states in $^{57}\text{Cu}$ with $E_\gamma > 2.5$ MeV contribute only at temperatures $T_\gamma > 1$. The thin solid line in Fig. 4 represents the result for the astrophysical reaction rate obtained in Ref. [18]. Since these authors used a smaller proton width for the $\frac{1}{2}^-\gamma$ state, their estimate of the reaction rate for the $^{56}\text{Ni}(p,\gamma)^{57}\text{Cu}$ reaction is lower by more than an order of magnitude in the temperature region below $T_\gamma = 1$.

This work was supported by U.S. Department of Energy, Nuclear Physics Division, under Contract No. W-31-109-ENG-38, the National Science Foundation, and by a University of Chicago/Argonne National Laboratory Collaborative Grant.

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### 68Ni(p,αp) 72Sr23,72Kr17 (continued)

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<th>Eγ</th>
<th>Eγ(c.m.)</th>
<th>Iγ</th>
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<td>1862.4</td>
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* From 72Sr23. Other: 72Kr17.
* From 71Kr17.
* Relative intensities at 0°=90°, Eγ=14 MeV from 71Kr17, unless indicated otherwise.
* Intensity: relative Iγ.

### Level Scheme

#### 68Ni(6He,t) 72Sr23,72Ba28

Resonances and fine structure of Gamow-Teller (G-T) and spin flip (SL) resonances, and data on 6He strength in 68Ni.

92V930,92V938: E=72 MeV, FWHM=50 keV; deduced effective projectile-nucleon force.

72Sr23: E=24 MeV, FWHM=40-60 keV.

72Ba28: E=24 MeV, FWHM=50-60 keV.

Measured: c(E,R), DWBA analysis.

#### 68Cu Levels

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<th>E(level)</th>
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<th>Comments</th>
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<td>141.18</td>
<td>(2+4)</td>
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<td>(0+4)</td>
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<td>143.16</td>
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<tr>
<td>155.16</td>
<td>(4)</td>
<td>L; from 72Ba28.</td>
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</table>

Continued on next page (footnotes at end of table)
n-p Pair Transfer Probability

$G^{T=1} = 0.33$ MeV

Single Particle Energies $^{57}$Ni Levels

- T=1 Pair Transfer
- T=0 Pair Transfer

Initial State $<^{56}$Ni Q=1
Final State $<^{58}$Cu Q=1
Final State $<^{58}$Cu Q=2

Transfer Probability

$G^{T=0}$ (MeV)
$^{58}\text{Cu}$

$Q=1$ and $Q=2$ N-P Pair Transfer Spectroscopic Factors

- $G_{ij}^{T=1} = 0.33$ MeV
- $G_{ij}^{T=0} = 0.30$ MeV

Excitation Energy (MeV)

- $Q=1$: 14.97
- $Q=2$: 11.73

- 1.32
- 2.55
- 3.40
Summary
Developed a treatment of $T=0$ n-p pairing and $T=1$ n-n p-p and n-p pairing that includes:

- 4 nucleon $\alpha$-like correlations $W^\dagger$
- triple projection before variation $Z,N,Q$
- blocked orbitals complex amplitudes
- $\Omega$-blocked orbitals $K$-isomers
- amplitude interchange excited states
- configuration interaction non-orthogonal basis
Results

Low-lying States in O-O E-E and Odd-mass nuclei

Low level density near ground in N=Z Nuclei

Q-degeneracy in O-O Nuclei

Ladders of $0^+$ and $1^+$ states in O-O Nuclei

Pair (n-n n-p and p-p) transfer spectroscopic factors

Splitting of $0^+$ and $1^+$ states in O-O nuclei

Explain Wigner Energy

Explain Symmetry Energy

Asymmetry of Particle and Hole

Excitation Energies in Odd Mass Nuclei
How does large binding of $W^+$ affect rotational properties?