Outline

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  - 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
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  - 0^+ and 1^+ Ladders in o-o Nuclei
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  - 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

$\sim 6MeV$ near A=30

Large Excitation Energy of T=1 States

in E-E N=Z Nuclei

> 7 MeV near A= 30

v Odd-Odd N=Z Nuclei

<< 1 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

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

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

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

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

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

Symmetry Energy

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

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

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

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

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These diagrams give the calculated energies of nuclear levels as a function of ellipsoidal deformation, defined by the eccentricity coordinate ε. Positive values of ε correspond to prolate (cigar) shape. The energy scale for Z≤50 (Fig. 10a) is given in units of MeV$(A/100)^{1/3}$; for Z≥50 (Figs. 10b–10e) the energy is given in units of $\hbar\omega_0$, the oscillator quantum for the deformed potential. The positions of levels at zero deformation have been adjusted empirically.

Levels are labelled by the asymptotic quantum numbers $K[Nn_z\Lambda]$ and at zero deformation by the quantum numbers ℓ_j (ℓ=0,1,2,3... for s, p, d, f... states). Even parity levels are given as solid lines, odd parity levels as dashed lines.

Fig. 10a is taken from *Nuclear Spectroscopy Tables*,[1] Figs. 10b–10e from a paper by C. Gustafson, et al.[2] For further explanation of the calculations the reader is referred to these works and to the additional references included below.[3-5]

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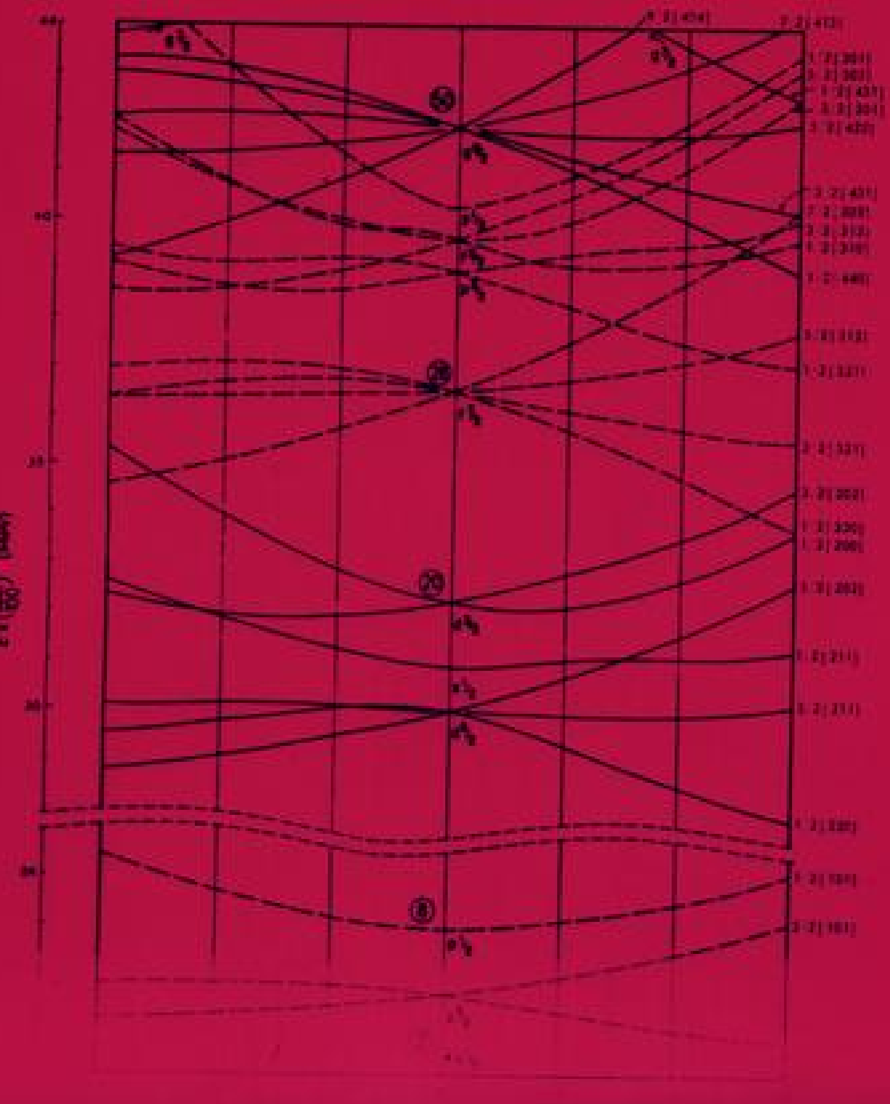
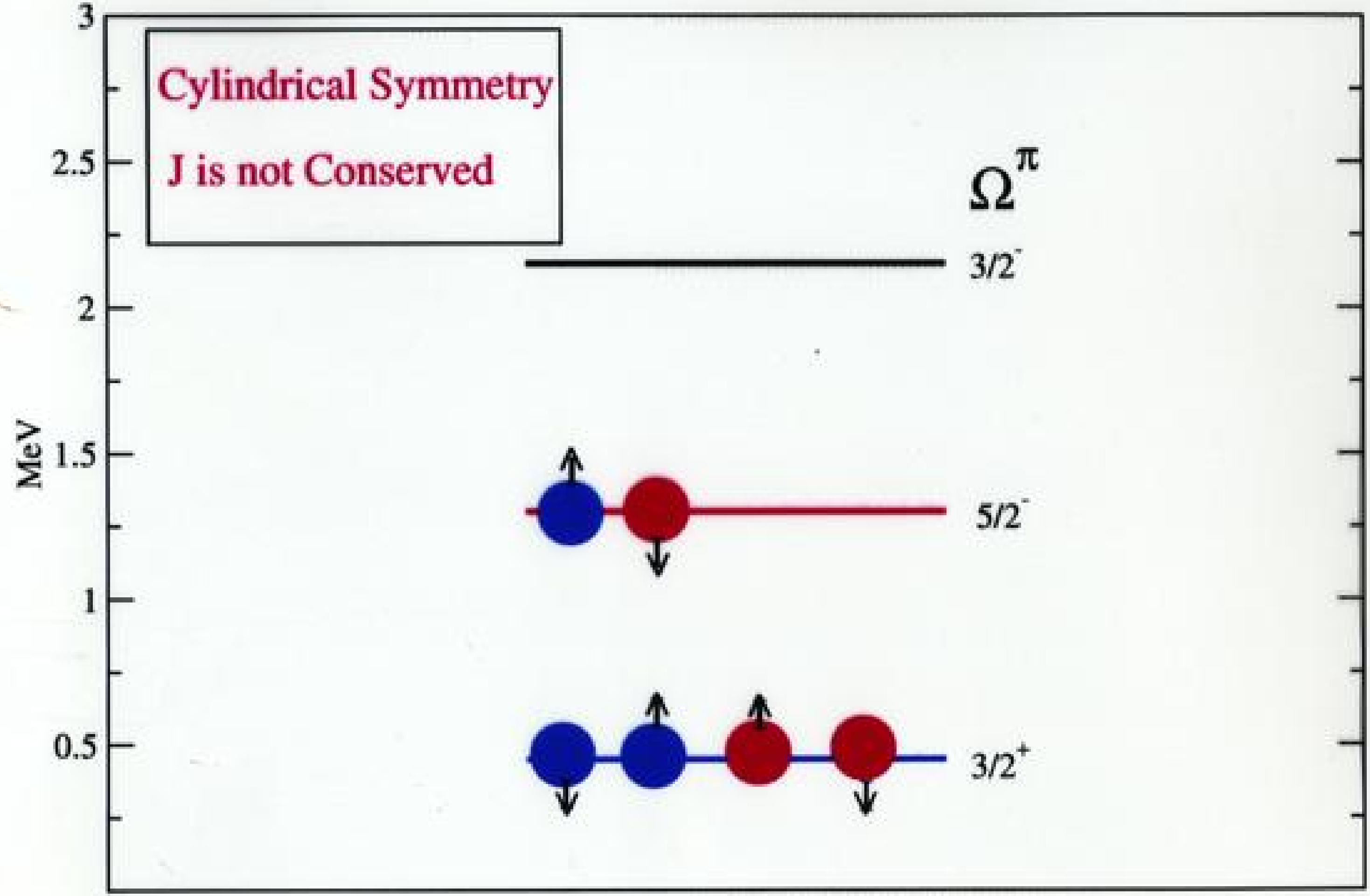
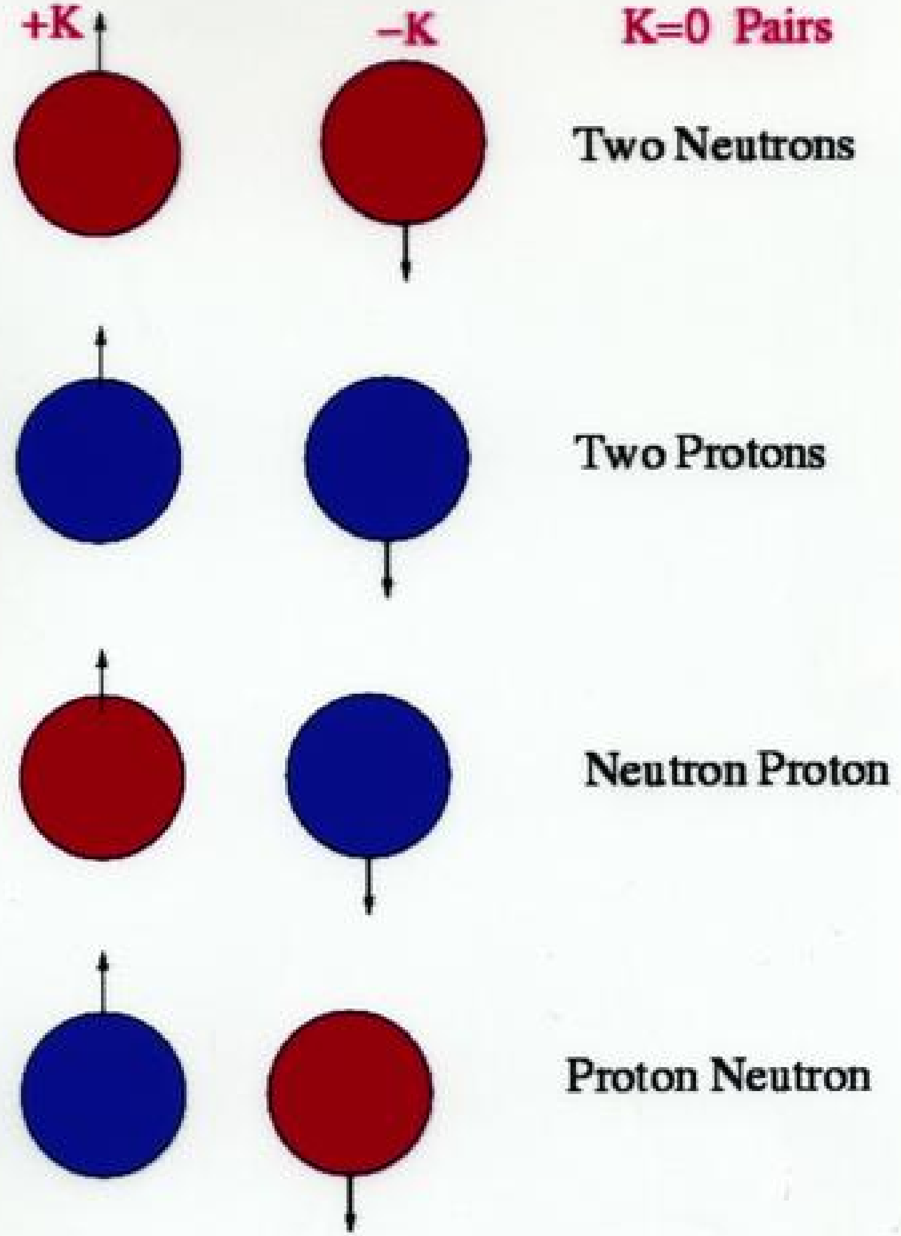
Fig. 10a. Nilsson diagram for protons or neutrons, Z≤50



Nilsson Levels




+K
−K
K=0 Pairs
Two Neutrons
Two Protons
Neutron Proton
Proton Neutron

$$H = \sum_{k>0} \epsilon_k [a_k^\dagger a_k + a_{-k}^\dagger a_{-k} + b_k^\dagger b_k + b_{-k}^\dagger b_{-k}]$$

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

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

$a_k^\dagger \left(b_k^\dagger\right)$ 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

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

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 $a_i^\dagger a_{-i}^\dagger a_{-j} a_j$ 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 Ω-blocked

$$\Psi_k = [1 + U(1,k)A_k^\dagger + U(2,k)B_k^\dagger$$
$$+U(3,k)C_k^\dagger + U(4,k)D_k^\dagger + U(5,k)W_k^\dagger\,]|0\rangle$$

$$W_k^\dagger = A_k^\dagger B_k^\dagger = C_k^\dagger C_k^\dagger = D_k^\dagger D_k^\dagger$$

$$\Phi_m = [V(1,m)a_m^\dagger + V(2,m)b_m^\dagger$$
$$+V(3,m)A_m^\dagger b_m^\dagger + V(4,m)a_m^\dagger B_m^\dagger]|0\rangle$$

$$\Xi_n = \left[a_n^\dagger b_n^\dagger\right]|0\rangle$$

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

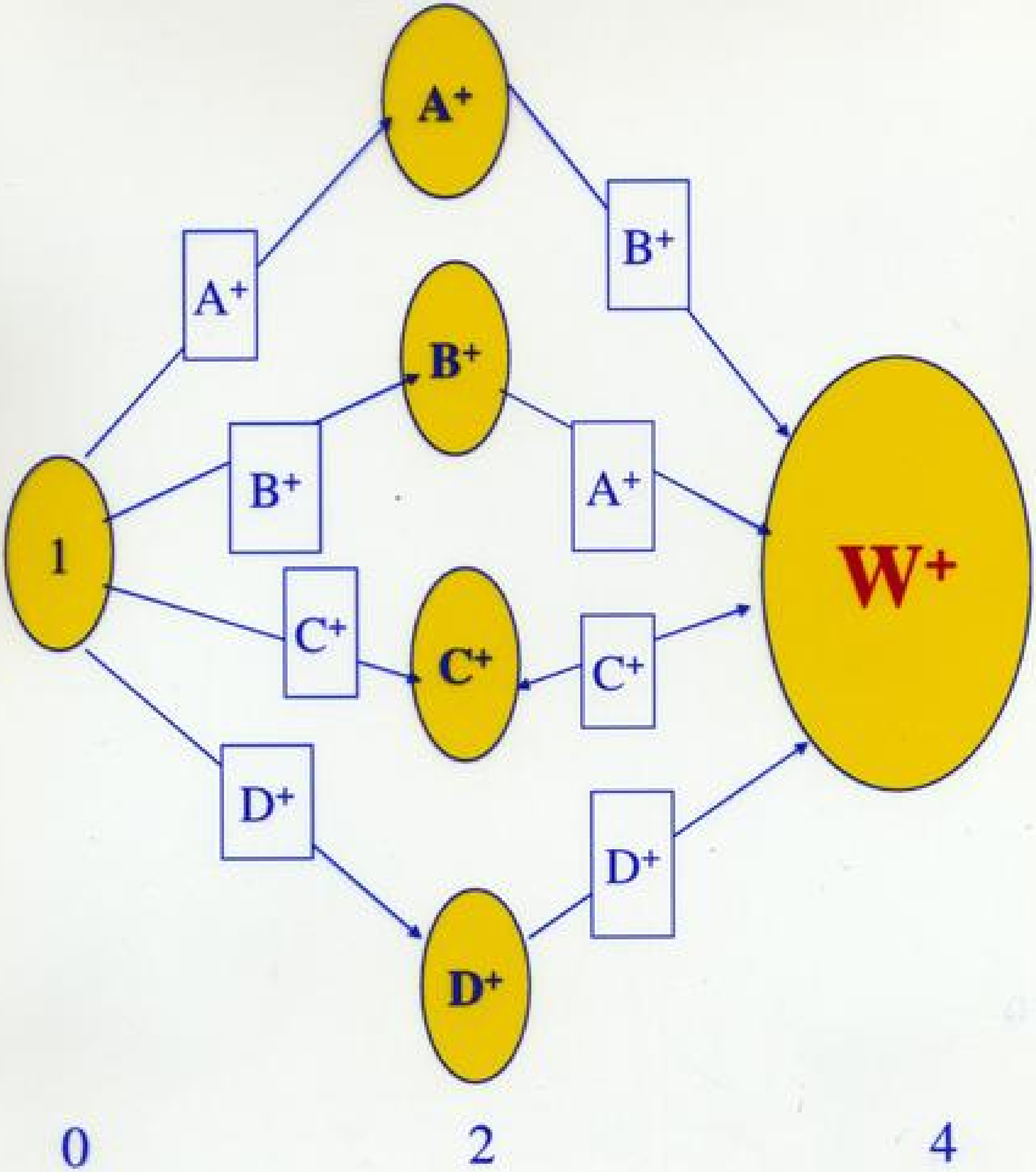
For states in which all orbitals are unblocked, or Ω-blocked, there is no interaction between configurations with Q=1 and configurations with Q=2

Number Parity and Parity Projection

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

assume $D^\dagger$ negative parity

Projection would be Parity Projection



A+
B+
1
W+
C+
D+
0
2
4

Triple Projection - Two Levels

Two Protons and Two Neutrons

Excluded Configurations

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

Q=1 Configurations

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

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

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

Q=2 Configurations

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

$$G_{i,j}^{T=1} = G_{i,j}^{T=0} = G$$

$$G_{i,i}^{T=1} = G_{i,i}^{T=0} = 1.9 * G \quad \delta\text{-interaction}$$

$$G_{i,i}^{T=1} = G_{i,i}^{T=0} = 1.94 * G \quad \text{surface-}\delta$$

$$G_{i,i}^{T=1} = G_{i,i}^{T=0} = 2.4 * G \quad \text{Gogny}$$

$$G_{i,i}^{\Omega-blocked} = G_{i,i}^{T=0}$$

$$E(A_k^\dagger) = E(B_k^\dagger) = E(C_k^\dagger) = 2 * \epsilon_k - G_{i,i}^{T=1}$$

$$E(D_k^\dagger) = E(M_k^\dagger) = E(N_k^\dagger) = 2 * \epsilon_k - G_{i,i}^{T=0}$$

$$E(W_k^\dagger) = 4 * \epsilon_k - 3 * G_{i,i}^{T=1} - 3 * G_{i,i}^{T=0}$$

Variational Wavefunction

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

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

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

where $P|\Theta\rangle$
is a triple projection carried out
before variation when no blocked levels.

Project Proton Number, Neutron Number and Q

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

Project Proton Number, Neutron Number

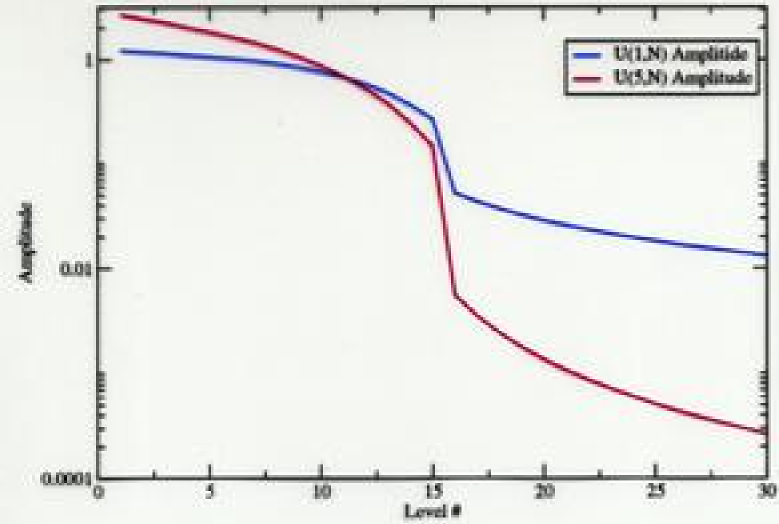
Parameters A=60

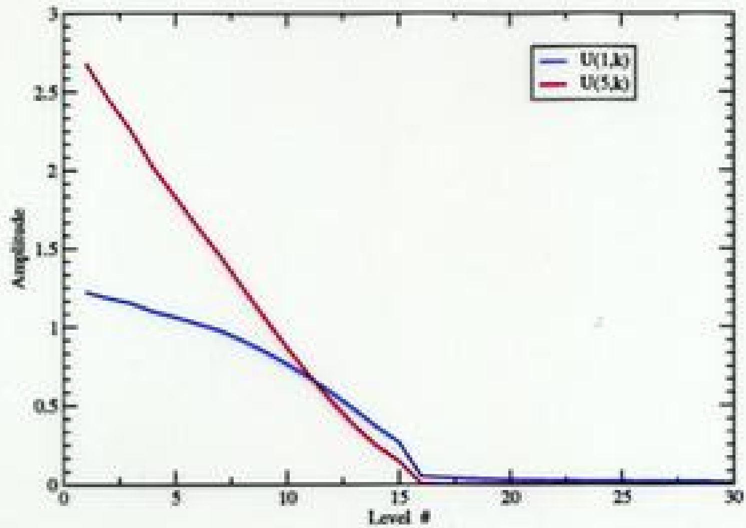
$G_{i,j} = 0.316$ MeV

Single Particle Spacing = 0.85 MeV

Comparison Of Amplitudes

N=Z =30 $G^{T=0} = G^{T=1}$





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

$1.74492 * 10^{22}$ 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

$$H_0 = H[G_0^{nn}, G_0^{pp}, G_0^{npT=1}, G_0^{npT=0}]$$

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

$$H_0\Psi_0 = E_0\Psi_0.$$

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

$$H_1\Psi_1 = E_1\Psi_1$$

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

$$\langle\Psi_i|\Psi_j\rangle \neq 0$$

Amplitude Interchange

$$1 + U(1,1)A_1^\dagger + U(2,1)B_1^\dagger + U(3,1)C_1^\dagger + U(4,1)D_1^\dagger + U(5,1)W_1^\dagger$$

Row Interchange

Old Wavefunction

U(1,1) U(2,1) U(3,1) U(4,1) U(5,1)

U(1,2) U(2,2) U(3,2) U(4,2) U(5,2)

New Wavefunction

U(1,2) U(2,2) U(3,2) U(4,2) U(5,2)

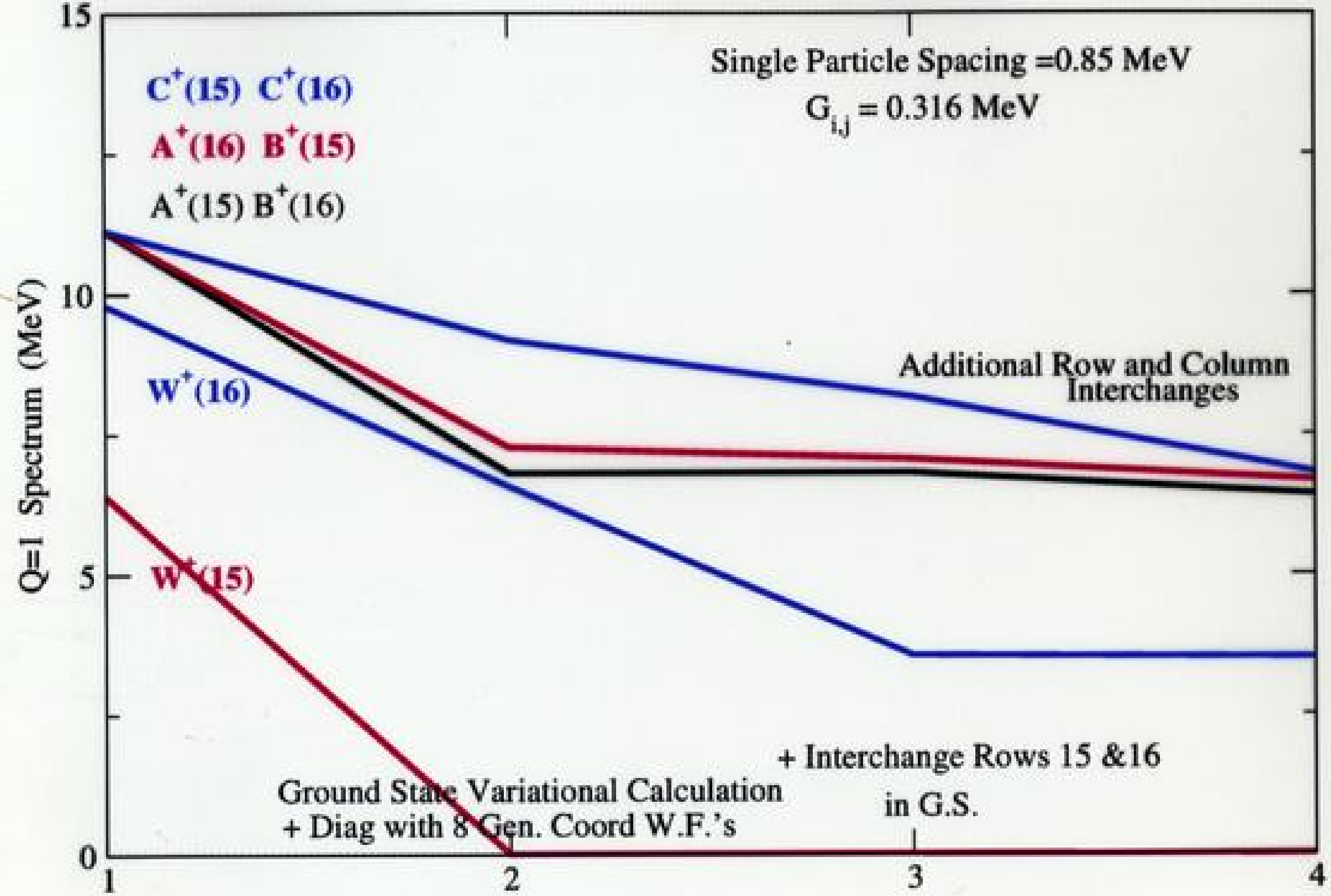
U(1,1) U(2,1) U(3,1) U(4,1) U(5,1)

Column Interchange

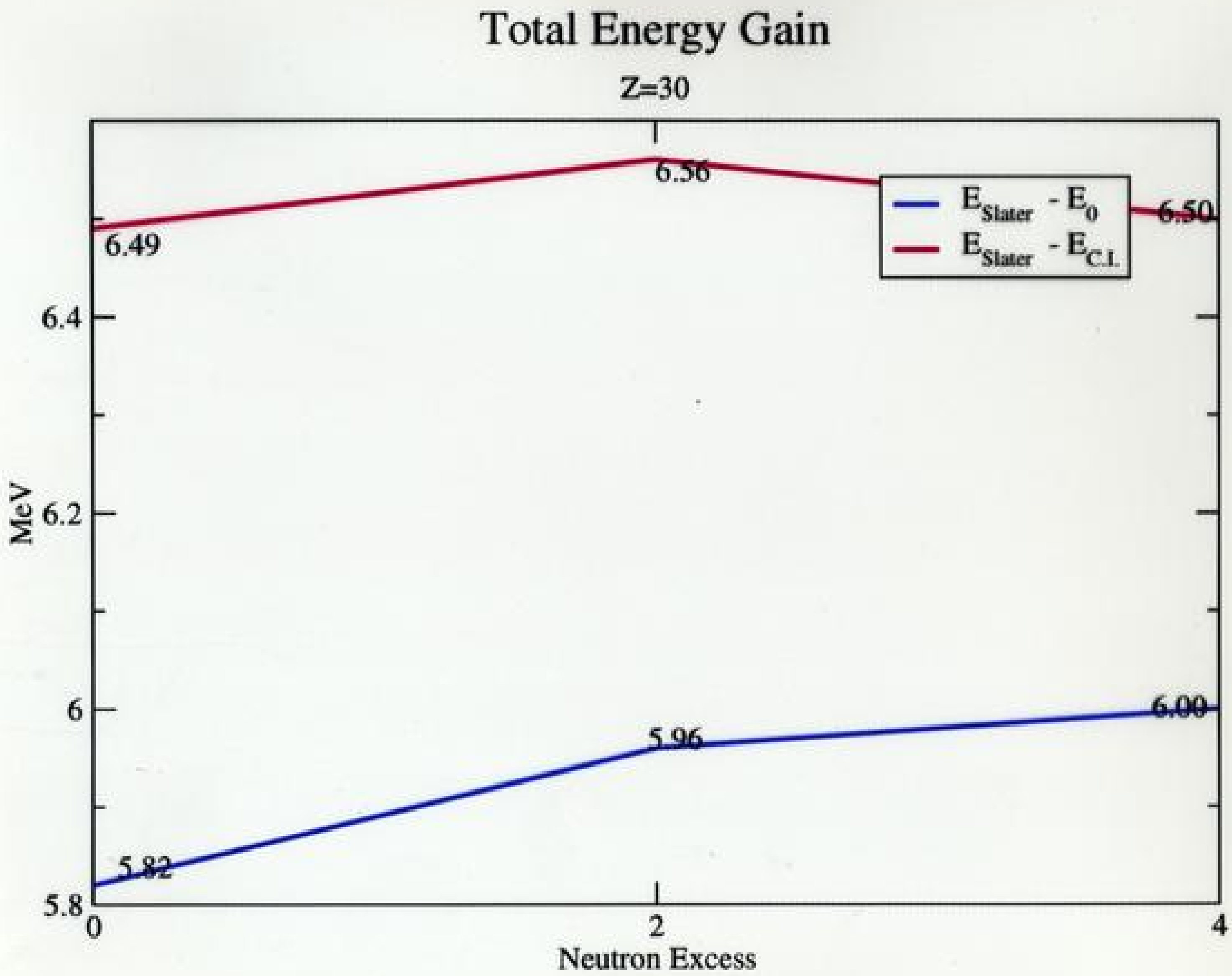
U(1,1) U(2,1) U(3,1) U(4,1) U(5,1)

U(1,2) U(2,2) U(3,2) U(4,2) U(5,2)

N=30 Z=30



Single Particle Spacing =0.85 MeV
G_{i,j} = 0.316 MeV
C+(15) C+(16)
A+(16) B+(15)
A+(15) B+(16)
W+(16)
W+(15)
Additional Row and Column Interchanges
+ Interchange Rows 15 &16 in G.S.
Ground State Variational Calculation
+ Diag with 8 Gen. Coord W.F.'s
Q=1 Spectrum (MeV)
15
10
5
0
1
2
3
4



Total Energy Gain
Z=30
E_{Slater} - E_0
E_{Slater} - $E_{C.I.}$
6.49
6.56
6.50
5.82
5.96
6.00
6.4
6.2
6
5.8
MeV
0
2
4
Neutron Excess

Diagonal Pairing Energy

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

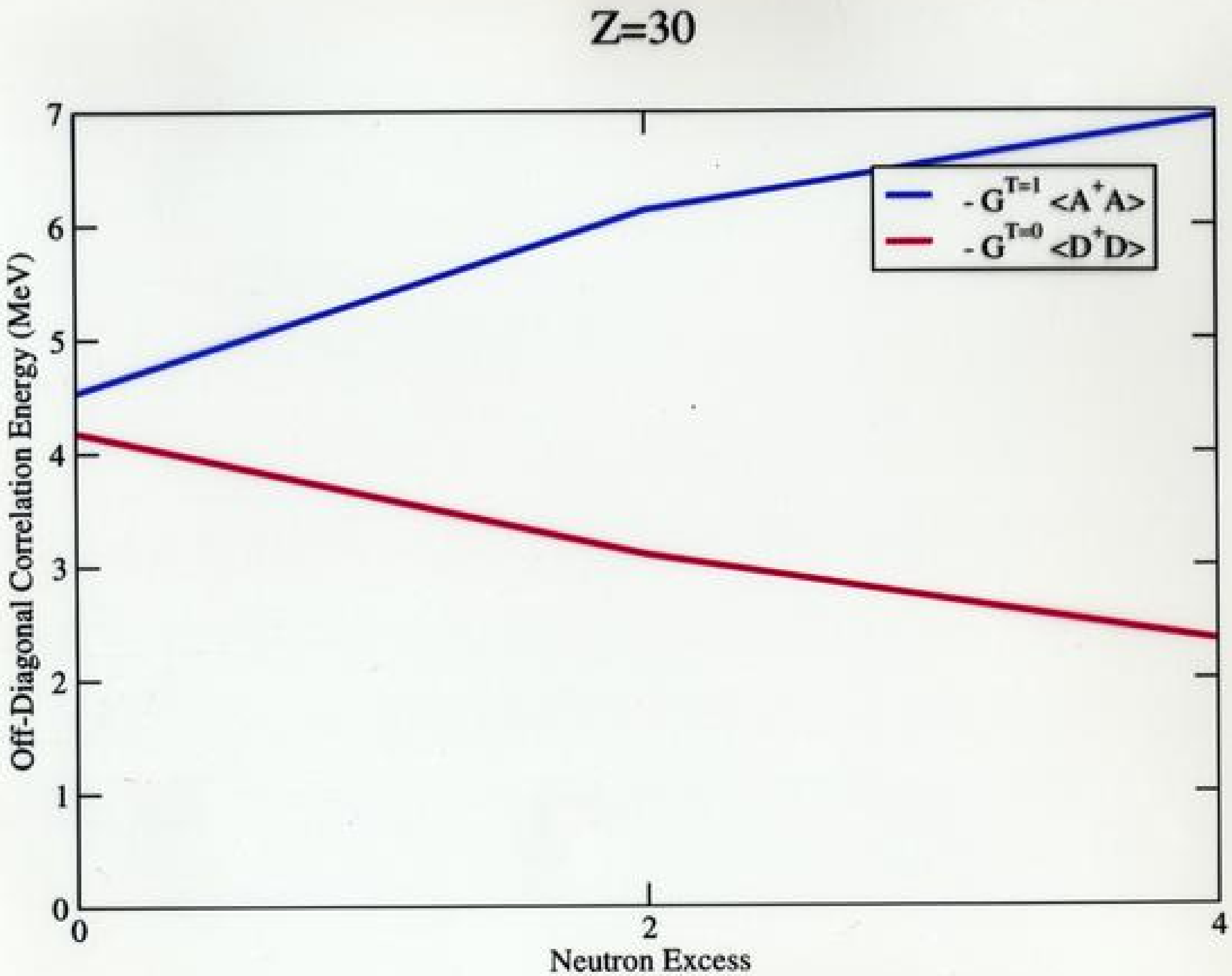
The diagonal pairing energy is just a number operator and insensitive to the details of the wavefunction. It is large for a single Slater deteminant wavefunction.

$W^\dagger$ '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)
Neutron Excess
0
1
2
3
4
5
6
7
0
2
4
- G^T=1 <A^+A>
- G^T=0 <D^+D>

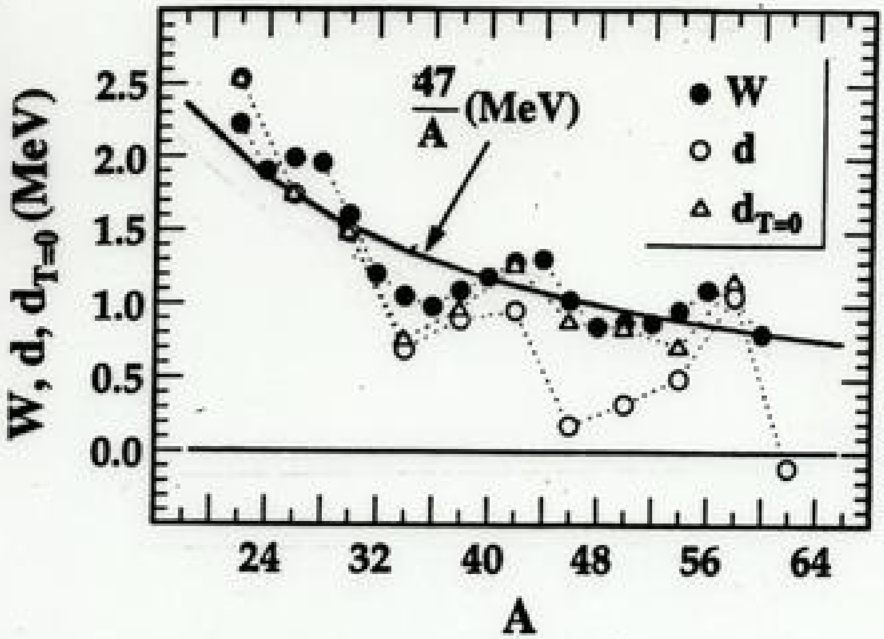


Fig. 1. Experimental values of W (filled circles) and d [Eq. (6), open circles] in $N = Z$ nuclei extracted from measured binding energies [24]. The values of W were obtained using the indicators given by Eqs. (4) and (5). The triangles mark the values of d calculated with Eq. (6) using experimental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

Wigner Energy

$-4 * E_{Wig} = [E(N, Z) - E(N-2, Z)$

$-E(N, Z-2) + E(N-2, Z-2)]$

empirical smoothed value $47/A$

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

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

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

For E-E nuclei and equally spaced levels

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

is independent of $N1$ and $Z1$

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

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

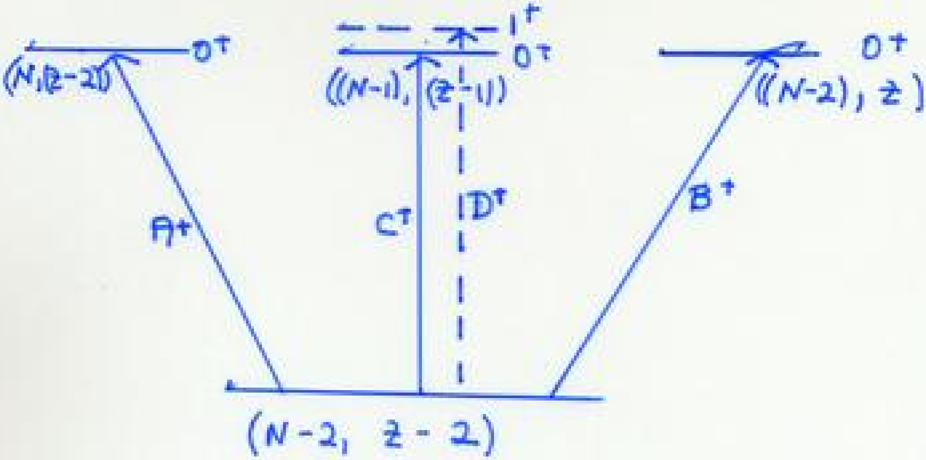
$[E_0(N, Z-2) - E_0^0] = 2 * \epsilon - G^{T=1}$

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

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

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

$E(Wigner) \sim 46/A$



$$E_0\,(N-1,\,Z-1) = 2\varepsilon - G_{i,i}^{T=1} \qquad E(C^+)$$

$$E_0^*\,(N-1,\,Z-1) = 2\varepsilon - G_{i,i}^{T=0} \qquad E(D^+)$$

$$-4\,E_{wig} = [E(N,Z) - 2E(N-1,Z-1) + E(N-2,Z-2)]$$

$$\sim 0.25\,[G_{i,i}^{T=1} + 3\,G_{i,i}^{T=0}]$$

$$-4\,E_{wig} = [E(N,Z) - 2E^*(N-1,Z-1) + E(N-2,Z-2)]$$

$$\sim 0.25\,[3\,G_{i,i}^{T=1} + G_{i,i}^{T=0}]$$

0.90–0.95 with $\Theta_{\rm Var}$, Θ_2. We repeat this procedure for $G^{p\text{-}p}$, $G^{n\text{-}p,T=1}$, and $G^{n\text{-}p,T=0}$. This gives eight wavefunctions in addition to $\Theta_{\rm Var}$. 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 $9n$ 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

$$\delta V(N,Z)=\frac{1}{4}\big[\mathrm{BE}(N,Z)-\mathrm{BE}(N-2,Z)-\mathrm{BE}(N,Z-2)+\mathrm{BE}(N-2,Z-2)\big]. \tag{11}$$

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

$$\delta V(N,Z)=\frac{1}{4}\big(G_{i,i}^{T=1}+3G_{i,i}^{T=0}\big)\quad \text{for } N=Z \tag{12}$$

and

$$\delta V(N,Z)=0\quad \text{for } N\neq Z. \tag{13}$$

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

$$\delta V(N,Z)=\frac{1}{2}G_{i,i}^{>}\quad \text{for } N=Z \tag{14}$$

and

$$\delta V(N=Z+2,Z)=\frac{1}{8}G_{i,i}^{T=1}+\frac{3}{8}G_{i,i}^{T=0}-\frac{1}{4}G_{i,i}^{>}\quad \text{for } N=Z+2, \tag{15}$$

where $G_{i,i}^{>}$ 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 $\delta V(N=Z+2,Z)=(1/4)G_{i,i}$.

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

$$W(A)=\delta V\left(\frac{A}{2},\frac{A}{2}\right)-\frac{1}{2}\left[\delta V\left(\frac{A}{2},\frac{A}{2}-2\right)+\delta V\left(\frac{A}{2}+2,A\right)\right]. \tag{16}$$

For odd–odd nuclei, the Wigner energy is

$$W(A)=\frac{1}{2}\left[\delta V\left(\frac{A}{2}-1,\frac{A}{2}-1\right)+\delta V\left(\frac{A}{2}+1,\frac{A}{2}+1\right)\right]-\delta V\left(\frac{A}{2}+1,\frac{A}{2}-1\right). \tag{17}$$

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.

$$d(A)=2\left[\delta V\left(\frac{A}{2},\frac{A}{2}-2\right)+\delta V\left(\frac{A}{2}+2,\frac{A}{2}\right)\right]-4\delta V\left(\frac{A}{2}+1,\frac{A}{2}-1\right). \tag{18}$$

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}OO, 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

$$W(A)^{e\text{-}e}=\frac{1}{4}\big(3*G_{i,i}^{T=0}+G_{i,i}^{T=1}\big), \tag{19}$$

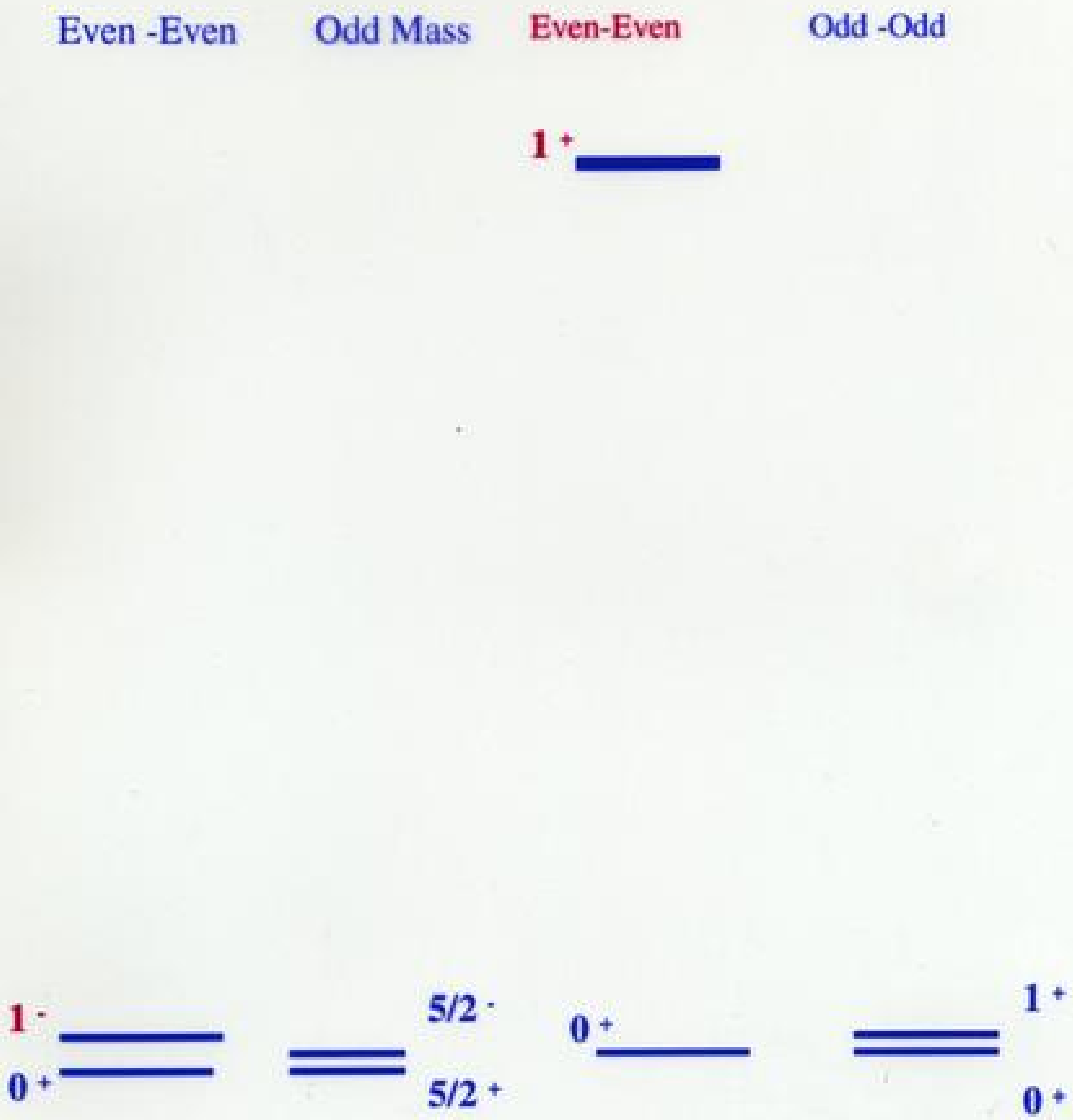
$$W(A)^{o\text{-}o}=\frac{1}{4}\big(3*G_{i,i}^{T=0}+G_{i,i}^{T=1}\big), \tag{20}$$

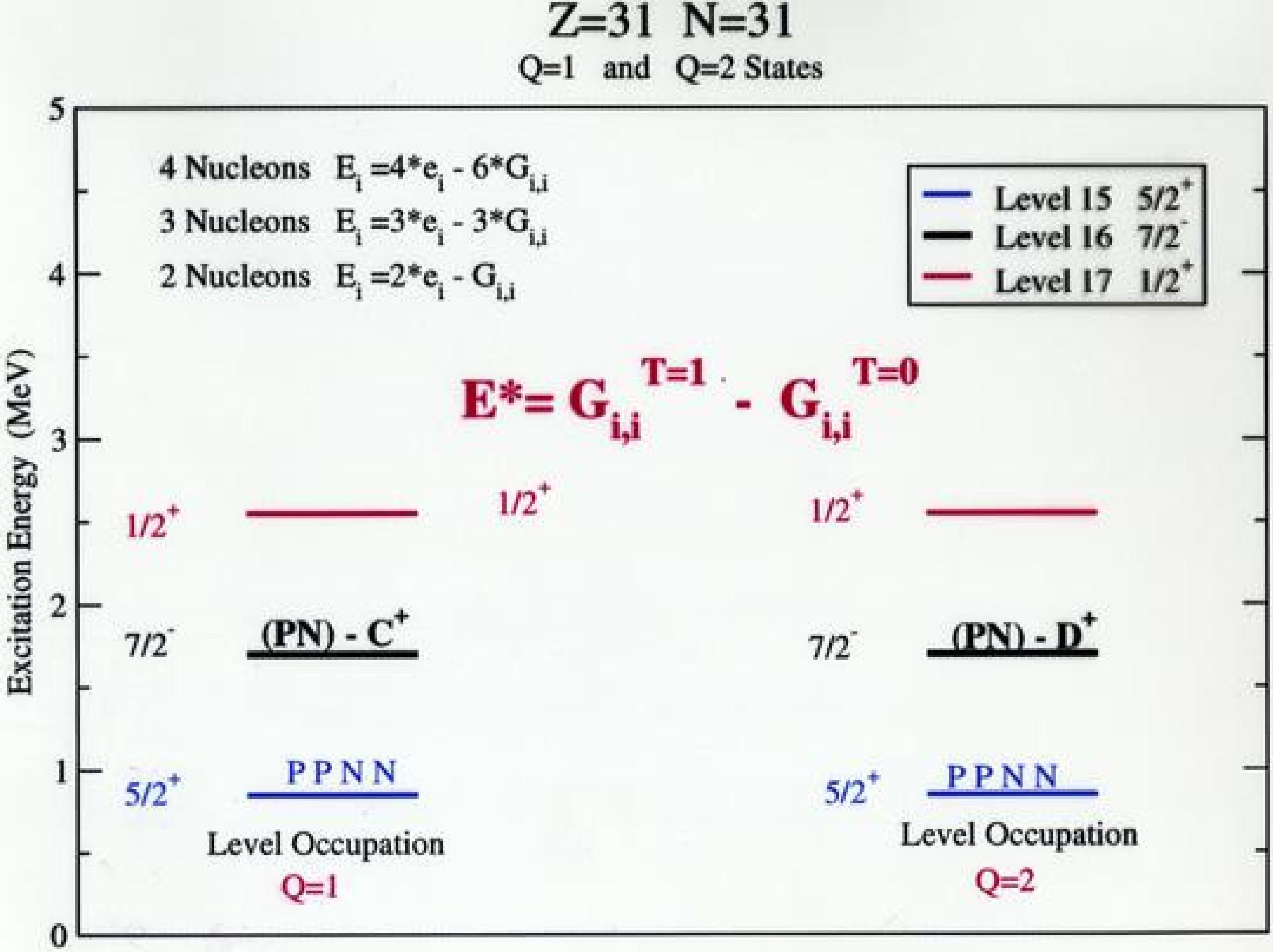
$$d(A)=\frac{1}{2}\big(G_{i,i}^{T=0}+G_{i,i}^{T=1}\big)+\big(G_{i,i}^{T=0}-G_{i,i}^{>}\big). \tag{21}$$

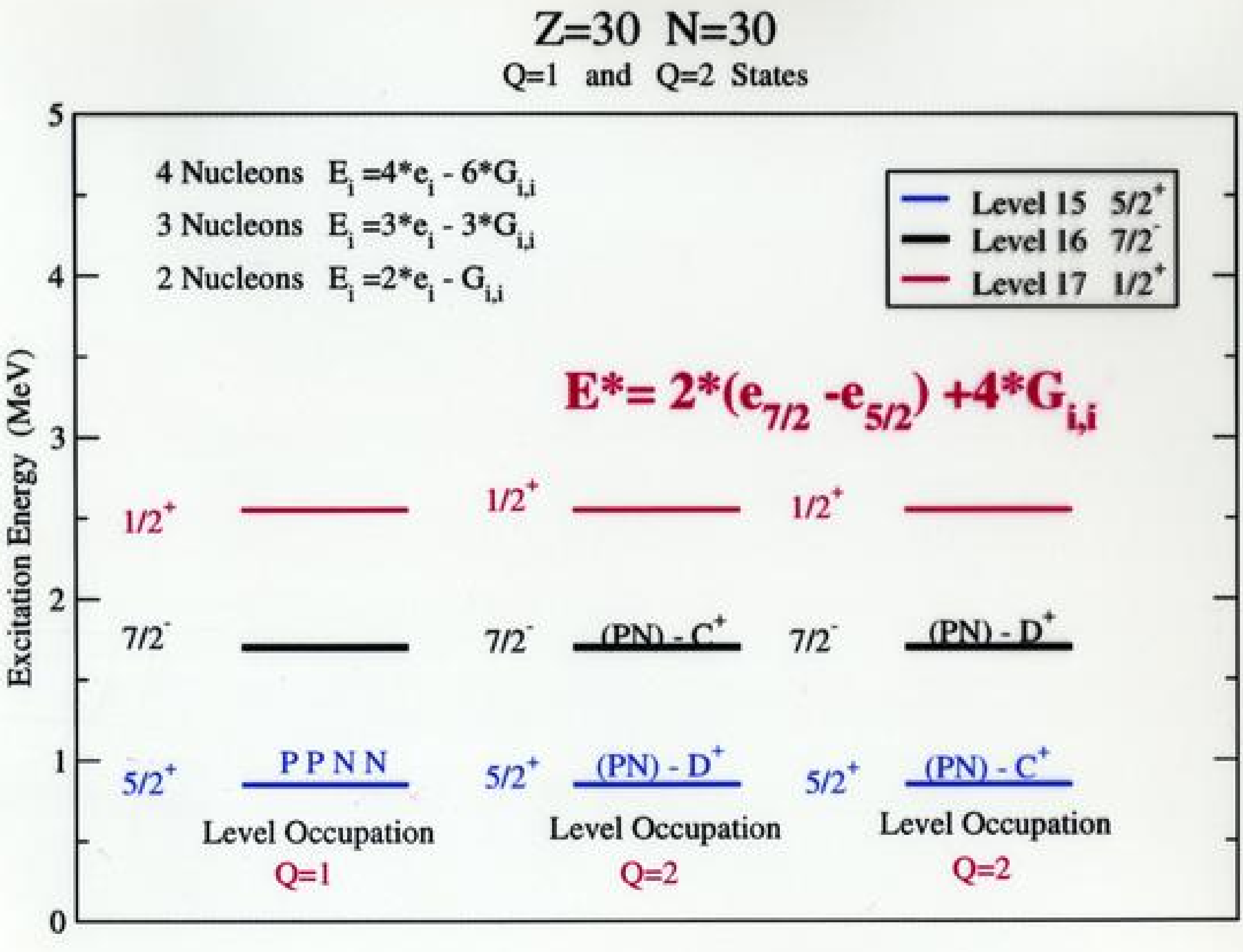
The fact that the $T=0$ matrix elements dominate the expression for $W(A)$ does not mean that $T=0$ pairing

Octupole Deformation

n-p Pairing



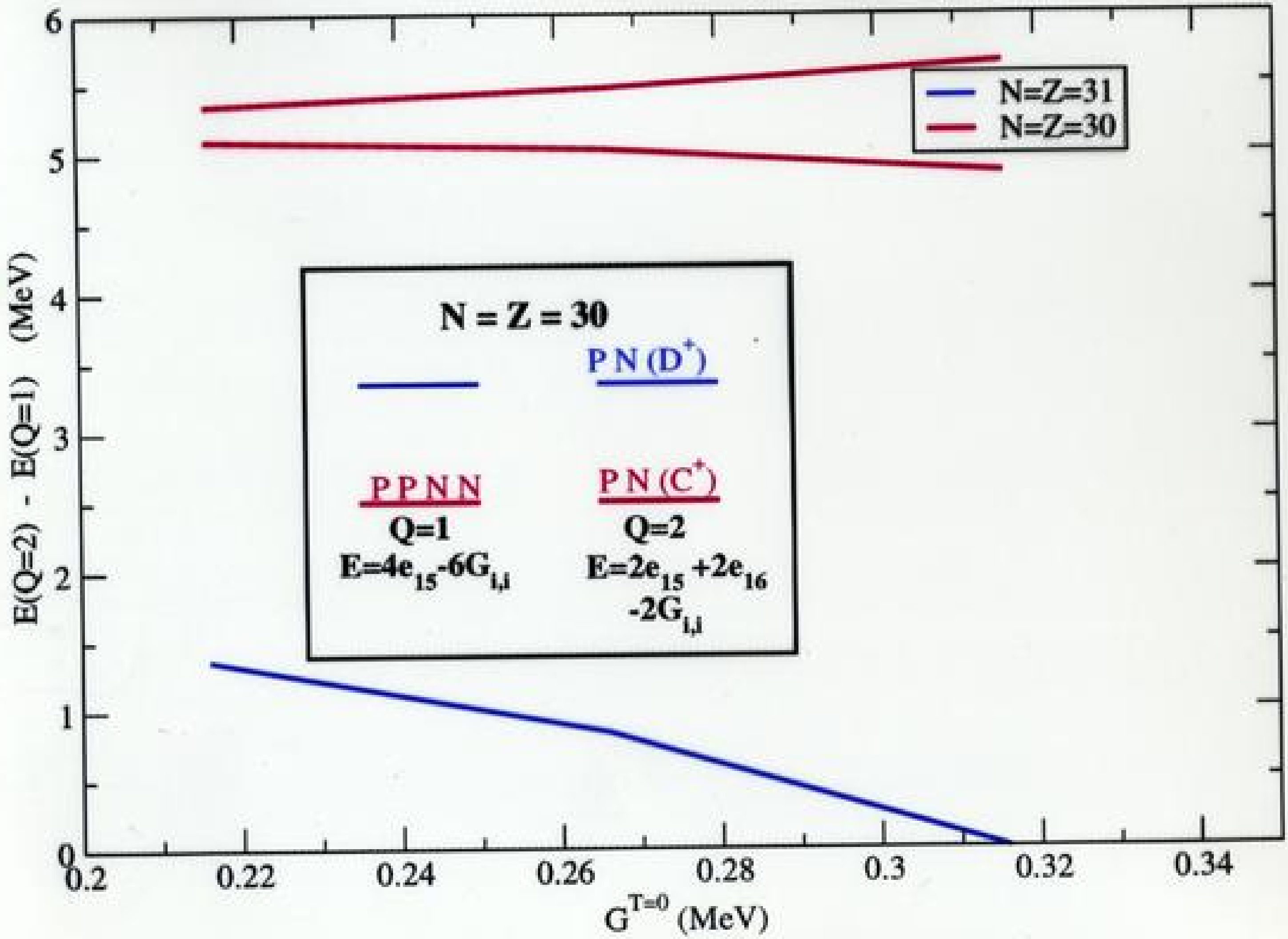

Z=31 N=31
Q=1 and Q=2 States
4 Nucleons E_i =4*e_i - 6*G_i,i
3 Nucleons E_i =3*e_i - 3*G_i,i
2 Nucleons E_i =2*e_i - G_i,i
Level 15 5/2+
Level 16 7/2-
Level 17 1/2+
E*= G_i,i^T=1 - G_i,i^T=0
1/2+
7/2-
(PN) - C+
(PN) - D+
5/2+
P P N N
Level Occupation
Q=1
Q=2
Excitation Energy (MeV)
0
1
2
3
4
5



Z=30 N=30
Q=1 and Q=2 States
4 Nucleons $E_i = 4*e_i - 6*G_{i,i}$
3 Nucleons $E_i = 3*e_i - 3*G_{i,i}$
2 Nucleons $E_i = 2*e_i - G_{i,i}$
Level 15 $5/2^+$
Level 16 $7/2^-$
Level 17 $1/2^+$
$E^* = 2*(e_{7/2} - e_{5/2}) + 4*G_{i,i}$
Excitation Energy (MeV)
0
1
2
3
4
5
$1/2^+$
$7/2^-$
$5/2^+$
P P N N
(PN) - C^+
(PN) - D^+
Level Occupation
Q=1
Q=2

Q-splitting in N=Z Nuclei

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



Excitation Of 1^+ States in E-E N=Z Nuclei

Systematics

E(T=1) - E(T=0) =

$150/A + 24/A^{1/2}$

$\sim 5.6 MeV$ at $A = 60$

A.O. Macchiavelli et al.
AIP Conf. Proc. 656 (2003) 241

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

$$G_{i,j} = 19/A; \;\; G_{i,i} = 45.6/A$$

$\Delta\epsilon = 0.85 MeV$ for $A \sim 60$

Even - Even Nuclei

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

$E(Q=2) - E(Q=1) \sim 182/A + 2 * \Delta\epsilon$

Odd - Odd Nuclei

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

Wigner Energy

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

$E(Wigner) \sim 46/A$

Conclusion

Both Wigner Energy

and Symmetry Energy

are relatively insensitive to Many Body Correlations in Ψ

They depend primarily on diagonal matrix elements

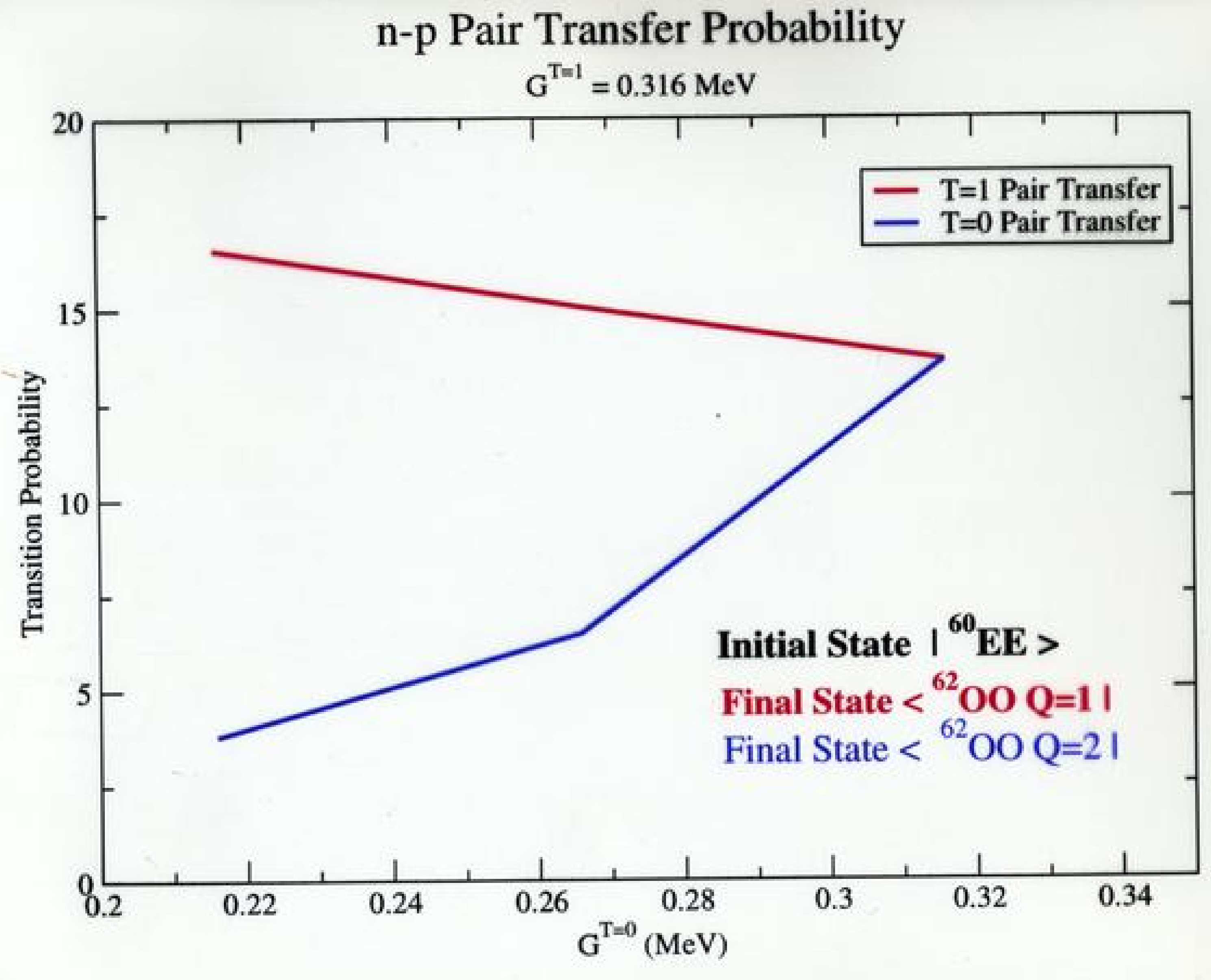
'The Smoking Gun'
Pair Transfer Spectroscopic Factor

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

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

In the no correlation limit

the spectroscopic factor is 1.0



n-p Pair Transfer Probability
G^{T=1} = 0.316 MeV
T=1 Pair Transfer
T=0 Pair Transfer
Initial State | 60EE >
Final State < 62OO Q=1 |
Final State < 62OO Q=2 |
Transition Probability
G^{T=0} (MeV)
0
5
10
15
20
0.2
0.22
0.24
0.26
0.28
0.3
0.32
0.34

K E Rehm et al.

TABLE I. Excitation energies, resonance energies, spectroscopic factors, widths (calculated using R-matrix [RM] theory or a Woods-Saxon [WS] potential), and resonance strengths for the astrophysical reaction rate calculations. For comparison, the last column gives the proton widths calculated in Ref. [18].

J^π	E_x (MeV)	E_r (MeV)	C^2S	Γ_p^{RM} (eV)	Γ_p^{WS} (eV)	Γ_γ^a (eV)	$\omega\gamma^{RM}$ (eV)	Γ_p^* (eV)
$5/2^-$	1.028	0.333	0.9	9.1×10^{-12}	5.6×10^{-12}	3.8×10^{-6}	2.7×10^{-11}	6.1×10^{-11}
$1/2^-$	1.106	0.411	0.9	1.9×10^{-7}	1.8×10^{-7}	1.3×10^{-2}	1.9×10^{-7}	1.5×10^{-8}
$5/2^-$	2.398	1.703	<0.2	<1	<0.8	2.3×10^{-2}	6.9×10^{-2}	8.5×10^{-2}
$7/2^-$	2.520	1.825	<0.2	<2.5	<1.6	1.3×10^{-2}	5.2×10^{-2}	7.0×10^{-2}

^{a}From Ref. [17].

The astrophysical reaction rates are shown in Fig. 4 as a function of the temperature T_9. Since the proton widths are much smaller than the γ widths, the yield from the first two ($5/2^-$ and $1/2^-$) resonances is proportional to these widths and not sensitive to the precise values of the γ widths. In the temperature region $T_9 < 1$, the $1/2^-$ state completely dominates (see dot-dashed line in Fig. 4). Higher-lying states in ^{57}Cu with $E_x > 2.5$ MeV contribute only at temperatures $T_9 > 1$. 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 $1/2^-$ state, their estimate of the reaction rate for the ^{56}Ni$(p,\gamma)^{57}$Cu reaction is lower by more than an order of magnitude in the temperature region below $T_9 = 1$.

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.

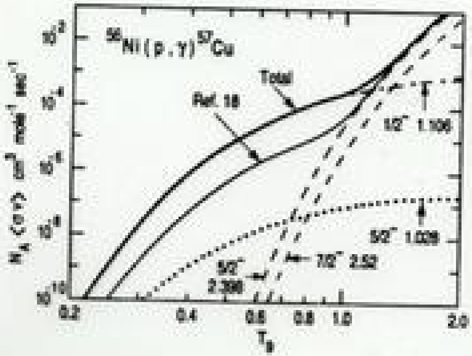


FIG. 4. Astrophysical reaction rates $N_A\langle\sigma v\rangle$ for the ^{56}Ni$(p,\gamma)^{57}$Cu reaction calculated with the resonance strengths $\omega\gamma$ given in Table I. The contributions from various low-lying states are presented. The total rate is also compared with that of Ref. [18].

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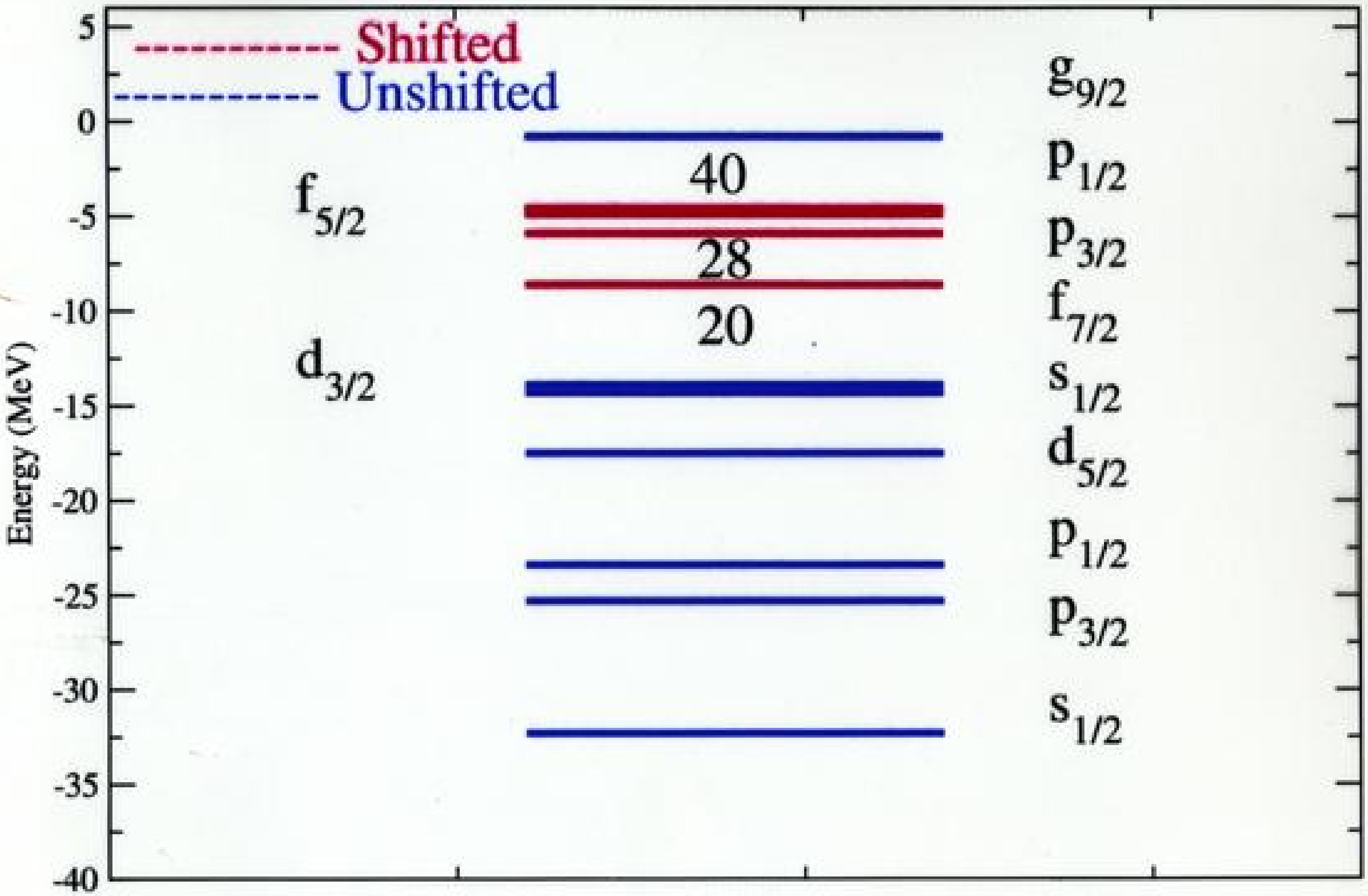
Adjusted Woods-Saxon Levels



^{58}Ni(p,nγ) 72So26,71Ki17 (continued)

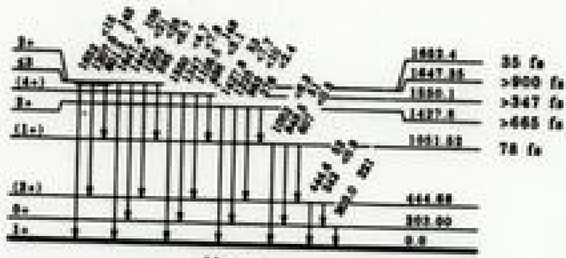
γ(^{58}Cu) (continued)

Eγ[†]	E(level)	Iγ[§]
1647.4 2	1647.35	100 #
1682	1682.4	<15[#]
*2165[‡] 2		

† From 72So26. Other: 71Ki17.
‡ From 71Ki17.
§ Relative intensities at θ=90°, E(p)=16 MeV from 71Ki17, unless indicated otherwise.
# γ not seen by 71Ki17. Iγ based on upper limit of branching reported by 72So26.
* γ ray not placed in level scheme.

Level Scheme

Intensities: relative Iγ



$^{58}_{29}Cu_{29}$

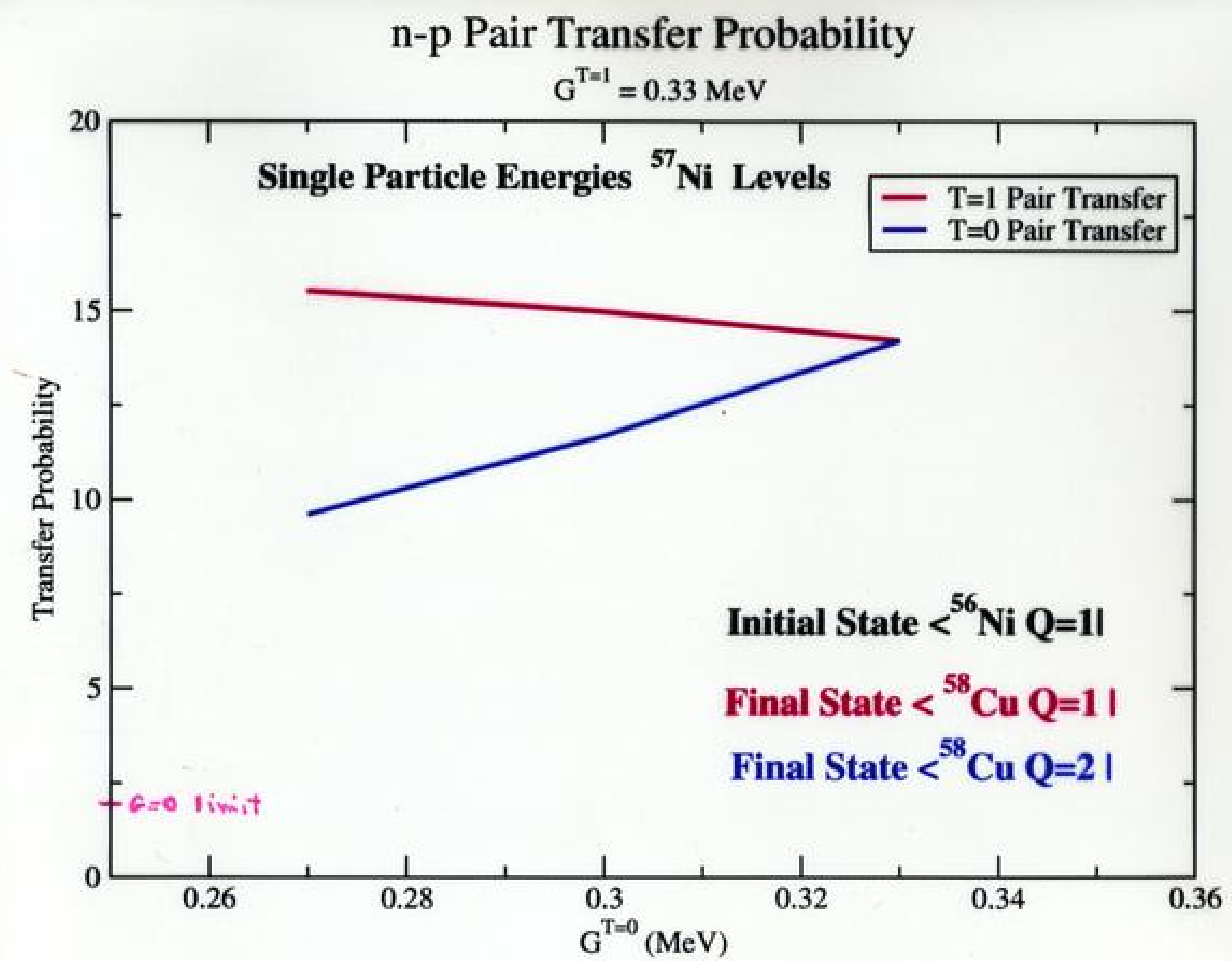
^{58}Ni(^{3}He,t) 72Ru03,72Be38

94Ak02,93Fu2X: E=450 MeV, FWHM=210 keV; observed strong excitation of Gamow-Teller (G-T) and spin flip (ΔL) resonances and fine structure of G-T strength in ^{58}Cu.
90Va06,89Va09: E=72 MeV, FWHM=80 keV; deduced effective projectile-nucleon force.
72Ru03: E=24 MeV, FWHM=40-60 keV.
72Be38: E=24.6 MeV, FWHM=10 keV.
Measured: σ(E,θ), DWBA analysis.

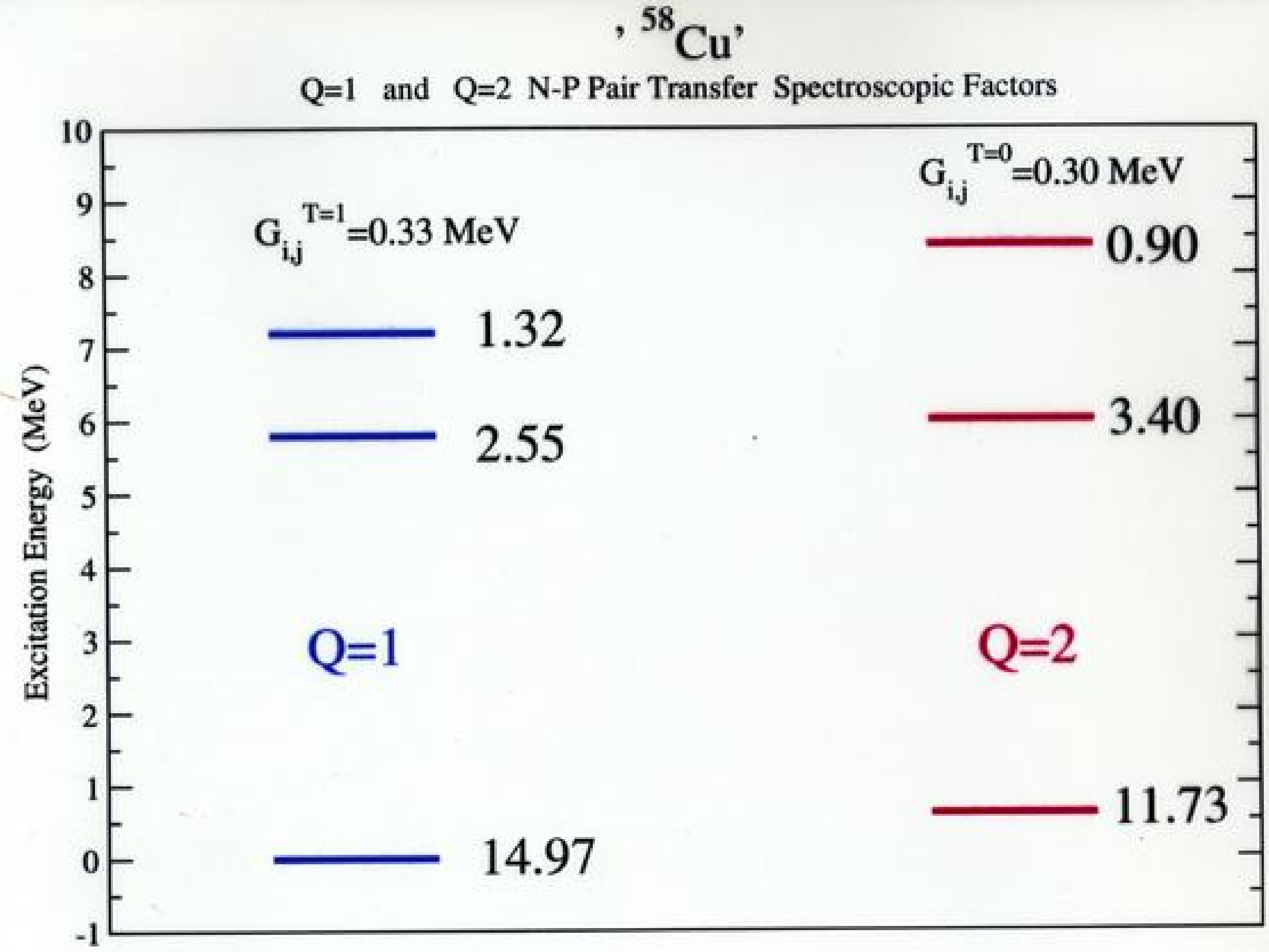
^{58}Cu Levels

E(level)[†]	L[‡]	Comments
0.0	0+2	
202 15	0	
441 15	(2+4)	
1051 15	(0+2)	
1426 15	2	
1556 15	(4)	L: from 72Be38.
1667 15	2	
2070 20		
2170 20		
2270 20		
2680 20	4	
2780 20		
2840 20		
2940 20	(4+6)	
3230 20		
3310 20		

Continued on next page (footnotes at end of table)



n-p Pair Transfer Probability
G^T=1 = 0.33 MeV
Single Particle Energies 57Ni Levels
T=1 Pair Transfer
T=0 Pair Transfer
Transfer Probability
Initial State <56Ni Q=1|
Final State < 58Cu Q=1 |
Final State <58Cu Q=2 |
0
5
10
15
20
0.26
0.28
0.3
0.32
0.34
0.36
G^T=0 (MeV)


, 58Cu'
Q=1 and Q=2 N-P Pair Transfer Spectroscopic Factors
Excitation Energy (MeV)
10
9
8
7
6
5
4
3
2
1
0
-1
G i,j T=1 =0.33 MeV
G i,j T=0 =0.30 MeV
1.32
2.55
14.97
0.90
3.40
11.73
Q=1
Q=2

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 α-like correlations $W^\dagger$
- triple projection before variation Z,N,Q
- blocked orbitals complex amplitudes
- Ω-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?


השמים מספרים כבוד אל