Toward a Refinement of the Brink Hypothesis

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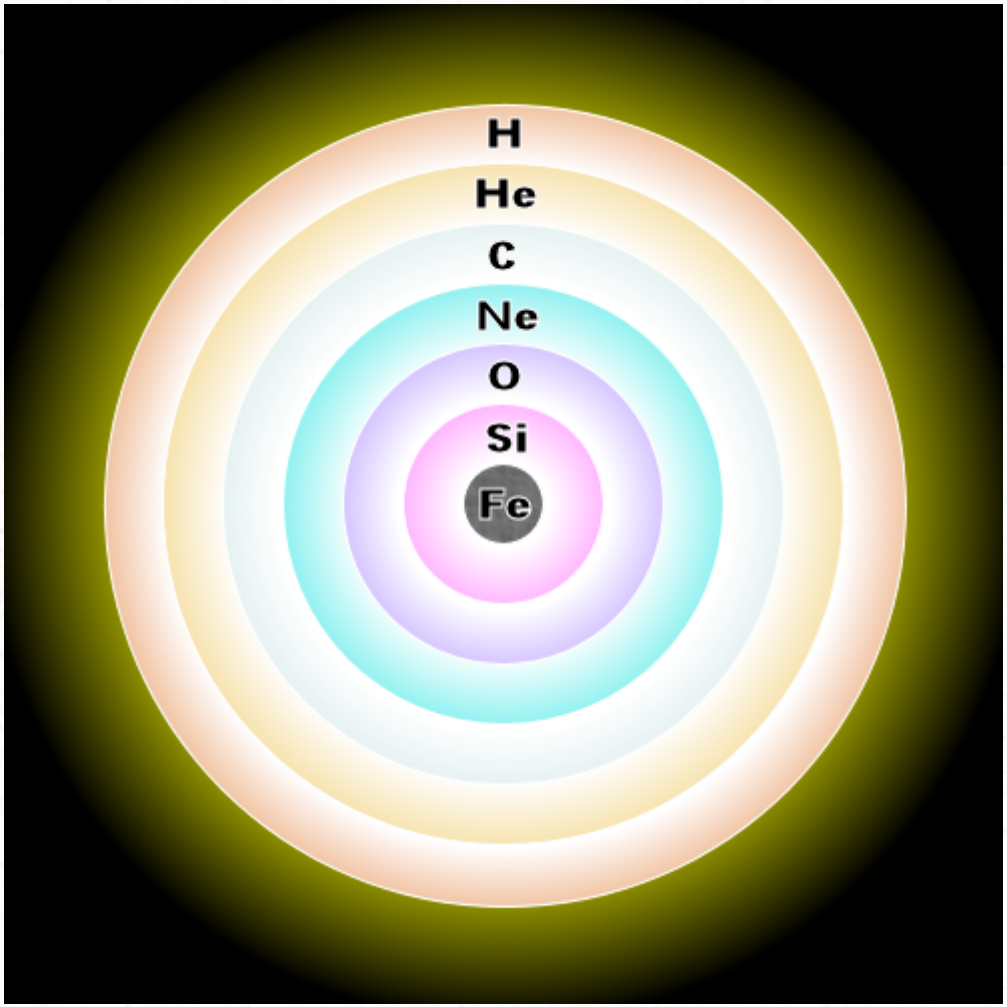
Outline

- Supernova environment
- Nuclear excitations
- Shell model
- Results so far
- Next steps
- Conclusions

Supernova Review

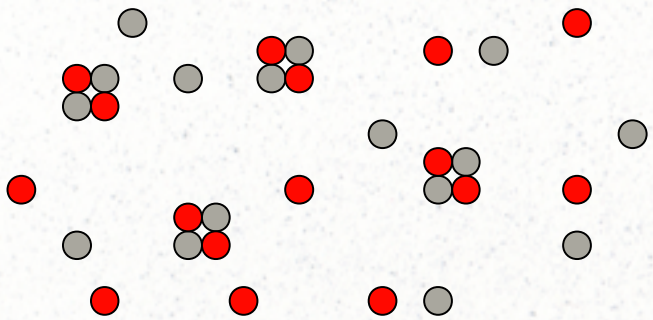
- 8+ solar mass star
- Iron core reaches 1.4 solar masses
- Collapses from GR instability



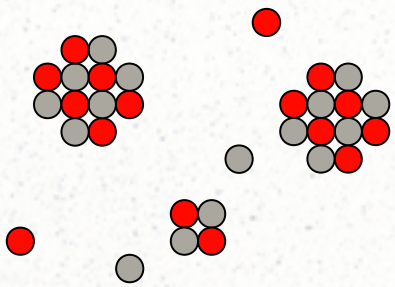
Collapsing core conditions

- Density is high, proceeding from ~10^9 g/cm^3 to >10^{14} g/cm^3 at bounce
- Temperature is ~1-2 MeV
- Electrons degenerate: Fermi energy ~35 MeV
- Entropy is very low: ~1 k_B per baryon
- Consequently, nuclei are large: A ~120

Low entropy, large nuclei



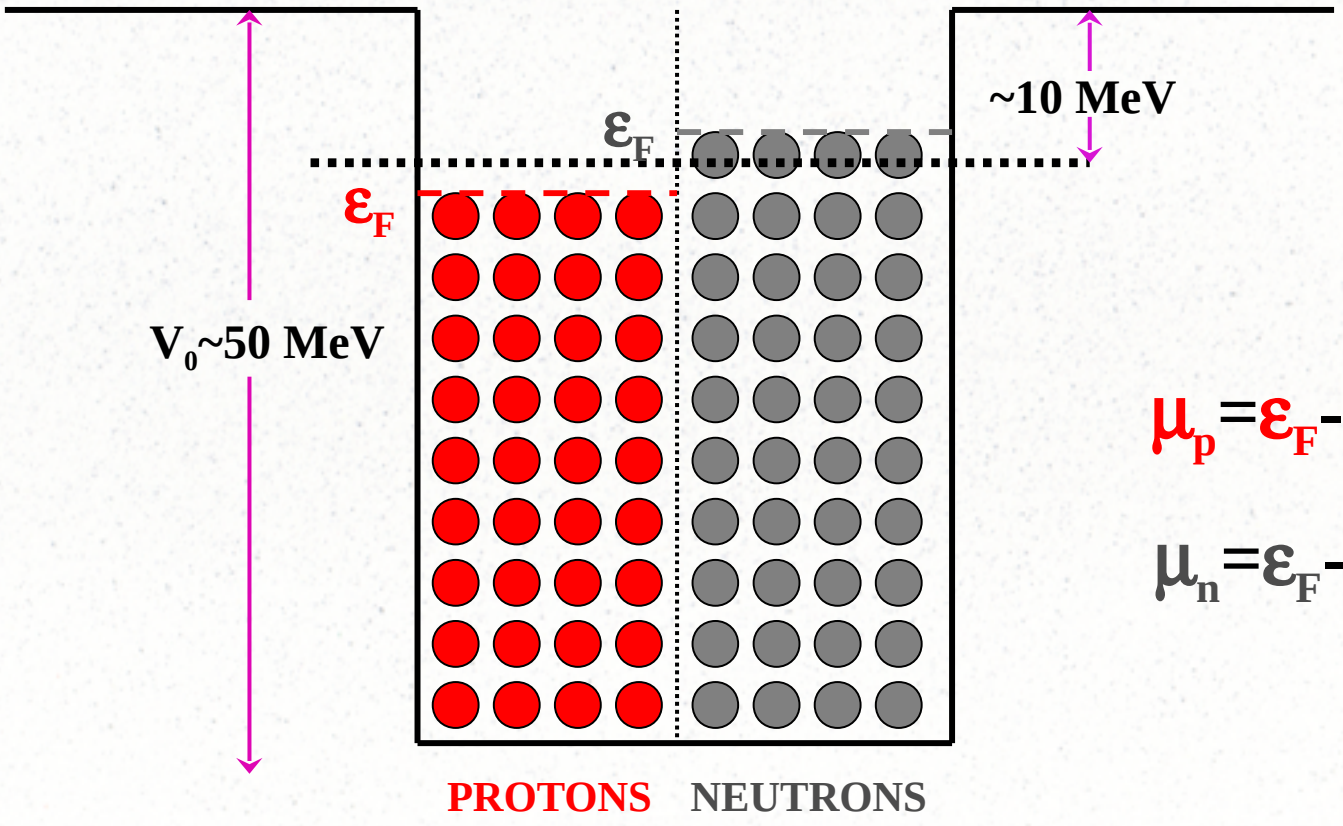
High entropy



Low entropy

Nuclear Excitations

Approximate nuclei as **non-interacting** plane waves in collective spherical potential

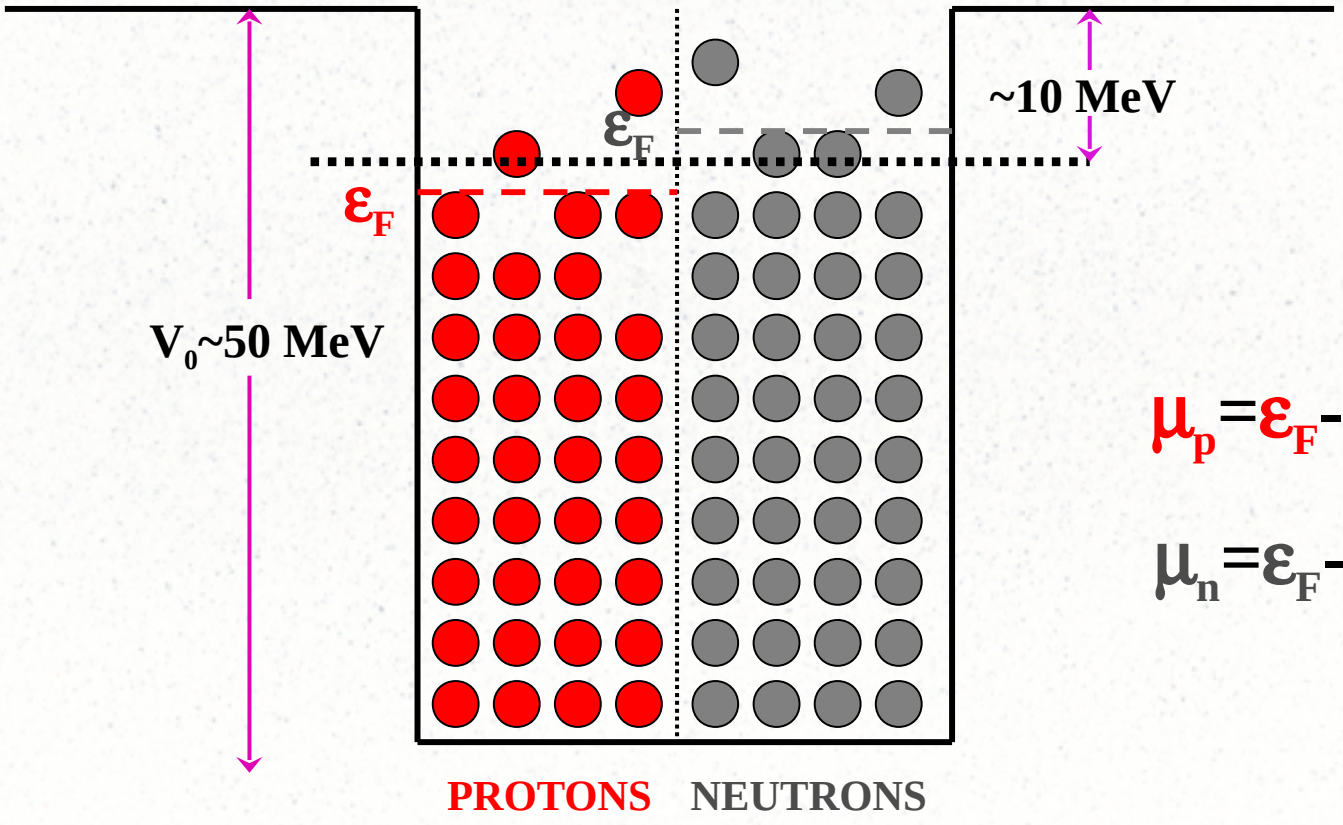


$$\mu_p = \varepsilon_F - V_0$$

$$\mu_n = \varepsilon_F - V_0$$

Nuclear Excitations

Populate thermally by exciting many nucleons a small amount



$\mu_p = \varepsilon_F - V_0$

$\mu_n = \varepsilon_F - V_0$

Nuclear excitation energy

$$\text{level density parameter } a \approx \frac{A}{8}\,\text{MeV}^{-1}$$

$$\text{number of excited nucleons} \approx a \times k_b T$$

$$\text{total excitation energy} \approx a \times \left(k_b T\right)^2$$

$$\text{Typical nucleus:}\quad E \approx \frac{120}{8} \times 1.5^2 = 34\,\text{MeV}$$

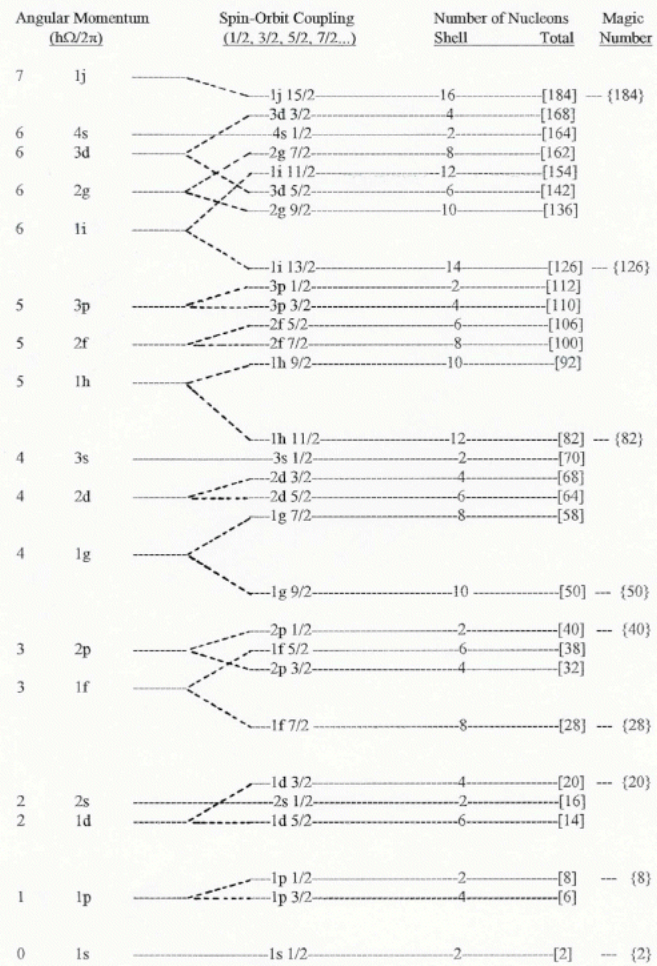
Stage is set

- Degenerate sea of electrons
- Handful of free protons
- 10% free neutrons
- **90% big, highly excited nuclei**
- Thus, physics of nuclei plays important role, and we need something more sophisticated than Fermi gas

Shell Model

- Single particle states in a collective potential
- Construct Slater determinants of configurations with good J and T
- Diagonalize residual Hamiltonian

Table 1 -- Nuclear Shell Structure (from *Elementary Theory of Nuclear Shell Structure*, Maria Goeppert Mayer & J. Hans D. Jensen, John Wiley & Sons, Inc., New York, 1955.)



^{28}Si configuration

^{28}Si completely calculable in sd shell

	p	n
1d 3/2		x
2s 1/2	xx	x
1d 5/2	xxxx	xxxx
	^{16}O	

^{28}Si eigenstate

A_1

	p	n
1d 3/2		
2s 1/2		
1d 5/2	xxxxxx	xxxxxx

+ A_2

	p	n
1d 3/2		
2s 1/2	x	x
1d 5/2	xxxxx	xxxxx

+

A_3

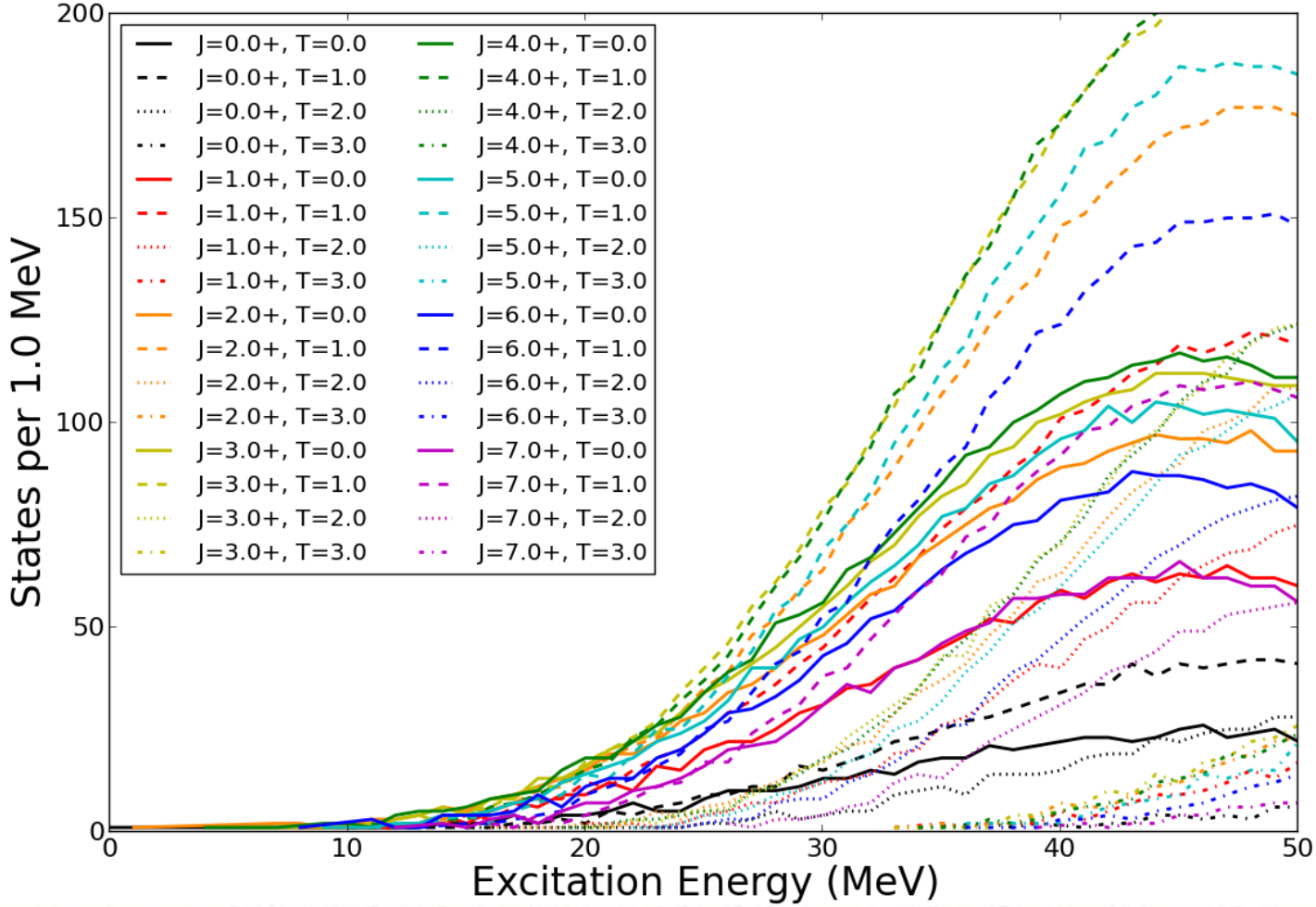
	p	n
1d 3/2	x	x
2s 1/2		
1d 5/2	xxxxx	xxxxx

+ A_4

	p	n
1d 3/2	x	x
2s 1/2	x	x
1d 5/2	xxxx	xxxx

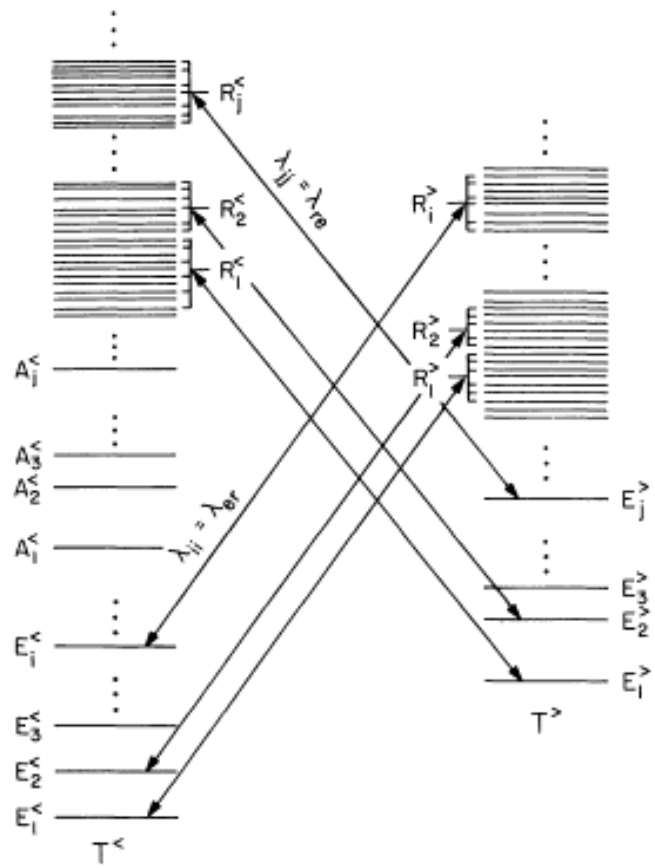
+ ...

Density of States



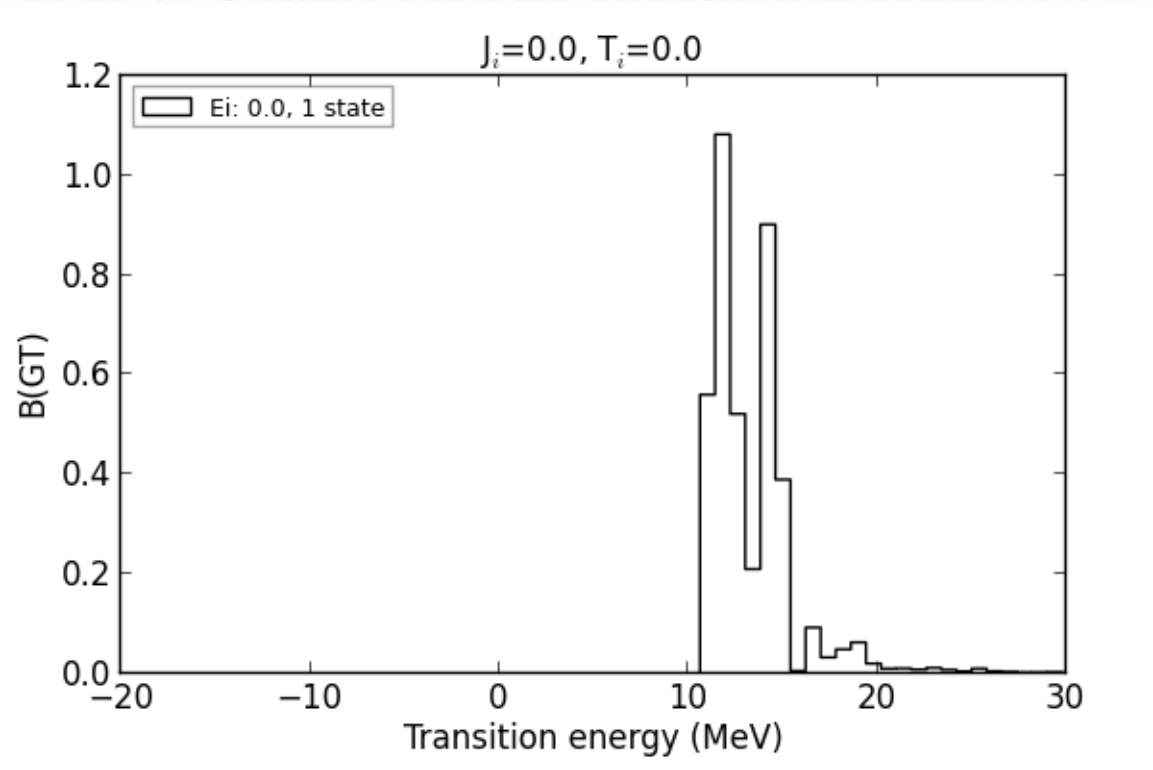
Brink Hypothesis

- Excited states have on average single particle occupations similar to ground state (so similar strength)
- Gamow-Teller resonances at same relative energy in daughter

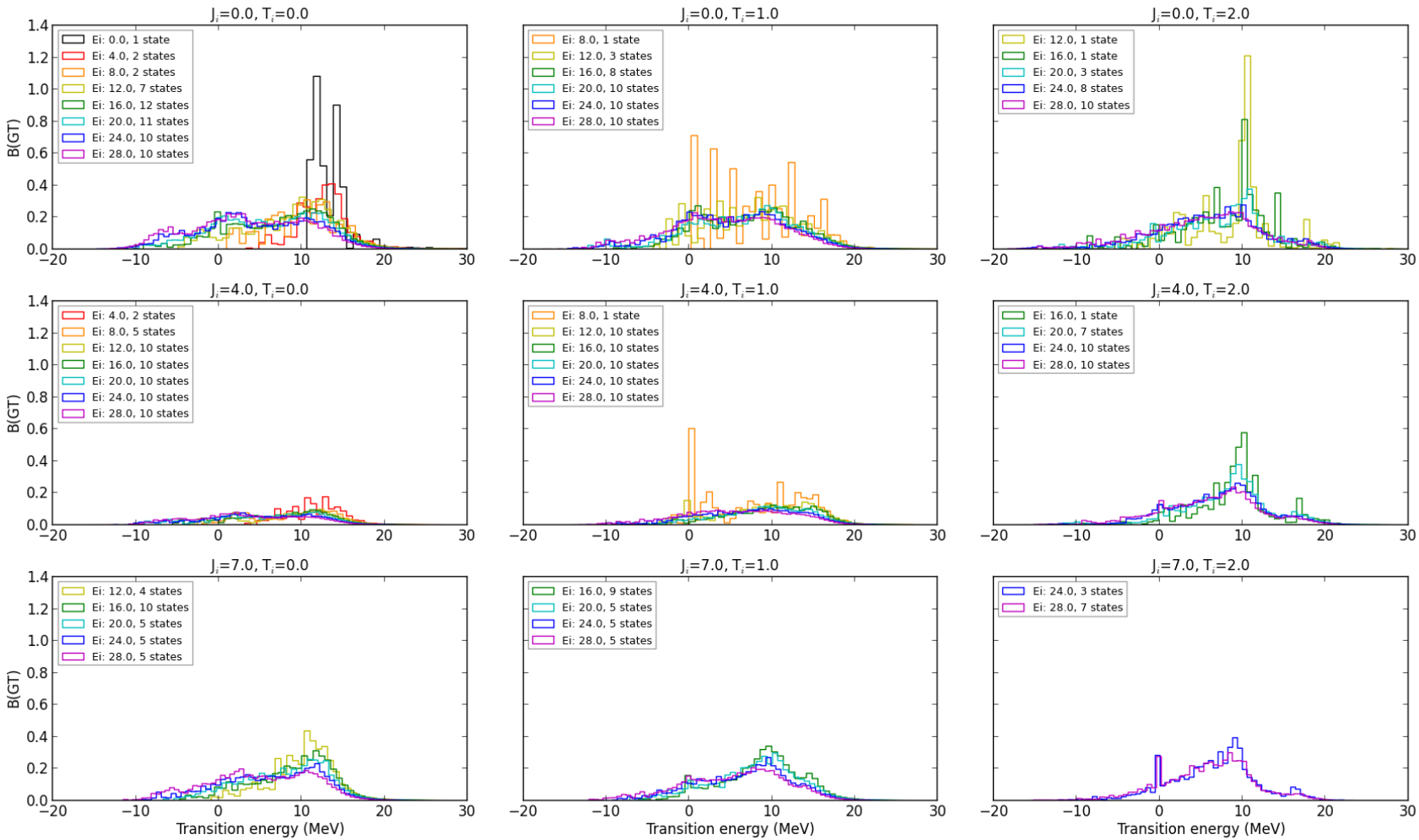


Fuller, Fowler, & Newman (1982)

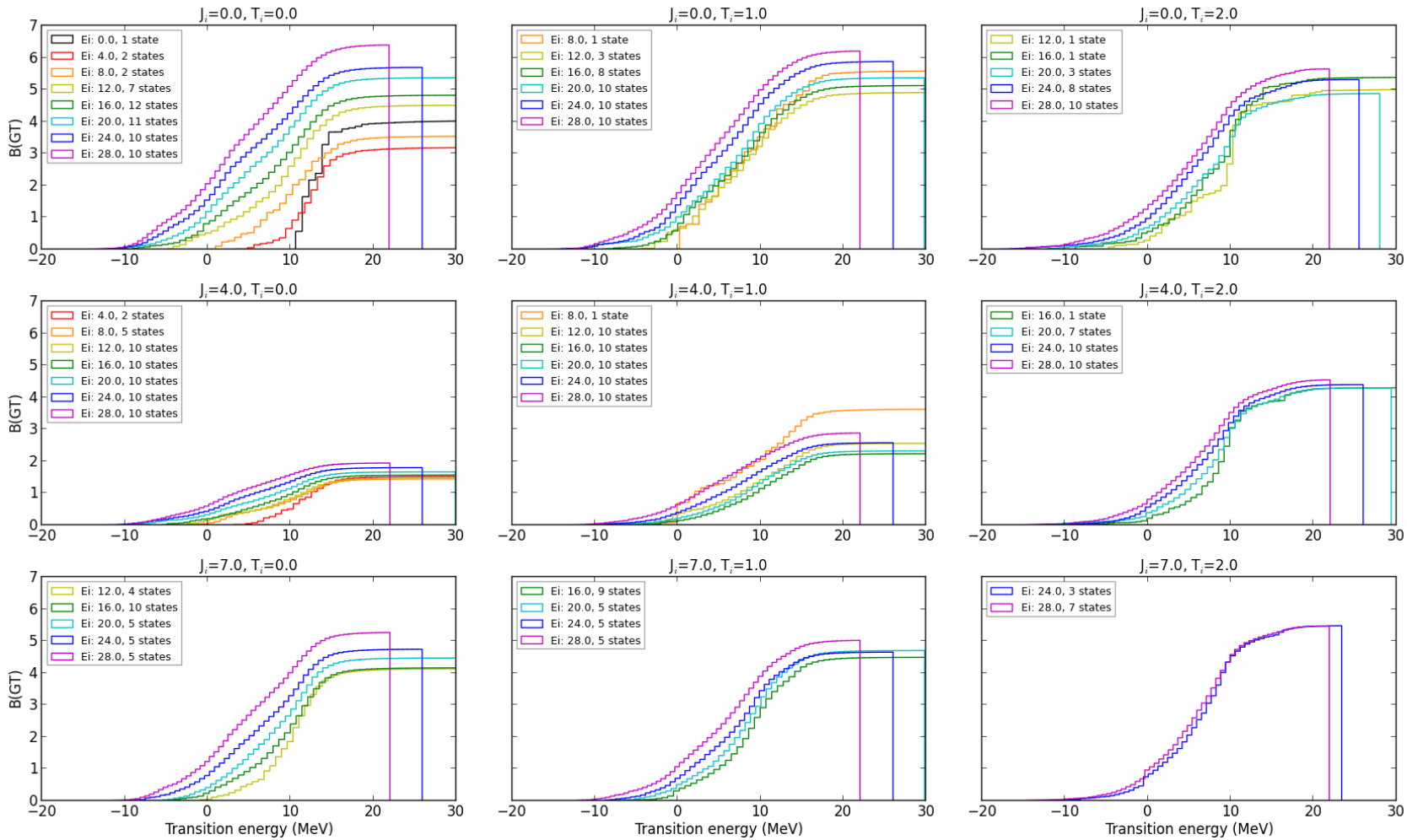
^{28}Si ground state electron capture strength



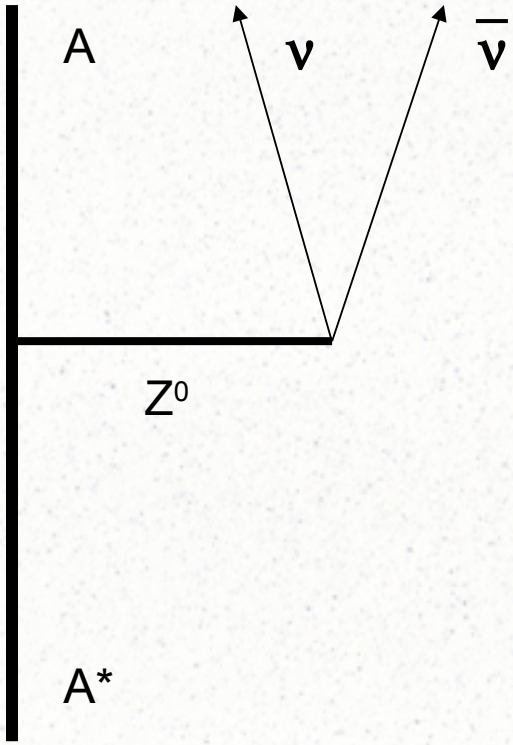
^{28}Si electron capture strength



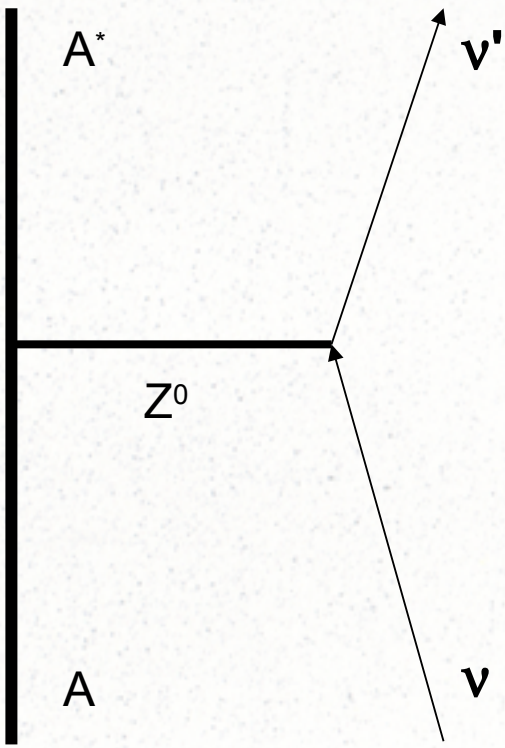
Total Strength



Neutral Current

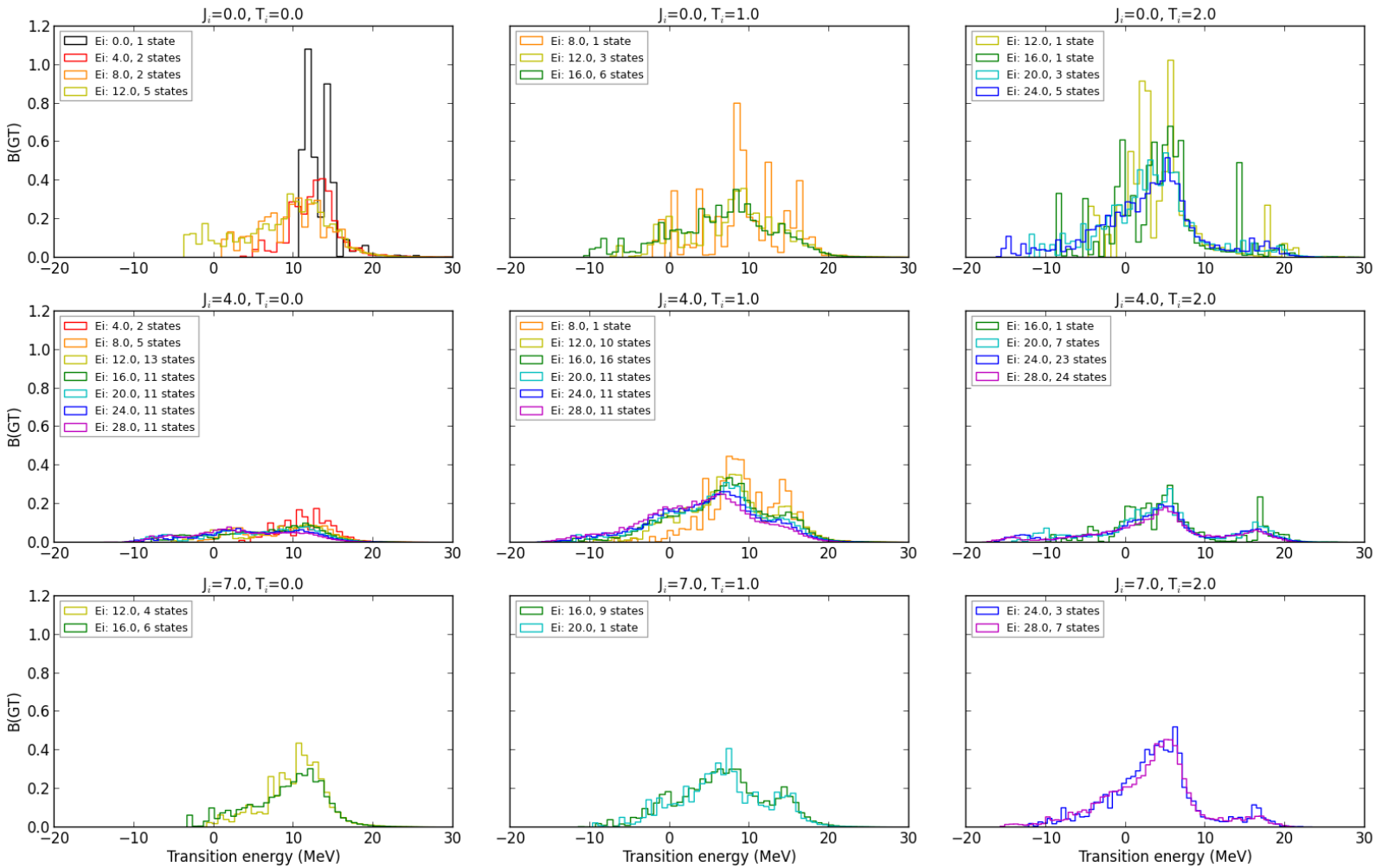


De-excitation: dominant source of low energy **pairs.** Misch, Brown, & Fuller (2013)



Inelestic downscatter: possibly dominant source of low energy neutrinos.

^{28}Si neutral current strength



Modify Brink

- Try to understand shape of distributions and work toward analytic model (possibly difficult)
- But, for given J and T at high enough excitation, Brink seems to work
- Compute table of mini Brink hypotheses, weighted by contribution to partition function (we'll make it work)

Partition Function

1) Sum over "believable" states, integrate from there to cutoff energy

$$Z = \sum_i g_i e^{(-E_i/T)} + \int_{E_0}^{E_{cutoff}} \rho(E) e^{(-E/T)}$$

2) Or, see what people who know better are doing

This seems like a good place to start...

Conclusions

- Nuclear structure plays a key role during infall phase of core collapse
- Important determinant of electron capture and neutrino transport
- Calls for deeper investigation to understand strength distributions and partition function, particularly with an eye toward extension to much more massive, neutron rich nuclei