Nuclear Level Densities Off the Stability Line

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Nuclear Level Densities Off the Stability Line

Fermi Gas assumptions:

1.) Non-interacting fermions

2.) Equi-distant single particle spacing

$$\rho(U) \propto \exp\left[2\sqrt{aU}\right] / U^{3/2}$$

generally successful

Most tests at U < 20 MeV for nuclei near the bottom of
The valley of stability

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Data:

(1) Neutron resonances

U ≈ 7 MeV	near valley of stability

(2) Evaporation spectra

U ≈ 3 to 15 MeV	near valley of stability

(3) Ericson fluctuations

U ≈ 15 to 24 MeV	near valley of stability

(4) Resolved levels

U ≤ 4 to 5 MeV	most points for nuclei in bottom of valley of stability

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Study of Al-Quraishi, et al. $20 \leq A \leq 110$

Found $a = \alpha A \exp[-\gamma (Z-Z_0)^2]$

$\alpha \approx 0.11$ $\gamma \approx 0.04$

Z is Z of nucleus

Z_0 is Z of β stable nucleus of that A

Reduction in a is negligible if $|Z-Z_0| \leq 1$

Significant effect for $|Z-Z_0| = 2$

Large effect for $|Z-Z_0| \geq 3$

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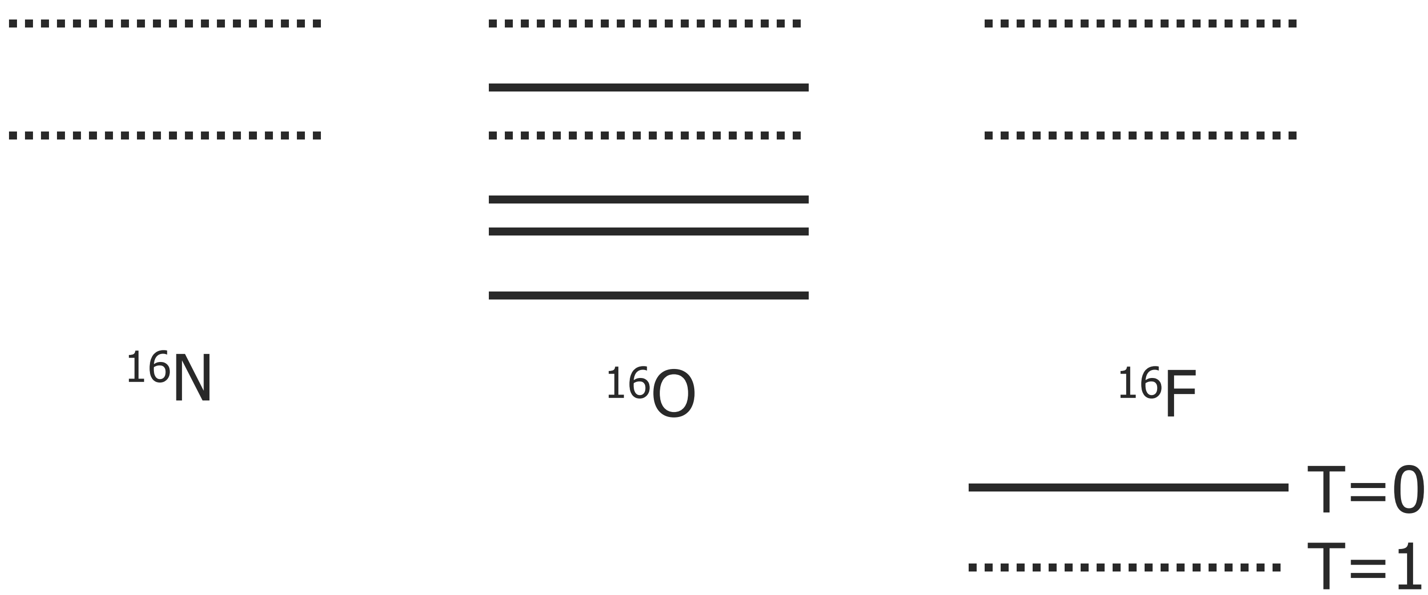
Isospin: $(N\text{-}Z) / 2 = T_Z$



At higher energies, have T=2 multiplets

^{16}C, ^{16}N, ^{16}O, ^{16}F, ^{16}Ne

$\rho(T_Z=0) > \rho(T_Z=1) > \rho(T_Z=2)$ predicts $a = \alpha A \exp[\gamma (N\text{-}Z)^2]$

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COMPLICATION

For $A \leq 40$, $Z\text{-}Z_0 \approx N\text{-}Z$

Thus, there is ambiguity as to whether χ^2 reduction comes from (N-Z) or $(Z\text{-}Z_0)$

Slightly improved χ^2 for $(Z\text{-}Z_0)$

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CONCLUSION

Only one analysis finds a lower off of stability line

Limited data is the central problem

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The bulk of level density information comes from neutron resonances

Example: n + $^{32}S \rightarrow {}^{33}S^*$

At low energy (neutrons) find ½⁺ levels at about 7 MeV of excitation

- Not feasible for unstable targets
- Only get density at one energy
- Need σ (= $\langle J_Z^2 \rangle^{1/2}$) to get total level density

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PREDICTIONS

A compound nucleus state must have a width which is narrow compared to single particle width.

This indicates compound levels will not be present once occupancy of unbound single particle states is substantial.

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Assume we can use Boltzmann distribution as approximation to Fermi-Dirac distribution

Since

$$U = a\theta^2, \quad \theta = \sqrt{U / a}$$

θ is temperature

a is level density parameter

U is excitation energy

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If occupancy of state at excitation energy B is less than 0.1

$$\exp[-B/\theta] = \exp[-B\sqrt{a/U}\,] \le 0.1$$

$$a \approx A/8$$

$$\exp[\,-B\,\sqrt{A/8U}\,] \le 0.1,$$

$$\text{So, } -B\,\sqrt{A/8U} \le -2.3$$

$$U_C \le (\,AB^2 / 42.3\,)$$

Above this energy we will lose states

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A	B (MeV)	U (MeV)	A	B (MeV)	U (MeV)
20	8	30.3	200	8	303.
20	6	17.04	200	6	170.0
20	4	7.58	200	4	75.8
20	2	1.9	200	2	19

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DRIP LINE SYSTEMATICS

A	Z_n	Z_0	Z_p
20	7.2	9.5	11.3
40	12.4	18.4	21.7
60	18.3	27.0	31.4
80	26.7	36.0	40.6
100	30.5	43.2	50.5
150	48.4	62.2	69.5
200	58.3	80.0	88.1

Z_n is Z of neutron-drip-line nucleus; Z_0 is Z in the valley of stability; and Z_p is Z of proton-drip-line nucleus

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For nucleosynthesis processes, we will frequently have

B ~ 4 MeV for proton or neutron

For A ~ 20 level density is substantially reduced by

10 MeV if B = 4

For A ~ 20 level density limit is ≈ B if B = 2 MeV

Substantial reduction in compound resonances

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Will also reduce level density for final nucleus in capture.

We also must consider parity.

In *fp* shell even-even nuclei have more levels of + parity at low U than – parity

Even-odd or odd-even have mostly negative parity states

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Thus, compound nucleus states not only have reduced ρ(U) but also suppress *s*-wave absorption because of parity mismatch

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Experimental Tests

Measure:

$^{55}Mn(d,n)^{56}Fe$

$^{58}Fe(^{3}He,p)^{60}Co$

$^{58}Fe(^{3}He,\alpha)^{57}Fe$

$^{58}Fe(^{3}He,n)^{60}Ni$

$^{58}Ni(^{3}He,p)^{60}Cu$

$^{58}Ni(^{3}He,\alpha)^{57}Ni$

$^{58}Ni(^{3}He,n)^{60}Zn$

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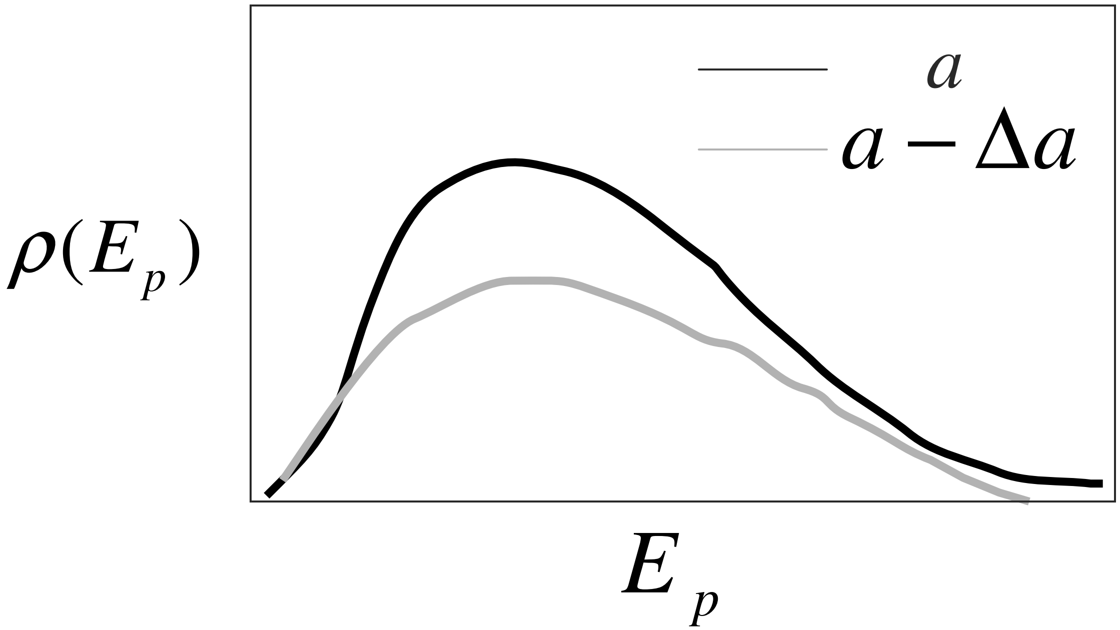
Change in a



Result: lower $a \rightarrow$ higher average E $\rightarrow$ lower multiplicity

If compound nucleus is proton-rich, Al-Quraishi term will further inhibit neutron decay

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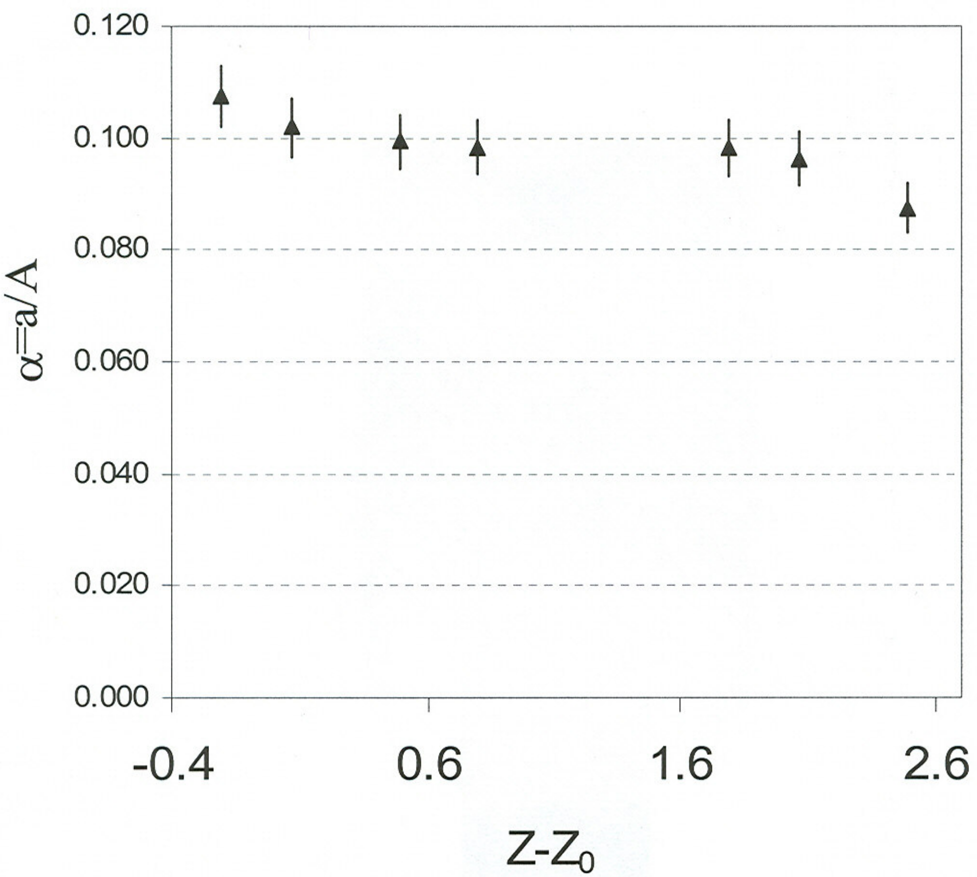

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Expect reduction in a if $|Z-Z_0| \approx 2, 3$

As $|Z-Z_0|$ increases, new form with peak at 5 - 10 MeV may emerge (i.e. $\rho(20) \approx 0$)

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Further Measurements

$^{6}Li + ^{58}Fe \rightarrow ^{64}Cu$ $^{7}Li + ^{57}Fe \rightarrow ^{64}Cu$

$^{7}Li + ^{55}Mn \rightarrow ^{61}Ni$ $^{7}Li + ^{58}Fe \rightarrow ^{65}Cu$

$^{6}Li + ^{59}Co \rightarrow ^{65}Zr$ $^{7}Li + ^{58}Ni \rightarrow ^{65}Ga$

Measure proton and alpha spectra

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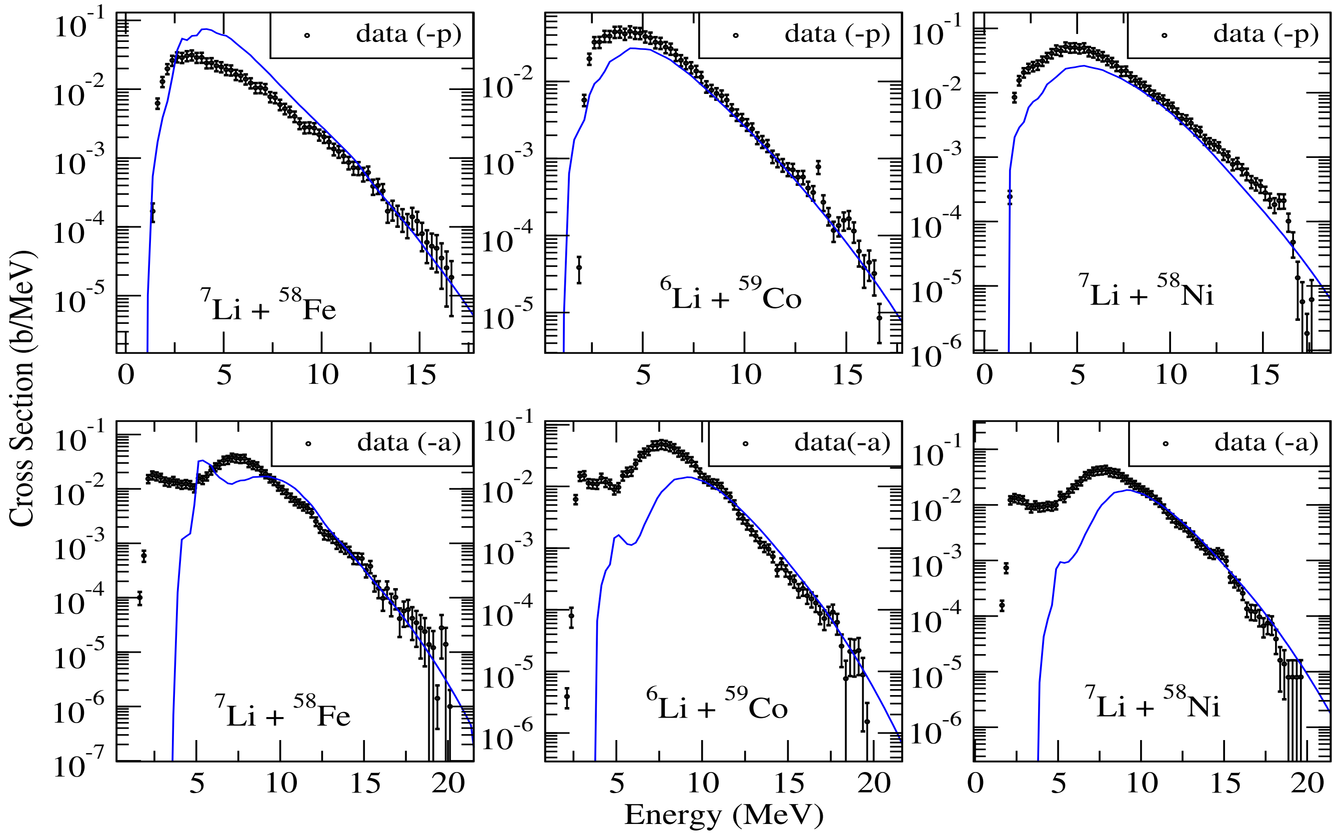
Level Densities for ^{58}Fe, ^{60}Co, ^{61}Co, ^{62}Co, ^{62}Ni, ^{62}Cu, ^{63}Ni, ^{64}Ni, ^{64}Cu, ^{64}Zn

At 15 MeV breakup contributions give E_p, $E_d < 5$ MeV

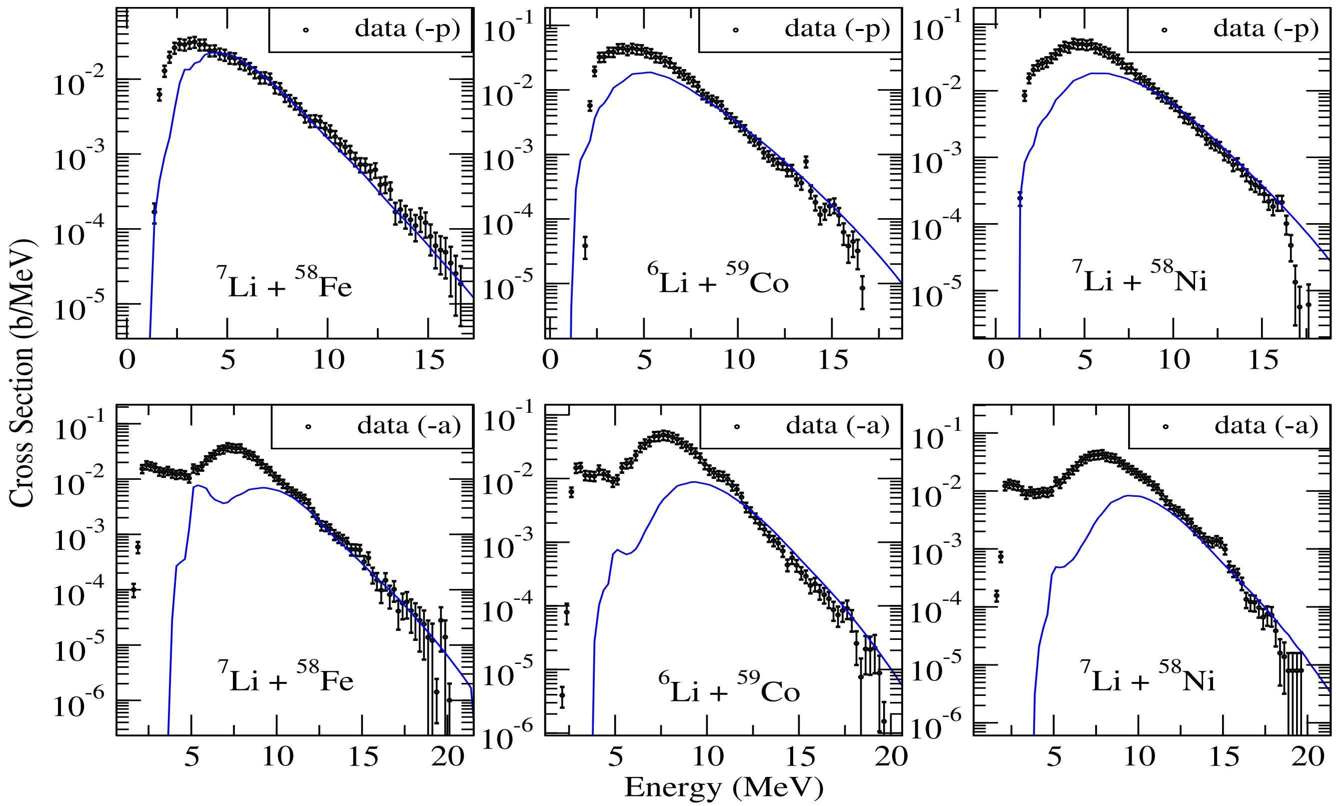
Get spectrum above 5 MeV which is 95% compound based on energy and angle dependence

Nuclear Level Density



Rohr model compared to data

Nuclear Level Density



Al Quraishi model compared to data

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Heavy Ion Reactions

Can get to 30-40 MeV of excitation with lower pre-equilibrium component

Cannot use projectile with A about equal to target (quasi-fission)

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REACTIONS

$^{24}Mg + ^{58}Fe \rightarrow ^{82}Sr^*$

$^{24}Mg + ^{58}Ni \rightarrow ^{82}Zr^*$

$^{18}O + ^{64}Ni \rightarrow ^{82}Kr^*$

Excitation energy $\approx$ 60 MeV

^{82}Kr has $Z = Z_0$

^{82}Sr has $Z = Z_0 + 2$

^{82}Zr has $Z = Z_0 + 4$

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Decay Fractions

	Rohr	Al-Quraishi
^{82}Kr	0.96 n	0.93 n
	0.04 p	0.06 p
	0.005 α	0.01 α
^{82}Sr	0.67 n	0.61 n
	0.25 p	0.33 p
	0.05 α	0.05 α
	0.02 d	0.01 d

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Decay Fractions

	Rohr	Al-Quraishi
^{82}Zr	0.43 n	0.36 n
	0.49 p	0.55 p
	0.06 α	0.07 α
	0.02 d	0.02 d

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If Γ_p and Γ_n are altered, get more important effects for multi-step reactions

Find (x,4p), (x,α+2n2p) and (x,4n) have different ratios for

Conventional level density $a = \alpha A$

Al Quraishi level density $a = \alpha A \exp\left[\gamma (Z - Z_0)\right]$

Can infer even-even nucleus population from $2^+ \rightarrow 0^+_{g.s.}$ gamma cross section

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Rohr: Higher *a* for $|Z-Z_0| \geq 2$

Al-Quraishi: Lower *a* for $|Z-Z_0| \geq 2$

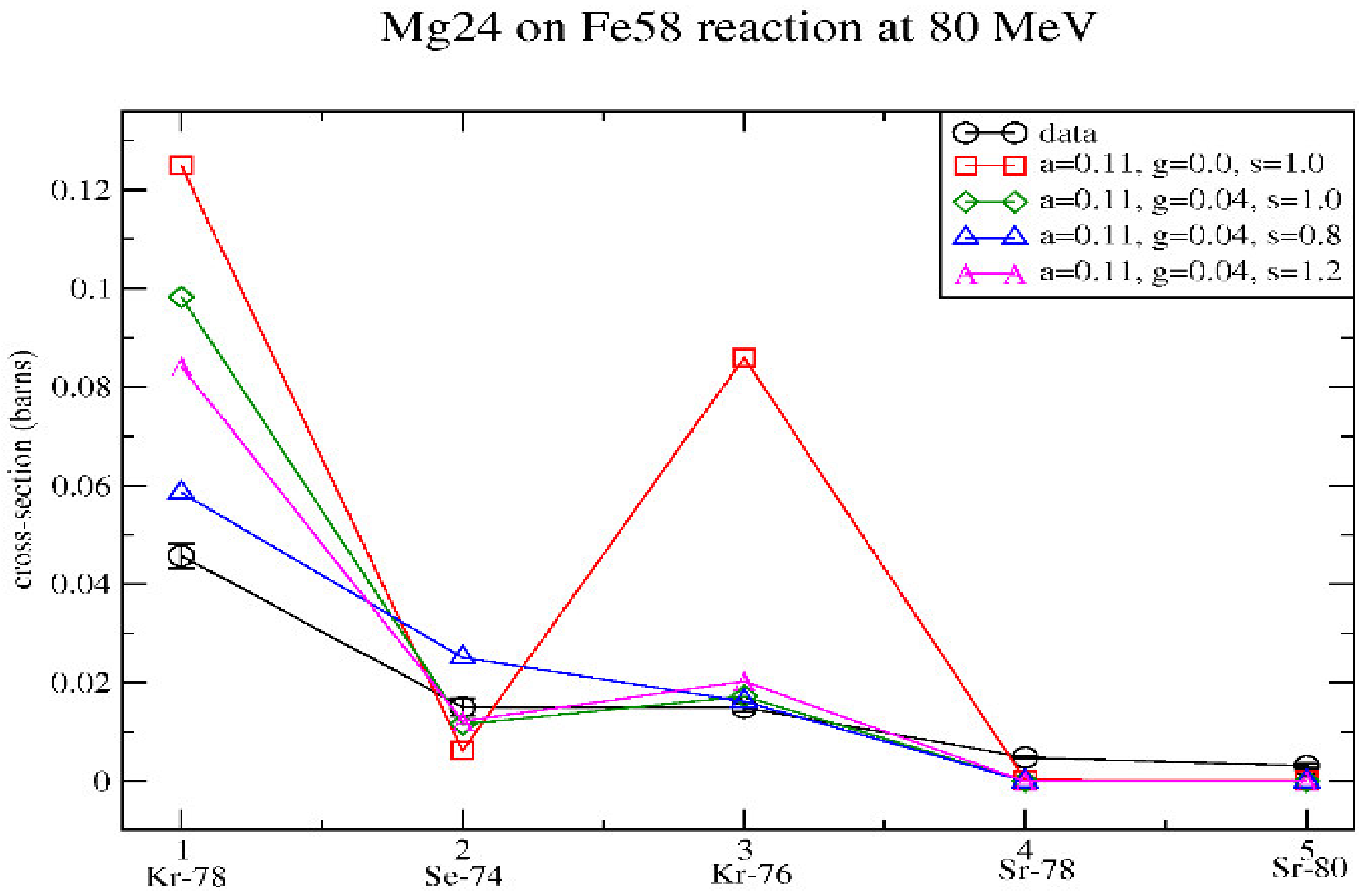
Get softer spectrum with Rohr

More 4-6 particle emissions than Al-Quraishi

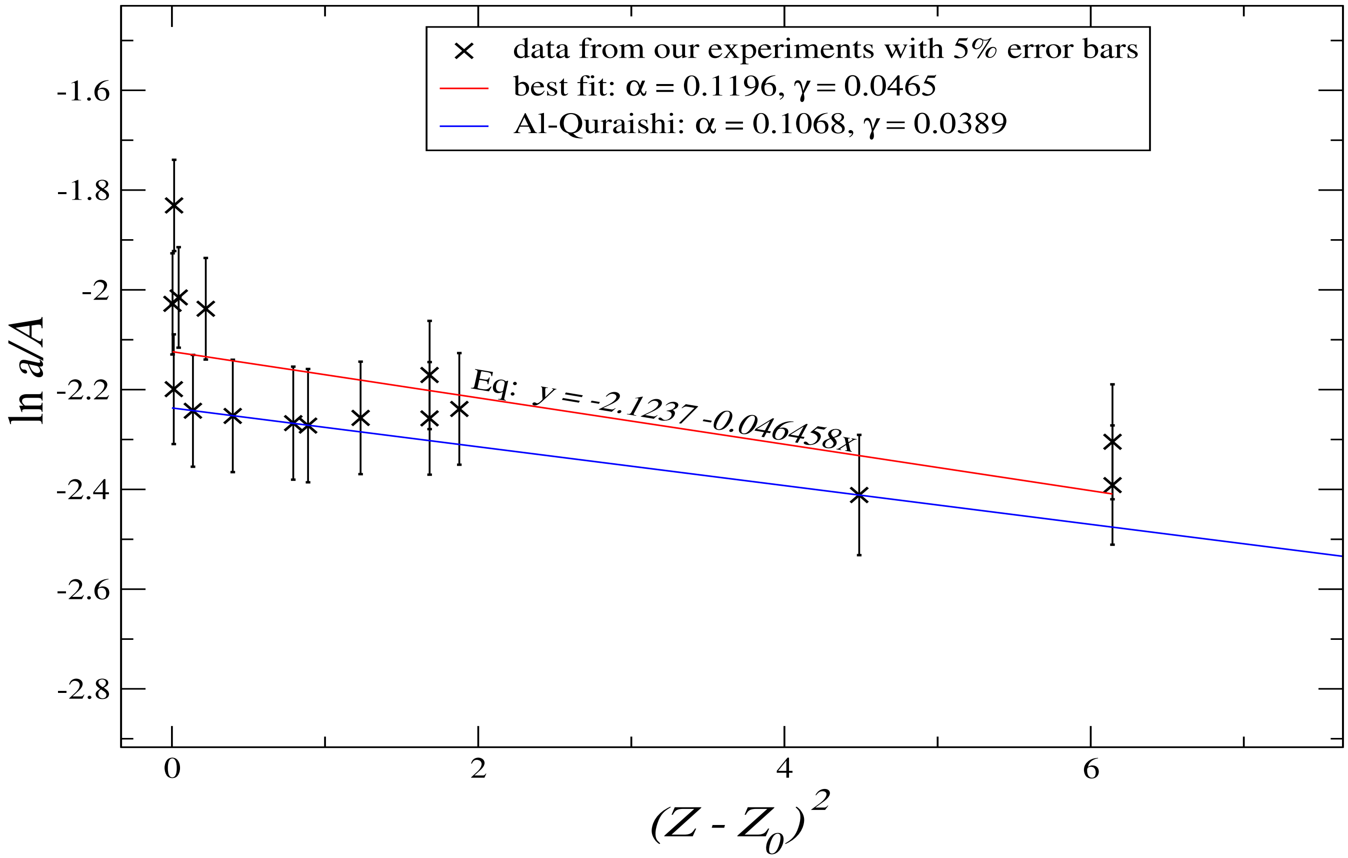
Compare: Rohr $a \propto \alpha A$

Al Quraishi $a \propto \alpha A \exp[\gamma (Z - Z_0)^2]$

Nuclear Level Densities Off the Stability Line



Nuclear Level Densities



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Combination of Li-induced reactions with ^{18}O and ^{24}Mg induced reactions

Better fit with term reducing *a* with $|Z-Z_0|$

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Calculations

- Solve for single particle energies in a single particle (Woods-Saxon) potential
- Compare level density including all single particle states with level density including only those with $\Gamma < 500$ keV
- Small effects for $Z \approx Z_0$
- Large effects for $|Z-Z_0| \geq 4$
- Looking at including two body effects in these calculations with moment method expansions

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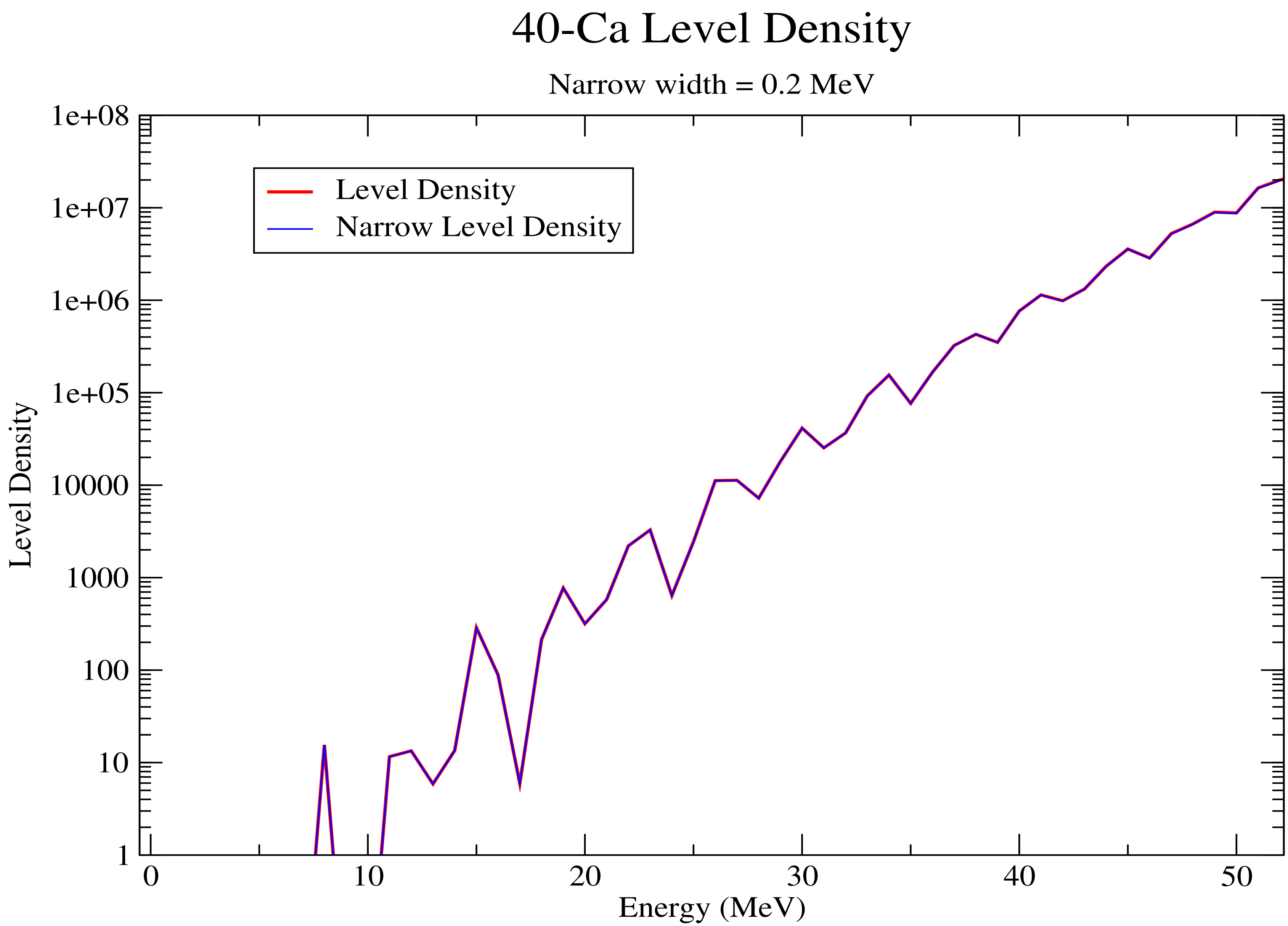
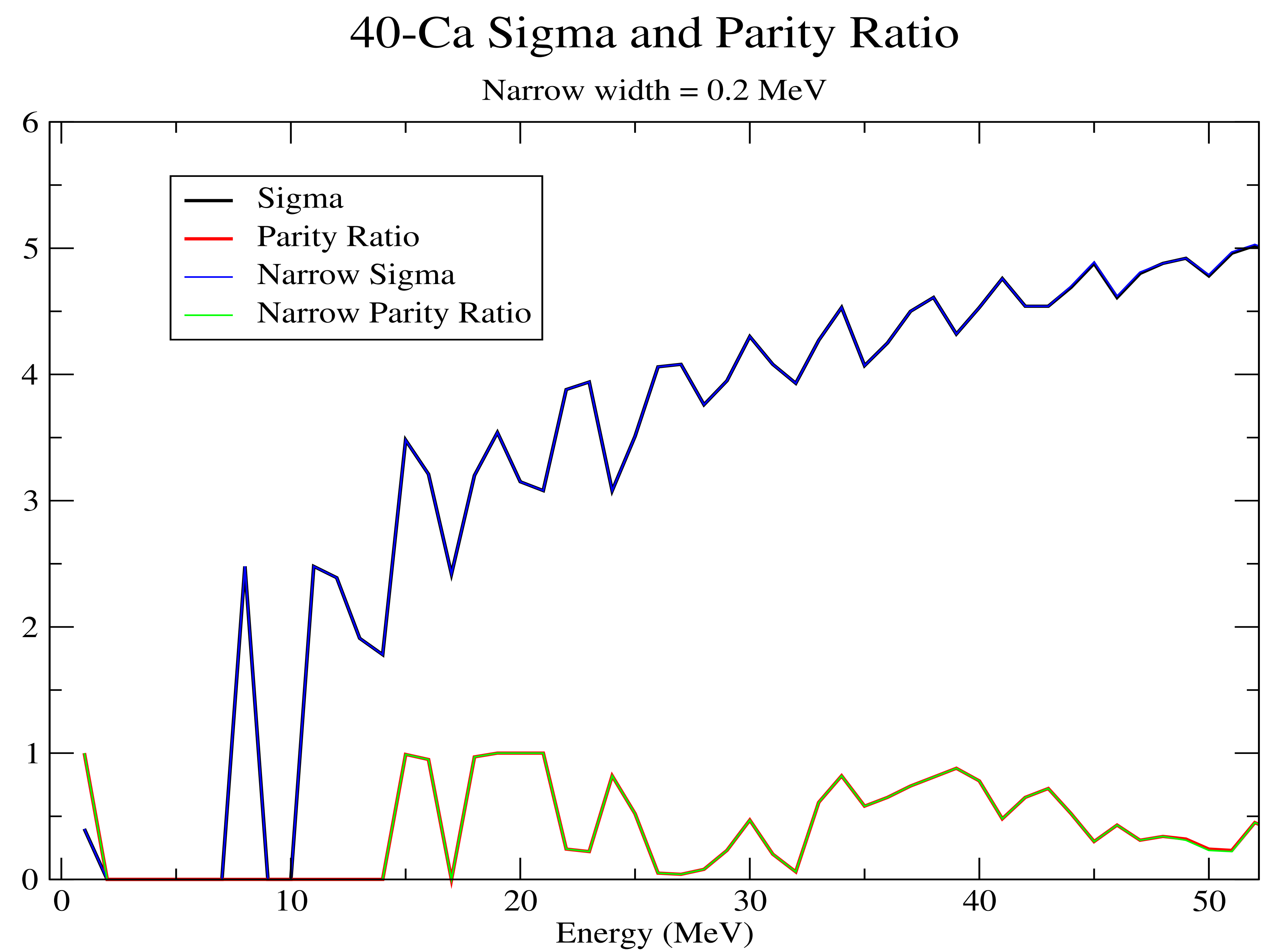
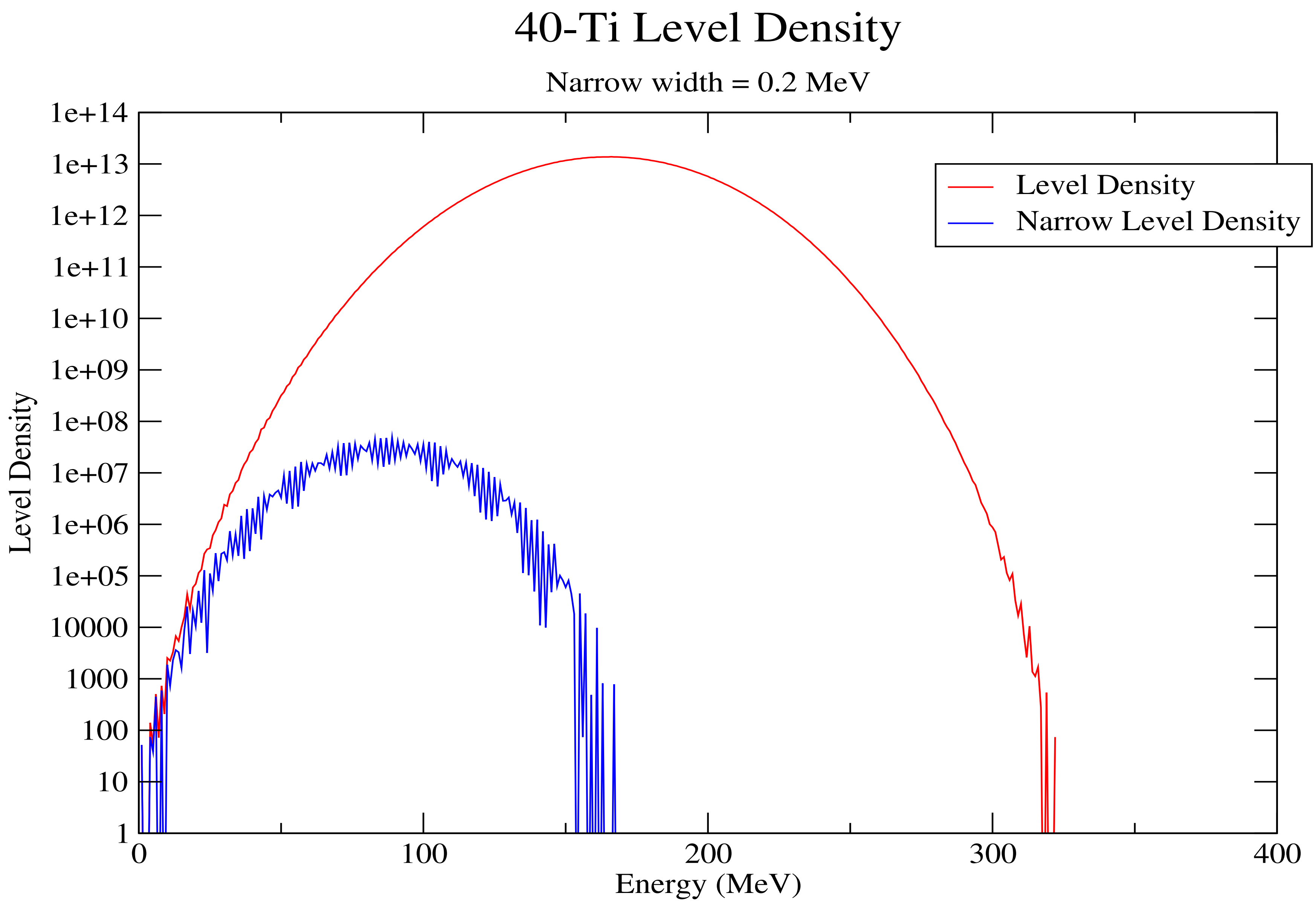
Calculations show negligible loss if

Γ ~ 500 keV for U < 40 MeV on stability line

Near drip line have substantial loss at U ~ 5 to 10 MeV

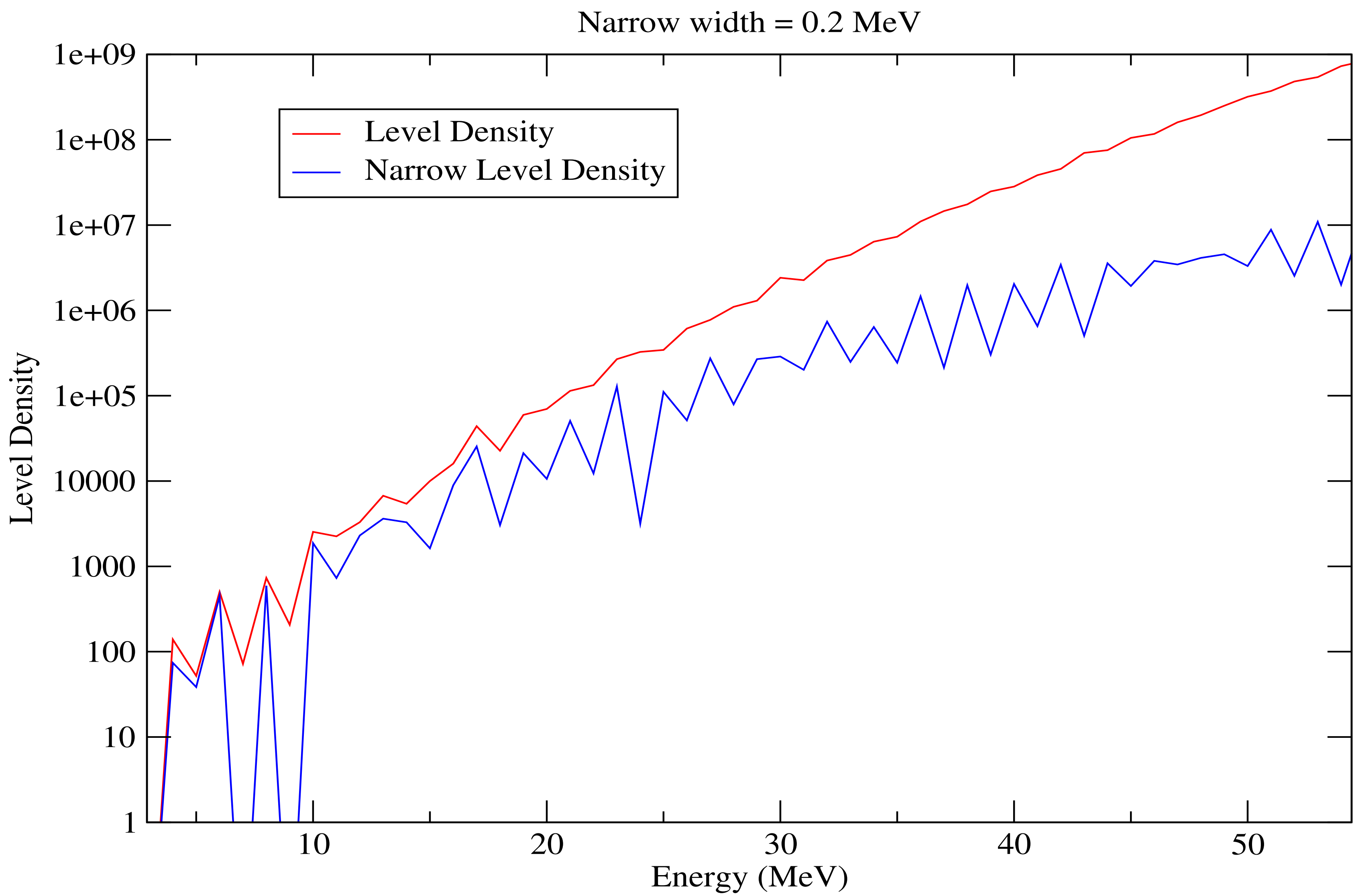

40-Ca Level Density
Narrow width = 0.2 MeV
Level Density
Narrow Level Density
1e+08
1e+07
1e+06
1e+05
10000
1000
100
10
1
0
10
20
30
40
50
Energy (MeV)
Level Density


40-Ca Sigma and Parity Ratio
Narrow width = 0.2 MeV
Sigma
Parity Ratio
Narrow Sigma
Narrow Parity Ratio
0
1
2
3
4
5
6
0
10
20
30
40
50
Energy (MeV)

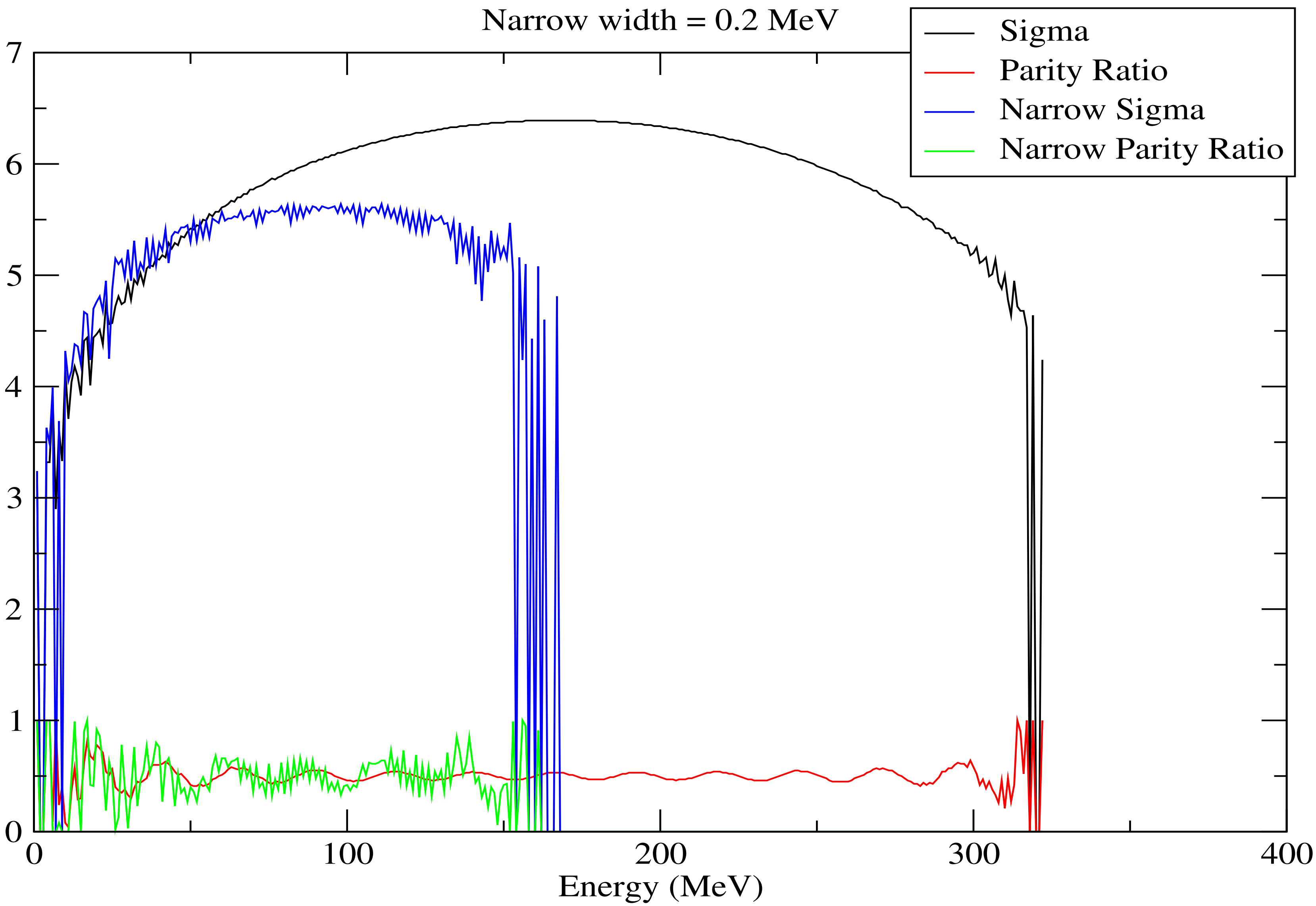


40-Ti Level Density
Narrow width = 0.2 MeV
Level Density
Narrow Level Density
1e+14
1e+13
1e+12
1e+11
1e+10
1e+09
1e+08
1e+07
1e+06
1e+05
10000
1000
100
10
1
0
100
200
300
400
Energy (MeV)

40-Ti Level Density



40-Ti Sigma and Parity Ratio



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SUMMARY OF INITIAL CALCULATIONS

A = 40: $\rho \approx 0$ for Z = 12, Z = 24; a reduced by 15 to 20%
for Z = 14 and Z = 18 (fit 0 to 20 MeV).
Reduced by 30 to 40% for 0 to 100 MeV.

A = 45: $\rho \approx 0$ for Z = 14, Z = 26; a reduced by 20-25%
for Z = 16 and Z = 24 (fit 0 to 20 MeV).
Reduced by 40% for 0 to 100 MeV.

A = 50: $\rho \approx 0$ for Z = 16, Z = 28; a reduced by 25% for
Z = 18 and Z = 26 (fit 0 to 20 MeV)

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Other effects:

Increase fluctuations in ρ with U as $Z \rightarrow Z_n$, $Z \rightarrow Z_p$

Increase fluctuations in $\rho_+ / (\rho_+ + \rho_-)$

Increase fluctuations in σ(U)

More likely that CN formation inhibited

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Results for A = 55, 60,70,80,90,100 are similar

Effects in astrophysics most important for A < 70

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CONCLUSIONS

Astrophysics has need for level densities off of the stability line for $A \leq 100$.

Data base in this region ($|Z-Z_0| \geq 2$) is poor

Model predicts that *a* decreases with $|Z-Z_0|$

Need more reaction data for nuclei in the region of $|Z-Z_0| \geq 2$

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The End