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

$U \approx 7$ MeV	near valley of stability

(2) Evaporation spectra

$U \approx 3$ to 15 MeV	near valley of stability

(3) Ericson fluctuations

$U \approx 15$ to 24 MeV	near valley of stability

(4) Resolved levels

$U \leq 4$ 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 Z

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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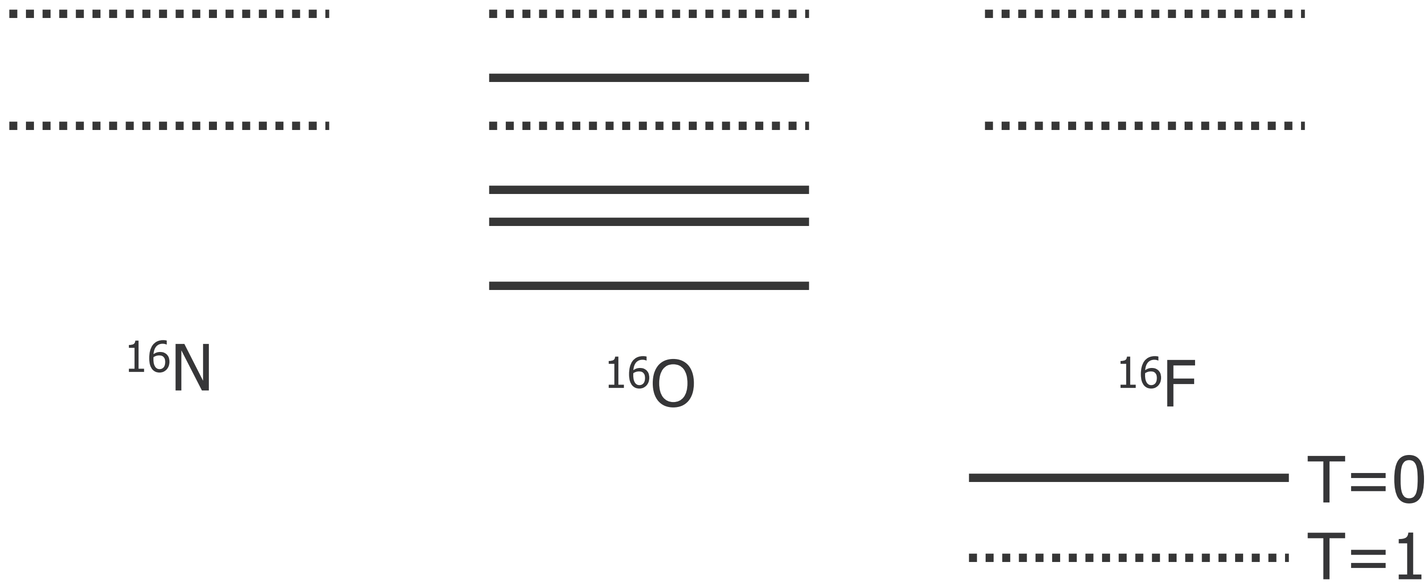
Isospin: (N-Z) / 2 = T_Z



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

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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

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

$$a \approx A/8$$

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

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

$$U_C \leq (\ AB^2 / 42.3\ )$$

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 $\rho(U)$ but also suppress *s*-wave absorption because of parity mismatch

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Experimental Tests

Measure:

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

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

$^{58}Fe(^{3}He,\alpha)^{59}Fe$

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

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

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

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

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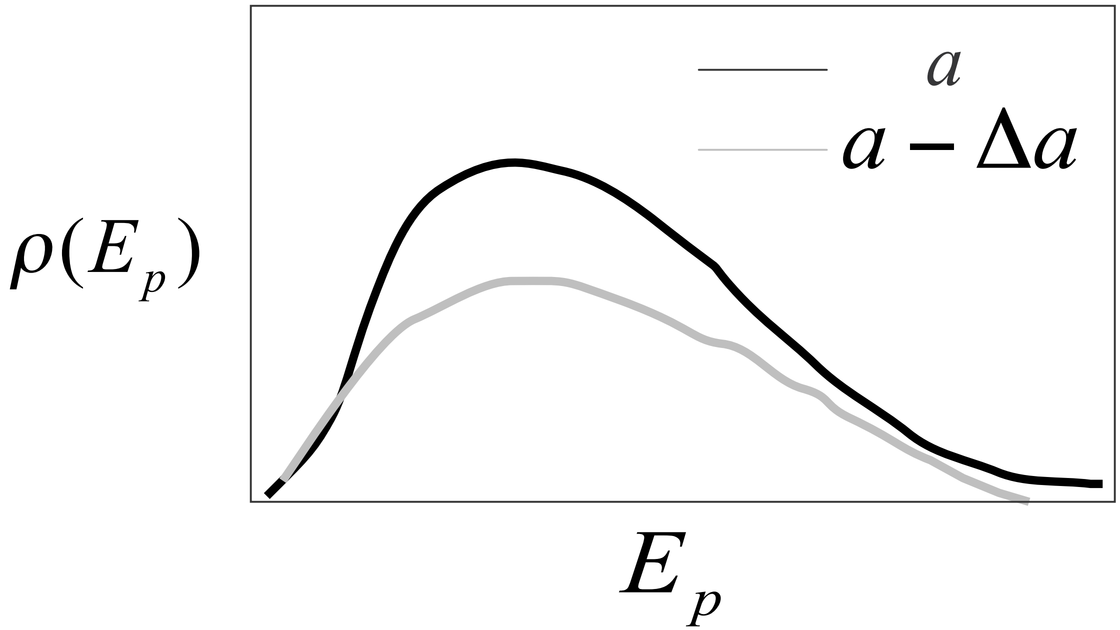
Change in a



Result: lower a → higher average E → lower multiplicity

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

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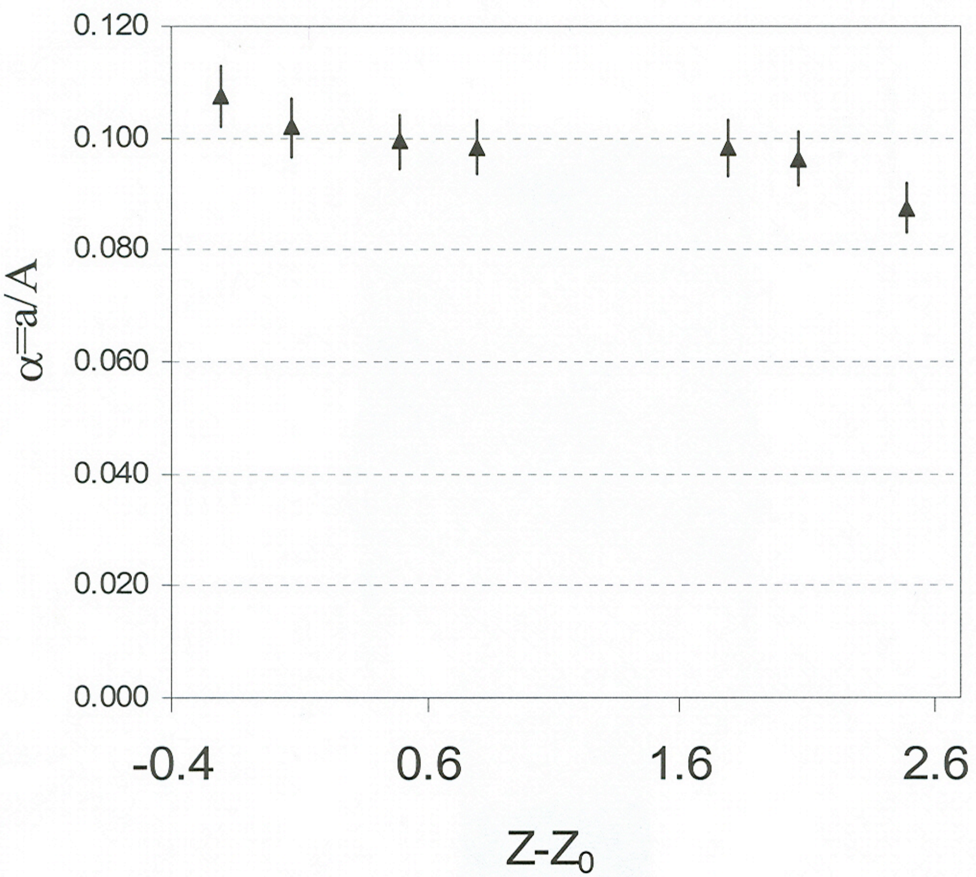

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Span range of $|Z-Z_0|$ values up to ~ 2.5

Find evidence that a/A decreases with $|Z-Z_0|$ increasing

Currently calculating these effects:

Woods-Saxon basis

Find single particle state energies and <u>widths</u>

Compare ρ with all *sp* states with ρ including only bound <u>or</u> quasi-bound orbits

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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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Calculations and measurements underway:

1.) Hope to determine whether off of stability line a drops

2.) Is form $a = \alpha$ A exp[$-\gamma$ $(Z-Z_0)^2$] appropriate?

3.) As the drip line is approached, we may have to abandon Bethe form and switch to Gaussian

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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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Heavy Ion Reactions

Recent Argonne measurements

$^{60}Ni + {}^{92}Mo$ $^{60}Ni + {}^{100}Mo$

got only 30-35% compound nuclear reactions

$J_{contact}$ too high

Not enough compound levels

Projectiles with A < half of target A are better

Want compound nuclei with $|Z-Z_0| \geq 2$ to compare with $|Z-Z_0| \approx 0$

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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 ≈ 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
	0.43 n	0.36 n
^{82}Zr	0.49 p	0.55 p
	0.06 α	0.07 α
	0.02 d	0.02 d

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

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

Get softer spectrum with Rohr

More 4-6 particle emissions than Al-Quraishi

Compare: Rohr $a \propto \alpha A$

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

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Additional Measurements:

$^{40}Ca + ^{3}He \rightarrow$ $^{42}Ti + n$; $^{42}Se + p$; $^{39}Ca + \alpha$

$^{40}Ar + ^{3}He \rightarrow$ $^{42}Ca + n$; $^{42}K + p$; $^{39}Ar + \alpha$

$^{40}Ca + ^{6}Li \rightarrow$ $^{45}V + n$; $^{45}Ti + p$; $^{42}Sc + \alpha$

$^{40}Ar + ^{6}Li \rightarrow$ $^{45}Sc + n$; $^{45}Ca + p$; $^{42}K + \alpha$

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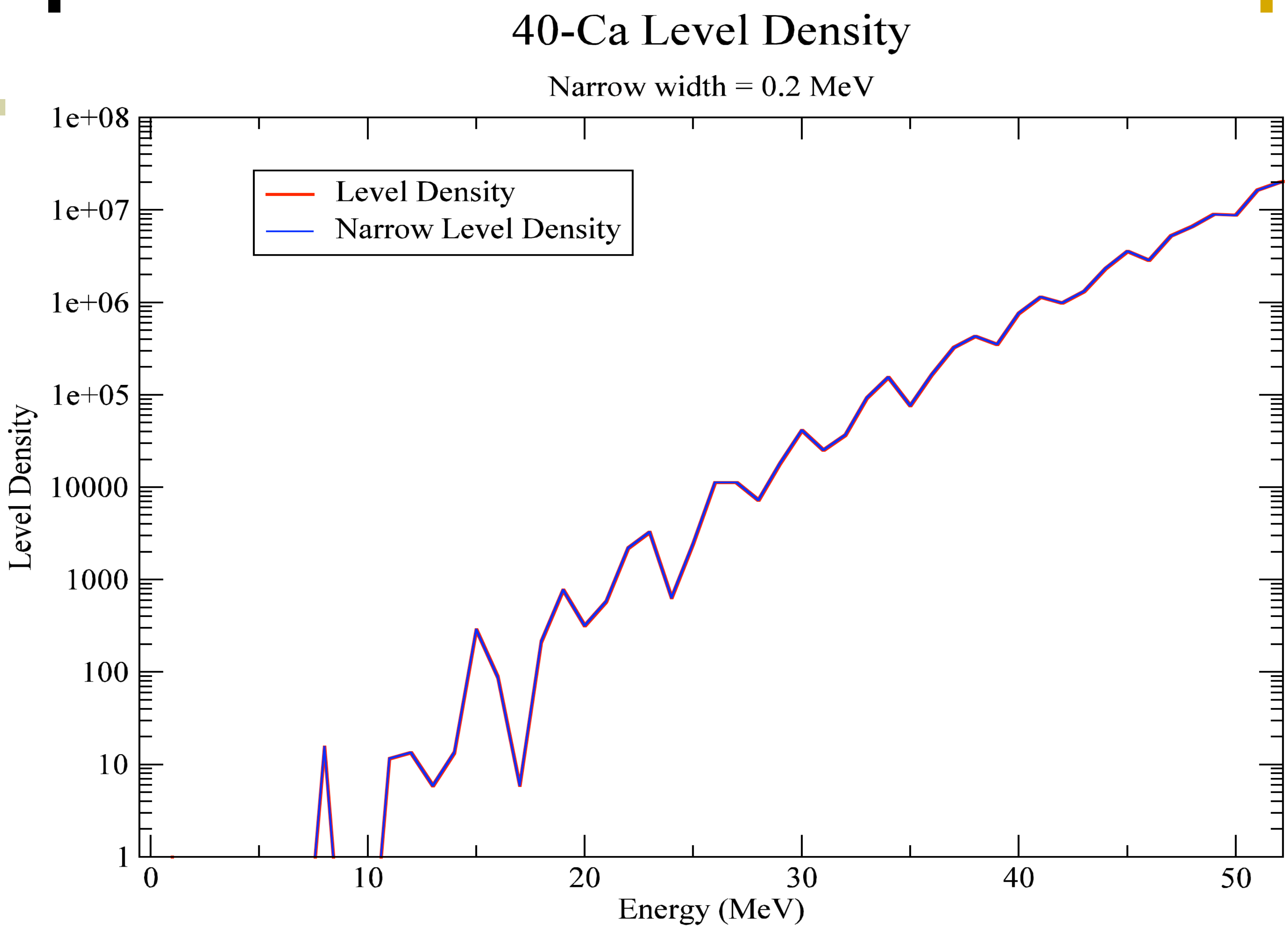
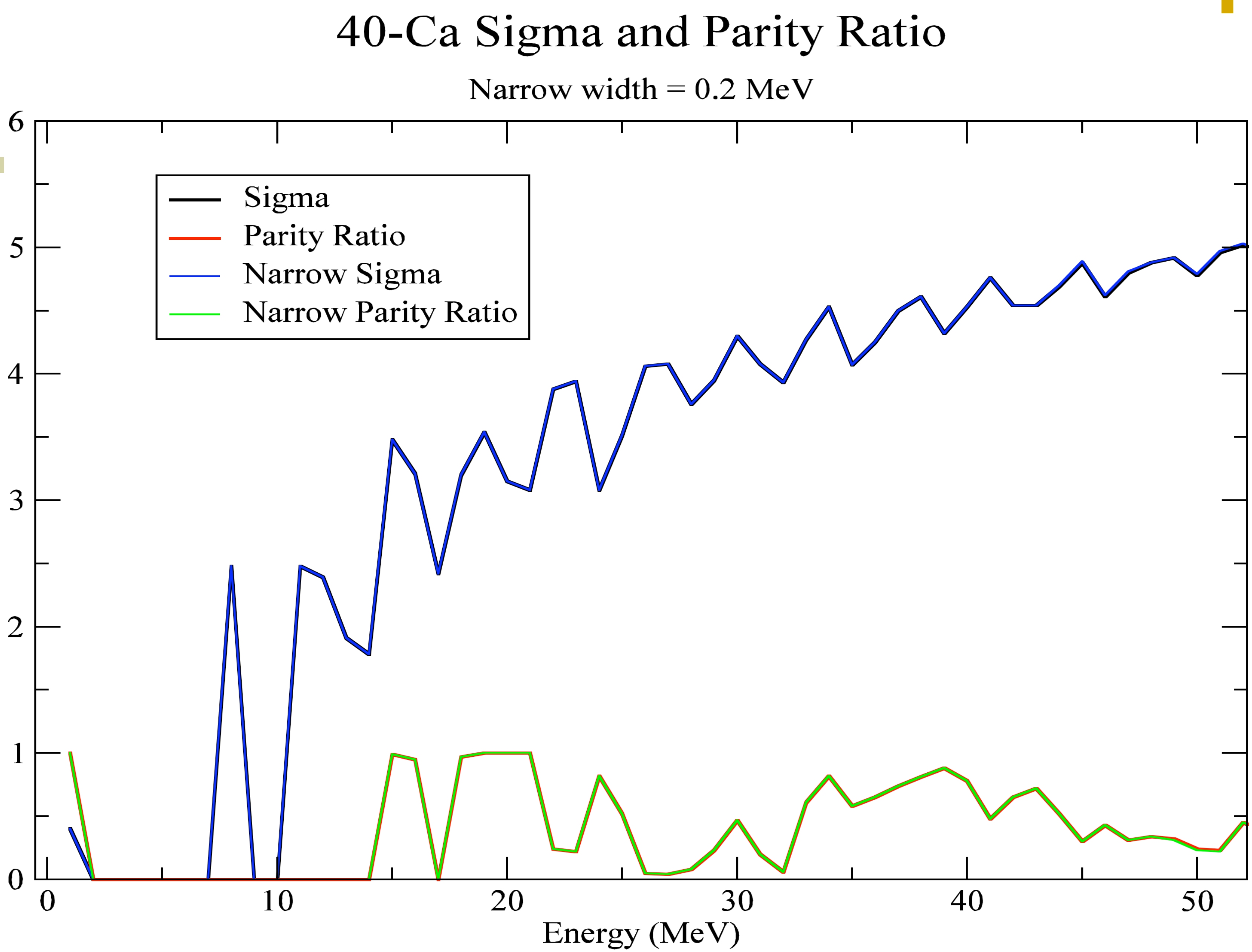
Calculations

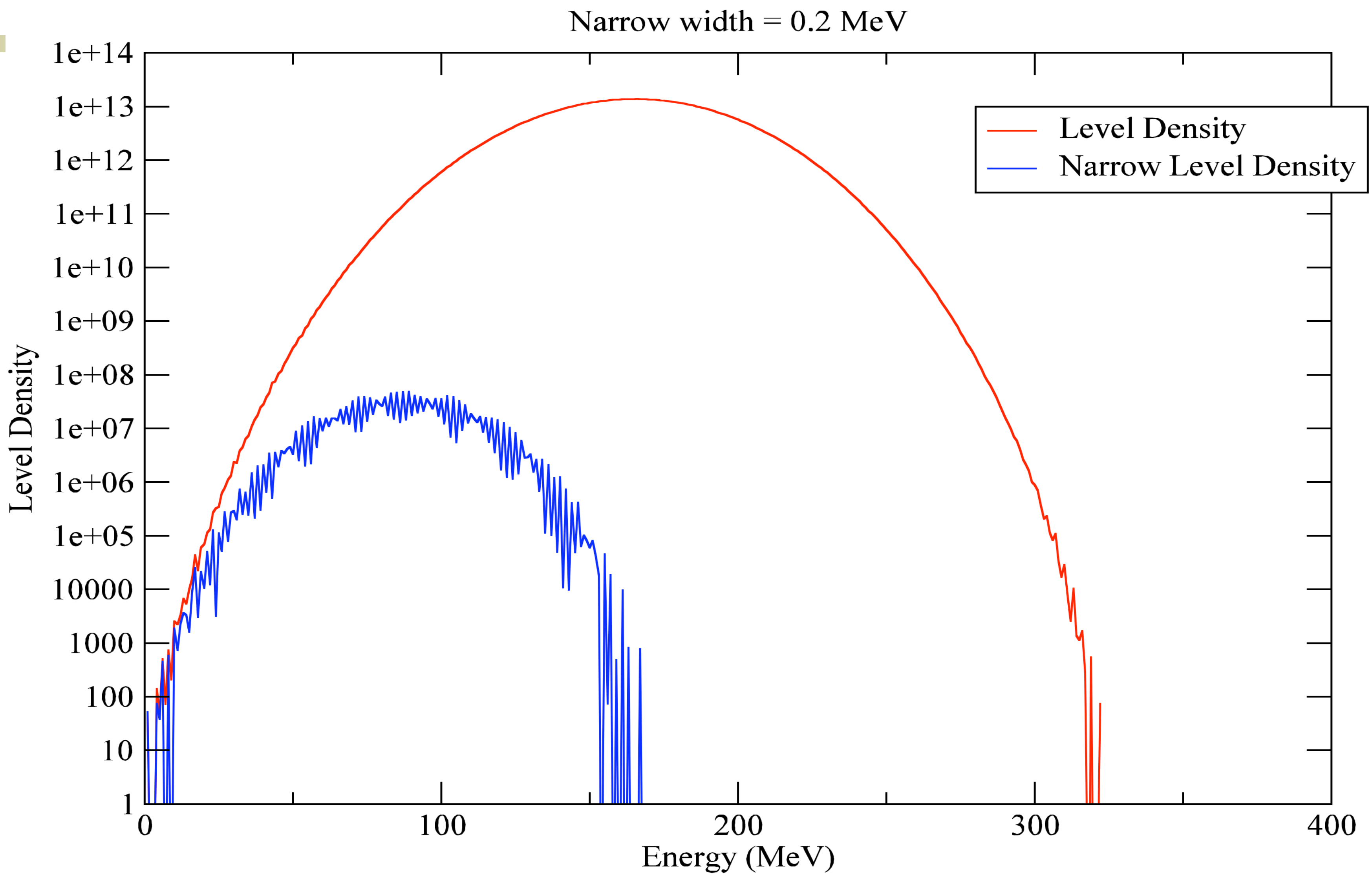
- Solve for single particle energies in a single particle (Woods-Saxon) potential
- Compare level density including all single particle states with level density including only those with $\Gamma < 500$ keV
- Small effects for $Z \approx Z_0$
- Large effects for $|Z-Z_0| \geq 4$
- Looking at including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


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
Level Density
0
10
20
30
40
50
Energy (MeV)

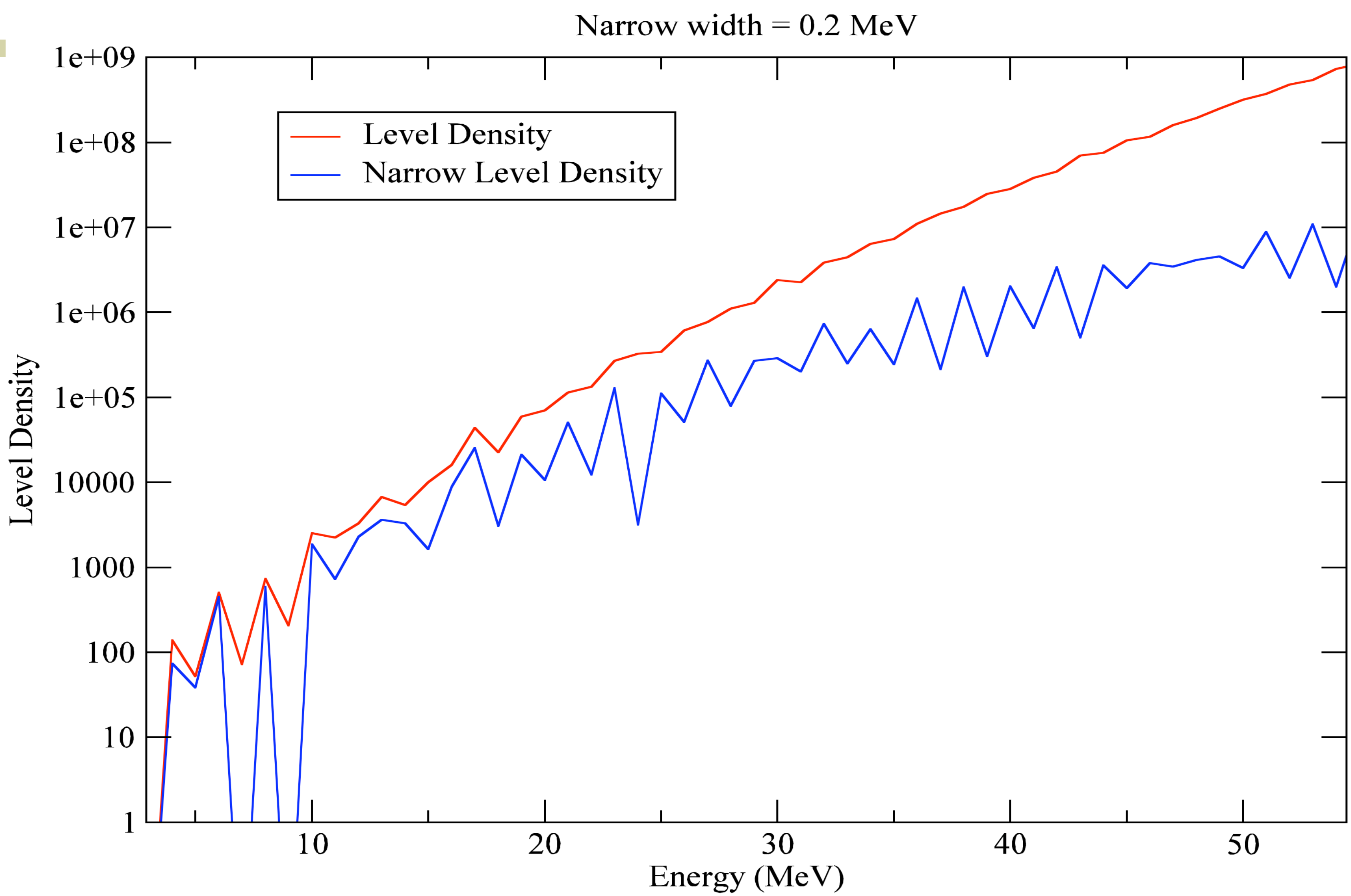


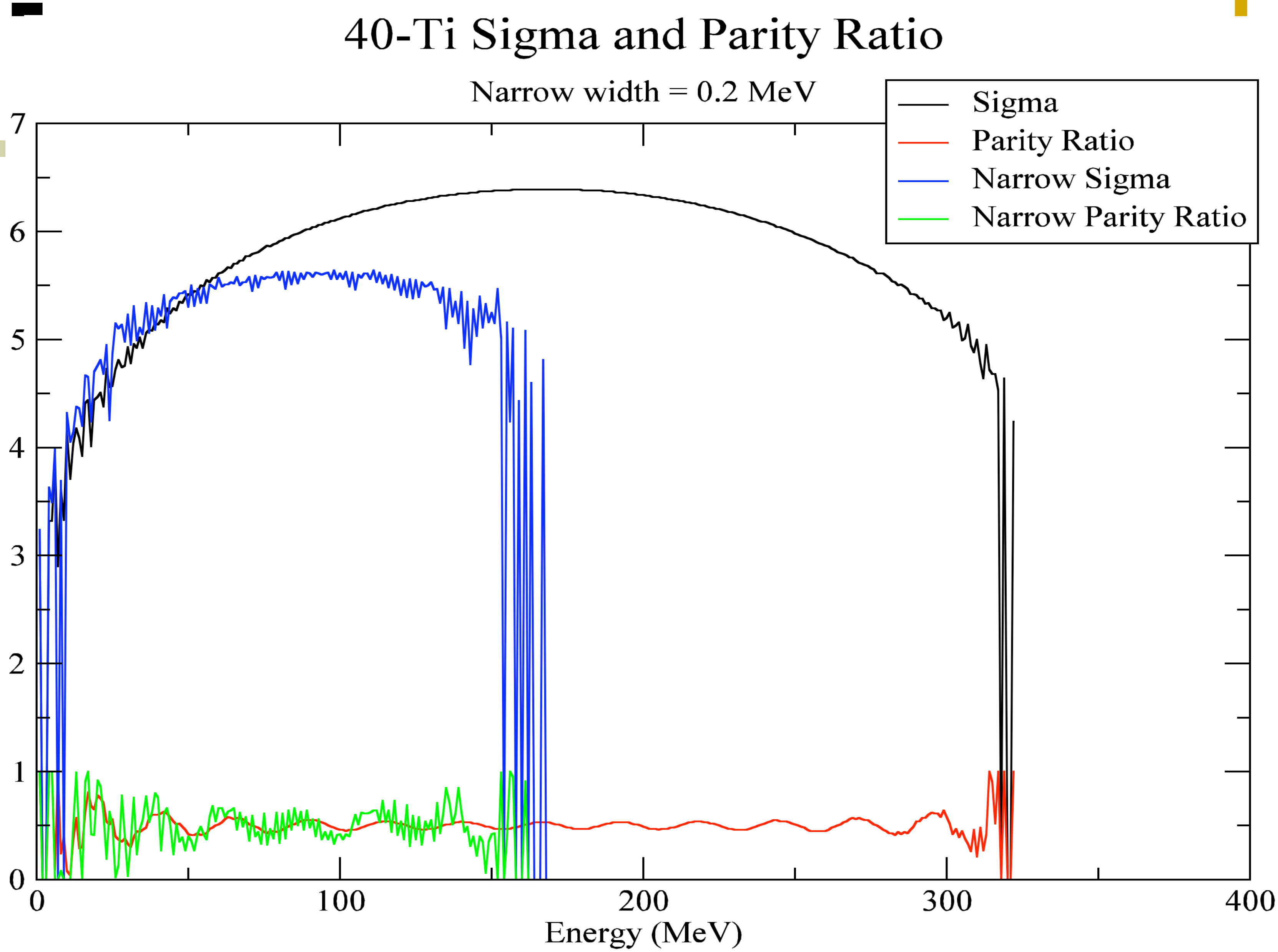
40-Ca Sigma and Parity Ratio
Narrow width = 0.2 MeV
Sigma
Parity Ratio
Narrow Sigma
Narrow Parity Ratio
0
1
2
3
4
5
6
0
10
20
30
40
50
Energy (MeV)

40-Ti Level Density



40-Ti Level Density




40-Ti Sigma and Parity Ratio
Narrow width = 0.2 MeV
Sigma
Parity Ratio
Narrow Sigma
Narrow Parity Ratio
0
1
2
3
4
5
6
7
0
100
200
300
400
Energy (MeV)

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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

Will examine A = 60, 70, 80, 100

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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