LEMAR
Low-Energy Magnetic Radiation

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[arXiv:1310.7667]

PRL 111, 232504 (2013)

New: arXiv:1407.1721

In collaboration with:

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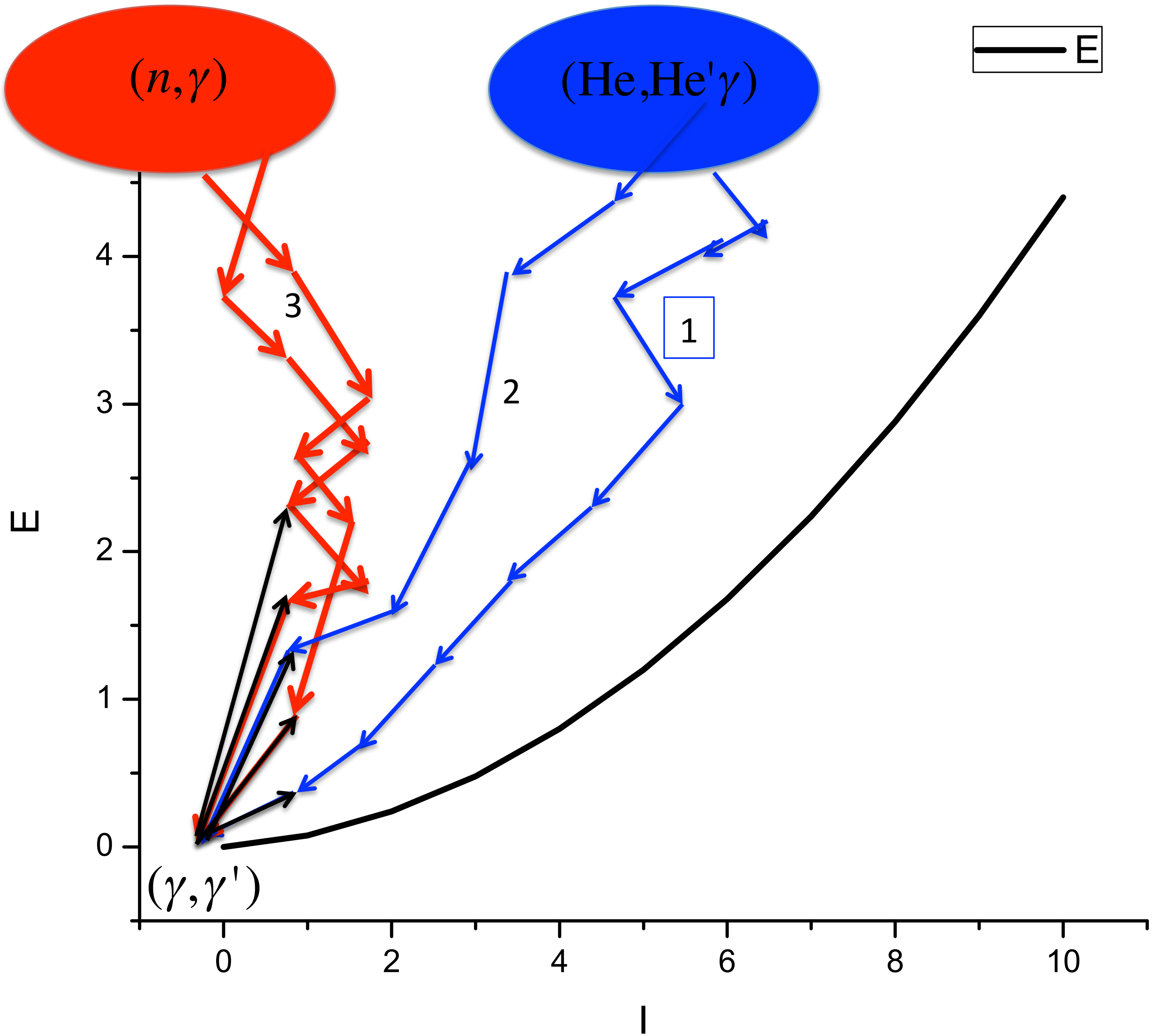
Low-Energy MAgnetic Radiation
LEMAR

- Description by Shell Model
- Mechanism that generates radiation
- Statistical properties of the transitions
- Prediction of regions/relevance
- Impact on r-process
- Low-Energy Electric Radiation



(n,γ)
(He,He'γ)
E
4
3
2
1
0
E
3
2
1
(γ,γ')
0
2
4
6
8
10
I

many transitions $\Rightarrow$ average properties

transmission coefficient

(average rate to decay with E_γ / energy unit)

$T_\gamma(E_\gamma,E_i)=2\pi f(E_\gamma,E_i)E_\gamma^3$

$\propto$ strength function x photon phase space

radiatve strength function

$f(E_\gamma,E_i)\propto \bar{B}(E1,M1,E_\gamma,E_i)\ \rho(E_i)$

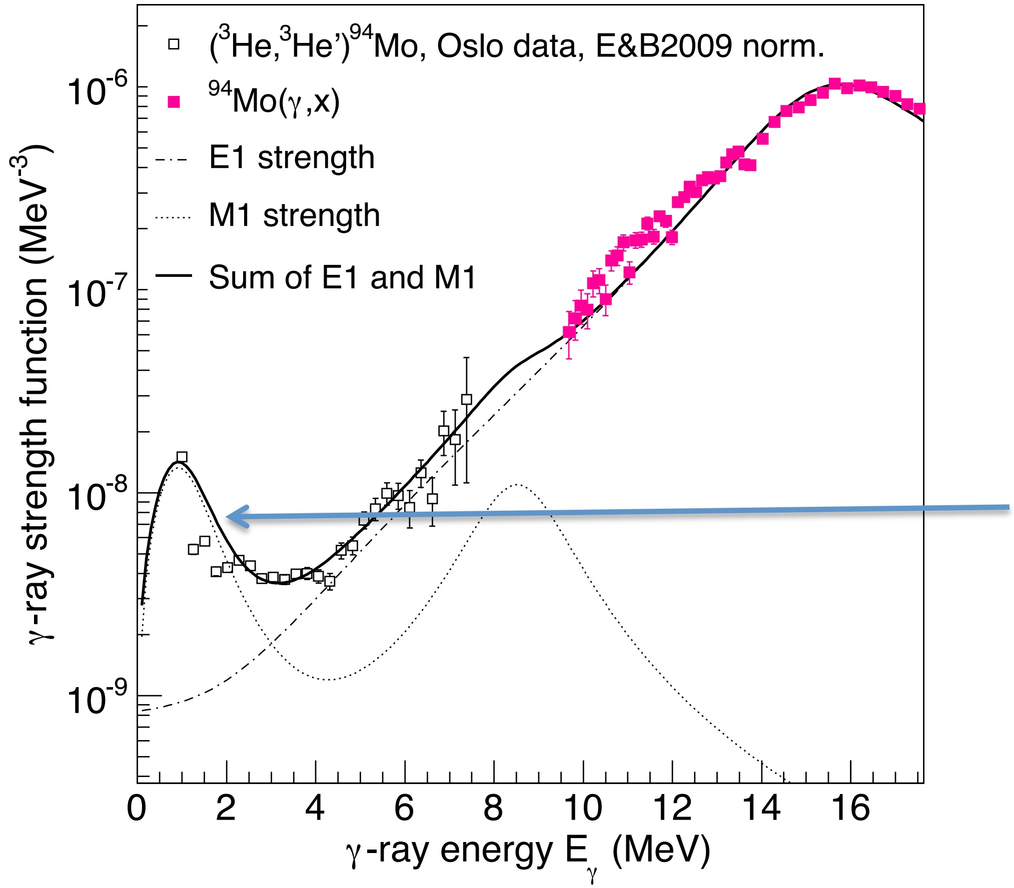
number states /energy unit $\rho(E)$

average reduced transition probability/state $\bar{B}(E1,M1,E_\gamma,E_i)$

common assumption: $f(E_\gamma,\not{E}_i)$ "Brink- Axel hypothesis"

Dipole strength in ^{94}Mo

Emission from the compound nucleus



Dipole strength function

$$f_1 = \sigma_\gamma / [3(\pi\hbar c)^2 E_\gamma]$$

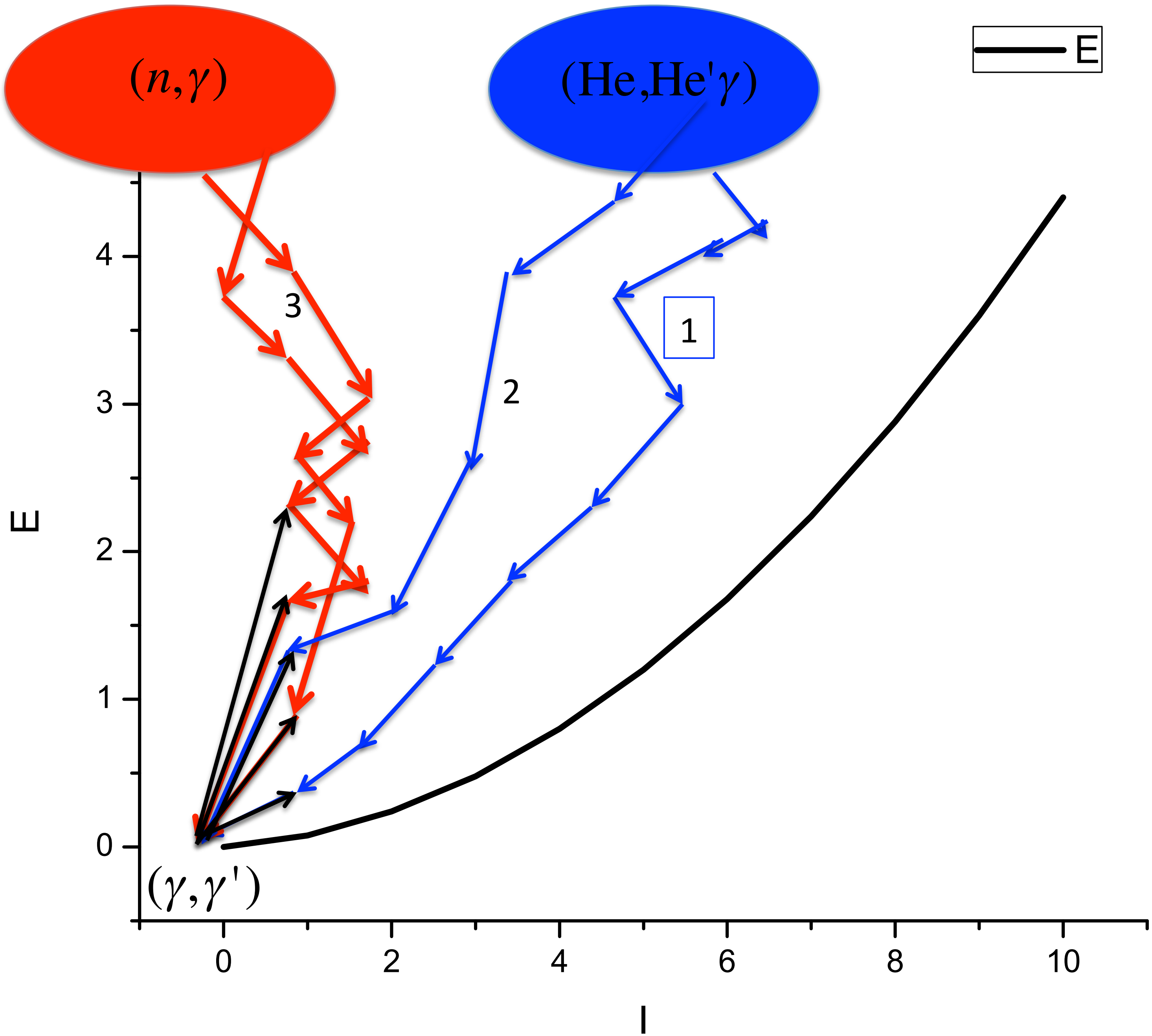
$$f_1 = \overline{\Gamma}\ \rho(E_x, J) / E_\gamma^3$$

What is it?

^{94}Mo(^{3}He,^{3}He'):

M. Guttormsen et al.,

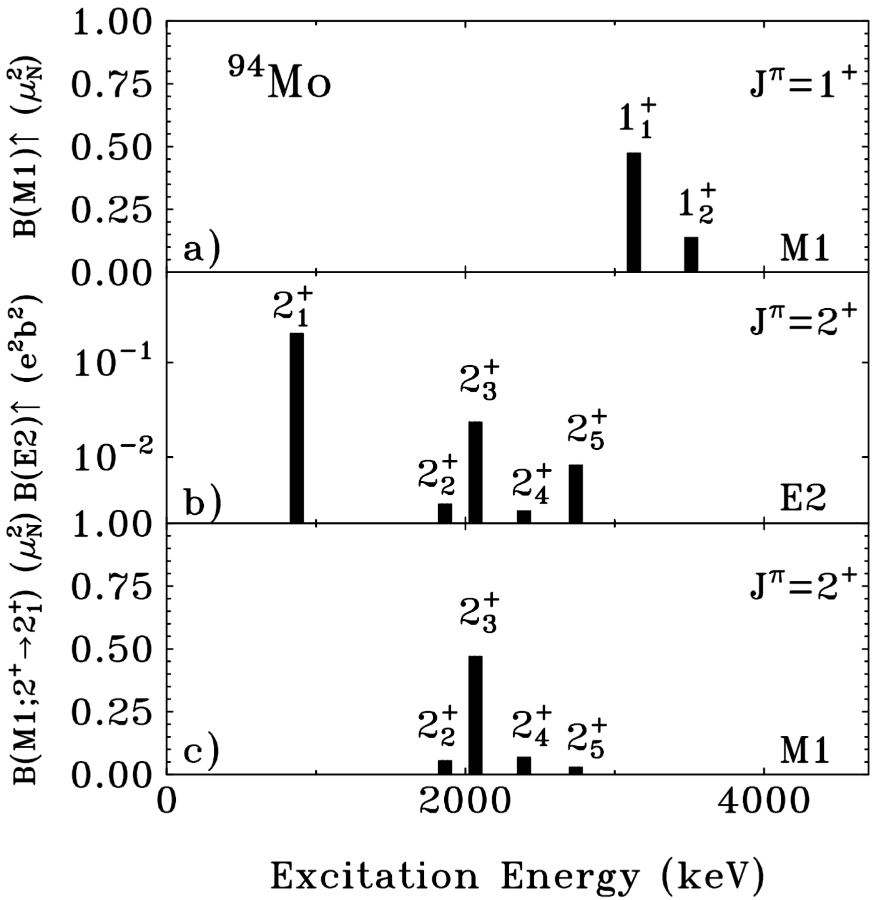
PRC 71, 044307 (2005)



(n,γ)
(He,He'γ)
E
1
2
3
4
3
2
1
0
E
0
2
4
6
8
10
I
(γ,γ')

Dipole strength in ^{94}Mo

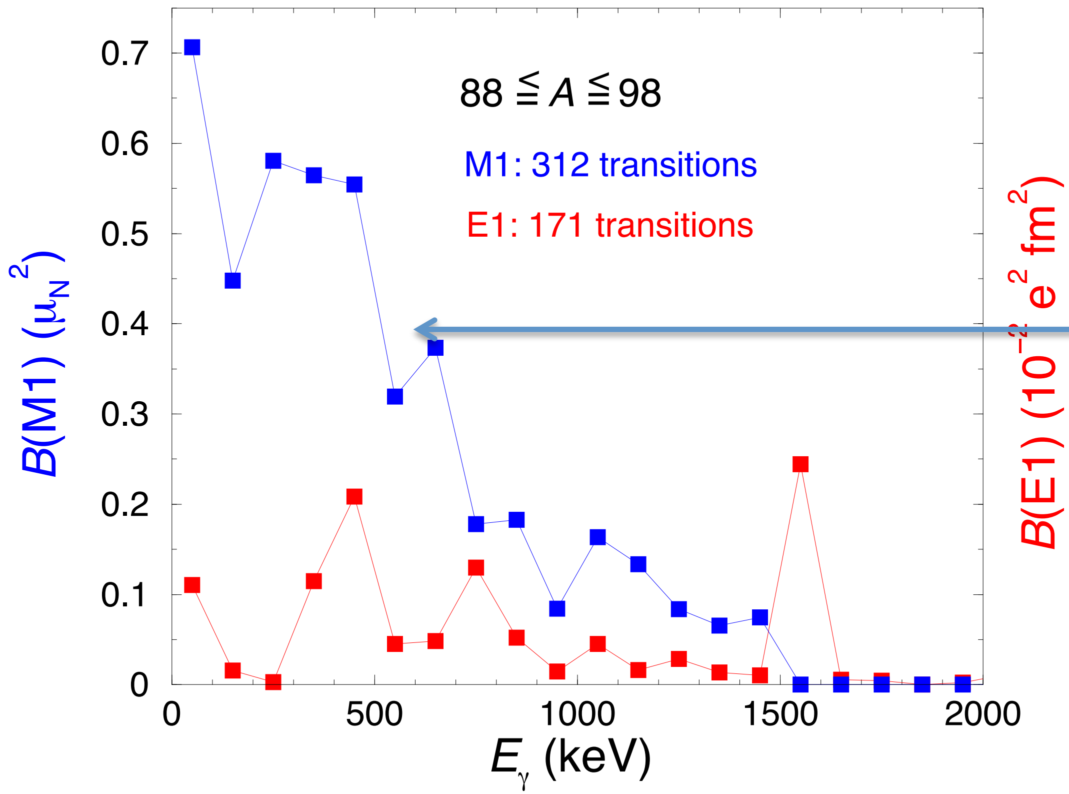
Absorption from the ground state



(γ, γ') up to 4 MeV:

N. Pietralla et al., PRL 83, 1303 (1999)

Experimental B(M1) and B(E1) values in nuclei around A = 90



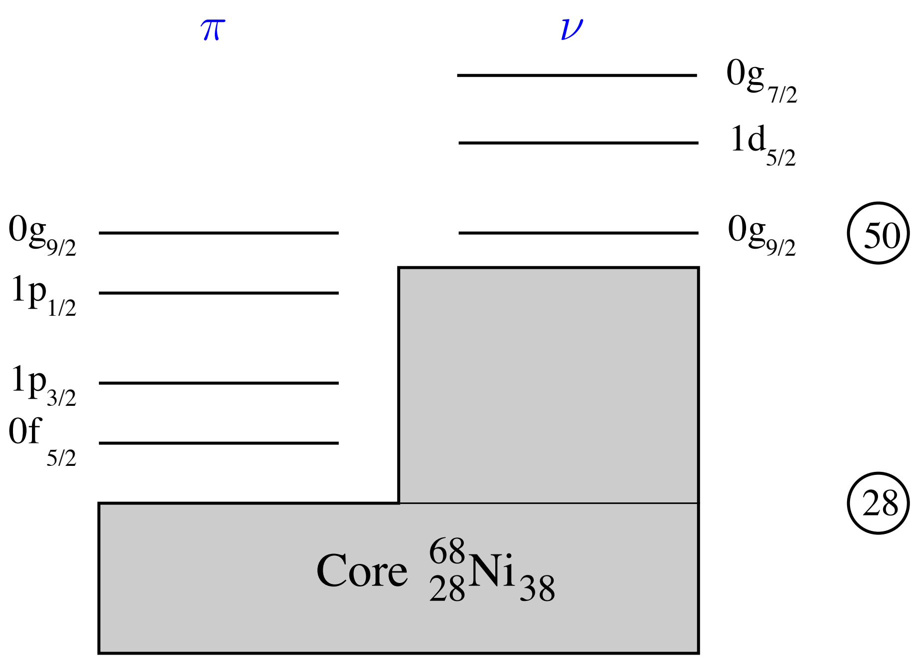
What is it?

Data taken from NNDC data base:

http://www.nndc.bnl.gov/nudat2/

Shell-model calculations around N = 50

Configuration space SM2:



Code: RITSSCHIL

Two-body matrix elements:

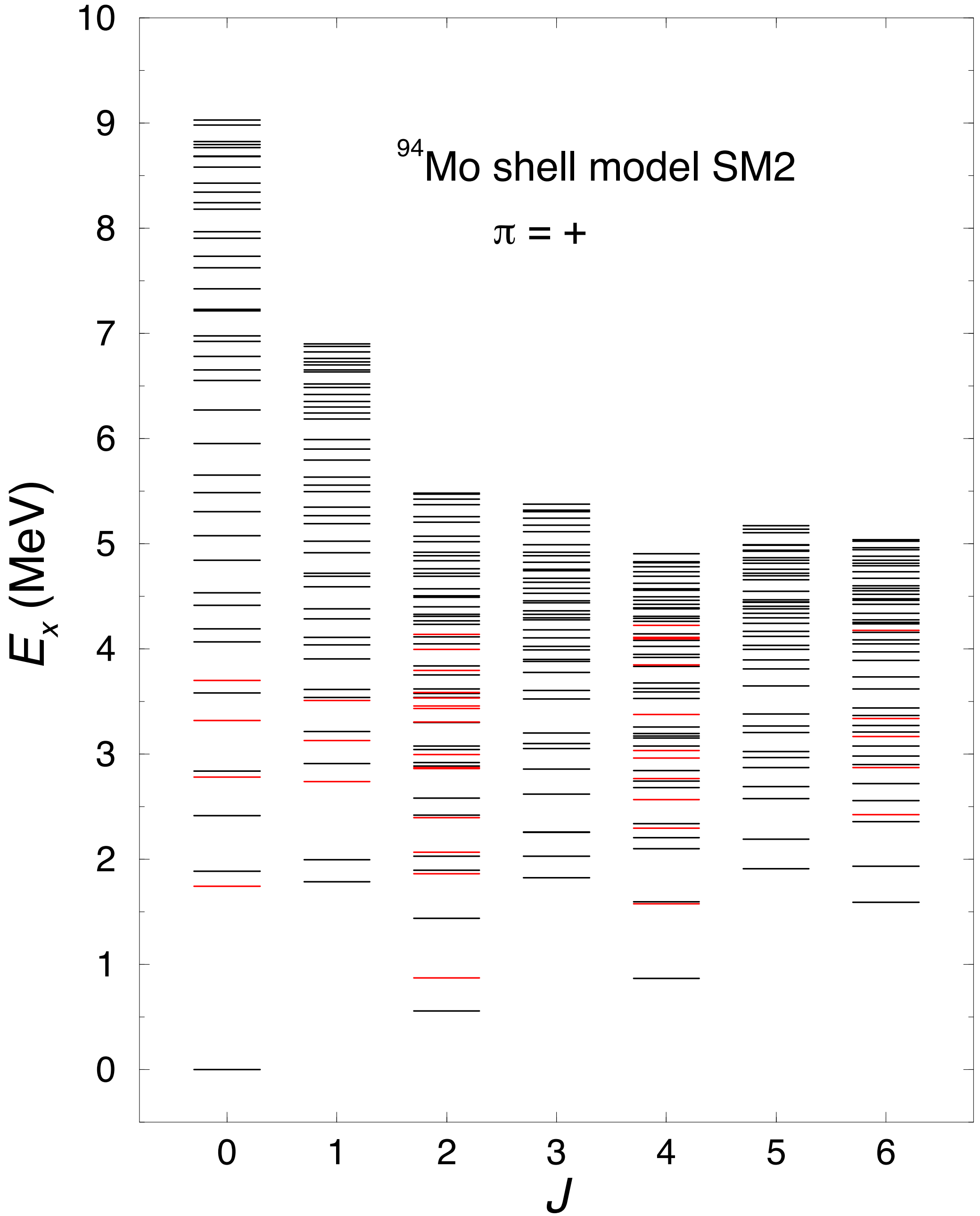
$\pi\pi$:
empirical from fit to N=50 nuclei, ^{78}Ni core;
X. Ji, B.H. Wildenthal, PRC 37 (1988) 1256

$\pi\nu, \nu\nu$ $(0g_{9/2}, 1p_{1/2})$:
emp. from fit to N=48,49,50 nuclei, ^{88}Sr core;
R. Gross, A. Frenkel, NPA 267 (1976) 85

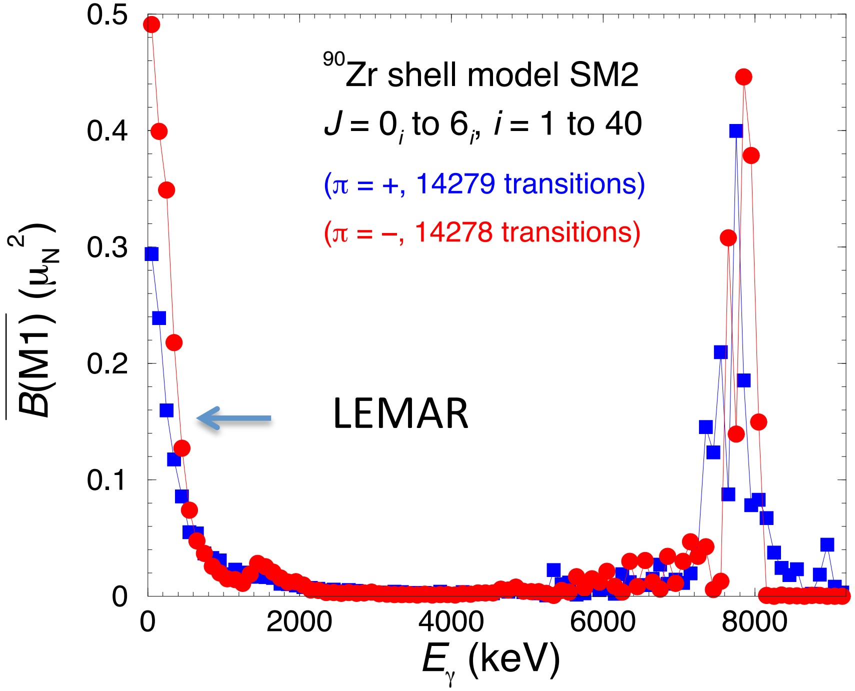
$\pi\nu$ $(\pi 0f_{5/2}, \nu 0g_{9/2})$:
experimental from transfer reactions;
P.C. Li et al., NPA 469 (1987) 393

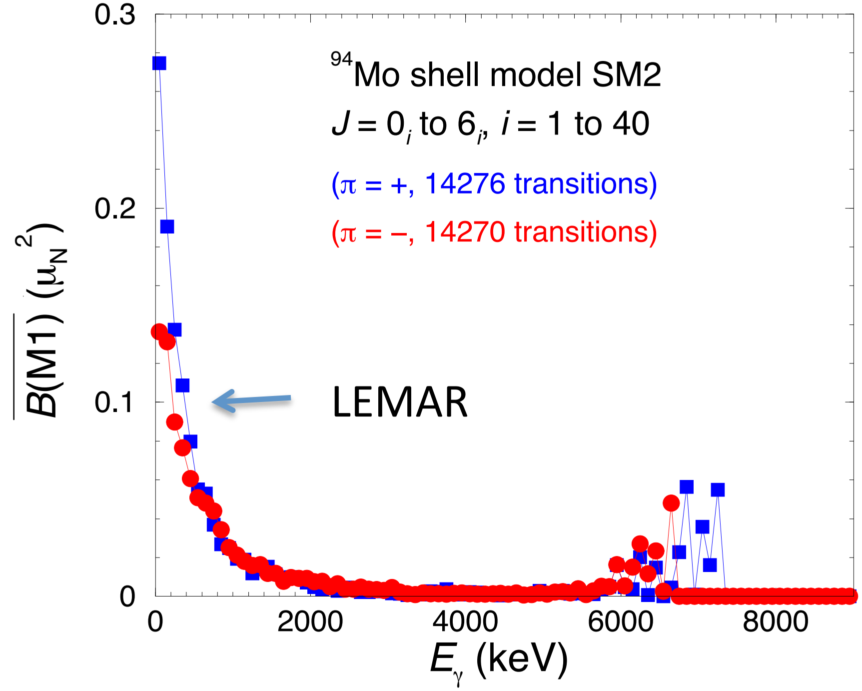
$\nu\nu$ $(0g_{9/2}, 1d_{5/2})$:
exp. from energies of the multiplet in ^{88}Sr;
P.C. Li, W.W. Daehnick, NPA 462 (1987) 26

remaining:
MSDI;
K. Muto et al., PLB 135 (1984) 349


94Mo shell model SM2
π = +
E_x (MeV)
J
0
1
2
3
4
5
6
7
8
9
10

Average M1 strengths in ^{90}Zr and ^{94}Mo



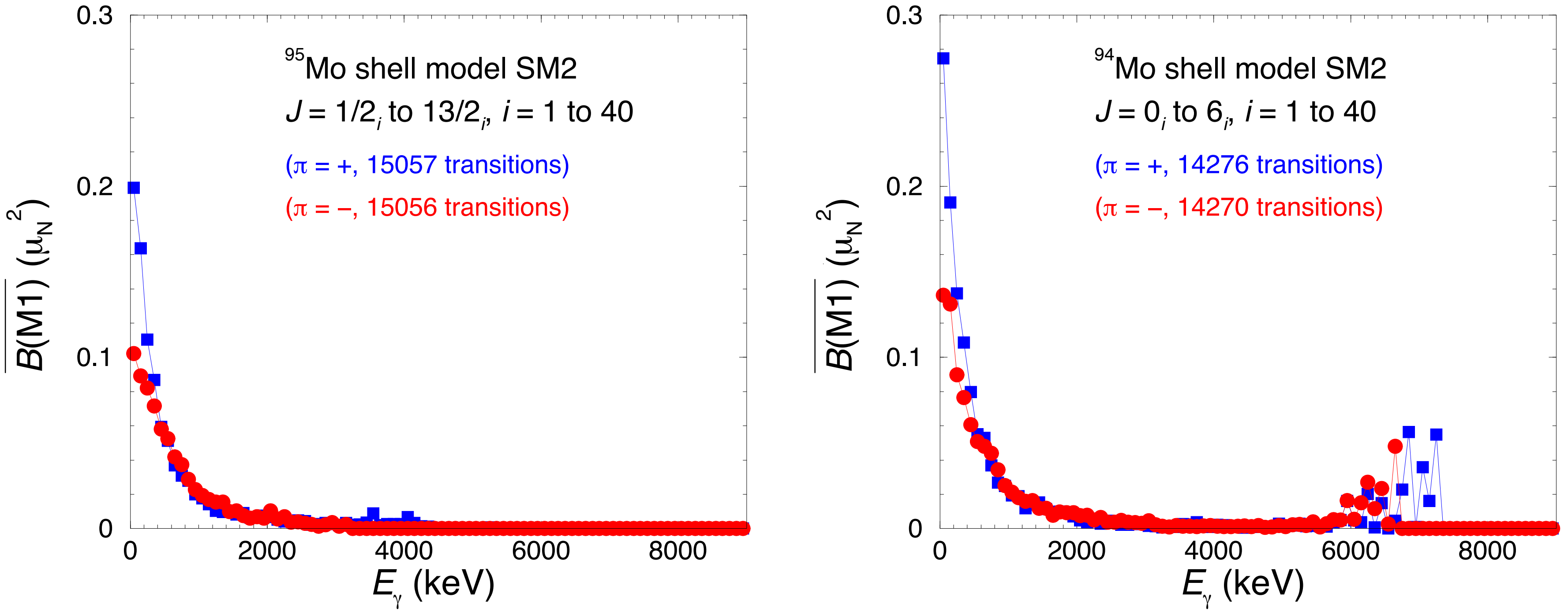


$\Rightarrow$ Enhancement of M1 strength toward very low transition energy in the $N = 50$ nuclide ^{90}Zr as well.

$\Rightarrow$ Total M1 strength of $1^+ \rightarrow 0_1^+$ transitions around 8 MeV in ^{90}Zr is in agreement with results of an experiment at HIγS [G. Rusev et al., PRL 110, 022503 (2013)].

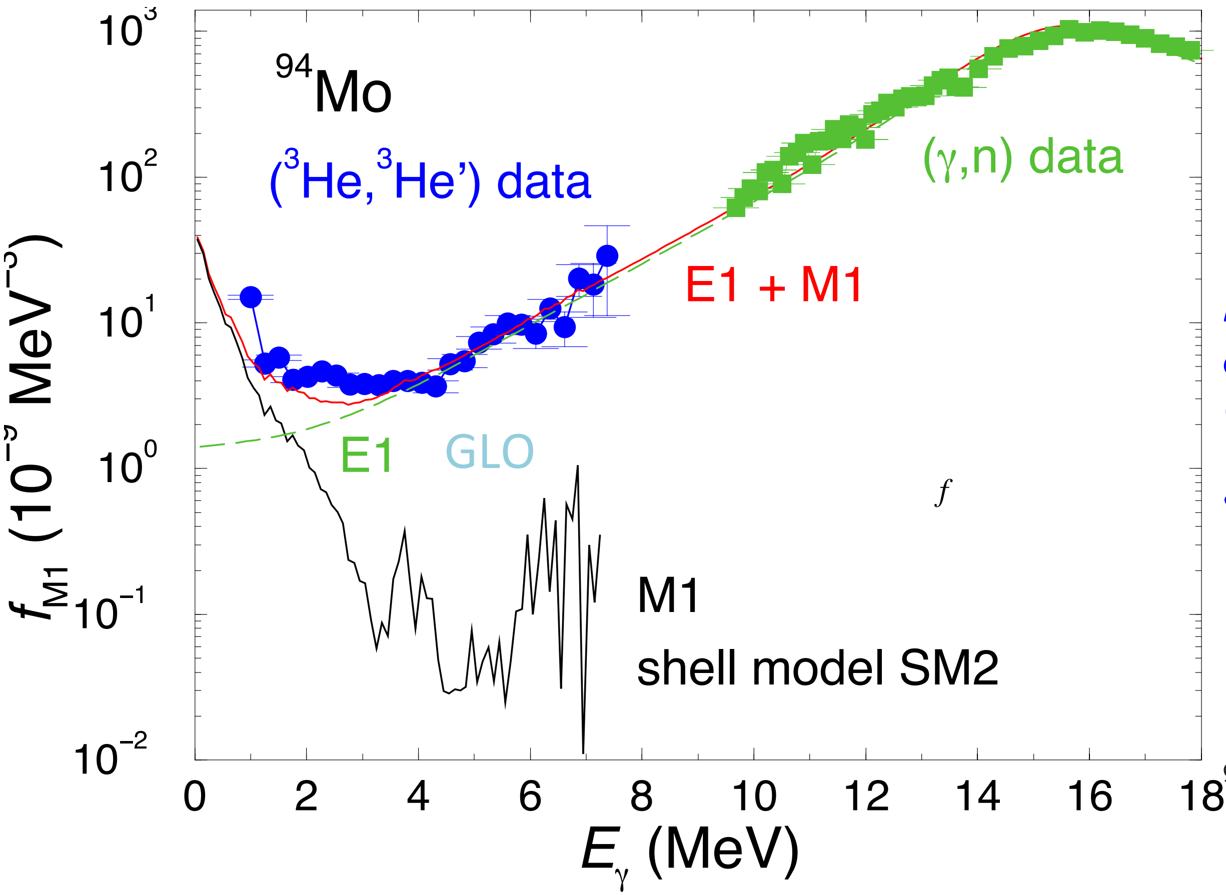
averages over bins of 100 keV

Average M1 strengths in ^{95}Mo and ^{94}Mo



- ○ Average B(M1) values in bins of 100 keV of transition energy.
- ⇒ Enhancement of M1 strength toward very low transition energy in the two isotopes.
- ⇒ $\nu(1d^2_{5/2}0g^1_{7/2})$ configuration preferred to $\nu(1d^3_{5/2}0g^{-1}_{9/2}0g^1_{7/2})$ configuration in ^{95}Mo.

LEMAR accounts for the Oslo experiments



Dipole strength function

$f_1 = 11.5473\ \overline{B(M1)}\ \rho(E_x, J)$

$\rho(E_x, J)$ - level density of the shell-model states, includes $\pi = +$, $\pi = -$, all spins from 0 to 6.

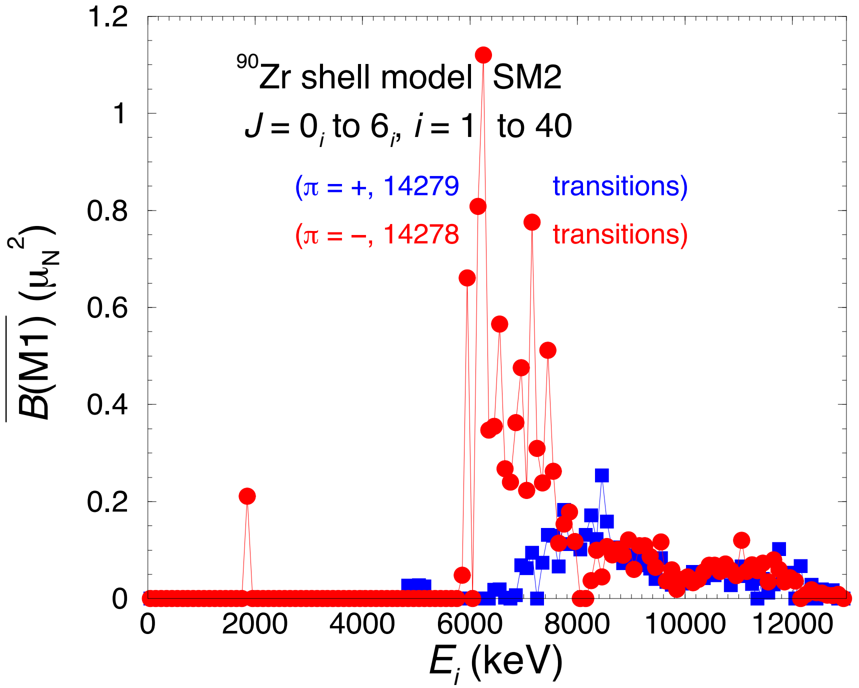
^{94}Mo(^{3}He,^{3}He'): M. Guttormsen et al., PRC 71, 044307 (2005)

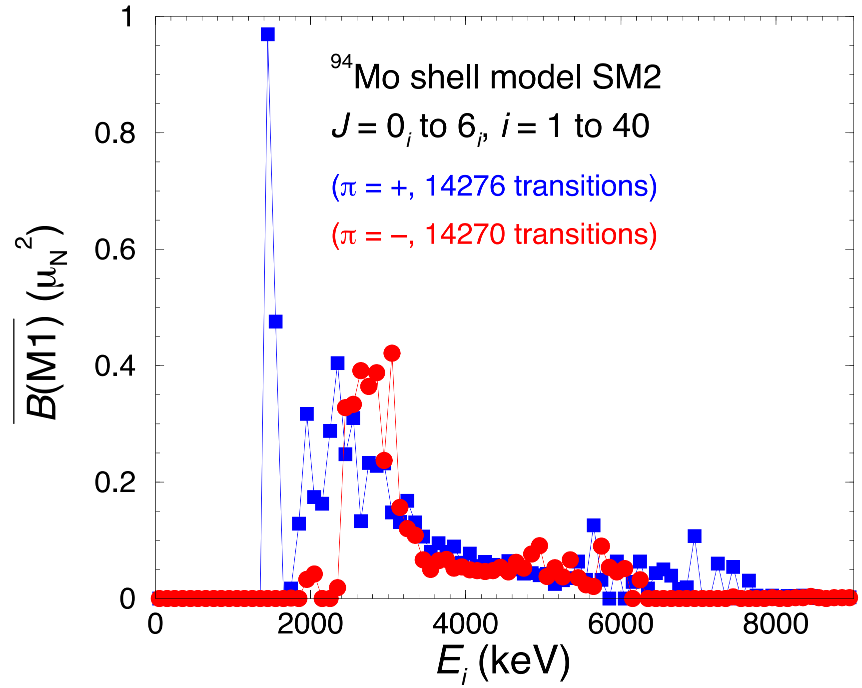
LEMAR is an exponential function of gamma energy

$$f_{M1} \approx f_0 \exp(-E_\gamma / T_F), \quad f_0 = 37\,10^{-9}\,MeV^{-3}, T_F = 0.50\,MeV$$

Where does the strength come from?

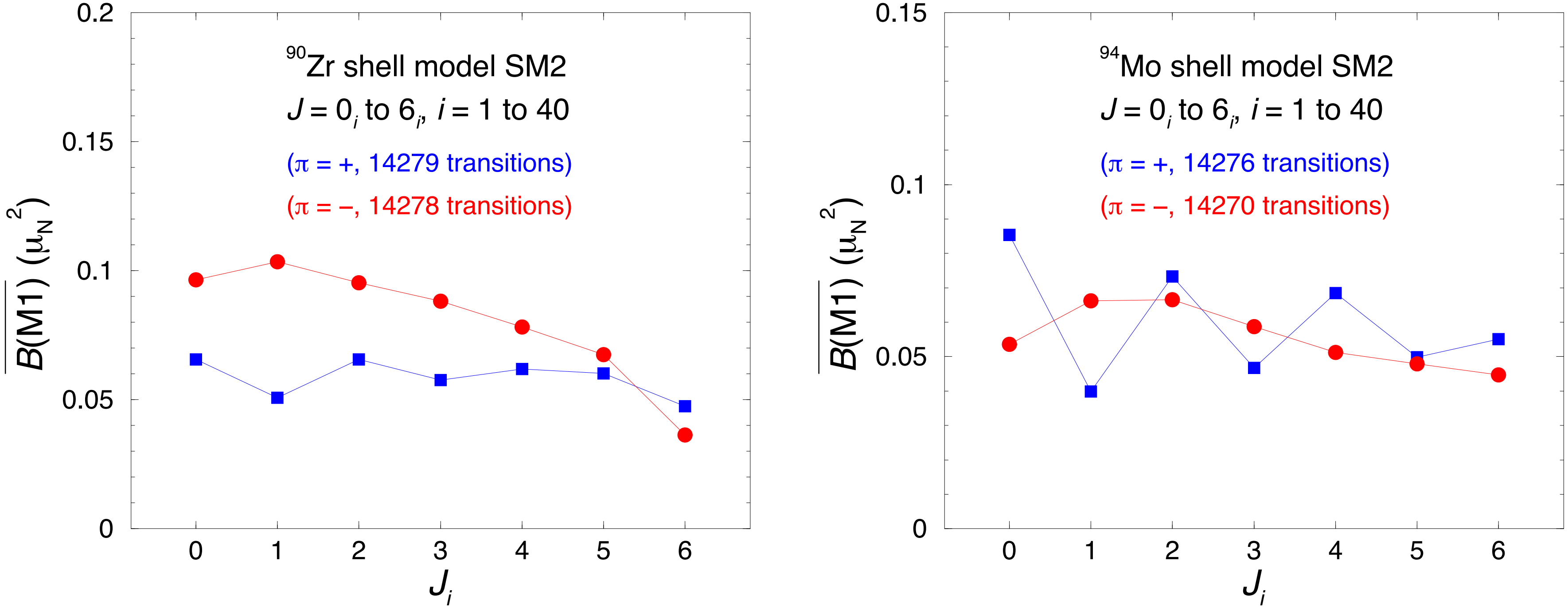
Average M1 strengths in ^{90}Zr and ^{94}Mo





- Average $B(\mathrm{M1})$ values in bins of 100 keV of excitation energy.
- ^{90}Zr: Large peaks between about 5.9 and 7.5 MeV for $\pi = -$ arise from states dominated by the configuration $\pi(1p_{1/2}^{-1}\ 0g_{9/2}^{1})\ \nu(0g_{9/2}^{-1}\ 1d_{5/2}^{1})$.
- ^{94}Mo: Large peaks between about 1.5 and 3.0 MeV for $\pi = +$ and $\pi = -$ arise from states dominated by the configurations $\pi(0g_{9/2}^{2})\ \nu(1d_{5/2}^{2})$ and $\pi(1p_{1/2}^{-1}\ 0g_{9/2}^{3})\ \nu(1d_{5/2}^{2})$, respectively.

Average M1 strengths in ^{90}Zr and ^{94}Mo



- Average $B(\mathrm{M1})$ values vs. initial spin.
- ^{94}Mo: Staggering of the values for $\pi = +$. Large $B(\mathrm{M1})$ values for transitions from states with the main configuration $\pi(0g^2_{9/2})\ \nu(1d^2_{5/2})$ and even spins.

The M1 strength comes from many small transitions
Between states at 4-6MeV and I=0-6

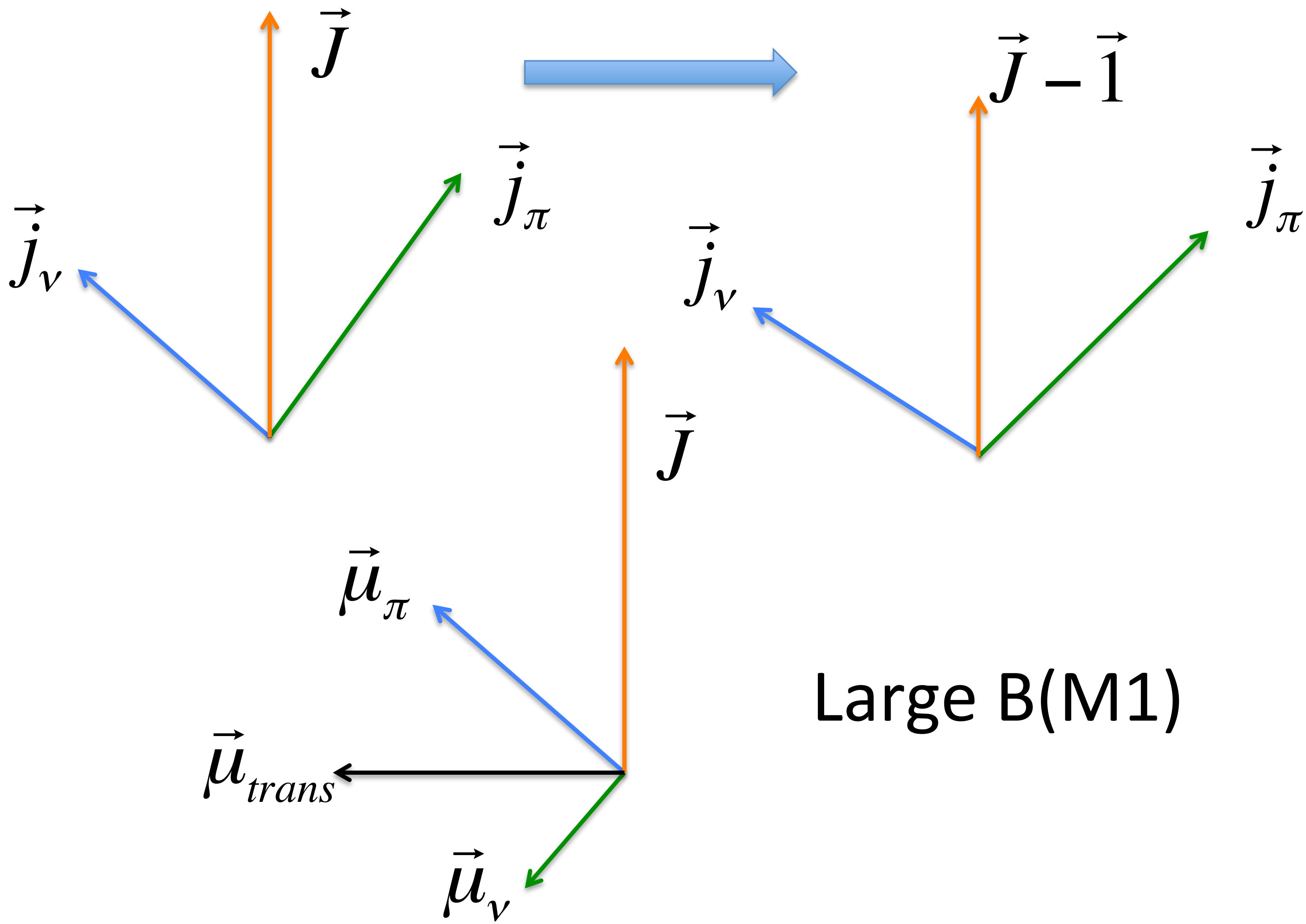
Mechanism that generates radiation

Shell-model calculations for ^{94}Mo

Configurations that generate large M1 transition strengths (active orbits with $j_\pi \neq 0$ and $j_\nu \neq 0$):

- $\pi = +$: $\pi(0g^2_{9/2})$ $\nu(1d^2_{5/2})$
  $\pi = -$: $\pi(1p^{-1}_{1/2}\ 0g^3_{9/2})$ $\nu(1d^2_{5/2})$
- $\pi = +$: $\pi(0g^2_{9/2})$ $\nu(1d^1_{5/2}\ 0g^1_{7/2})$
  $\pi = -$: $\pi(1p^{-1}_{1/2}\ 0g^3_{9/2})$ $\nu(1d^1_{5/2}\ 0g^1_{7/2})$
- $\pi = +$: $\pi(0g^2_{9/2})$ $\nu(1d^2_{5/2}\ 0g^{-1}_{9/2}\ 0g^1_{7/2})$
  $\pi = -$: $\pi(1p^{-1}_{1/2}\ 0g^3_{9/2})$ $\nu(1d^2_{5/2}\ 0g^{-1}_{9/2}\ 0g^1_{7/2})$.
- $\pi = +$: $\nu(1d^2_{5/2}\ 0g^{-1}_{9/2}\ 0g^1_{7/2})$

$\Rightarrow$ "Mixed-symmetry" and spin-flip configurations.


$\vec{J}$
$\vec{j}_\pi$
$\vec{j}_\nu$
$\vec{J}-\vec{1}$
$\vec{j}_\pi$
$\vec{j}_\nu$
$\vec{J}$
$\vec{\mu}_\pi$
$\vec{\mu}_{trans}$
$\vec{\mu}_\nu$
Large B(M1)

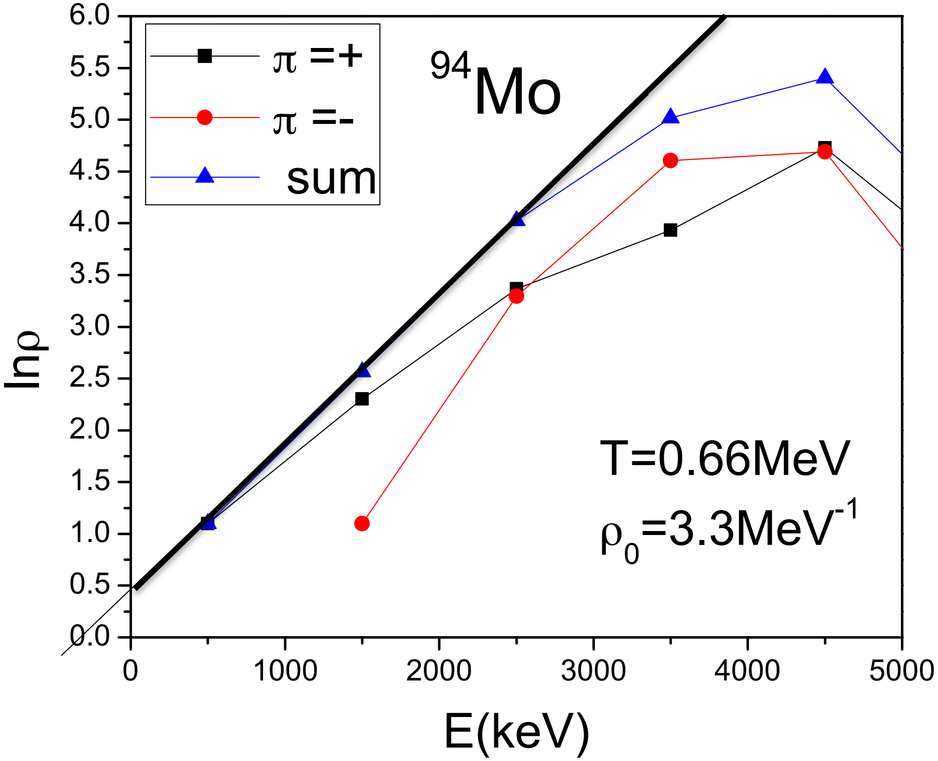
Large matrix elements between different states of one and the same configuration that are related by mutual re-alignment of the spins of the active high-j orbitals.

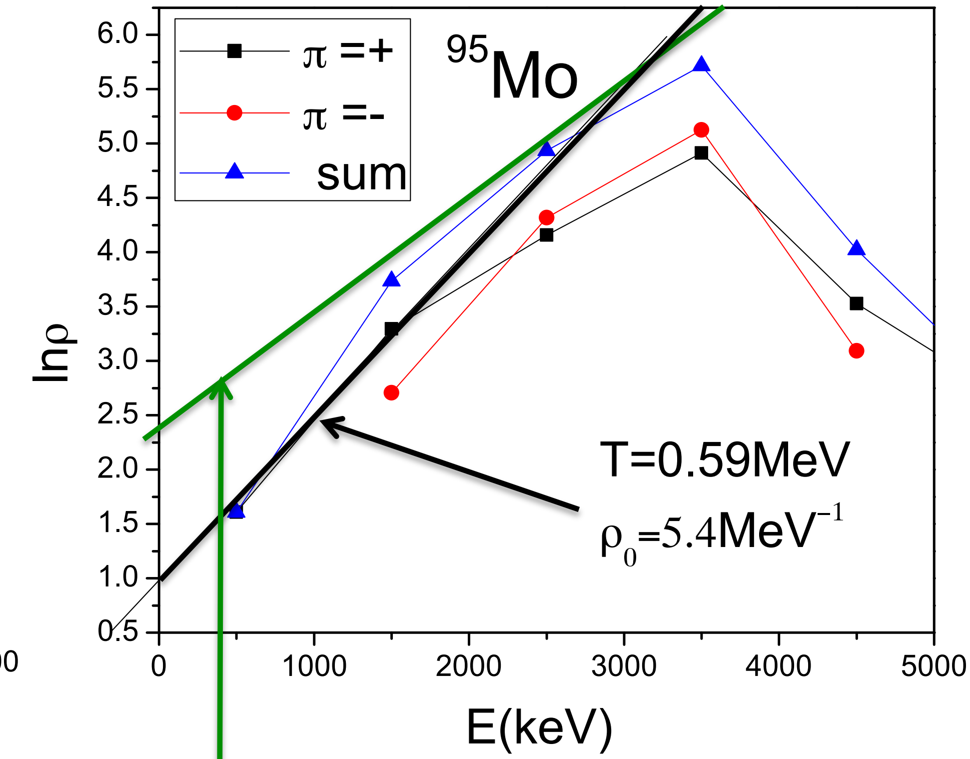
Without residual interaction the states have the same energy
-> no radiation

Residual interaction mixes the states and generates the energy differences between them. Introduces randomness.
->LEMAR

The radiating mixed states still contain a substantial components of the re-aligned multiplet states

Statistical properties of the transitions





Constant temperature level density $\rho(E) = \rho_0 \exp(E / T)$

v. Egidy, Bucurescu PHYSICAL REVIEW C 72, 044311 (2005)

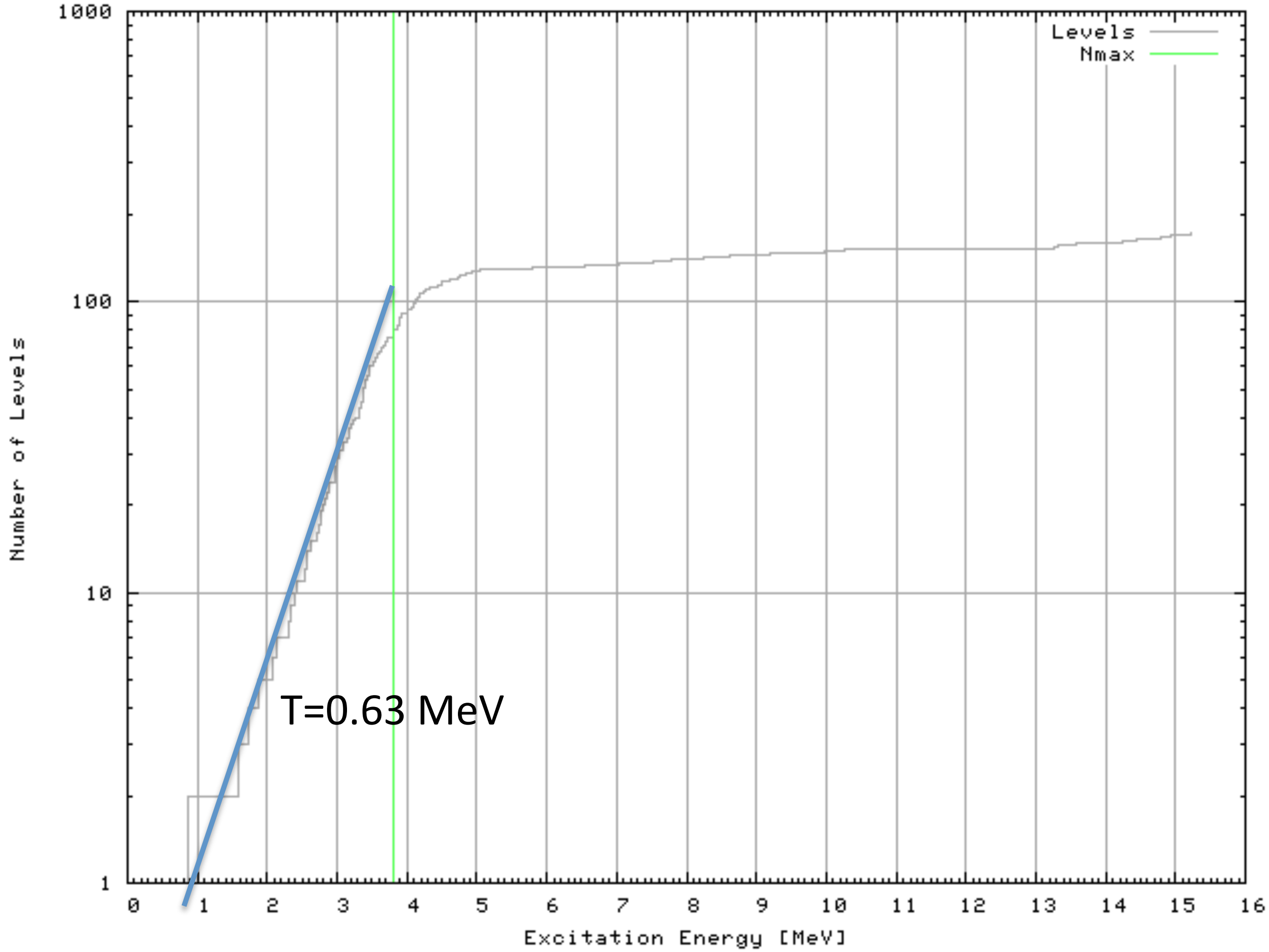
^{95}Mo $\rho_0 = 10.3 MeV^{-1}, T = 0.87 MeV$

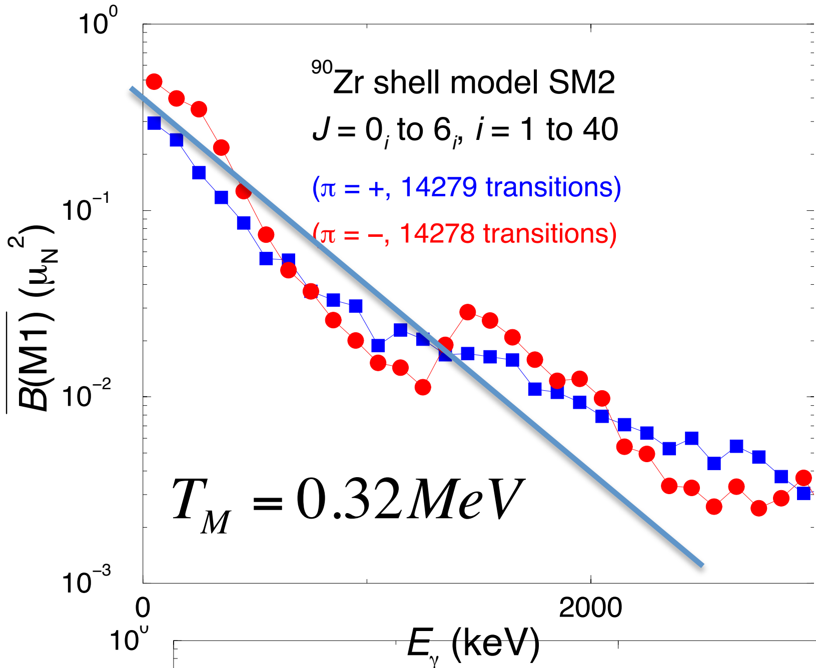
Transition from paired to unpaired state

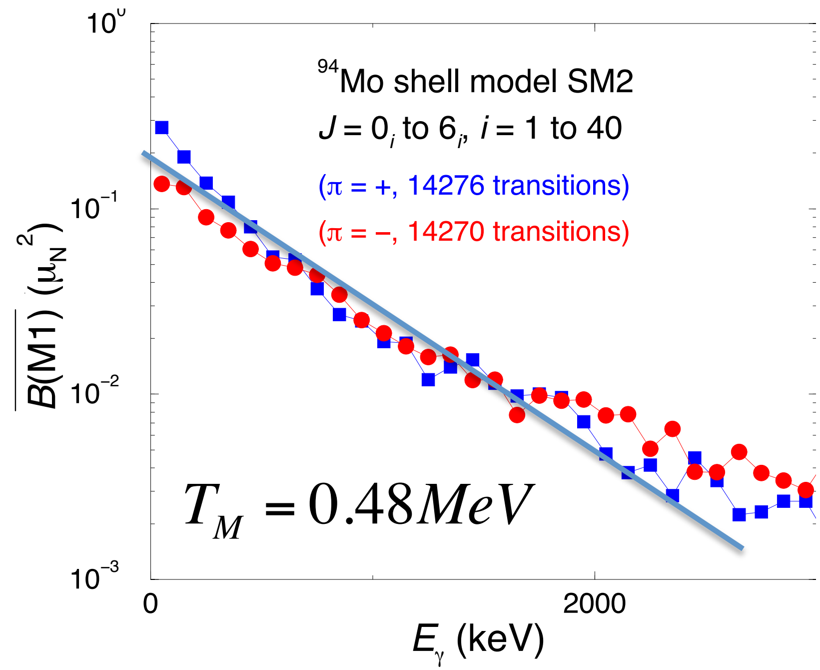
Plot of Total Level Densities

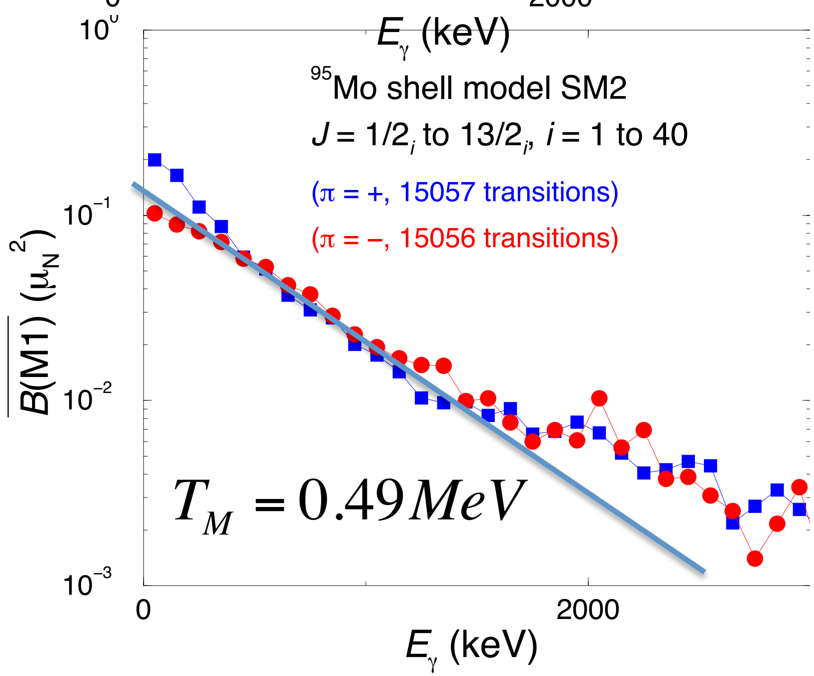
Z=42, A=94

from RIPL3





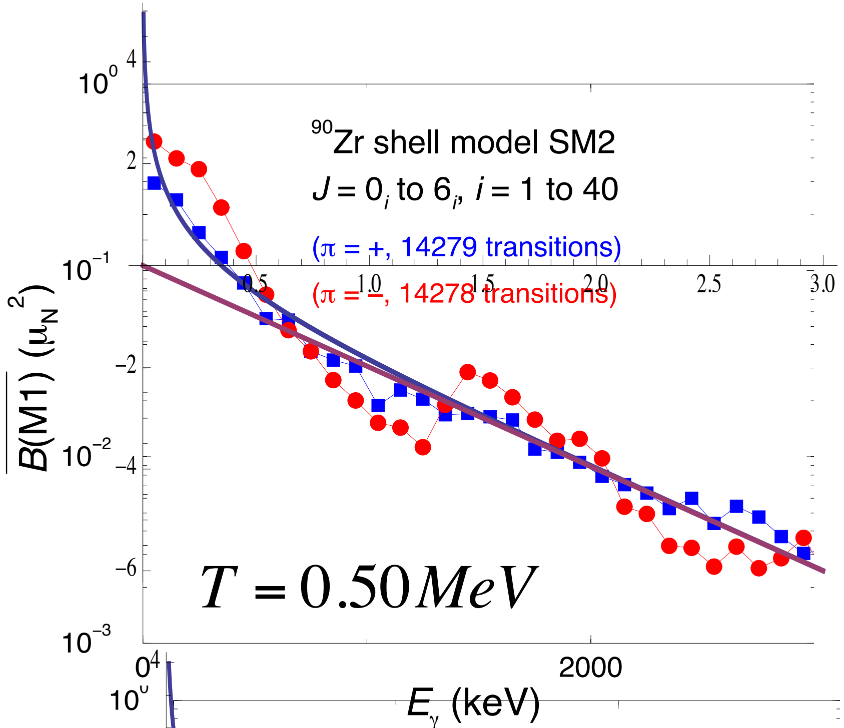


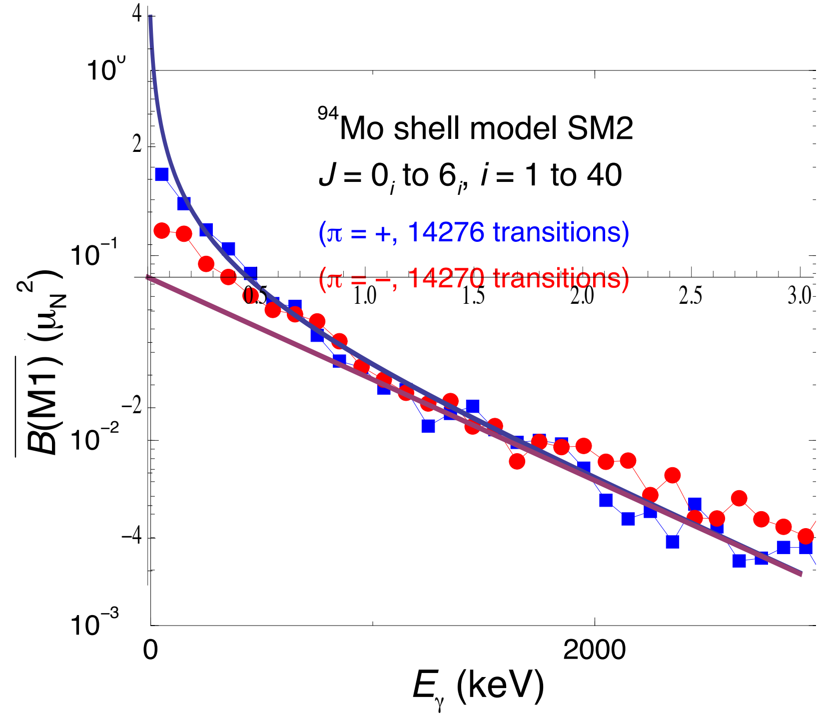


Dependence on γ – energy

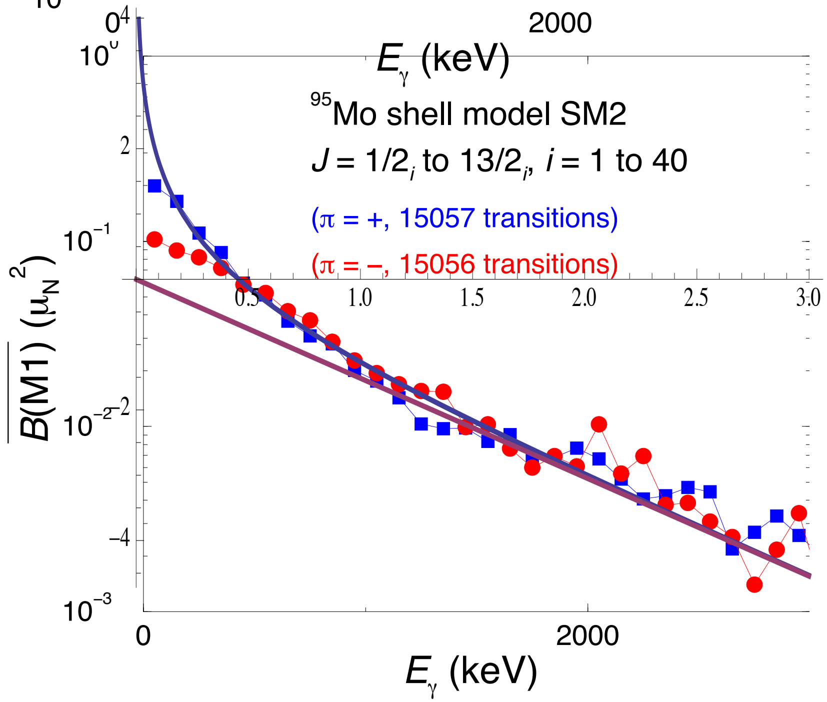
nearly exponential decrease

$$B(M1, E_\gamma) \approx B_0 \exp(-E_\gamma / T_B)$$





$T = 0.66\, MeV$ from level density



$T = 0.59\, MeV$ from level density

Better described by

$$B(M1, E_\gamma) = \frac{B_0}{\exp(E_\gamma / T) - 1}$$

T from level density

"thermal temperature"

Spectral distribution of the emission probability

$$P \propto E_\gamma^3 B(M1, E_\gamma)$$

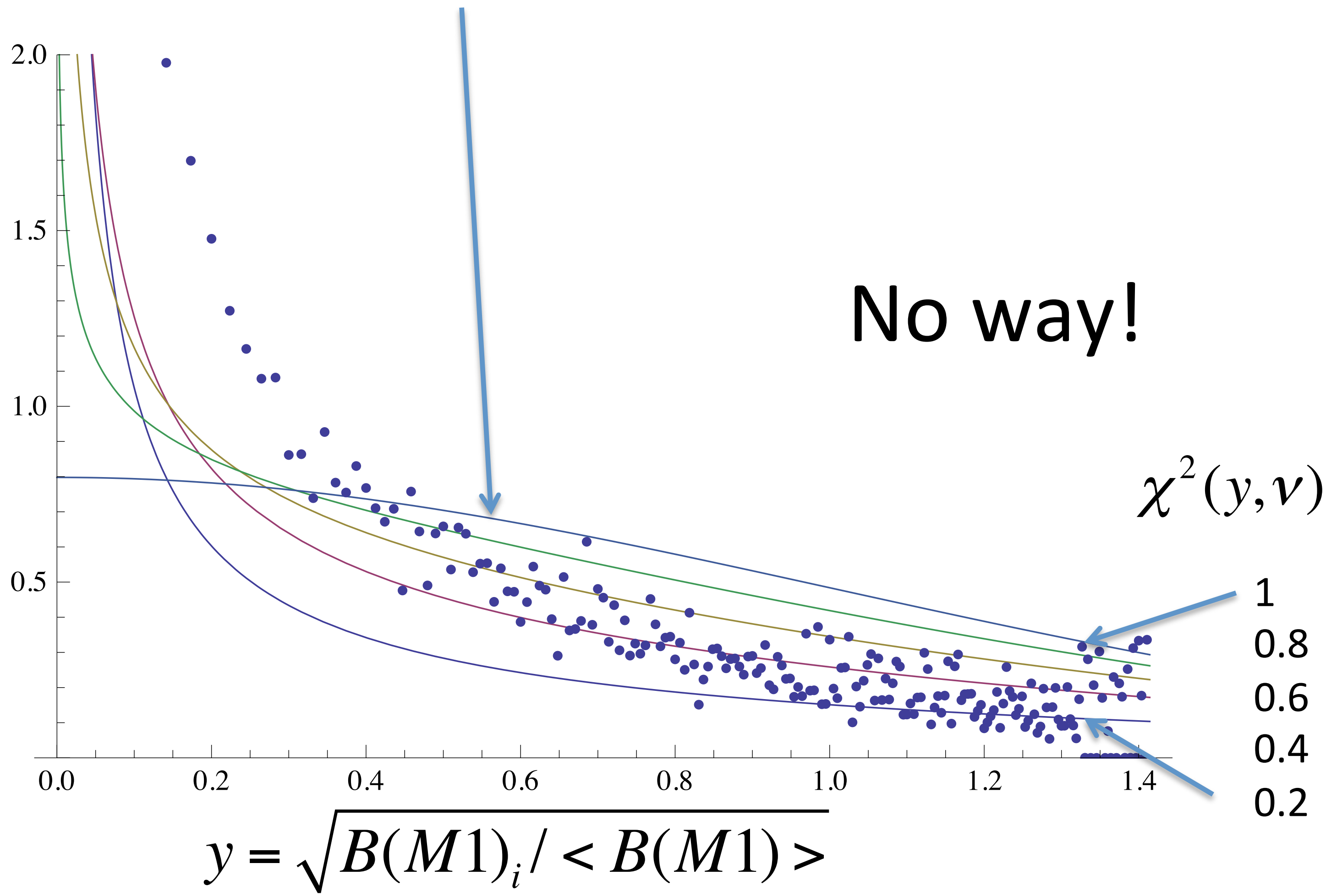
$$P(E_\gamma) = P_0 \frac{E_\gamma^3}{\exp(E_\gamma / T) - 1}$$

T from level density "thermal temperature"

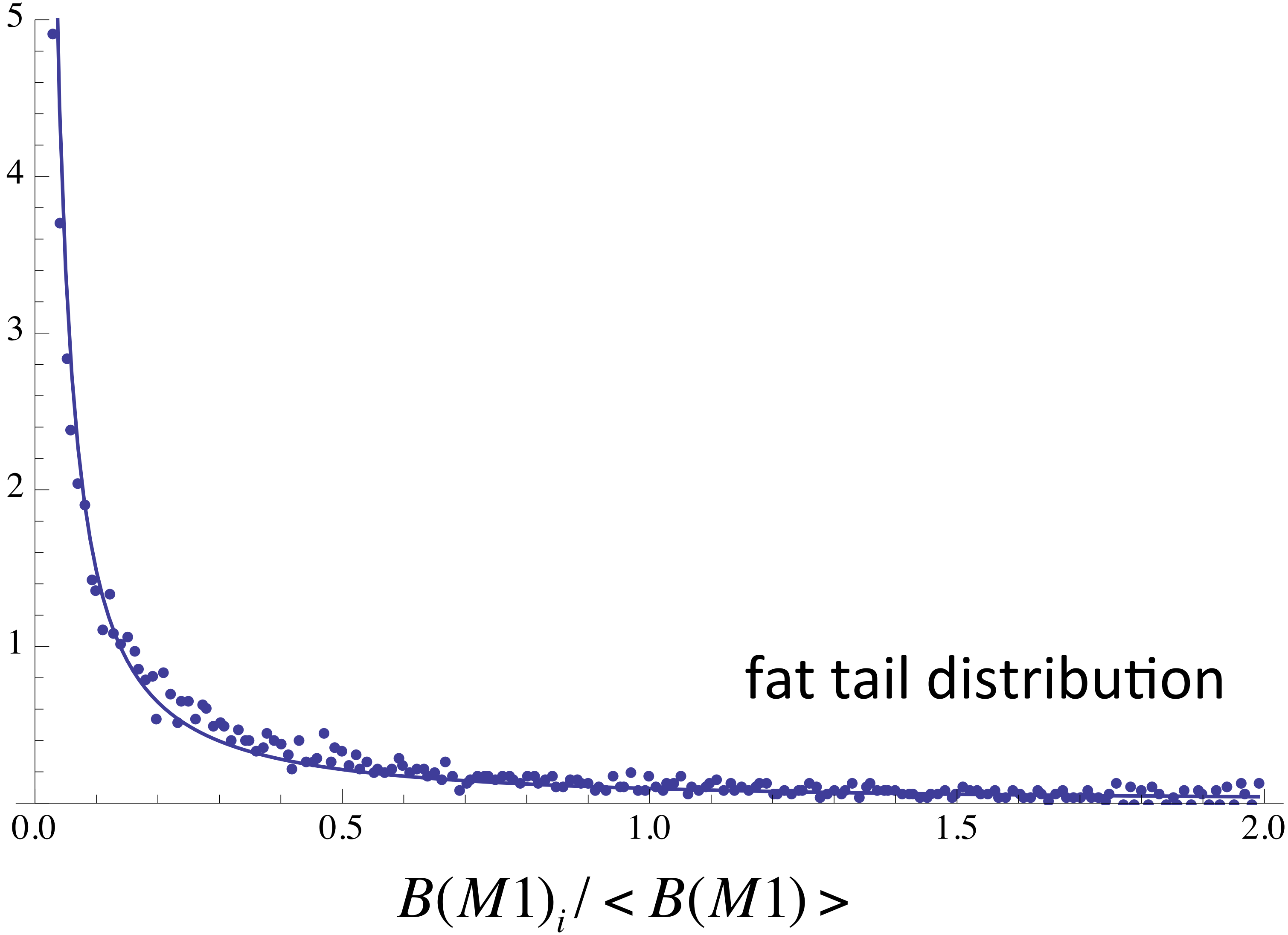
Planck's Law for black body radiation
Could be used as a thermometer.

Distribution of the reduced transition probabilities

Expectation: Porter-Thomas



It is a power law distribution! $P(x) = Ax^{\nu}, \nu = 1.2$



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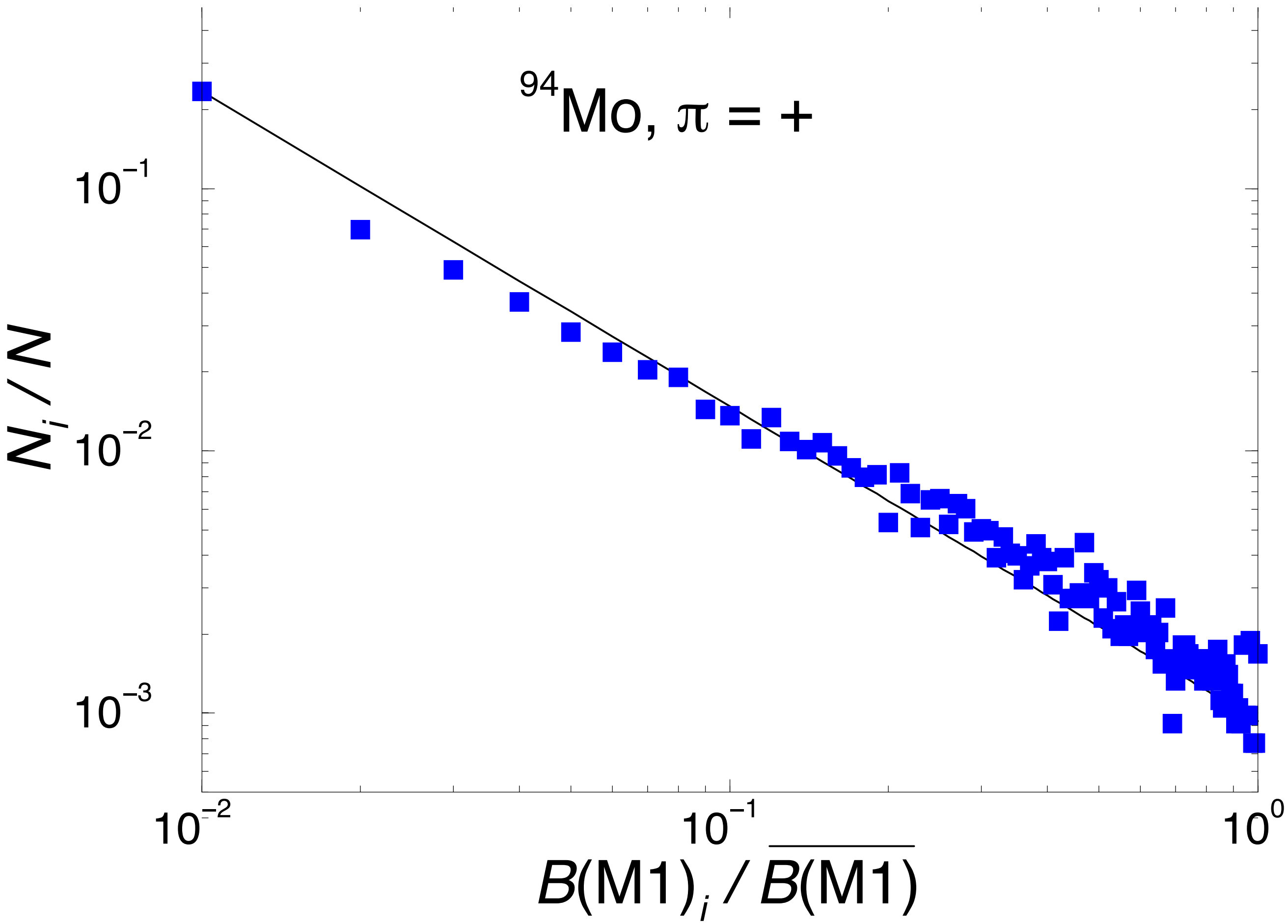


Power laws describe the distribution of fluctuations near a second order phase transition

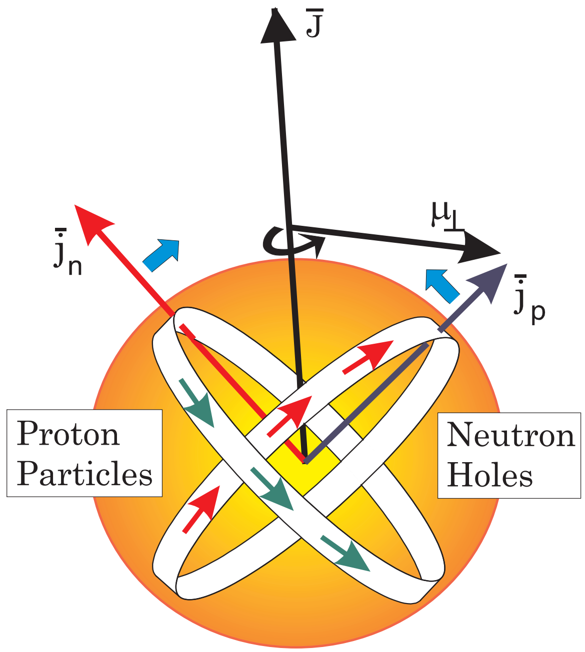
paired->normal phase ?

Magnetism is sensitive to pair correlations

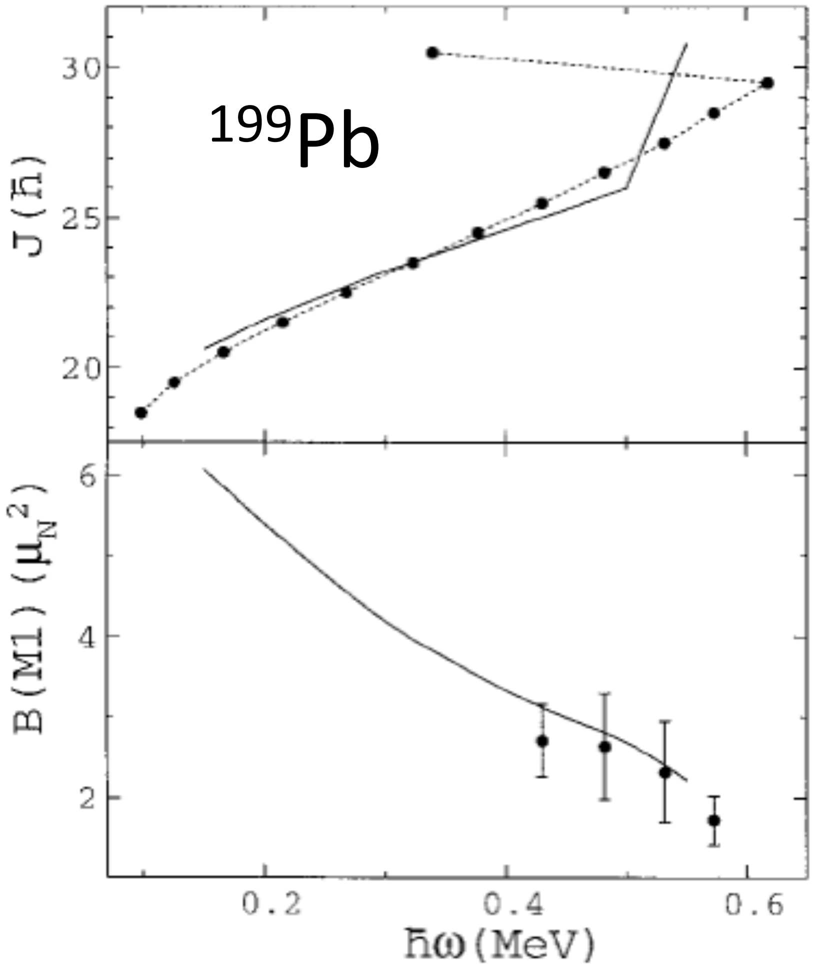
Prediction of regions/relevance

Generation of large M1 strengths

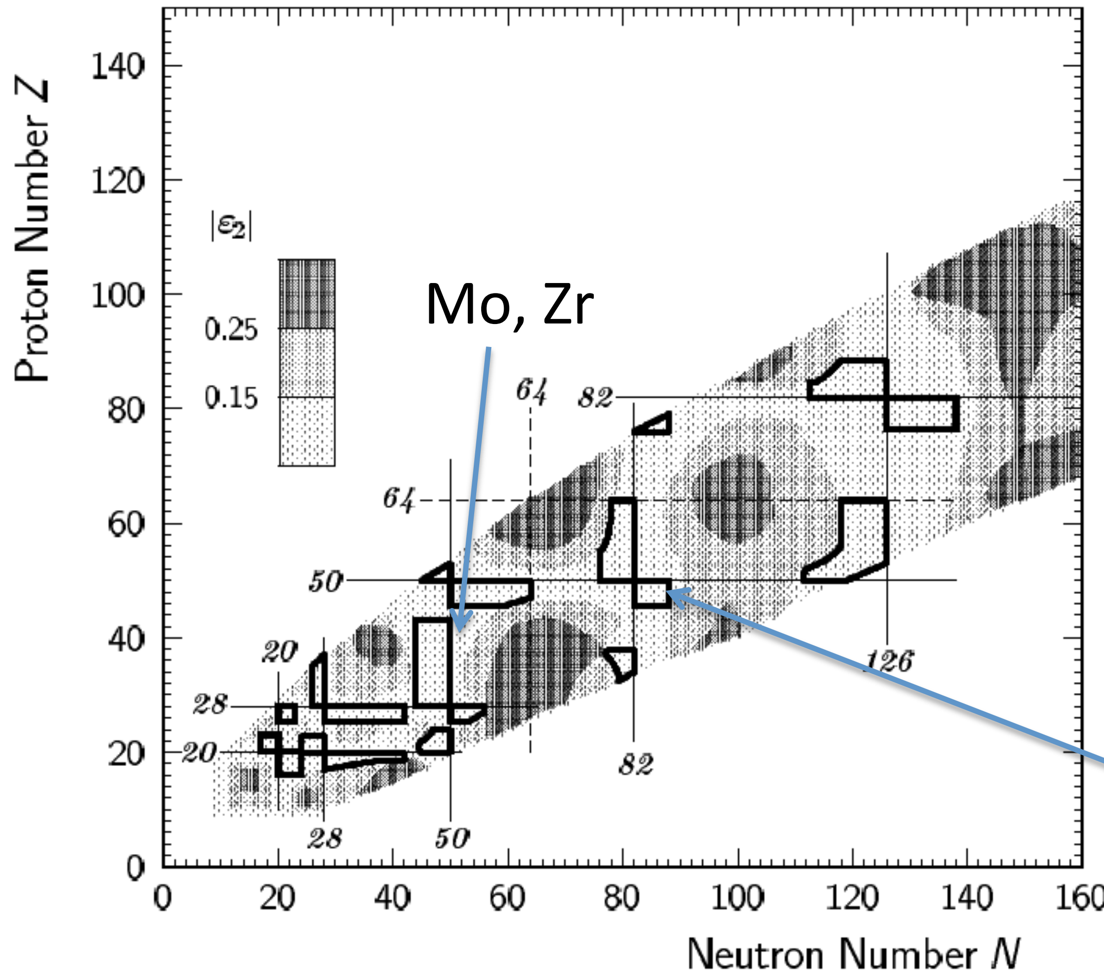
Magnetic Rotation



$B(\mathrm{M1}) \sim \mu_\perp^2$

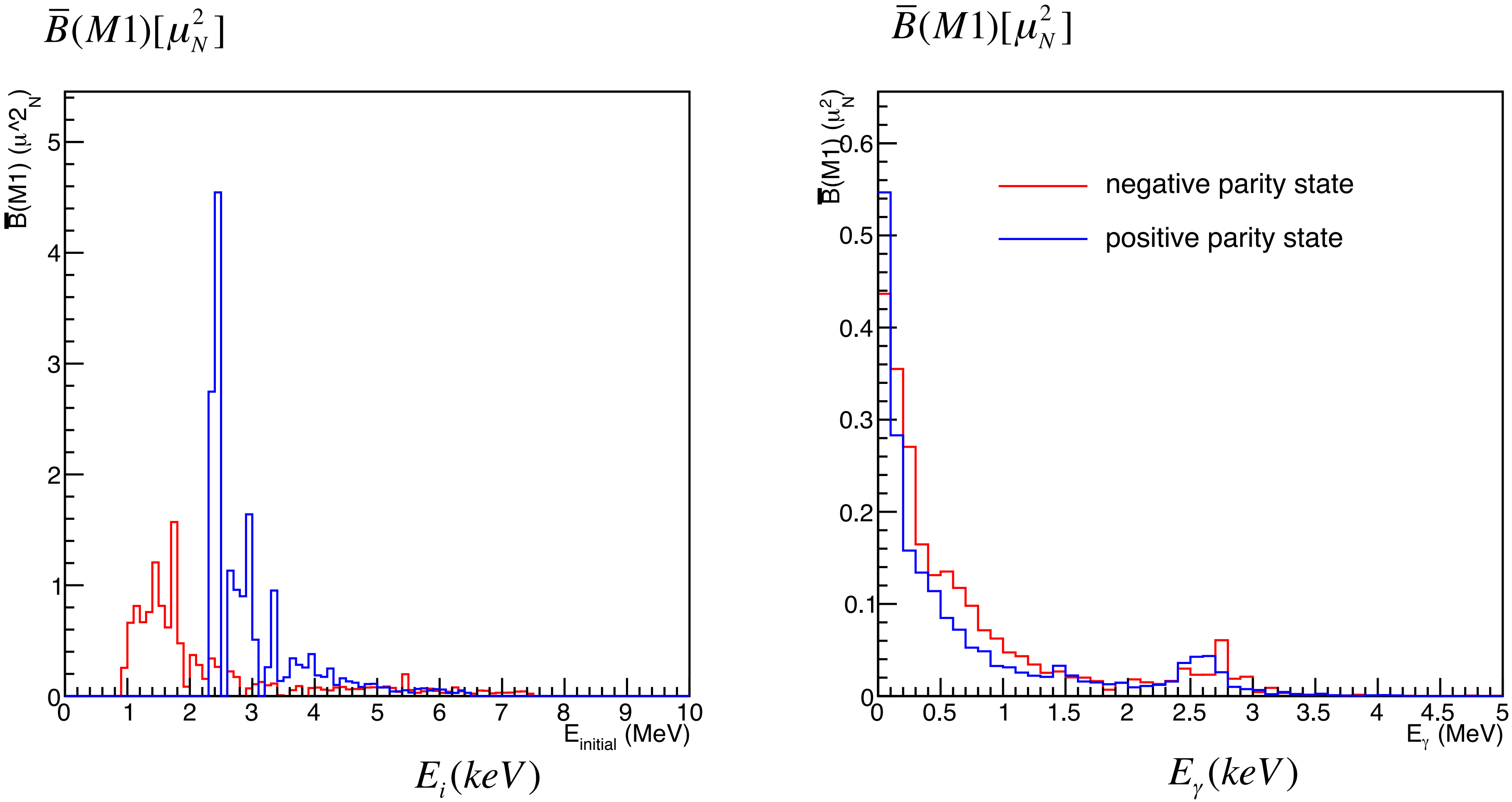


Appearance of magnetic rotation



^{131}Cd
a key player
in the r-process

LEMAR in the same regions?

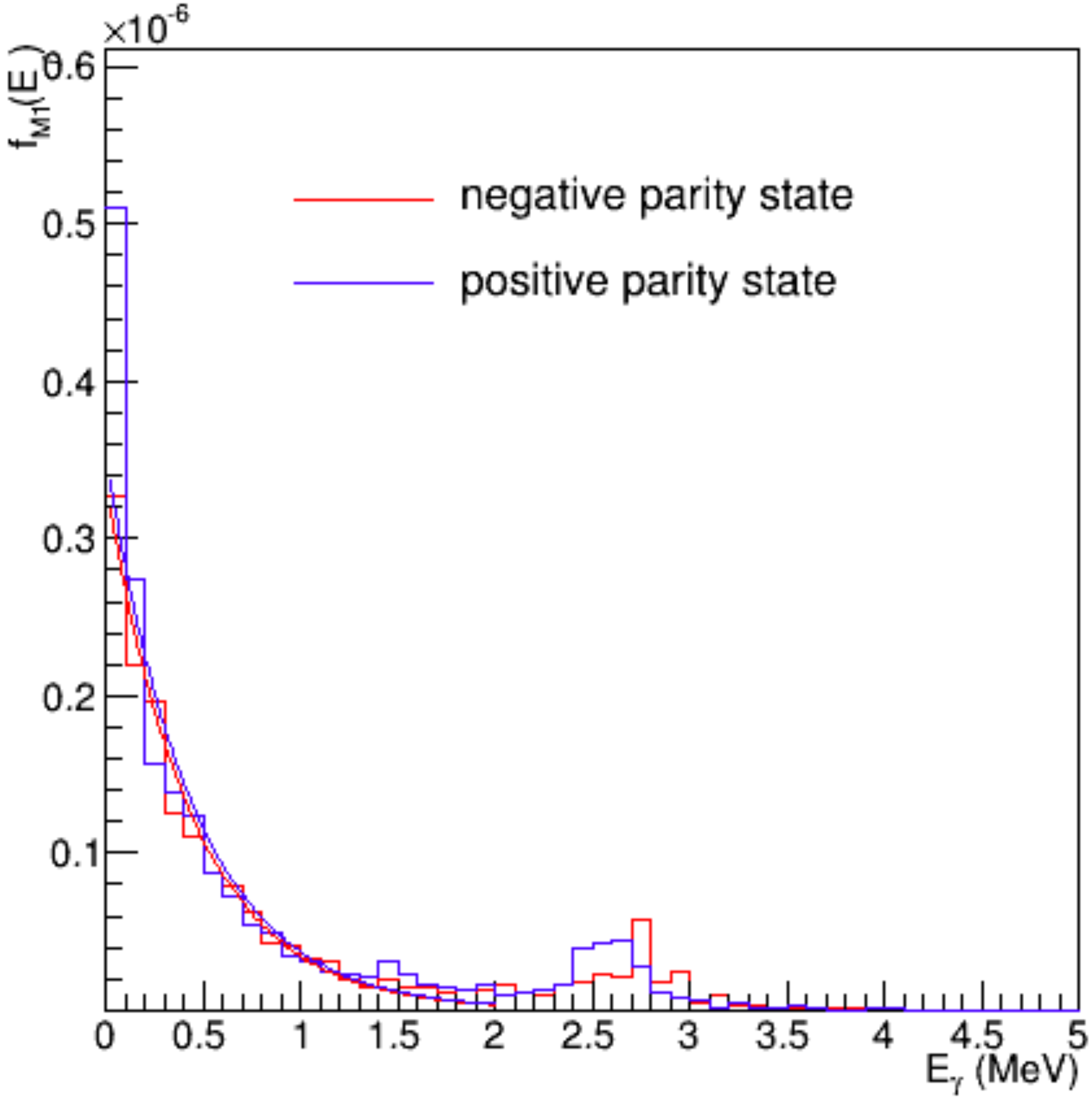


Shell model with Z=50 and N=82 core

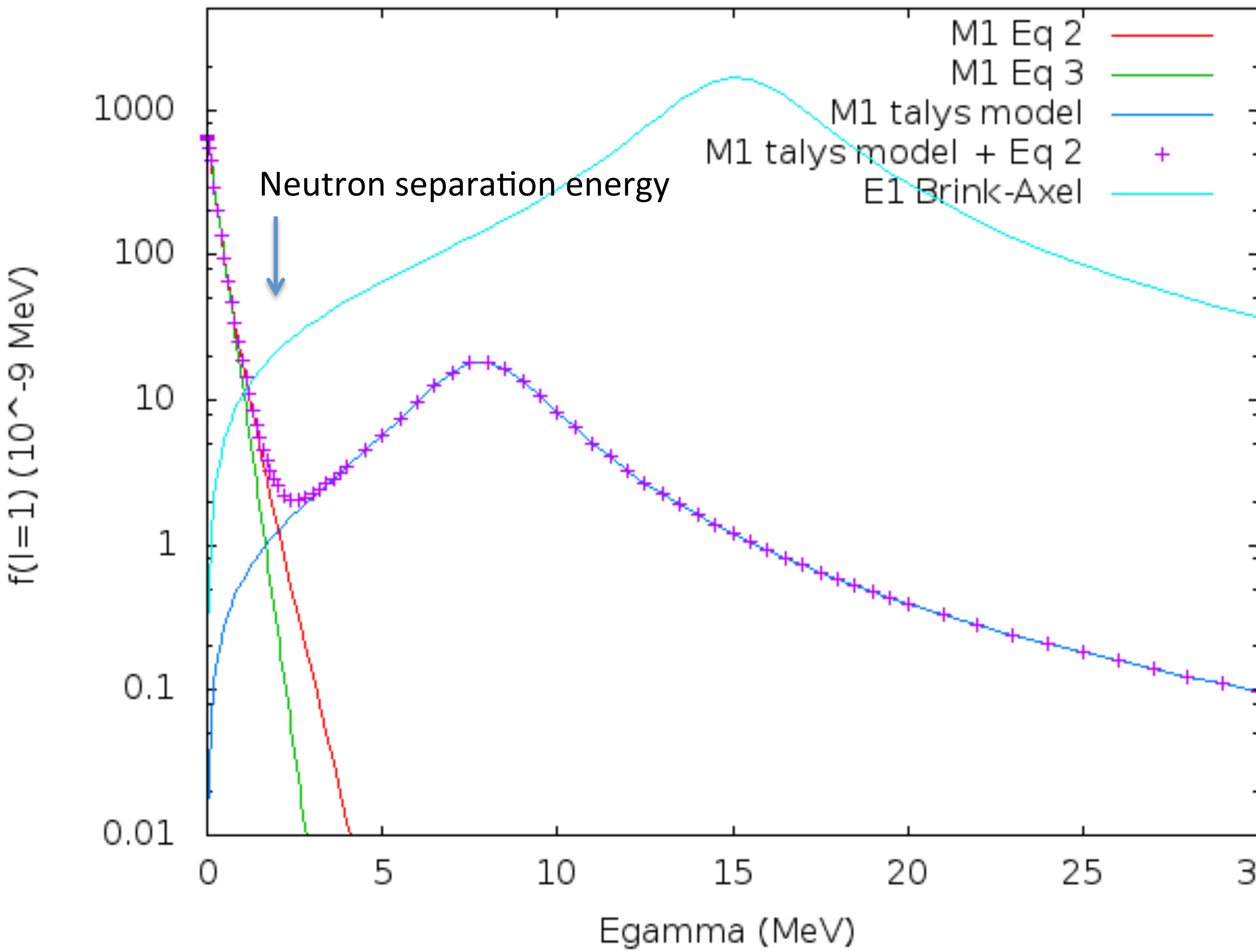
valence orbitals:

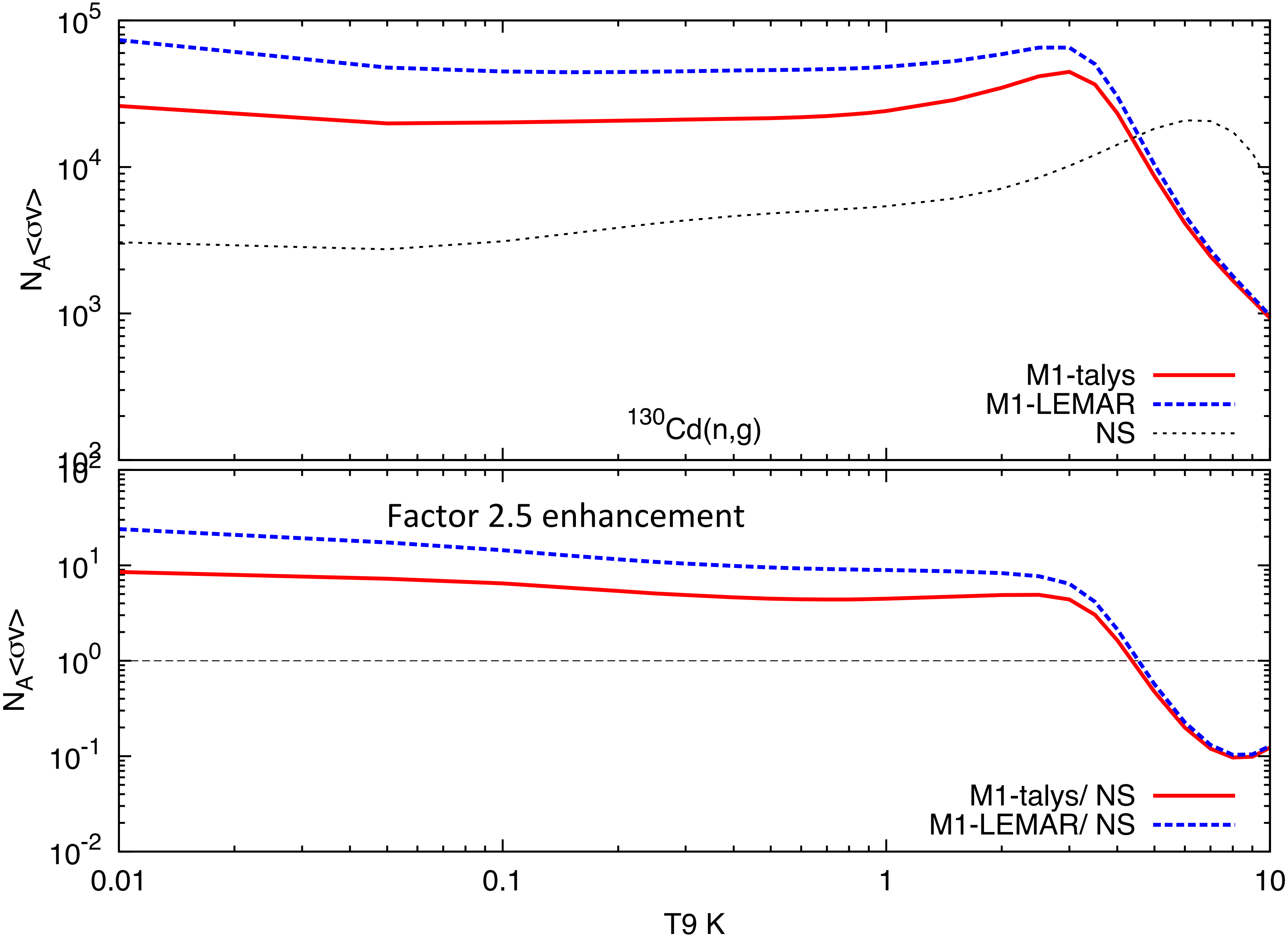
proton holes $1p_{3/2}, 0f_{5/2}, 1p_{1/2}, 0g_{9/2}$ neutron particles $0h_{9/2}, 1f_{5/2}, 2p_{3/2}, 2p_{1/2}$

G-matrix derived from CD-Bonn NN interaction

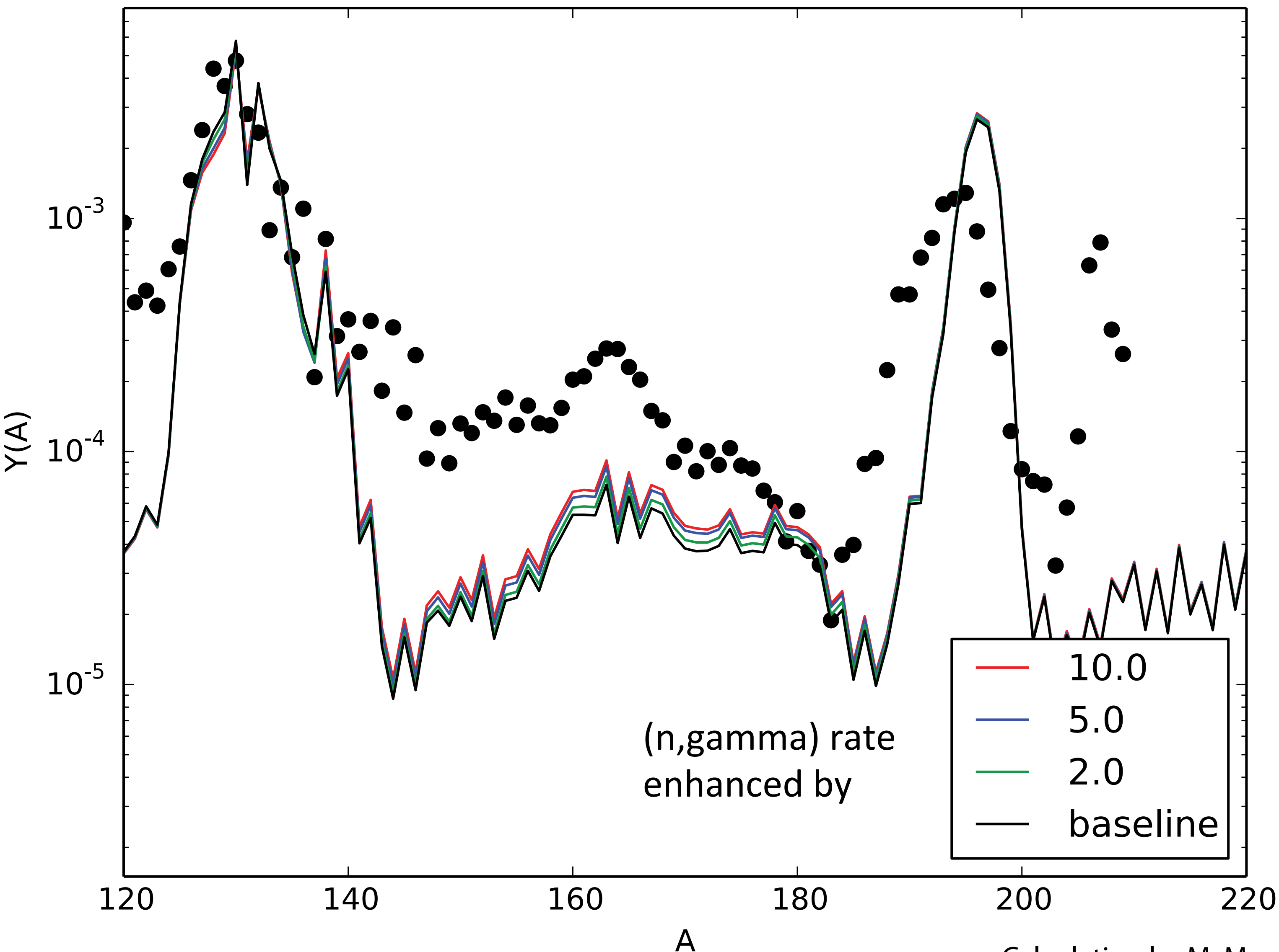


$f_{M1}(E_\gamma)$
$\times 10^{-6}$
0.6
0.5
0.4
0.3
0.2
0.1
negative parity state
positive parity state
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
E_γ (MeV)


M1 Eq 2
M1 Eq 3
M1 talys model
M1 talys model + Eq 2
E1 Brink-Axel
Neutron separation energy
1000
100
10
1
0.1
0.01
f(l=1) (10^-9 MeV)
0
5
10
15
20
25
30
Egamma (MeV)



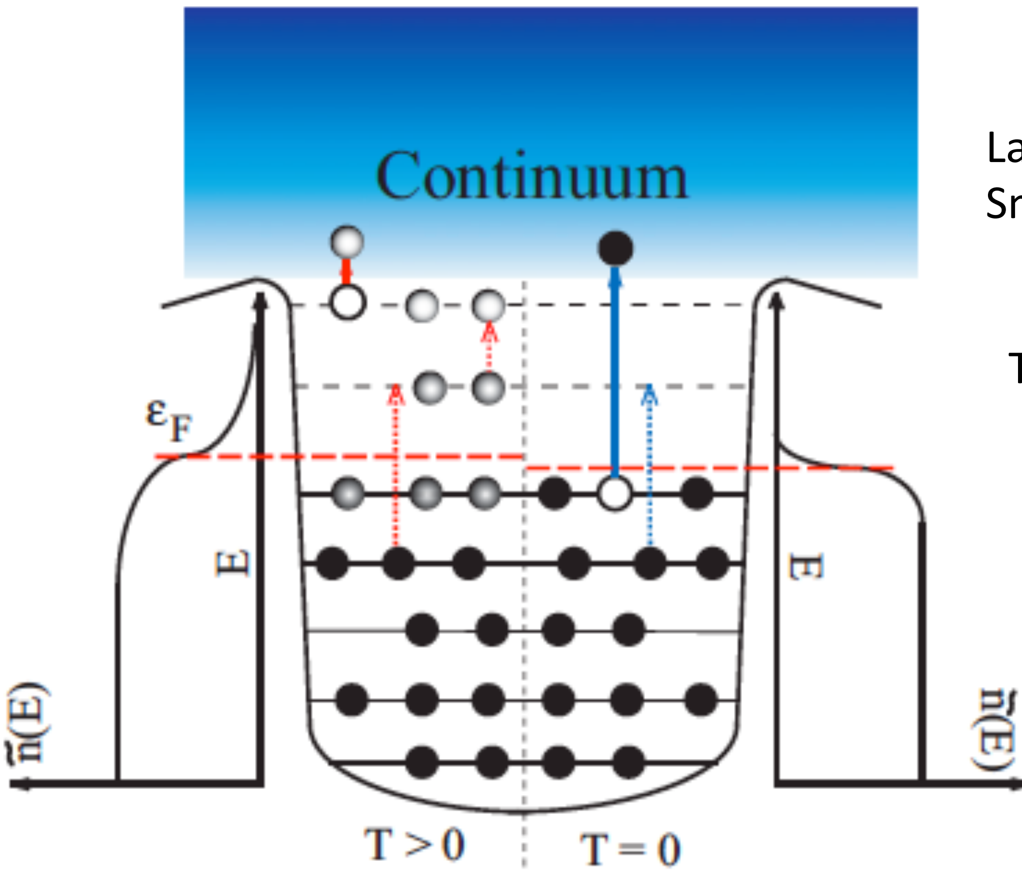
10^5
10^4
10^3
10^2
$N_A<\sigma v>$
M1-talys
M1-LEMAR
NS
$^{130}Cd(n,g)$
Factor 2.5 enhancement
10^2
10^1
10^0
10^{-1}
10^{-2}
$N_A<\sigma v>$
M1-talys/ NS
M1-LEMAR/ NS
0.01
0.1
1
10
T9 K



Calculation by M. Mumpower

r-process yields in a neutron star merger

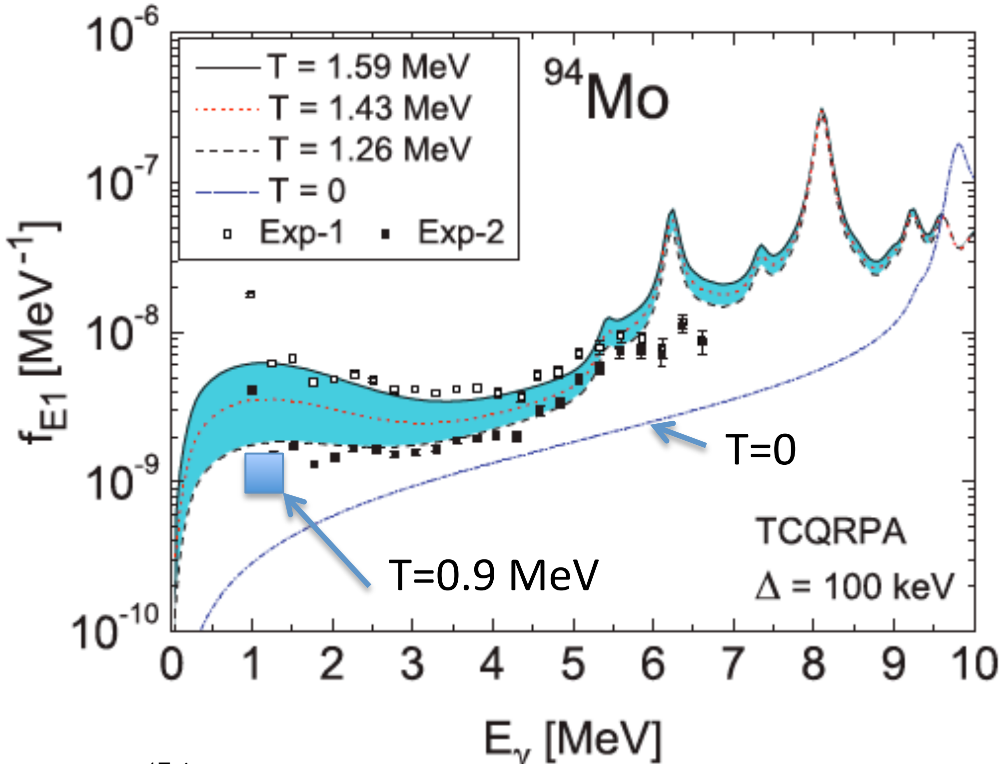
Low Energy Electric Radiation

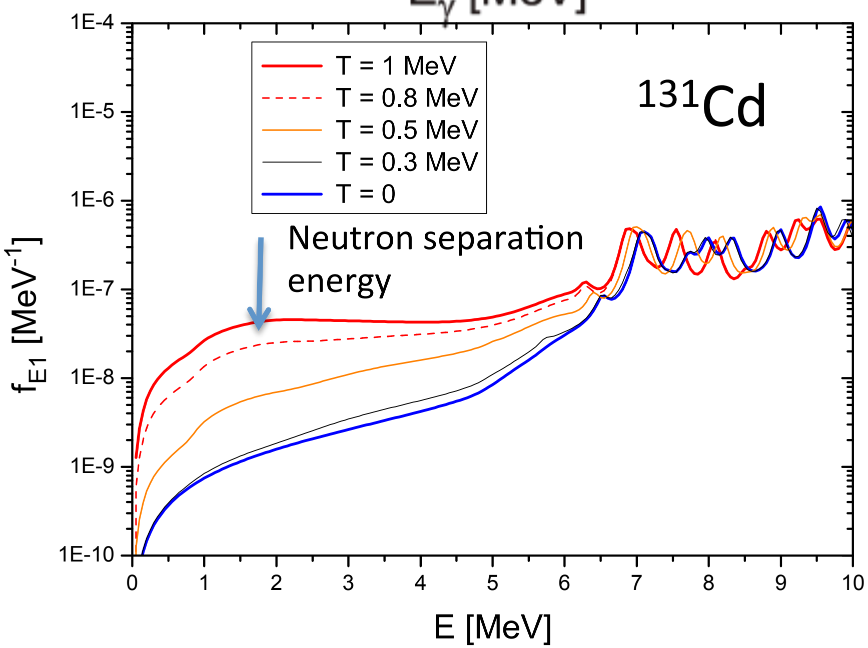


Large dipole moments
Small distance

Thermal excitation

E. Litvinova, N. Belov, PHYSICAL REVIEW C **88**, 031302(R) (2013)





T=0.6MeV

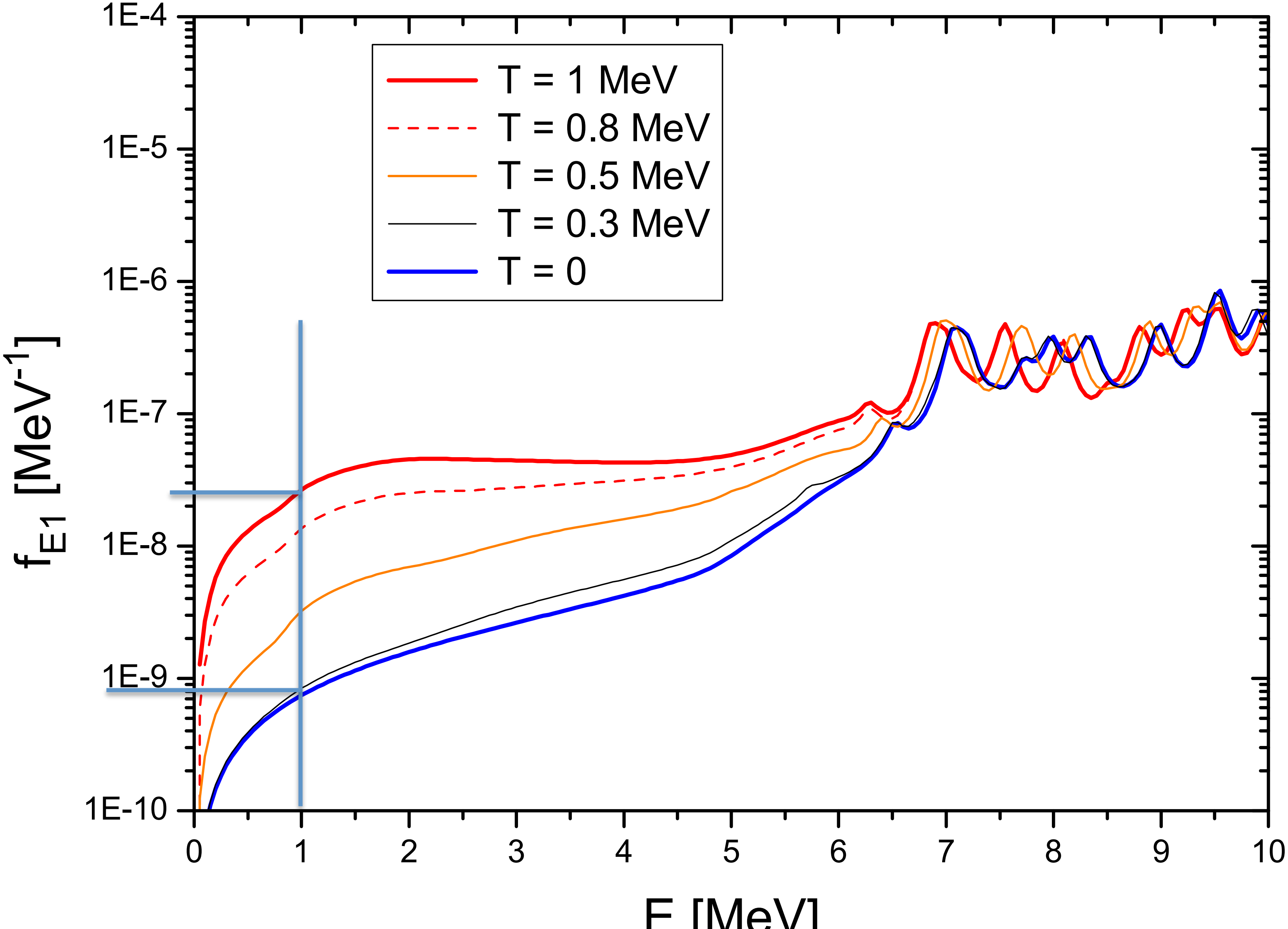
1 MeV radiation
3 times enhanced

T estimated according to
V. Egidy, Bucurescu
PRC 72(2005)044311

T=1MeV

1 MeV radiation
30 times enhanced

Statistical approach at
2 MeV excitation energy???



T = 1 MeV
T = 0.8 MeV
T = 0.5 MeV
T = 0.3 MeV
T = 0
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
0
1
2
3
4
5
6
7
8
9
10
E [MeV]
f_{E1} [MeV^{-1}]

Summary-questions

- LEMAR accounts for experimental enhancement
- M1 radiation generated by re-alignment of high-j orbitals
- B(M1) dependence Eγ is black body
- Power law distribution of B(M1) (not Porter Thomas!)
- Which nuclei show it, which not?
- Role of deformation: Shift of strength into scissors mode?
- 5-10 times enhanced r-process rates/abundances