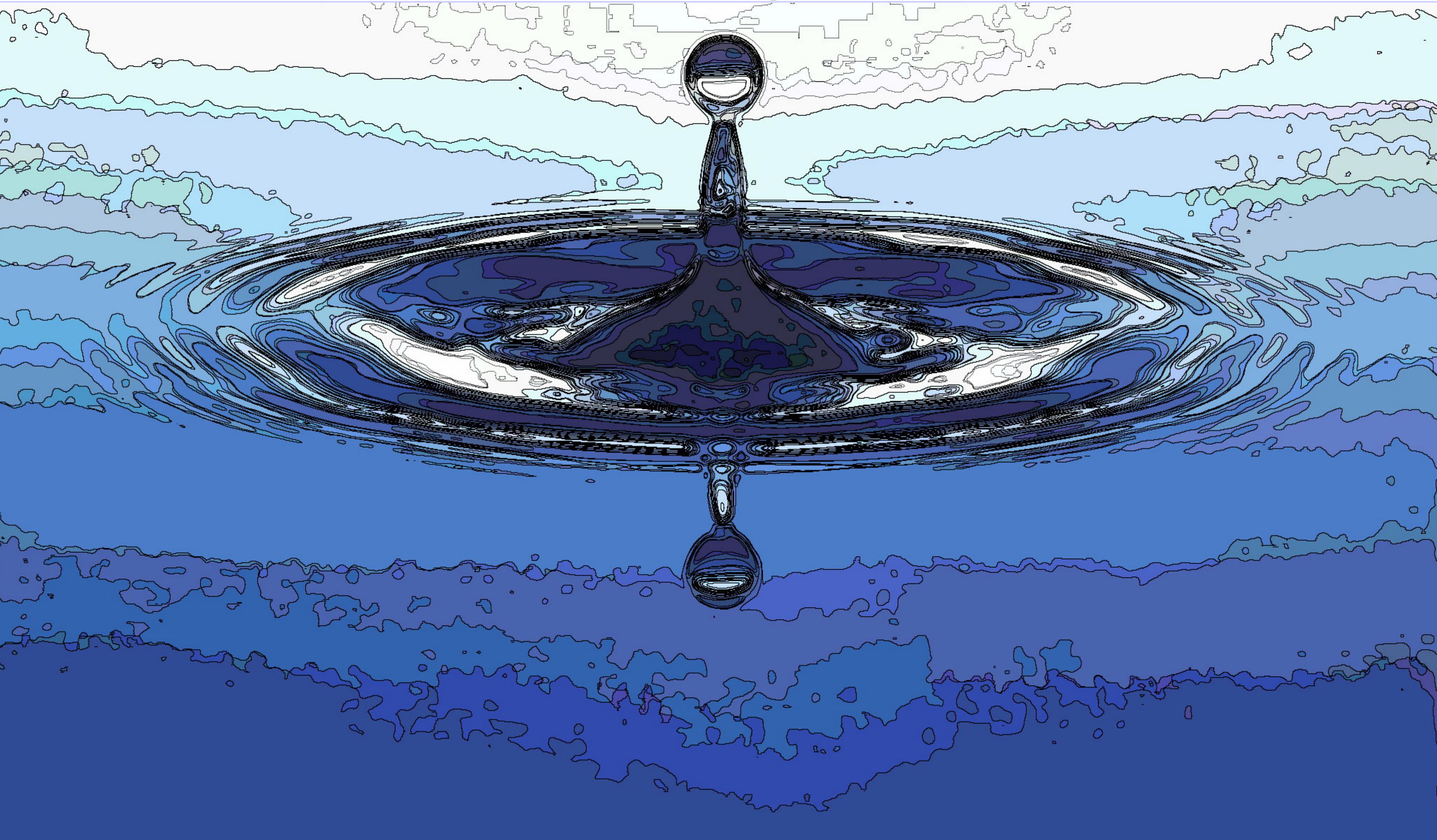
Challenges in Nuclear Structure Theory for Astrophysics

B. Alex Brown

JINA Frontiers, August 20-22, 2005



End results

- Binding energies, (S_n, S_p, neutron matter…)
- $T_{1/2}$ for beta decay (Gamow-Teller, First Forbidden)
- (p,γ) (E_x, proton and γ decay widths)
- (n,γ)
- (α,γ), (α,p)….
- Neutrino inelastic cross sections

Tools and Input

- Shell model phenomenology
  Mean-field (Skyrme) – RPA
  Configuration mixing (model space)
  Large-basis, Monte-Carlo, IBM…

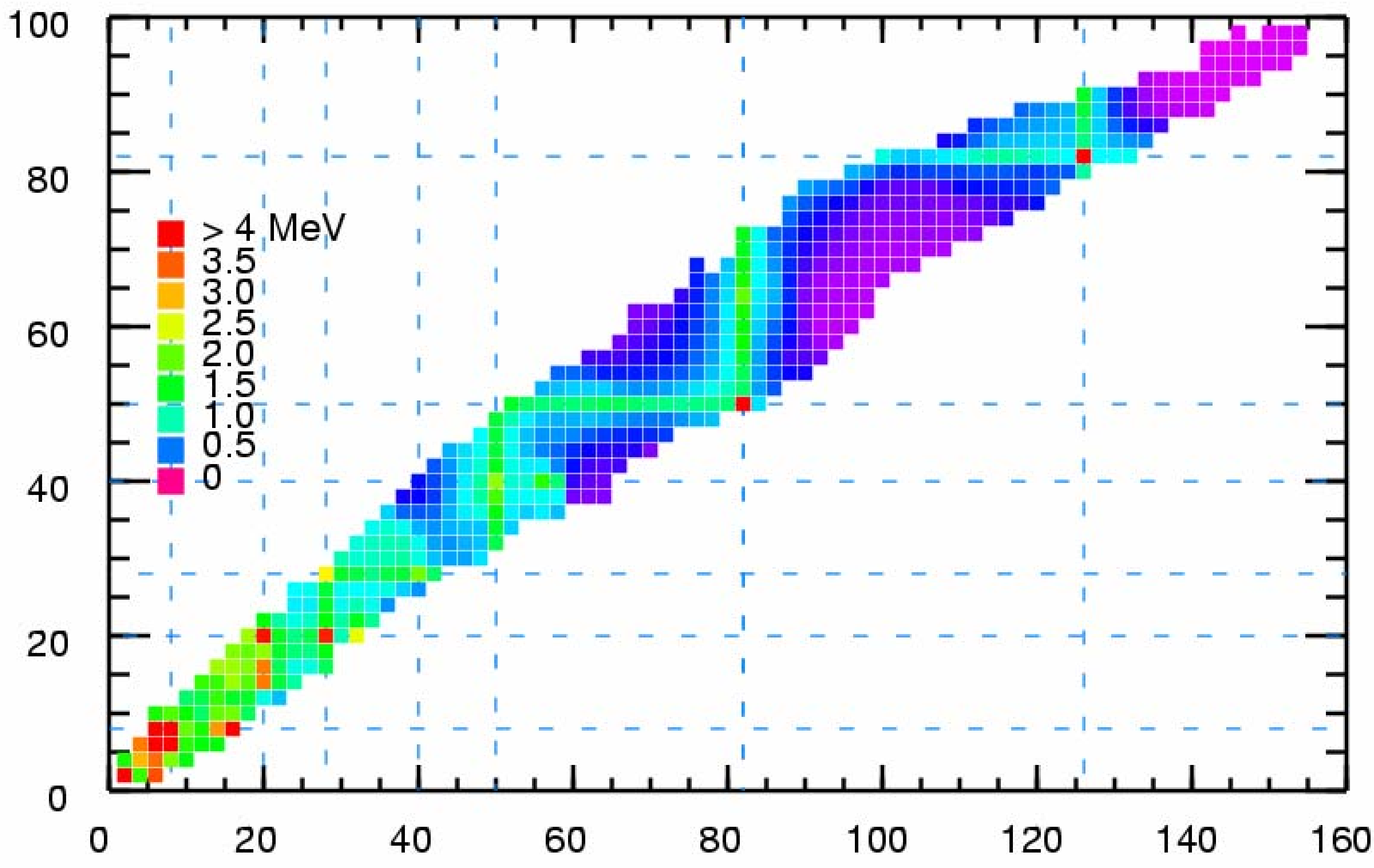
  Renormalized G matrix
  GFMC, variational methods
  (light nuclei and nuclear matter)

- NN and NNN interaction

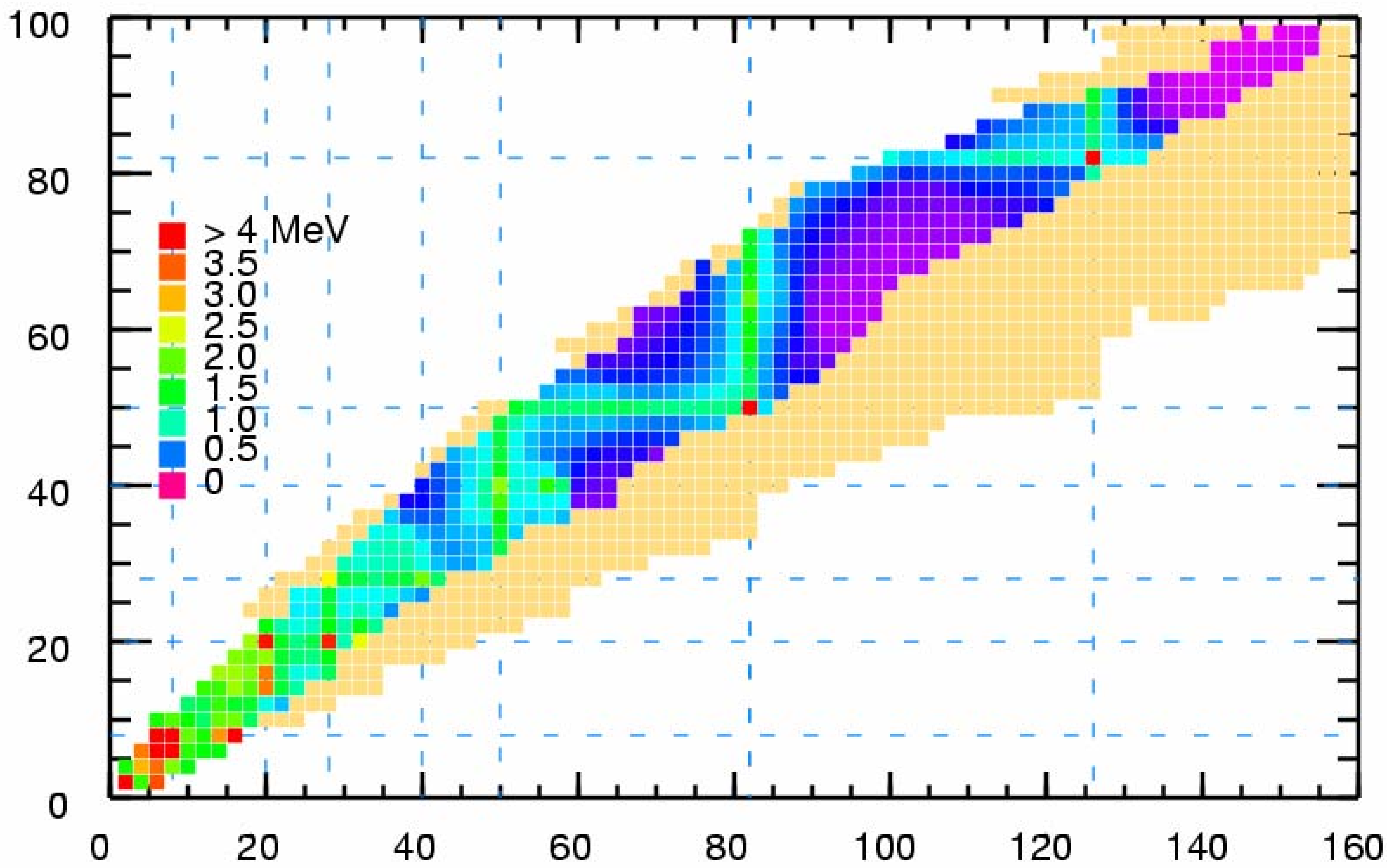
Minimal model for low-lying states

- Full configuration mixing for the closely spaced orbitals near the Fermi surface
- Complete set of levels up to about 5 MeV.
- Model space for a few orbitals, but matrix dimensions grow beyond computational limits
- Mixing with other orbitals must be taken into account (renormalization, perturbation…)

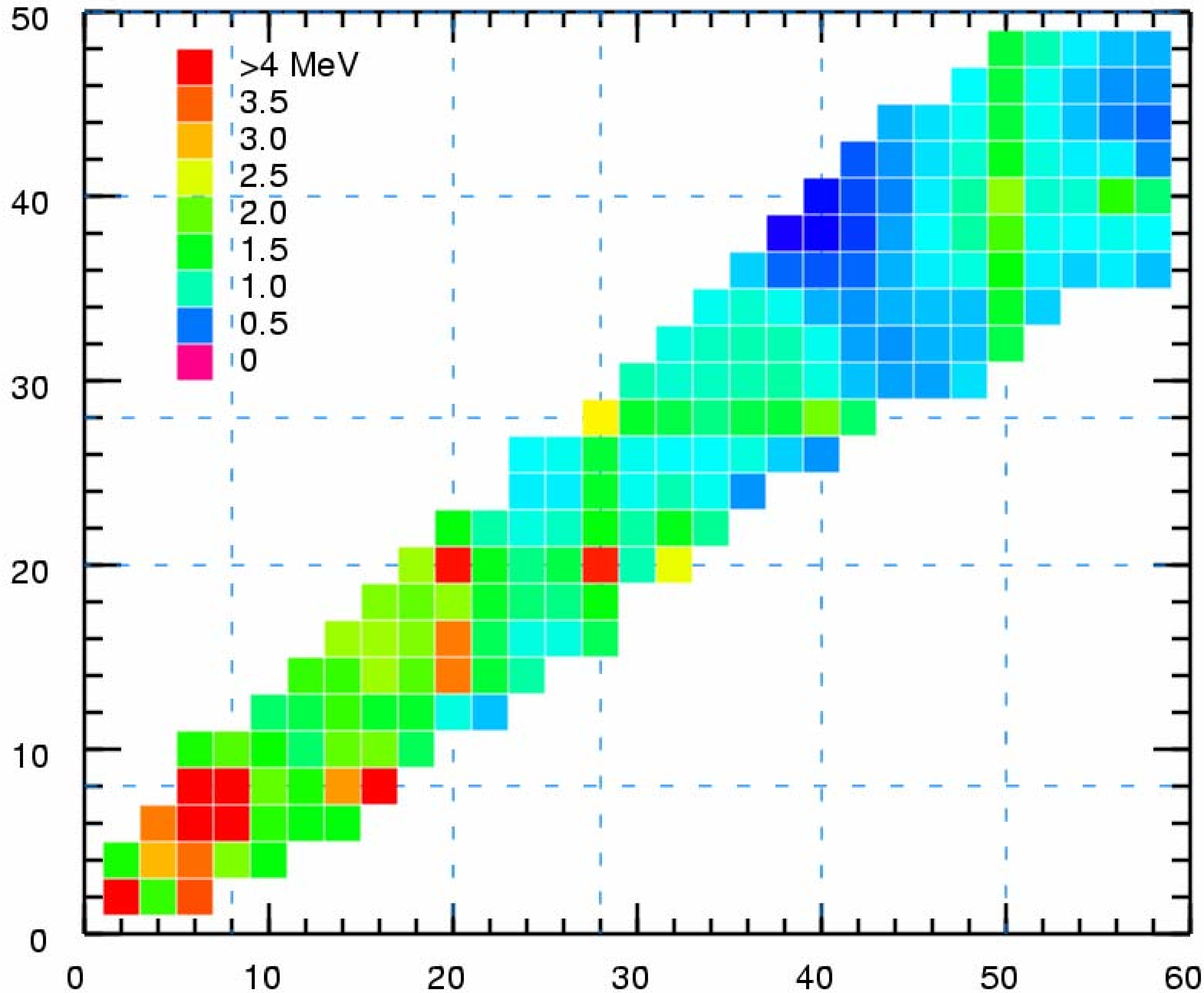
Energy of first excited 2^+ states



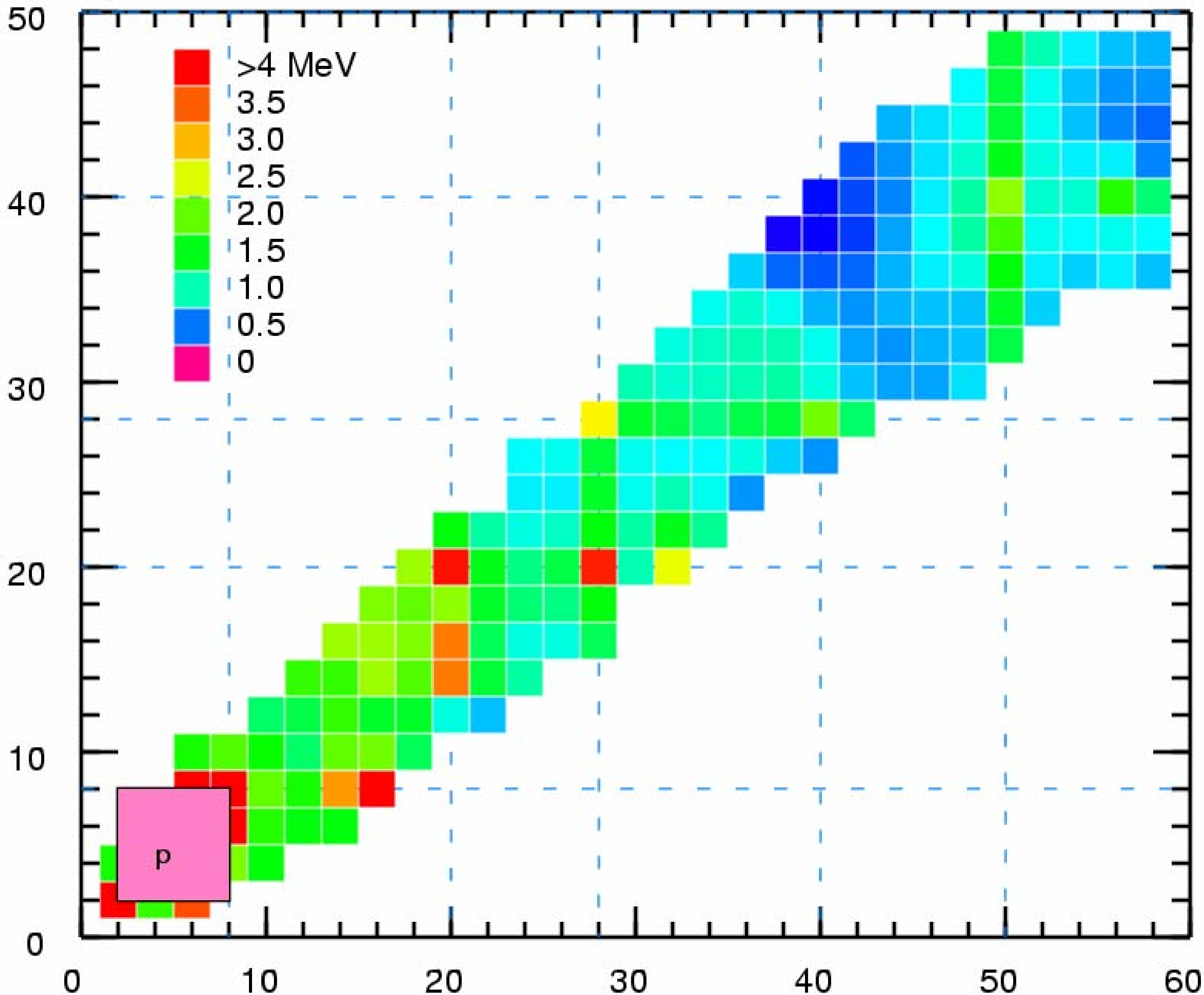
NSCL



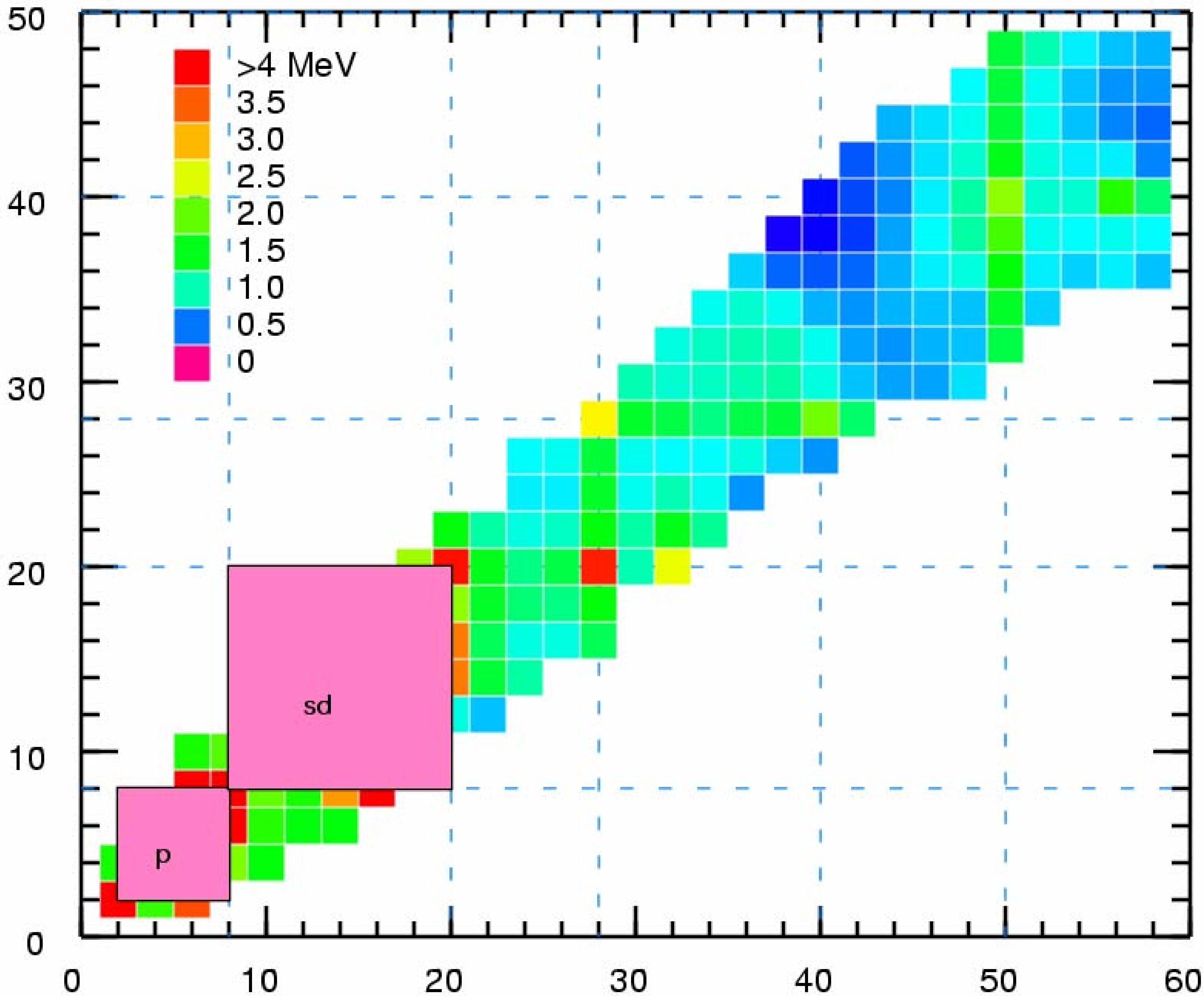
100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
> 4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0



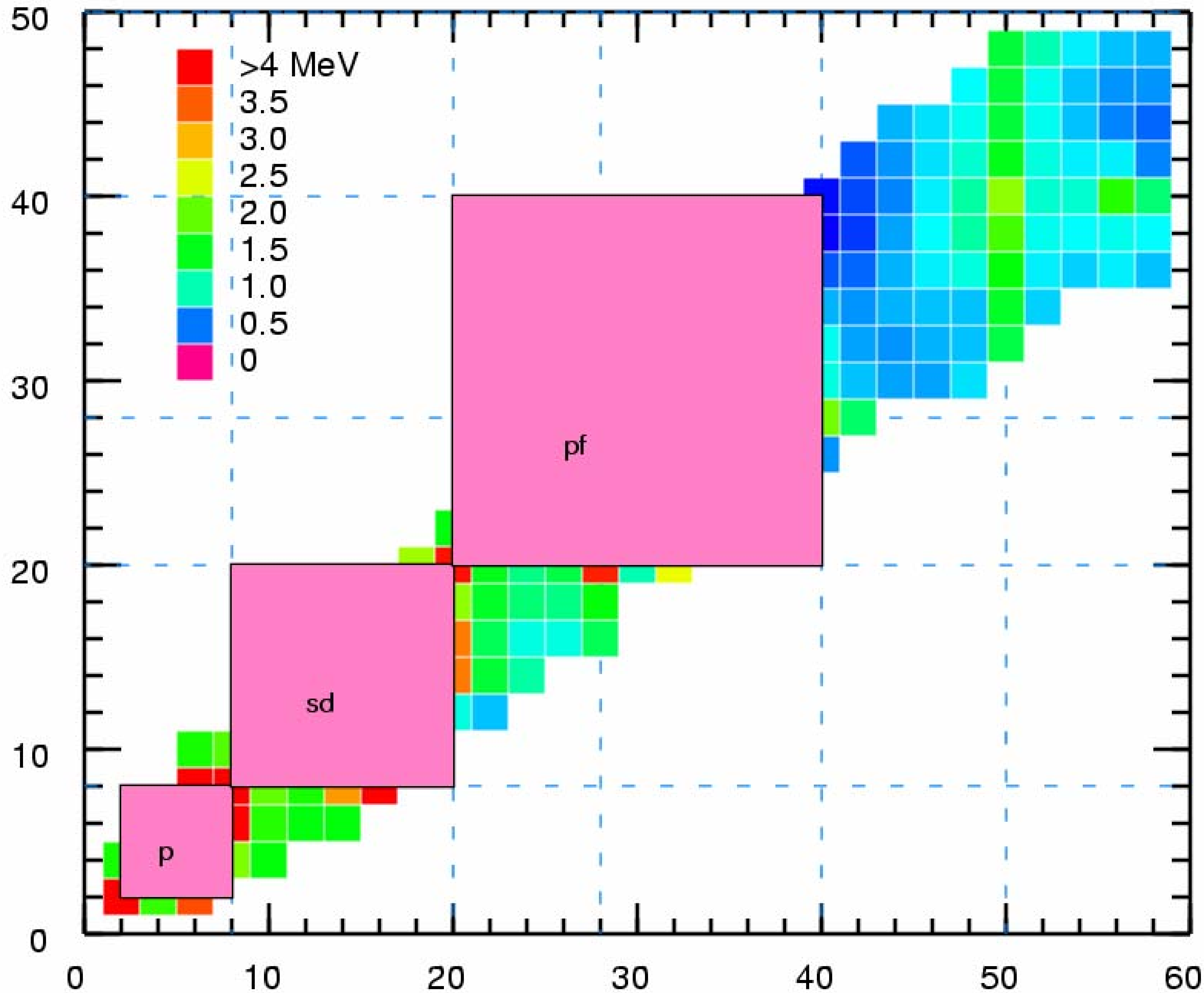
>4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
0
10
20
30
40
50
0
10
20
30
40
50
60



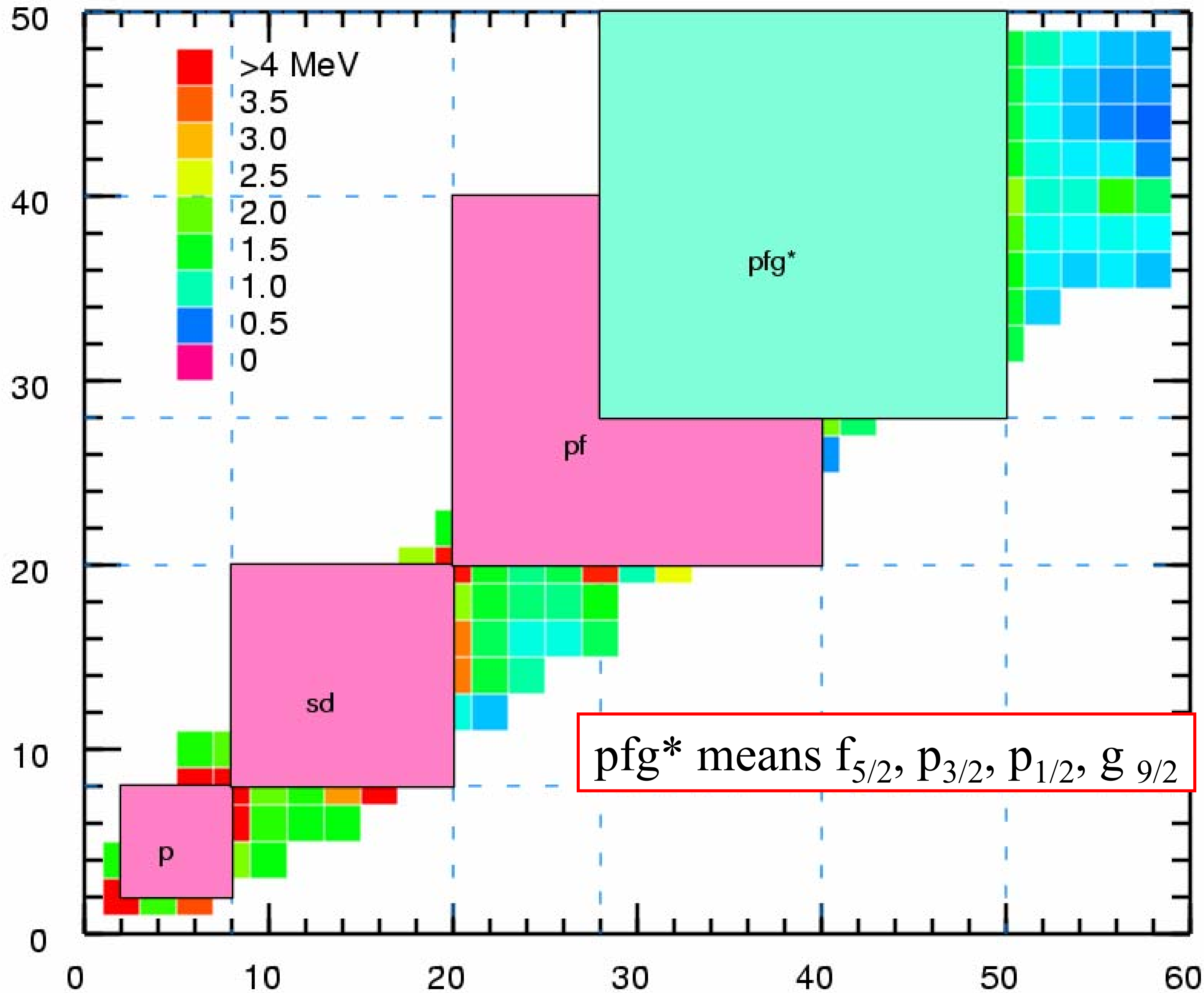
>4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
p
0
10
20
30
40
50
60



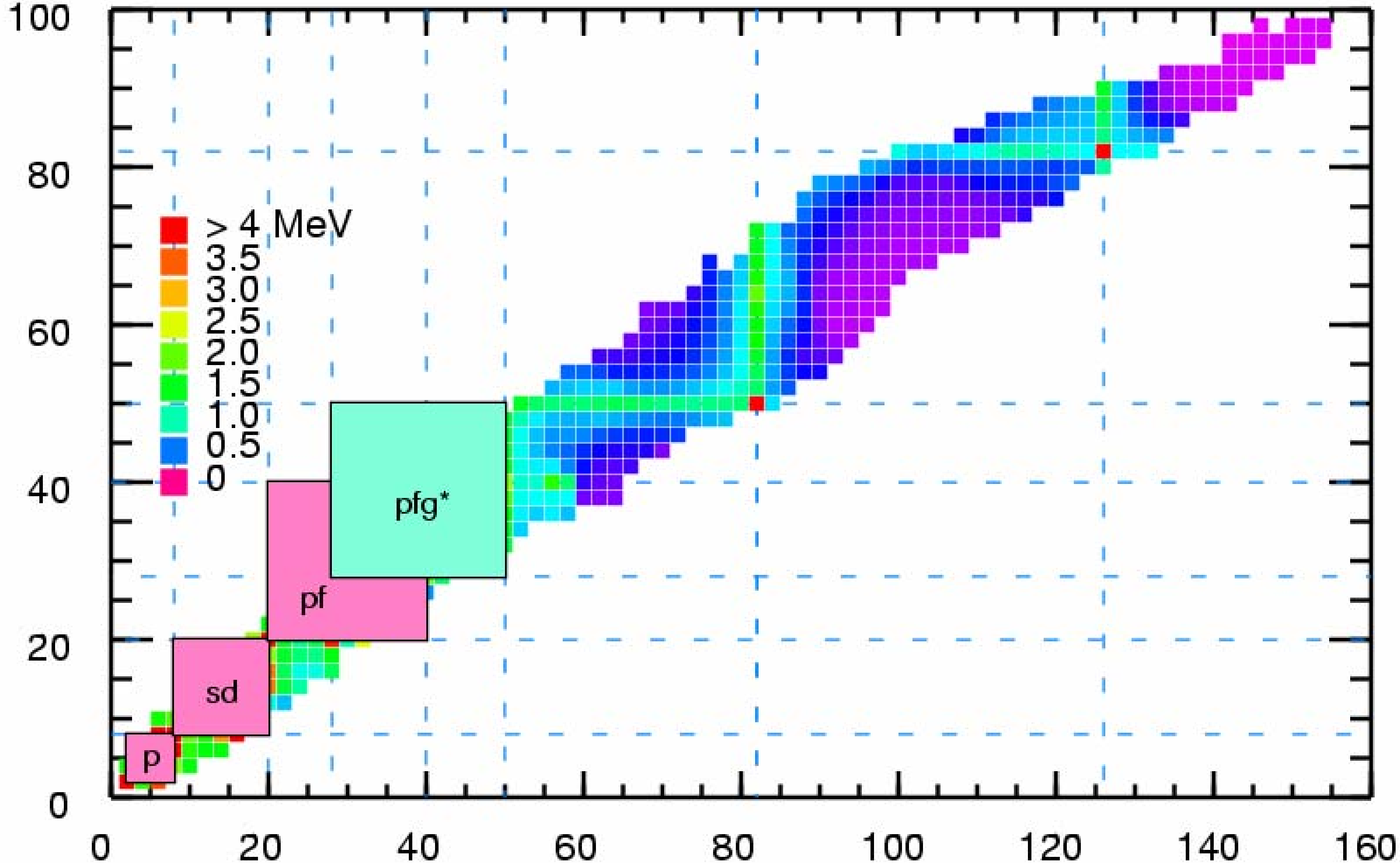
>4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
sd
p
0
10
20
30
40
50
60



>4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
p
sd
pf
0
10
20
30
40
50
60

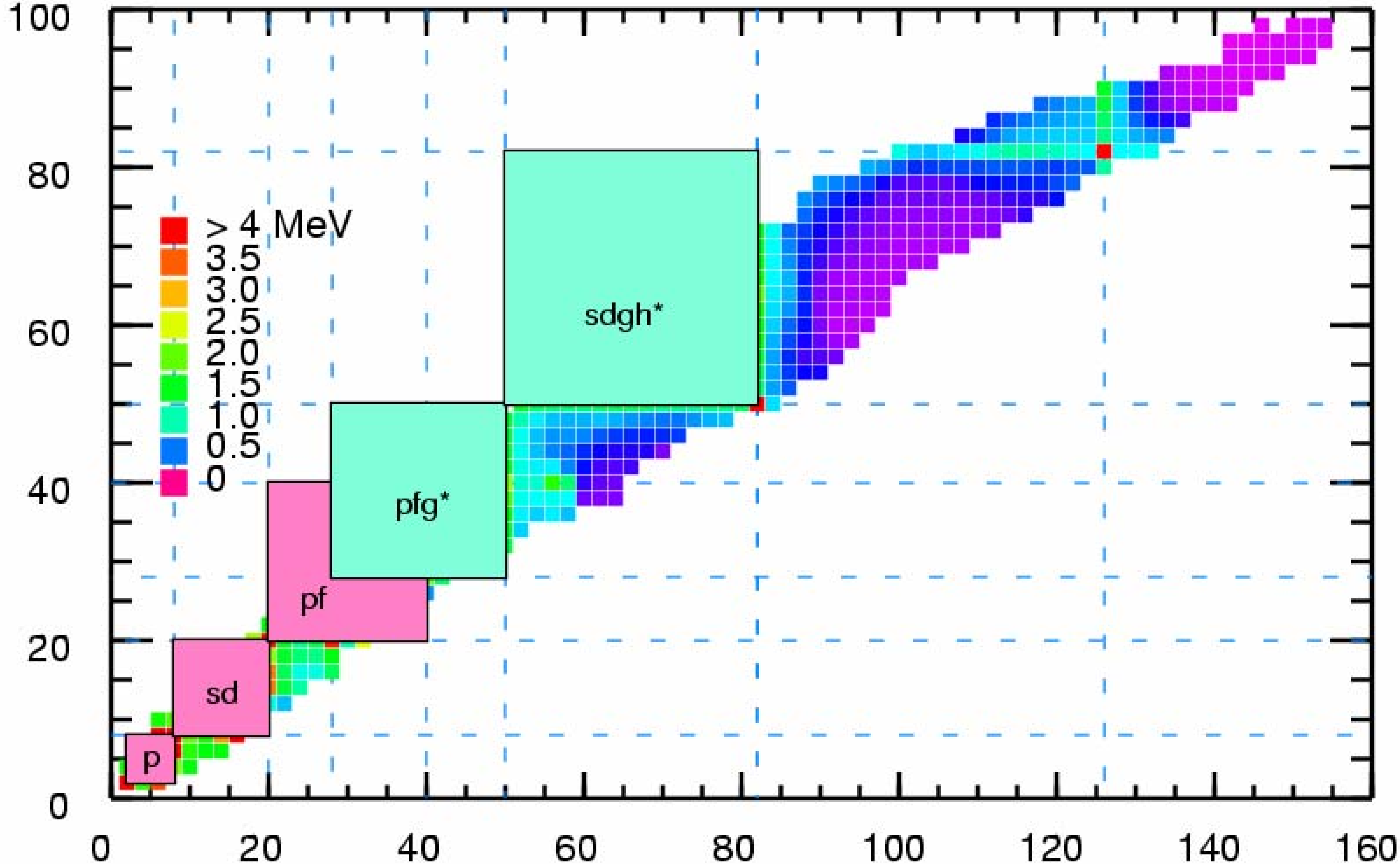


pfg* means $f_{5/2}$, $p_{3/2}$, $p_{1/2}$, $g_{9/2}$



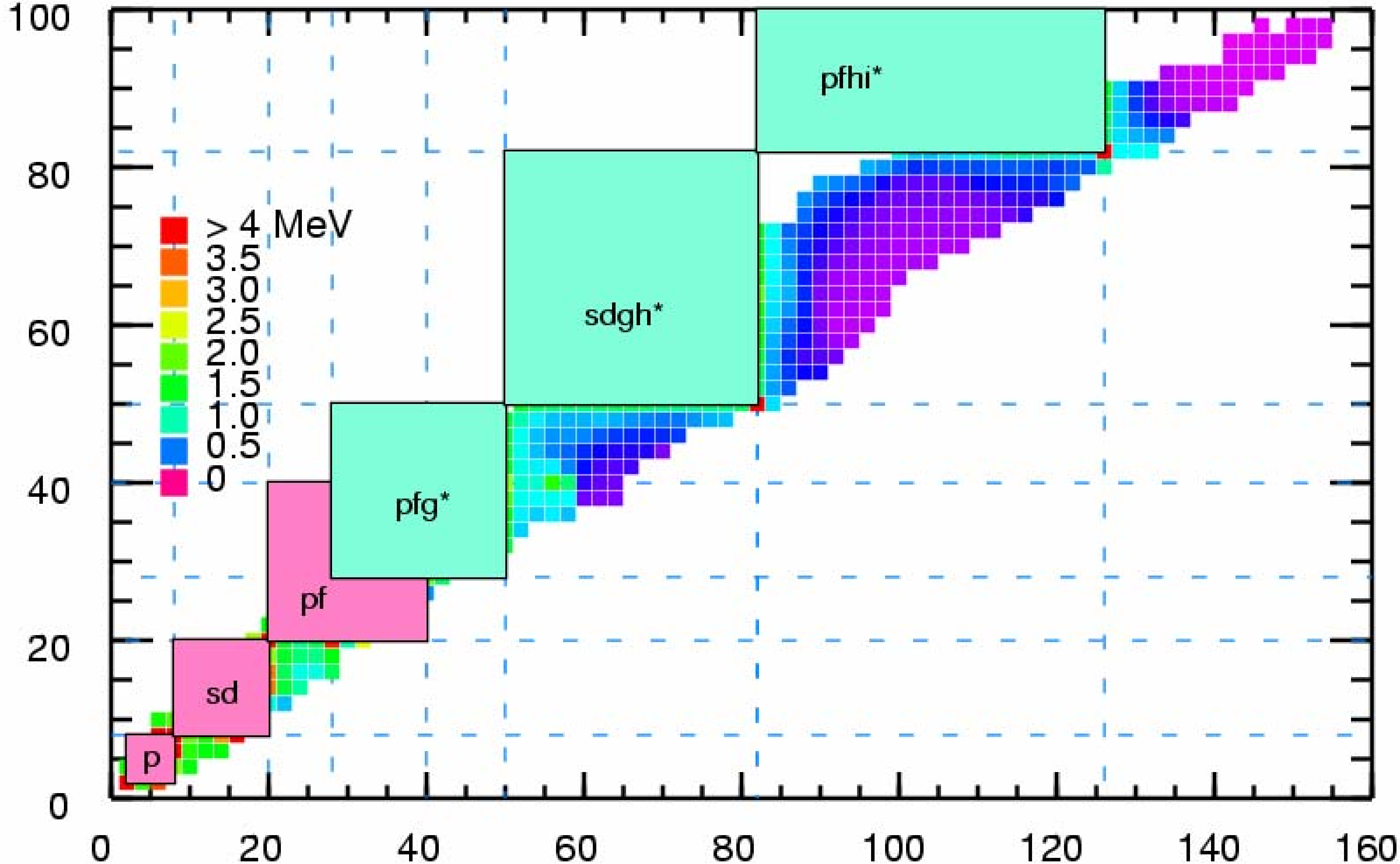
> 4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
p
sd
pf
pfg*
0
20
40
60
80
100
0
20
40
60
80
100
120
140
160

NSCL



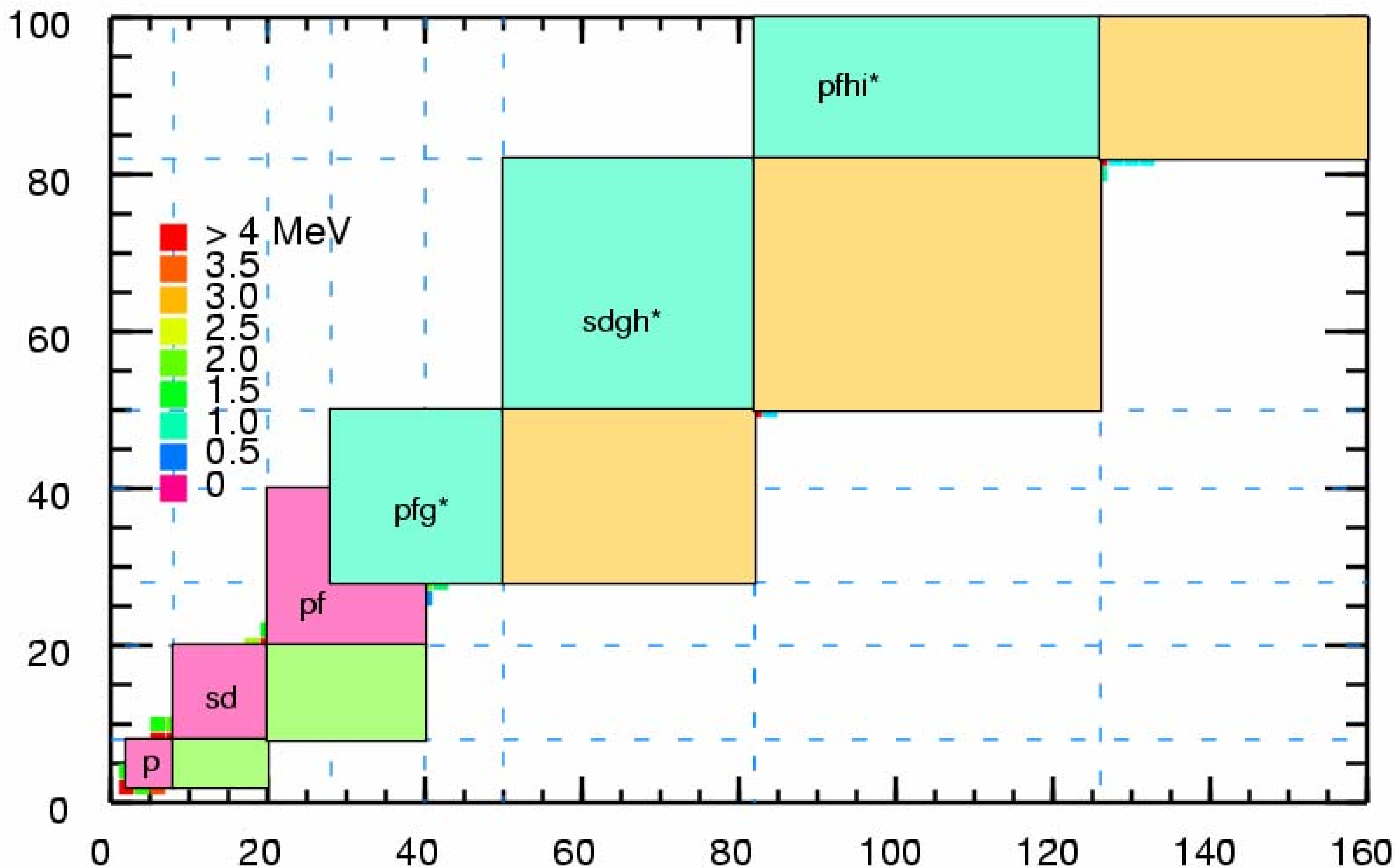
100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
> 4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
sdgh*
pfg*
pf
sd
p

NSCL



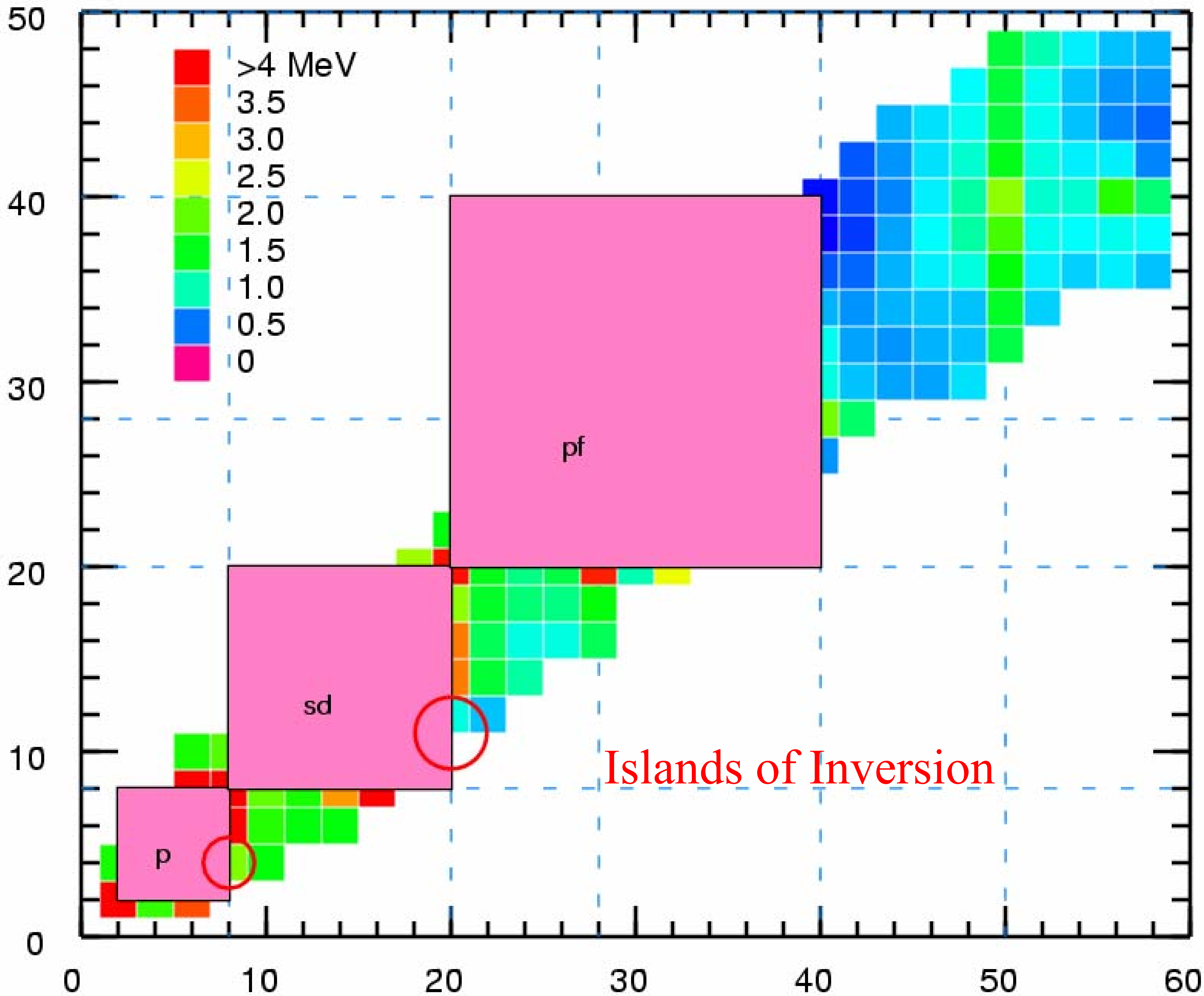
100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
> 4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
p
sd
pf
pfg*
sdgh*
pfhi*

NSCL

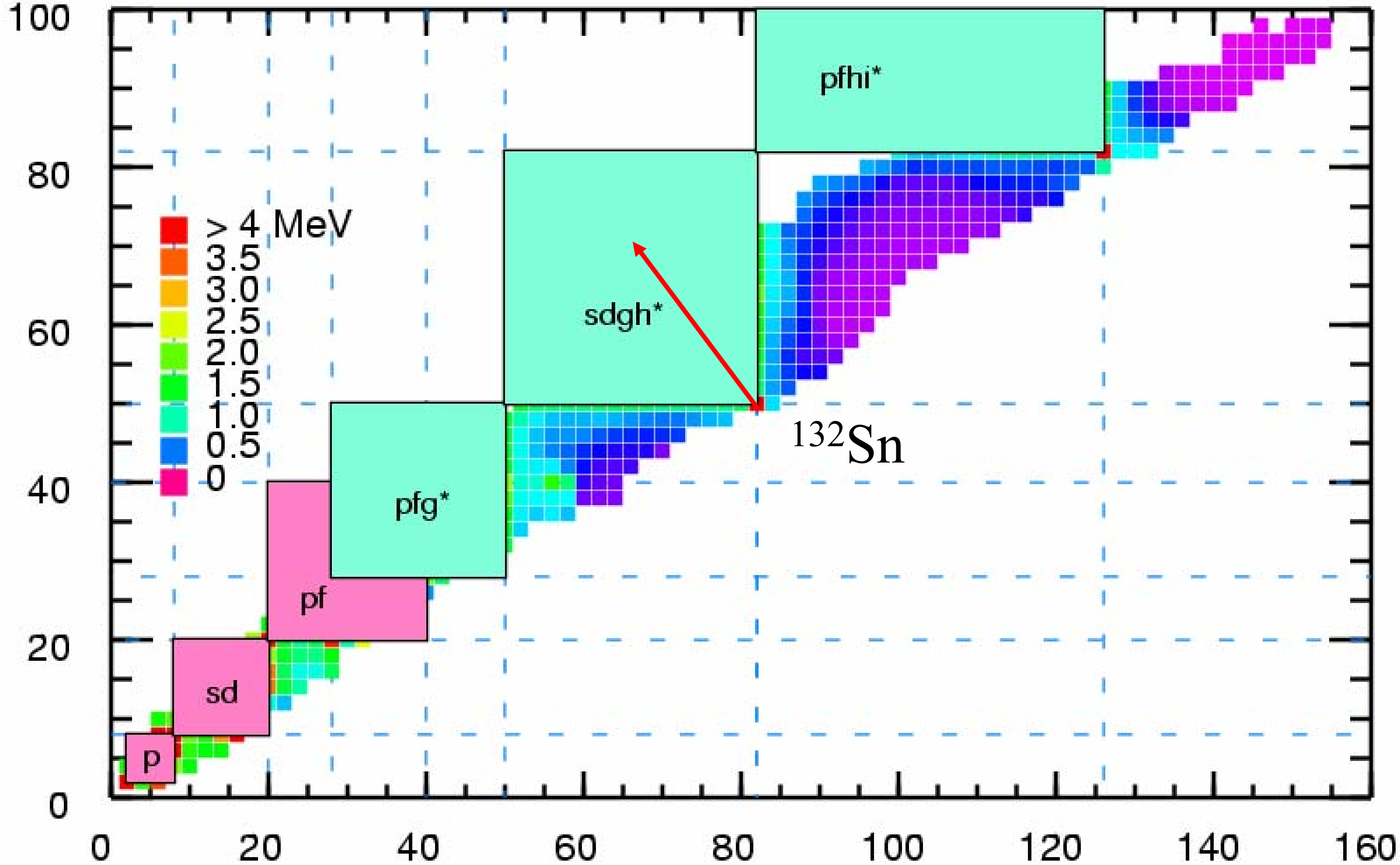


100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
> 4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
pfhi*
sdgh*
pfg*
pf
sd
p

NSCL



>4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
pf
sd
p
Islands of Inversion
0
10
20
30
40
50
60



> 4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
p
sd
pf
pfg*
sdgh*
pfhi*
132Sn
0
20
40
60
80
100
120
140
160

NSCL

Real vacuum – up to about A=12

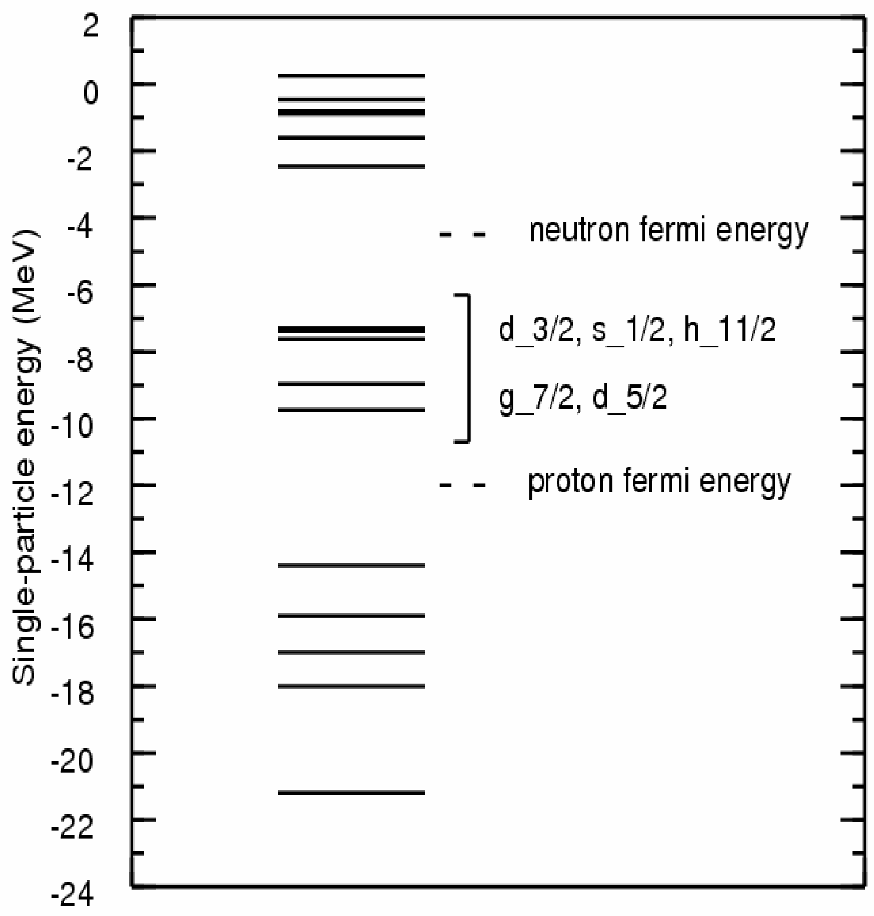
$$\hat{H} = \sum_{\alpha\beta} < \alpha \mid T \mid \beta > a_\alpha^+ a_\beta + \frac{1}{4} \sum_{\alpha\beta\gamma\delta} < \alpha\beta \mid V_{NN} \mid \gamma\delta > a_\alpha^+ a_\beta^+ a_\delta a_\gamma$$

Closed-shell vacuum – “all” nuclei

$$\hat{H} = \sum_{\alpha\beta} < \alpha \mid U \mid \beta > a_\alpha^+ a_\beta + \frac{1}{4} \sum_{\alpha\beta\gamma\delta} < \alpha\beta \mid \tilde{G} \mid \gamma\delta > a_\alpha^+ a_\beta^+ a_\delta a_\gamma$$

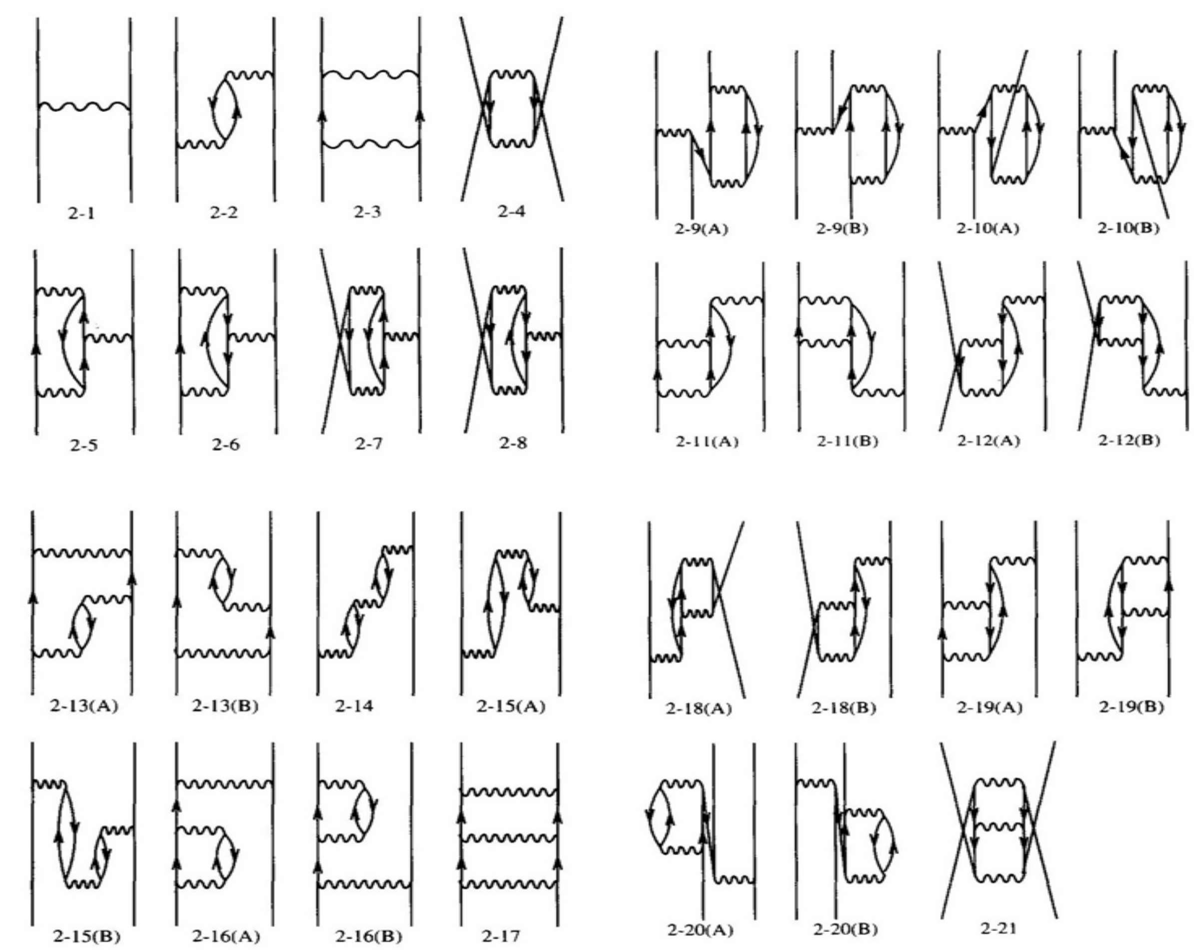
- Start with one of the doubly-magic nuclei as the vacuum
- Exact solution of *H* within the model space for the orbits inside the shell gaps
- Single-particle energies *U* from experiment
- Two-body matrix elements (G) from NN interaction renormalized to the model space

Single-particle energies for ^{132}Sn from data on ^{131}Sn, ^{133}Sn and ^{133}Sb



NSCL

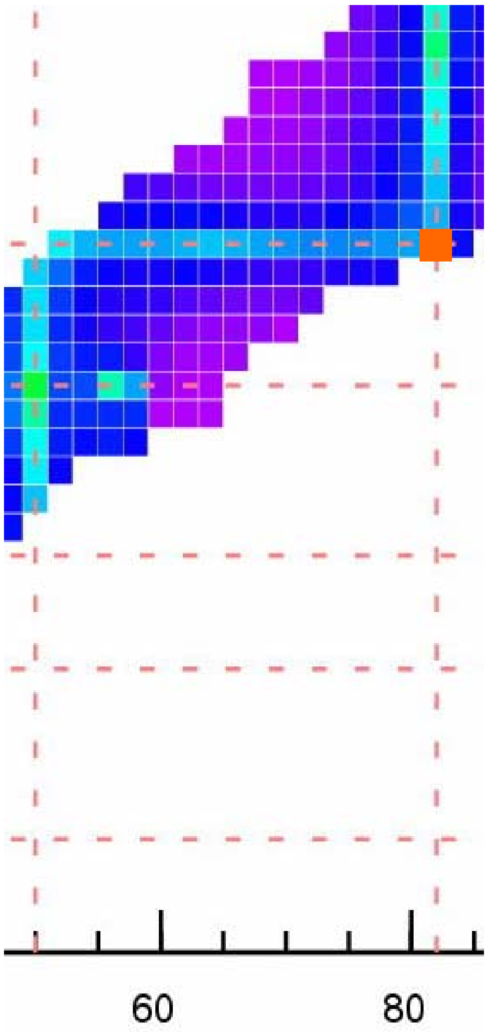
Renormalization of NN

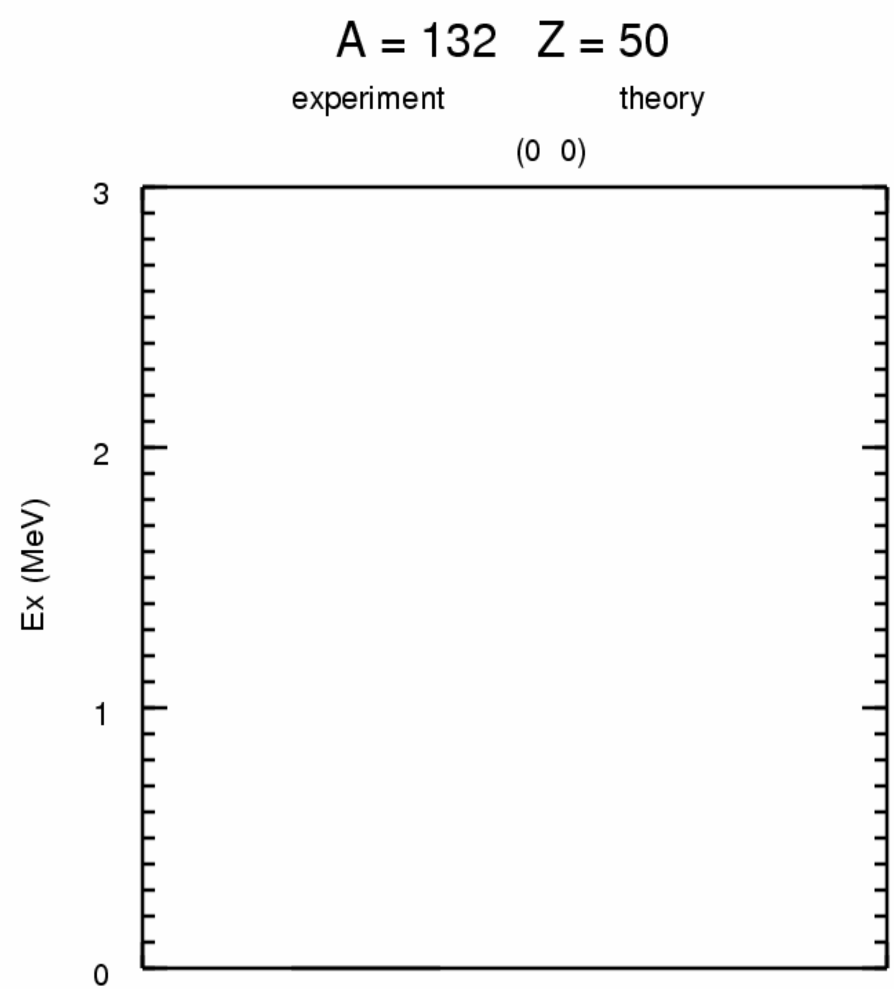


Morten Hjorth-Jensen

Physics Reports 261 (1995)

NSCL





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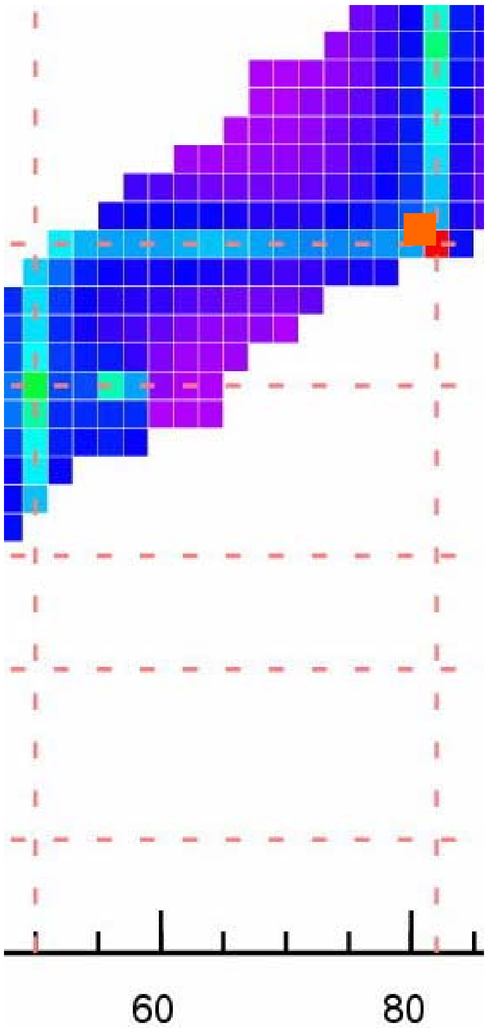
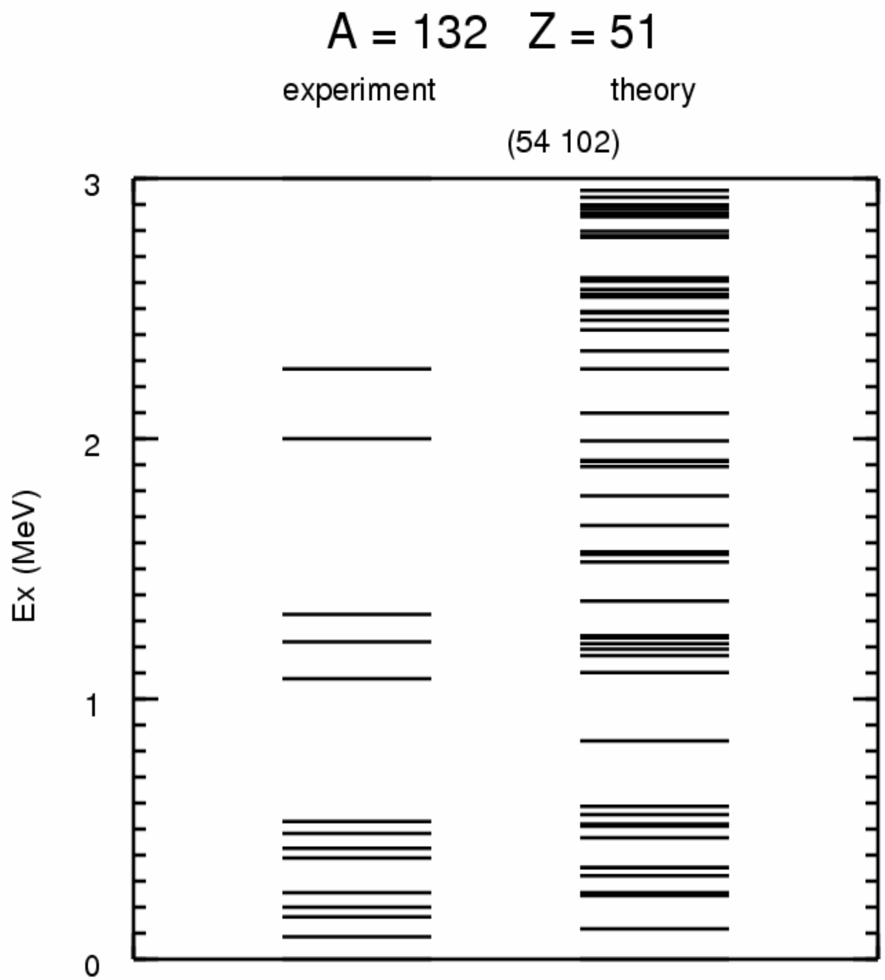
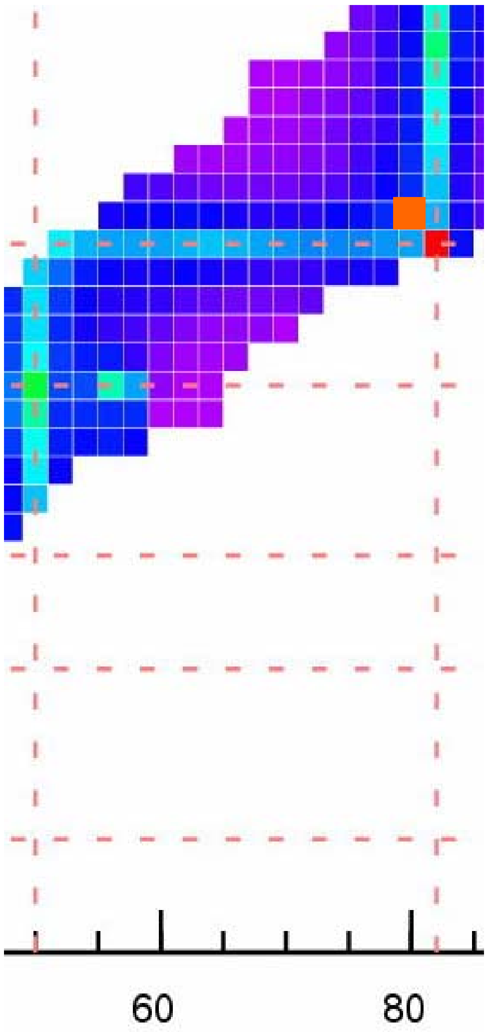
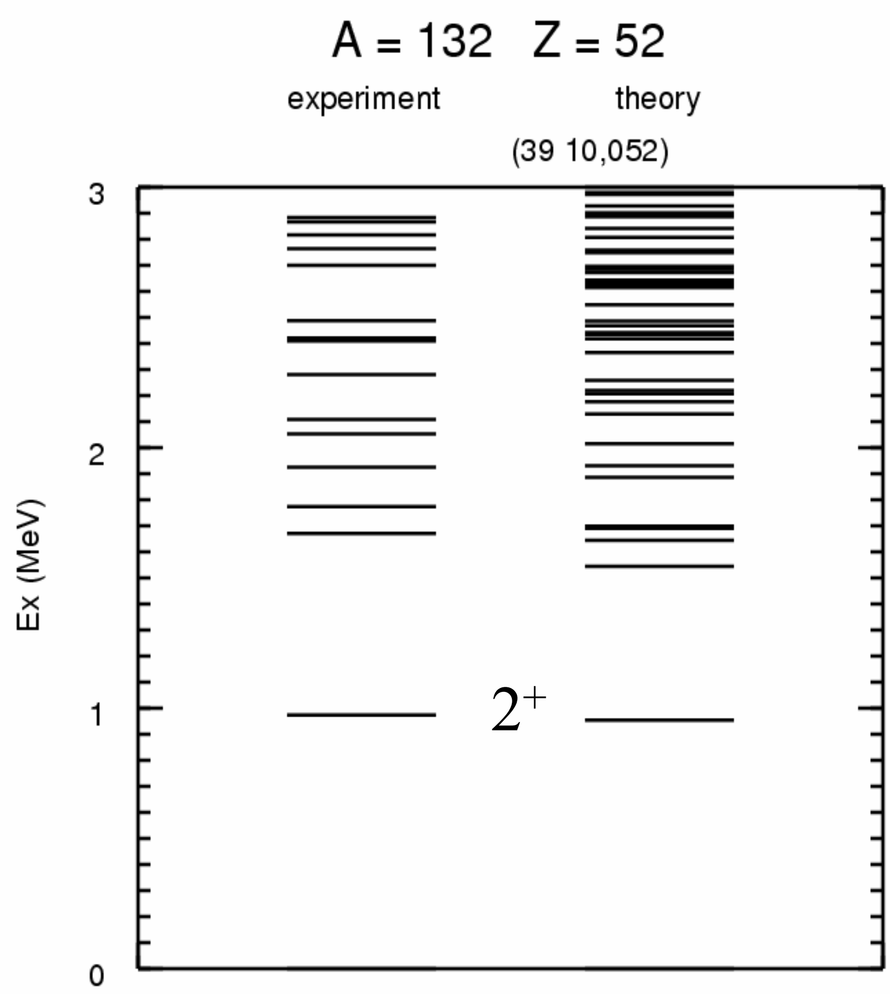


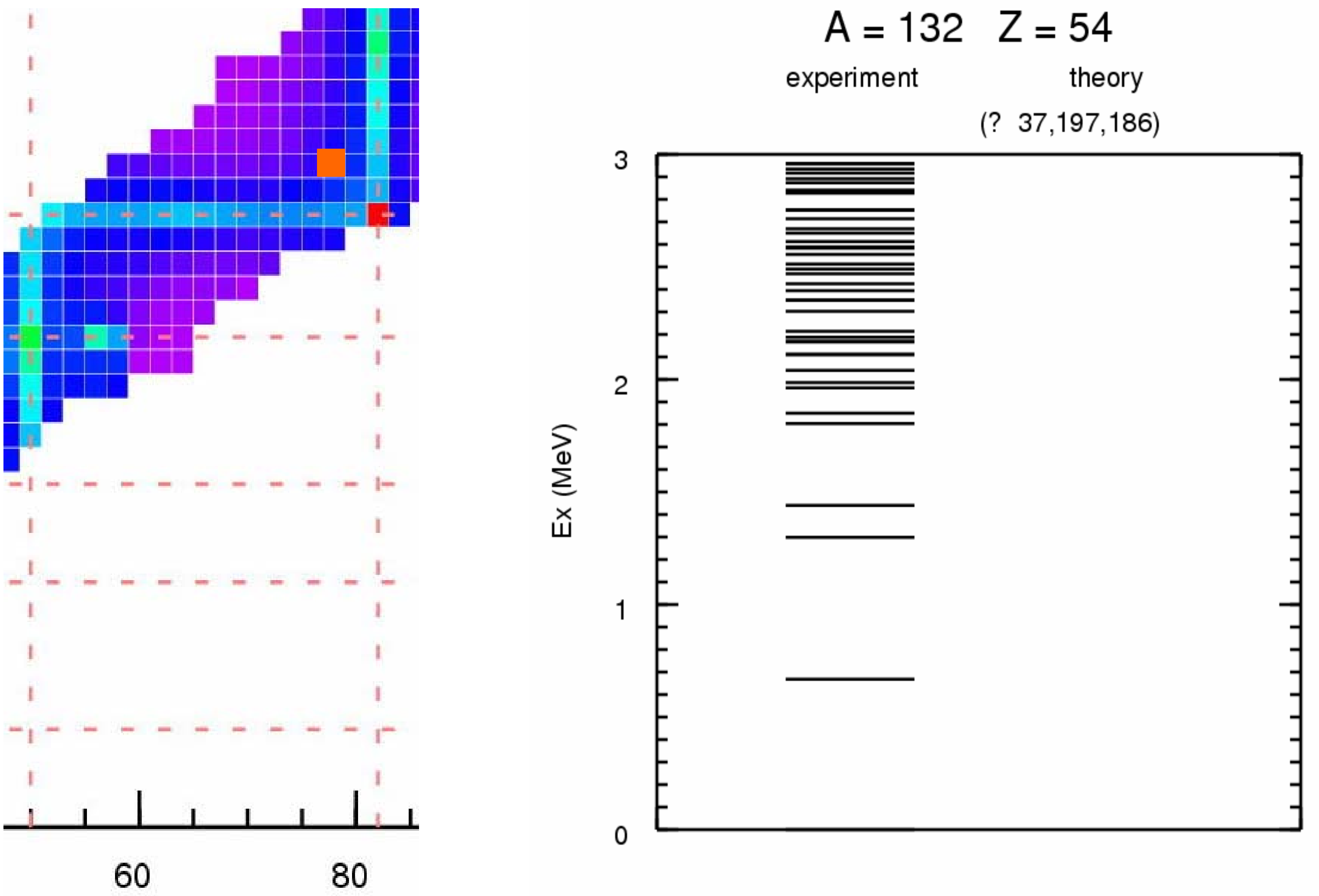
60
80



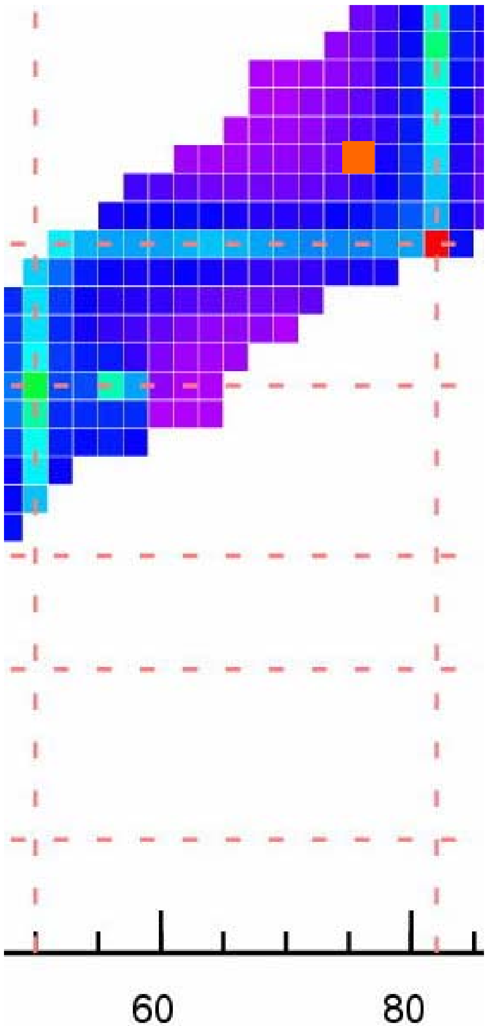
A = 132 Z = 51
experiment
theory
(54 102)
Ex (MeV)
0
1
2
3


60
80

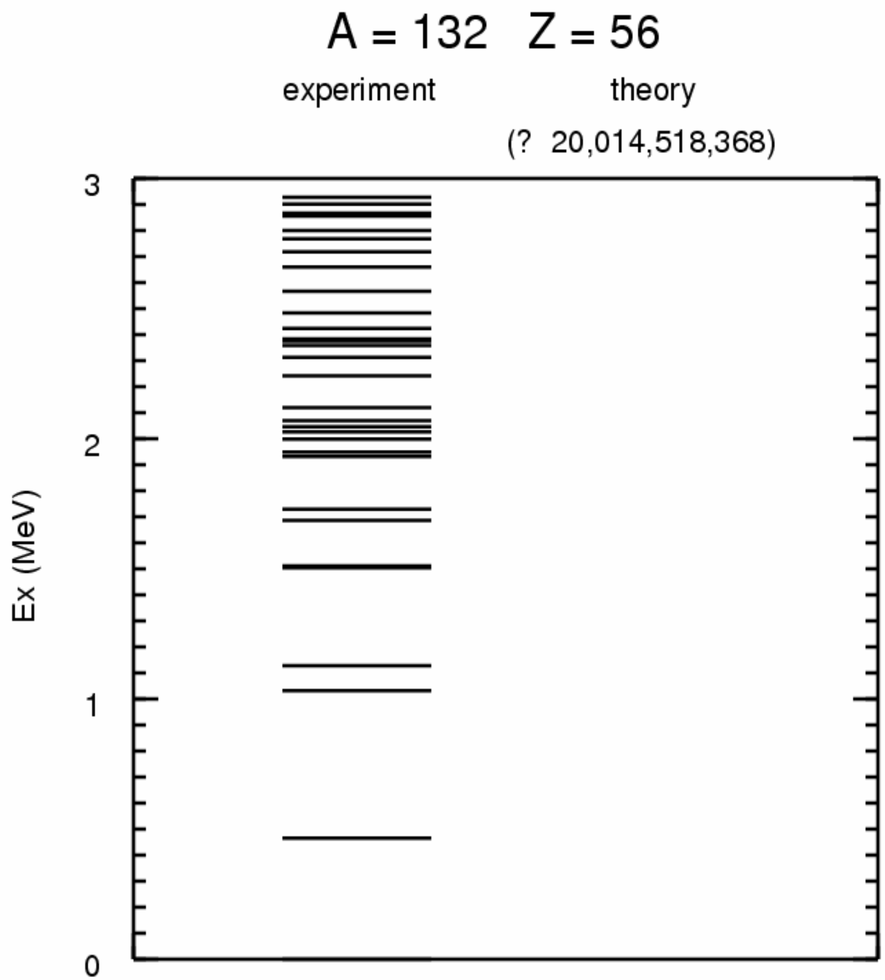

A = 132   Z = 52
experiment
theory
(39 10,052)
Ex (MeV)
0
1
2
3
2+



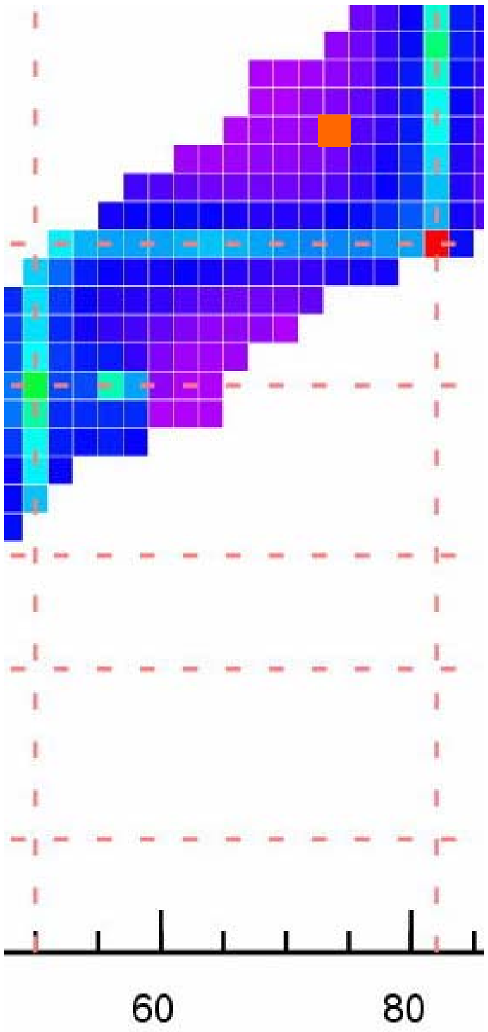
60
80
A = 132 Z = 54
experiment
theory
(? 37,197,186)
Ex (MeV)
3
2
1
0



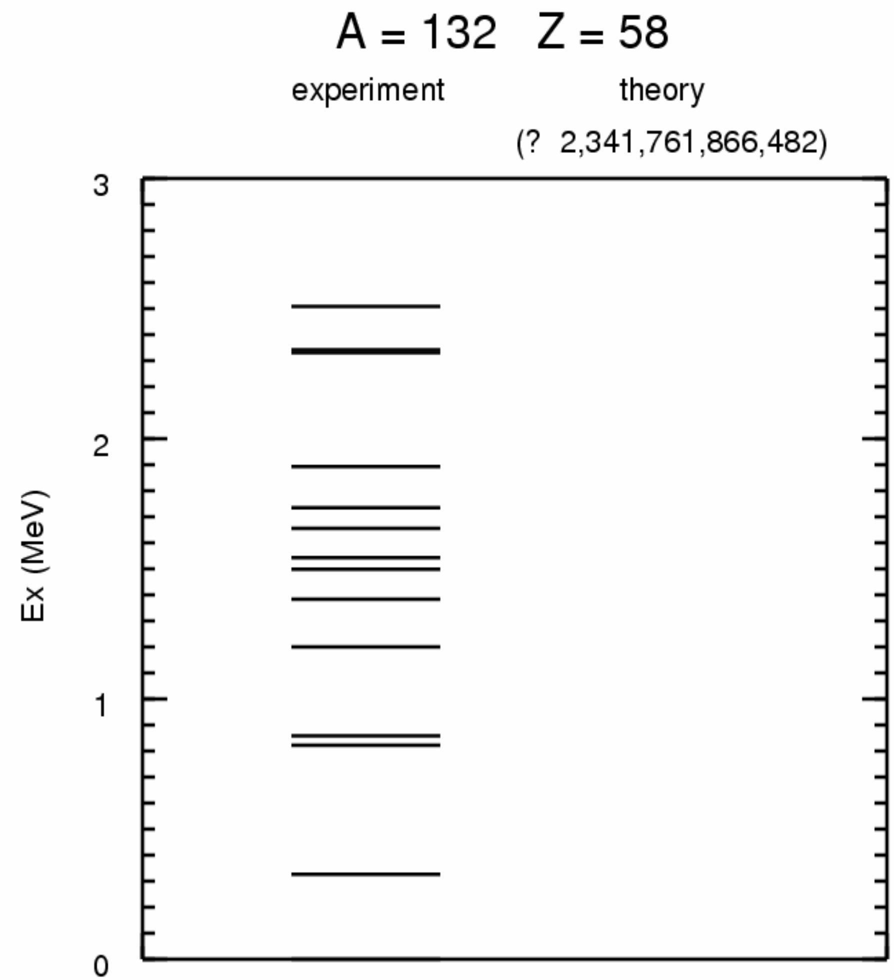
60
80



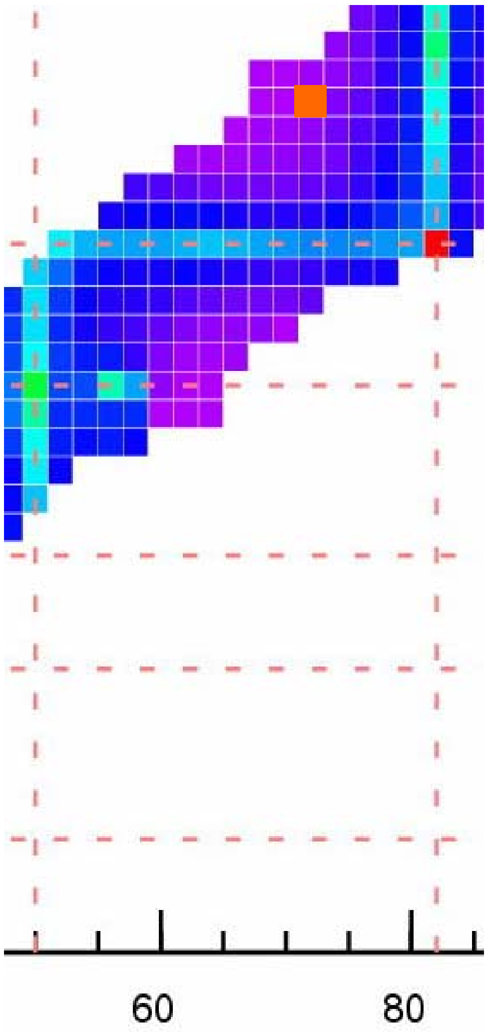
A = 132 Z = 56
experiment
theory
(? 20,014,518,368)
Ex (MeV)
0
1
2
3

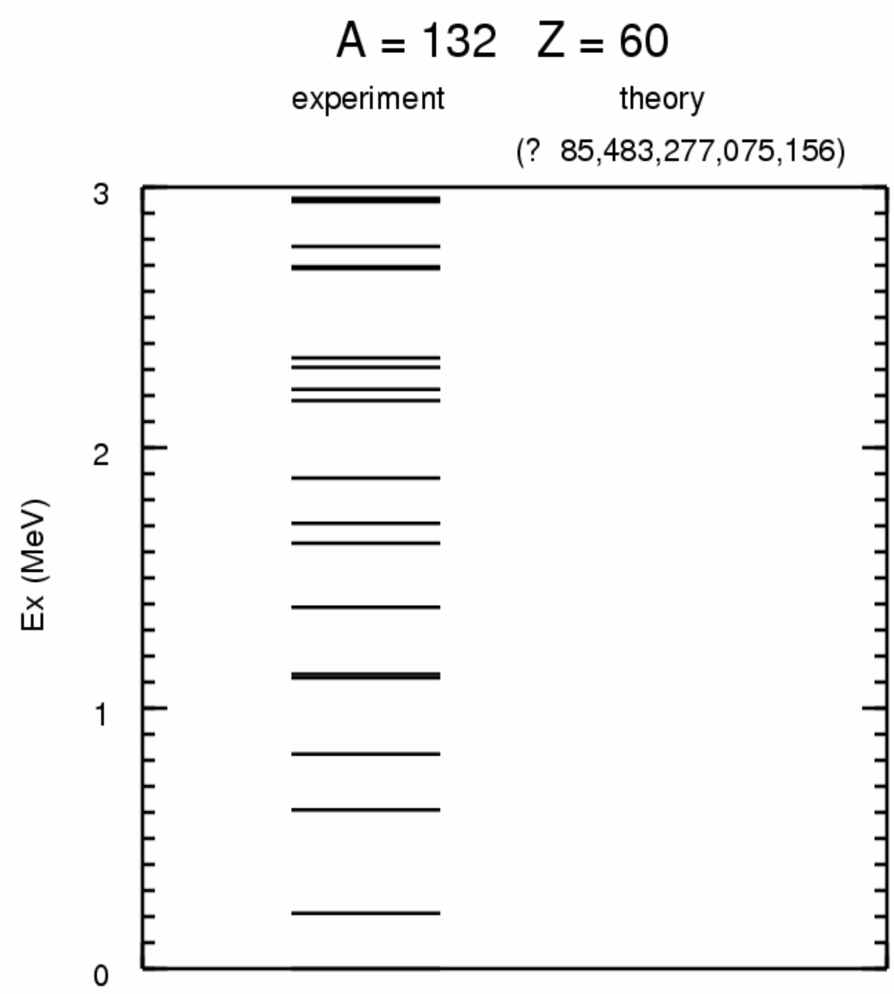


60
80



A = 132 Z = 58
experiment
theory
(? 2,341,761,866,482)
Ex (MeV)
0
1
2
3


60
80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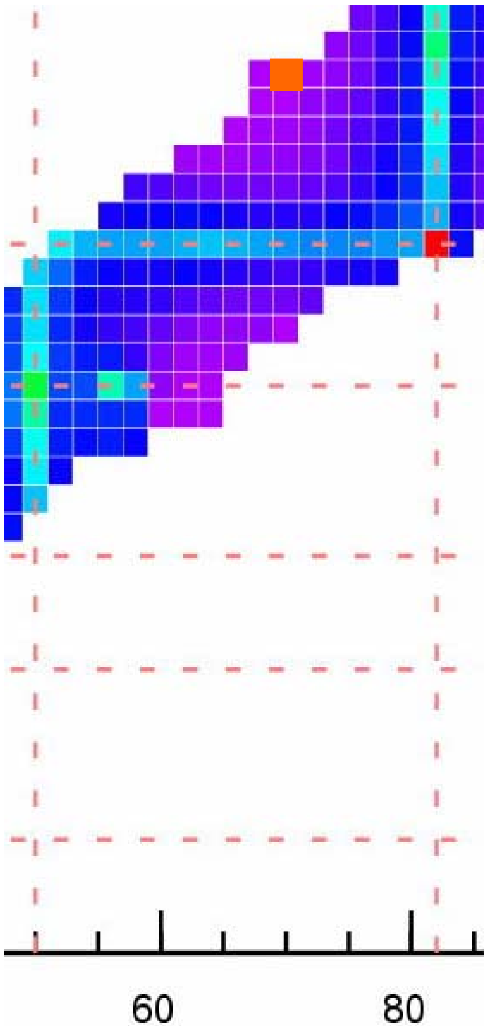
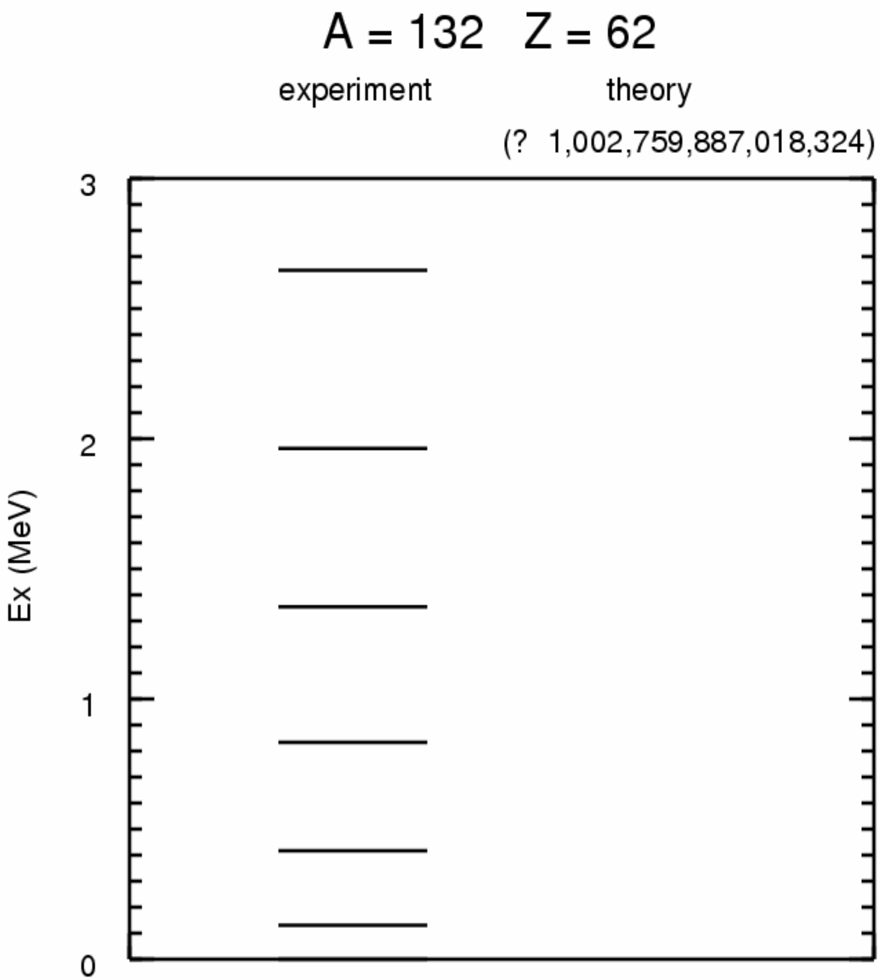
experiment
theory
(? 85,483,277,075,156)
Ex (MeV)
0
1
2
3


60
80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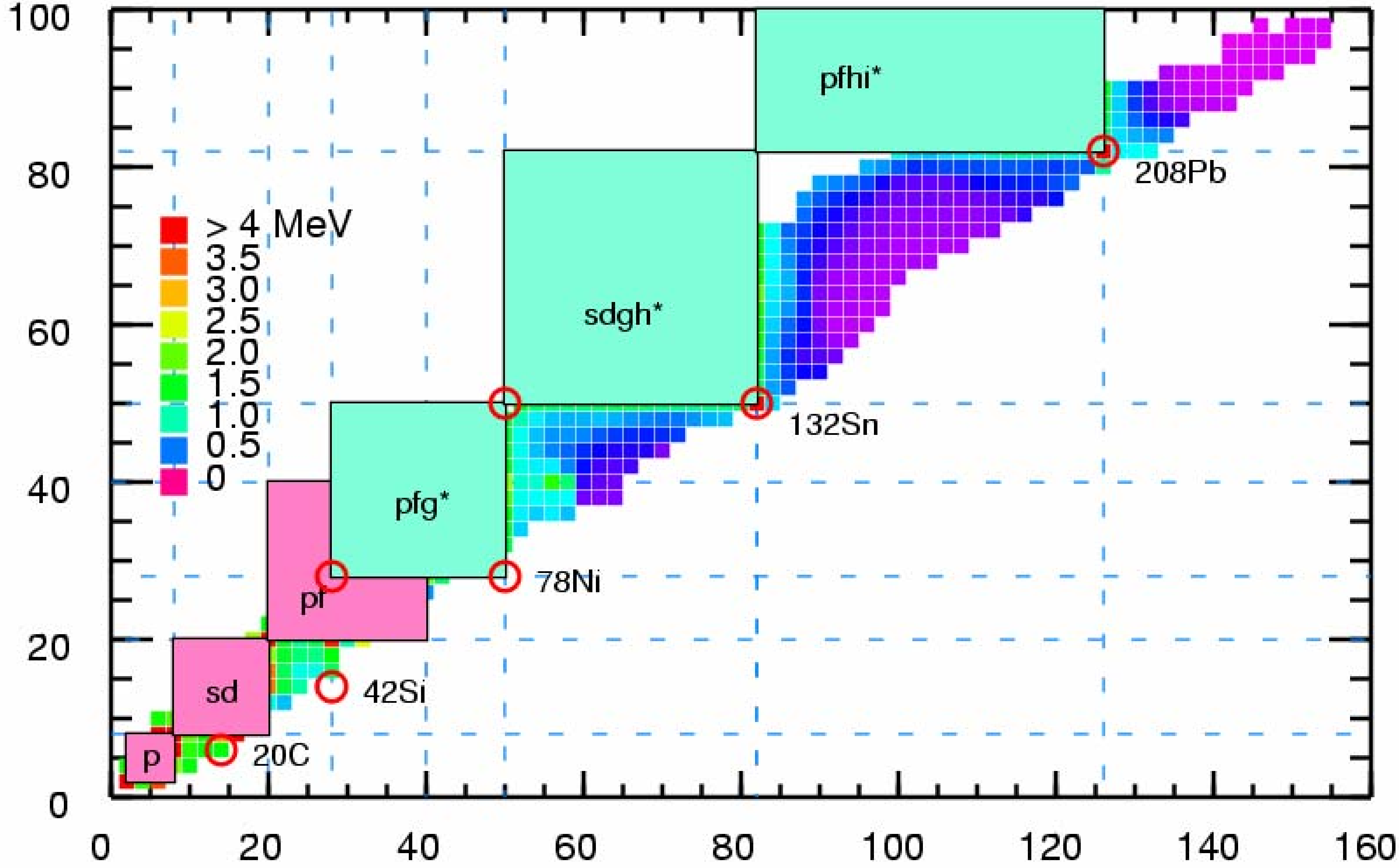
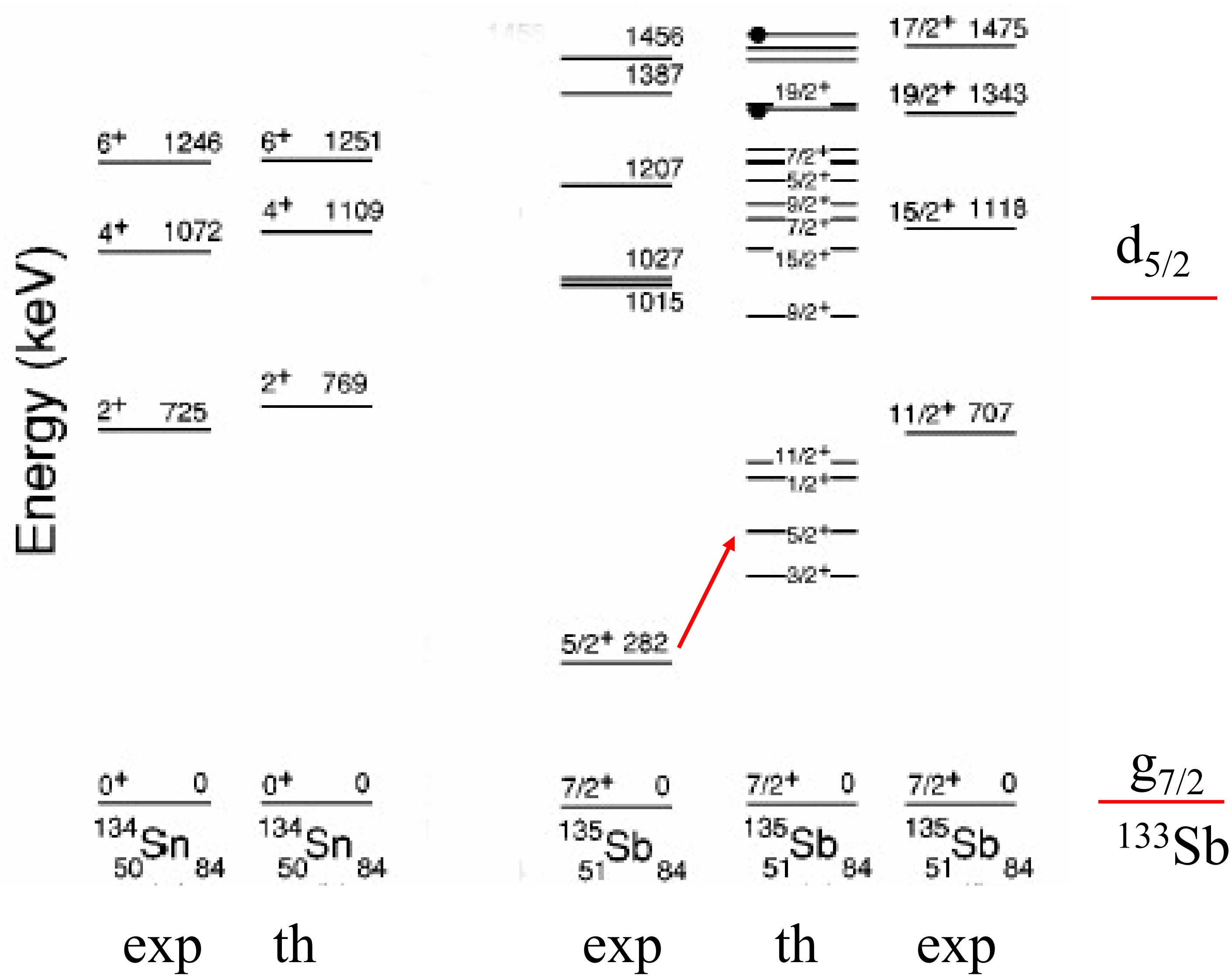
experiment
theory
(? 1,002,759,887,018,324)
Ex (MeV)
3
2
1
0

jj closed shells

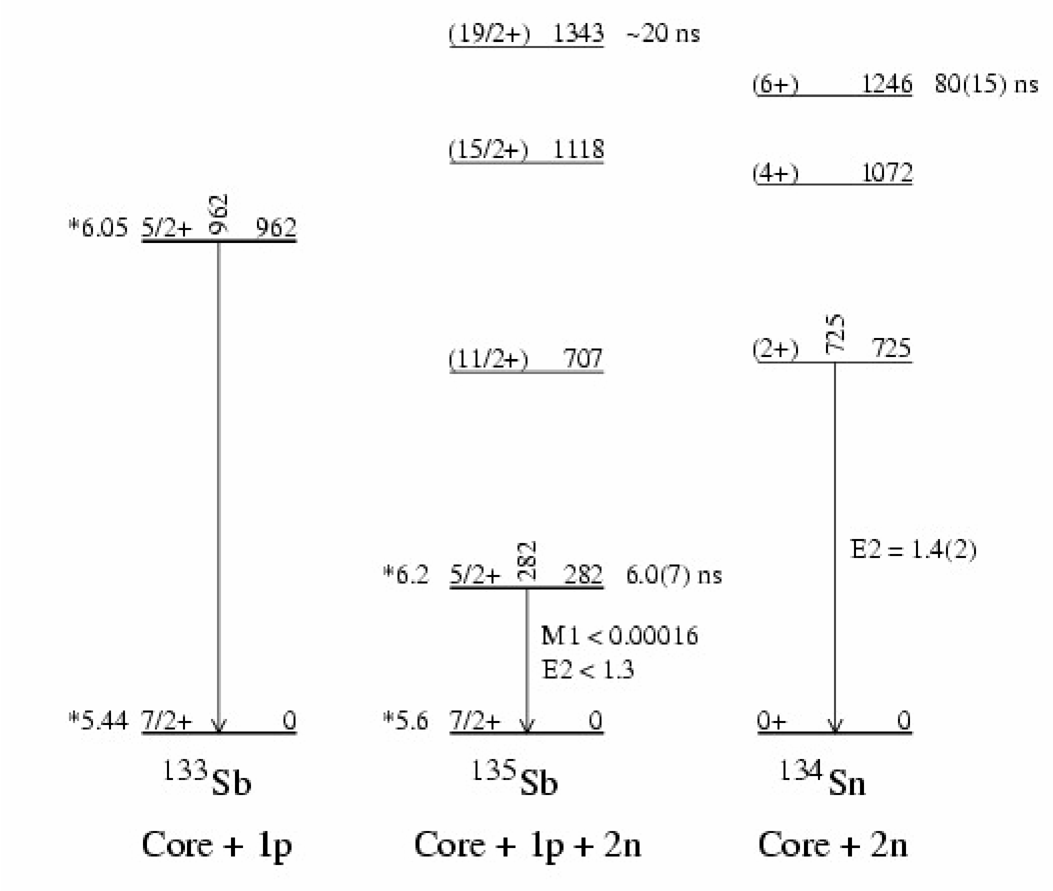


NSCL



J. Shergur et al., PRC 65, 034313 (2002)

A. Korgul, H. Mach et al.



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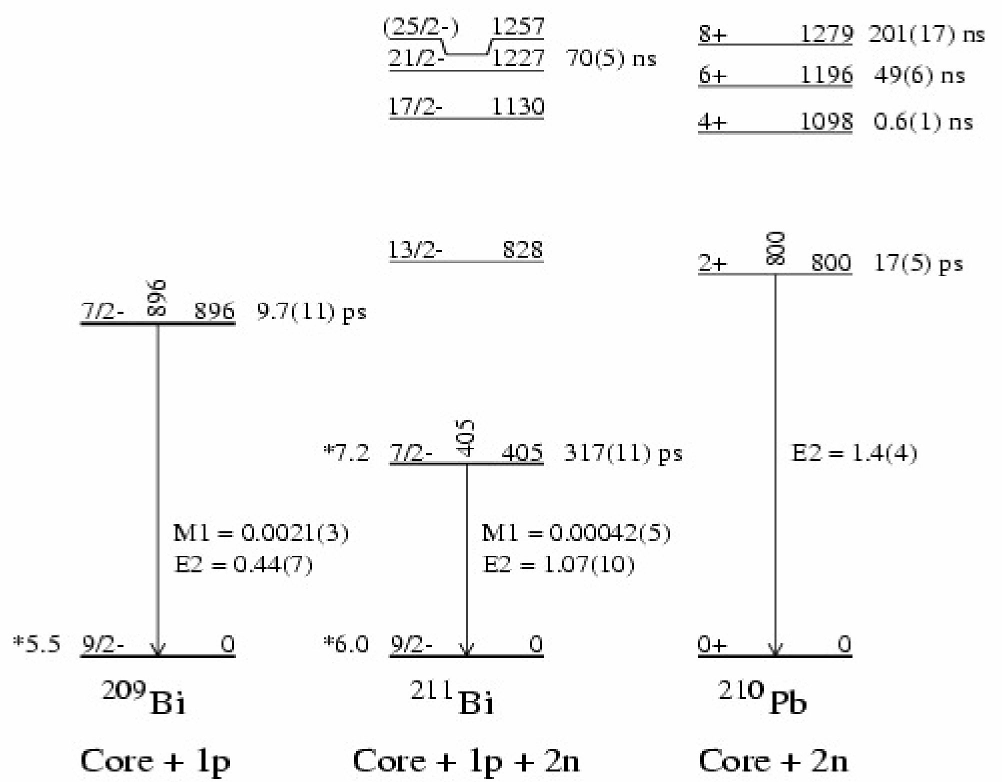
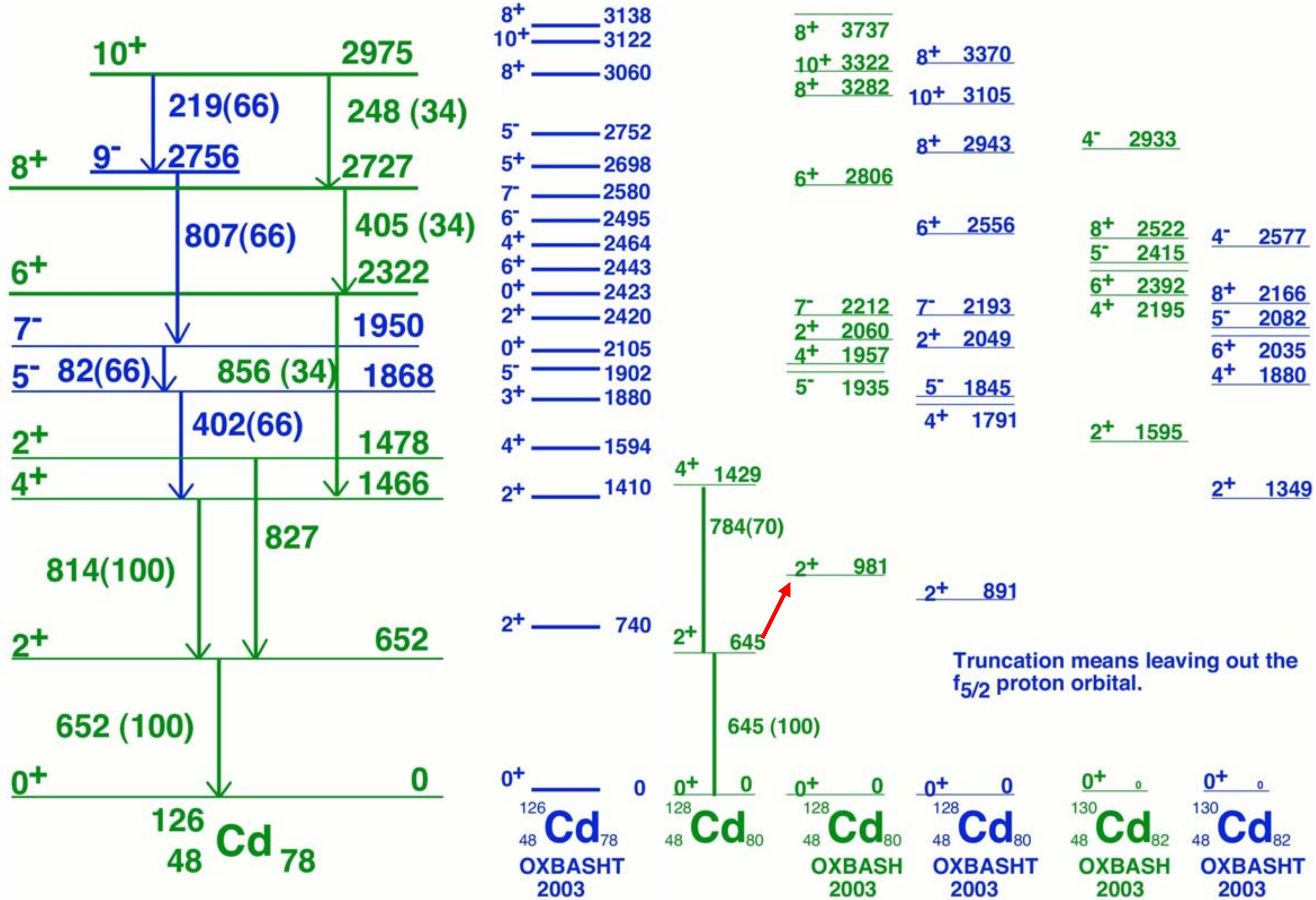
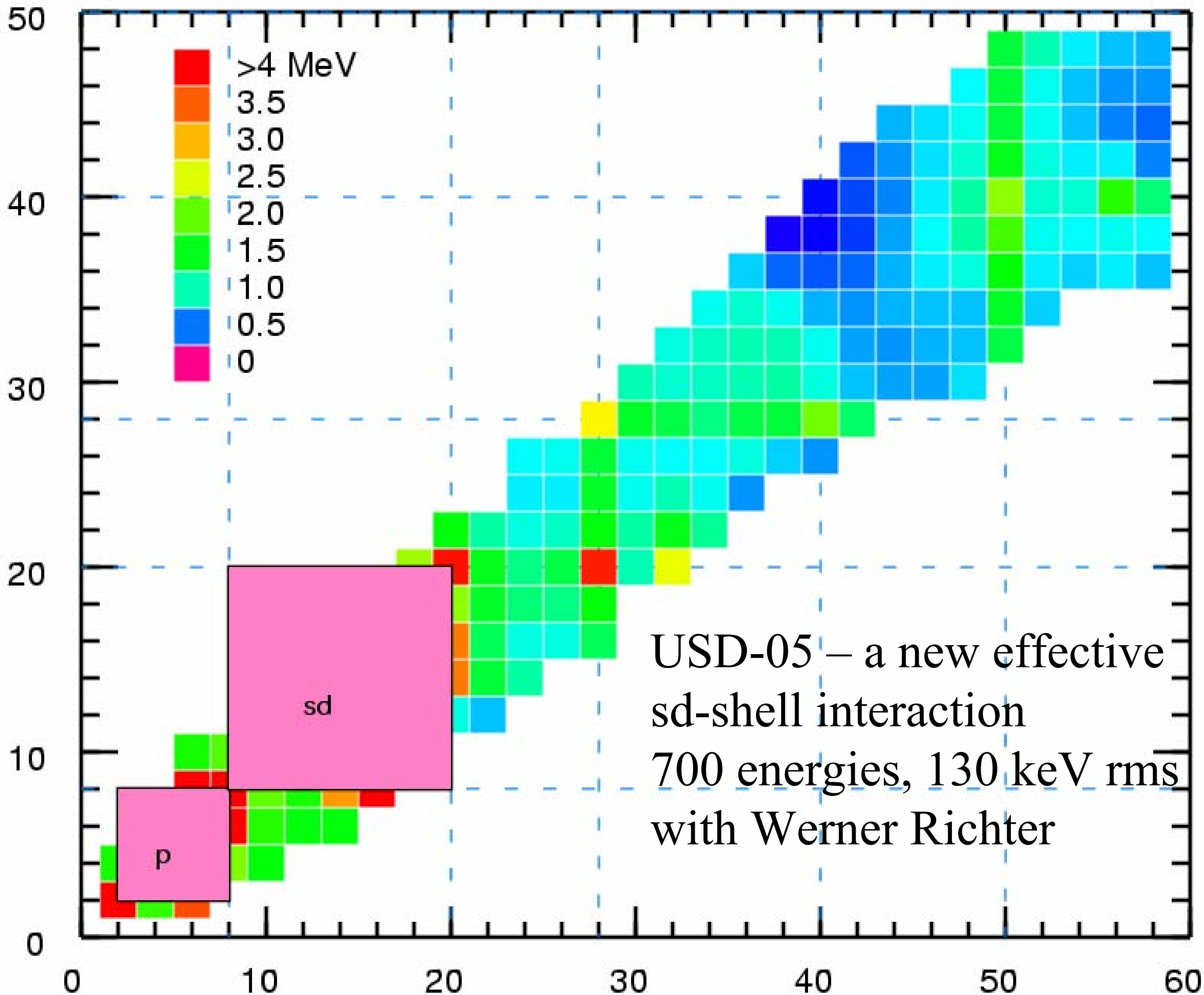


(25/2-) 1257
21/2- 1227 70(5) ns
17/2- 1130
13/2- 828
8+ 1279 201(17) ns
6+ 1196 49(6) ns
4+ 1098 0.6(1) ns
2+ 800 800 17(5) ps
7/2- 896 896 9.7(11) ps
*7.2 7/2- 405 405 317(11) ps
E2 = 1.4(4)
M1 = 0.0021(3)
E2 = 0.44(7)
M1 = 0.00042(5)
E2 = 1.07(10)
*5.5 9/2- 0
*6.0 9/2- 0
0+ 0
209Bi
211Bi
210Pb
Core + 1p
Core + 1p + 2n
Core + 2n

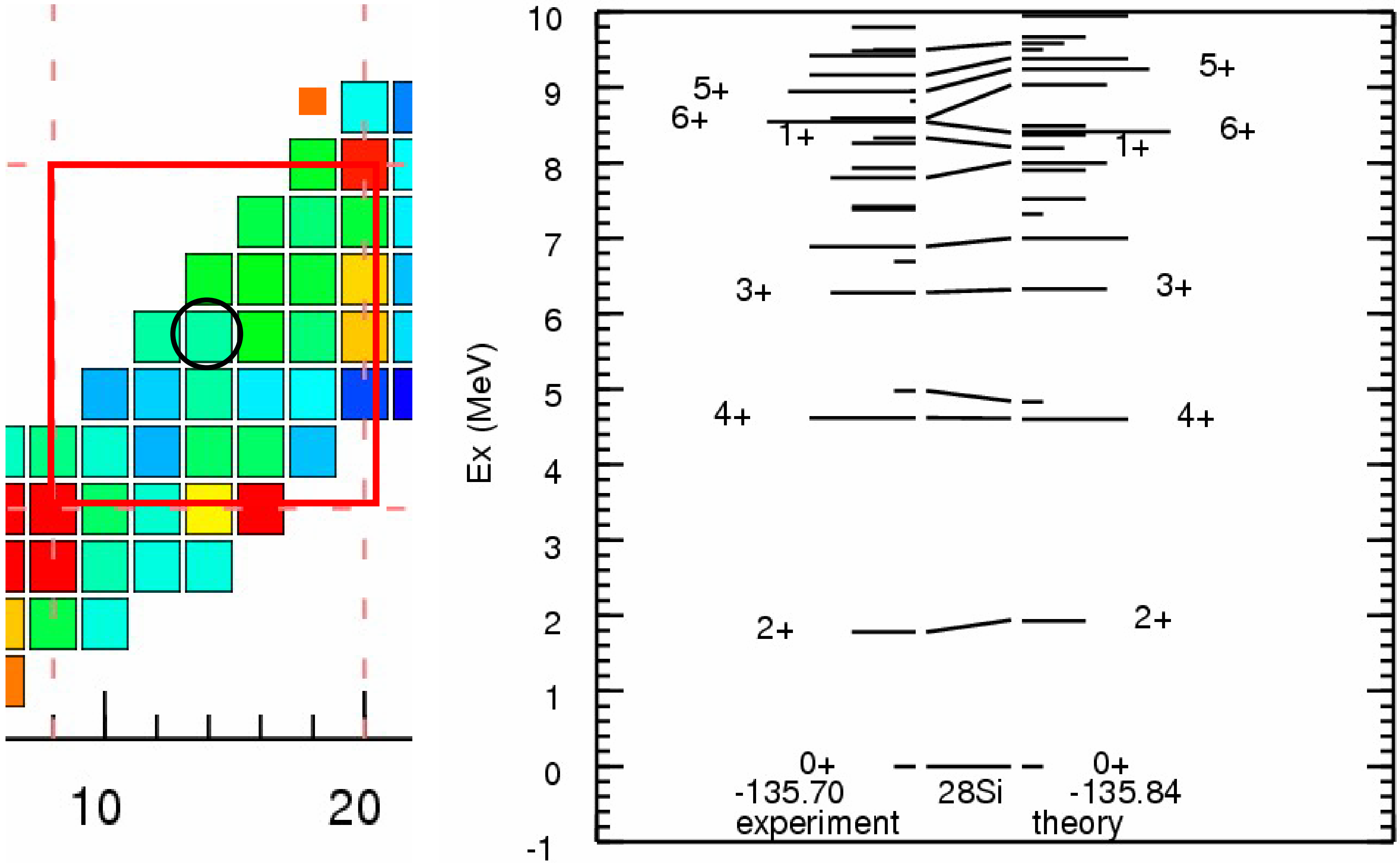


10+ 2975
219(66)
248 (34)
8+ 9- 2756 2727
807(66)
405 (34)
6+ 2322
7- 1950
5- 82(66) 856 (34) 1868
402(66)
2+ 1478
4+ 1466
827
814(100)
2+ 652
652 (100)
0+ 0
126 48 Cd 78
8+ 3138
10+ 3122
8+ 3060
5- 2752
5+ 2698
7- 2580
6- 2495
4+ 2464
6+ 2443
0+ 2423
2+ 2420
0+ 2105
5- 1902
3+ 1880
4+ 1594
2+ 1410
2+ 740
0+ 0
126 48 Cd 78
OXBASHT 2003
4+ 1429
784(70)
2+ 645
645 (100)
0+ 0
128 48 Cd 80
8+ 3737
10+ 3322
8+ 3282
6+ 2806
7- 2212
2+ 2060
4+ 1957
5- 1935
2+ 981
0+ 0
128 48 Cd 80
OXBASH 2003
8+ 3370
10+ 3105
8+ 2943
6+ 2556
7- 2193
2+ 2049
5- 1845
4+ 1791
2+ 891
0+ 0
128 48 Cd 80
OXBASHT 2003
4- 2933
8+ 2522
5- 2415
6+ 2392
4+ 2195
2+ 1595
0+ 0
130 48 Cd 82
OXBASH 2003
4- 2577
8+ 2166
5- 2082
6+ 2035
4+ 1880
2+ 1349
0+ 0
130 48 Cd 82
OXBASHT 2003
Truncation means leaving out the $f_{5/2}$ proton orbital.



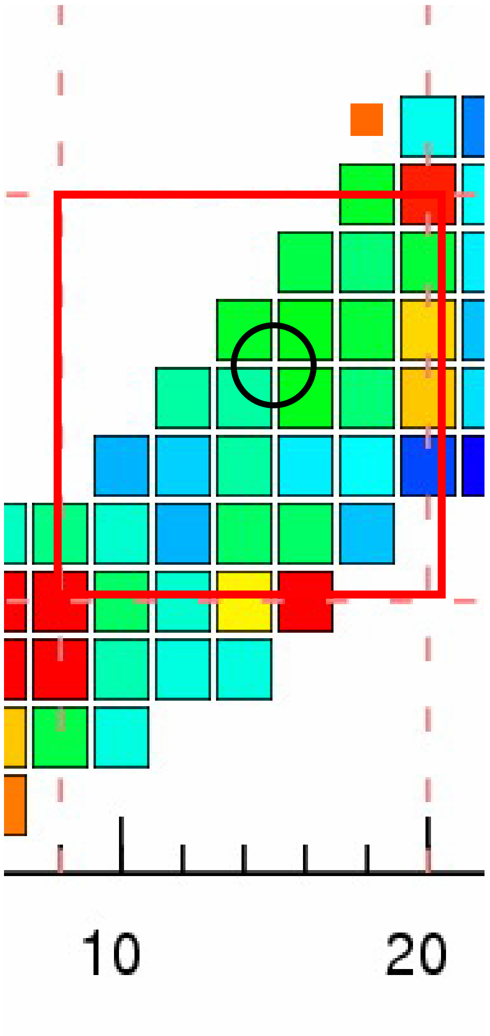
>4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
sd
p
0
10
20
30
40
50
60
USD-05 – a new effective sd-shell interaction
700 energies, 130 keV rms
with Werner Richter

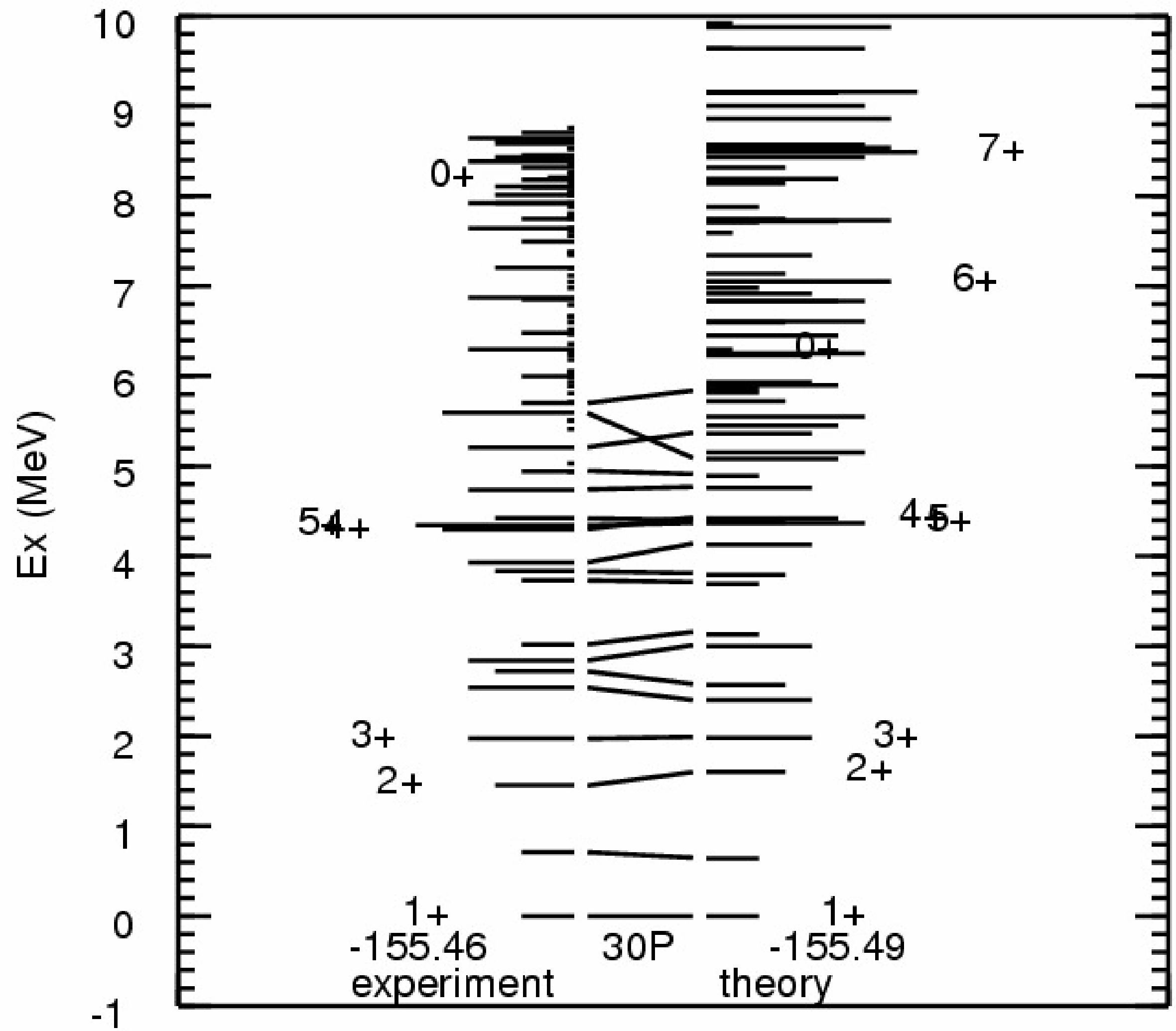
^{28}Si with USD-05 ($d_{5/2}$ $d_{3/2}$ $s_{1/2}$ model space)



NSCL

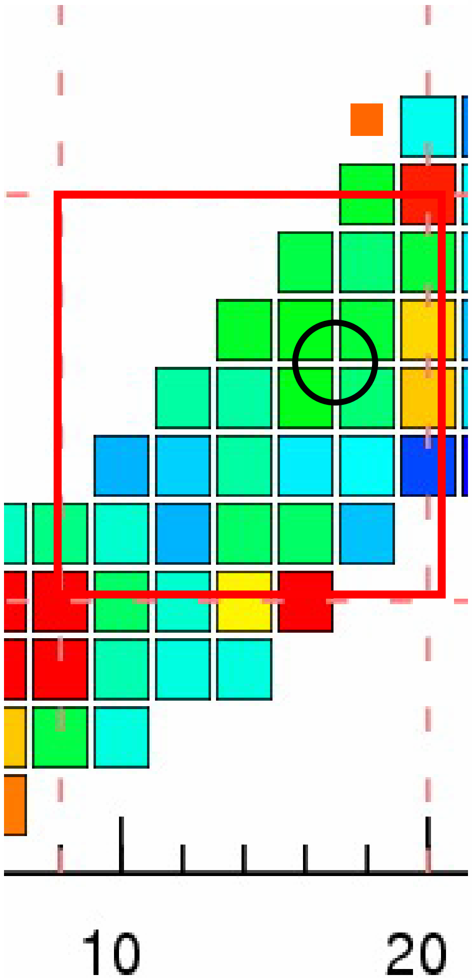
^{30}P with USD ($d_{5/2}$ $d_{3/2}$ $s_{1/2}$ model space)

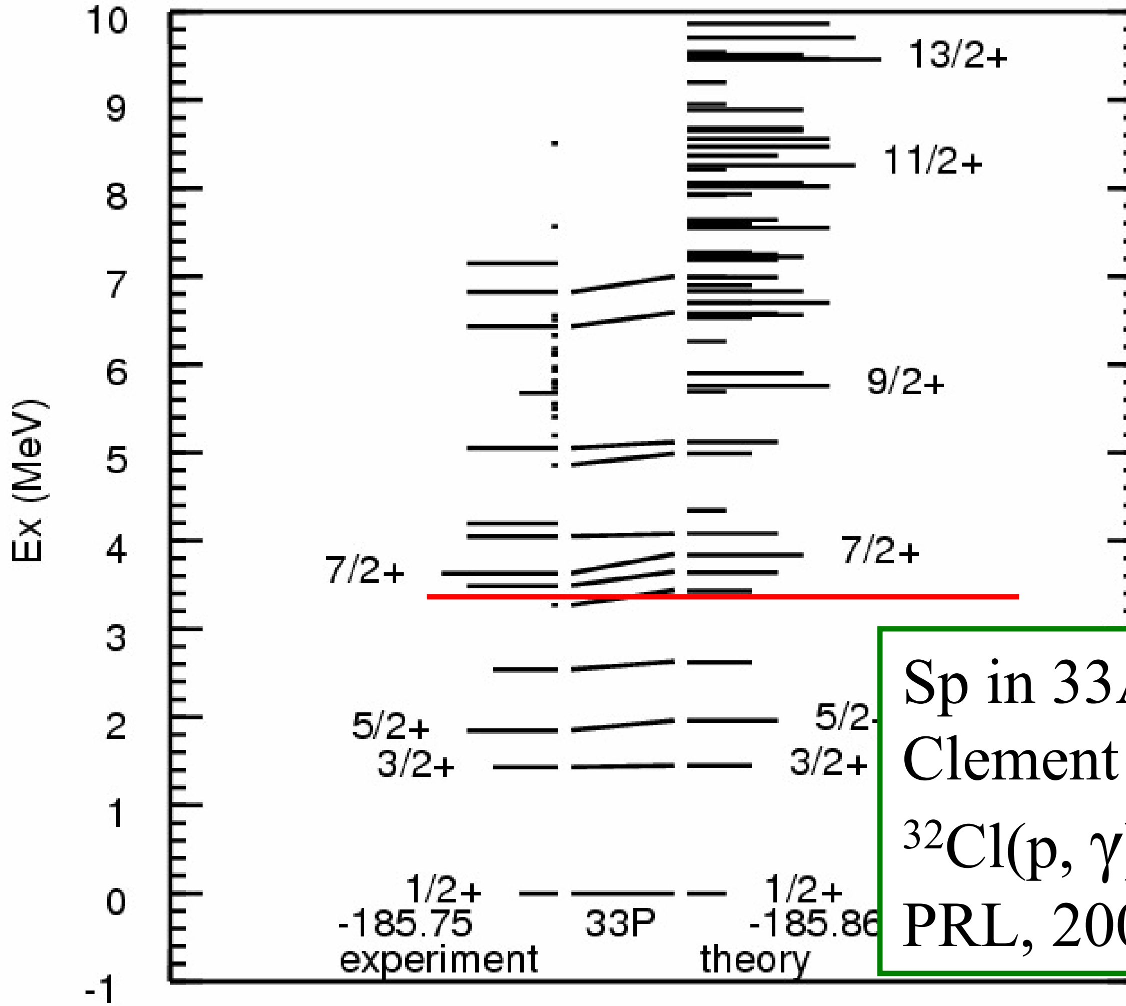




NSCL

^{33}P with renormalized USD-05 ($d_{5/2}\ d_{3/2}\ s_{1/2}$ model space)

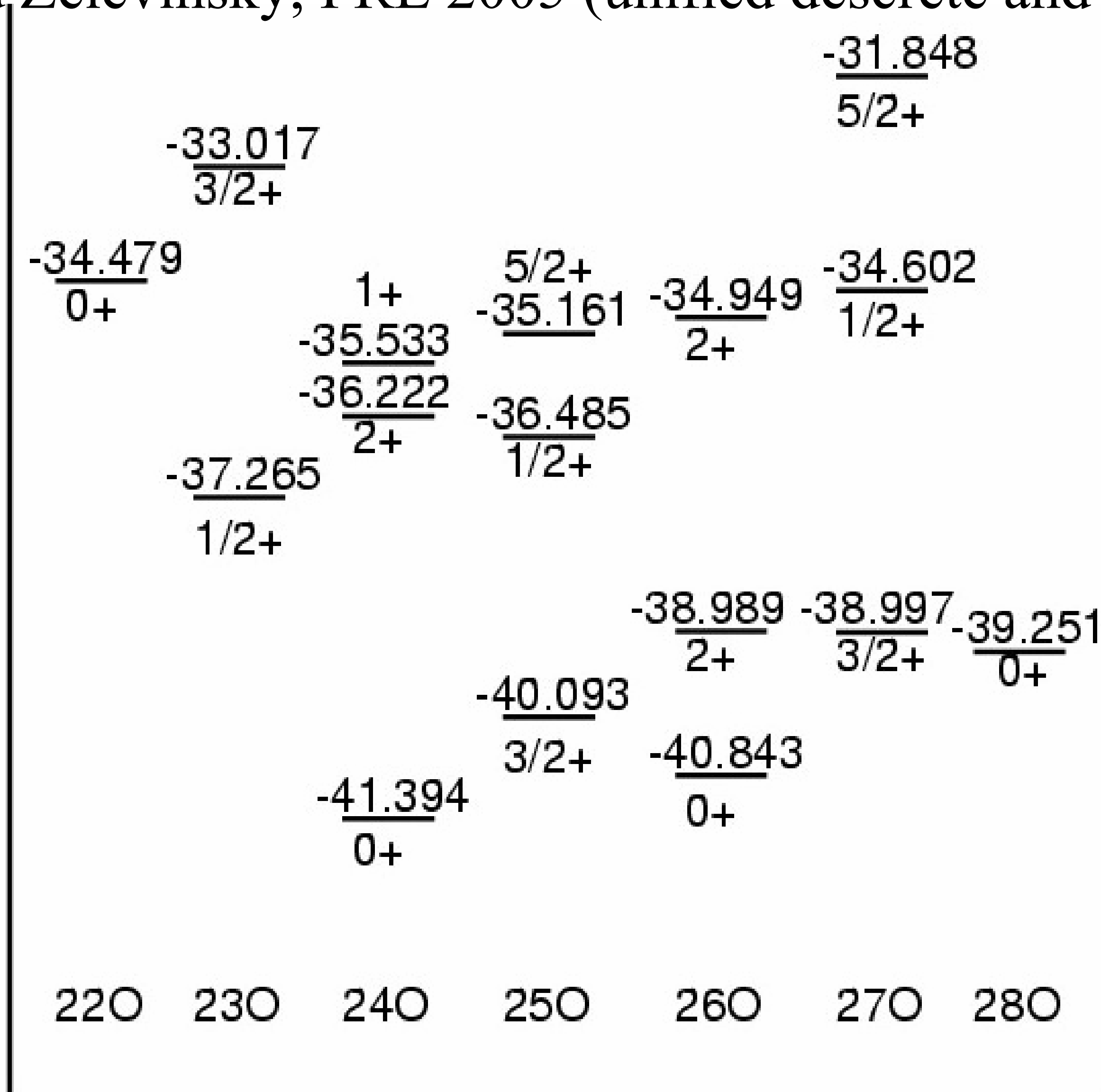




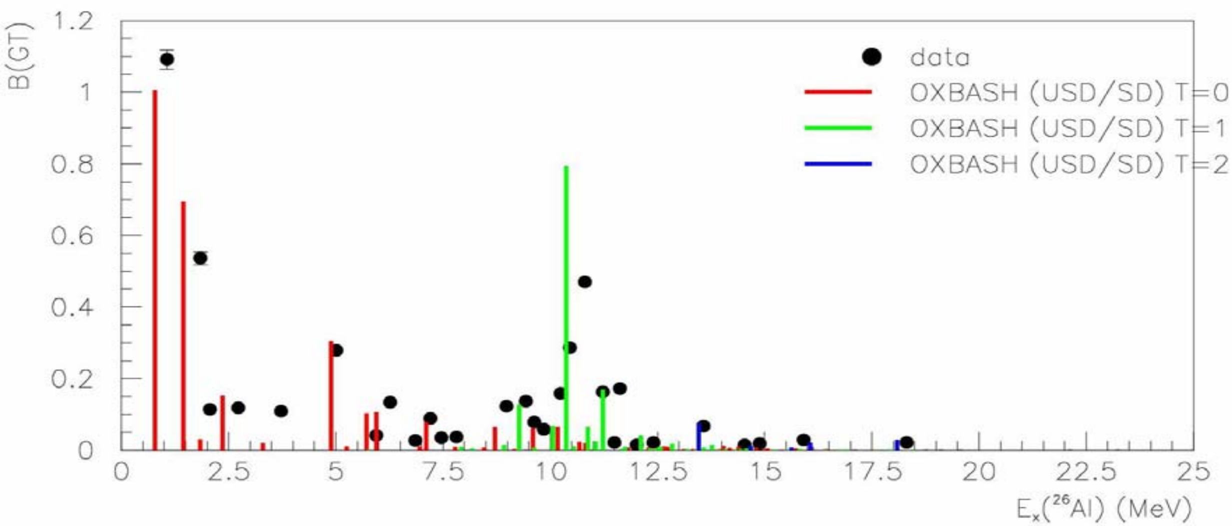
Sp in 33Ar
Clement et al
^{32}Cl(p, γ)
PRL, 2005

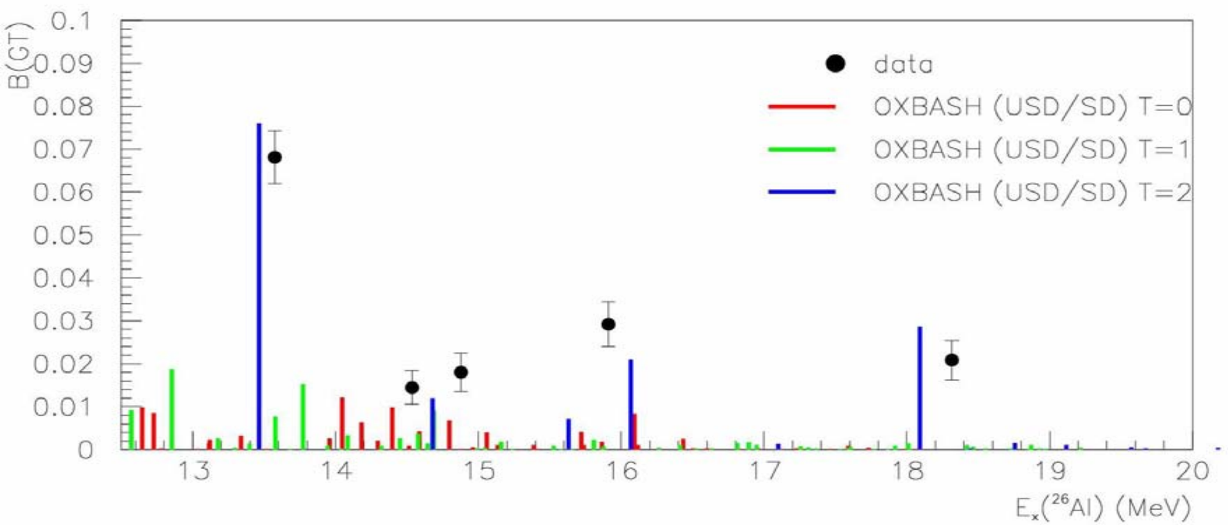
REU project with Angelo Signoracci (Notre Dame)

Volya and Zelevinsky, PRL 2005 (unified descrete and continuum)

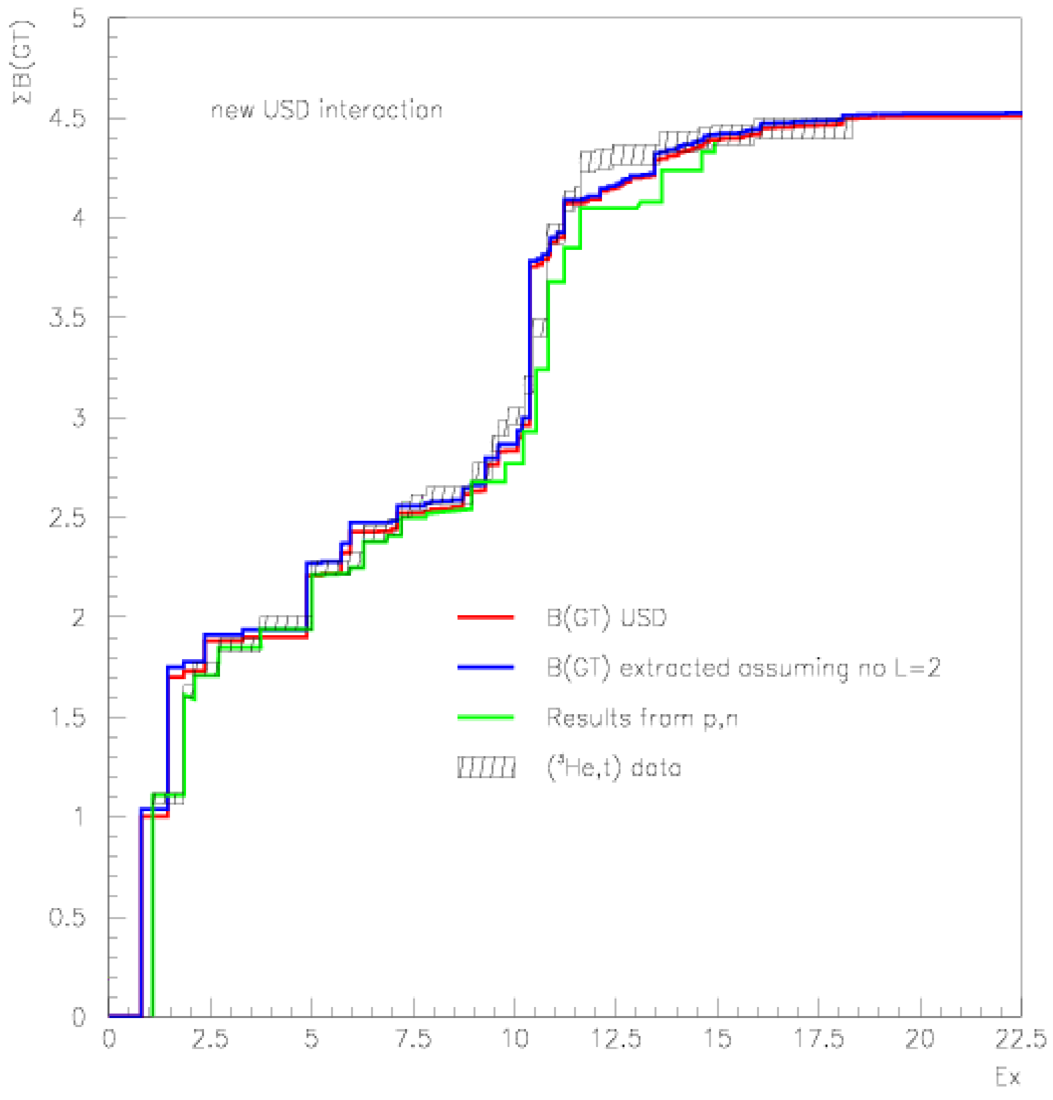


Gamow-Teller strength from $^{26}Mg(^{3}He,t)$, R. Zegers et al.

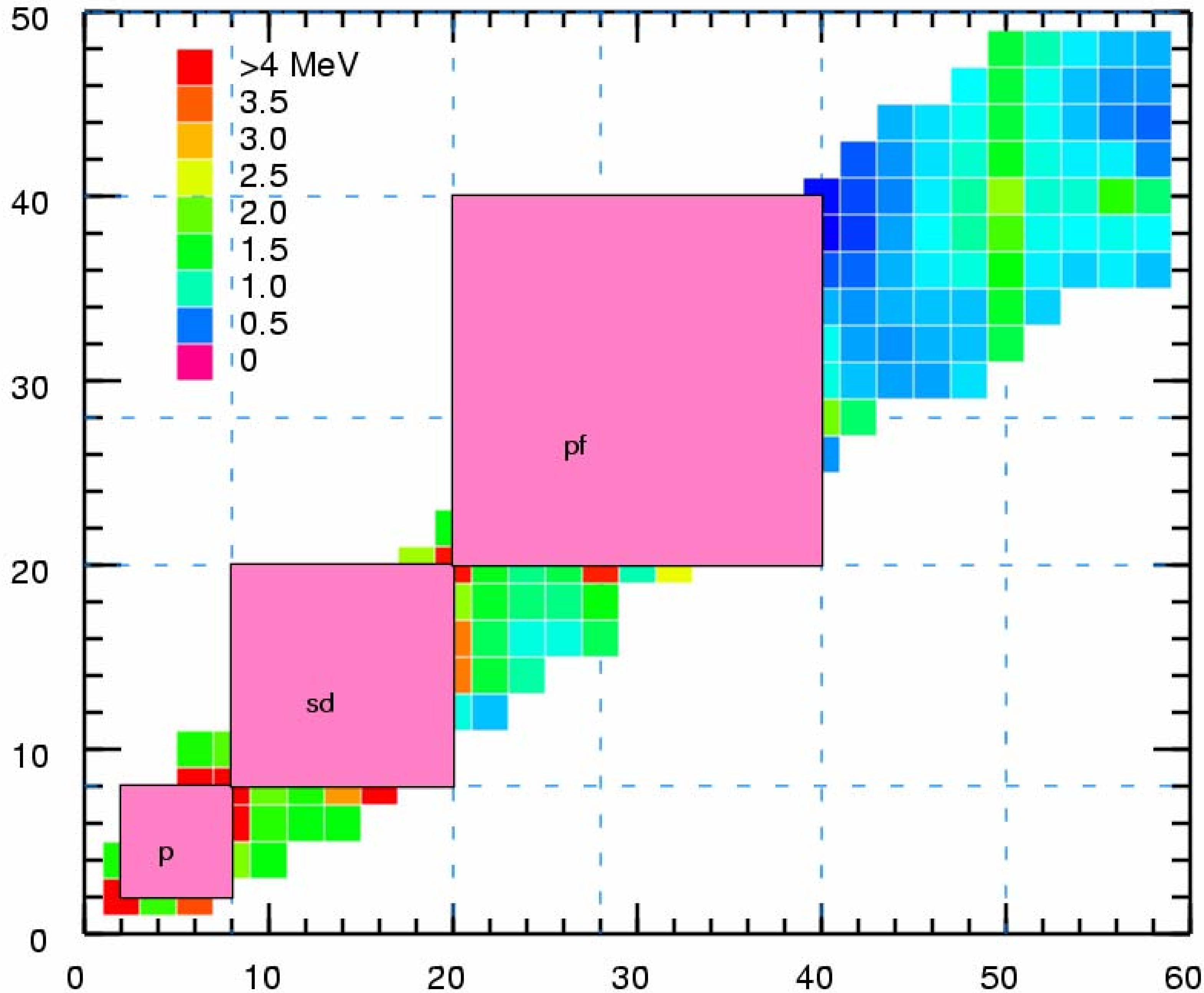




Gamow-Teller strength from $^{26}Mg(^{3}He,t)$, R. Zegers et al.

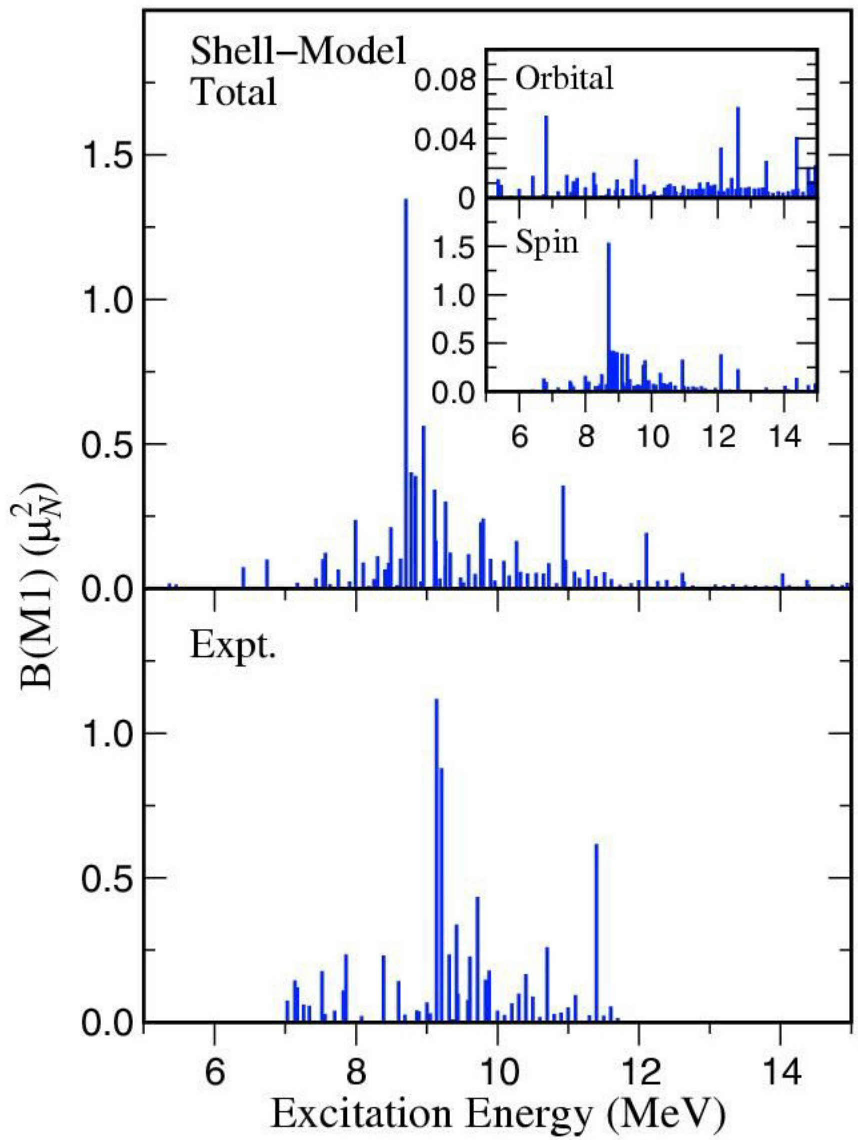


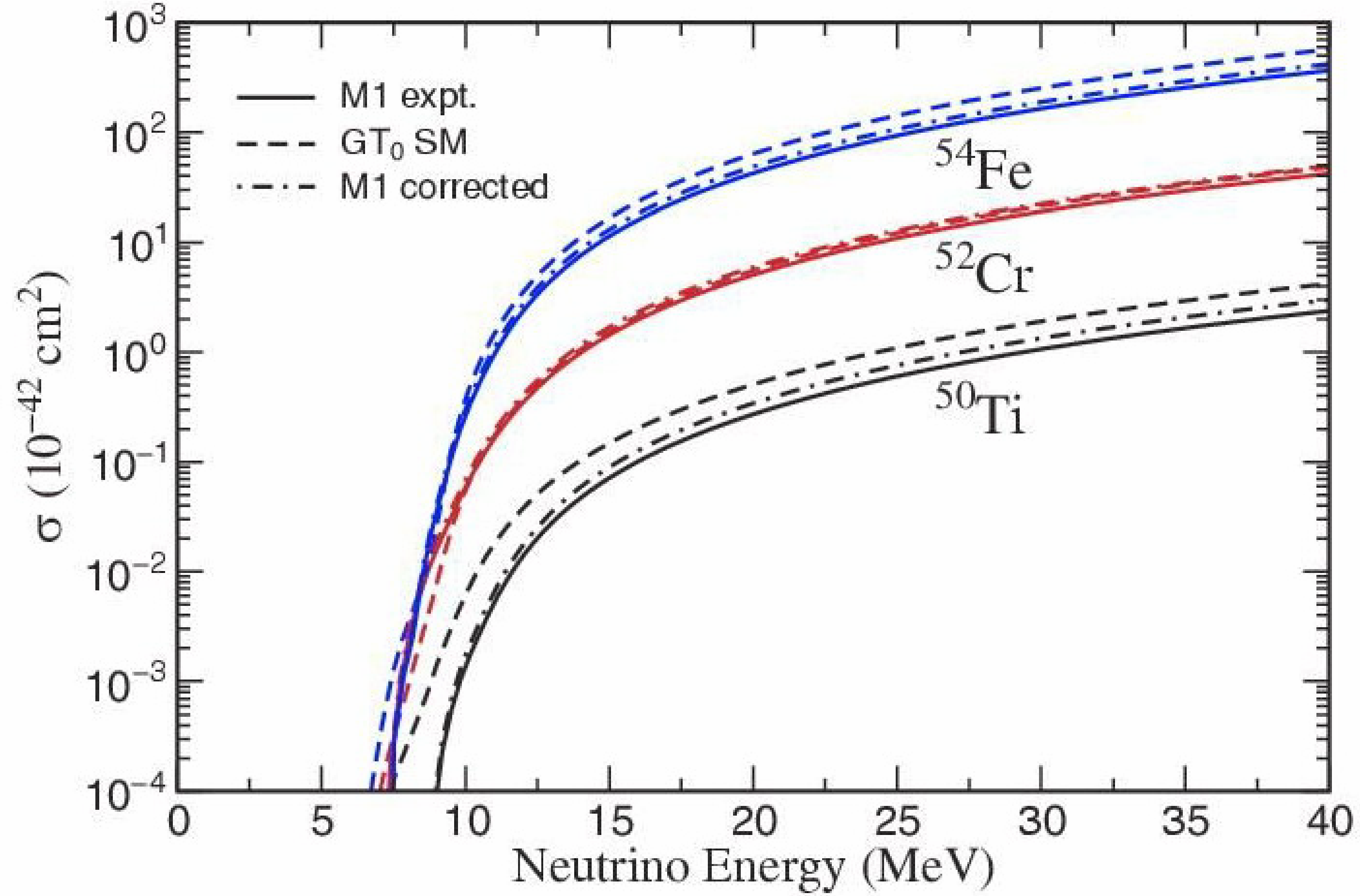
NSCL



>4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
p
sd
pf
0
10
20
30
40
50
0
10
20
30
40
50
60

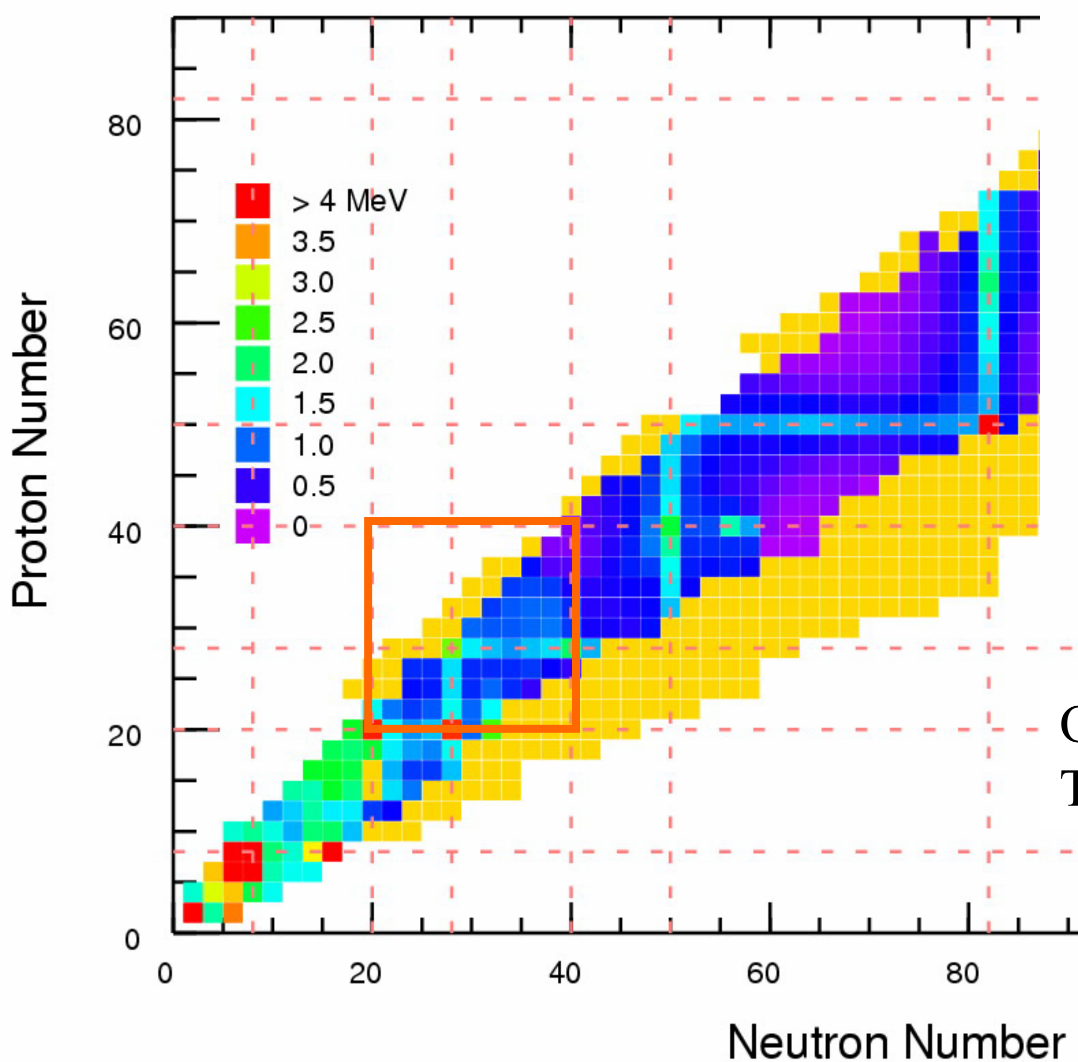
Langanke et al PRL, 2004

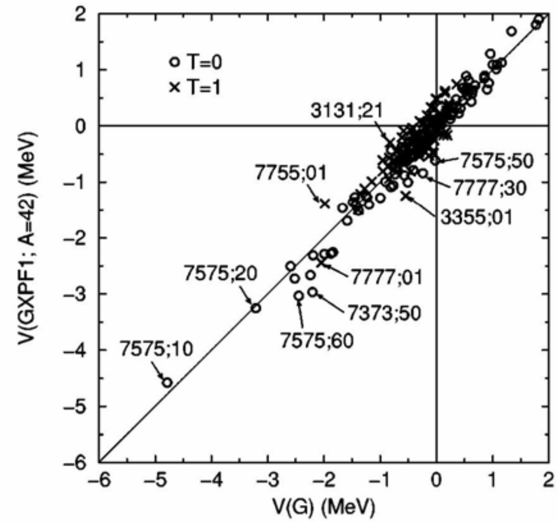




M1 expt.
GT$_0$ SM
M1 corrected
^{54}Fe
^{52}Cr
^{50}Ti
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
5
10
15
20
25
30
35
40
Neutrino Energy (MeV)
σ (10^{-42} cm^2)

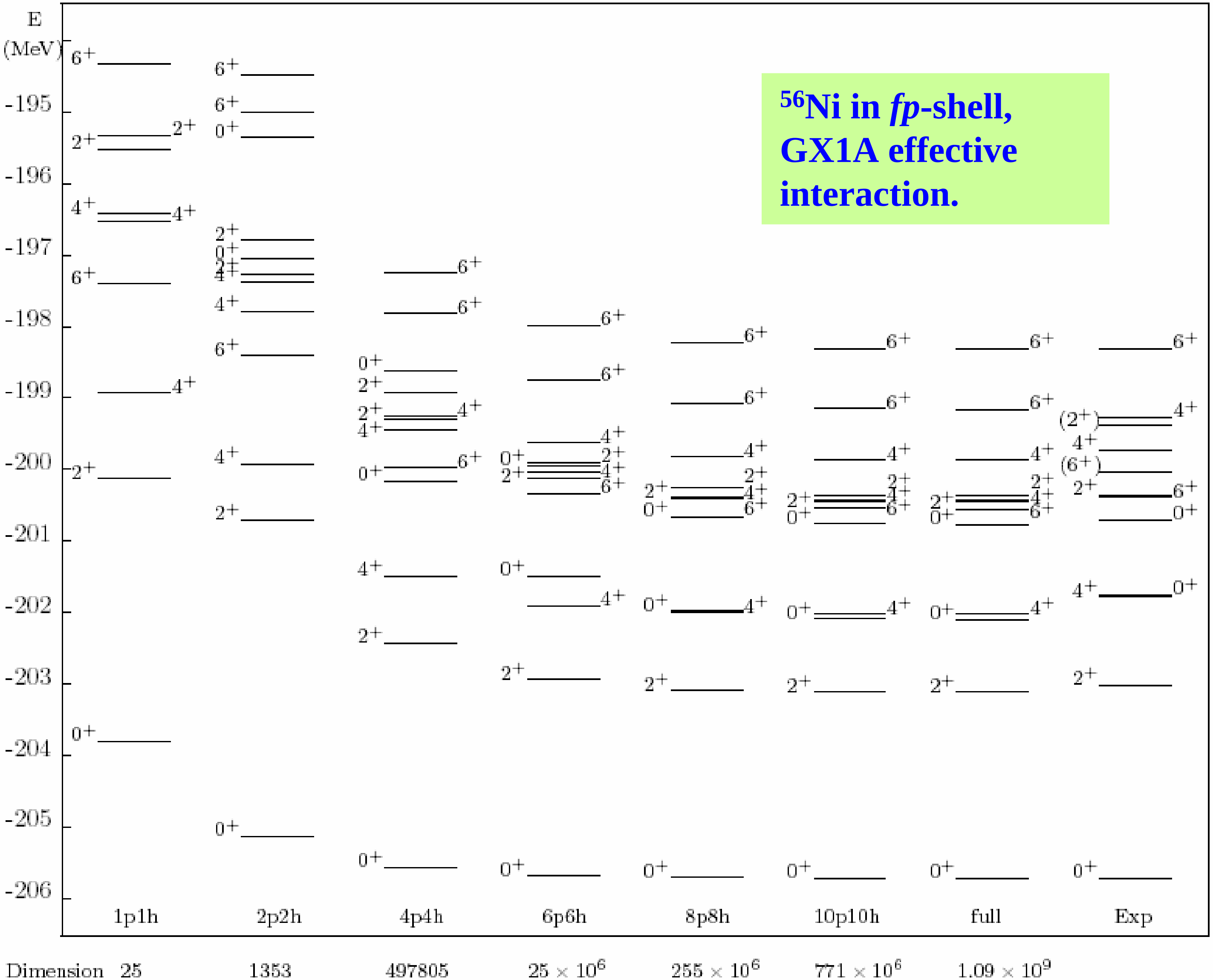
Energy of 2+ States in Even-Even Nuclei





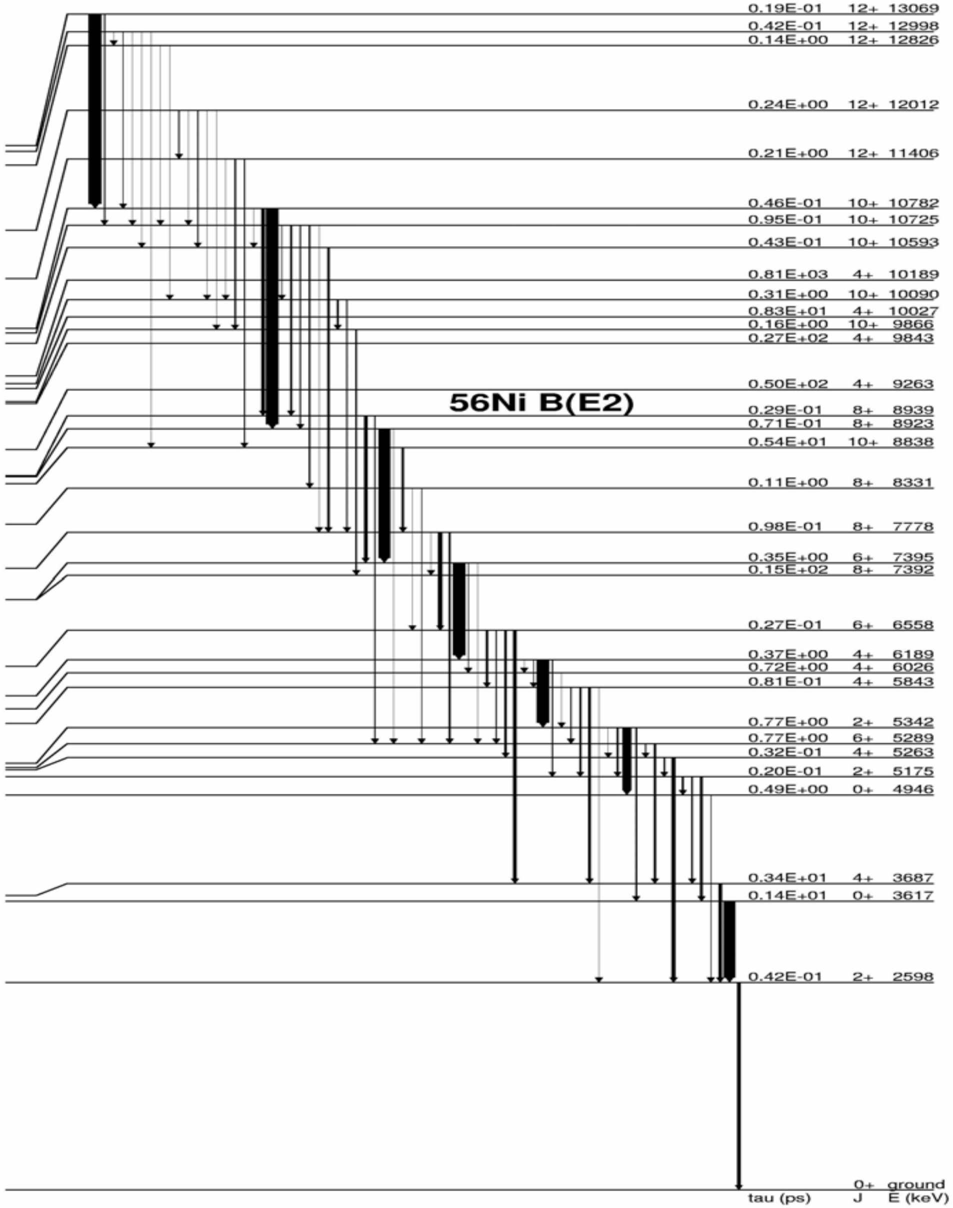
Ongoing project with
Taka Otsuka and Michio Honma

^{56}Ni in *fp*-shell, GX1A effective interaction.

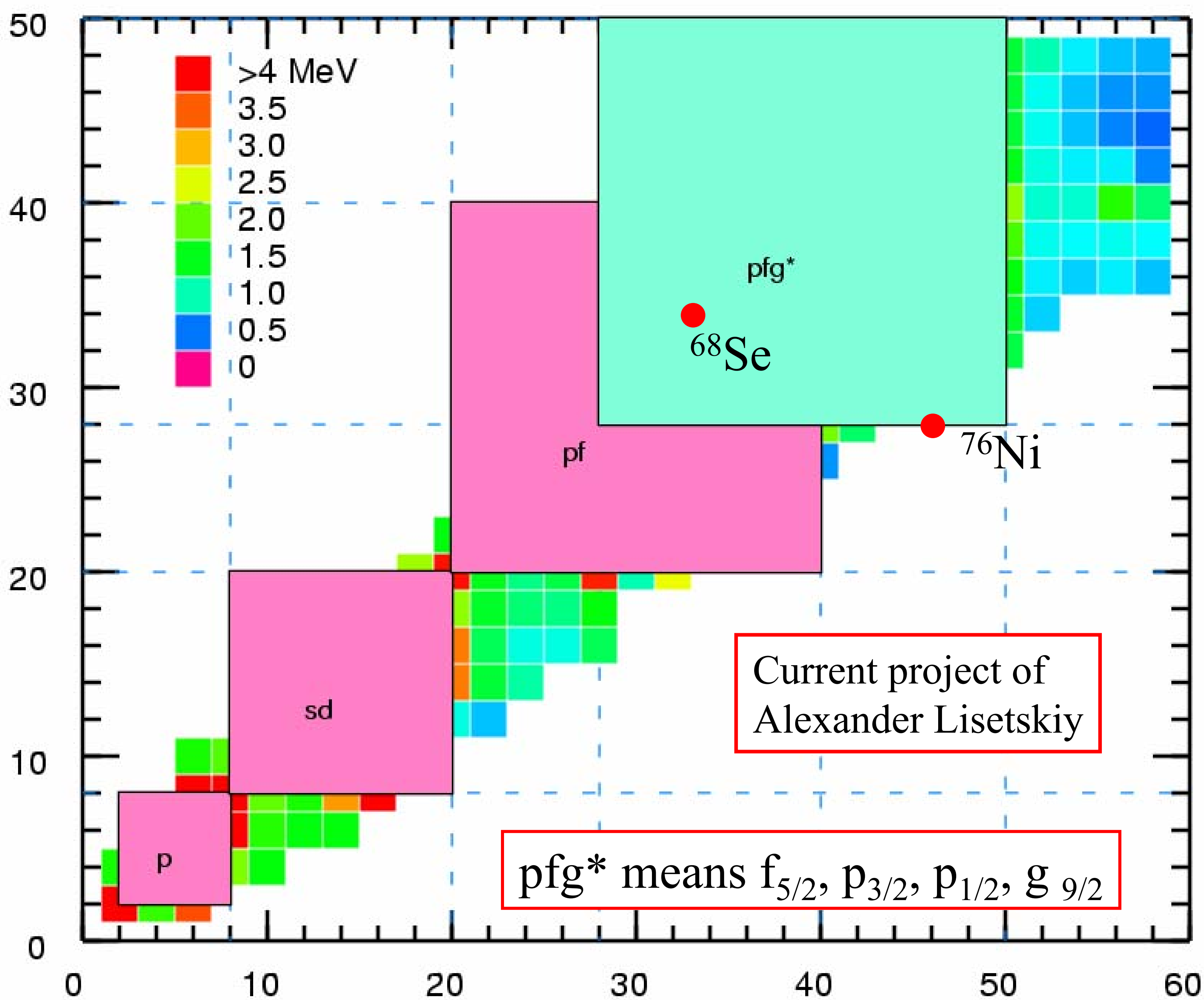


M. Horoi and B.A. Brown, to be submitted.

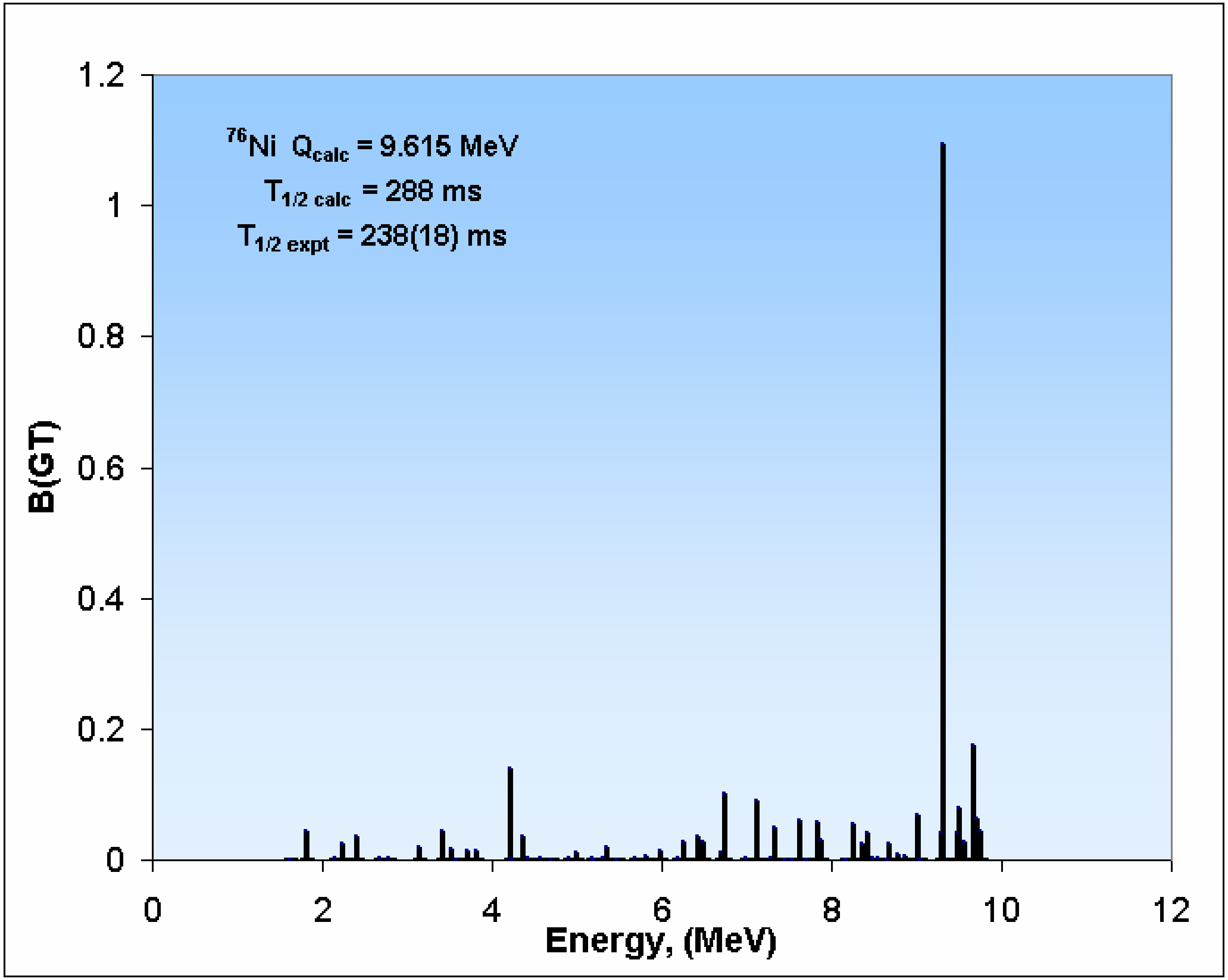
NSCL



56Ni B(E2)
0.19E-01 12+ 13069
0.42E-01 12+ 12998
0.14E+00 12+ 12826
0.24E+00 12+ 12012
0.21E+00 12+ 11406
0.46E-01 10+ 10782
0.95E-01 10+ 10725
0.43E-01 10+ 10593
0.81E+03 4+ 10189
0.31E+00 10+ 10090
0.83E+01 4+ 10027
0.16E+00 10+ 9866
0.27E+02 4+ 9843
0.50E+02 4+ 9263
0.29E-01 8+ 8939
0.71E-01 8+ 8923
0.54E+01 10+ 8838
0.11E+00 8+ 8331
0.98E-01 8+ 7778
0.35E+00 6+ 7395
0.15E+02 8+ 7392
0.27E-01 6+ 6558
0.37E+00 4+ 6189
0.72E+00 4+ 6026
0.81E-01 4+ 5843
0.77E+00 2+ 5342
0.77E+00 6+ 5289
0.32E-01 4+ 5263
0.20E-01 2+ 5175
0.49E+00 0+ 4946
0.34E+01 4+ 3687
0.14E+01 0+ 3617
0.42E-01 2+ 2598
0+ ground
tau (ps) J E (keV)

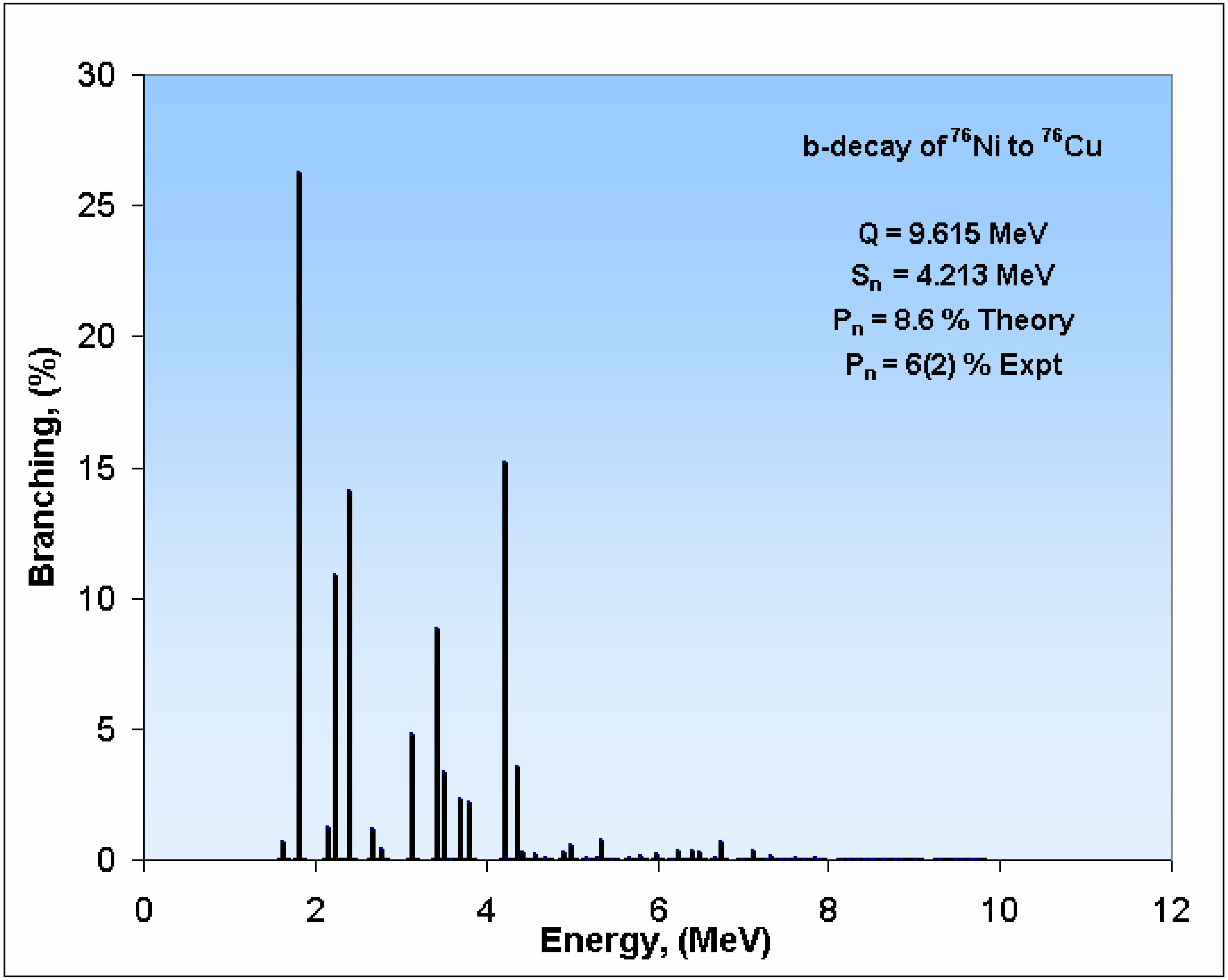


>4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
pfg*
68Se
76Ni
pf
sd
p
Current project of Alexander Lisetskiy
pfg* means f5/2, p3/2, p1/2, g 9/2
0
10
20
30
40
50
60
NSCL

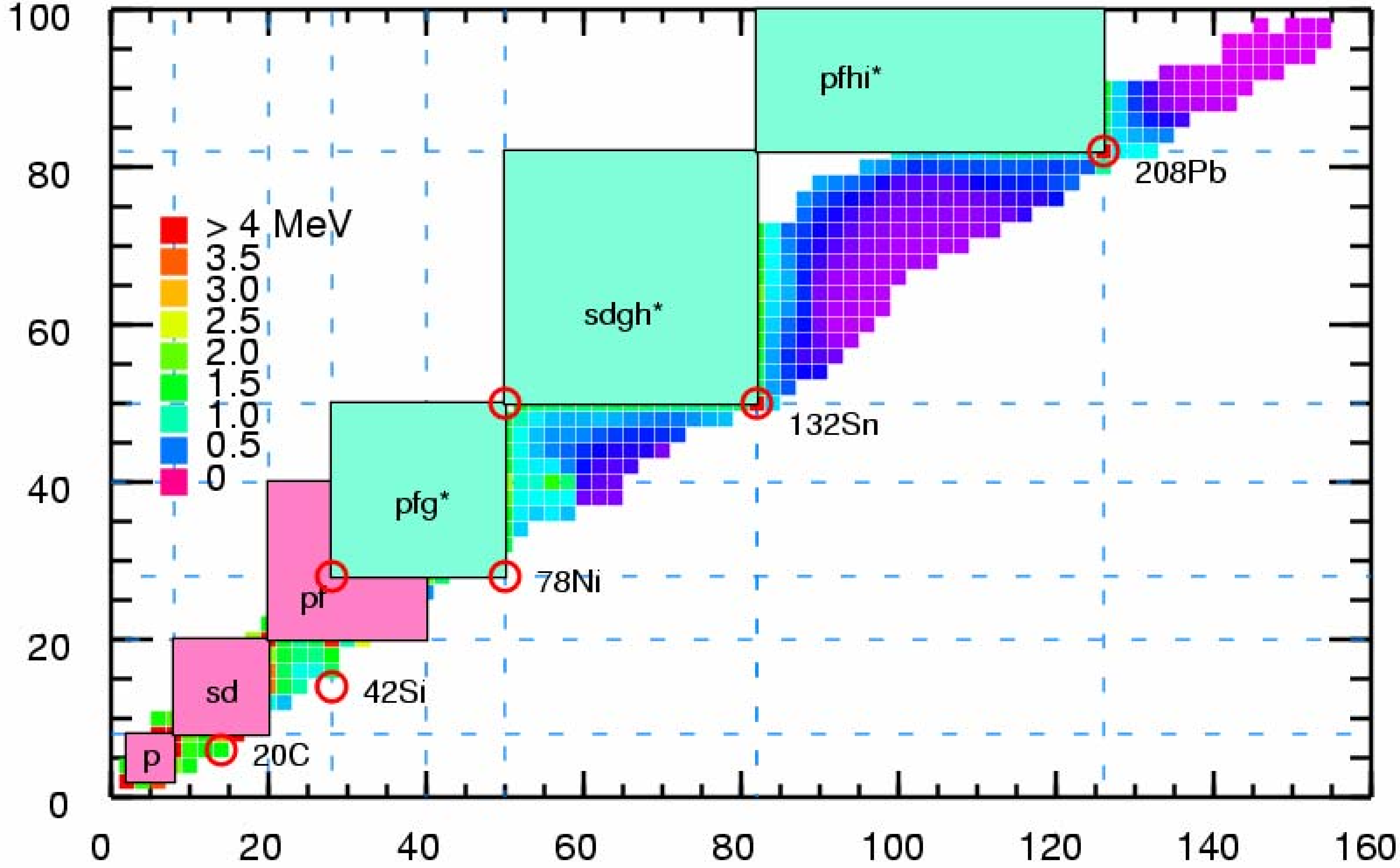


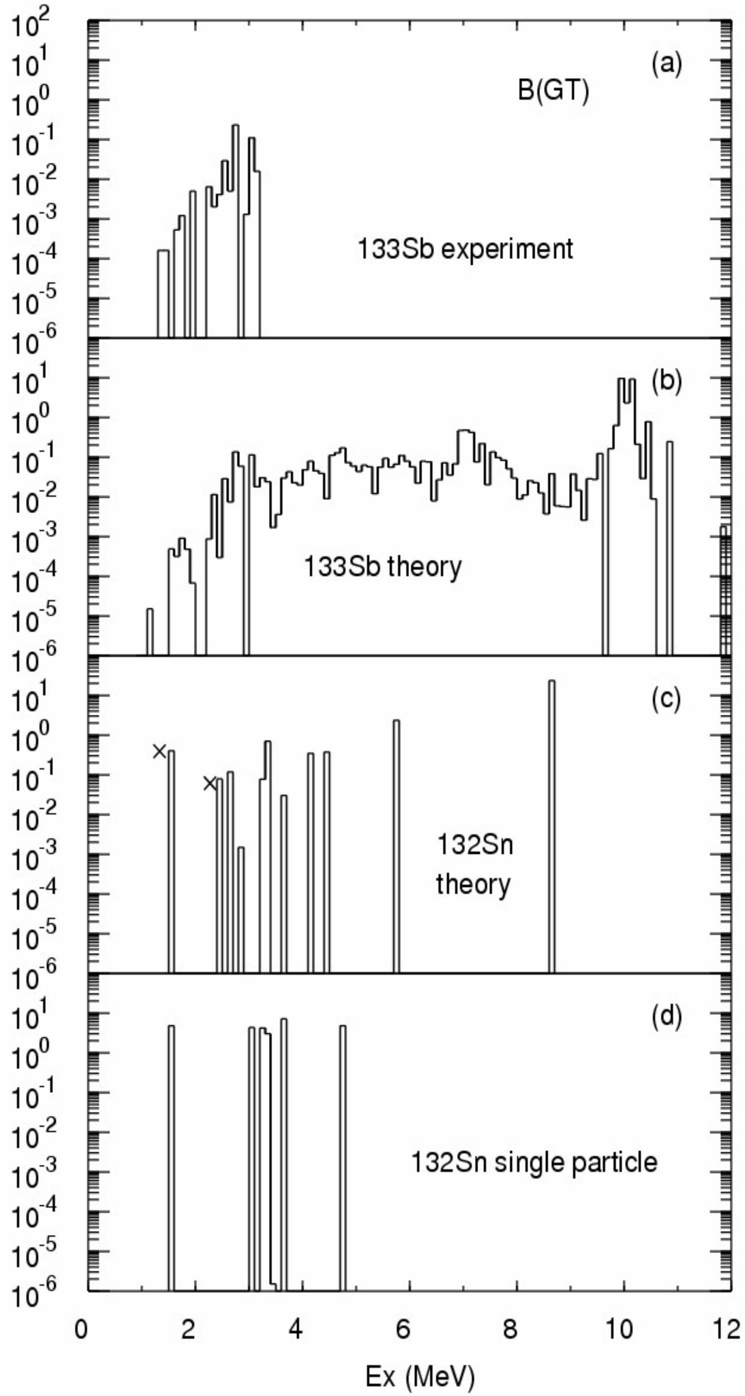
^{76}Ni Q_{calc} = 9.615 MeV
$T_{1/2\ calc}$ = 288 ms
$T_{1/2\ expt}$ = 238(18) ms
B(GT)
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
Energy, (MeV)

NSCL


b-decay of 76Ni to 76Cu
Q = 9.615 MeV
Sn = 4.213 MeV
Pn = 8.6 % Theory
Pn = 6(2) % Expt
Branching, (%)
Energy, (MeV)
0
5
10
15
20
25
30
0
2
4
6
8
10
12

jj closed shells




B(GT)
(a)
133Sb experiment
(b)
133Sb theory
(c)
132Sn
theory
(d)
132Sn single particle
Ex (MeV)

Real vacuum – up to about A=12

$$\hat{H} = \sum_{\alpha\beta} < \alpha \mid T \mid \beta > a_\alpha^+ a_\beta + \frac{1}{4} \sum_{\alpha\beta\gamma\delta} < \alpha\beta \mid V_{NN} \mid \gamma\delta > a_\alpha^+ a_\beta^+ a_\delta a_\gamma$$

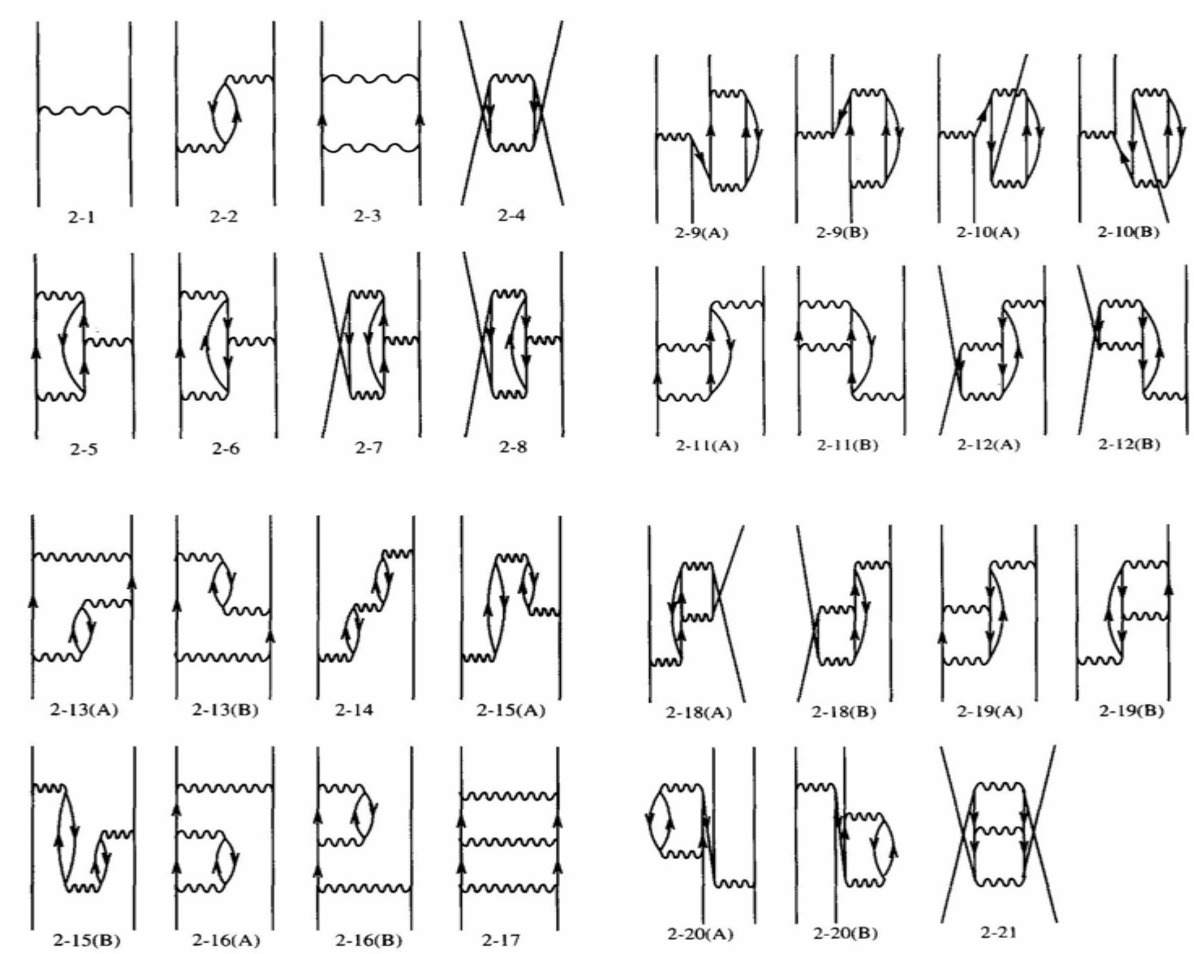
Closed-shell vacuum – "all" nuclei

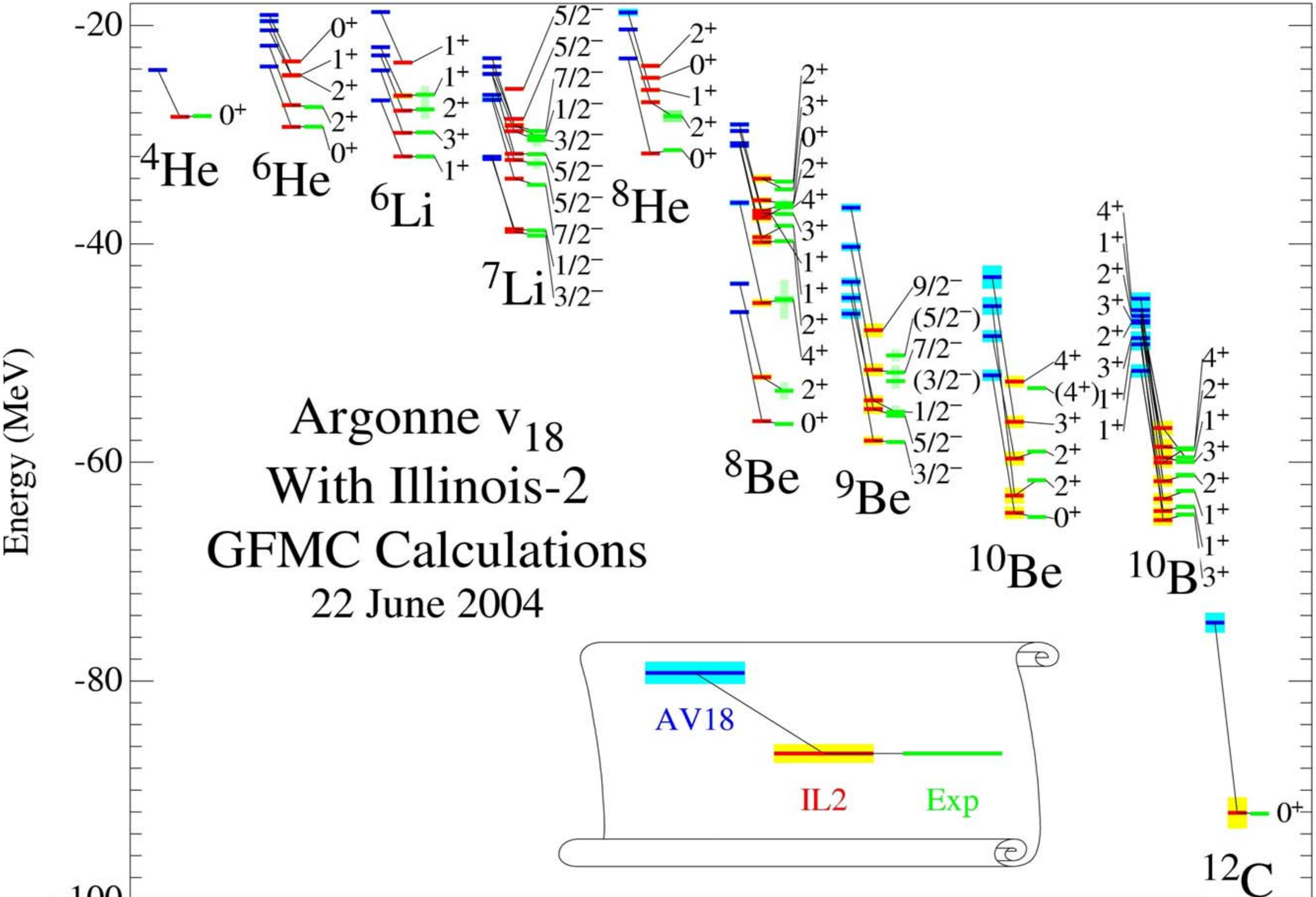
$$\hat{H} = \sum_{\alpha\beta} < \alpha \mid U \mid \beta > a_\alpha^+ a_\beta + \frac{1}{4} \sum_{\alpha\beta\gamma\delta} \boxed{< \alpha\beta \mid \tilde{G} \mid \gamma\delta >} a_\alpha^+ a_\beta^+ a_\delta a_\gamma$$

- Start with one of the doubly-magic nuclei as the vacuum
- Exact solution of *H* within the model space for the orbits inside the shell gaps
- Single-particle energies *U* from experiment
- Two-body matrix elements (G) adjusted to obtain a "best fit" to known data – to get the USD interaction

NSCL

Renormalization of NN





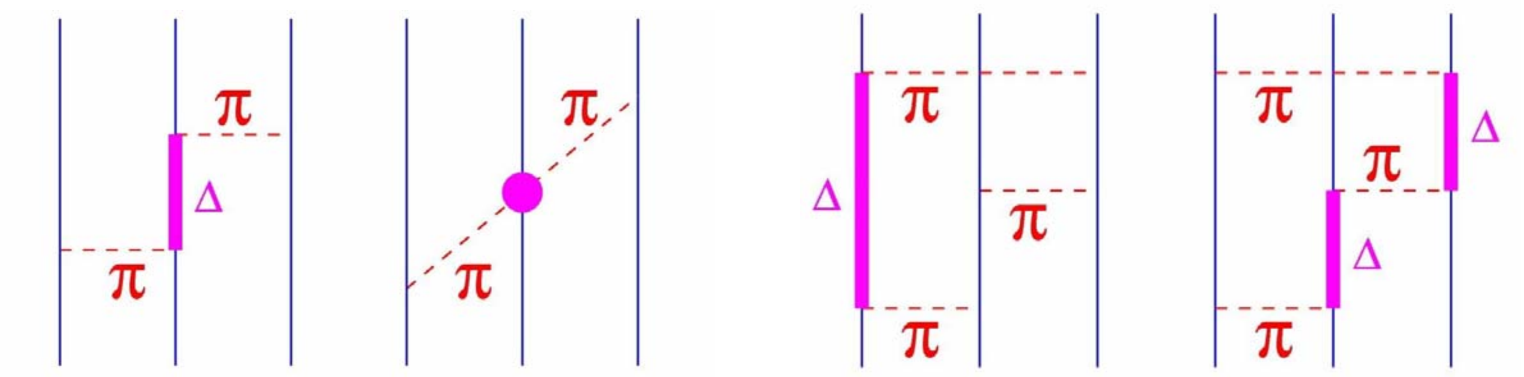
^{12}C results are preliminary.

Real vacuum – up to about A=12

$$\hat{H} = \sum_{\alpha\beta} < \alpha \mid T \mid \beta > a_\alpha^+ a_\beta + \frac{1}{4} \sum_{\alpha\beta\gamma\delta} < \alpha\beta \mid V_{NN} \mid \gamma\delta > a_\alpha^+ a_\beta^+ a_\delta a_\gamma$$

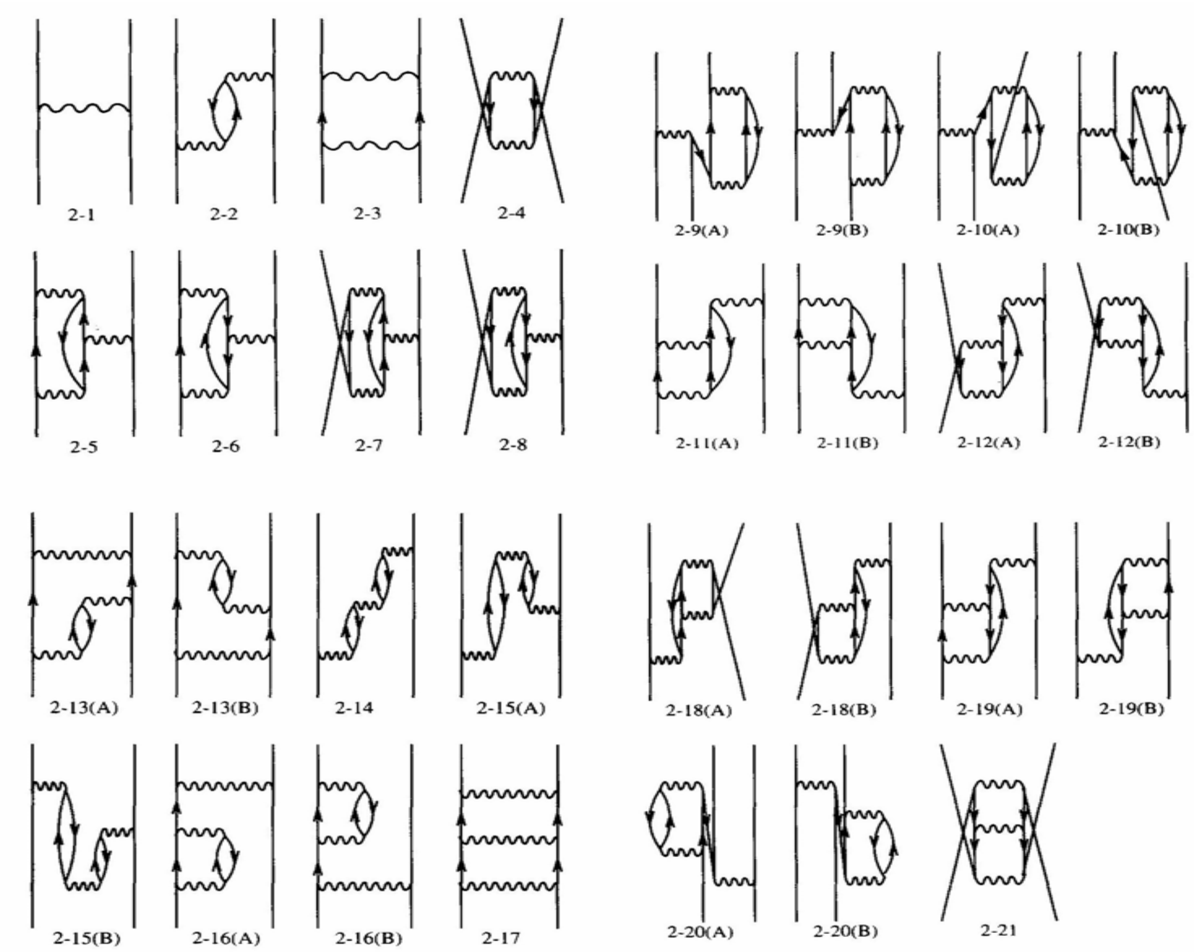
Requires the addition of three-body interactions

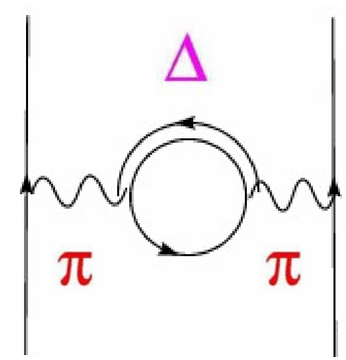
$$\frac{1}{36} \sum_{\alpha\beta\gamma\delta\epsilon\nu} < \alpha\beta\gamma \mid V_{NNN} \mid \delta\epsilon\nu > a_\alpha^+ a_\beta^+ a_\gamma^+ a_\nu a_\epsilon a_\delta$$



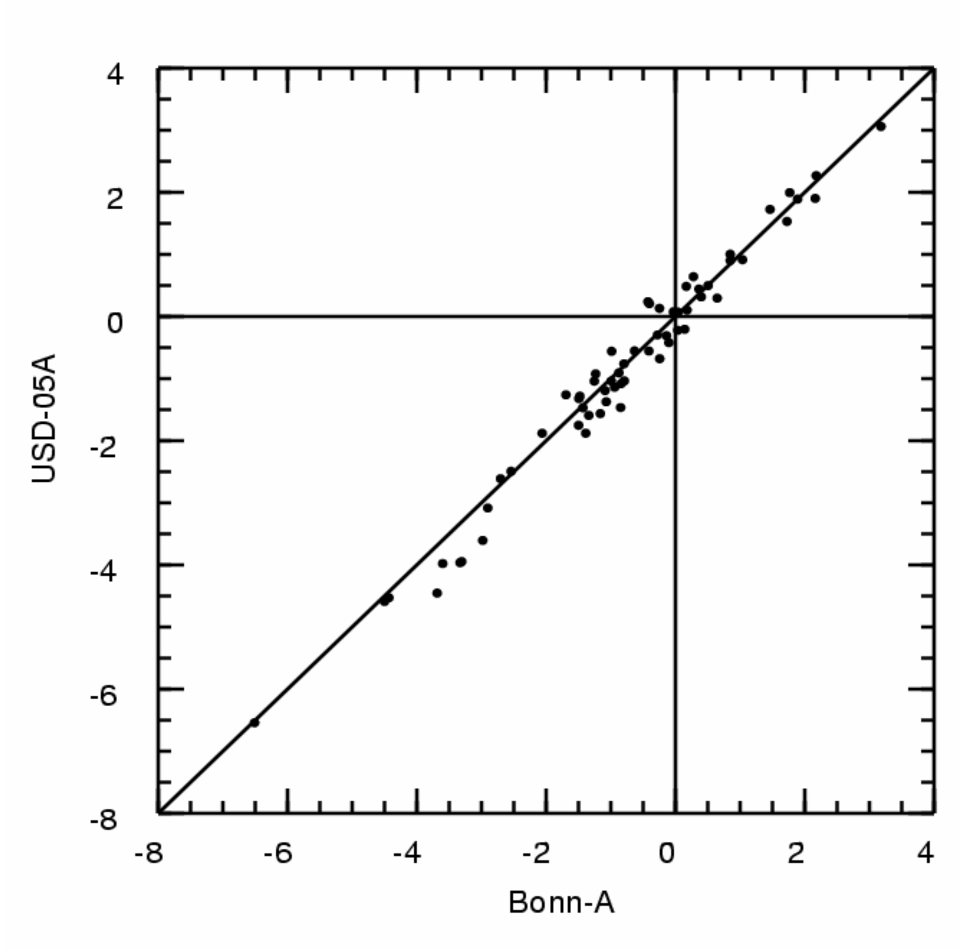
NSCL

Renormalization of NN



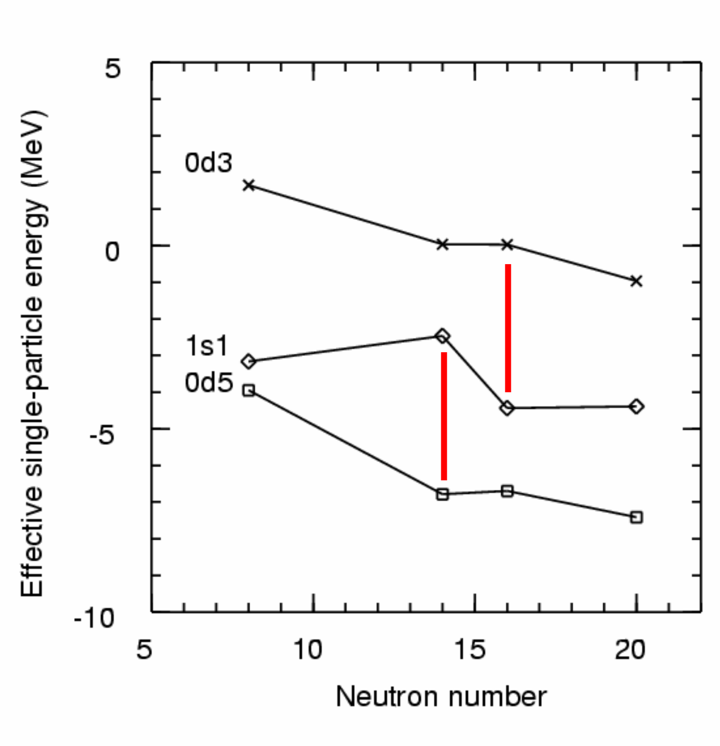


Two-body matrix elements – USD-05 vs NN



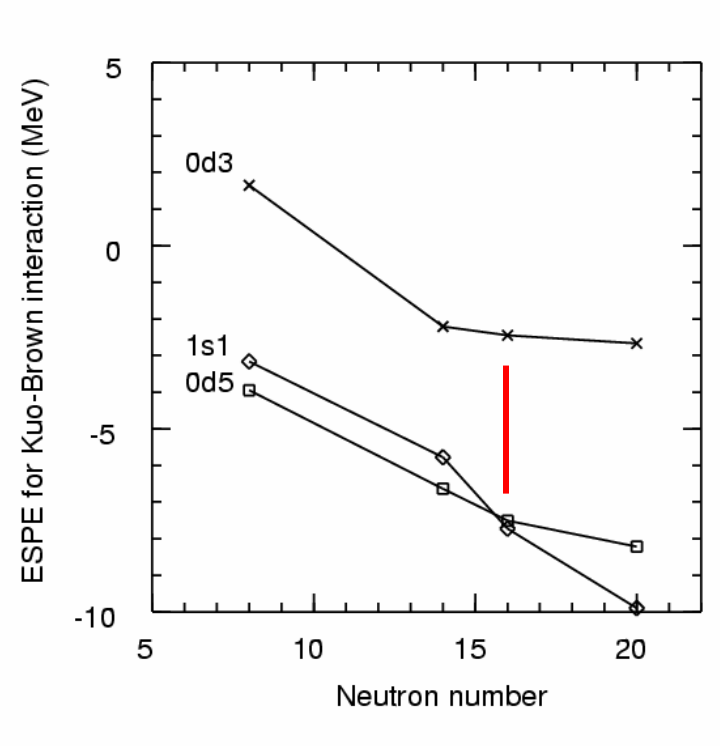
NSCL

USD

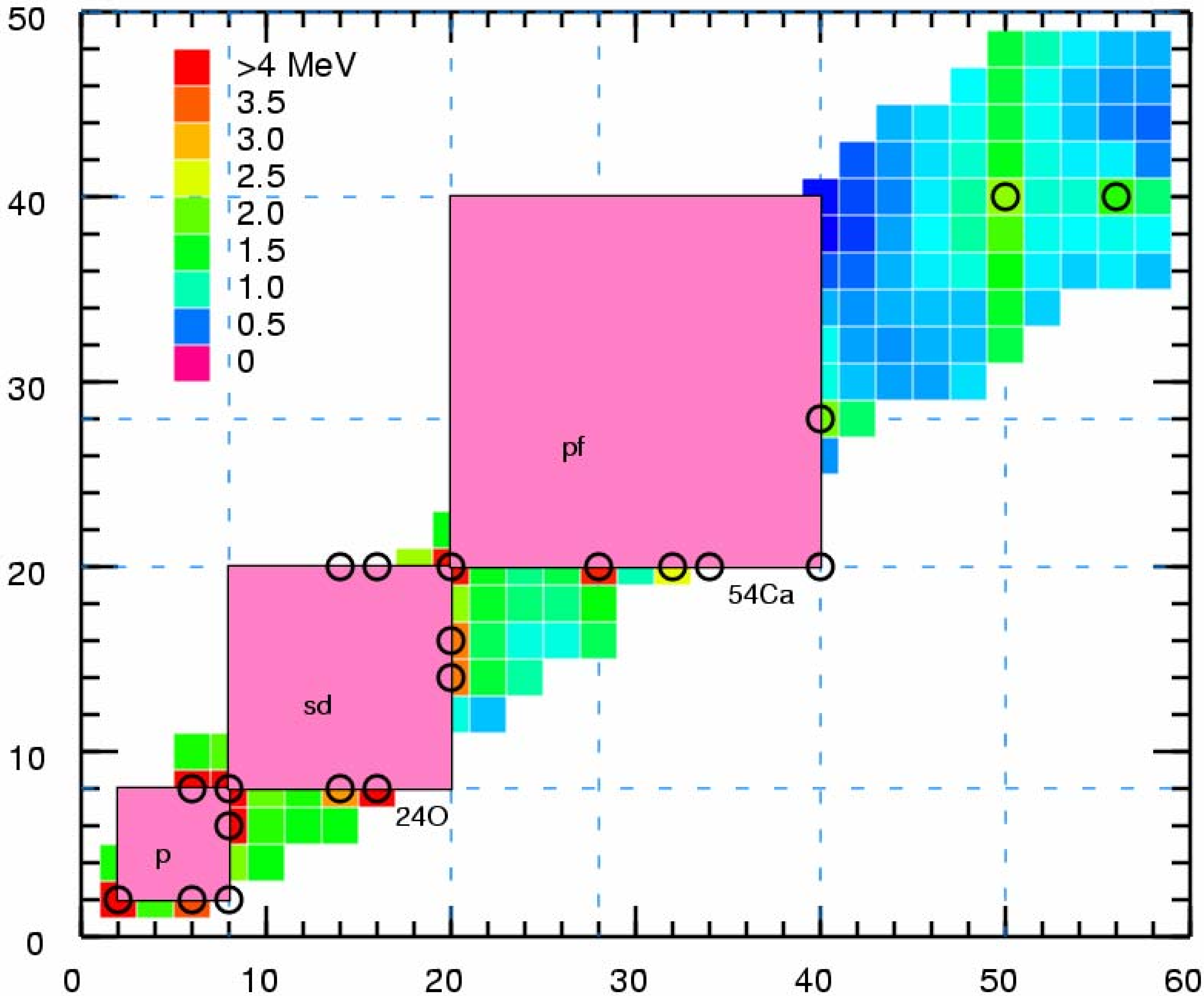


5
0
-5
-10
5
10
15
20
Neutron number
Effective single-particle energy (MeV)
0d3
1s1
0d5

NN



5
0
-5
-10
5
10
15
20
Neutron number
ESPE for Kuo-Brown interaction (MeV)
0d3
1s1
0d5


>4 MeV
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
pf
sd
p
54Ca
24O
0
10
20
30
40
50
60

Collaborations

- Mihai Horoi
  Alexander Lisetskiy
  Vladimir Zelevinsky
- Morten Hjorth-Jensen
- Taka Otsuka
  Michio Honma
  Taka Mizusaki
- The NSCL experimental groups
- JINA
- Experimental input from ANL, GANIL, GSI and RIKEN
- Funding from the NSF

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