High spin states in 208Pb and weak coupling of one-particle one-hole states to platonic shapes

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Andreas Heusler (*Heidelberg*, Germany)

* ***adapted from*** *Fig. 1 in* Phys. Rev. **C97**(R) 011301 (2018)

States in the heavy nucleus 208Pb

- about 500 neutron and proton bound states are known

  S(n)=7368 keV S(p)=8004 keV
- mean distance between any two states is *3.0 keV*
- uncertainty of excitation energy is *10 eV* for lowest states and up to *500 eV* for highest states
- all (150) states at *Ex < 6.2 MeV* are completely known with spin, parity, and dominant structure [6]
- most (60) negative parity states at *Ex < 7.0 MeV* are (completely) known with spin and dominant structure
- states in a γ-cascade from *Ex=17 MeV* to *Ex=9 MeV* are explained by a weak coupling model [2]

[6] A. Heusler et al., Phys. Rev. C **93**, 054321 (2016)

[2] A. de-Shalit, Phys. Rev. **122**, 1530 (1961)

Structure of states in 208Pb

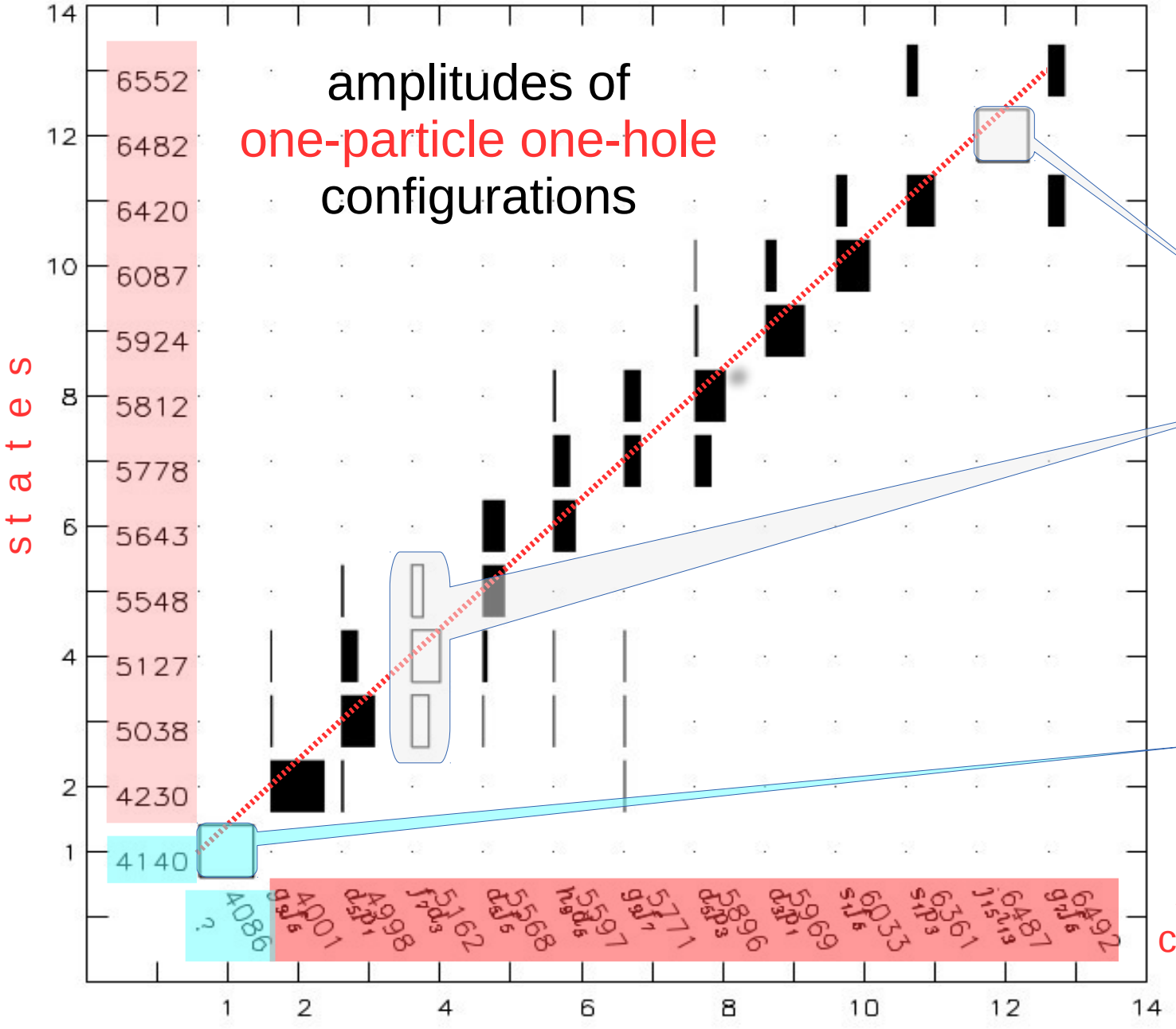
- most known (500) states are described by the shell model as one-particle one-hole configurations

three dozen states have another structure:

- 18 states are 1p1h configurations coupled to the 3- yrast state
- 4 states are pairing vibrations
- 10 states are tetrahedral rotations and vibrations
- 5 states (3-, 5-, 6+, 12+) are collective of another type (¿ icosahedral ?)

1p1h states in 208Pb

up to ten 1p1h amplitudes are determined in each of about 150 states



amplitudes of
one-particle one-hole
configurations

2-

unobservable
configuration

determined by orthogonality,
sum rule,
and normality relations
by knowledge
of some signs of amplitudes

the 2- yrast state
is of collective
tetrahedral type

shell model
configurations

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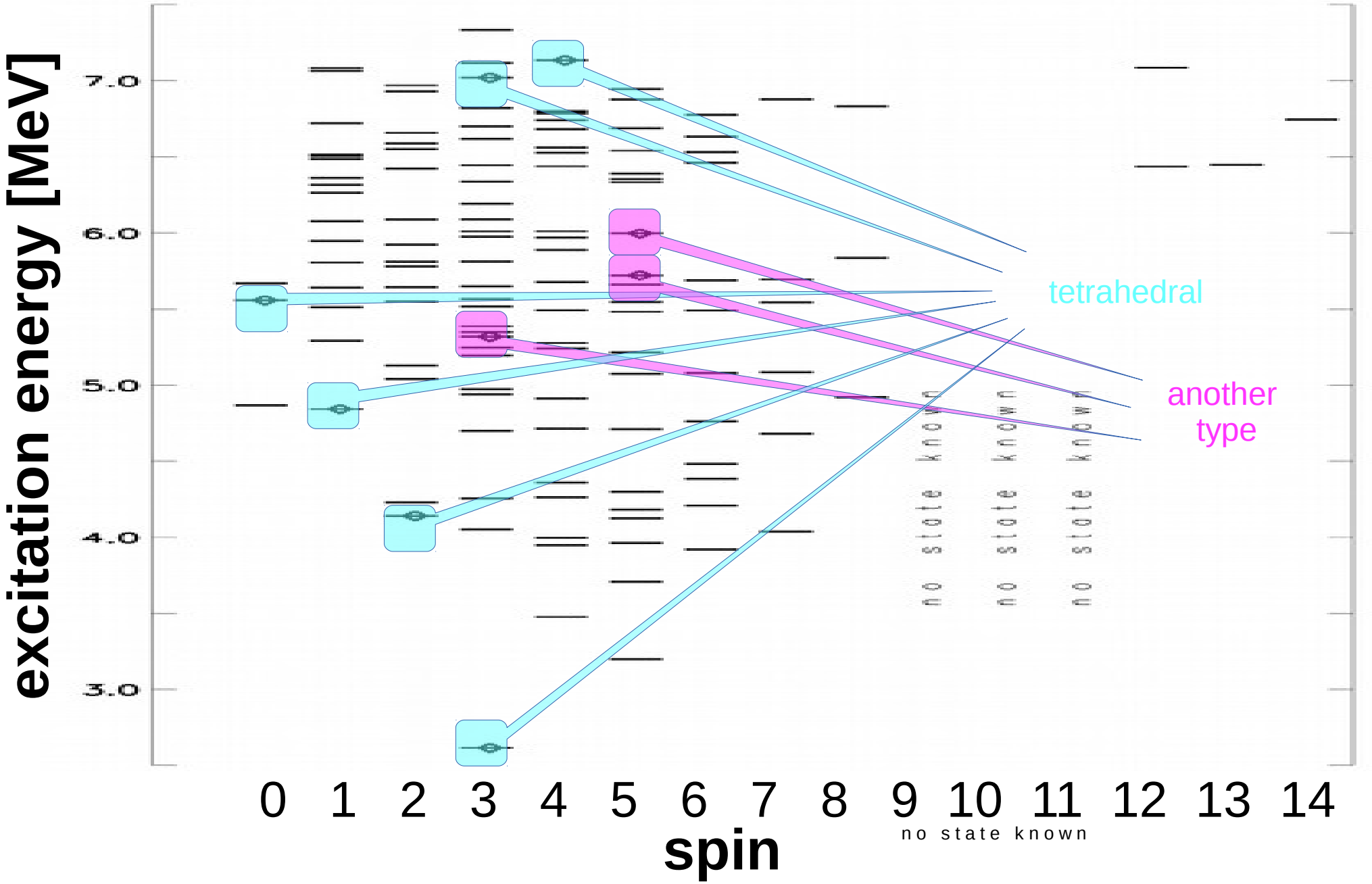
Negative parity states in 208Pb

most states are 1p1h configurations



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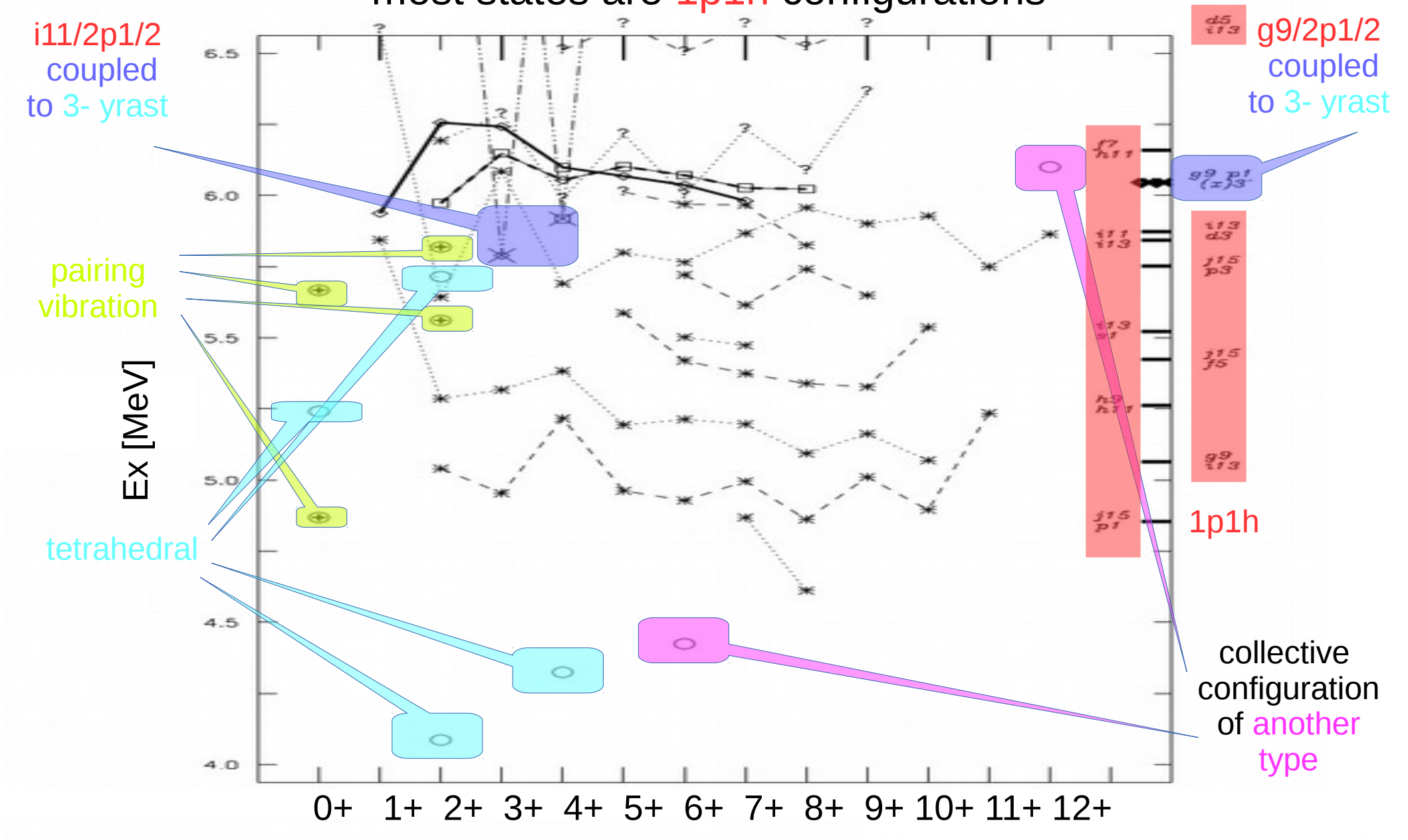
Positive parity states in 208Pb

most states are 1p1h configurations



[8] A. Heusler et al., Phys. Rev. C **99**, 034323 (2019)

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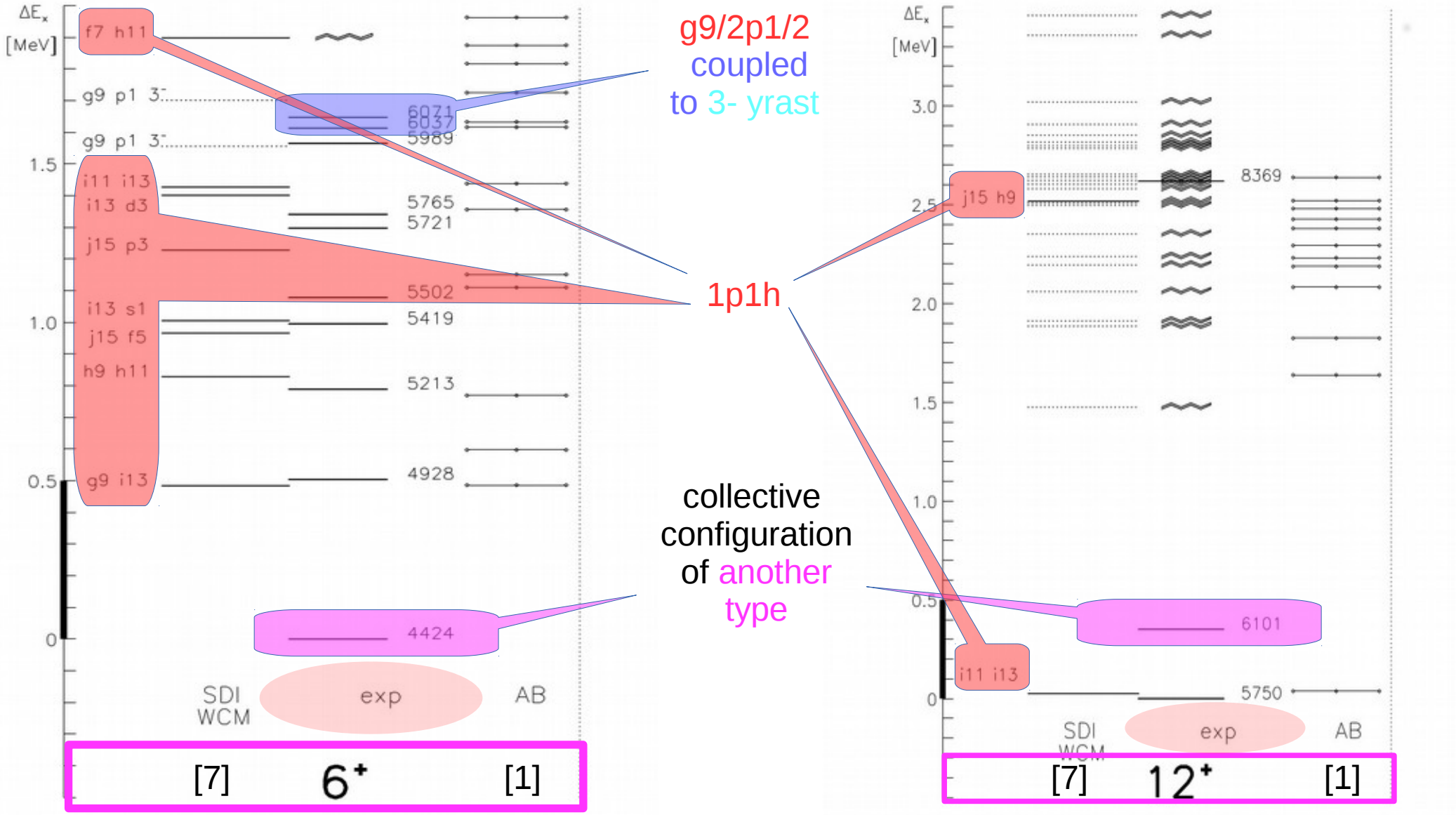
Collective states in 208Pb of unknown type



[7] A. Heusler et al., Yad. Fiz. **76**, 860 (2013); Phys. Atomic Nuclei **76**, 807 (2013)

[1] R. Broda et al., Phys. Rev. C **95**, 064308 (2017)

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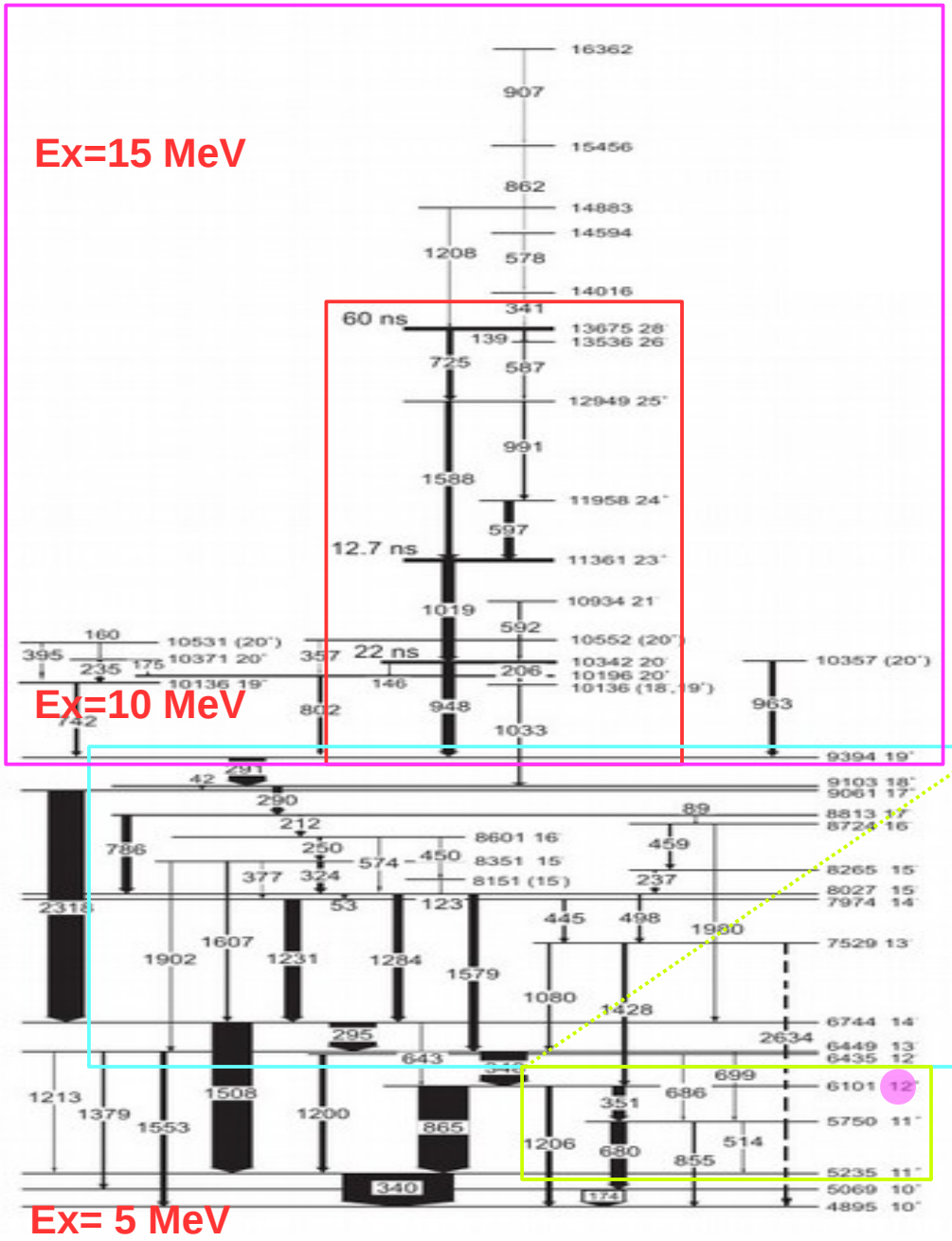
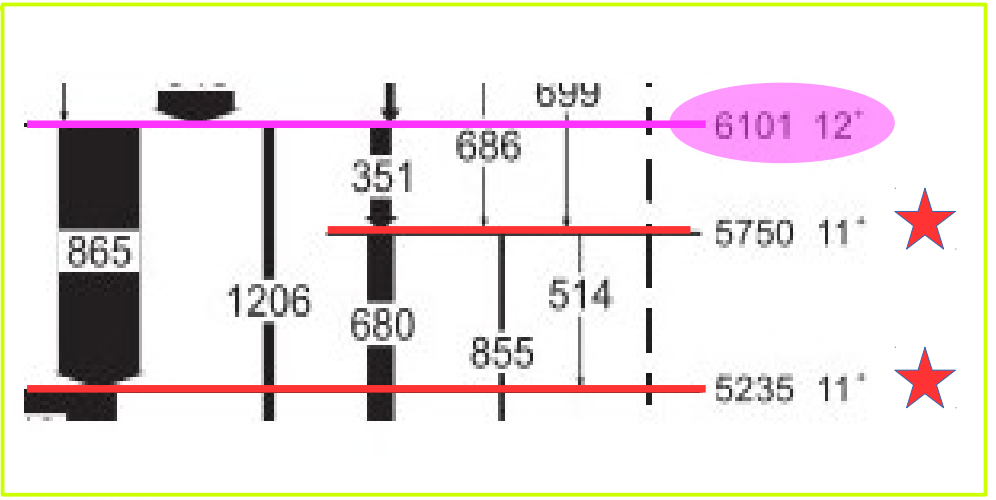
High spin states in 208Pb below Ex =10 MeV

from [1] R. Broda et al., Phys. Rev. C **95**, 064308 (2017)



spin/parity
of the collective
12+ state
of unknown type
verified



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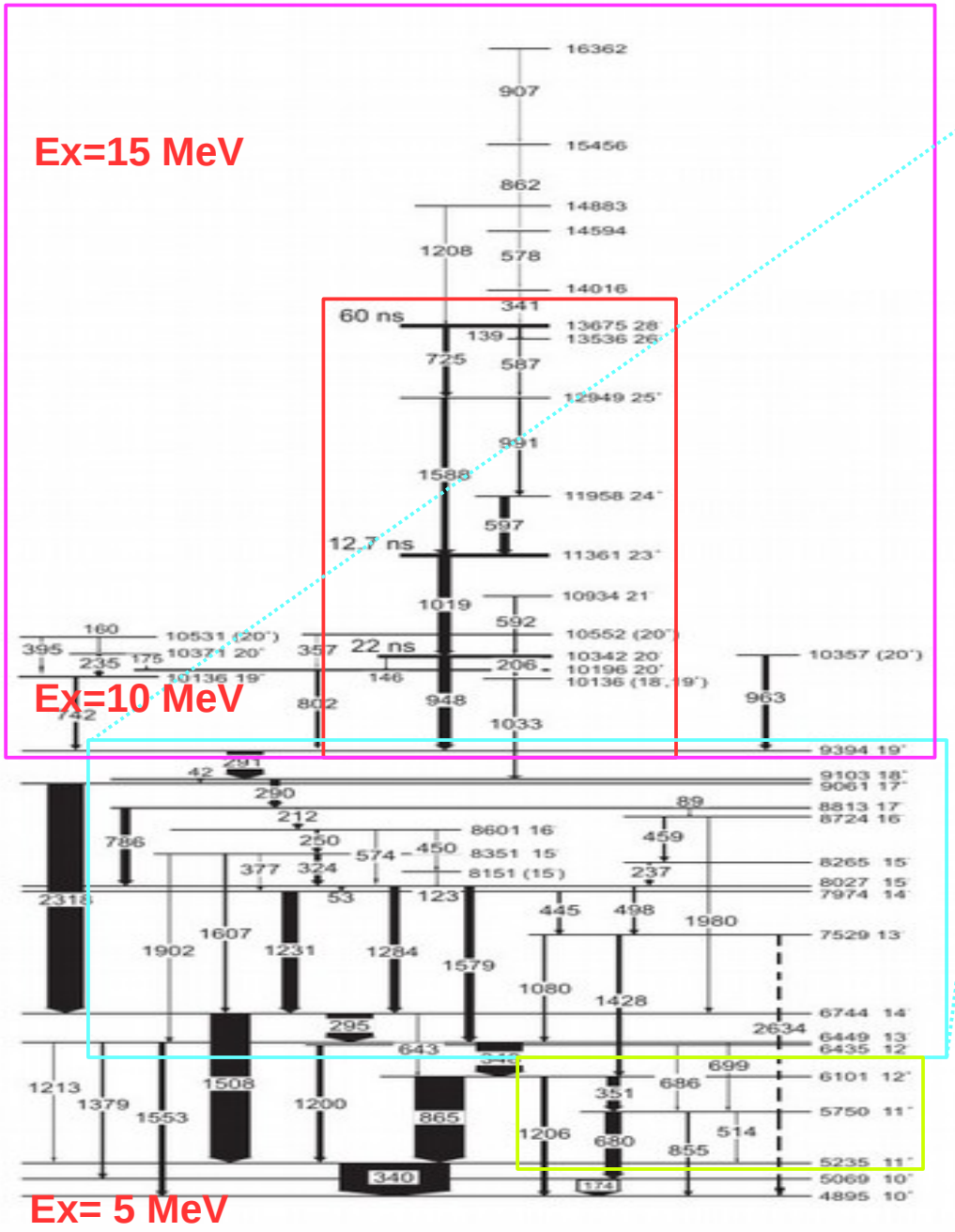
High spin states in 208Pb below Ex =10 MeV

Ex=15 MeV

Ex=10 MeV

Ex= 5 MeV



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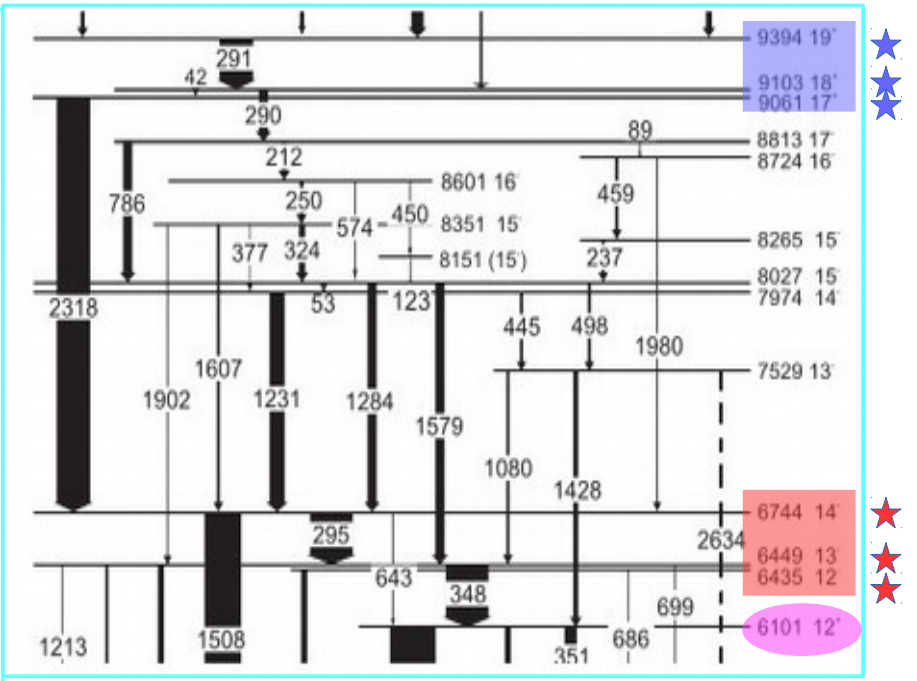

coupling of the
j15/2 i13/2
12-, 13-, 14- states
to the 3- yrast state

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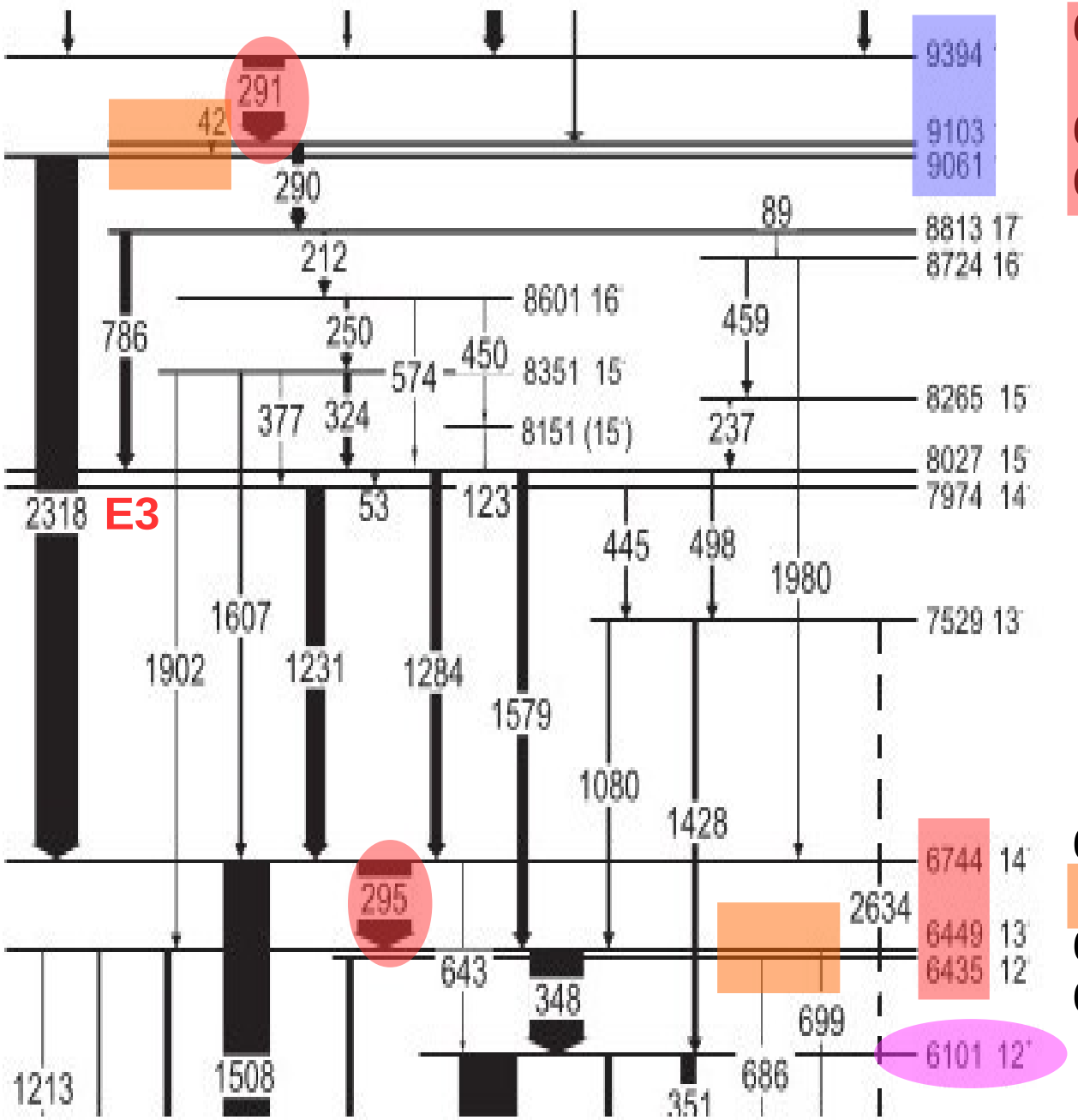
High spin states below Ex =10 MeV



6744+2615–9394 = -35 **17+**

42

6449+2615–9103 = -39 **16+**

6435+2615–9061 = -11 **15+**

3- *(x)* ***j15/2 i13/2***

coupling of the
j15/2 i13/2
12-, 13-, 14- states
to the 3- yrast state

6744 ***j15/2 i13/2*** **14-**

14

6449 ***j15/2 i13/2*** **13-**

6435 ***j15/2 i13/2*** **12-**

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The weak coupling model in 208Pb [2]

In the weak coupling model the hamiltonian $\mathcal{H}^{WCM}$ has four constituents derived from the 3^-_1, 6^+_1, 12^+_2, and the 1p1h states,

$$(1)\quad \mathcal{H}^{WCM} = \mathcal{H}^{3^-_1} + \mathcal{H}^{6^+_1} + \mathcal{H}^{12^+_2} + \mathcal{H}^{p-h} + \mathcal{H}^{residual}$$

$$\mathcal{H}^{residual} \approx 0$$

The sum of the excitation energies of the constituents defines the energy E_x^{WCM}, the sum of the spins the spin I^{WCM}, the product of the parities the parity π^{WCM}

$$(2)\quad E_x^{WCM} = E_x^{3^-_1} + E_x^{6^-_1} + E_x^{12^-_2} + E_x^{p-h}$$
$$(3)\quad I^{WCM} = I^{3^-_1} + I^{6^-_1} + I^{12^-_2} + I^{p-h}$$
$$(4)\quad \pi^{WCM} = \pi^{3^-_1} \times \pi^{6^-_1} \times \pi^{12^-_2} \times \pi^{p-h}$$

[2] A. de-Shalit, Phys. Rev. **122**, 1530 (1961)

Weak coupling (WCM) in 208Pb

The weak coupling model [2] has four constituents

– **1** – 1p1h shell model configurations $LJ^{+1} + LJ^{-1}; I^{\pi}_{M}$ with spin I, parity π, and order number M
– **2** – the 3^{-}_{1} and 4^{+}_{1} states considered as tetrahedral configurations [5]
– **3** – the 6^{+}_{1} state recognized as non-1p1h configuration [6]
– **4** – the 12^{+}_{2} state recognized as non-1p1h configuration [6]

The 1p1h configurations with spin $|J^{+1} - J^{-1}| \leq I \leq J^{+1} + J^{-1}$ are assumed to have low order numbers, **(A)** $M \leq 2$,
and to be (nearly) stretched, **(B)** $I = J^{+1} + J^{-1} - x, \quad x = 0(1, \cdots)$.

The assumption of a negligible residual interaction restricts the range of the deviation of the excitation energies from the WCM energies to
(C) $-100 \lesssim E_x^{WCM} - E_x^{exp} \lesssim +100$ [keV].
Namely, for 1p1h configurations the mean deviation of all experimental energies of 1p1h states from shell model calculations is about 30 keV [6].

[5] A. Heusler, EPJ A **53**, 215 (2017)
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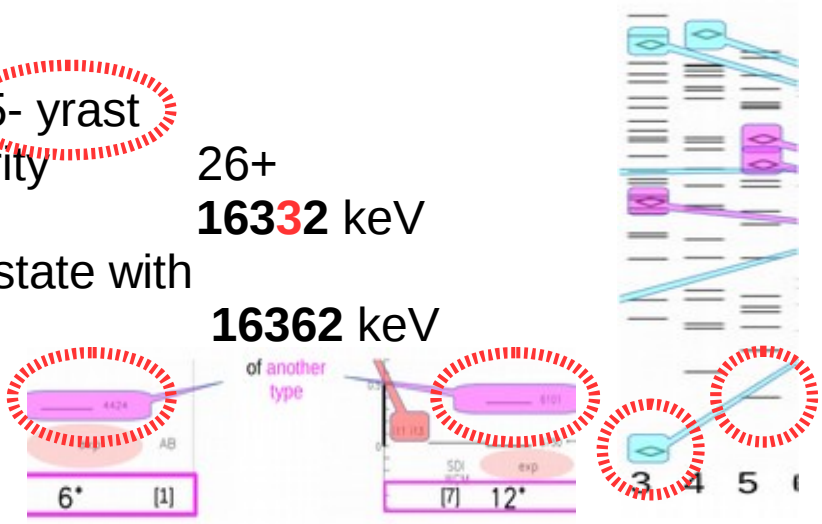
Example:

3- yrast (x) 6+ yrast (x) 12+ yrare (x) 5- yrast
yields spin/parity 26+
Ex = 2615 + 4424 +6101 + 5292 **16332** keV
explaining the state with
Ex = **16362** keV



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Starting from one state with spin I^i and parity π^i the measured $BE(\lambda)$ value leads to possible spin and parity assignments I^f and π^f in a higher excited state

$$(\alpha) \quad |I^i - \lambda| \leq I^f \leq I^i + \lambda, \qquad \text{with } 2\lambda + 1 \text{ choices}$$
$$(\beta) \quad \pi^f = \pi^i \times (-1)^{\lambda}$$

For each possible spin/parity the number of WCM configurations in the intervall $-100 \lesssim E_x^{WCM} - E_x^{exp} \lesssim +100$ [keV] [Eq. (C)] is calculated.

Often there is no WCM configuration at all or the WCM configuration does not have a low order number $M \leq 2$ [Eq. (A)]
or is not (nearly) stretched $I = J^{+1} + J^{-1}\ (-1)$ [Eq. (B)]

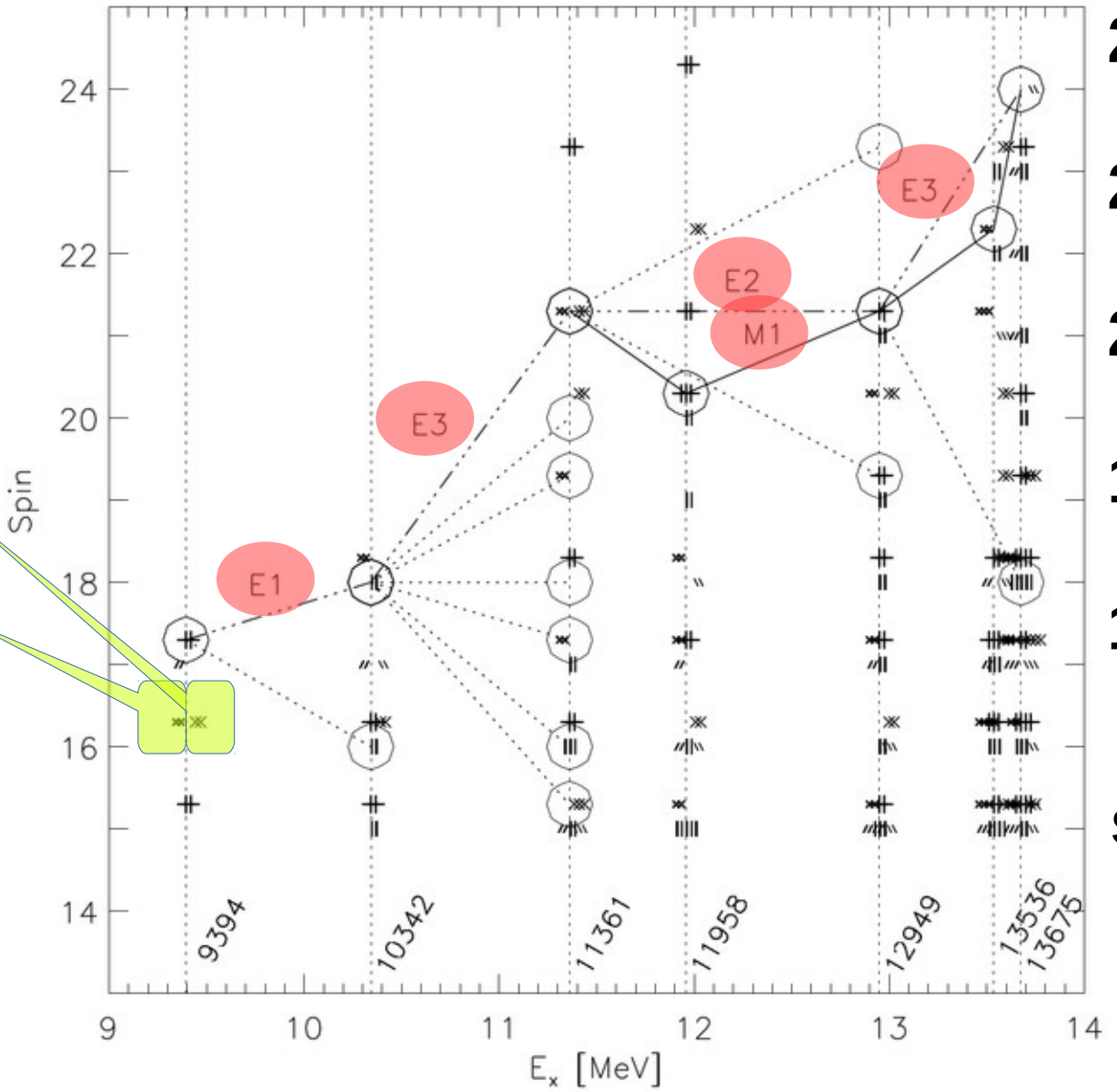
States in 208Pb predicted by the weak coupling model (WCM)

number of WCM configurations around Ex(exp)

+Ex(WCM) - Ex(exp) < 100 keV

-Ex(WCM) + Ex(exp) < 100 keV

there are ~2000 WCM configurations with spin *I* I≥ 15 at 9 < Ex < 14 MeV



24+ 24-

22+ 22-

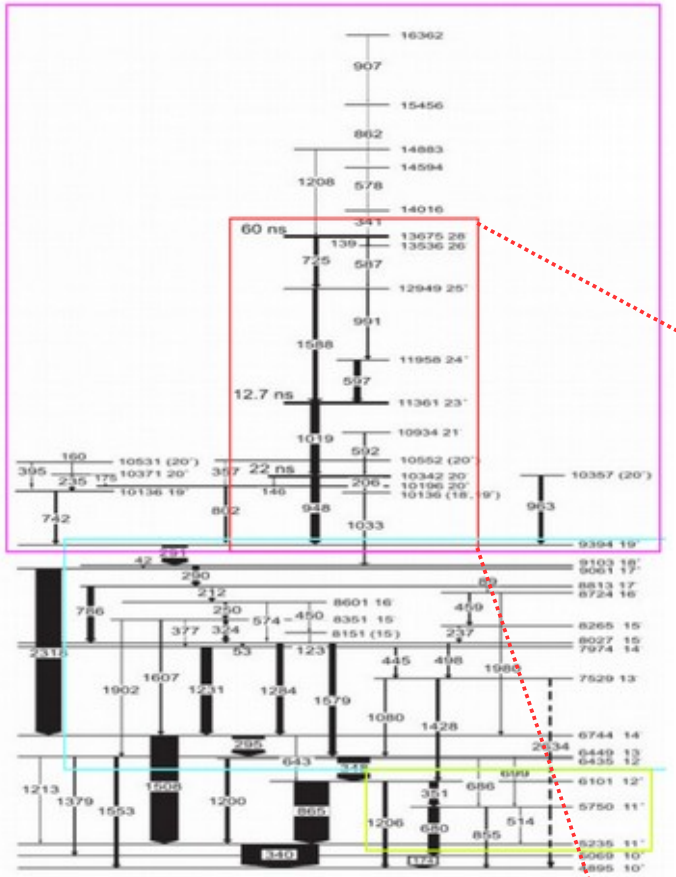
20+ 20-

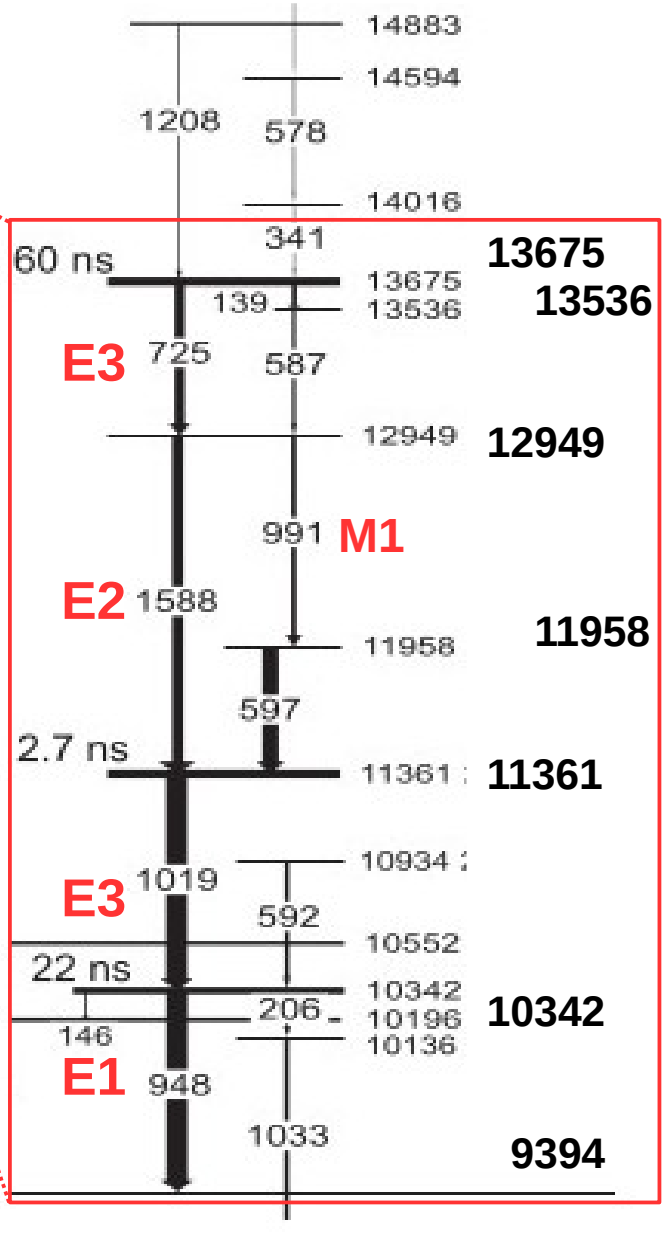
18+ 18-

16+ 16-

spin/parity

States in 208Pb described by the WCM at 9 < Ex < 14 MeV





24- **g9/2 i13/2; 9+** *yrast (stretched)*
(x) **3-** (x) **12+**

22+ **j15/2 i13/2;13-** *yrast stretched*
(x) **3-** (x) **6+**

21+ **i11/2 p1/2; 6-** *yrast stretched*
(x) **3-** (x) **12+**

20+ **g9/2 p1/2; 5-** *yrast stretched*
(x) **3-** (x) **12+**

21+ **h9/2 h11/2; 9+** *yrast (stretched)*
(x) **12+**

18- **i11/2 p1/2; 6-** *yrast stretched*
(x) **12+**

17+ **j15/2 i13/2;14-** *yrast stretched*
(x) **3-**

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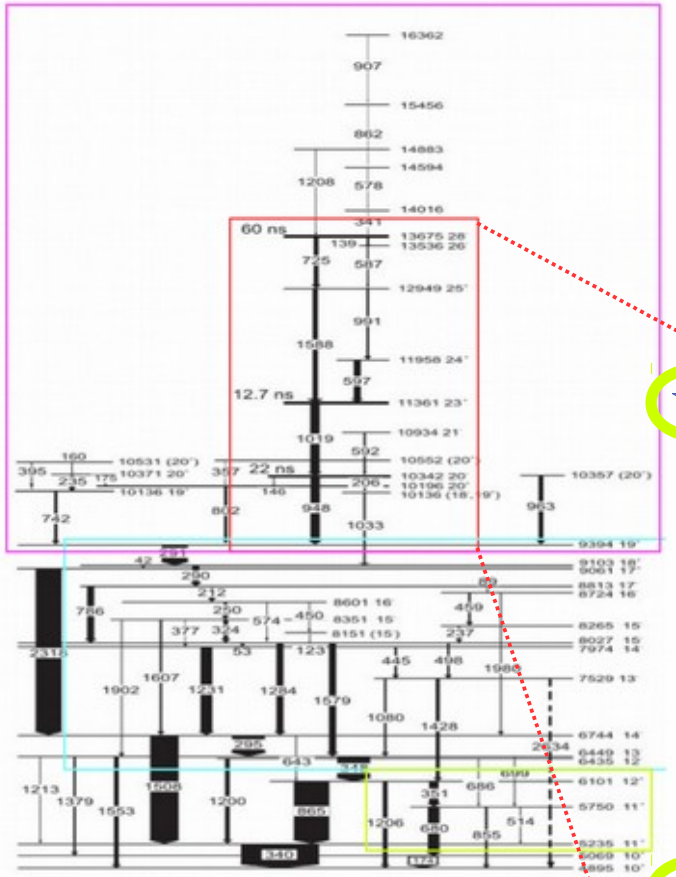
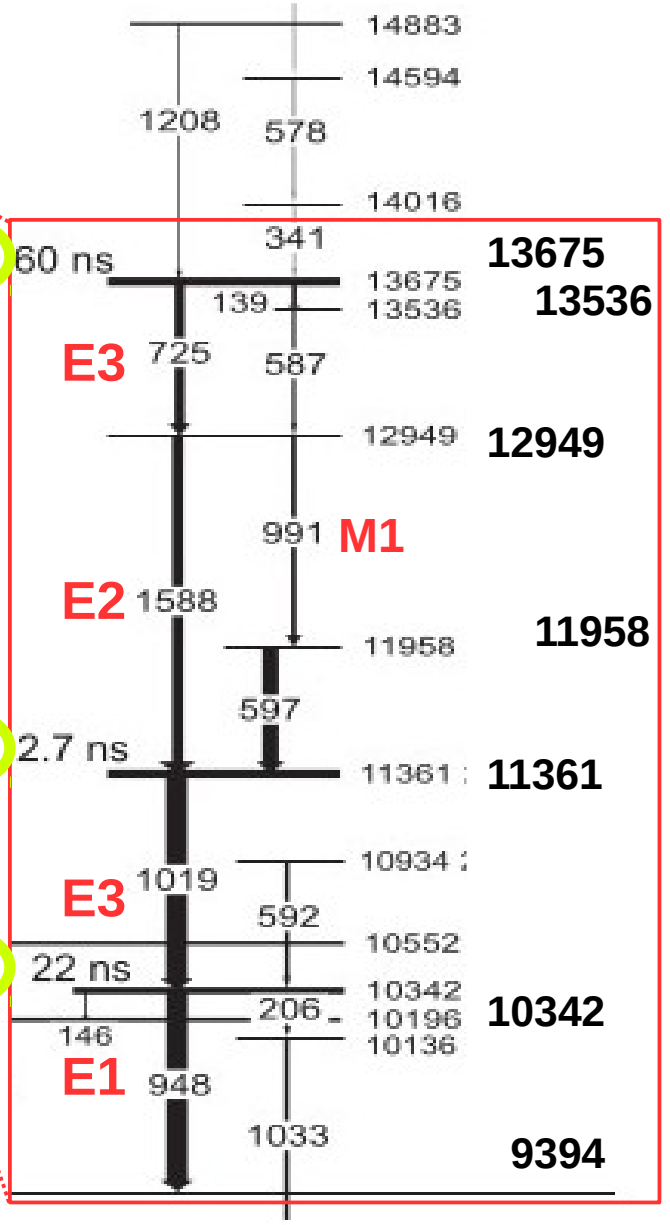
States in 208Pb described by the WCM at 9 < Ex < 14 MeV





ns-isomers

24- **g9/2 i13/2; 9+** *yrast (stretched)*
(x) **3-** (x) **12+**

22+ **j15/2 i13/2;13-** *yrast stretched*
(x) **3-** (x) **6+**

21+ **i11/2 p1/2; 6-** *yrast stretched*
(x) **3-** (x) **12+**

20+ **g9/2 p1/2; 5-** *yrast stretched*
(x) **3-** (x) **12+**

21+ **h9/2 h11/2; 9+** *yrast (stretched)*
(x) **12+**

18- **i11/2 p1/2; 6-** *yrast stretched*
(x) **12+**

17+ **j15/2 i13/2;14-** *yrast stretched*
(x) **3-**

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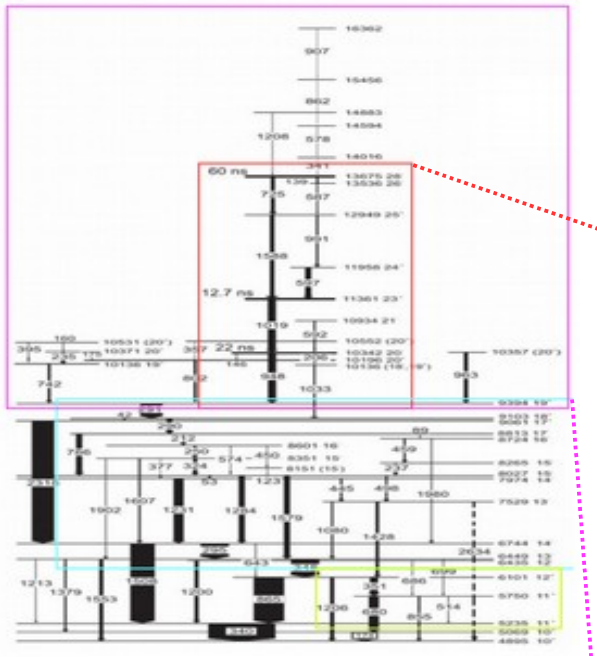
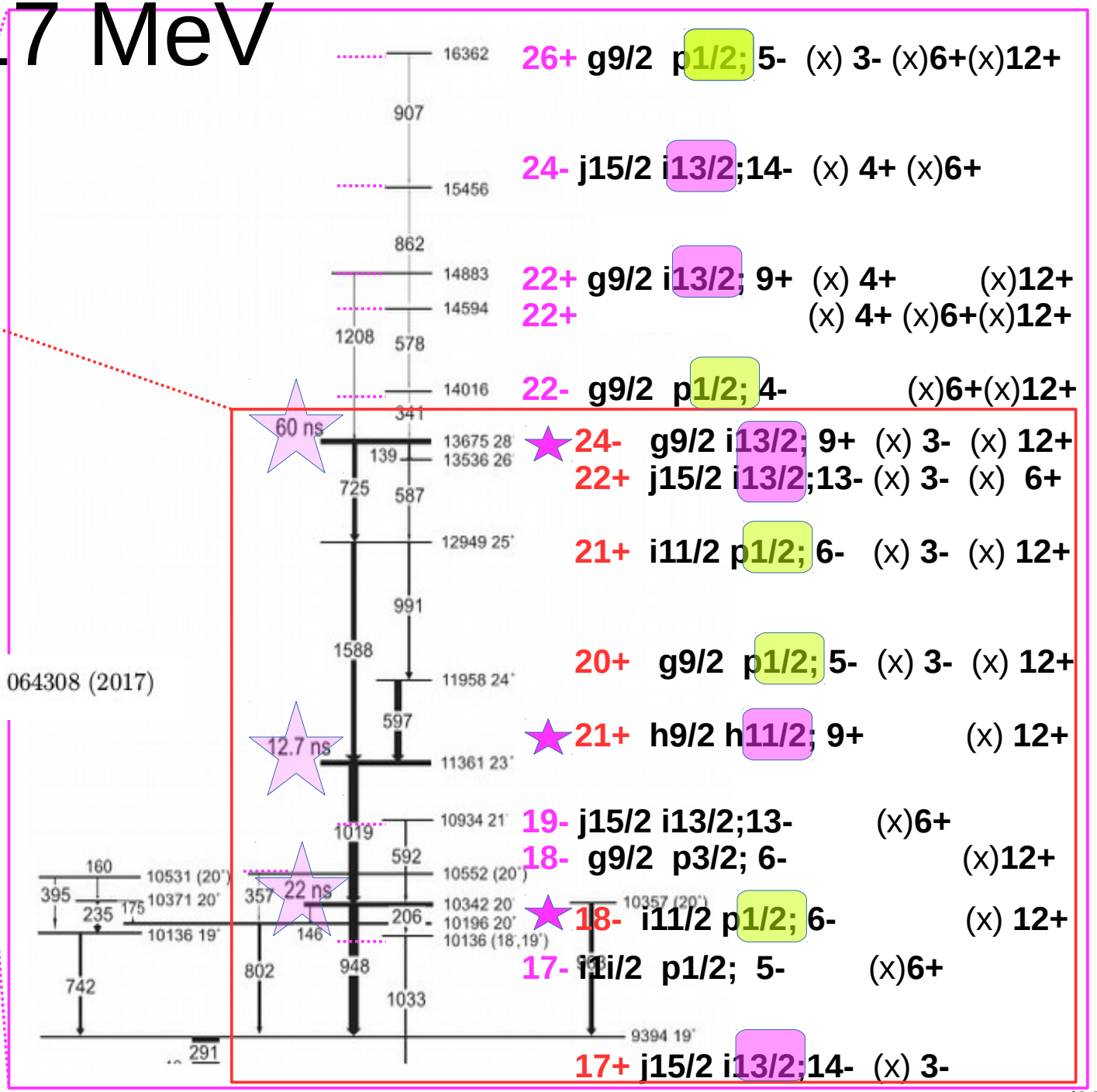
States in 208Pb described by the WCM at 9 < Ex < 17 MeV



from [1] R. Broda et al., Phys. Rev. C **95**, 064308 (2017)



A weak coupling model (WCM) describes states in 208Pb at 9 < Ex < 17 MeV with spins from 17+- to 26+-

The **model** assumes the **coupling** of
yrast or yrare and (*nearly*) *stretched* 1p1h states
with the 3- yrast or 4+ yrast states
and with the 6+ yrast state
and with the 12+ yrare state
with **weak** residual interaction
| Ex(exp) – Ex(WCM) | < 100 keV

median deviation
for 24 states

Ex(exp) – Ex(WCM) = + 35 +- 30 keV

three ns-isomers are explained by the exchange
of a high spin hole *[i13/2, h11/2]* with the *p1/2* hole