Connecting high-K and low-K isomers in Ta-180 and Lu-176 (Production and destruction in stars)

Laboratory Photoexcitation with Bremsstrahlung

Activation "resonances" and individual states in Ta-180
Search for Predicted "back-decays"

Production/destruction status

Possible gateway states in Lu-176:

- the 835 keV 5^- state properties
- Chance mixing in 7^- states: interactions
- The 4^- band : Isomers in Deep Inelastic reactions

Rate implications...

Are we there yet?

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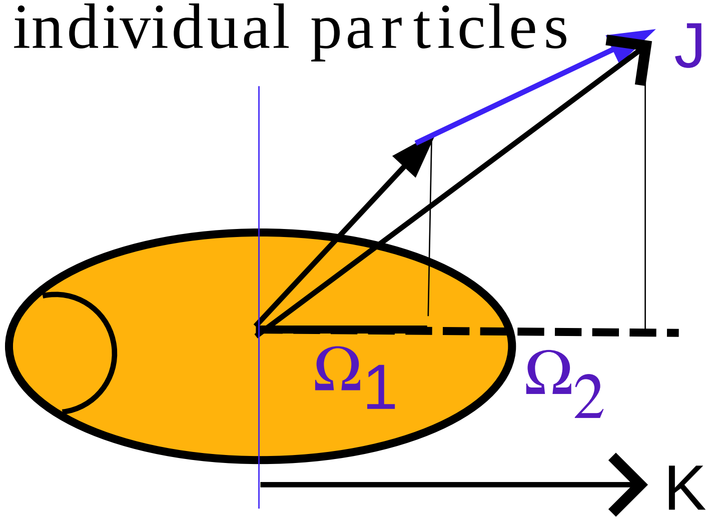
odd-proton odd-neutron coupling

$$\Omega_\nu + \Omega_\pi = K_> \qquad E_o \mp V_{res.}$$

$$\Omega_\nu - \Omega_\pi = K_< \qquad E_o \pm V_{res.}$$

low-lying high-J/low-J doublets

sum projections of individual particles



preferred axis

$K = \Omega_1 + \Omega_2$

connecting transitions very high multipolarity

decays "out" (γ and β) often K-forbidden

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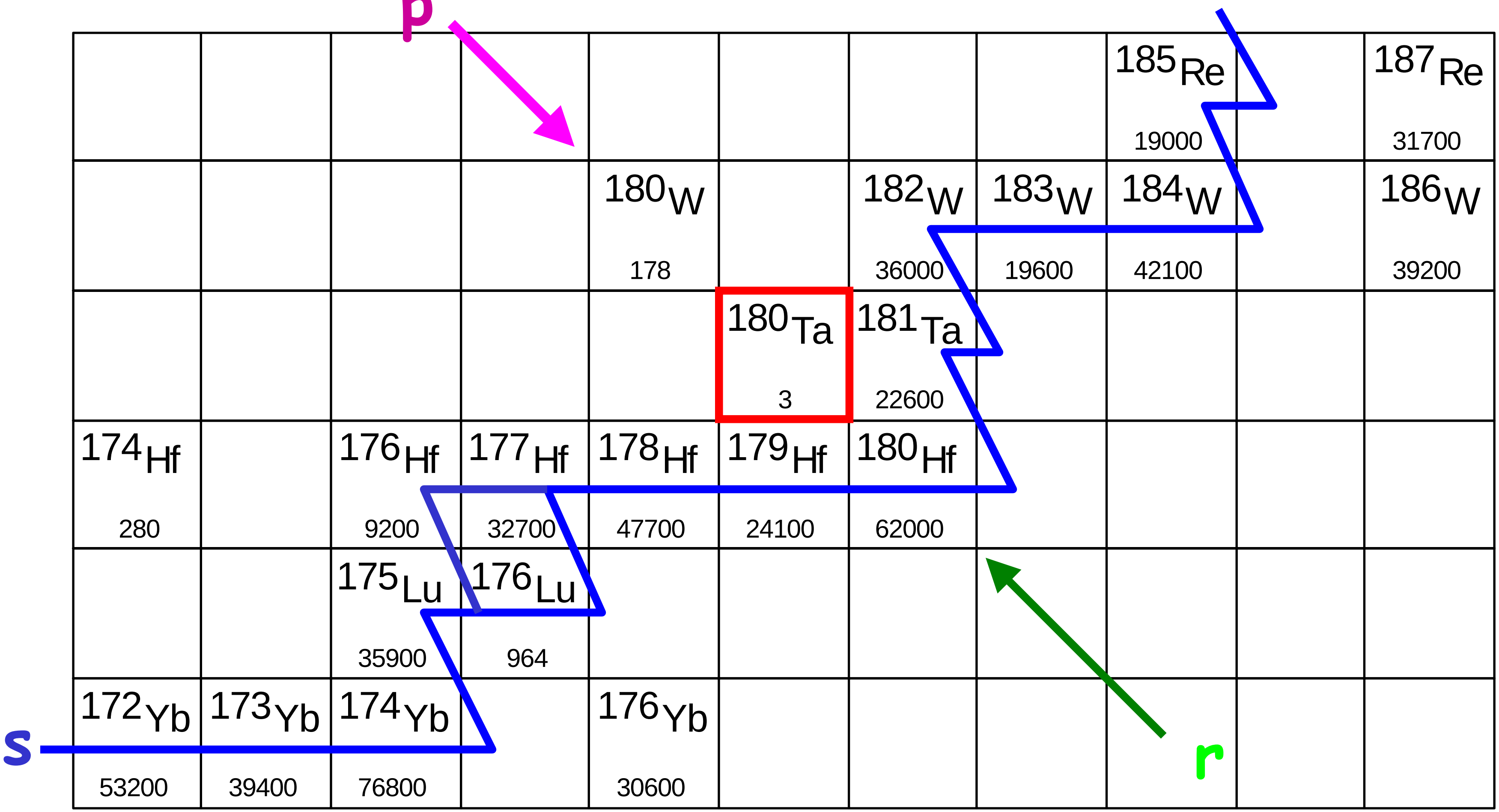
.Ta180] odd-odd-coupling

The heaviest natural odd-odd nuclei

^{180}Ta

^{176}Lu

^{180}Ta production

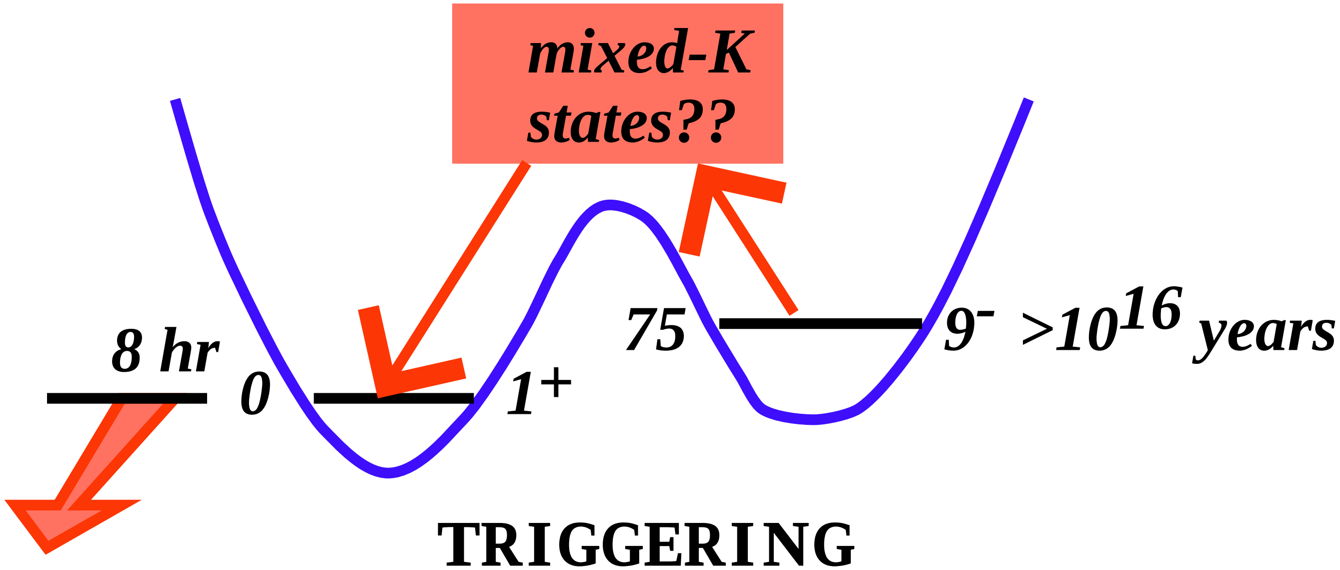


Shielded from the r-, s- and p- processes

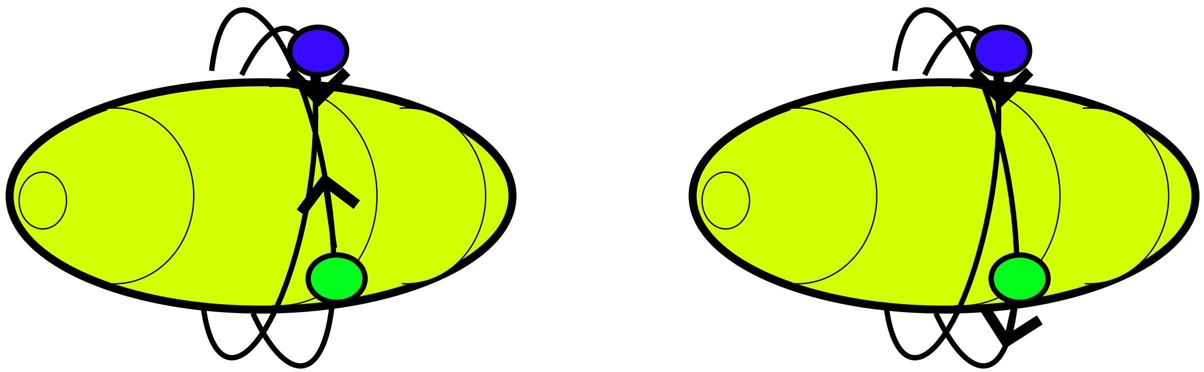
Ta: the least abundant element
^{180}Ta: the least abundant isotope
the only naturally occurring isomer

Si:	10^{12}
Ta:	22600
^{180}Ta:	3

$^{180}_{73}Ta_{107}$



TRIGGERING



$\Omega\pi - \Omega\nu = 1+$
$7/2^{+}[404]x9/2^{+}[624]$

$\Omega\pi + \Omega\nu = 9-$
$9/2^{-}[514]x9/2^{+}[624]$

PRODUCTION ?
shielded from most processes

explosive nucleosynthesis?
neutrino spallation?
fingerprint of type-II SN?

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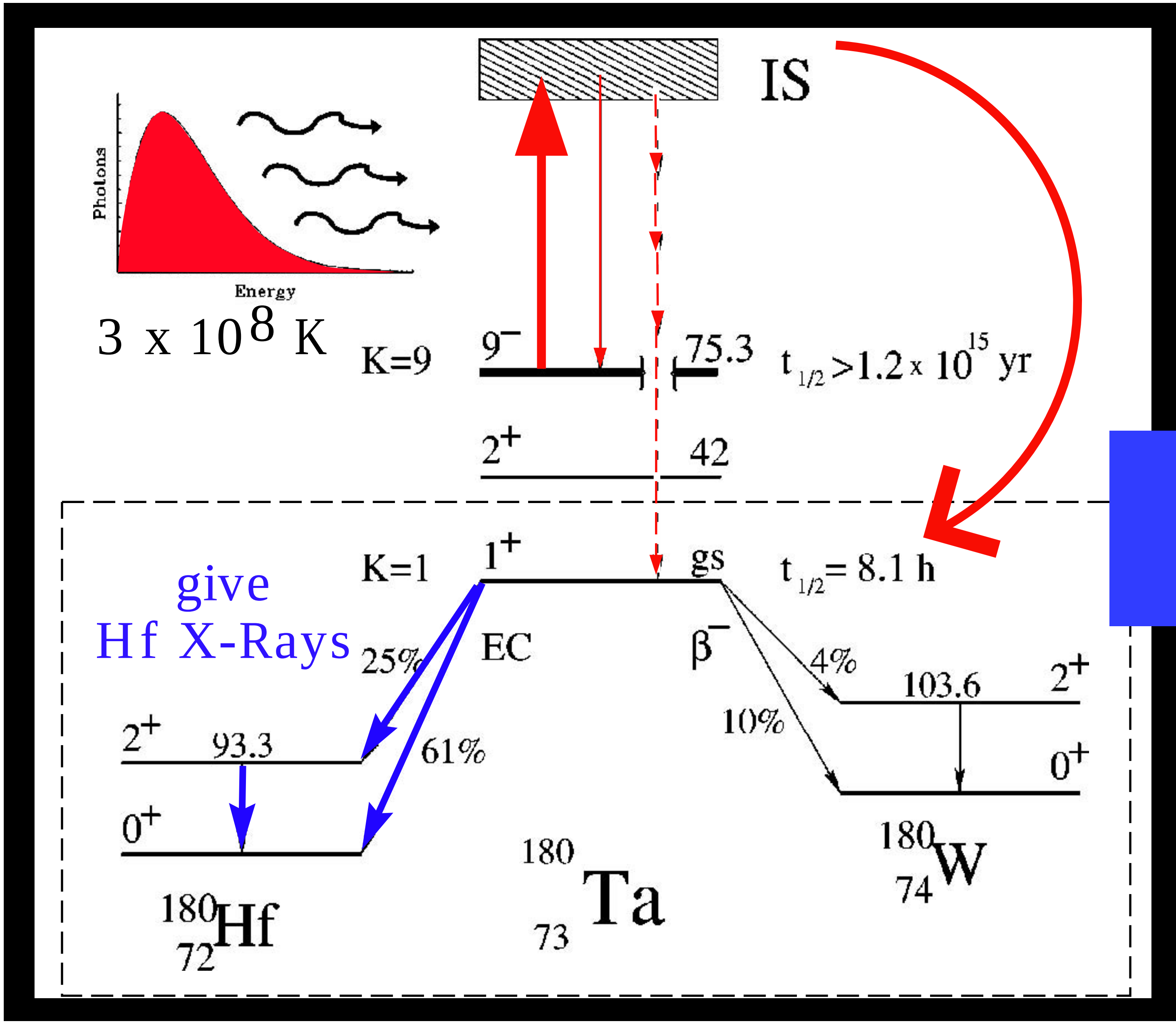
DESTROY VIA INTERMEDIATE STATES (IS)



$^{180}_{73}$Ta 107

Convert to Short-lived Decay

Laboratory destruction of the K =9⁻ isomer

Coulomb excitation:

C. Schlegel et al, Phys. Rev. C 50 (1994) 2198.
M. Schumann et al, Phys. Rev. C 58 (1998) 1790.
M. Loewe et al, Acta. Phys. Pol. B 30 (1999) 1319.
C. Schlegel et al, Eur. Phys. J. A 10 (2001) 135.
M. Loewe et al, Phys. Lett. B 551 (2003) 71.

Photoactivation:

J.J. Carroll et al, Astrophys. J. 344 (1989) 454.
C.B. Collins et al, Phys. Rev. C 42 (1990) R1813.
D. Belic et al, Phys. Rev. Lett. 83 (1999) 5242.
I. Bikit et al, Astrophys. J. 522 (1999) 419.
D. Belic et al, Phys. Rev. C 65 (2002) 035801.

LABORATORY MEASUREMENT
RESONANT ACTIVATION

[Booth and Brownson, Nucl Phys A 98, 529,(1967)]
[Berg and Kneissl, Ann Rev Nucl Part Sci 37, 33 (1987)]

Filler-lab-measurement

"LABORATORY EXCITATION WITH BREMSSTRAHLUNG

Flux at E_R increases linearly with endpoint

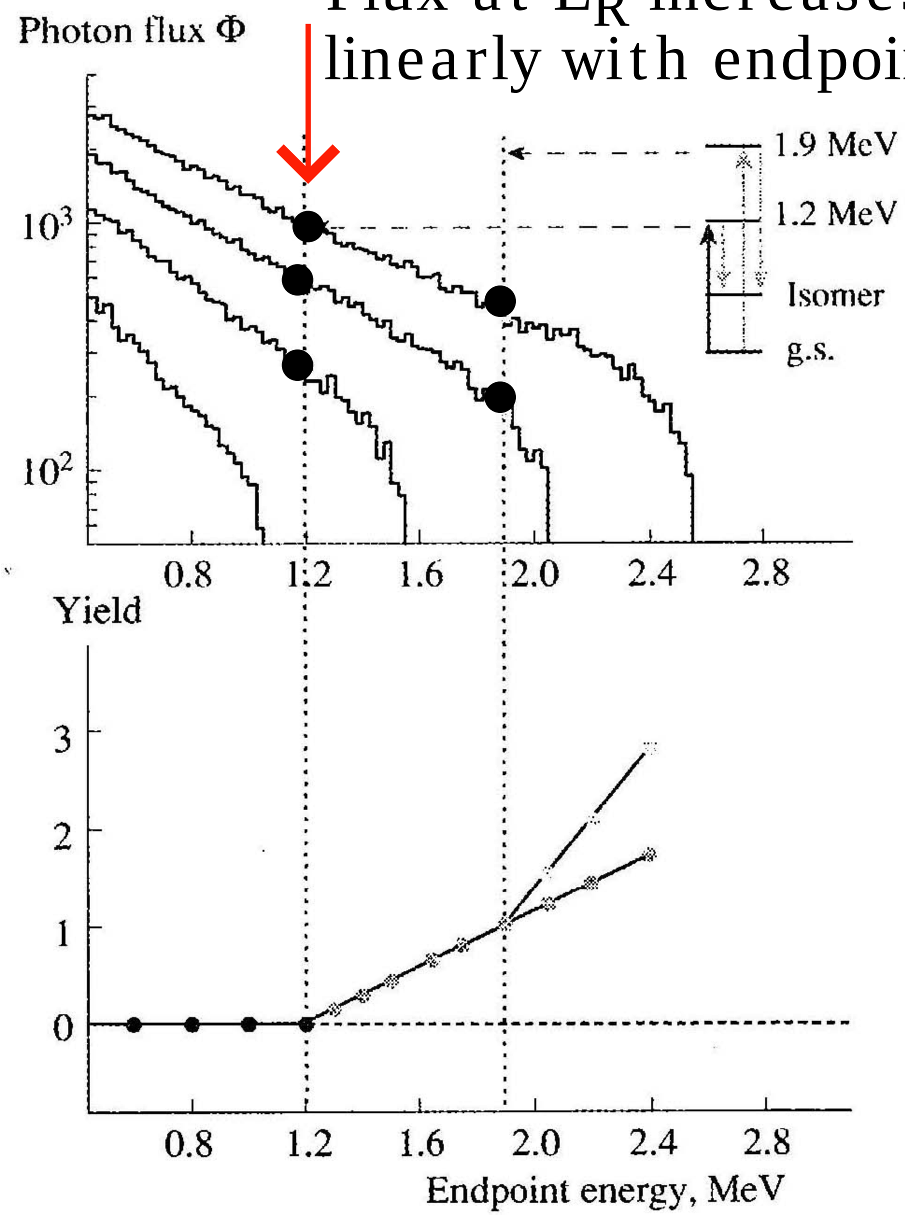
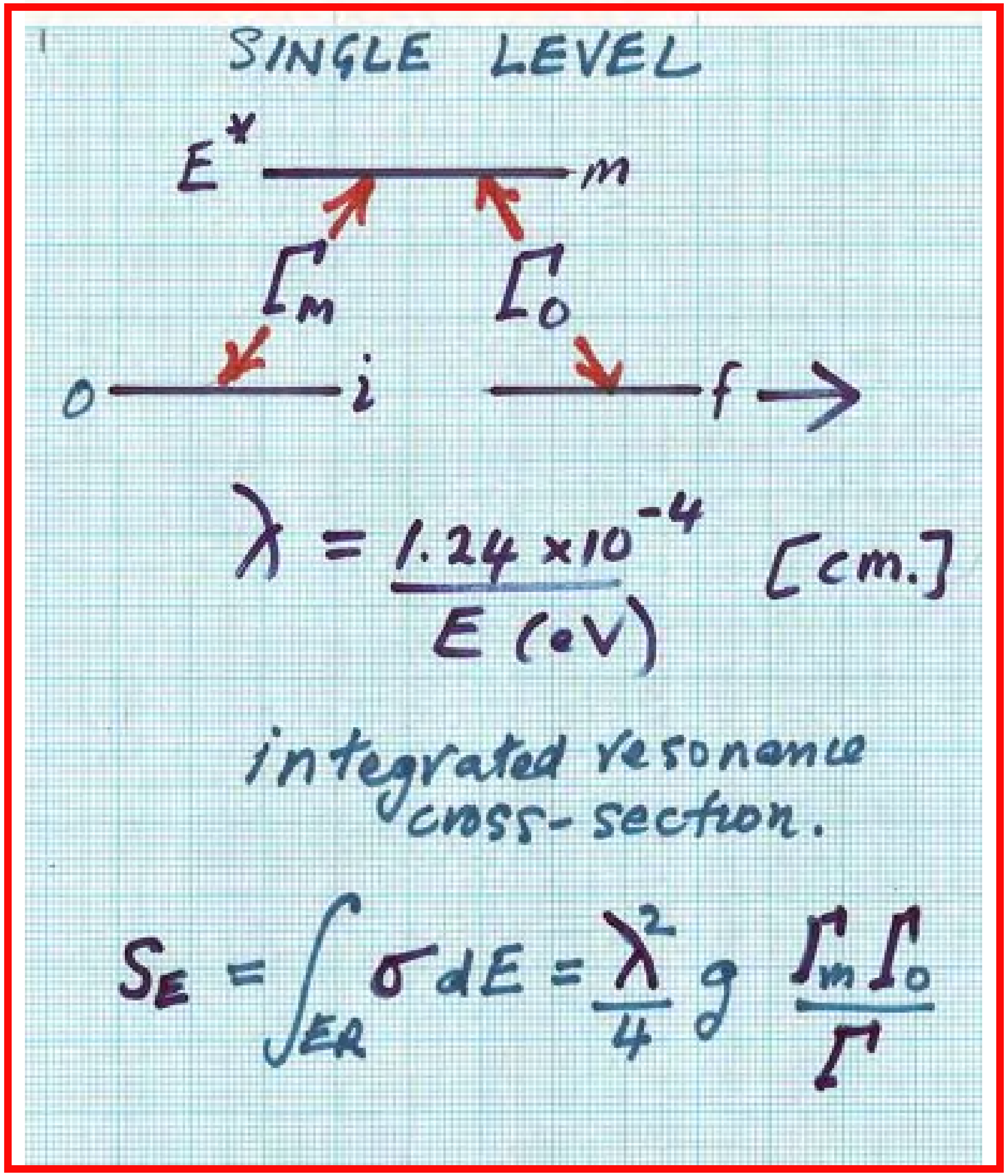


Fig. 4. The principle of photoactivation with bremsstrahlung. The figure depicts the activation of a fictitious nucleus with mediating states at 1.2 and 1.9 MeV.



Belic et al . NIM A 463 (2001) 26

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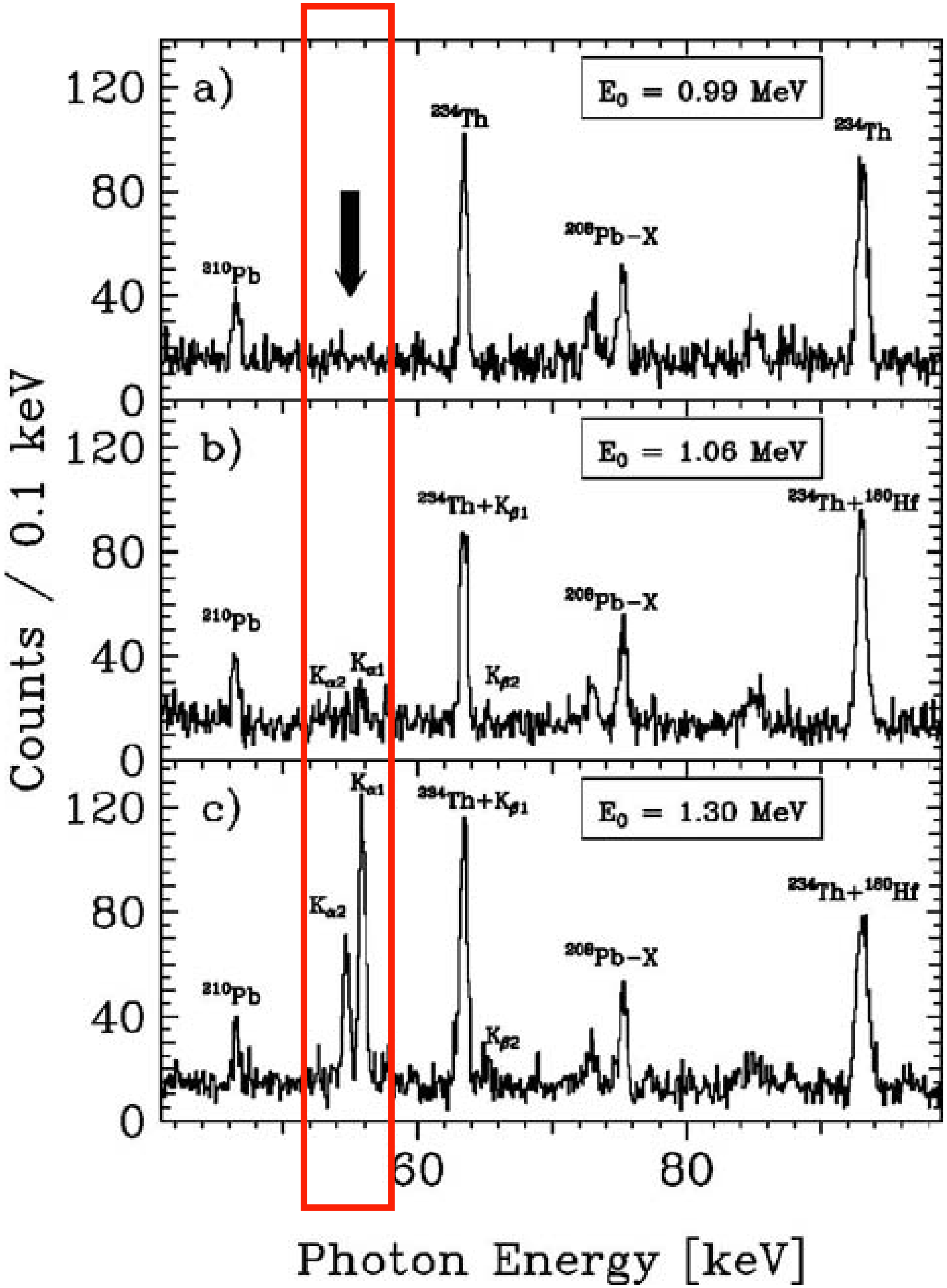
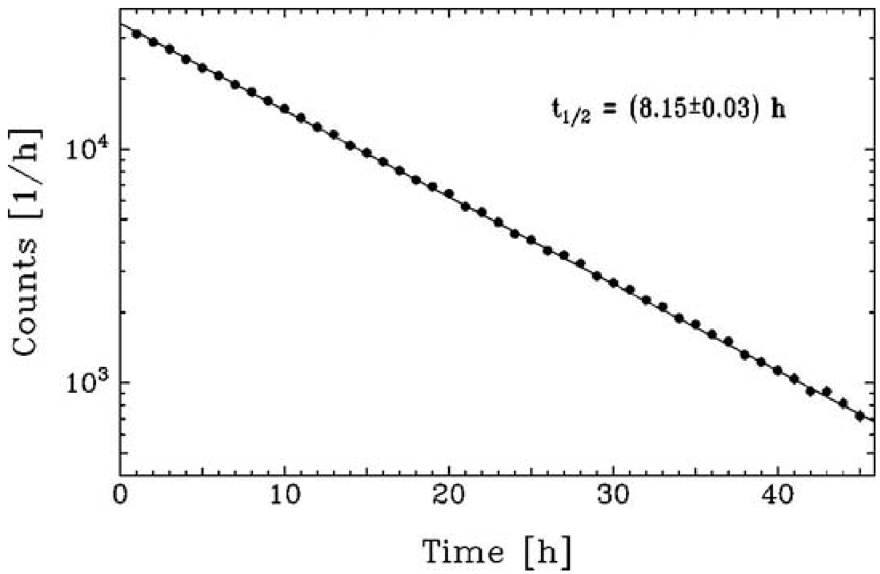
NRF-Bremsstrahlung.md

Activation [Belic et al.]



Clear Hf X-rays



TRIGGERING BY PHOTOEXCITATION IN LABORATORY
A question of survival in stars

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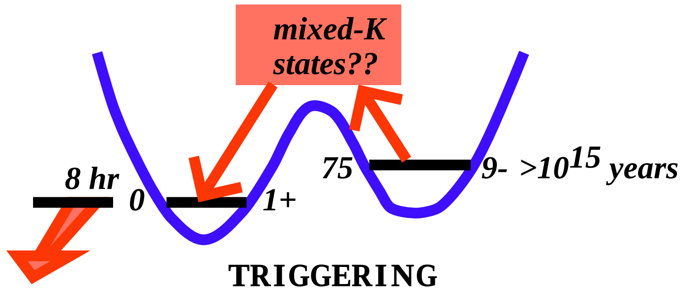
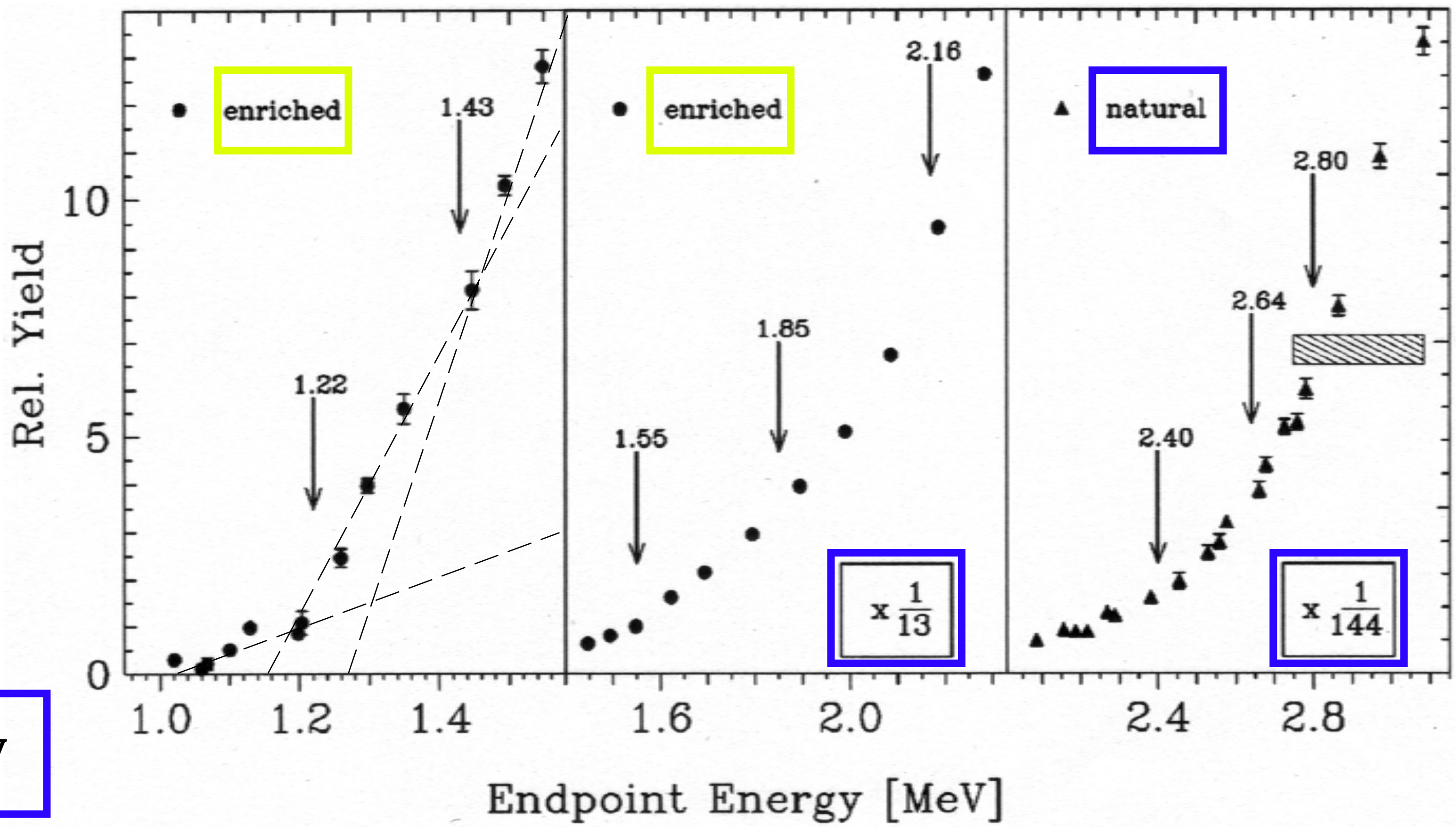
Activation with Bremsstrahlung
Ta180 target enriched to 5.5%(!)
[Stuttgart Dynamitron]



Vary endpoint:

off-line:
measure
Hf X-rays
with
8 hour
half-life



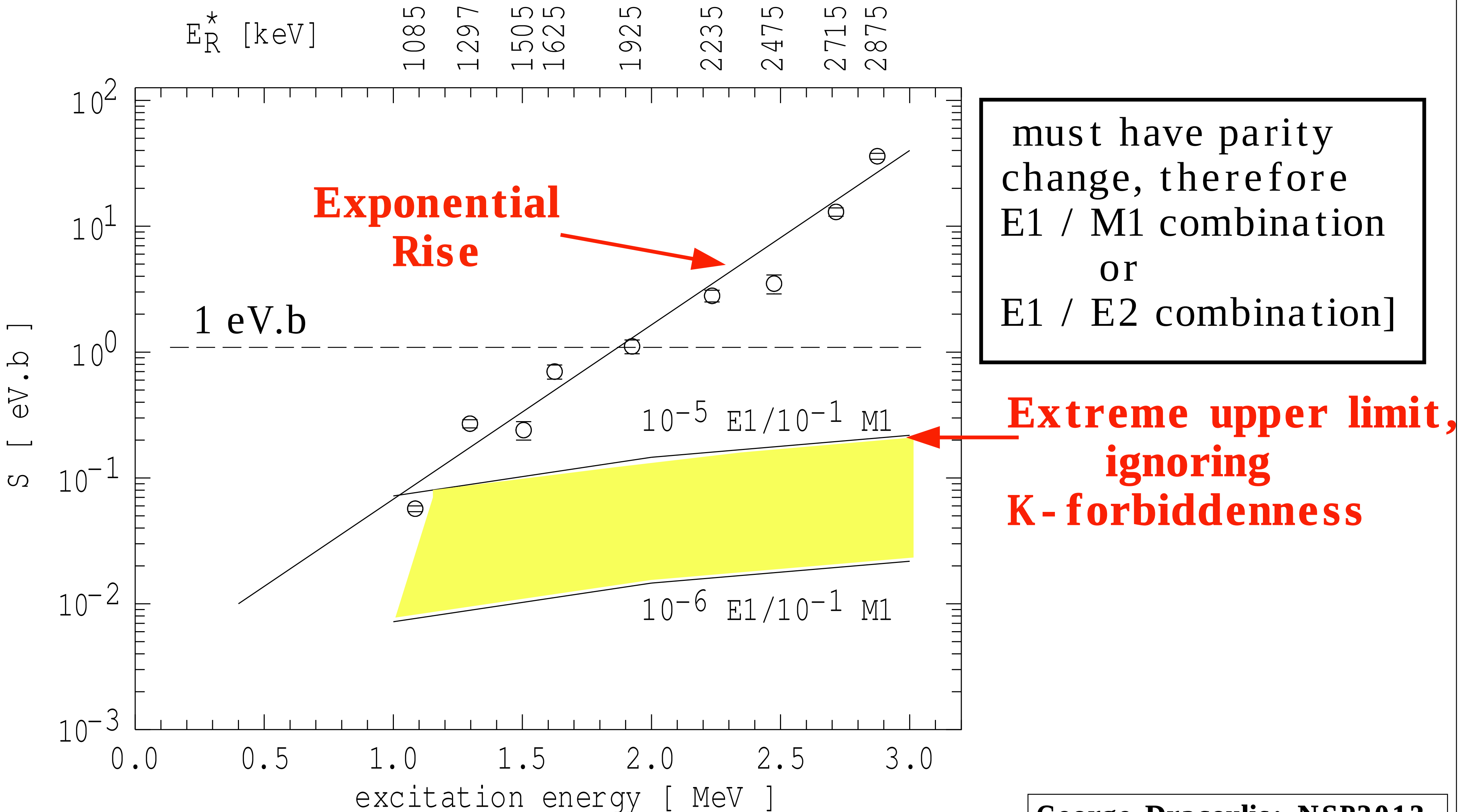
Note Intensity

Ta180-photoexcitation-briefer.md

Belic et al Phys Rev C 65 (2002) 035801 Phys Rev Lett. 83 (1999) 5242

TA-180 - observed resonances are strong

DATA from Belic et al. PRC 65 (2002) 035801



must have parity change, therefore E1 / M1 combination or E1 / E2 combination]

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See Hayakawa, et al., PRC 81, 052801R (2010). for effect of strengths

ta180-sigma-I.md

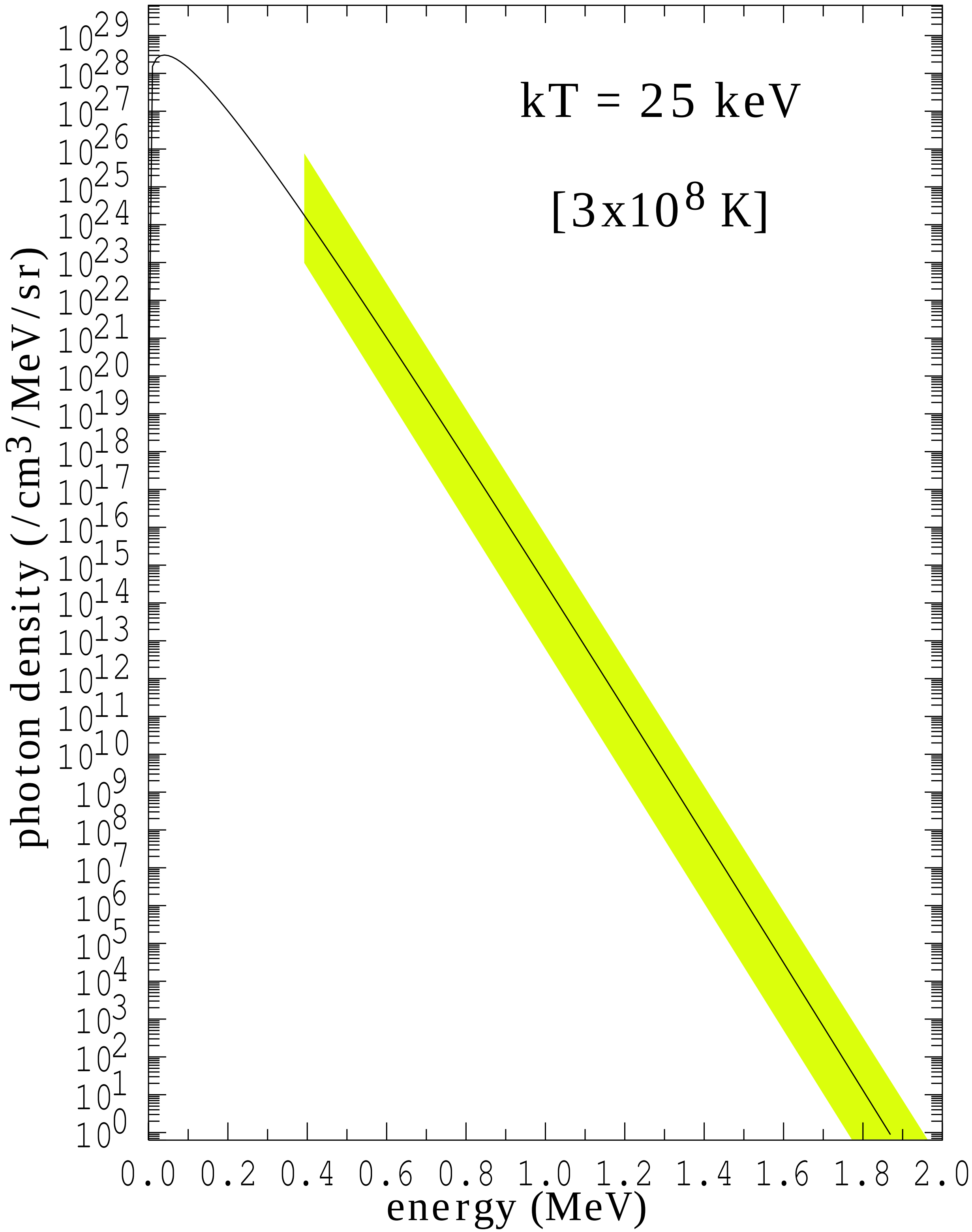
s_E max. (simple case)

1 MeV photon:

s_E (max.) ~ 2000 x Γ_m (eV.b)

s_E = 1 eV.b means $\Gamma_m \sim 5\text{x } 10^{-4}$ eV

E1: $2\text{x}10^{-4}$ W.u.
M1: $2.5 \text{ x } 10^{-2}$ W.u
E2: 10 W.u.
E3: $6\text{x}10^{5}$ W.u.



planck etc.

Stellar ingredients
(equilibrium)

1. Photon flux
2. Maxwellian state population
3. ionisation (reduced internal conversion)

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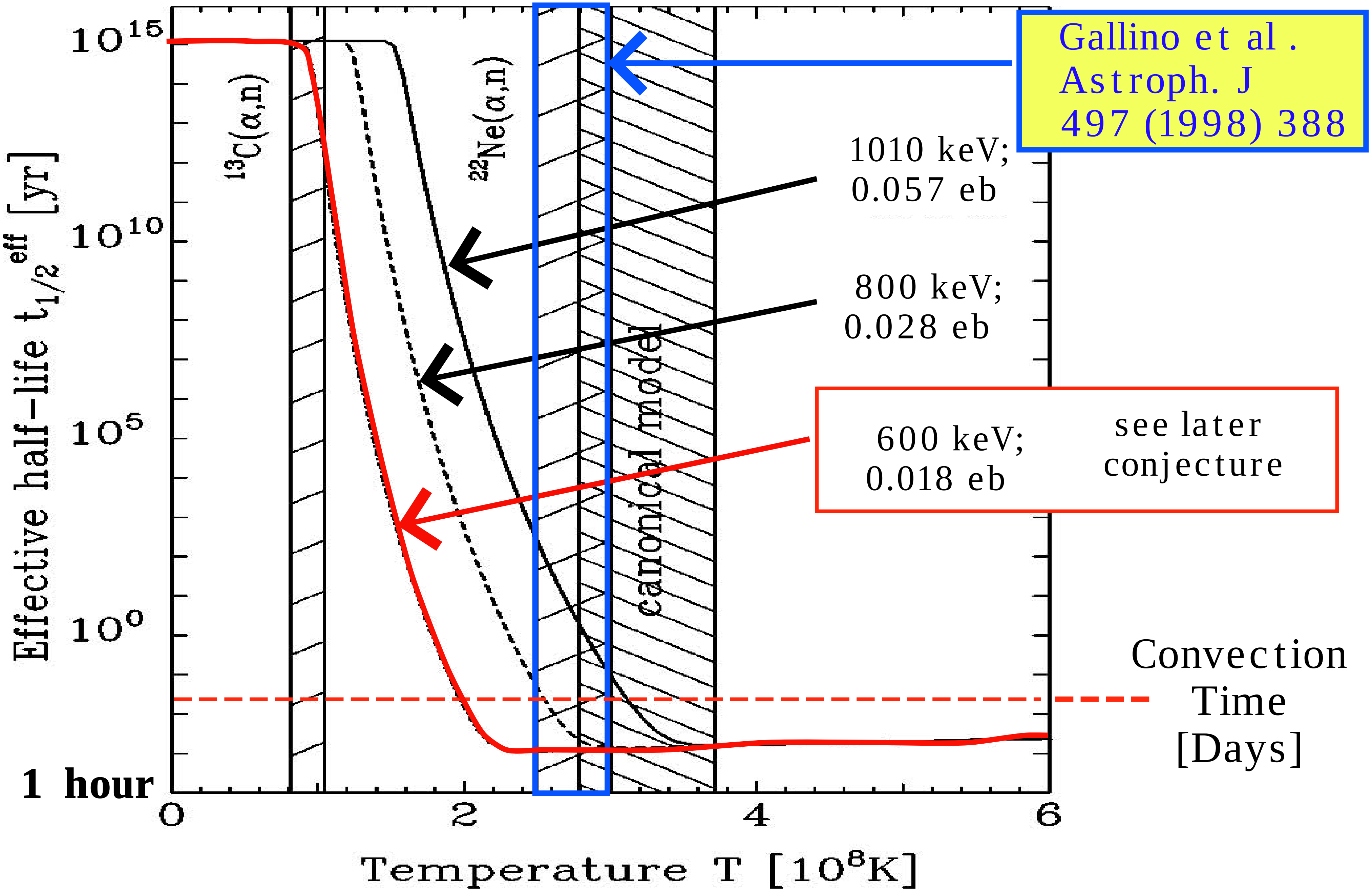
"TA-180 - effective half-life; SINGLE IMS



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Belic et al . PRC 65 (2002) 035801

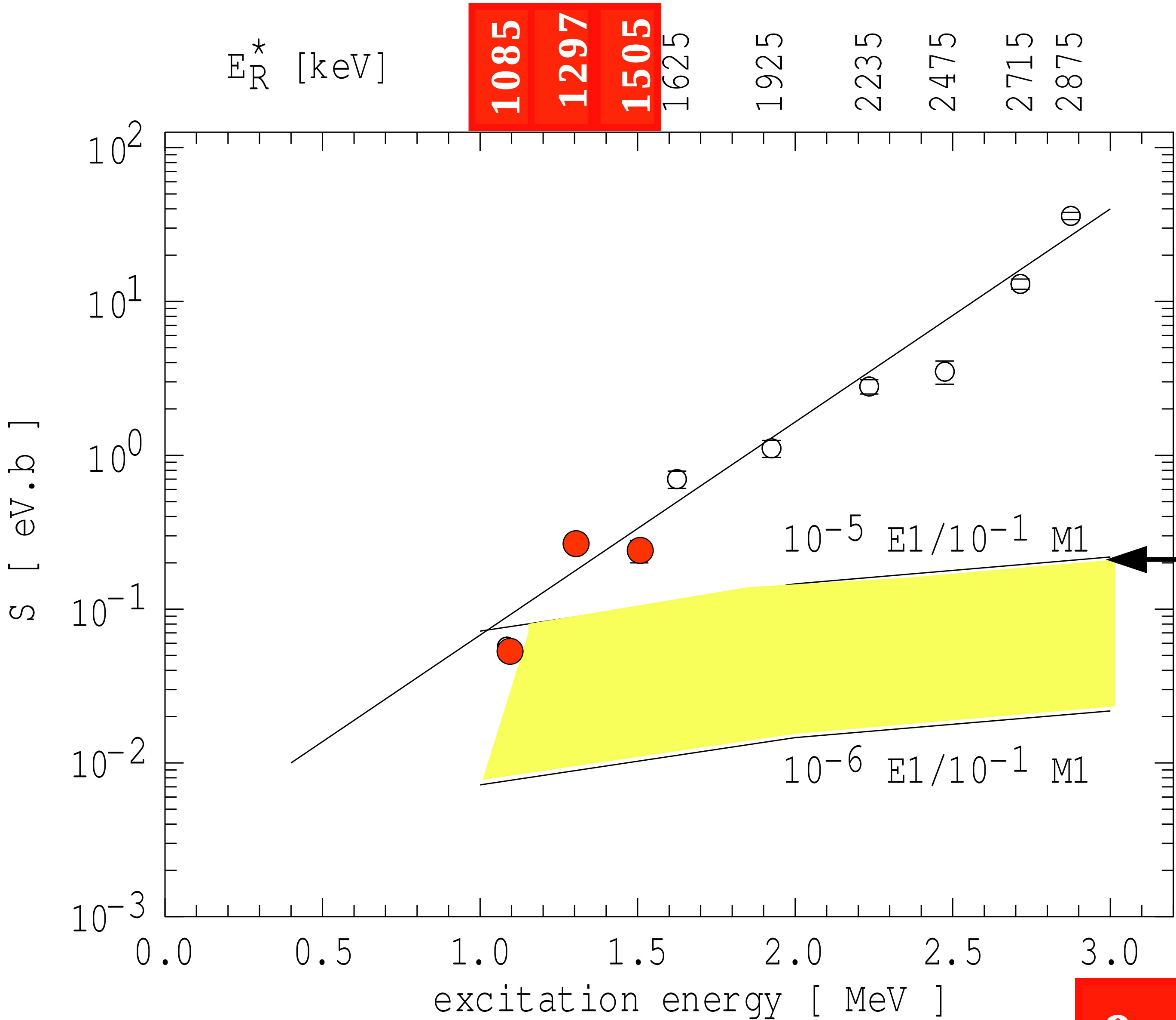
WHAT ARE THE CORRESPONDING STATES ?

CAN THE RESONANCE STRENGTHS BE EXPLAINED??

[NUCLEAR STRUCTURE]

TA-180 - observed resonances are strong

DATA from Belic et al . PRC 65 (2002) 035801



must have parity change, therefore E1 / M1 combination or E1 / E2 combination]

Extreme upper limit, even ignoring K-forbiddenness

9^- (E1) to 8^+, 9^+, 10^+

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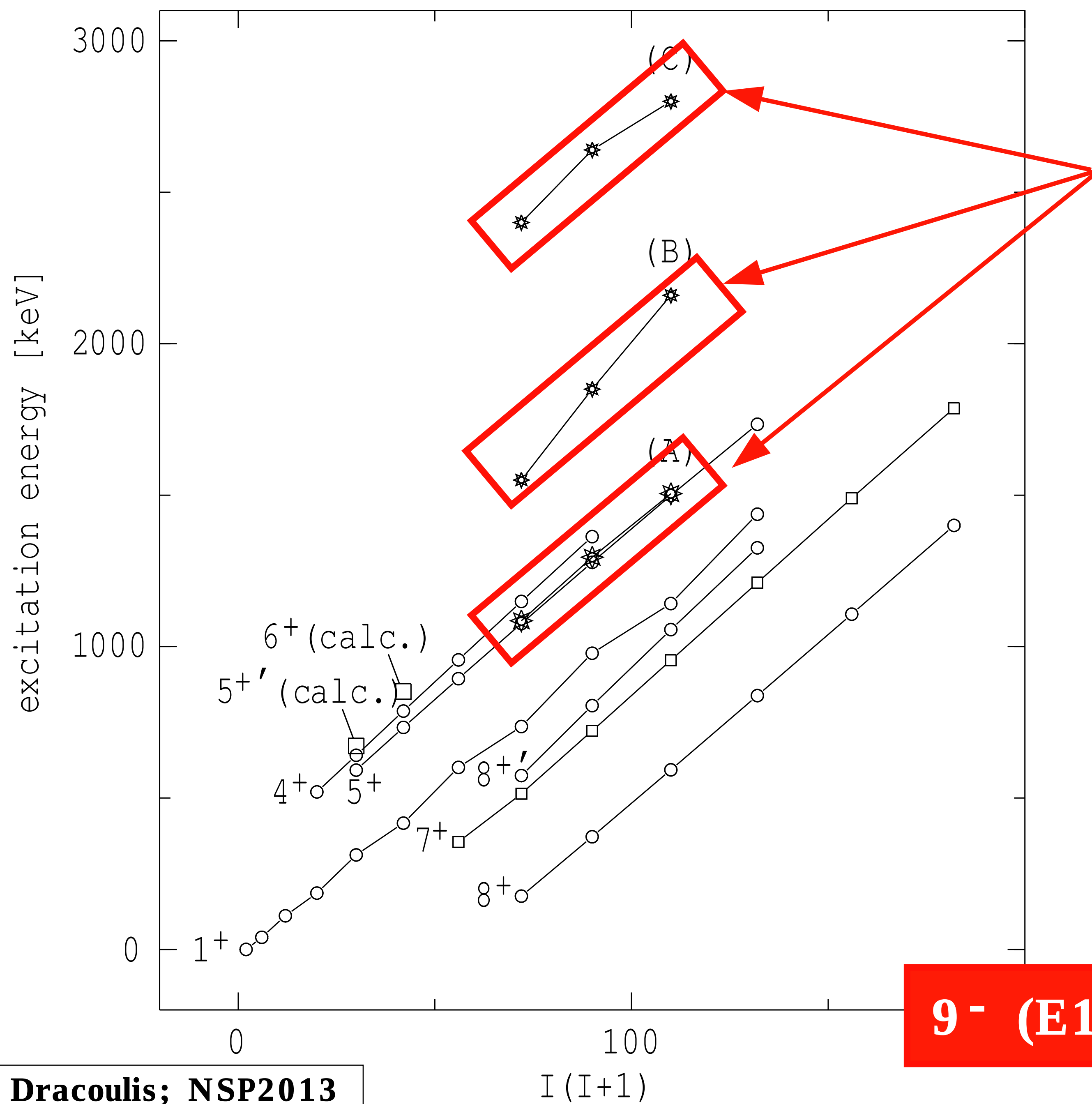
ta180-sigma.md

TA-180 - $8^+, 9^+, 10^+$ groups of three



Sequential groups of three from Belic data

9^- (E1) to 8^+, 9^+, 10^+

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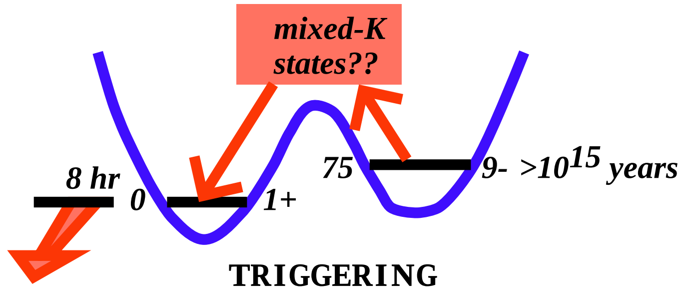
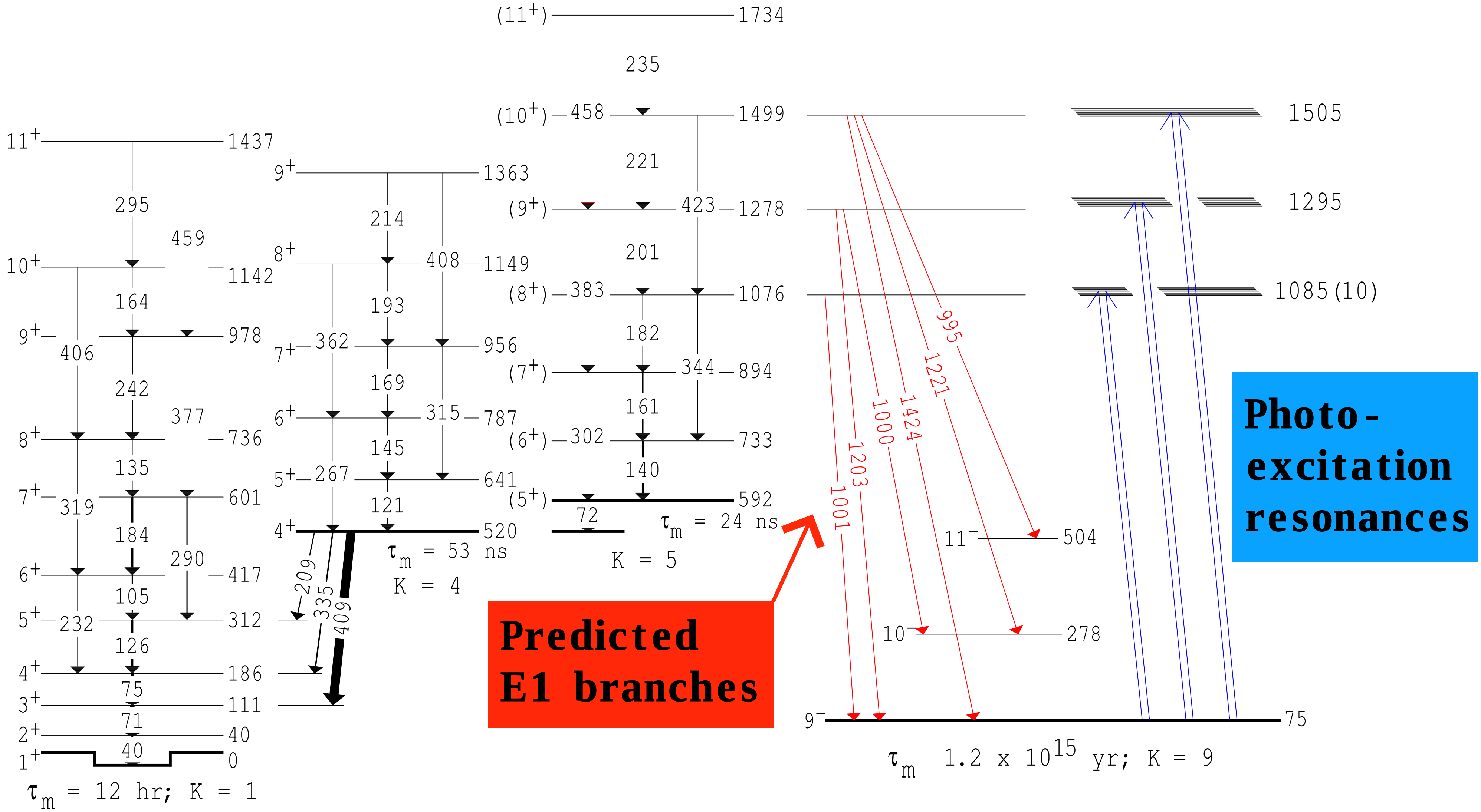


"RESONANCES MATCH WITH NEW STATES IN TA180 "



Walker, Dracoulis and Carroll Phys RevC 64 (2001) 061302 (R)
Full schemes see:Dracoulis et al Phys Rev C 58 (1998) 1444; ibid 62 (2000) 037301;
Saitoh et al Nucl. Phys. A 660 (1999)121; Wendel et al. Phys Rev C 65 (2001) 014309

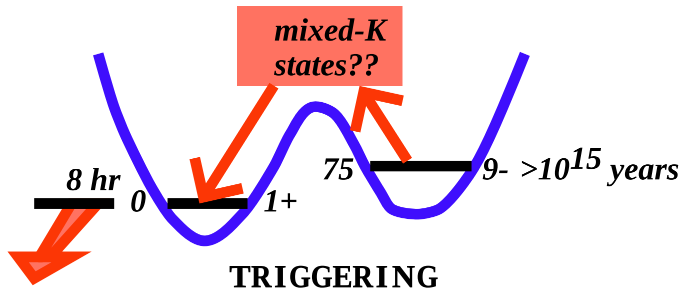
EXTRACT "BACK-DECAY" WIDTH CONSISTENT WITH RESONANCE YIELD

$$s_E = \int_{ER} \sigma \, dE = \frac{\lambda^2}{4} \frac{(2I_a+1)}{(2I_m+1)} \frac{\Gamma_m \Gamma_0}{\Gamma} \quad \text{(eV.b)}$$

Γ – total width
Γ_0 – path to .. 1^+
Γ_m - back decay

$$\Gamma_m = \frac{s_E}{(\lambda^2/4)g} \Big/ \left[1 - \frac{s_E}{(\lambda^2/4)g} \frac{1}{\Gamma_0} \right] \quad \text{(eV)}$$

measured and
estimated (rotational model)



Walker, Dracoulis and Carroll Phys RevC 64 (2001) 061302 (R)

Predicted E1 Branches

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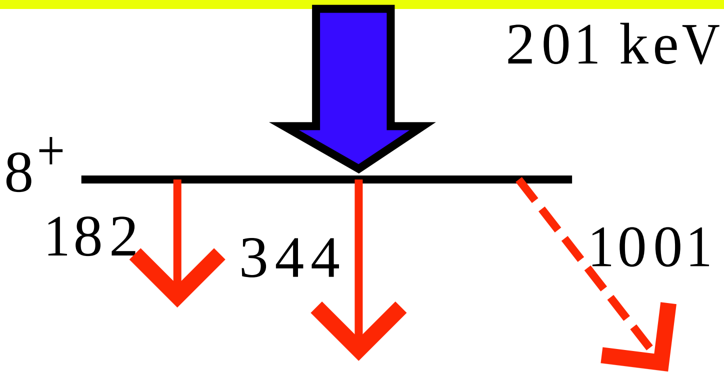
Initial State		Eγ	Γγ [10^{-5} eV]	%
1499: 10^+		423 221	8.8 4.7	
	E1	**1424** **1221** **995**	**8.7** **5.5** **3.0**	**28%** **18%** **10%**
1278: 9^+		383 201	4.3 2.7	
	E1	**1223** **1000**	**5.2** **3.0**	**34%** **20%**
1076: 8^+		344 182	1.8 1.2	
	E1	**1001**	**3.0**	**50%**

Where is the Back-Decay ? "

$^{180}Hf(d,2n)^{180}Ta$

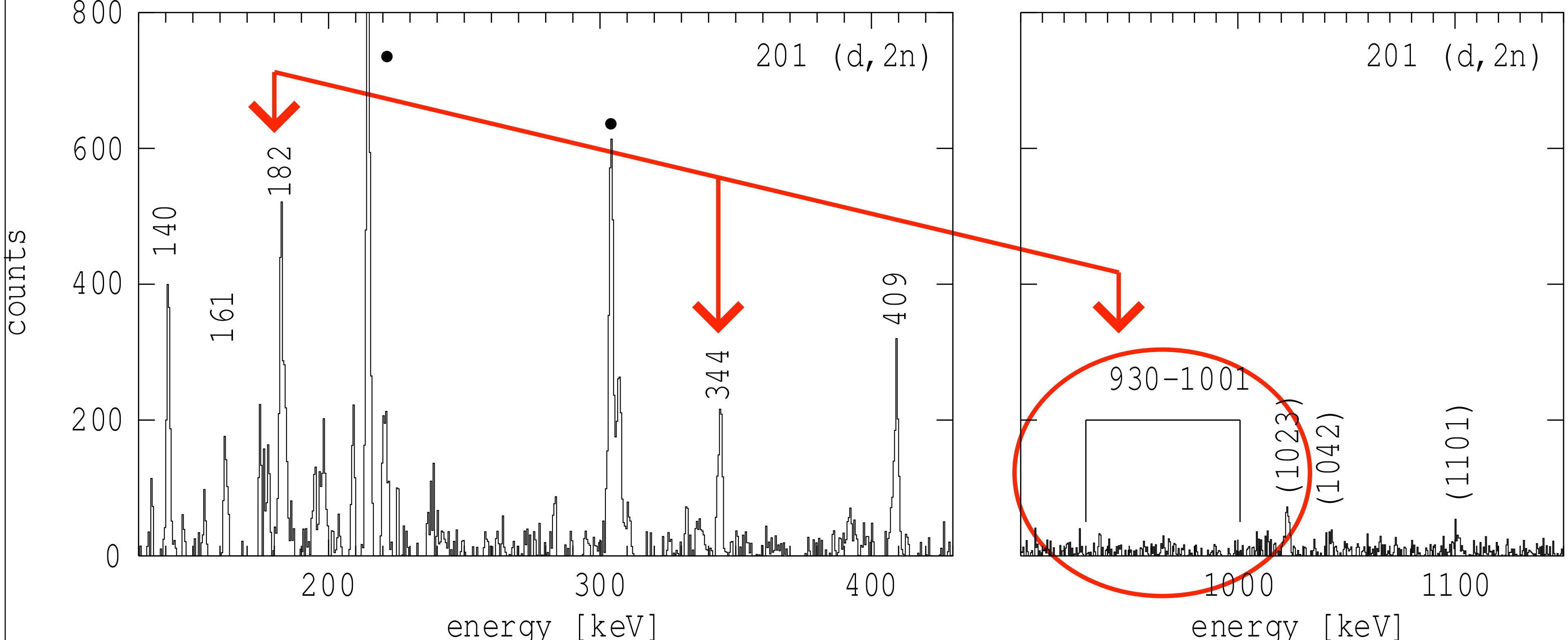
non-yrast; gate from above



$^{176}Yb(^{11}B,\alpha 3n)^{180}Ta$

$^{176}Yb(^{7}Li,3n)^{180}Ta$

$^{176}Lu(^{136}Xe,...)^{180}Ta$



Optimum reaction; γ–γ coincidences [ANU]

Lane et al, to be published

NON-OBSERVATION OF BACK-DECAYS:

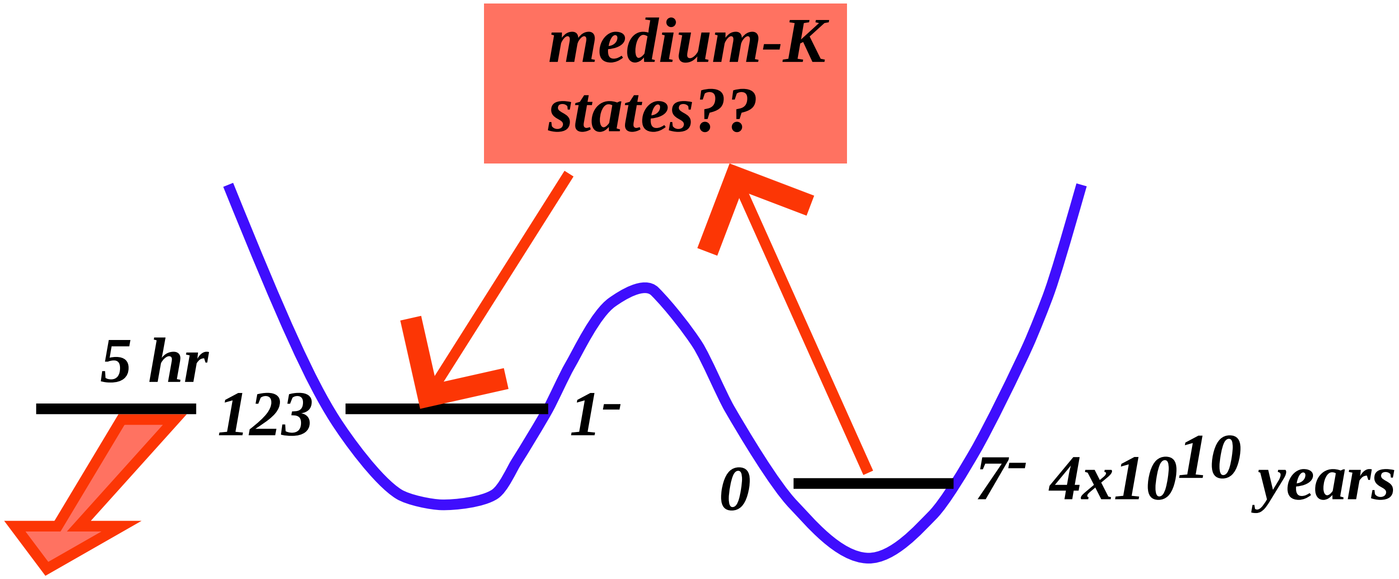
a) Association incorrect ? (despite match)
b) What are the states that produce resonances ?
c) How can the laboratory cross-sections be so large??

not such a rarity... ^{176}Lu

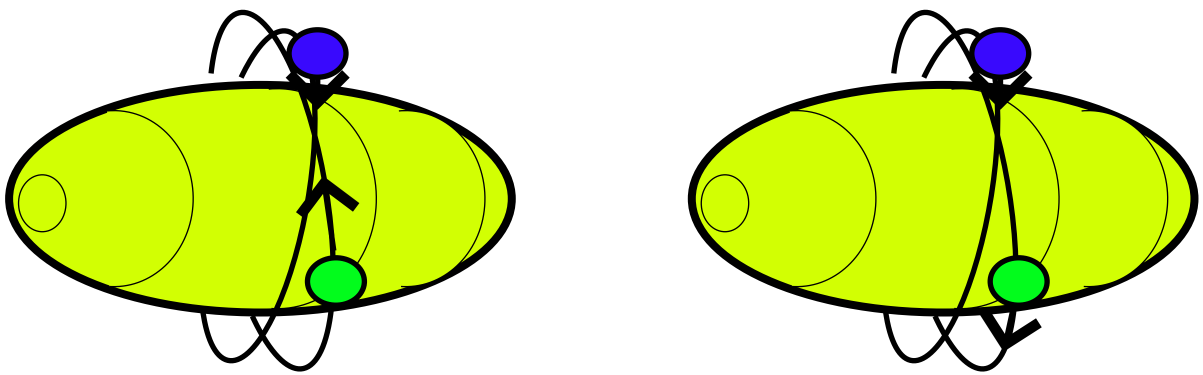
Lu-176 : The Sister

PRODUCTION s-process
(shielded from r-processes)

$^{176}_{71}Lu_{105}$



TRIGGERING



$\Omega\pi - \Omega\nu = 0^-$
$7/2^+[404]\times 7/2^-[514]$

$\Omega\pi + \Omega\nu = 7^-$
$7/2^+[404]\times 7/2^-[514]$

ABUNDANCE ?
Temperature-
(and Nuclear
Structure)
Dependent
Equilibrium

~~CHRONOMETER~~?

THERMOMETER?

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Lu-176

s-process...

In the lab., most neutron capture goes to 1^- isomer under quasi-stellar conditions [kt ~ 25 keV]

see Heil et al Astroph. J. 673 (2008) 434

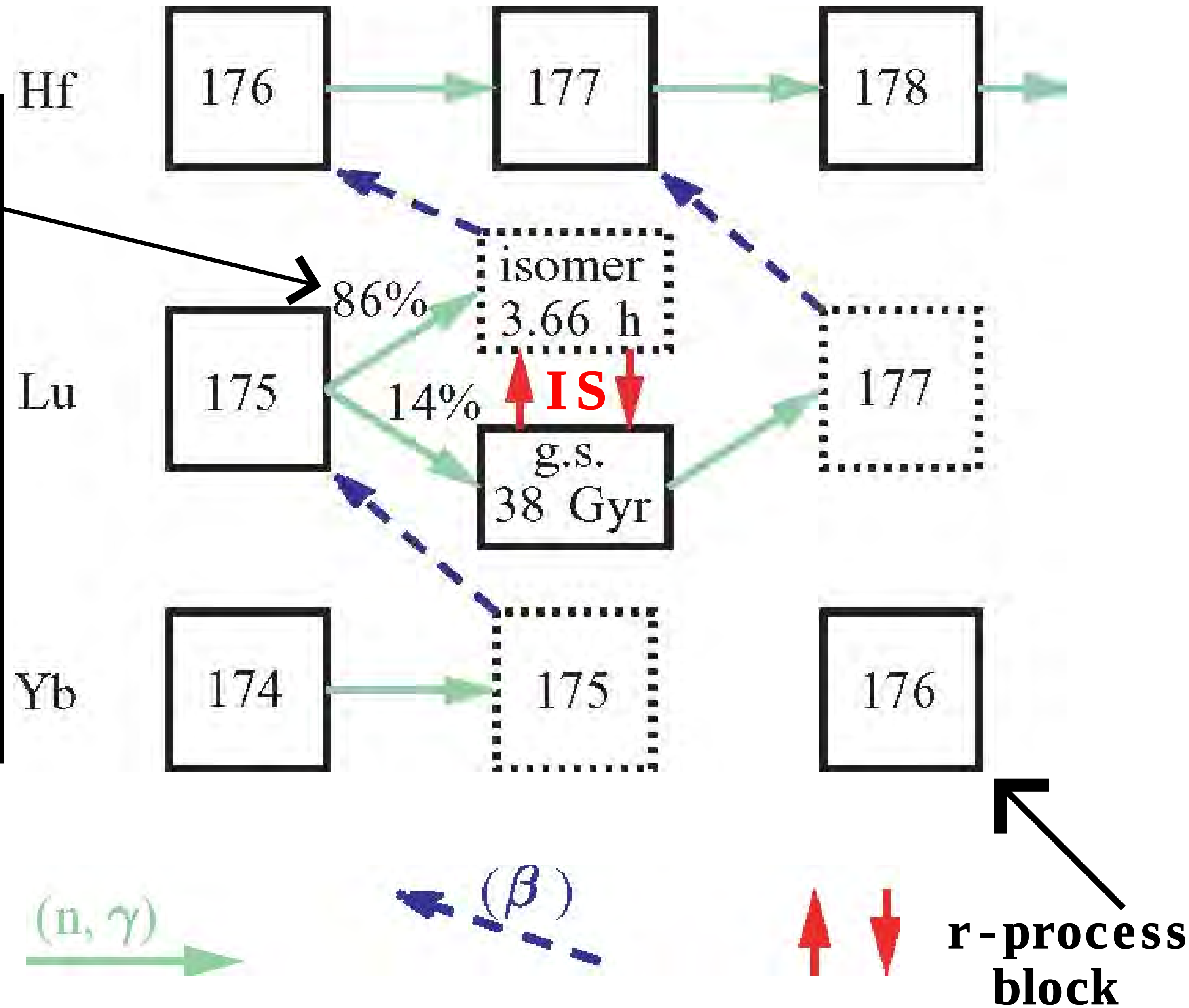

figure from Mohr et al PRC 79 (2009) 045804

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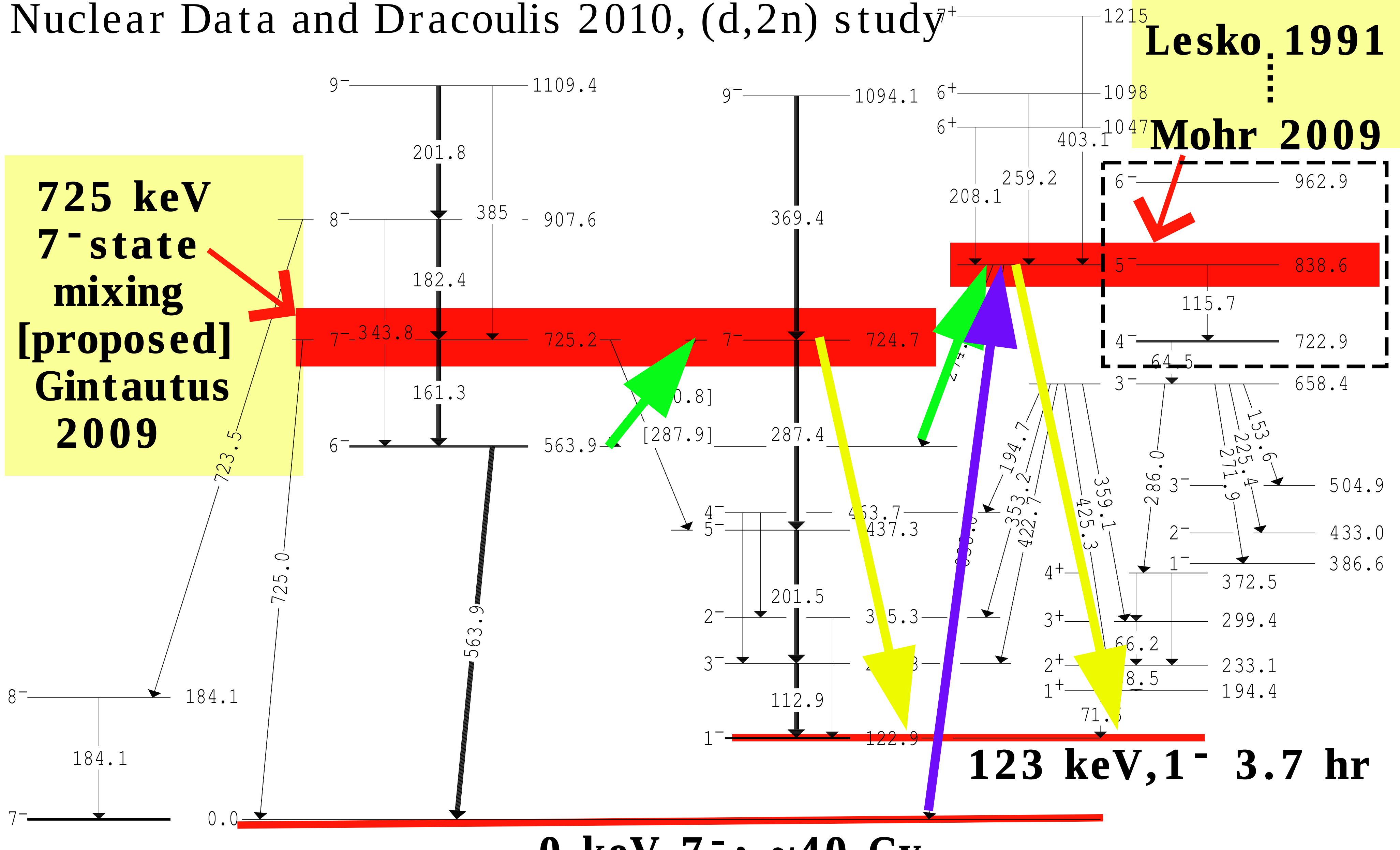
Lu-176; 839 keV, 5⁻ and 725 keV 7⁻ states

updated scheme from
Nuclear Data and Dracoulis 2010, (d,2n) study



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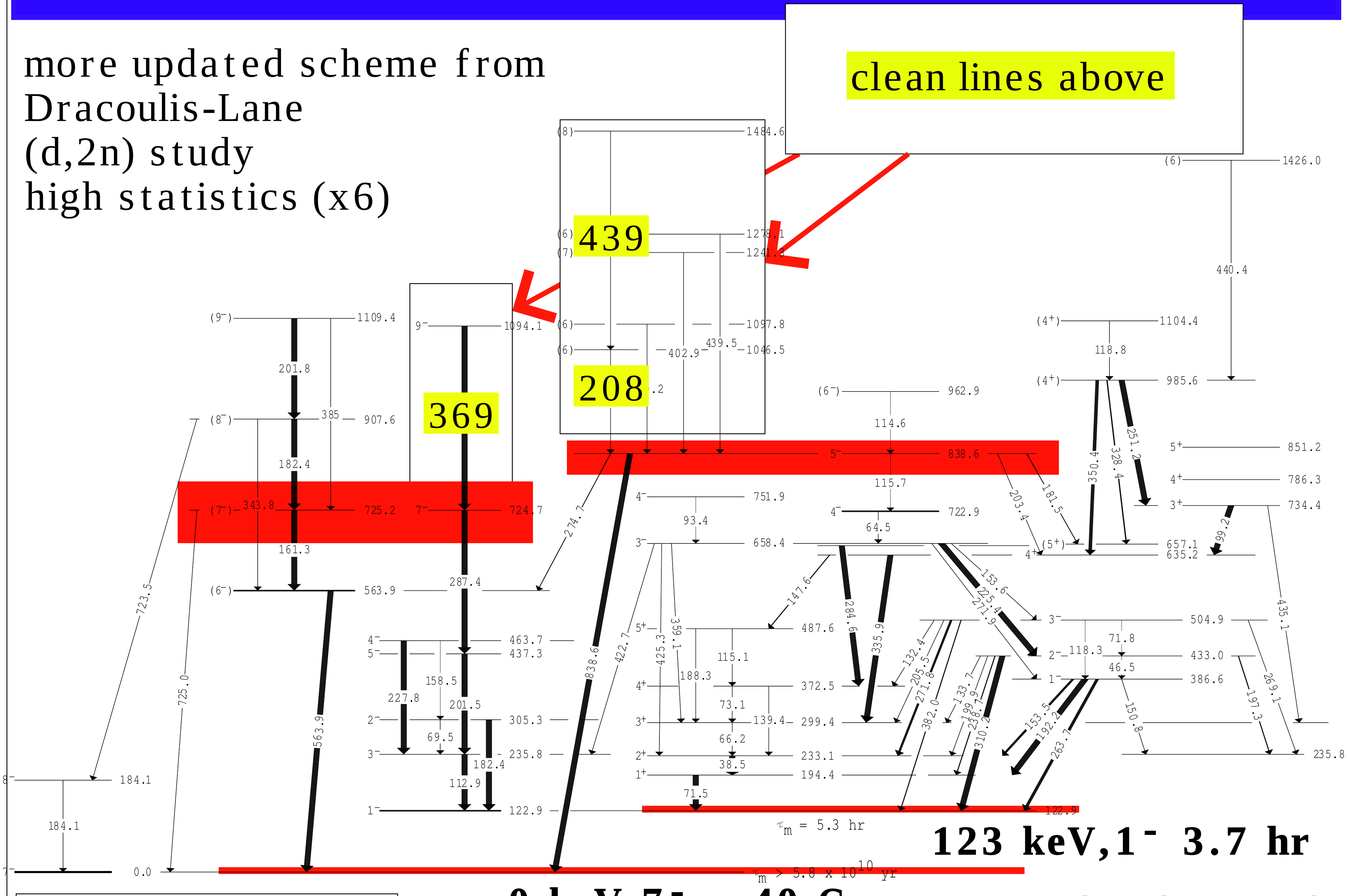
lu176-7m-full-2.md

Lu-176 new scheme: in progress;

more updated scheme from
Dracoulis-Lane
(d,2n) study
high statistics (x6)



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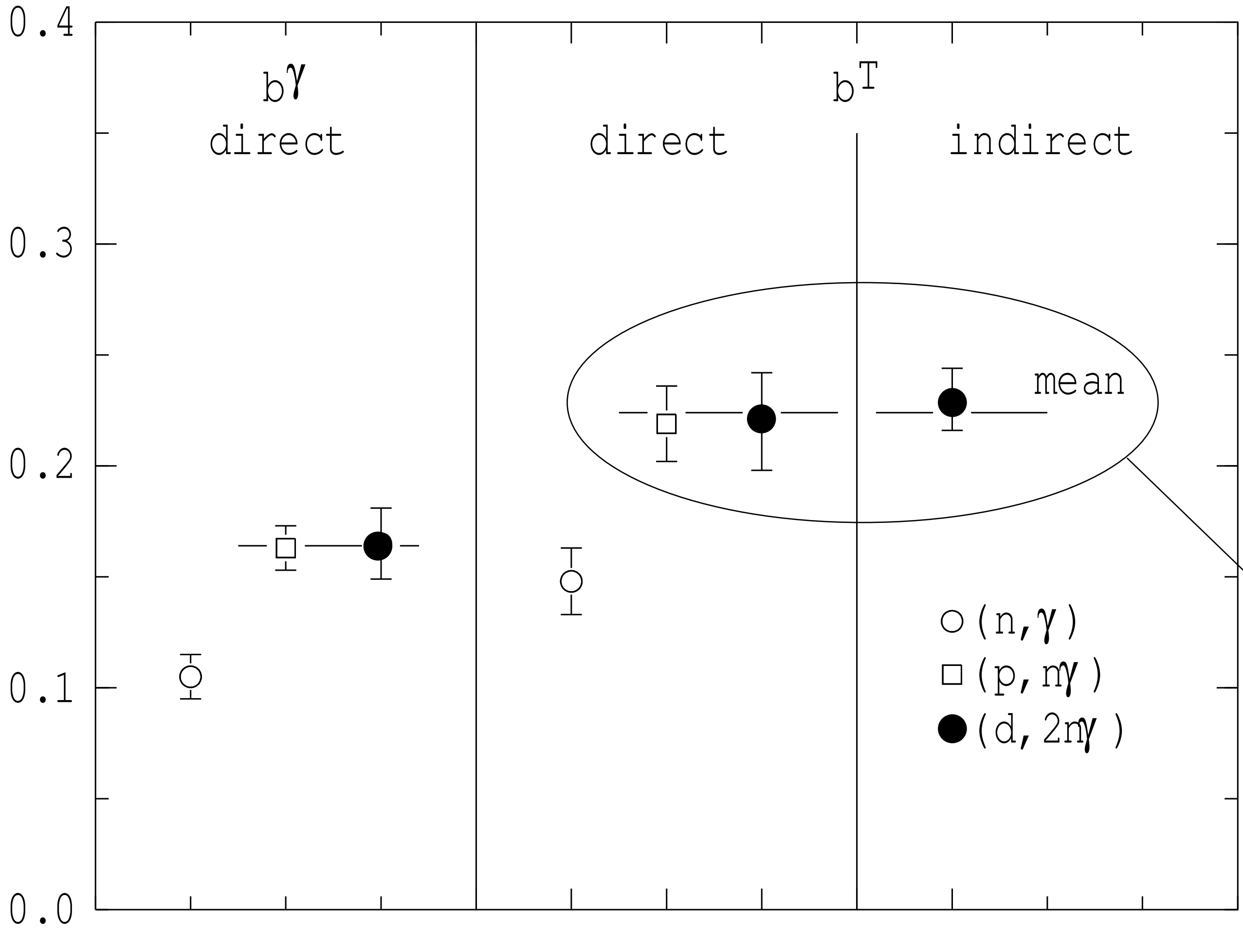
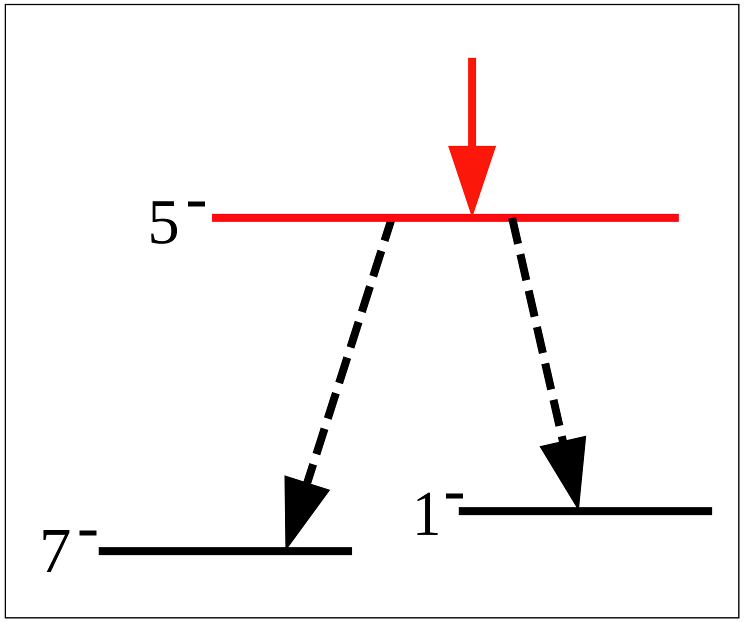
lu176-lowspin-1.md

Branching ratio to 1^- state

(i) branches confirmed
(ii) branching ratio defined





22% goes to 1^-

lu176-839-branch..md

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Lu-176, 839 keV, 5^- state, $K=4^-$ band: Status

limits $10 < \tau < 433$ ps
uncertain low-energy branches confirmed
band member would have $\tau \sim 15$ ps

BUT

X 182 keV E1 branch to 657 keV 5^+ state is $1.6\text{x } 10^{-4}$ W.u.
too fast **and** involves configuration change **v. slow**
$\nu\ 7/2^-[514]\ \pi\ 1/2^+[411]$ to $\nu\ 1/2^-[510]\ \pi\ 9/2^-[514]$

X 839 keV E2 branch to 7- ground state is 1.4 W.u !!.
expect $< 10^{-3}$ W.u. **known in ^{177}Lu**
$\nu\ 7/2^-[514]\ \pi\ 1/2^+[411]$ to $\nu\ 7/2^-[514]\ \pi\ 7/2^+[404]$

X Rotational band structure inconsistent with isotone g.s in ^{174}Tm - Hughes et al. Phys Rev C in press (2013)

Mixing of 7^- states through chance degeneracy

Limit on 725 keV 7⁻ state mixing [0.5 keV separation*]

Typical mixing: see
Dracoulis et al PRL 97-12251-2006

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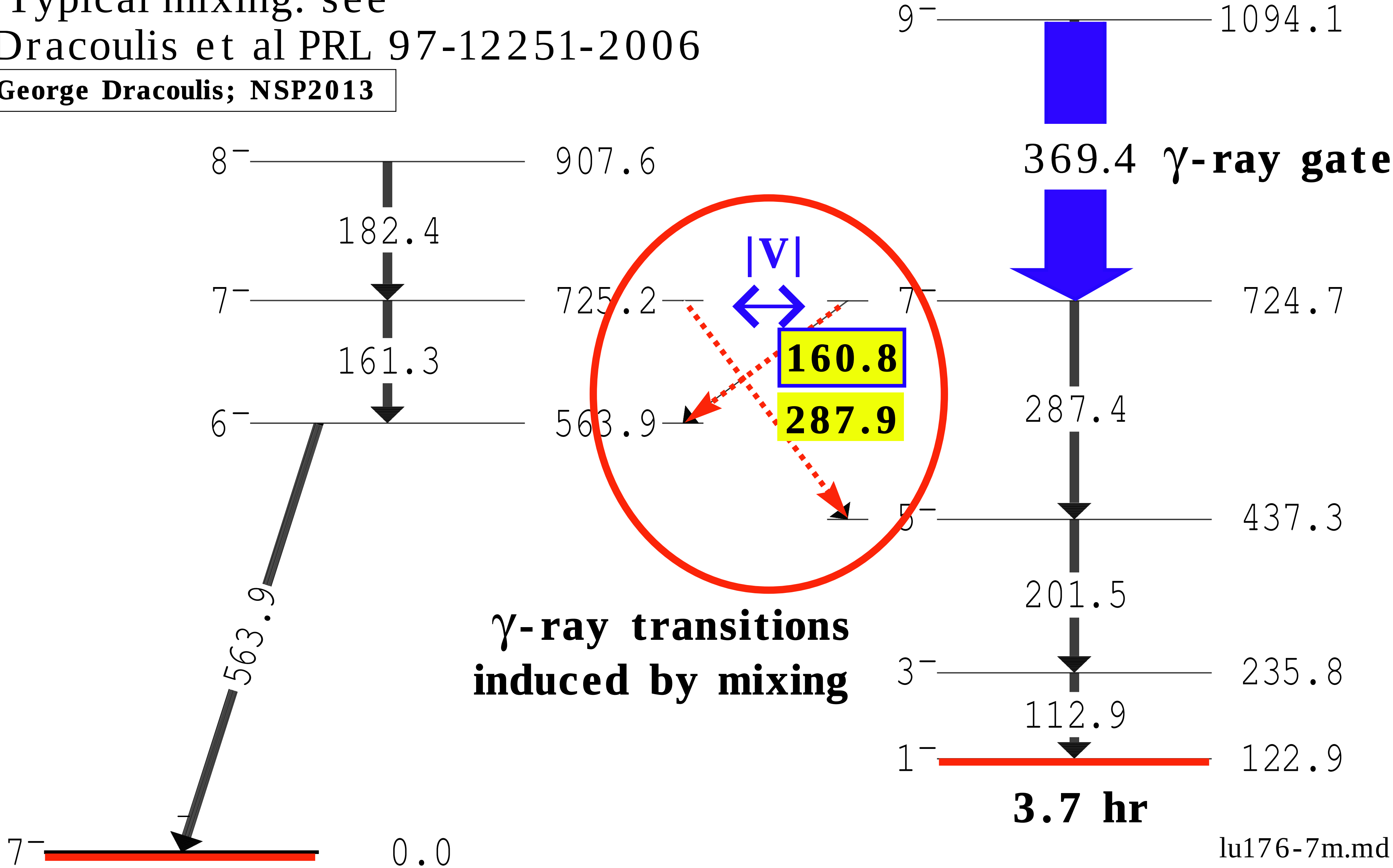


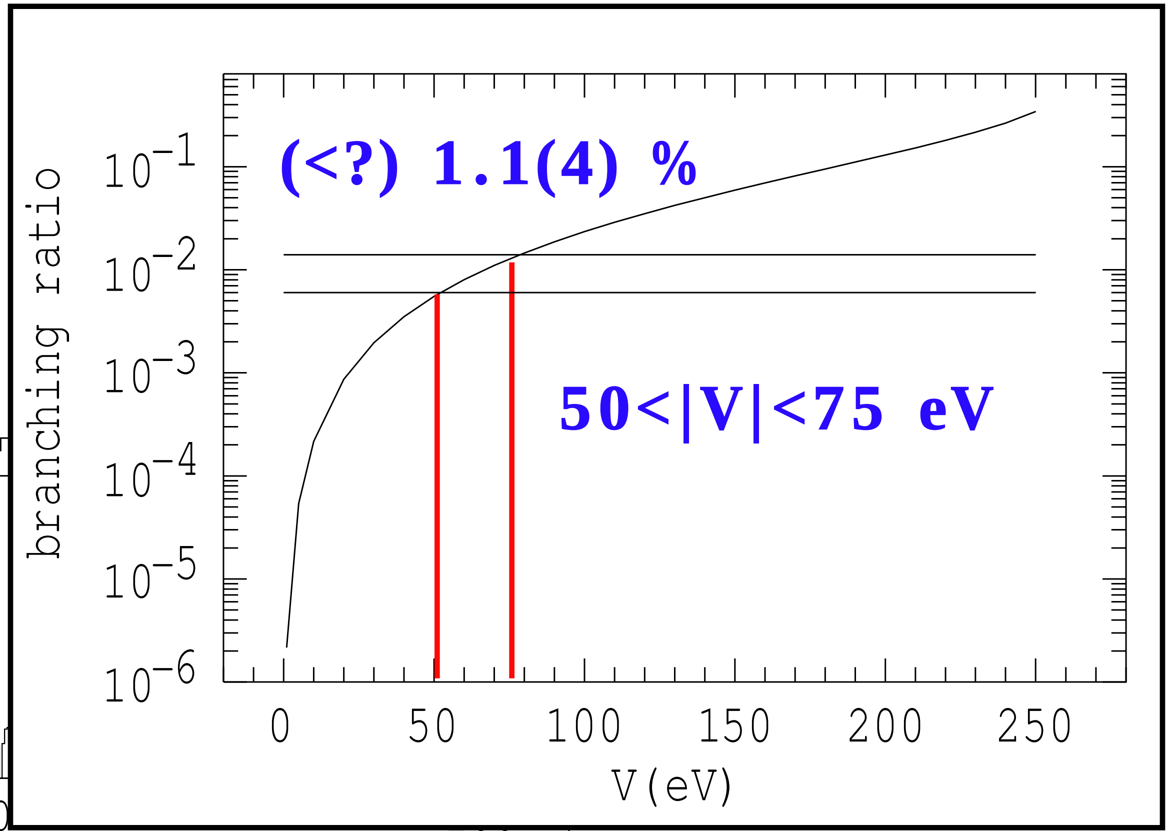
~40 Gy

lu176-7m.md

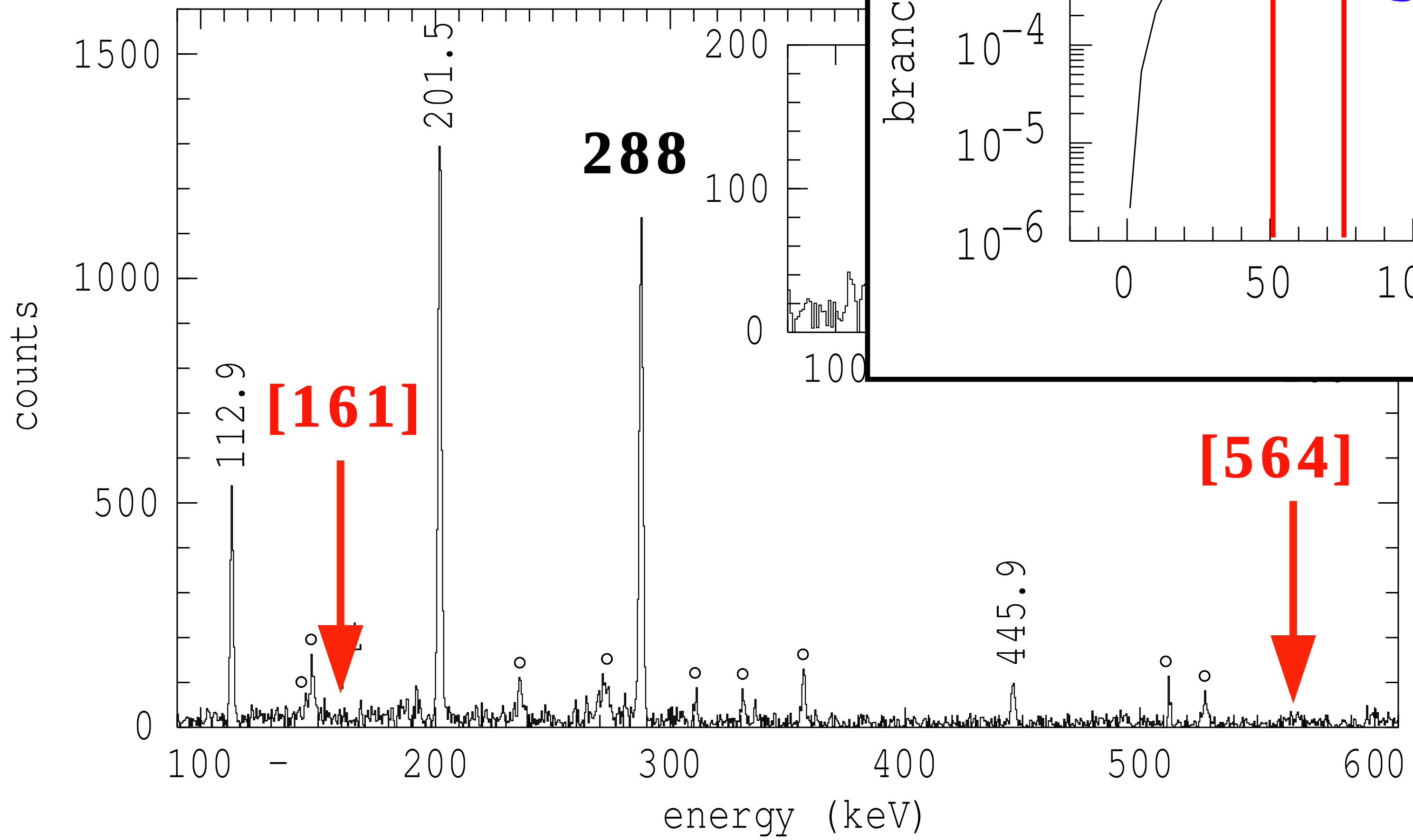
Suggested by Gintautus et al PRC 80-015806-2009

(Limit on ?) 725 keV 7^- state mixing

Dracoulis 2010, (d,2n) study



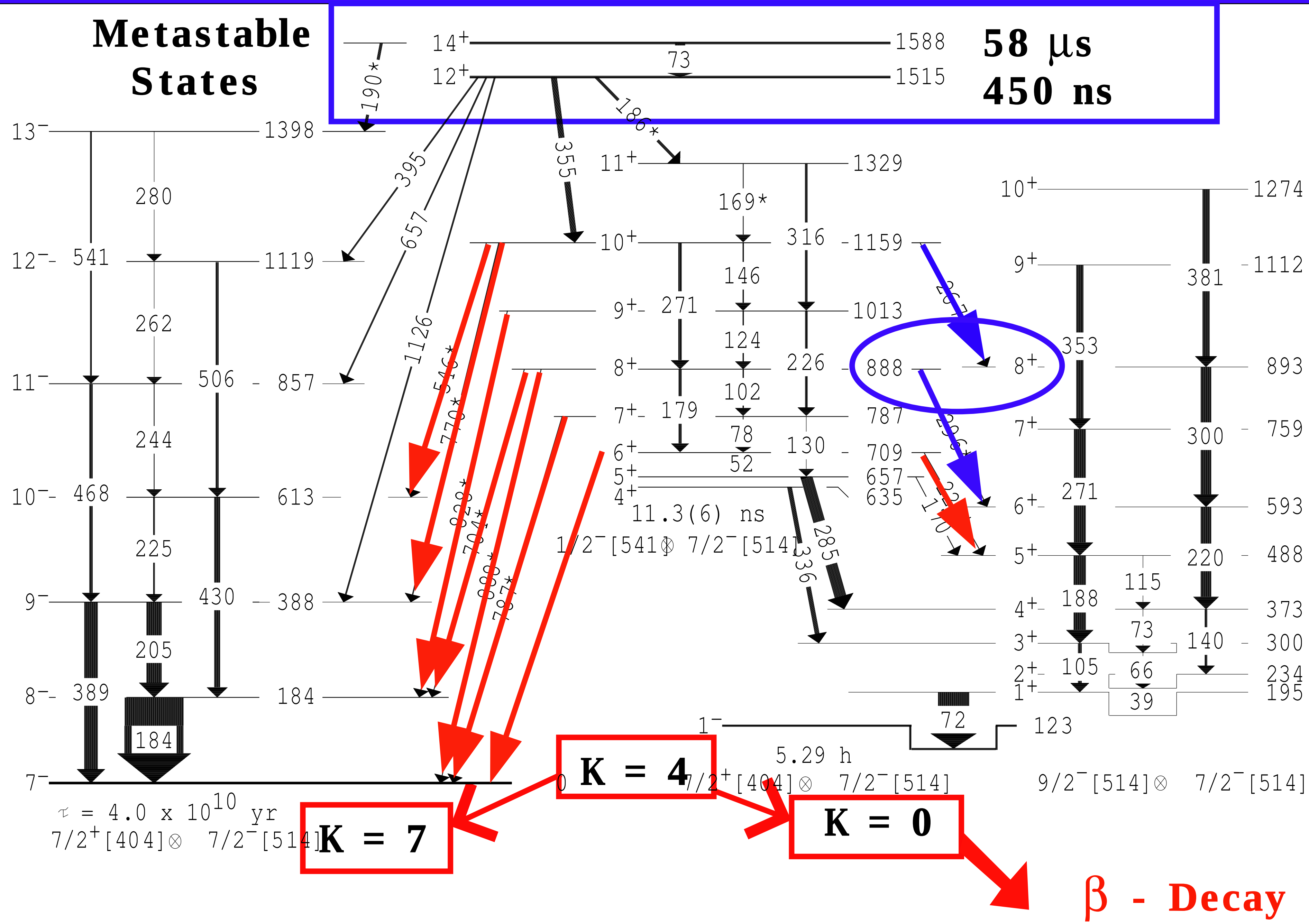
369 keV γ-ray gate



See
Dracoulis et al
Phys. Rev. Lett.
97(2006)122501
V vs. ΔK

Neutron-rich nuclei via deep-inelastic reactions
High-spin isomers
Intermediate-K bands (4^+)

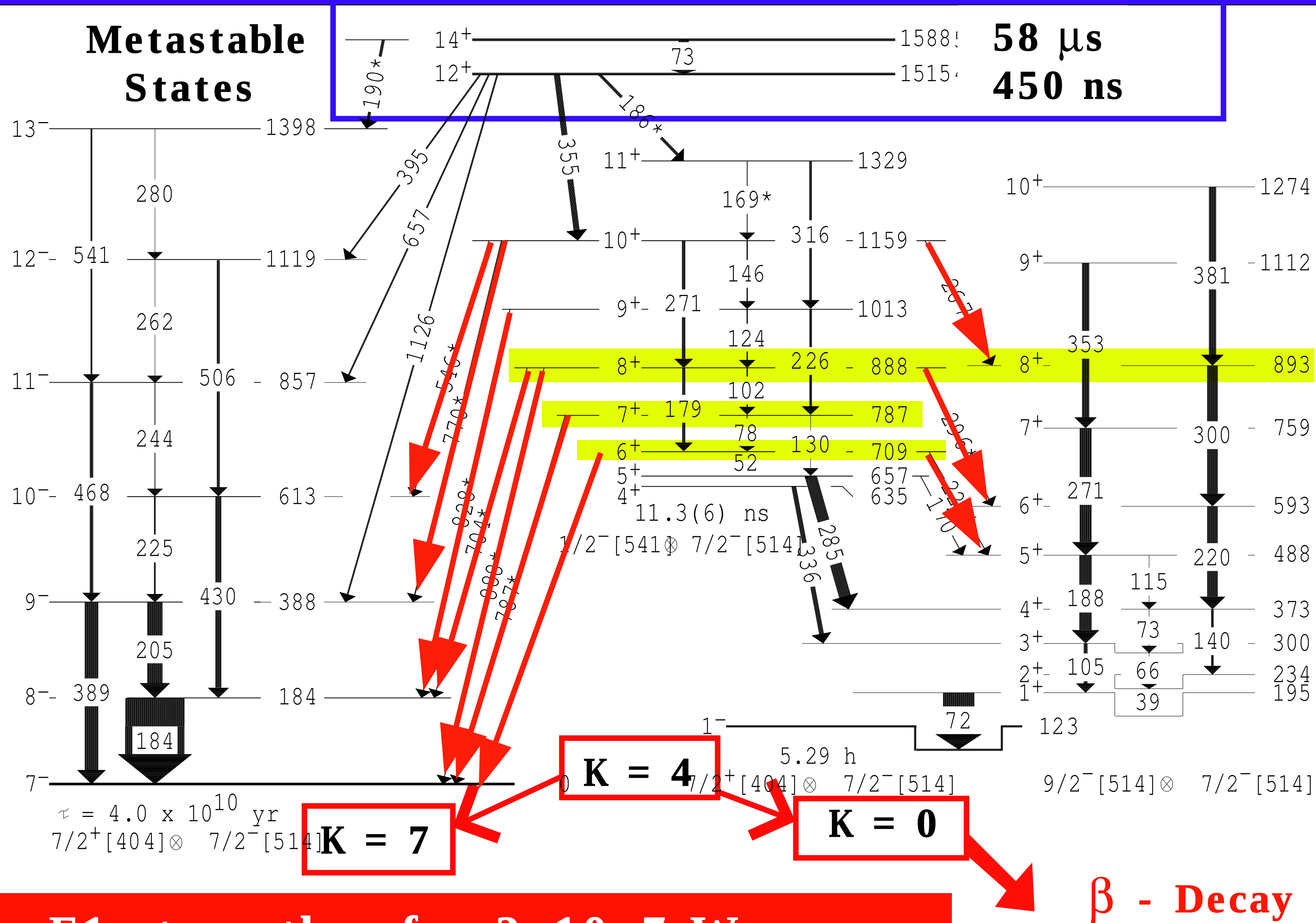
ISOMERS/GAMMASPHERE- HIGH SENSITIVITY



Dracoulis et al; [Deep Inelastic/Gammasphere]
Phys Rev C 81, 011301(R) (2010)

lu176-scheme-IIa.md

EXPECTED LABORATORY RESONANCES: E1 to $6^+, 7^+, 8^+$



E1 strengths of ~ 2x10-7 W.u.

Dracoulis et al; Phys. Rev.C 81-011301(R) 2010

George Dracoulis; NSP2013

"Transfer Rate" Implications?

"Transfer Rate" $7^- \text{ to } 1^-$

In stellar environment
$E = E_{IS} - E_0$ = lower photon energy

$$\lambda^* (T) = c \sum_i n_\gamma(E_{IS,i},T) \;\; x \;\; I\sigma\, (E_{IS,i}) \; x \; Pi\,(E_0,T)$$

Photon density

Higher

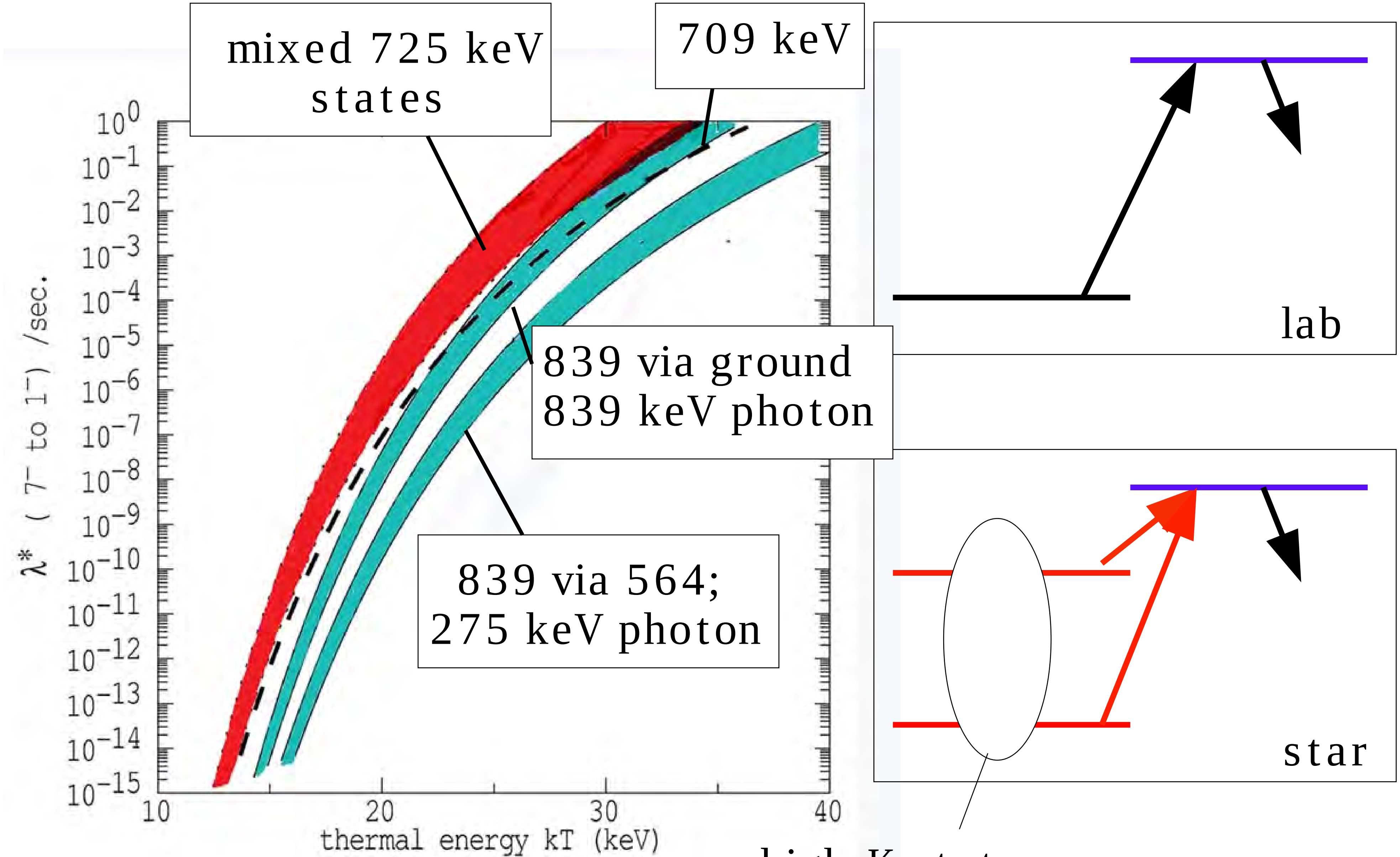
Temperature Dependent

S_E

Resonance cross section
from excited state

Temperature Dependent
Maxwellian Population

Transfer probabilities (inverse lifetime)



839g: 1-45 meV.b
725: V = 50-75 eV

Mohr et al: 839 keV state; S_E = 0.0004 - 0.033 eV.b
GDD etc: S_E = 0.0010 - 0.045 eV.b
Update [JJC, 2012]; S_E = 0.003(1) eV.b

GDD (d,2n):7^- 725 keV state mix: 50 eV <|V|< 75 eV)
[stellar via 564 keV state] S_E = 0.0230 -0.524 eV.b

GDD et al. Deep Inelastic
709 keV state; S_E ~ 0.0002 eV.b
787 keV state; S_E = 0.0005 eV.b
880 keV state; S_E = 0.0006 eV.b

Van Horenbeeck Coulomb Excitation (activation)
Integrated < 1000 keV ; S_E = 0.0300 eV.b

Most (i) significant in stellar environment ; $e^{-(E^*/kT)}$
(ii) probably insignificant in laboratory photoactivation
Inconsistent with lab. Coulomb Excitation??

^{180}Ta :

K = 5^+ band Back-Decays - not observed

K = 5^+ bandhead link to 7^+ - not observed

^{176}Lu :

5^-, 839 keV state; branch defined, τ to be measured ?

7^-, 725 keV state mixing measured - significant

Observation of multiple decays connecting 6^+,7^+,8^+ states of K = 4^+ band connecting 7^- and 1^- states

^{176}Lu : Strength observed in Coulomb excitation missing?

Challenges:

[1] To measure weak γ-branches in the laboratory

Not clear that one can measure down to the levels required to account for random (isolated) state mixing where < 1% g-ray branches are implied

[2] To identify and understand the properties of states that lead to increasingly larger photoactivation resonances in the laboratory

[Dream] Intense, quasi-monoenergetic low energy Photon source (<500 kev to 4MeV)

conclusion ?

There are more questions than answers,
And the more I find out, the less I know

...Johnny Nash 1972