# NUCLEAR ISOMERS AND THEIR IMPLICATIONS IN THE STELLAR ENVIRONMENTS

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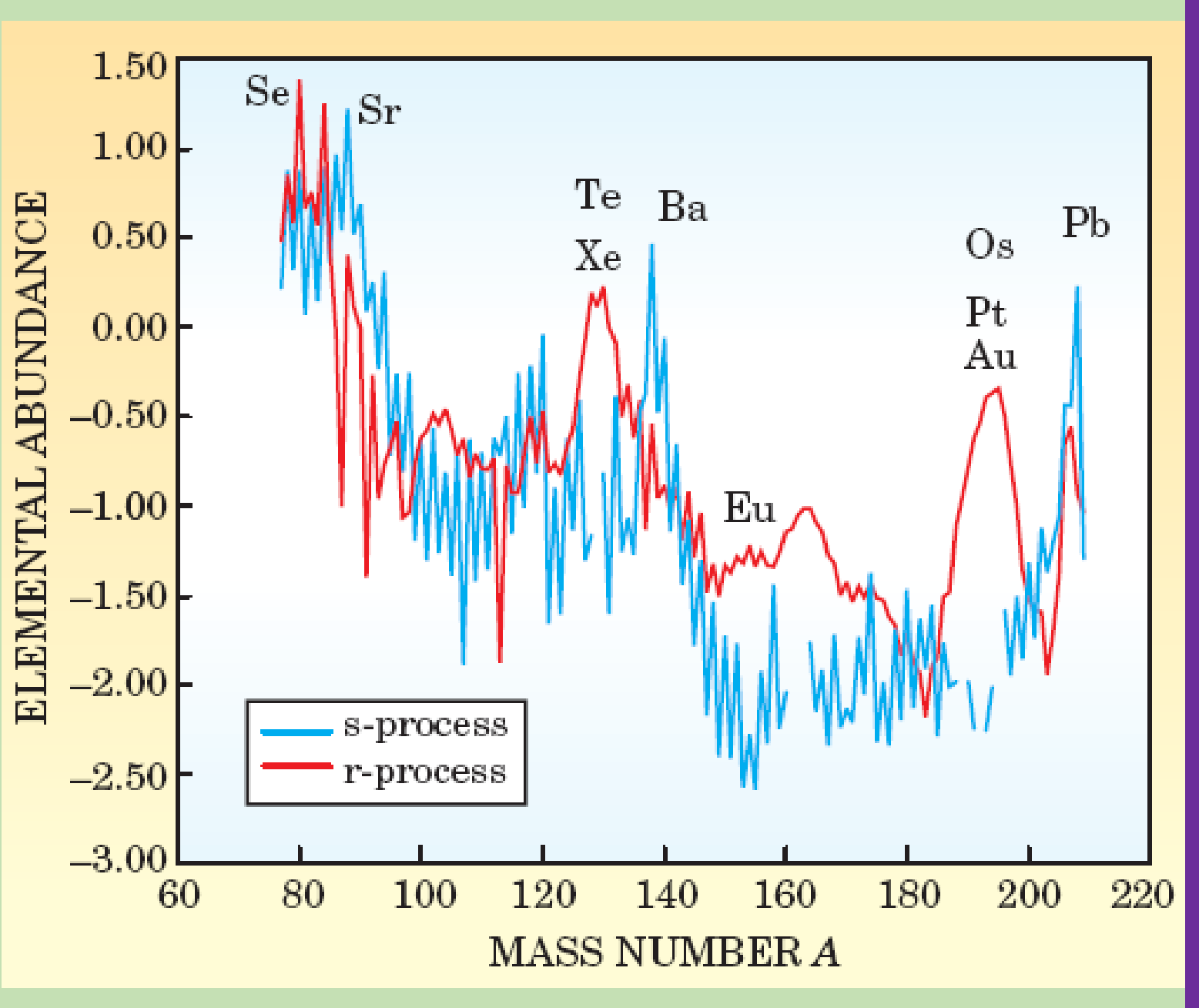
## Introduction:

Study of exotic nuclei revealed novel phenomena which have not been observed in stable nuclei. As we move away from the line of stability towards the driplines, traditional spherical shell closures disappear and deformed shell gaps emerge. The deformed shell gap in single particle structures stabilize nuclei with large deformation in similar way spherical shell closures do for the traditional magic nuclei

Study of neutron-rich nuclei far from the line of beta-stability is also important from the astrophysical point of view. The elements heavier than Fe are known to be synthesized by s-, r- and p-processes. The r-process abundance distribution has large peaks at A ~ 80, 130 and 195. The neutron shell closures are responsible for the observation of these peaks. This is because the closed-shell nuclei have longer beta-decay lifetimes and capture neutrons reluctantly. There is a small but distinct peak at A~160 in the rare-earth region. This is well known as the rare earth element (REE) peak. In contrast to the large peaks, the origin of this peak or bump like structure in the abundance pattern has not been understood clearly. It has been suggested that the deformation plays important role in the formation of the REE peak [ Surman, et al, Phys. Rev. Lett. 79, 1809 (1997).].

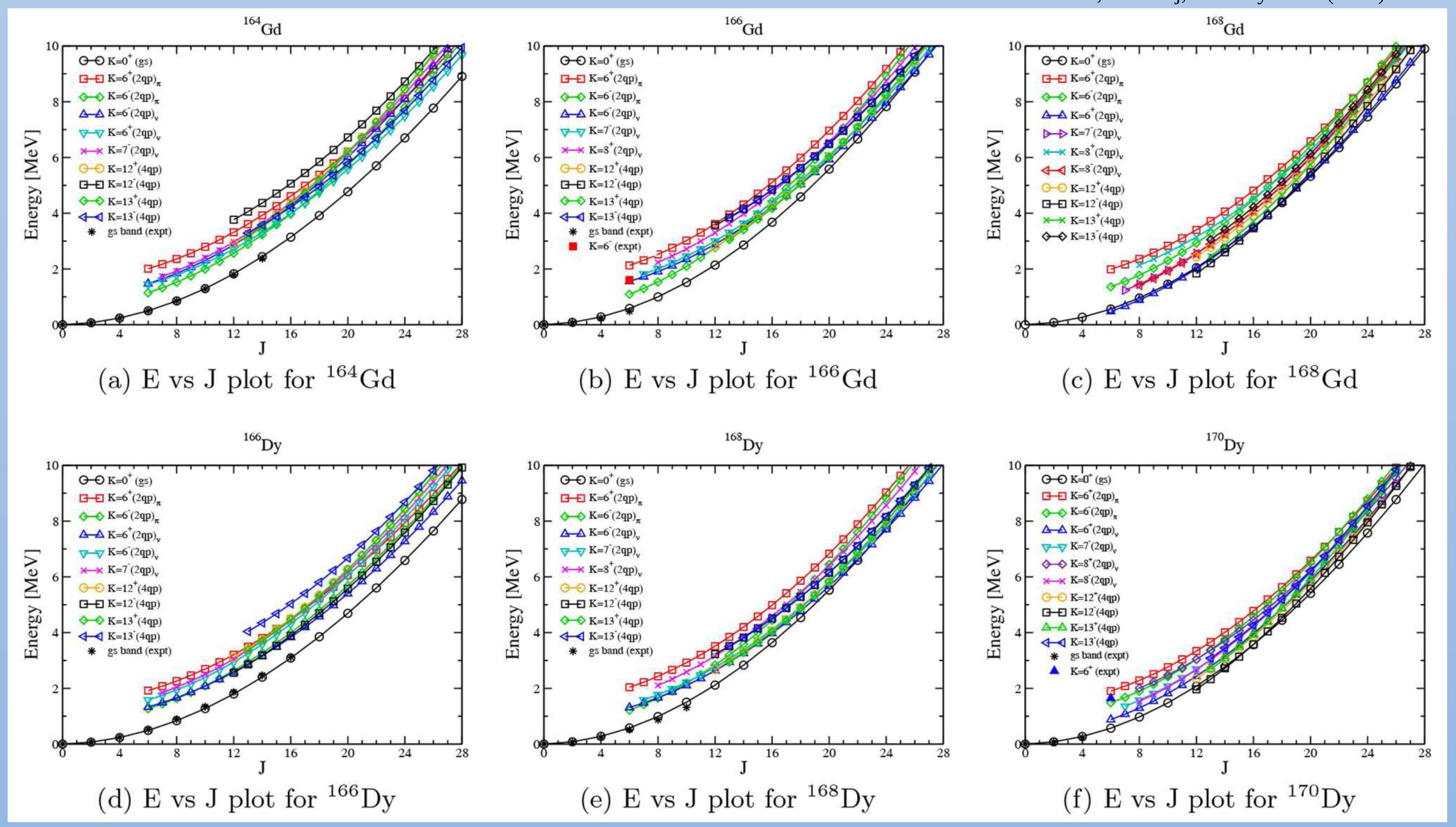
Astrophysical nucleosynthesis calculations rely on accurate nuclear reaction rate inputs. Indeed, even a single reaction rate can profoundly influence astrophysical evolution (see, e.g., Kirsebom et al. Phys. Rev. C, 100, 065805 (2019)). Typically, one of two treatments is used to compute nucleosynthesis rates. Either only the ground-state rate is used, or the levels are considered to be in a thermal-equilibrium probability distribution. The presence of an isomeric state can diminish the accuracy of both approaches. We see that some isomers can play an influential role in astrophysical nucleosynthesis, but most do not. This distinction defines astrophysical isomers, or **"astromers": they are nuclear isomers that have influence as such in an astrophysical environment of interest**.



Adapted from Sneden and Cowan, Science (2003)

## Ground and isomeric bands

SKG, Praharaj, Eur. Phys. J. A (2018) 54: 163

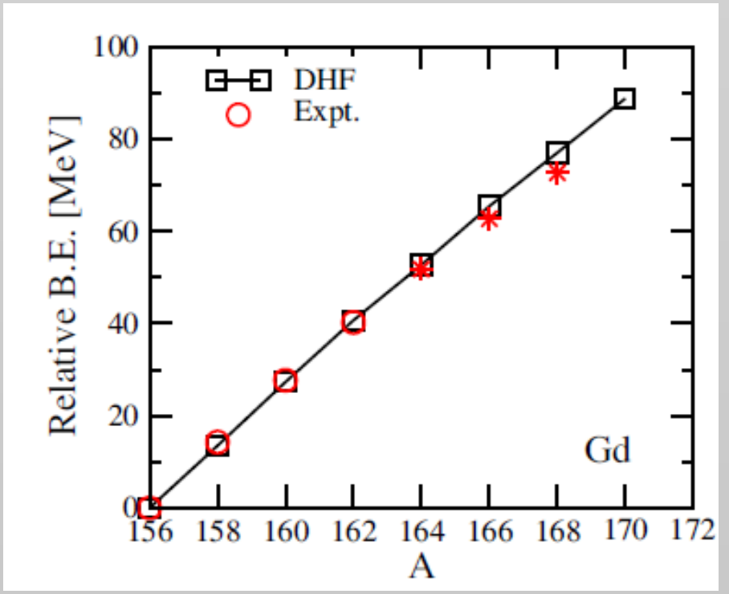


(a) E vs J plot for $^{164}$Gd (b) E vs J plot for $^{166}$Gd (c) E vs J plot for $^{168}$Gd

(d) E vs J plot for $^{166}$Dy (e) E vs J plot for $^{168}$Dy (f) E vs J plot for $^{170}$Dy

## Deformed Hartree-Fock Calculation

| Proton | $3s_{1/2}$ | $2d_{3/2}$ | $2d_{5/2}$ | $1g_{7/2}$ | $1h_{9/2}$ | $1h_{11/2}$ |
|---|---|---|---|---|---|---|
| spe [MeV] | 3.654 | 3.288 | 0.731 | 0.0 | 6.96 | 1.705 |
| **Neutron** | $3p_{1/2}$ | $3p_{3/2}$ | $2f_{5/2}$ | $2f_{7/2}$ | $1h_{9/2}$ | $1i_{13/2}$ |
| spe [MeV] | 4.462 | 2.974 | 3.432 | 0.0 | 0.686 | 1.487 |



Surface delta residual interaction $V_{pp}=V_{pn}=V_{nn}=0.3$ MeV

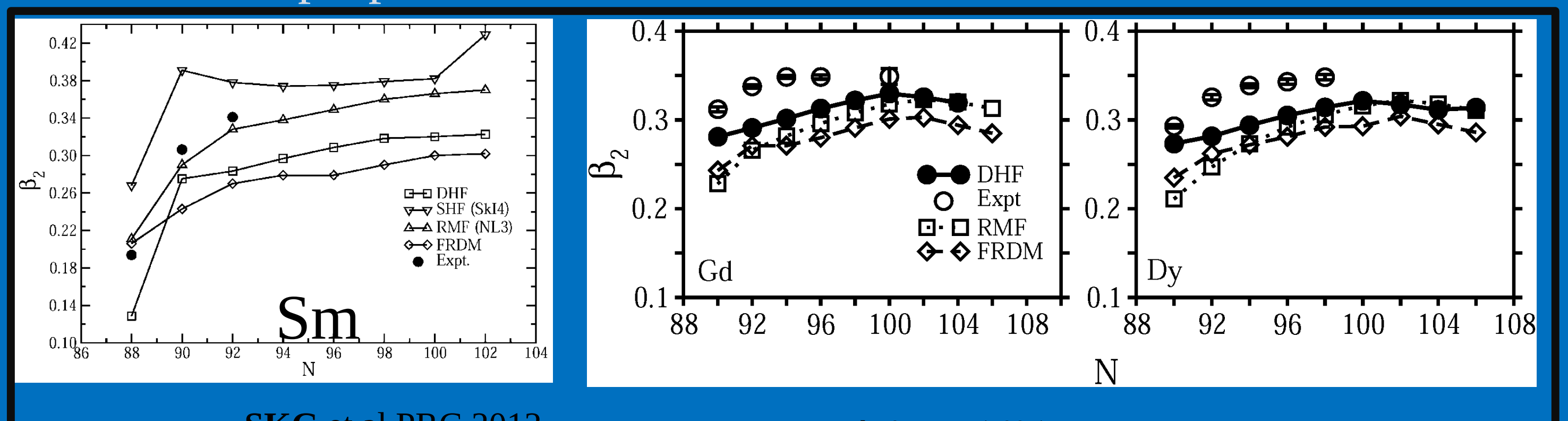
Angular Momentum Projection => states with good angular momentum

$$P_K^{JM} = \frac{2J+1}{8\pi^2} \int d\Theta\, D_{MK}^J(\Theta)^* R(\Theta)$$

Reduced matrix elements of tensor operator $T^L$ between projected states

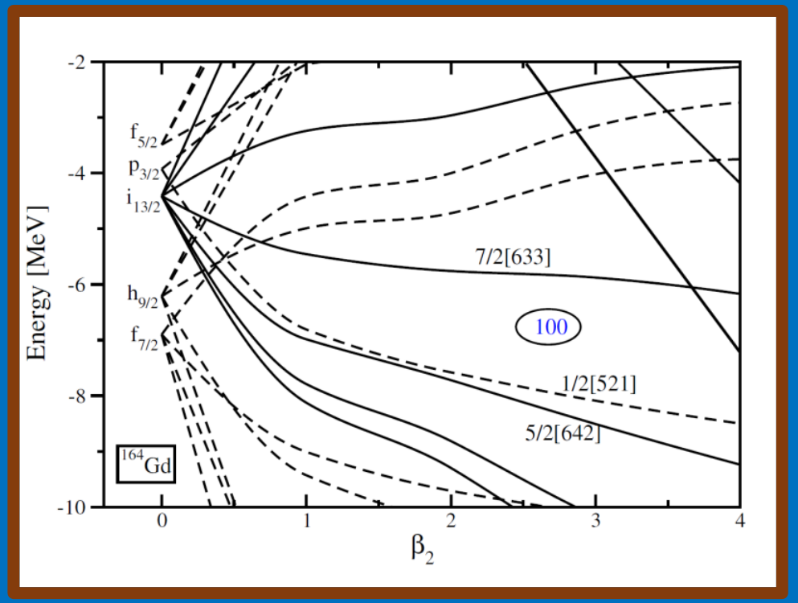
$$\langle \psi_{K_1}^{J_1} || T^L || \psi_{K_2}^{J_2} \rangle = \frac{1}{2} \frac{(2J_2+1)(2J_1+1)^{1/2}}{(N_{K_1K_1}^{J_1} N_{K_2K_2}^{J_2})^{1/2}} \sum_{\mu\nu} C_{\mu\nu K_1}^{J_2 L J_1} \times \int_0^\pi d\beta \sin(\beta) d_{\mu K_2}^{J_2}(\beta) \times \langle \phi_{K_1} | T_\nu^L e^{-i\beta J_y} | \phi_{K_2} \rangle,$$

## Deformation properties

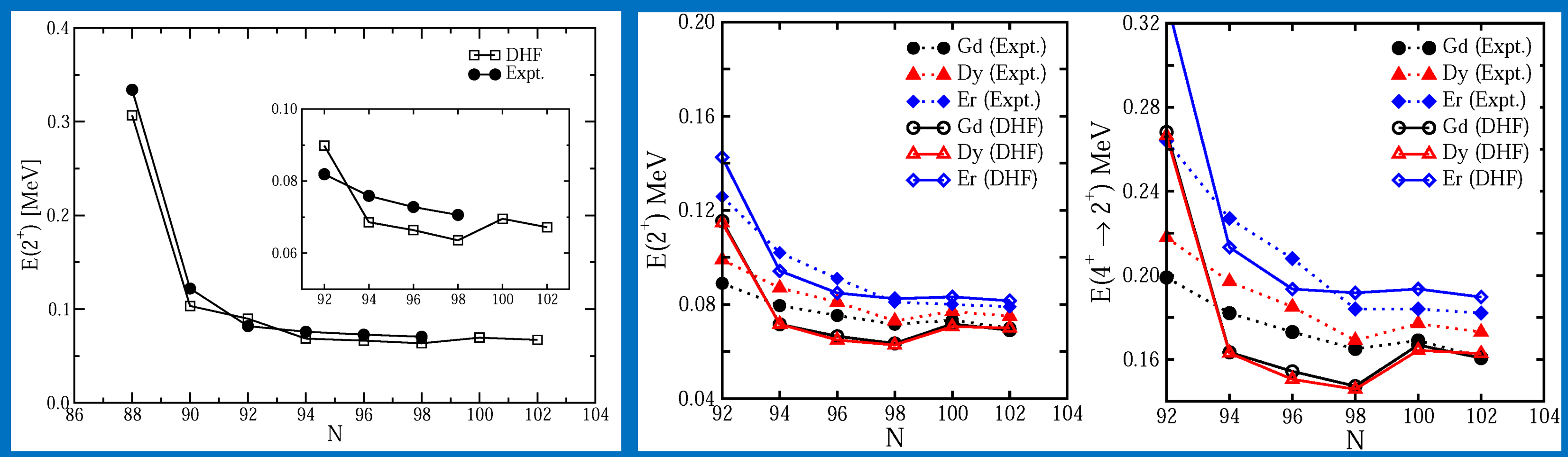


**SKG** et al PRC 2012 Expt.: Raman et.al., ADNDT(2001)

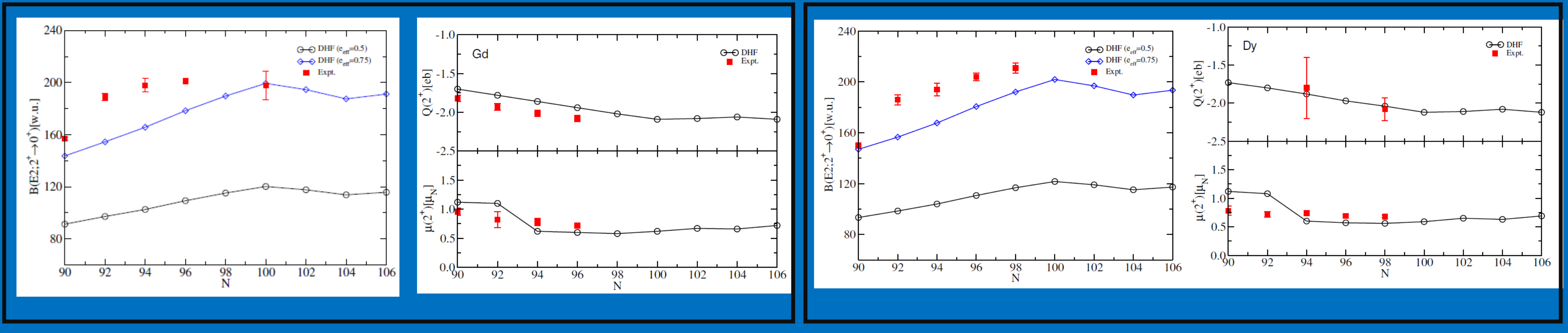
Neutron single particle levels for nuclei near $^{164}$Gd



## E(2+) systematic in Sm (Z=62), Gd (Z=64) and Dy (Z=66) isotopes



## Electromagnetic Properties



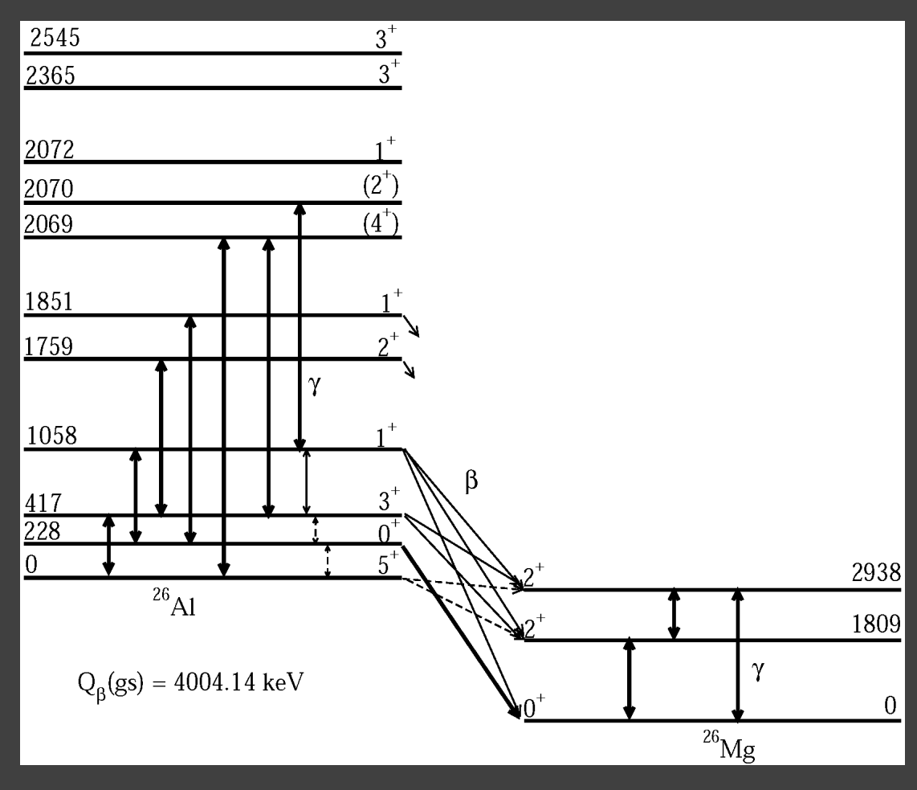
## Effective stellar $\beta$-decay rate of $^{26}$Al

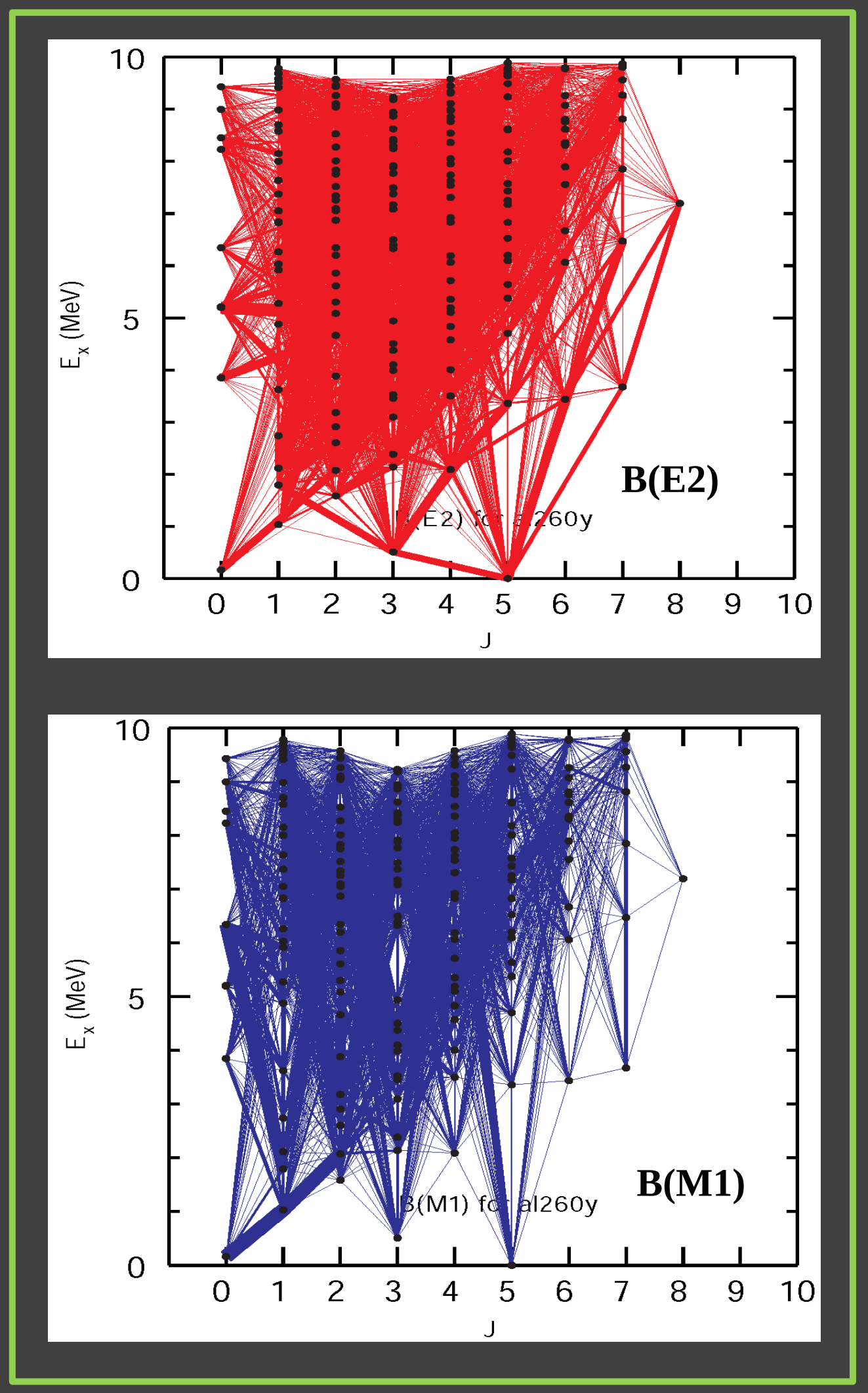
$$\lambda_{\mathrm{eff}}^{\beta}(T) = \sum_i n_i(T) \lambda_i^{\beta}$$

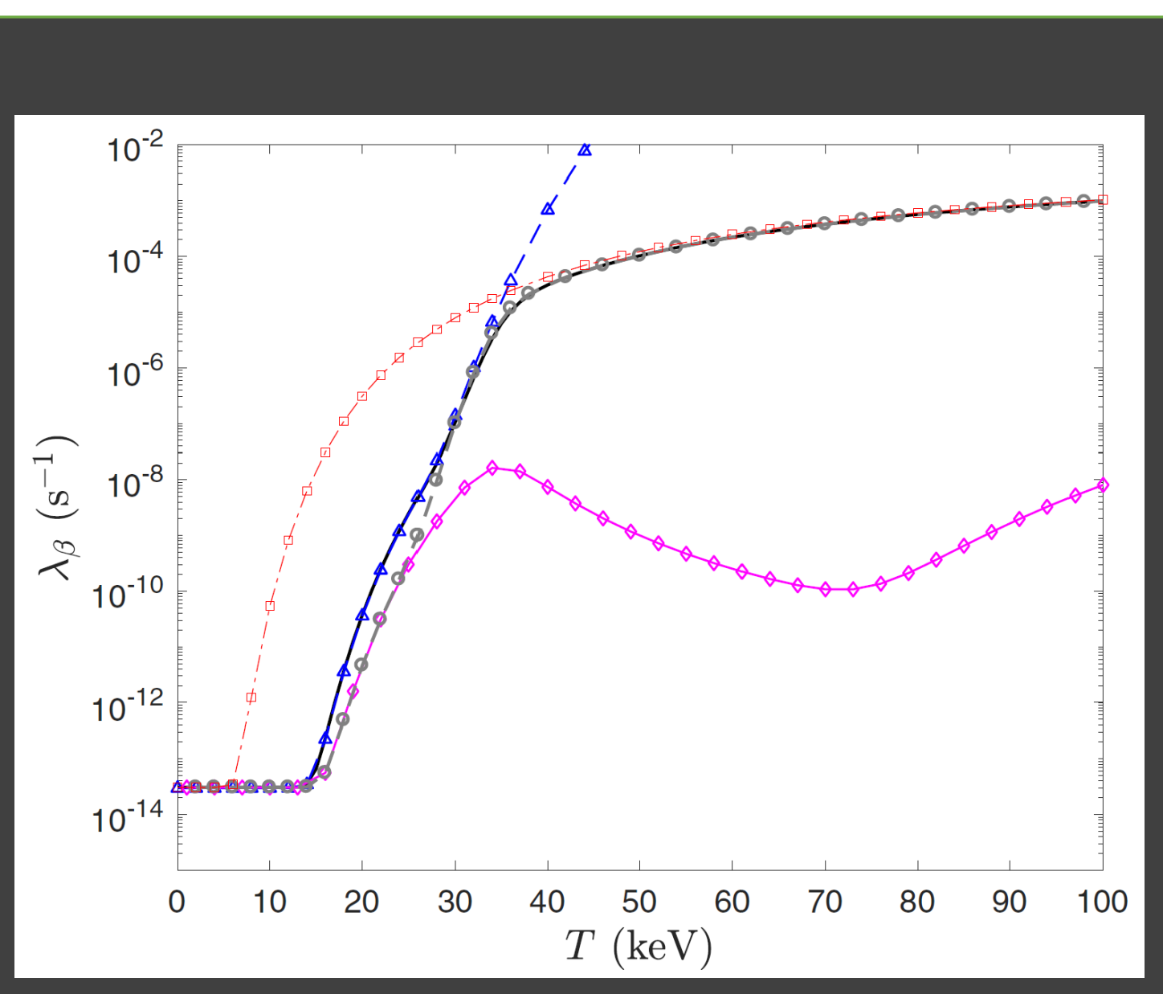
where $n_i$ and $\lambda^{\beta}_i$ are the thermal occupation probability and $\beta$-decay rate of state $i$, respectively. Usually, $n_i$ increases with temperature for the excited states, and their contribution to $\lambda^{\beta}_{\mathrm{eff}}$ increases accordingly. The values of $n_i$ come from the Boltzmann distribution

$$n_i(T) = \frac{2J_i+1}{G(T)} e^{-E_i/T}$$

Here, $J_i$ and $E_i$ are the spin and energy of state $i$, respectively, and $G(T)$ is the nuclear partition function at temperature $T$.







**Solid black**: ground-state effective rate as computed in this work.
**Dashed gray circles:** ground-state effective rate as calculated in this work with Weisskopf rates for unknown internal transitions.
**Dashed blue triangles:** off-equilibrium rate from Coc et.al 1999.
**Solid magenta diamonds:** rate calculated by Raifarth et.al.,2018.
**Dashed-dot red squares:** rate calculated assuming thermal equilibrium.

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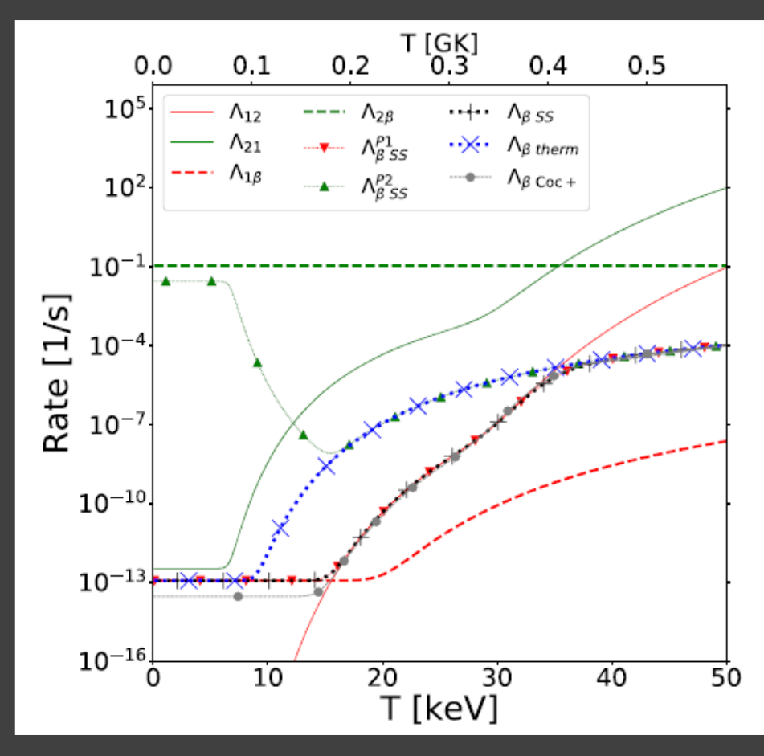
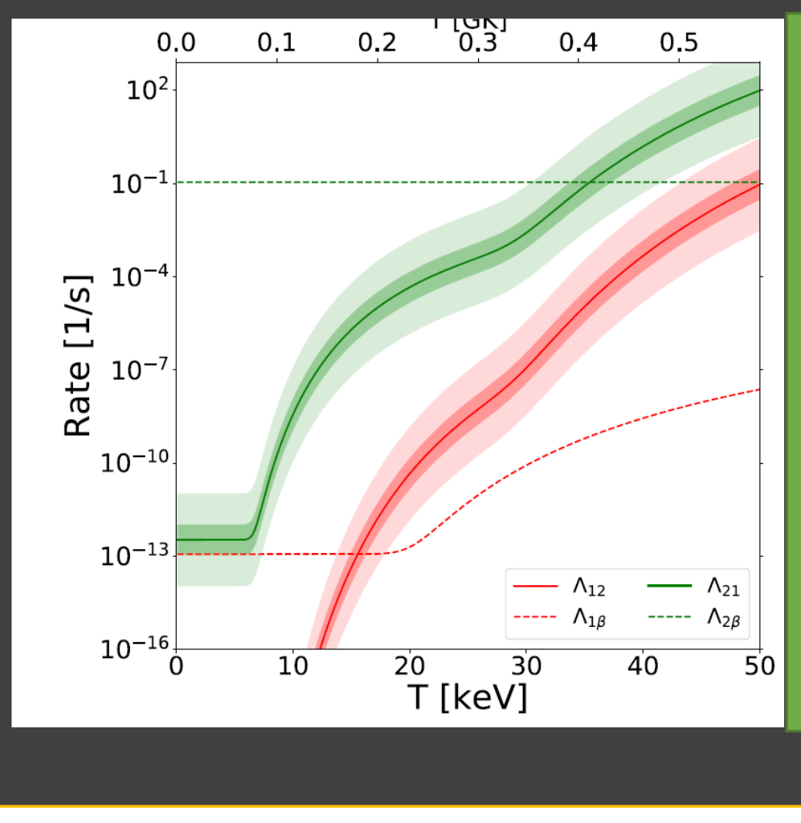
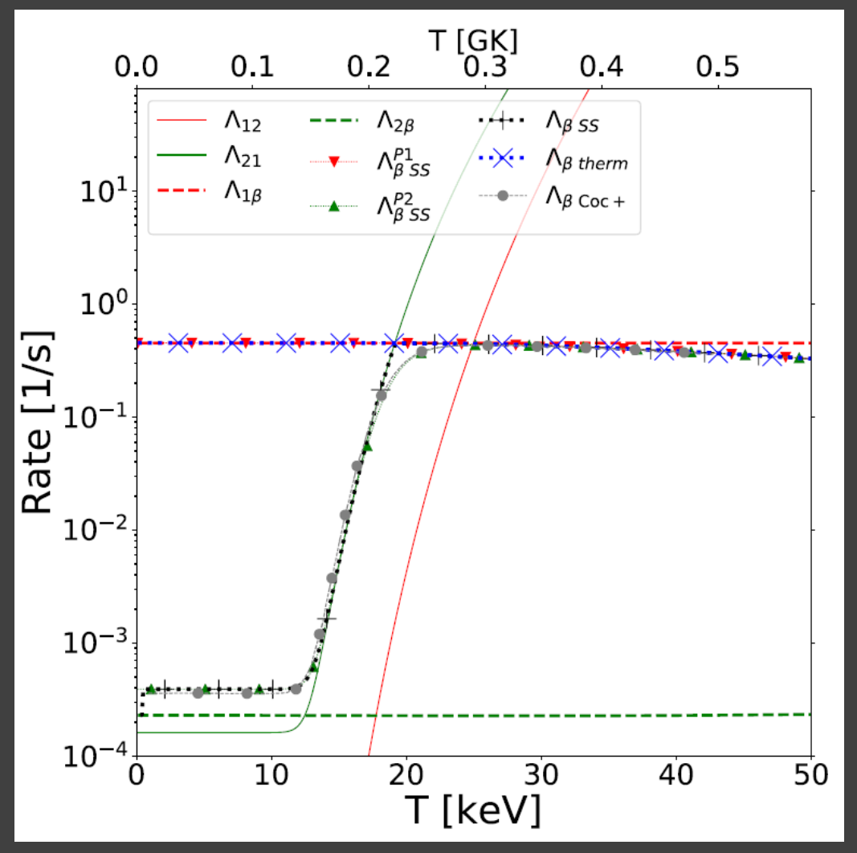
## The effective ground ↔ isomer transition rates



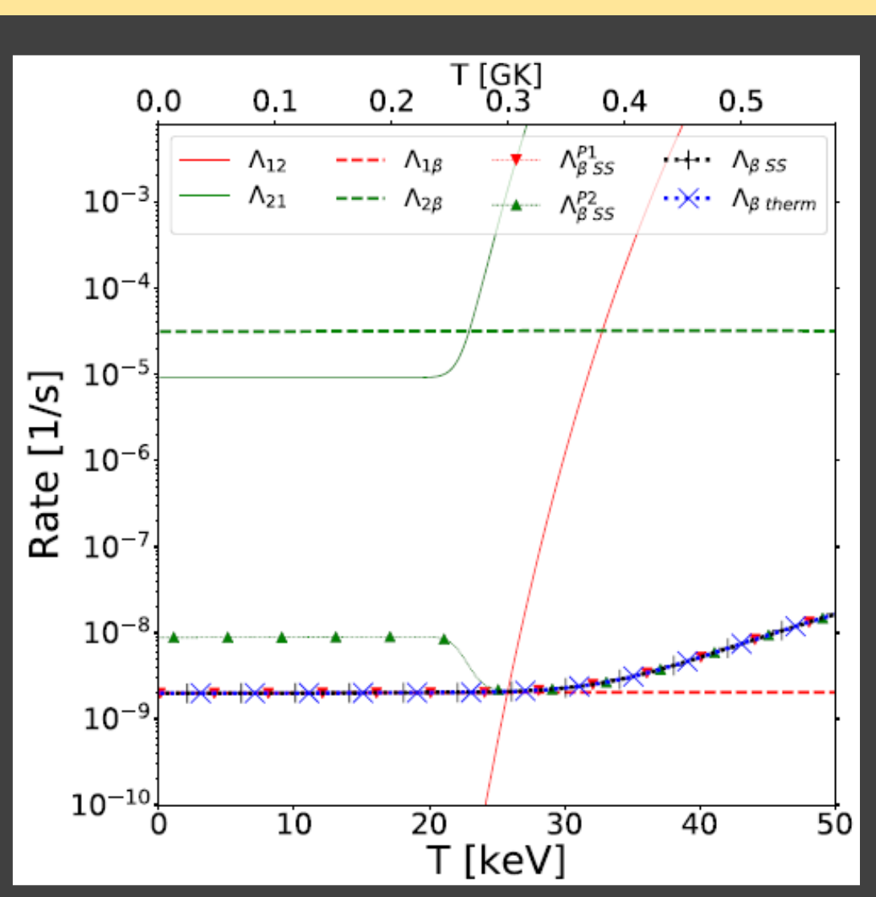
$^{26}$Al transition rates and β-decay rates. Solid lines with no markers show the effective ground ↔ isomer transition rates, and other lines show β-decay rates. Red: ground-state ensemble transition and β-decay rates; down triangles show the steady-state decay rate when only the ground state is produced. Green: isomer ensemble transition and β-decay rates; up triangles show the steady-state decay rate when only the isomer is produced. Black (crosses): steady-state β-decay rate in the absence of production. Blue (X): thermal-equilibrium β-decay rate. Gray (circles): effective decay rate from Coc et al. (1999).



Range of 26Al effective transition rates. Dark bands: measured rates increased/ decreased by one standard deviation, shell model rates multiplied/ divided by a factor of 3. Light bands: measured rates increased/ decreased by two standard deviations, shell model rates multiplied/divided by a factor of 30.



$^{34}$Cl transition and β-decay rates. The lines are as in above



$^{85}$Kr transition and β-decay rates. The lines are as in above

Note: A nuclear isomer has astrophysical consequences and is hence an **"astromer"** below the thermalization temperature. This temperature is sensitive to the various destruction rates that the nuclear species faces, with rapid rates increasing the temperature, thereby widening the range of conditions for which a metastable state is an astromer. At sufficiently high temperatures, the transition rates dominate the destruction rates, the astromer property fades, and the isotope may be considered a single species.

THANK YOU!