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DEGLI STUDI  
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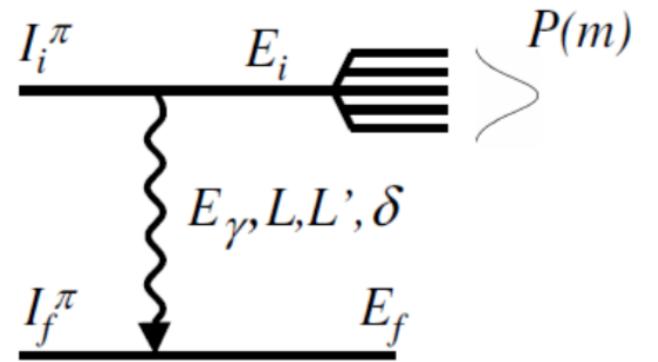
## Angular distribution analysis

The case in  $^{92}\text{Mo}$  formed in  $^6\text{Li} + ^{89}\text{Y}$  fusion-evaporation reaction on  
GALILEO array at INFN-LNL

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## Basic logic:

$$W(\theta) = A_0 \left( 1 + \frac{A_2}{A_0} \cdot B_2 \cdot Q_2 \cdot P_2(\cos\theta) + \frac{A_4}{A_0} \cdot B_4 \cdot Q_4 \cdot P_4(\cos\theta) \right)$$

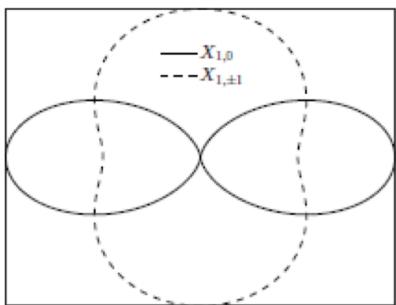


(1) the details of the transition and the spins of the level  $\gg A_k$

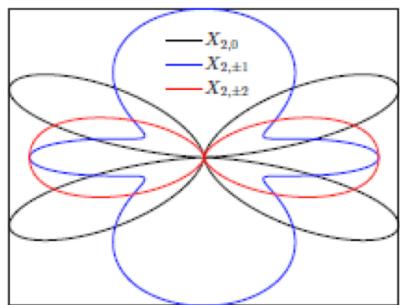
(2) the alignment of initial state  $\gg B_k$

$$A_k(\gamma) = [F_K(LLJ_f J_i) + 2\delta F_K(LL'J_f J_i) + \delta^2 F_K(L'L'J_f J_i)]/(1 + \delta^2).$$

$\ell = 1$



$\ell = 2$



Ferentz-Rosenzweig coefficients

$$F_k(LL'I_1I_2) = (-1)^{I_1+I_2+1} \sqrt{2k+1} \sqrt{2L+1} \sqrt{2L'+1} \sqrt{2I_2+1} \begin{pmatrix} L & L' & k \\ 1 & -1 & 0 \end{pmatrix} \begin{Bmatrix} L & L' & k \\ I_1 & I_1 & I_2 \end{Bmatrix}$$

## Basic logic:

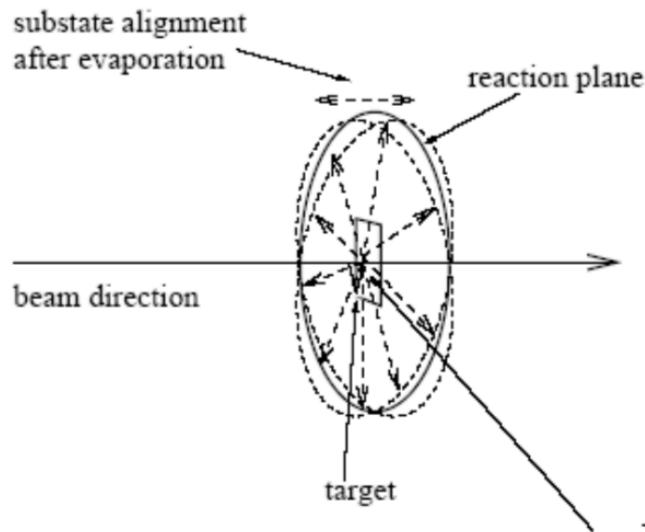
$$W(\theta) = A_0 \left( 1 + \frac{A_2}{A_0} \cdot B_2 \cdot Q_2 \cdot P_2(\cos\theta) + \frac{A_4}{A_0} \cdot B_4 \cdot Q_4 \cdot P_4(\cos\theta) \right)$$

(1) the details of the transition and the spins of the level  $\gg A_k$

**(2) the alignment of initial state  $\gg B_k$**

*Aligned nuclei:  $P(m)=P(-m) \gg B_k$*

*Complete aligned nuclei:  $P(0)=1, P(m \neq 0) = 0 \gg B_k^{max}$*



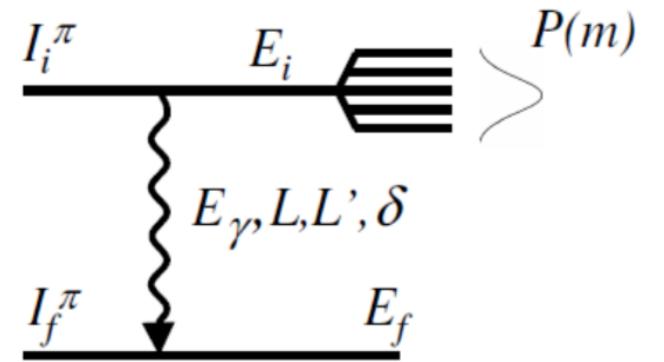
attenuation factor

$$\alpha_k = B_k(J_i)/B_k^{max}(J_i),$$

$$B_k(I_i) = \sqrt{2I_i + 1} \sum_{m=-I}^{+I} (-1)^{I_i-m} \langle I_i m | I_i - m | k 0 \rangle P(m)$$

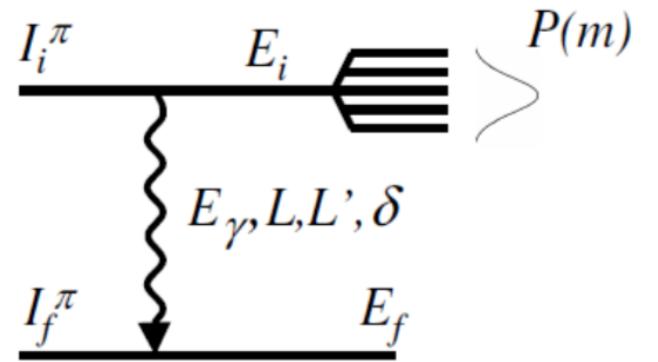
3

$$P(m) = \frac{\exp\left(-\frac{m^2}{2\sigma^2}\right)}{\sum_{m'=-I}^{+I} \exp\left(-\frac{m'^2}{2\sigma^2}\right)}$$



## Basic logic:

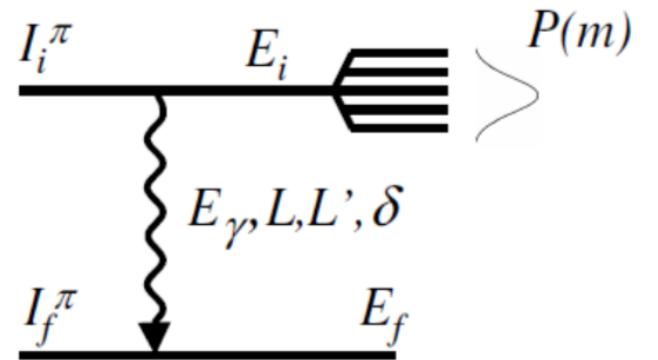
$$W(\theta) = A_0 \left( 1 + \frac{A_2}{A_0} \cdot B_2 \cdot Q_2 \cdot P_2(\cos\theta) + \frac{A_4}{A_0} \cdot B_4 \cdot Q_4 \cdot P_4(\cos\theta) \right)$$



- (1) the details of the transition and the spins of the level  $\gg A_k$
- (2) the alignment of initial state  $\gg B_k$
- (3) The solid angle of detector (measure not only the gamma-ray intensity at one angle but the integral of  $\theta - d\theta \rightarrow \theta + d\theta$ )  $\gg Q_k$**

## Basic logic:

$$W(\theta) = A_0 \left( 1 + \frac{A_2}{A_0} \cdot B_2 \cdot Q_2 \cdot P_2(\cos\theta) + \frac{A_4}{A_0} \cdot B_4 \cdot Q_4 \cdot P_4(\cos\theta) \right)$$



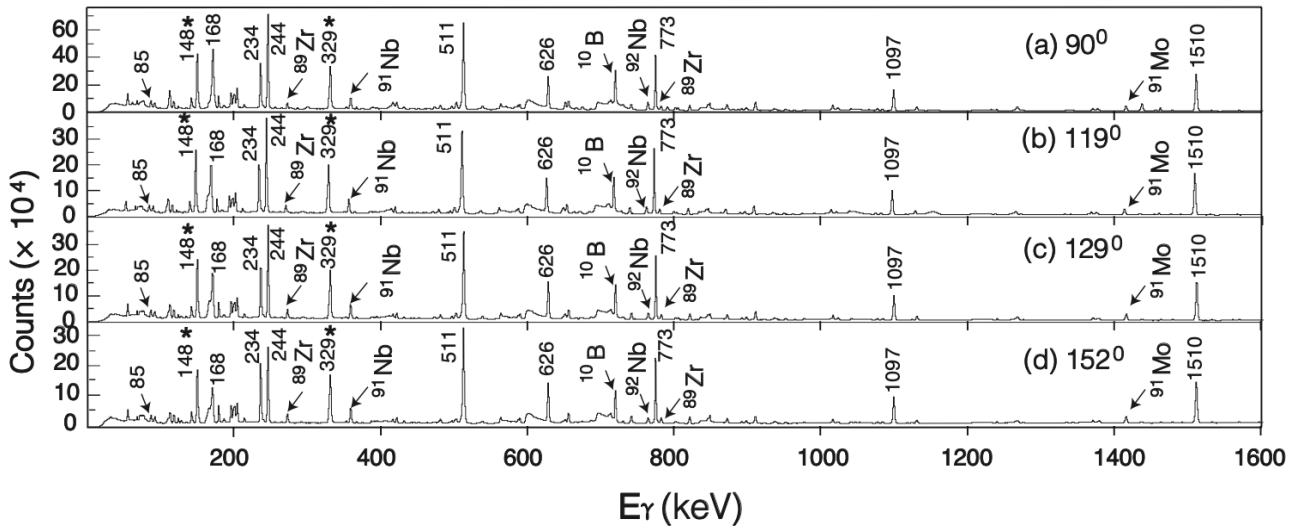
- (1) the details of the transition and the spins of the level  $\gg A_k$
- (2) the alignment of initial state  $\gg B_k$

In the real case, if one of (1) and (2) information is known, the fitting angular distribution coefficient ( $A_{k^*} B_{k^*} Q_k$ ) can give the other information.

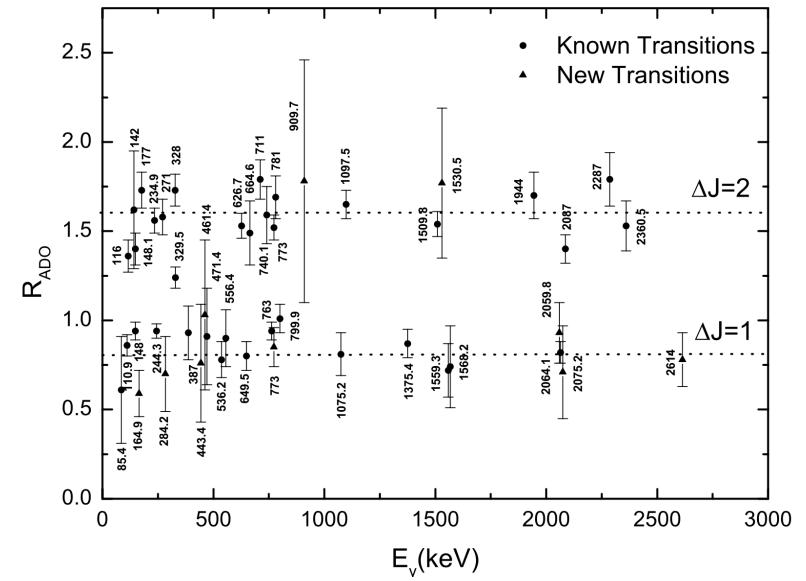
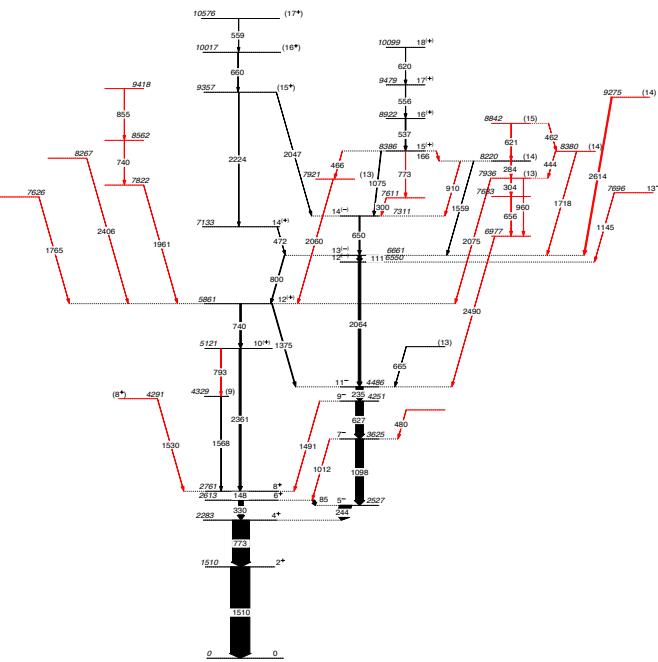
- (1) If the multi-polarity of transition is known, the alignment of initial state can be obtained,**
- (2) If the alignment of initial state is known, the multi-polarity can be deduced.**

# The case of $^{92}\text{Mo}$

- ✓ Beam:  $^6\text{Li}$  @ 34MeV;
- ✓ Target:  $^{89}\text{Y}$  @  $550 \mu\text{g}/\text{cm}^2$  backing on  $340 \mu\text{g}/\text{cm}^2 ^{12}\text{C}$
- ✓ Tandem LNL-INFN, Italy
- ✓ GALILEO array



$$R_{ADO} = \frac{I_{\gamma_1} \text{ at } 152^\circ, \text{ gated with } \gamma_2 \text{ at any detector angle}}{I_{\gamma_1} \text{ at } 90^\circ, \text{ gated with } \gamma_2 \text{ at any detector angle}},$$

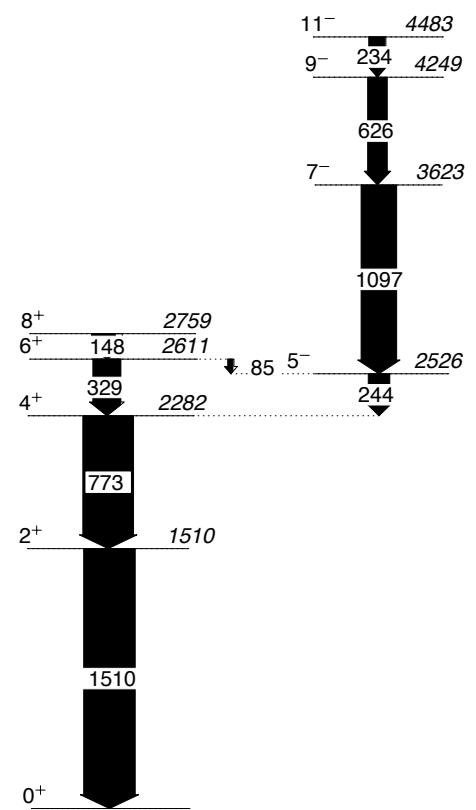
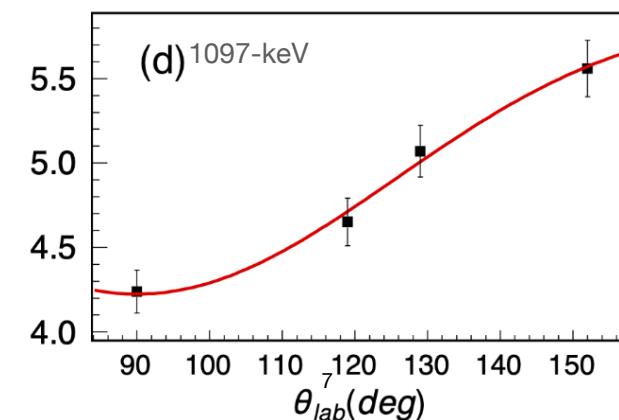
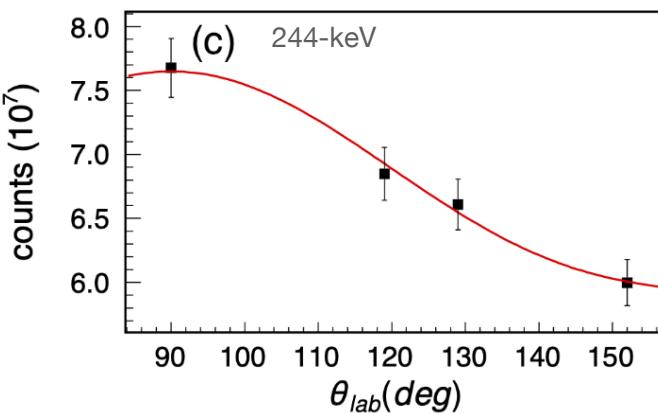
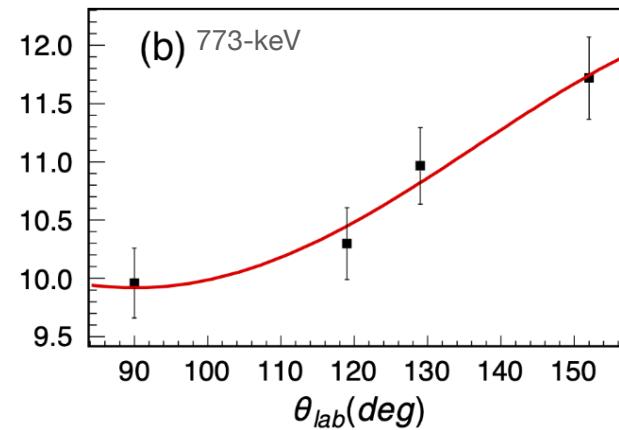
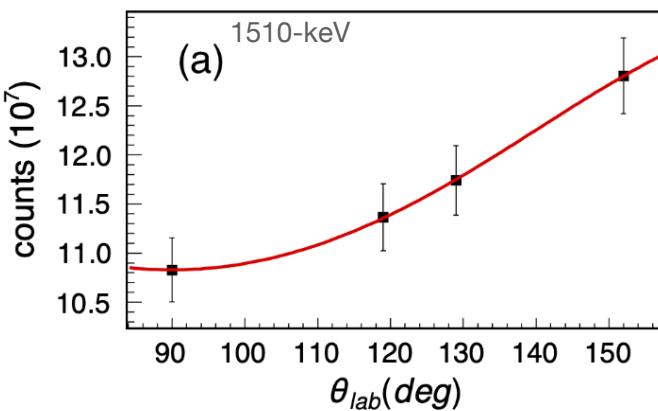


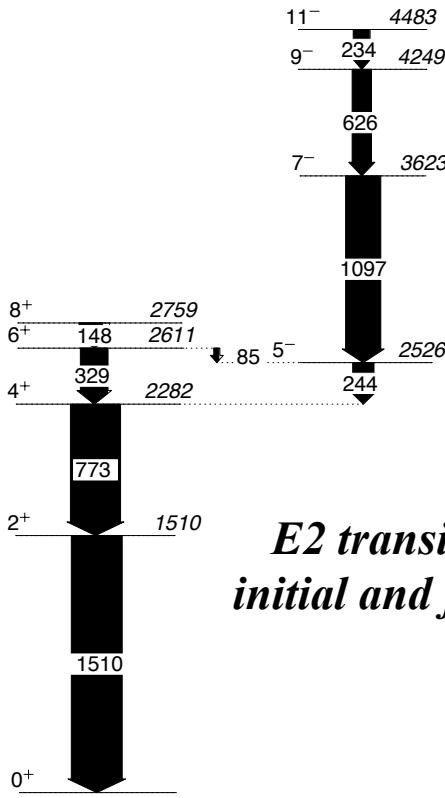
## Angular distribution fitting

$$W(\theta) = N \sum_k A_{kk} P_k(\cos\theta),$$

$E_\gamma$ (keV)	$N (\times 10^7)$	$A_{22}$	$A_{44}$	$J_i^\pi$	$J_f^\pi$
1510	11.64 (18)	+0.15 (4)	+0.01 (5)	$2^+$	$0^+$
773	10.69 (16)	+0.15 (4)	+0.003 (49)	$4^+$	$2^+$
244	6.84 (11)	-0.19 (3)	+0.06 (5)	$5^-$	$4^+$
1097	4.84 (7)	+0.23 (4)	-0.03 (5)	$7^-$	$5^-$
626	4.70 (7)	+0.19 (4)	-0.005 (49)	$9^-$	$7^-$
234	4.08 (6)	+0.24 (4)	+0.0004 (487)	$11^-$	$9^-$

Here ( $A_{kk}=A_{k^*} B_{k^*} Q_k$ )





$$W(\theta) = N \sum_k A_{kk} P_k(\cos\theta),$$

$$A_k(\gamma) = [F_K(LLJ_f J_i) + 2\delta F_K(LL'J_f J_i) + \delta^2 F_K(L'L'J_f J_i)]/(1 + \delta^2).$$

$$A_{kk}(\gamma) = B_k(J_i) A_k(\gamma),$$

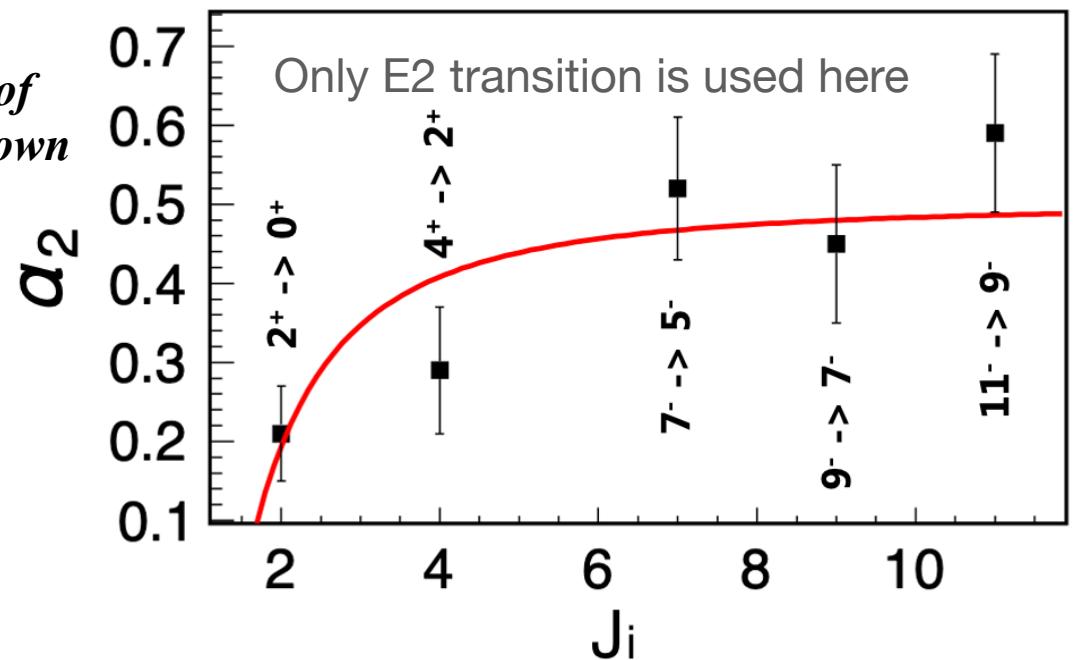
$$\alpha_k = B_k(J_i)/B_k^{\max}(J_i),$$

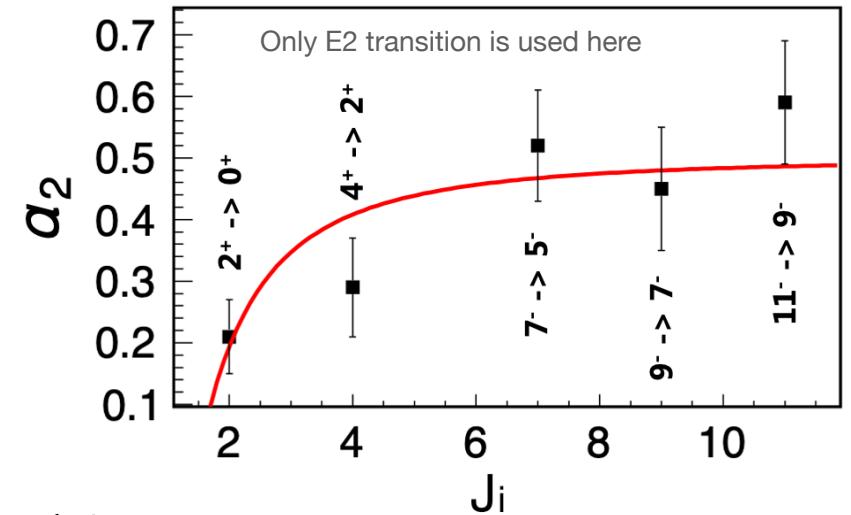
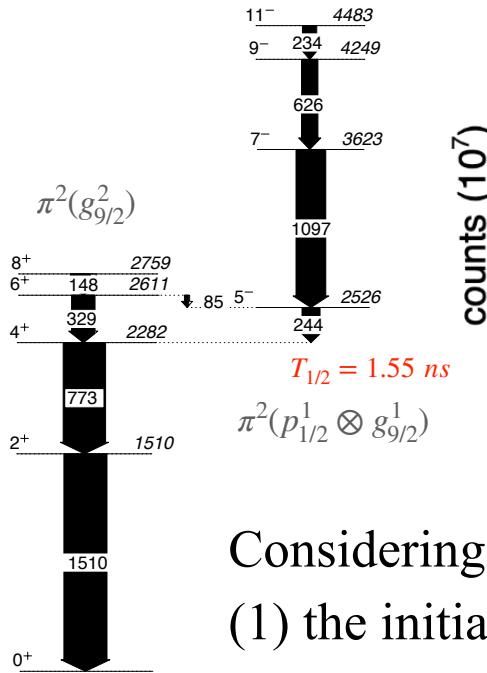
*E2 transitions: the multi-polarity, spin of initial and final states are fixed in the known seniority scheme*

$$\alpha_2 = D(1 - \frac{3\sigma^2}{J_i(J_i + 1)}),$$

### Conclusion:

- (1) The alignment degree of excited states follows a certain pattern in one residual nuclei
- (2) Keep similar value for high spins state, and decrease when approaching spin 0



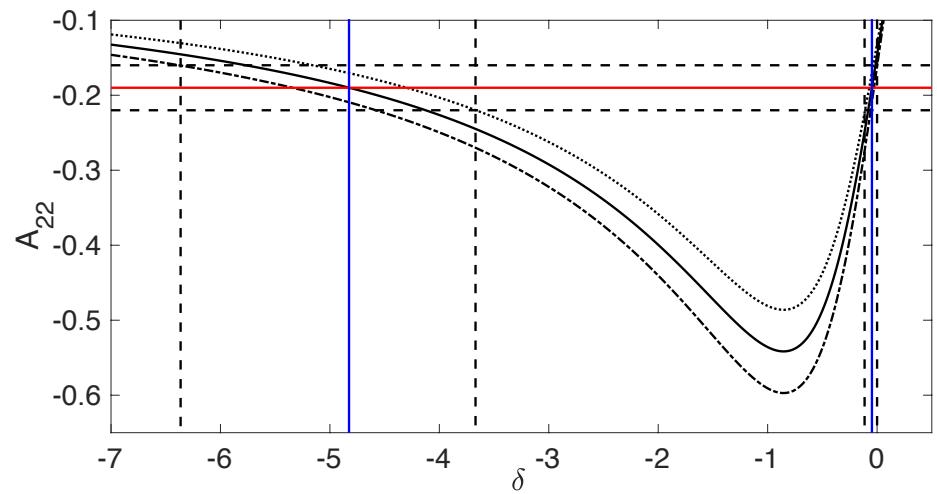


Considering the 244-keV transition between 5- and 4+ state:

- (1) the initial state is long-lived isomer,
- (2) The E1 strength is strongly hindered since no nearby orbitals satisfy the E1 operator.

**If the alignment degree of the initial state 5- can be derived from the fitted curve of attenuation factor, the E1/M2 mixing ratio can be obtained from the angular distribution analysis.**

As a result, two values of  $\delta(E1/M2)$  are obtained in Fig. 5:  $-0.05^{+0.05}_{-0.06}$  and  $-4.82^{+1.15}_{-1.56}$ . The former value

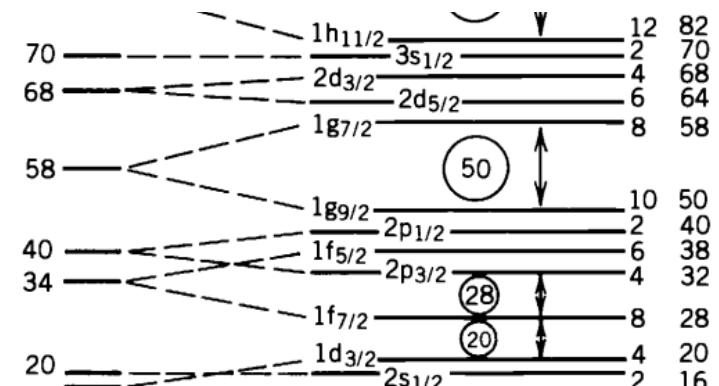


<sup>92</sup> Mo: Z=42, N=50			
11 <sup>-</sup> 4486.0	11 <sup>-</sup> 4519.0	11 <sup>-</sup> 4628.0	
9 <sup>-</sup> 4251.0	9 <sup>-</sup> 4248.0	9 <sup>-</sup> 4357.0	
7 <sup>-</sup> 3624.1	7 <sup>-</sup> 3528.0	7 <sup>-</sup> 3651.0	
8 <sup>+</sup> 2760.5	8 <sup>+</sup> 2707.0	5 <sup>-</sup> 2695.0	
6 <sup>+</sup> 2612.4	6 <sup>+</sup> 2527.0	6 <sup>+</sup> 2482.0	4 <sup>+</sup> 2490.0
5 <sup>-</sup>	6 <sup>+</sup> 2524.0	5 <sup>-</sup> 2297.0	6 <sup>+</sup> 2239.0
4 <sup>+</sup> 2282.6	4 <sup>+</sup> 2032.0		
2 <sup>+</sup> 1509.5	2 <sup>+</sup> 1499.0	2 <sup>+</sup> 1312.0	0 <sup>+</sup> 0.0
0 <sup>+</sup> 0.0	0 <sup>+</sup> 0.0	0 <sup>+</sup> 0.0	

Exp

**jjglek**

**jjglem**



**jjglek    jjglem**

E <sub>γ</sub> (keV)	J <sub>i</sub> <sup>π</sup>	J <sub>f</sub> <sup>π</sup>	B(E2) Theory <sup>a</sup>	B(E2) Theory <sup>b</sup>	B(E2) Expt. <sup>c</sup>
1510	2 <sup>+</sup>	0 <sup>+</sup>	6.24 W.u	5.27 W.u	8.4(5) W.u
773	4 <sup>+</sup>	2 <sup>+</sup>	4.40 W.u	5.07 W.u	< 24 W.u
330	6 <sup>+</sup>	4 <sup>+</sup>	2.96 W.u	3.45 W.u	3.26(11) W.u
627	9 <sup>-</sup>	7 <sup>-</sup>	5.66 W.u	5.92 W.u	no value
235	11 <sup>-</sup>	9 <sup>-</sup>	3.09 W.u	3.61 W.u	3.47(8) W.u

jjglek (proton model space: 1f <sub>5/2</sub> , 2p <sub>3/2</sub> , 2p <sub>1/2</sub> , 1g <sub>9/2</sub> )			jjglem (proton model space: 1f <sub>7/2</sub> , 1f <sub>5/2</sub> , 2p <sub>3/2</sub> , 2p <sub>1/2</sub> , 1g <sub>9/2</sub> )			Expt.
B(E1)	B(M2)	T <sub>1/2</sub>	B (E1)	B(M2)	T <sub>1/2</sub>	T <sub>1/2</sub>
no	8.71×10 <sup>-4</sup> W.u	2.01 ms	8.96×10 <sup>-5</sup> W.u	7.69×10 <sup>-5</sup> W.u	0.25 ns	1.55(4) ns

**jjglek** proton (1f<sub>5/2</sub>, 2p<sub>3/2</sub>, 2p<sub>1/2</sub>, 1g<sub>9/2</sub>)

**jjglem** proton (1f<sub>5/2</sub>, 2p<sub>3/2</sub>, 2p<sub>1/2</sub>, 1g<sub>9/2</sub>) + f<sub>7/2</sub>

As a result, two values of  $\delta(E1/M2)$  are obtained in Fig. 5:  $-0.05^{+0.05}_{-0.06}$  and  $-4.82^{+1.15}_{-1.56}$ . The former value

## Summary

The angular distribution analysis will be powerful to show insight of transition if one of the following information is known:

- (1) the details of the transition and the spins of the level  $\gg A_k$
- (2) the alignment of initial state  $\gg B_k$

The application to AGATA will

- (1) gain larger angle range, better angular resolution
- (2) Open a new window to study mixing ratio of E1/M2 or M1/E2 transitions in low-lying states (if the alignment of initial states can be fixed).