Implementation of the E0 decay into the GOSIA analysis

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3rd GOSIA Workshop, Warsaw 9-10.04.2018

Conversion electrons in GOSIA

- Coulex cross section calculation → matrix elements determined from the γ-ray decay.
- A competetive to γ-ray emission is another electromagnetic process → internal conversion.
- Usually electrons are not measured in Coulex run → GOSIA evaluates the loss in conversion.
- OP, YIEL in GOSIA → **Internal Conversion Coeffcients** for the **Eλ** and **Mλ** transitions (for **λ > 0** !).

$$\boxed{\alpha = \lambda_e / \lambda_\gamma}$$

the ratio of the decay probability arising from γ emision (λ_γ) and from electron emision (λ_e).

- A nonrelativistic calculation gives the analytic relations for α:

$$\alpha(EL) \cong \frac{Z^3}{n^3}\left(\frac{L}{L+1}\right)\left(\frac{e^2}{4\pi\epsilon_0\hbar c}\right)^4\left(\frac{2m_ec^2}{E}\right)^{L+5/2}$$

$$\alpha(ML) \cong \frac{Z^3}{n^3}\left(\frac{e^2}{4\pi\epsilon_0\hbar c}\right)^4\left(\frac{2m_ec^2}{E}\right)^{L+3/2}$$

Depend on :

- element (Z)
- the multipolarity
- γ-ray energy

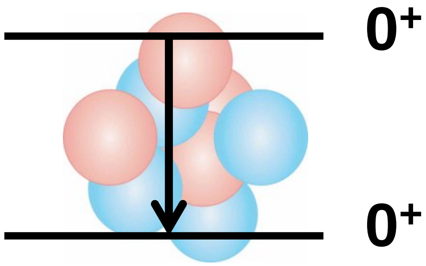
The probability decreases rappidly with energy → *Z* = 80, *E2* transitions **α = 136** @ 50 keV

= **5.5** @ 100 keV

= **2.7 10^{-2}** @ 500 keV

Adopted from: E. Clement, GOSIA Workshop HIL Warsaw 2008

A special case: the *E0* transition



- Occurs between states of the same spin and parity and no momentum is transferred.
- Cannot occur in the emission of a single photon.
- Energy is transferred to a high energy atomic electron.

The E0 transition probability:

$$W(E0)=\frac{1}{\tau(E0)}=\underset{\substack{\swarrow\\\text{internal conversion}}}{W_{ic}(E0)}+\underset{\substack{\downarrow\\\text{electron-positron}\\\text{pair emission}}}{W_{\pi}(E0)}=\underbrace{\rho^{2}(E0)}_{\substack{\text{monopol}\\\text{transition strength}}}\cdot\underbrace{\left[\Omega_{ic}(E0)+\Omega_{\pi}(E0)\right]}_{\substack{\text{„electronic” (non-nuclear)}\\\text{factors (function of Z, ΔE,}\\\text{independent of}\\\text{nuclear properties)}}}$$

Monopole transition strength:

$$\rho(\mathrm{E0})=\frac{\langle f|M(\mathrm{E0})|i\rangle}{eR^{2}}$$

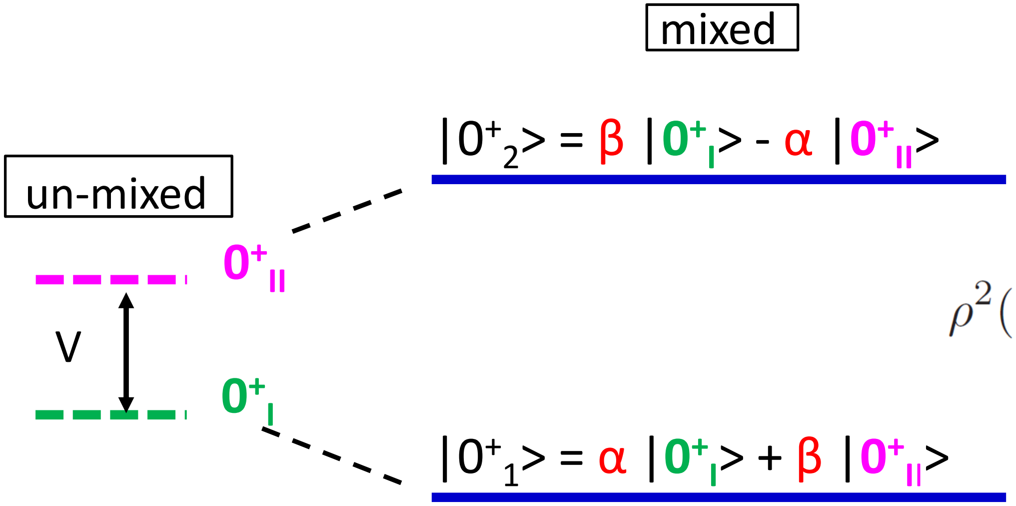
monopole matrix element

nuclear radius

T. Kibedi, R.H. Spear Atomic Data and Nuclear Data Tables 89 (2005) 77–100
J. L. Wood et al., Nuclear Physics A 651 (1999) 323-368

The $E0$ transitions and shape coexistence

J. L. Wood et al.,
NP A 651 (1999) 323



mixed

un-mixed

$|0^+_2\rangle = \beta\,|0^+_I\rangle - \alpha\,|0^+_{II}\rangle$

0^+_{II}

V

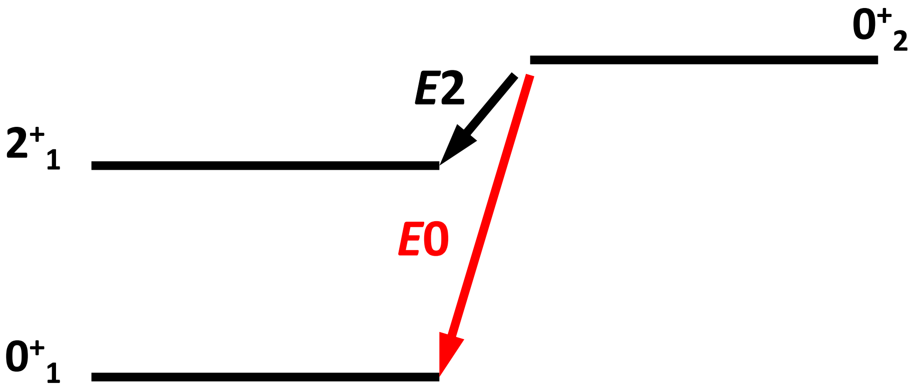
0^+_I

$|0^+_1\rangle = \alpha\,|0^+_I\rangle + \beta\,|0^+_{II}\rangle$

$$\rho^2(E0) = \frac{Z^2}{R_0^4} \cdot \alpha^2(1-\alpha^2)\left[\Delta\langle r^2\rangle\right]^2$$

- **Large $\rho^2(E0)$** values can be associated with **strongly mixed** states in nuclei that exhibit **shape coexistence**.
- Thus the measure of the *E*0 transition is a very common tool to study shape coexistence phenomena.
- The probability to decay through the *E*0 transition contains ***nuclear structure information*** that GOSIA cannot estimate.

The *E0* transition: $0^+_1 \rightarrow 0^+_2$

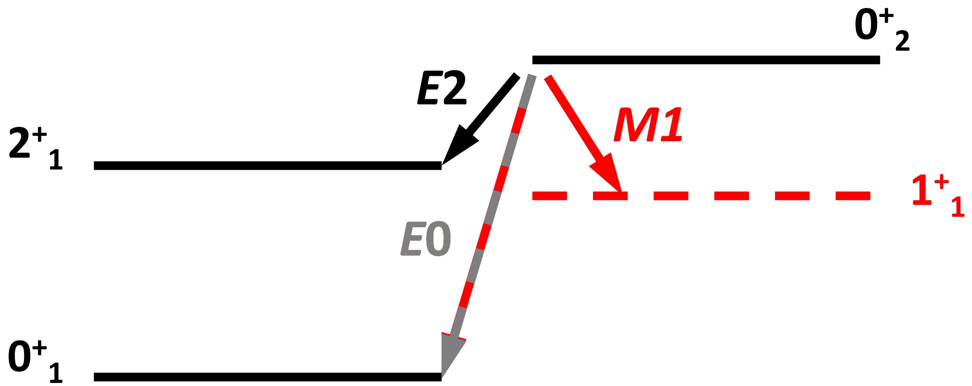


- If the 0^+_2 is populated, the decay can occur through a γ (*E*2) or electrons (*E*0 and *E*2).
- Electrons are **not measured** in typical Coulex experiments and the *E*0 is **not included** in the de-excitation cross section.
- From the *point of view of GOSIA:* the 0^+_2 will decay **entirely through the *E*2** transition. → important effect on the matrix elements connected to 0^+_2

Adopted from: E. Clement, GOSIA Workshop HIL Warsaw 2008

The *E0* transition: $0^+_1 \rightarrow 0^+_2$

Procedure tested and validated for Mo, Kr, Hg, Po, Pb and very recently for Ca and ***Sr***



- The $(0^+_2 \rightarrow 0^+_1)$ / $(0^+_2 \rightarrow 2^+_1)$ branching ratio known.
- Direct inclusion the *E0* decay data into the GOSIA input file currently not possible.

➔ an indirect method need to be utilized:

- in addition to the known level scheme an extra 1^+ state is declared connected to the 0^+_2 state by a M1 transition.
- Since population of excited states proceeds almost exclusively via *E2* transitions, introduction of such an additional state does not affect the calculated excitation pattern.
- The $\langle 1^+_1 || M1 || 0^+_2 \rangle$ matrix element has been fitted in such a way to reproduce known E0/E2 branching ratio.

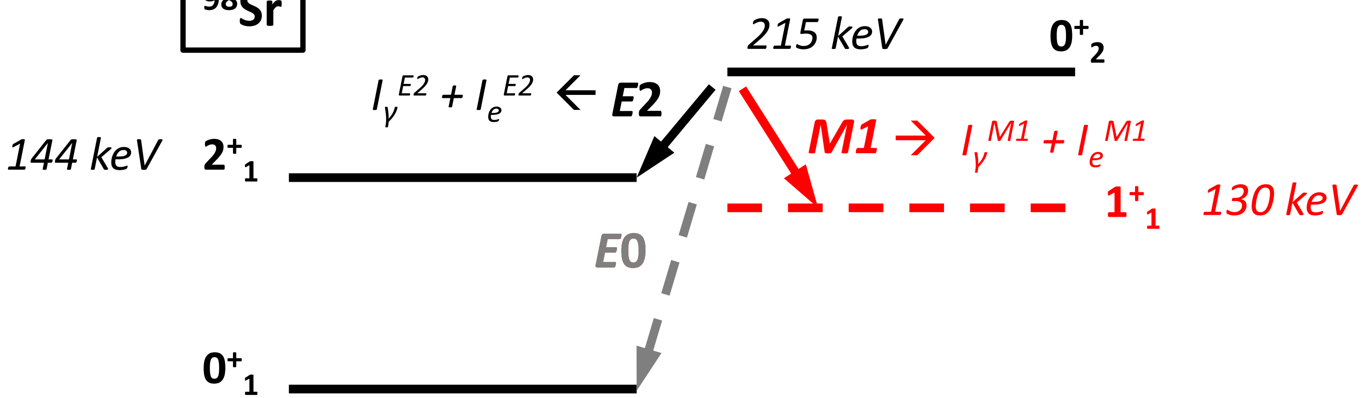
In this way, an alternative decay path of the 0^+_2 state has been included in the calculation !

The *E0* transition: $0^+_1 \to 0^+_2$

Procedure tested and validated for Mo, Kr, Hg, Po, Pb and very recently for Ca and ***Sr***

An example:

^{98}Sr



215 keV **0^+_2**

$I_\gamma^{E2} + I_e^{E2}$ ← **E2**

144 keV **2^+_1**

M1 → $I_\gamma^{M1} + I_e^{M1}$

1^+_1 *130 keV*

E0

0^+_1

E. Clement, M. Zielińska et al., PRC ***94****, 054326 (2016)*

R(*E*0/*E*2) measured in electron spectroscopy following the β decay of ^{98}Rb*

Branching ratios in GOSIA are defined in terms of **γ-ray branching ratios.**

Thus the branching ratio measured in electron spectroscopy, $R(E0/E2) = I_e^{E0} / I_e^{E2} + I_\gamma^{E2}$, needs to be corrected for internal conversion:

$$\boxed{\mathcal{R} = \frac{I_\gamma(0_2^+ \to 1^+)}{I_\gamma(0_2^+ \to 2_1^+)} = R(E0/E2) \times \frac{1+\alpha_{E2,71\,\mathrm{keV}}}{1+\alpha_{M1,85\,\mathrm{keV}}}}$$

additional data point need to be declared in OP, YIEL in GOSIA

* F. Schussler *et al., Nucl. Phys. A* ***339, 415 (1980),*** J. Park *et al., Phys. Rev. C* ***93, 014315 (2016)***

The *E0* transition in the GOSIA analysis

Each case is probably slightly different !

⬇

The *E0* transitions can also occur between 2+, 4+, 6+ … states

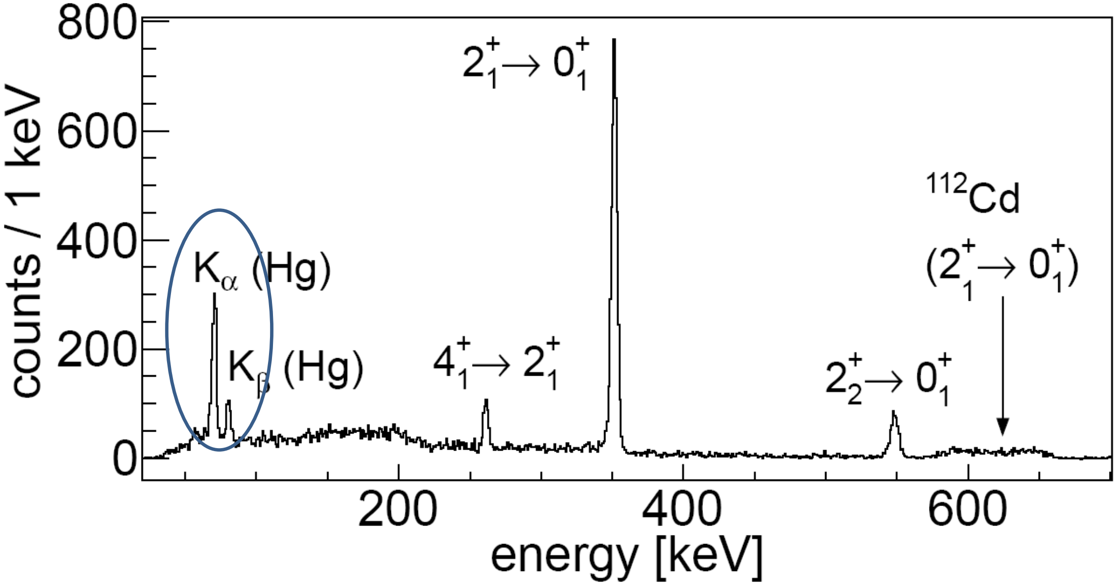
- less known / measured
- such information will soon become available → future **Coulex** + **SPEDE** experiments at **HIE-ISOLDE**.

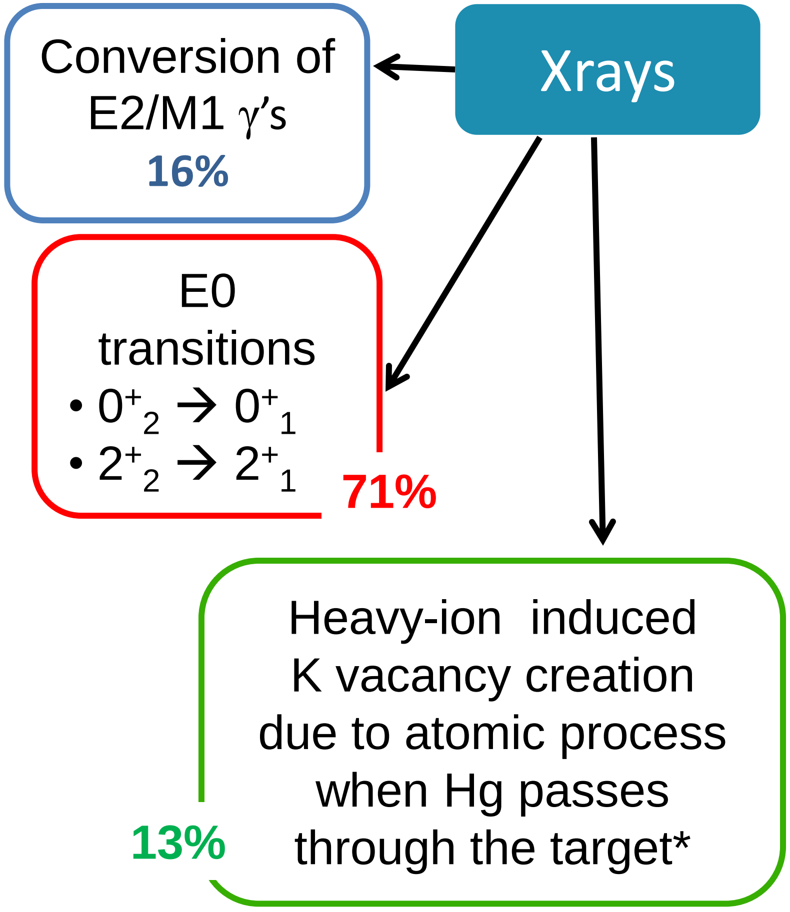
Strongly converted transitions between lowest lying 2^+ states in ^{182,184}Hg

The *E*0 transitions in ^{82}Hg:

N. Bree, KU Leuven, PhD thesis

^{182}Hg@2.85 MeV/u on ^{112}Cd target





Conversion of E2/M1 γ's **16%**

← Xrays

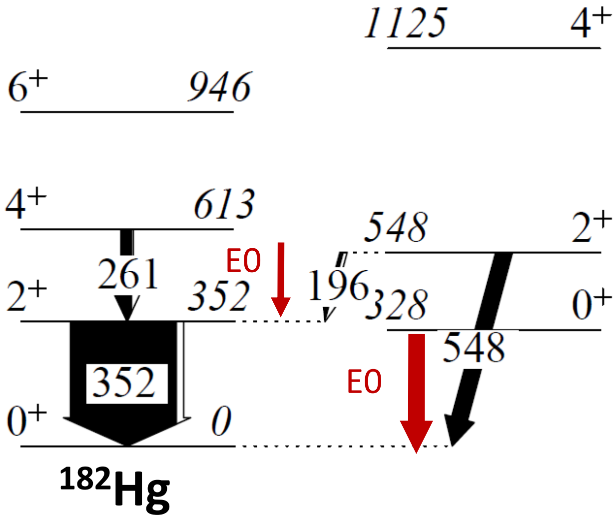
E0 transitions
- $0^+_2 \rightarrow 0^+_1$
- $2^+_2 \rightarrow 2^+_1$

71%

Heavy-ion induced K vacancy creation due to atomic process when Hg passes through the target*

13%

N. Bree, KWL, et al., NIM B 360 (2015) 97



- the K_α and K_β X rays originating from mercury:
  - ✓ in prompt coincidence with a particle
  - ✓ Doppler broadened

Complex information on the *E*0 transitions in ^{182,184}Hg:

1. The analysis of the K X-ray peaks measured for ^{182,184}Hg revealed that the $2^+_2 \rightarrow 2^+_1$ transitions are strongly converted

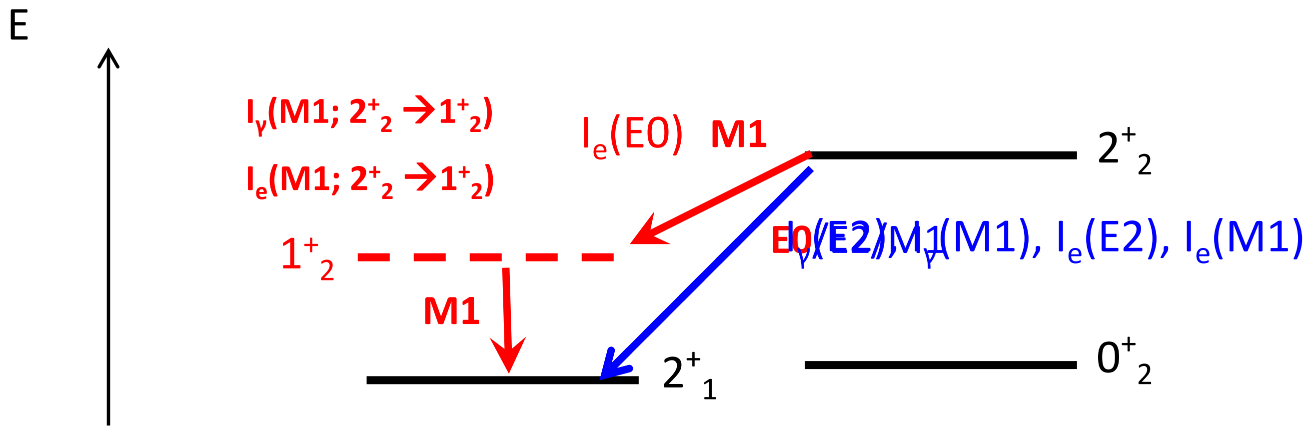
   → intensities of the $0^+_2 \rightarrow 0^+_1$ and $2^+_2 \rightarrow 2^+_1$ E0 transitions deduced

2. Moreover, the total conversion coefficient $\boldsymbol{\alpha_{tot}(2^+_2 \rightarrow 2^+_1)}$ measured in β/EC decay of ^{182,184}Tl , was extracted for ^{182}Hg (**7.2 +/- 1.3**) and ^{184}Hg (**14.2 +/- 3.6**).

E. Rapisarda et al., J. Phys. G: Nucl. Part. Phys. 44, 074001 (2017).

Crucial for the Coulomb excitation analysis as they contain large E0 components which need to be taken into account !

E0 transition in the GOSIA analysis



- declare a ”virtual” state (e.g. 1^+) in the LEVE section in GOSIA;
- declare the *M*1 matrix elements connecting 1^+ states with the 2^+ states (NOTE → the 1^+ state will not be populated in the excitation);
- the $2^+_2 \rightarrow 1^+$ branch simulates the *E*0 -decay of the 2^+_2 state to the 2^+_1 while the $2^+_2 \rightarrow 2^+_1$ branch describes the $I_\gamma(E2)$, $I_\gamma(M1)$, $I_e(E2)$, $I_e(M1)$ decay paths.

The *E*0 components are represented in the GOSIA analysis by an *M*1 γ-ray decay.

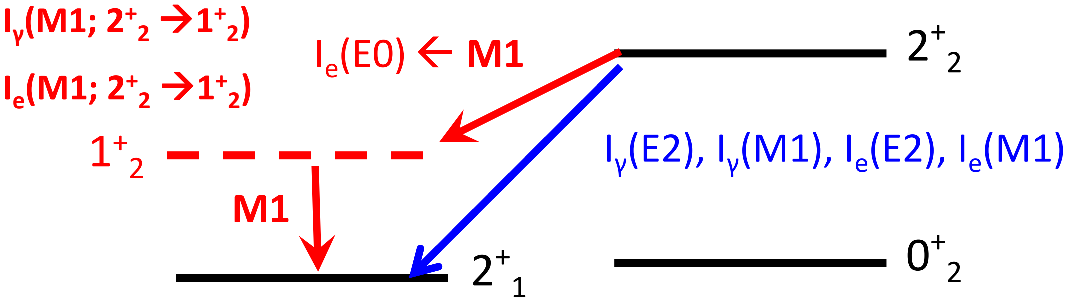
The experimental intensity $I^{E0}\,(2^+_2 \rightarrow 2^+_1)$, declared in GOSIA (tape3), needs to be corrected for internal conversion:

$$I^{E0,corr}(2^+_2 \rightarrow 2^+_1) = \frac{I^{E0}(2^+_2 \rightarrow 2^+_1)}{1+\alpha(M1; 2^+_2 \rightarrow 1^+_2)}$$

$\alpha_{tot}(2^+_2 \to 2^+_1)$ in the GOSIA analysis

K. Wrzosek-Lipska, et al.,
PRC to be published

- $\alpha_{tot}\,(2^+_2 \to 2^+_1)$ **cannot be directly included** in the GOSIA analysis.



- $\alpha_{tot}\,(2^+_2 \to 2^+_1)$ is represented in the GOSIA analysis by branching ratio which is interpreted as:

$$BR\left(\frac{2_2^+\to 1_2^+}{2_2^+\to 2_1^+}\right)=\frac{I^{E0}(2_2^+\to 2_1^+)}{I_\gamma^{E2+M1}(2_2^+\to 2_1^+)}=\alpha_{tot}\left(2_2^+\to 2_1^+\right)-\frac{I_e^{E2}}{I_\gamma^{E2}+I_\gamma^{M1}}-\frac{I_e^{M1}}{I_\gamma^{E2}+I_\gamma^{M1}}$$

- this ratio can be further expressed by the $\alpha_{tot}\left(2_2^+\to 2_1^+\right)=\dfrac{I_e^{E0}+I_e^{E2}+I_e^{M1}}{I_\gamma^{E2}+I_\gamma^{M1}}$

$$BR\left(\frac{2_2^+\to 1_2^+}{2_2^+\to 2_1^+}\right)=\alpha_{tot}(2_2^+\to 2_1^+)-\frac{I_\gamma^{E2}(2_2^+\to 2_1^+)\cdot\alpha(E2;2_2^+\to 2_1^+)}{I_\gamma^{E2+M1}(2_2^+\to 2_1^+)}-\frac{I_\gamma^{M1}(2_2^+\to 2_1^+)\cdot\alpha(M1;2_2^+\to 2_1^+)}{I_\gamma^{E2+M1}(2_2^+\to 2_1^+)}$$

- correcting for the experimental intensity $I^{E0}\,(2^+_2 \to 2^+_1)$ (→ see previous slide) and expressing ($I_\gamma^{E2/M1}$ / I_γ^{M1} + I_γ^{E2}) term by $\delta(E2/M1)$:

$$\boxed{BR\left(\frac{2_2^+\to 1_2^+}{2_2^+\to 2_1^+}\right)=\left[\alpha_{tot}(2_2^+\to 2_1^+)-\frac{\delta^2}{\delta^2+1}\cdot\alpha(E2;2_2^+\to 2_1^+)-\frac{1}{\delta^2+1}\cdot\alpha(M1;2_2^+\to 2_1^+)\right]\cdot\frac{1}{1+\alpha(M1;2_2^+\to 1_2^+)}}$$

Future:

- Experimental information on the *E*0 transitions between non-zero spin states will be more and more available.
- Particularly future Coulomb excitation experiments at **HIE-ISOLDE** will benefit from the use of electron spectrometer **SPEDE** → a direct way of detecting the ***E*0 transitions**, which are of great importance for nuclei from the **light lead region**.

See the next talk of Ph. Papadakis: „The SPEDE spectrometer for Coulomb excitation experiments at HIE-ISOLDE"

- The *E*0 transitions may play an important role between non-yrast 2^+, 4^+,... states

Y. Xu et al., PRL 68 26 (1992) 3853, γ-ray and EC spectroscopy:

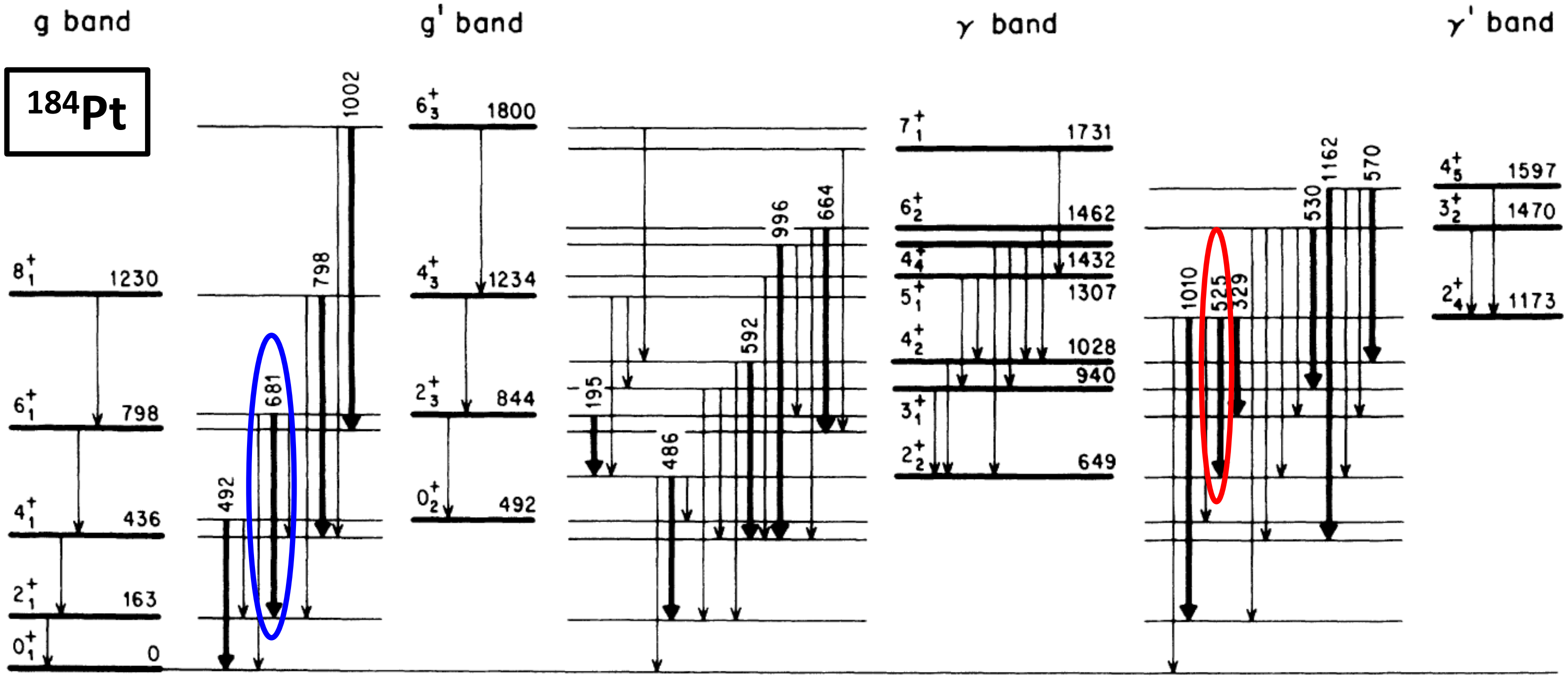


TABLE I. Low-lying $\Delta I = 0$ transitions in ^{184}Pt.

Assignment[a] $I_i \rightarrow I_f$		E_γ(keV)	α_K(expt.)	Theory[b] α_K(M1)	α_K(E2)	$\frac{\alpha_K\text{(expt.)}}{\alpha_K\text{(M1,th.)}}$	%E0	%M1	%E2
$0_2 \rightarrow 0_1$	g' → g	492	>5.3	0.071	0.019	> 75			
$2_2 \rightarrow 2_1$	γ → g	486	0.051(5)	0.073	0.020	0.7(1)	0(1)	82(5)	18(4)
$2_3 \rightarrow 2_1$	g' → g	681	0.30(3)	0.030	0.0095	10(1)	22(2)	32^{+21}_{-29}	46^{-21}_{+29}
$2_3 \rightarrow 2_2$	g' → γ	195	0.9(3)	0.86	0.18	1.0(3)	< 15		
$2_4 \rightarrow 2_1$	γ' → g	1010	0.012(4)	0.011	0.0044	1.1(4)	<0.75		
$2_4 \rightarrow 2_2$	γ' → γ	525	0.36(4)	0.060	0.017	6.0(7)	22(2)		
$2_4 \rightarrow 2_3$	γ' → g'	329	0.19(5)	0.21	0.049	0.9(3)	< 12		

Example adopted from: E. Clement, GOSIA Workshop HIL Warsaw 2008

Future:

- Experimental information on the *E*0 transitions between non-zero spin states will be more and more available.
- Particularly future Coulomb excitation experiments at **HIE-ISOLDE** will benefit from the use of electron spectrometer **SPEDE** → a direct way of detecting the ***E*0 transitions**, which are of great importance for nuclei from the **light lead region**.

See the next talk of Ph. Papadakis: „The SPEDE spectrometer for Coulomb excitation experiments at HIE-ISOLDE"

- The *E*0 transitions may play an important role between non-yrast 2^+, 4^+,... states populated in multistep Coulomb excitation → the use of indirect method to implement the *E*0 components becomes rather impossible then due to the complexity of the analysed level scheme.
- We may end up with a nice set of experimental Coulex data but not being able to analyze them or to obtain an unambiguous results !
- Direct inclusion of the *E*0 decay into the GOSIA code is strongly needed.

Summary:

1. The ***E0*** decay is currently **not directly included** into the GOSIA.
2. An indirect method is utilized:
   → the **fake 1^+** state is declared in addition to know level scheme and the E0 decay is simulated via ***M*1 transition**.

2. The choice of the excitation energy of the virtual 1^+ state is arbitrary.
   It was checked that changing this energy does not influence the final results.

3. The use of *M*1 multipolarity to represent the *E*0 decay paths is also an arbitrary choice, however, it **does not affect the excitation process.**

4. Other possibilities e.g., ***M*2 transitions**, were also considered and no influence on the final solution was noted (for the Hg case).

5. Although the method seems to be rather *„straight forward"* in practice each case may require slightly different treatment depending on what kind of experimental data are known for the *E*0 transitions (*I*(*E*0), *E*0/*E*2, α_{tot}).

6. This method becomes unpractical when *E*0 transitions occur between higher-lying, non-yrast 2^+, 4^+,… states populated in multistep Coulex.

7. Direct inclusion of the *E*0 decay into the GOSIA code is currently a strong need !