# Introduction to GOSIA calculations

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# What do you need...

http://www-user.pas.rochester.edu/~gosia/mediawiki

- GOSIA source code (you need fortran compiler)
- GOSIA manual (pdf file)

**More reliable manual:**
www.slcj.uw.edu.pl/gosia

- The current version (20120510) of the Gosia manual
- The latest release (20110524.2) of Gosia
- The latest release (2_20081208.14) of Gosia2, for analysing simultaneous Coulomb excitation of target and projectile, using a common normalization.
- The current version of Rachel, the Gosia interface, can be downloaded as a zip file or a Git repository here: master branch . Feel free to fork and contribute.
- Pawel, the Gosia version to treat excitation of a nucleus in an isomer state
- ANNL (Anneal), a special version of Gosia developed by Rich Ibbotson that uses simulated annealing techniques to locate minima
- Sigma, the 2006 Fortran source code for deducing the quadrupole invariants from the E2 matrix elements determined by Gosia
- GREMLIN, the gamma-ray detector efficiency code developed for use with GOSIA in 1987 by Alexander Kavka
- The set of demonstration files to accompany the Gosia tutorial in chapter 14 of the Gosia Manual

- Sample input file
- Some research done before

  and
- ...a lot of patience

# Some basic facts

- GOSIA is a Rochester – Warsaw **semiclassical coupled-channel Coulomb excitation least-squares search code**, developed 30 years ago by T.Czosnyka, D.Cline, C.Y.Wu and continuously upgraded.

  http://www.pas.rochester.edu/~cline/Gosia/index.html
  www.slcj.uw.edu.pl/gosia

- GOSIA is used for:

  - **analysis** (multidimensional fit of matrix elements to the data)

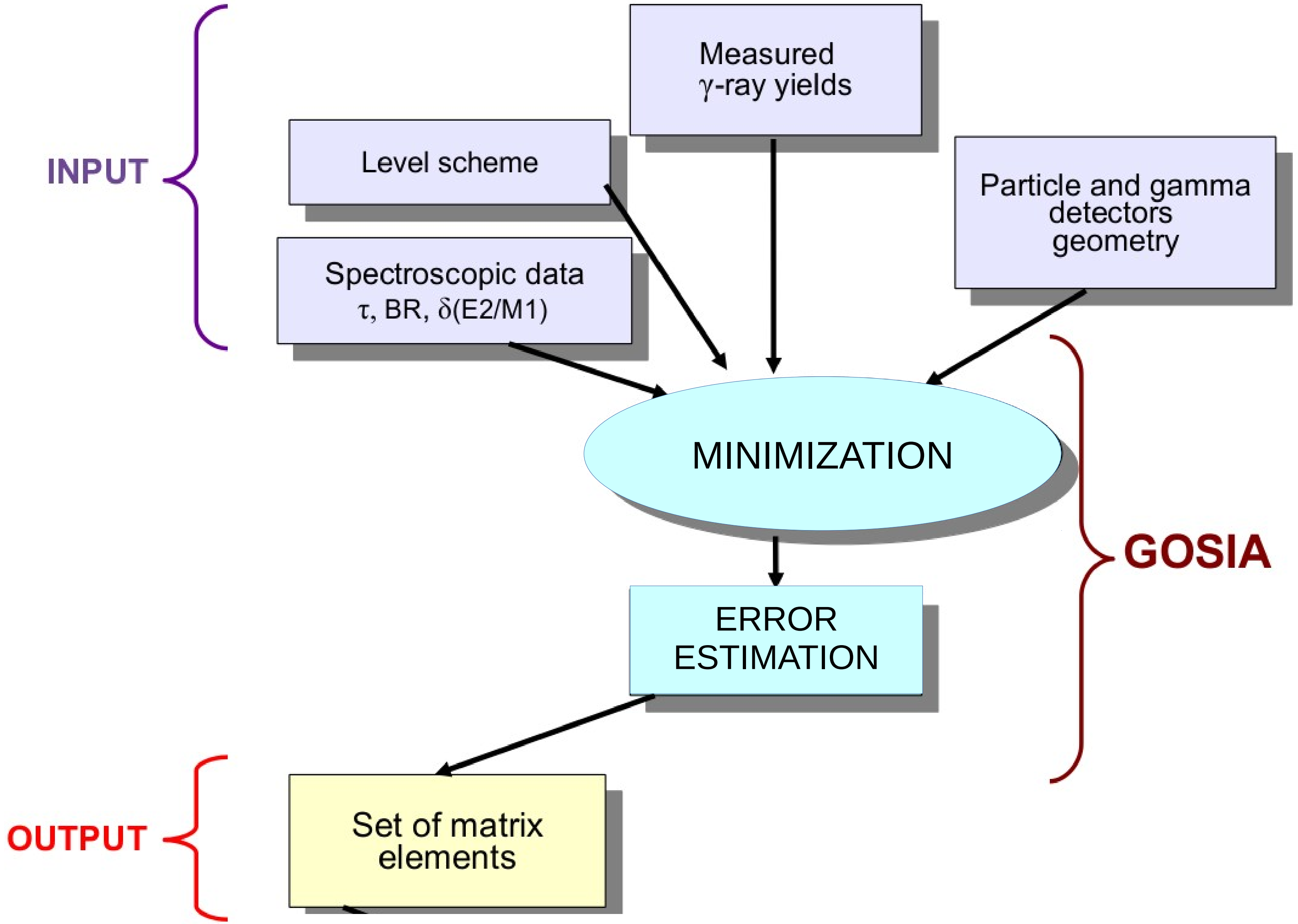
  - **simulations** (probability of excitation, intensities of the gammas)

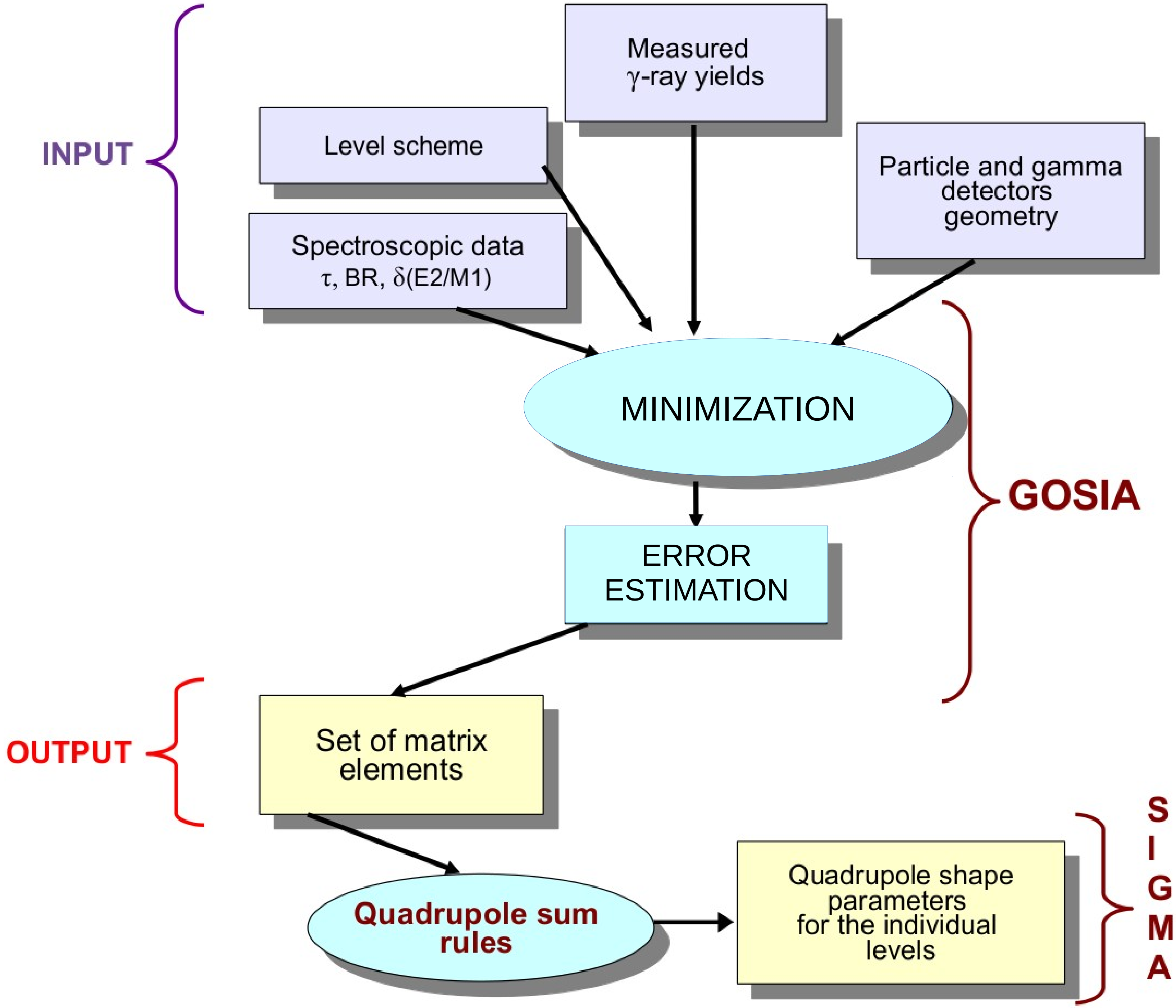
- GOSIA is a **fortran** code so better get used to reading it (*errors send you to the line number, not to the line in your input file)
- GOSIA is a command line program (unless you use GUI)
- Input file looks strange and scary..
- **Different files needed** (options: POIN, STAR, INTG/INTI, MINI, ERRO... require separate input files)
- Be critical and use GOSIA with caution

We are here to help you! :)

# How does it work?

- GOSIA solves the set of differential equations, calculates the **excitation probabilities**, gives you the **level populations** and **gamma-ray intensities**
- To get the numbers you **MUST** specify the **experimental conditions** (level scheme, matrix elements, spectroscopic data, gamma and particle detection system)
- Additional effects are considered here: gamma detection material and **efficiency**, internal electron conversion


Measured
γ-ray yields
Level scheme
Particle and gamma
detectors
geometry
Spectroscopic data
τ, BR, δ(E2/M1)
INPUT
MINIMIZATION
GOSIA
ERROR
ESTIMATION
OUTPUT
Set of matrix
elements


INPUT
Measured
γ-ray yields
Level scheme
Particle and gamma detectors geometry
Spectroscopic data
τ, BR, δ(E2/M1)
MINIMIZATION
GOSIA
ERROR ESTIMATION
OUTPUT
Set of matrix elements
Quadrupole sum rules
Quadrupole shape parameters for the individual levels
S I G M A

# Before you start

- Do the **research**: what do you know about the isotope of interest: go through the data base, check the **level scheme**, look for known **lifetimes**, **branching ratios**, B(E0,E1,E2,E3..), B(M1), **mixing ratios, quadrupole moments**. If you are lucky and you find some spectroscopic data for your nucleus, recalculate the transition strengths into matrix elements. Read the papers. If something is evaluated in the data basis as an average value it doesn't mean it is the value you should use!
- **Ask theorists!**
- http://bricc.anu.edu.au/ - **electron conversion coefficient** calculator
- Calculate the **SAFE energy** (simulations)
- What is the **beam**? Be sure about the energy and scattering angles
- What is the **target**? How thick? How complex? Energy loss of the beam in the target material is important (ELO, SRIM programs)
- **Normalization** method: known target excitation or lifetimes?
- **Detectors**:
  - **Gamma array:** how many? How far from the target? Material? Size? Efficiency?
  - **Particle array:** theta and phi angles, the geometry (CD, PIN, MCP...), dead pixels, useful detection range?

# GOSIA input structure

1. OP,FILE – header files (TAPEs)

2. OP,TITL

3. OP,GOSI (with fit) - OP,COUL (without fit)

- LEVE

- ME

- EXPT

- CONT

END,

4. OP,YIEL

5. OP,RAW

6. OP,INTG/INTI

7. OP,MINI

8. OP,ERRO

9. OP,POIN

10. OP,STAR

11. OP,THEO

12. OP, MAP

13. OP, REST

14. OP,GDET

15. OP,SIXJ

# GOSIA input file: OP,FILE

| | |
|---|---|
| **22 3 1** | |
| **mini.out** | ← Output file name |
| **9 3 1** | |
| **gdet.f9** | ← OP,GDET output |
| **8 3 1** | |
| **gdet.f8** | ← OP,GDET (if OP,RAW used) |
| **12 3 1** | |
| **matrix.me** | ← Matrix elements |
| **3 3 1** | |
| **yield.f3** | ← Gamma yields |
| **4 3 1** | |
| **corr.f4** | ← Corrected gamma yields (after OP,INTG / INTI) |
| **7 3 1** | |
| **map.f7** | ← OP,MAP output |
| **14 3 1** | |
| **sixj.14** | ← OP,SIXJ output (if this option used) |
| **0 0 0** | |

# GOSIA input file: OP,GDET

```
OP,FILE
22 3 1
gdet.out
9 3 1
gdet.f9
8 3 1
gdet.f8
0 0 0
OP,TITL
Gamma detectors
OP,GDET
-1
0 9.5 14.0 22
0 0 0 0 0 0 0
OP,EXIT
```

**This option gives the information about the gamma detectors**

# GOSIA input file: OP,GDET

```
OP,FILE
22 3 1
gdet.out
9 3 1
gdet.f9
8 3 1
gdet.f8
0 0 0
OP,TITL
Gamma detectors
OP,GDET
-1
0 9.5 14.0 22
0 0 0 0 0 0 0
OP,EXIT
```

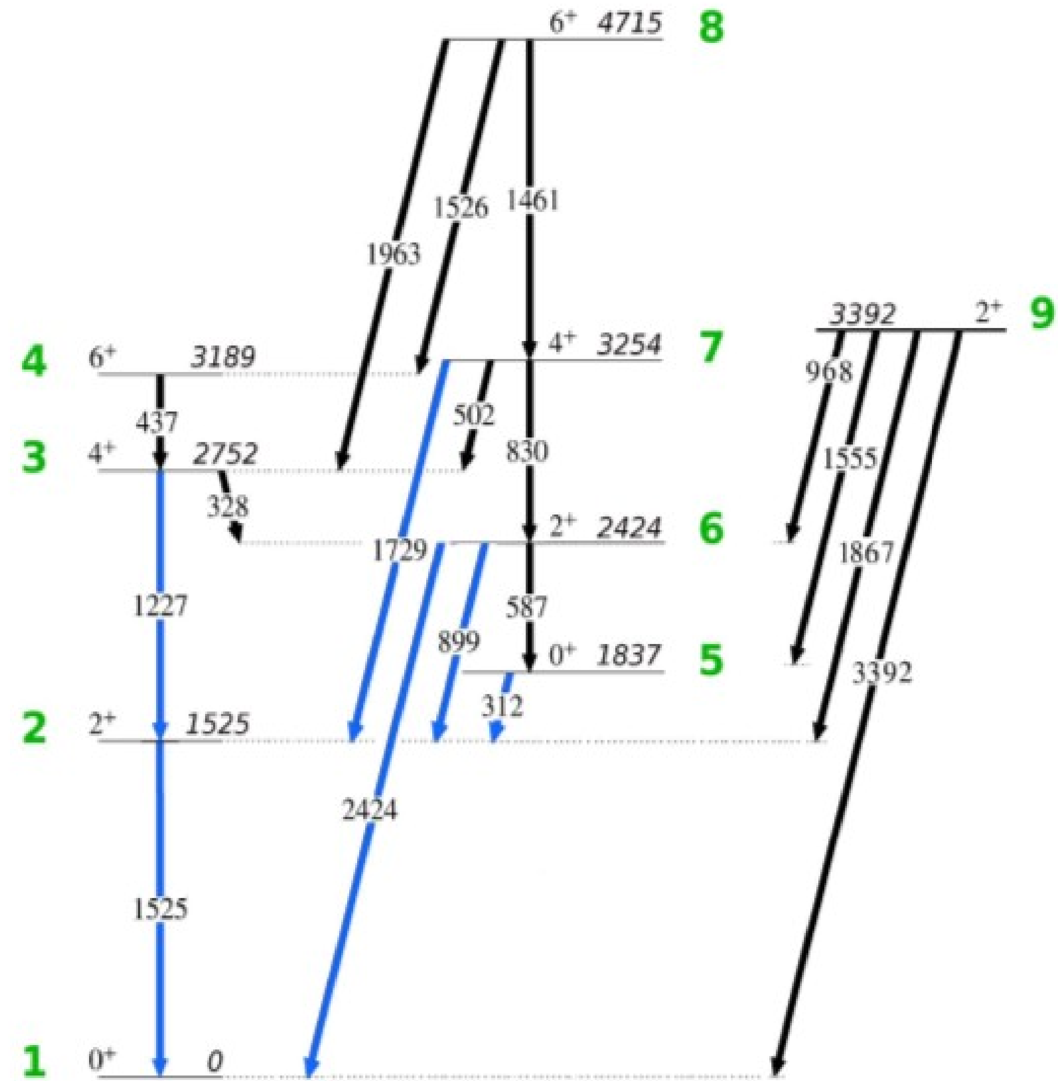
- 22 3 1 / gdet.out: 22 – output name
- 9 3 1 / gdet.f9: GDET output file – parameters needed to reproduce γ energy dependence of the gamma detector solid angle attenuation coeff. $Q_k$
- 8 3 1 / gdet.f8: GDET output file – absorption coeff. needed to reproduce the detector efficiency, created if NPD is **negative** – related to “raw” spectra defined in OP,RAW
- 0 0 0: End of OP,FILE
- OP,TITL / Gamma detectors: Title
- OP,GDET block: OP,GDET input options

# GOSIA input file: OP,GOSI

**LEVE**
1 1 0 0.0
2 1 2 1.525
3 1 4 2.752
.
.
.
0 0 0 0

**1 = GROUND STATE**

**Which nucleus?**



# GOSIA input file: OP,GOSI

```
ME
2 0 0 0 0
  1  2 0.20   0.0001  1.5
  2  6 0.08   -1.5      1.5
  .
  .
7 0 0 0 0
  2 6 1.01   -2.        2.
  .
  .
0 0 0 0 0
```

INDEX1

INDEX2

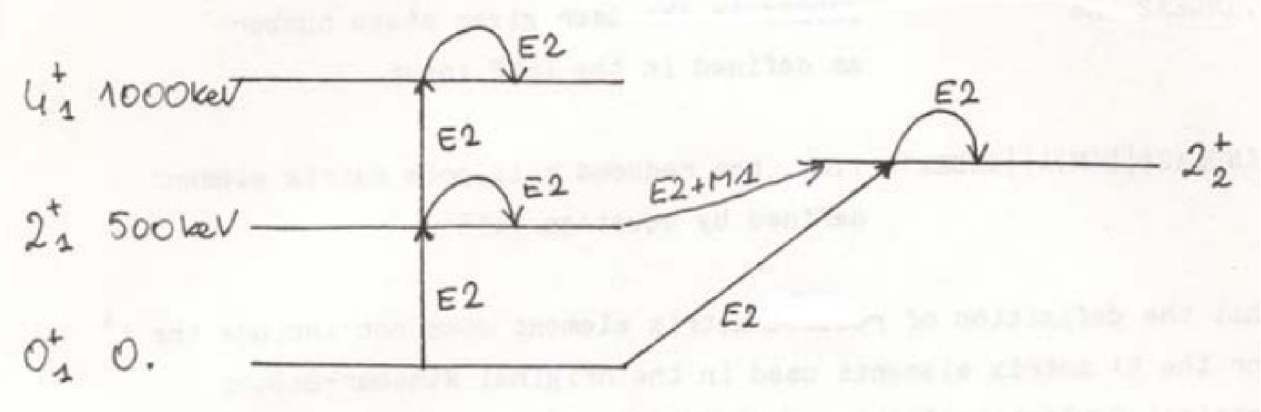
ME

Limits for ME
(R1 and R2)

**Multipolarity E(M)λ:**
**1 E1**
**2 E2**
**3 E3**
**..**
**7 M1**
**8 M2**

**< INDEX1 || E(M)λ || INDEX2 >**

**INDEX1 and INDEX2 are given in increasing order (start with INDEX1)**



# We need a set of ME to start with

**levels.inp**

```
1 1 0 0.0
2 1 2 0.413
3 1 4 1.005
4 1 0 0.825
5 1 2 0.881
6 1 4 1.208
0 0 0 0
```

Level E[MeV]

SPIN

Parity

Level number

**megen levels.inp**

```
1
Create setup for this multipolarity (y/n)
n
2
Create setup for this multipolarity (y/n)
y
Do you want them coupled ?
n
Please give limit value
-1.5 1.5
3
Create setup for this multipolarity (y/n)
n
(...)
7
Create setup for this multipolarity (y/n)
y
Do you want them coupled ?
n
Please give limit value
-1 1
8
Create setup for this multipolarity (y/n)
n
```

E2

M1

# We need a set of ME to start with

**levels.inp**

```
1  1  0  0.0
2  1  2  0.413
3  1  4  1.005
4  1  0  0.825
5  1  2  0.881
6  1  4  1.208
0  0  0  0
```

Level E[MeV]

SPIN

Parity

Level number

**me.out**

```
2 0 0 0 0
  1  2 1   1.5  -1.5
  1  5 1   1.5  -1.5
  2  2 1   1.5  -1.5
  2  3 1   1.5  -1.5
  2  4 1   1.5  -1.5
  2  5 1   1.5  -1.5
  2  6 1   1.5  -1.5
  3  3 1   1.5  -1.5
  3  5 1   1.5  -1.5
  4  5 1   1.5  -1.5
  5  5 1   1.5  -1.5
  5  6 1   1.5  -1.5
  6  6 1   1.5  -1.5
 7 0 0 0 0
  2  2 1   1.0  -1.0
  2  5 1   1.0  -1.0
  3  3 1   1.0  -1.0
  3  6 1   1.0  -1.0
  5  5 1   1.0  -1.0
  6  6 1   1.0  -1.0
 0 0 0 0 0
```

E2

M1

initial level | final level | starting value (1) | low limit | high limit

# **OP,THEO** - COLLECTIVE MODEL ME

- generates the ME from rotational model
- generates only the matrix specified in the ME input and writes them to the output file
- For **in-band or equal-K** interband transitions only one intrinsic moment for a given multipolarity marked **Q1** is relevant.
- For **non-equal-K** values generally two moments with the projections equal to the **sum and difference of K's** are required (**Q1 and Q2**), (unless one of the K's is zero, when again only Q1 is needed)
- For the **K-forbidden** transitions a three parameter Mikhailov formula is used.

# OP,THEO for $^{188}$Hg (EXAMPLE)

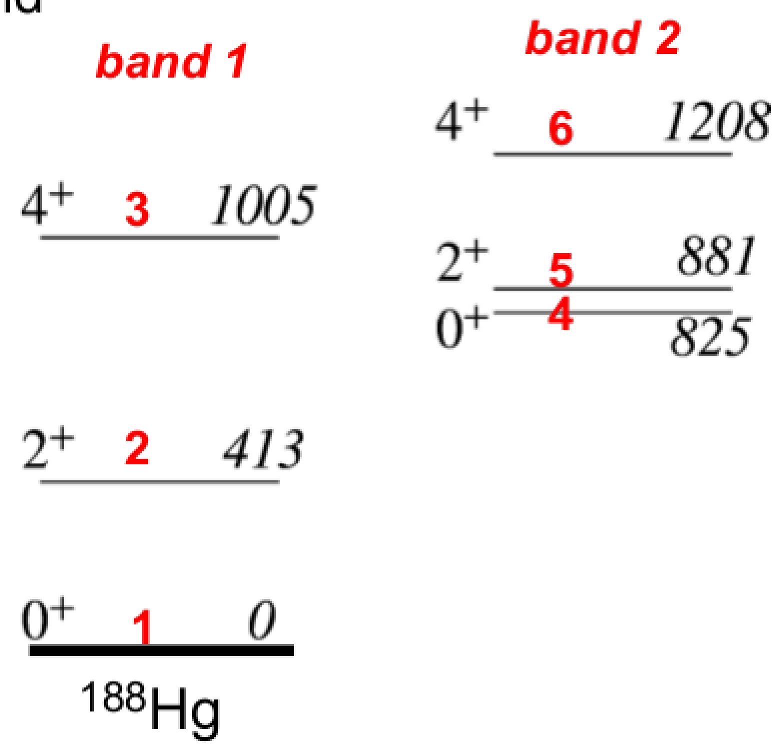
$$\langle K I_f \| \hat{M}(E2) \| K I_i \rangle = \sqrt{(2I_i+1)} \langle I_i, K, 2, 0 \mid I_f K \rangle \sqrt{\frac{5}{16\pi}} e Q_0$$

```
OP,THEO
2
0,3
1,2,3
0,3
4,5,6
2
1,1
Q1,0,0
1,2
Q1,0,0
2,2
Q1,0,0
0,0
0
```

number of bands (2)
First band, K and number of states
band member indices
Second band, K and number of states
Multipolarity E2
Bands 1 and 1 (in-band)
Moment Q1 of the rotational band

end of multipolarities loop

end of band-band input




*Courtesy: K. Wrzosek-Lipska*

# GOSIA input file: OP,GOSI: EXPT

Here we declare the most important details about the experiment:

**Energy, angles, Z+A target and projectile**

**EXPT**

**NEXP Z1 A1**

**+/-Z2 A2 Ep +/-$\theta_{proj}$ Mc Ma IAX φ1 φ2 IKIN LN**

**EXPT**

2 20 42

-79 197 167 122 3 1 1 -170 172 0 1

-82 208 167 122 3 1 1 -170 172 0 2

**$^{42}$Ca beam on $^{197}$Au and $^{208}$Pb targets**

# GOSIA input file: OP,YIEL

```
OP,YIEL
0
5 2
0.1 0.3 0.5 1.0 1.5
1
0.000829  2.41E-5  5.60E-6  1.143E-6  0.000269
2
0.01175   0.0001328  2.06E-5  2.59E-6  8.94E-5  0.000314
5 2
1  2  3  4  5
25  55  85   130  172
40  75  270 325  59
1  2  3  4  5
25  55  85   130  172
40  75  270 325  59
2 1
1                                        !EXP1
0.001 0.001 0.001 0.001 0.001
1 1 1 1 1
1                                        !EXP2
0.001 0.001 0.001 0.001 0.001
1 1 1 1 1
3
```

**Here we put Information about electron conversion coefficients, gamma detection geometry, type of our analysis, normalization details**

# GOSIA input file: OP,YIEL

```
2     1.0
      4 5 4 2   0.007  0.003
      5 1 5 2   0.34   0.02
2     1.0
      2     1.19  0.04
      3     4.45  0.10
1     1.0
      6 2  -0.18     0.02
1     1.0
      2  2  2    -0.25  0.051
```

Here we put Information about the spectroscopic data:
- lifetimes,
- branching ratios,
- mixing ratios,
- known transition probabilities

```
0 0
0 0     in case nothing is known
0 0     about the investigated nucleus
0 0
```

# YIELD definition

## POINT

- **One** energy (E)
- **One** angle (Θ)

  as defined in EXPT

  use **OP,POIN**

## INTEGRATED

- Energy **range**

  ($E_{min}$-$E_{max}$)
- Angular **range**

  ($\Theta_{min},\varphi_{min} – \Theta_{max},\varphi_{max}$)

  as defined in **OP,INTG / INTI**

**Matrix elements values, excitation probability**

# GOSIA input file: OP,POIN

- This option evaluates the point gamma yield in the laboratory frame for the $I_i \rightarrow I_f$ transition for **one energy** and **one particle scattering angle** given in **EXPT**

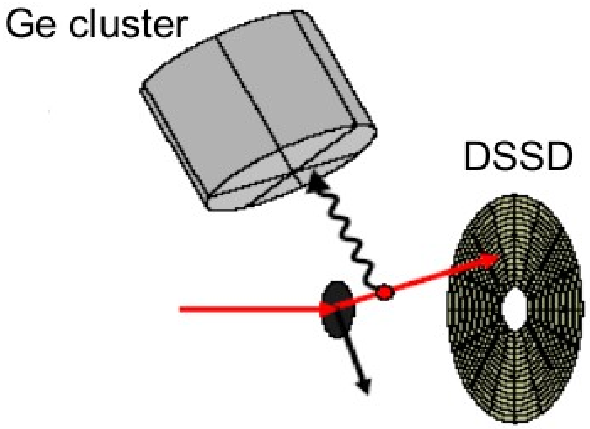
$$Y^{Point}(I \rightarrow I_f) = \sin(\theta_p) \int_{\phi_p} \frac{d^2\sigma(I \rightarrow I_f)}{d\Omega_\gamma d\Omega_p} d\phi_p$$

- includes the **Rutherford cross section**, the sin(Θ) term, integration over the projectile φ scattering angle, the deorientation effect and gamma-detector attenuation coefficients (from OP,GDET)
- Calculates the yield for one system – defined as one **θ-E** point
- We use OP,POIN after OP,YIEL
- We use REAL detectors with continuous dimensions

# Why INTEGRATION?

- REAL conditions - GOSIA calculates **yields** from ME to get **realistic comparison** with experimental data
- integration over **solid angle** of the particle detectors, **energy loss in the target,** full correction for the velocity of the deexciting nucleus and the **deorientation effect** is included
- the Rutherford scattering is integrated over the particle detectors and energy loss in the target – an absolute normalization.
- the '**GOSIA yield**' may be understood as a mean differential cross section multiplied by a target thickness (in mg/cm$^2$)

[Y] = [mb/sr] × [mg/cm$^2$]



# GOSIA input file: OP,INTG

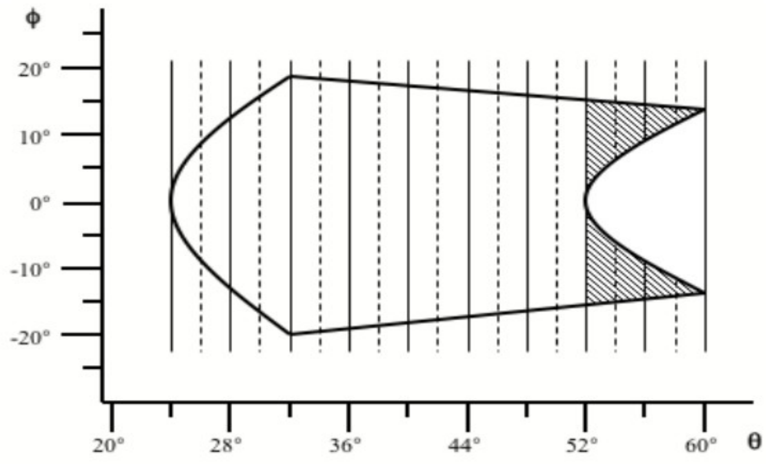
**2 stages:**

- γ yields integrated over azimuthal angle **φ** for each energy **E** and center-of-mass scattering angle **θ** meshpoint (stored as an external array). The calculation of the meshpoint yields is repeated for each experiment (**as declared in EXPT**)

- integrate over bombarding energy **E** and the range of scattering angles **θ** of the particle detectors which is performed by **interpolating** between the yields calculated at each **E-θ** meshpoint

(*circular detectors option recommended)

**OP,INTG**
**NE +/-NT $E_{min}$ $E_{max}$ $θ_{min}$ $θ_{max}$**
**$E_1$ $E_2$... $E_{NE}$**
**$+/-θ_1$ $+/-θ_2$ ... $+/-θ_{NE}$**
**NFI**
**$φ_1$ $φ_2$ ...**
**NP**
**$E_1$ $E_2$... $E_{NP}$**
**$(dE/dx)_1$ $(dE/dx)_2$ … $(dE/dx)_{NP}$**
**$NI_1$ $NI_2$**



# GOSIA input file: OP,INTG - circular

Intensities **<u>for each Ge detector</u> – circular <u>particle detector</u> option (with PIN diodes)**

Calculate the Δφ at each subdivision of θ
Circular det. approximation for PiN diodes

**OP,INTG**
**NE +/-NT $E_{min}$ $E_{max}$ θ φ $θ_{1/2}$**
**$E_1$ $E_2$ ... $E_{NE}$**

**Sample input:**

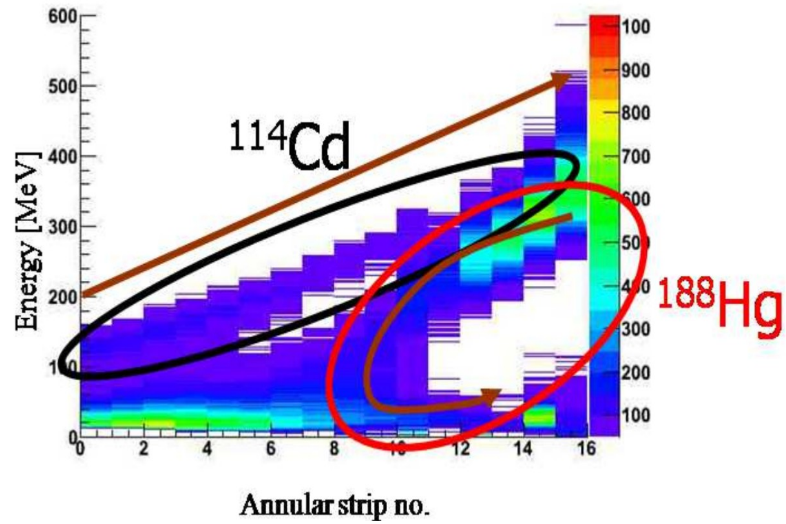
```
OP,INTG
7    3    146. 152.      123.9     242.32     4.4 ! PIN63
146 147 148 149 150 151 152
7    3    146.  152.     123.9     298.28     4.4 ! PIN62
146 147 148 149 150 151 152
7    3    140.  152.     123.9     226.27     4.4 ! PIN68
146 147 148 149 150 151 152
7    3    140.  152.     123.9     98.32      4.4 ! PIN75
146 147 148 149 150 151 152
...
```

# GOSIA input file: OP,INTI

Developed to handle problems that occur for integration of systems involving inverse kinematics when the **recoiling target nucleus is detected** (2 kinematic solution).

For each beam E and each angle the subroutine INVKIN calculates the appropriate value of kinematic flag and set it **automatically**

**Θ** angles always positive and correspond to laboratory scattering angles of the **detected particle**, that is, the angle of the scattered projectile if it is detected and the angle of the recoiling target nucleus if it is detected.




*N. Bree, PhD thesis, KULeuven,*

**OP,INTI**
**NE +/-NT $E_{min}$ $E_{max}$ $\theta_{min}$ $\theta_{max}$**
**$E_1$ $E_2$ ... $E_{NE}$**
**$\theta_1$ $\theta_2$ ... $\theta_{NE}$**
**NFI**
**$\varphi_1$ $\varphi_2$ ...**
**NP**
**$E_1$ $E_2$ ... $E_{NP}$**
**$(dE/dx)_1$ $(dE/dx)_2$ … $(dE/dx)_{NP}$**
**$NI_1$ $NI_2$**

```
OP,INTI                  !for axial sym. and circ. det.
8 9 226 240 133 168
226 228 230 232 234 236 238 240
133 135 140 145 150 155 160 165 168
8
226 228 230 232 234 236 238 240
12.2 12.17 12.13 12.10 12.05 12.00 11.90 11.80
20,20
```

# YIELD correction

- Minimization of is usually performed using **corrected** yields
- Correction depends on the set of ME: GOSIA calculates the **point** yield (**$Y_p$**) and the **integrated** yield (**$Y_I$**) from the ME and gives the **correction factors CF** for each experimental yield (**OP,CORR** needed):

$$CF = \frac{Y_P}{Y_I} \longrightarrow Y^c_{exp} = Y_{exp} \cdot CF$$

After minimization the correction procedure should be repeated with a new set of ME (better fit, different correction) → until the solution is converged

- CF are calculated for **each** experimental yield

**$^{42}Ca$ on $^{197}Au$**

**$E_{av}$ = 167 MeV**

**$\Theta_{av}$ = 122°**

EXPERIMENT 2 DETECTOR 1

| NI | NF | YEXP | YCOR | COR.F |
|---|---|---|---|---|
| 3 | 2 | .112E+00 | .113E+00 | .101E+01 |
| 6 | 1 | .380E-01 | .374E-01 | .984E+00 |
| 6 | 2 | .106E+00 | .102E+00 | .966E+00 |
| 5 | 2 | .854E+00 | .822E+00 | .962E+00 |
| 2 | 1 | .124E+02 | .120E+02 | .969E+00 |

# GOSIA AS A SIMULATION TOOL: YIELD ⇒ COUNT RATE

$$Counts = 10^{-27} \cdot \left[\frac{Q}{\hat{q}e}\right] \cdot \left[\frac{N_A}{A}\right] \cdot [\rho dx] \cdot \quad \textbf{Yintg} \quad \cdot \Delta\theta_p \cdot \varepsilon_p \cdot \varepsilon_\gamma \cdot \Delta\Omega_\gamma$$

where:

$Q$ is the integrated beam charge $[C]$

$\hat{q}$ the average charges state of the beam

$e$ the proton charge $[1.602 \times 10^{-19} C]$

$N_A$ Avogadro number $[6.022 \times 10^{23} atoms/mol]$

$A$ Target mass number $[g/mol]$

$\rho dx$ areal target thickness in $[g/cm^2]$

**Yintg from INTG or INTI** $[\frac{mb}{sr \cdot rad}]$

$\Delta\theta_p$ Projectile scattering angle range $[rad]$

$\varepsilon_p$ particle detection efficiency per unit solid angle

$\varepsilon_\gamma$ $\gamma$-ray detector efficiency excluding the geometrical solid angle

$\Delta\Omega_\gamma$ geometrical solid angle of the $\gamma$-ray detector. Note that usually one only knows the product $\varepsilon_\gamma \cdot \Delta\Omega_\gamma$

$$\textbf{Count Rate} = \frac{7.6 \times 10^{-6} \times yield \times current[pps] \times eff}{A_{target}}$$

# GOSIA input file: OP,RAW

- This option needs energy-dependent efficiency calibration for each individual gamma detector (GREMLIN, EFFIT..)
- the first entry of OP,GDET should be **negative** to produce the **TAPE8**
- Need to declare which efficiency parametrization you need!
- **Do not use if all gamma intensities are efficiency-corrected**

```
OP,RAW
IEXP
A1 A2 A3 A4 A5 A6 A7 A8
A1 A2 A3 A4 A5 A6 A7 A8
…
...
A1 A2 A3 A4 A5 A6 A7 A8
NC
ID1
I1 I2 … I(ID1)
ID2
I1 I2 … I(ID2)
...
…
0
```

# GOSIA input file: OP,MINI

# χ2 function minimization

$$\chi^2 = \frac{1}{p}\left\{ \sum_{i=1}^{N\exp} \sum_{j=1}^{N\det} \sum_{k=1}^{N\gamma} \left[ \left( \frac{C_{ij} Y_k^{(T)} - Y_k^{(E)}}{\Delta Y_k^{(E)}} \right)^2 \right. \right. + \left. \sum_{i=1}^{Ns.d.} \left( \frac{d_i^{(T)} - d_i^{(E)}}{\Delta d_i^{(E)}} \right)^2 \right\}$$

experimental yield

calculated yield

normalisation factor

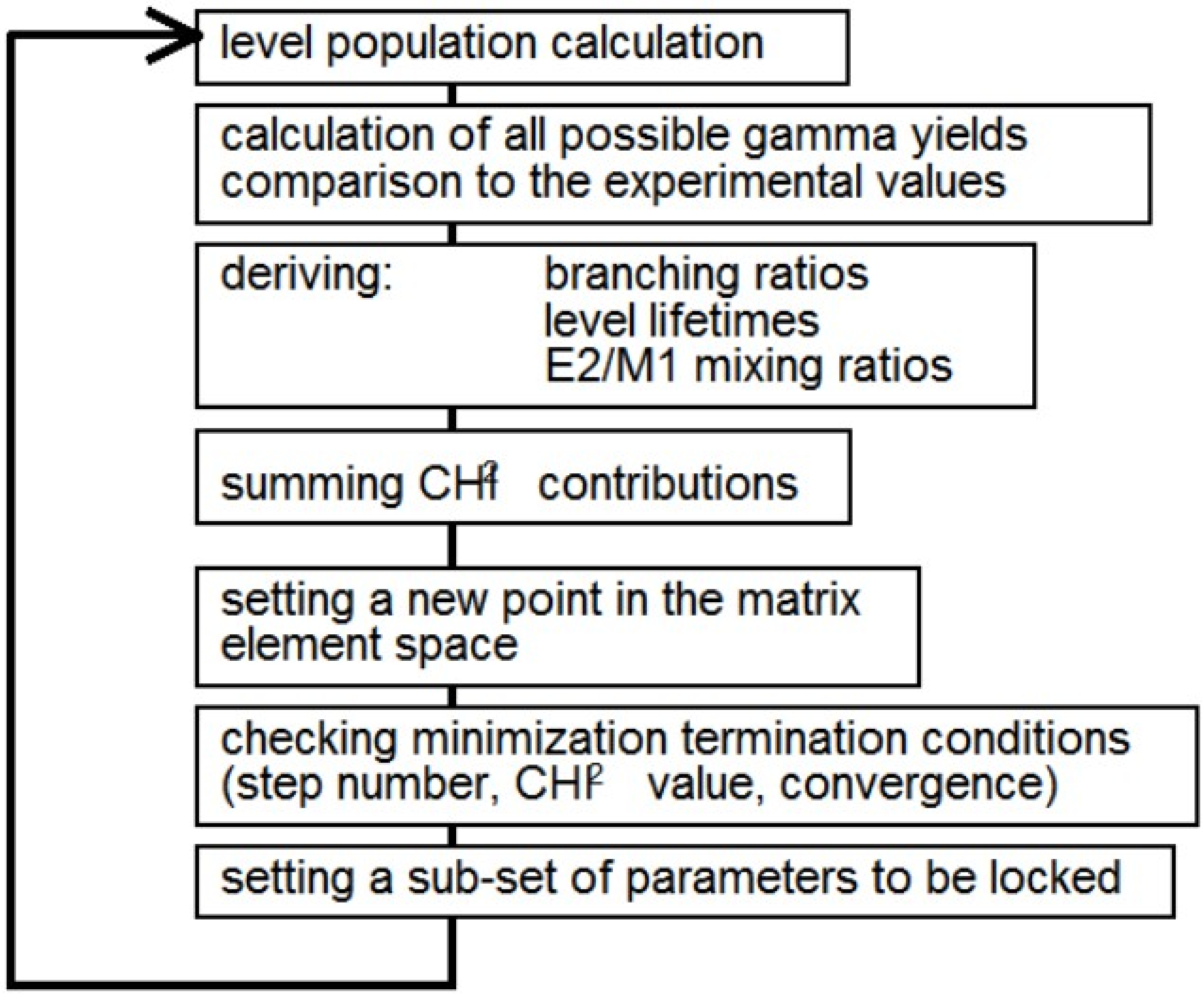
spectroscopic data point

calculated magnitude

The fitting procedure is continued, until the convergence of the $\chi^2$ is achieved and the set of matrix elements optimally reproduce the experimental data.

Remember to run OP,MAP before OP,MINI, each time you change something in ME (insert OP,MAP command directly after OP,YIEL). This option stores the **q-parameters** important for **reorientation effect** (effective strength, related to the magnetic substates coupling) on **TAPE7**

# GOSIA input file: OP,MINI



# GOSIA input file: OP,ERRO

- for estimating the error bars to be assigned to the set of matrix elements corresponding to the minimum value of $\chi^2$

Mode flag:
0 – diagonal
1 – correlated

```
OP,ERRO
IDF   MS   MEND   IREP   IFC   RMAX
```

- **two separate stages:**

1. the **"diagonal",or uncorrelated errors** (calculated individually for each matrix element) and write them on TAPE15

**0 MS MEND 0 0 RMAX**

2. the **"overall", or correlated errors** (the total errors which are the widths of projections on each matrix element's axis of the minimum at the $\chi^2 = \chi^2 + 1$ level).

**1 MS MEND 1 1 RMAX**

# What else is there?

- There are **other options**, which can or should be used depending on the analysis needs (OP,STAR; OP,SIXJ; OP,RAND; OP,TROU; OP,BRIC..)
- **GOSIA2** for the radioactive beam experiments →target normalization tool
- **RACHEL** (GUI gosia)
- **SIGMA** – quadrupole sum rules code → shape invariants → deformation parameters