GOSIA hands-on sessions

- ^{74}Zn projectile excitation
- ^{196}Pt target, 4 mg/cm^2
- Beam energy (LAB): 4 MeV/A (296 MeV), intensity: 10^6 pps
- Gamma-ray detection: 24 detectors of MINIBALL, 14 cm from the target; for simplicity we provide files that describe them, assuming all detectors are identical (miniball.f8 and miniball.f9, generated with GOSIA's OP,GDET)
- Scattered beam and recoil detection: an annular detector covering forward angles: 18-50° in LAB

We will introduce:

- OP,INTI → calculation of counting rates for ^{74}Zn
- OP,MINI → fit of matrix elements (gamma-ray yields will be provided)

GOSIA – 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.

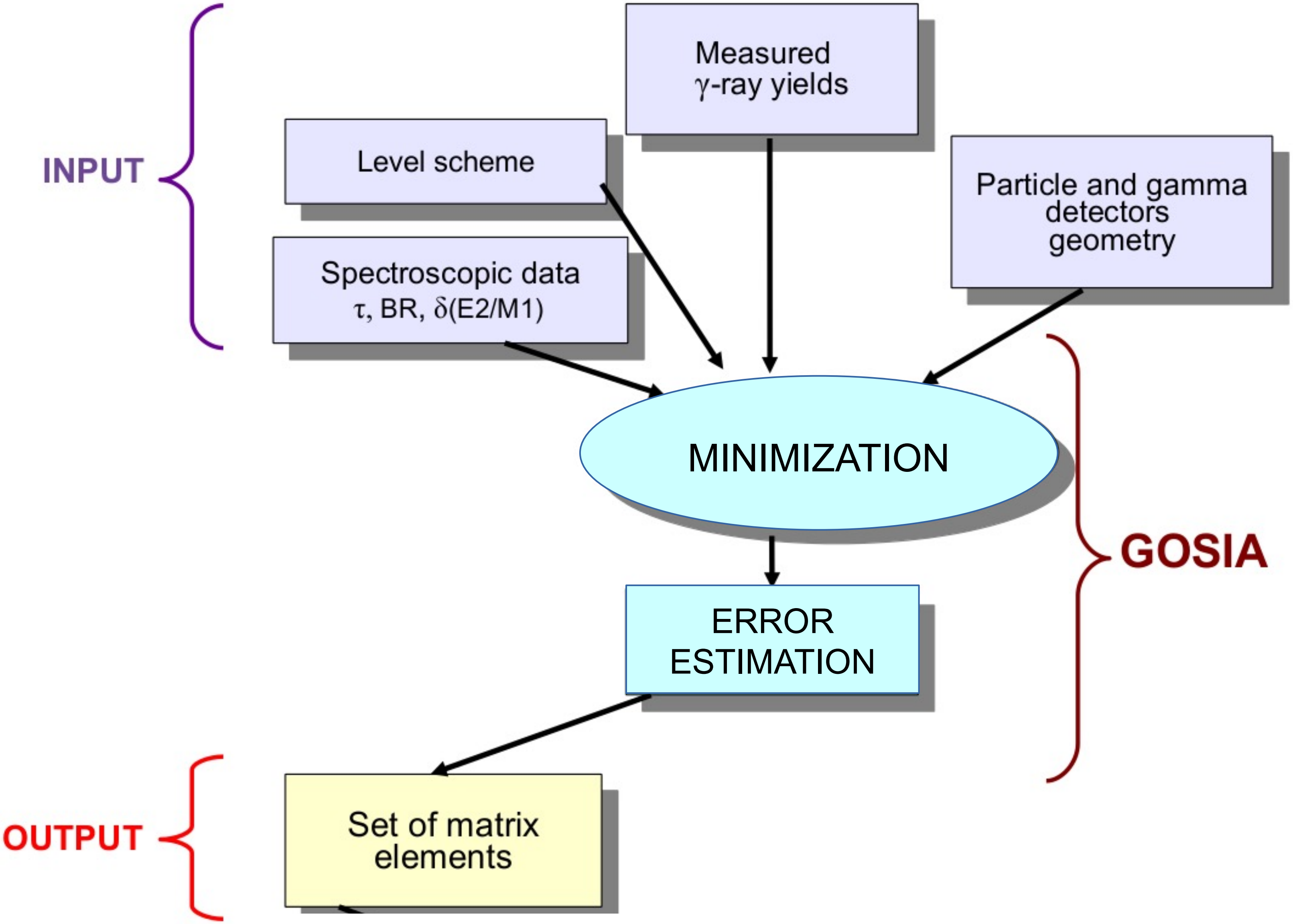
  http://www.pas.rochester.edu/~cline/Gosia/index.html
  www.slcj.uw.edu.pl/gosia
  https://www.ikp.uni-koeln.de/~warr/gosia/

- GOSIA can be used for:
  - **data analysis** (multidimensional fit of matrix elements to the data)
  - **simulations** (state populations, cross sections, counting rates)
- GOSIA is written in fortran, and sometimes error messages may be difficult to interpret. Start from calculating simple things, and only if you're convinced they work, proceed toward more complicated tasks.
- Many options to fine-tune the calculations are available at the level of the input file, which consequently can become quite complex.
- Multiple input and output files are used by various options.
- GOSIA has been tested by many users (hundreds?) over the years, but minor bugs are still being found (and fixed - thank you Nigel and Paweł!)

We are here to help you! :)

How does it work?

- For the **experimental conditions** specified by the user (level scheme, matrix elements, collision partners, reaction kinematics) **GOSIA solves a set of coupled differential equations** for level excitation amplitudes using electromagnetic matrix elements as parameters.
- Subsequently, the **decay of the populated states is calculated**, using user-provided information on gamma-ray detection geometry and efficiency, internal conversion etc.
- A standard χ^2 function comparing calculated and experimental relative gamma-ray intensities, as well as other spectroscopic data related to electromagnetic matrix elements, is created and minimised.
- A set of matrix elements that optimally reproduces the experimental data corresponds to the minimum of the χ^2 function, and from the analysis of the shape of the multidimensional χ^2 surface in the vicinity of the minimum uncertainties of matrix elements are deduced, including cross correlations.



INPUT

Level scheme

Spectroscopic data
τ, BR, δ(E2/M1)

Measured
γ-ray yields

Particle and gamma
detectors
geometry

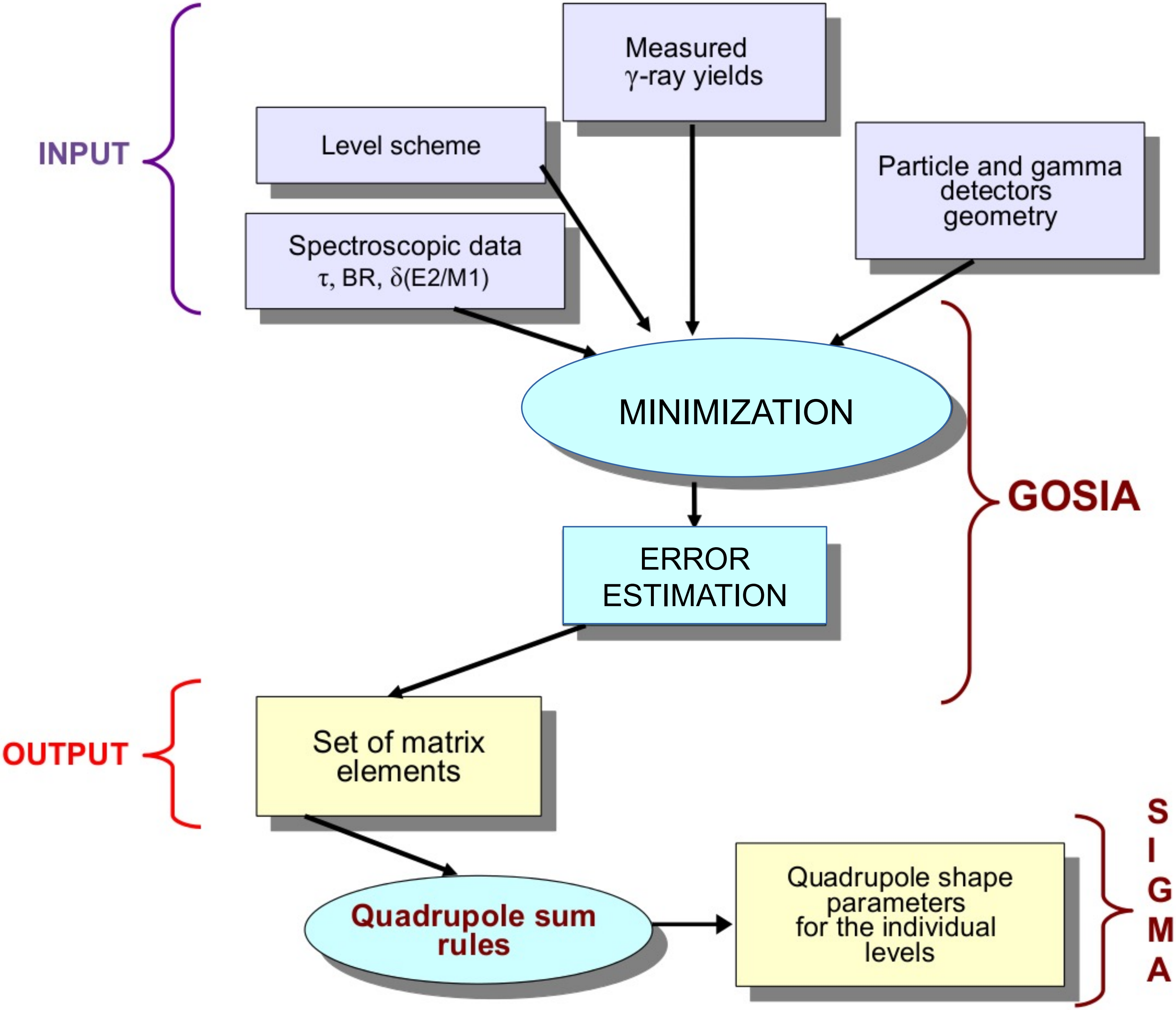
MINIMIZATION

ERROR
ESTIMATION

GOSIA

OUTPUT

Set of matrix
elements



INPUT

Measured
γ-ray yields

Level scheme

Spectroscopic data
τ, BR, δ(E2/M1)

Particle and gamma detectors geometry

MINIMIZATION

ERROR ESTIMATION

GOSIA

OUTPUT

Set of matrix elements

Quadrupole sum rules

Quadrupole shape parameters for the individual levels

SIGMA

Simulations - before you start

- Check the databases (ENDSF/XUNDL) and/or publications for existing data: **level scheme**, known **lifetimes**, **branching ratios**, **transition strengths** (E0, E1, E2, E3, M1, …), **mixing ratios, quadrupole moments**.
- Calculate matrix elements from transition strengths (or deformation parameters).
- If experimental data is missing – maybe theoretical predictions exist?
- http://bricc.anu.edu.au/ - **electron conversion coefficient** calculator
- Calculate the **safe energy** for your system.
- What is the **beam**? Isotope, energy, intensity, purity (if applicable).
- What is the **target**? How thick? Can you distinguish beam and target with your particle detector? Calculate energy loss of the beam in the target material (SRIM, ELO, or equivalent codes).
- **Normalization** method: target excitation, lifetimes, Rutherford cross section?
- **Detectors**:
  - **Gamma-ray array:** how many detectors? How far from the target? Size? Efficiency?
  - **Particle detectors:** theta and pi range, lowest beam energy that can be measured?

GOSIA compilation and manual

LINUX:

```
> f77 gosia.f -o gosia -fno-automatic
> gfortran gosia.f -o gosia
```

MAC:

```
> ifort gosia.f -o gosia
> gfortran gosia.f -o gosia
```

GOSIA Manual:

- Original version provided in your package
- A newer version (but unfortunately containing some errors, including the formula for counting rate calculation) available from https://www.pas.rochester.edu/~cline/Gosia/

GOSIA input structure

- **1. OP,FILE** – definition of other files used by the code (referred to as “TAPES”)
- **2. OP,TITL**
- **3. OP,GOSI** (with fit) / **OP,COUL** (without fit)
- **- LEVE**
- **- ME**
- **- EXPT**
- **- CONT**
- **END,**
- **4. OP,STAR**
- **5. OP,POIN**
- **6. OP,YIEL**
- **7. OP,RAW**

- **8. OP,INTG/INTI**
- **9. OP,MAP**
- **10. OP,MINI**
- **11. OP,REST**
- **12. OP, ERRO**

- **OP,GDET**
- **OP,SIXJ**
- **…**

GOSIA input structure - example

```
OP,FILE
          22 3 1
          star.out
          0 0 0
OP,TITL
          OP,STAR output test
OP,GOSI
          LEVE
                    1,1,0,0.0
                    2  1  2  0.606
                    3  1  4  1.419
                    4  1  2  1.670
                    0,0,0,0
          ME
                    2 0 0 0 0
                    1  2 0.1   1.0  -1.0
                    2  2 0.1   1.0  -1.0
                    2  3 0.1   1.0  -1.0
                    0 0 0 0 0
          EXPT
                    1 30 74
                    -78 196 271 30 3 1 1 0 360 0 1
          CONT
                    INR,
                    INT,1.
                    1,1000
                    PRT,
                    0 0
END,

OP,STAR
OP,EXIT
```

OP,STAR

Calculation of Coulomb-excitation amplitudes and populations of individual states (not gamma-ray yields)

OP,FILE – file assignments in GOSIA

22 3 1 **mini.out**	Output – “TAPE” 22; “3” – if the file doesn’t exist, it will be created; “1” – text file (alternative: “2” – binary)
9 3 1 **miniball.f9** **8 3 1** **miniball.f8**	“TAPE8” and “TAPE9” – two files describing opening angles of germanium detectors (not their angles!) as well as effect of degraders in front of them on the efficiency. Files generated with GOSIA’s OP,GDET
12 3 1 **matrix.me**	“TAPE12” – values of matrix elements as a single column text file, ordered as in LEVE section of the input file
3 3 1 **yield.f3**	“TAPE3” – “corrected” gamma-ray yields (we will come back to that later). File created by OP,INTG/OP,INTI
4 3 1 **corr.f4**	“TAPE4” – measured gamma-ray yields (provided by the user) or “point” gamma-ray yields calculated by OP,POIN
7 3 1 **map.f7**	“TAPE7” – map of approximate strength parameters used for fast approximation in the minimisation procedure. File required by OP,MINI, created by OP,MAP
0 0 0	Three zeros finish OP,FILE output

OP,GOSI – level scheme

```
LEVE
1  1  0  0.0
2  1  2  0.606
3  1  4  1.419
4  1  2  1.670
.
.
0  0  0  0
```

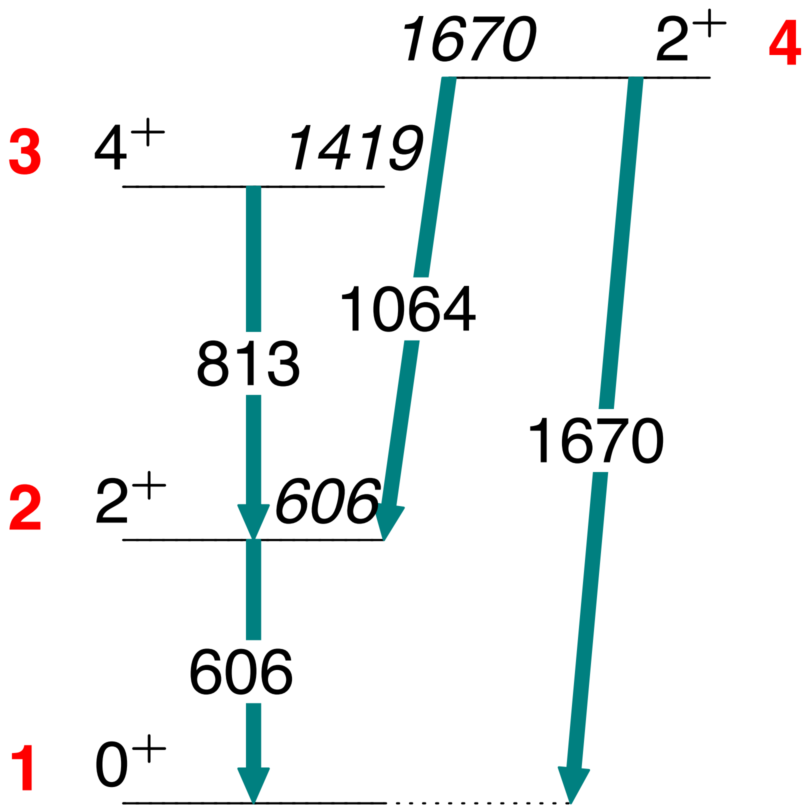
Excitation energy [MeV]

Spin

Four zeros finish input of LEVE

Parity (“1” – positive, “-1” – negative)

Level index



Level ordering is arbitrary (they may be arranged according to excitation energy, or band structure…)

OP,GOSI – matrix elements

```
ME
2 0 0 0 0
  1  2 0.442   0.0001  1.5
  2  4 0.1     -1.5     1.5
  .
  .
7 0 0 0 0
  2  4 1.01      -2.       2.
  .
  .
0 0 0 0 0
```

Multipolarity E(M)λ:

1 E1

2 E2

3 E3

..

7 M1

8 M2

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

Limits for ME in the minimization process (lower and upper)

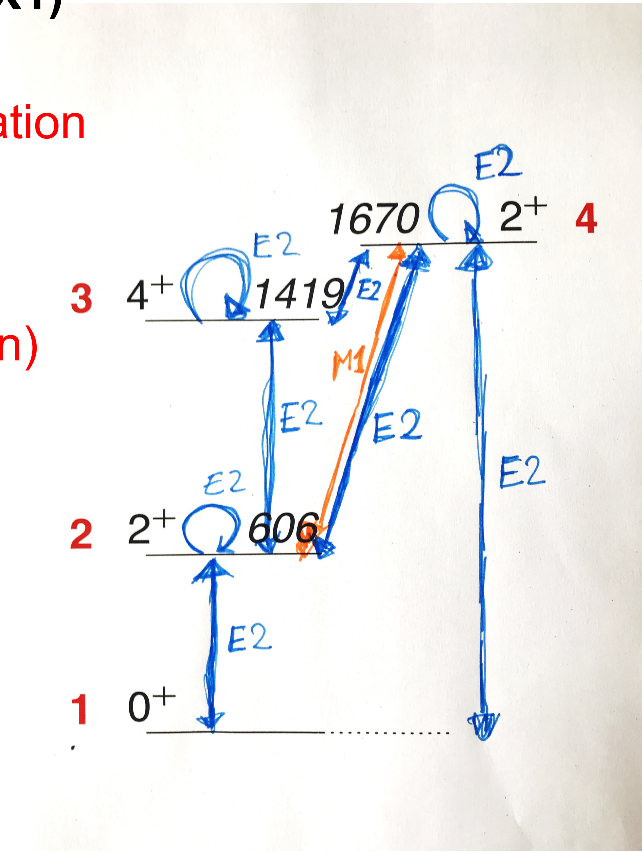
Initial value of matrix element (with sign)

< INDEX2 || E(M)λ || INDEX1 >

Five zeros finish input of ME

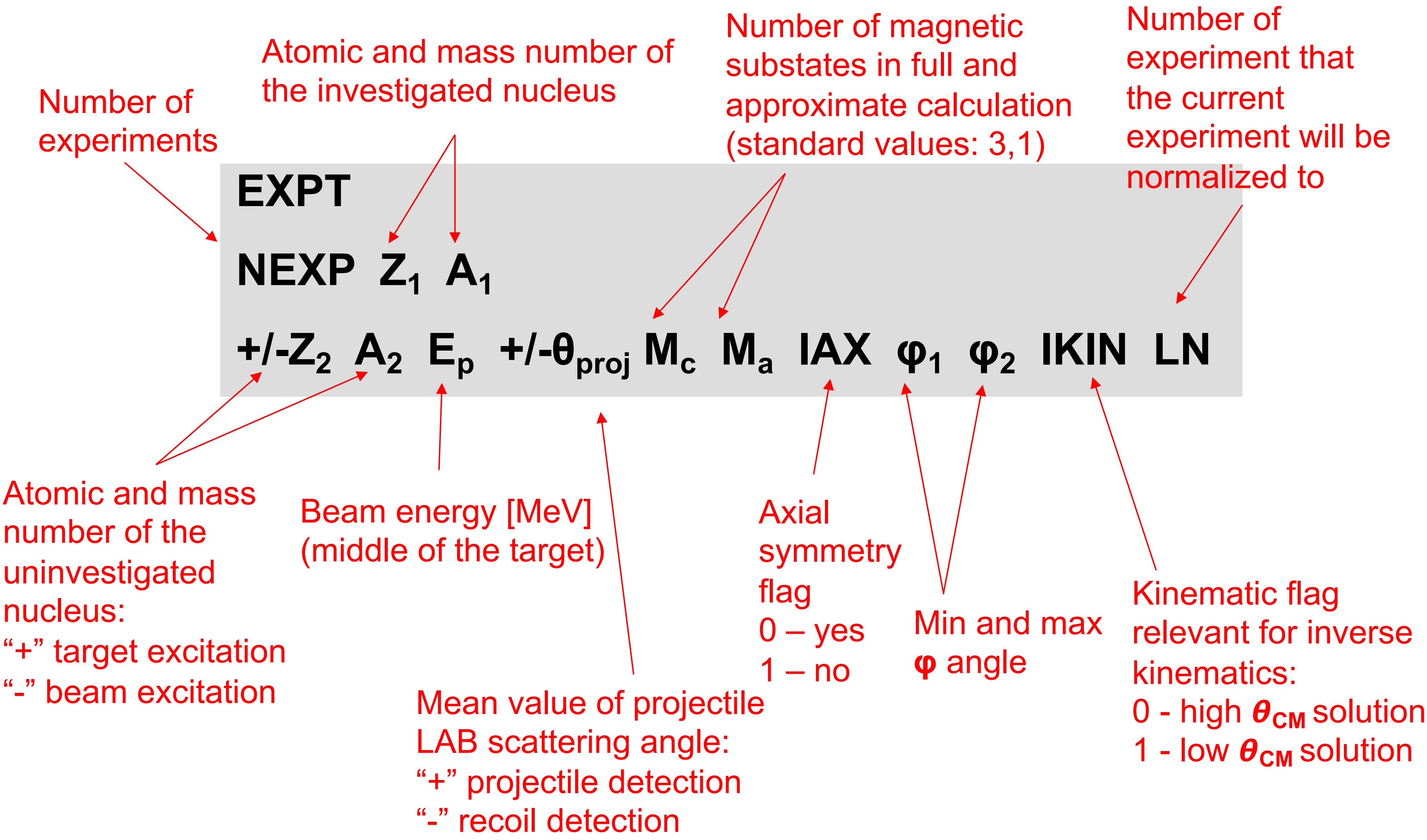
INDEX2

INDEX1



EXPERIMENT

OP,GOSI: EXPT



EXPT

NEXP Z_1 A_1

$+/-Z_2$ A_2 E_p $+/-\theta_{proj}$ M_c M_a IAX φ_1 φ_2 IKIN LN

Number of experiments

Atomic and mass number of the investigated nucleus

Number of magnetic substates in full and approximate calculation (standard values: 3,1)

Number of experiment that the current experiment will be normalized to

Atomic and mass number of the uninvestigated nucleus:
"+" target excitation
"-" beam excitation

Beam energy [MeV] (middle of the target)

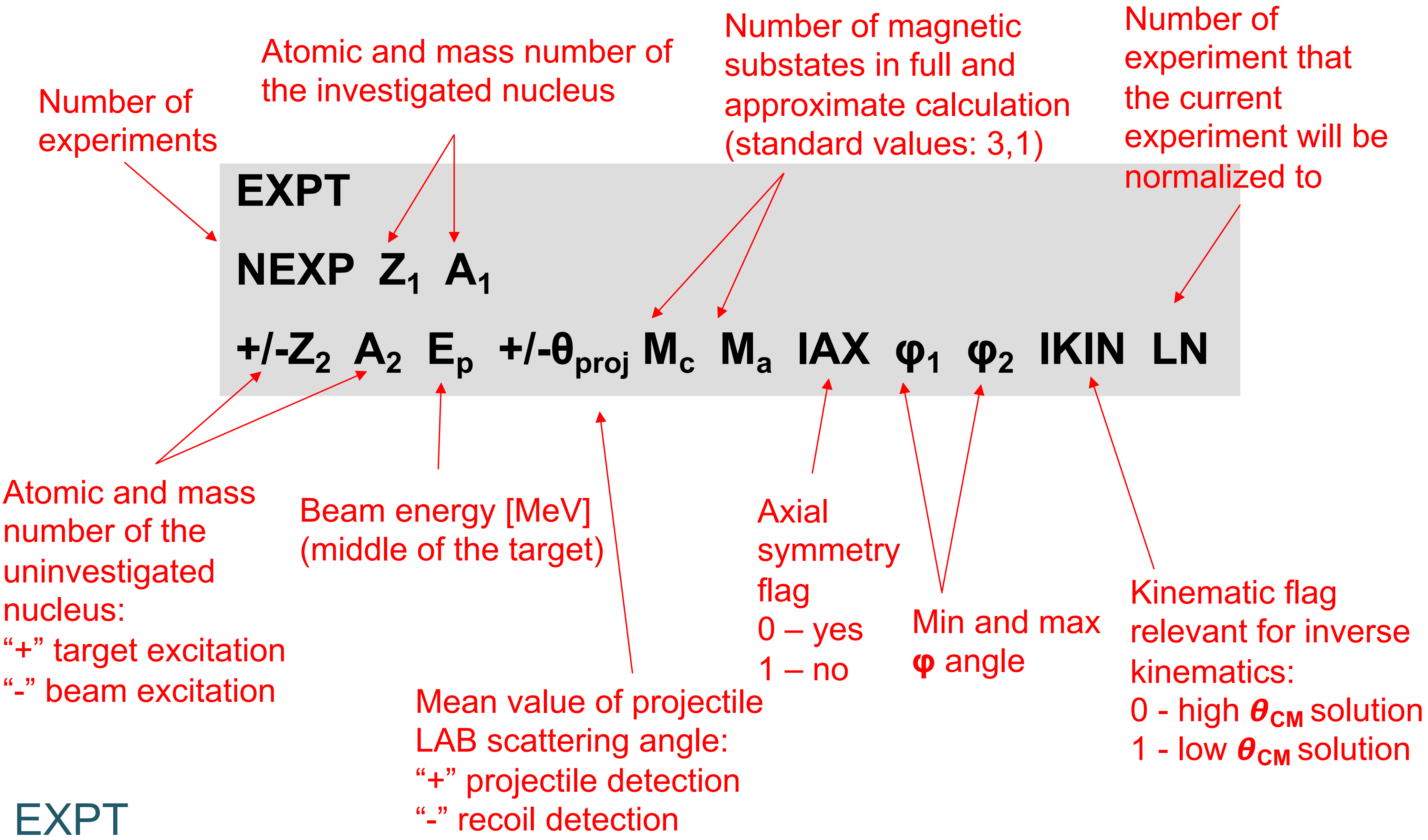
Mean value of projectile LAB scattering angle:
"+" projectile detection
"-" recoil detection

Axial symmetry flag
0 – yes
1 – no

Min and max **φ** angle

Kinematic flag relevant for inverse kinematics:
0 - high θ_{CM} solution
1 - low θ_{CM} solution

OP,GOSI: EXPT



EXPT

NEXP Z_1 A_1

+/-Z_2 A_2 E_p +/-θ_{proj} M_c M_a IAX φ_1 φ_2 IKIN LN

Number of experiments

Atomic and mass number of the investigated nucleus

Number of magnetic substates in full and approximate calculation (standard values: 3,1)

Number of experiment that the current experiment will be normalized to

Atomic and mass number of the uninvestigated nucleus:
"+" target excitation
"-" beam excitation

Beam energy [MeV] (middle of the target)

Mean value of projectile LAB scattering angle:
"+" projectile detection
"-" recoil detection

Axial symmetry flag
0 – yes
1 – no

Min and max **φ** angle

Kinematic flag relevant for inverse kinematics:
0 - high θ_{CM} solution
1 - low θ_{CM} solution

```
EXPT
1       30      74
-78     196     271     30      3       1       0       0       360     0       1
```

OP,YIEL

```
OP,YIEL
0
5 2
0.2 0.3 0.5 1.0 2.0
2
0.048,0.011,0.002,0.0003,0.00038
7
0.001,0.0037,0.0011,0.00025,0.00033
5 5
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
100000
1
1
100000
1
3
```

Electron conversion coefficients (BRICC)

number of energies and multipolarities
Energy meshpoints [MeV]
Multipolarity E1
Coefficient for each energy meshpoint
Multipolarity E2
Coefficient for each energy meshpoint

Total number of gamma-ray detectors for each experiment
Indices of gamma-ray detectors in GDET for EXP 1
Θ, EXP 1
Φ, EXP 1
Indices of gamma-ray detectors in GDET for EXP 2
Θ, EXP 2
Φ, EXP 2

In our example: detector at Θ = 55 deg and Φ=75 deg is defined as the second one in OP,GDET

Normalising transition (for printout only!)

Number of data sets (i.e. gamma-ray spectra) for EXP 1
Upper limits for each data set in EXP 1
Relative normalisation factors for each data set in EXP 1

From what “TAPE” we want to read gamma-ray yields?
0 for OP,POIN, OP,STAR
3 for OP,INTI+OP,CORR
4 for OP,MINI, OP,ERRO

OP,YIEL – input of spectroscopic data

```
1         1.0
    4,1, 4,2, 0.58, 0.05
```

Number and weight of known branching ratios:
Transition 1 (I2, I1), Transition 2 (I2, I1), BR, ΔBR

```
2         1.0
     2    25.5        1.9
     3    20.0        5.1
```

Number and weight of known mean lifetimes [ps]
Level index, τ, Δτ

```
1         1.0
     4 2            -1.13      0.06
```

Number and weight of of known δ(E2/M1) mixing ratios
Transition, δ, Δδ

```
1         1.0
     2  2  2        -0.09  0.11
```

Number and weight of of known matrix elements
Multipolarity, I1, I2, ME, ΔME

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

OP,YIEL for ^{74}Zn

```
OP,YIEL
0
5 2
0.2 0.3 0.5 1.0 2.0
2
0.048,0.011,0.002,0.0003,0.00038
7
0.001,0.0037,0.0011,0.00025,0.00033
24                                          ! number of detectors per experiment
1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1
43.5,51.6,71.0,36.7,65.9,57.9,39.0,50.4,67.0,64.7,36.7,61.9,
122.6,144.4,115.2,112.3,129.5,140.4,120.9,108.3,137.5,108.3,136.9,124.3
21.8,60.2,35.0,143.8,146.7,114.6,207.6,246.6,217.9,310.2,
321.6,342.8,155.8,127.2,123.2,29.2,57.3,17.8,299.8,329.1,331.4,250.6,258.6,223.1
2,1                                         ! normalisation transition
1                                           ! data sets see also op,raw
10000
1                                           ! Normalisation of several datasets
3                                           ! Gamma-ray yields file
1,1                                         ! Branching ratios
4,1,4,2,0.58, 0.05
2,1                                         ! Lifetimes
2, 25.5, 1.9
3, 20.0, 5.1
1,1                                         ! Mixing ratios
4,2, -1.13, 0.06
0,0                                         ! known matrix elements
```

OP,RAW

- By default, gamma-ray intensities in GOSIA are supposed to be efficiency-corrected. An exception to this rule is when OP,RAW is invoked.
- Moreover, this option makes it possible to sum together spectra from multiple detectors, not necessarily identical.
- For each gamma-ray detector an efficiency curve should be provided. Five different parametrisations are currently included in the code:

0-Gremlin, 1-Jaeri, 2-Fiteff, 3-Leuven, 4-Radware (to be selected in **CONT**, flag **EFF**)

- “TAPE8” file produced by OP,GDET is required to use OP,RAW.

```
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
```

Experiment number (according to the sequence in **EXPT**)

Efficiency parametrisation for detector 1 defined in OP,GDET

Efficiency parametrisation for detector 2 defined in OP,GDET

(for “Gremlin” efficiency, 0 0 0 0 0 0 -50 0 is a “flat” efficiency curve)

number of “clusters” (summed Ge spectra)

total number of Ge detectors in cluster 1

indices of Ge detectors in cluster 1 (corresponding to their theta and phi angles in OP,YIEL)

total number of Ge detectors in cluster 2

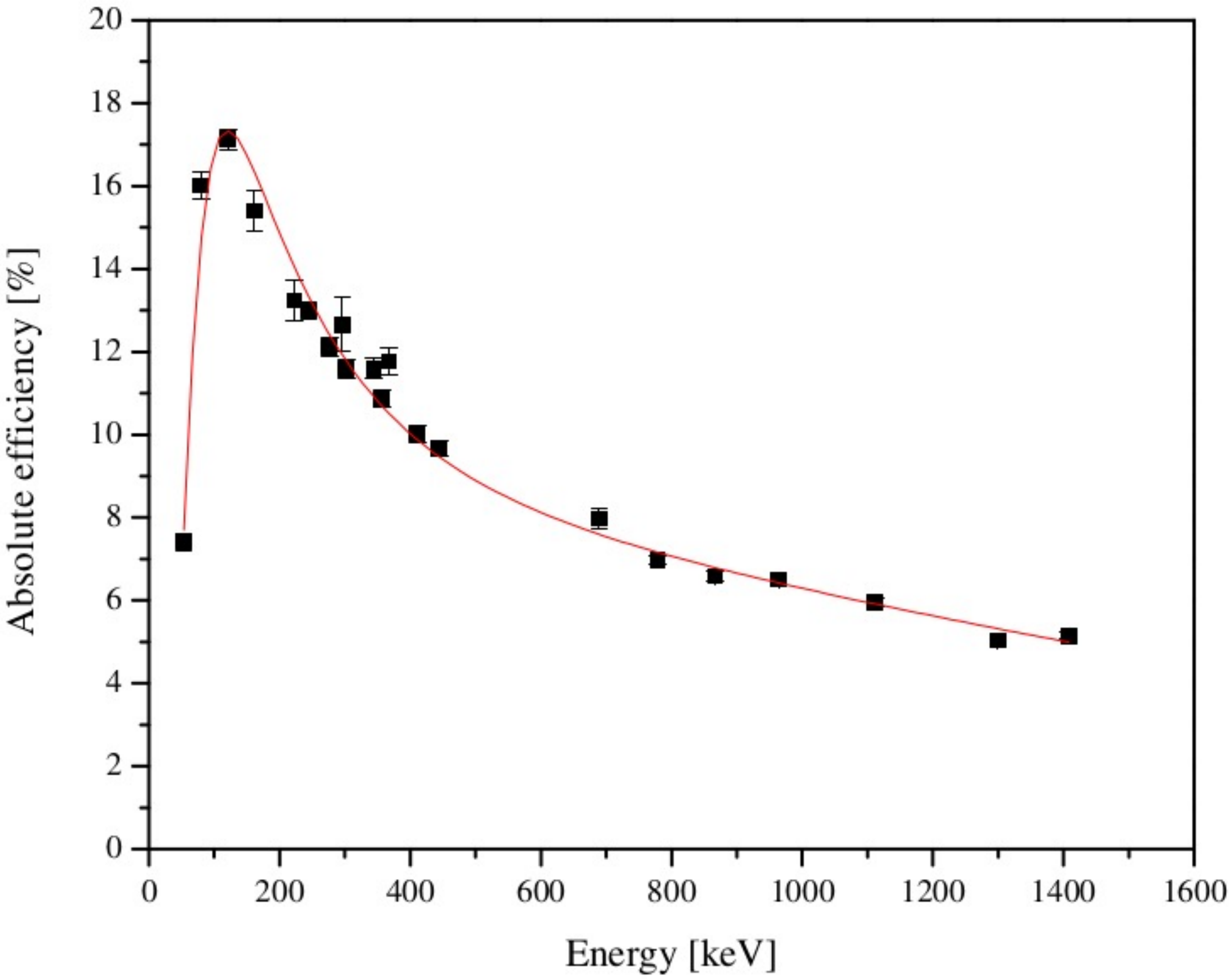
indices of Ge detectors in cluster 2

End of OP,RAW input

CONT	
EFF,1.	one experiment in OP,RAW
1 0	parametrization 0 “Gremlin” for experiment 1

EFFICIENCY CURVE

“Leuven” parametrization: $$\ln(\epsilon_\gamma) = \sum_{i=0}^{4} a_i \cdot \left[\ln\left(\frac{E_\gamma}{200}\right)\right]^i.$$



GAMMA-RAY YIELDS: SIMULATIONS and ANALYSIS

OP,POIN

- Calculation of gamma-ray yields in the laboratory frame for **the specific beam energy** and **specific particle scattering angle** declared in the **EXPT** section:

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

- The calculation includes the **Rutherford cross section**, the sin(Θ) term, integration over the projectile φ scattering angle, and effects influencing the decay, such as the deorientation effect (can be adjusted via the CONT section) and attenuation related to finite size of gamma-ray detectors (attenuation factors in the "TAPE9" file)
- OP,POIN needs to follow OP,YIEL which provides necessary information on internal conversion and gamma-ray detection geometry. User-defined gamma-ray yields do not need to be provided.

YFL=0: calculated gamma-ray yields appear in the output file ("TAPE22") only →

```
OP,POIN
YFL YLIM
```

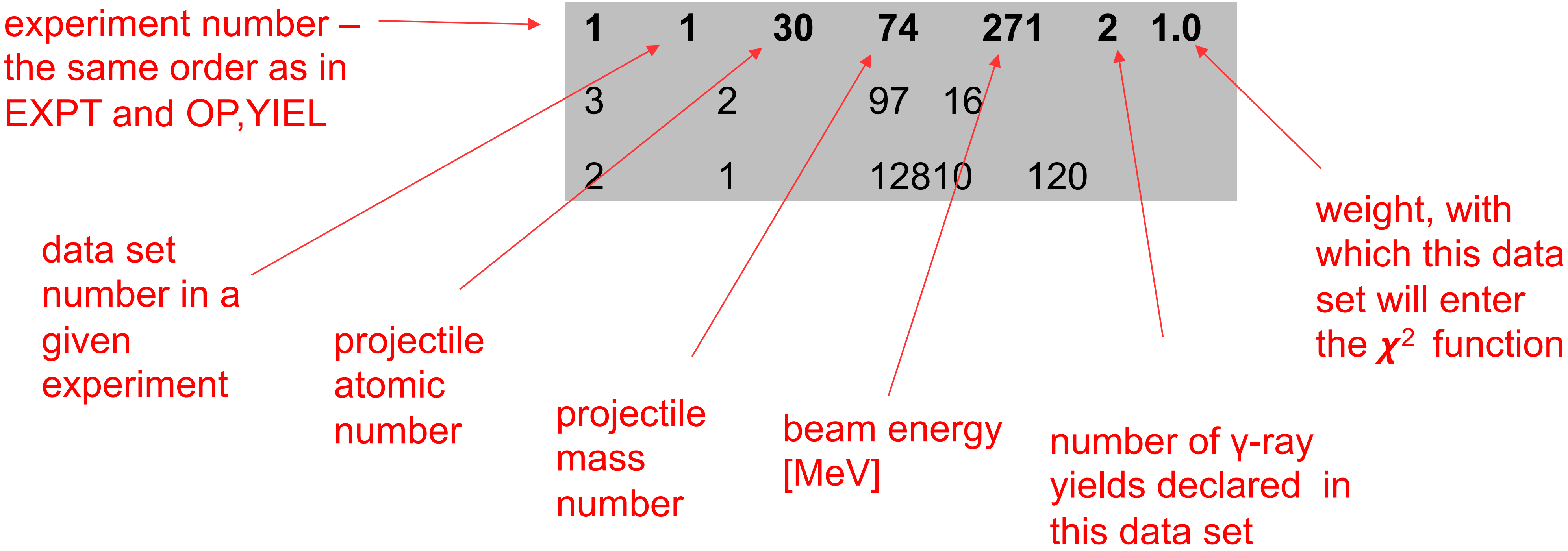
← If **YFL=1** – gamma-ray yields for all transitions whose intensities divided by that of the normalising transition exceed YLIM will appear in the "TAPE4" file

YFL=1: some calculated gamma-ray yields may appear in the "TAPE4" file, which will be overwritten

```
OP,POIN
1 0
```

← All gamma-ray yields corresponding to the declared set of matrix elements will appear in the "TAPE4" file

"TAPE3" / "TAPE4" file contents



experiment number – the same order as in EXPT and OP,YIEL

```
1     1     30     74     271     2   1.0
3           2            97   16
2           1            12810      120
```

data set number in a given experiment

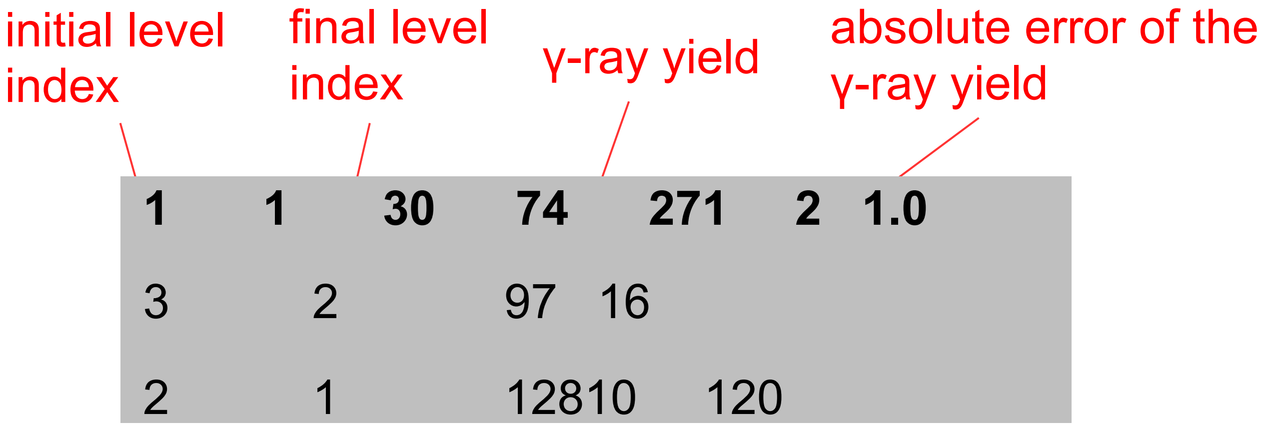
projectile atomic number

projectile mass number

beam energy [MeV]

number of γ-ray yields declared in this data set

weight, with which this data set will enter the χ^2 function



initial level index

final level index

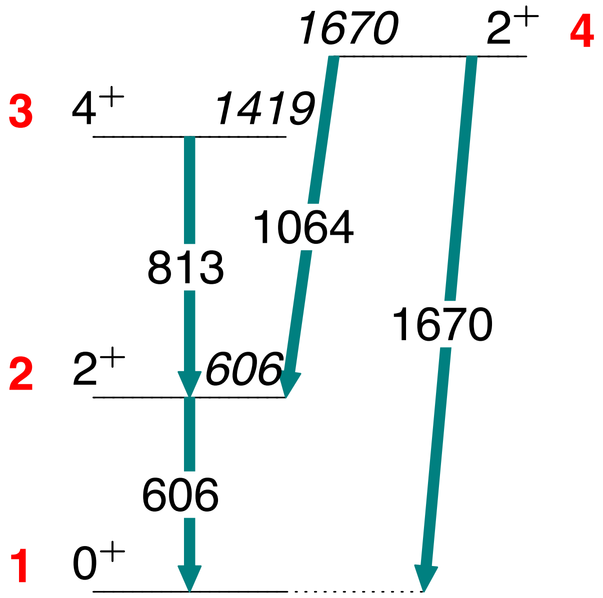
γ-ray yield

absolute error of the γ-ray yield

```
1     1     30     74     271     2   1.0
3           2            97   16
2           1            12810      120
```

Ordering of gamma-ray transitions is arbitrary

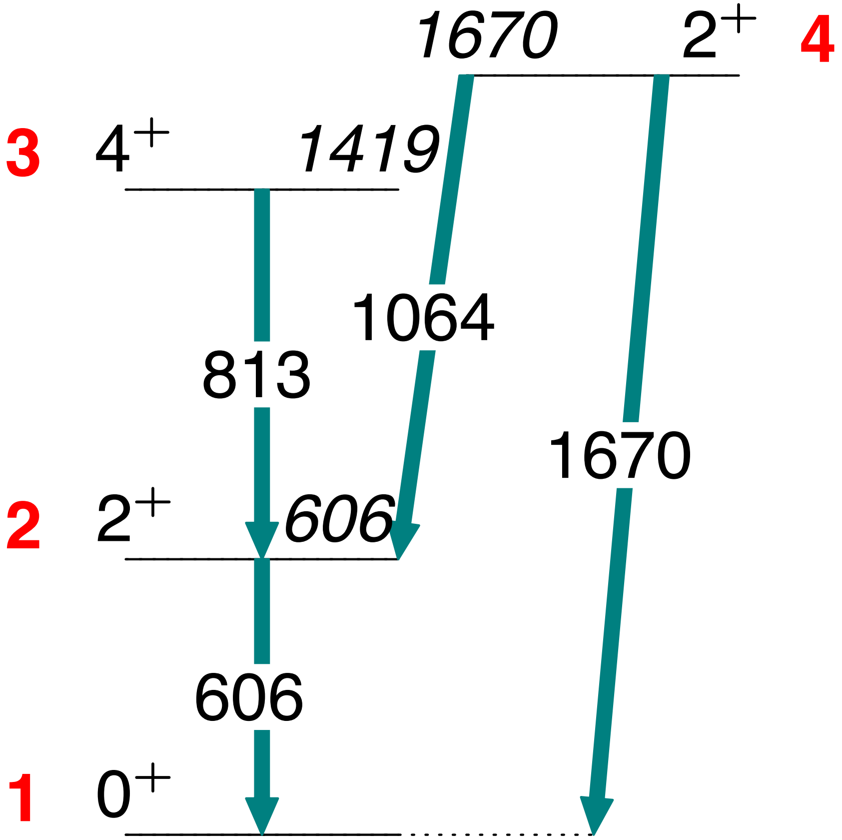
Normalised gamma-ray yields can be input, if preferred



“TAPE3” FILE for ^{74}Zn

```
1 1 30  74  271. 3  1.
 4 2  26 10
 3 2  97 16
 2 1 12810 120
```

(projectile detected in the CD)



“point” versus “integrated” yield in GOSIA

The experimental gamma-ray yields often correspond to wide ranges of scattering angles covered by particle detectors. Incident energy decreases as beam slows down in the target material – not all events correspond to the nominal beam energy

For a realistic comparison with experimental data, these effects must be accounted for
→ integrated yields are calculated

POINT YIELD

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

(as defined in EXPT)

Calculated with **OP,POIN**

INTEGRATED YIELD

- Energy **range** (E_{min}-E_{max})
- Angular **range** ($(\Theta_{min},\varphi_{min})$–$(\Theta_{max},\varphi_{max})$)

Calculated with **OP,INTG / INTI**

Fit of matrix elements to experimental data is performed to “point”-like yields to speed up calculations

Correction factors are introduced to translate experimental yields (“TAPE3”) into their point-like equivalents, stored on TAPE4.

OP,INTI+OP,CORR – yield correction

For each transition in the “TAPE3” file, GOSIA calculates the **point** yield (**Y_p**) and the **integrated** yield (**Y_I**) using the current set of matrix elements.

The correction factors **CF** are defined as:

$$\mathrm{CF}=\frac{Y_P}{Y_I}$$

→

They are applied to experimental gamma-ray yields **Y_{exp}** provided in “TAPE3” file

$$\mathbf{Y}^{\mathbf{c}}_{\mathbf{exp}}=\mathbf{Y}_{\mathbf{exp}}\cdot\mathbf{CF}$$

The resulting “corrected” experimental gamma-ray yields **Y^c_{exp}** are written to the “TAPE4” file.

This correction depends, although rather weakly, on the assumed set of MEs: after minimization the correction procedure should be repeated with a new set of MEs (better fit, different correction), until a converged solution is found.

```
EXPERIMENT  2        DETECTOR  1
NI     NF     YEXP        YCOR        COR.F

 3       2   .112E+00   .113E+00   .101E+01
 2       1   .124E+02   .120E+02   .969E+00
```

How to calculate counting rates?

Integrated gamma-ray yields are expressed in units of milibarns par steradian of gamma-ray emission angle, multiplied by the target thickness (in mg/cm^2):

[Y] = [mb/sr] × [mg/cm^2]

In general, counting rate is related to the cross section as follows:

$$Counts = \left[\frac{Q}{\mathrm{q}e}\right] \cdot \left[\frac{N_A}{A}\right] \cdot \frac{d^2\boldsymbol{\sigma}}{d\Omega_\gamma d\Omega_p} \cdot \rho\mathrm{d} \cdot \varepsilon_p \cdot \varepsilon_\gamma \cdot \Delta\Omega_\gamma \cdot \Delta\Omega_p$$

Where:
Q – integrated beam charge [C]
q – average charge state of the beam
e – elementary charge [1.602 x 10^{-19} C]
N_A – Avogadro number [6.022 x 10^{23} atoms/mol]
A – target mass number [g/mol]
ρd – target thickness [g/cm^2]
ε_p – particle detection efficiency excluding the geometrical solid angle
ε_γ – gamma detection efficiency excluding the geometrical solid angle
$\Delta\Omega_p$, $\Delta\Omega_\gamma$ – solid angle for particle and gamma-ray emission

How to calculate counting rates?

Integrated gamma-ray yields are expressed in units of milibarns par steradian of gamma-ray emission angle, multiplied by the target thickness (in mg/cm^2):

$[Y] = [\mathrm{mb/sr}] \times [\mathrm{mg/cm}^2]$

In general, counting rate is related to the cross section as follows:

$$Counts = \left[\frac{Q}{\mathrm{qe}}\right] \cdot \left[\frac{N_A}{A}\right] \cdot \frac{d^2\boldsymbol{\sigma}}{d\Omega_\gamma d\Omega_p} \cdot \rho d \cdot \varepsilon_p \cdot \varepsilon_\gamma \cdot \Delta\Omega_\gamma \cdot \Delta\Omega_p$$

GOSIA integrated yields already include the target thickness and integration over the particle solid angle, thus the formula reduces to:

$$Counts = \left[\frac{Q}{\mathrm{qe}}\right] \cdot \left[\frac{N_A}{A}\right] \cdot \mathrm{Y}^{\mathrm{INTG}}\ (\mathrm{I_i} \rightarrow \mathrm{If}) \cdot \varepsilon_p \cdot \varepsilon_\gamma \cdot \Delta\Omega_\gamma$$

Plugging in all constants, after unit conversion produces:

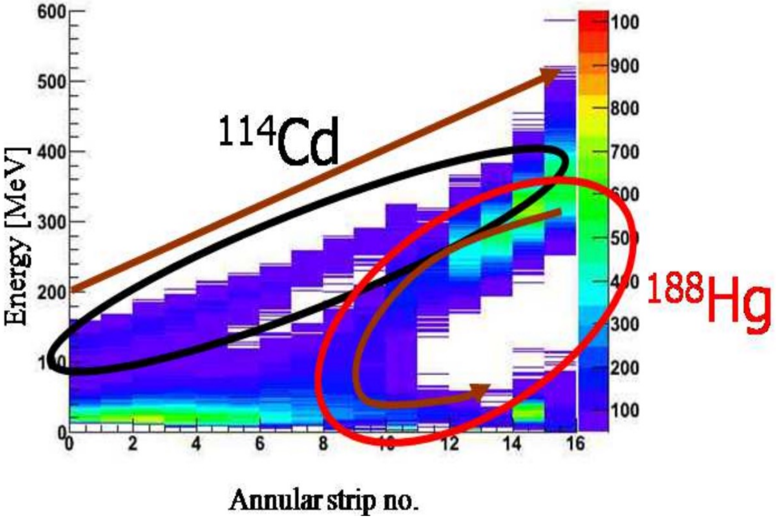
$$\boxed{\textbf{Count Rate} = \frac{7.6 \times 10^{-6} \times yield \times current[pps] \times eff}{A_{target}}}$$

NOTE: If you declare N gamma-ray detectors with flat efficiency curves, GOSIA will interpret this as “N detectors, each with 100% efficiency”, so the integrated yield needs to be divided by N to obtain correct counting rates. Same if we use absolute efficiency curves defined for the entire spectrometer, and repeat it N times for N detectors.

OP,INTI

The original integration routine in GOSIA, OP,INTG, for inverse kinematics did not permit to perform integration over a range of scattering angles that would encompass two kinematic solutions.

Low-statistics radioactive beam experiments often required integration over all detector angles and thus OP,INTI has been developed by Nigel Warr.



N. Bree, PhD thesis, KU Leuven

This option performs identically to OP,INTG for normal kinematics. For inverse kinematics, the user provides **Θ** meshpoints that correspond to laboratory scattering angles of the **detected particle**, which means they should simply describe the actual geometry of the particle detector (it used to be much more complicated with OP,INTG).

GOSIA “knows” from the EXPT section if the target or the projectile has been detected, and sets automatically the appropriate value of kinematic flag (identifies if this is the high θ_{CM} or the low θ_{CM} solution).

OP,INTI

STEP 1:

- γ-ray yields are calculated for each combination of incident energy **E** and scattering angle **θ** meshpoints provided for the user.
- They are also integrated over the azimuthal angle **φ.**

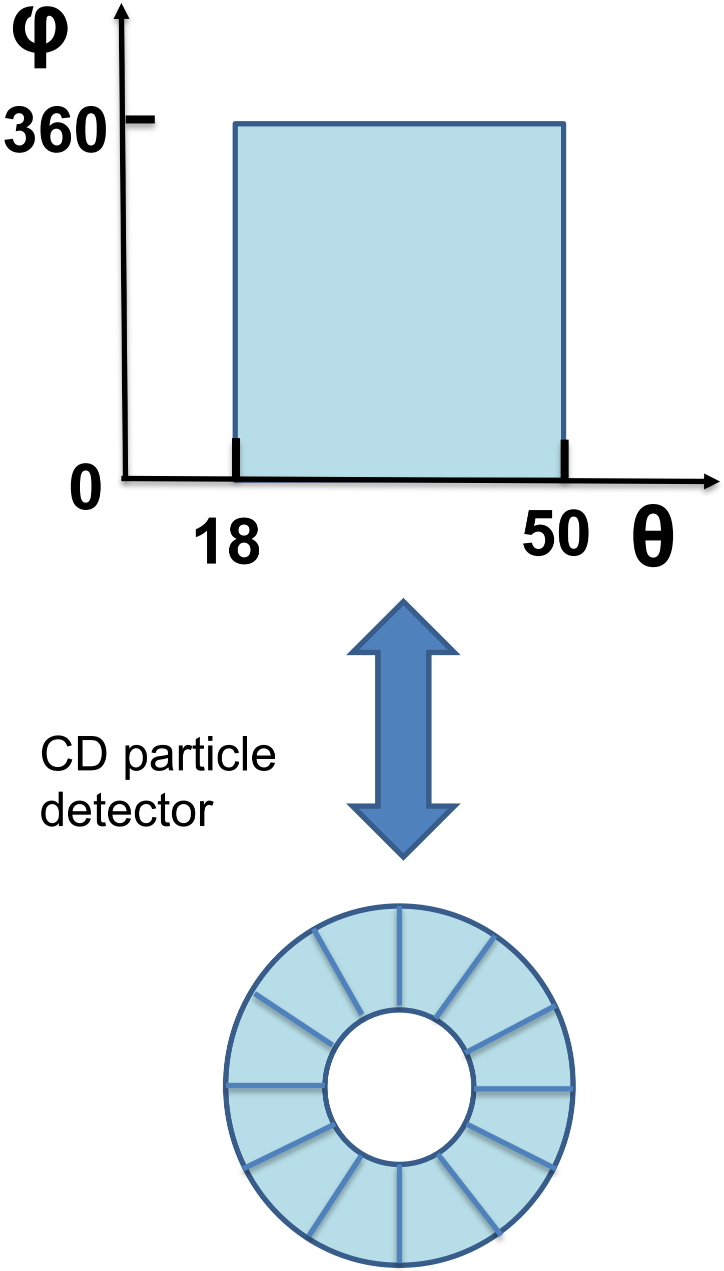
STEP 2:

- Integration over energy **E** and the range of scattering angles **θ** of the particle detector is performed by interpolation between the yields calculated at each **E-θ** meshpoint.
- The user provides the number of subdivisions in **E** and **θ** that will be used for the integration (γ-ray yields at subdivision points are calculated via interpolation).
- Stopping powers are also provided and interpolation between their values is performed.

SPL flag in the CONT section – use of spline interpolation instead of Lagrange interpolation (option introduced by P.J. Napiorkowski)
Not default, but highly recommended!

```
CONT
SPL,1.
(…)
END,
```

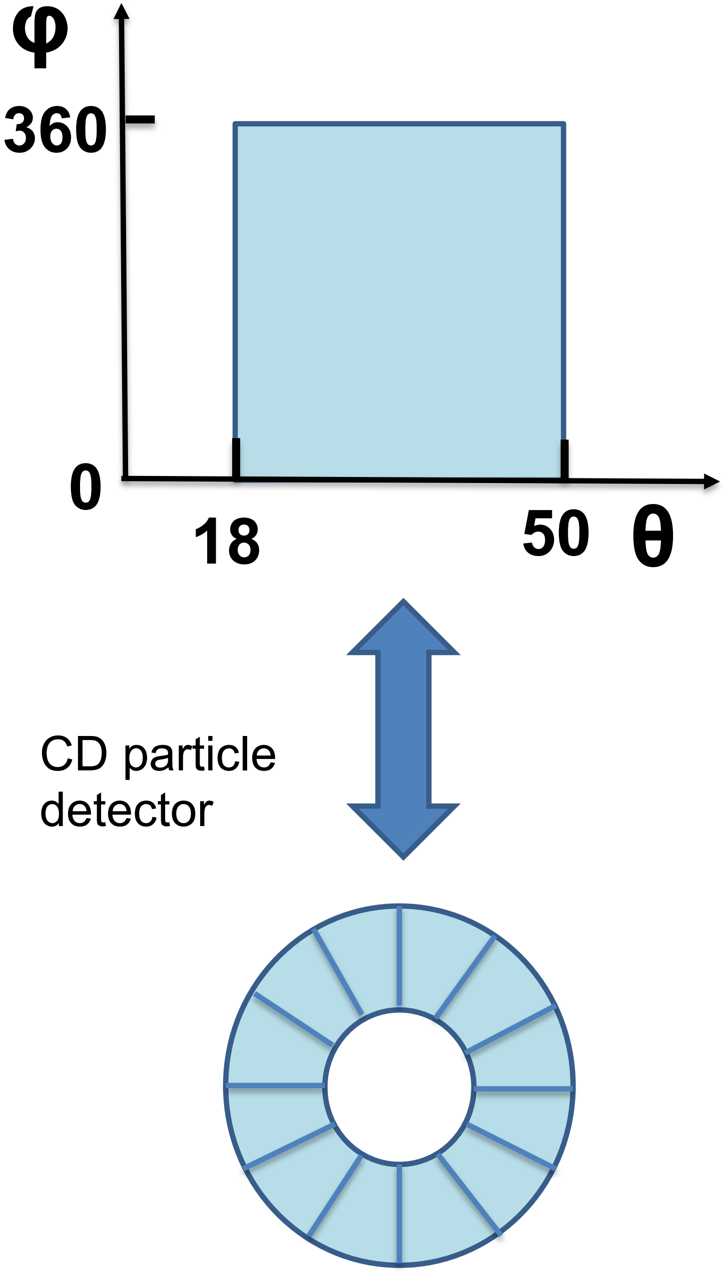
OP,INTI (axial symmetry case)



OP,INTI
3

- number of energy meshpoints

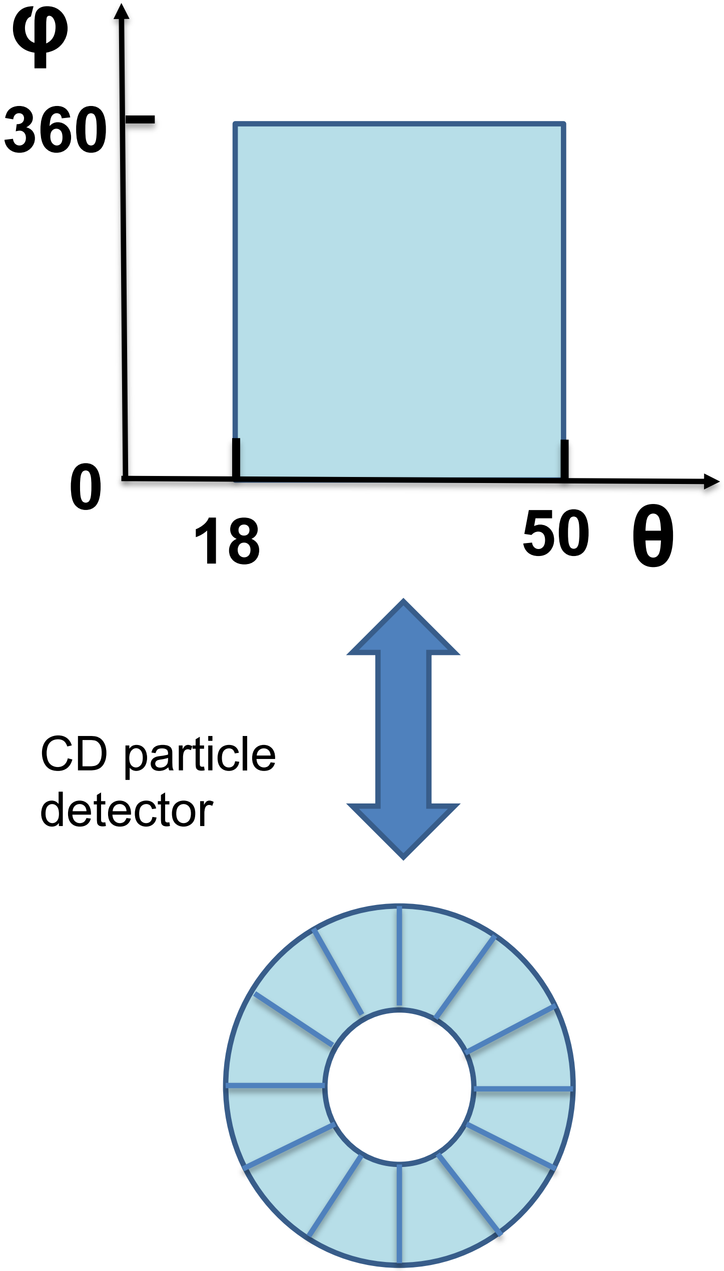
OP,INTI (axial symmetry case)



```
OP,INTI
3,5
```

- number of energy meshpoints
- number of θ meshpoints

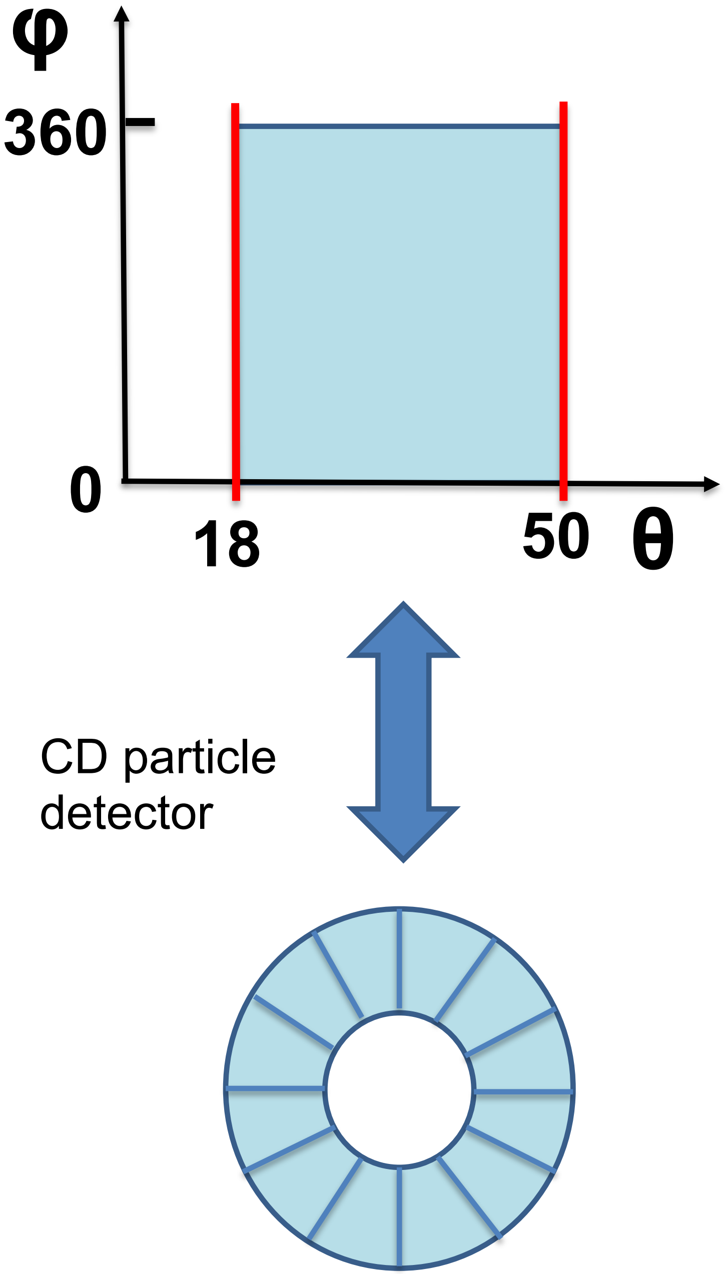
OP,INTI (axial symmetry case)



```
OP,INTI
3,5,246,296
```

- number of energy meshpoints
- number of **θ** meshpoints
- minimum and maximum bombarding energy

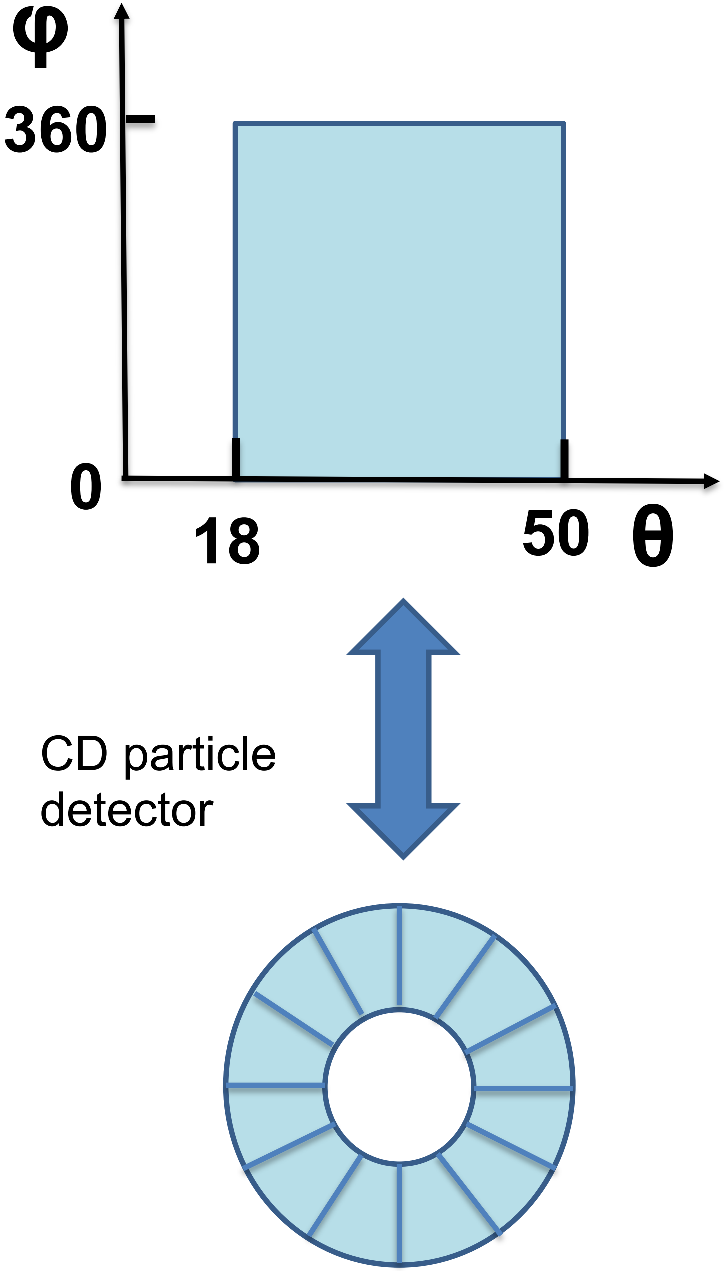
OP,INTI (axial symmetry case)



```
OP,INTI
3,5,246,296,18,50
```

- number of energy meshpoints
- number of θ meshpoints
- minimum and maximum bombarding energy
- minimum and maximum θ angles

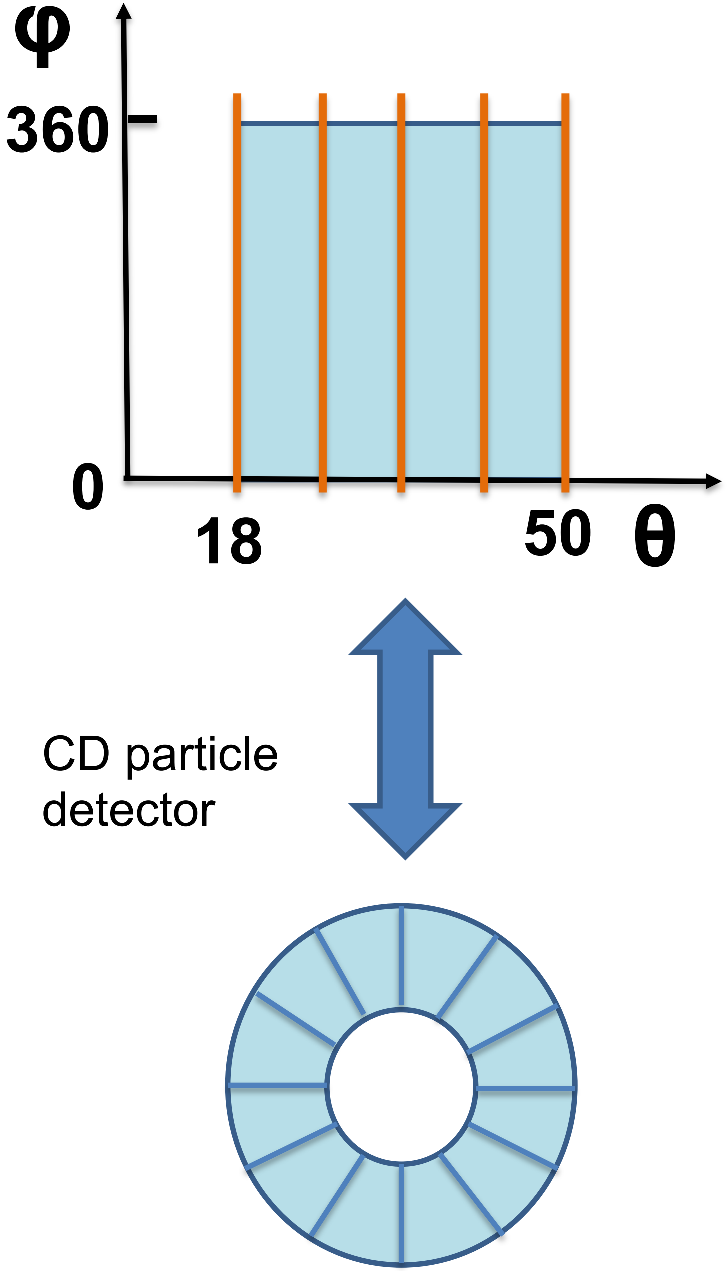
OP,INTI (axial symmetry case)



```
OP,INTI
3,5,246,296,18,50
240,270,300
```

- number of energy meshpoints
- number of **θ** meshpoints
- minimum and maximum bombarding energy
- minimum and maximum **θ** angles
- energy meshpoints

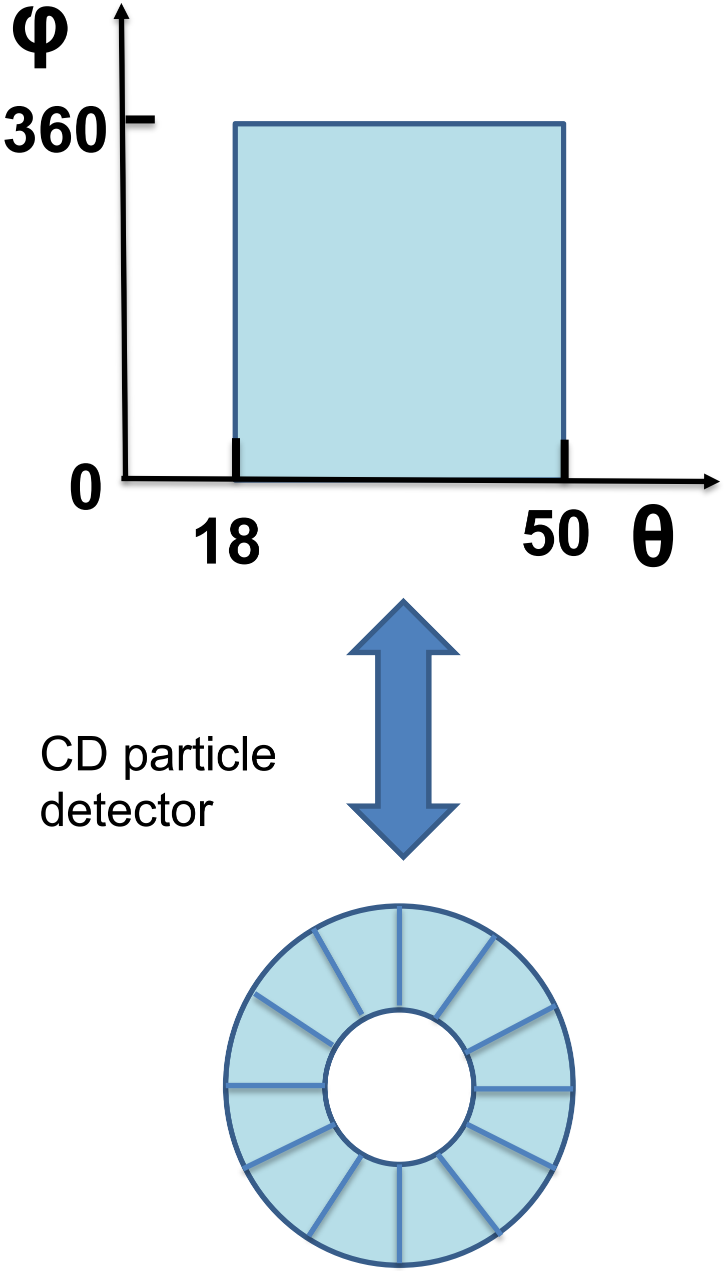
OP,INTI (axial symmetry case)



```
OP,INTI
3,5,246,296,18,50
240,270,300
18,26,34,42,50
```

- number of energy meshpoints
- number of **θ** meshpoints
- minimum and maximum bombarding energy
- minimum and maximum **θ** angles
- energy meshpoints
- **Θ** meshpoints

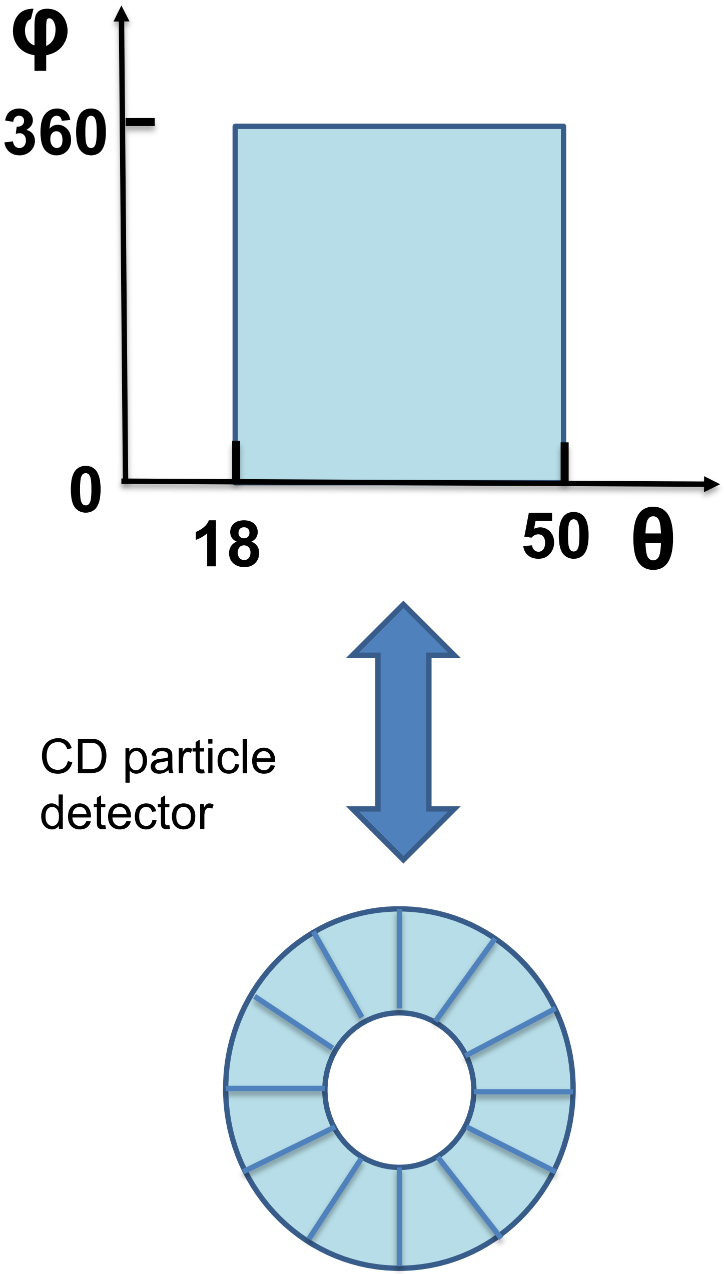
OP,INTI (axial symmetry case)



```
OP,INTI
3,5,246,296,18,50
240,270,300
18,26,34,42,50
3
```

- number of energy meshpoints
- number of **θ** meshpoints
- minimum and maximum bombarding energy
- minimum and maximum **θ** angles
- energy meshpoints
- **Θ** meshpoints
- number of meshpoints for stopping power interpolation (between 3 and 20)

OP,INTI (axial symmetry case)

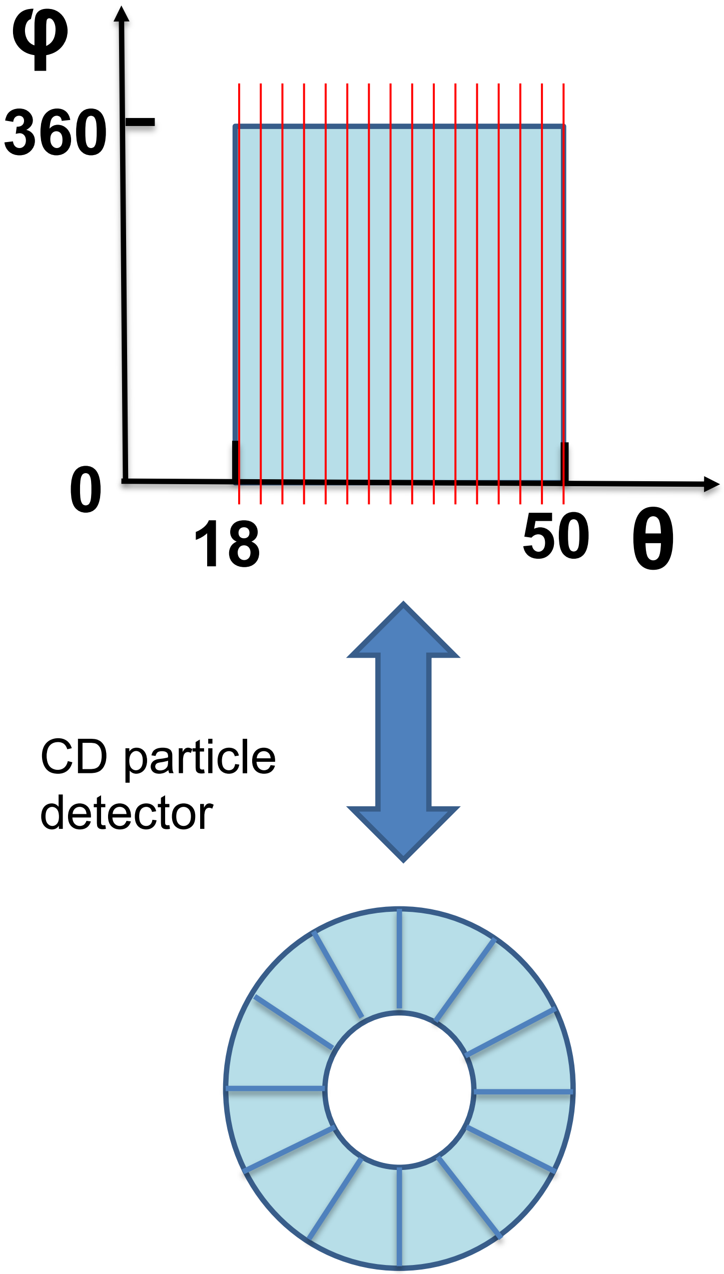


CD particle detector

```
OP,INTI
3,5,246,296,18,50
240,270,300
18,26,34,42,50
3
240,270,300
12.6,12.6,12.5
```

- number of energy meshpoints
- number of θ meshpoints
- minimum and maximum bombarding energy
- minimum and maximum θ angles
- energy meshpoints
- Θ meshpoints
- number of meshpoints for stopping power interpolation
- energies
- corresponding stopping powers [MeV/(mg/cm^2)]

OP,INTI (axial symmetry case)



```
OP,INTI
3,5,246,296,18,50
240,270,300
18,26,34,42,50
3
240,270,300
12.6,12.6,12.5
16,16
```

- number of energy meshpoints
- number of **θ** meshpoints
- minimum and maximum bombarding energy
- minimum and maximum **θ** angles
- energy meshpoints
- **Θ** meshpoints
- number of meshpoints for stopping power interpolation
- energies
- corresponding stopping powers
- number of equal subdivisions of energy used for interpolation, number of equal subdivisions of **θ** (both ≤ 100)

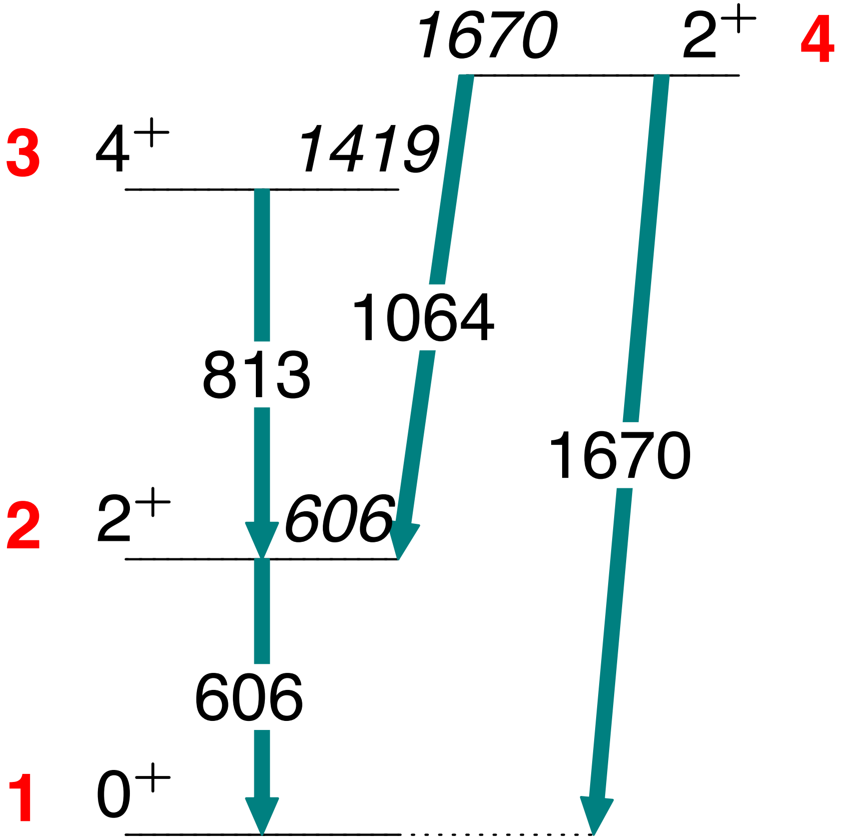
“TAPE3” FILE for ^{74}Zn – second experiment

projectile detected in the CD:

```
1 1 30  74  271. 3  1.
 4 2  26 10
 3 2  97 16
 2 1 12810 120
```

recoil detected in the CD:

```
2 1 30  74  271. 3  1.
 4 2  126 40
 3 2  570 50
 2 1 16310 200
```



FIT of MATRIX ELEMENTS TO EXPERIMENTAL DATA:

OP,MINI

OP,MINI: χ^2 function

weights ascribed to the
various subsets of data

normalisation constants

$$\chi^2 = \sum_{i=1}^{N\,\mathrm{exp}} \sum_{j=1}^{N\,\mathrm{det}} w_{ij} \sum_{k(ij)}^{N\,\gamma\mathrm{exp}} \frac{1}{\sigma_k^2} \left(C_{ij} I_k^c - I_k^e\right)^2$$

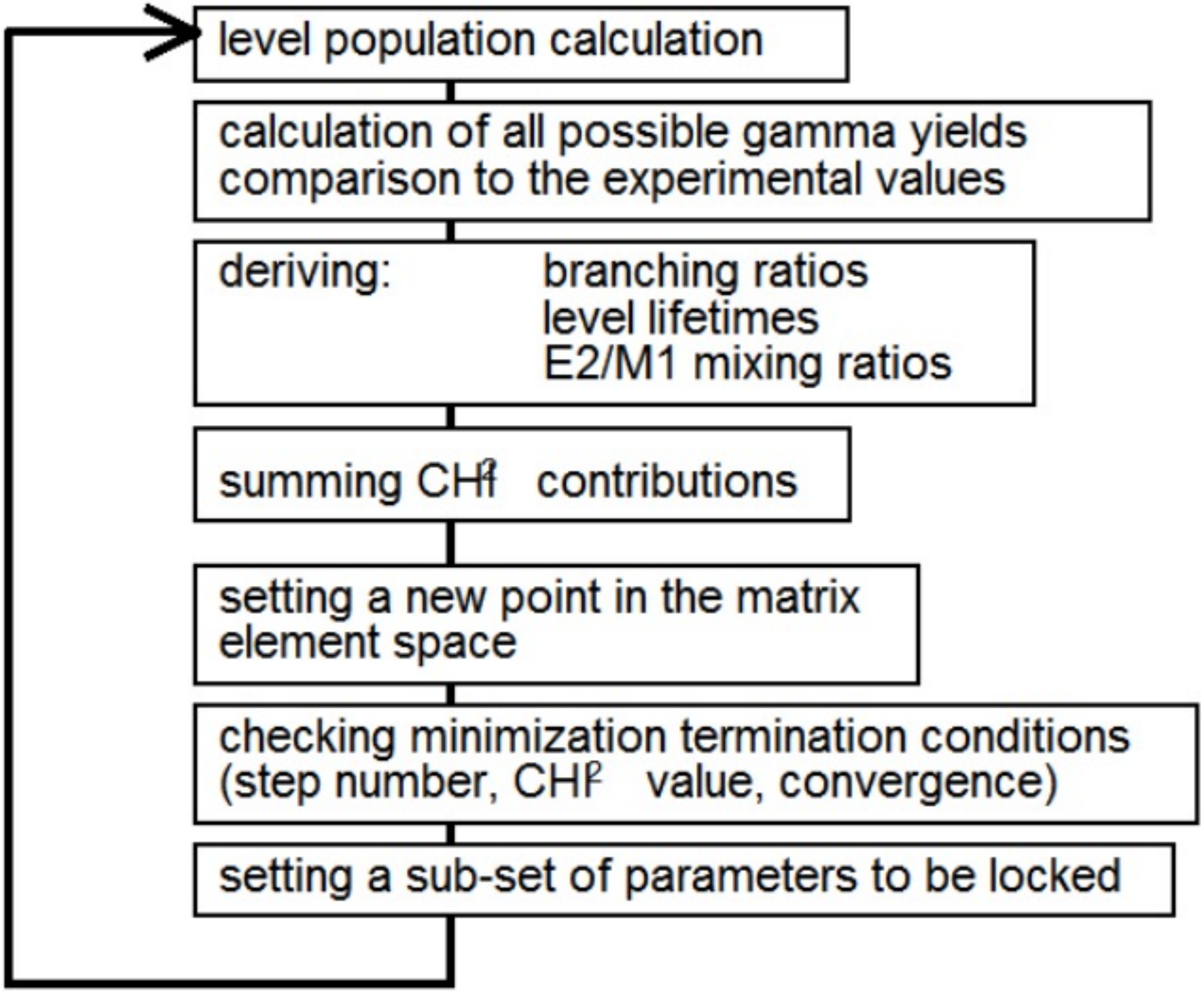
$$+ \sum_{d} w_d \sum_{n_d} \frac{1}{\sigma_{n_d}^2} \left(D_{n_d}^c - D_{n_d}^e\right)^2$$

spectroscopic data points
(lifetimes, BR, mixing coefficients …)

$$+ \sum_{m\,(i\,j)}^{N\,\gamma\mathrm{calc}} \left(\frac{I_j^c(i,j)}{I_n^c(i,j)} - u(i,j) \right)^2 \cdot \frac{1}{u^2(i,j)}$$

„observation upper limit”
of γ-ray intensities

OP,MINI



level population calculation

calculation of all possible gamma yields
comparison to the experimental values

deriving: branching ratios
level lifetimes
E2/M1 mixing ratios

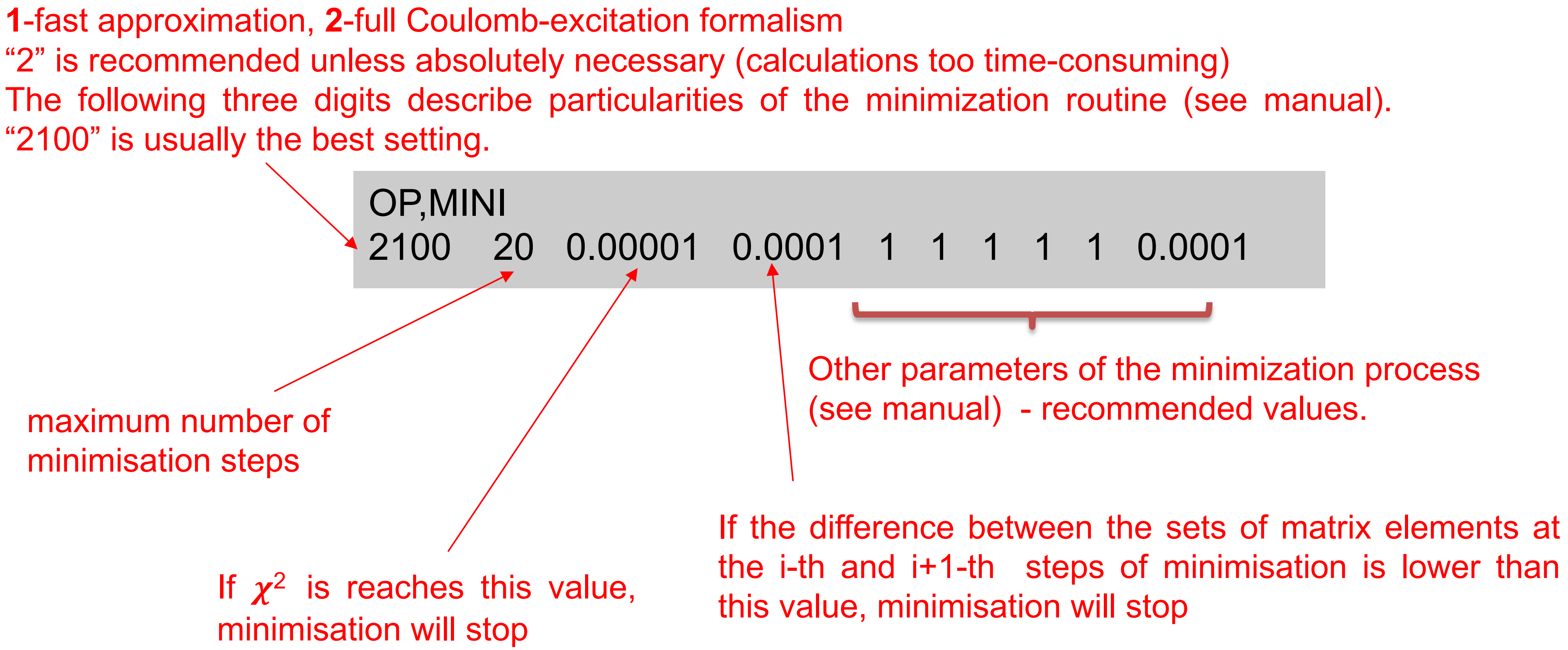
summing CHI^2 contributions

setting a new point in the matrix element space

checking minimization termination conditions
(step number, CHI^2 value, convergence)

setting a sub-set of parameters to be locked

OP,MINI



1-fast approximation, **2**-full Coulomb-excitation formalism
“2” is recommended unless absolutely necessary (calculations too time-consuming)
The following three digits describe particularities of the minimization routine (see manual).
“2100” is usually the best setting.

```
OP,MINI
2100   20   0.00001   0.0001   1   1   1   1   1   0.0001
```

maximum number of minimisation steps

If χ^2 is reaches this value, minimisation will stop

If the difference between the sets of matrix elements at the i-th and i+1-th steps of minimisation is lower than this value, minimisation will stop

Other parameters of the minimization process (see manual) - recommended values.

- Minimisation will start from the values of matrix elements declared in the ME section.
- After the requested number of steps (or reaching requested χ^2 /convergence) it will stop and the final values of matrix elements will be written on “TAPE12” file as a single column.
- If

  ```
  OP,REST
  0,0
  ```

  is added before OP,MINI, values from TAPE12 will be read and minimisation will continue from this point.
- An OP,MINI sequence can follow another OP,MINI sequence:

```
OP,MINI
2100 20   0.1   0.1   1   1   1   1   1   0.01
OP,MINI
2100 20   0.1   0.1   1   1   1   1   1   0.01
```

OP,MAP

```
OP,MAP
OP,EXIT
```

- A parameterless option that causes calculation of the q-parameters map used in GOSIA's fast approximation procedure. They are stored in the "TAPE7" file.

- q parameters depend on excitation energies and maximum allowed values of matrix elements, so if there are changes in LEVE or ME sections of OP,GOSI (even increasing ranges in which matrix elements can vary), OP,MAP should be run again

- They also depend on the reaction kinematics and are calculated for each experiment separately, so if new experiments are declared, OP,MAP should be run again.

- Even if fast approximation is not used ("2100" mode selected in OP,MINI), GOSIA will require the "TAPE7" file to be present when running OP,MINI.

ERROR CALCULATION:

OP,ERRO

OP,ERRO

STEP 1: the “diagonal”, or **uncorrelated errors** are calculated for each matrix element:

the effect on the χ^2 value of changing values of one single matrix element at a time is investigated

STEP 2: the “full”, or **correlated errors** are calculated:

GOSIA defines in the vicinity of the χ^2 minimum a “**maximum correlation path**” (a curve in the matrix-element space $\bar{x}$ for which the effect of varying the matrix element in question, x_i, is to the greatest extent balanced by changes of other matrix elements).

The uncertainty is found by requesting that the integral of the normalised probability distribution contained within error bars equals to the confidence limit of 68.3%:

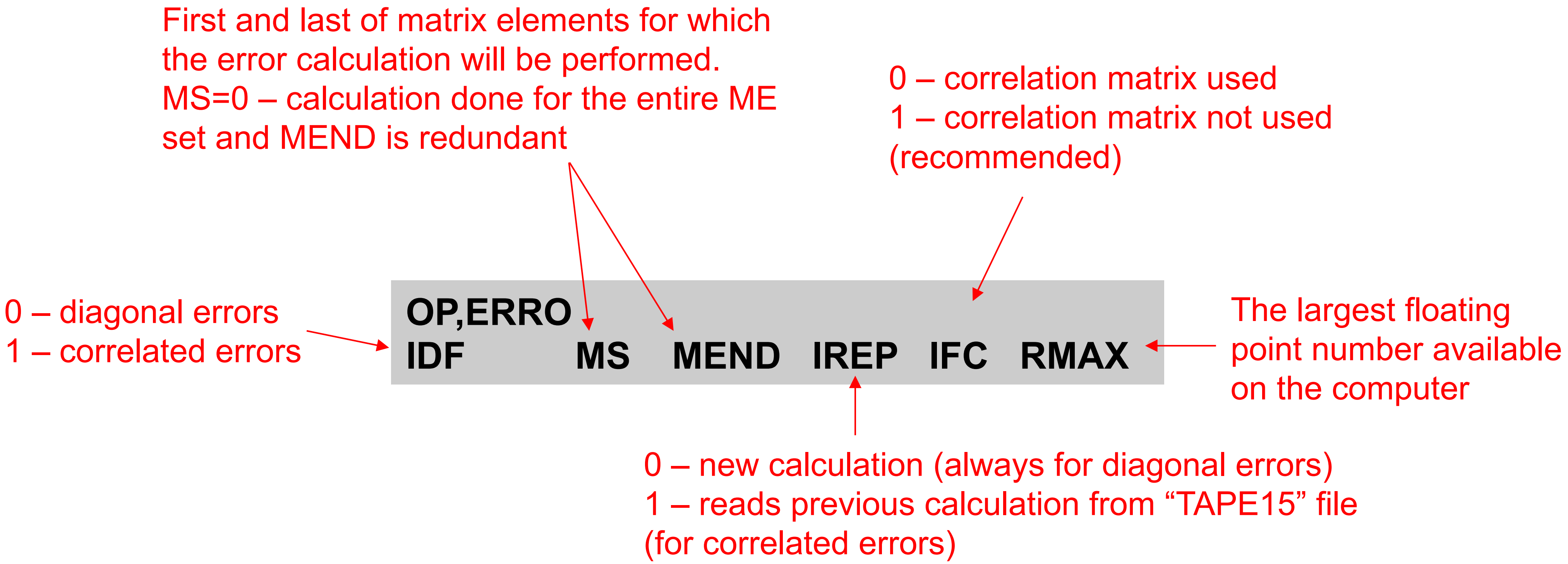
$$\frac{\int_l \exp\left(-\frac{1}{2}\chi^2(\bar{x})\right) \mathrm{d}\bar{x}}{\int \exp\left(-\frac{1}{2}\chi^2(\bar{x})\right) \mathrm{d}\bar{x}} = 68.3\% \;,$$

Numerator: integration along the maximum correlation path l

Denominator: integration over all possible values of matrix elements (limits declared in the ME section)

Results of error calculation are written in the “TAPE15” file.

OP,ERRO



First and last of matrix elements for which the error calculation will be performed.
MS=0 – calculation done for the entire ME set and MEND is redundant

0 – correlation matrix used
1 – correlation matrix not used (recommended)

0 – diagonal errors
1 – correlated errors

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

The largest floating point number available on the computer

0 – new calculation (always for diagonal errors)
1 – reads previous calculation from “TAPE15” file (for correlated errors)

Diagonal error calculation for all matrix elements:

0 0 0 0 0 1.e+36

Full error calculation for all matrix elements:

1 0 0 1 1 1.e+36