Coincidence Summing Corrections in GESPECOR

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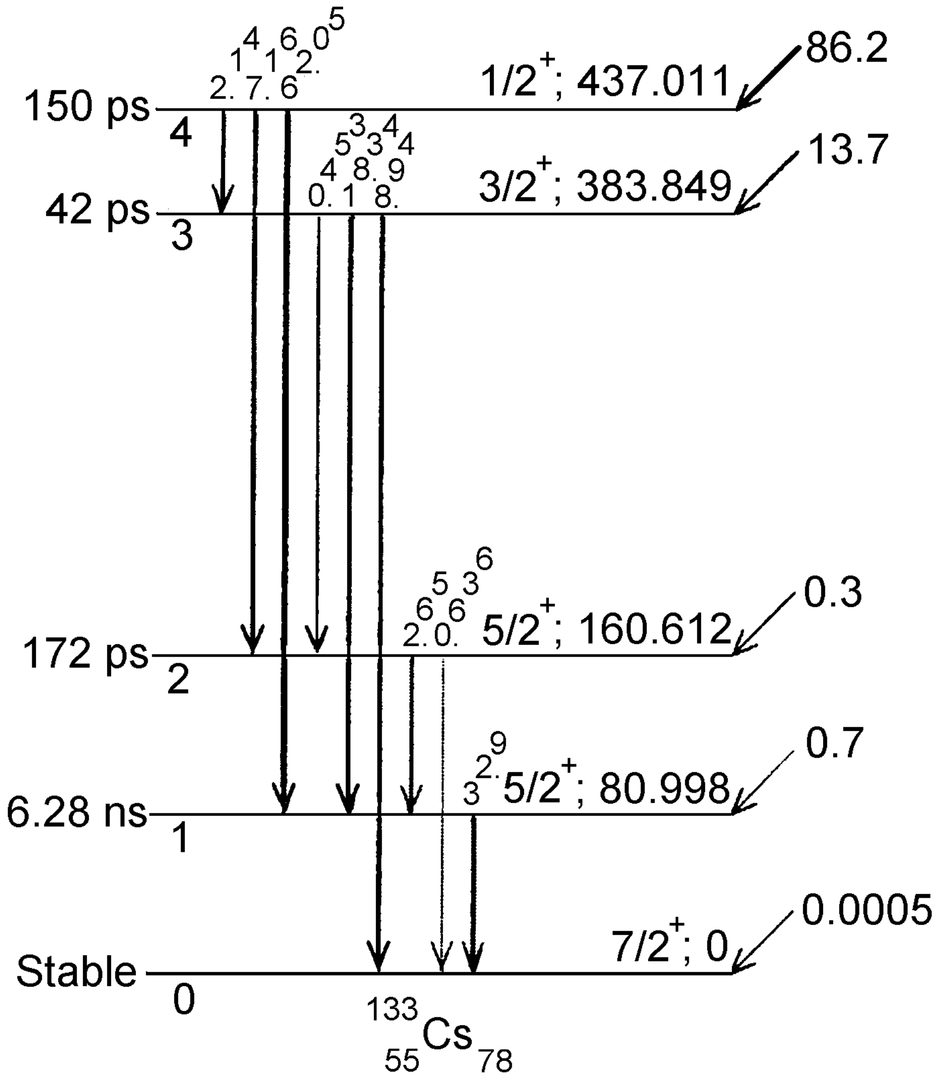


Ba-133 EC decay

E (keV)	Iγ (per 100 Dis)
53.1622	2.14±0.03
79.6142	2.65 ±0.05
80.9979	32.9 ±0.3
160.6121	0.638 ±0.004
223.2368	0.453 ±0.003
276.3989	7.16 ±0.05
302.8508	18.34 ±0.13
356.0129	62.05 ±0.19
383.8485	8.94 ±0.06

Data source: Nucleide

Ex: 302 keV peak

But: 302 keV photon is emitted together with other radiations!

1 Kα(EC4)-53-302-81

2 Kα(EC4)-53-302-Kα(81)

3 Kα(EC4)-53-302-Kβ(81)

4 Kα(EC4)-53-302-other(81) (other => no signal in detector)

5 Kα(EC4)- Kα(53)-302-81

6 Kα(EC4)- Kα(53)-302- Kα(81)

And so on, ending with

48 other(EC4)-other(53)-302-other(81)

Other decay paths start by feeding the 383 keV level (EC3):

49 Kα(EC3)-302-81

50, 51, 52, 53, 54, 55, 56, 57, 58, 59

60 other(EC3)-302-other(81)

Each combination i has a specific **joint emission probability** p_i

$$p(302)=p_1+p_2+p_3+\ldots+p_{60}$$

Each combination has a specific probability to contribute to the count-rate in the 302 keV peak, e.g. combination (1)

$K\alpha(EC4)$-53-302-81 => $\varepsilon_1=[1-\mu(K\alpha)][1-\mu(53)]\ \varepsilon(302)\ [1-\mu(81)]$

$\mu(E)$= total detection efficiency for photons of energy E

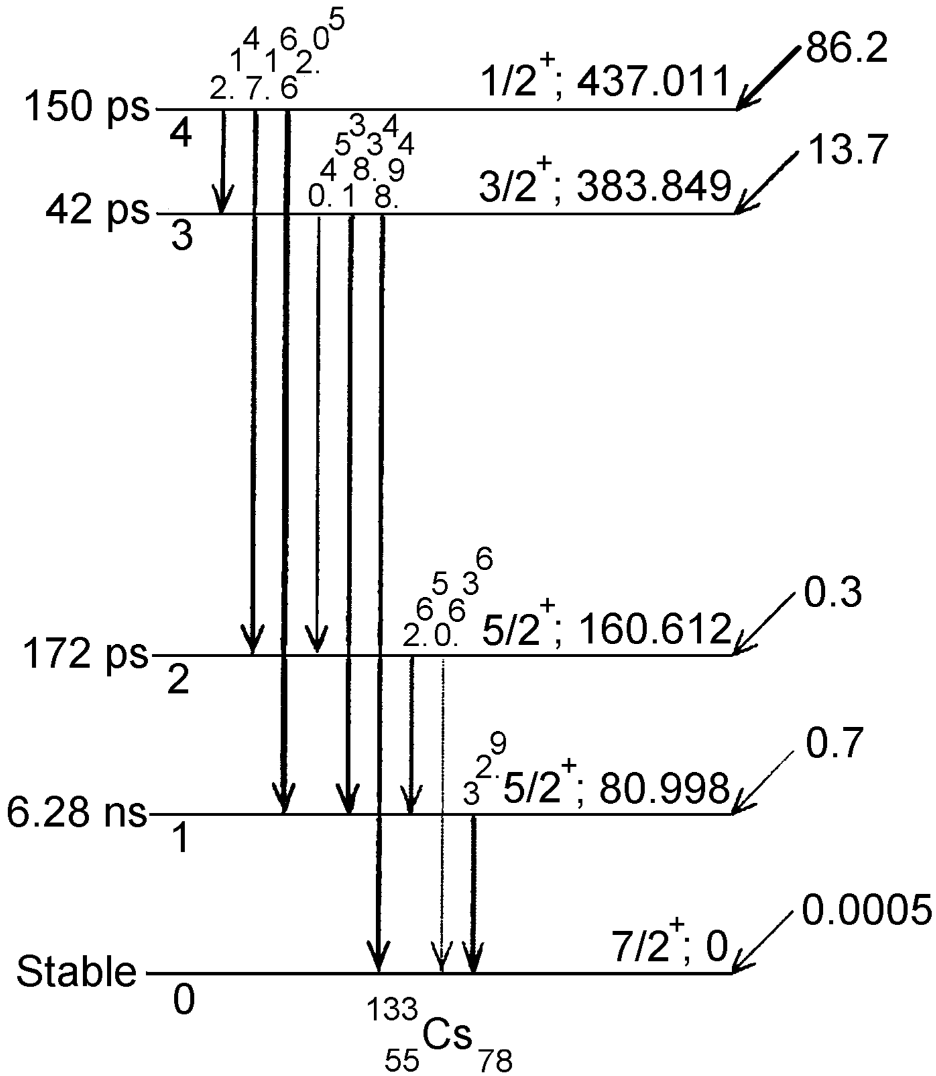
$\varepsilon_i < \varepsilon(302)$ => **coincidence losses from the 302 keV peak**

Additional complication – angular correlation of photons

Apparent efficiency for 302 keV peak of Ba-133 would be:
$\varepsilon(302,\text{Ba-133})=(p_1\,\varepsilon_1 + p_2\,\varepsilon_2 + p_3\,\varepsilon_3 + \ldots + p_{60}\,\varepsilon_{60})/p(302)$

Note that any secondary photon (e.g. 53 keV) is included in several terms, in each through $\mu(53)$
$\Rightarrow$It is better to use hierarchically ordered groups, by transforming the above expression:
$\varepsilon(302,\text{Ba-133}) = \varepsilon(302)\,[1 - p_{302,K\alpha}\,\mu(K\alpha) - p_{302,K\beta}\,\mu(K\beta) - ..\, p_{302,81}\,\mu(81) + p_{302,K\alpha,K\beta}\,\mu(K\alpha)\,\mu(K\beta) + \ldots\, p_{302,53,81}\,\mu(53)\,\mu(81) - ..p_{302,K\beta,53,81}\,\mu(K\beta)\,\mu(53)\,\mu(81)$
$p_{302,\,K\beta,53,81}$ = joint emission probability of the group if the main radiation (302) has been emitted

Advantage of new decomposition: decoupling of decay scheme data evaluation from efficiency computations
- especially important for volume sources



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Data source: Nucleide

Sum peak contributions to the 302 keV peak:

Combinations like:
Kα(EC4)-53-223-79-81 contribute to the 302 keV peak with a probability $[1-\mu(K\alpha)][1-\mu(53)]\ \varepsilon(223)\ \varepsilon(79)\ [1-\mu(81)]$

Other 59 similar contributions

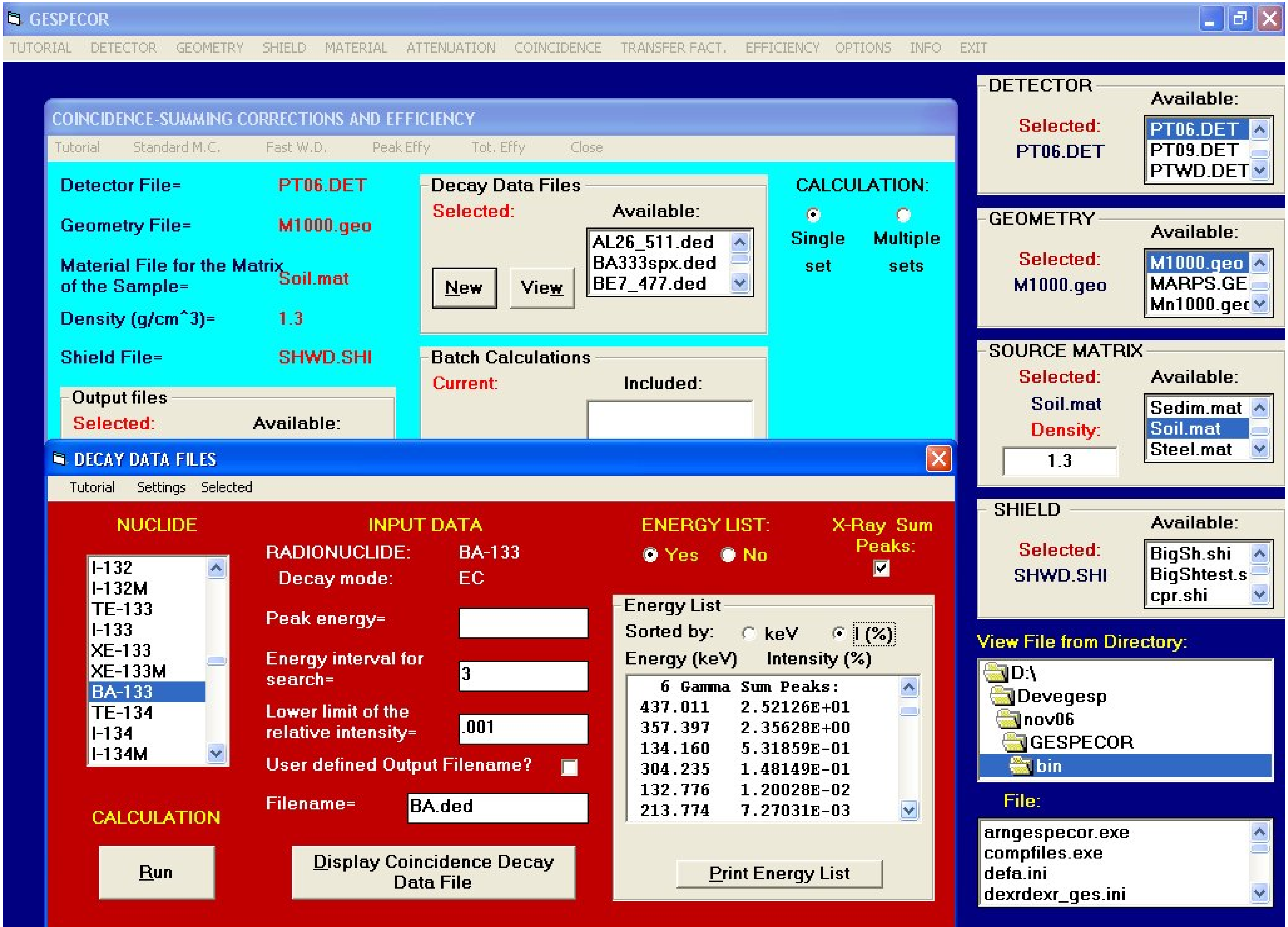
In the presence of coincidence summing
$R(E) \neq \varepsilon(E)\ I(E)\ A$, but
$R(E) = F_C\ \varepsilon(E)\ I(E)\ A$
F_C = coincidence summing correction factor, depends on:

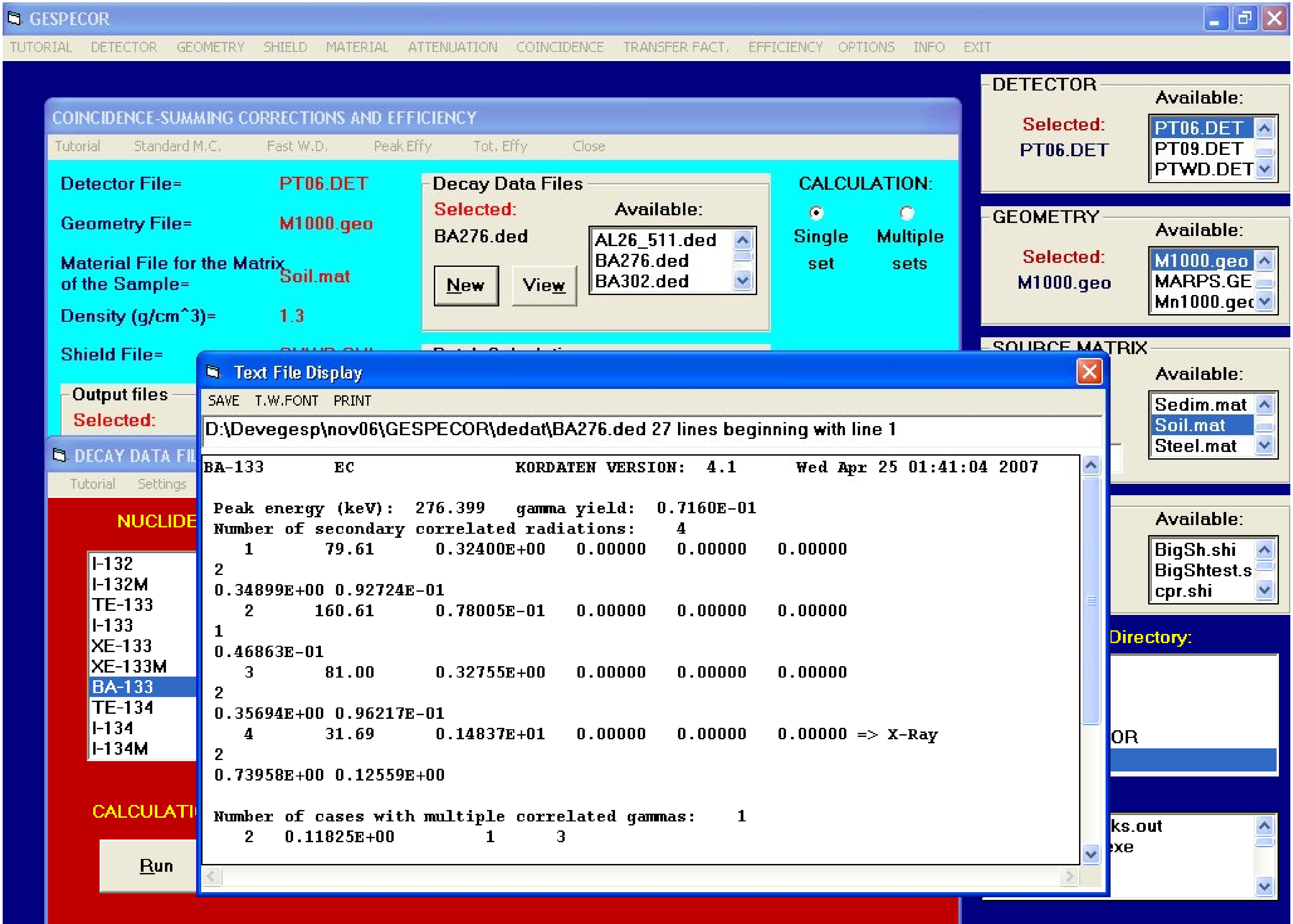
- **decay scheme parameters**
- **peak and total efficiency for the set of energies of all the photons**

Computation of decay scheme parameters in GESPECOR:

Data source: DDEP (Nucleide) or ENSDF
-automatic extraction procedure and formatting in the style of KORDATEN file (initially developed by Debertin and Schotzig)
-presently about 225 nuclides

Decay scheme parameters:
=> Joint emission probabilities, hierarchically ordered, combining all the possible decay paths
-computation by a fast algorithm [Sima and Arnold, ARI 66 (2008)]
-nuclides with less than 100 levels, otherwise arbitrary decay scheme
-radiations considered: gamma photons, $K\alpha$, $K\beta$ X-rays, annihilation photons
-angular correlations can be easily incorporated
-user friendly interfaces


GESPECOR
TUTORIAL DETECTOR GEOMETRY SHIELD MATERIAL ATTENUATION COINCIDENCE TRANSFER FACT. EFFICIENCY OPTIONS INFO EXIT
COINCIDENCE-SUMMING CORRECTIONS AND EFFICIENCY
Tutorial Standard M.C. Fast W.D. Peak Effy Tot. Effy Close
Detector File= PT06.DET
Geometry File= M1000.geo
Material File for the Matrix of the Sample= Soil.mat
Density (g/cm^3)= 1.3
Shield File= SHWD.SHI
Output files
Selected: Available:
Decay Data Files
Selected: Available:
AL26_511.ded
BA333spx.ded
BE7_477.ded
New View
Batch Calculations
Current: Included:
CALCULATION:
Single set
Multiple sets
DECAY DATA FILES
Tutorial Settings Selected
NUCLIDE
I-132
I-132M
TE-133
I-133
XE-133
XE-133M
BA-133
TE-134
I-134
I-134M
INPUT DATA
RADIONUCLIDE: BA-133
Decay mode: EC
Peak energy=
Energy interval for search= 3
Lower limit of the relative intensity= .001
User defined Output Filename?
Filename= BA.ded
ENERGY LIST:
Yes No
X-Ray Sum Peaks:
Energy List
Sorted by: keV I (%)
Energy (keV) Intensity (%)
6 Gamma Sum Peaks:
437.011 2.52126E+01
357.397 2.35628E+00
134.160 5.31859E-01
304.235 1.48149E-01
132.776 1.20028E-02
213.774 7.27031E-03
CALCULATION
Run
Display Coincidence Decay Data File
Print Energy List
DETECTOR
Selected: PT06.DET
Available: PT06.DET PT09.DET PTWD.DET
GEOMETRY
Selected: M1000.geo
Available: M1000.geo MARPS.GE Mn1000.gec
SOURCE MATRIX
Selected: Soil.mat
Density: 1.3
Available: Sedim.mat Soil.mat Steel.mat
SHIELD
Selected: SHWD.SHI
Available: BigSh.shi BigShtest.s cpr.shi
View File from Directory:
D:\
Devegesp
nov06
GESPECOR
bin
File:
arngespecor.exe
compfiles.exe
defa.ini
dexrdexr_ges.ini


GESPECOR
TUTORIAL DETECTOR GEOMETRY SHIELD MATERIAL ATTENUATION COINCIDENCE TRANSFER FACT. EFFICIENCY OPTIONS INFO EXIT
COINCIDENCE-SUMMING CORRECTIONS AND EFFICIENCY
Tutorial Standard M.C. Fast W.D. Peak Effy Tot. Effy Close
Detector File= PT06.DET
Geometry File= M1000.geo
Material File for the Matrix of the Sample= Soil.mat
Density (g/cm^3)= 1.3
Shield File=
Output files
Selected:
Decay Data Files
Selected: BA276.ded
Available: AL26_511.ded BA276.ded BA302.ded
New
View
CALCULATION:
Single set
Multiple sets
DETECTOR
Selected: PT06.DET
Available: PT06.DET PT09.DET PTWD.DET
GEOMETRY
Selected: M1000.geo
Available: M1000.geo MARPS.GE Mn1000.geo
SOURCE MATRIX
Available: Sedim.mat Soil.mat Steel.mat
Available: BigSh.shi BigShtest.s cpr.shi
Directory:
DECAY DATA FIL
Tutorial Settings
NUCLIDE
I-132 I-132M TE-133 I-133 XE-133 XE-133M BA-133 TE-134 I-134 I-134M
CALCULATI
Run
Text File Display
SAVE T.W.FONT PRINT
D:\Devegesp\nov06\GESPECOR\dedat\BA276.ded 27 lines beginning with line 1
BA-133 EC KORDATEN VERSION: 4.1 Wed Apr 25 01:41:04 2007
Peak energy (keV): 276.399 gamma yield: 0.7160E-01
Number of secondary correlated radiations: 4
1 79.61 0.32400E+00 0.00000 0.00000 0.00000
2
0.34899E+00 0.92724E-01
2 160.61 0.78005E-01 0.00000 0.00000 0.00000
1
0.46863E-01
3 81.00 0.32755E+00 0.00000 0.00000 0.00000
2
0.35694E+00 0.96217E-01
4 31.69 0.14837E+01 0.00000 0.00000 0.00000 => X-Ray
2
0.73958E+00 0.12559E+00
Number of cases with multiple correlated gammas: 1
2 0.11825E+00 1 3

Computation of the efficiencies:

-Decoupled from the evaluation of the decay scheme

(a) Standard:

1. Full Monte Carlo simulation

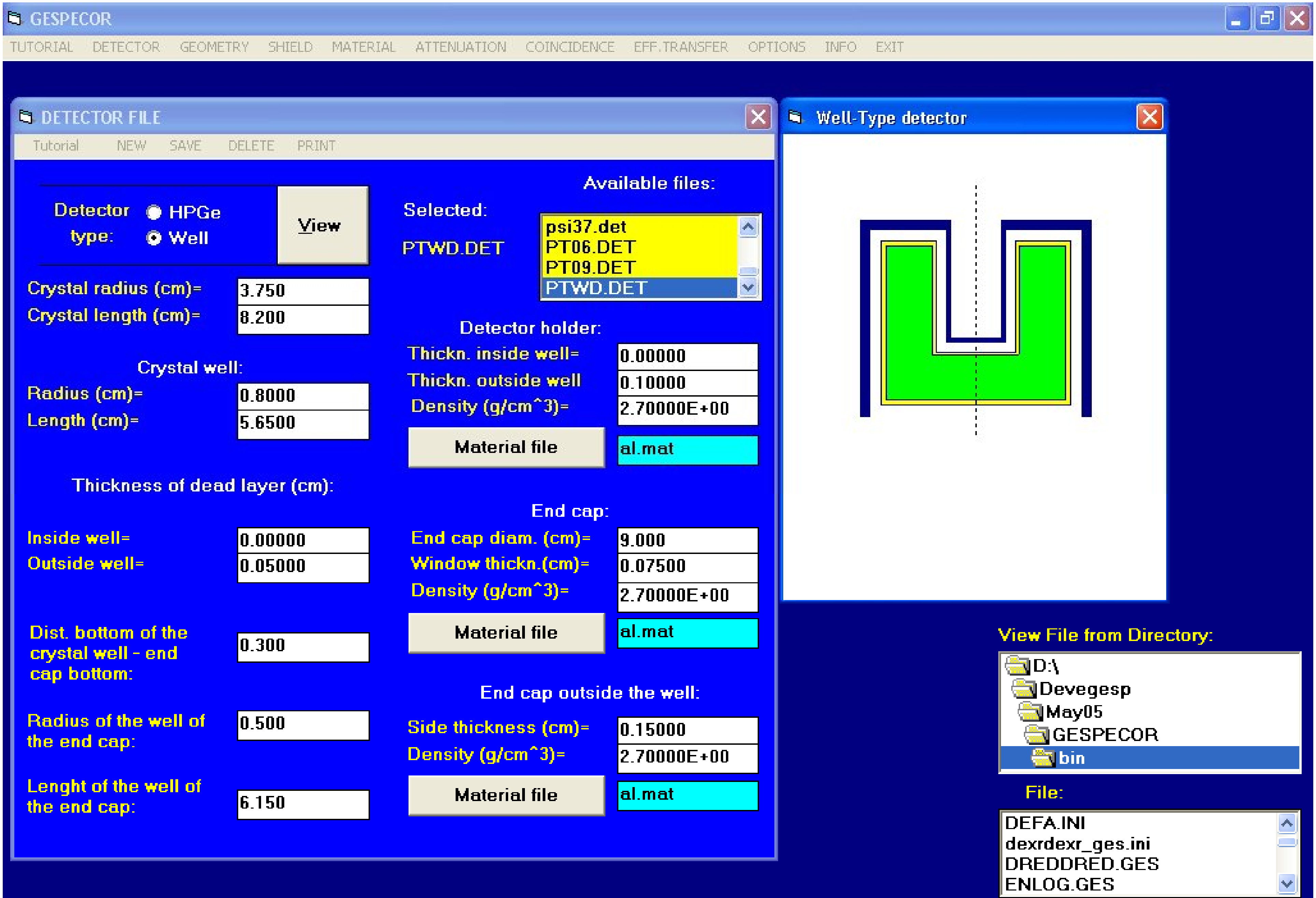
-Variance reduction techniques

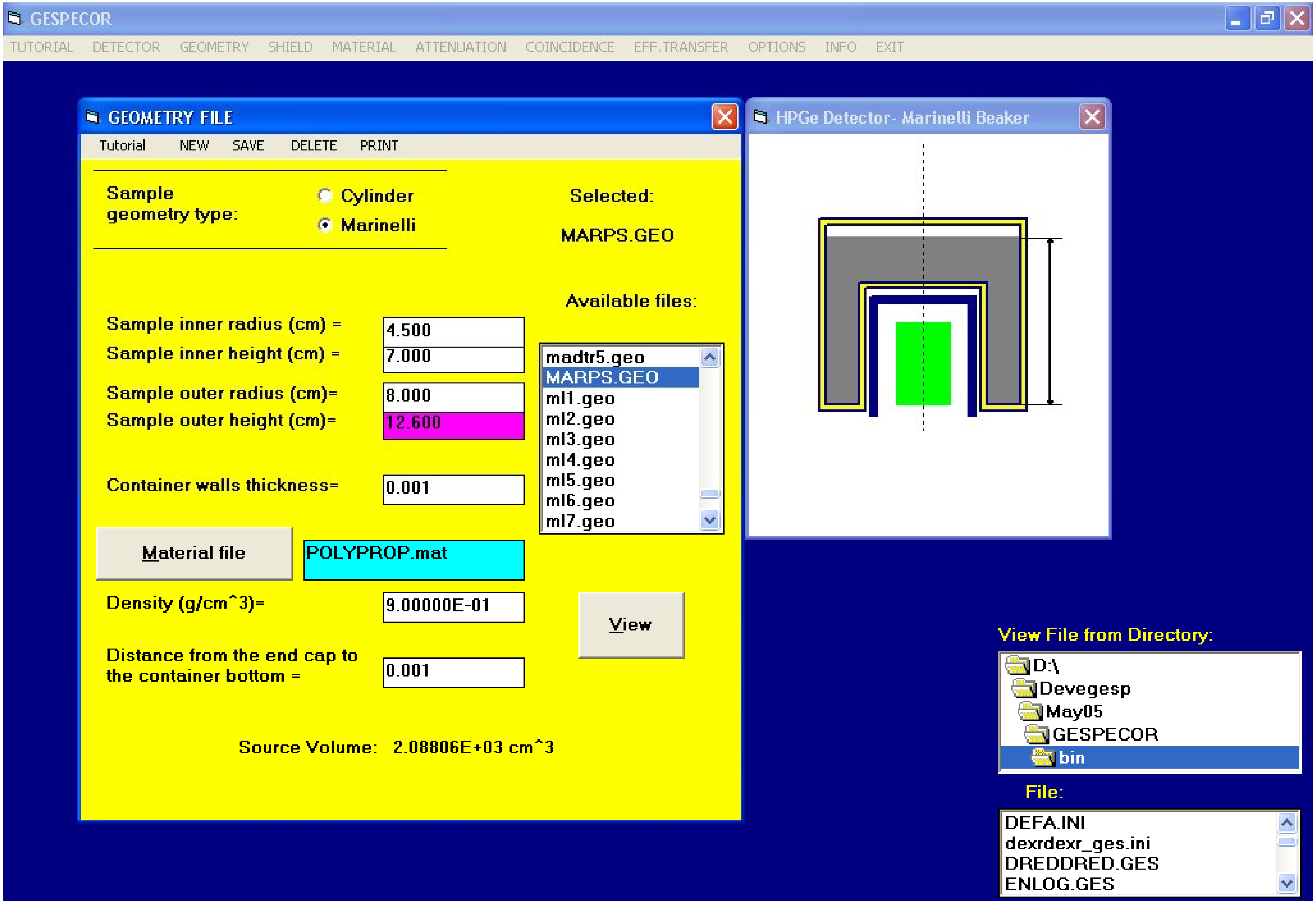
-Very important for volume sources

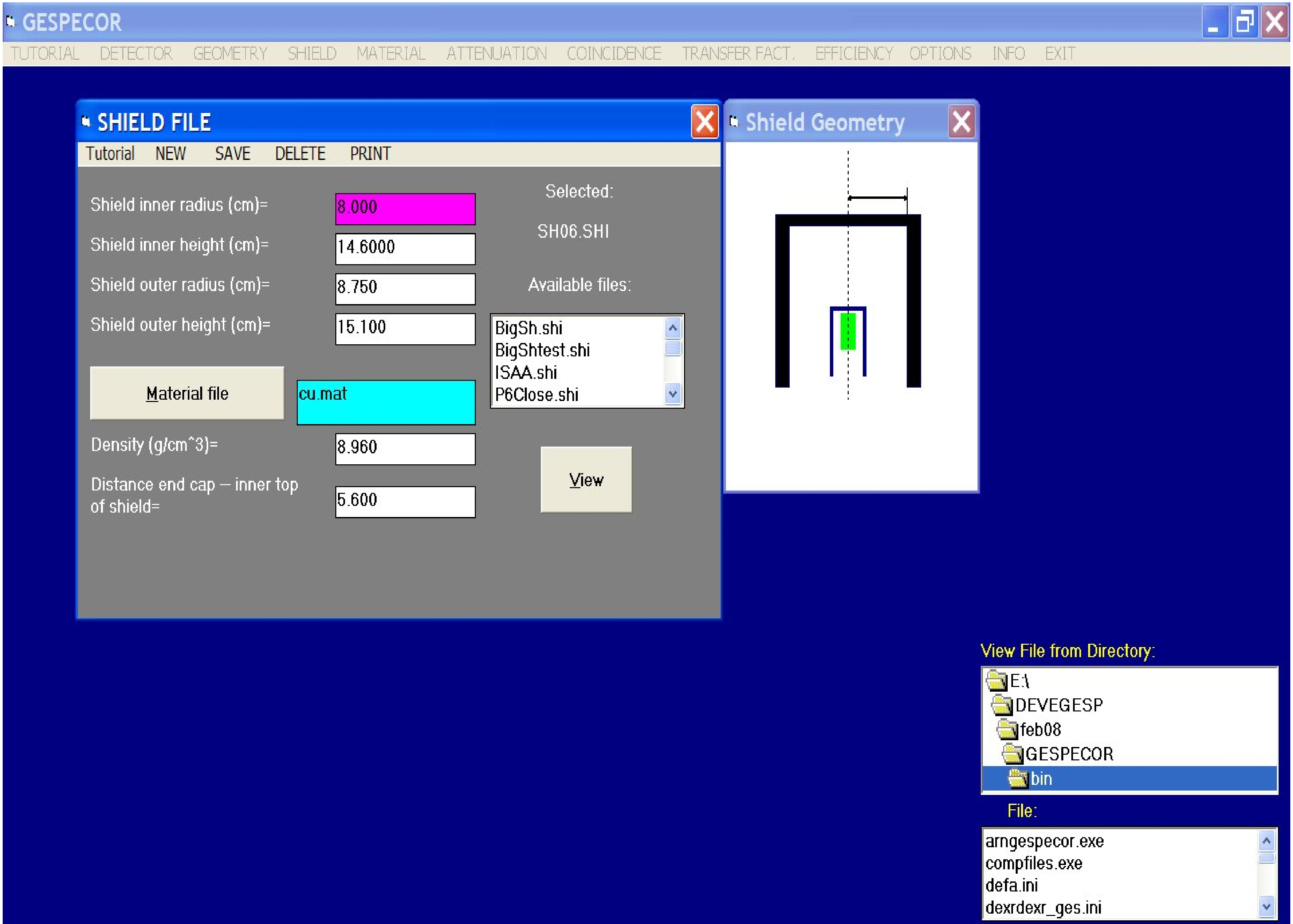
2. Well-type detector: combination of experimental peak efficiencies with an accurate analytical formula for the total efficiency [Sima, Nucl. Instrum. Meth. A 450 (2000)]

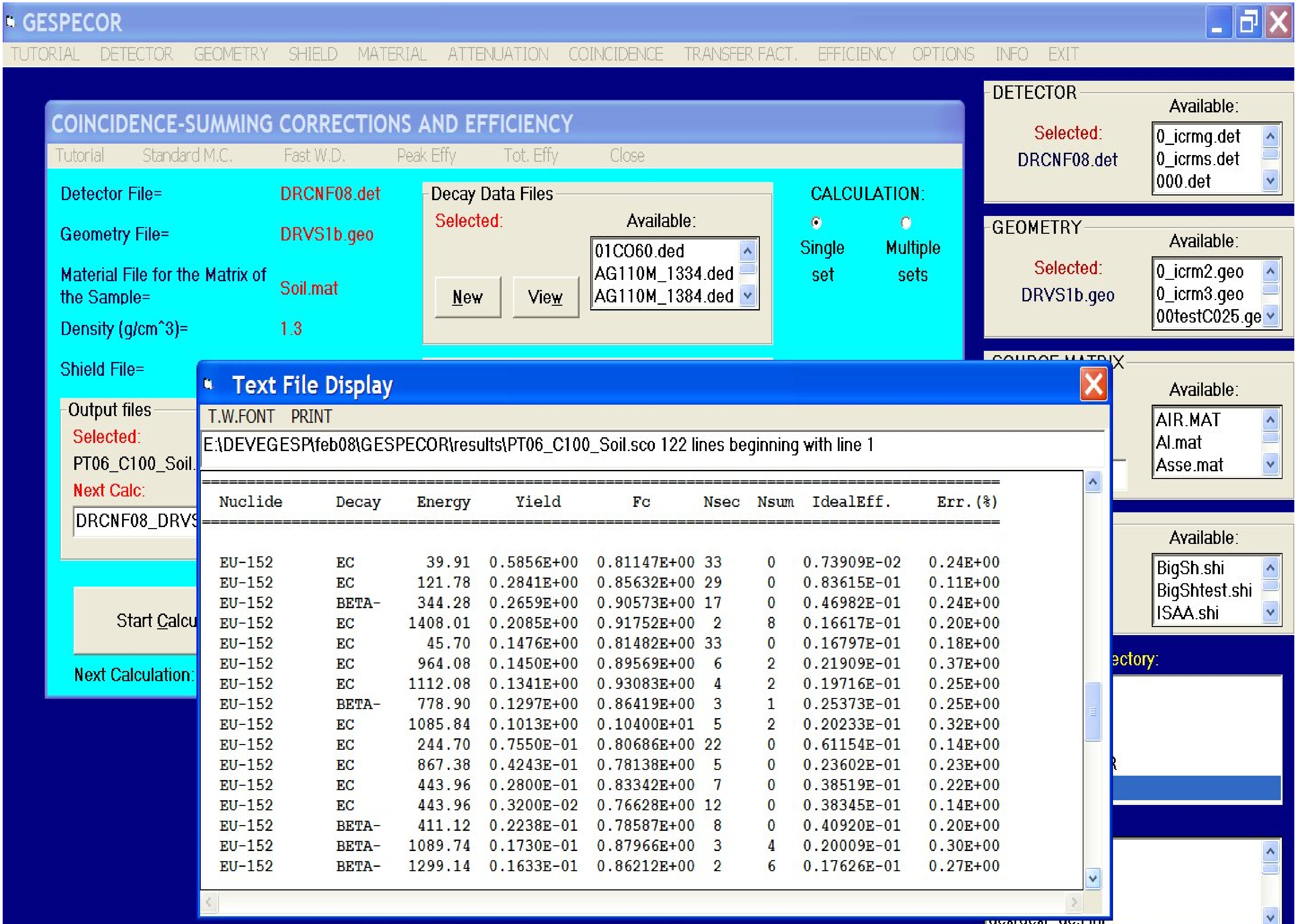
(b) Non-standard: application of fitted formulae for peak and total efficiency

User friendly interfaces for the detector, geometry and shield


GESPECOR
TUTORIAL DETECTOR GEOMETRY SHIELD MATERIAL ATTENUATION COINCIDENCE EFF.TRANSFER OPTIONS INFO EXIT
DETECTOR FILE
Tutorial NEW SAVE DELETE PRINT
Detector type: HPGe Well
View
Selected: PTWD.DET
Available files:
psi37.det
PT06.DET
PT09.DET
PTWD.DET
Crystal radius (cm)= 3.750
Crystal length (cm)= 8.200
Crystal well:
Radius (cm)= 0.8000
Length (cm)= 5.6500
Thickness of dead layer (cm):
Inside well= 0.00000
Outside well= 0.05000
Dist. bottom of the crystal well - end cap bottom: 0.300
Radius of the well of the end cap: 0.500
Lenght of the well of the end cap: 6.150
Detector holder:
Thickn. inside well= 0.00000
Thickn. outside well 0.10000
Density (g/cm^3)= 2.70000E+00
Material file al.mat
End cap:
End cap diam. (cm)= 9.000
Window thickn.(cm)= 0.07500
Density (g/cm^3)= 2.70000E+00
Material file al.mat
End cap outside the well:
Side thickness (cm)= 0.15000
Density (g/cm^3)= 2.70000E+00
Material file al.mat
Well-Type detector
View File from Directory:
D:\
Devegesp
May05
GESPECOR
bin
File:
DEFA.INI
dexrdexr_ges.ini
DREDDRED.GES
ENLOG.GES


GESPECOR
TUTORIAL DETECTOR GEOMETRY SHIELD MATERIAL ATTENUATION COINCIDENCE EFF.TRANSFER OPTIONS INFO EXIT
GEOMETRY FILE
Tutorial NEW SAVE DELETE PRINT
Sample geometry type:
Cylinder
Marinelli
Selected:
MARPS.GEO
Available files:
Sample inner radius (cm) = 4.500
Sample inner height (cm) = 7.000
Sample outer radius (cm)= 8.000
Sample outer height (cm)= 12.600
Container walls thickness= 0.001
madtr5.geo
MARPS.GEO
ml1.geo
ml2.geo
ml3.geo
ml4.geo
ml5.geo
ml6.geo
ml7.geo
Material file
POLYPROP.mat
Density (g/cm^3)= 9.00000E-01
View
Distance from the end cap to the container bottom = 0.001
Source Volume: 2.08806E+03 cm^3
HPGe Detector- Marinelli Beaker
View File from Directory:
D:\
Devegesp
May05
GESPECOR
bin
File:
DEFA.INI
dexrdexr_ges.ini
DREDDRED.GES
ENLOG.GES


GESPECOR
TUTORIAL DETECTOR GEOMETRY SHIELD MATERIAL ATTENUATION COINCIDENCE TRANSFER FACT. EFFICIENCY OPTIONS INFO EXIT
SHIELD FILE
Tutorial NEW SAVE DELETE PRINT
Shield inner radius (cm)= 8.000
Shield inner height (cm)= 14.6000
Shield outer radius (cm)= 8.750
Shield outer height (cm)= 15.100
Material file cu.mat
Density (g/cm^3)= 8.960
Distance end cap – inner top of shield= 5.600
Selected:
SH06.SHI
Available files:
BigSh.shi
BigShtest.shi
ISAA.shi
P6Close.shi
View
Shield Geometry
View File from Directory:
E:\
DEVEGESP
feb08
GESPECOR
bin
File:
arngespecor.exe
compfiles.exe
defa.ini
dexrdexr_ges.ini



Nuclide	Decay	Energy	Yield	Fc	Nsec	Nsum	IdealEff.	Err.(%)
EU-152	EC	39.91	0.5856E+00	0.81147E+00	33	0	0.73909E-02	0.24E+00
EU-152	EC	121.78	0.2841E+00	0.85632E+00	29	0	0.83615E-01	0.11E+00
EU-152	BETA-	344.28	0.2659E+00	0.90573E+00	17	0	0.46982E-01	0.24E+00
EU-152	EC	1408.01	0.2085E+00	0.91752E+00	2	8	0.16617E-01	0.20E+00
EU-152	EC	45.70	0.1476E+00	0.81482E+00	33	0	0.16797E-01	0.18E+00
EU-152	EC	964.08	0.1450E+00	0.89569E+00	6	2	0.21909E-01	0.37E+00
EU-152	EC	1112.08	0.1341E+00	0.93083E+00	4	2	0.19716E-01	0.25E+00
EU-152	BETA-	778.90	0.1297E+00	0.86419E+00	3	1	0.25373E-01	0.25E+00
EU-152	EC	1085.84	0.1013E+00	0.10400E+01	5	2	0.20233E-01	0.32E+00
EU-152	EC	244.70	0.7550E-01	0.80686E+00	22	0	0.61154E-01	0.14E+00
EU-152	EC	867.38	0.4243E-01	0.78138E+00	5	0	0.23602E-01	0.23E+00
EU-152	EC	443.96	0.2800E-01	0.83342E+00	7	0	0.38519E-01	0.22E+00
EU-152	EC	443.96	0.3200E-02	0.76628E+00	12	0	0.38345E-01	0.14E+00
EU-152	BETA-	411.12	0.2238E-01	0.78587E+00	8	0	0.40920E-01	0.20E+00
EU-152	BETA-	1089.74	0.1730E-01	0.87966E+00	3	4	0.20009E-01	0.30E+00
EU-152	BETA-	1299.14	0.1633E-01	0.86212E+00	2	6	0.17626E-01	0.27E+00

BA-133	EC	31.692	0.894	4.53	0.104
0.000	5.000E-04	0.000E+00	0.000E+00	STABLE	
80.998	7.000E-01	8.800E-01	0.000E+00	6.280E-03	
160.612	3.000E-01	7.900E-01	0.000E+00	1.720E-04	
383.849	1.370E+01	7.734E-01	1.761E-01	4.200E-05	
437.011	8.620E+01	6.720E-01	2.520E-01	1.500E-04	
2 1	80.998	3.290E+01	1.740E+00	1.460E+00	2.200E-01
3 1	160.612	6.380E-01	3.100E-01	2.400E-01	5.400E-02
3 2	79.614	2.650E+00	1.770E+00	1.515E+00	2.040E-01
4 1	383.849	8.940E+00	2.030E-02	1.690E-02	2.730E-03
4 2	302.851	1.834E+01	4.430E-02	3.810E-02	4.960E-03
4 3	223.237	4.530E-01	9.950E-02	8.530E-02	1.130E-02
5 2	356.013	6.205E+01	2.560E-02	2.110E-02	3.510E-03
5 3	276.399	7.160E+00	5.690E-02	4.610E-02	8.550E-03
5 4	53.162	2.140E+00	6.020E+00	4.930E+00	8.600E-01

Evaluation of Fc is very difficult for nuclides with complex decay schemes and for volume sources

Methods developed for this purpose differ in the way in which

- evaluate the necessary decay scheme parameters
- evaluate the necessary peak and total efficiencies
- combine the decay data with the efficiency data

(1) Recursive formulae (Andreev et al, McCallum & Coote, Debertin & Schotzig, Morel et al , Jutier et al)
(2) Matrix formalism (Semkow et al, Korun et al)
(3) Generalized lists (Novkovic et al)
(4) Monte Carlo simulation of the decay paths and of detection efficiencies (Decombaz et al)
(5) Analytic evaluation of decay scheme parameters decoupled from Monte Carlo evaluation of efficiencies (Sima and Arnold)

Computation of joint emission probability of groups of photons

Search of all the decay paths (Sima and Arnold, ARI 2008):
• the decay scheme is considered an oriented graph
• the levels are the nodes of the graph
• the transitions are the edges of the graph
• the problem of finding the decay paths is equivalent with finding the paths with specific properties in the graph
- a fast algorithm of the breadth-first type was implemented

Joint emission probabilities can be computed for any nuclide with less than 100 levels
-radiations considered: gamma photons, Kα, Kβ X-rays, annihilation photons

Computation of the efficiencies:

Monte Carlo simulation, decoupled from the evaluation of the decay scheme

-Variance reduction techniques

Peak efficiency:

- -focalized emission towards the detector
- -attenuation between the emission point and detector

treated analytically

- -forced first interaction in the detector
- -stop at first energy loss outside detector

Total efficiency

- -stop at first interaction in the detector

User friendly interfaces for the detector, geometry and shield