



Radioactivity

FLUKA Advanced Course

Residual radiation: evaluation and transport

The generation and transport of decay radiation (γ , β^- , β^+ , X-rays, Conversion Electrons emissions and now also α) is possible during the same simulation which produces the radio-nuclides (**one-step method**).

For that, a dedicated database of decay emissions is used, based mostly on information obtained from **NNDC**, sometimes supplemented with other data and checked for consistency.

Two modes:

(1) semi-analytical mode (“Activation study case”)

Monte Carlo to produce the residual nuclei
+ Bateman Equations to evaluate decays and further residual nuclei from the decay chain

(2) semi-analog mode (pure Monte Carlo method)

Residual radiation: evaluation and transport

(1) “Activation study case”

For an arbitrary irradiation pattern, the time evolution of the system (build-up and decay during the irradiation and cooling) is obtained runtime for fixed cooling times via the exact analytical solution of the **Bateman equations**:

$$\frac{dN_i}{dt} = - \sum_{j \neq i} \left[\lambda_{ji}^d + \bar{\sigma}_{ji} \bar{\varphi} \right] N_i + \sum_{j \neq i} \left[\lambda_{ij}^d + \bar{\sigma}_{ij} \bar{\varphi} \right] N_j$$

where for each radionuclide in the material:

λ_{ji}^d → decay probability of the residual nucleus i in the residual nucleus j

σ_{ji} → cross section for transmutation of the residual nucleus i in the residual nucleus j

$$\bar{\varphi} = \int \varphi(E) dE \quad \bar{\sigma}_{ji} = \frac{1}{\bar{\varphi}} \int \varphi(E) \sigma_{ji}(E) dE$$

In the simplified case of residual nuclei of one type, without other residual nuclei decaying in that species, at the cooling time t_{cool} we find the known formula for the specific activity:

$$a(t_{cool}) = N \sigma \phi (1 - e^{-\lambda t_{irr}}) e^{-\lambda t_{cool}}$$

(2) Semi-analogue mode

Each radioactive nucleus is treated like all other unstable particles (**pure Monte Carlo method**: times are sampled randomly from the correspondent exponential distribution, radiation and daughters also randomly)

- all secondary particles/nuclei carry **time stamp** (“**age**”)

This mode is called semi-analogue because the radiation spectra are **inclusive** (no correlation in the emitted radiation! i.e. no correlated gamma cascade). In an event-by-event analysis a full correlation is not guarantee

In **all cases** FLUKA can perform the **generation and transport of the decay radiation**



As a consequence, in the same run **results for production of residuals, their time evolution and residual doses due to their decays** can be obtained, for an arbitrary number of decay times and for a given irradiation profile.

FLUKA-Implementation – *Main features*

- up to 4 different decay branching for each isotope/isomer
- all gamma lines down to 0.1-0.01% branching, including X-ray lines following conversion electron emissions
- all beta emission spectra down to 0.1-0.01% branching: sampling of the beta+/- spectra includes screening Coulomb corrections
- Auger and conversion electrons
- **Isomers:** production can be activated via what(2) in RADDECAY
The present models do not distinguish among ground state and isomeric states (it would require spin/parity dependent calculations in evaporation).
- * for all isomer production a rough estimate, based on **equal sharing among states**, can be performed
- **Different transport thresholds can be set for the prompt and decay radiation parts**, as well as some (limited) biasing differentiation (see later)

Input options - *Overview*

Input card: **RADDECAY**

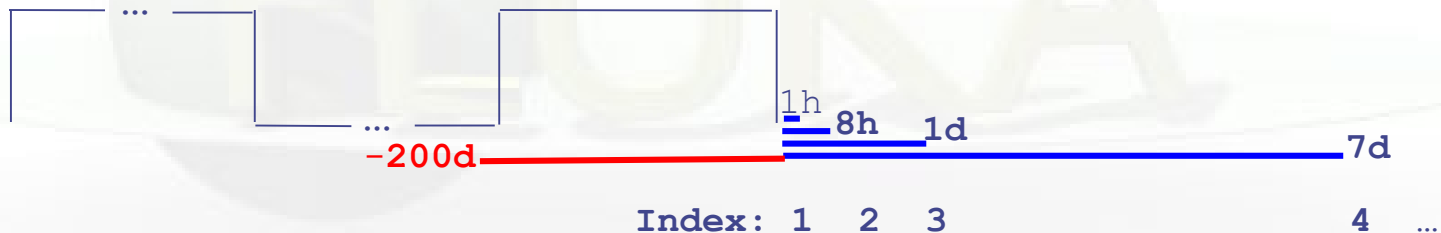
requests simulation of decay of produced radioactive nuclides and allows to modify biasing and transport thresholds (defined with other cards) for the transport of decay radiation

Input card: **IRRPROFI**

definition of an irradiation profile (irradiation times and intensities)

Input card: **DCYTIMES**

definition of decay (cooling) times



Input card: **DCYSCORE**

associates scoring detectors (radio-nuclides, fluence, dose) with different cooling times

Input card: **AUXSCORE**

allows to associate scoring estimators with dose equivalent conversion factors or/and to filter them according to (generalized) particle identity

allows to filter individually isotopes (ACTIVIY / ACTOMASS and USBIN)

Particle Types

Name	Number	Units	Description
DOSE	228	GeV/g	Dose (energy deposited per unit mass)
DOSE-EQ	240	pSv	Dose Equivalent (AUXSCORE)
ACTIVITY	234	Bq/cm ³	Activity per unit volume
ACTOMASS	235	Bq/g	Activity per unit mass
SI1MEVNE	236	cm ⁻²	Silicon 1 MeV-neutron equivalent flux
HADGT20M	237	cm ⁻²	Hadrons with energy > 20 MeV

Normalization

All quantities are expressed:

- per primary particle if they are not connected to a specific decay time
- per time unit (per s) if they are related to a specific decay time via DCYSCORE (and they are referred to this time)

Card: RADDECAY [1/2]

```
* 1) request radioactive decays
RADDECAY          1.0          0          3.0          0000099999          0
```

RADDECAY	Decays: Active ▼	Patch Isom: ▼	Replicas: 3.0
h/μ Int: ignore ▼	h/μ LPB: ignore ▼	h/μ WW: ignore ▼	e-e+ Int: ignore ▼
e-e+ LPB: ignore ▼	e-e+ WW: ignore ▼	Low-n Bias: ignore ▼	Low-n WW: ignore ▼
	decay cut: 0.0	prompt cut: 99999.0	Coulomb corr: ▼

- WHAT(1)** = 1 **radioactive decays activated for requested cooling times**
 Decays: Active "activation study case": time evolution calculated analytically for *fixed* (cooling) times. Daughter nuclei as well as associated radiation is considered at these (fixed) times
- > 1 **radioactive decays activated in (semi-)analogue mode**
 Semi-Analogue each radioactive nucleus is treated like all other unstable particles (random decay time, daughters and radiation), all secondary particles/nuclei carry time stamp ("age")
- WHAT(2)** > 0 **isomer "production" activated**
 Patch Isom: On
- WHAT(3)** **number of "replicas" of the decay of each individual nucleus**
 Replicas: #

Card: RADDECAY [2/2]

RADDECAY

h/μ Int: ignore ▼
e-e+ LPB: ignore ▼

Decays: Active ▼
h/μ LPB: ignore ▼
e-e+ WW: ignore ▼
decay cut: 0.0

Patch Isom: ▼
h/μ WW: ignore ▼
Low-n Bias: ignore ▼
prompt cut: 99999.0

Replicas: 3.0
e-e+ Int: ignore ▼
Low-n WW: ignore ▼
Coulomb corr: ▼

WHAT(4)

h/μ Int .. Low-n WW

switch for applying various biasing features only to prompt radiation or only to particles from radioactive decays

9 digits, each responsible for a different biasing

Example:

5th digit, e+/e-/gamma leading particle biasing applied
000010000 to prompt radiation only
000020000 to decay radiation only
000030000 to both

Default: 111111111 (or blank as above)

WHAT(5)

decay cut: #
prompt cut: #

multiplication factors to be applied to e+/e-/gamma transport energy cutoffs

10 digits, first five for decay radiation, second five for prompt radiation (see manual)

Special cases:

0000099999 kill EM cascade for prompt radiation
9999900000 kill EM cascade for residual radiation

Card: IRRPROFI

```
* 2) definition of irradiation pattern
*          180days    part/s    185days          180days    part/s
IRRPROFI  1.5552E7    5.9175E5    1.5984E7          0.0    1.5552E7    5.9175E5

      180days  part/s  185days      180days  part/s
IRRPROFI                                Δt: 1.5552E7          p/s: 5.9175E5
                                Δt: 1.5984E7          p/s: 0.0
                                Δt: 1.5552E7          p/s: 5.9175E5
```

WHAT(1,3,5) irradiation time (second)

Δt: #

WHAT(2,4,6) beam intensity (particles per second)

p/s # Note: zero intensity is accepted and can be used e.g., to define beam-off periods

Note: Several cards can be combined up to a maximum of 2500 irradiation intervals.

Example (see above):

180 days	185 days	180 days
5.9×10^5 p/s	0 p/s	5.9×10^5 p/s
	(beam-off)	

Card: DCYTIMES

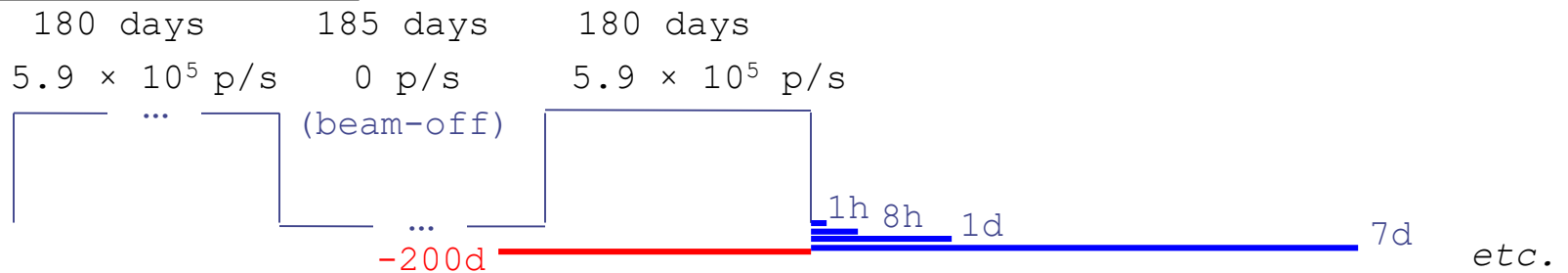
* 3) definition of cooling times						
*	1hour	8hours	1day	7days	1month	4months
DCYTIMES	3600.	28800.	8.64E4	6.048E5	2.592E6	1.0368E7

	1hour	8hours	1day	7days	1month	4months			
DCYTIMES				t1: 3600.			t2: 28800.		t3: 8.64E4
				t4: 6.048E5			t5: 2.592E6		t6: 1.0368E7

WHAT(1) – WHAT(6) cooling time (in seconds) after the end of the irradiation
 t1 .. t6 Note: Several cards can be defined.

Each cooling time is assigned an index, following the order in which it has been input. This index can be used in option DCYSCORE to assign that particular cooling time to one or more scoring detectors. A negative decay time is admitted: scoring is performed at the chosen time "during irradiation"

Example (see above):



Card: DCYSCORE [1/2]

```

* Associate scoring with different cooling times
DCYSCORE          1.0                      Shielding                      USRBIN
USRBIN            10.0          201.      -70.0          150.0          200.0          5000.0Shielding
USRBIN            -250.0         -200.          0.0           80.0           80.0           1.0&

DCYSCORE          Cooling t: 3600. ▼          Kind: USRBIN ▼
                   Det: Shielding ▼          to Det: ▼          Step:

USRBIN          Unit: 70 BIN ▼          Name: Shielding
Type: X-Y-Z ▼          Xmin: -250.0          Xmax: 150.0          NX: 80.0
Part: ALL-PART ▼          Ymin: -200.          Ymax: 200.0          NY: 80.0
    
```

WHAT(1) Cooling time index to be associated with the detectors

Cooling: # Drop down list of available cooling times

WHAT(4)..WHAT(5) Detector index/name of kind (SDUM/Kind)

Det .. to Det Drop down list of available detectors of kind (Kind)

WHAT(6) step lengths in assigning indices

Step #

SDUM Type of estimator

Kind RESNUCLE, USRBIN/EVENTBIN, USRBDX, USRTRACK...

Units: All quantities are expressed per unit time. For example:

RESNUCLE Bq

USRBIN fluence rate / dose rate

Card: DCYSCORE [2/2]

In the *semi-analogue decay mode*, estimators can include the decay contribution (on top of the prompt one) through association by **DCYSCORE** with a cooling time index ≤ -1.0



Card: AUXSCORE

* associate scoring with dose equivalent conversion factors

AUXSCORE USRBIN PHOTON Target EWT74

AUXSCORE

Type: USRBIN ▼

Part: PHOTON ▼

Set: EWT74 ▼

Det: Target ▼

to Det: ▼

Step:

WHAT(1)

Type:

Type of estimator to associate with

drop down list of estimator types (USRBIN, USRBDX...)

WHAT(2)

Part:

#

particle or isotope to filter scoring

Particle or particle family list. If empty then flair will prompt for Z, A, and State for filtering on specific isotopes

WHAT(4,5)

Det .. to Det

Detector range

Drop down list to select detector range of type WHAT(1)

WHAT(6)

Step:

#

Step in assigning indices of detector range

SDUM

Set:

Conversion set for dose equivalent (DOSE-EQ) scoring

Drop down list of available dose conversion sets

Since 2016 release possibility to select an individual isotope (ACTIVITY or ACTOMASS with USRBIN)

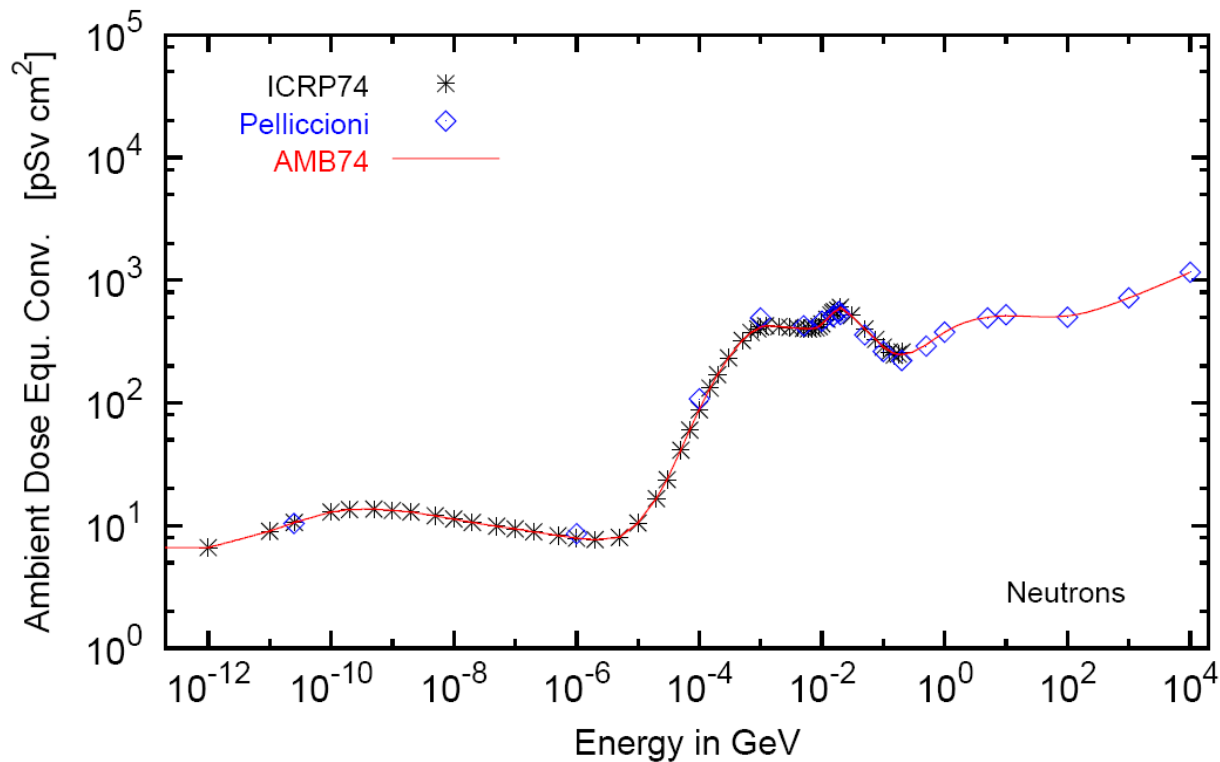
Available Conversion Coefficients

The following dose conversion coefficients sets are available:

- 1) Effective dose sets from ICRP74 and Pelliccioni data calculated with ICRP radiation weighting factors W_r
 - (a) **EAP74** : Anterior-Posterior irradiation
 - (b) **ERT74** : Rotational irradiation geometry
 - (c) **EWT74** : WORST possible geometry for the irradiation
- 2) Effective dose sets from ICRP74 and Pelliccioni data calculated with the Pelliccioni radiation weighting factors W_r
 - (a) **EAPMP** : Anterior-Posterior irradiation
 - (b) **ERTMP** : Rotational irradiation geometry
 - (c) **EWTMP** : WORST possible geometry for the irradiation
- 3) Ambient dose equivalent from ICRP74 and Pelliccioni data
 - (a) **AMB74** : **[Default]**
- 4) Ambient dose equivalent with old "GRS"-conversion factors
 - (a) **AMBGS**

Conversion Coefficients

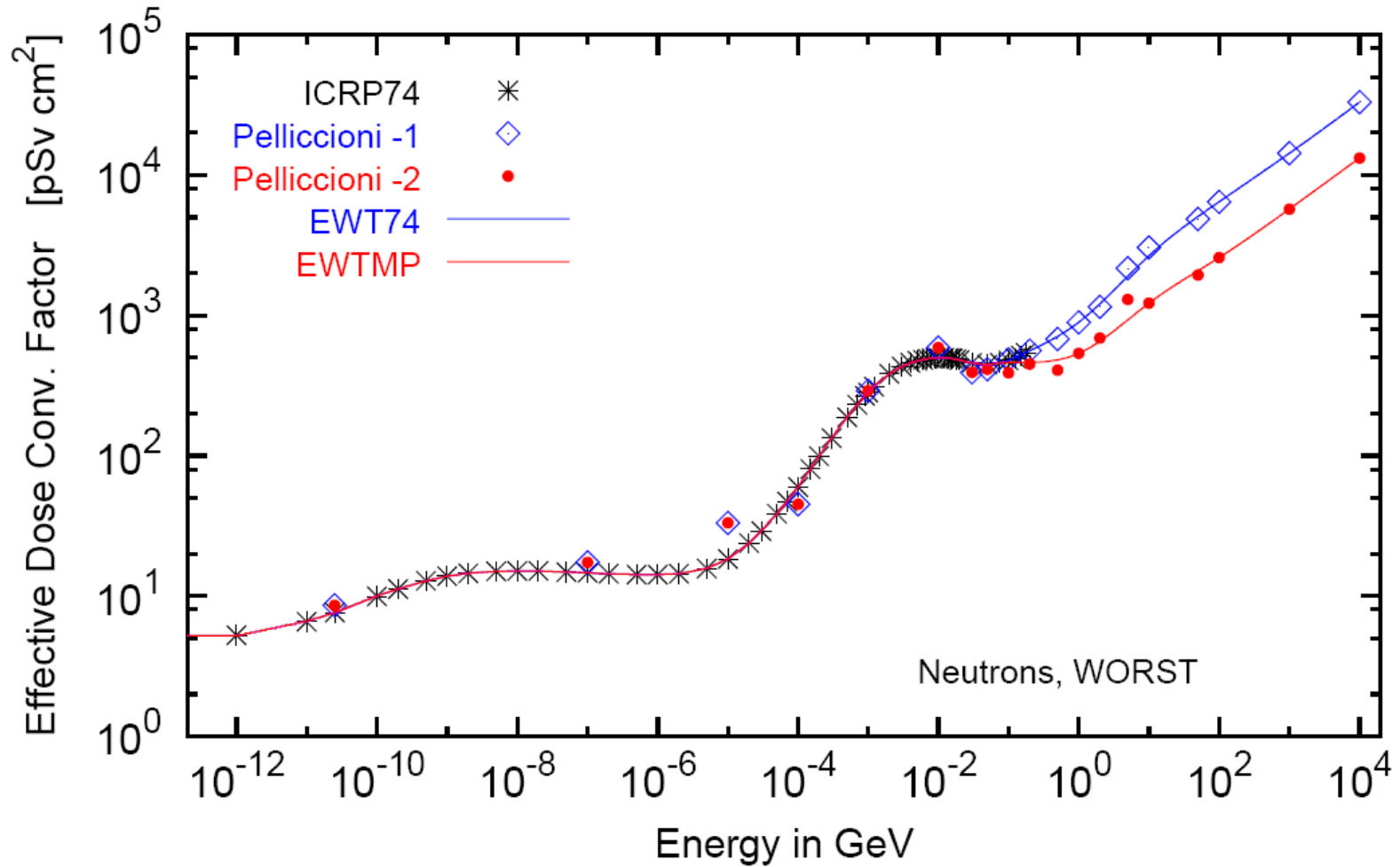
Conversion coefficients from fluence to ambient dose equivalent are based on ICRP74 values and values calculated by M.Pelliccioni. They are implemented for **protons, neutrons, charged pions, muons, photons, electrons** (conversion coefficients for other particles are approximated by these). AMB74 is the default choice for dose equivalent calculation.



Fluence to effective dose coefficients

- Conversion coefficients from fluence to effective dose are implemented for three different irradiation geometries:
 - ◆ anterior-posterior
 - ◆ rotational
 - ◆ WORST (“Working Out Radiation Shielding Thicknesses”) is the maximum coefficient of anterior-posterior, posterior-anterior, right-lateral and left-lateral geometries. It is recommended to be used for shielding design.
- Implemented for radiation weighting factors recommended by ICRP60 (e.g., **SDUM=ETW74**) and recommended by M.Pelliccioni (e.g., **SDUM=EWTMP**). The latter anticipate the 2007 recommendations of ICRP.
- Implemented for **protons, neutrons, charged pions, muons, photons, electrons** (conversion coefficients for other particles are approximated by these)
- **Zero** coefficient is applied to all **heavy ions**

Fluence to effective dose coefficients



Card: RESNUCLEi [1/3]

RESNUCLE	3.0	-26.	0	0	FLOOR	TUN_FLOO
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RESNUCLE	Type: All ▼	Unit: 26 BIN ▼	Name: TUN_FLOO
Max Z:	Max M:	Reg: FLOOR ▼	Vol:

Scoring of residual nuclei or activity on a region basis

WHAT(1)

Type:

1.0	spallation products (except from low-energy neutron interactions)
2.0	products from low-energy neutron interactions (provided the information is available)
3.0	all residual nuclei are scored (if available, see above)
<= 0.0	resets the default (= 1.0)

type of products to be scored

WHAT(2)

Unit:

logical output unit (Default = 11.0)

logical output unit (Default = 11.0)

WHAT(3)

Max Z:

Maximum atomic number Z of the residual nuclei distribution
Default: according to the Z of the element(s) of the material assigned to the scoring region

Maximum atomic number Z of the residual nuclei distribution

WHAT(4)

Max M:

Maximum M = N - Z - NMZ_min
of the residual nuclei distribution (NMZ_min = -5)
Default: maximum value according to the A, Z of the element(s) of the material assigned to the scoring region.

Maximum M = N - Z - NMZ_min

Card: RESNUCLEi [2/3]

RESNUCLE	Type: All ▼	Unit: 26 BIN ▼	Name: TUN_FLOO
Max Z:	Max M:	Reg: FLOOR ▼	Vol:

WHAT(5) scoring region number/name
Reg: (Default = 1.0 ; -1.0 or @ALLREGS all regions)

WHAT(6) volume of the region in cm³
Vol: (Default = 1.0)

SDUM character string identifying the detector
Name: (max. 10 characters)

Notes:

1. In the case of **heavy ion** projectiles the default NMZ, based on the region material, is not necessarily sufficient to score all the residual nuclei, which could include possible ion fragments
2. Residual nuclei from low-energy neutron interactions are only scored if that information is available in the **low-energy neutron data set** (see Manual)
3. **Protons** are scored, together with ²H, ³H, ³He, ⁴He, at the end of their path

Card: RESNUCLEi [3/3]

```
**** Isotope Yield as a function of Mass Number ****
**** (nuclei / cmc / pr) ****
```

```
A_min: 1 - A_max: 198
```

```
A:      186  1.5870372E-08 +/-  9.9000000E+01 %
A:      185  3.7605012E-09 +/-  9.9000000E+01 %
A:      184  1.4581326E-08 +/-  9.9000000E+01 %
A:      183  1.0712972E-08 +/-  9.9000000E+01 %
A:      182  7.4882118E-09 +/-  9.9000000E+01 %
```

```
**** Isotope Yield as a function of Atomic Number ****
**** (nuclei / cmc / pr) ****
```

```
Z_min: 1 - Z_max: 78
```

```
Z:      74  5.2413383E-08 +/-  9.9000000E+01 %
Z:      42  3.0072785E-07 +/-  9.9000000E+01 %
Z:      41  4.7906228E-08 +/-  9.9000000E+01 %
Z:      40  3.7605012E-09 +/-  9.9000000E+01 %
Z:      38  3.7605012E-09 +/-  9.9000000E+01 %
```

```
**** Residual nuclei distribution ****
**** (nuclei / cmc / pr) ****
```

A \ Z	68	69	70	71	72	73	74	75	76	77	78
186	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.59E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/-99.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %
185	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.76E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/-99.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %
184	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.46E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/-99.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %
183	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.07E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/-99.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %	+/- 0.0 %

Units:

- nuclei/cm³ per primary particle if RESNUCLEi is not connected to a cooling time
- Bq /cm³ for a specific cooling time assigned via DCYSCORE

Card: PHYSICS

Please activate the following two cards if residuals are of interest:

switch to activate the evaporation of heavy fragments (up to $A=24$)

PHYSICS 3.0

EVAPORAT

PHYSICS 1.0

COALESCE

special options for coalescence treatment

Warning: manual edit of Flair card is required!

ISOTOPE 'beam'

to simulate a radioactive source:

Radioactive source of ^{60}Co (two main γ -emissions: 1332.5 keV and 1173.2 keV)
cylindrical shape, 2cm diameter, 2mm height along z, centre of base of cylinder at origin

BEAM						ISOTOPE
HI-PROPE	27.0	60.0				
BEAMPOS	0.0	0.0	0.1	0.0	0.0	0.0
BEAMPOS	0.0	1.0	0.0	0.2	0.0	0.0CYLI-VOL

→ request decay by the RADDECAY card

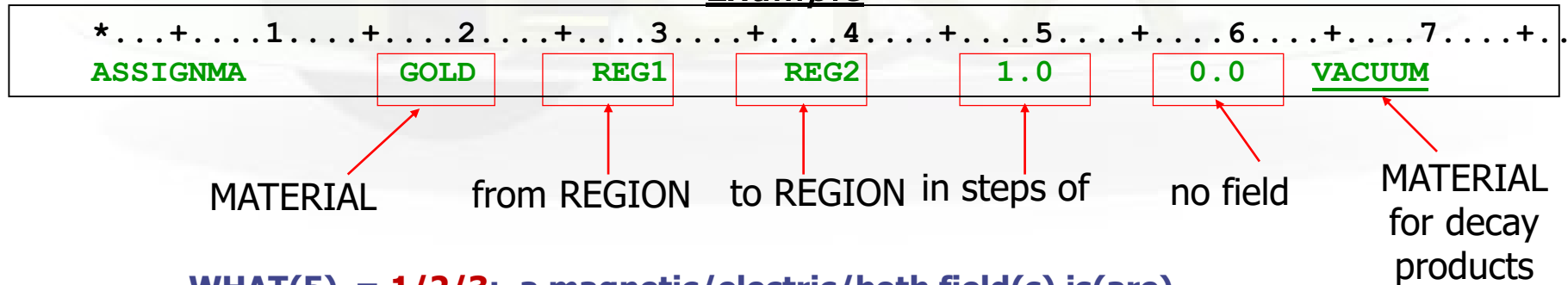
Geometry modifications [1]

FLUKA.2011 contains the possibility of selectively changing a region material (and/or switching on/off possible fields) when transporting radioactive decay products. Radioactive decay products originating from that regions are ignored. This is helpful for situations where the emissions of an activated object in a complex environment have to be evaluated standalone.

Through Input card: **ASSIGNMA**

(a (single-element or compound) material is assigned to each geometry region)

Example



WHAT(5) = 1/2/3: a magnetic/electric/both field(s) is(are) present in the region(s) defined by WHAT(2), (3), and (4), for **both prompt and radioactive decay products**

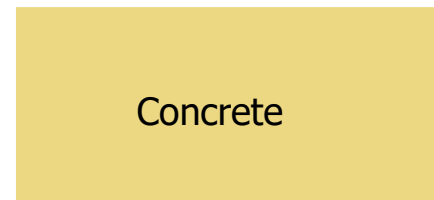
= **4/5/6:** same as above, but for **prompt products only**

= **7/8/9:** same as above, but for **radioactive decay products only**

Note: so far distinction between lattices (all instances are affected)

Geometry modifications - 1

120 GeV
protons



Concrete



Stainless steel target



Concrete

1) Target only (shielding set to vacuum)

```

ASSIGNMA    BLCKHOLE    EXTVOID
ASSIGNMA      VACUUM    VACTRGT
ASSIGNMA      SS316L    TARGET
ASSIGNMA    CONCRETE    SHIELDIN
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7...
    
```

2) Shielding only (target set to vacuum)

```

ASSIGNMA    BLCKHOLE    EXTVOID
ASSIGNMA      VACUUM    VACTRGT
ASSIGNMA      SS316L    TARGET
ASSIGNMA    CONCRETE    SHIELDIN
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7...
    
```

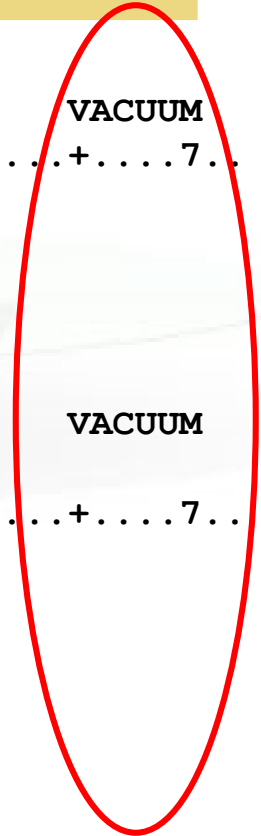
3) Target and shielding

```

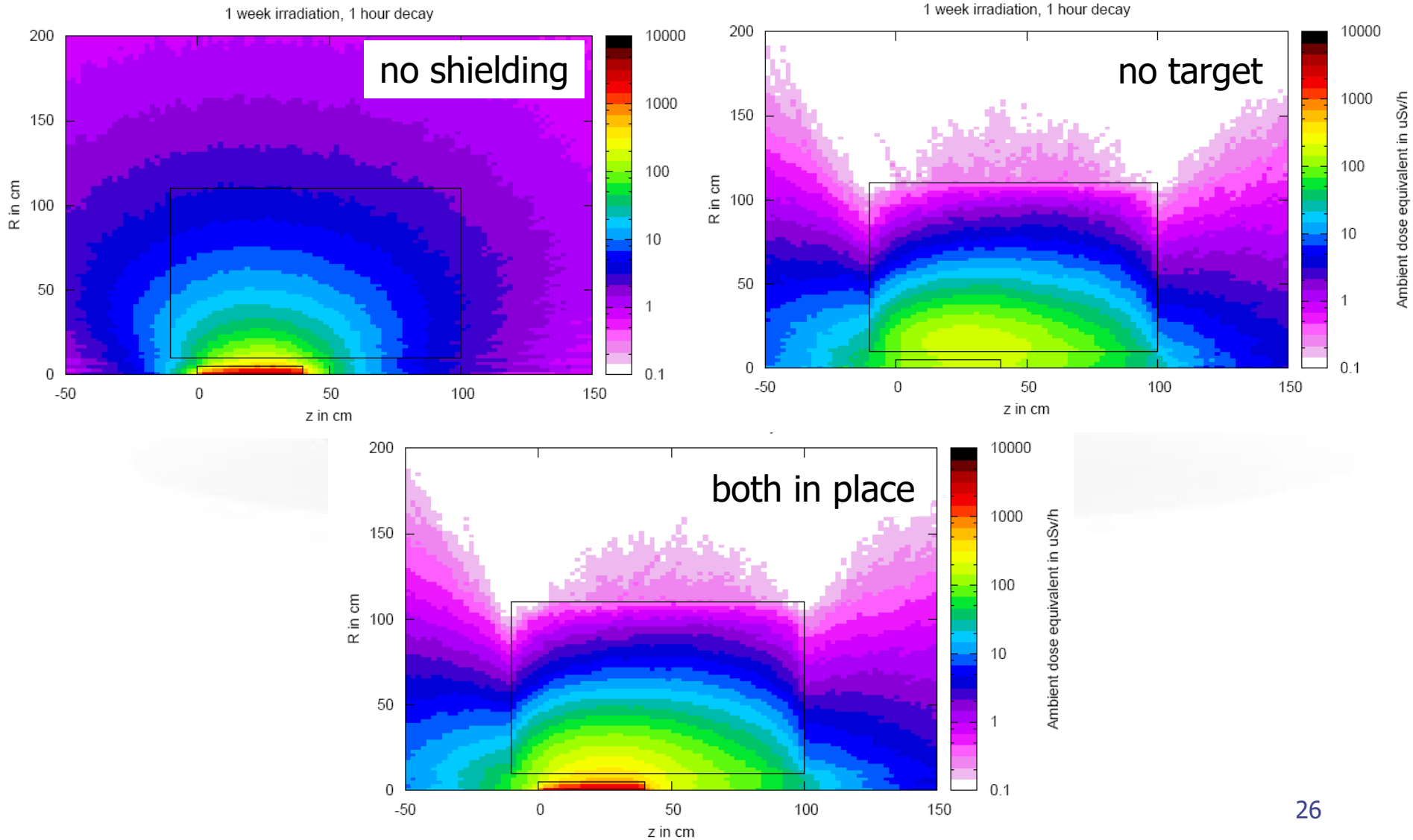
ASSIGNMA    BLCKHOLE    EXTVOID
ASSIGNMA      VACUUM    VACTRGT
ASSIGNMA      SS316L    TARGET
ASSIGNMA    CONCRETE    SHIELDIN
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7...
    
```

VACUUM

VACUUM

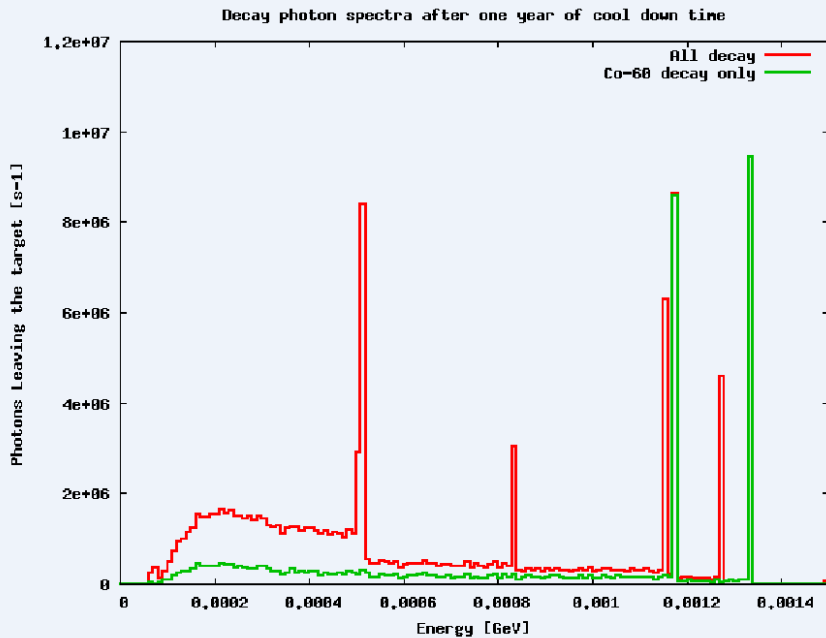


Geometry modifications - 2



Filtering contribution of particles from decay

- Possibility to use the Iaztrk (variable in common block (TRACKR)) to flag parent isotope if any
- $Iaztrk = A + 1000 Z + 1000000 * m$
- The variable is propagated throughout the code to daughters
- Convenient to use it in comscw or fluscw (see exercise)



Example: Photons out of a steel target (USRBDX) after one month of irradiation and one week of cool down time. The spectrum in red has the contribution of all decay inside the target while the one in green has the contribution from the ^{60}Co decay only

"FILTER" : AUXSCORE

There is the possibility to **filter** the estimators, restricting the scoring to a selected subset of particles.

Warning: filtering energy deposition (or similar) by particle type has small physical meaning, because the result depends on the delta ray threshold

New: possibility to filter activity with respect to parent isotope:

```
USRBIN      1.0  ACTIVITY  -87.      10.0      1.0Co60
USRBIN      0.0      0.0      0.      10.0      0.0      10.0&
AUXSCORE    USRBIN -6002700.      Co60
```

The requested ion is coded in $WHAT(2) = - (100 * Z + 100000 * A + m * 100000000)$

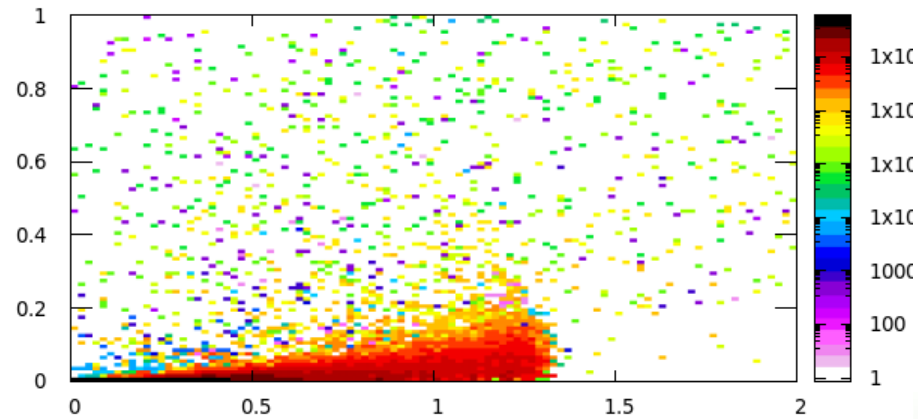
according to its **A**, **Z** and (optionally) isomeric state **m**

with 0==all, i.e. -2700 == all Cobalt isotopes

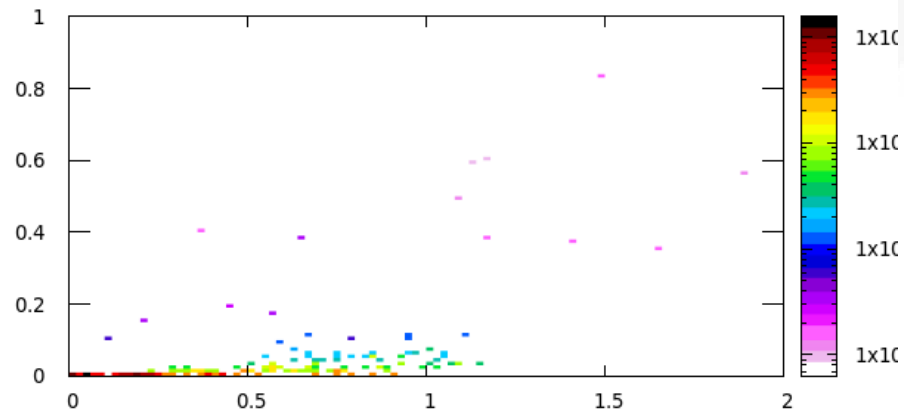
M=0 → ground + isomeric states. M=9 → only ground state

"FILTER" : AUXSCORE

Full activity map



⁶⁰Co activity map



Summary of main input cards

RADDECAY

requests simulation of decay of produced radioactive nuclides and allows to modify biasing and transport thresholds (defined with other cards) for the transport of decay radiation

IRRPROFI

definition of an irradiation profile (irradiation times and intensities)

DCYTIMES

definition of decay (cooling) times

DCYSCORE

associates scoring detectors (radio-nuclides, fluence, dose equivalent) with different cooling times

AUXSCORE

allows to associate scoring estimators with dose equivalent conversion factors or/and to filter them according to (generalized) particle identity

PHYSICS

switch to activate the evaporation of heavy fragments (up to $A=24$) and the simulation of coalescence