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FLUKA MC for FOOT: the case of gamma de-excitations *[some unexpected changes in MotherID]*

Gamma de-excitation of nuclei: what is changed

Until version 2020:

De-excitation of excited nuclear states is performed “instantaneously” during a nuclear interaction (i.e. in the same place where interaction occurs)

- Drawback 1: at high energy (eg LHC or CR energies) even ps/fs mean lives correspond to measurable decay distances:
  - LHC Pb-Pb ($\gamma \approx 2500$): 1 ns $\rightarrow$ 750 m!, 1 ps $\rightarrow$ 0.75 m
  - CR, 1-100 PeV/n ($\gamma \approx 10^6$-10^8): 1 ps $\rightarrow$ 0.3 – 30 km!, 1 fs$\rightarrow$ 0.3 - 30 m, often excited nuclei can interact even before de-exciting!!
- Drawback 2: at “therapy” energies, Doppler broadening of both target/projectile emitted γ lines is overestimated:
  - Target like: ^{16}O, E~0.1 MeV/n: 1 ps $\rightarrow$ 4.4 μm, R $\approx$ 3 μm, many excited states will decay at rest
  - Projectile like: ^{12}C, E~150 MeV/n: 1 ns $\rightarrow$ 15 cm, 1 ps $\rightarrow$ 150 μm

Since version 2021:

By default excited nuclei with measurable/known mean life will not de-excite during the nuclear interaction which produced the excited state, but rather will fly until decay according to the level mean life

Old behaviour was justified by very short half-times. Examples of gamma-decays:

Isotope	E* (MeV)	$T_{1/2}$ (s)
$^{7}Be^{1*}$	0.43	$1.33\ 10^{-13}$
$^{10}B^{1*}$	0.72	$7.07\ 10^{-10}$
$^{10}B^{3*}$	2.25	$1.48\ 10^{-12}$
$^{10}B^{4*}$	3.59	$1.02\ 10^{-13}$
$^{10}C^{1*}$	3.35	$1.07\ 10^{-13}$
$^{11}C^{4*}$	6.34	$7.62\ 10^{-14}$
$^{12}C^{1*}$	4.44	$4.22\ 10^{-14}$
$^{12}C^{3*}$	3.85	$8.60\ 10^{-12}$
$^{14}C^{2*}$	6.59	$3.00\ 10^{-12}$
$^{14}C^{3*}$	6.73	$6.60\ 10^{-11}$

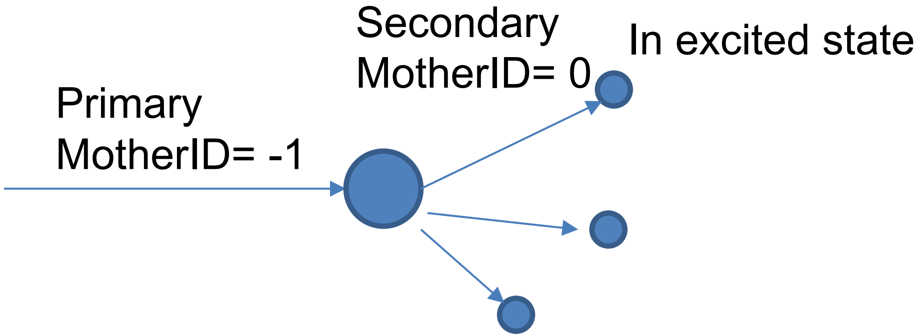
Isotope	E* (MeV)	$T_{1/2}$ (s)
$^{15}O^{2*}$	5.24	$2.25\ 10^{-12}$
$^{15}O^{6*}$	7.28	$4.90\ 10^{-13}$
$^{16}O^{2*}$	6.13	$1.84\ 10^{-11}$
$^{16}O^{7*}$	8.87	$1.25\ 10^{-13}$
$^{17}O^{1*}$	0.87	$1.79\ 10^{-10}$
$^{17}O^{2*}$	3.06	$8.00\ 10^{-14}$
$^{18}O^{1*}$	1.98	$1.94\ 10^{-12}$
$^{18}O^{2*}$	3.55	$1.72\ 10^{-11}$
$^{18}O^{3*}$	3.63	$9.60\ 10^{-13}$

Isomers do not decay in flight: isomers are currently decayed only when at rest, since "isomers" in Fluka are defined as excited states with $T_{1/2} > 1\ \mu s$, usually this is a very good approximation, unless for very large set-ups

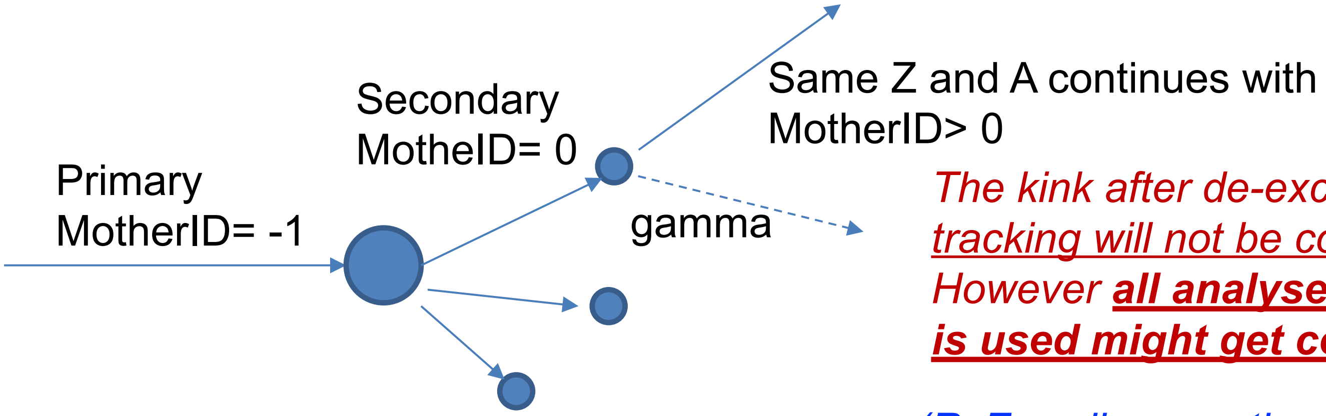
Problem in our simulation

- The FOOT MC output is built constructing an indexing method invented "*ad hoc*" to retrieve the history of particles in one event, and is managed by UpdateCurrentParticle routine(*) (see Simulation/ROUTINES)
- It has a "complex" logic *(complex=contorted…)* which sometimes fails to recognize if, after an interaction vertex, a particle (or nucleus) remains the same or if has to be considered a new particle (this is artificial, the physics meaning of that is sloppy…)
- MotherID is invented there (it is not a concept existing in FLUKA!)
- *We realize now that gamma de-excitation is one of the cases that brings UpdateCurrentParticle in confusion: MotherID is changed…*

(*) Invented and developed by V. Patera and G. Battistoni



Even for very short $T_{1/2}$ it may happen that de-excitation actually occurs outside the target



The kink after de-excitation is negligible: tracking will not be confused.
*However **all analyses where MotherID is used might get confused***

(R. Zarrella recently pointed out this issue)

Solutions for next simulations

- Trying to touch and correct UpdateCurrentParticle is dangerous…
- The old behaviour can be restored giving a proper directive to FLUKA:

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    PHYSICS -1.0                                                  INFLDCAY
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- The new behaviour was important for people working on gamma prompt monitoring in hadrontherapy. It is probably not important for FOOT

To be discussed:

- Which are the situations in which the new behaviour may cause problems? *(Marco is pointing out the case of efficiency evaluation)*
- Do we prefer to restore the old behaviour in out FOOT simulations? Let us think a bit if there any drawback

The suppression of in-flight de-excitation does not solve the issue of mother-id change

Along their path from target to TW, our secondary particles F (fragments) have a probability to perform an inelastic interaction (according to the nuclear physics terminology) with a nucleus of air or other material outside the target:
F + N → F’ + N* or F + N → F’* + N or F + N → F’* + N*

In all these cases a gamma de-excitation will occur (with of course the exception of He)

Then it is irrelevant if the in-flight de-excitation is activated or not: the gamma will be attributed to F, which is going to change its total kinetic energy be few MeVs, and the mother-id will be changed

Maybe we can avoid this just by switching off gamma transport, but we are not 100% sure.
Still to be tested