C.3 GEANT4 PHYSICS MODELS INVOLVED IN SIMULATIONS

The list of available physical processes and corresponding options employed in the ELI-GANT-TN and ELI-GANT-GN array full simulations are numerous and extremely flexible.

A dedicated "*Messsenger*" class was written in order to select various physics lists and options. This class allows users to change some of the problem properties without changing or recompiling the source code. Thus, physics processes desired to be used in simulations can be selected with the help of several macro-commands given in "*SetPhysics.mac*" macro-command file that is called by the main "*commands*" macro-command file, or they can be given directly in the GEANT4 terminal at command prompt in the initial phase (before "`/run/initialize`" macro-command).

The directory and sub-directory of the macro-commands responsible selecting physics models is "`/eli/phys/SelectPhysics`". This command has to be followed by a keyword which selects the desired physics package. These keywords can be classified in several groups depending on their usage. For example a first group of macro-commands is dedicated to the selection of electromagnetic physics only. This constructor can be chosen independently from the hadronic physics. In Table 1, the list with available options for the EM physics with a short description is presented. Of course, only one of these options can be chosen at once for a particular simulation.

`emstandard_opt0`	The default EM constructor
`emstandard_opt1`	Designed for high energy physics (HEP) CMS focused. It includes some modifications for electron and positron transport with respect to the default EM physics.
`emstandard_opt2`	Also designed for HEP physics (LHCb focused). Comparing to the *option1*, the cuts are disabled and a different angular generator for bremsstrahlung process is used.
`emstandard_opt3`	Designed for any applications required higher accuracy of electrons, hadrons and ion tracking without magnetic field.
`EmPenelope`	It is based on *option3* constructor, but adds corresponding *Penelope* models for photoelectric, Compton, pair creation, Rayleigh, ionization and bremsstrahlung processes.
`EmPenelope_usr`	It is basically the same with previous option, but user has direct access to each Penelope model in order to activate/deactivate or change options. These changes have to be done by user in specially written corresponding class `eliPhysListEmPenelope_usr`, but the code have to be recompiled after.
`EmLivermore`	Still based on *option3* constructor, but adds corresponding *Livermore* models for photoelectric, Compton, pair creation, ionization and bremsstrahlung processes.
`EmLivermore_usr`	The same as previous option, but user has complete access to the used models through the `eliPhysListEmLivermore_usr` class.

EmLivermorePolarized	Still based on *option3* constructor, but adds corresponding *Livermore* models for photoelectric, Compton, pair creation, Rayleigh, ionization and bremsstrahlung processes taking into account also the polarization effects.
EmLivermorePolarized_usr	The same as previous option, but user has complete access to the used models through the eliPhysListEmLivermorePolarized_usr class.

Table C.11 List of macro-commands used to select electromagnetic physics.

Among the above options, we can distinguish three particular ones, ending with "_usr" suffix. For these options, specially dedicated classes are called, where user has direct access to activate/deactivate or change options for several processes treated in the corresponding model that are involved in the simulation. In Table C.12 are listed the model classes that can be accessed by user within "_usr" macro-commands in order to build custom electromagnetic physics.
Another set of macro-commands that can be called independently and separately from the ones from the first group, are designated to set the models for hadronic interactions. They are listed in Table C.13. Only one of these options can be chosen at once in order to specify the desired hadronic to be used in simulation.

FTFP_BERT	Fritiof precompound (>10 GeV) + Bertini (<10 GeV) models
FTF_BIC	Fritiof(>10 GeV) + Binary Cascade (<10 GeV) models
LHEP	Low and High energy parameterization model (fastest)
QGS_BIC	Quark gluon string (>20 GeV) + Binary Cascade (<10 GeV) models
QGSP	Quark gluon string precompound model (>20 GeV)
QGSP_FTFP_BERT	Quark gluon string precompound (>20 GeV) + Fritiof precompound (>10 GeV) + Bertini (<10 GeV) models
QGSC_BERT	Quark gluon string CHIPS (>8 GeV) models
QGSP_BERT	Quark gluon string precompound (>20 GeV) +Bertini cascade (<10 GeV) models.
QGSP_BERT_HP	Same as previous but with high precision neutron model for neutrons below 20 MeV.
QGSP_BIC	Quark gluon string precompound (>20 GeV) +Binary Cascade (<10 GeV) models
QGSP_BIC_HP	Same as previous but with high precision neutron model for neutrons below 20 MeV.
Hadron_usr	Custom defined hadronic physics

Table C.13 List of macro-commands used to select hadronic physics.

Particle		GEANT4 process class name	Model class name		
			Penelope	Livermore	Livermore polarized
γ		`G4PhotoElectricEffect`	`G4Penelope` `PhotoElectricModel`	`G4Livermore` `PhotoElectricModel`	
γ		`G4ComptonScattering`	`G4Penelope` `ComptonModel`	`G4Livermore` `ComptonModel`	
γ		`G4GammaConversion`	`G4Penelope` `GammaConversionModel`	`G4Livermore` `GammaConversionModel`	
γ		`G4RayleighScattering`	`G4Penelope` `RayleighModel`	`G4Livermore` `RayleighModel`	`G4LivermorePolarized` `RayleighModel`
e^+	e^-	`G4eIonisation`	`G4Penelope` `IonisationModel`	`G4Livermore` `IonisationModel`	
e^+	e^-	`G4eBremsstrahlung`	`G4Penelope` `BremsstrahlungModel`	`G4Livermore` `BremsstrahlungModel`	
e^+		`G4eplusAnnihilation`	`G4Penelope` `AnnihilationModel`		
γ		`G4Polarized` `PhotoElectricEffect`			`G4LivermorePolarized` `PhotoElectricModel`
γ		`G4PolarizedCompton`			`G4LivermorePolarized` `ComptonModel`
γ		`G4PolarizedGammaConversion`			`G4LivermorePolarized` `GammaConversionModel`
e^+	e^-	`G4ePolarizedIonisation`			`G4Livermore` `IonisationModel`
e^+	e^-	`G4ePolarizedBremsstrahlung`			`G4Livermore` `BremsstrahlungModel`

Table C.12 List of model classes accessible with "`_usr`" macro-commands.

In general, these models designated to describe the hadronic interaction are designated to be used in high energy physics. In our particular case of simulating GANT-TN and GANT-GN arrays we are more interested in describing with high accuracy hadronic interactions (especially for neutrons at) low energies (<20 MeV). Thus, the most indicated options from those enumerated in Table C.13, are `QGSP_BERT_HP` and `QGSP_BIC_HP` because they involve the data driven high precision neutron package (NeutronHP) to transport neutrons below 20 MeV down to thermal energies. These packages rely on tabulated cross sections existing as files in G4NDL format.

These files are part of GEANT4 data library and are obtained from ENDF database, but translated into G4NDL format. Unfortunately, the standard GEANT4 data library does not contain the entire data contained in ENDF databases. For example, cross section for $^{3}He(n,p)^{3}H$, essential for ^{3}He counters, was missing. For this reason, the G4NDL library was updated with the latest data existing in ENDF-B/VII.0 database, found on IAEA site due to the useful work of E. Mendoza and D. Cano-Ott. Of course, on the IAEA site are also present in G4NDL format other databases (JEFF (EU), JENDL (Japan), BROND/ROSFOND (Russia), CENDL (China)…).

	Process	Energy	GEANT4 model	Dataset
neutron	Elastic	<4eV	NeutronHPThermalScattering	G4NeutronHPThermalScatteringData
		<20 MeV	NeutronHPElastic	G4NeutronHPElasticData
		>20 MeV	G4LElastic	-
	Inelastic	<20 MeV	G4NeutronHPInelastic	G4NeutronHPInelasticData
		>20 MeV	G4BinaryCascade	-
		>10 GeV	G4TheoFSGenerator QGSP	-
	Fission	<20 MeV	G4NeutronHPFission	G4NeutronHPFissionData
		>20 MeV	G4LFission	–
	Capture	<20 MeV	G4NeutronHPCapture	G4NeutronHPCaptureData
		>20MeV	G4LCapture	-
proton	Elastic	>0 MeV	G4LElastic	-
	Inelastic	<10 GeV	G4BinaryCascade	-
			G4TheoFSGenerator QGSP	-

Table C.14 List of the GEANT4 classes for neutrons and protons used in "`Hadron_usr`".

But it is well known fact that the moderation of neutrons with kinetic energies below 4 eV in polyethylene moderator (one of the most important components of GANT-TN array) should be considered in a special way. In this low-energy region the scattering of neutrons on the hydrogen nuclei in polyethylene cannot be treated as scattering on free protons due to the possible excitation of vibrational modes in polyethylene molecules. Such collective motion of molecules significantly change the thermal neutron scattering characteristics in polyethylene, so dedicated thermal scattering dataset and model should be included for neutron energies less than 4 eV to allow the correct treatment of neutron moderation and capture processes in the elements of GANT setups.

Thus, below 4 eV, the "*Thermal Scattering*" package was added to the standard G4NDL database. This package accurately accounts for the low energy neutron interactions with matter, and consider the structure of the material/molecules (crystaline liquid...).
Due to the above enumerated reasons, a dedicated class for hadronic interactions was written, and can be called with the keyword "`Hadron_usr`". A summary with all included models on different energy ranges for distinct processes possible for neutrons and protons are given in Table C.14.

In usual simulations, it is recommended to use one macro-command from the first group to set the electromagnetic physics, and one macro-command from the second group that sets the hadronic physics. However, if user does not use any macro-command, the default physics will be used, meaning *option1* for electromagnetic processes and no hadronic interactions will be considered.

Other two keywords (`ExtraEmPhys` and `ExtraEmPhys_usr`) can be used in order to activate photonuclear and electronuclear reactions.

Keyword `RadDecay_usr` can activate radioactive decay of non-stable isotopes. In addition, internal conversion, atomic rearrangement and atomic de-excitation through fluorescence, Auger electrons and PIXE are enabled.

Finally a third group of macro-commands are designated to activate both electromagnetic and hadron physics. They are standalone commands and cannot be used in combination with any of the macro-commands enumerated in the first two groups. We just enumerate the keywords (their name is self-explanatory): `FTFP_BERT_EMV`, `FTFP_BERT_EMX`, `LHEP_EMV`, `QBBC`, `QGSP_BERT_EMV`, `QGSP_BERT_EMX`, `QGSP_BIC_EMY`.

In the same file of macro-commands, we can set cuts for every particle individually, but also for all of them, or separately for detectors and target regions, using the keywords `setGammaCut`, `setElectronCut`, `setPositronCut`, `setProtonCut`, `setNeutronCut`, `setCuts`, `TargetCuts`, `DetectorCuts` followed by a number and a length unit accepted by GEANT system of units.