Custom Physics Lists in larg4 and Updates

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Recap

- As mentioned in my presentation for the DUNE collaboration meeting, the StepLimit in the geometry was set too finely resulting in very large ouput files
- Other contributing factors:
  - Zero energy tracking cut
  - storing all MCParticle information for daughters from EM interactions
  - storing SimEnergyDeposits
  - zlib compression setting of 0 i.e. no compression [1]

[1] This was intentionally set to zero to favor faster output write speed.

Tests

- Used a corsika-generated event
- Used the same event for all tests
  - The number of primary particles for the various tests was the same: 686
  - the number of secondaries can vary, but for the most part, the number of hits was consistent between all tests (>800,000 hits)
- the Legacy standard is:
  - **KeepEMShowerDaughters:** false # minimal info will be stored for EM daughters
  - **EnergyCut:** 1e-5 # [GeV], below this kinetic energy, particles will not be tracked
  - **compressionLevel:** 1 # output file zlib compression level

- Output file size (**Out Size**) in MB
- Peak virtual memory usage: (**Virtual**) in MB
- Peak resident memory usage: (**Resident**) in MB
- Time to write output: (**Write time**) in seconds

	Out Size (MB)	Virtual	Resident	Write time
Legacy	134 MB	3488.9 MB	2810.7 MB	7.35 s
Refactored	114 MB	2752.5 MB	2043.8 MB	5.75 s
% change	-14.9%	-21.1%	-27.3%	-21.8%

Conclusions

Refactored looks good so far in terms of output size, memory consumption and output write time, but with some **caveats:**

- the refactored larg4 is still missing some data products in my tests (photon and crt products)
- I used **QGSP_BERT_HP** in refactored

Will continue benchmark tests as things evolve to ensure that resource consumption remains reasonable

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- A. Higuera has proposed a study on pion quasi-elastic scattering cross sections that would require distinguising between outgoing particles from the QE vertex and outgoing particles resulting from the intranuclear cascade process at the $\sim$1GeV range
- One would ideally like to “turn off” the cascade process; however, it is not sufficient to push the energy range of validity for the cascade model as mentioned in item 1 of slide ??
- Would have to define an alternative model to apply to the hadrons from 0 to 1GeV
- Alternatively one can perhaps change the behavior of the Cascade model itself OR
- it may suffice to extract information about the interactions themselves

Since it's far easier to extract the information from the Cascade model, I have started with that

- See this document for more details and for the figure shown on the right

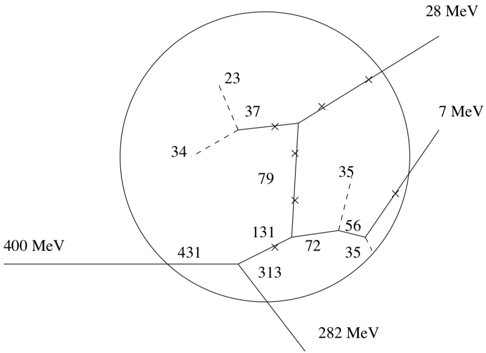


Figure 1: Schematic presentation of the intra-nuclear cascade. A hadron with 400 MeV energy is forming an INC history. Crosses present the Pauli exclusion principle in action. (The picture is a reproduction from original work of Bertini [4].)

- In order to have full control over the cascade model I have copied and rebranded the Inelastic Physics constructor under the **QGSP_BERT_HP** physics list (namely G4HadronPhysicsQGSP_BERT_HP) and all associated headers and source code to the same area where I have my custom physics list to be declared and registered as a physics constructor
- The Pion builder class also had to be copied
- The Bertini Cascade model is itself implemented in the G4CascadeInterface which I have copied and rebranded as well

After many failed attempts:

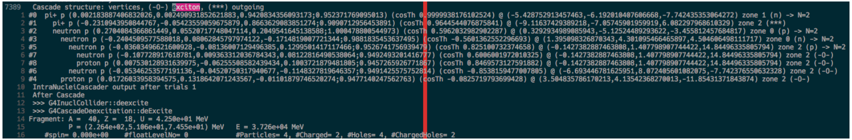
```
 >>> G4CascadeHistory::Print
 Cascade structure: vertices, (-O-) exciton, (***) outgoing
#0  neutron p (-0.02913238440364647,0.01527703980790919,0.3804225069217336;1.014192503053972) (cosTh 0.9962823254767051) @ (9.815764768540232,-5.147392916293244,-13.26419068176589) zone 2 (n) -> N=2
#1    neutron p (0.153117539724997,-0.04629765817050494,0.3268919343572946;1.007586153429717) (cosTh 0.8982215803428377) @ (10.30196587007747,-5.294403980091177,-12.22619582596029) zone 2 (n) -> N=2
#3      neutron p (0.1284273918200907,0.1367780778302243,0.2254045700718699;0.9842723827609184) (cosTh 0.7685827308527144) @ (10.30196587007747,-5.294403980091177,-12.22619582596029) zone 2 (***)
#4      neutron p (-0.1098190408329762,-0.07467476972257432,0.1885768592661283;0.9674610279102726) (cosTh 0.8176014724689113) @ (8.287797224915842,-12.69615640524514,-6.087829495373893) zone 2 (n) -> N=2
#5        neutron p (-0.08379425704381073,-0.1628548431766251,0.0890856425847717;0.9613857159778684) (cosTh 0.4374126426274674) @ (7.74988050155642,-13.74160208034649,-5.515944754722582) zone 2 (n) -> N=2
#7          neutron p (-0.06580123596133194,-0.01277091141039565,0.1420207332657859;0.9525995240506747) (cosTh 0.9043377707578295) @ (7.74988050155642,-13.74160208034649,-5.515944754722582) zone 2 (-O-)
#8          neutron p (-0.09817003373930802,-0.1107201382845191,-0.05238226528473341;0.9525876715423151) (cosTh -0.3337045330693694) @ (7.74988050155642,-13.74160208034649,-5.515944754722582) zone 2 (-O-)
#6        neutron p (-0.00404211456499176,0.02002325863576827,0.1311805400881912;0.9488986612838647) (cosTh 0.9880920712511041) @ (8.287797224915842,-12.69615640524514,-6.087829495373893) zone 2 (-O-)
#2    neutron p (-0.06352611755725476,0.01942899132903319,0.1238246430120143;0.9500150847459972) (cosTh 0.8811948822554886) @ (-9.07016766111661,6.940050059796436,6.283161658383091) zone 2 (-O-)
 IntraNucleiCascader output after trials 1
 After Cascade
 >>> G4InuclCollider::deexcite
 >>> G4CascadeDeexcitation::deExcite
Fragment: A =  40, Z =  18, U = 2.953e+01 MeV
          P = (2.010e+01,-1.065e+02,1.313e+02) MeV   E = 3.725e+04 MeV
    #spin= 0.000e+00    #floatLevelNo= 0            #Particles= 4, #Charged= 0, #Holes= 4, #ChargedHoles= 0
```

Bertini Cascade Internal Types

The G4ElementaryParticle class includes a creator model type which identifies the process that created the particle in question. The list of these is shown below:

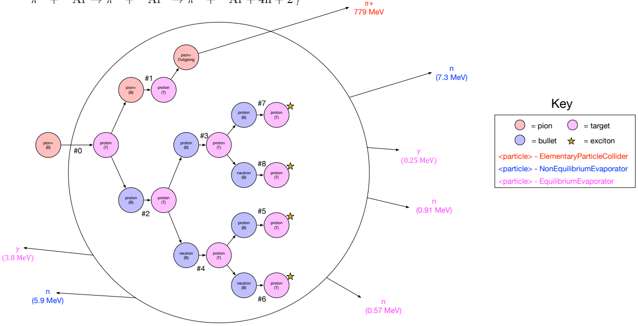
- 0 - default
- 1 - bullet
- 2 - target
- 3 - G4ElementaryParticleCollider
- 4 - G4IntraNucleiCascader
- 5 - G4NonEquilibriumEvaporator
- 6 - G4EquilibriumEvaporator
- 7 - G4Fissioner
- 8 - G4BigBanger
- 9 - G4PreCompound
- 10 - G4CascadeCoalescence

π^+ Example



```
Cascade structure: vertices, (-0-) exciton, (***) outgoing
#0  pi+ p (0.002183887406832026,0.002490931852621883,0.9420834356093173;0.952371769095013) (cosTh 0.9999938176102524) @ (-5.428752913457463,-6.192010407606668,-7.742435353064272) zone 1 (n) -> N=2
#1    pi+ p (-0.2310943950844767,-0.05423559059675879,0.8663629083851274;0.9090712956453891) (cosTh 0.9644544076875841) @ (-9.11637429389218,-7.05745901959919,6.0822979686 10329) zone 2 (***)
#2    neutron p (0.2704084366861449,0.05520717748047114,0.2049541645138588;1.000478800544973) (cosTh 0.5962032982902287) @ (0.3292934989085943,-5.12524489293622,-3.455812457684817) zone 0 (p) -> N=2
#3      neutron p (-0.2404509577588018,0.08062845797974122,-0.1714819007721344;0.9881835453637495) (cosTh -0.5601362552296693) @ (1.395098326870343,4.301095466465897,4.504606498111717) zone 0 (n) -> N=2
#5        neutron p (-0.03603496621600928,-0.08136007129496385,0.1299501417117466;0.9526741756939479) (cosTh 0.825100732374658) @ (-0.1427382887463808,1.407798907744422,14.84496335805794) zone 2 (p) -> N=2
#7          neutron p (-0.107728917618781,0.009363312036784343,0.08122816490538064;0.9492493201416777) (cosTh 0.6006001972010325) @ (-0.1427382887463808,1.407798907744422,14.84496335805794) zone 2 (-0-)
#8          proton p (0.007530128931639975,-0.06255508582439434,0.1003721879481805;0.9457265926771867) (cosTh 0.8469573127591882) @ (-0.1427382887463808,1.407798907744422,14.84496335805794) zone 2 (-0-)
#6        neutron p (-0.05346253577191136,-0.04520750317940677,-0.1148327819646357;0.9491425575752814) (cosTh -0.8538159477007805) @ (-6.693446781625951,8.072405601082075,-7.742376550632328) zone 2 (-0-)
#4      proton p (0.01726033958394575,0.1318642071243567,-0.01101879746520274;0.9477140247562763) (cosTh -0.0825719793699428) @ (3.504835786170213,4.13542368270013,-11.85431371843874) zone 2 (-0-)
IntraNucleiCascader output after trials 1
After Cascade
>>> G4InuclCollider::deexcite
>>> G4CascadeDeexcitation::deExcite
Fragment: A =  40, Z =  18, U = 4.250e+01 MeV
          P = (2.264e+02,5.106e+01,7.455e+01) MeV   E = 3.726e+04 MeV
    #spin= 0.000e+00    #floatLevelNo= 0            #Particles= 4, #Charged= 2, #Holes= 4, #ChargedHoles= 2
```

$$\pi^+ + {}^{40}\text{Ar} \rightarrow \pi^+ + {}^{40}\text{Ar}^* \rightarrow \pi^+ + {}^{36}\text{Ar} + 4\text{n} + 2\gamma$$



- π^+ undergoes quasi-elastic scattering
- No secondary particles from the primary pion vertices exit the nucleus directly
- A proton from the primary pion collision cascades
- The secondaries go on and each yield a proton-hole and neutron-hole pairs
- Non-equilibrium evaporation is applied do de-excite the nucleus
- the post equilibrium evaporation models are applied

Extracting More Information

- Only models: 0, 3, 4, 5, 9, and 10 seemed to show up (at least in my 100 π^+ sample)
- Would be ideal to have G4IntraNucleiCascader to differentiate further

```
Outgoing Particles: 7
px 0.166497 py 0.143907 pz 0.881688 pmod 0.908738 E 0.919393 creator model 3
Particle: pi+ type 3 mass 0.13957 ekin 0.779823
px 0.0569471 py 0.0453398 pz 0.0921119 pmod 0.117402 E 0.946872 creator model 5
Particle: neutron type 2 mass 0.939565 ekin 0.00730651
px 0.0115864 py 0.0793499 pz -0.0682639 pmod 0.105312 E 0.945449 creator model 5
Particle: neutron type 2 mass 0.939565 ekin 0.00588357
px 0.00122572 py 0.00190195 pz -0.00308868 pmod 0.0038288 E 0.0038288 creator model 6
Particle: gamma type 9 mass 0 ekin 0.0038288
px -0.00514606 py -0.0174351 pz 0.0372365 pmod 0.0414369 E 0.940479 creator model 6
Particle: neutron type 2 mass 0.939565 ekin 0.000913287
px -0.0293422 py -0.0021225 pz 0.0146091 pmod 0.0328466 E 0.940139 creator model 6
Particle: neutron type 2 mass 0.939565 ekin 0.000573971
px -9.68127e-05 py -0.000105685 pz 0.000199748 pmod 0.000245848 E 0.000245848 creator model 6
Particle: gamma type 9 mass 0 ekin 0.000245848
Outgoing Nuclei: 1
px -0.201671 py -0.250836 pz 0.0122798 pmod 0.322088 E 33.4959 creator model 6
Nucleus: Ar36 A 36 Z 18 mass 33.4944 Eex (MeV) 0.0076702
```

```
Test of analyzer!
 Number of events 59
 average multiplicity 9.50847
 average proton number 2.38983
 average neutron number 3.84746
 average nucleon Ekin 0.0461663
 average proton Ekin 0.0576069
 average neutron Ekin 0.03906
 average pion number 0.830508
 average pion Ekin 0.27091
 average pi+ 0.474576
 average pi- 0.118644
 average pi0 0.237288
              59      9.50847      2.38983      3.84746      0.0461663      0.0576069      0.03906      0.830508      0.27091
End of test of analyzer!
```

TO DOs

- Document the custom physics list
- Agree on a place to store the physics list example