Complete description of the $^{12}C(n,n'3\alpha)$ and $^{12}C(n,\alpha)^{9}Be$ reactions in the High Precision neutron model

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Limitations of G4ParticleHP to describe breakup reactions

G4ParticleHP does not always provide a complete description of breakup reactions:

- Incomplete or missing evaluated data (e.g., angular distributions for $^{12}C(n,\alpha)^{9}Be$)
- Incomplete model implementation (e.g., breakup of $^{12}C^*$ in $^{12}C(n,n'3\alpha)$).

G4ParticleHPInelasticBaseFS

- Reactions with **MORE THAN ONE** particle and a residual nucleus in the final state.
- Uses evaluated energy-angle distributions **OR** n-body phase space distribution if data are not available.
- No energy and momentum conservation in an event-per-event basis.

G4ParticleHPInelasticCompFS

- Reactions with **ONLY ONE** particle and a residual nucleus in the final state.
- **DOES NOT** describe the breakup of the residual nucleus (when LR>0).
- Residual nucleus in breakup reactions is decayed to the GS without particle emission.

INCOMPLETE!

"Complete description of the $^{12}C(n,n'3\alpha)$ and $^{12}C(n,\alpha)^{9}Be$ reactions in the High Precision neutron model", A. R. Garcia et al. | 22nd GEANT4 Collaboration Meeting, 27-29 of September, 2017, University of Wollongong, Wollongong, Australia.

Model for the $^{12}C(n,n'3\alpha)$ reaction

NRESP7

- Developed at the Physikalisch-Technische Bundesanstalt (PTB), Germany, to study the response of organic scintillation detectors to fast neutrons between 0.02 and 20 MeV.

- Successful description of the response function of NE213 organic scintillation detectors (uncertainty lower than 2%).

  (See e.g.: D. Schmidt et al, NIM A 476, 186–189, 2002)

Step 1	Step 2	Step 3		
$n+^{12}C \rightarrow n'+^{12}C^*$	$^{12}C^* \rightarrow \alpha+^{8}Be$	$^{8}Be \rightarrow 2\alpha$	(I)	… E_n>8.29 MeV
$n+^{12}C \rightarrow \alpha+^{9}Be^*$	$^{9}Be^* \rightarrow n'+^{8}Be$	$^{8}Be \rightarrow 2\alpha$	(II)	… E_n>8.81 MeV

- Relativistic kinematics applied at each step.
- Isotropic angular distribution in the center-of-mass system.

Nuclear data sources

- GEANT4 and NRESP take neutron data from different releases of ENDF.

ENDF/B-VII.1

- NRESP also uses data measured at PTB.

(I)
$n + {}^{12}C \rightarrow n' + {}^{12}C^*$
${}^{12}C^* \rightarrow \alpha + {}^{8}Be$
${}^{8}Be \rightarrow 2\alpha$

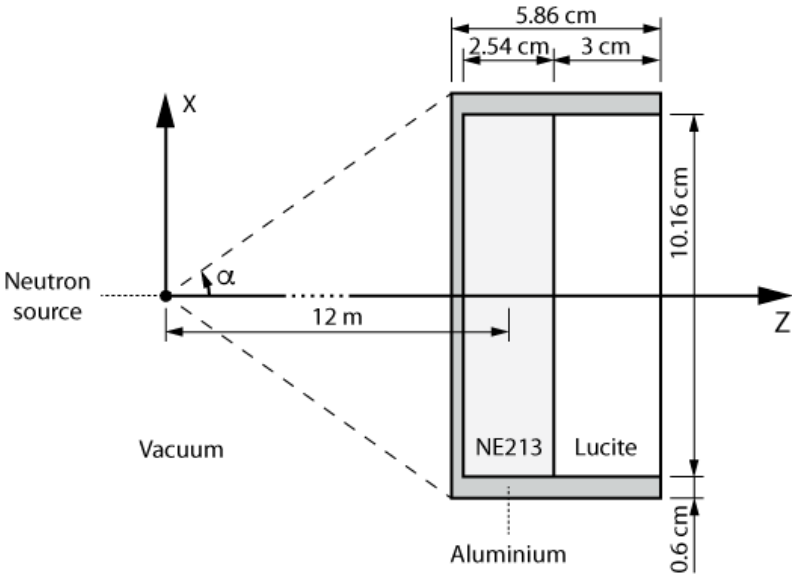
(II)
$n + {}^{12}C \rightarrow \alpha + {}^{9}Be^*$
${}^{9}Be^* \rightarrow n' + {}^{8}Be$
${}^{8}Be \rightarrow 2\alpha$

```
C-0(N,TOT),SIG          MT1   QM=0 QI=0 LR=0
C-0(N,EL)C-L0,SIG       MT2   QM=0 QI=0 LR=0
C-0(N,NON),SIG          MT3   QM=0 QI=0 LR=0
C-0(N,INL)C,SIG         MT4   QM=0 QI=-4.439e+6 LR=0
C-0(N,X),SIG            MT5   QM=0 QI=0 LR=0
C-0(N,N+P)B,SIG         MT28  QM=-1.5957e+7 QI=-1.5957e+7 LR=0
C-0(N,N`)C-L1,SIG       MT51  QM=0 QI=-4.439e+6 LR=0
C-0(N,N`)C-L2(3A),SIG   MT52  QM=-7.275e+6 QI=-7.653e+6 LR=23
C-0(N,N`)C-L3(3A),SIG   MT53  QM=-7.275e+6 QI=-9.638e+6 LR=23
C-0(N,N`)C-L4(3A),SIG   MT54  QM=-7.275e+6 QI=-1.08e+7 LR=23
C-0(N,N`)C-L5(3A),SIG   MT55  QM=-7.275e+6 QI=-1.18e+7 LR=23
C-0(N,N`)C-L6(3A),SIG   MT56  QM=-7.275e+6 QI=-1.27e+7 LR=23
C-0(N,N`)C-L7(3A),SIG   MT57  QM=-7.275e+6 QI=-1.335e+7 LR=23
C-0(N,N`)C-L8(3A),SIG   MT58  QM=-7.275e+6 QI=-1.408e+7 LR=23
C-0(N,N`)C-L9(3A),SIG   MT59  QM=-7.275e+6 QI=-1.508e+7 LR=23
C-0(N,N`)C-L10(3A),SIG  MT60  QM=-7.275e+6 QI=-1.608e+7 LR=23
C-0(N,N`)C-L11(3A),SIG  MT61  QM=-7.275e+6 QI=-1.708e+7 LR=23
C-0(N,N`)C-L12(3A),SIG  MT62  QM=-7.275e+6 QI=-1.808e+7 LR=23
C-0(N,N`)C-C(3A),SIG    MT91  QM=-7.275e+6 QI=-7.275e+6 LR=23
C-0(N,G)C,SIG           MT102 QM=4.94638e+6 QI=4.94638e+6 LR=0
C-0(N,P)B,SIG           MT103 QM=-1.2588e+7 QI=-1.2588e+7 LR=0
C-0(N,D)B,SIG           MT104 QM=-1.3733e+7 QI=-1.3733e+7 LR=0
C-0(N,A)BE,SIG          MT107 QM=-5.702e+6 QI=-5.702e+6 LR=0
```

Angular distribution data for the $^{12}C(n,\alpha)^{9}Be$ reaction (E_n>6.19 MeV) taken from NRESP.

Verification against NRESP

- Equivalent simulations performed with NRESP7.1, and the standard (std) and modified (mod) versions of GEANT4.10.01.p01.
- The modified version incorporates angular distributions for the $^{12}C(n, \alpha)^{9}Be$ reaction and multistep breakup model for the $^{12}C(n,n'3\alpha)$ reactions from NRESP.



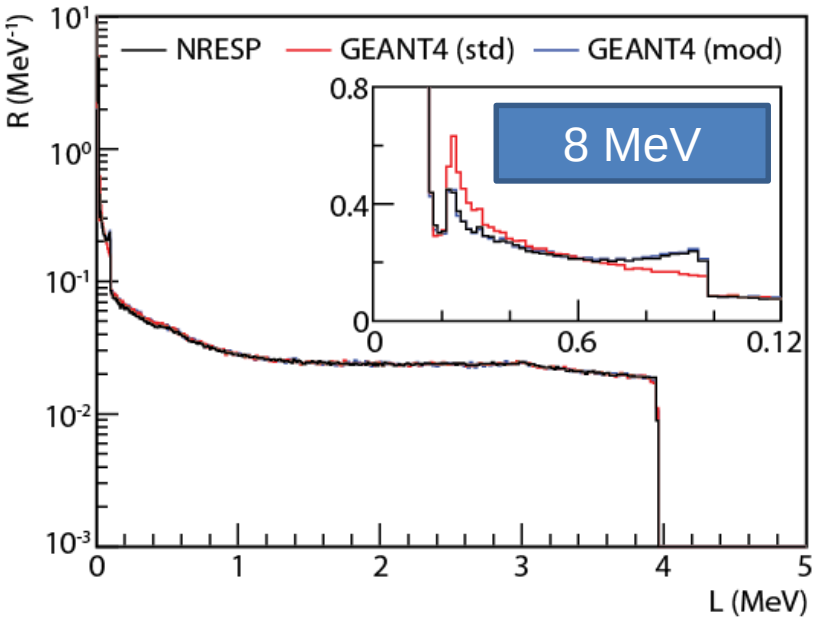
(More details in A. R. Garcia et al, NIM A 868, 73–81, 2017)

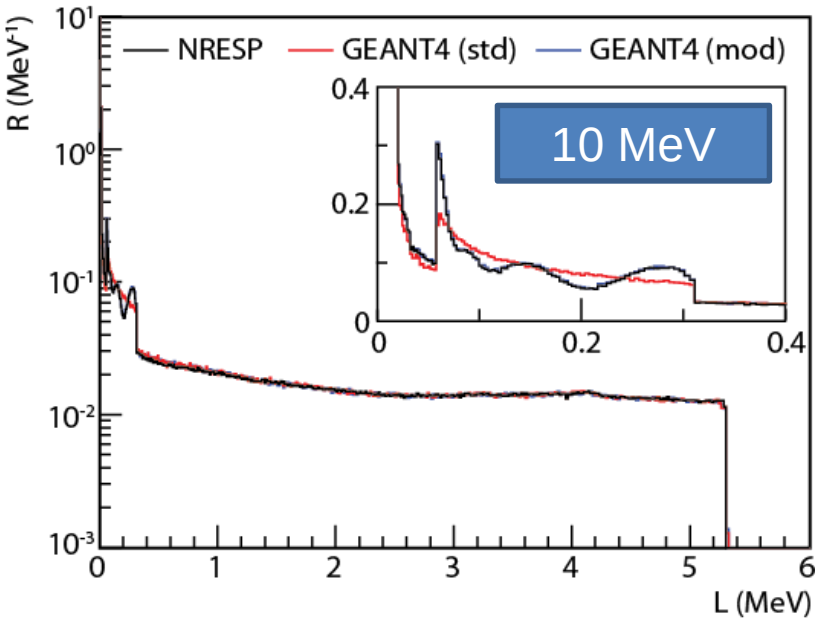
Standard physics list "Shielding" used with GEANT4:

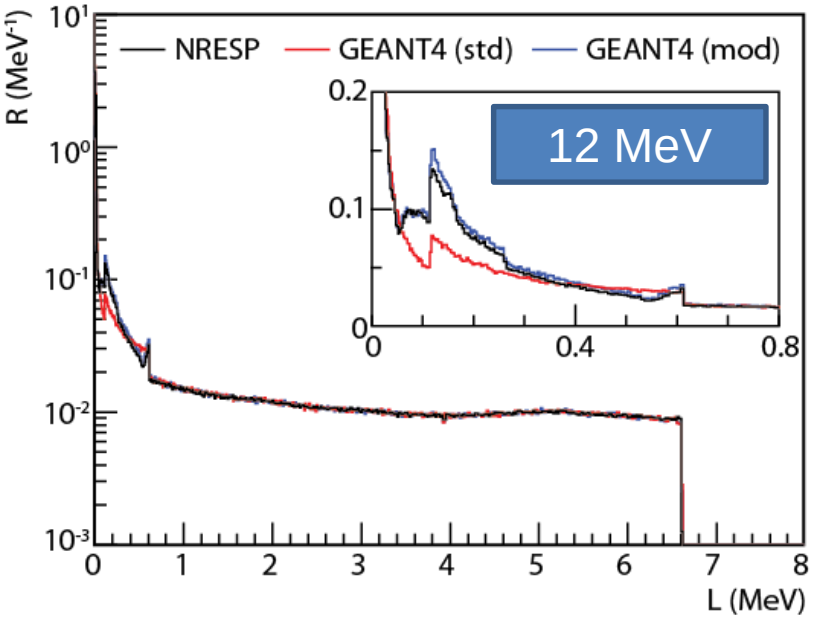
- Standard electromagnetic + High Precision neutron models.
- Production cuts for protons and heavy ions set to 0 mm → production of recoils.
- Electron production cut set to 0.7 mm → no electrons produced.
- Same results obtained with other physics lists using the same neutron models and cuts.

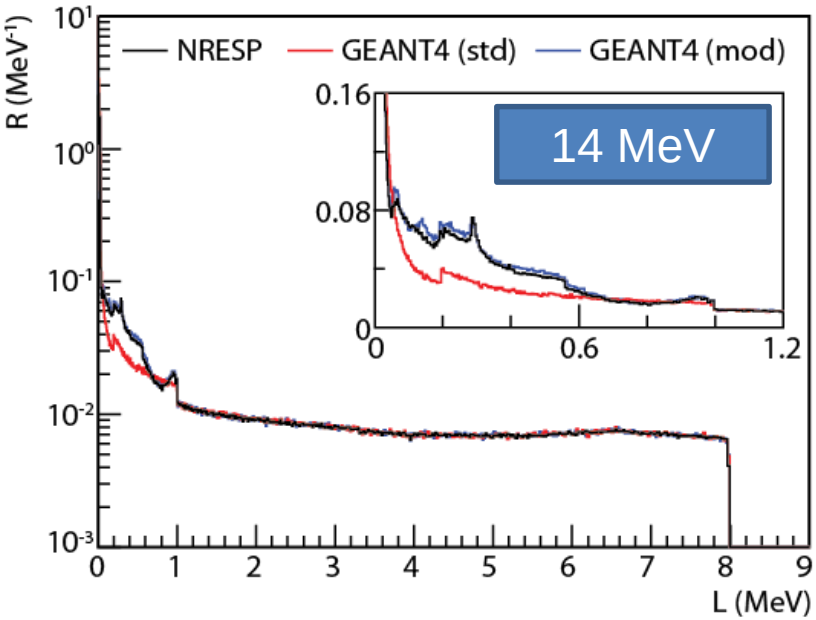
Verification against NRESP

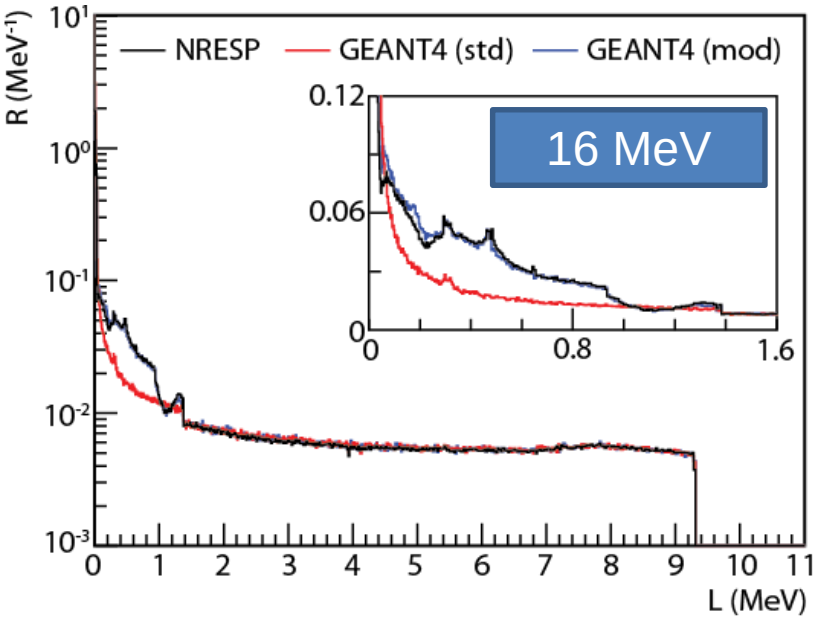
- Threshold for $^{12}C(n,n'3a)$ reactions is 8.81 MeV. So, the effect of using angular distributions for $^{12}C(n,a)^{8}Be$ reaction can be better observed for 8 MeV neutrons.
- Also observed for 10 MeV neutron since cross sections for $^{12}C(n,n'3a)$ reactions are negligible at this energy.

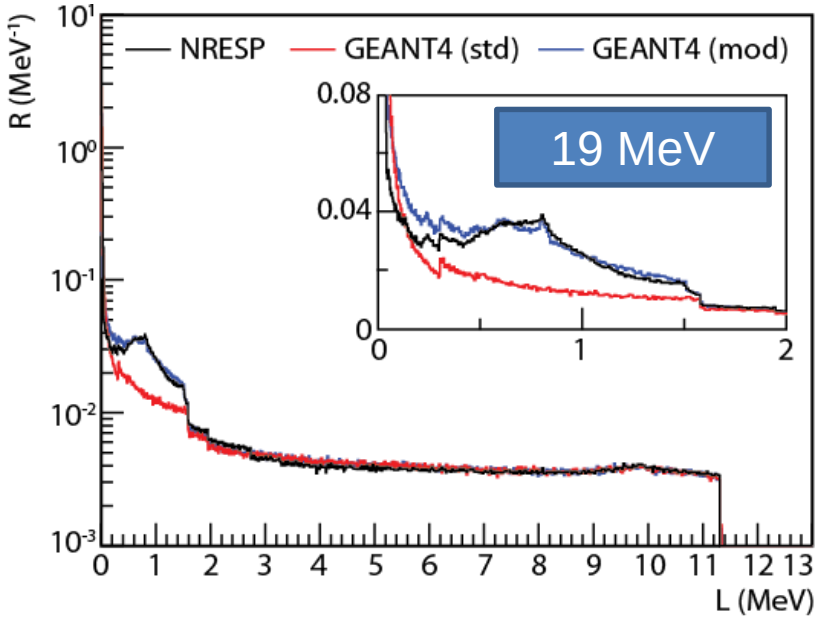












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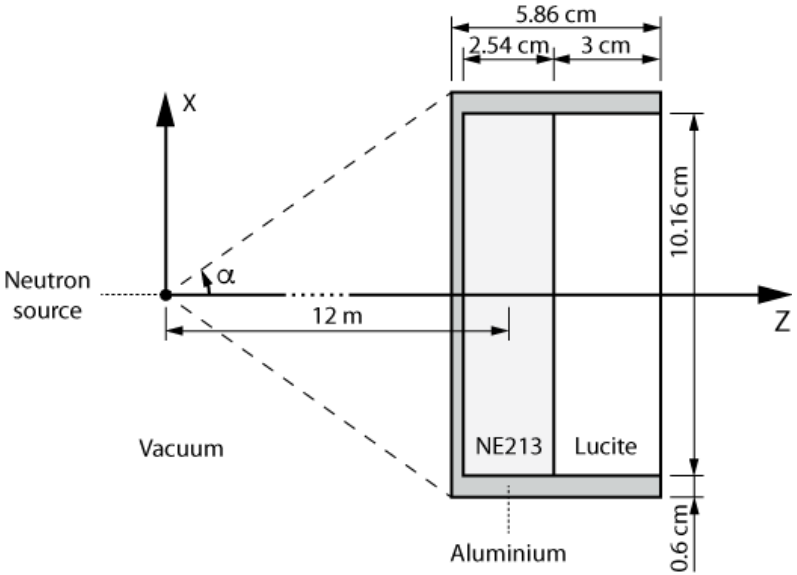
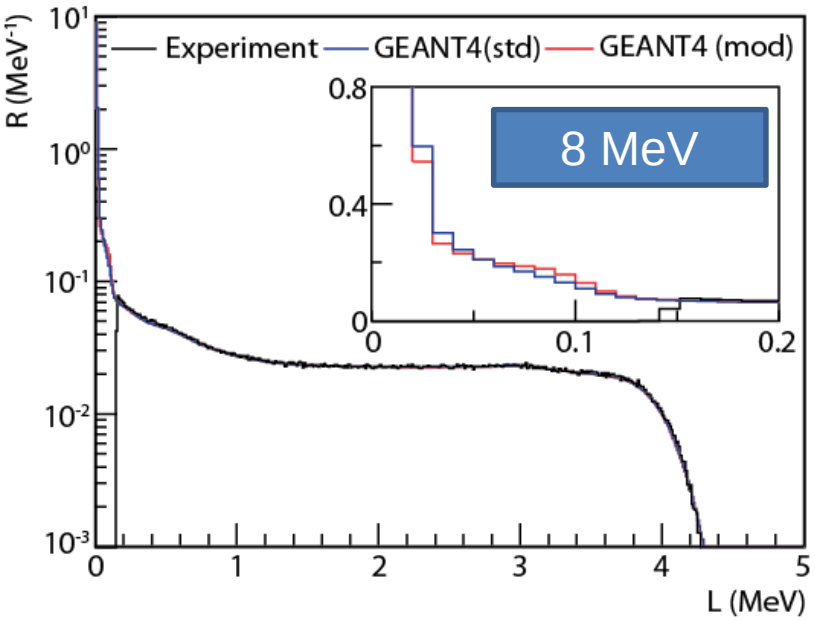
Validation against Time-Of-Flight measurements

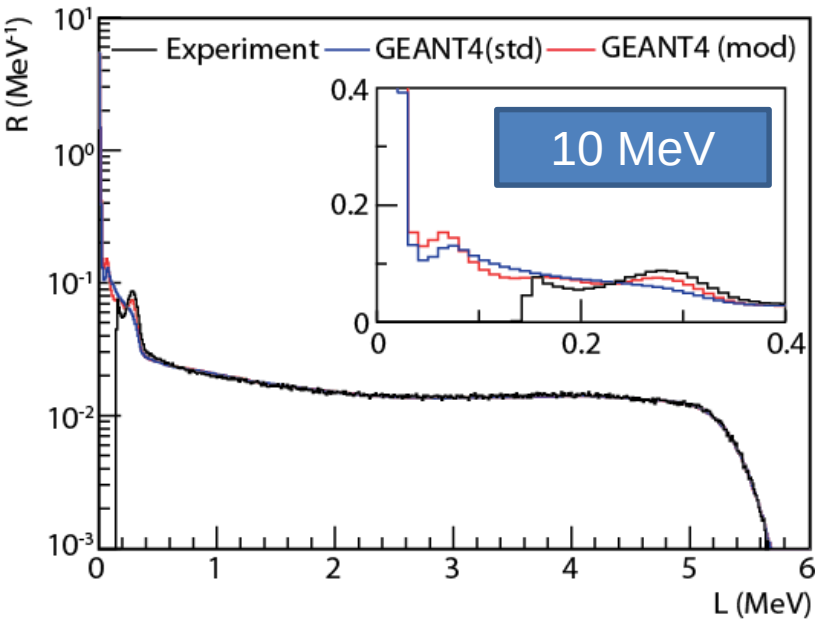
- Time-Of-Flight (TOF) measurements at the PTB Ion Accelerator Facility (PIAF).
- Quasi-monoenergetic neutrons produced by inducing the D(d,n)^{3}He reaction in a gas target with a deuterium beam delivered by the variable energy isochronous cyclotron CV28.

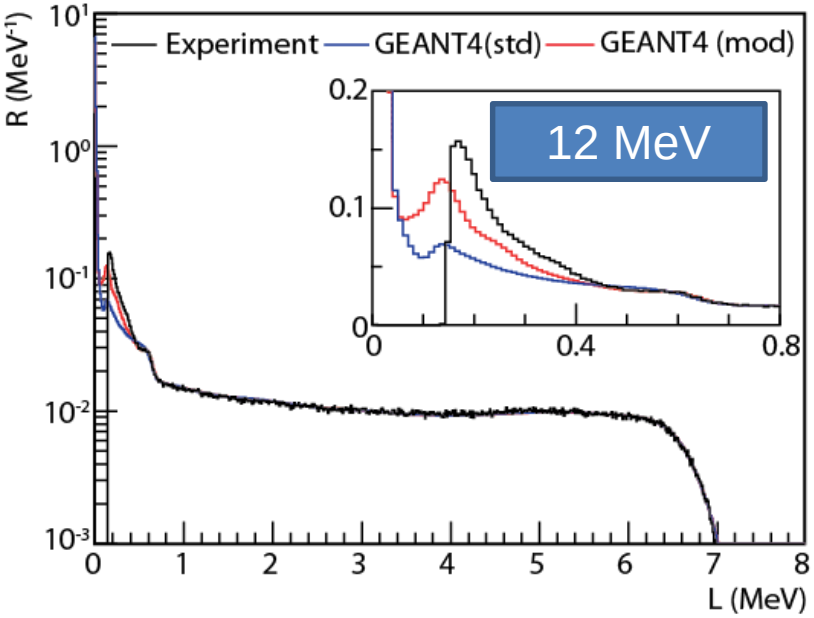


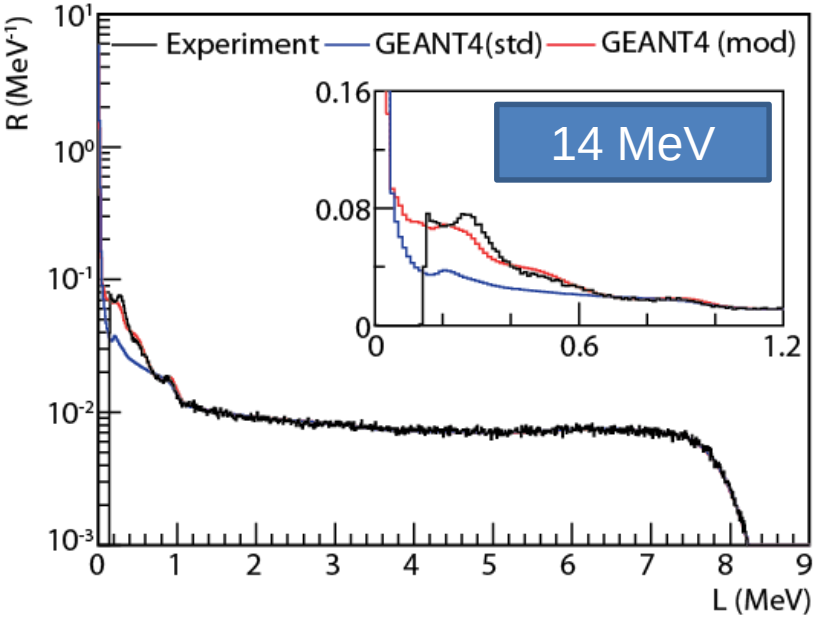
- Gas-in/gas-out measurements and appropriate TOF window.
- Pulse shape analysis performed on each signal from the photomultiplier anode to separate neutron and γ events to produce pulse height spectra.
- Start signal provided by the cyclotron.

(More details in A. R. Garcia et al, NIM A 868, 73–81, 2017)









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How to include it into GEANT4

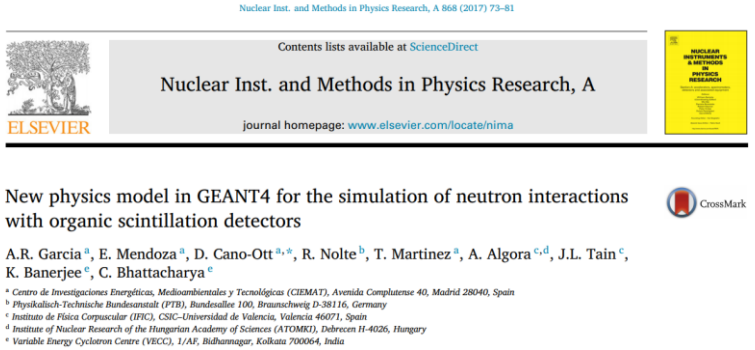
- The model only applies to $^{12}C(n,n'3\alpha)$ reactions, i.e., not a general model for multistep breakup reactions.

```
G4ParticleHPInelasticCompFS::CompositeApply(…)
        {
        …
        Right after sampling the exit channel, insert:

        if ( reaction induced on carbon )
                {
                if ( outgoing particle in the first step is a neutron )
                        {
                        Apply the multistep breakup model for the 12C(n,n'3α) reactions.
                        }
                else if ( outgoing particle in the first step is an alpha particle )
                        {
                        Sample final state using angular distributions for the 12C(n,α)9Be
                        reaction from NRESP ().
                        }
                }
        …
        }
```

Conclusions

- Completed the description of neutron induced alpha production reactions on Carbon in the High Precision neutron model (G4ParticleHP), i.e., angular distributions for $^{12}C(n,\alpha)^{9}Be$ reaction and multistep breakup model for $^{12}C(n,n'3\alpha)$ reactions.
- Results verified against simulations with NRESP and validated against Time-Of-Flight measurements performed at PTB.
- Potential applications of this work extend beyond organic scintillation detectors, to other types of fast neutron detectors where carbon reactions require an accurate description, e.g., diamond detectors.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New physics model in GEANT4 for the simulation of neutron interactions with organic scintillation detectors

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- These and other results (e.g., performance of the modified version of GEANT4 with different evaluated nuclear data libraries) already published.

  (See A. R. Garcia et al, NIM A 868, 73–81, 2017)
- Inclusion in next GEANT4 release already in progress (by Dr. Tatsumi Koi).