# Research project

## Title of the project
GeNIALE - Geant Nuclear Interaction At Low Energy

## Name of the principle investigator
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## Short abstract
A reliable Monte Carlo (MC) code to simulate the interaction of particles with matter is fundamental to a successful physics experiment. Today, Geant4 is one of the most comprehensive and widely used MC packages; however, the physics models currently available in Geant4 fail to reproduce the nuclear fragmentation process below 100MeV/A.
GeNIALE aims at improving the Geant4 performance in this energy domain, through the implementation of a new model for the first stage of the interaction between a hadron -or a nucleus- and a target nucleus. Indeed, hadronic interactions are usually simulated in two different stages: the first one describes the interaction from the collision until the excited nuclear species produced in the collision are in equilibrium, i.e. the excitation energy is shared among all the nucleons; the second one, such as the Fermi break-up, models the emission of such excited, but equilibrated, nuclei. The model will be coupled with the models already implemented in Geant4 for the second stage, and with the Geant4 framework in general.
Improving the description of hadronic interactions in the low-energy domain would be of interest to many physics experiments. A first direct beneficiary will be FOOT, an experiment recently approved by INFN, which will measure the fragmentation of various isotopes on thin targets between 80 and 400 MeV/A: GeNIALE will provide a better simulation tool for FOOT at, and around, the lower end of the explored energy range. In addition, these models are also relevant to simulate the tails of hadronic showers in high-energy physics experiments.
Besides its use in fundamental physics research, a reliable MC simulation in this energy domain is of utmost importance in hadron therapy, where MCs are used to compute the input parameters of the treatment planning software, to validate the deposited dose calculation, to evaluate the biological effectiveness of the radiation, to correlate the β+ emitters production in the patient body with the delivered dose, and to allow a non-invasive treatment verification (e.g., emitted prompt gamma and secondary charged particles).
MC simulation also supports dosimetric and biological experiments: for instance, Geant4 is being extended with processes for the modelling of early biological damage induced by ionizing radiation at the DNA scale (Geant4-DNA).
Finally, simulations for space radiation dosimetry and nuclear spallation sources will greatly benefit from such an improvement in the Geant4 models.

## Scientific background
Geant4 is a comprehensive Monte Carlo (MC) toolkit that describes the passage and the interactions of particles through matter. It covers an extensive range of physics processes, including electromagnetic, hadronic, and optical. Geant4 is the outcome of a worldwide collaboration of physicists and software engineers. It is used in a variety of research fields, including particle physics, nuclear physics, accelerator design, space engineering, and medical physics. Beyond physics, Geant4 usage range from radiation analysis for space applications to biological damage induced by ionizing radiation at the DNA scale.
The successful application of Geant4 in high-energy physics experiments, space and material science domains, as well as in medical physics, is due to the toolkit's structure and openness,

its wealth of physics models and customized configuration, and its open architecture. The feedback from a wide and diverse user community, together with the use of open source, have resulted in the transparency of physics results and have contributed to make Geant4 a mission-critical tool in many domains.

Despite its widespread use, recent literature has shown the limitations of the models implemented in Geant4 in reproducing the measured secondaries yields in ion interactions below 100 MeV/A, in term of production rates, and of angular and energy distributions.

For example:

- Braunn et al. have shown discrepancies up to one order of magnitude in $^{12}C$ fragmentation at 95 MeV/A on thick PMMA target[i], as shown in Fig. 1
- de Napoli et al. showed discrepancy specially on angular distribution of the secondaries emitted in the interaction of on 62 MeV/A $^{12}C$ thin carbon target[ii] , as an example Fig. 2 shows the comparison of the cross section from two Geant4 models and the experimental data
- Dudouet et al. found similar results with a 95 MeV/A $^{12}C$ beam on H, C, O, Al and Ti targets.[iii]

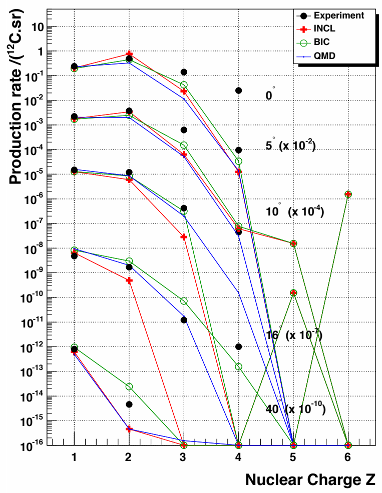


**Fig. 1 Nuclear charge distribution produced in the interaction of a 95 MeV/A $^{12}C$ beam on a 40 mm thick PMMA target. The INCL++ prediction is in red, BIC in green and QMD in blue compared with experimental data (in black). Plot from Braunn et al.**

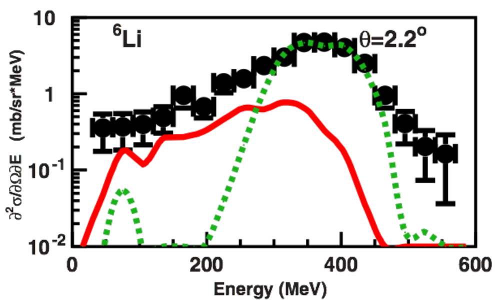


**Fig. 2 Double-differential cross section of the $^{6}Li$ production at 2.2 degree in a $^{12}C$ on $^{12}C$ reaction at 62 MeV/A. The data (black) are compared with BIC (red) and QMD (green). Plot from de Napoli et al.**

Full MC simulations are considered the gold standard for dosimetric calculations in conventional radiotherapy and hadron therapy[iv], hence the high relevance of a reliable MC simulation between few hundreds and few tens of MeV/A.
For instance, MC codes are used in hadron therapy to:

- generate input parameters, such as the depth-dose distribution in water for different ions[v], of the deterministic codes (pencil beam algorithms) for treatment planning in the regular clinical use;
- validate the dose calculation of the pencil beam algorithms, especially in cases with great tissue heterogeneities[vi];
- estimate the risk of secondary cancer induction[vii];
- estimate the production of beta emitters, such as $^{11}C$ and $^{15}O$, which would allow a non-invasive verification of the treatment via Positron Emission Tomography (PET) imaging during, or shortly after, the treatment itself. However, the density of activated isotopes is not directly proportional to the delivered dose, and MCs are used to infer the dose as a function of the measured density of annihilation photons[viii].

MC codes are also used in radiobiology to link the physical dose deposited to the biological effectiveness. Indeed, biological effects are a function not only of the dose but also of the quality of incident radiation: it is believed that sparsely ionizing radiation damages mainly by creating free radicals, predominantly ionizing oxygen[ix], while dense ionizing radiation can cause direct damage to the DNA through high Linear Energy Transfer (LET)[x].

As it can be seen in Fig.3, the typical energy range of hadron therapy is between few hundreds a few tens of MeV/A.

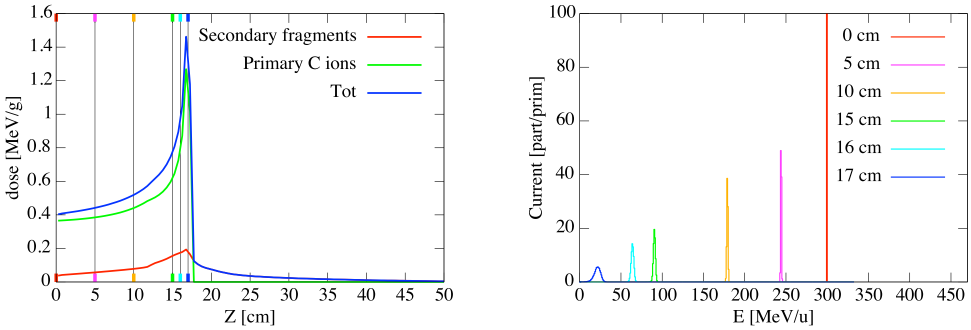


**Fig. 3** The left panel shows the dose deposited by 300 MeV/A $^{12}C$ ions as a function of their penetration in water. In blue the total dose deposited, the green line shows the fraction of the total dose deposited directly by the primary beam particles and the red line shows the dose fraction deposited by secondary fragments. The right panel shows the spectra of the primary 12C at 5 different depths in the target, namely 5, 10, 15, 16 and 17 cm. These depths are indicated in the left panel by the colored lines on the x-axis.

In Fig.3 it is also possible to see the important contribution of secondaries produced in the beam interaction with the patient: in particular, secondaries are responsible of the tail after the Bragg peak.

The radiobiological applications are so many and so relevant, that a dedicated package for the modelling of early biological damage induced by ionizing radiation at the DNA scale (Geant4-DNA)[xi] has been developed.
GeNIALE is complementary to Geant4-DNA, indeed in this package the physical processes implemented are all electromagnetic, while this project will focus on the nuclear fragmentation.

GeNIALE is also complementary to FOOT, a nuclear fragmentation experiment recently approved by INFN. Its main goal is to perform systematic experimental measurements of target fragmentation induced by a proton beam in tissues. The resulting fragments would have a very short range, at maximum of the order of tens of microns, and hence would remain trapped inside the target. FOOT will use an approach based on inverse kinematics to be able to detect the fragments. It will measure the fragmentation cross sections of He, C, O, N, Si and Fe on CH (poliethylene and graphite) targets in the energy range between 80 and 400 MeV/A. For such an approach, a reliable MC simulation is key to success; GeNIALE will develop an enhanced Geant4 simulation that will be essential for FOOT at, and around, its lower energy range.

## State of the art

Total nucleus-nucleus cross sections are calculated in Geant4 with the Glauber-Gribov model[xii], which provides inelastic, elastic, quasi-elastic, and particle production cross-sections for all incident energies above 100 keV/A.
The nuclear interactions are then described in two steps, usually called "entrance channel" and "exit channel". The first step describes the collision, the production of excited nuclear states, their possible pre-equilibrium emission, and the sharing of the energy among the nucleons, process usually called "thermalization". The second step deals with the decays of such excited states after the thermalization. In Geant4 it is possible to choose different models for both interaction phases.

The most important models already available to simulate the entrance channel and the pre-equilibrium stage for the energy domain of interest for this project are:

- **Binary Intra-nuclear Cascade (BIC)**[xiii] This is an extension of the Binary Cascade model[xiv], a model in which primary or secondary particles, usually called "participating" particles, are tracked in the nucleus. The interactions are between them and an individual nucleon of the nucleus, thus the name. The model can be seen as a hybrid between a classical cascade code and a Quantum molecular Dynamics (QMD) model, as the participating particles are described by Gaussian wave functions. The cross sections are the ones for free particles, experimental measurements are used where available. In order to take into account the Pauli exclusion principle, it is assumed that all states below the Fermi energy are occupied; therefore, if a candidate secondary has a momentum below the Fermi momentum, the collision is rejected. The cascade terminates when the average energy is below 15 MeV, or when the maximum energy of secondaries is below 75 MeV.
- **Quantum Molecular Dynamics (QMD)**[xv] Similarly to the BIC model, each nucleon is described by an independent Gaussian wave function. However, in QMD all the nucleons are considered as "participants", and the scattering between participants is included. The time evolution is followed in steps of 1fm/c up to a given time, typically 100 fm/c.
- **Liège Intranuclear Cascade (INCL++)**[xvi] The nucleons are modeled as a free Fermi gas in a static potential well. The radius of the well depends on the nucleon momentum. The particles are assumed to propagate along straight-line trajectories. The algorithm calculates the time at which events will happen, and propagates the particles directly to their positions at that particular point in time. This means that the length of the time step in simulation is not constant. The stopping time is a function of the target nucleus mass. If the projectile is a nucleus, a random impact parameter is sampled and an overlap volume between the two nuclei is calculated accordingly to it. The participants are all the nucleons from projectile and target inside this volume. The participants that traverse the nucleus without undergoing any collision are coalesced

with any existing geometrical spectators to form an excited projectile-like pre-fragment. A particle-hole model generates the excitation energy of the pre-fragment.

As already mentioned, after the thermalization, the particle emission from the excited nuclear species produced in the entrance channel is simulated with the so-called exit channels modes. In this stage, the excitation energy is supposed to be shared among all the nucleons, and the nucleus is described only by its mass, charge, and excitation energy, neglecting the steps that led to its formation. The most relevant models already implemented in Geant4 in the energy domain of interest to GeNIALE are:

- **Evaporation Model.** It is based on the first statistical theory of compound nuclear decay Weisskopf-Ewing[xvii], and it is an application of the balance principle. It associates the probability that a nucleus with *A* nucleons emits one of them, remaining with *A-1* nucleons, to the probability that the produced nucleus, with *A-1* nucleon, captures the nucleon in object. The latter probability is calculated using the energy level density of the evaporating nucleus and an empirical cross section for the inverse reaction. The Geant4 implementation is based on the work of Dostrovsky et al. [xviii]
- **Generalized Evaporation Model (GEM)**. This model uses the same approach of the previous one, but it takes into account the emission of fragments heavier than α particles and uses a more accurate level density function, based on the Fermi gas model, for total decay width instead of the approximation used by Dostrovsky.
- **Fermi Break-up**. This model considers the decay of an excited light ($Z<9$ and $A<17$) nucleus into several stable fragments. The break-up probabilities for each decay channel are calculated by considering the n-body phase space distribution. Such probabilities are then used to sample the decay channel.

As explained in the introduction, these models works well above 100 MeV/A but theiy has shown great limits below such threshold.

## Objectives of the proposal

The goal of GeNIALE is to benchmark and improve the capacity of Geant4 to simulate nuclear fragmentation in the energy range between 10 and 100 MeV/A. Benchmarking will be done using data already published, data measured at the iThemba Laboratories, South Africa, (in the energy range of few tens of MeV/A) and from FOOT, as soon as they will be available (for the range of a hundreds of MeV/A). The core mission of GeNIALE is to implement a new model for the first stage of the interaction of a hadron –or a nucleus- with a target nucleus in Geant4. This goal will be reached through a concerted effort in four Work Packages (WPs):

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***WP 1 – Model selection*** | | | | | | 1.1 | | | | | | | | | | | | | | | | | | |
| ***WP 2- Benchmarks*** | | | | | | 2.1 | | | | | | | | | | | | | | | | | | 2.2 |
| ***WP 3 – Implementation of the new model in G4*** | | | | | | | | | | | | | | | | | | 3.1 | | | | | | |
| ***WP 4 – Data analysis*** | | | | | | | | | | | | | | | | | | 4.1 | | | | | | |
| ***Milestone*** | | | | | | 1.1 | | | | | | | | | | | | 3.1 | | | | | | 2.2 |

**Table 1 Gantt chart with the time line of the WPs. The colors represent the duties of each unit. Yellow for LNS, green for iThemba and blue for Roma1. The numbers in the WPs line are the deliverables. The deliverables considered milestones are indicated also in the dedicated line.**

- **WP1 – Review of the existing models not implemented in Geant4** and estimate of the most suitable one for Geant4, in the energy range of interest.
- **WP2 – Benchmarks.** The WP2 is divided in two phases, in the first one it will be done the benchmark of the models already existing in Geant4 with published data, in the second the benchmark of the new model with the data from iThemba (see WP4) and the first data from FOOT.
- **WP3 – Implementation in Geant4 of the chosen model**.
- **WP4 – Data analysis** analysis of the data from the iThemba laboratories.

A detailed description of each WP, and of the commitments of each participating research unit, is provided in the following section.

The Gantt chart in Table 1 shows the activities of the units. The deliverables and the milestones will be described in the following section.

## Description of the proposed research activity underlying research units description and duties

As mentioned in the previous section, the implementation of GeNIALE will be divided in four Working Packages:

- **WP1 – Review of the existing models not implemented in Geant4** and estimate of the most suitable one for Geant4, in the energy range of interest. In literature, there is an ample variety of models that could be of interest to better reproduce the nuclear interactions below 100 MeV/A.
  Given the work recently done by Quesada and collaborators on the Fermi break-up[xix] and the statement of Dudouet and collaborators[iii] that the entrance channel model characteristics have a larger effect on particles and fragments production as compared to the choice of the exit channel, GeNIALE will focus on the entrance channel models.
  In particular, with respect to the already existing QMD model, it would be important to consider more recent developments, which better preserve the fermionic nature of the nuclear system. We describe below a few selected models, which are possible candidates for our purpose.
  One possible choice could be the **Boltzmann-Uehling-Uhlenbeck (BUU)** model. The approach of this model is to describe the time evolution of the density distribution, instead of the tracking of each nucleon, in a semi-classical approach, i.e. taking into account the Pauli principle.
  It involves the implementation of an effective mean-field nuclear interaction. The model consists of an attractive and a repulsive part, both of which are a function of the density. In such an effective interaction are included the many-bodies correlations. Two-body effects are explicitly treated as nucleon-nucleon collisions. The **Boltzmann-Langevin (BL)**[xx] model is an enhancement of the BUU. It adds some fluctuations in the dynamics treating the nucleon-nucleon collisions as a stochastic process.
  Another possible choice could be a model similar to QMD, such as **Antisymmetrized Molecular Dynamics (AMD)**[xxi] or **Fermionic Molecular Dynamics (FMD)**[xxii]. As QMD, these are stochastic models that try to reproduce the molecular dynamics in the nuclear field. However, the many-body state is represented as an anti-symmetrized product, i.e. Slater determinant, of single particle wave packets, thus ensuring a better description of fermionic systems, with respect to QMD.
  Moreover, owing to the localization of the nucleon wave packet, which is assumed to have a Gaussian shape, these models are able to describe typical clustered structures inside the nuclei, both in the ground state and during the interaction. Such a feature could be crucial for the main fragmentation channel of the $^{12}C$: the fragmentation in

three $^{4}He$[xxiii]. Indeed, a deficiency in the production of $^{4}He$ in the $^{12}C$ fragmentation has been observed in the aforementioned work of Dudouet et al.
We will evaluate, as a first option, the BUU and BL models, given the experience and the work that the LNS theory group -that will support this project- has already done. Indeed, the LNS theory group worked on the implementation of such models and already showed their potentiality in reproducing the fragmentation of nuclei heavier than the ones of interest for GeNIALE, for example in the interaction of $^{129}Xe$ and $^{nat}Sn$[xxiv], $^{155}Gd$ on $^{238}U$[xxv] and Sn on Ni[xxvi]. This project will also give the opportunity to test such models in the same energy region with lighter nuclei.

- **WP2 – Benchmarks** The WP2 is divided in two phases, in the first one it will be done the benchmark of the models already existing in Geant4 with published data, coupling the different models for the entrance and exit channels. In the last semester of the project, will be done the benchmark of the new model with the data already used in the first part of WP2, with the iThemba data (see WP4).
  Thanks to the proximity of the coordinator of FOOT and the participation of some of the unit members to such experiment, as soon as the first FOOT data will be available, they will also be used for the benchmark with the new-implemented model. Indeed, the first FOOT data, taken with nuclear emulsion, are expected to be available within two years.

- **WP3 – Implementation in Geant4 of the chosen model**. The Roma1 unit will work on the implementation of the model that will be found the more appropriate to the description of the nuclear reaction dynamics below 100 MeV/A (see WP1) in Geant4. The implementation of the core of the model in C++ will be done checking the consistency of the new implementation with the original model with the help of the LNS theory group, which has a long-standing tradition in the theoretical description of nuclear collisions at intermediate energy (10-100 MeV/A)
  The good integration of the new entrance channel model in the Geant4 framework, and with the exit channel models in particular will be checked with the help of the LNS unit, given their experience in the development of Geant4
  The interest of the Geant4 collaboration for this work has been already manifested by its responsible for the hadronic interaction, Alberto Ribon.

- **WP4 – Data analysis.** The iThemba laboratories have a long tradition in the measurement of nuclear fragmentation (see next section). They recently acquired data on the fragmentation of $^{12}C$ and $^{14}N$ in the interaction with thin targets of different materials. The targets and all the detectors were in a vacuum chamber. The detector consisted of a telescope made of a first thin (500 μm) silicon detector and a NaI scintillator, which allowed particle identification through the measurement of their energy loss in a thin layer as a function of their energy. To obtain the double differential yields, several runs have been carried out with the telescope placed at various angles, namely 8, 10, 12, 15, 20, 25, 30, 40, 50, 60, 80, 100 and 120 degrees with respect to the beam direction.
  With the $^{12}C$ beam it has been added a second telescope. With respect to the first one, in this one the silicon thin detector was larger and divided in strip. With this setup it had been possible to measure the most relevant break-up channel of $^{12}C$ in this energy range, $^{12}C \rightarrow {}^{8}Be + {}^{4}He$, in an exclusive way. The $^{8}Be$ decays almost immediately in two $^{4}He$, thus only measuring all the three $^{4}He$ in correlation is possible to understand which are coming directly form the break-up of the $^{12}C$ and which from the $^{8}Be$ intermediate state. Such data are of particular interest in benchmarking a model

because they include the energy and the emission angle of all the fragments produced. Moreover, these data could test the capacity of the models to predict the emission of nucleons cluster. The analysis of the latter data sample has already partially done.
The iThemba researchers, in collaboration with the Roma1 unit, will carry out the data analysis. The Roma1 effort will focus on the full development of the MC simulation of the experimental setup.
This data set will enrich the available experimental data, and will allow a better benchmarking of the models already included in Geant4 (see WP2)

GeNIALE will be implemented as a collaboration of three units, two from INFN (one in the Roma1 section and the other one in the Laboratori Nazionali del Sud), and one from the iThemba Laboratories. The project will also be supported by the CERN Geant4 development group.

- **INFN Roma1**
  In recent years, INFN has been supporting a large number projects related to nuclear physics and its applications in various fields. As an example, the experimental programme of FOOT will produce the reference light-ion fragmentation measurements in the coming years. The Roma1 INFN section is deeply involved in FOOT, and GeNIALE would represent a perfect complement to it, as it will improve the Geant4 adherence in the energy range of interest. Below the energy domain investigated by FOOT, GeNIALE will use the data already published in literature as well as those taken at the iThemba Laboratories. The Roma1 unit will participate, in collaboration with the iThemba researchers, in the data analysis and the related MC simulations. The Roma1 unit will work on all the WPs. The PI, together with Prof. Riccardo Faccini, Dr. Elena Solfaroli, and Giacomo Traini, will compose the Roma 1 INFN unit. The PI will work in the WP2, WP3. The WP2 will be done in collaboration with Riccardo Faccini, who will involve a master student for his thesis work. Elena Solfaroli Camillocci will work on the WP4, in collaboration with the iThemba unit, working with Giacomo Traini, being such a topic related with his PhD thesis on the development and test of a dose profiler for hadrontherapy.
  The Full Time Equivalent (FTE) for each member of the unit will be:
    - Carlo Mancini Terracciano 100%
    - Riccardo Faccini 20%
    - Elena Solfaroli Camillocci 20%
    - Giacomo Traini 20%

- **INFN Laboratori Nazionali del Sud (LNS)**
  LNS are one of the four national laboratories of INFN. Their research activity is mainly devoted to the study of structure and properties of atomic nuclei. The Theory group has a long tradition in studying nuclear dynamics, based on the development of suitable transport approaches and microscopic techniques to evaluate the properties of the nuclear interaction in the medium and corresponding effective interactions. They also worked on the development of some of the models cited in the description of the WP1, namely the BUU and BL. Also for this reason, the LNS theory group is interested in the project and will provide support. Moreover, many researchers from LNS are deeply involved in the Geant4 collaboration and have a long experience in the development of applications using the Geant4 framework. Dr. G. A. Pablo Cirrone will be the only member of the unit. He is involved in the Low Energy Electromagnetic and Advanced Examples Geant4 working groups.
  The FTE for the LNS unit are:

- G. A. Pablo Cirrone 15%

- **iThemba Laboratories**
  The iThemba Laboratories are a multidisciplinary facility located near Somerset West in Cape Town, South Africa. This laboratory provides accelerator and ancillary facilities that are used for research and training in nuclear and accelerator physics, radiation biophysics, radiochemical and material sciences, radio nuclide production and radiotherapy. Patients are treated during the day, and between treatments the beam is switched to the radionuclide production vault. Over the weekend, beams of light and heavy ions and of polarized protons are used for nuclear physics experiments.
  The iThemba cyclotron can accelerate proton beams up to 200 MeV. It can also accelerate heavier ions, such as $^{12}C$ and $^{14}N$ to energies up to 33.3 MeV/A. The Nuclear Physics Group at iThemba Laboratories has a long-standing experience in experiments made to measure nuclear fragmentation in the low energy regime. In particular, they took data to study the double differential yields of $^{4}He$ and $^{3}He$ in the interaction of $^{12}C$ and $^{14}N$ with thin targets of several materials. The unit leader for this project will be Dr. Deon Steyn
  The iThemba Laboratories unit will perform the data analysis and will participate, with the Roma1 unit, in the development of the MC simulation to compare the experimental data with the models prediction.
  The FTE for the iThemba unit are:
    - Deon Steyn 25%

## Milestones and timeline for each research Institution

**Month 6 - Milestone 1.1**

The LNS unit will choice the most suitable model for the entrance channel stage of the hadronic interaction for Geant4 in the energy range of interest

**Month 6 – Deliverable 2.1**

The Roma1 unit will benchmark the models already existing in Geant4 with the data published in literature

**Month 18 Milestone 3.1**

The Roma1 unit will implement of the new entrance channel interaction model proposed in the Milestone 1.1 and will integrate it in Geant4. It will be realized also a Physics list that integrates the just implemented model. The good integration with the exit channel models already existing in Geant4 and in general with the Geant4 framework will be checked with the help of the LNS unit and the responsible for the hadronic interaction of the Geant4 collaboration.

**Month 18 Deliverable 4.1**

The iThemba unit, in collaboration with the Roma1 unit, will analyze the data they recently acquired on the fragmentation of $^{12}C$ and $^{14}N$ on different thin targets.

**Month 24 Milestone 4.1**

The new-implemented interaction, with the aforementioned physics list, will be benchmarked with the data used also for the Deliverable 2.1 and with the data analyzed in the Deliverable 4.1. Moreover, as soon as the first FOOT data will be available, they will also be used for the benchmark with the new-implemented model. Indeed, the first FOOT data, taken with nuclear emulsion, are expected to be available within two years.

## Impact (scientific, technological, socioeconomic)

As already mentioned, all experiments that use Geant4 for their MC simulation will in some way benefit from GeNIALE: while experiments at low energies will benefit directly, it must not be forgotten that low-energy nuclear simulation are also used by high-energy experiments, to simulate the ending part of the hadronic showers.
In the very short term, the FOOT experiment will take full advantage of this work, as it will acquire nuclear fragmentation data in the energy range 80 – 400 MeV/A on thin targets and it will have a MC more reliable to perform a data-MC comparison at, and around, the lower end of the explored energy range.

Initially developed to address the numerous high-energy requirements of the LHC experiments, Geant4 is today adopted also by thousands of users worldwide for application in domains beyond high-energy physics. For instance, one of the fields that will more benefit from this project is hadrontherapy.
Indeed reliable nuclear reaction models in MC code are needed for:

- a better evaluation of the ratio of the dose deposited in the entrance channel and in the Bragg peak;
- the evaluation of the broadening of the dose deposition due to the secondary production, responsible of the tail after the Bragg peak. This evaluation is of utmost importance if an organ exceptionally sensible to radiation, and the considered at risk, is after the tumor lesion.
- a better evaluation of the biological effectiveness and the prediction of secondary cancer risk of the deposited dose, as it depends on the ion species that deposited the dose.

The importance of MC simulation in this field is evident from the large number of simulation packages based on Geant4 and tailored for hadrontherapy. Among these, the most widely used are probably TOPAS[xxvii] and GATE[xxviii], which will both profit from an improved description of the nuclear reactions.

As detailed in an ESA (European Space Agency) report presented at the Geant4 Space Users Workshop in Hiroshima in August 2015, software packages based on Geant4 have been extensively used in past, recent and future ESA missions, leading to the development of radiation engineering tools and models.
Geant4 is being used to study the radiation environment on the ISS, as well as radiation aspects on possible future manned space missions to the Moon or Mars. In this framework, the most recent developments related to the simulation of DNA damage from radiation are especially relevant, and are included in the latest Geant4 release (10.2, from December 2015). This very low-energy extension (Geant4-DNA) now offers the possibility to model physical, physicochemical, and chemical processes up to the microsecond scale, therefore allowing for the simulation of early biological effects induced by ionizing radiation at the subcellular scale. However all these upgrades need another effort to improve the description of the nuclear fragmentation, especially in the low-energy domain, which is the purpose of GeNIALE.

GeNIALE will also seed future projects aimed at improving the accuracy of the implementation of physical processes in Geant4. Moreover, GeNIALE could also strengthen international collaborations for joint experimental projects to measure the nuclear fragmentations below 100 MeV/A, involving two of the research centers with the highest expertise in the field (LNS and iThemba). To benchmark the MC models could be very useful to have exclusive data (as the one available for this project on $^{12}C$), while most part of available data in the literature describe the inclusive productions of nuclear species.

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