BambooMC – A Geant4-based simulation program for the PandaX experiments

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\textbf{ABSTRACT:} The purpose of the PandaX experiments is to search for the possible events resulted from dark matter particles, neutrinoless double beta decay or other rare processes with xenon detectors. Understanding the energy depositions from backgrounds or calibration sources in these detectors is very important. The program of BambooMC is created to perform the Geant4-based Monte Carlo simulation, providing reference information for the experiments. We introduce the design and features of BambooMC in this report. The running of the program depends on a configuration file, which combines different detectors, event generators, physics lists and analysis packs together in one simulation. The program can be easily extended and applied to other experiments.

\textbf{KEYWORDS:} Simulation methods and programs, Software architectures

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1 Introduction

The early stages of the PandaX experiments located in the China Jinping underground laboratory (CJPL) [1], namely PandaX-I [2] and PandaX-II [3], are designed to search for the dark matter in the local halo with dual-phase xenon time projection chambers (TPCs). The physics goals are extended to search for the coherent elastic scattering of solar neutrinos, neutrinoless double beta decay...
(NLDBD) of $^{136}$Xe and other rare events in the current stage, PandaX-4T [4]. Another detector, called PandaX-III, equipped with a high pressure TPC with enriched gaseous $^{136}$Xe to search for the NLDBD, is under construction [5]. One key problem of the experiments is to understand the background level caused by material radioactivity in the energy region of interest (ROI), as well as their spatial distribution. It could only be answered with the Geant4-based [6, 7] full simulation together with radioactivity levels given by material screening [8]. Another key problem is to understand the various distributions resulted from the calibration sources. The program of BambooMC is created to perform the Monte Carlo (MC) simulation for different types of detectors in PandaX experiments. It is designed in a modular architecture, in which the different geometry descriptions of the detector, physics lists, event generators and data analysis codes can be combined as required with a configuration file provided by the user. The program has been used in the different simulation tasks in the PandaX experiments, such as the background estimation of the PandaX-I, PandaX-II, PandaX-4T detectors as well as in the early stage design of the PandaX-III detector. It is also used in the development of a new method to estimate the neutron background in dark matter search [9].

In this report, we give a detailed description of the features and application of BambooMC. In section 2, we give an overview of the program, including the usage and modules. In section 3, the core features provided by the BambooCore are described. Then we introduce the specialized features for PandaX and other low background experiments in section 6. The extensibility of BambooMC and the possible usage in other experiments as a starter toolkit is discussed in section 5. Selected application of the BambooMC program in the PandaX experiments are presented in section 6. Finally, a brief summary and conclusion is given in section 7.

2 Overview of BambooMC

The main purpose of BambooMC is to perform Geant4-based MC simulation with the help of an input configuration file. It can also be used to export the detector geometry to a GDML (Geometry Description Markup Language) file when a special command line option of “-g” is provided. Such feature is convenient for the visualization of the detector geometry in other applications together with the output data, such as the ROOT analysis framework [10]. The typical usages of BambooMC are given in Appendix A. In any cases, the configuration file must be provided.

2.1 The configuration file

The configuration file is specified by the command line option of “-c”. The file content can be organized in the format of XML, JSON or YAML. \(^1\)

The following information may be presented in the top level entries in the configuration file:

- the run number (optional);
- the geometrical information, which includes sub level entries about the possible global geometrical parameters, materials, combination of detectors and related parameters;

\(^1\)XML is a type of markup language, see https://www.w3.org/XML/. JSON is a data-interchange format, see https://www.json.org. YAML is a human-friendly language for data serialization, see https://yaml.org.
• the physics list, with name and possible parameters;
• the event generator, with name and possible parameters;
• the analysis package, with name and possible parameters.

An exemplary configuration file in the YAML format is presented in Appendix B. The run number is set to be 1234. The final geometry consists of four “detector”s and a material construction. The “detector”s are organized in a hierarchical manner using the key of “parent”. The definition of the keys will be explained in section 3.1. The physics list of “PandaXPhysics” and the generator of “SimpleGPSGenerator” are used. The analysis pack “PandaXAnalysis” with 7 parameters, is used to control the output and some internal behaviors of the program. Detailed description of these parts will be given in following sections.

More examples of the configuration file can be found in the “config” directory in the public repository.

2.2 Modules

With the configuration file, different detector geometries, physics lists, event generators and analysis modules can be combined to perform different simulation tasks with a single BambooMC executable.

The publicly released program consists of 4 modules, as shown in Figure 1.

1. The BambooCore module provides the BambooControl class to parse the configuration file and store the different parameters. Different types of objects can be created using the so called “factory” design pattern with 5 different “Factory” classes.

2. The PandaXMC module defines physics lists, event generators and one analysis pack used in the PandaX experiments. The module is built on top of the corresponding 3 “Factory” classes.

3. The UserMC module gives the additional physics lists, event generators and analysis packs. It is left for users to extend it with new requirements besides the default ones. It has similar dependency as that of the PandaXMC module, but the source files are placed in a different directory.

4. The UserDetector module provides detector definition. It is built on top of the BambooDetectorFactory and the BambooMaterialFactory class.

During the compilation, the UserDetector and UserMC modules can be customized with the “-D” option of CMake, a tool for build automation.

2.3 The main() function

The main() function defines the workflow of the program. It creates an object of the BambooControl class first, and use it to parse the command line options and arguments. The supported options and arguments are given in Appendix A. The provided configuration file will be loaded and validated during the process. An object of the “G4UIExecutive” class will be created if the “-i” option is given, which means the program will be executed in the interactive mode. An instance of the
“G4RunManager” will be created then. It initializes the detector and physics list through the BambooControl object. The BambooControl object will create the generator and analysis pack, which includes the possible definitions of sensitive detector and hits, manager of output data, and the objects of “UserAction”s. The “G4RunManager” instance registers the generator and the created “UserAction” objects, and performs initialization thereafter. If the “-g” option is provided together with an output file name, the main() function will dump the geometrical description of the detector to a GDML file and exit. In other cases, the visualization manager will be created and initialized. The provided macro file will be parsed by the UI manager of Geant4. Finally, the program will either start the simulation with the number of events provided by the command line option in the batch mode, or start an interactive session in the interactive mode.

3 Main features of BambooCore

The BambooCore module provides general functionalities, which can be used in different experiments.

3.1 Dynamic geometry construction

The idea of dynamic geometry construction in Geant4 application has been implemented in many different projects, such as Mokka[11] and CLAS12[12]. These packages choose to use external database to store the geometry information and parameters, increasing the complexity of the deployment and limited their usage.
The BambooCore module provides a more simple and straightforward way to define and load the different components of a detector dynamically. Each component inherited from the BambooDetector class might provide a “container” logical volume as a container for possible daughter volume. The top-level volumes created in a component, except for the world volume, should be placed in its parent's container volume. Different components are loosely coupled and the configuration file defines the “real” detector hierarchy in one simulation. A simplified example is given in Listing 1. Each component needs to provide a type, which is the class name of the component, and a name, which should be unique among the provided names in the same configuration file. Non-world component should provide the name of its parent. One and only one world component is required in a valid configuration file. A component could appear multiple times in the configuration file, with different names. In this case, user should be careful with the parameters provided to these components to avoid possible overlapping between volumes.

```
detectors:
  - type: SampleWorld
    name: World
  - type: SampleWater
    name: WaterShield
    parent: World
  - type: SampleSteelContainer
    name: Container
    parent: WaterShield
```

Listing 1: Example of detector hierarchy in a configuration file of YAML format.

The PandaX experiments benefited from this feature greatly. For example, the PandaX-I and PandaX-II experiments share the same passive shielding structure, so the geometrical construction codes for the shielding can be used in both of the simulations directly. The codes for the water shielding in CJPL-II are also shared by different purpose of simulation tasks with different detector constructions, such as the study of the shielding power and the background contributed from radon resolved in the water for the PandaX-4T experiment.

### 3.2 Generic parameterization system

BambooMC provides a convenient way for users to customize the program behavior through its generic parameterization system. Users can provide parameters in the configuration file for the selected detectors, generator, physics list and analysis package. Functions to storage and fetching parameters in the string and arithmetic types, like int and double, are implemented in the class BambooParameters. Special parameter values with simple units provided, like “5.0*m”, can be parsed with the “evaluateParameter()” function.

The most important usage of the generic parameterization system is to customize the detector construction in combination with the dynamical geometry construction feature. In the PandaX experiments, such features are heavily used in the MC simulation on the understanding of material screening results. Due to the fact that counting samples have different materials, shape and geometrical parameters, the general geometry construction codes of the samples are created, leaving the user to provide the shape, material and related parameters in the configuration file.
3.3 Dynamical loading of modular physics list

In BambooMC, different modular physics lists can be loaded in different simulations. A specific physics list is loaded through the name provided in the configuration file. BambooMC provides an abstract class of “BambooPhysics”, which is inherited from “G4VModularPhysicsList”, to support the dynamical loading. The name of its concrete daughter class created by users can be used in the configuration file. The pre-packaged reference modular physics lists provided by Geant4 can also be used directly by name, such as “FTFP_BERT” for the simulation of high energy physics. This feature enables BambooMC to be used easily in experiments other than PandaX.

4 The PandaXMC module

Now we introduce the specialized features by the PandaXMC module according to the requirements of the PandaX experiments.

4.1 Physics lists for PandaX

The energy ROI of PandaX experiments ranges from sub-keV to a few MeV level. In the corresponding MC, the background events are mainly from the decay of radioactive isotopes, resulting in different processes with the similar range of energies inside the sensitive region of the detector. The construction of the default physics list for PandaX experiments, PandaXPhysics, is based on the following consideration.

First of all, the radioactive decay of isotopes need to be included. That is been done by registering the G4RadioactiveDecayPhysics. The decay of other possible particles, such as muons, is included by registering the G4DecayPhysics.

For the electromagnetic physics, the “Livermore” implementation (G4EmLivermorePhysics) in Geant4 is chosen, together with the G4EmExtraPhysics class, which provides processes related to synchro-radiation of charged particles.

To simulate the elastic scattering of hadrons, mostly of the neutrons, G4HadronElasticPhysicsHP is used. The inelastic and capture processes of neutrons are provided by G4HadronPhysicsShielding. G4StoppingPhysics is employed for the possible nuclear capture of negative charged particles or neural anti-hadrons.

Finally, the class of G4IonQMDPhysics is selected as part of the physics list, though it may not be used in PandaX simulation.

This physics list is very similar to the pre-packaged modular physics list of “Shielding” provided by Geant4.

Another physics list, PandaXOpticalPhysics, is created on top of PandaXPhysics, adding the support of G4OpticalPhysics and enabling the creation of Čerenkov and scintillation photons. This list is used to study the distribution of detected scintillation photons for position reconstruction.

4.2 Event generators

In the PandaX experiments, the majority of the simulation tasks are focusing on the background contribution from the radioactive isotopes in detector materials. These tasks can be done by placing the ions inside the volume of different part of the detector, and leaving Geant4 do the rest of works
with selected physics lists. We created a simple wrapper called SimpleGPSGenerator around the Geant4 general particle source (GPS, implemented in the class of “G4GeneralParticleSource”) to accomplish the function. The type and spatial distribution of the source ions can be configured easily by commands supported by GPS. These commands should be placed in the traditional macro file supported by Geant4, which will be feed to BambooMC using the command line option of “-m”.

Additionally, another generator called “HEPEvtLoader”, which uses the Geant4 interface to read the HEPEvt format, is created. The generator can be used in the simulation of collider physics, by reading the output from generator programs like PYTHIA [13].

4.3 Output data
The output data by the PandaXMC is organized as the ROOT TTree data format so that it could be analyzed easily.

By default, the run number and event number are saved in every entry of the output data. The other variables can be customized in the configuration file inside the block of “PandaXAnalysis”.

Two types of sensitive detectors have been defined in PandaXMC. The first one is used to record the energy deposition of each steps (hits) inside the sensitive volume. This information is necessary in most of the simulation tasks to study the background of the PandaX detector. The related variables in the output data includes:

- total energy deposited in the volume;
- number of hits;
- id number and particle type of each hit;
- id number and name of the parent particle of each hit;
- name of the physical process of creation and energy deposition for each hit;
- position and time of each hit.

Another type of sensitive detector is used to record the information of particle (especially, the gamma) passing through the surface of a given volume. The output information can be used as input of other simulations. For example, the stopping effect of the high purity water shielding system to environment gamma is obtained by the simulations combining the sensitive detector together with the variant-size water box. The variables in the output data includes:

- number of tracks;
- name and parent name of each track (particle);
- energy and momentum of each track;
- position and time of each track.
The output of above two types of data can be controlled by the parameters of “EnableEnergyDeposition” and “EnableSurfaceFlux” in the configuration file.

Besides the data generated during the simulation, the information of the input particles, i.e., the primary particles, can be saved in the output file by set the value of “EnablePrimaryParticle” to be 1. The related variables include the type, energy, momentum and initial position of the particle. By default, when no energy deposition or track is caught by the activated sensitive detectors in an event, the event will not be saved in the output data. The “empty” event can be forced to be save by set the parameter of “SaveNullEvents” to be 1.

The random seed for each events is also saved in the output file. This variable is useful for debugging. User can repeat the simulation of a single event by assigning the seed to the parameter of “UserSeed” in the configuration file.

4.4 Breaking up of long decay chain

Some radioactive isotopes, such as the $^{238}$U and $^{232}$Th, have a long decay chain and long half-life time at the order of billion years. To study the background contribution from these isotopes, the corresponding ion is used as the primary particle in the simulation. Geant4 will not stop the simulation of an event until the primary ion and all its descendant particles get into the special “stop” states, such as “disappeared”, “out of world”, or being killed explicitly by user actions. One entry in the output data may contain the contribution not only from the input isotope, but also from all its descendants, spanning billions of years. Due to the fact the detectors record event in a very short time window, the simulation data could not be used directly. One straightforward solution is to use the timestamp of each step as the reference of each “reality” collisions. But the internal type of time in Geant4 simulation is in “double”, which is not precise enough for a variable ranging across more than 15 orders of magnitudes. Another solution is to “kill” the radioactive descendant particle in the simulation explicitly in the user tracking action. This means to study the contributions from one isotope and its descendants, one need to perform simulation for each isotope on the decay chain, with greatly increasing work loads and complexity.

The PandaXMC module provides a mechanism to break up the long decay chain based on the daughter nuclei and store them in different entries in the output data. This can be controlled in the configuration file by setting the value of parameter “EnableDecayChainSplitting” to be 1 in the block of “PandaXAnalysis”. Once a radioactive ion is found to be in the “stop but alive” state, with zero kinematic energy, it might be put into the internal particle stack, with time reset to 0. After tracking of all other particles, the existing hits information will be extracted and written to the output file as one entry. Then the tracking of the stacked ion will start again. The procedures will be repeated until no radioactive particle would be produced. The hits generated by radioactive isotopes with small half life, such as $^{214}$Po ($\tau = 164.3\,\mu s$), may be saved together with those from its parent isotope. This can be customized by setting a half life threshold for the short-lived isotopes with the parameter of “ChainSplittingLifeTime”, which default value is 300$\mu s$. Isotopes with a decay half life smaller than the threshold will not be separated from their parent. This feature is important to study the special events like the successive decays of $^{214}$Bi-$^{214}$Po. This treatment also works for the radioactive nuclei generated in the process of neutron capture. Figure 2 gives the distributions of primary particles in the cases of decay of $^{222}$Rn and neutron scattering, by enabling the breaking up of long decay chains.
**Figure 2**: The distributions of primary particles in the simulation by enabling the breaking up of long decay chains. Left: Decay of $^{222}\text{Rn}$ resolved uniformly in the xenon target, 10,000 events; Right: neutrons of 2.5 MeV pass through a shell of stainless steel and hit the xenon target, 100,000 events.

5 Extensibility

BambooMC can be extended easily without modifying the structure of the program, making it useful to be reused in different experiments.

5.1 Sets and adding classes

BambooMC uses the concepts of detector/MC sets to accomplish the tasks of extending the geometry (physics, generator and analysis), and the newly created source files will be compiled into the UserDetector and UserMC modules. A set is a collection of related source files, and will only be compiled after it is enabled explicitly during the configuration step with options of “ENABLE_DETECTOR_SETS” and “ENABLE_USER_MC”. The definition of detectors and materials should be placed in a detector set, and the definition for event generator, physics and analysis packs should be placed in a MC sets. Multiple detector/MC sets can be enabled simultaneously with comma separation. Two detector sets (example and optical_example) and one MC set (pandax) are shipped with the source code, within the “user” directory. To enable these sets, one can configure the compilation with following command, assuming that “..” is the root of the BambooMC source tree:

```
cmake -DENABLE_DETECTOR_SETS=example,optial_example \ 
   -DENABLE_USER_MC=pandax ..
```

BambooMC also provides three scripts to help the generation of extended codes. These functions and the usage of the scripts are given below.

- **add_detector.pl**: to generate the definition of a sub-class of “BambooDetector” in a given detector set. The set name and the class name should be provided.

- **add_material.pl**: to generate the definition of a sub-class of “BambooMaterial” in a given detector set. The set name and the class name should be provided.
• add_mc_class.pl: to generate the definition of a sub-class of either “BambooGenerator”, “BambooPhysics” or “BambooAnalysis” in a given MC set. The set name, type of class and the class name should be provided.

The scripts will generate the class definitions, with codes related to the factory method in the source files so that they can be used in the configuration file. The scripts will also add CMake rules to compile the created source files.

5.2 The pandax set in UserMC

Besides the generators, physics list and analysis package in the PandaXMC module, following functionalities are provided in the pandax set within UserMC.

An event generator called “EventLoader” is provided to read the modified output of the Decay0 package [14], which contains information of electrons generated in double beta decay events, and create electrons as primary particles in the simulation. User can specify the shape of the spatial distribution of the electrons and confine them in given physical volumes. The generator is useful when studying the signals from the rare double beta decay events.

Some simulation tasks in the PandaX experiments require the simulation of optical photons. The detection of photon and output of the photon information, including the position, time, energy, and creation process, is packed in the PandaXOpticalAnalysis.

5.3 BambooMC as a starter toolkit

BambooMC is widely used in the different tasks in the PandaX experiments, with different combination of geometric definitions, generators, physics lists and analysis packs. Actually, the features provided by BambooMC makes it to be an ideal starter toolkit for different particle experiments.

For example, in the early design stage of an experiment, only simple events with a single type of particle are required. So the SimpleGPSGenerator can work. The optimization of the final detector always includes the frequent updating of the size of different components of the detector. User can create class for each of the components, use free parameters to control their properties, and combine them in the configuration file. By updating the configuration file, different detector concepts can be simulated and tested. Most of the underground experiments can use the PandaXPhysics directly as their default physics list. The collider experiments can select one of the pre-packaged physics lists provided by Geant4. In most of the experiments, information of energy deposition is the only required output data from the Geant4 MC simulation, thus the output from the PandaXAnalysis can be used. By using of BambooMC as the starter toolkit, a lot of repeated work can be avoided.

6 Selected applications in the PandaX experiments

BambooMC is widely used in the PandaX experiments for different purpose, including the calculation of the detection efficiency of the counting stations, estimation of the background contribution from the detector materials in various PandaX detectors, study of event distributions of different calibration sources, and the correlated production of high energy gammas and neutrons in detector materials. Since the background estimation results and the comparison with calibration data have been described in other publications [4, 5, 15, 16], we only introduce how the BambooMC program
is used in the estimation of detection efficiency for the counting stations and the improvement of neutron event generator.

### 6.1 Detection efficiency of the counting station

Two high purity germanium (HPGe) counting stations for the material screening of PandaX are operational in CJPL currently. A detailed introduction to the station equipped with an Ortec GEMMX HPGe detector (GEMMX) is presented in Ref. [8]. Another station equipped with a Canberra BE3830 HPGe detector (BE3830), was firstly set up in the Minhang campus of Shanghai Jiao Tong University [17], and was delivered to CJPL in 2019. Both stations have a similar structure, with a passive shield constructed with lead and copper. The HPGe detector is placed inside a chamber enclosed by the shield and cooled by liquid nitrogen with a specially designed cold finger. Samples to be screened are placed on top of the detector inside the chamber. The HPGe detector measures the energy spectrum of a sample. By subtracting the background spectrum without samples, the characteristic gamma energy peaks resulted from the radioactive isotopes in the sample can be recognized. The event number within a specified peak can be used to estimate the activity of the corresponding nuclei by considering the time of screening and the detection efficiency.

Due to the fact that different samples have different shapes and materials, the detection efficiency can only be estimated with the MC simulation. The works are carried out with BambooMC. The default physics list of *PandaXPhysics*, the generator of *SimpleGPSGenerator*, and the analysis package of *PandaXAnalysis* are used in the simulation. A detector set of “counting” is created for the geometric description of the stations and samples. Two classes of *CSGEMMXDetector* and *CSBEDetector* are created for the two stations GEMMX and BE3830, respectively. Container logical volumes are provided by the classes so that the geometric description of different samples can be placed in. The simulated geometry of the BE3830 station with a sample is shown in Figure 3. For the samples with regular shapes, several classes are created, with material names and geometric parameters dynamically loaded from the configuration files. The dynamic geometry construction feature of BambooMC simplified the simulation works for the sample counting in PandaX. A standard water resolved source of $^{60}$Co and $^{137}$Cs with known activities is used to validate the simulation results [8, 17]. The relative difference between the detection efficiencies obtained from simulation and measurement is smaller than 5%, and is accounted as one of the systematic errors.

### 6.2 Improved neutron generator for dark matter search

In the liquid xenon detectors, single scattering nuclear recoil events generated by neutron can not be distinguished from those generated by the weakly interactive massive particles (WIMPs). Thus the precision estimation of neutron backgrounds is critical for these experiments. The main sources of neutron are from the $(a,n)$ reactions and spontaneous fission of radioactive nuclei in the detector materials.

In the conventional treatment, the package of a modified SOURCES-4A [18, 19], which can calculate the rate and energy spectrum of neutrons for given radioactive nuclei in given type of materials, is served as the neutron generator in subsequent simulations. But the correlated production of neutrons and gammas are not considered in this approach, leading to the over-
Figure 3: Simulated geometry of the BE3830 station, with a sample on the top edge of the cylinder shaped HPGe detector, which is placed in the chamber enclosed by the shield of lead (grey) and copper (brown). A zoom-in view of the sample is shown in the top right.

estimation of neutron background. An improved approach to estimate the neutron background is developed for the PandaX-II experiment [9, 20], using the BambooMC program.

The new approach employs Geant4 to perform the simulation of the \((\alpha, n)\) and spontaneous fission processes of radioactive nuclei in different materials, and uses the output from the simulation as the input of rest simulations. For example, to study the neutron produced resulted from \(^{238}\text{U}\) in the polytetrafluoroethylene (PTFE), a simple geometry of a small PTFE sphere, with a radius of 0.1 mm, is created, and \(^{238}\text{U}\) sources are sampled in the center of the sphere, using the SimpleGPSGenerator. Then the information of neutron and gamma tracks passing through the surface of the sphere is recorded by the PandaXAnalysis. A modified version of the PandaXPhysics, which uses the Liège cascade model INCL++ [21] to modeling the \((\alpha, n)\) process, is used in the BambooMC simulation, with the ABLA evaporation model enabled [22]. By assuming the activity of \(^{238}\text{U}\) is 1 mBq/kg inside the PTFE and the secular equilibrium of the \(^{238}\text{U}\) decay chain, the neutron production rate from the Geant4 simulation (version 10.04p02) is \(7.00 \times 10^{-11} \text{ s}^{-1} \cdot \text{cm}^{-3}\), which is at the same order of the calculation of \(1.37 \times 10^{-10} \text{ s}^{-1} \cdot \text{cm}^{-3}\) from SOURCES-4A. The detailed comparison of the fraction of neutron contributors and the neutron energy spectra are shown in Fig 4, with all the spectra normalized to those from SOURCES-4A. The neutron properties from the two approaches are consistent with each other.

In the PandaX experiments, different simulations with the \(^{238}\text{U}, ^{235}\text{U}, \) and \(^{232}\text{Th}\) chains in different materials are carried out using BambooMC. The correlated information of the neutrons and gammas in the output files are extracted out, and used as primary particles in the subsequent detector simulations, to provide a more realistic estimation of the neutron background.
Figure 4: Comparison of neutron production of the \(^{238}\text{U}\) chain in PTFE, using the simulation of Geant4 and the SOURCES-4A calculation.

7 Summary and Conclusion

We have developed a modular simulation framework, BambooMC, based on the widely used Geant4 toolkit, for the PandaX experiments. It has been used in many simulation tasks to study the background contribution, signal properties, or other aspects in these experiments. The generic parameterization system of the program provides a new way to customize the behavior of the simulation. User can freely change the simulation without rebuilding the program. The design of the program enables it to be extended easily and to be used in other types of experiments.

The current version of BambooMC is 2.0, which can be found in the online GitHub repository of https://github.com/pandax-experiments/BambooMC. The program is delivered under GUN Public License version 3. We hope it could benefit the community of particle experiments by reducing the possible repeat works.

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References

[1] Y.-C. Wu et al., Measurement of Cosmic Ray Flux in China JinPing underground Laboratory, Chin. Phys. C37 (2013) 086001 [1305.0899].
References:

[2] PandaX collaboration, *PandaX: A Liquid Xenon Dark Matter Experiment at CJPL*, *Sci. China Phys. Mech. Astron.* **57** (2014) 1476 [1405.2882].

[3] PandaX collaboration, *Dark Matter Search Results from the Commissioning Run of PandaX-II*, *Phys. Rev.* **D93** (2016) 122009 [1602.06563].

[4] PandaX collaboration, *Dark matter direct search sensitivity of the PandaX-4T experiment*, *Sci. China Phys. Mech. Astron.* **62** (2019) 31011 [1806.02229].

[5] X. Chen et al., *PandaX-III: Searching for neutrinoless double beta decay with high pressure$^{136}$Xe gas time projection chambers*, *Sci. China Phys. Mech. Astron.* **60** (2017) 061011 [1610.08883].

[6] GEANT4 collaboration, *GEANT4: A Simulation toolkit*, *Nucl. Instrum. Meth.* **A506** (2003) 250.

[7] J. Allison et al., *Geant4 developments and applications*, *IEEE Trans. Nucl. Sci.* **53** (2006) 270.

[8] X. Wang, X. Chen, C. Fu, X. Ji, X. Liu, Y. Mao et al., *Material Screening with HPGe Counting Station for PandaX Experiment*, *JINST* **11** (2016) T12002 [1608.08345].

[9] PandaX-II collaboration, *An Improved Evaluation of the Neutron Background in the PandaX-II Experiment*, *Sci. China Phys. Mech. Astron.* **63** (2020) 231011 [1907.00545].

[10] R. Brun and F. Rademakers, *ROOT: An object oriented data analysis framework*, *Nucl. Instrum. Meth. A** **389** (1997) 81.

[11] P. Mora de Freitas and H. Videau, *Detector simulation with MOKKA / GEANT4: Present and future*, in *International Workshop on Linear Colliders (LCWS 2002)*, 8, 2002.

[12] M. Ungaro et al., *The CLAS12 Geant4 simulation*, *Nucl. Instrum. Meth. A** **959** (2020) 163422.

[13] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [1410.3012].

[14] O. A. Ponkratenko, V. I. Tretyak and Y. G. Zdesenko, *The Event generator DECAY4 for simulation of double beta processes and decay of radioactive nuclei*, *Phys. Atom. Nucl.* **63** (2000) 1282 [nucl-ex/0104018].

[15] PandaX-II collaboration, *Dark Matter Results From 54-Ton-Day Exposure of PandaX-II Experiment*, *Phys. Rev. Lett.* **119** (2017) 181302 [1708.06917].

[16] PandaX-II collaboration, *Results of dark matter search using the full PandaX-II exposure*, *Chin. Phys. C** **44** (2020) 125001 [2007.15469].

[17] X. Wang, *Radioactive Background Control for PandaX Experiment and Corresponding Analysis*, Ph.D. thesis, Shanghai Jiao Tong University, 2017.

[18] W. Wilson et al., *SOURCES4A: A Code for Calculating ($\alpha$, n), Spontaneous Fission, and Delayed Neutron Sources and Spectra*, Tech. Rep. LA-13639-MS, Los Alamos National Laboratory, 1999.

[19] V. Tomasello, V. A. Kudryavtsev and M. Robinson, *Calculation of neutron background for underground experiments*, *Nucl. Instrum. Meth. A** **595** (2008) 431 [0807.0851].

[20] Q. Wang, *PandaX-II Experiment for Dark Matter Search*, Ph.D. thesis, University of Chinese Academy of Science and Shanghai Institute of Applied Physics, Chinese Academy of Science, 2020.

[21] D. Mancusi, A. Boudard, J. Cugnon, J.-C. David, P. Kaitaniemi and S. Leray, *Extension of the Liège intranuclear-cascade model to reactions induced by light nuclei*, *Phys. Rev. C** **90** (2014) 054602 [1407.7755].

[22] A. Heikkinen, P. Kaitaniemi and A. Boudard, *Implementation of INCL cascade and ABLA evaporation codes in Geant4*, *J. Phys. Conf. Ser.* **119** (2008) 032024.
A Usage of BambooMC

User need to provide command line options to have the BambooMC to run. The supported command line options are:

- `-c`: need an argument to specify the input configuration file.
- `-m`: need an argument to specify the Geant4 macro file.
- `-i`: run in interactive, no argument required.
- `-n`: need an argument to specify the number of events to be simulated.
- `-o`: need an argument to specify the name of the output ROOT file.
- `-g`: need an argument to specify the output GDML file.

Following are some examples:

```bash
BambooMC -c config.json -m radon.mac -n 10000 -o out.root
```

Listing 2: The program will simulate 10000 events and write the output to file “output.root”

```bash
BambooMC -c config.json -i
```

Listing 3: The program will run in interactive mode

```bash
BambooMC -c config.json -g out.gdml
```

Listing 4: The program will dump the detector geometry into an GDML file “out.gdml”

B Examples of configuration file

```
run: 1234
geometry:
  material:
    name: SampleMaterial
detectors:
  - type: SampleWorld
    name: World
    parameters:
      half_x: 4*m
      half_y: 4*m
      half_z: 4*m
  - type: SampleWater
    name: WaterShield
    parent: World
    parameters:
      width_x: 4*m
      width_y: 4*m
      width_z: 4*m
```

- type: SampleSteelContainer
  name: Container
  parent: WaterShield
  parameters:
    radius: 1.05\text{m}
    height: 2.1\text{m}
- name: XenonDetector
  type: SampleCylinder
  parent: Container
  parameters:
    radius: 1\text{m}
    height: 2\text{m}
  physics:
    name: PandaXPhysics
    parameters:
      cutlength: 0.1\text{mm}
  generator:
    name: SimpleGPSGenerator
  analysis:
    name: PandaXAnalysis
    parameters:
      EnableEnergyDeposition: 1
      EnableSurfaceFlux: 0
      EnablePrimaryParticle: 1
      SaveNullEvents: 0
      EnableDecayChainSplitting: 1
      ChainSplittingLifeTime: 400\text{us}
      UserSeed: 0

Listing 5: An example configuration file in YAML format.