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Research Article

DEVELOPING A VISUAL SIMULATION SOFTWARE FOR THE INTERACTION OF RADIATION WITH MATERIALS

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ABSTRACT

People who study and research nuclear radiation face problems of safety, limited time for experiments, high-cost equipment, and especially the non-visual in observing interactions of radiation with matter. The application of computer science to build simulation software in nuclear radiation is an optimal solution to overcome the above limitations. However, the amount of software that supports simulating the interaction of radiation with matter is minimal and their features are quite monotonous. Therefore, we have been building a new software named VIRMG4, based on Geant4/Gamos code. The goal of VIRMG4 is to visualize radiation interactions using VRML files, helping to observe the radiation path, and allowing users to freely build desired systems with a variety of source types and geometries. Simultaneously supporting dose calculation for phantom (dose/energy distribution by space/depth). VIRMG4 is currently under development, and future updates will introduce additional features to meet diverse user needs.

Keywords: GAMOS; GEANT4; Monte Carlo; Phantom, simulation software; the interaction of radiation

1. Introduction

Even though radiation is hazardous for its ionizing ability, if we understand the mechanism of its interaction and apply it safely, radiation brings many benefits to humans in life, export (disinfection of food and agricultural products), military, and health care (Nguyen et al., 2022).

When studying the interaction of radiation with matter and the human body, difficulties in visualizing the interaction processes are evident as the naked eye cannot directly observe these processes. In addition, experiments are limited due to the high cost of

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many equipment and radioactive sources, as well as we have to comply strictly with the safety rules when observing X-rays penetrate several materials such as air, water, and lead. In this case, equipping a lead sheet is costly and how to design safe shielding when using X-rays is also a problem. Moreover, people cannot be experimented regularly or at home and cannot be free to explore and discover.

By constructing simulation software for virtual experiments, we can overcome these difficulties. The software is required to describe the interactions of radiation inside the materials and visualize them in images and also allowing users to establish virtual experiments as a substitute for using expensive equipment and resources. The software saves time and cost as well as is safe and more intuitive (Šiđanin et al., 2020).

To track the interaction of radiation with matter, the Monte Carlo (MC) method is considered a flexible, powerful simulation method, which is widely supported and applied in nuclear physics (Kwak & Ingall, 2007; Nguyen et al., 2010). The CIEMAT Center (from Spain) has developed the GAMOS software (Geant4-based Architecture for Medicine-Oriented Simulations), a medical simulation software written based on the GEANT4 code (Arce et al., 2008; Carrier et al., 2004). GAMOS has features to track the details of each radiation interaction and allow us to observe the trajectory of particles inside materials. This software can also display energy/dose distributions by depth/space. However, GAMOS does not primarily exploit the intuitive nature of radiation interaction research. Users have to command separately to observe the path of radiation, how radiation leaves energy, or the dose distribution in space. Operating GAMOS with Terminal (a device that combines the functions of a computer and display) is also a challenge for those who are not experts. Moreover, GAMOS cannot display the type of interaction at its particular places.

In 2021, Mehrdad at el. developed a platform called "MCHP," which uses the MCNP code and a geometric phantom of an adult male body to describe the interaction of radiation inside the body (Beni et al., 2021). MCHP helps users to see what is happening inside matter. However, it is quite limited in its simulation features: source type, energy, geometry, and materials, representing the human body by the geometric phantom. For educational purposes, this platform does not exploit the "intuitiveness" when describing interactions. MCHP is one of a few visualization platforms.

Since the scarcity of radiation visualization software that exploits the strengths of the MC code to understand the interaction mechanism of radiation with matter, we have been developing a visualization software named VIRMG4 (Virtual Machine based on Geant4) which:

- allows users to visualize the interaction of radiation with matter (the path of particles, how particles deposit energy).
- allows users to set up and simulate experiments freely, quickly, and easily, then helps them save costs and time.

- takes advantage of the strengths of MC code in tracking particles
- and can classify interactions at interaction locations

In this work, we will demonstrate how to build the software as well as illustrate specific examples for each feature. We will also evaluate the performance of the software and discuss its potential applications.

2. Materials and methods

2.1. Building the visual simulation software VIRMG4

VIRMG4 is built on the Ubuntu operating system and has a simple user interface. Each function button of VIRMG4 will call the Geant4 code and the Gamos command packages in the background. Users do not need to be MC experts or have programming knowledge to operate it. For CT images, the software supports the DICOM format with image types including CT, PET, and SPECT.

The software uses the Livermore Physics model. This model describes the interactions of electrons, photons, hadrons, and ions with the energy from 250 eV to 100 GeV. The data used for the determination of cross-sections and sampling of the final state are extracted from a set of publicly distributed evaluated data libraries [https://geant4-userdoc.web.cern.ch/UsersGuides/PhysicsReferenceManual/fo/PhysicsReferenceManual.pdf]:

- EPDL97 (Evaluated Photons Data Library);
- EPICS2014 (Evaluated Photons Data Library);
- EPICS2017 (Evaluated Photons Data Library);
- EEDL (Evaluated Electrons Data Library);
- EADL (Evaluated Atomic Data Library);
- Binding energy values based on data of Scofield.

These libraries provide the following data [https://geant4-userdoc.web.cern.ch/UsersGuides/PhysicsReferenceManual/fo/PhysicsReferenceManual.pdf]:

- Total cross-sections for the photoelectric effect, Compton scattering, Rayleigh scattering, pair production, and bremsstrahlung;
- Subshell integrated cross sections for photo-electric effect and ionization;
- Energy spectra of the secondaries for electron processes;
- Scattering functions for the Compton effect;
- Binding energies for electrons for all subshells;
- Transition probabilities between subshells for fluorescence and the Auger effect.

To describe the geometry, random generator, or physics vectors, Geant4/Gamos uses the CLHEP library – a class library for high-energy physics. CLHEP is now a CERN Gitlab project (CERN is The European Organization for Nuclear Research).

2.2. Using the VIRMG4

The software is designed to be simple, with the primary purpose of being used by those who are new to the study or research of radiation-matter interactions.

Software structure includes three main modes:

Figure 1. *The main interface of VIRMG4*

Mode 1: Demo

This section is for users to observe the trajectory of radiation as it enters the material. We provide features that allow users to compare the paths of different particles entering the same material or the path of the same radiation entering different materials. Users can freely choose materials from the Geant4 library and desired energy values (kinetic energy). The source type used is a single-energy source. The phantom used is a wide homogeneous flat plate. Details of each button will be explained in Appendix 1.

By default, Geant4/Gamos code can observe the trajectory of particles but may not specify the interaction occurring at each position. To address this, we utilize the tracking verbose feature to monitor interaction positions and program to generate a VRML file classifying interactions by color.

In addition to tracking particle trajectories, users can also obtain energy distribution values by depth or dose distribution by depth.

Figure 2. *Deme Mode*

Mode 2: Simple

This section provides similar features to section 1 but allows the use of a wider variety of source types and geometric phantoms. Users can choose any geometry from the Geant4 geometry library and freely define parameters such as material and size. Sources can be selected as single particle or isotope sources, with various distribution types (random distribution, constant distribution, or cone distribution). Details of each section are explained in Appendix 1.

Mode 3: Expert

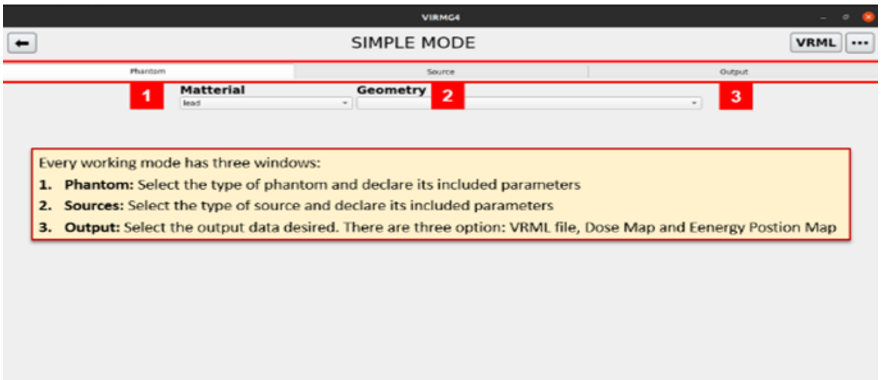

Figure 3. *Simple Mode of VIRMG4*

This section primarily performs calculations on the voxel phantom, describing the human body. Due to the large number of voxels in a phantom, it is not possible to observe the trajectory of particles through a VRML file. Users are allowed to perform dose/energy distribution calculations in space. The computation time for each calculation in this section is also quite long to achieve small errors. Users need to select the path to the directory containing the voxel phantom, and the source file is the Nuclear Medicine image. Both the phantom and Nuclear Medicine images are required to be in DICOM format converted to ASCII. Details of each button are presented in Appendix 1.

The next section presents some illustrative calculation results for the features of the VIRMG4 software.

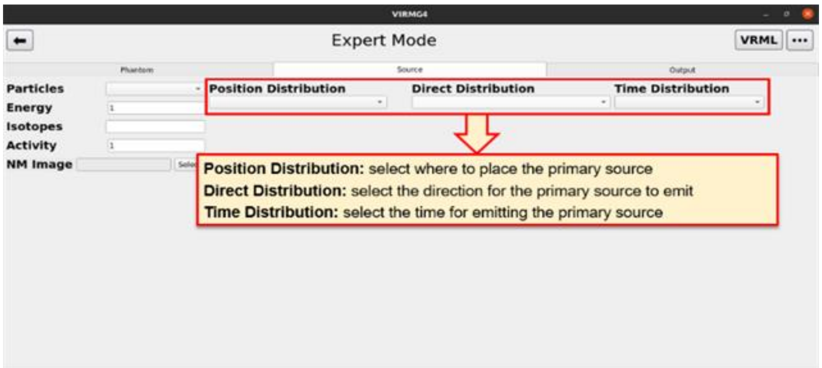

Figure 4. *Expert Mode*

3. Results

3.1. The penetration of radiation through various materials

Figure 5 illustrates the penetration of 0.1 MeV energy gamma radiation through various materials. Due to its significant levels of penetration, gamma radiation can traverse through multiple types of materials. Simultaneously, the interaction with matter also generates some secondary rays. It can be observed that among the mentioned materials, lead exhibits the best shielding effectiveness against gamma radiation.

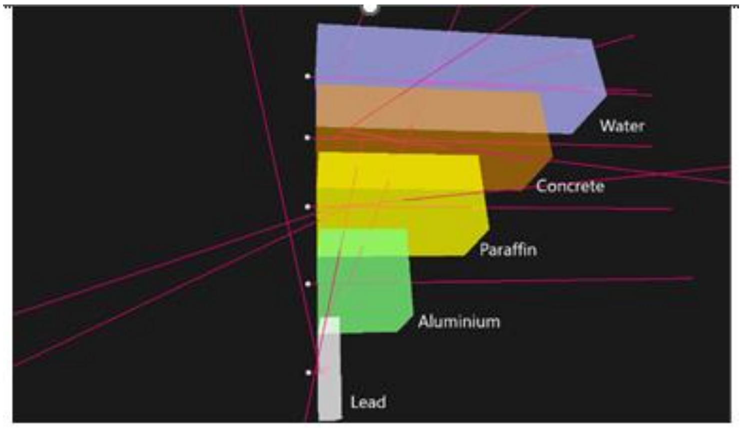

Figure 5. *The penetration of radiation through many materials*

3.2. The penetration of different types of radiation through the same material

Figure 6 illustrates the penetration capabilities of two different types of radiation, gamma and electron, with the same energy of 0.1 MeV through a block of aluminum. The radiation source is positioned in front of and approximately 1mm away from the material block. The straight path of gamma rays indicates strong penetration. Despite having the same energy, electrons are mostly retained within the material. Additionally, some secondary gamma rays generated during the interaction (highlighted in red) can penetrate outside.

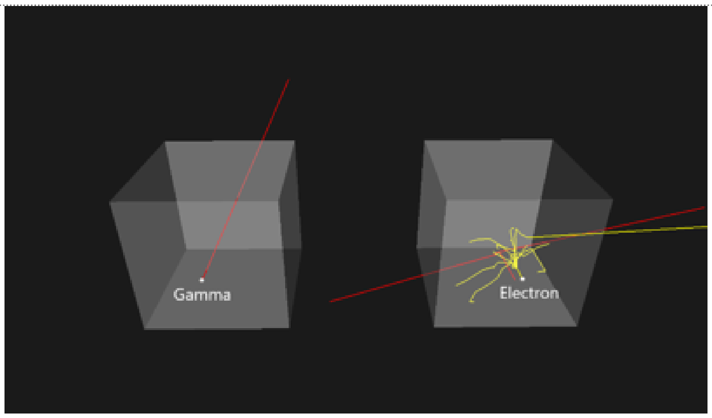

Figure 6. *The penetration abilities of different types of radiation through the same material (aluminum)*

Similarly, Figure 7 illustrates the penetration abilities of various types of radiation, including beta minus, beta plus, gamma, and neutron, all with an energy of 1 MeV, through a spherical water volume.

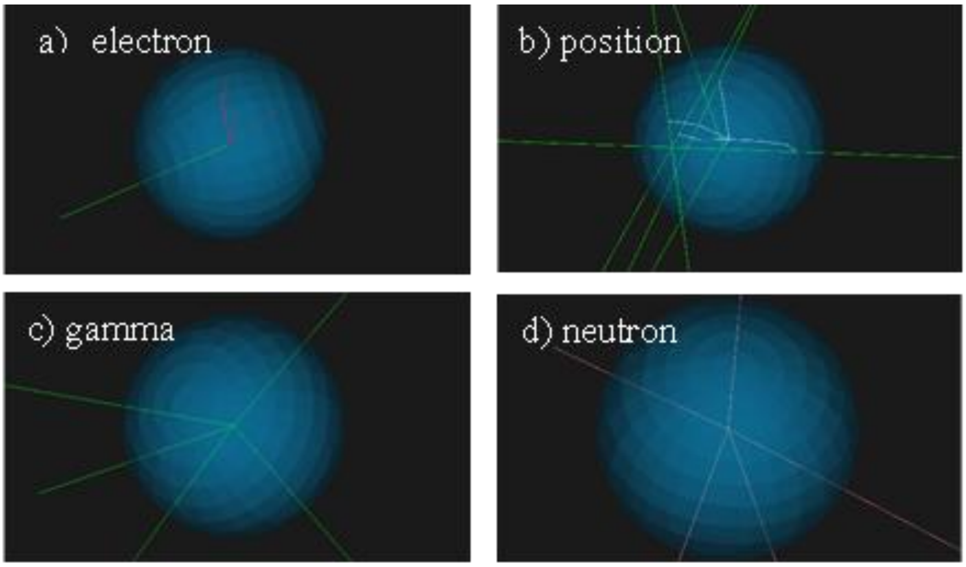

Figure 7. *The penetration capabilities of various types of radiation through the same spherical material (water)*

3.3. The positions of each type of interaction

We developed a new feature that the Geant4/Gamos code does not have, which is to indicate the type of interaction at each interaction position. Figure 8 presents the results of positron radiation entering a block of water and lead. It can be observed that upon entering the material, positron radiation interacts with the electrons of the material's atoms, leading to positron annihilation. Subsequently, two gamma rays with 511 keV energy are produced, traveling in opposite directions. Square-shaped regions with different colors appear at the interaction positions. This allows users to easily observe the interaction locations and identify the types of interactions corresponding to each position. The color coding for each interaction type is presented in Table 1.

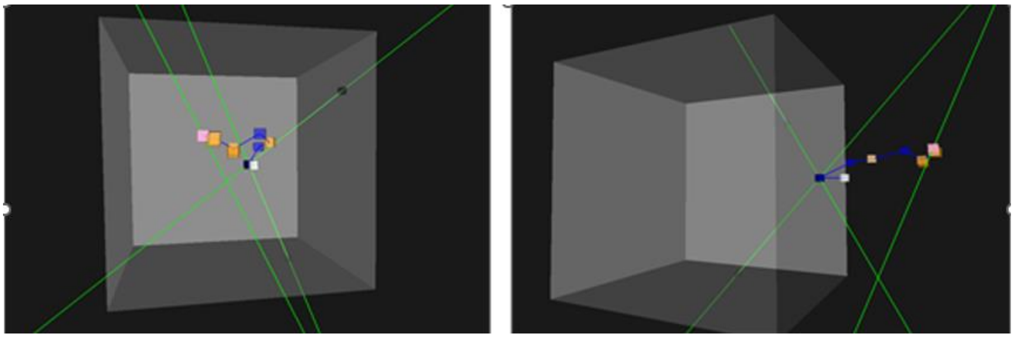

Figure 8. *Location and type of interaction*

Table 1. *Color table corresponding to different types of interactions*

Interactions	Color
Initiating Radiation	White
Exit from Material	Black
Photoelectric	Red
Ionization	Orange
Compton Scattering	Yellow
Elastic Scattering	Green
Coulomb Scattering	Blue
Multiple Scattering	Indigo blue
Bremsstrahlung Radiation Emission	Purple
Pair Annihilation Phenomenon	Pink

3.4. Dose depth curve

We also allow users to perform more in-depth calculations, for example, dose depth curve or energy depth curve. In Figure 9, gamma with energy 1 MeV enters soft tissue material (G4_TISSUE_SOFT_ICRP). The phantom thickness along the z-axis is 100 mm. The y-axis represents the absorbed dose (Gy). The user can select any type of source, with any energy, any material, or density, to observe how radiation deposits energy or dose with depth.

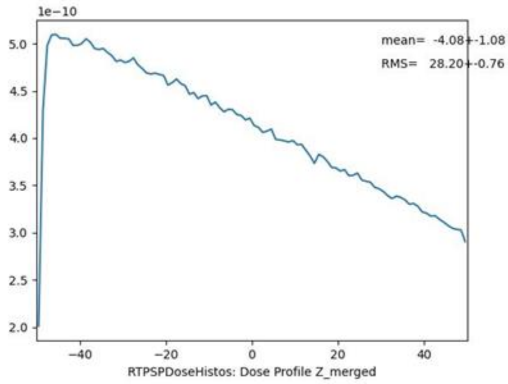

Figure 9. *The dose depth curve*

3.5. Spatial Dose Distribution using Voxel Phantom

In the illustration in Figure 10, we use the female ICRP 110 phantom, the I-131 isotope distributed homogeneously in the thyroid gland. The dose maps help users observe the absorbed dose at any position in a body. The units of the coordinates and the dose are mm and Gy.

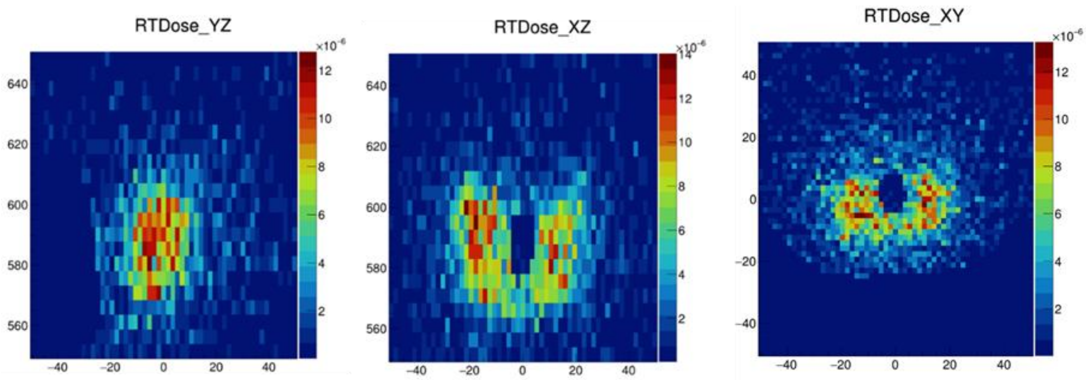

Figure 10. *Dose distribution in voxel phantom*

4. Conclusion

The preceding segment offers several fundamental examples to introduce the VIRMG4 software. This application is built upon Geant4/Gamos, a flexible, robust, and versatile Monte Carlo code. Its interface is crafted to be straightforward and intuitive, particularly tailored for individuals who are unfamiliar with particle nuclear radiation. With visualization purposes, VIRMG4 helps users comprehend fundamental knowledge such as types of interaction and how radiation interacts. It also allows users to build simulation systems in their own way. Additionally, this software is safer, helps resolve financial issues, and can be practiced to simulate regularly while learning and researching radiation.

VIRMG4 is accessible for educational purposes across different levels, catering to the teaching and learning needs of undergraduate students studying nuclear physics, nuclear medicine, or related subjects in high school physics programs, among others. The software helps learners distinguish the penetrating capabilities of various types of radiation, thereby deducing the most effective shielding materials accordingly and gaining a deeper understanding of the ALARA radiation safety principles.

Nevertheless, VIRMG4 has been developing, so it still needs to be completed in terms of features. In the future, we will continue to research and develop new features for VIRMG4 to meet the diverse needs of users, including designing the accelerators and allowing the processing of mesh phantoms. Because it is an open-source code system, the user can add new code themselves, expanding features to serve their diverse purposes.

❖ ***Conflict of Interest:*** *Authors have no conflict of interest to declare.*

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XÂY DỰNG PHẦN MỀM MÔ PHỎNG TRỰC QUAN VỀ TƯƠNG TÁC CỦA BỨC XẠ VỚI VẬT CHẤT VÀ CƠ THỂ

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TÓM TẮT

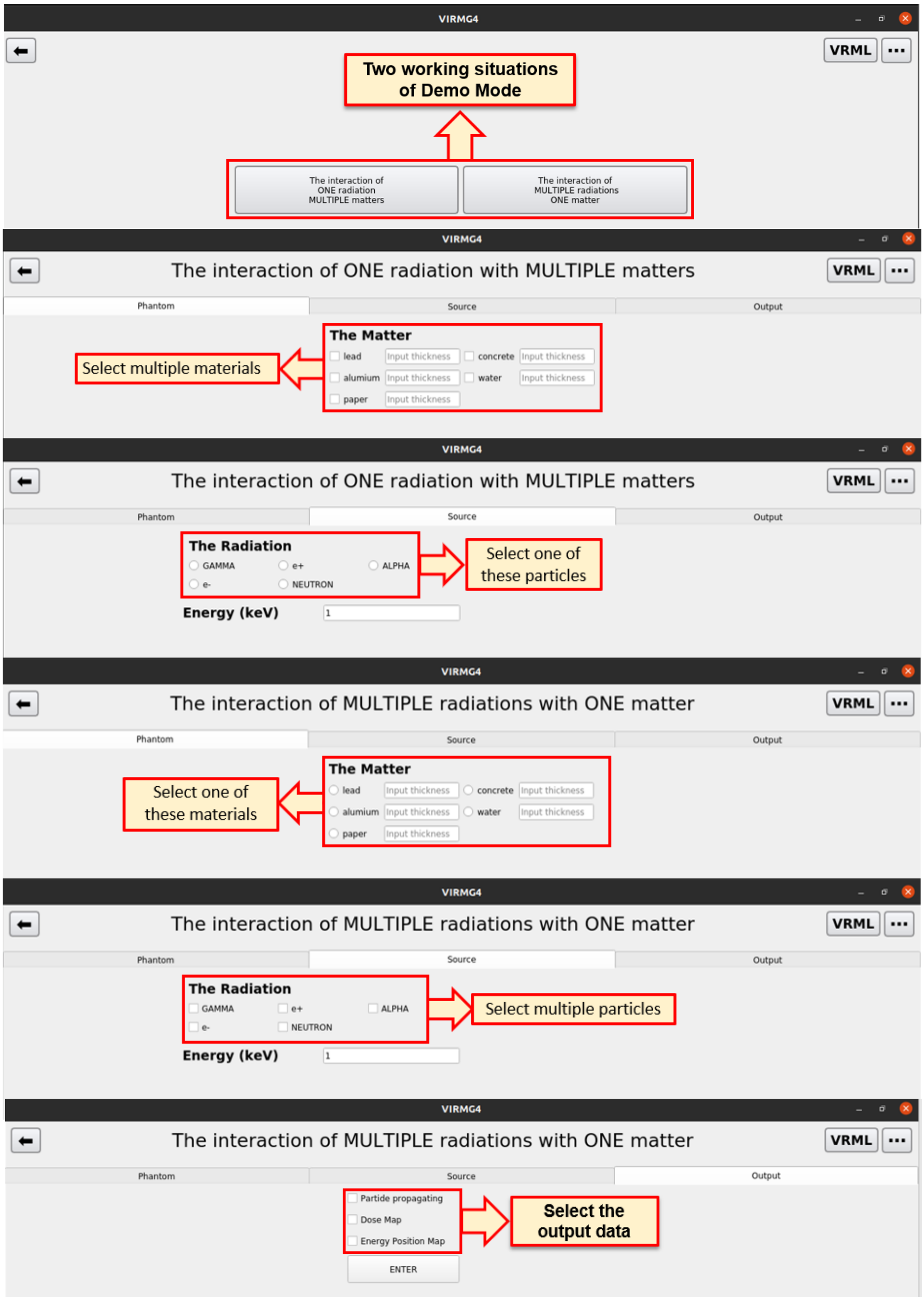
Người học và làm nghiên cứu đối với bức xạ hạt nhân cũng phải đối mặt với những vấn đề về đảm bảo an toàn bức xạ, hạn chế về mặt thời gian thực hiện thí nghiệm, thiết bị vận hành đắt đỏ và đặc biệt là hạn chế về tính trực quan trong quan sát các tương tác của bức xạ với vật chất. Việc ứng dụng khoa học máy tính để xây dựng phần mềm mô phỏng trong lĩnh vực bức xạ hạt nhân là một giải pháp tối ưu để khắc phục các hạn chế trên. Tuy nhiên, số lượng phần mềm hỗ trợ mô phỏng tương tác của bức xạ với vật chất rất ít ỏi và tính năng của chúng còn khá đơn điệu. Do đó, chúng tôi xây dựng một phần mới là VIRMG4, được viết dựa trên code Geant4/Gamos. Mục tiêu của VIRMG4 là trực quan hóa các tương tác của bức xạ bằng các file VRML, giúp quan sát đường đi của bức xạ, cho phép người dùng tự do xây hệ mô phỏng theo mong muốn với đa dạng các loại nguồn và hình học, đồng thời hỗ trợ tính toán liều cho phantom (phân bố liều theo không gian/độ sâu). Phần mềm VIRMG4 hiện vẫn đang trong quá trình phát triển, trong tương lai nhóm sẽ cập nhật thêm các tính năng để đáp ứng nhu cầu đa dạng của người dùng.

Từ khóa: GAMOS; GEANT4; Monte Carlo; Phantom; phần mềm mô phỏng; tương tác của bức xạ

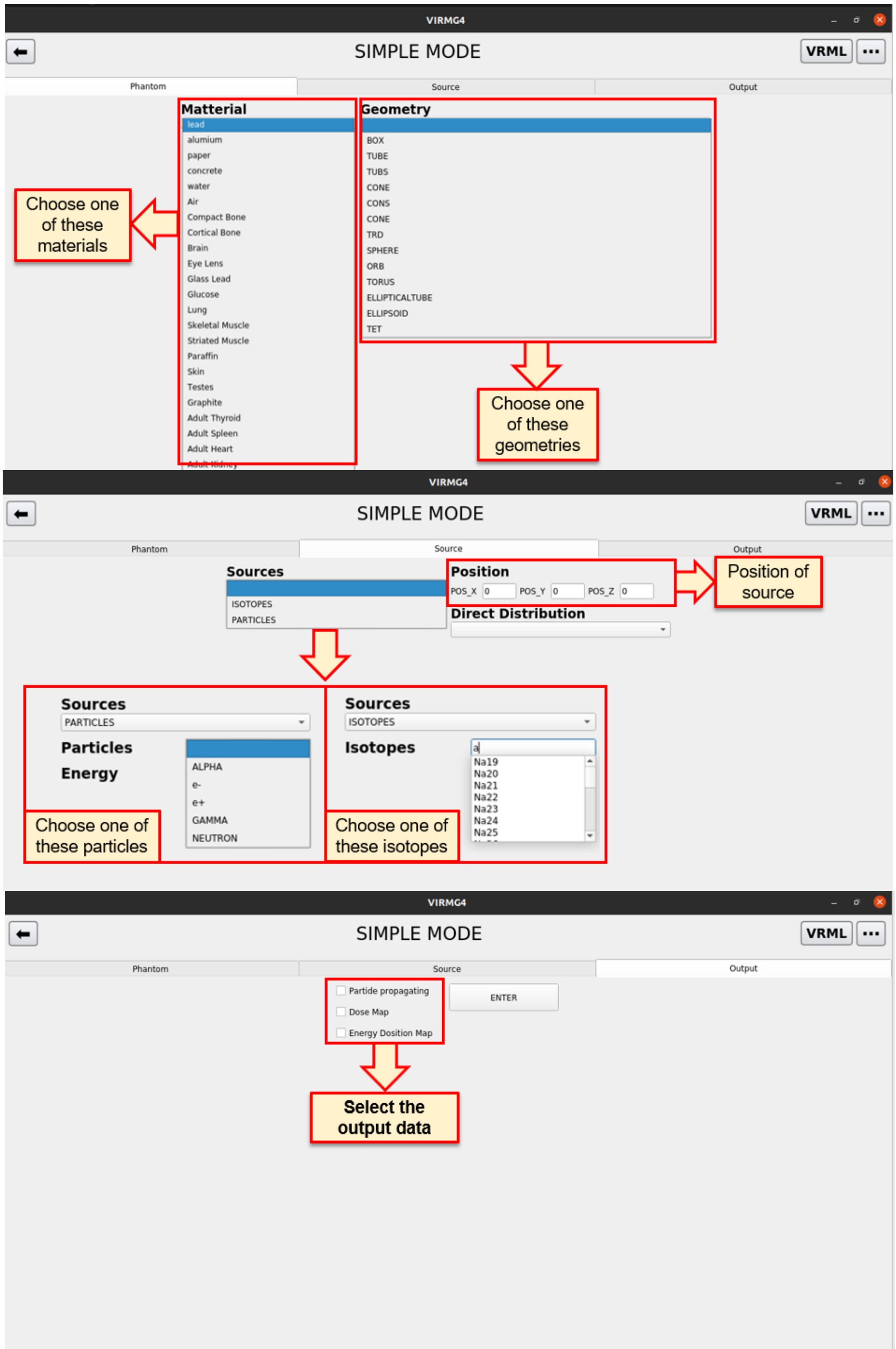
APPENDIX 1
VIRMG4 OPERATING INTERFACE

❖ **Demo:**

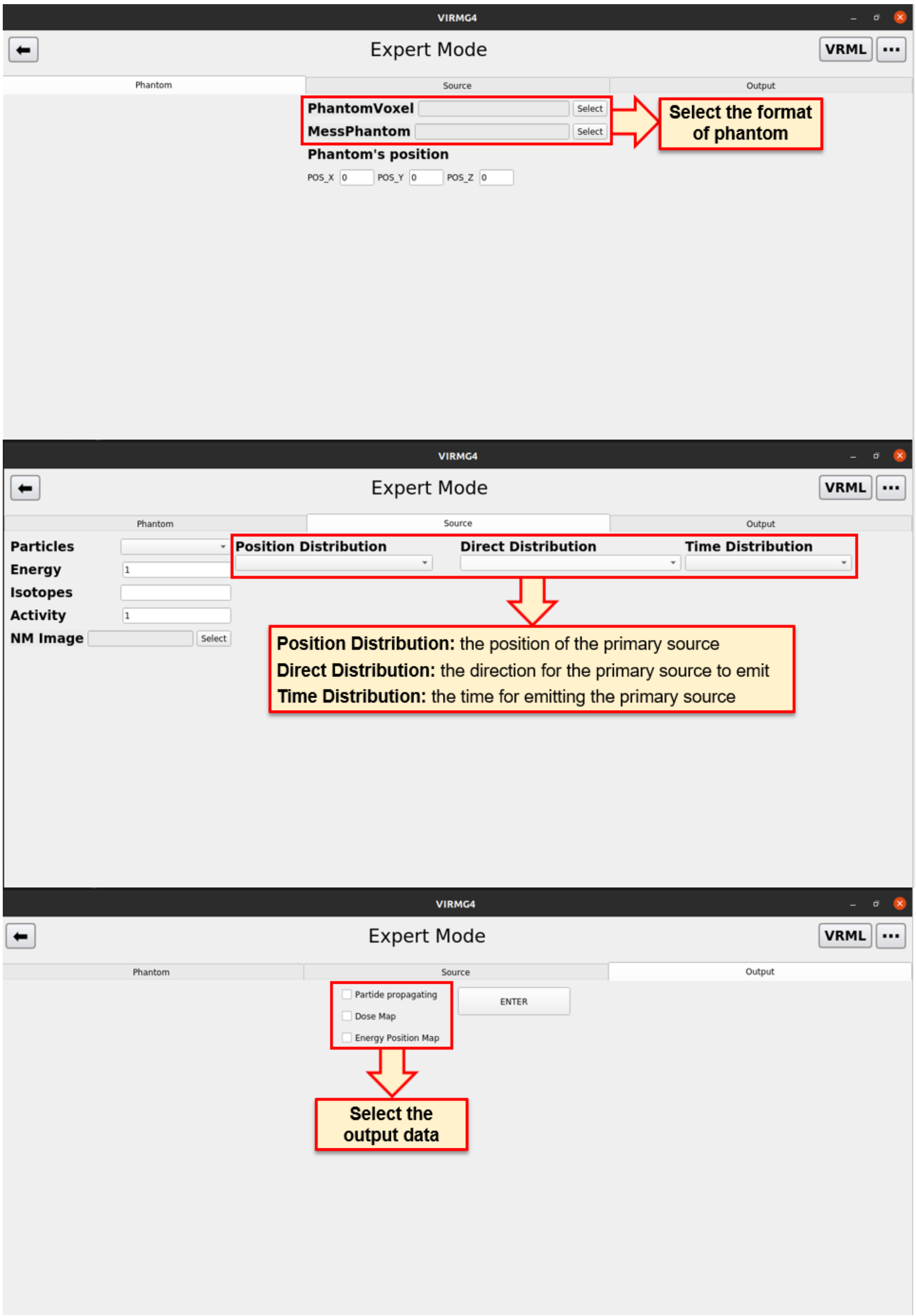
Demo mode includes 2 sub-modes: (1) Interaction of a radiation with multiple materials; (2) Interaction of multiple radiations with one material.



❖ **Simple Mode:**


VIRMG4
SIMPLE MODE
VRML
Phantom
Source
Output
Matterial
lead
alumium
paper
concrete
water
Air
Compact Bone
Cortical Bone
Brain
Eye Lens
Glass Lead
Glucose
Lung
Skeletal Muscle
Striated Muscle
Paraffin
Skin
Testes
Graphite
Adult Thyroid
Adult Spleen
Adult Heart
Choose one of these materials
Geometry
BOX
TUBE
TUBS
CONE
CONS
CONE
TRD
SPHERE
ORB
TORUS
ELLIPTICALTUBE
ELLIPSOID
TET
Choose one of these geometries
VIRMG4
SIMPLE MODE
VRML
Phantom
Source
Output
Sources
ISOTOPES
PARTICLES
Position
POS_X 0 POS_Y 0 POS_Z 0
Position of source
Direct Distribution
Sources
PARTICLES
Particles
Energy
ALPHA
e-
e+
GAMMA
NEUTRON
Choose one of these particles
Sources
ISOTOPES
Isotopes
Na19
Na20
Na21
Na22
Na23
Na24
Na25
Choose one of these isotopes
VIRMG4
SIMPLE MODE
VRML
Phantom
Source
Output
Partide propagating
Dose Map
Energy Dosition Map
ENTER
Select the output data

❖ **Expert Mode:**


VIRMG4
Expert Mode
VRML
Phantom
Source
Output
PhantomVoxel
Select
MessPhantom
Select
Phantom's position
POS_X 0
POS_Y 0
POS_Z 0
Select the format of phantom
VIRMG4
Expert Mode
VRML
Phantom
Source
Output
Particles
Energy 1
Isotopes
Activity 1
NM Image
Select
Position Distribution
Direct Distribution
Time Distribution
Position Distribution: the position of the primary source
Direct Distribution: the direction for the primary source to emit
Time Distribution: the time for emitting the primary source
VIRMG4
Expert Mode
VRML
Phantom
Source
Output
Particle propagating
Dose Map
Energy Position Map
ENTER
Select the output data