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GEANT4 ELECTROMAGNETIC PHYSICS

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Abstract

An overview of the main features of Geant4 electromagnetic physics is presented. The role played by advanced software engineering methodologies and by Object Oriented technology is illustrated. The main physics functionalities are described.

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1 The Geant4 Object Oriented Simulation Toolkit

Geant4 [1] is a simulation toolkit designed for a variety of applications, including HEP, astrophysics and nuclear physics experiments, as well as medical physics and space science. Geant4 provides functionalities for all the typical domains of simulation: geometry, tracking, detector response, run, event and track management, Particle Data Group compliant particle management, visualisation and user interface, as well as a large variety of physics processes and models. It is also complemented by specific modules for space science applications.

Since the *R&D* phase of the Geant4 project, Software Engineering has played a fundamental role [1]. User Requirements were formally collected during the initial phase of the project, and were systematically reviewed and updated following the ESA PSS-05 framework [2] Standards. Object-Oriented methods (and the respective tools) have been employed for the analysis and design of the software, and to produce the corresponding deliverables. The spiral iterative approach for the development process demonstrated to be very effective also in the Production phase of the software product, allowing to apply successive refinements to the existing architecture, and experienced solutions to OOAD iterations. Software Processes have been monitored by following the ISO/IEC 15504 (SPICE) exemplar model [3], through regular assessments and improvements also from external professional companies.

By adopting OOP methodologies through the use of Software Engineering CASE tools and Quality Assurance techniques one guarantees that the code quality will not degrade with time and a coherent development is also assured, where coupling will not increase with the complexity of the software.

Tools such as Insure++, CodeWizard, Purify and Logiscope have been used to assure and improve software quality and reliability. Scripts to automatically check the C++ coding guidelines recommended in the Project have been developed. Code inspections have been regularly held. Testing procedures are applied extensively, both at granular unit level and integration level, the latter being coordinated by a dedicated team through automated procedures based on the WWW.

The Geant4 source code is publicly distributed from the WWW [4], together with ample documentation.

2 General features of Geant4 physics

Object Oriented design provides the possibility to implement or modify any physics process in Geant4 without changing other parts of the software. This feature makes Geant4 open to the extension of its physics capabilities and to the implementation of alternative physics models. Via the use of virtual functions Geant4 provides transparent access to cross-sections (formulae, data sets, tables, etc.) and to models underlying the physics processes. For each process the generation of the final state is independent from the access and use of the cross sections. The transparency of physics implementation contributes to the validation of the experimental physics results.

By design Geant4 is independent from the units chosen by the user, so that one can use the most adequate units in different parts of the code.

In Geant4 there are no tracking cuts, but only production thresholds. Each physics process has its intrinsic limits to produce secondary particles, which can be tracked down to zero range; the cut associated to each particle represents only a recommended production threshold. In Geant4 the thresholds for producing secondaries are expressed in range, universal for all media. This range is converted in energy for each kind of particle and each material. The cuts in range allow one to say that the energy has been released at the correct space position, limiting the approximation within a given distance, while cuts in energy would imply accuracies of the energy depositions, which depend on the material.

Geant4 physics makes ample use of public evaluated databases, distributed by a variety of international sources; this feature also contributes to the reliability and the transparency of the physics implementation.

3 Overview of Geant4 electromagnetic processes

Geant4 Electromagnetic Physics manages electron processes, γ, X-ray and optical photon physics, muon processes and electromagnetic interactions of charged hadrons and ions. It exploits the features of transparency and extensibility provided by the Object Oriented technology. As shown in the top level class diagram of Geant4 electromagnetic processes (figure 1), alternative models, obeying the same abstract interface, are often provided for the same physics interaction.

3.1 Standard electromagnetic processes

Geant4 *standard* electromagnetic physics provides a variety of implementations of electron, positron, photon and charged hadron interactions. Photon processes include Compton scattering, γ conversion and photoelectric effect. Electron/positron processes handle Bremsstrahlung, ionisation and δ ray production, positron annihilation and synchrotron radiation. The energy loss process manages the continuous energy loss of particles due to ionisation and Bremsstrahlung. An algorithm [5] is available to optimise the generation of δ rays only where they are needed, i.e. near the boundaries. The result can be a drastic improvement of the performance of the simulation, keeping the same quality of physics results as with the lowest cut. The ionisation and energy loss of hadrons can be simulated optionally with different models, including the PhotoAbsorption Interaction (PAI) one.

Geant4 multiple scattering [4] process can handle all the charged particles. It is based on a new model, which simulates the scattering of the particle after a step, computes the mean path length correction and the mean lateral displacement. Its performance is compared with experimental data in figure 2.

The ionisation, Bremsstrahlung, positron annihilation, energy loss and multiple scattering processes have been implemented both in the differential and in the so called 'integral' approach as well.

A shower profile resulting from Geant4 standard electromagnetic physics process is compared to experimental data in figure 3.

3.2 Low energy extensions

A set of physics processes is implemented in Geant4 to extend the validity range of electromagnetic interactions down to lower energy than the standard Geant4 electromagnetic processes. The currently available extensions cover processes for electrons, photons, positive and negative charged hadrons and positive ions; further extensions to cover positron and negative ion interactions are in progress.

3.2.1 Processes for low energy photons and electrons

The current implementation of Geant4 Low Energy electron and photon processes [8] covers the energy range from 100 GeV down to 250 eV for elements with atomic number between 1 and 99. It includes photoelectric effect, Compton scattering, Rayleigh effect, Bremsstrahlung and ionization; for completeness, a photon conversion process has also been implemented based on the same data sources as the other Low Energy ones. In addition, fluorescence emission from excited atoms is also generated; the implementation of the Auger effect is in progress. The implementation is based on the exploitation of evaluated data libraries (EPDL97 [9], EEDL [10] and EADL [11]), that provide data for the determination of cross-sections and the sampling of the final state. A simulation based on Geant4 Low Energy processes for photons and electrons is compared with experimental data in figure 4, with evidence of shell effects.

3.2.2 Processes for low energy hadrons and ions

A Low Energy process is available in Geant4 to handle the ionisation by hadrons and ions [12] [13]. It adopts different models depending on the energy range and the particle charge. In the high energy ($E > 2\ MeV$) domain the Bethe-Bloch formula and in the low energy one ($E < 1\ keV$ for protons) the free electron gas model are applied respectively. In the intermediate energy range parameterised models based on experimental data from the Ziegler [14] and ICRU [15] reviews are implemented; corrections due to the molecular structure of materials [16] and to the effect of the nuclear stopping power [15] are taken into account. The Barkas effect is taken into account [17]; a specialised quantum harmonic oscillator model [18] for negative charged hadrons, valid down to 50 keV, is available; this model has been compared to experimental data for a set of materials, for which data are available; further extensions are in progress. Figure 5 shows a comparison with experimental data for ions.

3.3 Muon processes

Muon processes available in Geant4 include Bremsstrahlung, ionisation and δ ray production, nuclear interaction and direct pair production. The Bremsstrahlung, ionisation and pair production processes give contributions to the total continuous energy loss.

The validity range of Geant4 muon processes, based on theoretical models, scales from 1 keV up to the 1000 PeV region, allowing the simulation of ultra-high energy and cosmic ray physics.

3.4 Physics processes for optical photons

A photon is called optical when its wavelength is much greater than the typical atomic spacing, for instance when $\lambda \geq 10nm$ which corresponds to an energy $E \leq 100eV$. Production of an optical photon in a HEP detector is primarily due to Čerenkov effect and scintillation. In Geant4 optical photons are subject to in-flight absorption, Rayleigh scattering and medium boundary interactions.

3.5 Conclusions

An abundant set of physics processes is available in the Geant4 Toolkit for the simulation of electromagnetic interactions of electrons and positrons, photons, muons, charged hadrons and ions over an extended energy range. Many processes are available through alternative models. The Object Oriented technology plays a key role to achieve transparency of physics implementation and openness to extension to new physics processes and models. Geant4 electromagnetic physics is exercised in a variety of simulation domains; a selection of space and medical applications is presented elsewhere in these Proceedings [23] [24].

References

[1] S. Giani *et al.*, Geant4, an Object-Oriented toolkit for simulation in HEP, CERN/LHCC/98-44 (1998)

[2] ESA, Guide to User Requirements Definition Phase, ESA PSS-05 (1994)

[3] T. Rout Project Editor, ISO/IEC DTR 15504 Software Process Assessment

[4] The Geant4 Collaboration, http,//wwwinfo.cern.ch/asd/geant4/geant4.html

[5] J. Apostolakis *et al.*, CERN-OPEN-99-299 (1999)

[6] S. Giani *et al.*, Phys. Lett., **B460** 467 (1999)

[7] J. Apostolakis *et al.*, An implementation of ionisation energy losses in very thin absorbers for the Geant4 simulation package, To be published in Nucl. Instr. Meth.

[8] J. Apostolakis *et al.*, CERN-OPEN-99-034 and INFN/AE-99/18 (1999)

[9] D. Cullen *et al.*, EPDL97, the Evaluated Photon Data Library, 97 version, UCRL–50400, Vol. 6, Rev. 5 (1997)

[10] S.T. Perkins *et al.*, Tables and Graphs of Electron-Interaction Cross Sections from 10 eV to 100 GeV Derived from the LLNL Evaluated Electron Data Library (EEDL), UCRL-50400 Vol. **31** (1997)

[11] S.T. Perkins *et al.*, Tables and Graphs of Atomic Subshell and Relaxation Data Derived from the LLNL Evaluated Atomic Data Library (EADL), Z=1-100, UCRL-50400 Vol. **30** (1997)

[12] S. Giani *et al.*, CERN-OPEN-99-121 and INFN/AE-99/20 (1999)

[13] S. Giani *et al.*, CERN-OPEN-99-300 and INFN/AE-99/21 (1999)

[14] H.H. Andersen and J.F. Ziegler, The Stopping and Ranges of Ions in Matter, Vol.3, Pergamon Press (1977)

[15] ICRU (A. Allisy et al), ICRU Report 49 (1993)

[16] J.F. Ziegler and J.M. Manoyan, NIM **B35** 215 (1988)

[17] S. Chauvie *et al.*, INFN/AE preprint, in preparation

[18] P. Sigmund, Light-ion stopping near the maximum, NIM **B85**, 541-550 (1994)

[19] J. Vincour and P. Bem, NIM **148**, 399 (1978)

[20] J. H. Crannel, Phys. Rev. **184** (1969)

[21] R. Shimizu *et al.*, J. Phys. **D9** 101 (1976)

[22] H. Paul, http://www.uni-linz.ac.at/fak/TNF/atomphys/STOPPING/welcome.htm

[23] E. Daly *et al.*, Space Applications of the Geant4 Simulation Toolkit, These Proceedings

[24] S. Chauvie *et al.*, Medical Applications of the Geant4 Simulation Toolkit, These Proceedings

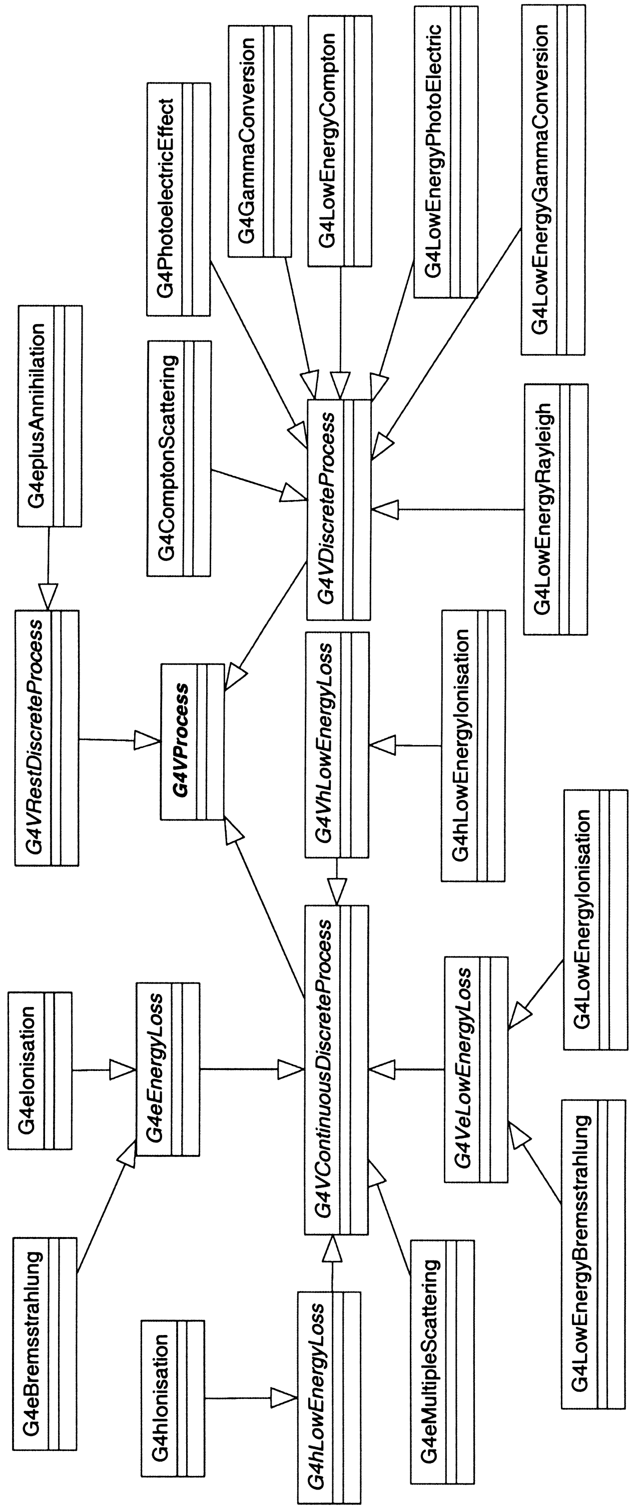

Figure 1: Class diagram of electromagnetic processes

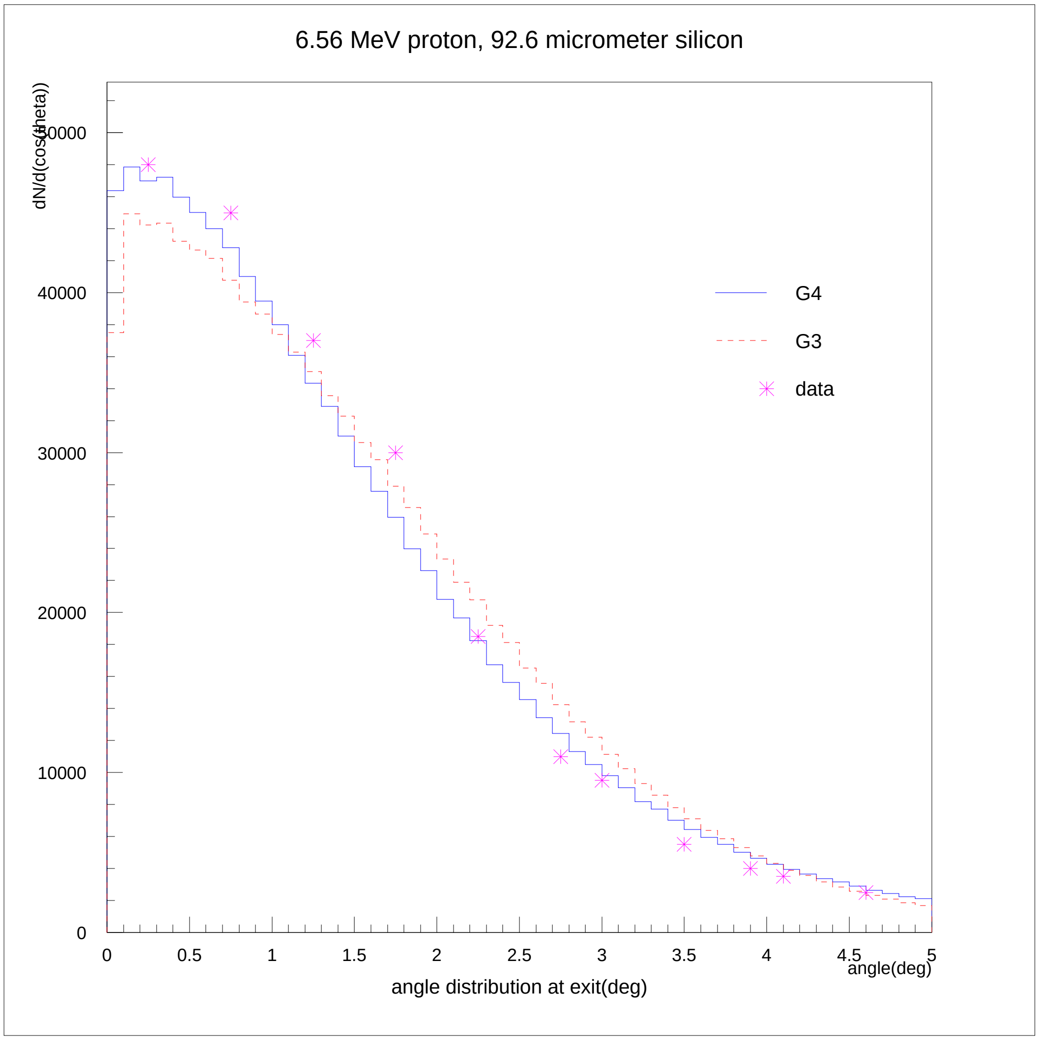

Figure 2: Multiple scattering of 6.56 MeV protons on 92.6 μm Silicon: comparison of Geant4, Geant3 and experimental data from [19]

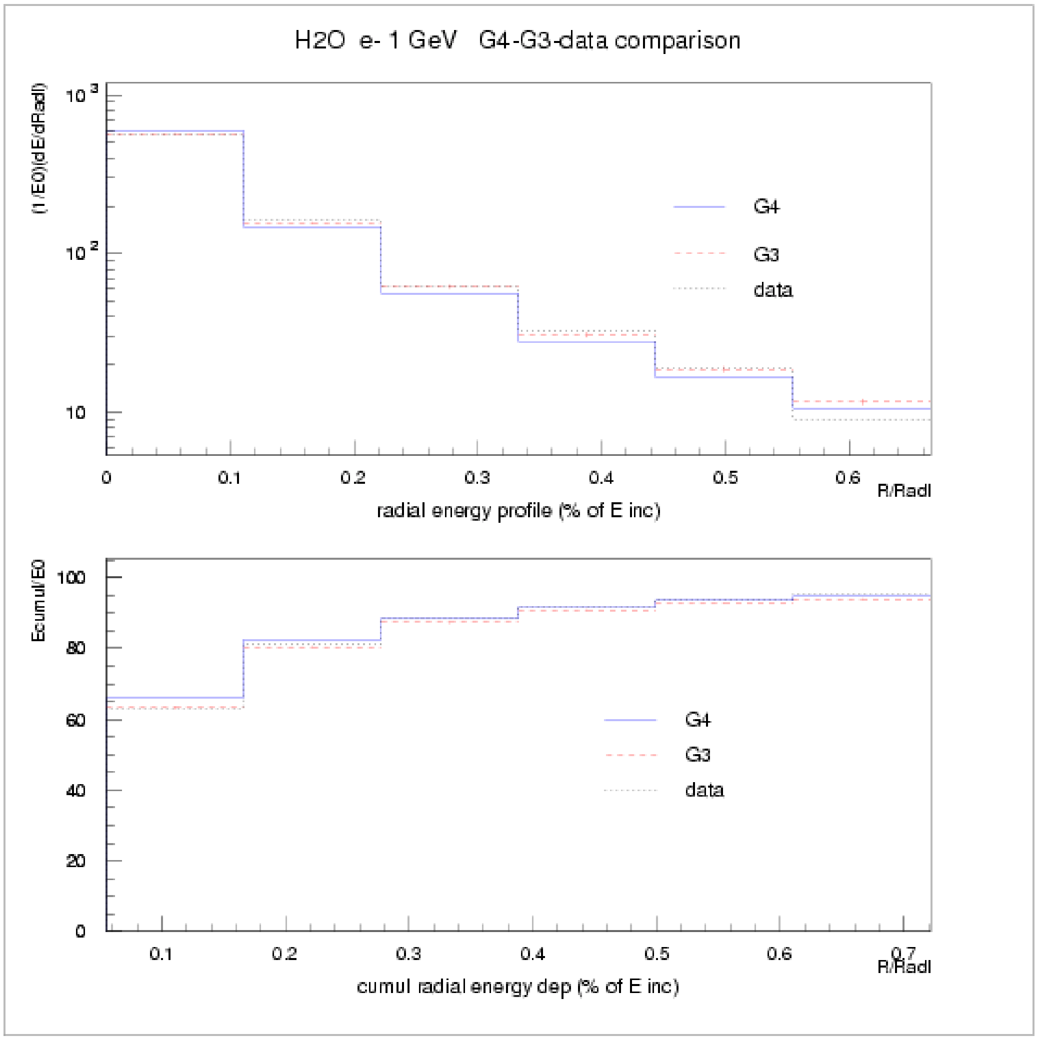

Figure 3: Shower profile of 1 GeV electrons in water: Geant4, Geant3 and experimental data from [20]

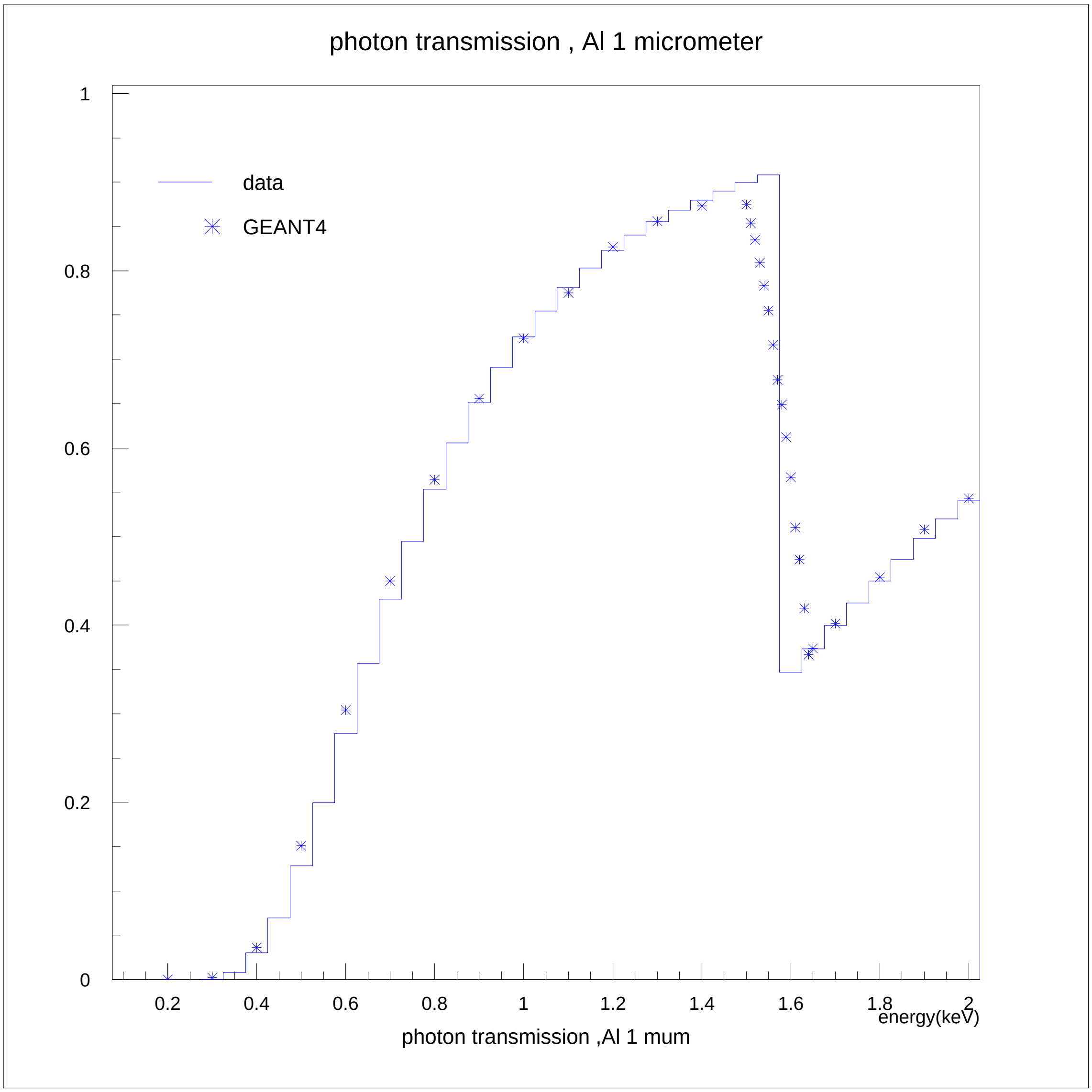

Figure 4: Comparison of the Geant4 Low Energy photon simulation and experimental data, with relevance of shell effects: photon transmission in 1 μm Al; data from [21]

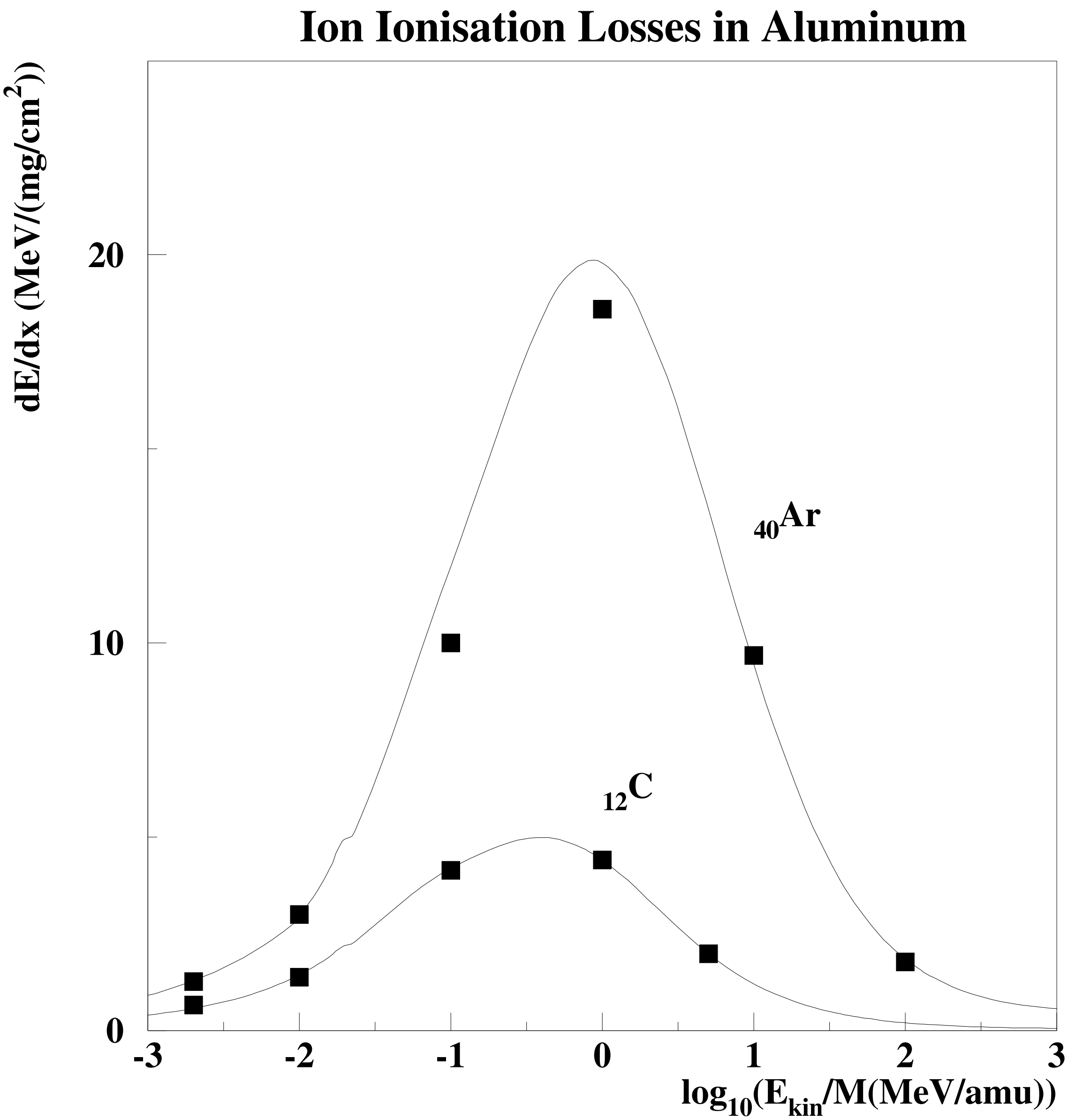

Figure 5: Electronic stopping power of ions in Al; the accuracy of the data is approximately 5%; experimental data from [22]