APPLICATION OF THE S^{3}M CODE IN TRANSPORT OF ION BEAMS IN MATTER

Jozef Bokor[1], Márius Pavlovič[1], Andrea Šagátová[1,2]

[1] Institute of Nuclear and Physical Engineering, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava, Ilkovičova 3, 81219 Bratislava, Slovak Republic

[2] University Centre of Electron Accelerators, Slovak Medical University, Ku kyselke 497, 91106 Trenčín, Slovak Republic

E-mail: jozef.bokor@stuba.sk

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1. Introduction

The interaction of ion beams with matter involves many physical processes that alter original incoming beam as well as the properties of the target material. A tutorial description of ion-beam interaction with matter can be found in Refs. [1, 2]. In the present paper, the basic processes of interaction of ion beams with matter are explained with emphasis on their statistical analysis. The tools for this analysis have been implemented in the S^{3}M code that is described in this paper. The statistical modules of the S^{3}M code are demonstrated using a particular application for research and development of fast-neutron semiconductor detectors as an example.

2. Interaction of ion beams with matter

Interaction of ion beams with matter is a complex process that consists of many physical processes. These processes alter the parameters of the original beam as well as the properties of the target. Most of them are related to kinetic energy loss of the primary particles. There are two main mechanisms of the energy-loss process: 1) interaction with the target electrons (electronic stopping) and 2) interaction with the target nuclei (nuclear stopping). In case of electronic stopping, a part of the projectile kinetic energy is transferred to the target electrons that may leave their origin in the central part of the projectile track. The target atoms get ionized and/or excited. The nuclear stopping can be caused by elastic as well as inelastic collisions. In case of an elastic collision, the projectile and target nucleus get close enough to each other (small impact parameter) and a part of the projectile kinetic energy is transferred to the target nucleus. This also changes significantly the direction of the projectile movement. That is why this process is also referred to as a scattering event. Nuclear scattering contributes to a so-called Multiple Coulomb scattering – a sequence of numerous collisions that change the angle of particle trajectory inside matter. This increases beam-divergence and geometrical beam emittance. Consequently, it blows-up the beam spot-size after the beam has travelled certain distance through matter. The inelastic nuclear collisions may lead to nuclear reactions or projectile or target fragmentation.

2.1 Energy-loss and range

The energy-loss process can be quantified by so-called stopping power, *S(E)*. It is the average energy-loss per unit path-length of the projectile travelling through matter:

$$S(E) = -\frac{dE}{dx} = \lim_{\Delta x \to 0} \frac{\Delta E}{\Delta x} = S_e(E) + S_n(E) \qquad (1)$$

where ΔE is the average energy-loss of the projectile traversing a slice of material with the thickness Δx. $S_e(E)$ represents the electronic stopping and $S_n(E)$ represents the nuclear stopping. Fig. 1 (left panel) shows the stopping power of alpha-particles in air as a function of their kinetic energy. After loosing all kinetic energy, the projectiles remain at rest implanted in material. The average distance, the projectiles have travelled until losing all kinetic energy, is called the range, R. It can be derived directly from the stopping power definition Eq. 1 as follows:

$$R = \int_0^R dx = \int_0^{E_0} \frac{1}{S(E)} dE \qquad (2)$$

where E_0 is the initial kinetic energy of a projectile. Right panel of Fig. 1 shows the range of alpha-particles in air as a function of their kinetic energy.

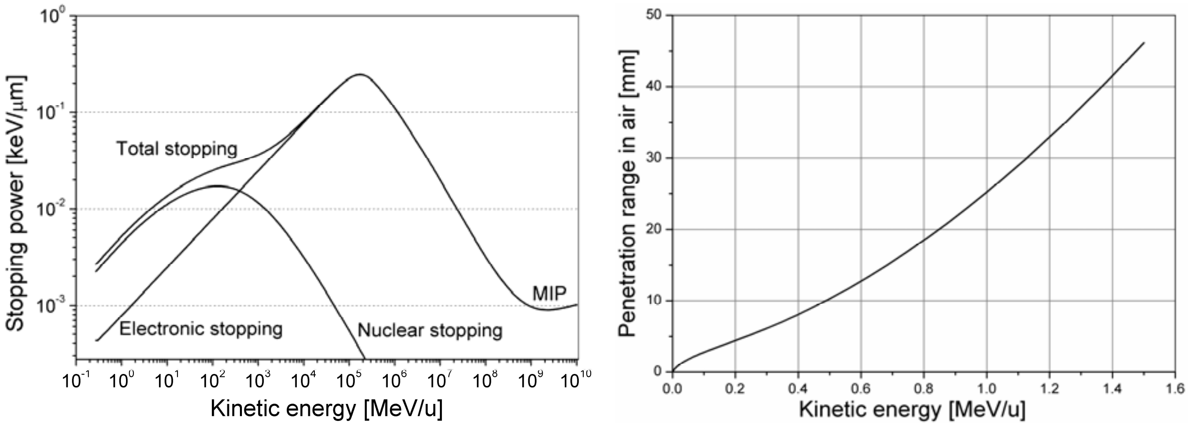

Fig. 1: *Dependence of the stopping power (left) and range (right) of alpha particles in air on their kinetic energy. MIP = minimum ionizing particle.*

3. The S^{3}M – SRIM Supporting Software Modules

The S^{3}M code is a package of supporting modules for the SRIM code (Stopping and Range of Ions in Matter). It represents a comprehensive means for the statistical analysis of selected quantities related to the above described interaction processes, namely: *1) energy distribution, 2) momentum distribution, 3) position distribution* and *4) angular distribution.* S^{3}M uses results from Monte Carlo simulations containing data on individual particles and provides global parameters characterizing the beam.

3.1 Energy and momentum statistics

The energy and momentum statistics modules process data on energy and momentum distributions of the particles leaving a target that is thinner than the range. Generating a record of these particles in a form of an ASCII – TRANSMIT.TXT file can be activated in SRIM. Basic analysis yields mean-value and standard deviation of the energy (momentum) spectrum together with minimum, maximum values in the data-set and the total spectrum span, i.e. maximum value minus the minimum one. There is also a possibility to filter the spectrum and to analyze the filtered spectrum. The filtering function rejects particles with parameters beyond certain user-specified threshold from the spectrum. The spectra can be represented by histograms displayed either in graphical or tabular form.

In ion-optics, momentum-spread is used instead of the energy-spread. That is why a statistical module for momentum statistics is included in the code as well. Its features are analogical to the module for energy statistics.

3.2 Position and angle statistics

In addition to the energy losses, Multiple Coulomb scattering changes the positions and angles of all particles traversing matter. This effect can be statistically analyzed by position and angle statistics modules of the S^3M code. Analysis of the lateral particle positions is of particular concern, because it corresponds to the beam profile. A Cartesian (X, Y, Z) coordinate system is used. A beam profile can be analyzed in horizontal (Y-X) and vertical (Z-X) planes. Other functions are analogical to the energy (momentum) statistics modules.

3.3 Application of the S^3M code in fast-neutron detector development

Principle of the fast-neutron (energy range from 100 keV up to several tens of MeV) detection by semiconductor detectors is based on neutron-to-proton conversion mainly through elastic nuclear scattering in a conversion layer deposited on the top of a detector surface. The protons generated by this conversion mechanism are then detected with a charged particle detector (e.g. a semi-insulating GaAs or SiC semiconductor detector). The conversion layer should be made of a hydrogen-rich material like high-density polyethylene (HDPE) that provides good conversion efficiency [3, 4]. The principal scheme of a fast-neutron detector is shown in Fig. 2.

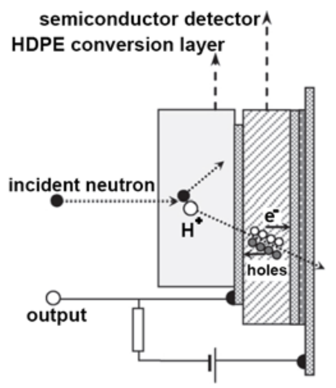

Fig. 2: *Principal scheme of a fast-neutron semiconductor detector with a conversion layer.*

The energy calibration of this type of detector was made by an ^{241}Am α-radiation source. It emits α-particles with two discrete energies: $E_{\alpha 1} = 5.480\ MeV$ (yield 84.5%) and $E_{\alpha 2} = 5.437\ MeV$ (yield 13%). Technically, it is not possible to put ^{241}Am in electric contact with the detector surface. Therefore, it was put in front of the detector separated from the conversion layer by 1 mm air-gap. Transport of the α-particles through the air-gap causes both the energy loss (including energy straggling) and Multiple Coulomb scattering. Consequently, it changes the original mono-energetic peaks of the ^{241}Am energy spectrum. The peaks get shifted to lower energies (energy loss) and acquire some energy spread (energy straggling). This is crucial for the energy calibration. Therefore, these processes must be analyzed accurately. It was found out that the S^3M code is a suitable tool for such analysis. Its main purpose is to calculate parameters of the α-particles entering the conversion layer, i.e. leaving the air-gap.

4. Results and discussion

Fig. 3 shows the energy spectrum of α-particles emitted from ^{241}Am after passing through 1 mm air-gap. $E_{\alpha 1}$ and $E_{\alpha 2}$ are rather similar therefore the corresponding energy losses are also similar. In both cases, the energy loss in the air-gap is about 90 keV. Furthermore, the energy peaks get spread. Fig. 3 shows the incident spectrum of α-particles entering the detector after passing the air-gap. However, the corresponding signal measured by the semiconductor detector is more complicated because the conversion layer provides a broad energy-spectrum of protons even for a mono-energetic incident radiation. An example of a detector response to the double-peak of ^{241}Am a-particles is shown in Fig. 4.

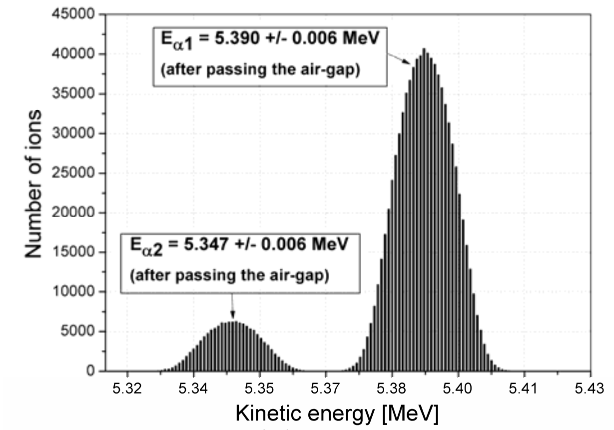

Fig. 3: *Energy spectrum of the ^{241}Am α-particles entering the detector.*

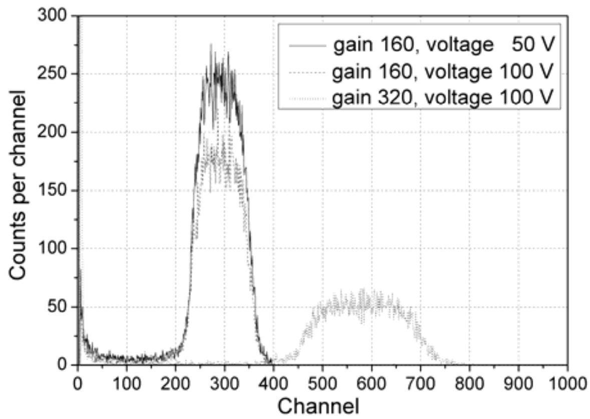

Fig. 4: *Measured signal of a SiC semiconductor detector corresponding to the ^{241}Am.*

5. Conclusion

Transport and interaction of ion beams in matter is described in this paper. The S^3M code, as a package of supporting modules for analysis of the ion-beam transport in matter, is presented. The particular application of the S^3M code is discussed in fast-neutron detector development. The energy loss and energy-straggling of the α-particles passing through 1 mm air-gap is studied.

Acknowledgement

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