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Low-energy electron transport in non-uniform media

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ABSTRACT

We simulated the transport of low and medium energy electrons with energies between 1.26 eV and 10 keV in non-uniform carbon targets using the track structure Monte Carlo code TRAX which has several applications in biophysics and radiation physics. Cross sections for electrons incident on carbon have been critically assessed. Furthermore the code has been extended to handle non-uniform targets allowing a complex geometry description. Solid state targets, which are commonly used as targets in electron spectrometers and other devices can be non-uniform, e.g. have highly irregular surfaces or pinholes. The resulting electron spectra can be significantly affected by these non-uniformities. We reproduce experimental data obtained by GSI's Toroid electron spectrometer using thin solid state foils as targets. This unique experiment was designed to gain further insight in the emission and transport of low energy electrons in solids to improve the description of microscopic energy deposition. The realistic implementation of non-uniform targets in TRAX was verified by comparison with available experimental data. The increased backscattering due to the roughness of an unpolished target in comparison with polished ones could be reproduced as well as secondary electron spectra from the Toroid.

1. Introduction

Low energy electrons contribute most to radiation damage in solid or liquid state targets. Electrons with energies below 1 keV have ranges in media on the micrometer down to nanometer scale and play the most important role in biological damage as their mean free path is on the order of the size of critical objects like the DNA. Low energy electrons also play a dominant role as secondary radiation when energetic ions traverse matter, since the distribution of electron energy E scales as $1/E^2$ with the centroid below 100 eV [1]. This is of particular importance for the prediction of biological effectiveness in radiotherapy with ion beams [2]. For example, the radial dose deposition on the nanoscopic scale is input to determine the relative biological effectiveness of ions in comparison to photons in the biophysical model LEM (Local Effect Model) [3]. Moreover, nanoscopic energy deposition is important for the biological damage of cosmic rays in space [4]. Furthermore, nanoscopic energy deposition is also important for dosimetric assessments, e.g. to determine the efficiency of solid state radiation detectors [5].

To verify transport models for nanoscopic energy deposition, measurements of low energy electron creation and transport are necessary. Few experimental data for low energy (sub-keV) electron production and transport exist [6]. To improve on this situation for solid state targets, the Toroid experiment [7] was designed and performed at GSI, which will be briefly introduced in chapter 2.

One reason for the scarcity of low-energy electron cross section data for solid state targets is that these measurements are difficult to perform and to analyze. In contrast to experiments using gaseous targets, single collision conditions are not fulfilled. In the Toroid experiment thin foils were bombarded with ions or electrons. Although the thinnest foils were only a few nanometer thick, they still contained several atomic layers. Hence, the spectra of created electrons are modified by transport phenomena as the mean free path of low energy electrons is less than the thickness of the target foils. Moreover, solid state targets can be non-uniform and the non-uniformities of the target can lead to substantial differences in the resulting electron spectra. Evidence for the non-uniformity of a thin carbon foil can be seen in Fig. 1. Bräuning et al. [8] took electron microscope images of carbon targets that were made by the GSI target laboratory. They observed, that the thin carbon foils contained small holes and had a rough surface.

To interprete the resulting electron spectra from the Toroid experiment, a simulation code is helpful to model both secondary electron creation and transport. Presumably, Monte Carlo (MC) codes are suitable since in contrast to analytical expressions, they

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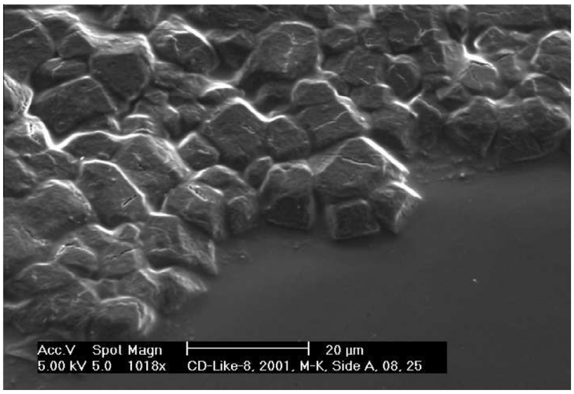

Fig. 1. Electron microscope picture of a thin carbon solid state target on top of a smooth supporting surface exhibiting local non-uniformities (rock-like structure with sizes around 5–10 µm and pinholes) [8].

can deal with the stochastic nature of electron emission and transport as well as complex geometries like those of Fig. 1.

The approach of condensed random walk and multiple scattering are the basis for many conventional simulation packages as introduced by Berger in [9]. In a review of 2006 by Nikjoo et al. [10], several radiation transport and track structure MC codes are presented. A drawback of many MC codes is, especially those designed for condensed random walk, that they have a cutoff energy and a limitation on the travelling distances of the particles they treat. Some are restricted to a few target materials like water or cannot handle both ions and electrons as projectiles. PENELOPE [11,12] for example, is capable to handle electrons and positrons down to 100 eV. Other codes, mentioned in [10], have an even higher cutoff energy limit or are restricted to some biological molecules as target materials. In contrast to codes using condensed histories, track structure codes in principle do not have a limitation on distance size as they calculate each interaction individually. Depending on the implemented cross sections, track structure codes can follow particles down to very low energies.

For the transport of low energy electrons in solids a variety of elaborate simulation codes exist which are mentioned in [13]. Studies on the impact of complex surface geometries on electron backscattering or secondary electron yields have been done before but were restricted mainly to some metal targets [14–17]. However, for the simulation of the Toroid data, we needed a code which is readily available and capable to perform calculations for both ions and electrons in materials such as carbon, nickel, silver and gold. We chose our inhouse TRAX code [18,19] which is a single interaction track structure code and will be briefly presented in chapter 3. Our current implementation uses electron cross sections down to 1–10 eV. Due to the scarcity of appropriate solid state cross sections, most calculations are mainly based on data and theory for gaseous targets. The cross sections (and hence mean free paths) for interactions with solids are scaled by density from gaseous data. A review which explains the method of scaling with the density ratio is given by Rossi [20].

For the analysis of experiments using thin solid state targets, the consideration of the non-uniformity of the target might be crucial. Most MC codes assume the target to be uniform. On the microscopic or even nanoscopic scale this assumption might no longer be fulfilled. A solid-state target can show pin-holes and the surface of the target can be rough. The target could also vary in thickness. In order to reproduce the data from the Toroid experiment, TRAX had to be extended to handle non-uniform targets, as explained in chapter 4.

In order to test these modifications for correctness, we compared our simulation results with experimental data from Verma [21] and others [22–30] for low energy electron backscattering from polished and unpolished carbon foils. The simulation results are discussed in chapter 5. Additionally we present some results for the reproduction of data from the Toroid experiment.

Finally we give a brief summary in chapter 6.

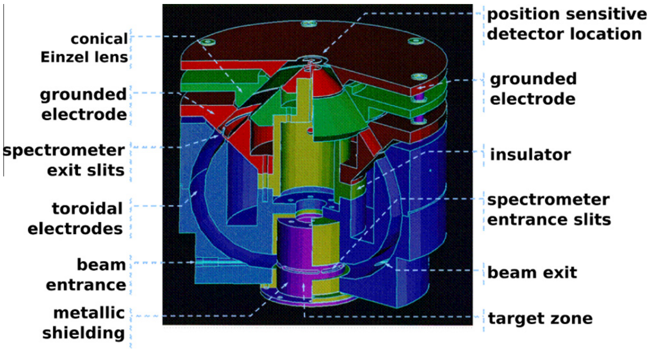

Fig. 2. Layout of the Toroid electron spectrometer with its components. Taken with permission from [7].

2. The Toroid spectrometer

Experiments with the Toroid Spectrometer (see Fig. 2) were performed in the Atomic Physics department at GSI by Lineva et al. [7]. The spectrometer allows to measure angular and energy resolved electron spectra emitted from target foils after ion or electron bombardment. It was designed to perform systematic investigations of low energy (sub-keV) electron emission from solids. The Toroid Spectrometer is suitable to measure low energy electrons down to about 50 eV.

Calibration measurements were performed using 500 eV and 1 keV electrons as projectiles. Thin solid state carbon foils were used as targets. In addition to the carbon foils, nickel, gold and silver targets were irradiated with 3.6 MeV/u and 11.4 MeV/u carbon beams [7].

Even though the targets were only a few nanometers thick, they still contained several atomic layers. Electrons emitted inside the thin target are stopped or slowed down before leaving the target. The resulting electron spectra therefore reflect a combination of electron creation and transport processes.

Experimental data showed evidence for pinholes inside the thin carbon target as transmitted electrons could be detected without any energy loss. Electron microscope pictures of the carbon target confirmed the non-uniform structure of the thin foil (see Fig. 1).

Furthermore, due to the non-uniformities of the target, an effective thickness had to be considered. Simulations reproducing the measured electron emission yields showed that for the 20.7 nm thick carbon target, an effective thickness of 15.9 nm had to be assumed, while for the 48.5 nm thick target the effective thickness has been 23.8 nm. [7]. The problem of methods using effective thicknesses is, that the latter might not be the same for simulations of different processes. Besides that, using an uniform reduced target thickness was not sufficient to explain other deviations between experiment and simulation like a shift in the maximum position of the electron loss peak in the electron spectra detected behind the target.

3. The TRAX code

The MC code TRAX has been developed over several years at GSI [18,19]. It is a track structure code which handles each single interaction individually. Considered are elastic scattering, electronic