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Investigations of heavy-ion tracks' energy deposition inside solid media by methods of x-ray spectroscopy

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Abstract

In this paper, we present experimental results on the excitation of solid-state matter by single, energetic heavy ions. The method of x-ray spectroscopy with spatial resolution along the projectile stopping path inside solids was applied to investigate the state of the medium inside the area of heavy-ion tracks. Spectral data of quartz and aluminium media excited by Ni, Ca and Mg ions from the GSI UNILAC accelerator are presented. The ions' initial energies of 11.4 and 5.9 MeV$/u$ and the beam current on the target in the order of 1 μA were chosen. The observation was focused on relative intensities of K_α satellite lines radiated by Si and Al multicharged ions with different charges. The aerogel medium with extremely low bulk density (0.04 g cc^{-1}) was used to investigate the evolution of target media radiation properties during the projectile ions' stopping and, respectively, the change of the ion's energy deposition into the solids. Due to very short lifetimes of the excited levels for the observed multicharged ions, the data for heavy-ion track area were obtained on tens of femtoseconds time scale after excitation. For further analysis and obtaining quantitative description of heavy-ion track parameters, the methods of numerical simulation are suggested.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

The application of intense heavy-ion beams to generate extreme conditions of high energy density in solid-state matter is a very actual topic. Due to the specific nature of the ion stopping process in matter, ion beams in solids induce plasma states with high temperature and density

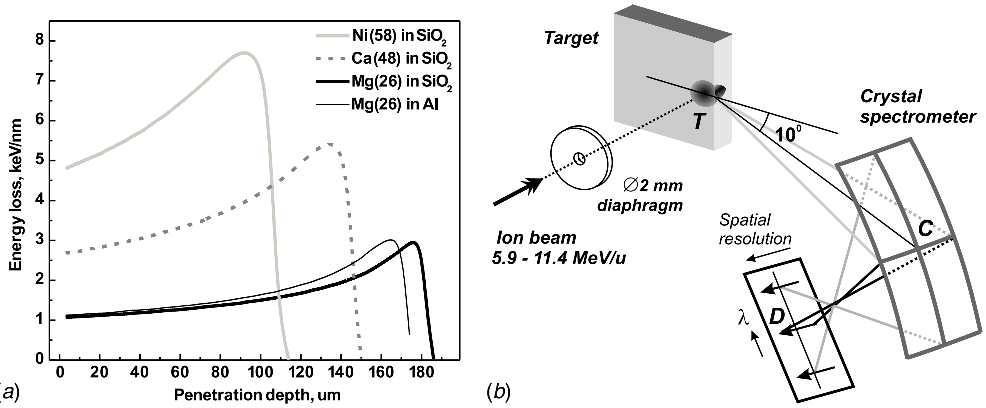

Figure 1. (*a*) Dependences of energy deposition of used heavy ions into solid quartz and aluminium media from penetration depth (calculated by SRIM code [8]). (*b*) Experimental scheme and its main principles. The spectrometer has the spatial resolution along the beam track inside solid media.

(see e.g. [1, 2]). Due to the feature of the Bragg peak at the end of the ion range in matter [3], the local area of energetic impact by ion beams is situated deep inside the solids, which is very useful for a number of applications and fundamental researches.

At the same time, it is well known that the track is formed in solids by a single heavy ion penetrating the matter [4]. The transversal dimensions of the track are much larger than the size of ion itself, which corresponds to the presence of intense load higher than the viscous–elastic limit of matter. It means that the energetic impact from a single projectile ion is sufficient to produce extreme conditions for condensed matter during a very short time after the heavy ion has penetrated.

However, the relaxation time of these extreme conditions is so short that it is necessary for the experimental investigation to use a method which can provide the data obtained immediately after energy deposition of a projectile ion. For that purpose, the registration of x-ray spectra radiated by ionized target atoms was proposed as a diagnostic method due to the very short time-of-life for excited electronic levels (about tens of femtoseconds). For the first time, the K-shell x-ray radiation of a solid target interacting with heavy ions was investigated by Kaufmann *et al* [5]. The quantitative investigations of excited media parameters in the ion track area by methods of radiation kinetics simulations of measured spectra (for principal idea see [6, 7]) are ordered now.

2. Experimental setup

The conditions, which are created within the ion track, are determined mainly by the value of the energetic impact of heavy ion on the unit volume of the media. This value depends on the atomic number and mass of the projectile and on its energy. Therefore, in the experimental setup the following conditions were provided for the complex investigations and the possibilities for further comparative analysis. First, different types ($^{58}Ni^{13+}$, $^{48}Ca^{6+}$, $^{26}Mg^{5+}$) of ions were chosen characterized by different absolute values and dynamics of energy deposition inside the matter (see figure 1(*a*)). Second, it is necessary to have a spatial resolution in the direction of projectile propagation in media, which will allow us to observe the excitation evolution of target media depending on the projectile energy deposition. As a measurement

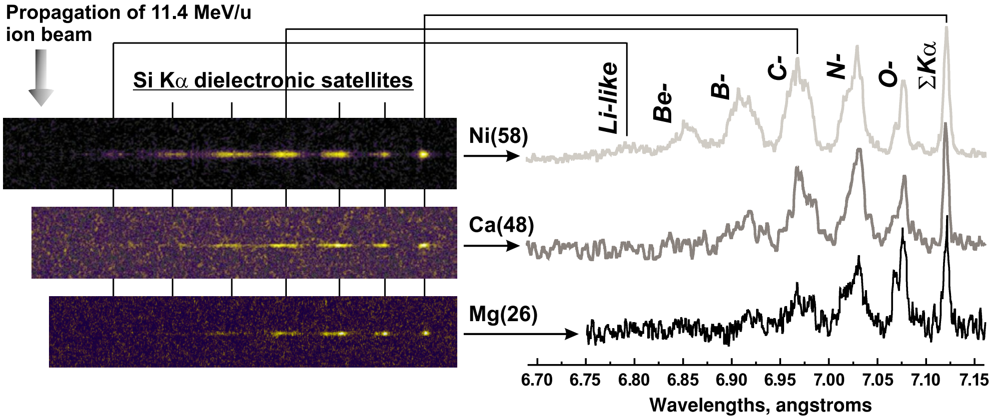

Figure 2. Spectral data of dielectronic satellites to Si K_α transitions in solid quartz media excited by Ni, Ca and Mg ions (from up to down) under the same conditions.

device, the x-ray spectrometer based on spherically bent crystal as dispersive element (FSSR [9]) was used. It provides excellent spectral resolution of $\lambda/\delta\lambda \sim 5000$ and spatial resolution along the beam axis. The experiments were carried out at the UNILAC facility at GSI, Darmstadt. The principal scheme of the experimental setup is shown in figure 1(*b*) and also described in detail in [10, 11]. To provide the independence of each single ion interaction with media, the beam current of about 1 μA was chosen, which corresponds to a repetition rate of 1 ps between two incident ions in the total interaction volume. With that, the area of the beam focal spot (the transversal dimension of volume) was ~3 mm^2, the cross section of single ion interaction with media was about 1 nm^2 and, statistically, each interaction occurred in stable solid matter, undisturbed by previous ions. The exposure time to obtain one spectral data was varied from 1 to 3 h.

3. Quarz media excitation

In the experiments, the spectra of K_α satellite transitions for target ions with different multiplicities of ionization were observed. In figure 2, the spectra of Si ions' radiation during the interaction of three types of projectile ions with solid fused quartz media are shown. Here and further, in the spectra the spatial distribution along the ion beam propagation is represented from top to bottom. In the data, the groups of K-shell transitions in multicharged ions from O- to Li-like are resolved. The transitions in the ions with lower charge are integrated in the right spectral line marked as ΣK_α. It is obvious that the increase of energy deposition to the media (for more massive projectiles—see figure 1(*a*)) results in the appearance of higher charged states for excited atoms. The mean charge of ions is growing up, which corresponds to deeper excitation of heavy-ion track area in condensed media.

In spite of the fact that the diagnostic used in our experiments has the spatial resolution along the ion beam propagation, the total stopping range for the projectile ions with considered energies in solids is essentially short (of about 100 μm). There is a complication to resolve the evolution of radiated spectra along the projectile stopping path with available spatial resolution. To solve this problem, solid media with extremely low bulk density were used, which are formed by the chains of solid quartz beads with nanometre scale and pores with diameter of tens of nm—the aerogel with density of 0.04 g cc^{-1} [12].

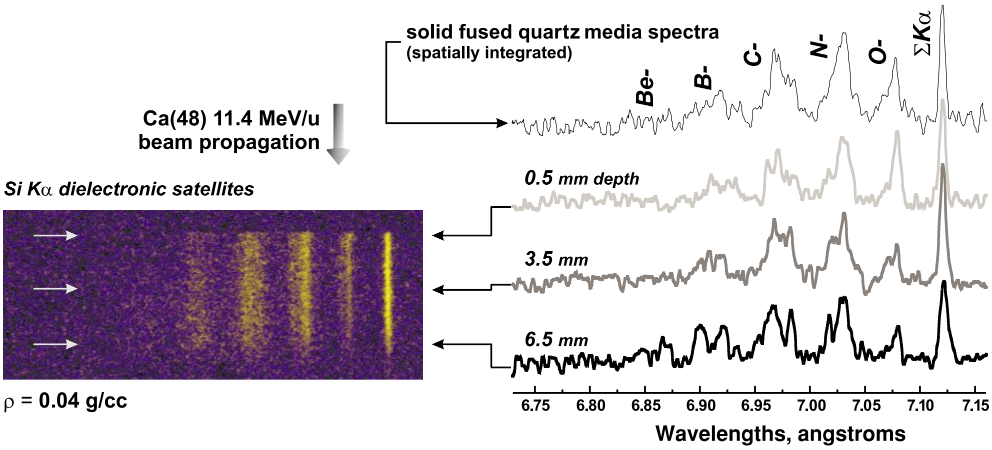

Figure 3. Target K-shell radiation caused by slowing down Ca(48) ions with an initial energy of 11.4 MeV/u. The spatially resolved spectral data are compared for solid quartz and SiO_2 aerogel ($\rho = 0.04$ g cc^{-1}).

For aerogel targets, the stopping range was increased up to 50 times, which allowed us to determine the change of target ionization degree which depends on projectile ions' penetration depth. Experimental data for aerogel media excited by Ca projectile ions with an initial energy of 11.4 MeV/u are presented in figure 3. For this case, the growing of target media mean charge so far the projectile penetrates to the target is seen, due to the increase of L-shell ionization cross sections and projectile energy deposition at lower ion velocities. The principal possibility of adequately representing solid targets by spatially stretched ones such as aerogels is described in detail in [13, 14]. Indeed, the qualitative identity of spatially integrated spectra radiated by solid and aerogel quartz media under the same excitation confirms the correctness of that approach.

4. Aluminium media excitation

The considered process due to the spatial scale of nanometres could be numerically simulated in the part of deposed energy relaxation [15]. To supply that calculation, it is necessary to know the equation of state for condensed matter in the extreme conditions. Because the equation of state for quartz media under shock excitation is not described so precisely, for the further analysis the experiments on Mg ions' energy deposition inside solid aluminium were carried out. Due to the absence of spatially stretched aluminium media and the lack of spatial resolution, the measurements for two initial projectile energies of 11.4 and 5.9 MeV/u were carried out. For the first case, the data acquisition time of only 1 h was chosen, so the spectral data intensity is not enough to observe ion tracks inside the media and the data represent the radiation from the beam entrance target surface and not deeper than 10 μm into the target. By this way, the evolution of the excited media state was obtained, which depends on the projectile ions' energy. The data are presented in figure 4, where the dynamics of increasing the relative intensities for the transitions in higher charge ions (Be-, B-like) is easily seen. It corresponds to increasing the mean charge of ionized target media, because of the growing up of the ionization cross sections and the projectile energy loss inside the media. This picture corresponds to that for solid quartz and aerogels described before. At the present time, the

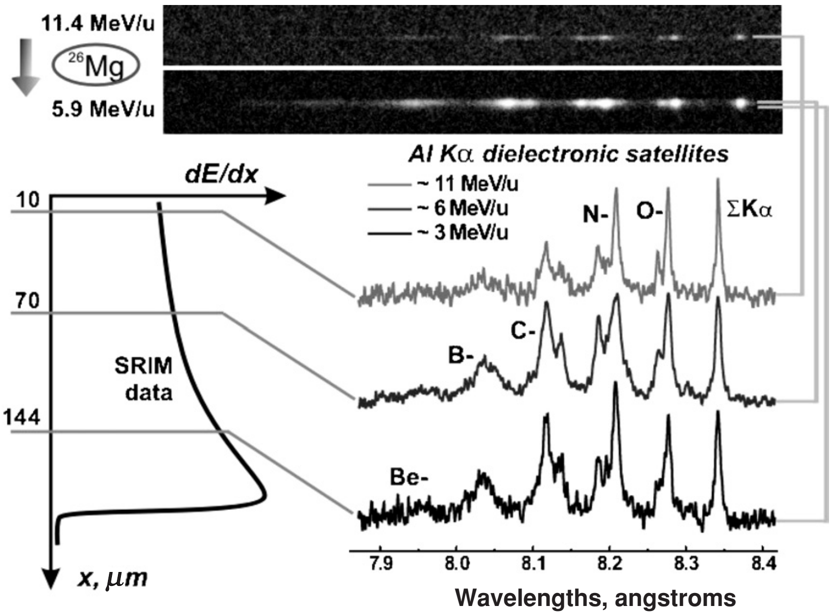

Figure 4. The measured x-ray spectra for solid Al media excited by Mg ion beams with initial energies of 11.4 and 5.9 MeV/u.

quantitative description of obtained experimental data is in progress. For that purpose, the use of numerical simulations of radiation kinetics in multicharged ions and hydrodynamics of single ion track in solids has been proposed in [7].

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