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Analysis of photon emission induced by light and heavy ions in time-of-flight medium energy ion scattering

S. Lohmann *, M.A. Sortica, V. Paneta, D. Primetzhofer

Department of Physics and Astronomy, Ångström Laboratory, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden

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ABSTRACT

We present a systematic analysis of the photon emission observed due to impact of pulsed keV ion beams in time-of-flight medium energy ion scattering (ToF-MEIS) experiments. Hereby, hydrogen, helium and neon ions served as projectiles and thin gold and titanium nitride films on different substrates were employed as target materials. The present experimental evidence indicates that a significant fraction of the photons has energies of around 10 eV, i.e. on the order of typical valence and conduction band transitions in solids. Furthermore, the scaling properties of the photon emission with respect to several experimental parameters were studied. A dependence of the photon yield on the projectile velocity was observed in all experiments. The photon yield exhibits a dependence on the film thickness and the scattering angle, which can be explained by photon production along the path of the incident ion through the material. Additionally, a strong dependence on the projectile type was found with the photon emission being higher for heavier projectiles. This difference is larger than the respective difference in electronic stopping cross section. The photon yield shows a strong material dependence, and according to a comparison of SiO_2 and Si seems to be subject to matrix effects.

1. Introduction

Medium energy ion scattering (MEIS) is an ion-beam based tool that allows for high-resolution depth profiling of structure and composition of materials [1,2]. Hydrogen and helium ions with energies of several ten up to a few hundred keV are commonly employed as probes, and backscattered particles are detected. The first detectors used in MEIS were electrostatic [3,4]. However, in the mid-2000s the combination of a time-of-flight (ToF) system with a position sensitive detector was shown to be a powerful alternative for MEIS analysis [5]. In addition, the usage of pulsed ion beams and a time-resolving micro-channel plate (MCP) detector allows for the observation of secondary particles like photons. Photon emission has been seen in several similar set-ups [6–8], but to our knowledge no systematic analysis of it has been attempted.

X-ray emission caused by incident ion beams forms the basis of another well-established technique: Particle-induced X-ray emission (PIXE), for the identification of elements via their characteristic X-rays [9]. Typically, PIXE employs ion beams of a few MeV as probes and has found, particularly in combination with microbeams, widespread application within materials research, cultural heritage [10], earth sciences [11] and medicine [12]. Sub-MeV ions, thus overlapping with the MEIS energy regime, have also been used for several applications [13,14]. A review of this method called low energy PIXE (LE-PIXE) can be found in [15]. Photon transitions of lower energies, more precisely in the deep ultraviolet (UV) regime, correspond to typical valence and conduction band transitions, and they are thus related to the electronic structure of a material. These transitions can be studied by UV photoelectron spectroscopy (UPS) [16], UV photon excitation by ion beams is, however, scarcely investigated. Unlike the solid state detectors commonly used in PIXE, MCPs can detect deep UV photons with rather high efficiency down to energies of around 7 eV [17]. Within a single classical ion scattering measurement elemental depth profiles and complementary information on deep UV photon transitions can therefore be obtained. In other words, spectroscopy could serve as an additional analytical tool in near-surface science and enhance our understanding of the complex interaction of slow ions with solids.

In this work we present a systematic analysis of photon yields induced by pulsed ion beams. ToF-MEIS experiments employing thin films of Au and TiN as well as Si, C, SiO_2 as bulk and substrate materials were performed. Hereby, hydrogen, helium and neon ions served as projectiles. Estimates – based on experimental

* Corresponding author.
E-mail address: svenja.lohmann@physics.uu.se (S. Lohmann).

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evidence – on the energy and origin of the observed photons are given. In addition, we investigate dependencies on film thickness, target material, scattering angle, incident ion species and velocity.

2. Experiment & sample preparation

Gold thin films were prepared using a MED-010 thin film deposition set-up from Balzers operated in the magnetron sputtering mode. The base pressure was better than 5×10^{-5} mbar, and the argon pressure during sputter deposition was 5×10^{-5} mbar. Silicon (100) wafers and glassy carbon were used as substrate materials.

The polycrystalline TiN film has a NaCl-like B1 cubic structure and was deposited on a Si(100) wafer. It was synthesised via cathodic arc evaporation using an Oerlikon Balzers INGENIA P3e industrial batch coating system. The base pressure was below 5×10^{-5} mbar, and synthesis took place at 420 °C in an Ar/N_2 atmosphere.

The areal thickness of all thin film samples was determined by Rutherford backscattering spectrometry (RBS), while the purity and the stoichiometry of the films were verified with ToF elastic recoil detection analysis (ToF-ERDA). These experiments were performed employing the 5 MV 15SDH-2 Pelletron tandem-accelerator at the Ångström laboratory at Uppsala University. For the RBS studies at hand a 2 MeV $^{4}He^{+}$ beam was used, and backscattered ions were detected under a scattering angle of 170° with a surface barrier detector. The accuracy with which the areal thickness was determined is estimated to be about 4%. ToF-ERDA experiments were carried out with a $^{127}I^{8+}$ beam.

The ToF-MEIS set-up at Ångström laboratory is based on a 350 kV Danfysik implanter. The use of pulsed ion beams and a time-of-flight detection system (time resolution Δt typically 1.0–2.0 ns (unbunched) and 0.3 ns (bunched)) lead to relative energy resolutions $\delta E/E$ of about 0.01–0.02 [18]. In Fig. 1 the detector set-up and the experimental scattering geometry are illustrated. The detector used is a delay line detector (DLD120) from Roentdek [19] and it consists of two stacked MCPs with a diameter of 120 mm and two delay-line anodes (to determine x and y position). The detector can be rotated on a circular path around the sample, and the radius of this circle, i.e. the distance from the scattering point to the centre of the detector, is 290 mm. This set-up results in a total solid angle covered by the detector of 0.13 sr and the possibility to detect particles at a large range of scattering angles. A time-to-digital converter determines the flight time, which is given as the difference between a signal from the electrostatic chopper and the signal when a particle hits the MCP. MCPs are sensitive to ions, neutral particles, electrons, UV rays and X-rays [17], however, the ToF technique does not allow to determine the energy of UV and X-rays. Therefore, the absolute number of photons reaching the detector can be counted, but no spectroscopy can be performed. More details on the experimental set-up can be found in [6].

An example of raw data from a ToF-MEIS measurement with 80 keV H_2^+ ions directed at the TiN film is shown in Fig. 2. At longer flight times, seen on the left of the spectrum, the particles backscattered from the substrate and the film are detected. Note that the typical combination of keV ions with very thin films implicates that the beam is not stopped in the film. On the contrary, it only transfers a small amount of its initial energy. At shorter flight times (on the right side of the spectrum) a very narrow photon peak can be observed. Photons need 1 ns from the sample to the detector. From this information the actual flight time and thus the energy of the backscattered particles can be determined. The inset of Fig. 2 illustrates the width of the photon peak, which is found identical to the time resolution of the system.

3. Results

3.1. Analysis of photon yields

For a thin film target, the yield of produced photons of a specific energy E can be written as

$$dY(E) = N_I N_t \sigma(E), \tag{1}$$

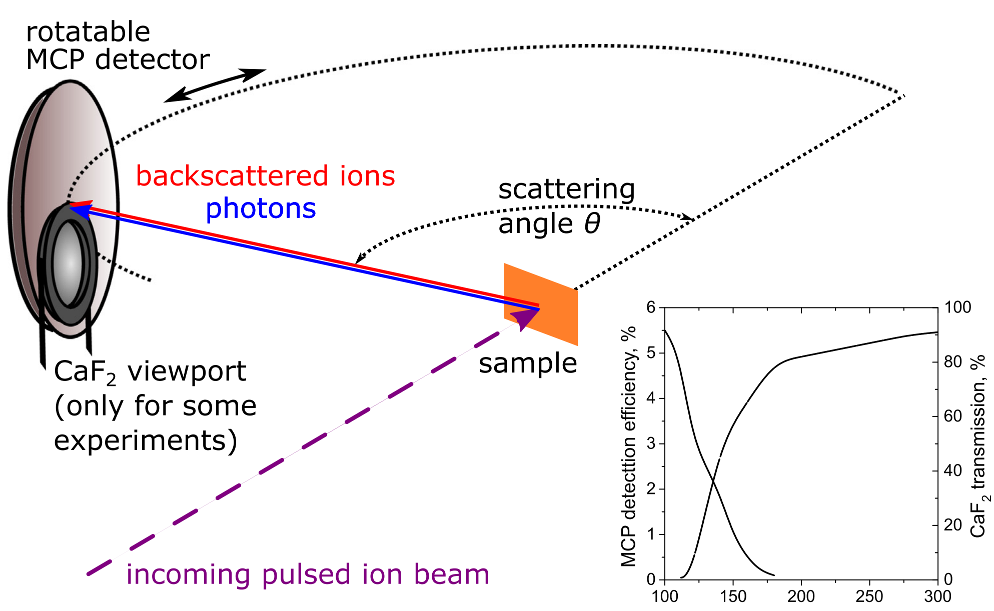

Fig. 1. Sketch of the experimental geometry inside the MEIS scattering chamber. The detector used is a delay line detector (DLD120) from Roentdek, which consists of two stacked MCPs. The detector can be rotated on a circular path with a radius of 290 mm around the scattering point. This enables varying the angle θ, under which backscattered particles and emitted photons are detected. For a specific set of experiments, performed to investigate the photon energies, a calcium fluoride (CaF_2) view port (Hositrad, HOBVPZ38CaF2) was mounted in front of the detector to partly mask its active area. The inset shows a typical MCP detection efficiency curve and a transmission curve for the CaF_2 viewport in the UV wavelength range. Note that both curves are approximations based on literature, which can vary for the used set-up. For more details see text.