AN X-RAY METHOD FOR IDENTIFICATION OF THE ATOMIC NUMBER OF THE ACCELERATED HEAVY ION BEAMS*

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Accelerated heavy ions are identified by the characteristic X-rays they emit as a result of inelastic collisions with target atoms. Detection sensitivity of the projectiles passing thin carbon foils is discussed.

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1. Introduction

Swift ions slowing down in the matter (among other effects) cause the emission of X-rays characteristic of both the projectiles and the target atoms due to filling of inner-shell vacancies. The X-ray spectra emitted by fast heavy ions ($Z \geq 12$) as they traverse matter are useful tool for testing the atomic number of the ions passing the target. Characteristic X-rays have been used as a method for detection and identification of ions in accelerator mass spectrometry so called PXAMS (Projectile X-ray Accelerator Mass Spectrometry) [1].

In this paper we would like to present a simple and fast method for Z-value determination of heavy ions accelerated by tandem Van de Graaff accelerators and cyclotrons. This problem is particularly important for heavy ions emitted from tandem accelerator sputtering ion sources with small mass resolution injection system.

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2. Experimental procedure

In our experiments projectiles of S^{q+}, Ti^{q+}, and Fe^{q+} at various energies were provided by the tandem accelerator at Erlangen-Nürnberg University and S^{q+} by U-200P cyclotron at the Heavy Ion Laboratory of the Warsaw University. The Erlangen tandem is equipped with a 20° entrance magnet with relatively poor mass resolution and with two 90° exit magnets. The exit deflection system filters out particles of constant magnetic rigidity ($mE/q^2 =$ const). In most cases this eliminates all mass impurities in the beam. It is obvious, however, that magnetic selection alone does not guarantee a unique mass, *e.g.* the $^{48}Ti^{6+}$ ions have the same magnetic rigidity as the $^{56}Fe^{7+}$ ones for the same ion velocity ($v = \sqrt{2E/m}$). With this problem we have met during our experiments when we accelerated Ti and Fe ions.

Heavy ion beams with a typical intensity about 1 nA, after collimation to a diameter of 2 mm produced X-rays passing a thin (30 and 70 μg/cm^2) carbon target tilted at 30° to the beam direction. The X-rays were detected by a 30 mm^2 Si(Li) detector placed perpendicularly to the beam direction outside the target chamber, while elastically scattered ions were detected at 150° (or for light targets with mass $M_{\rm T} < M_{\rm HI}$ at forward angle) by a Si detector for normalisation purposes. The geometry of the experiment is shown in Fig. 1. Further details concerning the measurements can be found

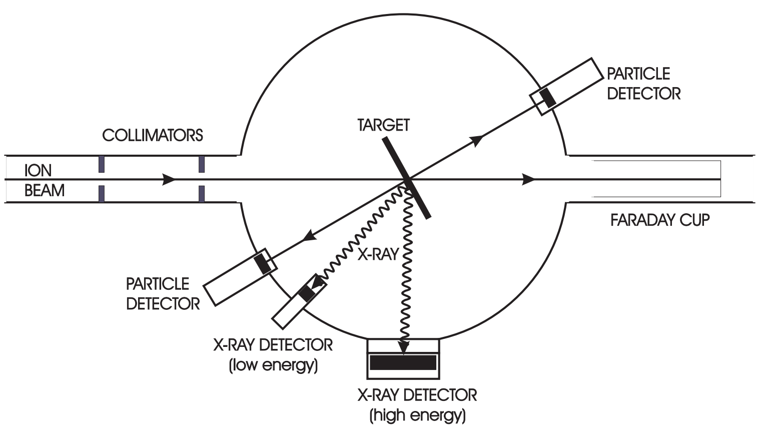

Fig. 1. Schematic (not to scale) diagram of the experimental arrangement.

elsewhere [2,3]. The X-rays emerged from the vacuum chamber through the 25 μm mylar window and passed a few millimetre air gap before striking the 25 μm Be window of the Si(Li) X-ray detector with the energy resolution of about 180 eV for 6.4 keV X-rays.

3. Results

Typical X-ray spectra emitted by S, Ti and Fe projectiles with 0.7 MeV/u energies passing the 30 μg/cm^2 carbon target are shown in Fig. 2(a), (b), (c), respectively. The purity of the foil was tested by PIXE method (shown in Fig. 2(d)) using 3 MeV protons and the presence of Al, S, Ca, Mn, and Fe elements was proved. The impurity levels of these elements are less than few ng/cm^2. The measured values of K_α X-rays energies of highly

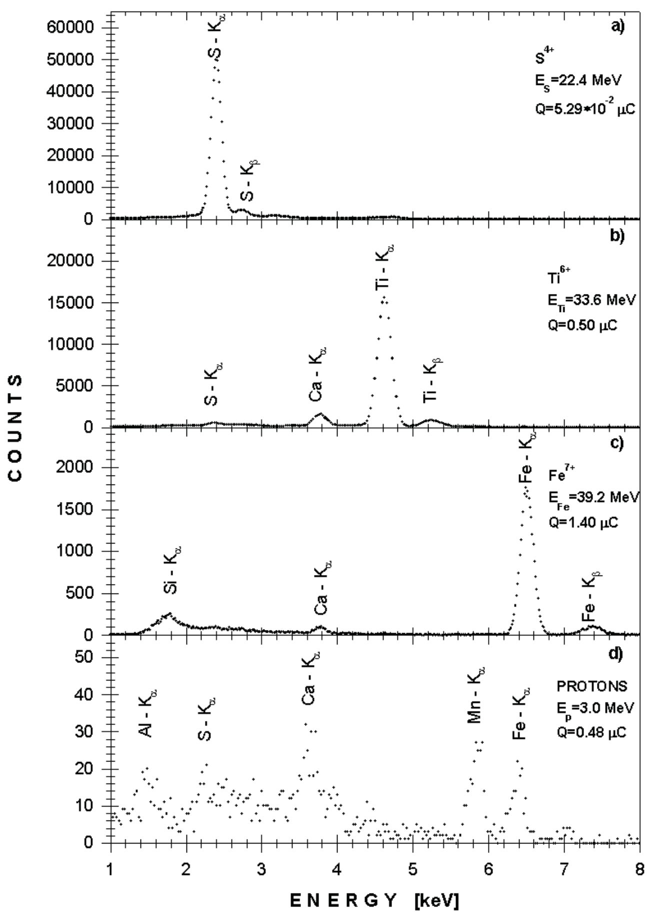

Fig. 2. The X-rays spectra of a thin carbon foil bombarded by S (a), Ti (b), Fe (c), and protons (d).

ionised sulphur, titanium and iron projectiles passing through carbon foil are presented in Table I, together with the projectiles energies (MeV/u), average equilibrium charge state $\bar{q}$ (according the Ref. [4]) and diagram values of the K_α X-ray energies [5].

TABLE I

The parameters of K_α X-ray spectra from highly ionised projectiles (S, Ti, and Fe) passing through thin carbon foil of different incident energy and average equilibrium charge state $\bar{q}$.

Incident energy [MeV/u]	S^{q+} ions		Ti^{q+} ions		Fe^{q+} ions	
	$\bar{q}$	K_α energy (keV)	$\bar{q}$	K_α energy (keV)	$\bar{q}$	K_α energy (keV)
—	—	2.308*)	—	4.511*)	—	6.404*)
0.3	7.8±0.1	2.353±0.009	10.5±0.1	4.569±0.009	12.0±0.1	6.461±0.010
0.5	9.1±0.1	2.371±0.009	12.2±0.1	4.592±0.009	14.2±0.1	6.475±0.010
0.7	9.9±0.1	2.388±0.009	13.3±0.1	4.611±0.009	15.5±0.1	6.501±0.010
1.0	10.8±0.1	2.390±0.008				
1.2	11.3±0.1	2.408±0.008				
2.1	12.7±0.1	2.410±0.010				
3.1	13.7±0.1	2.421±0.010				
3.8	14.3±0.1	2.422±0.010				

*) diagram values of the K_α X-rays lines according the Ref. [5] for S, Ti, and Fe, respectively.

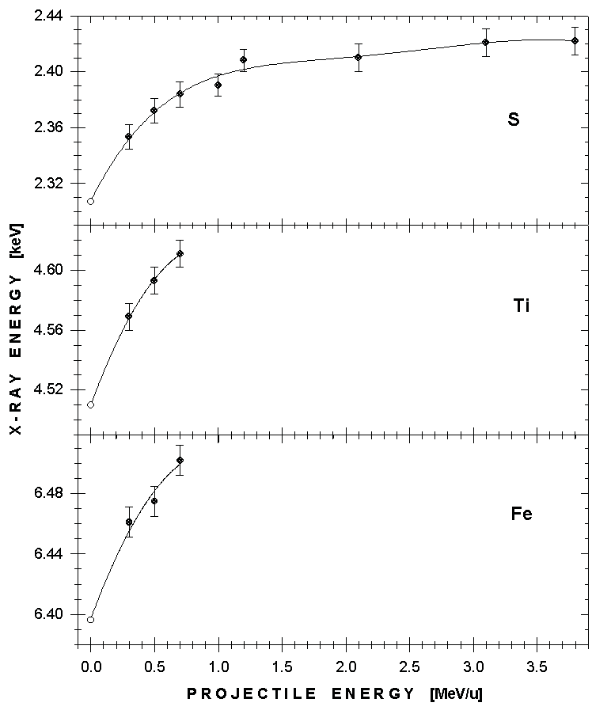

Fig. 3. Experimental K_α energy for S, Ti, and Fe projectiles passing the 30 μg/cm^2 carbon foil (black circles). The open circles indicate the diagram values of the K_α X-ray lines [5]. The solid lines are the results of the polynomial fit.

According to Ref. [4, 6] heavy ions are highly ionised when they pass through the target. In our experiments its thickness is much enough to provide an equilibrium charge state distribution. The effective charge state of the projectile depends on its energy and produces an energy shift of the emitted characteristic X-rays relative to the diagram values [5]. The energy shifts of the K_α X-ray lines are the same for both carbon foils used and justify the assumption that the 30 μg/cm^2 carbon foil is thick enough to obtain charge state equilibrium. In Fig. 3 we present the dependence of the energy of the K_α lines emitted by S, Ti, and Fe ions passing through the carbon target relative to their bombarding energies. The open circles in Fig. 3 indicate the K_α diagram energies [5] of the projectiles (S, Ti, and Fe). From this figure and Table I it can be seen that the K_α energy shifts are significant and increase with increasing beam energy, which means that the incident projectiles are multiply ionised in the L and M shells at the time of emission of the K X-rays. As shown in Refs. [7, 8] the energy shifts of the $K_{\alpha\beta}$ X-rays for sulphur ions versus incident energy are explained (on the basis of single configuration Dirac–Fock calculation) by removing electrons from L and M shells.

The sensitivity of the method is limited by the competition between the emission of X-rays from the projectile, from the target trace elements and the background radiation from the target.

In the spectrum shown in Fig. 2(a) the detector solid angle was $\Delta\Omega = 2.9 \times 10^{-3}$ sr, the target thickness $t_z = 30$ μg/cm^2, and the accumulated charge $Q = 5.29 \times 10^{-2}$ μC (corresponding to $N_p = 8.26 \times 10^{10}$ particles of S^{4+}). Thus the ratio of the number of incident particles N_p to the number of recorded X-rays is $N_p/N_x \cong 1.03 \times 10^5$. This value for higher energy of S ions (32 MeV) is 1×10^4. Significant improvements in sensitivity (about 10^3) can be easily realised by increasing the solid angle of the X-rays detector to 10^{-1} sr, by increasing 2–3 times the thickness of carbon foil, and reducing the absorption of the X-rays on their way from the target to the detector. In the case when windowless X-ray detector will be located as closed as possible to the target the detections of X-rays can reach 1 X-ray photon per few incident ions. It is close to the result published by McAninch *et al.* [1].

4. Conclusions.

The results reported here indicate that characteristic X-rays provide an effective tool for the "on-line" identification of the atomic number of the projectiles (with $Z \geq 12$) and for detection with high efficiency extremely weak (*e.g.* 10^3 p/s) ion beams. The detection efficiency strongly depends on the geometry of the measurements, energy of the projectiles, target foils thickness and from the attenuation of the X-rays on their way from the target to the detector. For practical reasons it is necessary to use thin, pure, and light element targets (to reduce the interfering X-ray peaks) for example: clean C or Al foil with thicknesses of 20–40 μg/cm^2.

Additionally X-rays emitted by S ions can be observed when projectiles pass the target chamber (without carbon foil) with relatively poor vacuum (few 10^{-5} Torr), see Fig. 4. In this case sensitivity is few orders of magnitude smaller in comparison when carbon foil is used.

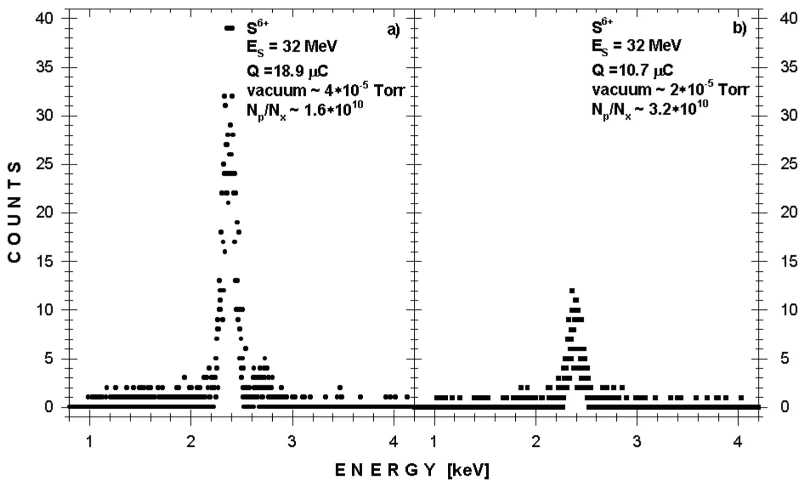

Fig. 4. The X-rays spectra measured by Si(Li) detector from the 32 MeV, S^{6+} ions passing the target chamber with vacuum 4×10^{-5} Torr (a), and 2×10^{-5} Torr (b), respectively.

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