



K-, L- and M-shell X-ray productions induced by oxygen ions in the 0.8–1.6 MeV/amu range



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ABSTRACT

The X-ray production cross sections induced by oxygen ions with projectile energies from 12.8 to 25.6 MeV for the elements from Al to Bi were measured. The applied approach is based on calculation of X-ray production cross sections through the cross section of Rutherford backscattering, which can be calculated with high accuracy using the Rutherford formula. The experimental results are compared to the predictions of ECPSSR and PWBA theories calculated with the ISICS code.

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1. Introduction

Particle induced X-ray emission (PIXE) is a powerful non-destructive elemental analysis technique currently used routinely for determination of major, minor and trace constituents of metallurgical, biological, environmental and other samples [1–4]. The PIXE technique provides simultaneous analysis of 72 elements from sodium to uranium on the periodic table in various samples. The PIXE technique offers the advantage of analysis without the necessity for sample preparation, thereby minimizing the potential errors resulting from sample preparation.

As a rule, proton and helium beams with the energies in the range of 1–3 MeV are used for analysis with the PIXE technique. It can be explained by widespread application of light ion accelerators in the world and simplicity of the X-ray spectra obtained using the advanced software. Recently, however, the research groups working on the accelerated beams of charged particles show a growing interest for heavy ions application (HIPIXE technique). In this case, a greater production of characteristic X-rays per incident ion can provide the improving PIXE sensitivity [5–8]. As shown in [5], the analysis of heavy water samples from the nuclear power plant with 50 MeV ¹⁶O can provide the detection limit less than 0.01 ppb (part per billion) for the chemical elements

from Cr to Zn. Such sensitivity is not available not only for the proton induced X-ray emission technique, but for ICP MS technique that is normally used for water analysis.

The main features of HIPIXE technique, restraining its application for analytical goals, are the limited X-ray production cross sections database and the complexity of X-ray spectra processing. In recent years, several research groups have obtained the experimental data on X-ray productions in the interaction of heavy ions with target atoms [9–12]. However, these works are sporadic yet. The complexity of HIPIXE spectra processing is explained by shifting and broadening of X-ray lines as the result of multiple ionization effect of the target atoms. Therefore, for analytical goals it is advisable to use the relatively light ions like C, N, O, for which this effect is not so much significant.

The aim of this work is updating of the database for oxygen induced X-ray production cross sections. The K-shell X-ray production cross sections of thirteen thin films Al, Ti, Cr, Cu, Zn, Zr, Nb, Mo, Ag, Cd, In, Sn, Sb, L-shell X-ray productions of the targets Zn, Zr, Nb, Mo, Ag, Cd, In, Sn, Sb, Ta, W, Pb, Bi and M-shell X-ray productions of the targets Ta, W, Pb and Bi induced by ¹⁶O with incident energies ranging from 12.8 to 25.6 MeV with the step of 3.2 MeV were obtained. The X-ray productions were calculated through the Rutherford backscattering cross sections which can be calculated from the Rutherford formula with high accuracy. This approach eliminates the uncertainties associated with target thickness and charge collection. The obtained experimental data were compared with the theoretical values calculated within the framework of

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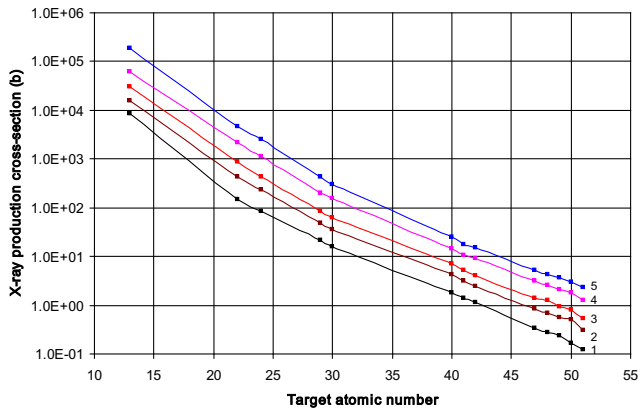


Fig. 1. Energy variations of ^{16}O induced K_{tot} X-ray production cross sections (1–12.8 MeV, 2–16.0 MeV, 3–19.2 MeV, 4–22.4 MeV, 5–25.6 MeV).

Plane Wave Born Approximation (PWBA) and its improved model – ECPSSR theory. The theoretical values were obtained by us using the ISICS code [13].

2. Results and discussion

Reference [14], where inner-shell X-ray production by argon ions was reported, provides a detailed description of the experimental set up. Using the efficiency curve as shown in Fig. 1 therein, X-ray production cross sections extracted and the data uncertainties are calculated as given by Eqs. (1)–(4) in [14].

Tables 1 (K-line), 2 (L-line) and 3 (M-line) include both individual and total X-ray cross sections of the K_{tot} , L_{tot} and M_{tot} series respectively, being the sum of the individual lines for 12.8 MeV, 16.0 MeV $^{16}\text{O}^{2+}$ and 19.2 MeV, 22.4 MeV and 25.6 MeV $^{16}\text{O}^{3+}$. In some cases, only the group of lines can be identified since the energy separation between some X-ray lines of one element is

Table 1

The measured and theoretical calculated K-shell X-ray production cross sections (in barns).

Target	E (MeV)	K_{α}	K_{β}	K_{tot}	K_{tot} ECPSSR	K_{tot} PWBA
Al	12.8			8360 ± 1350	27,000	34,100
	16.0			15,600 ± 3000	44,500	42,800
	19.2			30,300 ± 5800	60,500	49,900
	22.4			61,000 ± 12,000	73,800	55,700
	25.6			189,000 ± 41,000	84,300	60,300
Ti	12.8	133 ± 14	18.0 ± 1.9	151 ± 14	300	2640
	16.0	375 ± 40	57.5 ± 6.2	432 ± 41	793	4270
	19.2	744 ± 80	122 ± 13	866 ± 81	1650	6100
	22.4	1930 ± 250	285 ± 36	2220 ± 170	2900	8050
	25.6	4030 ± 690	660 ± 110	4690 ± 700	4520	10,000
Cr	12.8	72.2 ± 7.8	11.2 ± 1.2	83.4 ± 7.9	138	1490
	16.0	197 ± 22	32.4 ± 3.5	230 ± 22	369	2510
	19.2	362 ± 39	61.7 ± 6.7	424 ± 40	787	3720
	22.4	940 ± 120	169 ± 21	1110 ± 120	1430	5050
	25.6	2190 ± 260	398 ± 47	2580 ± 260	2310	6470
Cu	12.8	18.3 ± 2.0	2.82 ± 0.32	21.1 ± 2.0	26.3	355
	16.0	40.9 ± 4.4	6.64 ± 0.72	47.6 ± 4.4	69.2	654
	19.2	71.0 ± 7.6	21.0 ± 1.3	82.9 ± 7.7	149	1040
	22.4	173 ± 19	30.9 ± 3.4	204 ± 19	280	1510
	25.6	368 ± 41	66.4 ± 7.5	435 ± 42	474	2040
Zn	12.8	13.4 ± 1.5	2.14 ± 0.27	15.6 ± 1.5	19.6	267
	16.0	30.5 ± 3.3	4.99 ± 0.54	35.5 ± 3.3	51.2	498
	19.2	54.0 ± 5.8	9.35 ± 1.02	63.4 ± 5.9	110	804
	22.4	130 ± 15	22.1 ± 2.5	152 ± 15	207	1180
	25.6	250 ± 28	44.9 ± 5.0	295 ± 28	351	1610
Zr	12.8	1.51 ± 0.16	0.295 ± 0.035	1.80 ± 0.17	1.49	15.7
	16.0	3.55 ± 0.38	0.610 ± 0.082	4.16 ± 0.39	3.72	32.7
	19.2	5.81 ± 0.63	1.22 ± 0.15	7.03 ± 0.65	7.75	58.1
	22.4	12.0 ± 1.3	2.34 ± 0.29	14.3 ± 1.3	14.3	92.7
	25.6	21.0 ± 2.3	2.83 ± 0.50	24.8 ± 2.4	24.1	137
Nb	12.8	1.19 ± 0.13	0.207 ± 0.025	1.40 ± 0.13	1.19	12.0
	16.0	2.60 ± 0.28	0.489 ± 0.062	3.09 ± 0.29	2.96	25.1
	19.2	4.28 ± 0.46	0.89 ± 0.11	5.17 ± 0.48	6.16	45.0
	22.4	8.98 ± 0.97	1.73 ± 0.23	10.7 ± 1.0	11.3	72.2
	25.6	14.6 ± 1.6	3.05 ± 0.39	17.7 ± 1.7	19.1	107
Mo	12.8	0.964 ± 0.104	0.195 ± 0.022	1.16 ± 0.11	0.96	9.22
	16.0	2.04 ± 0.22	0.423 ± 0.051	2.46 ± 0.23	2.39	19.5
	19.2	3.34 ± 0.36	0.687 ± 0.084	4.03 ± 0.37	4.95	35.0
	22.4	7.49 ± 0.81	1.48 ± 0.19	8.97 ± 0.81	9.08	56.6
	25.6	12.6 ± 1.4	2.39 ± 0.33	15.0 ± 1.4	15.3	84.7
Ag	12.8	0.278 ± 0.030	0.054 ± 0.008	0.332 ± 0.031	0.330	2.43
	16.0	0.685 ± 0.076	0.176 ± 0.024	0.861 ± 0.079	0.866	5.54
	19.2	1.13 ± 0.12	0.290 ± 0.043	1.42 ± 0.13	1.77	10.3
	22.4	2.65 ± 0.29	0.497 ± 0.076	3.15 ± 0.30	3.22	17.0
	25.6	3.52 ± 0.38	1.60 ± 0.19	5.12 ± 0.42	5.36	26.1
Cd	12.8	0.241 ± 0.028	0.033 ± 0.012	0.274 ± 0.031	0.293	1.99
	16.0	0.548 ± 0.061	0.117 ± 0.019	0.665 ± 0.064	0.719	4.35

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