X-RAY PRODUCTION BY Pt AND Os PROJECTILES MOVING IN THICK Fe TARGETS WITH $E_p = 17 - 30$ MeV

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X-ray spectra produced by Pt and Os bombardment of Fe targets have been measured in the projectile energy range of $E_p = 17$ to $30$ MeV. The thick target yields of the Fe K-shell and Pt and Os M-shells were analyzed within the Landau–Zener model. M-vacancy fractions, their respective lifetimes, and the level-crossing radii for the Pt-Fe and Os-Fe encounters were deduced. The results are discussed with emphasis on the mechanism of transient magnetic fields.

1. Introduction

The excitation and decay of inner shell vacancies, created by projectiles traversing thick targets, have been studied extensively in the past [1]. Recently, efforts have been made by authors [2] who are mainly interested in understanding transient magnetic fields, in order to use this phenomenon as a tool for the measurement of magnetic moments.

Transient magnetic fields, experienced by ions traversing ferromagnetic materials, are attributed to polarized electrons populating bound states of the moving ion [3], and their strength is usually estimated by means of empirical relations [4]. Recently, an anomaly was found to occur in the Os-Pt region for ions passing through iron [5,6]. This effect was explained by some authors [7] as resulting from vacancies in the 6h shell of the united atom (Pt or Os plus the iron host) which are transferred according to the Eichler [8] rules to the 4s shell of the separated Pt or Os ion (fig. 1). In the case of Pt (but not of Os), the 4s transferred vacancy is shared with the 2p shell of iron, thereby reducing the transient field. Alternatively, the anomaly was attributed by other authors [9] to a lack of reliable Pt g-factors, measured through techniques independent of transient fields. A g-factor was proposed which cancels out
any anomaly in the $Z = 76-78$ region. This $g$ value was deduced under the assumption of no atomic fluctuations in the Os-Fe and the Pt-Fe interaction.

The aim of the present study is to obtain an insight into the creation of bound vacancies in heavy projectiles and also to distinguish any possible differentiation in the Os-Fe, Pt-Fe atomic interactions. This could be used for the prediction of the Os-Fe and Pt-Fe transient fields.

2. Experimental setup and results

Os and Pt beams were provided by the T11/25 tandem Van de Graaff accelerator of the Nuclear Research Center Democritos in the energy range between 17 MeV and 30 MeV, which covers the ion recoiling energies met in the transient field parametrizations. The momentum analyzed beams were used to bombard a thick Fe target placed in a T-shaped target chamber (fig. 2). The target was placed at a $45^\circ$ angle with respect to the beam, with the beam spot facing the detector. The X-rays produced were detected by an Si(Li) detector positioned in front of a Be window.
approximately 1.4 mg/cm$^2$ thick. The T-shaped chamber was electrically insulated from the rest of the beam tube and served as a Faraday cup for monitoring the beam current on the target ($\approx$ 1 nA). The beam was defined by two circular tantalum apertures placed upstream at distances of 30 cm and 60 cm from the target. The resulting beam spot area on the target was approximately 3 mm in diameter. The detector crystal thickness was 3 mm with an active area of 25 mm$^2$, and was placed behind a 1.4 mg/cm$^2$ entrance window. Standard electronics were employed for the accumulation of the data in a Prime 750 on-line computer.

A typical X-ray spectrum resulting from the bombardment of the Fe target with Os projectiles is shown in fig. 3. The two main peaks at 1.95 keV and 6.35 keV correspond to the de-excitation of the M-shell vacancies in Os ions and the K-shell vacancies in Fe target atoms, respectively. Initially, X-ray spectra were taken up to the energy of 20 keV. Since no peaks were observed in the high-energy part, all spectra collected subsequently were limited in energy ranges similar to the one shown in fig. 3.

In the reduction of the data, the two characteristic peaks were integrated and the results normalized with respect to the measured target current, the solid angle, the efficiency of the Si(Li) detector, and a factor (0.57 for 2 keV X-rays and 0.97 for 6 keV X-rays) due to the attenuation of X-rays in air. The efficiency of the Si(Li) detector in the range of 1–20 keV was measured through proton induced
Fig. 3. X-ray spectrum due to the bombardment of an Fe target with Os projectiles at $E_p = 27$ MeV. The low-energy part is suitably enlarged.

Table 1

Normalized X-ray yields from Pt-Fe per incoming particle from Pt-Fe and Os-Fe systems

<table>
<thead>
<tr>
<th>$E$ (MeV)</th>
<th>Pt-Fe $\times 10^{-2}$</th>
<th>Target $\times 10^{-3}$</th>
<th>$E$ (MeV)</th>
<th>Projectile $\times 10^{-2}$</th>
<th>Target $\times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.6</td>
<td>0.30</td>
<td>0.37</td>
<td>23.8</td>
<td>0.27</td>
<td>0.31</td>
</tr>
<tr>
<td>19</td>
<td>0.34</td>
<td>0.39</td>
<td>25.2</td>
<td>0.30</td>
<td>0.32</td>
</tr>
<tr>
<td>27</td>
<td>0.43</td>
<td>0.46</td>
<td>26.6</td>
<td>0.38</td>
<td>0.40</td>
</tr>
<tr>
<td>28.8</td>
<td>0.57</td>
<td>0.57</td>
<td>27.6</td>
<td>0.43</td>
<td>0.44</td>
</tr>
<tr>
<td>30</td>
<td>0.60</td>
<td>0.60</td>
<td>30</td>
<td>0.48</td>
<td>0.46</td>
</tr>
</tbody>
</table>
X-rays from thin targets, using known ionization cross sections [10] and fluorescence yields [11]. In particular, the detector efficiency was determined as 0.64 at $E = 2$ keV and 1.0 at $E = 6$ keV.

The normalized yields are shown in table 1 for both target and projectile X-rays, respectively.

3. Data reduction procedure

For the interpretation of the data, we have adopted the model described by Fortner and Garcia [12]. According to this model, if $f_1$ is the fraction of projectiles carrying one inner-shell vacancy, $N$ is the target-atom density, $u$ is the velocity of the projectile, $\tau$ is the mean life of the projectile's inner-shell vacancy, and $\sigma(x)$ is the cross section for the production of an M-shell vacancy in an Os(Pt)-Fe collision, then

$$\frac{df_1(x)}{dx} = N\sigma(x)(1 - f_1(x)) - \frac{f_1(x)}{u(x)\tau}$$

and

$$T_x = \frac{w_k}{N} \int_{0}^{x_0} f_1(x) \sigma(x) e^{-\mu_t x} dx$$

$$P_x = \frac{\bar{w}_p}{\mu_p} \left( \int_{0}^{x_0} \frac{f_1(x)}{u(x)\tau} e^{-\mu_p x} dx + f_1(x_0) e^{-\mu_p x} \right),$$

where $w_k$ is the Fe K-shell fluorescence yield, $w_p$ is the Os(Pt) M-shell mean fluorescence yield, $x_0$ is the total projectile range, $\mu_t$ and $\mu_p$ are the attenuation coefficients for K X-rays (target) and M X-rays (projectile), and $T_x, P_x$ are the target and the projectile yields, respectively.

In the present experiment with atomic numbers $Z_1 = 76 - 78$, $Z_2 = 26$ and projectile velocity $v \approx 2v_0$ (where $v_0$ is the Bohr velocity), the excitation of the bound shells proceeds via a molecular orbital (MO) process (see fig. 6.1 in ref. [1]). By assuming, in the framework of the Landau–Zener theory [13], that the electron transitions occur at the electronic state level crossing, and following Fortner et al. [14], the vacancy production cross section $\sigma(x)$ may be expressed as

$$\sigma(x) = 4\pi \alpha r_x^2 \left[ 1 - V(r_x)/E \right]$$

$$= \left[ Q_3 \left( \frac{2}{\mu} \left[ E - V(r_x) \right] \right)^{1/2} \right] - Q_3 \left( \frac{2}{\mu} \left[ E - V(r_x) \right] \right)^{1/2} ,$$

(4)
where

\[ Q_n(x) = \int_1^\infty e^{-xt} t^{-n} dt \]  

(5)

\[ V(r_x) = (Z_1 Z_2 e^2/r_x) \exp \left(-\frac{r_x}{a}\right), \]

\[ a = \frac{0.53 \times 10^{-8} \text{ cm}}{[Z_1^{2/3} + Z_2^{2/3}]^{1/2}}. \]  

(6)

In eq. (4), \( r_x \) is the level-crossing radius (the internuclear distance between the ion and the atom at level crossings), \( \alpha \) is the probability that an Os(Pt)-Fe configuration is formed so as to give rise to the creation of an inner shell vacancy, \( E \) is the ion energy in the center-of-mass system, \( \mu \) is the reduced mass of the projectile-target system, and \( y \) is a velocity scale factor which, according to the Landau–Zener theory, is given by

\[ y = 2\pi H^2/(d\epsilon/dR), \quad P = e^{-y}, \quad y \text{ in a.u.}, \]  

(7)

with \( H \) the off-diagonal matrix element coupling the crossing states, \( \epsilon \) the energy splitting between unperturbed MO states, and \( P \) the transition probability [15].

4. Results

The experimental data contained in table 1 were least-square fitted to eqs. (2) and (3). The fractions \( f_i \) were determined by numerically solving eq. (1) for various values of \( \tau \) and \( r_x \), while the quantitites \( \tau, r_x, \mu, w, \) and \( \alpha \) were taken as free parameters. The fit was first performed on the target data where only one subshell (K-shell) is involved in the interaction and the fluorescence yield is known to be \( \omega_t = 0.34 \) [16]. The results of the fit are summarized in table 2. A second fit on the projectile data with the probability \( \alpha \) taken from table 2 confirmed the results of the first fit. Results of the latter fit are shown in table 3.

5. Discussion and conclusions

Since there is no evidence in the Pt and Os spectra of L-shell X-rays, it is deduced that up to 30 MeV projectile energy the lowest open shell in the (Os, Pt)-Fe interaction is the M-shell. With regard to the subshell population in this shell, there is strong evidence in the spectra only of the M4 and M5 components which, however, are not resolved by the detector. However, according to Bambynek et al. [16],
Table 2
Parameters obtained from iron targets bombarded by platinum and osmium ions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fe (Pt)</th>
<th>Fe (Os)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$</td>
<td>$(1.5 \pm 0.3) \times 10^{-14}$ sec</td>
<td>$(1.5 \pm 0.3) \times 10^{-14}$ sec</td>
</tr>
<tr>
<td>$r_x$</td>
<td>$(2.01 \pm 0.05) \times 10^{-10}$ cm</td>
<td>$(2.02 \pm 0.04) \times 10^{-10}$ cm</td>
</tr>
<tr>
<td>$a$</td>
<td>$0.34 \pm 0.02$</td>
<td>$0.36 \pm 0.03$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$(3.0 \pm 0.5) \times 10^{-4}$ c</td>
<td>$(2.1 \pm 0.5) \times 10^{-4}$ c</td>
</tr>
</tbody>
</table>

Table 3
Parameters obtained from X-rays arising from Pt and Os ions traversing iron targets

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pt</th>
<th>Os</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$</td>
<td>$(0.9 \pm 3.6) \times 10^{-14}$ sec</td>
<td>$(1.5 \pm 4.5) \times 10^{-14}$ sec</td>
</tr>
<tr>
<td>$r_x$</td>
<td>$(2.00 \pm 0.08) \times 10^{-10}$ cm</td>
<td>$(2.01 \pm 0.08) \times 10^{-10}$ cm</td>
</tr>
<tr>
<td>$w_p$</td>
<td>$0.027 \pm 0.004$</td>
<td>$0.023 \pm 0.003$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$(3.0 \pm 0.7) \times 10^{-4}$ c</td>
<td>$(2.0 \pm 0.5) \times 10^{-4}$ c</td>
</tr>
</tbody>
</table>

\[ w_i = \frac{I_i}{nV_f}, \]  

(8)

where $I_i$ is the total number of the emitted X-rays from the $i$ shell, $n$ is the number of the primary vacancies in all M subshells (in this case, $n$ coincides with the fractions $f_1$ mentioned in sect. 2), and $V_f$ is the relative number of vacancies in the $M_f$ subshell. The measured average fluorescence yield for osmium $w_p = (I_5 + I_4)/n$ was measured equal to 0.023. Using eq. (8), $w_p$ can be written as $w_p = w_5 V_5 + w_4 V_4$. Since $w_5$ has been calculated [16] to be 0.023, it is deduced that $M_5$ is by far the predominant carrier of holes in the M-shell. This result follows the electron promotion model by Lichten [15,17], where the 4f or MO is promoted favouring the creation of holes directly in the $M_{4,5}$ shell. This promotion is not predicted by the Eichler model [8] (see fig. 1).

As expected, the fraction of the vacancies $f_1$ was found to be small for the M-shell at 30 MeV, amounting to 1% with an associated experimental error of 0.1%. The number of vacancies versus energy follows an increasing trend (fig. 4). The upper part of the curve shown in fig. 4, at energies near the bombarding energy, corresponds to a pre-equilibrium situation. The lower part falls to zero at 8 MeV, where the potential [eq. (6)] becomes smaller than the energy of the encounter and the vacancy cross section also falls to zero. This is an interesting point that should be taken into account when magnetic moment measurements are made in thick iron backings.
All parameters in the four independent fits for (Pt, Fe) and (Os, Fe) are in very good agreement, a fact that justifies the adopted model and suggests that there is no differentiation in the Os-Fe versus Pt-Fe atomic interaction for the M-shell. This, of course, does not preclude the differentiation of the two systems arising from contributions of higher shells. It should be pointed out, however, that if indeed the Pt-Fe transient field is weaker than the Os-Fe, this reduction cannot be accounted for by the sharing of vacancies between the 4s and 2p shells, as proposed by Stuchbery et al. [7]. According to the Lichten rule, which was found to apply here, there is no crossing point in the N-shell between the 6hσ and 4dσ orbitals of the Pt-Fe system. On the contrary, according to the same rule, there is such a crossing point between the 4sσ and 5gσ orbitals of the Os-Fe encounter, which could accommodate a lower field in Os rather than in Pt.

The vacancy lifetime $\tau = 1.5 \times 10^{-14}$ sec is in good agreement with the theoretical calculations (ref. [1], fig. 6.4) which give for a radiative lifetime the value of $\tau_r = 1.7 \times 10^{-14}$ sec. Finally, the velocity scale factor $\gamma \approx 0.00025c = 0.05$ a.u. corresponds to a transition probability $P = 0.95$ [eq. (7)], almost certainly, as predicted by Lichten [15] for collisions involving heavy atoms.
Acknowledgements

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[1] An extensive compilation of papers can be found in the review articles written by  
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