I. 15 M X Rays of Rare Earth Elements Produced by Heavy-Charged Particle Bombardments

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Characteristic x rays such as K-, L- or M-x rays can be produced by bombardments with electrons or ions, or by irradiation with x rays. Among these x rays, Mα- and Mβ-x rays of elements heavier than the rare earth elements are produced by the radiative transition between 3d- and 4f shells. Since the 4f shell of rare earth elements is not filled with orbital electrons while the 5S and 5P shells are filled, the Mα and Mβ x rays have especially been interested from the point of view of chemical effect. From experimental results on x-ray emission induced by electron bombardments and x-ray absorption, Bonnel and Karnatak1) have obtained that the Mα- and Mβ-x-ray spectra are consists of the diagram line (i.e. 3d⁹4f⁹N → 3d⁹4f⁹N⁺1 where N represents the number of 4f orbital electrons), the resonance line (i.e. 3d⁹4f⁹N⁺1 → 3d¹⁰4f⁹N) and the satellite line. Their interpretation of the production of the 3d⁹4f⁹N⁺1 state is as follows; when a hole is created in the 3d shell, the empty 4f level goes down under the Fermi level due to the interaction between the 3d- and 4f-shells, and electrons are supplied to the 4f shell. On the other hand, there is no interpretation of the satellite line for the moment. Under the assumption that the satellite line corresponds to a transition from the state which has one hole in 3d shell and one or several holes in N-shell, the intensity of the satellite line will depend strongly on the electric charge of projectile ions. By studying the projectile-charge dependence of the satellite line intensity, we therefore can find if the satellite line come from a multi-ionized state or not. This investigation of the satellite line cannot be achieved by electron bombardments or by x-ray irradiation. We report here the projectile-charge dependence of the M-x-ray spectrum of a rare earth element Ho bombarded with 3 MeV/amu protons and ³He²⁺ ions.

Figure 1 shows the Mα- and Mβ-x ray spectrum from holmium metal bombarded with 3 MeV/amu protons and ³He²⁺ ions and measured with a curved crystal spectrometer. In this figure, the data points shown with o and x represent those for proton and ³He-ions bombardments, respectively. D, R and S denote the diagram line, the resonance line and the satellite line, respectively. Intensities of x rays for proton and ³He²⁺ ion bombardments are normalized each other at D- and R-lines. The effect of self-absorption2) in the target can be seen at the R-line. D-, R- and S-lines can not be measured separately, since the natural-line breadth is large and the components of D-, R- and S-lines overlap with one another.1) Differences between the spectra for proton and for-
$^{3}\text{He}^{2+}$ ion can be found on S-lines. If the atomic number of projectile $Z_p$ is smaller than that of the target atom, the x-ray spectrum $I_{Z_p}^{\lambda}$ can be expressed by\(^3\)

$$I_{Z_p}^{\lambda} = z^2I_1^{\lambda} + z^4I_2^{\lambda}$$  \hspace{1cm} (1)

where, $\lambda$ is the wavelength, and $I_1^{\lambda}$ and $I_2^{\lambda}$ represent the x-ray spectra, respectively, from single and double ionizations for proton bombardment. Normalizing the x-ray intensity for $^{3}\text{He}$ ion bombardment to that of proton, we obtain

$$R(\lambda) \equiv I_{He}^{\lambda}(\lambda)/(4I_H^{\lambda}(\lambda))$$  \hspace{1cm} (2)

and

$$= 1 + 3 \times \frac{I_2^{\lambda}}{I_1^{\lambda}+I_2^{\lambda}}.$$ \hspace{1cm} (3)

In the region of wavelength where single ionization mainly contributes to the spectrum, $R(\lambda)$ becomes unity;

$$R(\lambda) \rightarrow 1 \hspace{1cm} \text{for } I_1^{\lambda}(\lambda) \gg I_2^{\lambda}(\lambda).$$ \hspace{1cm} (4)

On the other hand, in the region where double ionization is predominant, $R(\lambda)$ takes the maximum value 4;

$$R(\lambda) \rightarrow 4 \hspace{1cm} \text{for } I_1^{\lambda}(\lambda) \ll I_2^{\lambda}(\lambda).$$ \hspace{1cm} (5)

Figure 2 shows the normalized spectrum $R(\lambda)$ obtained from Fig. 1. We find that the contribution of double ionization is predominant in satellite lines. Therefore, we find that the satellite lines of $M_{\alpha}$- and $M_{\beta}$-x ray on holmium metal correspond to the transition $3d^{-1}N^{-1} \rightarrow N^{-2}$. Some information on $4f$-orbital electrons and chemical effects which are reflected in rearrangement effect\(^4\) may be expected in the projectile-charge dependence of satellite line. The experiment for studying the chemical effect on $M$ x rays of rare earth elements is now in progress.

References

Fig. 1. $M_\alpha$- and $M_\beta$-x-ray spectra for holmium metal bombarded with 3 MeV/amu protons and $^3\text{He}^{2+}$ ions. X-ray spectra have been measured with a curved crystal spectrometer. The symbols o and x are the data points for protons and $^3\text{He}^{2+}$ ion bombardments, respectively. D, R and S show diagram line, resonance line and satellite line, respectively. The intensities of X-rays for proton and $^3\text{He}$ ion bombardments are normalized each other at D- and R-lines.

Fig. 2. Normalized X-ray spectrum for holmium metal. The ordinate represents the X-ray intensity of $^3\text{He}$ ion normalized to that of protons as defined by eq. (2) in the text.