BOMBARDMENT-INDUCED PHOTON EMISSION FROM Sn AND Pb NEAR THE MELTING POINT*

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Photon emission from Sn and Pb surfaces bombarded by Ar^+ ions of 5 keV energy in a wide range of target temperature including both solid and liquid phases was observed. The constant value of the intensity of spectral lines indicates that the mechanism of excitation is independent of the long-range order of the atoms in the target.

1. Introduction

The radiation emitted by atoms sputtered from a target bombarded by ions of energy in the keV range gives information on most of the external surface layers of the target. The understanding of the mechanism of excitation of sputtered atoms seems to be a significant question. Recently, a number of papers dealing with the subject appeared [1–5]. The authors tried to explain the experimental data using a variety of models of excitation. The best agreement with experiment seems to be acquired by a promotion model applied for energetic atomic collisions [6–9]. This model rests on the following assumptions:

— the excitation is due to an energetic binary collision of the incident ion and target atom of the surface,

— the quantum states of the quasimolecule produced as a result of the collision transform to free atomic states of the participants of the collision,

— the interaction of the excited atom with the solid surface can be a reason for radiationless relaxation process.

We can expect that the basic assumptions of the model of excitation can be proved by observation of photon emission from metallic targets in the vicinity of the melting point. At this temperature the long-range order in the lattice is destroyed but this fact according to the binary collision model should not effect the efficiency of photon emission. The tin and the lead targets were chosen as a subject of our investigation due to the low

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melting point and satisfactorily low vapour pressure of these metals. Even for temperatures higher than 100 K above the melting point the partial pressure of metallic vapour is equal to $8 \cdot 10^{-7}$ Torr for Pb and is unmeasurably low for Sn.

2. *Apparatus and experimental techniques*

In the present experiment the accelerator of noble gas ions with a duoplasmotron ion source was used. A general sketch of the accelerator is shown in Fig. 1. The beam of Ar^+ ions of 5 keV energy was focused on the target by a system of electrostatic lenses.

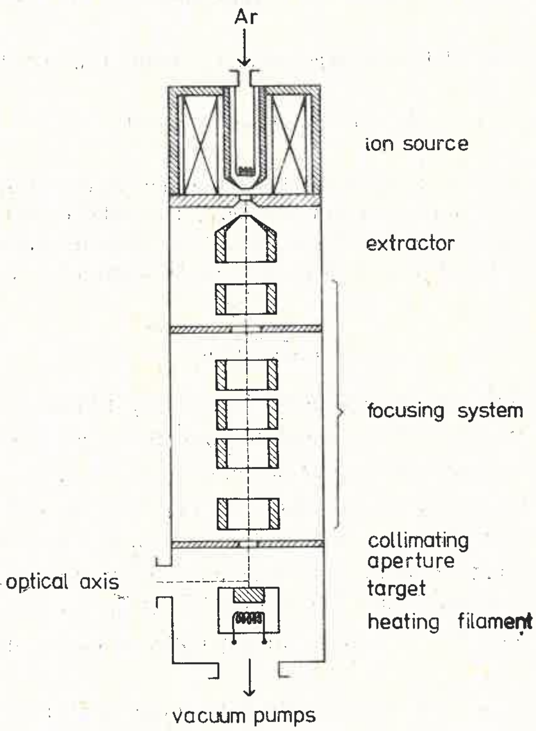

Fig. 1. General sketch of the ion accelerator

The ion-current density of 0.2 mA/cm^2 on the target was gained. Polycrystalline Sn and Pb samples were inserted in a special oven made of steel, heated by a tungsten filament supplied by the current. The samples were shaped with some overheight which flowed down the wall of the oven during melting under high vacuum. In this way the clean surface of the liquid metal was revealed. In addition, the surface was etched by ion bombardment before each measurement. The temperature of the target was varied from 450 K to 530 K and from 500 K to 680 K for Sn and Pb respectively. The actual temperature of the sample was measured by a NiCr–Ni thermocouple with an accuracy of ± 3 K. The pressure of the rest gases in the collision chamber was maintained at $3 \cdot 10^{-6}$ Torr. Due to the low pressure of tin and lead vapours the electric discharge inside the accelerator was avoided. Prior to the selection of lines, the total spectra were photographed using a quartz spectrograph in ultraviolet and glass spectrograph in the visible range of the spectrum. Ultrasensitive ORWO-plates ZU2 designed for astrophysical purposes were used. Photometric measurements of selected spectral lines were realized with narrow-band interference filters (type DIF by Carl Zeiss Jena) and photomultiplier (type K14FQS 50 of the same manufacturer) followed by a direct-current amplifier, voltage-frequency converter, pulse counter and printer system. The photomultiplier was cooled by liquid nitrogen vapour to decrease the dark current. In the transmission band of the filters, no spectral lines of other elements were found and therefore their application was possible.

3. Experimental results and discussion

The aim, assumed by the present authors, was to prove the conformity of experimental data on photon yield from metallic targets in the vicinity of the melting point with the model of excitation in energetic binary collision. As was mentioned above, the model requires only the interaction of two atomic particles, but does not take into account the influence of long-range order in the target. The loss of order during phase transition should not effect the excitation process.

The intensity of a spectral line registered by a photometric system can be expressed by the formula:

$$I = C N R P, \tag{1}$$

where C is a constant dependent on the geometry of the experiment, N is the number of target atoms ejected per second from the surface as a result of energetic collisions, P denotes the probability of excitation of the target atom in a violent collision with a pri-

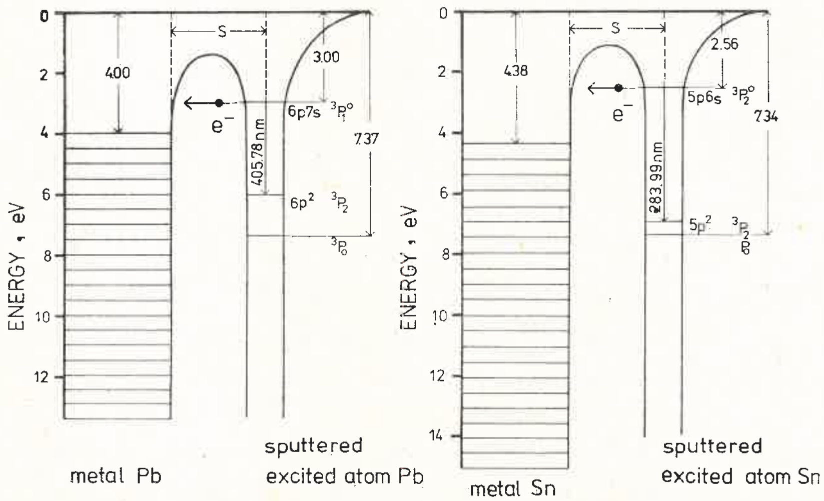

Fig. 2. Energy levels of excited Sn and Pb atoms in relation to metallic band structures. S is the atom-surface distance

mary ion, R is the probability that an excited atom can escape to infinity without undergoing radiationless relaxation [9]. The photon yield is proportional to the intensity of a spectral line. Prior to comparing the experimental results with the theoretical model, let us consider the influence of the phase transition on the factors existing in formula (1). The factors C and P essentially do not depend on phase transition in the target. The value of N depends on the density of surface atoms, but in the present range of temperature this density remains practically constant [10]. The radiationless relaxation predicted by Hagstrum [11], in principal, can be affected by phase transition. The diagrams presented in Fig. 2 indicate the possibility of such a process for both elements. However, the distribution of state density for Sn and Pb does not evidently change during melting [12, 13]. Therefore the factor R should be assumed constant. Thus the model of promotion in

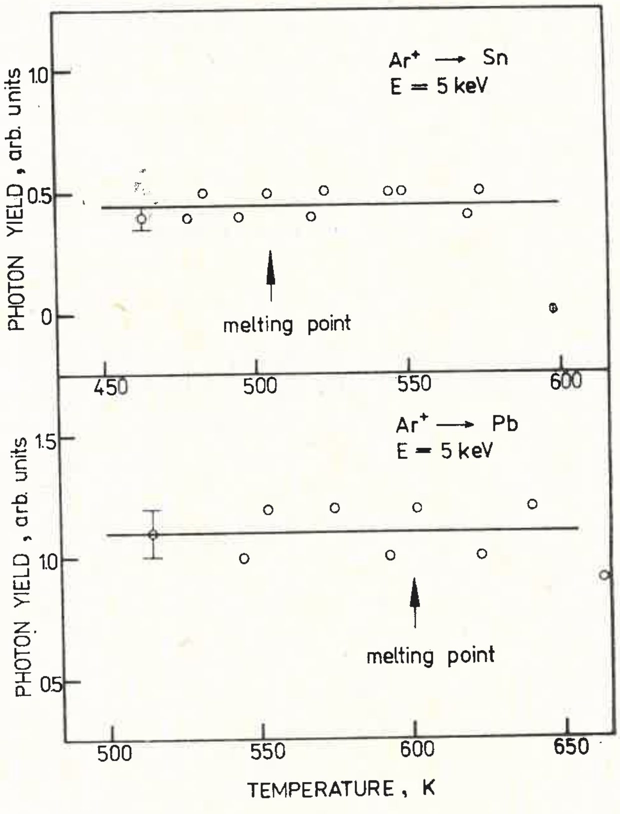

Fig. 3. Relative photon yield as a function of the target temperature

binary collision suggests the invariability of photon yield in the vicinity of the melting point. In fact, the photon yield observed for resonance lines SnI 283.99 nm and PbI 405.78 nm in the whole range of temperature in the present experiment remains constant within the experimental error. Typical plots are presented in Fig. 3.

In spite of the tact that the density of surface atoms and the density of electron states remain constant during melting a number of macrophysical parameters sharply vary at the melting point in a way characteristic for the phase transition. Some of these parameters are presented in Table I.

TABLE I

Metal	Temp. T [K]	Heat cap. C_p [cal/g mole · K]	Enthalpy $H_T - H_{st}$ [cal/g mole]	Entropy $S_T - S_{st}$ [cal/g mole · K]	Electric resistance [10^{-6} Ω cm]	References
Sn	298.15	6.45	0	0.00	—	[14]
	450	7.11	1030	2.78	—	[14]
	505 (sol)	7.35	1430	3.62	22.9	[14, 15]
	505 (liq)	7.10	3100	6.93	48.2	[14, 15]
	550	6.93	3415	7.53	—	[14]
Pb	298.15	6.32	0	0.00	—	[14]
	500	6.79	1320	3.58	—	[14]
	600.6 (sol)	7.02	2020	4.65	47.9	[14, 15]
	600.6 (liq)	7.32	3160	6.54	99.3	[14, 15]
	700	7.25	3880	7.66	—	[14]

Note: The subscript st, such as in H_{st}, is used to denote that the standard reference temperature is 2 98.15 K.

The variation of macrophysical parameters has no effect on the plots in Fig. 3, but this was expected from the model of energetic binary collisions. The present results are simply explained on the basis of this model and certify its advantage over competing models. One must remark that one of these models [1] provides the dependence of the photon yield on the shape of the wave function of free electrons inside the metal. Thus, the melting process should produce a steplike variation of the photon emission at the melting point. However, no variation within the limits of experimental error was observed.

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