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MEASUREMENT OF X-RAYS EMITTED FROM PROJECTILES MOVING IN SOLID TARGETS*

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ABSTRACT

In this paper the results of three separate experiments all dealing with the production of x-rays in projectiles moving in solids will be discussed. The first experiment[1] deals with the measurement of line widths of x-rays emitted from projectiles moving in solid targets. The effects of collisionally broadening of x-rays is found to dominate the line widths giving greater than an order of magnitude increase in the measured line widths. The second experiment[2] studies "solid target effects" in producing non-binomial distributions of characteristic K x-ray spectra in heavy ion-atom collisions. The third experiment[3] studies aluminum K x-ray production in Ar^{+} + Al collisions in very thin aluminum foils as a function of foil thickness. Parameterization of the observed non-linear dependence enables us to measure the lifetime of the argon 2p vacancy and total ionization cross sections for the argon L-shell in Ar + Al collisions.

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1. COLLISIONAL BROADENING OF X-RAYS

In Fig. 1b and 1c the neon K x-ray spectra for 3 types of collisions, 1.3 keV electrons incident on a neon gas target, and 90 keV neon ions incident on a neon gas target and a solid copper target. The gas target (Fig. 1c) spectra exhibit clean well resolved peaks and the origins of these peaks have been discussed extensively in the literature. Basically each line corresponds to an initial state involving one K-shell vacancy and fixed ionization in the L-shell. The peaks are designated as such in the figure where KL^n corresponds to the x-ray transition from an initial state having one K-shell vacancy and n L-shell vacancies. However, these well resolved discrete peaks are not observed for the neon K x-ray spectra emanating from ions moving in solid copper targets (Fig. 1b). The peak of this spectra occurs in the region of the normal KL^0 peak; however, the peak extends in energy over a very broad energy range with essentially no structure detectable in the spectra. This spectra is skewed toward the high energy side, probably indicating the existence of states of excitation higher than KL^0. On the low energy side of KL^0 the spectra extends to lower energies indicating that the individual lines are considerably broadened.

In Fig. 2 the boron K x-ray spectra for 2 types of boron-carbon collisions are presented. The first spectra is for a methane gas target. Basically the x-ray lines are from boron coming primarily from electron transitions in one, two, and three electron atoms. The second spectra is for a solid diamond target. The most obvious difference is the large carbon K line which dominates the solid target spectra but is not observed in a gas target. This peak occurs in the solid targets because of recoiling carbon atoms and subsequent C-C collisions. A more important difference with respect to this paper is the x-ray transitions emanating from the boron projectile. For the solid target only two broad continuous x-ray bands in the region where boron K x-ray transitions are expected are observed. The identification of the two bands is straightforward. The low energy band, centered near 190 eV, is consistent with calculations of the $2p \rightarrow 1s$ x-ray transitions in atoms having initial states involving one K-shell vacancy and one, two or three electrons in the L-shell. The second higher energy band, centered near 245 eV on the low energy tail of the carbon K x-ray is consistent with $2p \rightarrow 1s$ transitions in atoms having two K-shell vacancies in the initial state and one, two or three L-shell electrons. The significant point to be extracted from both Fig. 1b and Fig. 2 concerns the widths of the x-ray lines obtained from the projectiles moving in solid targets. In both figures the data obtained from gas target spectra exhibit clearly resolved peaks. However, when the x-ray spectra are measured using the same instrumental resolution for ions moving in a solid target all the sharply resolved x-ray structure disappears and only broad x-ray bands are resolved. This

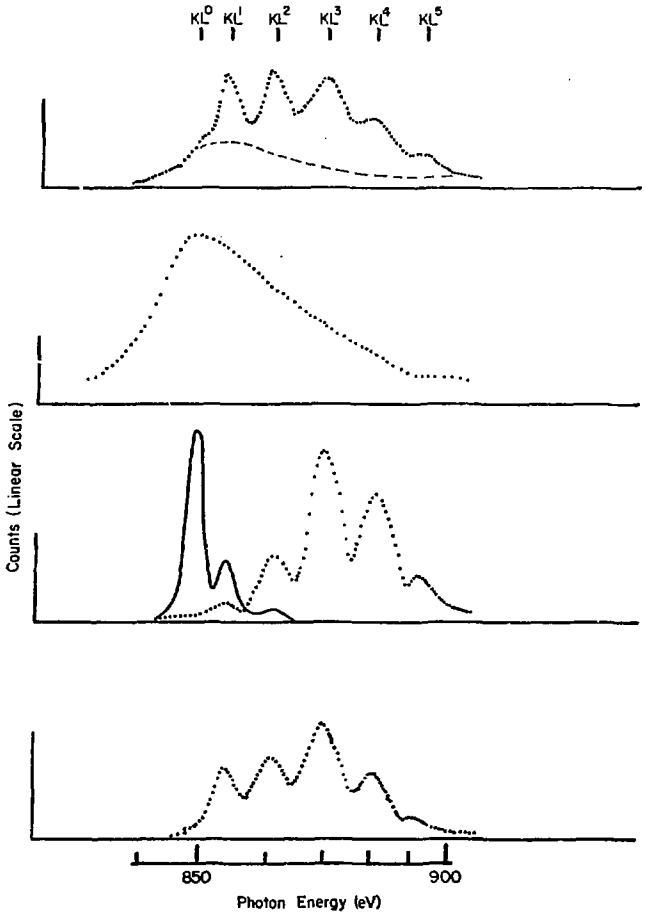
KL0 KL1 KL2 KL3 KL4 KL5
Counts (Linear Scale)
850
900
Photon Energy (eV)

Figure 1

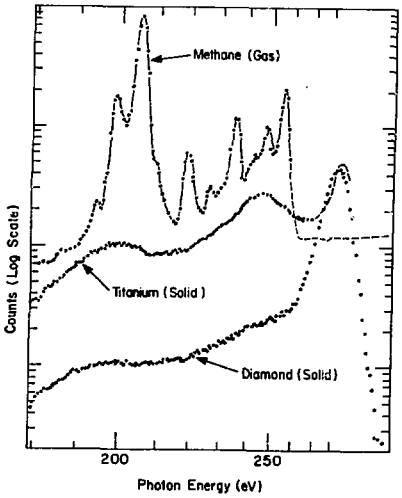

Figure 2

broadening of the x-rays in the solid is the x-ray analog to the collisional broadening of spectral lines observed in dense plasmas. It is the result of a disruption in the radiation field of the inner shell vacancy induced by multiple collisions which take place prior to the filling of the x-ray transition.

An estimate of the size of the collisional x-ray broadening can be obtained by unfolding the x-ray spectra in Fig. 1b and 2. In this unfolding of the data we used Gaussian line shapes and centroid energies as observed in gas target measurements. This unfolding of the $Ne^{+} \rightarrow Cu$ spectra indicated a width of 12 ± 3 eV for the peaks KL^0 to KL^4 respectively. The boron K x-ray spectra were unfolded using the double K-shell vacancy peak from Fig. 2b. The spectra indicated a width of 12 ± 5 eV and equal intensities of the K^2L^0 and K^2L^1 x-ray peaks.

2. NON BINOMIAL DISTRIBUTIONS OF HEAVY-ION INDUCED NEON K X-RAY SPECTRA

In Fig. 1a the neon K x-ray spectra produced in collisions of neons ions incident on a graphite (carbon) thick target. The spectra was observed only after long bombardment of neon ions and thus is attributed to Ne - Ne collisions taking place in the carbon solid. This spectra is expected to have two components: one from a moving neon projectile, and the second from implanted neon atoms at rest in the graphite. The projectile spectra is broadened as in Fig. 1b and the target spectra shows peaks. The dashed line in Fig. 1a indicates our estimate of the projectile contribution obtained by normalizing the spectra shown in Fig. 1b to the low energy part of the spectra in Fig. 1a. The difference spectra which would be associated with the implanted neon target is shown in Fig. 1d. Notice the difference in the two neon-neon spectra for a gas target (1c) and a solid target (1d). The x-ray line intensities from the gas target spectra are binomial in character and for the solid target spectra they are not. We can attribute this difference to the capture of target electrons into excited states when the neon is in the carbon solid. These electrons can auto-ionize filling L-shell vacancies prior to the K x-ray decay which then results in fewer number of L-shell vacancies as observed in the x-ray spectra and a non-binomial distribution.

3. LIFETIME STUDIES OF Ar-2p VACANCIES TRAVELING THROUGH SOLIDS

We report studies on the production of aluminum K x-rays in Ar-Al collisions using varying thicknesses of thin aluminum foils. It has been suggested that the mechanism for aluminum K vacancy production requires two collisions; the first collision produces an argon 2p vacancy in the argon projectile and the second collision transfers this 2p vacancy to the 1s level of the aluminum. The reasons for interest in these studies is that in very thin foils, i.e., thickness less than $v\tau$ where v is the velocity of the ion and τ is the lifetime of the argon L vacancy, the aluminum K yield is not a linear function of thickness and the shape of the curve will depend on the lifetime of the argon 2p vacancy. Thus, parameterization of this data enables us to infer an average lifetime for the argon 2p vacancy traveling through a solid.

The experiments used thin foils of carbon of thickness $\sim$10 $\mu g/cm^2$ with thin evaporated layers of aluminum ranging from 60 Å to 333 Å. In the first experiment the yield of aluminum K x-rays was measured for the argon beam incident, first on the carbon side and then on the aluminum side of the foil. Those yields are displayed in Fig. 3 as a function of energy. The aluminum yield for argon first traveling through carbon is considerably higher since there

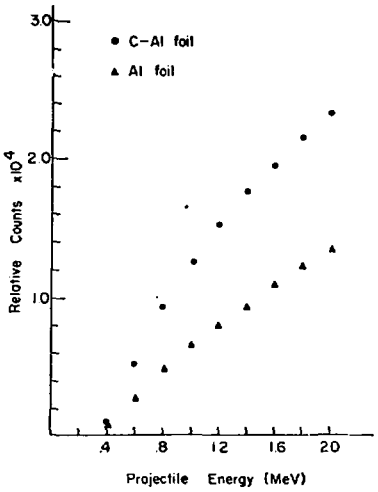

Figure 3

is a large steady state distribution of argon L vacancies established in this beam prior to penetration into aluminum. This observation confirms the basic explanation of Al-1s vacancy production mechanism discussed above.

In a second set of measurements the yield of aluminum K x-rays was measured as a function of aluminum thickness (T) by using different foils and various angles to the beam. In this case the fraction of beam with L vacancies, $f_l(t)$ at depth t, now due to Ar-Al collisions may be written as

$$f_l(t) = \frac{N\sigma v\tau}{1+N\sigma v\tau}\left(1-e^{-(N\sigma+\frac{1}{v\tau})t}\right)$$

where N is the atom density of Al, σ the cross section for argon L vacancy production. Then the total yield of Al, Y_{Al}, is proportional to

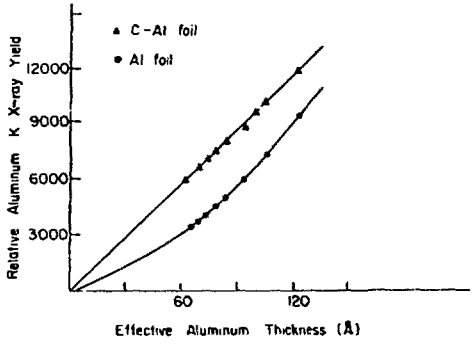

Figure 4

$$Y_{Al} \propto \int_0^T f_1(t)dt \propto \left[T + \frac{e^{-(N\sigma+\frac{1}{V\tau})T} - 1}{N\sigma + \frac{1}{V\tau}}\right] .$$

In Fig. 4 the yield of aluminum K x-rays as a function of foil thickness is shown. The data for the aluminum foils clearly shows the non-linear dependence of the aluminum K x-ray yield on foil thickness. Parameterization of these data enabled us to determine independently both σ and τ. A summary of the values of τ and σ obtained for a variety of projectile energies is shown in Table 1.

TABLE I

Energy (Mev)	σ ($\times 10^{-17}$ cm^2)	τ ($\times 10^{-15}$ sec)
.3	.35	1.50 (±.30)
.4	.59	2.15 (±.44)
.5	.90	4.8 (±.5)
1.0	1.58	11.0 (+2.5)
1.5	3.10	20. (±20)
2.0	4.10	-----

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