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Nonstatistical population of magnetic substates of the $(1s^{-1}2p^{-1})\,^1P_1$ state in Al

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We have measured the polarization of the $K\alpha'$ $[(1s^{-1}2p^{-1})\,^1P_1]$ to $[(2p^{-2})\,^1S_0]$ x ray from an Al target following bombardment by various ion beams at several different incident energies. The polarization of the $K\alpha'$ x ray is a measure of the ratio of the $2p$ substate populations σ_1 ($M_L = \pm 1$) and σ_0 ($M_L = 0$) of the $^1P_1$ state. We compare our results with recent collision-theory calculations which predict nonstatistical substate populations for simultaneous K- and L-shell ionization.

I. INTRODUCTION

Recently it has been reported[1] that the first satellite $(KL\text{-}L^2)$ of target K x-ray spectra produced by ion-atom collisions can exhibit polarization due to the nonstatistical population of the M_L substates. It was also suggested in Ref. 1 that the restricted range of impact parameters of the L shell, when there is simultaneous K- and L-shell ionization, could be responsible for the nonstatistical substate population. This observation prompted two calculations[2,3] of the single K-shell, single L-shell ionization which give a prediction of the magnitude and energy dependence of the substate populations. The purpose of the present paper is to report a measurement of the energy and projectile Z dependence of the polarization of the $(1s^{-1}2p^{-1})\,^1P_1$ to $(2p^{-2})\,^1S_0$ target x ray, $K\alpha'$, transition in Al. The measured polarizations are used to deduce the ratio of substate populations produced in the ion-atom collision. The results are compared to the recent theoretical predictions.

II. PROCEDURE

The experiment was performed with He, Li, and O beams from the Lawrence Livermore EN tandem Van de Graaff accelerator. The collimated ion beams were incident upon a thick slab of Al. The target x rays were viewed at 90° with respect to the beam axis by a 4-in. curved crystal spectrometer equipped with a 0.25×0.030 in. tubular entrance collimator. The detecting element was a flow mode proportional counter with a 2-μ Makrofol entrance window, supplied with a 90%-Ar–10%-CH_4 gas mixture. Collimation at the counter consisted of a slit 0.15 mm in width and perpendicular to the Rowland circle. The spectrometer was rotatable about the target-crystal axis and spectra were recorded for the Rowland circle coplanar with the beam axis $(I_\perp)$ and the Rowland circle perpendicular to the beam axis $(I_\parallel)$. Counting periods at a fixed angle were determined by beam charge integration. Crystal angle stepping was controlled automatically by a multichannel analyzer. The Bragg analyzing crystal was an ammonium dihydrogen phosphate (ADP) Johanson-type curved crystal. 2θ for $K\alpha'$ was 102° making the spectrometer a 91% efficient polarimeter assuming the $(1+\cos^2 2\theta)/(1-\cos^2 2\theta)$ imperfect-crystal reflectivity.[4]

III. EXPERIMENTAL RESULTS

The dependence of the relative $K\alpha'$ strength upon crystal orientation is shown in spectral form in Fig. 1 for two of the projectile-energy combinations, 14-MeV Li and 26-MeV O. An enhancement of the $I_\parallel$ intensity of $K\alpha'$ is especially evident in the Li spectra. Peak areas were extracted in the procedure used previously,[1] where a Gaussian was superimposed with a Lorentzian line shape fixed at 14% of the strength of the Gaussian. The Lorentzian successfully simulated the extended tails of the empirical resolution function, as determined by fitting the low-energy side of the $K\alpha_{1,2}$ peak. Further, a linear background was assumed in the least-squares fitting of the spectra. A summary of the relative intensities is presented in Table I, including He and Li at 1, 2, and 3 MeV/amu and O at 1.6 MeV/amu on Al.

The polarization fractions corresponding to the observed ratios of peak yields are given by the expressions[5]

$$P = \frac{\mathcal{I}_\parallel - \mathcal{I}_\perp}{\mathcal{I}_\parallel + \mathcal{I}_\perp} = \frac{I_\parallel - I_\perp}{I_\parallel + I_\perp}\,\frac{1+\cos^2 2\theta}{1-\cos^2 2\theta}\,, \tag{1}$$

where $I_\parallel$ and $I_\perp$ are the measured relative intensi-

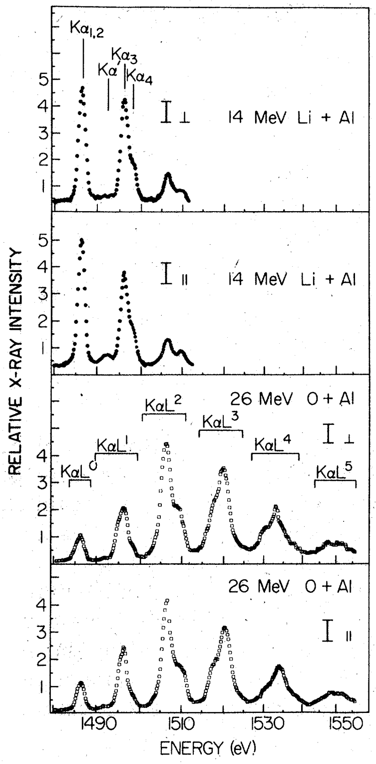

FIG. 1. X-ray intensity vs photon energy is depicted for an Al target following bombardment by 14-MeV Li and 26-MeV O. The spectra display the intensities of the Al x rays for the polarimeter sensitive to the perpendicular ($I_\perp$) and parallel ($I_\parallel$) components of the radiation.

ties with respect to $K\alpha_{1,2}$. The observed values are listed in Table II.

In terms of the partial ionization cross sections for the $2p$ substates, σ_0 for $M_L=0$ and σ_1 for $M_L=+1$ and $M_L=-1$, the polarization fraction at a 90° observation angle for the $K\alpha'$ transition (${}^1P_1 \rightarrow {}^1S_0$) is given by[5]

$$P(K\alpha') = (\sigma_0 - \sigma_1)/(\sigma_0 + \sigma_1)\,. \tag{2}$$

For the $K\alpha_3$ (${}^3P \rightarrow {}^3P$) and $K\alpha_4$ (${}^1P \rightarrow {}^1D_2$) transitions from the $1s^{-1}2p^{-1}$ configuration the polarization fractions are[1]

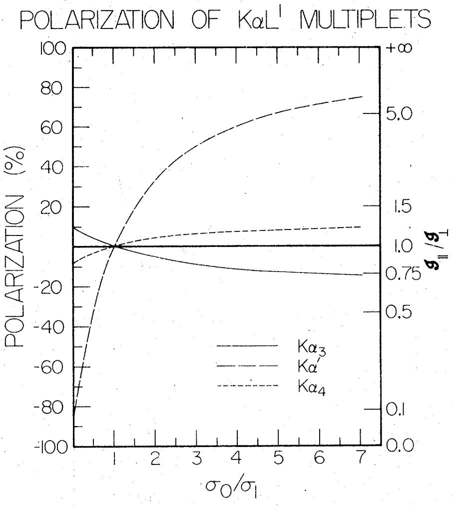

FIG. 2. Polarization and the ratio of the parallel to the perpendicular intensities of the radiation vs the ratio of sub state population (σ_0/σ_1) for each of the three multiplet transitions of the $K\alpha L^1$ x-ray satellite is presented.

$$P(K\alpha_3) = -15(\sigma_0 - \sigma_1)/(67\sigma_0 + 149\sigma_1) \tag{3}$$

and

$$P(K\alpha_4) = (\sigma_0 - \sigma_1)/(7\sigma_0 + 13\sigma_1)\,. \tag{4}$$

Equation (3) assumes a depolarization factor of $\frac{5}{18}$ as in Ref. 1. Figure 2 displays graphically the relationship between the polarization and the substate population for these three transitions. It is readily seen that the dependence of the polarization on the ratio of the substate populations for $K\alpha_3$ and $K\alpha_4$ is far less sensitive than it is for $K\alpha'$. Coupled with the fact that the $K\alpha_3$ and $K\alpha_4$ are not well resolved and the fact that they have opposite polarizations makes $K\alpha'$ the obvious choice for determining substate population ratios via observed x-ray polarizations.

A summary of the current experimental ratio (σ_0/σ_1) is plotted as a function of the projectile velocity in Fig. 3. Both the He and the Li projectile data exhibit the general trend of decreasing preferential population with increasing ion energy.

TABLE I. Relative intensity (in %) of $K\alpha'$ with respect to $K\alpha_{1,2}$.

Beam	Geometry	1 MeV/amu	1.6 MeV/amu	2 MeV/amu	3 MeV/amu
He	∥	8.9	⋯	3.1	1.6
	⊥	4.1	⋯	1.5	1.2
Li	∥	25.5	⋯	8.9	4.5
	⊥	9.9	⋯	4.0	3.1
O	∥	⋯	15.0	⋯	⋯
	⊥	⋯	12.6	⋯	⋯

TABLE II. Polarization fractions (in %) of the $K\alpha'$ transition in Al.

Beam	1 MeV/amu	1.6 MeV/amu	2 MeV/amu	3 MeV/amu
He	40 ±10	···	40 ±10	16 ±10
Li	48 ±10	···	41 ±10	19 ±10
O	···	10 ±10	···	···

Included for comparison are recent theoretical calculations based on the semiclassical impact parameter formulation by Kocbach and Taulbjerg[2] and the semiclassical oscillator model by Merzbacher and Wu.[3] Both theories are seen to give qualitative agreement with the He and Li experimental points. Both theories are projectile Z independent, however the Li data show a larger value of σ_0/σ_1 at each velocity measured.

A puzzling feature of the new data presented in this paper is the small polarization fraction measured for the collision involving the heavier projectile, oxygen. According to studies of L-hole filling prior to K transitions in single-K, multiple-L vacancy configurations produced in O + Si collisions,[6] approximately 60% of the observed $K\alpha L^1$ yield (including the $K\alpha'$) in our situation should be due to cascading from higher-L-shell satellites. Cascading contributions from higher-$K\alpha$ satellites imply a more complex origin of polarization. Multiple-L vacancy states created initially in the collision which decay to the ${}^1P_1$ initial state can alter the probabilities for distributions of vacancies in the $M_L = 0, \pm 1$ substates. A second question pertains to the role of the M shell or spectator electrons. In the previous analysis the coupling of the M or higher shells was ignored. The similarity of the experimental results for Al (Ref. 1) and Si (Ref. 7) indicates that coupling with the outer electrons can be neglected with some confidence when the limited ionization from light projectiles is concerned. Using the most prominent member of the $K\alpha L^1$ group as a gauge, we find that the energy centroids (which are affected by M-shell population) of the $K\alpha_3$ peaks to be within ±0.1 eV of a mean value of 10.4 eV higher than the $K\alpha_{1,2}$ line for bombardment by all ions (including oxygen). Hence, possible effects due to varying M-shell population should be small. In spite of the possible effects of rearrangement, the lack of a significant degree of polarization for the oxygen-induced spectrum implies minimal polarization resulting from the collision. The L-shell excitation probability by the O ion may not behave the same as the Coulomb ionization theories.[2,3] The difficulty may be traced to the impact parameter dependence of the vacancy production for the O + Al collision.

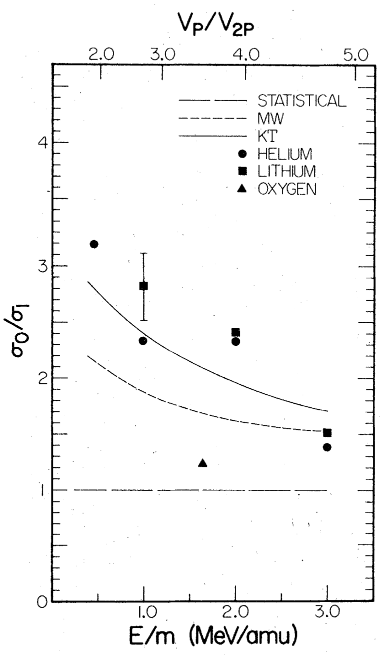

FIG. 3. Ratio of the M_L substate cross sections is plotted vs E/m in MeV/amu on the lower scale and vs the ratio of projectile velocity to Al $2p$ electron orbital velocity on the upper scale. The theoretical prediction labeled KT is taken from Ref. 2 and the prediction labeled MW is from Ref. 3. Typical uncertainty of each data point is shown on the 1-MeV/amu-Li datum point.

In summary a large polarization of the $K\alpha'$ x ray of Al is observed for He and Li beams in the 1–3 MeV/amu. The degree of polarization decreases with increasing energy in agreement with recent theoretical calculations of Coulomb ionization.

ACKNOWLEDGMENT

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