Anisotropy of characteristic K-shell x rays from heavy-ion–atom collisions*

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Angular distributions have been measured and polarization fractions determined for target and projectile x rays emitted in collisions of 3-MeV protons on argon and 33-MeV fluorine ions on argon and helium. The near isotropy in target x-ray emisssion that follows K-shell ionization is not unexpected; however, the anisotropic emission of projectile x rays contradicts the assumptions that are made in the analysis of x-ray cross sections. The polarization of ~23% in this characteristic K-shell radiation can be understood qualitatively from the alignment of excited states populated by electron capture in atomic collisions.

I. INTRODUCTION

Close collisions between fast heavy ions and atoms normally result in the emission of x rays or auger electrons from both the target and the projectile.[1] Although the spectral distributions and cross sections for these inelastic heavy-ion collisions have been studied extensively, the polarization and alignment of excited states with K-shell vacancies have not been previously investigated. The anisotropic x-ray angular distributions that have been measured in the present experiment provide the first evidence of the polarization of characteristic K-shell x rays. This radiation results from the de-excitation of an aligned population of excited states produced in projectiles by electron-capture processes. Since electron capture participates in the formation of atomic states with K-shell vacancies in many high-velocity atomic collisions, the substate populations formed by this process are of special interest. Although less than an 8% overestimate in projectile x-ray cross sections[1] arises from neglecting the anisotropic distributions observed, it is not clear what effect the polarization of projectile x rays has on high-resolution studies using dispersive instruments.[2] Any influence of the polarization of x rays on the efficiencies of these instruments has been neglected. In addition, the anisotropy of emitted x rays has been used recently to identify the formation of quasimolecular species[3]; however, the present results show that this phenomenon is not unique to continuum radiation from molecular states in heavy-ion collisions.

Calculations of substate populations produced by collisions of protons in hydrogen have been made in a Brinkman-Kramers approximation.[4] These results indicate that significant polarization fractions are expected for dipole radiation from states excited by a capture process. Although a similar estimate can be made for heavy ions,[5] the theoretical validity of the result is at best questionable, and no previous measurements have been made. In the present work, the angular distributions of fluorine K *projectile* x rays emitted from collisions of 33-MeV F^{7+} and F^{9+} on He, as well as from F^{9+} on Ar, have been measured; and significant anisotropy has been observed in all cases. The basic processes leading to F K x-ray emission for F^{9+} and F^{7+} impact are, respectively, electron-capture and electron-exchange reactions to excited states.[6] The polarization fractions determined from the anisotropy observed in the present angular-distribution measurements yield evidence for the selective population of magnetic substates following electron-capture and -exchange reactions.

For the case of the radiation emitted following inner-shell ionization of *target* atoms, an isotropic distribution is normally assumed.[1] This assumption has not previously been tested using heavy-ion impact. However, experimental data on the angular distributions of auger-electrons emitted after K- and L-shell ionization of Ar by protons show no significant deviation from isotropy,[1] whereas a maximum polarization fraction of about 5% has been found for L-shell ionization of Ar by electrons.[7] From these results an isotropic distribution of the x rays emitted after K-shell ionization of Ar by protons could be expected. However, if multiple ionization of the outer shells simultaneous with K-shell ionization[1,2] is selective with respect to the magnetic substates, the subsequent x-ray emission will be anisotropic. In the present experiment, the angular distributions of Ar K *target* x rays emitted from a thin argon gas bombarded with beams of 3-MeV protons, 33-MeV F^{6+}, and 33-MeV F^{9+} ions were measured. In the first two cases isotropic distributions were observed, while in the latter case a small, although possibly insignificant, departure from isotropy was found.

II. EXPERIMENT AND DATA ANALYSIS

After acceleration and collimation, the fast-ion beams used in this experiment were passed through a differentially pumped target-gas cell and collected in a Faraday cup for normalization (Fig. 1). Independent normalization was also provided by a KeVex Si(Li) detector. The angular distributions were measured in the range 25°–155° by a moveable flow-mode proportional counter equipped with a set of Soller slits which defined the viewing direction to within ±1.5°. The gas pressures used in the experiments were ~10 and ~50 mTorr for argon and helium targets, respectively. With these pressures, single-collision conditions for charge exchange were approximated (i.e., < 20 and 1% charge exchange occurred in the Ar and He targets, respectively). Because the attenuation of the Doppler-shifted x rays in the proportional counter window was angular dependent, Macrofoil[8] windows of different thicknesses (2–6 μm) were used to ensure that the polarization fractions were independent of this parameter.

Target x-ray data shown in Fig. 2(a) are symmetric about $\theta_L = 90°$, where θ_L is the laboratory angle between the beam direction and the detector. The distribution of projectile x rays is clearly asymmetric in Fig. 2(b). The polarization fraction P, which describes the angular distribution $I(\theta)$ of dipole radiation in the frame of the emitting atom, is given by

$$I(\theta) = I(90°)(1 - P\cos^2\theta).$$

In order to extract P from the observed data it is necessary to account for the length of the extended gas target ($dx \propto \csc\theta$) and angular-dependent transformations to the lab frame of the effective solid angle

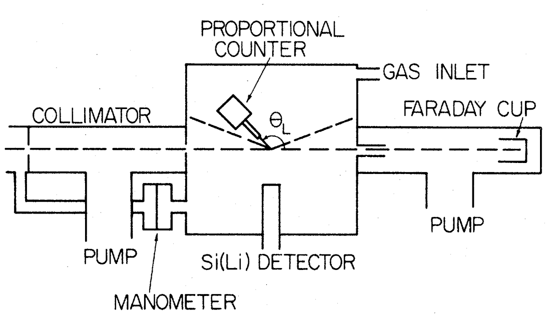

FIG. 1. Schematic diagram of the experimental arrangement.

$$\frac{d\Omega}{d\Omega_L} \propto (1 - \beta\cos\theta_L)^{-2},$$

target length

$$\frac{dx}{dx_L} \propto 1 - \beta\cos\theta_L,$$

and detector efficiency ϵ arising from the Doppler shift. The angular distribution measured directly in the laboratory for x rays from a long gas target is given by

$$I_L(\theta_L) = \frac{I_0(1 - P\cos^2\theta)\epsilon(\theta_L)}{\sin\theta_L(1 - \beta\cos\theta_L)G(\theta_L)}, \quad (1)$$

where θ is the emission angle relative to the beam direction in the moving frame so that

$$\cos\theta = (\cos\theta_L - \beta)/(1 - \beta\cos\theta_L),$$

$G(\theta_L)$ is a geometrical function that arises from the solid angle integration over the Soller slits and deviates from unity by less than 1.3%, and βc is the velocity of the emitting atoms. To choose the appropriate value of β to use in Eq. (1), it is a good approximation to assume forward scattering from large impact-parameter collisions. For radiation from the target, the recoil is perpendicular to the beam axis with $\beta \simeq 0$ and $\epsilon(\theta_L) = \epsilon_0$, so that the angular distribution of Eq. (1) is symmetric about 90° in agreement with the data shown in Fig. 2(a). However, for radiation from the projectile, the emitting atom moves in the beam direction with $\beta = 0.061$, and $\epsilon(\theta_L)$ must reflect the varying attenuation of the Doppler-shifted x rays. Because the product K of absorption coefficient and thickness of the detector windows is not accurately known, we have formulated

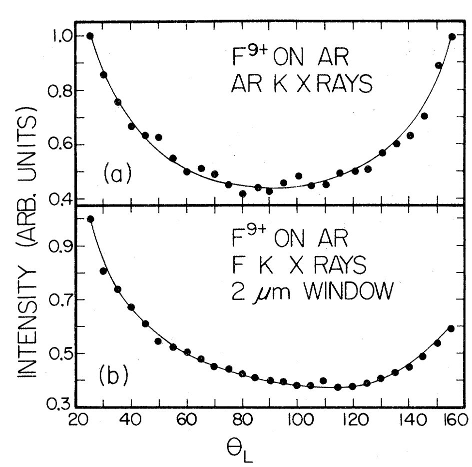

FIG. 2. Angular distributions of x rays as measured directly in the laboratory: (a) target x rays, (b) projectile x rays. The solid curves represent the best fits of Eq. (1) to the data.

$$\epsilon(\theta_L) = \epsilon_0 \sum R_x \exp[-K(1-\beta\cos\theta_L)^3 E_x^{-3}]$$

to account for the photoelectric absorption of the x rays with energy E_x and relative intensity R_x, and have considered K an unknown parameter. The summation is over the x-ray lines that have previously been reported for these highly stripped fluorine ions.[6]

III. RESULTS AND DISCUSSION

The unknown parameters P, K, and the scale factor I_0 were found by a least-squares fit of Eq. (1) to the angular distribution data (Fig. 2). The projectile x-ray intensities, corrected for the kinematic and geometric effects as plotted in Fig. 3, are symmetric around $\theta = 90°$, and fall on a straight line when plotted against $\cos^2\theta$. P is thus a good parameter which accounts for the large deviation from isotropy of the projectile radiation. Polarization fractions determined from the different sets of data are summarized in Table I together with the standard deviations from the least-squares-fitting routine. Although the angular-dependent attenuation of the different proportional counter windows varied substantially in these experiments, the derived polarization fractions are independent of this experimental parameter. The fitted values of the absorption coefficients are consistent with the manufacturer's data.[8] In addition, the polarization fractions obtained were insensitive to the relative intensities R_x of the x-ray lines in the spectrum.

The Ar K x-ray emission from the target atoms is found to be isotropic within the statistical error for both proton and F^{6+} excitation. In the former case, the results are in agreement with previous work.[1] Although for F^{9+} projectiles the measured polarization fraction of the Ar K radiation differs from zero by ~2 standard deviations, it is not clear at present whether this result is significant since a systematic error in the Ar K data, which would not be included in the 3% statistical standard deviation, might result from the difficulty in resolving this peak from the much larger F K peak. The absence of skewness in the angular distribution shown in Fig. 2(a) indicates no such systematic error in the present experimental data; however, thorough analysis has not ensured the significance of the 6% polarization fraction for the Ar K radiation in the presence of the 25% polarization fraction of F-K radiation obtained with F^{9+} ions. Further investigation is required to confirm the implication of these results that in F^{9+} collisions argon K vacancy states may be formed selectively to a small degree.

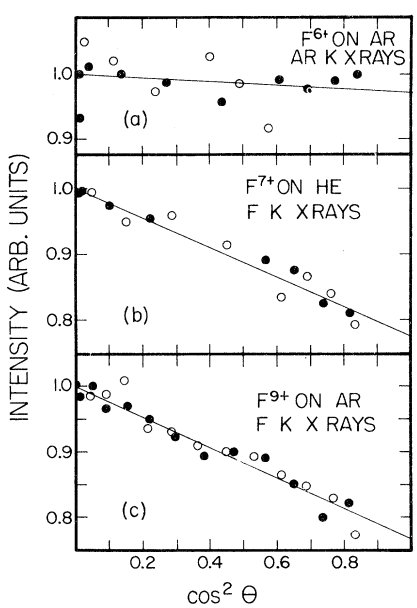

FIG. 3. Angular distributions of x rays corrected for kinematic and geometric effects as explained in the text. Closed circles: $\theta < 90°$; open circles: $\theta > 90°$. The solid curves represent the best straight lines through the data. The polarization fractions P are given by the slopes of these lines: (a) target x rays: $P = 0.028 \pm 0.030$; (b) projectile x rays: $P = 0.221 \pm 0.017$; (c) projectile x rays: $P = 0.234 \pm 0.014$.

TABLE I. Experimental polarization fractions obtained with a 3-MeV proton beam and 33-MeV fluorine beams. Nominal thicknesses of the proportional counter windows (consisting of 6-μm or multiple 2-μm foils) are listed in column 3.

Beam	Target	Window (μm)	Polarization fraction	Weighted average
ArK target x rays:				
proton	Ar	6	0.021 ± 0.040	
F^{6+}	Ar	6	0.028 ± 0.030	
F^{9+}	Ar	6	0.065 ± 0.029	
FK projectile x rays:				
F^{7+}	He	2	0.221 ± 0.017	0.210 ± 0.014
		2×2	0.210 ± 0.033	
		3×2	0.174 ± 0.030	
F^{9+}	He	2	0.234 ± 0.042	0.250 ± 0.015
		2×2	0.267 ± 0.073	
		2×2	0.268 ± 0.038	
		3×2	0.244 ± 0.026	
		6	0.251 ± 0.025	
F^{9+}	Ar	2	0.236 ± 0.034	0.226 ± 0.009
		2	0.222 ± 0.056	
		2	0.234 ± 0.014	
		2×2	0.224 ± 0.018	
		6	0.212 ± 0.018	

The measured polarization fractions listed in the table for the projectile F K x rays are clearly larger than zero, implying that the radiating P states are populated nonstatistically so as to favor $m_l = 0$ over $|m_l| = 1$ substates (where the quantization axis is defined by the beam direction). Observation of approximately the same polarization fraction (~23%) in the three cases studied here suggests that similar electron-transfer processes produce the excited-state populations which yield the observed polarized projectile x rays.

A Brinkman-Kramers calculation of capture to P states[4] predicts a polarization fraction of +0.34 in hydrogen. The same value is estimated for capture by fluorine nuclei by scaling the matrix elements[5] in the Brinkman-Kramers calculation. Because of the simplicity of the theoretical model, the agreement of this value with the results of the present experiment with F^{9+} ions is encouraging but may not be definitive. For direct excitation of hydrogen by protons, the sign of the polarization fraction is energy dependent and might be expected to be small or negative in the velocity range of the present experiments.[4] The large positive polarization observed for x-ray emission from F^{7+} on helium is further evidence that electron exchange dominates direct excitation in producing inner-shell excitation in the two-electron projectile.

Cascades from excited states to the various P states which ultimately decay by x-ray emission will reduce the polarization of the radiation. Cascades from S states might be particularly important since higher angular-momentum states are expected to be weakly populated in electron-capture processes at high velocities. On the other hand, immediately after the collision the electric field of the highly stripped target atoms will tend to mix the various orbital angular-momentum states of the projectile. The radiation emitted following this Stark mixing may also be anisotropic. Thus, it is not possible to associate the measured polarization fractions with electron capture to well-defined states in these collisions. Nevertheless, we conclude from the polarization of the x rays determined in this work that, for highly stripped projectiles, P substates with $m_l = 0$ are preferentially populated in heavy-ion collisions.

The results of this experiment show that electron capture to excited states of highly stripped heavy ions provides a source of highly polarized characteristic x rays. Although the observations are consistent with a simple electron-capture model, considerable study will be required to predict the intensity and degree of polarization of x rays produced following electron capture to excited states of various collision systems.

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[1]A review of collision studies involving inner-shell processes is given by J. D. Garcia, R. J. Fortner, and T. M. Kavanagh, Rev. Mod. Phys. 45, 111 (1973).

[2]A review of multiple ionization phenomena studied by high-resolution x-ray spectroscopy is given by P. Richard [in *Atomic Inner Shell Processes*, edited by B. Crasemann (Academic, New York, to be published); 1974 International Conference on X-Ray Processes in Matter at Otariemi, Finland, July 1974 (unpublished); and Physica Fennica 9, 3 (1974)].

[3]The theoretical formulation for this anisotropy is given by B. Müller and W. Greiner [Phys. Rev. Lett. 33, 469 (1974)]. Experimental observation of the anisotropy of continuum radiation is given by J. S. Greenberg, C. K. Davis, and P. Vincent [Phys. Rev. Lett. 33, 473 (1974)] and G. Kraft, P. H. Mokler, and H. F. Stein [Phys. Rev. Lett. 33, 476 (1974)].

[4]J. van den Bos and F. J. de Heer, Physica 34, 333 (1967); 40, 161 (1968).

[5]M. N. Saha and D. Basu, Indian J. Phys. 19, 121 (1945).

[6]J. R. Macdonald, P. Richard, C. L. Cocke, M. Brown, and I. A. Sellin, Phys. Rev. Lett. 31, 684 (1973).

[7]B. Cleff and W. Mehlhorn, J. Phys. B 7, 605 (1974).

[8]Siemens Corp., Karlsruhe, Germany.