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High-Resolution Study of Ne $K\alpha$ X-Ray Transitions as a Function of Oxygen-Projectile Charge State*

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$K\alpha$ transitions of neon are resolved, with a curved-crystal spectrometer, into eight components corresponding to varying amounts of multiple L-shell ionization. The degree of multiple L-shell ionization of neon increases with an increase of the projectile charge state of 30-MeV oxygen ions. The change in the neon satellite structure for the O^{+7} case as compared to the O^{+8} case (bare nuclear charge) is substantial. An effective fluorescence yield is extracted from the data and agrees with a recent value obtained from poor-resolution Auger-electron and x-ray measurements.

In this Letter we report for the first time high-resolution measurements of $K\alpha$ x rays produced in a *gas* target by high-energy heavy-ion projectiles. The $K\alpha$ x rays from Ne resulting from bombardment by 30-MeV oxygen beams of charge state +5, +7, and +8 are resolved into eight lines corresponding to transitions following single K-shell, multiple L-shell ionization.

Gas targets are of special interest since single-collision events can be studied. Furthermore in a gas the purity of the charge state of the projectile can be maintained. This condition makes the projectile charge a single and known parameter in the collision. Previous high-resolution measurements have been made with solid targets[1] and thus have been complicated by the resulting distribution of projectile charge states. Ne as a target is perhaps the best case to study $K\alpha$ x-ray satellite production. For single K-shell, multiple L-shell ionization, rearrangement cannot occur by Coster-Kronig transitions or by cascades from higher orbits. Also fluorescence yields have been calculated[2] for defect configurations of Ne.

Recent poor-resolution experiments involving heavy ions incident on Ar and Ne have been reported. Macdonald *et al.*[3] and Mowat *et al.*[4] have found that the target K x-ray production cross section is a strong function of the projectile charge state. The O + Ne case studied in this paper is of additional interest since Burch *et al.*[5] have recently measured an effective fluorescence yield for this case. In their measurements they were not able to resolve the K x rays into the satellite transitions.

This experiment was performed using the Kansas State University tandem Van de Graaff accelerator. Oxygen beams of charge states +7 and +8 were obtained by passing a 30-MeV O^{+5} beam through a thin (20 μ/cm^2) carbon foil. The O^{+5} beam was obtained by removing the secondary carbon foil. The different charge states were separated by a deflection magnet. The beam was then passed through a differentially pumped gas cell in which Ne gas was kept at a constant pressure. The pressure was controlled by a leak valve in conjunction with a capacitance manometer. The x rays were resolved using a curved-crystal vacuum spectrometer equipped with a rubidium acid phthalate (RAP) crystal mounted at

90° to the beam axis. The detector was a flow-mode proportional counter with a 2.0-μm foil.[6] Spectra for the O^{+5} beam were taken with pressures of 0.075, 0.10, and 0.15 Torr, and the relative intensities of the various lines did not vary significantly. The proton-, O^{+5}-, O^{+7}-, and O^{+8}-induced spectra were taken at 0.2 Torr in order to obtain good statistics. Each of the spectra was repeated at least twice and agreed within statistical certainty.

Figure 1 depicts the measured spectra. It is seen that the main feature of the Ne $K\alpha$ spectrum induced by 2-MeV protons is the normal Ne $K\alpha$ transition. Spectra taken with 30-MeV O^{+5}, O^{+7}, and O^{+8}, respectively, are shown. The neon peaks are labeled KL^n, corresponding to one K-shell vacancy and n L-shell vacancies (i.e., the KL^6 peak is due to the $K\alpha$ transition from the initial configuration with one K-shell vacancy and six L-shell vacancies). The first two peaks in the oxygen-induced spectra correspond to the $4p$-$1s$ and $5p$-$1s$ H-like oxygen transitions. A spectrum is shown for 30-MeV oxygen incident on a 20-μg/cm^2 carbon foil. In this spectrum the H-like oxygen transitions, including the series limit, are seen clearly. By comparing the O + C spectrum with the p + Ne and O + Ne spectra, it is seen that the series limit for H-like oxygen has a higher energy than the normal $K\alpha$ x ray for neon. The value of the series limit corrected for the transverse Doppler shift is 869.6 eV compared with a value of 848.6 eV for the normal Ne $K\alpha$ x ray.

Table I presents the measured and calculated[2] energies for the Ne $K\alpha$ transitions. The experimental values are based on an energy calibration

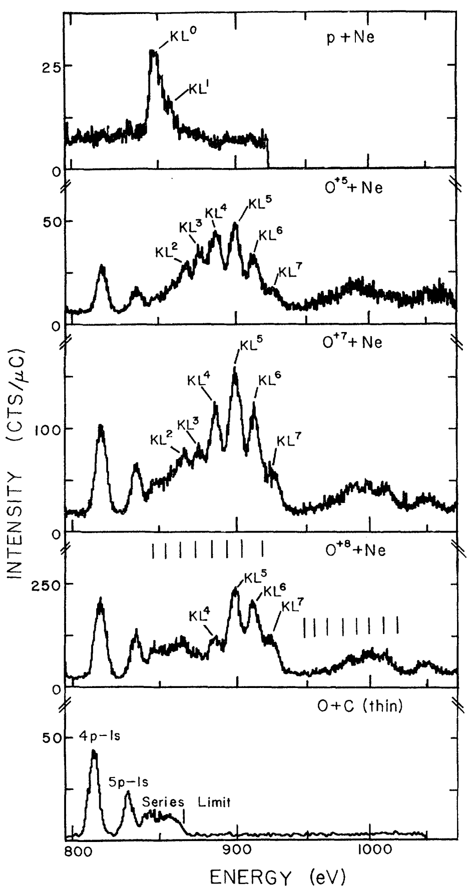

FIG. 1. Resolved $K\alpha$ spectra of Ne. KL^n refers to transitions from states with one K-shell vacancy and n L-shell vacancies. Shown are 2-MeV proton-induced, 30-MeV O^{+5}-induced, 30-MeV O^{+7}-induced, and 30-MeV O^{+8}-induced spectra of Ne, and H-like decays of oxygen after excitation by a thin carbon foil, for comparison. The ordinate axis is given in counts/μC of beam after passing through the gas cell. Two groups of eight vertical lines indicate calculated positions of $K\alpha$ transitions with single and double K-shell vacancies.

TABLE I. Theoretical and experimental neon energies for multiple ionization. In the first two columns the L-shell configuration of the atom is given for the atomic configuration ($1s\,2s^m\,2p^n$). On the right-hand side the degree of ionization of the shells is given as explained in the text.

m	n	E_{THEOR}[a] (eV)	E_{EXPT} (eV)	
2	6	848.6	848	KL^0
2	5	853.8	855	KL^1
1	6	854.7		
2	4	860.8	863	KL^2
1	5	861.0		
0	6	861.8		
2	3	869.1	873	KL^3
1	4	869.0		
0	5	869.3		
2	2	879.1	882	KL^4
1	3	878.6		
0	4	878.4		
2	1	890.8	895	KL^5
1	2	889.8		
0	3	889.1		
1	1	902.7	907	KL^6
0	2	901.7		
0	1	914.5	922	KL^7

[a]Taken from Ref. 2.

using the normal Ne $K\alpha$ x-ray energy[7] and the $4p$-$1s$ and $5p$-$1s$ H-like oxygen transition energies.[8] Because of uncertainties in the peak position and in the calibration, the experimental error is ± 2 eV. The calculated values presented in Table I and shown by vertical lines in Fig. 1 are those given by Bhalla and co-workers.[2] It is seen that the calculated values are consistently smaller than the measured values, with the discrepancy becoming larger for larger values of multiple ionization. The highest energy peak in Table I corresponds to decay of the Ne two-electron system $(1s)$ $(2p)$. Here the energies are especially sensitive to the approximations used. The broad peak in the oxygen-induced spectra from 955 to 1010 eV is due to double K-shell vacancy production. Resolution in this region is not sufficient to resolve this structure into transitions from different electron configurations. Bhalla and co-workers[2] predict these transitions to fall in the region between 946 and 1020 eV, which encompasses the region in which we observe these transitions. These predictions are also indicated in the figure by vertical lines. The vertical line of the highest energy corresponds to decay of the one-electron Ne system $(2p)$. The weak structure observed at an even higher energy is possibly due to a small amount of excitation or capture in orbitals with $n \geqslant 3$.

A comparison of the O^{+7}- and O^{+8}-induced spectra reveals a major difference in the Ne satellite structure. In the former case the intensities of the $K\alpha$ peaks below KL^5 are greater in proportion to the higher-energy lines. Table II includes the yields of the five peaks KL^n, $n=3, 4, 5, 6, 7$, normalized to their sum, for these two spectra as well as the O^{+5}-induced spectrum. The normalized yields include corrections for crystal reflectivity[9] and x-ray attenuation in the proportional-counter entrance foil.

TABLE II. Measured x-ray intensity ratios R_n of the different multiple configurations. Also given are the statistically weighted fluorescence yields derived as described in the text.

		R_n		
n	O^{+5}	O^{+7}	O^{+8}	ω_n
3	0.14	0.10	0.07	0.023
4	0.26	0.21	0.15	0.029
5	0.30	0.33	0.33	0.042
6	0.20	0.24	0.29	0.083
7	0.10	0.12	0.16	1.00

A semiempirical effective fluorescence yield $\overline{\omega}$ can be obtained from the relative x-ray intensities given in Table II. Defining $\overline{\omega}$ by $\sigma_I^{\text{tot}} = \sigma_X^{\text{tot}}\overline{\omega}$, where σ_I^{tot} and σ_X^{tot} are the total ionization cross section and total x-ray production cross section, respectively, $\overline{\omega}$ can be found by

$$\overline{\omega}^{-1} = \sum_n R_n/\omega_n.$$

R_n is the ratio of each $K\alpha$ satellite intensity to the total $K\alpha$ satellite intensity. The quantities ω_n are given in Table II and are average fluorescence yields derived for a given state of ionization by statistically weighting the fluorescence yields for specific defect configurations as calculated by Bhalla and co-workers.[2] Using this method we obtain values for $\overline{\omega}$ of $2.5\omega_0$, $2.8\omega_0$, and $3.2\omega_0$ for the O^{+5}, O^{+7}, and O^{+8} beams, respectively. The quantity ω_0 is the calculated $K\alpha$ fluorescence yield for Ne with a single K-shell vacancy. The error in the values of $\overline{\omega}$ is estimated to be 10% in each case. The effect on $\overline{\omega}$ of neglecting KL^2 which sits just below the oxygen-series limit is estimated to be less than 5%. The intensities of the KL^0 and KL^1 peaks are nearly zero. The value of $2.5\omega_0$ compares to the value of $\overline{\omega} = (2.4 \pm 0.5)\omega_p$ of Burch *et al.* obtained in a simultaneous measurement of x rays and Auger electrons with a 30-MeV oxygen beam in charge state[10] +5. The quantity ω_p is the effective fluorescence yield for the Ne bombarded by 5-MeV protons, as measured in that same experiment.

In summary, the relative intensities of Ne $K\alpha$ satellite lines resulting from collisions with 30-MeV oxygen are dependent on the charge state of the oxygen. The abruptness of the effect suggests that a process such as charge exchange might play an important role in the creation of vacancies in target atoms bombarded by highly stripped ions. A combination of Coulomb-ionization and charge-exchange processes has been employed by McGuire[11] with some success, to explain previous charge-state–dependence data.[3] Also, Halpern and Law[12] have recently used charge-exchange effects to explain some Z-dependence measurements by Macdonald *et al.*[13] Studies of simultaneous K-shell, L-shell ionization such as the one presented here should be especially useful in attempts to explain the nature of these effects.

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Excitation of the Plasmapause at Ultralow Frequencies

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Observational evidence and the theoretical interpretation indicate that magnetic disturbances exterior to the plasmasphere boundary (within the magnetosphere) can excite damped, sinusoidal oscillations, which can be inferred as a magnetohydrodynamic surface eigenmode, at the plasmapause. The wave frequency and damping rate can be used to infer the plasma density inside the plasmapause and the plasma density gradient at the plasmapause.

Earth's magnetosphere represents an excellent plasma laboratory for the study and understanding of naturally occurring ultralow-frequency magnetohydrodynamic (MHD) waves[1] in astrophysical plasmas. Indeed, except for the observations of such waves in the solar wind,[2] the magnetosphere is the only locale where these waves can be examined in detail and their growth and decay properties studied. Sugiura[3] reported the first evidence of elliptically polarized, geophysical hydromagnetic waves from observations made on the ground at College, Alaska. Evidence of ~200-sec waves in the magnetosphere was first reported from data obtained on an early Explorer satellite,[4] and later, satellite-measured waves were associated with similar frequency variations observed at a ground station.[5] Much recent work has been concerned with the use of magnetospheric MHD waves as diagnostic tools for studying magnetospheric properties from the ground,[6] even though the sources of these waves have, until now, not been positively identified.

In order to examine the role of the plasmapause[7] within the magnetosphere as a possible source and sink of wave energy, three digital-recording, three-axis magnetometer stations have been operated in a latitudinal array around the nominal location of the plasmapause.[8] These three stations are located at ~4°W geomagnetic longitude at latitudes corresponding to the intersection with Earth of the $L=4.4$, 4.0, and 3.2 magnetic shells. A similar station, operated at Siple station in the Antarctic at $L=4.0$ and at the same geomagnetic longitude as the northern stations, is magnetically conjugate to the northern station at $L=4.0$. The three orthogonal components (H,D,Z) of the total vector field $\vec{B}$ at each station are sampled and digitized at 2-sec intervals and written in a computer-compatible format on magnetic tape. The noise level of each detector system is ~0.2 γ over the bandwidth considered here ($\gamma=10^{-5}$ G).[9]

Shown in Fig. 1 are the H-component magnetic records for the three northern stations during the four time intervals 2104–2114 UT 19 December 1972, 1820–1830 UT 21 December 1972,