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OBSERVED $K\beta$ ENERGY SHIFT IN Cu AND Ni †

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The characteristic $K\beta$ x rays produced by 15.0-MeV oxygen (O^{4+}) ions on Ni are found to shift in the spectrum by 112 ±15 eV relative to the energies produced by x-ray and proton excitation in Ni. Similarly, in Cu an energy shift of 97 ±15 eV is observed. The observed shift is possibly due to the larger $K\beta$ energies of the multiply ionized Ni or Cu produced in O^{4+} bombardments as opposed to the singly ionized Cu or Ni $K\beta$ x rays.

The energies of characteristic x rays for singly ionized atoms are well known,[1] whereas the energies of x rays for highly ionized atoms are known for only a few atoms.[2] In this paper we discuss measurements of the energies of the $K\alpha_1+K\alpha_2$ and $K\beta_{1,3}$ x rays produced by bombarding thin targets of Ni and Cu with proton beams (6-MeV), x rays (^{109}Cd), and O^{4+} beams (15-MeV). We observe the Ni and Cu $K\beta$ lines to shift in the excitation of these lines by O^{4+} bombardments as compared with the excitation of these lines by proton or x-ray bombardments. The energy shift is possibly due to the production of multiply ionized Ni and Cu in the O^{4+} bombardments.

The University of Texas tandem Van de Graaff was used to produce beams of 6.0-MeV protons and 15.0-MeV O^{4+}. These beams were focused by means of a magnetic quadrupole lens onto a target and subsequently monitored in a Faraday-cup beam integrator. The x-ray yield was measured in a liquid-nitrogen cooled solid-state Si(Li) detector[3] (4 mm thick) placed at 90° to the beam direction. In a previous paper,[4] we discuss the use of Si(Li) detectors for observing x rays produced in proton and oxygen bombardments. The detector was placed outside the scattering chamber which contained a 0.5-mil Mylar x-ray window 0.5 in. in diameter. The pulses from the detector were fed into an amplifier-biased amplifier system and then to a 1024-channel analog-to-digital converter feeding into a PDP-7 computer. The system resolution for 8-keV x rays was ~280 eV with an efficiency near 100%. The energy calibration for the system was obtained from the x-ray excitation yield produced by a ^{109}Cd source on targets of Ni and Cu. An ^{55}Fe-source x-ray spectrum was also used in the energy calibration. The energy calibration was checked after each bombardment by repeating an x-ray excitation yield on Ni or Cu. Each x-ray spectrum was fitted, by a nonlinear least-squares fitting routine, with the background-plus-Gaussian function

$$Y(E)=(A+BE)f(E)+\sum_{n=1}^{2}[1-S_n(E-E_n)]H_n e^{-2.0(E-E_n)^2/\Gamma_n{}^2} \tag{1}$$

with $f(E)$ = (peak areas from E to $+\infty$)/(total area under peaks), E_n is the peak energy of the Gaussian, and H_n is the maximum height of the Gaussian at $E=E_n$. The parameters B and S_n were kept at zero in all the fits given here.

In Fig. 1 x-ray spectra for the case of a thin Ni target (~600 $\mu g/cm^2$) are given. By inspection we see that the $K\alpha$ lines[5] remain in nearly the same position and have approximately the same width in all the three cases shown; however, the $K\beta$ energy is increased in the case of the O^{4+} + Ni spectrum. The full width at half-maximum (Γ) is also increased. Table I contains the results of the least-squares fits to the various spectra. The $K\beta$ energy shifts are 112 ± 15 eV for O^{4+} and 22 ± 15 eV for protons; both shifts are relative to the x-ray excitation values. The widths Γ_α and Γ_β both increase going in the order from x-ray activation to proton bombardments to O^{4+} bombardments.

In Fig. 2 the same general results can be seen for the Cu x-ray spectra as was seen for the Ni x-ray spectra. In Table I the results of the least-squares fit to the Cu spectra are given. A $K\beta$ shift for O^{4+} + Cu relative to x rays (^{109}Cd) + Cu of 97 ± 15 eV is observed. The p + Cu shift is 0 ± 15 eV. The widths Γ_α and Γ_β are again largest for the O^{4+} + Cu spectra and smallest for the x-ray excitation. It should be noted that even though the difference $\Delta E = E_\beta - E_\alpha$ for x-ray and proton excitation yields are the same, the individual energies E_α and E_β are somewhat smaller for the proton excitation yield. This may be an analysis difficulty due to the somewhat larger background present in the proton beam experiment.

In conclusion we have observed a Ni and Cu energy line shift and a line broadening of the $K\beta$ line upon bombarding these atoms with O^{4+}. The energy shift is possibly characteristic of an average ionization of Cu atoms presumably following a single atomic collision with the O^{4+}. An increased K x-ray transition energy is expected when one or several of the outer shielding electrons are removed from the atom. The $K\alpha$ energies for highly ionized atoms between carbon and copper have recently been calculated by House.[6] Using these results a Cu $K\alpha$ shift <15 eV implies an ionization state <+18. Large energy shifts begin to occur, however, whenever one removes n = 2 electrons which occurs at an ionization state of +20. The energy shift associated with the removal of each n = 2 electron is approximately 50 eV. If one assumes that the $K\beta$ energies scale similarly to the $K\alpha$ energies, then doubly or triply ionized Ni or Cu could possibly explain the observed energy shifts. One can calculate very simply the maximum energy shift expected by

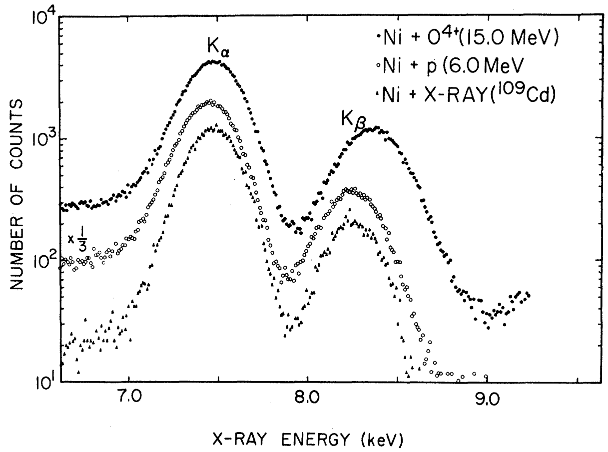

FIG. 1. The characteristic K x-ray spectra for Ni bombarded with the indicated beam. The $K\beta$ energy and width is largest for the Ni + O^{4+} case.

calculating the transition energies. The $K\beta$ energy is E_β = 10.15 keV for Cu^{28+} so that ΔE_β = 1250 eV, and the $K\alpha$ energy is E_α = 8.57 keV for Cu^{28+}

Table I. Results of a least-squares fit of the x-ray spectra by Eq. (1). The spectra were taken in the order given. The energies E and Γ (full width at half-maximum) are all in units of eV. $\Delta E = E_\beta - E_\alpha$.

Incident beam	E_α	Γ_α	E_β	Γ_β	ΔE	χ^2
			Cu parameters[a]			
X rays	8040 ±1	278 ±1	8893 ±2	288 ±2	853	2.31
O^{4+}	8035 ±1	299 ±1	8985 ±2	380 ±3	950	2.70
X rays	8047 ±1	281 ±1	8899 ±2	286 ±3	852	3.45
X rays	8041 ±1	279 ±1	8895 ±2	294 ±3	854	1.86
p	8018 ±1	296 ±2	8868 ±3	338 ±4	850	5.42
p (thin tgt)	8014 ±1	294 ±2	8870 ±2	307 ±4	856	5.37
			Ni Parameters[a]			
p	7450 ±1	291 ±1	8252 ±2	327 ±3	802	3.74
X rays	7472 ±9	279 ±1	8250 ±2	280 ±4	778	1.67
O^{4+}	7477 ±1	300 ±1	8369 ±1	359 ±3	892	3.46
X rays	7468 ±1	282 ±2	8250 ±2	281 ±2	782	1.81

Targets	Energy shifts $\Delta E(O^{4+}) - \Delta E$(x rays) (eV)	$\Delta E(p) - \Delta E$(x rays) (eV)
Cu	97 ±15	0 ±15
Ni	112 ±15	22 ±15

[a]The errors quoted in E_α, E_β, Γ_α, and Γ_β are fitting errors only. An absolute error of ±15 eV should be included in comparing magnitudes of E_α and E_β.

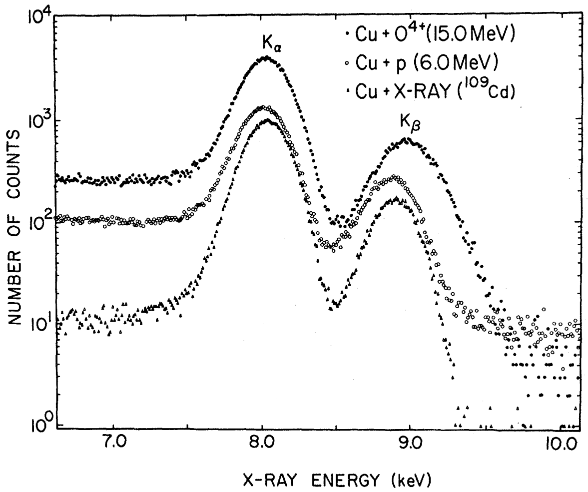

FIG. 2. Characteristic K x-ray spectra for Cu bombarded with the indicated beam. The $K\beta$ energy and width is largest for the Cu + O^{4+} case.

so that $\Delta E_\alpha = 530$ eV. House gives the energy shift for He-like atoms to be $\Delta E_\alpha = 330$ eV so that a large part of the maximum shift ΔE_β given above is probably due to removing one of the last two electrons.

It is thus anticipated that in the future the $K\alpha$ and $K\beta$ energies for many highly ionized atoms can be measured by means of high-energy bombardments using heavy ions. It is also anticipated that calculations of the $K\beta$ energies for highly ionized atoms will further aid in the identification of the charge states produced in this type of experiment. The identification of recently observed shifted lines in solar x-ray spectra[7] may be aided by the laboratory measurement of the type presented here.

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[1]J. A. Bearden, Rev. Mod. Phys. 39, 78 (1967).

[2]N. J. Peacock, R. J. Speer, and M. G. Hobby, At. Mol. Phys. 2, 798 (1969).

[3]KeVex Corp., Burlingame, Calif.

[4]P. Richard, T. I. Bonner, T. Furuta, I. L. Morgan, and J. R. Rhodes, to be published.

[5]The lines referred to loosely in this paper as $K\alpha$ and $K\beta$ are actually multiplets of closely spaced lines which are unresolved in the present experiment. From Ref. 1, $E_{\alpha_1} = 8.048$ keV, $E_{\alpha_2} = 8.028$ keV, $E_{\beta_{1,3}} = 8.905$ keV for Cu with intensity ratios of 0.50:1.0:0.17, respectively. For Ni, $E_{\alpha_1} = 7.478$ keV, $E_{\alpha_2} = 7.461$ keV, and $E_{\beta_{1,3}} = 8.265$ keV with the same intensity ratios as in Cu. A crystal diffraction system with sufficient resolution to resolve the lines could possibly be used, but at a great loss of efficiency as compared with the Si(Li) detector.

[6]L. L. House, Astrophys. J. Suppl. Ser. 18, 21 (1969).

[7]G. Fritz, R. W. Kreplin, J. F. Meekins, A. E. Unzicker, and H. Friedman, Astrophys. J. 148, L133 (1967).

AUTOIONIZING AND NEGATIVE-ION STATES IN NEON*

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The trapped-electron spectrum of Ne has been measured in the energy region from 40 to 50 eV. New negative-ion resonances are observed.

Recent improvements in spectroscopic techniques have led to the observation of new physical processes in the electronic behavior of several atomic species. Optical observations have been made of autoionizing states far into the ultraviolet[1] and collision spectroscopy has revealed additional states which are of even higher energy or are optically forbidden.[2] In the particular case of electron-collision spectroscopy, additional negative-ion or autodetaching states may also be observed.[3] The negative-ion states appear as resonances in one or more of the observed scattering channels. Observation and classification of atomic negative-ion resonances have been made for the noble gases,[3] hydrogen,[4] and mercury.[3] Only a few of the possible resonances which may be associated with the ordinary excited states and the autoionizing states of these