PHYSICAL REVIEW A VOLUME 7, NUMBER 4 APRIL 1973

$K\beta$ Hypersatellite Observation in Magnesium*

Patrick Richard, David K. Olsen, Robert Kauffman, and C. Fred Moore
Center for Nuclear Studies, University of Texas, Austin, Texas 78712

(Received 24 July 1972)

The K x-ray spectrum of Mg produced by 30-MeV oxygen ions is observed to consist of four regions of K x-ray excitations. These regions consist of the $K\alpha$ satellite lines, the $K\beta$ satellite lines, the $K\alpha$ hypersatellite lines, and the $K\beta$ hypersatellite lines. The last region is observed for the first time and corresponds to $1s\rightarrow 3p$ transitions in an atom consisting of double K-shell vacancies as well as multiple L-shell vacancies.

The observable K x-ray transitions from single-collision events have undergone a revolutionary change in the last three years with the use of high-energy heavy-ion beams. Multiple-ionization states dominate the spectra and lead to many new transitions. In this paper we present the observation of a group of x-ray transitions near the high-energy limit for K x rays in Mg. As will be shown, these x rays are $K\beta$ hypersatellites, that is, $1s\rightarrow 3p$ transitions in atoms with double K-shell ionization and a varying number of L-shell ionization states.

A 30-MeV oxygen beam from the University of Texas tandem electrostatic accelerator was bombarded on a 99.9%-pure Mg foil. The x rays were analyzed in a vacuum x-ray crystal (ADP) spectrometer placed at 90° to the beam line. A stepping motor interfaced to a PDP-7 computer controlled the crystal and detector movement. The pulses from a flow-proportional counter were histogrammed in a 20 480-channel array in the computer. The step size was 0.00011 Å.

The observed K x-ray transitions in the range of 10.0 to 7.2 Å are given in Fig. 1. The data are presented on a linear plot with three different scales in order to emphasize the various types of transitions. The long-wavelength or low-energy region of Mg is easily understood and has recently been discussed in detail.[1] This region, from about 9.5 to 9.9 Å, contains the $K\alpha$ satellites consisting of the $K\alpha$ transitions from initial states with the L-shell configurations $(2p)^n$ for $n=6$, 5, 4, ... , 1 and are thus designated as $K\alpha(2p)^n$. The observed energies, Hartree–Fock–Slater calculated energies, the configurations, and the structure designation are given in Table I. It is noted that the $K\alpha_4$ line is seen here where it was not seen in Ref. 1. The observed energy, 1264 eV, is the same as seen by Kunzl.[2] The reason that this line is observed here is that better statistics have been obtained. As discussed in Ref. 1, the absorption edge (1305 eV) falls below the $K\alpha(2p)^1$ transition which substantially decreases its intensity relative to the other $K\alpha$ satellites. The observed resolution is 1.1 eV.

The second region, from about 9.5 to 9.1 Å, of K x-ray transitions is the $K\beta$ satellite region. The transitions in this region do not lie in a self-contained energy range but rather overlap the $K\alpha$ satellites on the low-energy end and overlap the $K\alpha$ hypersatellites on the high-energy end. The characteristic $K\beta$ transition $K\beta(2p)^6$ is, in fact, buried beneath the $K\alpha(2p)^2$ peak and therefore not clearly defined. The two peaks above $K\alpha(2p)^1$ at energies of 1.322–1.324 keV (doublet) and 1.348–1.357 keV (resolved doublet) are, respectively, the $K\beta(2p)^5$ and $K\beta(2p)^4$ satellite transitions. The results are summarized in Table I. The observed resolution of these lines is about 4 eV.

The third region of excitation, from about 9.1 to 8.6 Å, consists of five closely spaced transitions

TABLE I. Magnesium K x-ray transitions.

Label	Observed energies (keV)	Calculated energies (keV)	Configuration	Structure designation
$K\alpha_{1,2}$	1.254	1.254	$K\alpha(2p)^6$	$K\alpha$ satellites
$K\alpha_3$	1.262	1.262	$K\alpha(2p)^5$	
$K\alpha_4$	1.264			
$K\alpha_8$	1.269			
$K\alpha_5$	1.271	1.272	$K\alpha(2p)^4$	
$K\alpha_7$	1.272			
$K\alpha_6$	1.274			
$K\alpha_9$	1.281	1.284	$K\alpha(2p)^3$	
$K\alpha_{10}$	1.284			
$K\alpha_{13}$	1.296	1.298	$K\alpha(2p)^2$	
	1.307	1.313	$K\alpha(2p)^1$	
$K\beta$	...	1.295	$K\beta(2p)^6$	$K\beta$ satellites
	1.322–1.324	1.321	$K\beta(2p)^5$	
	1.348	1.349	$K\beta(2p)^4$	
	1.357			
	1.373	1.364	$(K\alpha)^h(2p)^4$	$K\alpha$ hypersatellites
	1.378			
	1.388	1.378	$(K\alpha)^h(2p)^3$	
	1.390			
	1.401	1.392	$(K\alpha)^h(2p)^2$	
	1.410	1.409	$(K\alpha)^h(2p)^1$	
	1.414			
	1.424–1.427			
	1.502	1.471	$(K\beta)^h(2p)^4$	$K\beta$ hypersatellites
	1.520			
	1.531	1.506	$(K\beta)^h(2p)^3$	
	1.560	1.542	$(K\beta)^h(2p)^2$	
	1.589	1.581	$(K\beta)^h(2p)^1$	
	1.620	1.625	$(K\beta)^h(2p)^0$	

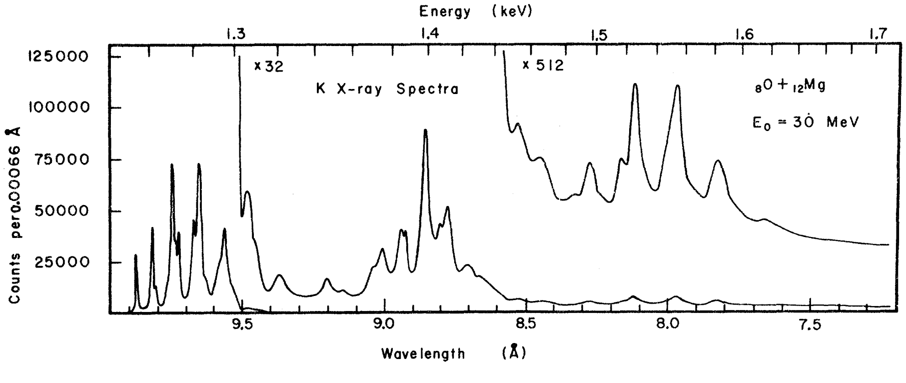

FIG. 1. The spectrum for Mg plus 30-MeV oxygen showing the $K\alpha$ satellite, $K\beta$ satellite, $K\alpha$ hypersatellite, and $K\beta$ hypersatellite structures.

(many being doublets) which cannot be explained as $K\beta$ transitions. These are assigned to the $(K\alpha)^h$ (K hypersatellite) transitions calculated nearest the observed peaks. This assignment is suggestive of the proper type transition and not intended to be a final assignment. These type $K\alpha$ hypersatellites were recently discovered[3] in ion-atom collisions for the case of Ca plus 30-MeV oxygen where the hypersatellites occur between the $K\alpha$ and $K\beta$ structures and there lend themselves to a unique identification. The $K\beta$-vs-$(K\alpha)^h$ interplay in this region of Z can be resolved by studying the systematics of the Mg, Al, and Si structure with the energy resolution obtained in the present experiment. A recently published letter[4] on Al, $K\alpha$, and $K\beta$ satellites implied that the structure above $K\alpha$ is all due to $K\beta$ transitions. Such indeed must not be the case. The observed resolution for these lines in the present experiment is approximately 2 eV.

The new fourth region of excitation, ranging from 8.6 to 7.6 Å, which is the main point of this communication, consists of x rays near the high-energy x-ray limit for Mg. Five transitions between 1.50 and 1.62 keV are consistent with energies for $1s \rightarrow 3p$ transitions fro~~m atom~~s with double K-shell vacancies, and could thus be given the name $K\beta$ hypersatellites $(K\beta)^h$. The results are summarized in Table I. There are many possible transitions in this energy region depending on the degree of ionization of the atom in the $2s$ and $3s$ shells in addition to the primary $2p$ shell used to assign the peaks. It should be pointed out that the maximum high-energy limit of this region is not reached in this experiment. According to hfs calculations the minimum energy is 1.410 keV, which corresponds to $(K\beta)^h(2p)^6$ transitions, and the maximum energy is 1.728 keV for the hydrogen-like $K\beta$ limit. The two peaks at 1.455 and 1.468 keV not given in Table I probably belong to the $(K\beta)^h$ group. The observed resolution for the $K\beta$ hypersatellite transitions is approximately 7 eV and is probably the natural width for these lines.

In summary, we have observed a new group of fairly strong lines above the $K\beta$ satellites and $K\alpha$ hypersatellites which are shown to be due to $K\beta$ transitions from atoms with double K-shell vacancies. The relative intensities of the various groups cannot be given accurately at this time owing to the partially unresolved structure in the $(K\alpha)^h$ region and to the K absorption-edge corrections in the thick target. The $(K\beta)^h/(K\alpha)^h$ ratio is nonetheless estimated at 9%. These type transitions are very likely to be observed in astronomical sources. A further study of these types of transitions is needed to get a complete understanding of ion-atom collisions, especially for light elements where the probabilities for multiple ionization are so predominant and lead to a multitude of states.

---

*Supported in part by the Research Corporation, the Robert A. Welch Foundation, and the U. S. Atomic Energy Commission.

[1] D. G. McCrary, M. Senglaub, and Patrick Richard, Phys. Rev. A **6**, 263 (1972).

[2] V. Kunzl, Z. Phys. **99**, 481 (1936).

[3] Patrick Richard, W. Hodge, and C. Fred Moore, Phys. Rev. Lett. **29**, 393 (1972).

[4] A. R. Kundson, D. J. Nagel, P. G. Burkhalter, and K. L. Dunning, Phys. Rev. Lett. **26**, 1149 (1971).