KLM Auger transitions in light atoms: $_{23}$V and $_{31}$Ga

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The *KLM* Auger spectra of vanadium and gallium have been studied. It has been found that in light atoms the probabilities for *KLM* transitions are described by a theory based on approximation of intermediate coupling. The energies of the *KLM* transitions, which include the 3*d* shell, according to the semiempirical calculations of Larkins [At. Data Nucl. Data Tables **20**, 311 (1977)], are clearly too high.

The relative intensities of *KLM* Auger transitions in atoms with $Z > 35$ can be described satisfactorily by relativistic *jj*-coupling calculations.[2] No experimental studies have been carried out for $Z < 35$. It has appeared that since the atom was left ionized in different shells as a result of the *KLM* transition the *jj*-coupling scheme would also apply to light atoms. We have measured the *KLM* spectra of vanadium ($Z = 23$) and gallium ($Z = 31$), and we have carried out some nonrelativistic calculations of the probabilities for the corresponding transitions in the intermediate-coupling approximation.[3] It has been found that the *jj*-coupling scheme is not suitable for describing *KLM* transitions for atoms with $Z < 35$.

In the present experiments we studied the spectra of *KLM* Auger electrons by methods of nuclear spectroscopy. For the measurements we use a magnetic beta spectrometer with a position-sensitive detector in the focal plane.[4] The use of this one-coordinate detector, consisting of a chevron of microchannel plates, increases the rate at which the spectra are measured by nearly two orders of magnitude, and there is also a significant improvement in the effect-to-background ratio.

The *K* Auger transitions accompany electron capture in $^{51}_{24}$Cr and $^{71}_{32}$Ge. The beta sources are synthesized by vacuum deposition on nonequipotential substrates bombarded in a flux of reactor neutrons $\sim 1.2 \times 10^{14}$ n/(cm^2·s) of $^{50}_{24}$Cr metal targets (88% enrichment in the isotope) and $^{70}_{32}$Ge metal targets (96%). The surface density of the beta sources is several tenths of a microgram per square centimeter.

For convenience in comparison with the theory, the measured intensities are divided by $10^{-3} \cdot \Sigma KL_{1-3}M_{1-3}$. Table I shows the results of relativistic Hartree–Fock–Slater calculations in the *jj*-coupling model[5] and the results of nonrelativistic Hartree–Fock–Slater calculations in the intermediate-coupling approximation.[3] In the calculations of Ref. 3 use was made of the Slater integrals from Ref. 1 and of the transition amplitudes tabulated in Ref. 6.

From this comparison we conclude the following:

1. Within the measurement errors, the intensities of the *KLM* transitions in vanadium agree with the results of the nonrelativistic Hartree–Fock–Slater calculations in the intermediate-coupling approximation.[3] The possible contribution of correlation effects does not exceed the measurement errors.

TABLE I.

	Vanadium, $Z = 23$					Gallium, $Z = 31$				
	Intensity			Rel. energy, eV		Intensity			Rel. energy, eV	
Line	Expt.	Theo.		Expt.	Calc.	Expt.	Theo.		Expt.	Calc.
		3	5		1		3	5		1
KL_1M_1	89 ∓ 3	88	93	− 138.5 ∓ 1.1	− 138.2	96 ∓ 4	84	102	− 209.8 ∓ 0.8	− 209.6
$KL_1M_{2,3}$	149 ∓ 5	141	169	− 108.3 ∓ 0.8	− 105.6	171 ∓ 7	140	150	− 154.0 ∓ 1.2	− 152.0
KL_2M_1	60 ∓ 9	56	45	− 28.9 ∓ 1.3	− 28.6	48 ∓ 5	47	38	− 54.3 ∓ 1.2	− 51.2
KL_3M_1	71 ∓ 10	74	83	− 21.1 ∓ 1.4	− 21.4	60 ∓ 8	78	84	− 24.4 ∓ 1.3	− 25.1
$KL_2M_{2,3}$	411 ∓ 11	397	206	0	0	298 ∓ 14	308	213	0	0
$KL_3M_{2,3}$	221 ∓ 9	244	403	8.9 ∓ 0.8	7.1	327 ∓ 14	344	413	23.3 ∓ 0.6	26.4
$KL_2M_{4,5}N$	12 ∓ 2	–	–	39.1 ∓ 1.5	55.0	27 ∓ 4	–	22	88.5 ∓ 1.5	95.7
$KL_3M_{4,5}N$	29 ∓ 2	–	–	50.6 ∓ 0.9	62.5	35 ∓ 4	–	40	111.4 ∓ 1.2	122.5

2. Relativistic effects are noticeable in gallium ($Z = 31$). The measured relative intensities of the KL_1M_1 and $KL_1M_{2,3}$ lines are higher than the nonrelativistic calculations.

3. Relativistic effects have little influence on transitions which lead to a final "hole" configuration $(2p)^{-1}(3p)^{-1}$, but intermediate coupling plays the major role for them. This conclusion also follows from an analysis of the nonrelativistic theory with *jj* coupling, which shows that the ratio of the intensities of the $KL_2M_{2,3}$ and $KL_3M_{2,3}$ line groups is 0.5 in this theory.

The measured relative intensities of the strongest KLM lines agree within 2–3 eV with the results of the semiempirical calculations by Larkins.[1] On the other hand, for transitions which involve $3d$ electrons, the data of Ref. 1 are clearly too high. In particular, the energies of the $KL_2M_{4,5}$ and $KL_3M_{4,5}$ line groups of vanadium, according to Ref. 1, are greater than the energies of the K_{α_2} and K_{α_1} x-ray transitions, in contradiction of energy conservation.

The energies of the Auger transitions were formed in Ref. 1 from the empirical electron binding energies in the atomic subshells and also the Slater integrals calculated for completely filled shells, along with corrections for adiabatic relaxation and a partial screening of the "holes" by electrons from the valence band. The first of these was calculated for the final hole configuration $(2s)^{-1}(3s)^{-1}$, and it was assumed that its value was nearly independent of the orbital quantum numbers of the holes. These corrections increase the energy of the KLM transitions by ~ 20 eV in vanadium and ~ 30 eV in gallium.

A detailed analysis of the expressions for the energies of $KL_{2,3}M_{4,5}$ transitions shows that, although the $3d$ shell is not filled in the case of vanadium, the discrepancy between the results of Ref. 1 and the experimental results could not be attributed entirely on the method developed by Larkins[1] for calculating the Slater integrals for filled shells. In the case of gallium, all of the $3d$ states are empty; nevertheless, the energies of these transitions in Ref. 1 remain considerably too high. It appears that the reason for the discrepancy is that the correction for the adiabatic relaxation for KLM transitions, including $3d$ electrons, differs noticeably from that used in Ref. 1 for atoms with $Z \lesssim 30$.

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