CONF-921116--22

BNL--48399

DE93 007275

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Presented at

Twelfth International Conference on the

Application of Accelerators in Research and Industry

Denton, Texas

November 2-5, 1992

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(Received September 26, 1992)

Energetic K and L Auger electrons produced by focussed, filtered, broad-band synchrotron radiation have been measured at the x-ray ring of the National Synchrotron Light Source (NSLS). The x-ray beam was used to study inner-shell photoionization of Ne and Ar gas and Fe and Cu solid film targets. The Auger electrons were analyzed by means of a semi-hemispherical electrostatic electron spectrometer at the energy resolution of ~3 %. The electrons were detected at both 90° and 0° with respect to the photon beam direction. Broad distributions of the inner-shell photoelectrons were also observed, reflecting the incoming photon flux distribution. The Fe and Cu K Auger electron spectra were found to be very similar to the Ar K Auger electron spectra. This was expected, since deep inner-shell Auger processes are not affected by the outer valence electrons. Above 3 keV in electron energy, there have been few previous Auger electron measurements.

* The work at BNL was supported by the Division of Chemical Sciences, Office of Basic Energy Sciences, Office of Energy Research, U.S. Department of Energy under contract no. DE-AC02-76CH00016.

I. INTRODUCTION

Auger electron spectroscopy has been applied to many disciplines of science [1]. Core-level Auger electrons and photoelectrons have been measured to investigate outer-shell electronic states of atoms, molecules, and material surfaces. The spectroscopy of these Auger electrons has been widely applied, complementing the method of photoemission spectroscopy or electron spectroscopy for chemical analysis (ESCA) [2].

In the field of atomic collisions with charged particles, Auger electron spectroscopy has been a powerful technique to study atomic inner-shell processes [3] such as inner-shell electron excitation and ionization followed by Auger emission (autoionization). This allows one to identify the collisionally-produced atomic states in the projectiles or targets. There have also been many measurements of Auger electrons produced by electron impact ionization of materials in gas-phase or solid targets [1, 4].

Inner-shell fluorescence producing characteristic K x-rays has been used routinely in the fields of basic and applied sciences using conventional x-ray or recent synchrotron radiation sources. However, few studies have been done with high-energy inner-shell Auger electrons at electron kinetic energy larger than 3 keV. In this article we report our recent observation of "energetic" deep inner-shell Auger electrons produced by x-ray synchrotron radiation.

II. EXPERIMENT

The experiments were performed at beamline X26C of the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory. The bending-magnet x-ray beam was first filtered by a Be window (10 mil thick) and then focused by an x-ray mirror into a spot whose size was smaller than 1 mm$\times$1 mm. A one-hundred fold increase in photon flux density was achieved [5]. The beam then entered the scattering chamber after passing three more Be windows (total 40 mil thickness) and an Al filter (1–22 mil). A computer-controlled 4-jaw slit was positioned before the scattering chamber and used to collimate the focussed photon beam. The energy distribution of the incoming photon beam ranged from 5 to 16 keV. The low energy photons below $\sim$ 5 keV were absorbed mostly by the Be windows and Al filters, and

the absorption of the high energy photons above $\sim$ 16 keV were due to the absorption in the platinum coating of the x-ray mirror [6].

A needle of 1 mm diameter was positioned in front of the spectrometer entrance to produce a gas jet of either Ne or Ar. The solid targets were chosen for use in complementary experiments on atomic Compton electrons [7]. By the method of Rutherford back scattering, it was found that an iron film of about 150 Å was deposited on the surface of the Be foil. The iron film was apparently coated on the surface of the Be foil in the construction process. The copper film target was prepared by depositing about 150 Å thickness of Cu on a Be foil by the method of vacuum evaporation.

The Auger electrons and photoelectrons were measured at both 90° and 0° with respect to the photon beam direction and in the plane of the electron orbit in the storage ring. The electrons were first energy-analyzed by a hemispherical electrostatic electron spectrometer at energy resolution of about 3% and then counted by a channel electron multiplier. High voltages applied to the outer and inner spherical plates of the spectrometer were controlled by computer. The relative signal of photon flux was monitored using a tantalum flag which was at about 1 m downstream from the spectrometer. This signal was used to normalize the electron counts at each analyzing voltage to a constant number of photons.

The base chamber pressure was $0.5\text{–}1\times10^{-6}$ torr. The flow of the target gas through the jet was adjusted to keep the chamber pressure below 3×10^{-5} torr.

III. RESULTS AND DISCUSSION

Fig. 1 shows K and L Auger electrons and photoelectrons from Ne and Ar gas targets measured at 90° in the horizontal plane. The Ne KLL Auger spectrum [see Fig. 1, inset (a)–1] is characteristic for single Ne K-vacancy production by any means. For example, higher resolution would reveal individual lines which were observed by electron or ion impact [1, 8].

As shown in Fig. 1(b), three groups of Ar K Auger lines; KLL, KLM, and KMM, are well identified. The KLL Auger group [see Fig. 1(b)–2] is very similar to the Ne KLL Auger group, which can be expected with the same number of L-

shell electrons in both targets. Many unresolved L-Auger transitions are observed as shown in Fig. 1(b)–1. Theoretically, the decay channels have been identified and described as the radiative Auger cascade [9]. Most of the L-shell vacancy production is indirect, that is it results from K Auger or K x-ray emission rather than direct L-shell ionization. Since the L- to K-shell photoionization cross section ratio for Ar is about 0.1 above the K-absorption edge, direct L-shell vacancy production should be an order of magnitude less probable than direct K-shell production. As in previous electron impact studies [1], numerous individual lines would be identified with a higher-resolution electron spectrometer. Then, the results could be compared with theoretical prediction of Auger electron transition energies and relative line strength.

The broad peaks for both Ne and Ar targets are attributed to K-shell photoelectrons. The photoelectron energy distributions reflect the incoming photon flux distribution shifted by the respective K-shell binding energy. Thus, the energy distribution of the photoelectrons provides an *in situ* method of determining the incoming photon flux distribution of such broad band, focussed synchrotron radiation [10].

Fig. 2 displays the K Auger electron spectra produced from Ar gas and Fe and Cu solid targets. The spectra were obtained at 0°. The Ar K Auger spectrum is very similar to the spectrum obtained at 90°. The Fe and Cu K Auger spectra are produced from atoms in the atomic layers near the film surface.

The escape depth [1, 11] of the electrons produced in solid targets is one of the most important factors in the electron emission measurements in surface analysis. For 1 keV electron energy, the escape depth of most elements has been observed to be a several $\AA$. The universal trend is that above 100 eV the escape depth increases roughly proportional to the electron energy. Thus, a several-keV-energy electron might have an escape depth of more than 20 $\AA$. Therefore, the high energy electrons can easily escape a large number of atomic layers without any considerable disturbance by the any atoms in their escape path. The escape depth of the Fe and Cu K Auger electrons was estimated to be larger than 10 monolayers [11].

The observed Fe and Cu K Auger spectra resemble the K Auger spectrum produced from the Ar gas target. This spectral similarity is expected, if one consider the fact that the inner-shell K Auger process is not affected by outer valence electrons.

Thus, K Auger characteristic lines of the elements may be used for surface analysis such as surface material identification or concentration. This method would be very similar to bulk-material characterization using x-ray fluorescence [12].

As expected from the accepted theory of photoemission [13], no photoelectrons are observed at 0° from the Ar gas target. However, 0° photoelectrons are clearly observed from the solid targets. These photoelectrons are attributed [10] to scattering of other than 0° photoelectrons from the neighboring atoms and/or photon scattering before photoelectron production occurs.

In summary, we have measured the high energy K Auger electrons produced from Ne and Ar gas and Fe and Cu solid film targets in interactions with broad-band x-ray (5–16 keV) synchrotron radiation. The electron spectra were recorded at 90° and 0° with respect to the beam direction. The K Auger electron spectra from Fe and Cu solid film targets exhibit the same spectral feature as the Ar K Auger spectrum.

In conclusion, atomic inner-shell processes with x-ray photons can be studied by using atomic solid film targets of medium- or high-Z metal elements or their compounds. Theoretical and experimental work is needed to further explore the deep inner-shell Auger transitions with "atomic" solid targets. High-resolution measurements of high energy Auger electrons produced by high energy photons of synchrotron radiation will be very promising in both practical and theoretical aspects.

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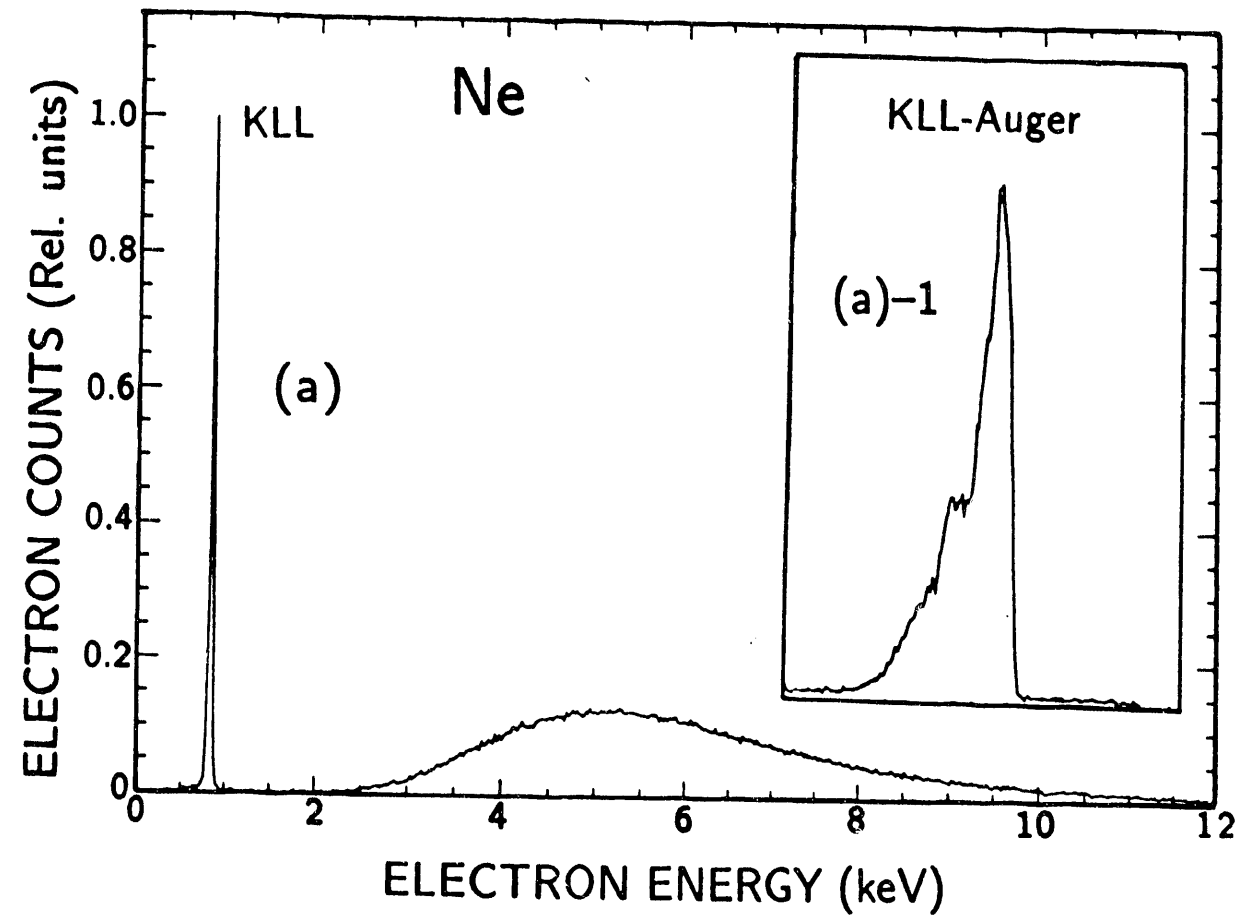
FIGURES

FIG. 1. Ne K and Ar K and L Auger electrons produced by inner-shell photoionization by x-ray synchrotron radiation. The spectra were obtained at 90° with broad energy distribution of photoelectrons, which reflects the incoming photon flux distribution [10].

FIG. 2. Spectral similarity of the K Auger group between "free" gaseous atoms and "bound" atoms in solid. The Auger electrons were measured at 0° together with the background of photoelectrons in the case of solid targets

FIG. 1.


Ne
KLL
(a)
KLL-Auger
(a)–1
ELECTRON COUNTS (Rel. units)
ELECTRON ENERGY (keV)
0
0.2
0.4
0.6
0.8
1.0
0
2
4
6
8
10
12

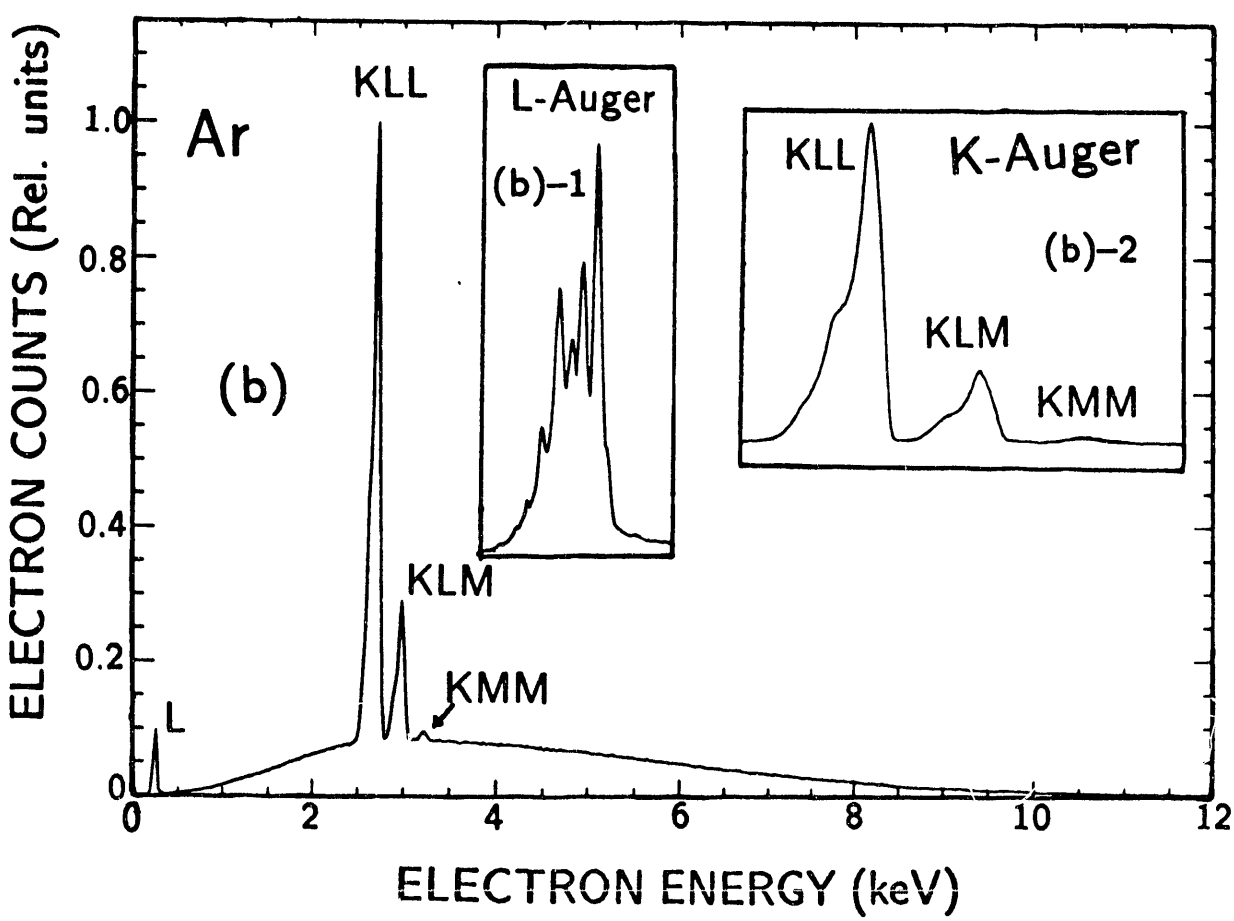
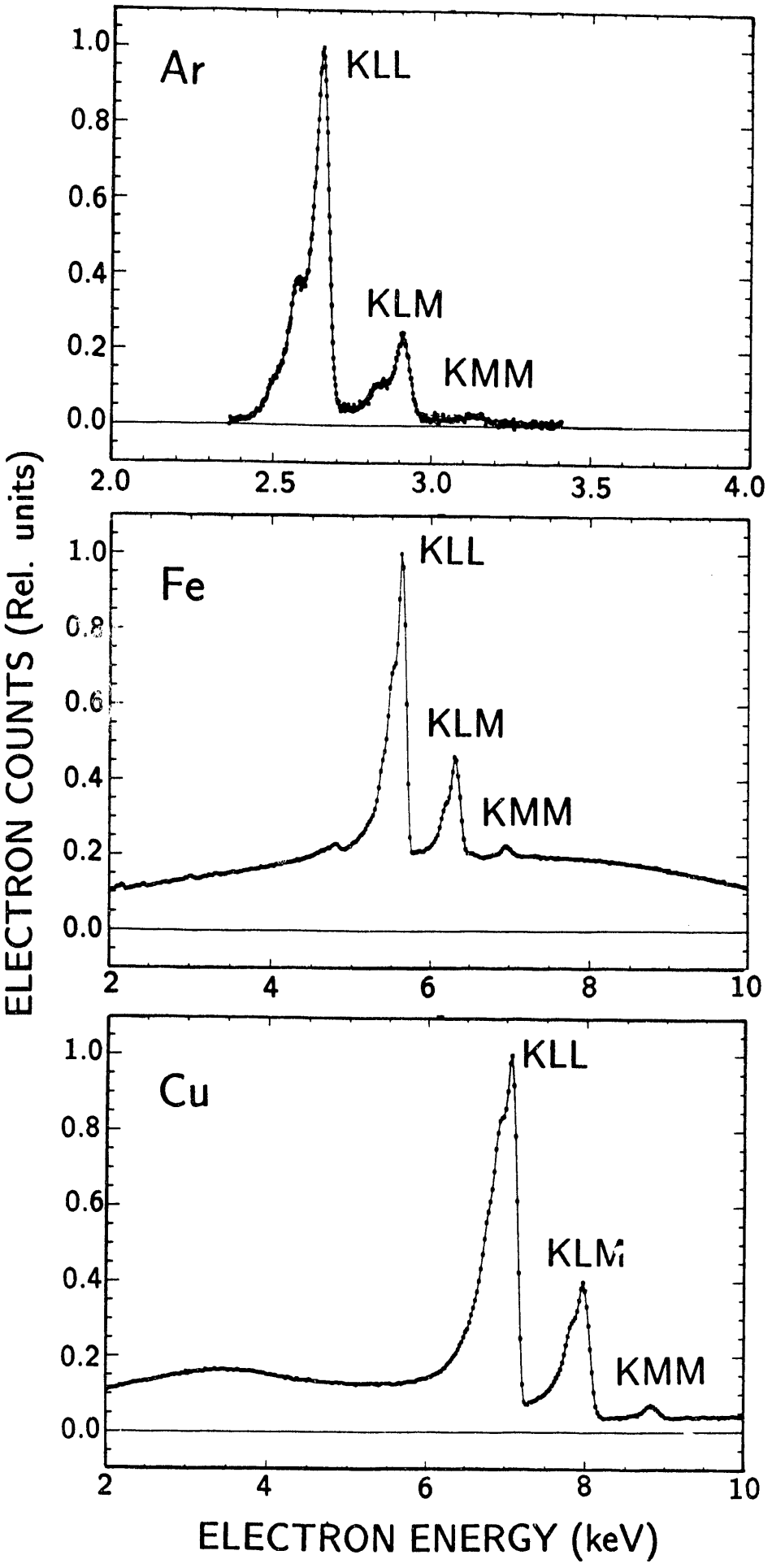

Ar
KLL
L-Auger
(b)–1
KLL
K-Auger
(b)–2
KLM
KMM
(b)
KLM
KMM
L
ELECTRON COUNTS (Rel. units)
ELECTRON ENERGY (keV)
0
0.2
0.4
0.6
0.8
1.0
0
2
4
6
8
10
12

FIG. 2.


Ar
KLL
KLM
KMM
Fe
KLL
KLM
KMM
Cu
KLL
KLM
KMM
ELECTRON COUNTS (Rel. units)
ELECTRON ENERGY (keV)
1.0
0.8
0.6
0.4
0.2
0.0
2.0
2.5
3.0
3.5
4.0
2
4
6
8
10

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