Transmission measurement of photo-absorption cross section of aluminum in soft X-ray region of 50 to 250 eV*

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Abstract The photo-absorption cross section of aluminum was obtained from the ratio of transmission of aluminum thin-films with different area densities from 50 to 250 eV with synchrotron radiation monochromatic beam. Two samples with different area densities were used to minimize the uncertainty caused by the sample surface oxidation and systematic factors of the X-ray source, beamline, and detector. The experimental results are in good agreement with the published data and FEFF program calculations in general.

Key words synchrotron radiation, soft-X-ray, aluminum thin-film, photo-absorption cross section

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1 Introduction

The atom photo-absorption cross section is a fundamental physical quantity characterizing the interaction between photons and matter. Accurate experimental data are important in material science, thin-film technique, X-ray spectroscopy and X-ray astronomy. The database of photo-absorption cross sections of different materials in certain energy region was created by Henke[1], Hubbell[2], and Chantler[3]. Some results were from the experimental data, and the other came from the theoretical calculations and interpolations which were not very accurate. There are many differences between the database and the experimental results, especially near the absorption edges. A lot of experimental results of photo-absorption cross section deduced from the optical constants were published[4, 5] which modify and supple the photo-absorption database, the FEFF program based on multiple scattering theory[6] is also used to calculate the atom photo-absorption cross section. More and more experimental results are needed to validate or modify the theory calculations and the photo-absorption cross section database.

In metal materials, two ways are used to obtain the photo-absorption cross section from the transmission measurement, one heats the metal into a gas[7], and the other uses thin film with no substrate[8]. For gases, the isolated atom approximation is adequate, but for thin films, solid state modifications are necessary, which lead to the differences near the photo-absorption edge and are caused by correlations, neighboring atom effects··· The results from films are more realistic for solid-state materials.

For aluminum is a very important material of multiplayer and filters, the atom absorption cross sections of aluminum need to be accurately measured. In the experiment, two kinds of samples with different area density were used to minimize the uncertainty caused by the sample surface oxidation and systematic factors of the X-ray source, beam-line, and detector[8]. The experimental results were compared with the data from the published literature, the database and FEFF program calculations; they are nearly the same after the L1 absorption edge of aluminum at 117.8 eV. Before the L1 edge they are different; especially before the L3 edge, from 50 eV to 72.55 eV. Before L3 edge, our data are in good agreement with the data of Henke[1], Smith[9], Shiles[10] and Keenan[11] which are about 10000 cm^2/g while the data of Gullikson[12] and Chantler[3] are only about 5000 cm^2/g, and the data of Windt[13] and Zheng[14] are much higher, nearly

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15000 cm^2/g. The reason of the differences is still unknown and needs future study.

2 Experiment

The freestanding aluminum films used in the experiment were deposited on the sample bracket of 5×10 mm^2 area, and they are provided by china insititute of atomic energy. The area densities (mass per unit area) of the two films were measured by the energy loss of α particles passing though them[15], and were 27 $\mu g/cm^2$, 54 $\mu g/cm^2$, with uncertainty of 2.7 $\mu g/cm^2$. The body density of aluminum is 2.7 g/cm^3, so the thicknesses of the two films are 100 ± 10 nm and 200 ± 10 nm. The experiment was performed on the reflectometer at Beam-line B12[16],the National Synchrotron Radiation Laboratory of China (NSRL). The transmission of each sample is measured using a photodiode (AXUV-100G, IRD, USA) and an electrometer (6517, Keithley, USA). The signals from Ni mesh before the sample are also recorded at the same time for modifications. The transmittance of sample is:

$$T_{\rm k}(E)=\frac{I_{\rm k}(E)/I_{\rm k(Ni)}(E)}{I_0(E)/I_{0({\rm Ni})}(E)}, \qquad (1)$$

where $I_{\rm k}$ is the transmission signal of the sample, I_0 is signal of light source, $I_{\rm (Ni)}$ and $I_{0({\rm Ni})}$ are the signals of Ni mesh. The energy dependent photo-absorption cross section σ can be obtained by the Beer law:

$$T_{\rm k}(E)=T_0(E)\exp(-\sigma(E)\rho d_{\rm k}), \qquad (2)$$

where T and T_0 are the transmission ratio of the certain sample and the contaminated layer on each sample, ρ is the bulk density, d is the thickness of the sample, and the products of ρ and d are the area density ρ'. For aluminum is easily oxidized, here we made an assumption that the thicknesses of contaminated layer on two samples are nearly the same. From two samples with different thicknesses, according to Eqs. (1) and (2), the photo-absorption cross section:

$$\sigma(E)=-\frac{1}{\rho}\frac{\ln T_{\rm ki}(E)-\ln T_{\rm kj}}{d_{\rm ki}-d_{\rm kj}} \ . \qquad (3)$$

Two samples with different thicknesses were used to minimize the uncertainty caused by the sample surface oxidation and systematic factors of the X-ray source, beam-line, and detector. From the transmission of two samples with the area density of 27 ± 2.7 $\mu g/cm^2$ and 54 ± 2.7 $\mu g/cm^2$, we can get the transmission ratio of a sample with the area density of 27 $\mu g/cm^2$, and the uncertainty is 3.8 $\mu g/cm^2$, which is the square root of the sum of square of uncertainty for two samples.

The transmission ratio of these two samples was measured and compared with the transmission ratio calculated from the CXRO photo-absorption cross section data[17]. As shown in Fig. 1, after the absorption edge of aluminum, the data we measured are nearly the same with the data from CXRO, and before the edge, is much lower, the transmission ratio we measured is about 0.76 while 0.88 from CXRO. Gullikson's data were used in CXRO, as we discussed later, the photo-absorption cross section data of Gullikson before the absorption edge are about only 50 pecerent of our results, that's the reason for the huge difference.

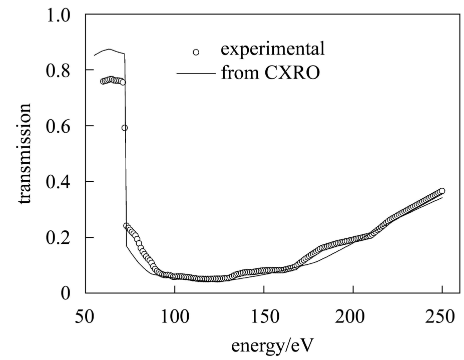

Fig. 1. Comparison of the transmission ratio between the experiment results and the calculation results from the CXRO data.

3 Results and discussions

The photo-absorption cross section of aluminum is obtained from Eq. (3), and Fig. 1 is T_1/T_2, the transmission ratio of two samples with different area density. Fig. 2 is the photo-absorption cross section data in the region of 50—250 eV from the experiment. The data of Henke, and the FEFF program calculation results are also shown for comparison. In general, our data agree with the published data well, except the data before the absorption edge and some details.

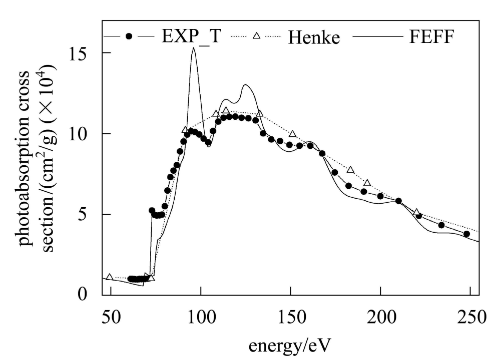

Fig. 2. Comparison of the photo-absorption cross section between the experimental results and the published data from 50 to 250 eV.

The published data of photo-absorption cross section, and the FEFF program calculations[18] were compared with the experimental results in the region of 45—75 eV, before the L2 and L3 absorption edge, as shown in Fig. 3. Comparison of the photo-absorption cross section was made between the experimental results and the published data from 50 to 250 eV. Most of the published data claimed that the photo-absorption cross section data before edge are more accurate than those after edge, but as shown in Fig. 3, they are different from each other. In the region of 45—75 eV, the FEFF program can't calculate well before edge. The data of Chantler and Gullikson here are about 5000 cm^2/g, and as the energy increases, the data of Chantler decrease while the data of Gullikson keep constant. Most of the data are about 10000 cm^2/g, including the experimental results, the data of Henke, Palik, Shiles, and Keenan. The data of Windt and Zheng are about 15000 cm^2/g before edge, which is nearly three times bigger than those of Chantler and Gullikson. Such differences may be caused by the surfaces oxidation of the samples used in the experiments, which is more obvious around the absorption edges. Including our experimental results, most of these data change little when the energy increases in this region of 45—70 eV. Two samples with different area densities were used in our experiment to minimize the uncertainty caused by the sample surface oxidation and systematic factors of the X-ray source, beam-line, and detector, the results we get are creditable.

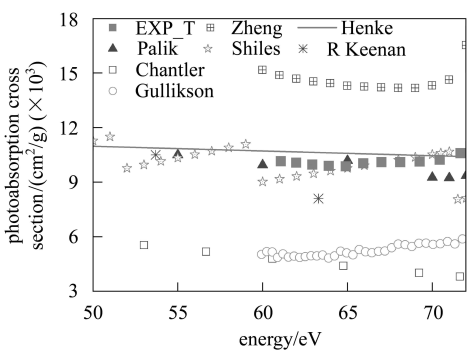

Fig. 3. Comparison between the experimental results and the published data, 45 eV to 70 eV.

In the region from 50 to 250 eV, L1 absorption edges of aluminum are included, L2 edge and L3 edge are 72.95 eV and 72.55 eV, while L1 edge is 117.8 eV. Data from 45 to 70 eV have been compared before, Fig. 4 is the comparison between the experimental results and the published data from 70 eV to 140 eV. There are still some differences between each other. As we know, the atom photo-absorption cross section is the sum of every inner electron photo-absorption cross section, here the data are the sum of L3, L2, and L1 electrons. In Fig. 4, the photo-absorption cross section data of experiment increase rapidly at the L3 (72.55 eV) and L2 (72.95 eV) edges, and increase slowly from 75 to 90 eV, they decrease from 90 to 106 eV, then they increase again till L1 edge (117.8 eV) as the vertex. The tendency is more obvious in the FEFF program calculations, and is different from the data of Henke and Chantler. We get the accurate photo-absorption cross section data of aluminum from L3, L2, to L1 absorption edge , from 50 to 140 eV. Besides L3 and L2 edges, L1 edge can also be found at 117.8 eV, which is in good agreement with the FEFF program calculation results. Compared with the commonly used database of Henke and Chantler, the experimental results agree with Henke's very well, and smaller than Chantler's.

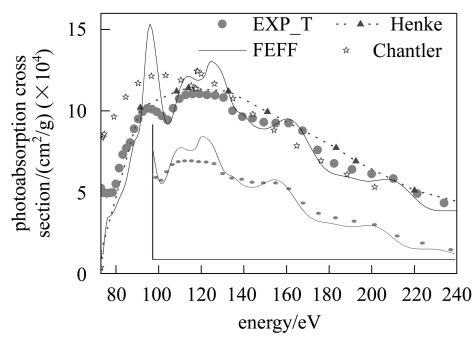

Fig. 4. Comparison between the experimental results and the published data, 70 eV to 140 eV.

From L1 edge to 250 eV, as shown in Fig. 2, the data of Henke and Chantler, the FEFF program calculations and our data agree very well. the FEFF program is based on multiple scattering from the neighbouring atoms, so we can see the oscillations after L1 edge of 117.8 eV to 250 eV. Oscillations are also found in our experiment data to be the same as the FEFF program calculations; it means the data we get are more suited for the film samples, which is the condensed matter modification for the atom photo-absorption cross section. Compared with the atom photo-absorption cross section data of Henke and Chantler, using two aluminum film samples, we get the photo-absorption cross section data with the condensed matter modification, which add the contributions from the potentials of the neighbouring atoms.

Let us now discuss the uncertainty of the experimental results. It mainly comes from the uncertainties of the area density u_t of aluminum thin-film. The accuracy of transmission signal from the electrometer and the uncertainty of current stability of Beam-line u_1 are also taken into account. Two samples with the area density of 27±2.7 μg/cm^2 and 54±2.7 μg/cm^2 were used, the key parameter is the difference in the area density, 27±3.8 nm, so the uncertainty of area density u_t is 14%, u_1 is estimated to be 2%, so the uncertainty of photo-absorption cross section we get:

$$u^2 = u_t^2 + \frac{2u_1^2}{\ln^2(1/T(E))} , \quad (4)$$

$T(E)$ is the transmission ratio of different energies of the two samples. So we get the uncertainty u is no more than 18% before L3 edge of 72.55 eV and 14% after it. For we used two samples with different area densities, the uncertainty of photo-absorption cross section mainly depends on the measuring of the area density of the samples.

4 Conclusions

The energy dependent photo-absorption cross sections of aluminum thin-film were measured from 50 to 250 eV using synchrotron radiation at Beam-line B12, NSRL. Two samples with different area densities were used in the experiment to minimize the uncertainty. The experimental results have been compared with the published data and the FEFF program calculation results. They are in good agreement in general though some differences occur. Before L3 absorption, our data approved the data of Henke and Palik, and were twice the data of Gullikson(CXRO). From L3 to L1 edge, we got the precise results and found the sudden increasing of photo-absorption cross section at L1 edge. The results we got were the same as the FEFF program calculations. After L1 edge, our data were consistent with the published data and the FEFF calculations. Moreover, compared with the atom photo-absorption cross section data of Henke and Chantler, we obtained the photo-absorption cross section data with solid state modification, which added the contributions from the potentials of the neighboring atoms.

Though many photo-absorption cross section data of aluminum have been published before, there are many differences between each other, especially before the L3 absorption edge, which needs future measurement and study. The sample surface oxidation may be one of the reasons for higher photo-absorption cross section before absorption edge. The uncertainty of the cross section comes mainly from the uncertainty in the density and the thickness measurement.

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