Study of the background in the experiments of inner-shell ionization of atoms by positron impact *

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Abstract One of main difficulties in the experiments of inner-shell ionization of atoms by positron impact near threshold energy region is the relatively high low-energy background, which is caused by the deposited part of energy in semi-conductor X-ray detectors of 0.511 MeV γ rays that are produced by positron annihilations in targets and target chamber. In this paper, by using the Monte Carlo method, we simulated the backgrounds for the X-ray detectors with the sensitive layer thickness of 0.3 mm and 3 mm in the case of 0.511 MeV γ rays impacting vertically on a Ti plate of 0.2 mm in thickness, and compared the simulation results with the experimental observations of the other research group and our own. Moreover, we also simulated the backgrounds for a simplified experimental setup in the case of 20 keV positrons impacting vertically on a thick Ti target and observed that the backgrounds for the X-ray detectors with the sensitive layer thickness of 0.3 mm and 3 mm, are very similar.

Key words positron, atomic ionization by positron impact, Monte Carlo simulation

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1 Introduction

Atomic inner-shell ionization cross sections by positron/electron impact near the threshold energy (i.e., from the threshold energy to several tens of keV) are of important significance both in theoretical studies and practical applications. For theoretical studies, these cross section data can deepen our understanding for the interaction between positrons/electrons and atoms, and accurate and systematic measured cross section data can examine various theoretical models and help improve these theoretical models. The Coulomb interaction and exchange effect (the exchange effect exists for the electron-atom interaction, and not for positron-atom interaction) are crucial in the processes of atomic inner-shell ionization by positron/electron impact, but now not yet well understood[1]. The studies for the atomic inner-shell ionization by positron/electron impact near the threshold energy are very helpful for understanding the Coulomb interaction and the exchange effect involved[1]. At present, the cross section data for the atomic inner-shell ionization by positron impact is very scarce. For practical applications, these cross section data are widely used in many fields, for example, in materials and surface science, plasmas physics, astrophysics, magnetic and inertial confinement fusion, medical diagnosis and therapy, dosimetry and numerical simulations and so on[2, 3]. Especially, in the most recent years, as an antimatter particle, the interaction between positron and matter attracts extensive attentions due to the needs from the fundamental studies and practical applications concerned[4]. For example[4], the formation of anti-

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hydrogen atoms by positron and antiproton can be used for the testing of QED theory and CPT theorem; the predictions for the bound state of positron with neutral atoms have important implications for positron and positronium chemistry; the annihilation radiation from positrons also provides an important tool for the astrophysical study. At the same time, the practical applications of positrons are also numerous and increasing. For example, the positron emission tomography (PET) is used to study the metabolic processes; positron annihilation spectroscopy is employed in materials science, and also in the future positrons may be used to catalyze reactions and create the annihilation gamma-ray laser. In a word, most of applications of positrons in fundamental researches and practical technologies depend on the understanding for the positron-matter interaction processes, and the interaction between positrons and atoms is the basis of the positron-matter interaction. Moreover, the atomic inner-shell ionization by positron impact is one of important processes of positron-atom interactions[4], therefore, the study for the atomic inner-shell ionization by positron impact is very important.

The theoretical and experimental studies for the atomic inner-shell ionization cross sections by electron impact have been carried out for a long time[2, 5]. However, the study for the atomic inner-shell ionization cross sections by positron impact is very lacking, especially in the experimental aspect. Although the experimental studies for the atomic inner-shell ionization cross sections by positron impact has begun since 60's last century[6, 7], most of experimental studies only focused on the higher incident energy region[6—9] or on the measurements of ratios of electron-impact to positron-impact atomic inner-shell ionization cross sections[10—13]. These limited the deeper studies for the positron-atom interaction processes[1, 14]. Since 80's last century, the slow positron beam technology has been developed rapidly[15, 16], and some absolute measurements for atomic inner-shell ionization cross sections by positron impact near the threshold energy have been performed[1, 14]. But these measurements are still very scarce in comparison with the measurements for electron impact. In our own knowledge, the atomic inner-shell ionization cross sections by positron impact near the threshold energy have been measured only for the K-shell of Cu[1] and Ag[14] elements, L-shell of Ag, In and Sn elements[1, 17] and L_3 shell of Au[14] element.

Comparing with the measurements of atomic inner-shell ionization cross sections by electron impact, one of the main difficulties for the measurements of atomic inner-shell ionization cross sections by positron impact is the relatively high low-energy background which is caused by the deposited part of energy in semi-conductor X-ray detectors of 0.511 MeV γ rays by Compton scattering that are produced by positron annihilations in targets and target chamber. In this paper, we will discuss this problem by performing Monte Carlo simulations and comparing with experiments.

2 Background studies

As mentioned above, the relatively high low-energy backgrounds come from the deposited part of energy in semi-conductor X-ray detectors of 0.511 MeV γ rays through Compton scattering that are produced by positron annihilations in targets and target chamber. To decrease this relatively high low-energy backgrounds, W. N. Lennard et al[1] adopted a method of lowering the bias voltage of Si(Li) detector and hence decreasing the sensitive layer's thickness of the detector; Y. Nagashima et al[1, 18] developed a Si(Li) detector with a thin sensitive layer thickness that is only about 1/10 of the sensitive layer thickness of conventional Si(Li) detector. By impacting the 0.511 MeV γ rays, emitting from a ^{22}Na positron sources, on a slab of Ti element, Y. Nagashima et al[18] measured the X-ray spectra with the thin Si(Li) detector developed by them and a conventional Si(Li) detector. They observed that the background of the X-ray spectrum obtained with the conventional Si(Li) detector is higher, and gradually increases from the high-energy region to the low-energy region and the characteristic X-rays from the K-shell ionization of Ti element by photoelectric ionizations can not be distinguished at all from the higher backgrounds. However, for the X-ray spectrum obtained with the thin Si(Li) detector, the background is relatively low, and still gradually increases from the high-energy region to the low-energy region and the characteristic X-rays from the K-shell ionization of Ti element can be clearly observed. We also carried out a similar experiment by using a conventional Si(Li) and an AMPTEK thermoelectrically cooled Si-PIN detector. The thickness values of sensitive layers of the conventional Si(Li) detector and the thermoelectrically cooled Si-PIN detector are about 3 mm and 0.3 mm, respectively. The ^{22}Na positron source was wrapped by a thin Ti film of 0.2 mm thickness. The experimental X-ray spectra are shown in Fig. 1. From Fig. 1, we can see that the background of the X-ray spectrum obtained with the conventional Si(Li) detector is higher, and gradually increases from the high-energy region to the low-energy region and the characteristic X-rays from the *K*-shell ionizations of Ti element can not be observed at all. For the X-ray spectrum obtained with the thin thermoelectrically cooled Si-PIN detector, the background is lower and flat, and the characteristic X-rays of *K*-shell ionizations of Ti element can be clearly observed with a higher signal-to-noise ratio. Comparing with the experimental observations of Y. Nagashima et al[18], our experimental results are very similar to that of Y. Nagashima et al. But, the background of our experimental X-ray spectrum for the thermoelectrically cooled detector is flat, and is different from the observation of Y. Nagashima et al. This phenomenon maybe has something to do with the electronics concerned.

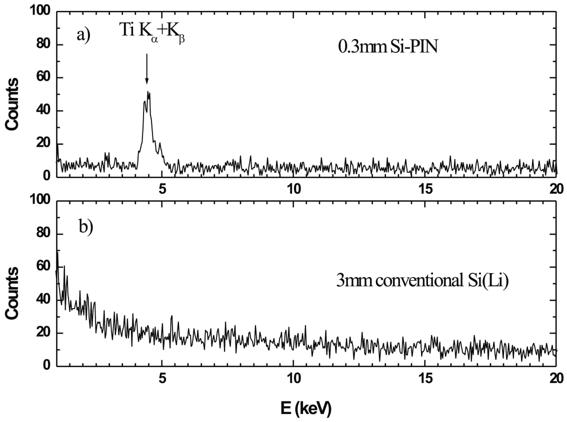

Fig. 1. X-ray spectra obtained by a) the thin thermoelectrically cooled Si-PIN detector and b) the thick conventional Si(Li) detector. The ^{22}Na positron source is wrapped by a thin Ti film.

We simply performed Monte Carlo simulations for the above cases, i.e., the 0.511 MeV γ rays impact on the thin Ti slab of 0.2 mm thickness, and the two Si(Li) detectors with the sensitive layers of 0.3 mm and 3 mm thickness are placed behind the thin Ti slab and record the X-ray spectra. The Monte Carlo code used is PENELOPE developed by F. Salvat et al[19]. The results of Monte Carlo simulations are shown in Fig. 2. From Fig. 2, we can observe that the shapes of the backgrounds for the Si(Li) detectors with 0.3 mm and 3 mm thick sensitive layers are flat, and the background level of the thick Si(Li) detector is about 4 times of that of the thin Si(Li) detector. Also, for the thin Si(Li) detector, the characteristic X-rays of *K*-shell ionization of Ti element can be clearly observed with a higher signal-to-noise ratio. These simulation results are consistent with the experimental observations described above. The only difference is that all backgrounds obtained from the Monte Carlo simulations are flat. The experimental results of Y. Nagashima et al[18] showed that all the backgrounds from their thick and thin Si(Li) detectors increased gradually from the high-energy region to the low-energy energy region. And our own preliminary experimental results showed that the shape of the background obtained with the thin thermoelectrically cooled Si-PIN detector is flat and consistent with our Monte Carlo simulation results, and the shape of the background obtained with the thick conventional Si(Li) detector gradually increases from the high-energy region to the low-energy region and is consistent with the experimental observation of Y. Nagashima et al[18].

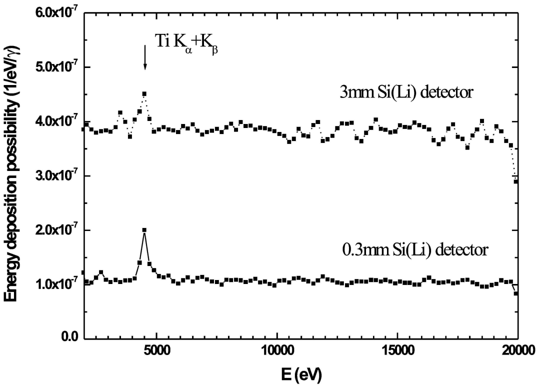

Fig. 2. X-ray spectra obtained by Monte Carlo simulations for 0.511 MeV γ rays impacting vertically on a 0.2 mm thick Ti slab. The X-ray detectors of 0.3 mm and 3 mm thick sensitive layers are placed behind the Ti slab, respectively.

Moreover, we also carried out the Monte Carlo simulations of the backgrounds for a simplified experimental setup in the case of 20 keV positrons impacting vertically on a thick Ti target. We assumed a spherical shell as the target chamber, its outer radius was set to be 20 cm, and its thickness was 2 mm. The semi-conductor X-ray detector was assumed as a ring shape in order to reduce the simulation time, and the thickness values of sensitive layers were assumed to have two values of 0.3 mm and 3 mm, respectively. The surfaces of the X-ray detectors and the thick Ti target were parallel, and the 20 keV positron beams went through the central hole of the ring-shape X-ray detectors and impacted on the Ti target. The Monte Carlo simulation results are shown in Fig. 3. From Fig. 3, we can observe that the X-ray spectra obtained by Monte Carlo simulations for the thin and thick detectors are very similar, i.e., the characteristic X-rays of the K-shell ionization of Ti element can be clearly observed for the thin and thick X-ray detectors and all the backgrounds are lower and flatter.

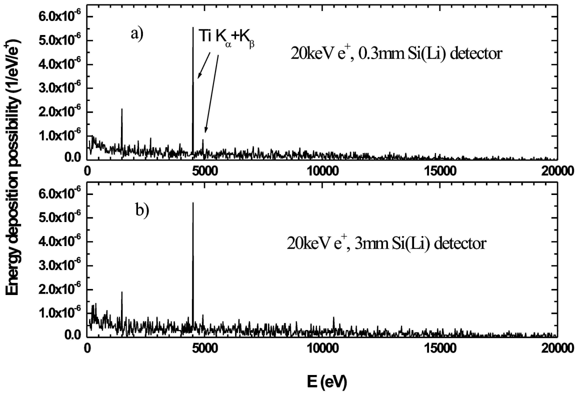

Fig. 3. X-ray spectra obtained by Monte Carlo simulations for a simplified experimental setup. The incident energy of positron beams is 20 keV. The thickness values of X-ray detector's sensitive layers are 0.3 mm and 3 mm, respectively. The other details see text.

3 Discussion

By the experimental studies performed by other people and our own and the comparison with Monte Carlo simulations, we indeed can observe the backgrounds in X-ray spectra caused by the deposited part of energy in semi-conductor X-ray detectors of 0.511 MeV γ rays produced by positron annihilations in targets and target chamber, and these backgrounds can be largely reduced by using thin X-ray detectors. From the inconsistency of the background shapes obtained by Monte Carlo simulations with some of the experimental background shapes, we also infer that the experimental background shapes perhaps are affected by other factors, such as the electronics concerned. However, from the Monte Carlo simulation results for a simplified experimental setup, in a real experiment the backgrounds recorded by a thick X-ray detector, caused by 0.511 MeV γ rays, maybe are not as serious as we image. This needs to be verified in the future experiment. In addition, the detector efficiency of the X-ray detector with 0.3 mm thick sensitive layer decreases rapidly when the X-ray energy is larger than 10 keV, therefore, the background level and detection efficiency should be taken into account comprehensively when an X-ray detector is chosen.

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