Applications of Imaging Plates to the Study of Positron and Muon Research

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Abstract. A muon beam intensity distribution perpendicular to the beam has been obtained using imaging plates which are commonly used in X-ray science, transmission electron microscopy, bio and medical analysis. The resolution of imaging plates depends on the resolution of an imaging plate reader. We have used BAS-TR2025 imaging plates and Bio-Imaging Analyzer BAS-2500 or BAS-3000. The positional resolution is 50 μm x 50 μm. When the beam is one kind, the coincidence measurement is not necessary so that the muon distribution perpendicular to the beam is taken in a very short time and the spatial resolution is 50 μm x 50 μm. Such a resolution cannot be obtained by usual muon measuring method. This is quite convenient to adjust muon beams. When FLA-8000 or FLA-9000 is used the resolution can be improved to 10 μm x 10 μm. Such intensity resolution of muon beams could not be imagined without using imaging plates. Transmission muon images obtained are also presented. This can be used as a non-destructive test.

1. Introduction

Imaging plates (IP) are widely used in X-ray science, medical analysis and in transmission electron microscopy. A plate is only a card which can be easily placed into a vacuum chamber without darkness. Darkness is required only during exposure and transfer imaging plate to an analyzer (reader). The images can be erased and imaging plates can be used many times. Imaging intensity is cumulative, it is not good for coincidence measurements. However, when the kind of particles arriving is known and particularly particles are one kind, not mixed, imaging plates are quite conveniently and usefully used. The sensitivity is quite high and proportional to the fluence in six digits [1]. Dead times in coincidence or anti-coincidence circuits are not problems in imaging plates. Imaging plates can be cut to the size we want. When a muon hits an electron in the valence band, the electron is excited to the conduction band of the fluorescent layer. The electron is trapped at an F⁺/F(Br) level or F⁺/F(F) level. The rapped electron at the F⁺/F(F) is excited to the conduction band by the laser light during reading. This emits fluorescent light which is called PSL. PSL [2] is used for
the unit of irradiation of particles on imaging plates and this is not an absolute unit. In this process positrons are not created. The contamination by positrons in the original beam has been eliminated.

2. First muon beam at J-PARC [3]
At a very early stage when the muon beam was first introduced in muon research facility at J-PARC, imaging plates (BAS-TR4025) were inserted in a plastic envelope coated with aluminium spattering to avoid penetration of light. The first positive muon intensity distribution of the beam [3] taken in September, 2008 is shown in Fig. 1.

![Figure 1. The first positive muon intensity distribution of the beam taken in September, 2008.](image)

3. Quantitative muon beam at J-PARC
Figure 2 shows an example of the intensity distribution of positive muon beam on Feb. 14, 2009 at J-PARC. The effect of positrons in the muon beam has been eliminated using a DC separator. (a) is a black and white image, but (b) is originally colored but changed to black and white according to the muon intensity grade. The picture size of Fig. 2 is about 15 cm x 15 cm. The wiggling line in Fig. 2(b) is PSL along the horizontal straight line. The intensity distribution can be expressed roughly by an error function. The positive muon beam was close to an ellipse.

![Figure 2. Positive muon image of positive muon beam intensity distribution. (a) IP image. (b) Color region depends on the value of PSL. The wiggly line shows PSL on the straight line. These are taken on Feb. 14, 2009.](image)

Figure 3 is a blank beam on May 31, 2009 at J-PARC, eliminated positron contamination using a DC separator and defocused. Figure 3(a) is a black and white image, (b) is originally colored but changed to black and white according to the muon intensity grade. According to Figs. 3(a) and (b), the blank muon intensities in the muon beam look like uniform, but adjusting the contrast, the beam is not uniform but right upper side is the strongest as shown in Fig. 3 (c). The wiggly line shows PSL on the straight line.

To measure the absorption coefficient of metal foils, tungsten foils (40 micron-m thick), copper foils (40 micron-m thick), aluminum foils (12 micron-m thick) and nickel foils (30 micron-m thick)
were taped on an imaging plate and inserted in an envelope with sputtered aluminum. The set was exposed in a positive muon beam at J-PARC on May 31, 2009. The beam was defocused. Figure 4 shows an image on an IP.

![Image](a) ![Image](b) ![Image](c)

**Figure 3.** Positive muon image of positive muon beam intensity distribution on May 31, 2009, defocused. (a) IP image. (b) Color region depends on the value of PSL. (a) and (b) look like the beam is uniform. (c) The same as (a) and (b) but the color separation grade is different. The wiggly line shows PSL on the straight line. The right side upper part is the strongest in the positive muon beam.

![Image](a) ![Image](b)

**Figure 4.** (a) Transmission positive muon image on IP. (b) With the intensity of PSL.

The strongest part of the muon beam was near the right upper corner. Adjusting the beam intensity distribution, figure 4(b) is obtained. The wiggling curve shows the PSL along the horizontal line. The PSL values from the left except the first one are 38.5, 39.2, 37.3 and 39.2. The average PSL under two sheets is about 39.0. Similarly the average PSL under 1 sheet was 44.2.

**4. Transmission muon bio-images**

Transmission positive muon bio-images were taken at KEK, Tsukuba. These images are shown in this section.
Figure 5 (a) shows a transmission muon image of a wing of a cicada. Figure 5(b) is a transmission positron image of the same wing of the cicada. The muon beam was restricted to the darker area. Figure 6 (a) shows transmission muon images of small shrimps. Figure 6 (b) shows the same specimen image by positrons taken at KEK, Tsukuba. Transmission positron images have lower contrast, but muon images have higher contrast compared with positron images, in general. Details of the imaging particles on imaging plates are not clear at present.

![Figure 5](image1.png) ![Figure 5](image2.png)

**Figure 5.** (a) Transmission muon image of a wing of a cicada. 50 μm x 50 μm/pixel was used. Fig. 5 (b) transmission positron image of the same wing of a cicada.

![Figure 6](image3.png) ![Figure 6](image4.png)

**Figure 6.** (a) a transmission muon image of small shrimps. The contrast of the image is high. (b) a transmission positron image. The contrast of the image is lower than that of muons.

5. **Most interesting transmission muon images**

Figure 7 shows a transmission muon image of copper (a) and tungsten (b) foils (40 μm thick each), taken at KEK, Tsukuba. At the cross part, the thickness is 80 μm. The light circle is the muon beam. The place where muons do not arrive, that is, outside the circle is black, no muons. The exposure time was 30 minutes. In Fig. 7(a), the place (Region 1) where muon passed a foil of 40 μm is lighter than the background of the circle. The place where muon passed two sheets (Region 2) of copper foils (80 μm) is the lightest in the circle. PSL is the highest in Region 2, nest in Region 1, and the least in Region 0, which is the beam. In Region 1, however, less muons should have arrived because muons should have been absorbed in copper foil. The Region 2 is the lightest (whitest), least muons should have arrived because muons passed two sheets. This is probably due to the fact that Bragg Peak is near the exit surface or the muon energies small.
Figure 7. Transmission Muon image of copper (a) and tungsten (b) foils (each thickness is 40 μm). 50 μm x 50 μm/pixel was used. Double layer in (a) is the lightest, but the double layer of (b) is the darkest.

Figure 8. Relation between momenta of positive muons and ranges. Upper curve is for copper and lower curve is for tungsten.

Figure 7(b) shows a transmission muon image of tungsten foils (each foil is 40 μm thick). At the cross part, the thickness is 80 μm (Region 2). At the place where muon passed tungsten foil of 40 μm (Region 1), the image is whiter than the background of the circle. This is the same reason for copper foils. At the place where muons passed two tungsten foils (80 μm thick) (region 2) the image is the darkest within the circle. This is reasonable because the least muons arrived in Region 2.

There are three reasons to be considered. One is due to the absorption of muons, the second is the Bragg peak and the other is due to the energies of muons arriving at the particle sensitive layer in IP. Muons with high energies pass the sensitive layer but muones with lower energies are trapped in the sensitive layers of imaging plates. In the case of positrons, the relation between PSL and positron energies has been studied 2. The relation between positive muon momentum and the range is shown in Fig. 8. Muons passed through a black envelope lost some of their energies. A tentative explanation of Fig. 7 is as follows: Near the center, the doubled zone (Region 2) is the lightest in Fig. 7(a) (copper). IP sensed the most in the circle. It looks more positive muons are reached to the imaging plate, but this is probably due to the peak of the Bragg curve of muons is near the exit surface or muon energies are lowest and IP sensed most. The place where no samples exist (Region 0), muon energies are high and some muons may have passed through the particle sensitive layer of the imaging plate with less fluorescent reaction. After muons passed one sheet of copper or tungsten foil, the kinetic energies of muons are lowered and absorbed more than in Region 0. Slower muons are trapped in the...
particle sensitive layer of the imaging plate. All the momentums used here are the momentums calculated from the tuned voltages.

In Fig. 7(b), the double layer part of tungsten foils (region 2) is whiter than the background. If the same positive muons with about 23 MeV/c momentums are arriving at the surface of the tungsten foil, the muon range is about 65 μm which is smaller than the thickness of two tungsten sheets, i.e. 80 μm. Therefore less muons reach to the imaging plate. More quantitative results will be published near future.

Imaging plates can be used to see the details of muon beams and inside of materials to positional resolution of 50 μm. Wide applications in the future can be expected. For detail explanations, more experiments are required.

Figure 9(a) is a transmission muon image of a plug, taken at KEK, Tsukuba. Positive muons penetrated the plug. The image shows the center hole. (b) is a picture by a digital camera.

![Image](image_url)

Figure 9. (a) A digital camera image of a plug. (b) Transmission muon image of the plug shown in (a). 50 μm x 50 μm/pixel was used.

6. Summary
Using imaging plates, muon intensity distribution of muon beam has been shown. The muon beam is not uniform. Transmission muon images of bio-materials are shown. Muons can be used for a non-destructive testing.

References
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