Development of MeV Carbon-ion PIXE

Ion Beam and Plasma Phsics

C. Chaiwai[1,*], L.D. Yu[1,2,*], U. Tippawan[1]

[1] *Plasma and Beam Physics Research Facility, Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand*
[2] *Thailand Center of Excellence in Physics, Commission on Higher Education, 328 Si Ayutthaya Road, Bangkok 10400, Thailand*

CARBON PIXE

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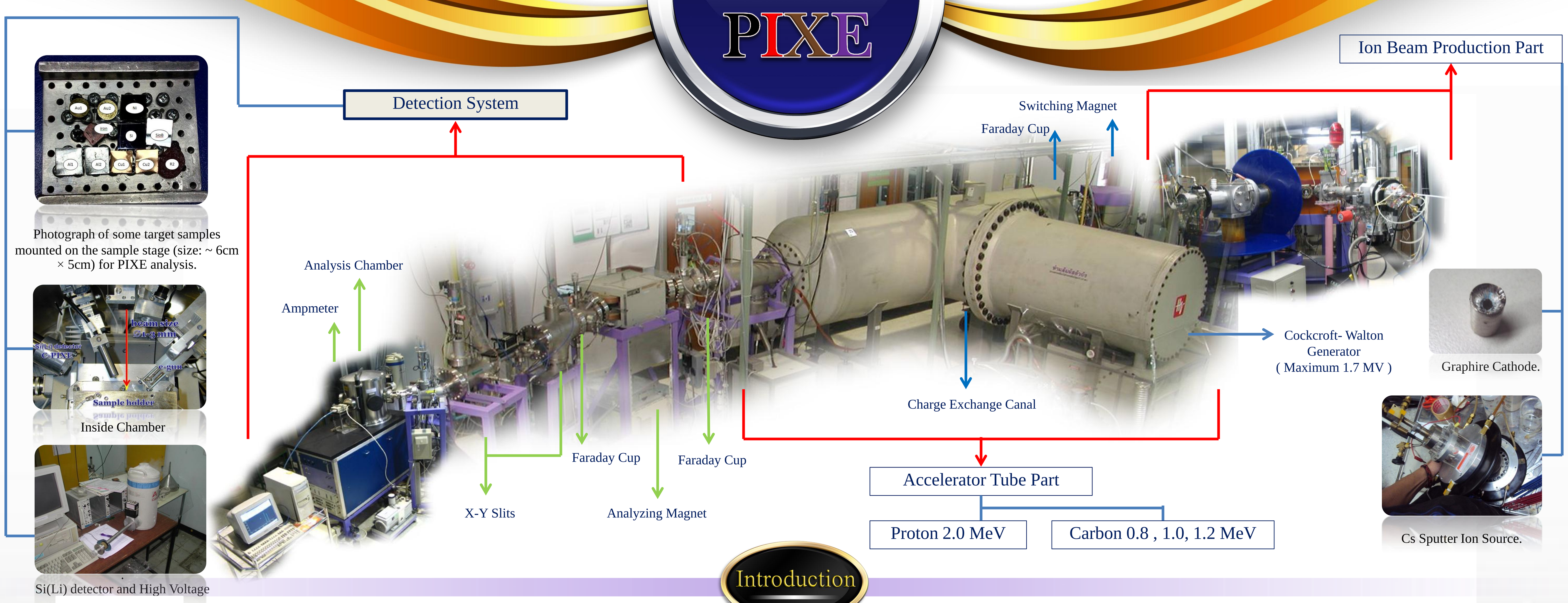


Introduction

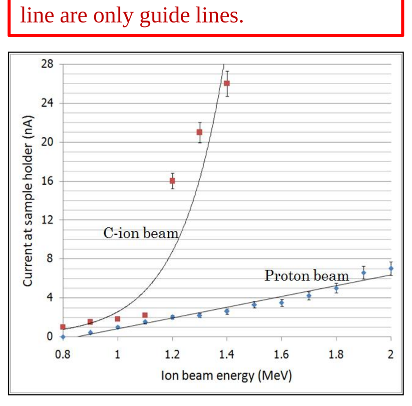
Particle Induced X-ray Emission (PIXE) is an important and routinely used ion beam analysis technique. PIXE was developed initially with using light proton beam but heavy ion PIXE later came into the researchers' vision owing to advantages such as larger ion-atom interaction cross section and stopping cross section which eventually led to higher detecting sensitivity The heavy-ion PIXE technique has been applied to analyze not only solid materials but also particularly biological soft materials.

It is well known that proton PIXE conventionally applies proton beams of ion energy higher than 2 MeV so that induced X-ray emission can be possible. With using heavy ion beam for PIXE, the scattering or interaction cross section between the incident ions and the target atoms is increased owing to the increased ion mass, but on the other hand the ion velocity is decreased if the ion energy of both proton and heavy ion is the same to reduce the ionization cross section which depends mostly on the ion velocity. Now we are having two heavy ion beam conditions to choose in order to operate applicable PIXE. One is using higher energy heavy ion beams to keep the same ion velocity with the lower energy proton beam. For carbon ion beam, since the carbon mass is 12 times that of proton, the C-ion beam energy should then be 12 times that of the proton beam. If a standard PIXE of proton beam uses energy of, for example, 2 MeV, the C-ion beam energy is then 24 MeV. Actually some studies using several-tens-MeV or MeV multiply charged heavy ion beams including C-ion beams have been carried out for PIXE analysis. The other is using relatively lower energy heavy ion beams so that the interaction cross section can still increase. For the first condition, certainly a high-energy accelerator or more powerful beam line is needed. However, for a resources-limited laboratory, this is not feasible. It turns out for us to choose the second condition. Then, the research question that challenges us is at how low energy of C-ion beam PIXE is still available and what the PIXE cross sections are for the lower-energy C-ion beams. Based on the technical capabilities of our 1.7-MV tandem accelerator beam line, the energy of C-ion beams was selected to be in the range of around 1 MeV. This is of great significance since this lower energy range of C-ion beams used for PIXE analysis might have never been tested before by any group.

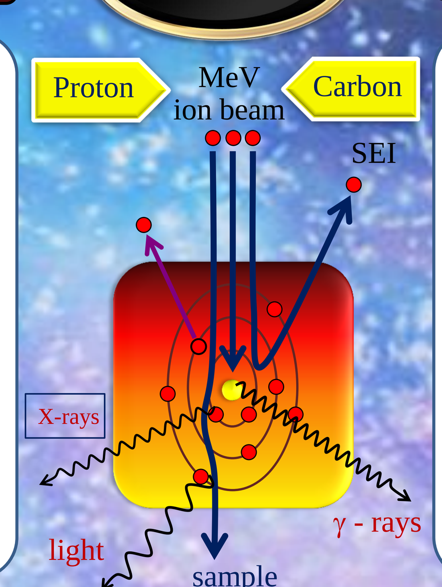
Experiment

Measurements of Ion Beam Current

Figure. : C-ion and proton beam currents at the sample holder as a function of ion energy. The curve and line are only guide lines.



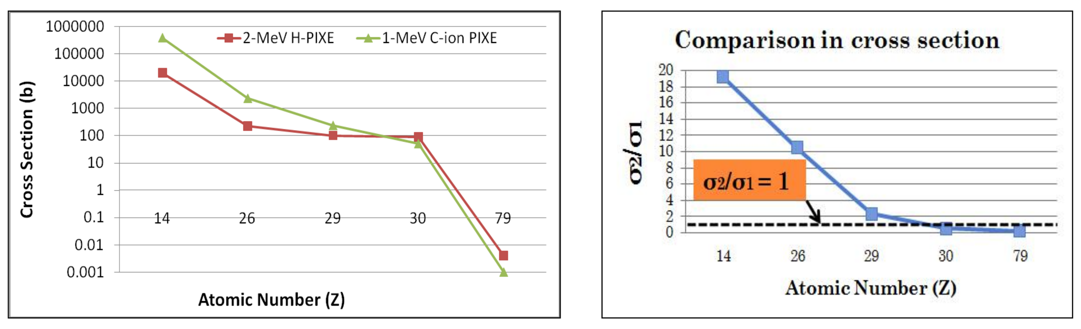
The proton beam current was nearly linearly increased with the ion energy but it was immeasurable or zero at 0.8 MeV. The C-ion beam current was similar with the proton beam current at energy around 1 MeV but from 1.2 MeV it suddenly increased drastically till 1.4 MeV, beyond which it stopped, indicating that the analyzing magnet reached its maximum beambending capacity.



MeV C-ion PIXE spectra compared with standard PIXE spectra

Since 1-MeV proton PIXE seemed almost not working, MeV C-ion PIXE spectra were compared with standard 2-MeV proton PIXE spectra, for investigation on the cross sections of MeV C-ion PIXE. It is seen that for certain materials the 1-MeV C-ion PIXE spectra are comparable with 2-MeV proton PIXE spectra after subtracting the latter's background. This also tells that the background of the 1-MeV C-ion PIXE spectra is obviously lower than that of 2-MeV proton PIXE spectra. This is believed to be due to less deceleration of ions and electrons which would cause Bremsstrahlung and less secondary irradiation effect from the lower-energy C-ion PIXE.

Calculation of MeV C-ion PIXE cross sections, compared with 2-MeV proton PIXE cross sections



(a) (b)

From the result a trend is noticed. The 1-MeV C-ion PIXE cross sections are higher than those of 2-MeV proton PIXE for elements with lower *Z* than Cu but lower than those of 2-MeV proton PIXE for elements with higher *Z* than Zn. Therefore, there is a transition around Cu and Zn. This indicates the MeV C-ion PIXE more sensitive in detecting lower *Z* elements. For the lower *Z* elements, the cross sections of MeV C-ion PIXE could be more than ten times those of 2-MeV proton PIXE.

Figure. Calculated PIXE cross sections for K_α lines from 1-MeV C-ion PIXE compared with 2-MeV proton PIXE at target materials of Si, Fe, Cu, Zn and Au, except Au for which the X-ray is L_α line. (a) The cross sections. (b) Comparison in the cross section between 1-MeV C-ion PIXE and 2-MeV proton PIXE by the ratio between the former and the latter.

Discussion

The result on low-velocity C-ion PIXE working implies mechanisms involved in the MeV C-ion PIXE probably different from that of standard MeV proton PIXE.

"The relative importance of the various interaction processes between the ion and the target medium depends mostly on the ion velocity and ion charges of the ion and target atoms". If the ion energy is taken as 1 MeV, the proton and C-ion velocities are $v_H \sim 1.4 \times 10^7$ m/s = 1.4×10^9 cm/s, and $v_C \sim 4 \times 10^6$ m/s = 4×10^8 cm/s, respectively. The Bohr velocity of an electron in the innermost orbit of a hydrogen atom is $v_0 \sim 2.2 \times 10^8$ cm/s. Comparing the ion velocity v_1 with $v_0 Z_1^{2/3}$ for estimating the effective charge of the ion using (for heavy ions, i.e. $Z > Z_{He}$) $Z^*/Z = 1 - \exp[-0.92 v_1/(v_0 Z_1^{2/3})]$, we have

for proton, $Z_1 = 1$, $v_0 Z_1^{2/3} = v_0 = 2.2 \times 10^8$ cm/s, so $v_H > v_0 Z_1^{2/3}$, $Z^* = Z_1 = 1$, but for C ion, $Z_1 = 6$, $v_0 Z_1^{2/3} \sim 3.3 v_0 \sim 7.3 \times 10^8$ cm/s, $v_C < v_0 Z_1^{2/3}$ and $Z^*/Z \sim 0.4$.

This means that if the ion energy is kept the same, e.g. 1 MeV, a proton is fully stripped to a bare nucleus, while a C ion is not fully stripped or partially stripped by 40%. This turns out that in the two cases, the physics involved in the ionization process is quite different. The electronic interactions are composed of two contributions: (1) close collisions with large momentum transfers, where the particle approaches within the electronic orbits, and (2) distant collisions with small momentum transfers, where the particle is outside the orbits. In the case of proton, it is the first contribution dominated, while in the case of C ion, both contributions exist. Moreover, the fast proton spends less time in the vicinity of the target atom and thus interacts with the atom, whereas the slow C ion spends more time in interaction with the atom, therefore the cross section of the former is smaller than that of the latter.

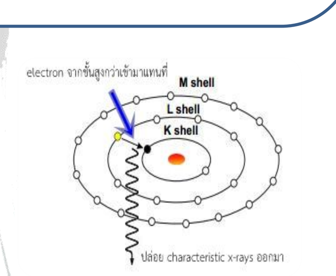


Figure : Characteristic X-rays Process

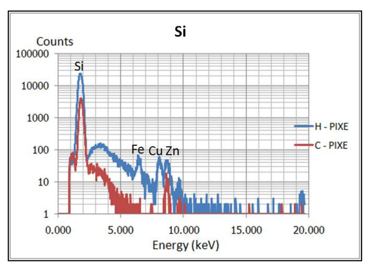
Conclusions

Our investigation and results on MeV C-ion PIXE clearly demonstrated that low-velocity MeV C-ion PIXE worked, but it could be in different mechanism from that of standard proton PIXE; at the same lower ion energy of 1 MeV, C-ion PIXE was superior to proton PIXE, which was actually impossible; and 1-MeV C-ion PIXE was comparable to 2-MeV proton PIXE particularly for certain materials. The 1-MeV C-ion PIXE cross sections were calculated with reference of 2-MeV proton PIXE based on measured spectral yields, showing an interesting trend which indicated a transition around Cu-Zn, for lower *Z* elements than Cu the former higher than the latter, while for higher *Z* elements than Zn the former lower than the latter. The lower-energy C-ion PIXE showed some advantages. It had considerably higher sensitivity than proton PIXE at the same ion-beam energy owing to larger cross sections. It was comparable to higher-energy proton PIXE but with lower background (Bremsstrahlung) and noises due to less deceleration of ions and electrons and less secondary irradiation effect than higher-energy proton PIXE. It was more sensitive in low-*Z* element detection owing to larger interaction cross sections, so better for biological or organic material analysis. Because of the low energy feature, it was available to resources-limited laboratories in developing countries, and also beneficial to power saving.

Result

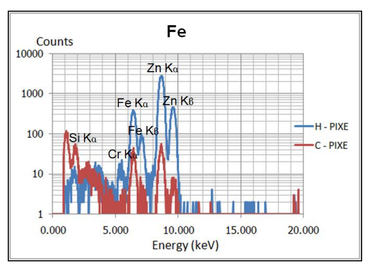
Si

➢ 1-MeV C-ion PIXE spectra compared with 2-MeV proton PIXE spectra from Silicon.



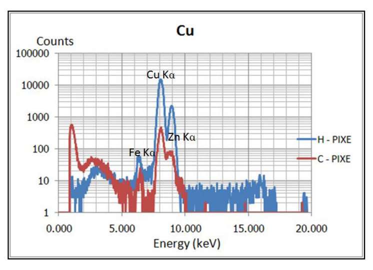
Fe + Zn

➢ 1-MeV C-ion PIXE spectra compared with 2-MeV proton PIXE spectra from Screw (Iron+Zinc).



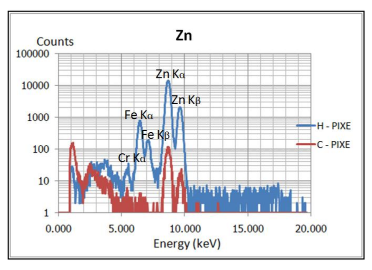
Cu

➢ 1-MeV C-ion PIXE spectra compared with 2-MeV proton PIXE spectra from Copper



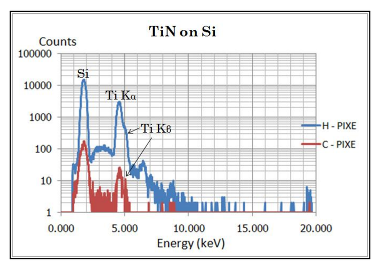
Zn

➢ 1-MeV C-ion PIXE spectra compared with 2-MeV proton PIXE spectra from Zinc.



Si + Ti

➢ 1-MeV C-ion PIXE spectra compared with 2-MeV proton PIXE spectra from Titanium on Silicon.



Au

➢ 1-MeV C-ion PIXE spectra compared with 2-MeV proton PIXE spectra from Gold.

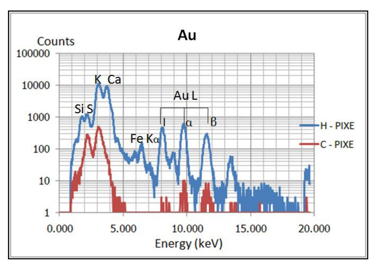


Figure. 1-MeV C-ion PIXE spectra compared with 2-MeV proton PIXE spectra from various materials, e.g. Si, Fe, Cu, Zn, Au and TiN thin film on Si.

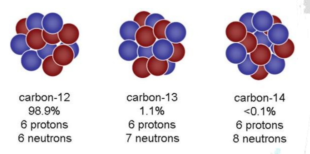


Figure : Type of Carbon