

Fundamental radiation effect on polymers energy transfer from radiation to polymer

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ABSTRACT Polymer modification as cross-link, chain scission, and graft-polymerization by radiation is initiated by the quantum energy transferred from radiation to polymers. The active species for chemical reactions are produced through ionization or activation of polymer molecules for any radiation source. The energy transfer occurs mainly by ionic interaction between radiation and polymer molecule, and the contribution from the collision interaction is minor. The radiation of electromagnetic wave as X-ray or γ -ray generates the energetic electron which induces ionic interaction with polymer molecule. The energy loss profile along the penetration to polymer material is much different among the radiation sources of EB, γ -ray, and ion beams in the macroscopic mechanism. In this article, the behavior of single event, that is, the event induced by one electron, γ -ray, ion, and neutron is described by the macroscopic mechanism and by the microscopic mechanism.

KEYWORDS Radiation, Polymer, Energy transfer, Electron beam, γ -ray, Ion beam

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1 Electron Beam (EB)

Fig.1 shows a typical case for polymer material by electron beam (EB) irradiation at 100 keV and 1 MeV. The accelerated electron beam penetrates into polymer material and the electron loses energy with increase of depth. For EB with 100 keV, 50% of electrons are lost within 0.1 mm thick polymer material (film) by scattering and the energy passed throughout 0.1 mm thick film is 50 keV. The electron of 50 keV could not pass through the next 0.1 mm film. For EB with 1 MeV, 99% of electrons pass through 0.4 mm thick material, and energy loss is 90 keV. The EB passed throughout 0.4 mm thick film can penetrate next 1.0 mm thick film and 1.4 mm thick film, and still remains the half quantity (50%) of EB and energy of 0.42 MeV. The mechanism in Fig.1 is the macroscopic behavior of electron energy and probability of penetration, and these values can be observed by experimental.

The energy loss per penetration length along the

EB direction as shown in Fig.1 is defined as a linear energy transfer (LET). In a case of 100 keV EB energy loss per 0.1 mm is 50 keV, then LET is 50 keV/0.1 mm, that is, 0.5 keV/ μ m. For 1 MeV EB, LET on the 0.4 mm film at first stage is 90 keV/0.4mm, 0.215 keV/ μ m. The energy loss or LET depends on the energy of EB, that is, LET is higher values at lower energy and decreases with increase of EB energy. The electron collides with atoms to result scattering in

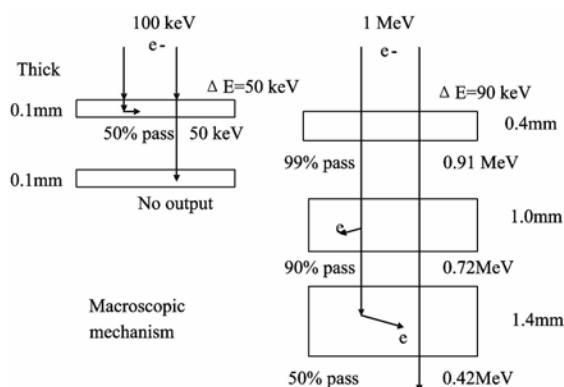


Fig.1 Electron beam penetration into polymer material

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polymer material, and sometimes emissions the secondary electron. The probability of electron beam scattering is the higher with the lower EB energy. Then the number of EB decreases with depth of penetration. The low energy electrons stop in polymer where the electric charge remains in a case of non-conductive matrix.

In principle, the energy loss of EB equals the energy absorption in polymer, that is, EB energy transfer to polymer. The microscopic mechanism of energy transfer is illustrated in Fig.2. The electron of EB behaves as same as wave according to the quantum theory, and the energy transfer to polymer occurs by quantum mechanism. The polymer molecule accepts the quantum energy from EB which is necessary for ionization or activation of polymer molecule. The quantum energy for ionization or activation would be 10-20 eV. EB losses the quantum energy at each site along penetration path. If the G-value of active site (free radical) is 8 (molecules/100eV) in a case of polyethylene, the quantum energy needed for an active site formation is 12.5 eV. When the incident EB is 1 MeV, the LET is 20 keV/100 μ m. Then the number of active sites produced along 0.1 mm (100 μ m) thick polyethylene is 1.6×10^3 as seen in Fig.2. The average distance from active site to neighbor site is 0.07 μ m along the EB penetration. In the scale of molecular size of polyethylene, about 500 CH₂ units are present between active sites.

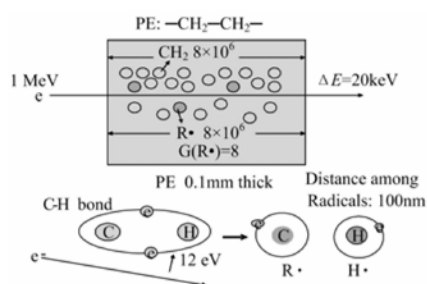


Fig.2 Microscopic mechanism in energy loss of electron

The secondary electron is produced by collision of EB. The primary electron loses the energy just of secondary electron and changes the direction, which causes scattering. The probability of collision is very small, and the distance among the collision sites would be micrometer or more for one primary electron. Of course the secondary electron with enough energy behaves as the same mechanism of the primary elec-

tron in polymer.

Although the energy transfer tends to increase with decrease of EB energy, the ionization or activation of polymers is same for EB energy. Then, the irradiation effect as chemical reaction is not affected by EB energy. High energy EB can only penetrate into the longer depth of polymer material.

The absorbed energy per unit weight of polymer is defined to dose [Gy: J/kg]. Dose is macroscopic determination, and the dose distribution is measured by dosimetry using film dosimeter. Fig.3 shows a typical dose distribution, which is closely related the energy loss in Fig.1. The dose is the product of LET and number of EB in microscopic scale. With increase of depth, LET increases but the number of EB decreases, then the dose shows the distribution in Fig.3 for respective EB energy.

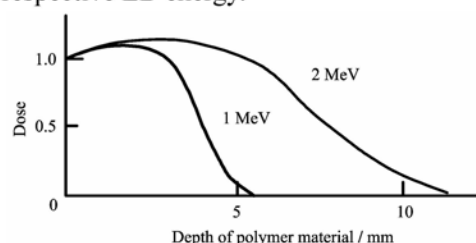


Fig.3 Dose distribution of EB

2 γ -ray

The γ -ray is well known as an irradiation source and has high energy of around 1 MeV. The energy transfer to polymer is much different from EB in a macroscopic scale. Fig.4 shows a model of ^{60}Co γ -ray energy absorption to polymer material. The ^{60}Co γ -ray is high frequent wave with 1.1 MeV and has no electric charge. Then the most of γ -rays pass through polymer without energy loss. However, sometimes it interacts with atoms of polymer and produces electron with relatively high energy around several keV or more (Compton effect). The γ -ray loses the energy by the interaction with atoms, and the frequency shifts to lower value. The γ -ray with lower energy produces electron (photo electron effect) and disappears. The overall γ -ray absorption can be explained by photon absorption equation as,

$$N = N_0 \exp(-\mu x)$$

where, N and N_0 is number of γ -rays at exit and enter of material, x is thickness of material, and μ is

absorption factor by interaction with atoms of polymer. For polymers, the half value of energy absorption is around 10 cm thick of polymer material, and the distribution of absorption energy or dose distribution from γ -ray source is the exponential decay curve when the distance between and polymer material is enough large than the thickness of polymer material as seen in Fig.5.

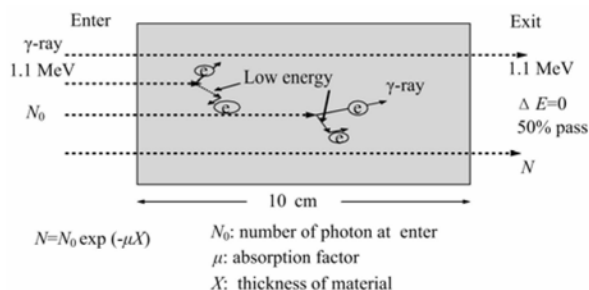


Fig.4 γ -ray energy absorption (Macroscopic mechanism)

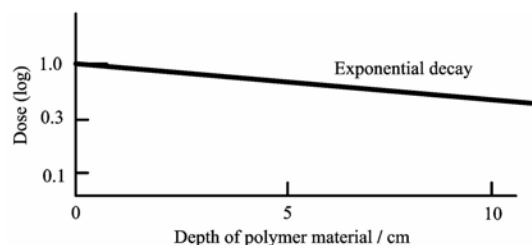


Fig.5 Dose distribution of γ -ray to polymer

As the produced electron interacts with polymer as same as EB, the irradiation effect to polymer in microscopic scale is the same with EB irradiation. However the dose distribution in macroscopic scale is different.

3 Ion beam

Ion beam is heavy particle and has plus (+) charge as normal. Proton (H^+) of the lightest ion is about 2 thousand times of electron by weight. As the scattering of ion by collision with atoms of polymer is small according to the weight increase, ion penetrates into polymer material with almost straight line as shown in Fig.6.

The energy transfer from ion to polymer proceeds mainly by ionic interaction process as like as electron beam, and the probability of energy transfer along ion penetration (LET) depends on the ion energy. LET is high for low energy and decreases with increasing ion energy. As the scattering is small, the number of ion is almost same through the penetration. Then, the dose

increases with depth and reaches maximum and drops to zero at around termination site of ion when the ion stops inside of polymer material (see Fig.6). The LET is much high comparing electron beam and increases greatly with increase of charge number of ion and also ion mass number.

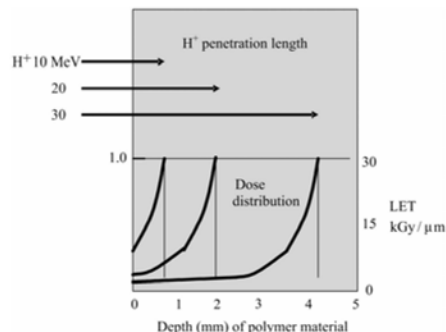


Fig.6 Ion beam irradiation effect to polymer macroscopic mechanism

The dose distribution is macroscopic data determined by experimental and the calculation program is constructed to adjust experimental data by parameters fitting. The LET is other description of the dose distribution. The dose distribution of ion beam is much different from EB or γ -ray, and high energy ion beam gives a high dose inside of material. At present the successful application of ion beam irradiation is a cancer therapy. The area of cancer can be selectively irradiated by the control of energy and figure.

The microscopic mechanism is not clear, and is under research. The models shown in Fig.7 are presented, and the trend model is an ion track structure, which induces high density ionization to result high density chemical reaction in a track. If the size of track is small as nm, the dose is calculated to be MGy order, where the chemical reaction would proceed with high density along an ion track. This model is supported by the formation of nano-size rod of silicone polymer which is densely cross-linking in a small track [1].

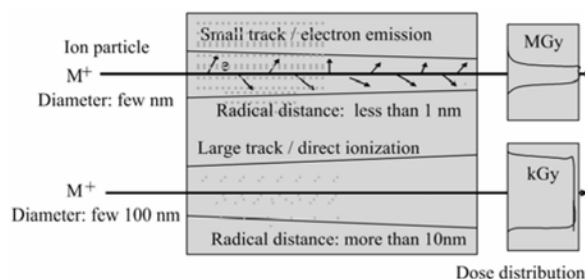


Fig.7 Microscopic mechanism of ion beam

When the diameter of track is large as several 100 nm, where the energy accepted sites are distributed in a long distance from ion path, the dose is not so high then the density of chemical reaction is also not high. This model is supported by the ion beam irradiation effect of polymers, which showed that the changes of mechanical properties, gel-fraction behavior, and gas evolution analysis are almost same with that of EB irradiation^[2].

4 Neutron beam

Neutron beam has no charge, so the main interaction with polymer is the collision with hydrogen (H). The probability of collision is expressed by cross section measurement. At present the practical cross section can be determined by computer code for different neutron energy beam. The collision interaction, other-

wise cross section, decreases with neutron energy.

By collision with H atom in polymer, proton is emitted and it induces the ionization just same with proton beam irradiation. The microscopic mechanism is similar to Fig.4 where emitted electron is replaced by proton in neutron irradiation.

The dose distribution is similar to γ -ray irradiation in Fig.5.

References

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聚合物的基本辐射效应辐射向聚合物的能量转移

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摘要 聚合物的辐射交联、降解和接枝改性都是由辐射向聚合物的能量转移引发的。任何一种辐射源的辐射，都可以引发聚合物分子的活化或电离，生成发生化学反应所需的活性粒子。能量转移的主要形式是射线通过电离与聚合物分子发生作用，而碰撞的贡献比较小。X 射线或 γ 射线等电磁波的辐射会产生高能二次电子，高能二次电子可以使聚合物分子发生电离。电子束、 γ 射线和离子束作为辐射源，其穿透聚合物材料过程中能量损失方式的宏观机理大相径庭。本文从宏观和微观两方面的机理分别对由电子、 γ 射线、离子和中子引发的单一辐射效应事件进行描述。

关键词 辐射，聚合物，能量转移，电子束， γ 射线，离子束

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