Proceedings of the 1st Annual Meeting of Particle Accelerator Society of Japan
and the 29th Linear Accelerator Meeting in Japan (August 4 - 6, 2004, Funabashi Japan)

Simulation of neutron beam with two accelerators

Kouichi Jimbo

Institute of Advanced Energy, Kyoto University,

Gokasho, Uji, Kyoto 611-0011

Abstract

Physical differences of neutrons and charged particles are exemplified so that understanding of *dual ion beam irradiation technique*, in which two accelerator systems are used, is promoted. Then low energy losing mechanism of charged particles in materials, which is quite different from that of neutrons, is discussed with a simple model.

1 INTRODUCTION

In nuclear fusion and fission materials research, *dual ion beam irradiation technique* is a powerful tool to simulate synergistic effects of displacement and transmutation damages introduced by high-energy neutrons.[1] In ordinary situation, it is very difficult to test a new material in a neutron environment. Two ion beams that are accelerated charged particles are used to understand dynamic behavior of a structural material in place of a neutron beam.

2 MATERIAL DAMAGE CAUSED BY NEUTRONS

A neutron collides directly with the nucleus of atom in the target material. The initial elastic collision of a neutron with an atom can lead to displacement of a target nucleus (which received a significant recoil energy and be displaced from its lattice site). The ejected target nucleus is called the primary knock-on atom (PKA). The PKA itself can take the roll of bombarding particle and displace other lattice atoms. A branching tree-like structure of successive collisions is produced and the initial PKA energy is dissipated. This cascade process of collisions ultimately gives rise to a number of changes in the physical state of the target material.[2] The displacement energy E_d is the minimum energy necessary to displace an atom permanently from its lattice site. Displacement per atom (*dpa*) is a calculated representation of the fraction of target atoms that are displaced from their lattice sites as a result of collisions with incident particles. In the calculation, $E_d \approx 25\text{eV}$ is widely used for any materials as a good approximation.

Neutrons may be replaced with charged particles kinetically unless charged particles induce additional chemical reactions in the target material. Especially useful are self-ions, which are chemically identical with atoms there. The initial elastic collisions of charged particles with atoms can lead to atomic displacements of target nuclei and PKAs will be created. Physically PKAs are charged particles and created when either a neutron or a charged particle collides with an atom in the target material. However, the damage profile that 1st PKAs are created is quite different between neutron and charged particle collisions.

3 PASSAGES OF CHARGED PARTICLES TROUGH MATERIALS

We had to recognize physical difference between neutrons and charged particles. The cross section for scattering of a charged particle is known as the Rutherford scattering. The motion of a charged particle through a target material is treated in two energy regions. They are the high-energy region where atomic electrons are excited and ionized, and the lower energy region where collisions with atoms are elastic. In the high energy region a charged particle loses its energy in collisions with atomic electrons, in each of which small energy transfer occurs without appreciable path deflection. A charged particle rarely collides with nuclei directly. The passage of charged particles (the range) in a target material is rectilinear. However, in the low energy region, charged particles displace target atoms and create PKAs if the kinetic energy is larger than but close to the displacement energy E_d. High energy PKAs are rarely created compared to the case of neutrons. Most of their damages are done when their energy is close to E_d, which is rarely discussed in nuclear physics. Charged particles gave most damages against the target material in low energies. Its physical mechanism was not discussed completely. We are going to discuss about it with a simple model.

4 COLLISIONS WITH A SIMPLE MODEL

4-1 Rutherford scattering formula

Rutherford scattering formula gives following differential cross section for charged particles,

$$\frac{d\sigma^C}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{E_{cm}} \frac{1}{4\sin^2 \frac{\theta_{cm}}{2}} \right)^2 . \tag{1}$$

E-mail: Jimbo@iae.kyoto-u.ac.jp

The differential cross section of Eq. (1) is not isotropic. It has especially forward peaked ($\frac{d\sigma^C}{d\Omega} \to \infty$ as $\theta_{cm} \to 0$), which indicates that glancing collisions are dominant. The integral of this formula over the total solid angle diverges. As it is well known in plasma physics, the extreme long range character of the coulomb interaction has serious consequences in practical application.[3] Even the coulomb cross section for momentum transfer diverges, albeit only logarithmically if $E_d \to 0$.

4-2 Massey scattering formula

Massey shows that if polarization effects are ignored the potential energy of an incident particle of charge Z at a distance *r* from a ground-state hydrogen atom is give as follows:[4]

$$V(r) = -Ze^2\left(\frac{1}{r}+\frac{1}{a_B}\right)\exp\left(-\frac{2r}{a_B}\right) . \quad (2)$$

Where $$a_B = \frac{\hbar^2}{m_e e^2} = 5.29\times 10^{-9}\,\text{cm}. \quad (3)$$

When the Born approximation is accurate,[5] this formula gives the shielding field of electron force falling off exponentially with distance.

Massey scattering formula that is the deferential cross section when a charged particle is scattered by a hydrogen atom is,[6]

$$\frac{d\sigma^H}{d\Omega} = 4a_B^2 Z^2 \frac{\left(K^2 a_B^2 + 8\right)^2}{\left(K^2 a_B^2 + 4\right)^4} . \quad (4)$$

Where $$K = 2k\sin\frac{\theta_{cm}}{2}, \quad (5)$$

$$k = \frac{p}{\hbar} = \frac{Mv}{\hbar}. \quad (6)$$

And M is the mass, and *v* is the velocity of the charged particle.

Massey scattering formula does not diverge in small angle scatterings. The cross section has a finite value at $\theta_{cm} \to 0$ as that of the rigid body scattering although it approaches Rutherford scattering formula asymptotically in large angle scatterings.

On the same way, the deferential cross section between an electron and a hydrogen atom is

$$\frac{d\sigma_e^H}{d\Omega} = 4a_B^2 \frac{\left(K_e^2 a_B^2 + 8\right)^2}{\left(K_e^2 a_B^2 + 4\right)^4} . \quad (7)$$

Where $$K_e = 2k_e\sin\frac{\theta_{cm}}{2}, \quad (8)$$

$$k_e = \frac{p_e}{\hbar} = \frac{m_e v_e}{\hbar} . \quad (9)$$

And m_e is the electron mass and v_e is the electron velocity.

5 DISCUSSIONS

Consider the case that a charged particle (of charge *Z* and atomic mass unit *A*) and an electron collide with a hydrogen atom. If their velocities are the same, the electron is considered to be an atomic electron of the atom. From Eqs.(4) and (7),

$$\frac{d\sigma^H}{d\Omega}\Big/\frac{d\sigma_e^H}{d\Omega} \sim 10^{-13}\frac{Z^2}{A^4} \ll 1 . \quad (10)$$

We infer from this result that collision with an atomic electron is dominant compared to collision with a nucleus when the atom collides with a hydrogen atom. We approximate atoms in the target material with Massey scattering formula since it shields the positive electrostatic field of nuclei of atoms there. Massey scattering formula represent more realistic situation compared to Rutherford scattering formula. In high energy, incoming charged particles lose most of their atomic electrons in the target material. However, as they lose energy, they start to pick up electrons there. Finally charged particles become neutral atoms. Then atomic electrons of incoming atoms interact with atomic electrons of the target material. As shown in Eq.(10), the electron cross-section which represents incoming neutral atoms is very large compared with the cross section of incoming charged particles. Therefore, charged particles turn to be neutral atoms, which gave most damages against materials in low energies. This explanation is consistent with observations.

REFERENCES

1) A. Kohyama, Y. Katoh, M. Ando and K. Jimbo, Fusion Eng. Design 51-52 (2000) 789-795.

2) C.Ishino:"*Shousha sonshou (Japanese)*" (Tokyo University Publication, 1979) , p25.

3) M.Mitchner and C.H.Kruger,Jr., "*Partially Ionized gases*", (John Wiley & Sons, New York, 1973), p57.

4) H.S.W.Massey,"*Negative ions*", (Cambridge university press, Cambridge, 1950) 2nd ed.,p5.

5) J.J.Sakurai, "*Modern quantum mechanics* ", (Addison-Wesley Publishing Company, Inc., New York, 1985), p386.

6) B.H.Bransden and C.J.Joachain, "*Physics of atoms and*", (Longman Scientific & Technical.), p509.