

# The Electron-phonon Mean Free Path as a Link between Electronic Energy Deposition and Track Size in Insulators

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When materials are irradiated by swift heavy ions, the energy loss ( $S_e$ ) is initially stored in the electronic subsystem with a radial distribution that can be estimated by MC calculations [1]. To quantify the size of such a distribution, we define a mean cylinder radius  $R_e$  in which 66% of the  $S_e$ -energy is deposited. This radius matches with measured track radii in insulators and varies, e.g. in  $Y_3Fe_5O_{12}$  [2], from 0.5 nm to 13 nm for projectile velocities from 0.1 MeV/u to 100 MeV/u, respectively. The energy density  $E_{de}$  deposited to the target electrons, is given by  $E_{de} = 0.66S_e/(N_y\pi R_e^2)$  (in eV/atom), where  $N_y$  is the atomic density of the target. An example of the energy dependence of  $E_{de}$  is given in Fig. 1 for U projectiles on a  $Y_3Fe_5O_{12}$  target. Note that  $E_{de}$  decreases towards higher energies due to the increasing electron range.

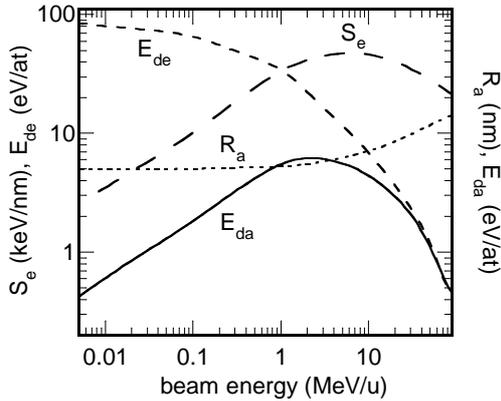


Fig. 1:  $S_e$ ,  $E_{de}$ ,  $R_a$ , and  $E_{da}$  versus U beam energy in  $Y_3Fe_5O_{12}$ .

Measured track radii in different insulators, however, do not simply scale with the energy of the projectile. For example, track radii from  $Y_3Fe_5O_{12}$  irradiations with different ions and energies (Fig. 2 left) are grouped in two branches: irradiations with ion velocities in the range of 0.1 - 1.0 MeV/u and those with 5 - 15 MeV/u (so-called velocity effect). On the other hand, the energy density  $E_{de}$  changes within this velocity range continuously from about 80 eV/atom to 2 eV/atom.

We have tried to understand this behavior on the basis of the inelastic thermal spike model, which takes into account the initial radial energy on the electrons. In this model the energy initially deposited on the electrons is spread out by diffusion prior its transfer to the lattice atoms by the electron-phonon interaction. The mean free path  $\lambda$  of this interaction depends on the considered material and ranges between about 12 and 3 nm. Combining  $\lambda$  with  $R_e$ , we define a cylinder radius  $R_a^2 = \lambda^2 + R_e^2$ , in which the en-

ergy is transferred to the lattice.  $R_a$  is plotted versus beam energy in Fig. 1, using  $\lambda = 5$  nm for  $Y_3Fe_5O_{12}$  [3]. At low energies,  $R_a$  is constant but increases above 3 MeV/u. The atomic energy density  $E_{da}$  (in eV/atom), equal to  $E_{da} = 0.66S_e/(N_y\pi R_a^2)$ , is also plotted versus beam energy in Fig. 1. Three regimes can be distinguished for  $E_{da}$ :

- an increase from 0.01 to 1 MeV/u
- a maximum around 2.2 MeV/u
- a continuous decrease for higher energies.

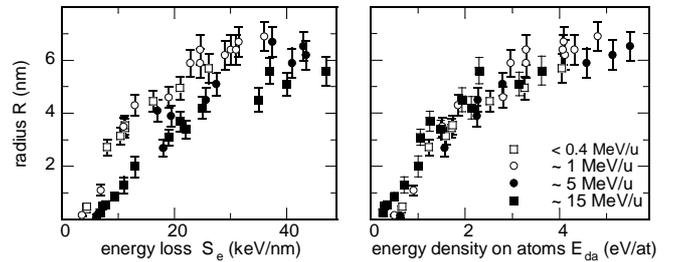


Fig. 2: Track radii in  $Y_3Fe_5O_{12}$  [2] versus  $S_e$  (left) and  $E_{da}$  (right).

These three regimes can be characterized by the following  $R_e$  vs.  $\lambda$  relations:

- For  $R_e \ll \lambda$ , the electron-phonon mean free path governs the volume in which the energy is deposited, independently of the beam velocity.
- For  $R_e \approx \lambda$ , there is an intermediate regime where both parameters are efficient. The beam energy at which this transition appears varies for different targets, since both parameters depend on material properties.
- For  $R_e \gg \lambda$ , the initial electronic energy deposition governs the energy density deposited on the atoms independently of  $\lambda$ . In this regime the material properties defining the strength of the electron-phonon interaction (e.g. crystalline or amorphous phase) will not influence the track size provided that all the other material parameters remain unchanged.

If measured track radii for  $Y_3Fe_5O_{12}$  irradiations are plotted vs.  $E_{da}$  (Fig. 2 right), a surprisingly systematic trend can be seen which points at the atomic energy density as the determining parameter for the created track radii. This has been found to be a general feature in insulators [4].

## References

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