

Chapter 2

Induction of Thermoluminescence

Abstract The essential condition for induction of thermoluminescence (TL) in a material is the presence of suitable defect centers. This chapter summarizes well-known type of point defects in the inorganic solids. These serve as simple examples of defect centers, the types of which may act as traps and recombination centers. However, the actual structure of the defect centers in different TL phosphors is not simple to find out, neither is it necessary for the application of TL in areas like dosimetry and archaeological and geological dating. Defect centers may be created by doping the material with suitable impurities and thermal treatments like heating at a high temperature and quenching. X-rays and nuclear radiations being the principal sources which induce the TL, their interaction with matter is summarized in this chapter. The interactions are discussed in the perspective of the TL induction by different types of radiations.

2.1 Essential Conditions for TL Induction

As discussed in Chap. 1, thermoluminescence (TL) in a sample may be described as a two-step process: (1) induction (excitation) of TL by exposure to ionizing radiations, (2) stimulation of TL emission by heating subsequent to exposure. The necessary condition for the induction of TL in a material is that the concerned material should contain certain types of defects in its regular structure. This means that very pure and defect free materials would not show TL. These defects should be capable of capturing electrons or holes during exposure to ionizing radiations. Further, the captured charges should be retained in that state until the sample is heated to an appropriate temperature to read the TL. These defect structures may be called the TL centers. The term “center” is used to designate these structures because these are present as isolated entities and are not a part of the regular lattice, which is a continuous repetition of the unit cell of a crystalline material. The function of irradiating the material with ionizing radiations is to produce free electrons and holes in abundance by the interaction of the incident radiation with

atoms of the bulk sample. Majority of the electrons and holes undergo recombination almost instantaneously during irradiation and in the process one may see the radioluminescence. Some of these free electrons and holes diffuse in the lattice and are ultimately captured (trapped) in the defect centers. Irradiation may also produce the defects in addition to producing ionization. This will be discussed in the following sections. In order that the trapped charge carriers (electrons and holes) are able to produce luminescence emission during thermal stimulation, it is necessary that the sample material contains also such defect species which capture the charge carriers liberated from the traps during heating and in the process undergo electronic transitions leading to the emission of light. These species are called *recombination centers* or luminescent centers. In the following, we briefly describe some of the well-known defect types primarily in alkali halides. These are given as mere examples, since the defect types in various TL materials depend on the material itself and one may or may not be able to know their exact structure. Notwithstanding this difficulty these materials are useful in applied disciplines.

2.2 Defect Centers in TL

The defect centers may be divided into two categories: (1) those inherently present in the material and (2) those produced by external means, such as by purposely doping the sample with impurities. The inherently present defect centers may appear simply due to thermodynamic reasons. They may appear also due to the presence of trace impurities, which may be difficult to be removed during the purification process. The equilibrium concentration of defects at any temperature due to thermodynamic reason may be calculated from statistical mechanics. The concentration of these defects at an ambient temperature may be increased by taking the sample to a higher temperature and then cooling it suddenly (quenching). In this way, the increased number of defects present at higher temperatures may be frozen. This method is quite common in the preparation of TL samples. When an ion or atom from its regular lattice position slips into an adjacent interstitial position, the defect formed is called Frenkel defect. It is thus a vacancy—interstitial pair. Cations due to comparatively smaller ionic radii than those of anions are more likely to form Frenkel defects in alkali halides. Cation and anion vacancy pairs are called Schottky defects. It is observed that Schottky defects are most numerous in ionic crystals. The concentrations of Frankel (n_i) and Schottky (n_v) defects in thermodynamic equilibrium at temperature T K are given by Schulman and Compton [1] as

$$n_i = (ANN_i)^{1/2} \exp(-W_i/2kT) \quad (2.1)$$

$$n_v = BN \exp(-W_s/2KT) \quad (2.2)$$

where

- n_i number of ions in interstitial positions
- n_v number of vacant lattice sites
- N total number of lattice points in the ideal crystal
- N_i total number of interstitial positions
- W_i energy required to form a Frankel defect
- W_s energy required to form a Schottky defect. A and B are constants

In alkali halides estimates of W_i and W_s are; $W_i = 2.9$ eV for Na^+ in NaCl and $W_s = 1.9\text{--}2$ eV for NaCl, KCl, and KBr. This shows that there will be more Schottky defects in alkali halides, since the energy requirement is less for the formation of these than for the Frankel defects. The F center, most commonly observed point defect is a negative ion vacancy, which has captured an electron. Lattice vacancies may also be caused by higher valency impurity atoms present substitutionally in the lattice. A divalent cation impurity in a monovalent lattice for example would induce the formation of a cation vacancy in the lattice to maintain charge neutrality. Similarly anionic vacancies may arise if for example an O^{2-} ion substitutes for a halide ion in alkali halides. The impurities (I) and the vacancies (V) tend to associate to form $I\text{--}V$ pairs at low temperatures. These pairs may further associate to form dimers, trimers or even larger clusters. In the following are listed examples of the defects under two categories namely those which trap electrons and those which trap holes.

2.2.1 Defects Which Trap Electrons

Often these consist of negative ion vacancies. A negative ion vacancy has a net positive charge. In alkali halides, for example, the negative ion vacancy, being surrounded by six cations, the vacant space is in the positively charged field. It can thus easily capture an electron. The electron is not stationary in the vacancy. ESR studies have shown that the trapped electron moves in an S type orbit. In fact the F center has been likened to a hydrogen atom, in which the electron is bound to a strong Coulombic central force. Like hydrogen atom it has finite number of bound states. The orbitals may overlap with those of other nearby F centers, if present. This leads to the formation of aggregates of F centers. These are named as M , R , N , etc., centers [2]. The various electron trap centers arising from the negative ion vacancies are listed in Table 2.1 and are shown in Fig. 2.1. In addition to those listed therein, varieties of electron traps are produced also by cationic substitutional impurities. For example, divalent impurities like Pb^{2+} , Mn^{2+} , Mg^{2+} , etc., in alkali halides act as strong electron traps. Similarly trivalent rare earth impurities (RE^{3+}) in alkaline earth compounds may form the main electron traps [3–5]. These may compete with F center formation at negative ion vacancies and play prominent role in the emission of TL. The extra positive charge of the

Table 2.1 Defect centers in alkali halides [2]

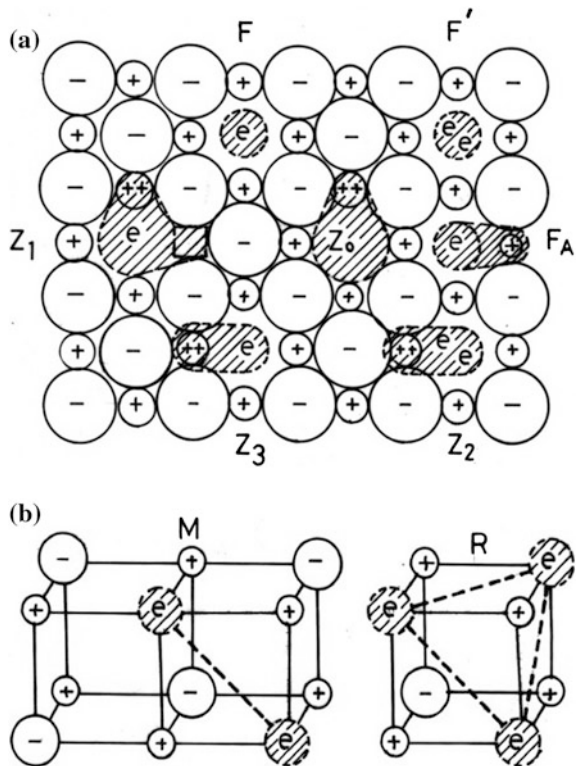
Name of the center	Description
<i>(a) Electron trap centers</i>	
F	An electron at a negative ion vacancy. Its name originates from the word farbzentren (farbe means color and zentren means center in German language)
F'	Two electrons associated with a negative ion vacancy
F_A	It is an F center adjacent to a substitutional impurity ion of same group, but with lesser atomic number, for example Li^+ or Na^+ in place of K^+ in KCl and KI
F^+	A negative ion vacancy
M	Two neighboring F centers in [110] axis
R	Three neighboring F centers forming an equilateral triangle in a [111] plane
Z	These centers are in a way similar to F_A centers except that the nearby impurity is of higher valency. There is a series of Z centers named Z_1, Z_2, Z_3 , etc. Z_1 is an F center with a cation impurity of higher valency and a cation vacancy nearby. Z_2 center is an F' center together with a substitutional cation impurity of higher valency. Z_3 is an ionized Z_2 center. Z_0 is a negative ion vacancy near a substitutional divalent impurity
<i>(b) Hole trap centers</i>	
V_K	One hole (absence of one electron) shared by two adjacent anions. It is a molecular ion, for example F_2^- , Cl_2^- , etc., in alkali halides. These centers are usually observed only at low temperatures. In alkali halides, these are stable only below about 80 K. The subscript K in V_K stands for Kanzig who discovered this center
V_{KA}	It is analogous to F_A . If one of the nearest neighbor lattice site of V_K center is occupied by an alkali impurity of lesser atomic number, for example Li^+ in place of Na^+ in NaF, it is called V_{KA} center
H	It is similar to V_K except that the hole has interaction with two more nearest halide ions. The hole is thus shared between four halogen ions in a straight line. It is represented by X_4^{3-} . This center is stable up to 130 K in LiF
H_A	It is analogous to F_A and V_{KA} . It is an H center adjacent to which there is a substitutional cation impurity of the same group as the host cation but of lesser atomic number
V_F	It is an antimorph of F center, it is a V_K center adjacent to a cation vacancy. Its absorption overlaps the V_K band but it is more stable than V_K

substitutional impurity in the cationic lattice is neutralized by electron capture in these during irradiation. This reduces the valence state of the impurity to render it similar to that of the host lattice ions.

2.2.2 Defects Which Trap Holes

Like the anionic vacancies which form the electron traps, the cationic vacancies are potential sites for trapping the holes. A hole located at the site of a cationic

Fig. 2.1 **a** Electron trap type defect centers. The vacancies in which electrons are trapped are shown by hatched parts. The F , F' , F_A and four types of Z centers. **b** The aggregates of F centers named M and R centers



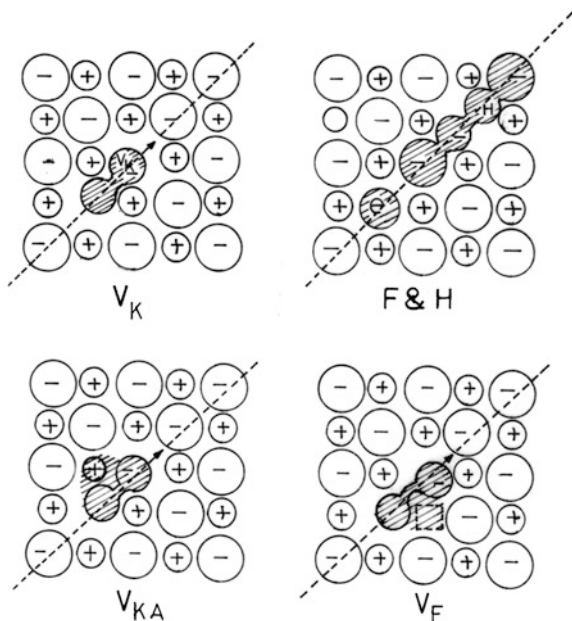
vacancy may be considered as an antimorph of an F center. However, whereas the F center has an S -type orbital, the hole in such a center has a P -type state in alkali halides. In the physical sense, one may understand the hole as the absence of an electron from the anion which is adjacent to the cationic vacancy. In alkali halides, the absence of the electron is in the closed P shell of the halide ion. In fact the hole is shared by two neighboring halide ions adjacent to the cation vacancy (V_F center in Fig. 2.2). Substitutional Na^+ and O^{2-} in cationic and anionic sites respectively in CaF_2 lattice are understood to act as hole traps. Similarly interstitial F^- ions also offer as hole traps in CaF_2 [3–5]. Some typical electron and hole type centers in alkali halides are listed in Table 2.1 (see also Fig. 2.2).

Some types of hole centers are shown schematically in Fig. 2.2.

2.3 Defect Generation by Irradiation

The incidence of ionizing radiations may produce defect centers in two ways: (1) ionization of a lattice ions leading to their displacement into interstitial position. (2) elastic collisions of heavy particles like alpha, energetic ions, and fast neutrons.

Fig. 2.2 Hole trap type centers. The vacancies where holes are trapped are shown as hatched parts in the same way as in Fig. 2.1



The former appears to be a predominant way of causing vacancy and interstitial related defects in alkali halides, particularly at low temperatures. Defect formation by ionization generally takes place in halide lattice. This is because most often it is the valence electrons, which are ejected out during ionization. It is so because the valence electrons are energetically least tightly bound. When an electron is removed from a halide ion, a halogen atom is formed in the anionic position. The halogen atom, being smaller than the halogen ion in size and not bound electrostatically to the lattice (because it is neutral), a relaxation of lattice takes place around the halogen atom. This sets the nearest neighbor ions into motion. As a result of this motion, the unbound neutral halogen atom is most likely candidate to diffuse away from the lattice site and occupy an interstitial position. This interstitial halogen atom, by sharing the deficiency of one electron with three other halide ions forms the so-called H center. The vacancy left behind in the anion lattice position forms an F center by trapping an electron (Fig. 2.1). A refined mechanism for the formation of an F and H center pair, which is now most widely accepted is as follows [2]: The halogen atom left behind after ionization of the halide ion, gets associated with its neighbor halide ion forming a halide molecule (X_2^-). This singly charged halide molecule in which one electron is shared between the two halogens is called a V_K (Fig. 2.2) type hole center or a “self trapped hole.” It is stable only at low temperatures. The two halide ions in this molecule are displaced from their normal lattice positions because of having smaller spacing between them than the normal negatively charged halide ions. At higher

temperatures, a displacement sequence is initiated which ultimately leaves a vacancy in the anionic position together with the formation of an H center. The H center is referred also as ‘crowdion’. It is a crowd of four halogens distributed over three lattice positions (X_4^{3-}). This is a hole center in which the hole is shared between four halogens in the same way as one hole is shared between two halogens in a V_K center. Recent treatments of this model propose appreciable migration of V_K center (through excited state, i.e., excitonic diffusion) before the final relaxation into F and H centers takes place [6, 7]. There is a strong probability that F and H pairs are stabilized near the impurities [7]. In real materials there may be a number of modifications of these basic centers in different substances. For example, the F , V_K or H centers are all modified generally with enhanced stability when these are located adjacent to substitutional cationic impurities. Monovalent alkali impurities such as Li or Na in KCl, KBr, KI, etc., which have trapped interstitial halide ions give rise to the so-called H_A centers. Similarly F centers stabilized near divalent substitutional impurity sites are called Z centers [8]. These modified forms may be involved in the TL process of individual materials.

Different types of centers irrespective of whether electron or hole type, may act as traps or recombination centers. Convention has it that those centers from which the charge carrier is liberated during thermal stimulation are called the traps and those with whom the thermally liberated charge combines are called recombination centers. Recombination centers are more stable than their counterpart traps. It is usually presumed that the luminescence emission occurs from the recombination center. This, however, may not be always so. Quite often the energy released during recombination is transferred to a neighboring impurity ion, which ultimately undergoes the light emitting transition. The light emitting entity may sometimes be identified from the wavelength spectrum of the emitted light. Examples of such cases are the rare earth doped calcium based TL phosphors [4, 9, 10]. Identification of either traps or recombination centers has not been successful in many TL phosphors used even in routine dosimetric applications. Correlative studies using optical absorption and EPR investigations [11, 12] together with the recording of TL glow curves and their wave length spectra may be useful for the identification of the traps and the recombination centers of the TL materials.

2.4 Interactions of Radiations

For the purpose of discussing the interactions of the incident radiations, which lead to the induction of TL in insulating solids like phosphors and minerals we may divide the radiations into the following four categories: (1) Heavy charged particles, such as alpha particles and protons. (2) Light charged particles, which essentially consist of electrons. These are also named as cathode rays or beta rays depending on their origin. Positrons also are included in the same category. These have same mass as electrons, but are positively charged. (3) Electromagnetic

radiations, i.e., gamma and X-rays. This category includes the vacuum ultraviolet rays. (4) Neutral particle radiations namely neutrons. There are other particle radiations like mesons which are present in cosmic rays but are not important for the present discussions.

2.4.1 Heavy Charged Particles

Under this category, let us consider alpha particles and protons. Alpha particles consist of two protons and two neutrons and are like helium nuclei. These thus have double the charge of protons and are four times as heavy. The protons are 1,840 times more massive than electrons and carry one unit of positive charge. The interaction of these heavy charged particle radiations can be divided into two major types: (1) inelastic collisions with atomic electrons. (2) elastic collisions with the nuclei of the atoms of the target material. The former is the predominant mechanism by which these charged particles lose their kinetic energy in a target sample. Being positively charged alpha particles and protons exert a coulomb force of attraction on the electrons and pull some of these away from their binding with the parent atoms. Being relatively massive, alpha particles have short range and consequently high specific ionization. Some of the collisions of the alpha particles with atomic electrons are so hard that the ejected out electron produces its own track of interactions with electrons of other atoms. These secondary energetic electrons are called delta rays. Alpha particles from usually available radioactive sources (4–7 MeV) produce a few tens of thousand ion pairs each when incident into a solid insulating medium. The excitation of TL is caused by these ions (electrons). Alpha particles and protons produce densely ionized isolated tracks in the sample volume with the result that the ionization is nonuniform with a large part of the sample volume remaining un-irradiated. The efficiency of TL induction by the heavy charged particles is therefore low. For alpha particles, it is only 4 % of that by β , X and gamma rays for a given dose [13].

2.4.2 Light Charged Particles

Under this heading we will consider the beta particles, energetic electrons, and positrons. The effect of both the electrons and positrons on the matter is similar except for the fact that the positron ultimately annihilates itself by combining with an electron giving rise to a pair of 0.51 MeV gamma photons. Let us consider the direct interaction between an incident electron and the target matter. Suppose an electron with velocity v is moving in the matter. The electron has a radial electric field. As it moves through the interstitial spaces of the atoms, it exerts Coulomb

force of repulsion on the orbital electrons of the target medium. The energy imparted to the orbital electrons depends on the length of the time the incident particle spends in the vicinity of the orbital electron and the approach distance. If enough energy is transferred, the orbital electron gets ejected out. Some of the interactions may occur at close distances, with the result that the bound orbital electron may be ejected with sufficiently high energy. Such electrons are called delta rays. These dissipate their energy in the same manner as the original incident beta particle. The energetic beta particles lose energy in yet another manner: when a beta particle passes through the Coulomb field of a nucleus, it experiences a strong force and loses its energy by the so called process of bremsstrahlung emission. The bremsstrahlung radiations are X-rays produced by the “braking action” of coulomb field of the nucleus on the passing electron. This process of energy loss becomes important for beta energies above several MeV and is greater for target elements of high atomic number, since higher the atomic number, greater is the nuclear charge and hence greater is the braking action. The bremsstrahlung radiations interact in the sample as discussed later for X and gamma rays. Unlike the alpha particles beta particles do not have a straight line path. Particularly at lower energies the path of an electron is apt to be tortuous due to multiple scattering in the Coulomb field of electrons or nuclei in its path. The ionization produced in the sample is thus uniform for a beta ray beam.

2.4.3 Electromagnetic Radiations (X and Gamma Rays)

X-rays are produced by the stoppage of fast moving cathode ray electrons in a target, which is referred above as bremsstrahlung radiation. Gamma rays are emitted from the nuclei of the radioactive elements during their disintegration. There is no basic difference between the properties of X and gamma rays notwithstanding the difference in their origin. When incident on a material these interact in the following three ways: (i) Photoelectric effect (ii) Compton effect and (iii) Pair production. In photoelectric effect, an electron is knocked out usually from the inner orbit of the target atom. The knocked out electron which is called photoelectron carries with it almost all the energy of the incident photon. The kinetic energy T of the photoelectron is given by

$$T = E - W \quad (2.3)$$

where E is the incident photon energy and W is the binding energy of the atomic orbit from which the electron is removed. W is also called the work function. The cross-section σ of photoelectric interaction is approximately given by $\sigma = AZ^4/E^{3.5}$ where A is a constant and Z is the atomic number of the target material. The strong dependence of photoelectric effect on Z and E is evident from this equation. In LiF phosphor, for example, most of the interactions would take place in Fluoride ion (Z of F being much higher than that of Li).

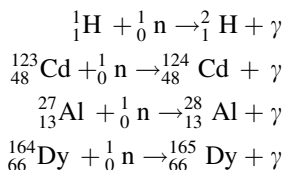
Compton Effect is a scattering phenomenon. In this, the incident X or gamma photon knocks out an electron from an orbit of the target atom by imparting part of its energy to the orbital electron. The incident photon is scattered, carrying with it the remaining energy. The scattered photon may undergo another Compton collision or it may interact photoelectrically, in either case imparting energy to yet another electron. The Compton scattering cross-section is a complicated function of the energy of the incident photon and the angle of scattering. It is independent of the atomic number Z of the target material. However, the Compton mass absorption coefficient (given in units of $\text{cm}^2 \text{g}^{-1}$) depends on the density of the electrons. It is thus greater for lighter elements since the number of electrons per atomic number is higher for lighter elements.

In the third type of interaction, namely the pair production, the X or gamma photon gets converted into a pair of positive and negative electrons when the photon passes near the nucleus of an atom. This effect takes place only when the incident photon energy is more than 1.02 MeV, which is the sum of the mass equivalent of one electron plus one positron. The excess energy of the incident photon over 1.02 MeV is carried by the electron and the positron in the form of their kinetic energy. The positron after spending its kinetic energy recombines with an electron producing two gamma photons of energy 0.51 MeV each. The process is called annihilation. The annihilation-generated gamma photons interact in the medium either by photo-electric or Compton process. The process of pair production is in a way the reverse of bremsstrahlung process, both taking place in the field of the atomic nucleus. Out of the three processes of X and gamma ray interaction, it is the Compton effect which predominates in most of the materials in the photon energy range of our interest. The photoelectric effect becomes comparable only at low energies, say below 30 keV in the case of low Z elements such as Li, Be, and B. For medium Z elements of importance in TL such as Al, Ca, Mg, Si, etc., its contribution is significant below 100–200 keV. Pair production makes significant contribution only above about 2–3 MeV.

Above summary shows that the interactions of X or gamma ray photons produce energetic electrons, which carry the energy of the incident photon in the form of their kinetic energy. These fast moving electrons liberate a large number of bound electrons from atoms of the target medium by exerting electrostatic force on them as discussed above. The most loosely bound electrons have the maximum chance of getting freed. In other words, the electrons are liberated from the valence band of a solid phosphor, since it is this energy state which has a minimum binding energy. The energy deposition by X and gamma ray photons in matter is thus a two step process. First, an energetic electron is produced. This electron is indistinguishable from any other incident electron like a beta ray or cathode ray. In the second step, this electron interacts in the matter exactly as described earlier in the case of beta particle. The TL induction rate per unit dose therefore is similar for beta and X/gamma rays of similar linear energy transfer (LET).

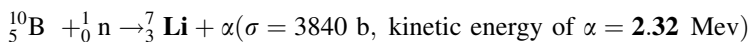
2.4.4 Neutrons

Neutrons are electrically neutral particles. They have mass of nearly 1 atomic mass unit like a proton. Being neutral they do not interact with atomic electrons and hence do not produce ionization directly. They undergo two types of reactions with the atomic nuclei, namely: (a) capture, in which the target nucleus absorbs the neutron. As a result of the neutron capture, another type of radiation leaves the nucleus which causes ionization. (b) elastic scattering in which the neutron collides with the nucleus of an atom and transfers some of its energy to it. The capture reactions are predominant for slow (or thermal) neutrons. There are four main types of slow neutron capture reactions. These are (n, γ) , (n, α) , (n, p) , and $(n, \text{fission})$ reactions. In (n, γ) reaction, the compound nucleus after the capture of the neutron is in an excited state. Emission of energy in the form of one or more gamma photons brings the compound nucleus to its ground state. Some examples of this reaction are



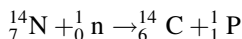
The gamma photon energy from the first reaction is 2.2 MeV. For all other nuclei, the total gamma energy released is 6–8 MeV, which is equal to the binding energy per nucleon in the compound nucleus. This energy, however, is emitted in the form of many photons of lower energy. These reactions are relevant in TL dosimetry of neutrons. The (n, α) and (n, p) reactions are not so common as (n, γ) . Following two reactions are important from the view point of application of TL in neutron dosimetry.

${}^6_3\text{Li} + {}^1_0\text{n} \rightarrow {}^3_1\text{H} + \alpha$ (reaction cross-section $\sigma = 950$ b, kinetic energy of $\alpha = 2.05$ MeV and that of ${}^3_1\text{H} = 2.73$ MeV, ${}^3_1\text{H}$ is stripped of the electron)



${}^6_3\text{Li}$ is used in the well-known TLD-600 phosphor which is used for thermal neutron dosimetry.

An important (n, p) reaction is:

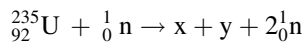


${}^{14}_6\text{C}$ is formed in the atmospheric air by the reaction of cosmic ray neutrons with nitrogen. It forms the basis of the dating of organic remains in archaeology.

One of the most important reactions of thermal neutrons is fission of uranium-235 atoms:

Table 2.2 Number of collisions a 2 MeV neutron suffers in different materials before thermalization [14]

Material	No. of collisions
Hydrogen	18
Water	19
Lithium	67
Beryllium	86
Carbon	114
Oxygen	150
Fluorine	177



This reaction is the basis of the nuclear chain reaction. X and Y are the fission product nuclides. Most of these are radioactive elements emitting beta and gamma radiations.

Elastic scattering of neutrons—it is the most common reaction in the case of fast neutrons. The process is like the collision of billiard balls. The energy ΔE imparted by an incident fast neutron of energy E to the target nucleus of mass A is given by the following equation.

$$\Delta E/E = 2A(1 - \cos \theta)/(A + 1)^2 \quad (2.4)$$

where θ is the scattering angle of the neutron in the center of mass system. It may be seen that the energy transfer increases as θ increases from 0 to 180°. Again the transfer is much more to the lighter nuclei than to the heavier ones. Obviously maximum energy transfer takes place when the target nucleus is that of hydrogen. In a bulk medium fast neutrons get thermalized by multiple collisions with the atoms of the medium. Estimate of the number of collisions that a neutron of energy 2 MeV makes before getting thermalized is given in Table 2.2 for different materials [14]. Fast neutron collisions have twofold importance in TL induction: (1) the nuclei which suffer collisions with neutrons get displaced into an interstitial position with the result that a vacancy is left behind in the lattice. It has been estimated that the number of vacancies produced by a fast neutron of energy up to 5 MeV runs in couple of hundreds in materials with $Z \leq 30$ [15]. These vacancies may function as traps for electrons or holes depending on whether the vacancy is of negative or positive ion. (2) when a hydrogenous material is kept in contact with a TL phosphor and exposed to fast neutrons, energetic recoil protons produced in abundance as a result of elastic scattering in the former cause ionization and induce TL in the phosphor. Fast neutron dose meters have been made based on this technique. (see for example, Sunta et al. [16] and Rzyzsky et al. [17]).

2.5 Dose Dependence of the Filling of Traps

As discussed earlier, the TL excitation process consists essentially of filling of the traps. The TL response of a given sample to a known dose depends on the number of the traps filled by the given dose. A simple way to estimate the number of the filled traps is to assume the filling rate to be directly proportional to the dose D and also directly proportional to the vacancies in the traps [18]. If the total number of trapping sites is N out of which n are already filled up at any time, the incremental filling dn by a small incremental dose dD may be given by

$$dn = \alpha(N - n) dD \quad (2.5)$$

where α is the fraction of vacant traps which get filled up per unit dose. Using the initial conditions that $n = 0$ when $D = 0$, the solution of (2.5) is

$$n = N [1 - \exp(-\alpha D)] \quad (2.6)$$

This equation shows that the dose at which all of the traps get filled up depends solely on α . It will be shown in Chap. 6 that the value of α may be determined from the growth curve of TL intensity versus dose, provided however, that the given growth curve fits into the above equation. Another way to monitor the trap filling is to measure the optical density (OA) or ESR signals from the traps responsible for the TL glow peak. This requires establishing a correlation between the given TL glow peak and an OA band or ESR signal of the sample. Such correlations seem to have been established for the prominent glow peaks of LiF:Mg,Ti (TLD-100) phosphor. The glow peaks appearing at about 200 and 400 °C of this phosphor are thought to be associated with the OA bands at 310 and 225 nm, respectively [18, 19]. Such correlated OA bands or ESR signals may, however not be available for the glow peaks of every sample.

An alternative to the above analytical approach to describe the trap-filling process is to use a set of rate equations, which represent the flow of charges between the valence band, the conduction band, and the electron traps and the hole centers following ionization by irradiation. Chen et al. [20] used this approach. The rate equations have to be solved numerically to find the number of filled electrons traps at the end of the irradiation which implies the dose. The results of the numerical computations depend on the values of the input parameters used in the equations. An important result, which has implication for experimental cases is that the population of the filled traps n , produced by irradiation depends on the electron-hole generation rate R by ionization, which means that the TL output for a given dose would depend on the dose rate as well. The authors also showed that the pattern of this dependence changes with the total generation of electrons and holes which means the total dose. The dose rate dependence of TL could have important consequences in dosimetric application. A summary of experimental data given by the authors, however, shows that most of the phosphors used in dosimetry do not display this effect.

References

1. J.H. Schulman, D.W. Compton, *Color Centers in Solids*, Chapter 7 (Pergamon Press, New York, 1962), pp. 10–11
2. W.B. Fowler (ed.), *Physics of Color Centers*, Chapter 2 (Academic Press, New York, 1968), pp. 53–179
3. J.L. Merz, P.S. Pershan, *Phys. Rev.* **162**, 217–235 (1967)
4. C.M. Sunta, *Radiat. Prot. Dosimetry* **8**, 25 (1984)
5. C.M. Sunta, *Nucl. Tracks* **10**, 47 (1985)
6. J.D. Comins, B.D. Carragher, *J. Phys.* **41**, 166 (1980)
7. P.D. Townsend, *Nucl. Instrum. Methods Phys. Res.* **197**, 9 (1982)
8. F. Augullo Lopez, F.L. Lopez, D. Jaque, *Cryst. Lattice Defects Amorphous Mater.* **9**, 227 (1982)
9. C.M. Sunta, *J. Phys. C: Solid State Phys.* **3**, 1978 (1970)
10. K.S.V. Nambi, V.N. Bapat, A.K. Ganguly, *J. Phys. C: Solid State Phys.* **7**, 4403 (1974)
11. B. Dhabekar, S. Menon, R. Kumar, T.K. Gundu Rao, B.C. Bhatt, A.R. Lakshmanan, *J. Phys. D: Appl. Phys.* **38**, 3376 (2005)
12. S. Watanabe, T.K. Gundu Rao, P.S. Page, B.C. Bhatt, *J. Lumin.* **130**, 2146 (2010)
13. M.J. Aitken, Dose rate evaluation, *Proceedings of Specialist Seminar on Thermoluminescence Dating, Research Laboratory for Archaeology and History of Art*, Oxford, PACT vol. 2, part 1 (Council of Europe, Strasbourg, 1978), p. 18
14. R. Stephenson, *Introduction to Nuclear Engineering* (McGraw-Hill, New York, 1954), p. 104
15. P.W. Levy, in *A Brief Survey of Radiation Effects Applicable in Geological Problems*, ed. by D.J. McDougall. Thermoluminescence of Geological Materials (Academic Press, New York, 1968), p. 25
16. C.M. Sunta, K.S.V. Nambi, V.N. Bapat, *Symposium on Neutron Monitoring for Radiation Protection Purposes, International Atomic Energy Agency, Vienna, IAEA/SM-167/10*, 11–15 Dec 1972
17. B. Rzysky, S. Watanabe, C.M. Sunta, *Fifth International Conference on Luminescence Dosimetry, University Sao Paolo, Brazil*, Paper no P-52, 14–17 Feb 1977
18. C.M. Sunta, E. Okuno, J.F. Lima, E.M. Yoshimura, *J. Phys. D Appl. Phys.* **27**, 2636 (1994)
19. L.V.E. Caldas, M.R. Mayhugh, T.G. Stoebe, *J. Appl. Phys.* **54**, 3431 (1983)
20. R. Chen, S.W.S. McKeever, S.A. Durrani, *Phys. Rev. B* **24**, 4931 (1981)



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