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Characteristics of Solid-State Nuclear Track Detectors for Heavy Charged Particles – A Review

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Abstract

Since Silk and Barnes observed the tracks of uranium fission fragments on the mica films, the formation of latent tracks by heavy charged particles in solids has been recognized as one of fundamental phenomena of the radiation damage. And then, the investigation of the latent tracks became an important device for detection of charged particles by the success of etch-pit technique developed by Price and Walker.

The technique to identify incident charged particles using their latent tracks in target solid-state detectors, especially CR-39, has been developed enthusiastically and used widely in many fields of science. While the application of this technique is in progress prosperously, the mechanisms of the latent track formation in the target solids have been under investigation and several proposals have been given for them. The "ion explosion mechanism" and the "electron thermal spike mechanism" are two main mechanisms considered as fundamental even if there remain many unknown factors in the relation between the characteristics of incident particles and their latent tracks in solids.

The technique to use the particle track detector in identification of charged particles is not an accomplished and completed one but is developing rapidly at present as introduced in our paper presented at this Conference for the identification of particles generated in the cold fusion phenomenon (CFP). We have to consider that the immediate and visible scientific problems of the particle track field are solid state physics questions not completely solved yet: How does a track form? What atomic processes take place? What is the ultimate atomic configuration along and around a track? Investigation of these problems is in progress and new knowledge about the mechanism of latent track formation and its investigation has been obtained, especially for organic detectors.

The proposed mechanisms of nuclear track formation are summarized and problems in visualization of the tracks by chemical etchings and possible application to identify charged particles and to determine their energies are reviewed in intimate relation to the CFP.

1. Introduction

Since Silk and Barnes [Silk 1959] observed the tracks of uranium fission fragments on the mica films, the formation of latent tracks by heavy charged particles in solids has been recognized as one of fundamental phenomena of the radiation damage. The formation of the latent tracks became an important device for detection of charged particles by the success of the etch-pit technique developed by Price and Walker [Price 1962].

The technique to identify incident charged particles using their latent tracks in target solid-state detectors, especially CR-39, has been developed enthusiastically and used widely in nuclear physics, nuclear chemistry, nuclear energy, space science and archeology. While the application of this technique is prosperous, the mechanism of the latent track formation in the target solids has been investigated actively and several proposals have been given. The "ion explosion mechanism" by Fleischer, Price and Walker [Fleischer 1959] and the "electron thermal spike mechanism" developed by Merkle [Merkle 1963], Chadderton [Chadderton 1966] and others are two mechanisms considered as fundamental even if there remain many unknown factors in the relation between the characteristics of incident particles and their latent tracks in solids.

The technique to use the particle track detector in identification of charged particles should not be considered as a completed one due to the complexity of materials used as the detector but as a developing one rapidly at present. We have to remember that the words expressed by pioneering researchers in this field are true even now; "The first, most immediate and visible scientific problems of the particle track field were solid state physics questions: How does a track form? What atomic processes take place? What is the ultimate atomic configuration along and around a track? Curiously enough these problems remain as some of the least studied, presumably because of the intense interest in the many applications of track etching that has directed attention to the assortment of fields considered in Chapter 4 through 10." [Fleischer 1975].

The situation around this field has been improved largely while there remain many problems to be solved to use the solid-state particle detectors for determination of characteristics of incident charged particles. One of recent works related to these problems is the investigation of nuclear tracks in CF-39 by Yamauchi et al. [Yamauchi 2005].

In this paper, we would like to summarize the mechanism of nuclear track formation and discuss its possible application to identify charged particles emitted in the cold fusion (CF) reactions. An interesting use of CR-39 to determine high energy neutrons [Mosier-Boss 2008] is introduced. The latent track formations by false causes (environmental radiation, surface defects in handling process etc.) will give uncertainty in the measurements but is not considered in this paper.

2. Stopping Powers of and Radiation Damages in Target Materials

Interaction of a charged particle and a target material has several facets depending on the point of view to observe the effect caused by the interaction. From a point looking into the behavior of the incident particle, we are interested in the behavior of the particle in the target in temporal sequence. How the particle decelerated and how far the particle reaches in the material. Stopping power of the target material is the title of the investigation in this case.

On the other hand, from a point looking into the effect in the target made by the particle, we are interested in the radiation damages induced by the particle in the material. While the two phenomena are closely related each other, there are characteristic factors in each and their investigation has been developed to form two big research fields neighboring each other. It is useful to survey essential points of these fields for investigation of solid-state particle detectors belonging to the field of radiation damage.

2.1 Stopping Powers of Target Material for Incident Heavy Charged Particles

Particle interaction of an incident charged particle with a target material is treated as a stopping power of the material for the particle on one side and as a radiation damage in the material given by the particle on the other. The two effects are of course closely related each other and the knowledge in each problem is useful to understand another problem.

The interaction of an incident charged particle and a target solid is not so simple with variety of interactions between component particles of the both incident and target agents explained below. Furthermore, the latent tracks remaining after the interaction contain many information in a part of which can be read out using the etching technique having been developed day by day.

As shown below, stopping power of and therefore radiation damage of a target material for an incident particle depends on the charge Z_1 of the incident particle and atomic number Z_2 of atoms in the target, on the velocity v_1 (or the ratio of the energy E_1 and the mass M_1 , E_1/M_1) of the incident particle. On the other hand, the structure of radiation damages or latent nuclear tracks in the target is a statistical result of individual atomic processes and depends on detailed dynamics of particles excited by the interaction between the incident particle and atoms in the target and it is necessary to take into consideration new factors not considered in the calculation of the stopping power.

We summarize the physics of stopping power in this section [Doke 1970] and that of radiation damage, especially nuclear tracks [Doke 1969] in next section.

2.1.1 Three Energy Regions of Incident Particles Characteristic for the Stopping Power

As Doke explains in his review article [Doke 1969], trajectory formation by heavy ions in solids has been investigated as a fundamental phenomenon in the radiation damage and also investigated widely as a characteristic detector of radiation in recent years after the development of the etch pit method by Price and Walker [Price 1962].

Due to the different effects of the interaction between the incident charged particles and the nuclei on the lattice of the target material, there are three regions of the incident particle energy, high, intermediate and low energy regions, in formulation of the stopping power for an incident charged particle in a target material. It should be noticed that the radiation damage from the initial to the final parts of the latent track relates to the energy regions as a whole while the stopping power has to be investigated in these energy regions separately,.

2.1.1a Theory for High Energy Region ($v \gg v_0 Z_1$)

The Bethe's formula of the energy dissipation rate for a high energy incident particle is written down as follows;

$$-dE/dx = (4\pi Z_1^2 e^4/m_e v_1^2)\, N_2 B, \qquad (1)$$

$$B = Z_2 \ln (2m_e v_1^2/I), \qquad (2)$$

where Z_1 and v_1 are the nuclear charge and the velocity of the incident heavy charged particle, respectively, N_2 and Z_2 are the number density and the atomic number of the atom in the target material, respectively, and e and m_e are the charge and the mass of an electron, respectively. The symbol I is the average excitation energy (potential) of the material and B given in Eq. (2) is the so-called "stopping number." The average excitation energy I is only calculated for simple nuclei such as proton and alpha. In general, the value of I is most questionable and gives ambiguity in the calculation of stopping powers.

In the non-relativistic approximation, the velocity v_1 is related to the energy of the particle by

$$E_1 = (1/2)M_1 v_1^2, \text{ or } v_1 = (2E_1/M_1)^{1/2}$$

The equation (1) shows a dependence of the stopping power on the charge Z_1, the velocity v_1 (or the ratio of energy E_1 and mass M_1, E_1/M_1) of the incident particle and on the charge Z_2 of the target atom.

1) Stopping number *B* and its inner-shell correction

The Bethe's formula is deduced using the Born approximation and applicable to high energy particles with velocity v_1 satisfying the following two conditions;

$$v_1 \gg Z_1 e^2/\hbar \equiv v_0 Z_1 \ (v_0 \equiv e^2/\hbar) \qquad (3)$$

related to the ionization of the incident particle and

$$v_1 \gg v_0 Z_2 \qquad (4)$$

related to the ionization of the inner shell electrons of the target atom.

For light incident particles proton p ($Z_1 = 1$) and deuteron d ($Z_1 = 2$), usually appear in the cold fusion phenomenon (CFP), the equation (4) is the more severe condition to satisfy.

The condition (3) with the value of $v_0 \equiv e^2/\hbar = 2.2 \times 10^8$ cm/s demands the energies of proton, deuteron and alpha to be $E_p \gg 25$ keV, $E_d \gg 50$ keV and $E_\alpha \gg 100$ keV:

$$E_p \gg 25 \text{ keV}, E_d \gg 50 \text{ keV and } E_\alpha \gg 100 \text{ keV}$$

The condition (4) should be remedied by the so-called the "inner-shell correction" *B'* instead of the stopping number *B* for an incident particle with energies not so large but satisfying the condition (3),

$$B' = Z_2 \ln (2mv^2/I) - \sum_i C_i \qquad (5)$$

where C_i is the correction for the *i*-th shell of the target nucleus and *I* is the average excitation potential already appeared in Eq. (2).

2) Average excitation energy of a compound material and Bragg's additivity law

The average excitation energy (AEE) I_c of a compound material is given by

$$\ln I_c = \sum_i N_i Z_i \ln Ii / \sum_i N_i Z_i \qquad (6)$$

where N_i, Z_i and I_i are the number density, the atomic number and the AEE of the *i*-th component of the compound material, respectively. This additivity is applicable to the compound material where the change of valence electrons by chemical bonds is ignored.

3) Organic material

There is an important question for organic materials how much the Bragg's additivity law is applicable especially at low energy region. The work by Sauter and Zimmermann [Sauter 1965] has shown that the Bragg's additivity law is not applicable below 150 keV for the stopping power of organic material for protons by experiments using $(CH_2)_n$, $(C_8H_8)_n$, (C_9H_{10}), $(C_3H_6)_n$, $(C_8H_8 + C_4H_6)_n$, (C_2H_4), and (C_3H_8).

Recently, Yamauchi et al. [Yamauchi 2005] investigated yields of CO_2 formation and scissions at ether bonds along nuclear tracks in CR-39. More details of their work will be given in Sec. 2.2.3.

2.1.1b Theory for Low Energy Region ($v \ll v_0 Z_1$)

The stopping power for heavy charged particles increases with the incident energy E until the velocity v becomes near $v_0 Z_1^{2/3}$ and then decreases gradually. For the region where $v \gg v_0 Z_1$, the theory given above is applicable. On the other hand, for the low energy region where $v \ll v_0 Z_1$, there are several theories applicable to this region.

When the velocity of heavy incident charged particles becomes less than $v_0 Z_1$, we can use a classical theory for the calculation of the stopping power. In this low energy region, the incident particles lose energy by i) excitation and ionization of atoms in the target and also by ii) elastic collisions with nuclei in the target. Therefore, the total stopping power $(\mathrm{d}E/\mathrm{d}x)_\mathrm{T}$ is expressed as a sum of two terms, $(\mathrm{d}E/\mathrm{d}x)_\mathrm{e}$ by the process i) and $(\mathrm{d}E/\mathrm{d}x)_\mathrm{n}$ by the process ii);

$$(\mathrm{d}E/\mathrm{d}x)_\mathrm{T} = (\mathrm{d}E/\mathrm{d}x)_\mathrm{e} + (\mathrm{d}E/\mathrm{d}x)_\mathrm{n}. \quad (7)$$

1) LSS theory for low energy particles

Lindhard et al. [Lindhard 1963] have given a formula (7) written in dimensionless parameters which is sometimes called "unified range-theory" for heavy ions.

The two terms on the right-hand side of the equation (7) applicable for $0 < v < v_0 Z_1^{2/3}$ are given as follows:

$$-(\mathrm{d}E/\mathrm{d}x)_\mathrm{e} = \xi_\mathrm{e}\, 8\pi e^2\, a_0\, N\, (Z_1 Z_2/Z)(v/v_0), \quad (8)$$

$$-(\mathrm{d}E/\mathrm{d}x)_\mathrm{n} = (2\pi/e)(Z_1 Z_2\, e^2\, a_0/S) M_1/(M_1 + M_2),\ (2Z_1 S\, e^4/\hbar v^2 \geq 1) \quad (8')$$

where $S = (Z_1^{2/3} + Z_2^{2/3})^{1/2}$, $v_0 = e^2/\hbar$, $a_0 = \hbar^2/m_\mathrm{e}\, e^2$.

Or

$$(\mathrm{d}\varepsilon/\mathrm{d}\rho)_\mathrm{e} = k\varepsilon^{1/2}, \quad (9)$$

$$(\mathrm{d}\varepsilon/\mathrm{d}\rho)_\mathrm{n} = (1/2\varepsilon)\ln(1.294\varepsilon), \quad (10)$$

where

$\xi_\mathrm{e} = Z_1^{1/6}$,

$Z^{2/3} = Z_1^{2/3} + Z_2^{2/3}$,

$$\varepsilon = EaM_2/ Z_1 Z_2 e^2 (M_1 + M_2), \quad (11)$$

$$\rho = RNM_2\, 4\pi a^2\, M_1/(M_1 + M_2)^2, \quad (12)$$

$$a = 0.8853\, a_0/(Z_1^{2/3} + Z_2^{2/3})^{-1/2} \quad (13)$$

$$k = \xi_\mathrm{e} \times 0.0793 Z_1^{1/2} Z_2^{1/2} (M_1 + M_2)^{3/2} /[(Z_1^{2/3} + Z_2^{2/3})^{3/4} M_1^{3/2} M_2^{1/2}], \quad (14)$$

2) Firsov's theory for low energy particles.

Because the formula (8) in the LSS's theory given without deduction process is inconvenient to use in analyses of experimental results, Firsov [Firsov 1959] has given a formula based on a model using a potential of the Thomas-Fermi type. The stopping power for $Z_2/Z_1 < 4$ is given as follows;

$$-(1/N)\,(\mathrm{d}E/\mathrm{d}x)_e = 5.15 \times 10^{-15}\,(Z_1 + Z_2)(v/v_0). \qquad [\mathrm{eV}\cdot \mathrm{cm}^2/\mathrm{atom}] \qquad (15)$$

2.1.1c Theory for the Intermediate Energy Region ($v \sim v_0 Z_1^{2/3}$)

At the intermediate energy region where $v \sim v_0 Z_1^{2/3}$ and the charge exchange is not negligible, theoretical treatment of stopping power of heavy ions ($Z_1 \geq 15$) is difficult and we have to use semi-empirical formulae. Sometimes, formulae deduced in high or low energy regions have been extended into this region.

2.2 Radiation Damages and Latent Tracks – Formation of Nuclear Tracks in Solids

The radiation damage depends sensitively on the energy of the incident particle. The latent track in a target material induced by an incident charged particle is determined by the whole process from the initial to the final (at rest) stage of the interaction between the particle and the target. Therefore, formation of a latent track is characterized by properties of the target material in relation to its interaction with the particle during deceleration to the stop.

Detection of an energetic charged particle is realized by using any recording medium which register the interaction of the particle and the medium. The first and simplest medium we used to register the charged particle is the cloud chamber invented by C.T.R. Wilson in 1911 which has been used in physics over the century.

Any detector of the charged particle is composed of three factors. (1) The first factor is the stopping power of the medium for the incident particle which we want to identify its characteristics; mass, charge and energy. (2) The second factor is the radiation damage or latent track of the passing particle in the medium induced by the incident particle. (3) The third factor is the visualization of the latent track.

The first factor was discussed in the previous section and showed its complexity already.

As is explained below, the second factor includes also complex atomic and sometimes nuclear processes and identification of the charged particle by the solid-state detector is not a simple and easy method if we use it alone. It is recommended to use it with other methods supplementing each other. The third factor depends strongly on the property of the target material and is considered in papers on practical application of the detector.

2.2.1 Formation of Nuclear Tracks in Solids

Silk and Barnes [Silk 1959] observed nuclear tracks of fission fragments of uranium in mica as a fundamental event of the radiation damage. Then, the etch pit method developed by Price and Walker [Price 1962a – c] has made the nuclear tracks a powerful method to detect charged particles and the mechanism of nuclear track formation had been investigated intensively.

Several mechanisms were proposed to explain experimentally observed nuclear tracks by heavy charged particles in solids. It is not easy to determine the mechanism that made the observed tracks. This situation means inevitably existence of ambiguity in determination of the characteristics of the incident particle generating the nuclear track. We have to remember the fundamental properties of the interaction between incident particle and the target resulting in the nuclear track.

There have been proposed four main mechanisms of the track formation by incident heavy ions, a) displacement cascade (spike) theory, b) "electron thermal spike" theory, c) "ion explosion" theory and d) "direct ionization damage" theory.

a) Displacement cascade (spike) theory

The energy loss of a heavy ion passing through a material is expressed by a term $(\mathrm{d}E/\mathrm{d}x)_e$ due to electronic processes (ionization and excitation) and another $(\mathrm{d}E/\mathrm{d}x)_n$ due to elastic nuclear collision (Coulomb scattering) as mentioned in Section 2. In the case of the fission fragment in mica, a large part (~ 95%) of the energy loss is by the electronic process and the remaining part by the nuclear process. Furthermore, the latter is eminent at the final part of the track where the knocked out atoms collide with other atoms causing the displacement cascade and finally the displacement spike [Silk 1959].

b) Electron thermal spike theory

The energy loss of heavy ions in a material is caused mainly by the electronic processes and the energy transferred to electrons may be consumed to heat up the crystal lattice along the particle tracks. The formation of nuclear tracks by this mechanism is called the electron thermal spike theory.

c) Ion explosion theory

Fleischer at al. [Fleischer 1965] proposed a mechanism of track formation by heavy ions as follows: A heavy charged particle passing through a material knocks out electrons along its path forming cylindrical region occupied by ions. The ions in this cylinder repel each other out from this region forming a cylinder made of vacancies surrounded by interstitial atoms (nuclear track) [Fleischer 1965].

d) "Direct ionization damage" theory.

To explain the nuclear track formation in organic materials, characteristics of the organic molecules have been taken into consideration. The broken bonds of organic molecules due to the ion propagation may be activity centers for etchant and molecular fragments produced by breaking bond may be more soluble by etching [Fleischer 1965].

Afterward, there have been proposed two new mechanisms by Katz and Kobetich [Katz 1968] and by Benton and Nix [Benton 1969] supplementing the theories explained above.

A recent work on the CR-39 detector by Yamauchi et al. [Yamauchi 2005] has given concrete data on the broken bond and molecular fragments in the detector (cf. Sec. 2.2.3).

In conclusion, there are proposed several theories or criterions for nuclear track formation in materials, especially in organic materials, to understand this complicated phenomena related to the interaction of incident charged particles and target materials which is sensitively dependent on the energies of the incident particles.

We have to careful to apply these theories to the CFP not falling into mistakes committed by blind people as told in a Buddhist parable [cf. Appendix].

2.2.2 Track Formation and Detection of Charged Particles

It should be noticed that we can not say at present which one of these mechanisms proposed is an appropriate one to explain the phenomena occurring in trajectory formation by heavy ions in solids. Especially, the trajectory formation by heavy ions in organic materials has been discussed thoroughly in relation to their application to detectors.

There have been proposed also several mechanisms including the "primary ionization" mechanism by Fleischer, Price and Walker [Fleischer 1965], the "electron thermal spike" theory by Chadderton, Morgan, Torrens and Van Vliet [Chadderton 1966], the "specific energy loss along the track" mechanism by Katz and Kobetich [Katz 1968], and the "restricted energy loss" mechanism by Benton and Nix [Benton 1969].

The latter two have been proposed to remedy the defect of the mechanism proposed by Fleischer et al. Doke [Doke 1969] commented his feeling to favor the mechanisms proposed by Katz et al. and Benton et al. rather than that proposed by Fleischer et al. Anyway, the method of heavy ion identification and energy determination by the etch pit methods is not so simple in principle and in application and should not be considered as a completed method without reservation.

A charged particle suffers inevitably deceleration in their passage from its origin to a detector by strong electromagnetic interaction with charged particles on the route in the target. Therefore, it is very difficult to identify the nuclear reaction causing the emission of the charged particle even if the existence of the nuclear reaction is confirmed.

2.2.3 Track Formation related to CR-39

We review the data of charged particles obtained extensively by CR-39 track detector in the cold fusion phenomenon (CFP) from about the year of 2000 in another paper presented at JCF13 [Kozima 2013]. In this section, we cite a recent remarkable paper on the CR-39 detector which shed a light on the discussion of the track formation.

Yamauchi et al. [Yamauchi 2005] investigated the chemical phase of track formation process by observation of CO_2 formation and scissions at ether bonds along nuclear tracks in CR-39. Their overview on the nuclear track formation process in CF-39 at present is summarized as follow:

(a) The parts between the two carbonate ester bonds should be segmented into small molecules, including CO_2 gases, along the particle trajectory;

(b) After the segmentation, the CO_2 gases were diffused away and a lower density region with chemically active end-points was formed simultaneously (the role of the other small molecules is unknown);

(c) Subsequent chemical modifications, including a reaction with dissolved oxygen, derived an OH group as new end-points in the polymer network.

This is surely one of steady steps to the determination of characteristics of the detector for identification of charged particles and determination of their energies.

Anyway, the method of heavy ion identification and energy determination by the etch pit methods depends sensitively on the target material and is not so simple in principle and in application and should not be considered as a completed method without reservation.

2.3 Etching of nuclear tracks does not give definite values of parameters of the incident particle

Etching of nuclear tracks in a target material is another process than the formation of latent nuclear tracks. In addition to the etching technique of latent tracks in a material, there is a fundamental problem about the mechanism of track formation as explained in Sec. 2.2. There are proposed several mechanisms for the formation of nuclear tracks in the target solids by incident heavy charged particles. Therefore, the analysis of the nuclear tracks in relation to the characteristics of the unknown incident particle is inevitably performed by analogy to a standard (or reference) track generated by known incident particles.

The etching process will give new data related to its formation process but give another problem than the formation of nuclear tracks. By using various etching techniques, we can obtain necessary information related to the mechanism that produced the nuclear tracks. If we know some factors of the incident particle out of the etched track, we can guess some unknown parameters related to the particle which produced the latent tracks. However, the latent nuclear tracks are results by complex interactions between the incident particle and the target and, therefore, the information we can get from the etched tracks is complex function of the parameters of the incident particle even if we know everything about the target. The information obtained from the latent tracks is inevitably qualitative and we have to rely on analogy between a calibration data (or reference) obtained by a known incident particle and experimental data registered by unknown particles which we want to identify.

2.3.1 Revealing nuclear tracks by etching

The observation of the nuclear tracks of fission fragment from uranium was made by Silk and Barnes on the mica films in 1959 [Silk 1959]. This experiment accelerated the use of nuclear tracks as a detector of charged particles in physics and astronomy.

Furthermore, the etch pit method developed by Price and Walker [Price 1962] made the observation of the nuclear tracks tractable with optical microscopes and the use of nuclear track detector prevailed to wider fields of researches including nuclear physics, nuclear chemistry, atomic power, cosmology, archeology etc.

2.3.2 Track-Diameter Kinetics in Dielectric Track Detectors [Somogyi 1973]

The diameters of the etched tracks are specifically sensitive to the parameters characteristic of the nuclear particles (the energy and the type of particle). The experimental methods based on the determination of the lengths (track-length method) and diameters (track-diameter method) of etch-pits can be regarded as natural complements of each other only when the etched tracks are completely determined throughout its length. Then, the track-diameter method is useful, in particular when track-length measurements give less reliable results, in the case of particles causing ionization energy losses near the so-called critical primary ionization $(\mathrm{d}J/\mathrm{d}x)_{\mathrm{c}}$, determining the detection limit [Somogyi 1973].

Concerning the track-length method several detailed theoretical and experimental works are available even if there are several assumptions about the mechanism of track formation. As is explained in Section 2.1, the mechanism of stopping power depends on the charge and the velocity (or the energy and the mass) of the incident particle and on the charge of target nucleus, and therefore the mechanism of track formation is too complex to be approximated by a specific assumption. We have to be cautious to apply the formulae obtained on rather simplified assumptions to a real situation too arbitrarily.

As Somogyi et al. have discussed [Somogyi 1973], the introduction of the parameters R_{c}, $V(x)$, the range R_0 and the angle θ is completely sufficient for the theoretical description of the most general details of track-diameter kinetics where R_{c} is the critical residual range along which the track etch rate ratio $V = V_{\mathrm{T}}/V_{\mathrm{B}} > 1$ is fulfilled (V_T and V_{B} are track and bulk etch rates, respectively), $V(x) = V_{\mathrm{T}}(x)/V_{\mathrm{B}}$ where $V_{\mathrm{T}}(x)$ is the track etch rate varying along the particle trajectory, R_0 is the etchable range of the solid detector from the original surface to the end of track, and θ is the incident angle measured from the original surface plane.

The function $V(x)$ is not definitely determined by experimental data and assumed rather arbitrary as the constant average value V of $V(x)$ for a shorter etched track portion of a length L defined as

$V^{-1} = (1/L) \int_0^L V(x)^{-1}\, \mathrm{d}x$.

In addition to introducing these parameters R_{c}, $V(x)$, R_0 and θ, some basic assumptions must be set up for isotropic and anisotropic solids separately to deduce relations describing etch-pit geometries and charged particle parameters.

Using these assumptions on the model of the latent tracks and etched tracks, Somogyi et al. deduced the relation between the etch-pit diameter and particle parameters for isotropic and anisotropic solids. Then, we can evaluate V, θ and R_0 from the experimentally measureable curves $d(h, \theta)$ and $D(h, \theta)$ using the theoretically obtained relations where $d(h, \theta)$ ($D(h, \theta)$) is the minor (major) axis d (D) of an etch-pit as a function of the surface removal h at an entrance angle θ.

Furthermore, it is necessary to make a standard (or reference) sample for comparison by irradiating know species of charged particles on the detector solid to evaluate V and θ distributions from tracks generated in the detector.

Thus, they have shown that the changes of the etch-pits revealed in dielectric track detectors through chemical etching can be described on the grounds of geometrical considerations and on some physically realistic basic assumptions. On the strength of this model, explicit relations and/or general methods can be given for the determination of the minor and major axes of the track pits in solids displaying isotropic and anisotropic etching properties.

If it is possible to determine the minor and major axes of the pit and the thickness of the layer removed from the detector surface accurately, we may be able to determine the values of the particle parameters inherent in the etch-pits as far as the conditions of the model satisfied. We have to be nervous to use the track-diameter method for identification of unknown charged particles in relation to the applicability of the model especially when there are several unknown particles to be identified.

2.3.3 Difficulty in Simultaneous Determination of Species and Energies of Incident Particles

Fleischer et al. say as follows [Fleischer 1965]:

"In short, widespread technical use is being made of defects whose real nature is relatively incompletely known. There are several levels on which we would like to develop our understanding of particle tracks.

Most of the existing work has taken its incentives from the desire to use tracks with more quantitative rigor, for example to identify individual particles and to measure their energies. Success here would lie in finding for each detector a precise function that relates etching rates to the velocity and nuclear species of the track-forming particle."

However, the track formation of the incident particle in the target solids is governed principally by the charge and the velocity (or the energy and the mass) of the incident particle and the charge of the target nucleus as shown in Sections 2.1.1 and 2.1.2. Therefore, the following condition expressed by Fleischer et al. is not easily satisfied experimentally even now: "- - - in finding for each detector a precise function that relates etching rates to the velocity and nuclear species (charge and mass) of the track-forming particle."

The recent work by Yamauchi et al. (cf. Sec. 2.2.3) [Yamauchi 2005] has shown clearly the difficulty in determination of the precise function that relates etching rates to the velocity and nuclear species of the track-forming particle. Therefore, we have to compare the tracks observed in the experiments with the standard (or reference) tracks obtained using a known particle and deduce our conclusion by analogy while we do not know the precise function. The conclusion thus deduced is not necessarily quantitative but qualitative. One of the most quantitative experiments we know at present is introduced in Section 3 where iron isotopes of known energy are discriminated their mass as precisely as 0.22 ± 0.03 amu in rms [Kodaira 2007]. So, we have to be similarly cautious to use the solid-state particle detector in the CFP quantitatively as the case of the mass resolution by Kodaira et al.

3. Application of Solid-State Track Detector to Several Problems

There are many applications of the solid-state track detector to problems where we want to know the energies and species of charged particles influencing target materials. We choose only two cases of these applications of CR-39 to show one for precision measurement with it and another used in the cold fusion phenomenon (CFP) where there are many difficulties due to the existence of several unknown particles with various possible energies.

3.1 **Identification of Heavy Ion Isotopes using CR-39:** An Example of Precision Measurement using CR-39 by Kodaira et al. [Kodaira 2007, 2008]

To determine chemical compositions of trans-iron nuclei ($Z \geq 30$) in galactic cosmic rays precisely, Kodaira et al. [Kodaira 2007, 2008] improved the accuracies of microscopic image analysis and detector thickness measurement of the CF-39 track detector to obtain the mass resolution for iron isotopes of 0.22 ± 0.03 amu in rms. To confirm this accuracy, they used ^{56}Fe and ^{55}Fe beams from the heavy ion accelerator HIMAC (Heavy Ion Medical Accelerator in Chiba) of the NIRS (National Institute of Radiological Sciences).

It is expected that the CR-39 detector will have better resolution of particle identification because the CR-39 detector essentially responds to only low-energy δ-rays (electrons emitted by the incident charged particle with energies enough for secondary ionization of atoms in the target) ejected by the “distant-collisions” in ionization energy loss [Benton 1969].

The range of a particle with a definite charge and velocity (energy) is proportional to tits mass. This is the principle we can determine the mass of charged particles

To improve the mass resolution of 0.28 ± 0.12 amu in rms for iron nuclei in the CR-39 detector, they improved their measuring system for 1) the “surface position” of the latent tracks (radiation damage trails) and 2) the “CR-39 sheet thickness.”

Improving their measuring apparatus for these two error causes, they obtained the mass resolution for iron isotopes in the CR-39 detector of 0.22 ± 0.03 amu in rms. It should be helpful to understand what the precision determination of parameters of an incident charged particle means by citation of essential parts of their experiment [Kodaira 2007]

A swift charged particle passing through the SSTD (solid-state track detector) leaves a radiation damage trail called a "latent track," that can appear by chemical etching in a suitable etchant. The etchant removes material in a very narrow region around the latent track at rate V_t, while it also removes material from undamaged regions at bulk etch rate V_b. As a consequence of chemical etching, a conical etch pit appears in the SSTD, as shown in Fig. 1 [Kodaira 2007].

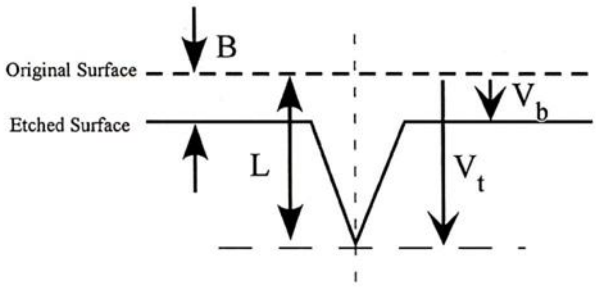

Fig. 3.1 Schematic cross-sectional view of etch pit geometry. An etch pit grows along the track with length L at etch rate V_t for the amount of bulk etch B at rate V_b [Kodaira 2007].

The track registration sensitivity (S) is defined as the ratio of etch rates ($V_t/V_b - 1$), and is thought to be a function of the restricted energy loss (REL) of the incident charged particle. REL is defined as the energy loss rate along the track core region near the particle trajectory. Namely, this criterion for track registration assumes that δ-rays with energies greater than the cut off-energy (ω_0) carry away their energy from the track core region and hence do not contribute to latent track formation. For the CR-39 detector, the cut-off energy (ω_0) has been considered to be 200 eV. By using the measurable parameters, that is the cone length (L) of the etch pit and amount of bulk etch (B), the track registration sensitivity (S) is obtained by

$S = (L/B) - 1.$

Here, L is a function of REL of the incident charged particle. The range of a particle with a definite charge and velocity is proportional to its mass. In this work, the mass of an incident charged particle is determined from the variation in the cone length (L) of the etch pit produced in the detector as a function of its residual range (R), as shown in Fig. 2 [Kodaira 2007], which shows the schematic drawing of the trajectory of stopping particles from the stopping layer (i = 0) to the upstream layers (i > 1) in a stack. In general, the so-called “L-R” technique in the SSTD is analogous to the $\Delta E - E$ technique in the Si detector telescope.

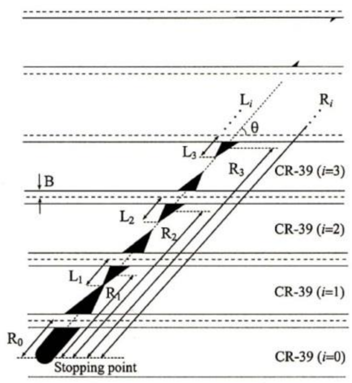

Fig. 3.2 Schematic drawing of etch pits produced in each CR-39 detector layer. Cone length (L_i) in the i-th layer is defined as the distance between the etched surface and the tip of the etch pit as shown in the figure. Residual range (R_i) is the distance from the stopping point in part of the spherical end to the center point of the cone length. In this work, only L_i produced in the upstream surface is measured [Kodaira 2007].

The incident angle θ is given by

$$\theta = \sin^{-1}\{(4B^2 + d^2)/[16D^2B^2 + (4B^2 - d^2)^2]\}$$

D and d denote the major and minor axes of the elliptical opening mouth of the etch pit on the detector surface, respectively, as shown in Fig. 4 and B is the amount of bulk etch as shown in Figs. 3.1, 3.2 and 3.3 [Kodaira 2007].

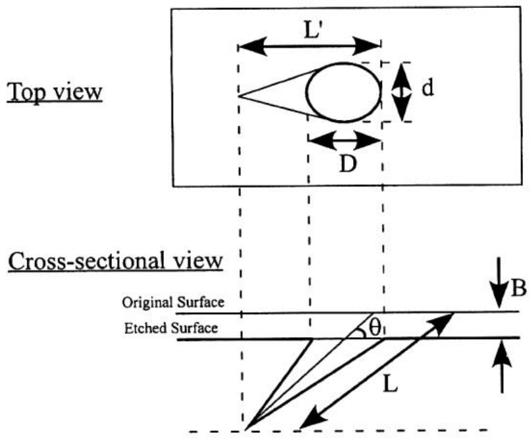

Fig. 3.3 Schematic drawing of geometrical structure of etch pit with incident angle θ [Kodaira 2007].

3.2 Identification of Charged Particles in the Cold Fusion Phenomenon (CFP)

We give here a short introduction of researches in the CFP using CR-39 to identify emitted charged particles from cold fusion (CF) materials composed of mainly transition metals and hydrogen isotopes. Details of the use of CR-39 detector in the CFP will be discussed in another paper presented at JCF13 and published in *Proc. JCF13* [Kozima 2013].

The first use of a plastic track detector CR-39 in the cold fusion research was performed by Chinese scientists [Li 1991] in the early days of cold fusion research after the discovery of the "cold fusion" by Fleischmann et al. [Fleischmann 1989]. In these researches, they have confirmed the nuclear nature of curious events related to extravagant excess energy and unbelievable generation of new nuclides occurring in cold fusion materials composed of transition metals and hydrogen isotopes.

After an interval of about ten years, there is a revival of the use of CR-39 in the cold fusion research to identify charged particles emitted from CF materials. Several of excellent works with CR-39 detector were reported by Mosier-Boss et al. [Mosier-Boss 2009] to confirm energetic neutrons emitted from a Pd/D co-deposition sample and Aizawa et al. [Aizawa 2012] to show two kinds of charged particles from NiD_x and NiH_x ($x < 1.0$) samples in electrolytic systems $Ni/Li_2SO_4 + D_2O$ (H_2O)/Pt and Ni/LiOH + D_2O (H_2O)/Pt. Other experiments with CR-39 performed to detect charged particles in the CFP be given in the paper given in JCF13 and published in *Proc. JCF13* [Kozima 2013].

4. Conclusion

In the long investigation of the cold fusion phenomenon (CFP) since 1989, we have tried to make clear the nuclear feature of the various events observed in CF materials mainly composed of transition metals (and carbon compounds) and hydrogen isotopes. The enormous amount of excess energy inexplicable with chemical reactions and generation of neutron, proton, tritium, alpha and transmuted nuclei with atomic numbers up to 92 are evidences showing the nuclear character of reactions occurring in the CF materials. It has been eager desire to detect charged particles with large energies of the order of several MeV emitted from CF materials which give also a decisive evidence of the nuclear nature of reactions in the CFP.

The solid-state nuclear track detectors, especially CR-39 used frequently recent years in this field, will be powerful tools to give us the above mentioned evidence to support our premise that the various events in the CFP are induced by some kind of nuclear reactions occurring in the CF materials at near room temperature without any artificial acceleration mechanism.

The detection of charged particles in the CFP is characterized by following points: (1) proximity of the source of charged particles to the detector and necessarily therefore a large variety of incident angles in the case of experiments at ordinary ambient conditions, (2) a variety of particles from proton, deuteron, triton, ${}^{3}_{2}He$ and ${}^{4}_{2}He$ expected by presumed nuclear reactions to unexpected ones, (3) necessity to discriminate species of charged particles incident to the detector and to determine their energies simultaneously, and accordingly (4) necessity to discriminate two kinds of particles, one generated by nuclear reactions and another accelerated by the former.

It is necessary to use the solid-state track detectors carefully to give persuasive data for people who are not necessarily favorable for the existence of the CFP. To do so, the careful use of the CR-39 detector given by Kodaira et al. in the determination of iron isotopes introduced in Section 3 is suggestive [Kodaira 2007]. We have to remember the fundamental nature of the radiation damage in solids by incident charged particles and characteristics of complex processes from latent track formation to the visualization of latent tracks by chemical etching.

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References

[Aizawa 2012] H. Aizawa, K. Mita, D. Mizukami, H. Uno and H. Yamada, "Detecting Energetic Charged Particle in D_2O and H_2O Electrolysis Using a Simple Arrangement of Cathode and CR-39," *Preprint of the ICCF-17 Proceedings*, P-1050.

[Benton 1969] E.V. Benton and W.D. Nix, "The Restricted Energy Loss Criterion for Registration of Charged Particles in Plastics," *Nucl. Instr. Meth.* **67**, 343 – 347 (1969).

[Bohr 1948] N. Bohr, Kgl. Danske Viennskab. Selskab. Matt.-Fys. Medd. 18, No.8 (1948).

[Chadderton 1966] L.T. Chadderton, D.V. Morgan, I.McC. Torrens and D. Van Vliet, "On the Electron Microscopy of Fission Fragment Damage," *Phil. Mag*. **13**, 185 – 195 (1966).

[Doke 1969] T. Doke, "Mechanisms of Trajectory Formation in Solid Track Detectors," (in Japanese), *Oyo Butsuri* (Applied Physics) **38**, pp. 1065 – 1076 (1969). UDC 539.1.073

[Doke 1970] T. Doke, "Stopping Powers of Gases and Solids for Heavy Charged Particles," *Oyo Butsuri*, **49**, 1086 – 1100 (1970). (in Japanese)

[Firsov 1959] O.B. Firsov, J.E.T.P., 36, 1076 (1959)

[Fleischer 1965] R.L. Fleischer, P.B. Price and R.M. Walker, "Ion Explosion Spike Mechanism for Formation of Charged-Particle Tracks in Solids," *J. Appl. Phys.* 36, pp. 3645 – 3652 (1965)

[Fleischer 1975] R.L. Fleischer, P.B. Price and R.M. Walker, *Nuclear Tracks in Solids*, University of California Press, 1975. ISBN 0-520-02665-9

[Fleischmann 1989] M. Fleischmann, S. Pons and M. Hawkins, "Electrochemically induced Nuclear Fusion of Deuterium," *J. Electroanal. Chem*., **261**, 301 – 308 (1989).

[Katz 1968] R. Katz and E.J. Kobetich, "Formation of Etchable Tracks in Dielectrics," *Phys. Rev*. **170,** 401 – 405 (1968).

[Kodaira 2007] S. Kodaira, N. Yasuda, N. Hasebe et al., "Improvement of Mass Resolution for Iron Isotopes in CR-39 Track Detector," *Jpn. J. Appl. Physics*, 46, pp. 5281 – 5287 (2007).

[Kodaira 2008] S. Kodaira, "Identification of Heavy-Ion Isotopes using CR-39 Solid-State Track Detector," *Oyo Butsuri* (*Applied Physics*), 77, pp. 36 – 40 (2008). (In Japanese)

[Kozima 2013] H. Kozima and M. Tada, "Emission of Charged Particles in the Cold Fusion Phenomenon," *Proc. JCF13* (Dec. 8 – 9, 2012, Nagoya, Japan), pp. 76 – 107 (2013). http://jcfrs.org/file/jcf13-proceedings.pdf
And also *Reports of CFRL* **13-2**, pp. 1 – 32 (2013).
http://www.geocities.jp/hjrfq930/Papers/paperr/paperr.html

[Li 1991] X.Z. Li, "Chinese Effort in Understanding the 'Cold Fusion' Phenomena," *Proc. ICCF2*, pp. 309 – 317 (1991). And also his private communication in the year of 2012.

[Lindhard 1963] J. Lindhard, M. Scharff and H.E. Schioff, *Danske Viennskab. Selskab. Matt.-Fys. Medd.* 33, No.14 (1963)

[Merkle 1962] K.L. Merkle, "Fission-fragment Tracks in Metal and Oxide Films," *Phys. Rev. Lett*. **9,** 150 – 152 (1962).

[Mosier-Boss 2009] P.A. Mosier-Boss, S. Szpak, F.E. Gordon, and L.P.G. Forsley, **"**Triple Tracks in CR-39 as the Result of Pd/D Co-deposition: Evidence of Energetic Neutrons," *Naturwissenschaften*, **96** (2009) 135-142.

[Price 1962a] P.B. Price and R.M. Walker, "Electron Microscope Observation of Etched Tracks from Spallation Recoils in Mica," *Phys. Rev. Lett.* 3, 217 – 219 (1962).

[Price 1962b] P.B. Price and R.M. Walker, "Chemical Etching of Charged Particle Tracks in Solids," *J. Appl. Phys*. 33, 3407 – 3412 (1962)

[Price 1962c] P.B. Price and R.M. Walker, "A New Track Detector for Heavy Particle

Studies," *Phys. Lett.* 3, 113 – 115 (1962).
[Sauter 1965] C.A. Sauter and E.J. Zimmerman, *Phys. Rev*. 140, A490 – A498 (1965).
[Silk 1959] E.C.H. Silk and R.S. Barnes, "Examination of Fission Fragment Tracks with an Electron Microscope," *Phil. Mag*. **4**, 970 – 972 (1959).
[Somogyi 1973] G. Somogyi and S.A. Szalay, "Track-Diameter Kinetics in Dielectric Track Detectors," *Nucl. Instr. Meth.*, 109, 211 – 232 (1973).
[Yamauchi 2005] T. Yamauchi, R. Barillon, E. Balanzat, T. Asuka, K. Izumi, T. Masutani, and K. Oda, "Yields of CO_2 Formation and Scissions at Ether Bonds along Nuclear Tracks in CR-39," *Radiat. Meas.* 40, 224 – 228 (2005).