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# Identification Model of Space Heavy Ions by CR-39 *

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**Abstract** A mathematical model $LET = cZ^dR^b$ for identifying space heavy ions is established based on energy loss rate of the heavy ions in CR-39. Coefficients of the model are acquired through correlative curves between linear energy transfer and residual range. Another relation $V_T = A \cdot (REL)^B_{E<350}$ between etched rate of CR-39 and restricted linear energy transfer of the ions, which is experimentally found, is used to connect the mathematical model for getting an equation $R = A0.0455\ Z^{3.18} V_T^{-1}$. Finally, an identification formula $Z^{3.18} = 64541.08 + 2.53\ (\mathrm{d}R/\mathrm{d}V_T^{-1})$ is obtained by means of calibration experiments.

**Key words** space heavy ion, identification, CR-39

## 1 Introduction

To ascertain the role of space heavy ions in mutation breeding and to find correlation between mutation type and ion parameter (kind, energy, hit number and hit site), it is necessary to set up a "sandwich" detection system. The system consisted of rice seeds and CR-39 (Diethyleneglycol-bis-allyl-carbonate, $H_{18}C_{12}O_7$) solid-state nuclear track detectors. CR-39 sheets can record tracks of energetic heavy ions in space (mainly from C to Fe ions). According to positions and parameters of the tracks, sites in the seeds hit by the heavy ions can be localized and type of the ions can be identified.

On the other hand, the rice seeds were cultivated in the fields and their variation was examined. Through correlation between mutagenic seed and hit seed, the role of space heavy ions in space breeding could be displayed.

## 2 Mathematical model

It is well known that the total energy loss rate of ion in medium can be formulated as follows[1],

$$(-\mathrm{d}E/\mathrm{d}x)_\infty = (C_1 Z^{*2}/\beta^2)\cdot[\ln(W_{\max}^2/I^2) - 2\beta^2 - \delta - U]. \quad (1)$$

Generally, the energy loss rate of ion $(-\mathrm{d}E/\mathrm{d}x)$ can also be called linear energy transfer ($LET$).

In Equation (1), $C_1 = 2\pi n_e e^4/mc^2$, where, $n_e$: electron number in unit volume, $e$: electron charge, $m$: electron mass, $c$: light velocity. $Z^* = Z[1-\exp(-125\beta Z^{-2/3})]$, where, $Z^*$: effective charge of ion, $Z$: atomic number of ion, $\beta = v/c$: relative velocity of ion, $v$: ion velocity. $W_{\max} = 2mv^2/(1-\beta^2)$, maximum kinetic energy of secondary electron. $I$: average ionization potential of detector. $\delta$: correction of polarization effect of medium under velocity of relativity. $U$: shell correction at low velocity.

Experimentally, etched situation in solid-state nuclear track detector correlates with restricted energy loss rate of ion $(REL)_{E<E_0}$. Eq.(1) should be expressed as

$$(-\mathrm{d}E/\mathrm{d}x)_{E<E_0} = (REL)_{E<E_0} = (C_1 Z^{*2}/\beta^2)\cdot[\ln(W_{\max}E_0/I^2) - \beta^2 - \delta - U]. \quad (2)$$

Where, $E_0$: cutoff energy of $\delta$ rays. In most experiments, its optimum value is 350 eV.

After combining Equations (1) and (2),

$$(REL)_{E<E_0} = (LET)_\infty + C_1 Z^{*2} + C_1 Z^{*2}\ln(E_0/W_{\max})/\beta^2 = (LET)_\infty - Q. \quad (3)$$

Therefore, $(REL)_{E<E_0}$ depends on relative velocity $\beta$ and effective charges $Z^*$ of ion, i.e., energy $E$ and atomic

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number $Z$ due to $\beta = \sqrt{(E^2 - M_0^2c^4)/E}$ and $Z^* = Z[1 - \exp(-125\beta Z^{-2/3})]$. Their relation will be

$$(REL)_{E<350} = f(\beta, Z^*) = f(E, Z). \quad (4)$$

Based on correlation between ion energy $E$ and its range $R$, thus, we suppose the above function as

$$(REL)_{E<350} = cZ^dR^b \quad (5)$$

and

$$cZ^d \equiv a, \quad (6)$$

then

$$(REL)_{E<350} = aR^b. \quad (7)$$

The coefficients $a$, $b$, $c$ and $d$ will be fixed with mathematical fit method.

### 2.1 Coefficient fit

At first, we can acquire the coefficients a and b through correlation curves between $(LET)_\infty$ and $R$. (At present, we temporarily employ $(LET)_\infty$ to substitute for $(REL)_{E<350}$ because the latter has not yet been got.) Here, six kinds of ions (C, O, Ne, Si, Ar and Fe ions) are selected to make the correlation curves between $(LET)_\infty$ and R in CR-39 (see Fig.1 for $^{12}C$ as an example) because of their larger abundance than other ions in cosmic space. 3 or more points were taken from straight line in falling part of above each curve, where energy of the ions is higher as in space. The 6 sets of data of $(LET)_\infty$ and $R$ were acquired. Thus, the coefficients a and b can be obtained through fitting Eq.(7) such as in Fig.2 and are shown in Table 1.

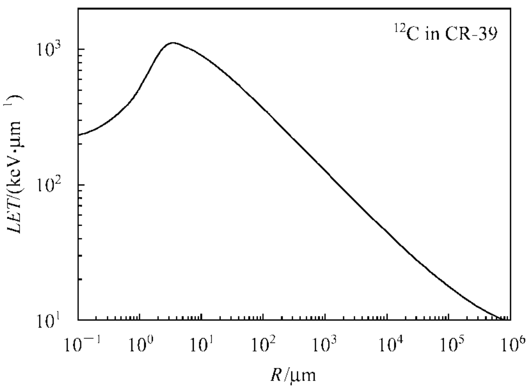


Fig.1. Correlation curves between $(LET)_\infty$ and $R$ for $^{12}C$ ion in CR-39.

**Table 1. Fitted coefficients $a$ and $b$ with Eq.(7).**

| Ion kind | C | O | Ne | Si | Ar | Fe |
|---|---|---|---|---|---|---|
| $Z$ | 6 | 8 | 10 | 14 | 18 | 26 |
| $a$ | 2.9785 | 4.5633 | 6.4148 | 11.0191 | 15.6076 | 25.6137 |
| $b$ | −0.4563 | −0.4522 | −0.4508 | −0.4531 | −0.4406 | −0.4314 |

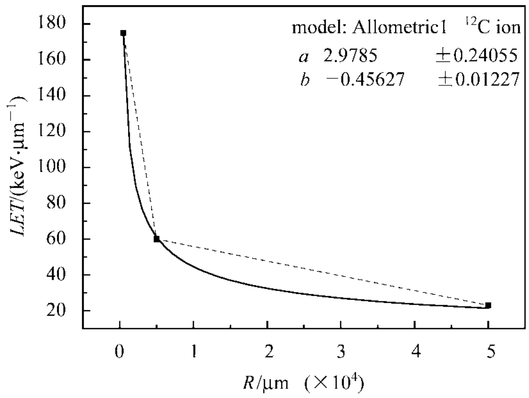


Fig.2. Fitted coefficients $a$ and $b$ for $^{12}C$ ion in CR-39.

It is seen in Table 1 that $b$ values of different ions are very similar each other. Their mean value is −0.4474.

Next, the coefficients $c$ and $d$ can be obtained with known $Z$ and $a$ value in Table 1 by fitting Eq.(6). The fitted results were $c = 0.25$ and $d = 1.42$ as shown in Fig.3.

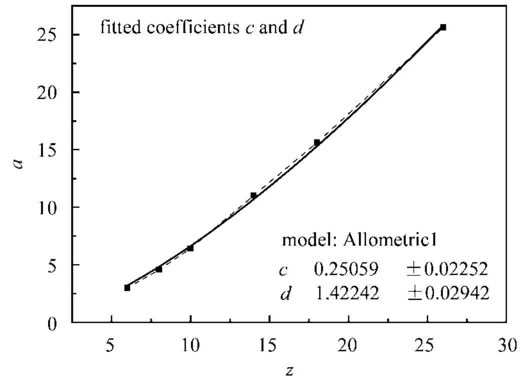


Fig.3. Fitted coefficients $c$ and $d$ in CR-39 for C, O, Ne, Si, Ar and Fe ions.

On the other hand, it was experimentally found[2] that the track etch rate ($V_T$) can also be represented as a power function of $(REL)_{E<350}$ as follows,

$$V_T = A\cdot(REL)^B_{E<350}. \quad (8)$$

Substituting Eq.(5) for $(REL)_{E<350}$ of Eq.(8), it becomes

$$V_T = A\cdot(cZ^dR^b)^B = Ac^B\cdot Z^{dB}\cdot R^{bB}. \quad (9)$$

For simplification, we assign $bB \equiv -1$.

Thus, $B = 2.235$ because of $b = -0.4474$ and the Eq.(9) becomes as follows due to $c = 0.25$ and $d = 1.42$,

$$V_T = A\cdot(0.25Z^{1.42}R^{-0.4474})^{2.235} = A0.0455Z^{3.18}/R. \quad (10)$$

Rewriting it,

$$R = A0.0455\ Z^{3.18}V_T^{-1}. \quad (11)$$

Taking derivative to two sides of Eq.(11), it becomes

$$Z^{3.18} = (1/A0.0455)\mathrm{d}R/\mathrm{d}V_T^{-1}. \qquad (12)$$

## 2.2 Calibration experiments

Track etch rate, $V_T$, of each sheet and its corresponding residual range $R$ for different known ion $Z$ can be measured (Table 2). Thus, the Eq.(11) can be fitted with $R$ in ordinate and with $V_T^{-1}$ in abscissa as in following Figs.4, 5 and 6. Slopes ($\mathrm{d}R/\mathrm{d}V_T^{-1}$) in the figures are got. So, a calibration curve can be drawn with known $Z^{3.18}$ in ordinate and slope ($\mathrm{d}R/\mathrm{d}V_T^{-1}$) in abscissa as shown in Fig.7. In this case a preliminary fitted formula is obtained as follows,

$$Z^{3.18} = 64541.08 + 2.53(\mathrm{d}R/\mathrm{d}V_T^{-1}). \qquad (13)$$

When more slopes are obtained, the calibration curve and its fitted formula will become more accurate.

In the above course, absolute residual range cannot be measured due to the ions with high energy penetrating through the detection system. However, relative residual range $R$ to a certain reference surface can be acquired after taking any surface of CR-39 (such as the bottom of the detection system) as a reference one.

**Table 2. $\mathrm{d}R/\mathrm{d}V_T^{-1}$ of 3 known ions in calibration experiments.**

| Ion kind | C | O | Ne | Si | Ar | Fe |
|---|---|---|---|---|---|---|
| $Z$ | 6 | 8 | 10 | 14 | 18 | 26 |
| $Z^{3.18}$ | 297.68 | 742.89 | 1510.08 | 4400.90 | 9783.88 | 31492.00 |
| $\mathrm{d}R/\mathrm{d}V_T^{-1}$ | −26293 | | | −22440 | | −13447 |

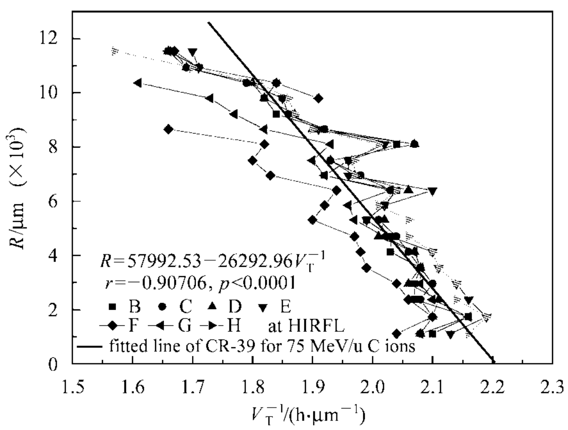


Fig.4. Fitted line of CR-39 for 75 MeV/u $^{12}C$ ions at HIRFL.

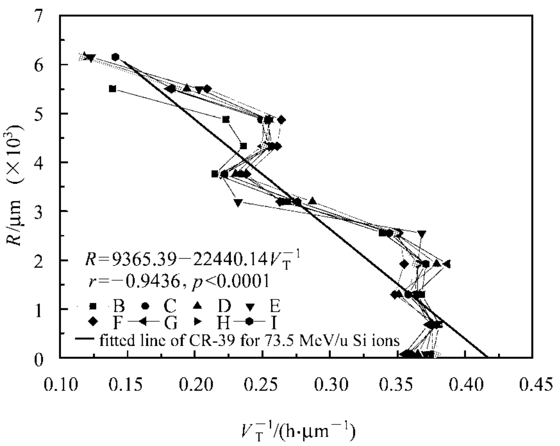


Fig.5. Fitted line of CR-39 for 73.5 MeV/u $^{28}Si$ ions at HIMAC.

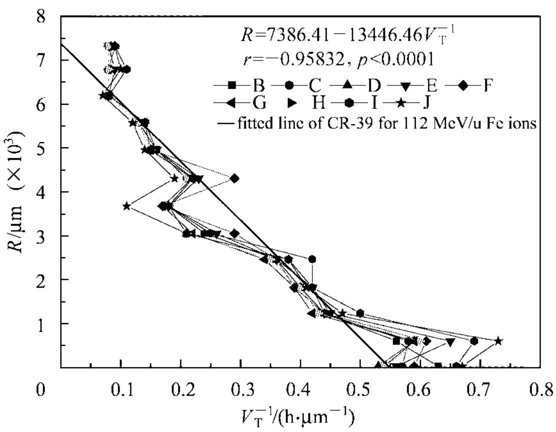


Fig.6. Fitted line of CR-39 for 112 MeV/u $^{56}Fe$ ions at HIMAC.

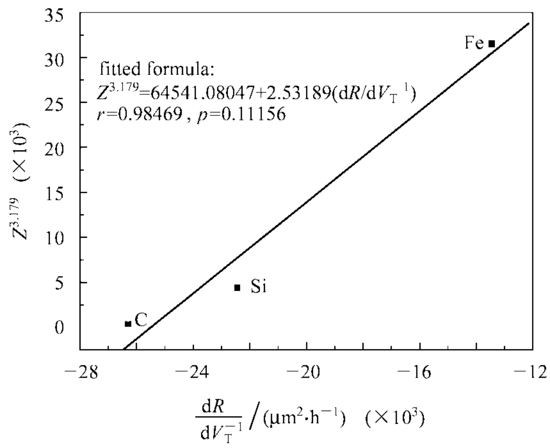


Fig.7. Calibration curve of CR-39 for C(at HIRFL, Nov.1999), Si(at HIMAC, Nov.2003) and Fe(at HIMAC, Nov.2003) ions.

## 3 Identification of heavy ions

$V_T$ of CR-39 from a space detection system and corresponding residual range $R$ to $V_T$ can be measured. We can just draw a figure for unknown $Z$ with the reciprocal of measured $V_T$ in abscissa and with the corresponding residual range $R$ to $V_T$ in ordinate, and its slope ($dR/dV_T^{-1}$) can be obtained. Thus, $Z$ can be determined from above calibration curve in Fig.7 based on the measured slope ($dR/dV_T^{-1}$), i.e., the ion is identified.

## 4 Determination of ion energy

Based on the fitted Eq.(13), the coefficient A equals 8.69. For the each set of measured CR-39 sheets, the smallest $V_T$ corresponding to ion incident sheet (in the 1st or the last sheet) can be found. Then, based on the Eq.(8), *LET* can be calculated with the determined coefficient $A$, $B$ and the smallest $V_T$. Based on the identified ion ($Z$), the energy of the ion (from C to Fe) can be determined in the correlative curve of *LET* with energy $E$.


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# 用 CR-39 对空间重离子的鉴别模型*


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**摘要** 根据重离子在CR-39中能量损失率公式,建立了一个鉴别空间重离子的数学模型 $LET = cZ^dR^b$.通过传能线密度与剩余射程之间的关系曲线,获得了该模型的系数.在实验中发现的CR-39蚀刻率与离子有限传能线密度的关系 $V_T = A\cdot(REL)^B_{E<350}$,被用来与该数学模型相关联,并得到一等式 $R = A0.0455Z^{3.18}V_T^{-1}$.最终,借助于标定实验得到了离子鉴别公式 $Z^{3.18} = 64541.08 + 2.53(dR/dV_T^{-1})$.



**关键词** 空间重离子 鉴别 CR-39



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