The conversion factor of K_{eff} to $K_{3.7}$ in thermoluminescence dating

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Abstract In the fine-grain TL dating the full α dose must be converted into the equivalent β dose. The conversion is finished by K_{eff}-value, which is an effective α effectiveness. But the K_{eff} can not be measured directly for each sample and only the external radiative efficiency $K_{3.7}$ can be measured. In order to obtain the K_{eff} a special study for the conversion factor of K_{eff} to $K_{3.7}$ has been made using the ultrathin TLD. The results show that the conversion factor of the TLD for archaeological samples is 0.847, which is in agreement with calculated value 0.85.

Keywords TL dating, Alpha efficiency, K_{eff}, $K_{3.7}$, Conversion factor

1 α-effectiveness for an external radiation

It is important in fine-grain TL dating that full α dose must be converted into equivalent β dose. The conversion is finished by K-value, that is the α effectiveness for thick source (or for internal radiation). Zimmerman[1] gave a definition for K-value: K-value equals TL per unit dose for 3.7 MeV α particles divided by TL per unit dose for β irradiation, and it is directed against quartz. In fact, this is $K_{3.7}$ that is an α effectiveness for external radiation (or for thin source). The internal radiation effectiveness K_{eff} can not be measured directly for each sample, we can measure only the external radiation effectiveness for certain α energy. Even so, the obtaining of $K_{3.7}$-value still is very difficult because it is essential that the energy of α particles irradiated on sample must be 3.7 MeV. Therefore, Aitken[2] have developed an "a-value system". In this system the source strength of α source is calibrated by "s". The s is density of track in sample per unit time, that is the total length of track of α particles in per unit volume of sample per unit time, expressed in $(\mu m/\mu m^3)$/min i.e. μm^{-2}/min. After s-value is determined for an α source the absorbed dose per unit time for variant irradiated samples can be calculated whether the α energy is 3.7 MeV or not. If irradiated sample is quartz and energy of α particles is 3.7 MeV, then

$$\text{absorbed dose rate for quartz} = (0.221 \times s \times 1.6 \times 10^2)/2.6 = 13.6s(\text{Gy/min}) \quad (1)$$

where $0.221(\text{MeV}/\mu\text{m})$ is a rate of energy loss in quartz for 3.7 MeV α particles, it is equal to $0.85(\text{MeV}\cdot\text{cm}^2/\text{mg})\times 2.6(\text{g/cm}^3)$. The $0.85(\text{MeV}\cdot\text{cm}^2/\text{mg})$ is stopping power of quartz for α particles of 3.7 MeV, and $2.6(\text{g/cm}^3)$ is density of quartz. The 1.6×10^2 is conversion factor for unit. If irradiated sample is $CaSO_4$ and the α energy is the same above,

$$\text{absorbed dose rate for } CaSO_4 = 12.8s(\text{Gy/min})$$

and so on. The dose rate in samples other than quartz can also be obtained only if 13.6 s is multiplied by the stopping power ratio between the sample and quartz. Hence, the α effectiveness for variant samples and 3.7 MeV α particle can be obtained by using the calculated absorbed dose rate in the sample.

2 Effective (or internal radiation) α-effectiveness

The a-value measured according to the method mentioned above is obtained by an ar-

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tificial α source (thin source), hence it is an effectiveness for external radiation. But the natural Th and U in sample is actually a "thick α source", the energy of α particles is from zero to the most (7.7 MeV), and its average energy is less than 3.7 MeV, hence the actual effectiveness i.e. effective α effectiveness K_{eff} is lower than $K_{3.7}$. Zimmerman has reported the conversion factor of K_{eff} to $K_{3.7}$ for three samples (see Table 1).[1] For the thorium series the conversion factor $K_{\text{eff}}/K_{3.7}$=0.86, and for uranium series the factor is 0.80 for Norway quartz, so that for equal activity of the two series the factor is 0.83, average of the factor used by Zimmerman for the three samples is 0.85, because the fine grain samples are not simple quartz, and are poly-mineral. Hence, the relation of K_{eff}-value to the a-value is

$$K_{\text{eff}} = 0.85a = 0.85K_{3.7} \tag{2}$$

Table 1 TL effectiveness comparison between the α particles in collision with fine-grains in pottery and the α particles from 3.7 MeV[1]

	$K_{\text{eff}}/K^{*}_{3.7}$	
	U	Th
Natural fluorite	0.85	0.93
$CaSO_4$:Mn	0.81	0.85
Norway quartz	0.80	0.86

* Zimmerman used the symbol ϵ(eff) and ϵ(3.7 MeV) in the place of K_{eff} and $K_{3.7}$, respectively

Afterwards, the factor has been not required by Aitken in the derivation of annual dose for the thick source α counting. The full annual α dose D_α is calculated by Aitken on the basis of total energy for 6 α particles in Th series and 8 α particles in U series. When the sample contains equal activities of Th and U the full annual α dose D_α (mGy/a) is

$$D_\alpha = 1.560\alpha \tag{3}$$

where α is α count-rate for a thick sample on a scintillator of diameter 42 mm and an electronic threshold factor of 0.835. When a phosphor is irradiated by natural U and Th within the sample the effective annual α dose D'_α (mGy/a) is

$$D'_\alpha = 1.280a\alpha \tag{4}$$

then the effective α effectiveness K_{eff} is equal to the effective annual α dose divided by the full annual α dose,

$$K_{\text{eff}} = D'_\alpha/D_\alpha = (1.280a\alpha)/(1.560\alpha) = 0.82a \tag{5}$$

and then

$$K_{\text{eff}}/a = K_{\text{eff}}/K_{3.7} = 0.82 \tag{6}$$

This factor is less than the Zimmerman's calculation. Maybe due to a mistake in stopping power is taken by Aitken. The stopping power of quartz for a 3.7 MeV α particle is 0.85 MeV·cm^2/mg.[2] If we insert a stopping power of 0.81 MeV·cm^2/mg (for 4 MeV α particle) into Eq.(1), the absorbed dose-rate for quartz=$(0.81\times2.6\times s\times1.6\times10)/2.6=13\,s$(Gy/min), according to 13s, the numerical factor in Eq.(4) is "1.280". After correcting the mistake the numerical factor in Eq.(4) becomes "1.334", i.e.

$$\begin{aligned} D_\alpha &= [(13.6a\times0.90\times4\alpha)/(13.85\times0.835)]\times10^{-8} \\ &= 4.23a\alpha\times10^{-8}(\text{mGy/s}) \\ &= 1.334a\alpha(\text{mGy/a}) \end{aligned} \tag{7}$$

where 0.90 is a ratio of TL per unit track length for an internal α radiation to that for external, it is an average value for 10 samples and the ratio of each sample was obtained by Bowman[2], 13.85(cm^2) is the area of the scintillator and 0.835 is an electronic threshold factor in thick source α counting. Hence

$$K_{\text{eff}} = (1.334a\alpha)/(1.560\alpha) = 0.85a$$

and so

$$K_{\text{eff}}/a = K_{\text{eff}}/K_{3.7} = 0.855$$

This result is in agreement with Zimmerman's, and it is just suitable for the polymineralic samples, because the 0.90 is an average value for 10 samples.

3 Direct measurement of the conversion factor

Zimmerman and Aitken obtained the conversion factor in theory, we measured the factor using the ultrathin thermoluminescence dosimeter (TLD), which is made of that the fine-grains (3-8μm diameter) of $CaSO_4$:Tm glued onto 10 μm thick aluminium foil, and the layer of $CaSO_4$:Tm on the foil is of about a few microns (corresponding to 1 mg/cm^2).

First, the external α effectiveness for TLD, i.e. $K_{3.7\,TLD}$, is measured. Taking a TLD is irradiated by an alpha source of ^{241}Am and then the TL is measured. The alpha absorbed dose in the TLD is calculated by 12.8 s Gy/min. At the end of the TL measurement,a beta dose is administered to the same TLD using a ^{90}Sr source, and then measure the TL again. The alpha efficiency of the TLD for an energy of 3.7 MeV is given by (TL per unit alpha dose for 3.7 MeV)/(TL per unit beta dose). Hence the $K_{3.7\,TLD}$=0.323 for 1 mg/cm^2 $CaSO_4$:Tm is obtained precisely. Second, the internal α effectiveness for TLD, $K_{eff\,TLD}$, is also measured. According to Eq.(5),

$$K_{eff\,TLD} = D'_{\alpha\,TLD}/D_\alpha \tag{8}$$

where $D'_{\alpha\,TLD}$ is effective annual α dose for TLD, and D_α is full annual α dose measured by the thick source α counting.

The measurement of internal effective α dose-rate and β dose-rate in powdered sample has been reported.[3,4] To obtain the α dose, the TLDs of two groups A and B are embedded in a glass container with powdered sample in the same time. The TLDs of the group B have been shielded on both sides by 8 mg/cm^2 thick polyethylene, so none of α particles reach the TLD. The TLDs of group A have been shielded only on aluminium foil by the same thick polyethylene, let phosphors in direct contact with the sample, so half of α particles can reach the TLD. Then the β dose-rate in 4π geometry is obtained by TLD of group B, α dose-rate in 2π is obtained by group A, and the effective annual α dose $D'_{\alpha\,TLD}$ is equal to doubling the difference of dose-rate between groups A and B. Finaly, we obtain

$$\text{Conversion factor of } K_{eff} \text{ to } K_{3.7} = K_{eff\,TLD}/K_{3.7\,TLD} = K_{eff\,TLD}/0.323 \tag{9}$$

Table 2 gives the conversion factor of TLD within the archaeological sample (pottery, brick

Table 2 Measurement of conversion factor for TLD within the archaeological samples

Lab.No.	$D'_{\alpha\,TLD}$/mGya^{-1} (TLD)	D_α/mGya^{-1} (α counting)	$K_{eff\,TLD}$	Conversion factor ($K_{3.7\,TLD}$ = 0.323)
SB98	3.20	12.30	0.260	0.805
SB110	4.72	17.16	0.275	0.852
SB111	3.36	11.86	0.283	0.915
SB112	4.31	16.07	0.268	0.830
SB125	3.84	14.82	0.259	0.802
SB210	5.04	17.92	0.281	0.870
SB220	4.24	14.80	0.286	0.887
SB235	4.36	16.77	0.260	0.805
SB236	8.60	35.15	0.245	0.757
SB405	5.06	16.40	0.309	0.955
SB406	3.34	13.31	0.251	0.777
SB408	4.26	14.18	0.300	0.930
SB409	5.44	20.76	0.262	0.811
SB410	4.88	18.14	0.269	0.833
SB412	4.88	16.07	0.304	0.940
SB416	5.46	21.59	0.253	0.783
Average			0.273	0.847

and tile). The average value of the factor is 0.847, this result is in agreement with Zimmerman[1] and Aitken.[2] The factor is suitable for quartz because it is about the same in quartz and $CaSO_4$ whether for U or Th (based on data reported by Zimmerman[1]). In Table 2, the factor is different in each sample, it is from different Th/U ratio in the sample and the measured errors in K_{TLD} including both the TLD method and the α counting. In addition, the average value in $K_{eff\,TLD}$, 0.273, is also given in Table 2. This value is less than the reported previously[4], the difference is related to Th/U ratio in the sample.

This factor can be reduced in the determination of the effective annual α dose using ultrathin TLD. The full annual α dose in TLD, $D_{\alpha\,\mathrm{TLD}}$, is

$$D_{\alpha\,\mathrm{TLD}} = D'_{\alpha\,\mathrm{TLD}}/K_{\mathrm{eff\,TLD}}$$
$$= D'_{\alpha\,\mathrm{TLD}}/0.85K_{3.7\,\mathrm{TLD}}$$

Hence the effective annual α dose in the sample, D'_{α} is given by

$$D'_{\alpha} = D_{\alpha\,\mathrm{TLD}} \times K_{\mathrm{eff}}$$
$$= D_{\alpha\,\mathrm{TLD}} \times 0.85a$$
$$= (D'_{\alpha\,\mathrm{TLD}}/0.85K_{3.7\,\mathrm{TLD}}) \times 0.85a$$
$$= D'_{\alpha\,\mathrm{TLD}}(a/K_{3.7\,\mathrm{TLD}})$$
$$= D'_{\alpha\,\mathrm{TLD}}(a/0.323) \quad (10)$$

The Eq.(10) gives the relationship of D'_{α} to $D'_{\alpha\,\mathrm{TLD}}$ in ultrathin TLD method and shows that the effective α dose-rate in the sample will be the effective α dose-rate in the TLD multiplied by the efficiency ratio between the sample and the TLD for an external α radiation of 3.7 MeV energy. In this equation, the TLD's α efficiency for an external α radiation, $K_{3.7\,\mathrm{TLD}}$, is a constant (equals 0.323) and the conversion factor is inexistent, therefore we can obtain the sample's effective α dose-rate so long as we measure the sample's α efficiency for an external α radiation and the effective α dose-rate in the TLD.

It is explained that the $K_{3.7}$ is related to the a-value system (developed by Aitken, 1985), for quartz $a = K_{3.7}$, for other samples $a = rK_{3.7}$, and where r is the stopping power ratio between the sample and quartz (Aitken, 1985). After the α source strength "s" has been calibrated we can obtain the a-value for the sample irradiated by the α source, and the a-value can insert directly into the age equation. Alternatively, if the full α dose rate has been obtained by some method other than α counting, the effective α efficiency of the sample, K_{eff}, should equals to a-value times 0.85 if the Th/U ratio in unknown and equal activities are assumed in the archaeological samples.

References

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