Beta dose attenuation in thin layers

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In attempting to date tooth enamel or thin mollusc shells by ESR or TL the beta-ray contribution from the surroundings may be the decisive factor in calculating the annual dose. Normally, the alpha-ray penetrated surface (up to 20µm) of a sample can be removed by etching or by means of a dentist's diamond drill. The gamma-ray contribution can be measured by TLD's or calibrated portable gamma spectrometers (Murray, 1981; Grün, 1985). The beta-ray contribution is, however, more difficult to estimate because the range of the beta particles is comparable to the thickness of the shell or enamel layer. In order to solve this problem, average beta dose curves were calculated according to modified formulas given by Yokoyama et al. (1982).

A beta particle with maximun energy E (Mev) has an effective beta-range P (in cm) into a sample with density ρ (in g/cm^3):

$$P = 0.0825\ [(1 + 22.4\ E^2)^{0.5} - 1]\ /\rho \qquad (1)$$

The average dose D received by a volume of thickness d cm subjected to a beta source with infinite matrix dose D_0 can be calculated by the following formula (assuming that the sample is irradiated from one side only (2π-geometry)):

$$D = [0.5\ D_0\ /\ \mu d]\ [1 - \exp(-\mu d)] \qquad (2)$$

where μ is the linear attenuation coefficient per cm ($\mu = 3.3\ /\ P$).

The average dose for a sample with total thickness d cm from which a surface layer of x cm has been removed can be calulated by (see also Aitken et al., 1985):

$$D_{(d-x)} = [0.5\ D_0 / \mu\ (d-x)]\ [\exp(-\mu x) - \exp(-\mu d)] \qquad (3)$$

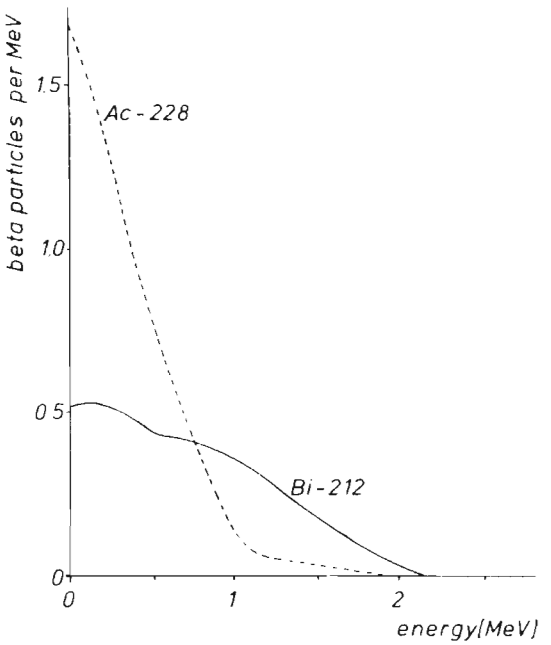

Figure 1: Beta spectra for Ac-228 and Bi-212 (Cross, pers. comm.).

In a β^- decay a negative electron (beta particle) and a neutrino are emitted from the nucleus. The released energy is divided statistically between the beta-particle and the neutrino. When observing a large number of transitions, the beta particle and the neutrino both have energy distributions ranging from zero to the maximum energy available, E_{max}. A beta transition to a particular energy level is characterized by E_{max} and the average energy, E_{av}, of the emitted beta particles. Within the beta decay from a parent to a daughter isotope various transitions with definite probabilities may occur. These processes produce characteristic beta spectra for each beta emitter as e.g. shown in Fig. 1 (Cross, pers. comm.). The spectra of Ac-228 and Bi-212 have about the same maximum energy (2.089 and 2.246, resp.), but very different shapes. These shapes reflect the E_{max} values of the constituent transitions; for instance, in the case of Ac-228 there are ten principal transitions with E_{max} values of 2.08, 1.82, 1.75, 1.18, 1.13, 1.03, 1.0, 0.62, 0.49, and 0.46 MeV, the probabilities being 6%, 2.7%, 14%, 39%, 11%, 3.5%, 7.9% 4.6%, 6.9%, and 5.3% respectively. (It may be noted that the E_{max} values given by Bell (1976) are weighted averages, the value given for Ac-228 being 1.21 MeV). Additionally, internal conversion electrons (IC) can be emitted from the nucleus as an alternative to gamma-ray emission. This process can produce a vacancy in the inner electron shell. The filling of this vacancy generates X-rays or Auger electron emission. Electron replacement of vacancies caused by the filling

of the initial vacancy can produce further Auger electrons (and X-rays).

In order to consider the characteristic beta spectra to some extent, the formulas (1) and (2) were applied to each electron transition occuring in the U- and Th-decay chains. Maximum and average beta energies have been published by Martin & Blichert-Toft (1970; K-40, Th-232 decay chain, and Ra-226 and daughters), Ellis (1977; Th-234 and Pa-234), Schmorak (1977 a&b; Th-231 and Tl-207), Maples (1977: Ac-227 and Th-227), and Martin (1978: Pb-211 and Bi-211). The energy values of the IC and Auger electrons were taken from Bell (1976, 1979). Transitions with an abundance of less than 0.1% were not considered.

In order to determine the average beta doses for a decay chain, formula (1) was applied to all transitions occurring within this chain. Formula (2) was weighted by the product of the average beta energy and the abundance of this transition, which is proportional to the dose transferred from these electrons to the sample. The sum of the latter agreed with the values given by Bell (1976) within less than 1%.

It should be kept in mind that the calculation presented here is only a first approach to this problem because, for example, the shapes of beta spectra of single transitions may vary (see Cross, 1983: spectra for K-40 and Tl-208). Baltakmens (1977) points out that the absorption coefficient of a beta emitter in Al is more likely to be proportional to the area under the curve of a beta spectrum than to its maximum or average energy. This effect cannot be considered in this attempt; it also gives evidence of the limited validity of formula (1). Mejdahl (1979) published beta attenuation data for quartz grains converting computerized beta attenuation curves of point kernels for water (Berger, 1971; 1973) to quartz using a scaling procedure developed by Cross (1968, 1982). A computer program for the planar case considered here could also be devised but would probably require about one year of effort (Prestwich, pers. comm.).

The results of the calculations are shown in Fig. 2. It is obvious that the average beta doses are considerably different for the various decay chains. Aitken et al. (1985) experimentally determined beta attenuation curves for the Th- and U-decay chains using an aluminum absorber and a wide area detector for beta TLD (see Bailiff & Aitken, 1980). They found an exponential relation between the beta dose behind the absorber and its thickness, with coefficients of 1.54 per mm (U-decay chains) and 1.78 per mm (Th-decay chain). A comparison of these results with the dose at a depth d (in cm) derived from formula (3) are shown in Fig. 3. The calculated values for the attenuation by an absorber with ρ = 2.7 g/cm^3 is higher in the first 0.1 mm than in the experiment, for both decay chains. The difference decreases with increasing thickness of the absorber up to about 1 mm, beyond which the curves diverge. The experimental attenuation curves give average beta doses (2π-geometry) for 0.1 mm thickness, which are 8.9% (U) and 18.7% (Th) higher than the calculated data. For 2.5 mm the values reach a relatively good agreement (1% (U); 6% (Th)). The experimental arrangement used by Aitken et al. (1985) was not able to detect beta rays with maximum ranges on the order of alpha-rays

(about 20 μm in solids with ρ = 2.7 g/cm^3) and the gamma component, which compensates this effect to some extent (Bailiff & Aitken, 1980), was subtracted in this experiment also for the zero-absorber dose. Therefore the experimental data cannot be compared directly with this calculation, because about 6% of the total beta dose of the U-decay chains and about 14% of the Th-decay chain are generated by beta emissions (mainly ICs), which have maximum ranges less than 20 μm. Assuming that the measured doses without absorber represent 47% and 43% of the infinite matrix dose of the U and Th source, respectively, the experimental data show good agreement with the calculated values (at 0.1 mm: 2% (U), 2% (Th); at 2.5 mm: 5% (U), 11% (Th)).

Yokoyama et al. (1982) published attenuation factors for the Th-232 decay chain, groups of emitters of the U-decay chains, and K-decay. The attenuation factor for the K-decay is the same as in the present paper since the K-decay consists of one transition only. The average beta doses applying Yokoyama's attenuation factors and relative abundances are nearly always higher (at 0.1 and 2.5 mm): Th-232 decay chain: + 10.6% and + 10%; U-238 - Th-230: + 6% and + 4%; Th-230 - Pb-206: + 5% and - 9.6%; U-235 decay chain: + 9% and + 1%. This can be explained by a different consideration of beta particles with low energies (the beta dose rates within the U-238 decay chain given by Yokoyama et al. (1982) are different to the values by Bell (1976, 1979) due to modifications for IC electrons).

When dating tooth enamel an additional effect has to be considered: an enamel lamella can be generally found within three different environments (Fig. 4):

- a single fragment of an enamel layer is embedded in sediment.
- an enamel layer lies between sediment and dentine/cement as, e.g., a broken part of a mammoth tooth-lamella.
- an enamel layer lies between dentine and cement as, e.g., in a fragment of a whole mammoth tooth.

The beta-ray contribution from the sediment can be derived from Fig. 2 assuming the decay chains to be in equilibrium. Dentine and cement, however, tend to accumulate uranium. The effect of U-uptake on ESR-age determination was discussed by Ikeya (1982) and Grün & Invernati (1985). The U-decay chain in the dentine/cement displays Th-230/U-234 disequilibrium. Fig. 5 shows that the integral beta doses produced by beta emitters from U-238 to Pb-206. Hence, when the Th-230/U-234 disequilibrium has to be considered in the dose calculation, the different beta-correction factors also have to be taken into account.

Table 1 gives the average beta doses for samples, which are irradiated from one side (as percentage of the infinite matrix dose) for the Th-232 and U-235 decay chains, the K-40 decay; for the U-238 decay chain the average doses were calculated for the beta decays above and below Th-230. The calculations were carried out for densities of 2.95 g/cm^3 (aragonite/hydroxyapatite) and 2.7 g/cm^3 (calcite). This table can be used when calculating the average beta dose of thin samples. Above 3 mm (ρ = 2·7 g/cm^3) the external beta radiation is negligible and, hence, the average beta dose can be calculated by linear extrapolation.

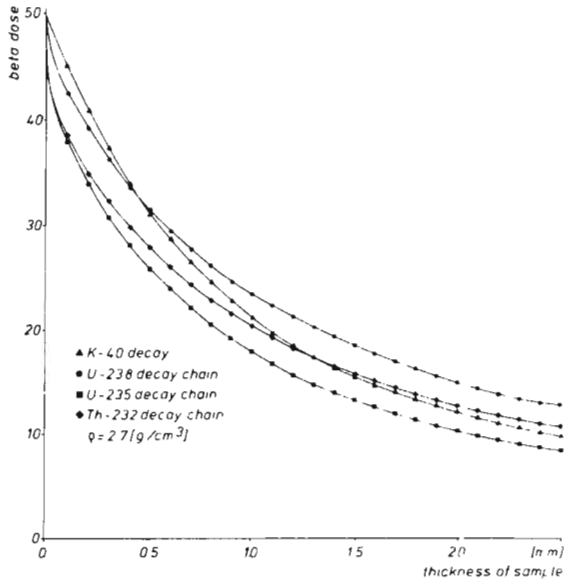

Figure 2: Average beta doses in samples, which are irradiated from one side (2π-geometry), as a percentage of the infinite matrix dose.

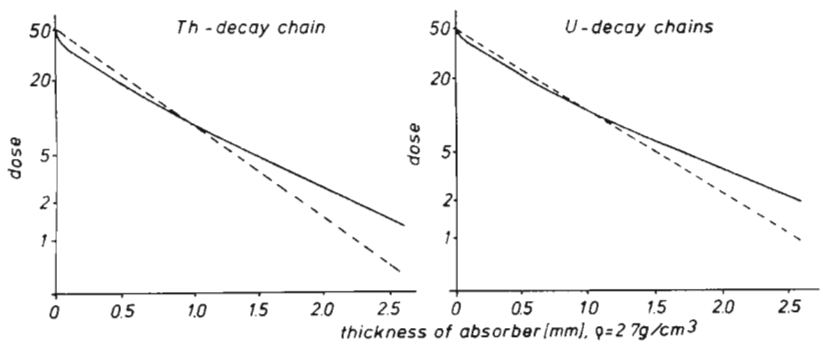

Figure 3: Comparison of the dose at depth d as derived from formula (3) (solid line) with the experimental lines as determined by Aitken et al. (1985) (dotted lines).

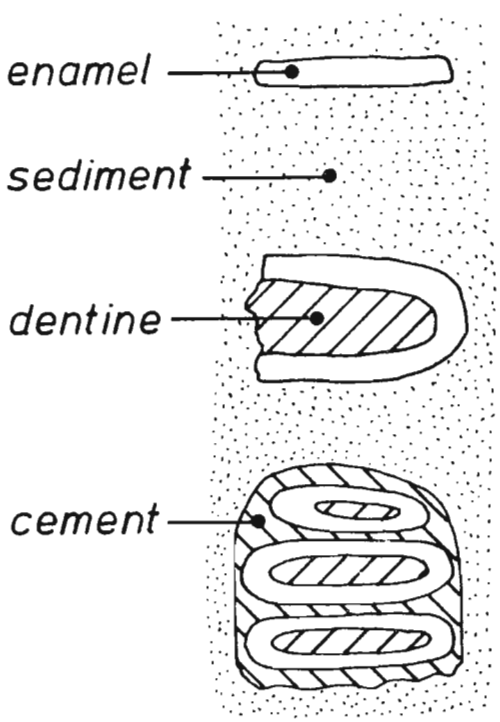

Figure 4: Possible environments of an enamel layer.

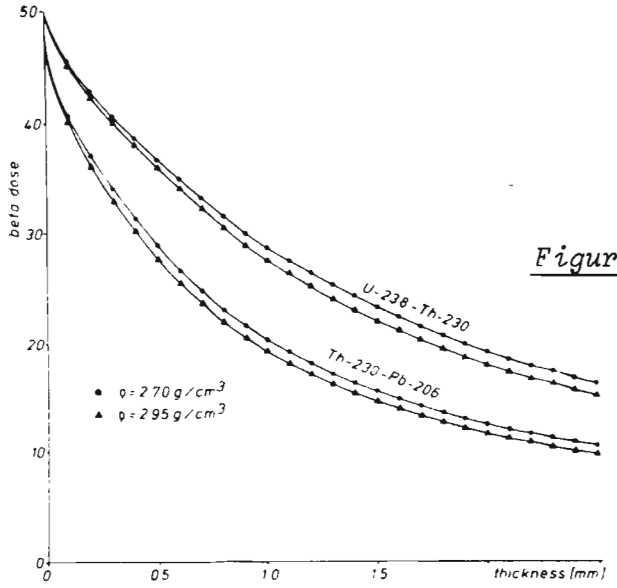

Figure 5: Average beta doses in samples (2π-geometry) for the beta decays between U-238 - Th-230 and Th-230 - Pb-206 as percentage of the infinite matrix dose.

Table 1 Average beta doses (as percentage of the infinite matrix dose) for samples with densities of 2.70 g/cm^3 (a) and 2.95 g/cm^3 (b) irradiated from one side (2π-geometry) and infinite matrix doses (imd) for 1ppm U and Th and 1% K (Bell, 1976; 1979).

Average beta dose (as percentage of the infinte matrix dose)										
	Th-232		U-238 - Th-230		Th-230 - Pb-206		U-235		K-40	
imd [mrad/a]:	2.90		5.49		8.81		0.34		83.0	
Thickness (mm)	a	b	a	b	a	b	a	b	a	b
0.02	42.8	42.6	48.7	48.6	44.8	44.7	43.2	43.0	49.0	48.9
0.05	40.3	40.6	47.4	47.2	43.1	42.9	40.6	40.3	47.5	47.3
0.1	38.6	38.2	45.6	45.3	40.8	40.4	37.9	37.5	45.2	44.8
0.2	35.1	34.5	42.9	42.5	37.0	36.3	34.0	33.3	41.1	40.3
0.3	32.3	31.6	40.6	40.0	33.7	32.9	30.9	30.1	37.4	36.5
0.4	29.9	29.1	38.5	37.8	31.0	30.0	28.2	27.4	34.2	33.0
0.5	27.9	27.0	27.3	35.7	28.6	27.6	26.0	25.0	31.4	30.2
0.6	26.4	25.1	34.8	33.9	26.5	25.4	23.9	22.9	28.8	27.6
0.8	23.0	22.0	31.6	30.5	23.0	22.0	20.6	19.5	24.7	23.3
1.0	20.5	19.5	28.8	27.6	20.3	19.3	17.9	16.9	21.3	20.0
1.2	18.4	17.4	26.4	25.1	18.1	17.1	15.7	14.7	18.7	17.4
1.4	16.6	15.7	24.2	23.0	16.4	15.4	14.0	13.0	16.5	15.3
1.6	15.2	14.2	22.3	21.1	14.9	13.9	12.5	11.6	14.7	13.6
2.0	12.8	11.9	19.2	18.0	12.5	11.7	10.3	9.5	12.1	11.1
2.5	10.6	9.8	16.2	15.0	10.5	9.7	8.3	7.7	9.8	8.9
3.0	9.0	8.3	13.9	12.8	8.9	8.3	7.0	6.4	8.2	7.5

It is hoped that in the near future a more complex calculation similar to the one performed by Mejdahl (1979) will be carried out. It has to be mentioned that even these calculations will exhibit some uncertainties since the calculations of beta-dose distributions performed by Berger (1971) show deviations of up to 6% from the values calculated by Cross et al. (1982). However, most of the thin samples investigated by ESR have rough and irregular shaped surfaces and , hence, it is difficult to determine the beta ray contribution with a good accuracy in any case. It should be noted that in a real case backscattering effects due to change of medium may be significant (see Baltakmens, 1975).

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P.R. **Reviewer's Comments (MJA)**

Its satisfying to find that values for beta attenuation coefficient measured by Chris Gaffney (Aitken et al., 1985) are in reasonable agreement with prediction, and this gives confidence in utilising Table 1 (which is presumed to be for the case of x = 0 in equation (3)). The prediction is ultimately based on the empirical equation given by Flammersfield (1946, Naturwissenschaft 33 p. 280); a slightly more recent, slightly more simple equation has been given by Katz and Penfold (1952, Revs.Mod.Phys. 24 p. 28); there may be others. Readers concerned with beta attenuation may find it useful to refer to p. 628 of Evans (1955, The Atomic Nucleus, McGraw Hill).

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