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The effect of backscattering on the beta dose absorbed by individual quartz grains

Autzen, M.¹, Guérin G.², Murray, A.S.³, Thomsen, K.J.¹, Buylaert, J.-P.^{1,3}, Jain, M.¹

¹ Center for Nuclear Technologies, Technical University of Denmark, DTU Risø Campus, Denmark

² UMR 5060 CNRS-IRAMAT-CRP2A, Université Bordeaux 3, Maison de l'archéologie, 33607 Pessac Cedex, France

³ Nordic Laboratory for Luminescence Dating, Department of Geoscience, Aarhus University, Denmark

*Corresponding author: maaut@dtu.dk

Abstract

We describe the effect on dose rates and over-dispersion (OD) of changing the spectrum of energies to which grains of various shapes and volumes are exposed during beta irradiation, either by changing the backscattering medium or attenuating the incident spectrum. Dose rates are found to increase when the atomic number of the backscattering substrate is increased (from 0.038 Gy/s on Al to 0.057 Gy/s on Pb), at the same time the dispersion due to grain shape and volume also increases slightly (9.4% on Al and 12.0% on Pb). By adding attenuators in front of the sample the net spectrum is also altered and the dispersion affected correspondingly. Our model prediction using various grain shapes and volumes are compared with experimental observations using sieved natural grains and the resulting dose rates are in good agreement, although the dispersions cannot be realistically compared in the absence of grain shape information for the natural material. We find from modelling that dose rates (both to grains in single grain discs and to those placed on the backscattering substrates) are sensitive to changes in shape and volume. A relative range across shapes of between 10 and 21% is observed from modelling on backscattering substrates, and of 7.4% from modelling in single grain discs. We conclude that it appears to be desirable to minimise shape and volume variations in grains if over-dispersion is also to be minimised.

1 Introduction

Dose distributions recorded by single sand-sized grains are now widely used in the dating of sediment samples, as a means of identifying and correcting for the effects of incomplete resetting prior to deposition and post-depositional mixing. However, for well-bleached unmixed natural samples the dose dispersion is much larger than that expected from known sources of uncertainty; even grains previously given a uniform dose by γ -irradiation show such over-dispersion (OD) when the dose is measured using a beta source, with the grains supported on some substrate. The dependence of dose rate on the atomic number of the substrate material has been investigated previously using both experiments (Murray and Wintle, 1979; Ingram et al., 2001) and modelling (Greulich et al, 2008); all 3 studies found that the dose rate increased with an increase in substrate atomic number. The dose rate also depended on the size of the sample grains; Wintle and Aitken (1977) observed a 25% lower dose rate at 4-11 μm than at $\sim 100 \mu\text{m}$, this was confirmed by Armitage and Bailey (2005) although they found the dose rate difference between that of 4-11 μm and 40 μm grains to be smaller ($\sim 12\%$). They also found no significant difference in dose rates for grain sizes $>40 \mu\text{m}$, observing a plateau in effective dose rates in the grain size range from 40-250 μm . Goedicke (2007) reported a sharp decrease in dose rate below a grain size of $\sim 40 \mu\text{m}$ while also observing no significant dependence for grain sizes between 40-130 μm . Above 180 μm the observed dose rates begin to decrease as the incident beam is attenuated while passing through the grains. Similar results were reported by Mauz and Lang (2005). Fain et al. (1999) used Monte Carlo modelling to investigate the effect of grain shape on absorbed beta doses; they concluded that for grains of $\sim 200 \mu\text{m}$ diameter there is no effect.

As part of our investigation into the importance of low energy beta particles in dosimetry, in this study we consider the effect of the backscattering substrate on the dispersion of dose distributions measured using individual grains, by beta irradiating a monolayer of quartz grains on substrates of different atomic numbers (Z) varying from 13 to 82. The doses absorbed by these grains are then measured in an Al substrate (single grain disc) in the usual manner. We also investigate the effect on the observed OD of changing the incident spectrum shape using attenuators. The dependence of average dose and the contribution from backscatter as a function of Z are compared with modelling predictions based on Geant4, and the expected dispersion due to grain shape effects discussed.

2 Backscatter

2.1 Backscatter - Modelling

We have used Geant4 (Agostinelli et al., 2003; Allison et al., 2006) to model beta dose absorption in quartz grains. A short summary of the physics involved is given in Supplementary Material Section 1. Similar work has been undertaken by Guérin (2011) and Guérin et al. (2012, 2015). Simulations were run using Geant4 version 10.02 patch 1 on the CentOS 7 distribution, run on a VMware workstation player 12 virtual machine, with the Penelope physics model (Salvat et al., 2001); this is well suited for the simulation of low energy particles and for electromagnetic interactions. A cut-off of 0.5 μm for the production of secondary particles was used (*i.e.* no particle is generated if its range is less than 0.5 μm , and the corresponding energy is instead deposited locally). This value was chosen to be less than 10% of the minimum dimension of our dose absorbers (grains).

In the model, primary particles are released individually and the release of the next particle does not occur until tracking of the previous primary and all generated secondary particles is complete. Tracking of a particle ceases when it reaches the boundaries of the world volume (at which point its energy is considered lost from the experiment) or its step size becomes shorter than the 0.5 μm cut-off. The release of primaries from the active source layer occurs isotropically. Each simulation is run for 10^8 primary electrons, corresponding to approximately 1/15 of a second of irradiation using a 1.5 GBq $^{90}\text{Sr}/^{90}\text{Y}$ source, this number of primaries provides us with good counting statistics (events per grain) as well as realistic computation times.

Individual geometrical components (structural, shielding and sample) are placed inside a predefined world volume otherwise filled with air and are given material properties based on user-defined elements and alloys. The irradiation geometry is constructed using the beta-source manufacturer's description (taken from Greilich et al., 2008), the characteristics of the irradiator and source flange (Dalsgaard, 2017 private communication), and a given grain geometry and substrate. The characteristic emission spectrum of the $^{90}\text{Sr}/^{90}\text{Y}$ active layer is defined as a cumulative probability distribution function (CDF) and given as input to the simulation. Beta particles were emitted with energies randomly sampled according to the Fermi model for beta spectra, modified by Behrens and Szybisz (1976). This spectrum is then modified by the source construction, the 0.125 mm thick Be window, and scattering by the flange, before arriving at the sample position. This part of the

simulation is substantially the same as that undertaken by Greulich et al. (2008), and details of the irradiation geometry are given in Supplementary Material (Figure S2).

The backscattering substrates used in the model are made of materials in the range $0 \leq Z \leq 82$. One hundred quartz grains are placed on a 10x10 grid, spaced with 600 μm between adjacent centres (this is similar to the layout of grains in a standard single-grain measurement disc; Bøtter-Jensen et al., (2003) except that in our case the grains are placed on the substrate surface rather than in holes in the substrate). Each quartz grain is uniquely labelled to allow the tracking of events within individual grains. The simulations record both the total energy deposited in each grain and the energy of any electron which enters any grain, the latter with a resolution of 1 keV.

To test the dependence of dose deposition on grain shape and volume, simulations were run for 7 different sizes and shapes of quartz grains: 100 μm or 200 μm diameter spheres, cylinders with a base radius of 150 μm and a height of 5 μm or 300 μm , and a cone of base radius and height of 150 μm . For comparing shape changes, a cylinder with base radius 50 μm and a height of 66 μm , as well as a cone of base radius 50 μm and a height of 200 μm were added. The latter two are chosen to have the same volume as the 100 μm diameter sphere; any differences in dose absorbed by these three grains types will thus arise because of shape and not volume. In contrast, dose absorption in the two spheres will be affected only by volume. In the two cylinders dose absorption will be affected by both shape and volume. Given that the backscattered spectrum should be softer than the incident spectrum, we expect to see a higher backscatter contribution to the absorbed dose in the short cylinder compared to the tall cylinder (See Supplementary Material Section 1, Figure S1). Note that all grains fit completely within the grain holes of standard single grain discs.

The simulation records the spectra as follows: the energy of an electron is recorded (1 keV bin width) only if it (a) leaves a volume which is not the backscattering material and then (b) immediately enters the backscattering substrate, i.e. when an electron originating outside the substrate takes a first step in the substrate; secondary electrons generated within the substrate are not recorded. In the case of the incident spectrum (Fig. 1), there is no absorber (quartz grains) sitting on the substrate, and the substrate is vacuum; this gives the incident spectrum with no backscattered contribution. Backscattered spectra are recorded in a similar manner, except that a separate 200 μm thick air volume is placed directly on the substrate, covering the entire sample surface; all electrons leaving the substrate and then entering the air volume are recorded (Fig.1)

1 **Figure 1 near here**

2 The energy distribution of the backscattered electron spectra (Fig.1a; for completeness,
 3 corresponding backscattered photon spectra and total photon and electron spectra are shown in
 4 Figure S3a and b, respectively) does not change substantially from substrate to substrate. In contrast
 5 the intensity does change substantially, and at low energies and high substrate Z the backscattered
 6 intensity is comparable to that of the incident spectrum. As expected, the backscattered spectrum is
 7 softer than the incident spectrum, i.e. it contains a relatively larger low energy component; this can
 8 be seen more clearly in the normalized cumulative spectra shown in Figure 1b (calculated by
 9 progressively summing all lower energy bins and then normalised by dividing by the total sum of
 10 all bins). It is clear that the backscattered spectrum tends towards the incident spectrum when the
 11 substrate Z increases.

12 **Figure 2 near here**

13 The dose rate to quartz grains sitting on a substrate increases with the atomic number of the
 14 substrate (Fig. 2), and there is a pronounced dose rate dependence on grain shape/volume. The dose
 15 rates to short and tall cylinders show the most difference, and this difference becomes more
 16 pronounced with an increasing substrate Z (although the model predicts slightly lower dose rates on
 17 copper ($Z=29$) than on stainless steel ($Z\sim 26$) for all shapes). As the substrate Z increases, the
 18 relative range with respect to the average in dose rates to the various grains shapes and volumes
 19 increases, from 11% on Al, 14% on stainless steel, 15% on copper, to 21% on lead (these data are
 20 presented graphically in Figure S4). Given the inevitable variation in natural grain shape, even for a
 21 tightly constrained sieve fraction, this observation suggests that we would expect to see the over-
 22 dispersion of experimentally-observed single grain dose distributions increase in a similar way.
 23 Rather surprisingly, for shapes of the same volume, the dose rate relative range decreases from 8%
 24 to 3% as the substrate Z increases from Al to Pb (see also Fig. S4, Table S1). On vacuum, the
 25 largest sphere also has the largest dose rate (102% of that to the smaller sphere), this reduces as the
 26 substrate Z increases, to only 91% of the dose rate to the smaller sphere on lead. This seems to
 27 support our explanation in Supplementary Material Section 1 that the dose derived from the
 28 backscattered spectrum contributes more to the total dose of small grains than of large.

2.2 Backscatter - Experimental

For comparison with model predictions, quartz grains were beta irradiated in a Risø reader (TL/OSL model DA-20) with a single grain attachment. A plastic mount was placed in the reader base-plate directly under the beta-source and cups (6 mm thick, 1mm internal depth, 8 mm internal diameter) of aluminium, 316-stainless steel, copper, and lead were inserted into this support (with the turntable wheel removed) to provide the backscattering medium.

Previously sensitised sieved quartz grains (180 – 212 μm , Hansen et al., 2015) were first heated to 450°C for 1 hour to thermally empty any trapped charge. The absence of apparent dose was confirmed before further exposing to the beta source. A SAR protocol (Murray and Wintle, 2000, 2003) with a 260°C preheat was used for all dose measurements, and the accuracy of our chosen protocol was confirmed using a standard dose recovery experiment using single-grains (measured/given dose ratio 0.973 ± 0.005 ; $n=352$). Undosed grains were placed loose in a monolayer in the substrate cup (i.e. without silicone oil, and not in the fixed 10x10 grid of the model), examined under a microscope to ensure a monolayer, and mounted in the reader before exposure to the beta source for 100 seconds. The grains were then loaded into standard single grain discs for measurement of absorbed dose.

The beta source employed was selected to give the smallest available spatial variation in dose rate across the sample area. Nevertheless, such variation is of significance; a contour map of the radiation intensity of our source (measured using GAF radiosensitive film according to Lapp et al., 2012) is shown in Figure S5. The standard deviation of source intensity across an 8 mm diameter circle (equivalent to the cup area holding the loose grains) is ~8%. The variation in dose rate between grains in a single grain disc is ~6%, based on the grain hole positions. We should thus expect a ~10% variation in measured dose from grain to grain arising simply from irradiation non-uniformity, unless the correction approach of Lapp et al. (2012) is applied.

2.3 Backscatter -Experimental results and comparison with model

A total of 6 single grain discs were run for each substrate, corresponding to 600 grains per substrate. After analysis using standard rejection criteria (test dose error <10%, recycling ratio within 10% of unity), 473 grains were accepted for Al, 483 grains for Cu, 507 grains for stainless steel and 515 grains for lead.

Table 1 near here

The grain-to-grain OD in dose rate increases slightly with Z , but any effect is masked by the variation resulting from source non-uniformity (Table 1). The component derived from regenerative irradiations in single grain discs (the 6% discussed above) can be removed using the source correction option (Lapp et al., 2012). This should reduce the OD resulting purely from source non-uniformity to about 8% (instead of the expected total of $\sim 10\%$ if no correction is applied). Because we cannot constrain the exact position of each grain on the existing design of substrate irradiation geometry, further reduction in OD arising from source non-uniformity can only be achieved by making single grain discs of the various substrate materials and holders to ensure the irradiation geometries are beta thick. This is challenging, and the feasibility is now being investigated.

After correcting for source non-uniformity during irradiation in single grain aluminium discs the calculated OD is indeed reduced (Table 1) without significantly changing the mean dose rates. On average the effect of correcting for source non-uniformity is to reduce the OD by 7.8% (contributions summed in quadrature); this is consistent with the expected correction from Figure S5. The ODs still tend to increase with increasing Z .

Figure 3 near here

From Fig. 3a it can be seen that the ratio of the modelled dose rates on different substrates to those modelled for single grain disc irradiations (see section 3.1) are generally consistent with the corresponding experimental dose rate ratios as the substrate Z increases. For aluminium, the model seems to have underestimated the dose rate ratio compared with the experiment while for lead, model and experiments are in agreement.

Model and experimental results (normalised to irradiation on an Al substrate) are shown together with the corresponding ratios obtained from Murray and Wintle (1979) and Greilich et al. (2008) in Fig. 3b. Note that Murray and Wintle's (1979) experiment used 100 μm diameter CaF_2 grains (modelled results within 1% of those of quartz) and the $Z=27$ result is for a 0.5 mm nichrome heater plate, which is not beta-thick. The observations are broadly consistent with the range of the modelled data for different grain shapes (Fig. 3b). Interestingly Murray and Wintle's (1979) experimental results appear to be most consistent with the model results, while our experimental data appear to be systematically lower than the model predictions for high Z . Since our data have been normalized to aluminium this can likely be explained by the fact that the dose rate ratio for aluminium was experimentally higher than that predicted by the model (Fig. 3a). This would lead to

ratios being underestimated when comparing experiments and model. The 100 μm diameter CaF_2 spheres of Greulich et al.'s model results appear to be consistent with our model results as well as the experimental data of Murray and Wintle (1979).

3 Attenuation of the incident beta-spectrum

3.1 Attenuation - Modelling

Another approach to investigating the importance of the spectrum shape is to irradiate on a fixed substrate, but to attenuate the incident spectrum through an absorber and so modify the energy distribution. This also has the advantage of fixing the grain location during all irradiations, and so allowing us to remove the effects of source non-uniformity more completely.

In our Geant4 simulation, the attenuator was added immediately below the Be window, and the grains were mounted in a standard Al single-grain disc (see Figure S6). It is clearly important that the attenuated dose rate should be large enough to give practical irradiation times, and at the same time the attenuator must be thick enough to significantly change the spectrum shape (the maximum practical attenuator thickness in the reader is 0.5 mm). As a result, our simulation used three different attenuators; 0, 0.2 and 0.4 mm of lead; the resulting spectra are summarised in Figure 4. These spectra are recorded in a similar manner to those described above (Section 2.1) but now all electrons entering the holes in the single grain disc for the first time from all directions are recorded, without any grains present (corresponding photon and total spectra are shown in Figure S7 a and b, respectively).

Figure 4 near here

Based on the model predictions, the dose rate attenuations are 0, $87.9 \pm 2.5\%$ and $98.9 \pm 0.3\%$ for 0, 0.2 mm and 0.4 mm of lead, respectively. As expected, attenuating the beta spectrum with different thicknesses of lead not only varies the intensity but also alters the energy spectrum of particles entering the grains. The normalized cumulative spectra are shown in Fig. 5, where it can be seen that 0.2 mm of lead hardens the spectrum up to ~ 0.8 MeV after which the spectrum softens compared with the unattenuated spectrum. In contrast, 0.4 mm of lead softens the spectrum across the entire energy range. For comparison, Fig. 5 also shows the incident spectrum from Fig. 1b; note the difference compared to the unattenuated spectrum, presumably due to presence of the walls of the single grain holes.

1 **Figure 5 near here**

2 Figure 6 presents the dose rate variation with grain size and shape. The unattenuated spectrum gives
 3 rise to a relative range of 7.4% compared to the average dose rate because of variations in grain
 4 shape/volume. This relative range increases to 11% when the spectrum is attenuated through 0.2
 5 mm of lead and to 20% when attenuated through 0.4 mm of lead.

6 **Figure 6 near here**

7 Considering only the grains with the same volume, the relative range in the dose rates from the
 8 unattenuated spectrum is only 1%. This increases slightly to 2% when the spectrum is attenuated
 9 through 0.2 mm of lead, and up to 20% when attenuated through 0.4 mm of lead. Thus, a change in
 10 shape without a change in volume appears to make the grain significantly more sensitive to the
 11 shape of the attenuated spectrum. For the same shape but different volumes, i.e. the spheres, the
 12 relative range in dose rates increases from 0.7% for the unattenuated spectrum, to 3.8% for 0.2 mm
 13 of lead, and finally to 9.9% for 0.4 mm of lead. Thus, a change in volume but not shape also
 14 appears to make the grains significantly more sensitive to a change in spectrum, although not to the
 15 extent of the change in shape.

16 It is also interesting to compare the 7.4% relative range in dose rates when irradiating grains
 17 mounted in holes in the single grain Al disc, with the 11% relative range (Section 2.1) when
 18 irradiating on Al without grain holes. It appears that the single-grain disc, primarily designed to
 19 hold the grains on a regular array, also serves to reduce the range in grain-to-grain variation in dose
 20 rates by ~8% compared to irradiation on a planar surface (dispersion summed in quadrature).

21 **3.2 Attenuation -Experimental**

22 An experiment was designed to test the above model predictions using annealed grains (180-212
 23 μm) loaded into 4 sets of 6 single grain discs (100 grains per single grain disc) with grains
 24 irradiated as follows:

- 25 1. Gamma irradiation of loose grains before loading into single grain discs, gamma dose 4.81 Gy from a
 26 ^{137}Cs source, with build up to give uniform dose deposition (see Hansen et al. (2015) for details).
- 27 2. Beta irradiation in single grain disc for 55 s, no attenuation.
- 28 3. Beta irradiation in single grain disc for 586 s through 0.2 mm of lead.
- 29 4. Beta irradiation in single grain disc for 5095 s through 0.4 mm of lead.

The thickness of the lead foil used for attenuation (supplied by Goodfellow) is known to within $\pm 10\%$. The irradiation times for the attenuated spectra were intended to deliver approximately the same dose as the 55 s of unattenuated irradiation but are based on a preliminary version of the model (not presented). Based on the predicted attenuation factors given in the previous section, these attenuated spectra irradiation times actually correspond to ~ 71 s and ~ 56 s of unattenuated irradiation, respectively. The doses given by these irradiations were then measured in the usual manner using our standard SAR protocol and the unattenuated spectrum from the beta source.

3.3 Attenuation – Experimental results and comparison with model

The results of the experimental measurements are summarised in Table 2. For gamma irradiated sample 490 grains were accepted, 352 grains were accepted for no beta attenuation, 526 grains for attenuation with 0.2 mm of lead, and 531 grains for attenuation with 0.4 mm of lead, all using the same rejection criteria as for backscatter. A typical single grain gamma dose distribution for this material can be found in Fig. 6b of Hansen et al. (2015). Attenuating the beta spectrum using 0.2 mm of lead gives an attenuation factor of $83 \pm 1.8\%$ (c.f. $87.9 \pm 2.5\%$ from the model). For the 0.4 mm lead attenuator the measured attenuation is $98.6 \pm 1.4\%$ (c.f. $98.9 \pm 0.3\%$ from the model). These results are consistent with the model predictions. The ODs resulting from irradiation using the gamma and unattenuated beta spectrum ($9.9 \pm 0.4\%$ and $5.8 \pm 0.4\%$, respectively) are similar to values reported before (Thomsen et al., 2005; Hansen et al., 2015) - Thomsen et al. (2005) reported $8.6 \pm 0.2\%$ for gamma dose recovery and $5.9 \pm 0.1\%$ for beta dose recovery. Despite the relative similarity in the given doses, the OD clearly increases when the spectrum is attenuated; this is consistent with the marked change in spectrum shape towards low energies in the attenuated spectra (Fig. 5). There is an apparent decrease in OD for 0.4 mm compared to 0.2 mm ($10.8 \pm 0.4\%$ to $12.1 \pm 0.5\%$); if this is real, it is unexpected, and needs further investigation.

Table 2 near here

4 Discussion

Modelling predicts that the dose deposited in grains should vary significantly with grain size and shape and that this effect should become more pronounced with higher substrate Z; in contrast, when the volume is kept constant across different shapes, an increase in substrate Z reduces the relative range in deposited dose. Nevertheless, the net effect is that the relative range in dose rates

increases with substrate Z, from 10% on Al to 21% on lead (Fig. 2). Our modelling data are in contrast with the modelling results of Fain et al. (1999) who did not observe a significant difference in beta dose absorption between different grain shapes.

Not surprisingly, the net dose rate to larger grains is less sensitive to changes in substrate than that to smaller grains (see Section 2.1 and Table S1 in Supplementary Material), with the largest grains experiencing an increase in dose rate between 100-118% when comparing lead to vacuum, whereas small grains experience an increase in dose rate between 144-167% for the same substrate changes. Experimentally we observe that the dose rate ratios (normalised to Al) for the smaller 90-112 μm CaF_2 grains of Murray and Wintle (1979) are consistent with model predictions, both ours and those of Greilich et al. (2008). However our experimental dose rate ratios are systematically lower than model predictions; this is likely to be because our experimental dose rate ratio of aluminium/single grain disc is experimentally higher than model predictions. As each subsequent data point is normalized to this ratio this will lead to a systematic underestimation when comparing experiment and model.

In real materials of mixed grain sizes and shapes, this shape/volume dependence should result in higher grain-to-grain dose dispersion, especially when dosing on heavier substrates. Although the OD data (Table 1) are probably dominated by the source non-uniformity, the OD nevertheless increases with substrate Z, supporting the model predictions.

Turning now to the attenuation experiment, as expected, the model predicts a significant softening of the spectrum as it is attenuated; this attenuation and scattering will also effectively smooth out the effects of source non-uniformity (although this has not been explicitly modelled). As a result, we can now be confident that the observed ODs in the attenuation experiments reflect only the effects of the changes in incident spectrum. The OD does increase significantly with the first increase in attenuation (from 0 to 0.2 mm) but we do not see a marked increase in OD for an attenuator thickness of 0.4 mm. This is currently not understood. We hypothesize that this could be connected with softening of the incident spectrum by the 0.4 mm of lead, whereas the 0.2 mm of lead initially hardens the spectrum (Fig. 5).

Finally, it is interesting to consider the implications of the backscattered modelling results for the well-established difference in OD between gamma and beta dose recovery experiments (e.g. Thomsen et al., 2005). Typical beta dose recovery experiments give ODs in measured/given dose

ratios of 6-7%. If we now accept the modelling prediction of a ~8% relative range in beta dose rates arising from grain shape/volume effects, this suggests a gamma OD of about 11%, consistent with experimental observations.

5 Conclusions

From the modelling of backscattering, we have shown that the OD increases with increased softening of the net spectrum (i.e. increasing substrate Z). Experimental results confirmed this trend. Modelling results also show that the effect of the backscattered material will vary with grain size/shape. The attenuation experiment showed that the OD was generally increased by attenuating the spectrum, with the 0.2 mm of lead leading to the largest OD. Surprisingly, further attenuation using 0.4 mm of lead gives the same or possibly smaller OD. This could be connected with the softening of the incident spectrum by the 0.4 mm of lead, whereas the 0.2 mm of lead initially hardens the spectrum. We conclude that there are good reasons to expect that grain shape and size will contribute significantly to the OD in measured single grain dose distributions, and that we can use Geant4 to simulate this dependence. It appears likely that shape/size variations in quartz or feldspar grains used for measurement should be minimised to reduce the OD in both dose recovery and natural dose distributions.

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Figure captions

Figure 1 a) Incident beta spectrum on backscattering substrate and backscattered spectra from perspex, aluminium, stainless steel, copper and lead. b) Normalized cumulative distribution function spectra for each of the spectra shown in a) All spectra are generated using the same number of primaries (10^8).

Figure 2 Modelled dose rates for various grain sizes and shapes on each of the modelled substrates. In the legend the numbers in parenthesis after each substrate give the relative range. The radius and

height of each shape are given for each grain shape in parentheses (r, h). Single grain disc from section 3.1 has been added.

Figure 3 a) Comparison of modelled dose rate ratio between substrate and single grain disc and the same ratio for experimental data. b) Model and experimental results compared with other studies. Dose rates normalized to irradiation on aluminium, and plotted against substrate atomic number; the grey band represents the range of our modelled data.

Figure 4 Spectrum with no attenuation, attenuation with 0.2 mm of lead and attenuation with 0.4 mm of lead for an Al single grain disc. All spectra were generated using the same number of primaries (10^8). Numbers in square brackets indicate the factor by which the entries have been multiplied to achieve the same scale.

Figure 5 Normalized cumulative spectra for each of the spectra shown in Figure 4.

Figure 6 Modelled dose rates for no attenuation, 0.2 mm of lead attenuator, 0.4 mm of lead attenuator. Numbers in parenthesis note the relative range, while numbers in square brackets indicate the factor by which each entry has been multiplied.

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Figure 1a

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Figure 1b

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Figure 2

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Figure 3a

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Figure 3b

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Figure 4

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Figure 5

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Figure 6

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1 Table 1. Experimental results for irradiation on various substrates and subsequent measurement in single
 2 grain discs. Doses are calculated using average dose rate to the single grain disc derived using Risø
 3 calibration quartz (Hansen et al., 2015). Correction for source heterogeneity was carried out following Lapp
 4 et al. (2012). Over-dispersion (OD) is calculated using CAM (Galbraith et al., 1999)

Substrate	No correction		Correction	
	Measured Average Dose (Gy) $\pm$ se	Relative OD (%) $\pm$ se	Measured Average Dose (Gy) $\pm$ se	Relative OD (%) $\pm$ se
Al	3.85 $\pm$ 0.03	12.5 $\pm$ 0.5	3.85 $\pm$ 0.02	9.4 $\pm$ 0.5
Stainless Steel	4.41 $\pm$ 0.03	13.1 $\pm$ 0.5	4.42 $\pm$ 0.02	10.3 $\pm$ 0.4
Cu	4.71 $\pm$ 0.03	13.7 $\pm$ 0.5	4.72 $\pm$ 0.03	11.4 $\pm$ 0.5
Pb	5.77 $\pm$ 0.04	14.0 $\pm$ 0.5	5.79 $\pm$ 0.03	12.0 $\pm$ 0.5

5

6 Table 2. Experimental results for different thickness of Pb attenuators mounted in front of the beta source.
 7 Over-dispersion (OD) is calculated using CAM (Galbraith et al., 1999)

	Attenuation factors $\pm$ SE	Relative OD (%) $\pm$ SE
Gamma dose recovery	-	9.9 $\pm$ 0.4
Beta dose recovery		
No attenuation	0	5.8 $\pm$ 0.4
0.2 mm Pb	83.0 $\pm$ 1.8%	12.6 $\pm$ 0.5
0.4 mm Pb	98.6 $\pm$ 1.4%	10.8 $\pm$ 0.4

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