Cosmic ray dose rates for luminescence and ESR dating: measured with a scintillation counter

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Abstract: *A method of finding the contribution of cosmic rays to dose-rates for luminescence and ESR dating is described, making use of the same field scintillometer as is used for the in situ determination of the concentrations of potassium, uranium and thorium.*

Introduction

This laboratory has published a number of works on estimating the contribution of gamma rays and cosmic rays to the dose-rate for luminescence and ESR dating (Prescott and Stephan 1982; Prescott and Hutton 1988, 1994). These are based on primary data for cosmic ray intensities extracted from the literature. Apart from the existing uncertainty in the long term primary cosmic ray intensity, there is no reason to suppose that the procedures described in these references need revision.

It is possible to measure the cosmic ray dose-rate at the actual site of the sample being dated by inserting solid state dosemeters and leaving them for twelve months (which gives enough time for a measurable dose to accumulate and, incidentally, averages over the round of the seasons). Of course, such *in situ* dosemeters measure not only the cosmic ray contribution but also the gamma ray contribution. It is usually of no consequence for luminescence dating that these two are measured together.

In situ scintillometry is used routinely to measure potassium, uranium and thorium and the author has sometimes been asked whether the same instrument can also be used for cosmic ray measurements. This would give an "instant" value for the local cosmic ray dose-rate, regardless of geographical location. In practice, scintillometry for the estimation of cosmic rays appears to have been rarely used in luminescence dating. Stokes and co-workers and Porat and co-workers do so, although the physical basis is not stated (see e.g. Stokes et al, 1997, Porat et al 1997). The latter compare scintillometer values for combined gamma ray and cosmic ray dose-rates with those found from chemical analysis and from Prescott and Hutton (1988). Aitken (1985 p 321) gives factors for a specific scintillometer.

The present note discusses the use of conventional scintillometers, for this purpose. It is based on measurements made with the Adelaide instrument.

The scintillation counter

For luminescence dating, the effective part of the cosmic ray flux, at all altitudes, is the so-called "hard component" which consists of muons and is, by convention, that component of the cosmic rays capable of penetrating 10 cm of lead or 167 g cm^{-2} of any other absorber. This corresponds to about 65 cm of standard rock or about 80 cm of sediment. The non-mesonic "soft component" is removed by this amount of absorber. The mean flux of muons, of all energies, integrated over all zenith angles at sea level, is about 0.019 cm^{-2} s^{-1} (Allkofer et al. 1975). It varies a few percent over the solar cycle (Allkofer 1975).

The Adelaide scintillometer uses a sodium iodide crystal 76 mm long and 76 mm in diameter; it can be used interchangeably with either URTEC UG-140 or EXPLORANIUM GR-256 field electronics boxes. Thus, in round figures, roughly one cosmic ray muon will pass through the detector per second. In passing, our crystal is deliberately rather bigger than most in order to reduce the counting time for the 2.61 Mev gamma ray from the thorium decay chain.

The specific energy loss of the muons is a slowly varying function of energy, with a value of 1.65 MeV g^{-1} cm^2 in sodium iodide at the average muon energy of 2 GeV. A typical muon travelling across the 76 mm diameter of a sodium iodide crystal of density 3.67 g cm^{-3} will therefore deposit 46 MeV of energy in the crystal. Meson tracks skewed to the axis will deposit more energy than this. Since the deposited energy is converted to light with almost the same efficiency as the energy deposited by gamma rays, the observed signal is considerably larger than that from the energy of the most energetic natural gamma ray--the 2.61 MeV gamma ray from ^{208}Pb in the thorium chain. This 2.61 MeV gamma ray occurs in 100% of all decays but it is accompanied by other decay-chain gamma rays in cascade, so that the energy release can sum to 3.20, 3.48 or 3.70 MeV if more than one gamma ray is stopped in the crystal at the same time.

Thus, in principle, muon events can be identified because of their large energy deposition. Any signal greater than about 4 MeV, say, in the scintillator will have been due to a muon and the muon flux can be counted on that basis. In fact, only a very small proportion of the muons passing through the crystal gives a signal less than 4 MeV. In the case of the Adelaide crystal, this fraction is calculated to be about 0.25%, taken over all angles of incidence. In passing, this means that Adelaide does not normally have to correct for muons in calibrating the crystal for gamma rays. For smaller crystals this fraction will be larger.

The Measurements

In order to test these ideas, we set up our scintillometer near sea level in one of the cosmic ray research laboratories in the Department of Physics and Mathematical Physics at the University of Adelaide. The concrete and masonry in the three floors above the laboratory is sufficient to eliminate the "soft" component of the cosmic rays, leaving essentially only muons. The "natural" radiation provided by the brick walls and concrete floor was equivalent to an environment having 0.78% potassium, 1.3 μg g^{-1} uranium and 6.0 μg g^{-1} thorium. This combination of conditions is much the same as one would normally find in the field. The crystal axis was horizontal.

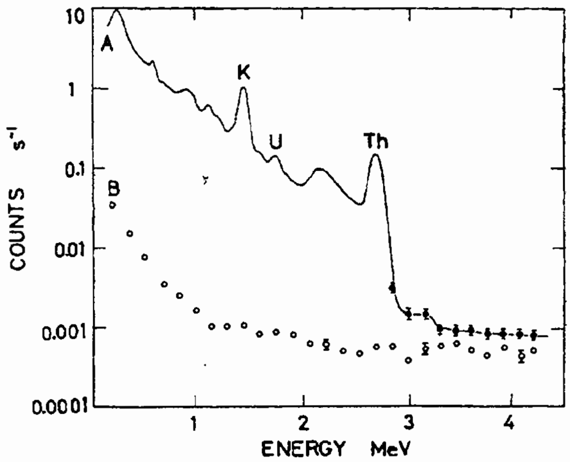

Figure 1.

Curve A: Gamma ray spectrum in a sodium iodide scintillator as used for in situ analysis of natural radioactive elements. Characteristic peaks for K (1.46 MeV), U (1.76 MeV) and Th (2.61 MeV) are indicated.

Curve B: Spectrum of energy deposited in the sodium iodide crystal by muons identified by a coincidence gate. The energy scale is that of gamma rays that produce the same pulse size.

Detailed features of the curves are discussed in the text.

The gamma ray spectrum is shown in figure 1, curve A; the spectrum is not recorded below 150 keV. For most of the spectrum, individual data points are not plotted. Above 3 MeV, because the count rate is low and the statistics are poor, the counts have been summed in groups of ten channels and scaled to the same scale as the rest of the spectrum. The 1.46 MeV potassium and 2.61 MeV thorium peaks are prominent and the uranium 1.76 Mev peak is also identified. A ledge from 3-4 MeV contains the thorium sum-peaks, where two cascade gamma rays from thorium happen to be recorded together. As expected, they are of very low intensity but they are there. In this region there is also an unresolved component, comparable in intensity, from random coincidences between the Th gamma ray and unrelated gamma rays from K and U, which happen to be detected in the crystal during the acceptance time of the amplifier. The spectrum shows that, in order to record muons free of contamination by sum or random peaks, a discriminator threshold of more than 4 Mev is needed, particularly if there is a high concentration of thorium in the environment.

To select muons, a 50 cm x 50 cm plastic scintillator was located immediately above the sodium iodide crystal and was used in electronic coincidence with it. Each time a muon was detected by the plastic scintillator, it opened a 4 μs coincidence gate for the sodium iodide signal, which was otherwise vetoed. Thus, any signal seen in the NaI crystal when the coincidence gate was opened must have been caused by a muon. In this configuration, not every detected muon passes through the NaI crystal so there are more triggers than NaI signals; but this does not affect the argument.

The "muon-gated" spectrum of events in the NaI crystal is shown in fig. 1, curve B.. These data have also been summed in groups of ten channels and scaled to the gamma ray spectrum. The coincidence spectrum is seen to be almost flat from about 2 MeV to the upper energy limit displayed in the figure and it would be expected to continue at a low level towards the 46 MeV figure mentioned above. The number of "overload" events, i.e. those events that exceed the upper limit of the displayed spectrum, was recorded and is consistent with this assumption, although details of the distribution are not known.

Below 4 MeV in fig. 1 there is a contribution from muons clipping the edges of the crystal. At about 2 MeV the coincidence spectrum begins to rise and from about 1 MeV it rises more steeply. These events are due to random coincidences between the muon gate and pulses anywhere in the gamma spectrum. Because the gamma pulse may occur anywhere in the 4 μs gate, these random pulses may be cropped in size and are spread through the low pulse-height end of the spectrum.

Conclusions

It can be seen from fig. 1 that, except for a small interval near 2.5 MeV, nowhere in the whole energy range covered by this particular gamma ray spectrum, does the muon count rate exceed 1% of the gamma ray count in the corresponding channel. Summed over the whole spectrum, the muons contribute 0.25% to the total count. The muon contribution in the Th window (2.46-2.77 MeV) is 0.68%, which is well within the 2.2% counting uncertainty. Thus, muons will not affect the individual analyses for K, U and Th, at least for our large crystal and at this site.

This may not be the case for sites which have unusually low radioactivity. To take a specific example, for most of our sampling sites in the south-east of South Australia the U and Th concentrations are of the order of 1 μg g^{-1} (e.g. Prescott and Hutton 1995, fig. 2). The above muon contribution would then amount to 4% of the counts in the Th window. Alternatively this can be stated as: the muon count corresponds to a Th concentration of 0.04 μg^{-1}. Similar arguments apply, *mutatis mutandis* for crystals smaller than ours.

Alternatively, a muon count background can be included in the background corrections for each of the element channels. In the present case this would be about 1 cpm in all of the K, U and Th channels; but it should be noted that these numbers are characteristic of the particular instrument and of the altitude and latitude (see e.g. Prescott and Stephan 1982).

The dose-rate can be found directly from the ungated spectrum using the integral count rate for all signals greater than 4 MeV. We recall that this count rate is due to mesons incident on the crystal from all directions and that the crystal therefore presents an "effective area" to the cosmic ray flux. Individual users will need to find an effective area for their own crystal. The muon flux is peaked at the zenith and the intensity per unit solid angle varies with zenith angle ζ as $\cos^{2.1}\zeta$ (Allkofer et al. 1975). Enthusiasts may calculate their effective areas accordingly. In practice, it is probably sufficient to use the horizontal projected area. In our crystal, for which diameter and length are equal, we approximated it by a sphere of equal volume. This approximation may be sufficient for crystals of other shapes but we have not tested this by calculation.

To find the dose-rate, the integral count rate must first be converted to counts per unit area per second N by dividing by the effective area of the NaI crystal. Then, using an energy loss rate of 1.85 MeV $gm^{-1}cm^2$ in standard rock (Hayakawa 1969) the dose-rate D' is given by:

$$D' = 9.37\,N \qquad .....1)$$

D' is in Gy ka^{-1} in standard rock when N is in units of $cm^{-2}\ s^{-1}$, with a typical uncertainty of about 10 %, which includes the systematic uncertainty in the primary cosmic ray intensity (Prescott and Hutton, 1994). Relation (1) is valid for all locations and crystal sizes

In the Adelaide case, the muon count rate from the data of fig. 1 was 0.020 $cm^{-2}\ s^{-1}$, giving a dose-rate of

0.188 Gy ka^{-1} which, in view of the uncertainty in the exact amount of absorber above the apparatus, is in satisfactory agreement with 0.183 found by applying Prescott and Hutton (1994).

The measurements confirm that it is possible to measure cosmic ray intensities with a scintillometer in the field. A counting threshold above 4 MeV is recommended.

Envoi

There is no compelling reason to prefer *in situ* measurements of cosmic ray dose-rates as opposed to the use of published procedures and tables, such as those in Prescott and Hutton (1994). However, if the count rate information is easily obtainable from the instrument, it provides an additional estimate of cosmic ray dose-rate. It has additional value in cases of unusual local geometry, such as caves, where the shape and density of the overburden may be uncertain (see e.g. Smith et al. 1997).

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