Revised decay energies of potassium, thorium and uranium, and the thermal history of the earth

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The elements K, Th and U between them are responsible for most of the radioactive heat production in the Earth. Mantle convection and the dynamic state of the Earth's surface at the present day are a direct consequence of dissipation of radiogenic and primordial heat from the Earth's interior. An accurate value for the rate of heat generation in the Earth today is therefore of paramount importance. For example, the ratio of present heat production to heat loss from the Earth - the Urey ratio - is a measure of the efficiency with which the Earth dissipates heat today. In addition, knowledge of how heat production has varied throughout geological time is a prerequisite for discussing the thermal and tectonic evolution of the Earth.

The heat production arising from the nuclides ^{40}K, ^{232}Th, ^{235}U and ^{238}U at any time depends upon: (1) the absolute abundance of each nuclide, (2) their respective decay constants, and (3) the decay energy per disintegration. Although (1) and (2) are known reasonably well, the decay energies still remain relatively uncertain. The reason for this is that during β-decay an antineutrino (ν) is emitted together with the β particle, and the ν carries off a substantial portion of the total disintegration energy from the Earth entirely. A neutrino is also emitted during electron capture (EC) reactions, accounting for >99% of the total transition energy. Thus, some of the total decay energy in the β-decay paths of the Th- and U-series chains and $^{40}K \rightarrow {}^{40}Ca$ and the EC reaction $^{40}K \rightarrow {}^{40}Ar$ is not deposited in the Earth. In such cases, the radiogenic heat generated cannot be simply calculated from the energy (or mass) differences of the parent nuclide and daughter products. This contrasts with α-decay and γ transitions for which all of the decay energy eventually emerges via recoil, scattering and absorption as heat.

The disintegration energies of K, Th and U currently in use were originally estimated by Birch (1954) and Urey (1955). These authors used the assumption that two thirds of the β transition energy was lost in each case. No refinements other that for changes in the decay constants (Wetherill, 1966; Turcotte and Schubert, 1982) have been made since then. In this study the mean ν energies for each transition have been determined from the calculated spectrum of β particle energies using classical Fermi theory. Since β decay can often occur to many excited states of the daughter nucleus (followed by γ emission) this has involved a consideration of 183 β transition pathways for the Th- and U- series (Lederer and Shirley, 1978). Central to the Fermi theory is the determination of the Fermi function $F(Z,W)$. This describes how the β spectrum becomes distorted to lower energies by the presence of the charge on the daughter nucleus. The calculation of $F(Z,W)$ involves the relativistic solution for the wave functions of the β and ν at the edge of the nucleus; this was done following the methods of Gove and Martin (1971). Additional corrections were applied for the effects of (1) finite nuclear size, and (2) screening from the extra-nuclear electrons using Garrett-Bhalla nuclear potential shifts. Transition branchings, their probabilities, the associated γ energies and the nuclear spin and parity changes were taken from the tables in Lederer and Shirley (1978). Most of the Th- and U-series transitions are of the 'first order non-unique forbidden' type based upon spin-parity selection rules. However, to simplify matters it was assumed that each transition was 'allowed' for which the Fermi theory is exact. In addition, the $^{40}K \rightarrow {}^{40}Ca$ transition is of 'fourth order unique forbidden' type for which the shape correction factor has been empirically measured (Behrens and Szybisz, 1976). The final decay energies of the Th- and U-series were calculated from the absolute masses of parent and final daughter nuclides and products minus the energy lost as neutrinos weighted by the respective transition probabilities and branching ratios. The energy lost with the ν was found to range between ~60 and 80% of the energy of each transition. However, most transitions leave the daughter nucleus in an excited state with some of the energy emerging in the form of delayed γ-rays.

The resulting decay energies of the ^{232}Th, ^{235}U and ^{238}U chains are within <5% of the presently accepted values (Wetherill, 1966; Turcotte and Schubert, 1982). However, the calculated value for ^{40}K is considerably higher. Radiogenic heating from ^{40}K may therefore have played a greater role during the early Earth than suggested previously.