PERSPECTIVES: RADIOISOTOPE DATING

Absolute Ages Aren't Exactly

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Our knowledge of the time scale of human evolution, the age of Earth and the solar system, and various geological and biological milestones in between is based on radioactivity. Decay rates and observed abundances of parent and daughter isotopes can be used to assign dates to various materials and, therefore, events. Determining causality in sciences like geology, paleontology, archeology, or cosmology often rests upon determining age relations, and the reliability of conclusions, therefore, depends on the accuracy of the dating. Various radioactive decay schemes are applicable to questions whose time scales are comparable to their half-lives ($t_{1/2}$); thus, the β^- decay of ^{14}C to ^{14}N ($t_{1/2}$ = 5730 years) is relevant to New World archaeological studies, whereas the serial α decay of ^{238}U to ^{206}Pb ($t_{1/2} = 4.468 \times 10^9$ years) extends to the early history of Earth and the solar system. Anomalous concentrations of parent/daughter isotopes extend the utility range of radioisotopic systems to large multiples of the half-life. Improved techniques and instruments for measuring isotope ratios have reduced measurement errors to the point that analytical precision is often less than 0.5% of the age (in some cases better than 0.1%), allowing increasingly sensitive resolution of time when the same isotopic system and methodology are used to date different samples.

Enhanced online at www.sciencemag.org/cgi/content/full/282/5395/1840

Unfortunately, accuracy has lagged behind precision in many radioisotopic dating methods, largely because of uncertainties in the decay constants themselves (see figure). The discrepancy between accuracy and precision is inconspicuous to nonspecialists because uncertainties in decay constants are, with few exceptions [see (*1*, *2*), for example] almost never propagated into the error reported for age determinations. Historic indifference to this source of systematic error may stem in part from the fact that it is unclear in many cases exactly what the uncertainty is in a quantitative sense.

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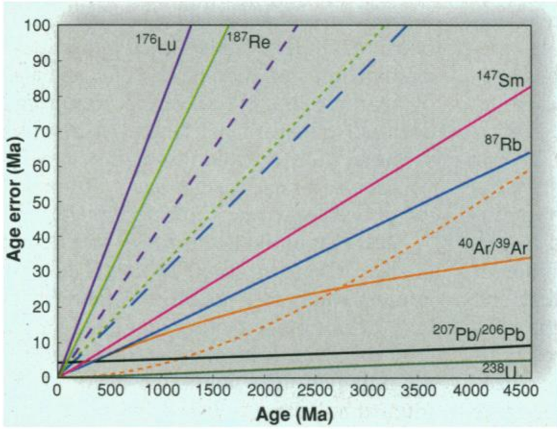
In several cases, different values for a given decay constant are used in different disciplines. The decay constants currently used by geochronologists and cosmochronologists for ^{238}U-^{206}Pb, ^{235}U-^{207}Pb, ^{232}Th-^{208}Pb, ^{87}Rb-^{87}Sr, ^{40}K-^{40}Ar, and ^{40}K-^{40}Ca were adopted by consensus in 1977 (*3*), but no values were explicitly recommended for their uncertainties. The decay constants used in the nuclear physics and chemistry literature (*4*) are based on counting experiments of α, β, or γ radiation activity, whereas the values used by



Growing apart. Error in age (at 95% confidence) due solely to decay constant uncertainties as a function of time. Solid lines show results of propagating errors from experimental data (*5*) used by geochronologists and cosmochronologists; dashed lines indicate difference between ages based on values used by geochronologists versus those used by nuclear physicists (*4*).

geochronologists also include, in some cases, the results of geologic intercalibrations or laboratory accumulation experiments. For ^{40}K, the two communities use values for the total decay constant that differ by 2.1%, simply because of different choices in filtering the same set of activity data. For ^{87}Rb, the value used by geochronologists, based on laboratory in-growth experiments (*5*), differs by nearly 3% from the value used in the nuclear physics and chemistry literature, a difference well beyond stated errors of the two values (see the figure).

Decay constant uncertainty is problematic when ages based on different systems are compared, as is routinely the case in calibration of the geologic time scale or in the fields of thermochronology and cosmochronology. Absolute discrepancies are most striking for meteorites about 4.6 billion years old. At this age, uncertainties from decay constant errors alone (see figure) are larger than 34 million years for all systems except for those based on decay of ^{235}U or ^{238}U (or both), which, through the ^{207}Pb/^{206}Pb method, has errors ranging from ±4 million years at 100 million years to only ±9 million years at 4600 million years.

Slow initial cooling or collisional reheating (or both) in the early solar system is implied by ^{40}Ar/^{39}Ar (based on ^{40}K-^{40}Ar) dating of meteorites, which tend to yield younger ages than the ^{207}Pb/^{206}Pb system, because of inferred diffusive loss of ^{40}Ar at relatively low temperatures. The ^{40}Ar/^{39}Ar system depends on two decay constants because of the branched decay of ^{40}K and also on standards that introduce additional decay constant uncertainty (*2*).

As shown in the figure, the age uncertainty in ^{40}Ar/^{39}Ar ages at 4.6 billion years due to decay constant effects alone is ~34 million years, and, therefore, a critical value test requires a minimum difference of 35 million years between ^{207}Pb/^{206}Pb and ^{40}Ar/^{39}Ar ages (neglecting analytical errors and errors in ^{40}K-^{40}Ar data for the standard) to infer that the ages are resolvable at the 95% confidence level. This resolvability threshold is a minimum because the uncertainties (*5*) for the ^{40}K decay constants are optimistic compared with those (*4*) based on less filtered treatments of the same data. The bottom line is that without consideration of the relevant decay constant errors, one could mistakenly conclude that the apparent discrepancy between ^{40}Ar/^{39}Ar and ^{207}Pb/^{206}Pb ages conflicts with the rapid-cooling chronologies implied by extinct-nuclide studies (*6*).

Calibration of the geologic time scale also requires consideration of all systematic errors, and here decay constant uncertainties have substantial and historically underappreciated effects. The end of the Paleozoic era, marked by the most extensive mass extinction in the geologic record, has been dated very precisely by ^{40}Ar/^{39}Ar methods at 250.0 ± 0.2 million years ago, enabling comparison with the inception of massive volcanism in the Siberian Traps—also dated by ^{40}Ar/^{39}Ar, at 250.0 ± 0.3 million years ago—appropriately neglecting decay constant and standard-related errors (*7*). These same two events have been dated by ^{206}Pb-^{238}U methods (*8*) at 251.4 ± 0.3 and 251.3 ± 0.2 million years ago. Both radioisotopic systems indicate synchrony of the two events, but comparison between the two systems would suggest discrepancies unless errors in decay constants (and standards for the ^{40}Ar/^{39}Ar method) are considered. Thus, the ages for the Permian-Triassic boundary are 251.4 ± 0.4 million years ago (^{206}Pb-^{238}U) and 250.0 ± 4.4 million years ago (^{40}Ar/^{39}Ar), clearly not statistically resolvable. Neglecting uncertainty in ^{40}K-^{40}Ar data for the ^{40}Ar/^{39}Ar standard, which compounds decay constant error, only decreases the absolute error to ±3.6 million years.

The precisely known decay constants for ^{238}U and ^{235}U, as well as the existence of internal reliability criteria in the U-Pb systems (*9*), offer a "gold standard" for geochronology and cosmochronology. Normalization of other radioactive systems' decay constants to those of ^{238}U and ^{235}U, either directly or indirectly by comparison with the ^{207}Pb/^{206}Pb system (*10*), provides advantages over disintegration counting in experimentally difficult cases such as the low-energy β decay of long-lived radionuclides. Naturally, such normalizations require propagation of the decay constant errors in ^{207}Pb/^{206}Pb ages (see above) and demonstrated absence of nonanalytical (that is, "geologic") errors but in principle can yield improved accuracy for many decay constants (those for ^{87}Rb, ^{147}Sm, ^{176}Lu, and ^{187}Re, for example).

Reconciliation of increasingly precise results from different dating methods is forcing geochronologists to confront systematic errors. Twenty-one years ago, Steiger and Jäger (*3*) stated that decay constants "will be reviewed by the subcommission from time to time so as to bring the adopted conventional values in line with significant new research data" (p. 359). It might be added that increased communication between geochronologists and nuclear chemists and physicists would be desirable. Additionally, evaluation of ^{40}Ar/^{39}Ar standards has never been formally undertaken by any international organization and is overdue.

References and Notes

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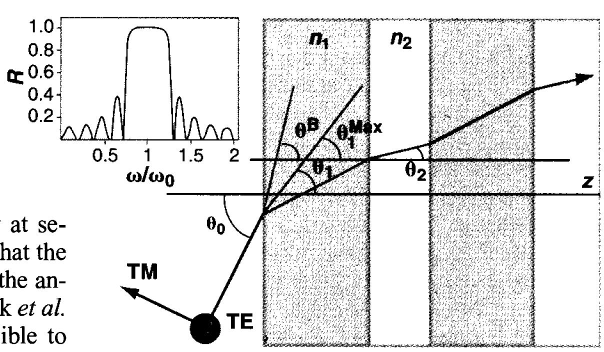
PERSPECTIVES: OPTICAL PHYSICS

Mirror on the Wall: You're Omnidirectional After All?

Jonathan P. Dowling

Every once in a while somebody comes up with an important new idea that, in hindsight, is so clear and obvious you could kick yourself for not having thought of it first. The mirror reported last week in *Science* and developed by Joannopoulos and his colleagues at the Massachusetts Institute of Technology is just such an idea (*1*). Dielectric mirrors are a special type of reflector carefully constructed out of thin layers chosen to create unusually high reflectivity at selected wavelengths. The problem is that the reflectivity is extremely sensitive to the angle at which light hits the mirror. Fink *et al.* (*1*) have now shown that it is possible to construct a periodic, multilayer, thin-film dielectric mirror that is highly reflective over a broad range of wavelengths at all angles—even up to 90° off axis (see figure).

Consider in the figure a light ray propagating through a periodic dielectric stack, entering at an angle of incidence θ_0. On axis ($\theta_0 = 0$), the fraction of radiant energy, *R*, reflected from the stack will look like the graph in the inset, which shows a broad frequency range over which the thin-film stack is highly reflective. (The graph was generated assuming a quarter-wave stack of indices of refraction $n_1 = 1$ and $n_2 = 2$ with five periods.) Midgap corresponds to a quarter-wave reference frequency ω_0. Dielectric mirrors made in this fashion can be made much more reflective and much less lossy than metal mirrors, and so they have many applications, such as in microcavity laser physics for the construction of high-gain, vertical-cavity, surface-emitting lasers (*2*) and the construction of lossless optical transmission filters (*3*).



A different angle. A light ray refracting and propagating through a multilayer thin-film stack. There are two polarization modes shown, indicating the TE mode with the electric field vector polarized parallel to the first interface plane (*s* polarized) and the TM mode with the magnetic field parallel to the plane (*p* polarized). If the difference between the incident index n_0 and that of the first layer n_1 is large enough, then the external light ray cannot couple to the internal mode at Brewster's angle inside the stack—where *p*-polarized light would otherwise propagate all the way through without reflection. **(Inset)** Reflectivity (*R*) of a five-layer thin-film stack as a function of frequency.

The first problem with these mirrors is that the broad reflection band shifts to higher frequencies ω as a function of incident angle, θ_0. The reflection bandwidth $\Delta\omega/\omega_0$ (where ω_0 is the center frequency of the mirror) is proportional to the difference between the indices of refraction of the layers, n_1 and n_2. The question is, can one make $\Delta\omega/\omega_0$ so big that one runs out of angle before one runs out of reflection band (photonic band gap)? The conventional wisdom was no, because of the "Brewster window" problem, which I now describe.

There are two independent light polarization modes to consider in this problem: TE (transverse electric) modes (*s* polarized) and TM (transverse magnetic) modes (*p* polarized) where the electric or the magnetic field vector, respectively, is parallel to the dielectric interface (shown in the figure). On axis, the reflection band for both polariza-

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