done: optimizing VCSEL cavity design, understanding and improving self-assembled quantum dot growth, or solving the longstanding problems of polarization control and emission-mode stabilization in VCSELs, for example. Gallium nitrides are now providing another dimension, with the discovery (*11*) that laser emission in the most recent InGaN lasers is probably from self-organized dots.

**References**

1. H. Saito, K. Nishi, I. Ogura, S. Sugou, Y. Sugimoto, *App. Phys. Lett.* **69**, 3140 (1996).
2. H. Soda, K. Iga, C. Kitahara, Y. Suematsu, *Jpn. J. Appl. Phys.* **18**, 2329 (1979); K. Iga, F. Koyama, S. Kinoshita, *IEEE J. Quantum Electron.* **24**, 1845 (1988).
3. R. Service, *Science* **267**, 1093 (1995).
4. H. Kosaka, H. K. Dutta, K. Kurihara, Y. Sugimoto, K. Kasahara, *IEEE Photon. Lett.* **7**, 926 (1995).
5. H. Hirayama, T. Hamano, Y. Aoyagi, *Appl. Phys. Lett.* **69**, 791 (1996).
6. L. Goldstein and F. Glas, *ibid.* **47**, 1099 (1985).
7. V. A. Shchukin, N. N. Ledentsov, P. S. Kop'ev, D. Bimberg, *Phys. Rev. Lett.* **75**, 2968 (1995).
8. J. M. Moison, F. Houzai, F. Barthe, L. Leprince, *App. Phys. Lett.* **64**, 196 (1994); R. Noetzel, J. Temmyo, T. Tamamura, *Nature* **369**, 131 (1994); N. P. Kobayashi, T. R. Ramachandran, P. Chen, A. Madhukar, *Appl. Phys. Lett.* **68**, 3299 (1996).
9. J. Tersoff, C. Teichert, M. G. Lagally, *Phys. Rev. Lett.* **76**, 1675 (1996).
10. Q. Xie, A. Madhukar, P. Chen, N. Kobayashi, *ibid.* **75**, 2541 (1995).
11. S. Nakamura and G. Fasol, *The Blue Laser Diode: GaN-based Light Emitters and Lasers* (Springer-Verlag, Heidelberg, 1997), chap. 14.

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METEORITICS

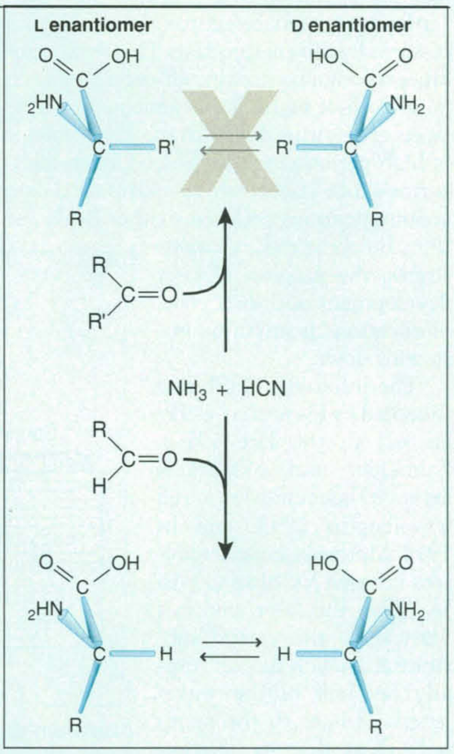
# Extraterrestrial Handedness?

Jeffrey L. Bada

Asymmetry in the handedness of molecules that arise through biosynthesis is perhaps one of the more unique features of life on Earth. A well-known example is that only L amino acids are incorporated into proteins during transcription even though amino acids with a chiral or asymmetric carbon atom can exist as two chemically equivalent optical isomers, the L and D enantiomers. How this L amino acid handedness, or homochirality, originated in terrestrial life has been an area of considerable discussion (*1*). Prebiotic syntheses of amino acids either on Earth or elsewhere would be expected to produce racemic mixtures (equal amounts of the L and D enantiomers, or D/L = 1.0). Therefore, an enantiomeric selection process was required at some stage in the origin or evolution of life on Earth. Because there is no apparent biochemical reason why L amino acids would be selected over D amino acids, the homochirality has been considered to be simply a matter of chance.

Analyses of carbonaceous chondritic meteorites have been of central importance in the debate about the origins of homochirality. The discovery in 1970 that the Murchison meteorite contained endogenous amino acids (*2*), some of which play an essential role in biochemistry as we know it, provided the first conclusive evidence that amino acids have been produced by abiotic cosmochemical reactions either somewhere in the solar system or in extrasolar environments. However, because those amino acids processing a chiral carbon were found to be racemic within the limits of the measurements, there appeared to be no evidence that the exclusive use of L amino acids in terrestrial biochemistry was preordained. Subsequent analyses of Murchison made more than a decade after the original reports indicated that some protein amino acids showed an apparent enrichment in the L enantiomers, but this excess was considered to be due to terrestrial contamination rather than the result of some sort of abiotic enantiomeric resolution or enrichment process (*3*). However, as reported by Cronin and Pizzarello on page 951 of this issue (*4*), some unusual amino acids present in the Murchison meteorite apparently do have small excesses of the L enantiomers (that is, D/L < 1.0). These measurements have minimized the contamination problem by focusing on amino acids that either are extremely rare or have never been reported in terrestrial organisms or the geosphere.

Four α-dialkyl amino acids—α-methylisoleucine and α-methylalloisoleucine (2-amino-2,3-dimethylpentanoic acid), α-methylnorvaline (2-amino-2-methylpentanoic acid), and isovaline (2-amino-2-methylbutanoic acid)—are reported to have an L enantiomeric excess of 2 to 9% (*4*). Only isovaline has been reported in some microbial peptides, where it is present as either the L or D enantiomer (*5*). The α-hydrogen analogs of two of these α-dialkyl amino acids, norvaline and α-amino-*n*-butamoic acid, are racemic, suggesting that enantiomeric excess is only preserved in amino acids that are resistant to racemization (see figure). The analyses were carefully carried out, and there is no obvious reason to believe that the enantiomeric excesses are analytical artifacts, although confirmation with other analytical methodologies, and the detection of similar excesses in other carbonaceous chondrites, are certainly required. Assuming that the enantiomeric excesses are indeed real, how were they generated and do they have anything to do with the L amino acid homochirality found in life on Earth?



**α–Amino acids in carbonaceous chondrites** are thought to have been formed by the Strecker synthesis reaction in aqueous solutions. The reaction of HCN with aldehydes and ammonia generates amino acids with an α hydrogen (lower branch), which can racemize. The similar reaction with ketones produces α-dialkyl amino acids (upper branch), in which racemization is prevented because of the absence of an α hydrogen.

α–Amino acids in carbonaceous chondrites are generally thought to have been generated by the reaction of aldehydes, ketones, ammonia, and hydrogen cyanide (the Strecker reaction shown in the figure) in aqueous fluids on the meteorite parent body (*6*). This synthetic pathway would produce racemic mixtures of amino acids with a chiral α carbon because the starting aldehydes are achiral (that is, they lack an asymmetric carbon); at chiral β carbons, racemic mixtures would also be expected, unless the starting chiral ketones were already enriched in one enantiomer by some process. The finding of L enantiomeric excesses in both α-methylisoleucine and α-methylalloisoleucine,

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The author is at Scripps Institution of Oceanography, University of California at San Diego, La Jolla, CA. 92093–0212, USA. E-mail: jbada@ucsd.edu

and similar L enantiomeric excesses in isovaline and α-methylnorvaline, thus challenges the accepted view that the Strecker pathway produced the Murchison α-amino acids. The nearly equivalent L enantiomeric excesses for these α-dialkyl amino acids suggest that they formed in an environment where an asymmetric influence was present in the synthetic environment, something that would appear to be unlikely on meteorite parent bodies. Cronin and Pizzarello propose (*4*) that α-amino-*n*-butamoic acid and norvaline are racemic, whereas their α-dialkyl analogs show an L enantiomeric excess could indicate that the enantiomeric excess in α-hydrogen amino acids was erased by subsequent racemization during parent body aqueous alteration (see figure). They also suggest that the α-dialkyl amino acids may have been produced in presolar environments, whereas the α-hydrogen amino acids were synthesized on meteorite parent bodies by way of the Strecker pathway. This latter proposal appears to me to be unlikely because both α-hydrogen and α-dialkyl amino acids are readily synthesized in laboratory-based abiotic simulations of the Strecker synthesis (*6*).

A number of possible mechanisms for generating enantiomeric excesses in cosmogeochemical environments have been suggested (*1*). Cronin and Pizzarello focus on the proposal that circularly polarized light associated with the synchrotron radiation of neutron stars could result in asymmetric organic synthesis or degradation, but other processes such as spontaneous physical symmetry breaking in β decay and in weak neutral currents seem equally plausible from the theoretical point of view. None of the proposals are overly compelling, and there is a general lack of convincing experimental evidence for any of them. Although very small enantiomeric excesses (~2%) have been generated from racemic leucine irradiated with circularly polarized ultraviolet light, there was extensive decomposition (59 to 75%) during the experiment (*7*). This implies that amino acid survival during this type of enantiomeric enrichment process would be extremely poor. The findings of Cronin and Pizzarello are probably the first demonstration that there may be a natural L-enantiomeric enrichment process in certain cosmochemical environments. This discovery of L enantiomeric excesses for the α-dialkyl amino acids in Murchison, if verified, is certain to generate a flurry of new experiments and proposals by theorists.

Could these enantiomeric excesses be linked to the origin of L amino acid homochirality in life on Earth? First of all, the enantiomerically enriched α-dialkyl amino acids would have to be delivered to Earth without extensive decomposition. Whether exogenous delivery could have provided sufficient amounts of organic compounds necessary for the origin of life, or to sustain life once it started, is largely unknown, although extraterrestrial organic compounds, including racemic (within the precision of the measurements) isovaline, have been detected in deposits associated with impact events (*8*). The reported L amino acid excesses are very small and would need to be amplified by some process in order to generate homochirality. Even if this did take place, the L amino acid homochirality would be associated with α-dialkyl amino acids, which are not major players in modern protein biochemistry. If α-dialkyl amino acids had an important role during the origin of biochemistry, then initially life may have been based on a different protein architecture because peptides made primarily of these amino acids tend to form $3_{10}$-helical structures rather than the α-helical conformation associated with proteins made of α-hydrogen amino acids (*5, 9*). Finally, the homochirality of α-dialkyl amino acids would need to be somehow transferred to the α-hydrogen protein amino acids either during the origin or early biochemical evolution of life on Earth.

If the origin of the homochirality of amino acids in terrestrial life was preordained, then extinct or extant life elsewhere in the solar system would likely be based on the same amino acid handedness. If this is the case, it will make it more difficult to ascertain whether life arose independently elsewhere in the solar system, especially Mars, unless the extraterrestrial life was based on a different suite of L amino acids, such as α-dialkyl amino acids.

An enhanced version of this Perspective, with live links, can be seen in *Science* Online at http://www.sciencemag.org/

**References**

1. For example, see J. L. Bada, *Nature* **374**, 594 (1995); D. B. Cline, Ed., *Physical Origin of Homochirality in Life* (American Institute of Physics, New York, 1996), and references therein.
2. K. Kvenvolden *et al.*, *Nature* **228**, 923 (1970); K. Kvenvolden, J. G. Lawless, C. Ponnamperuma, *Proc. Natl. Acad. Sci. U.S.A.* **68**, 486 (1971); G. E. Pollack, C. Cheng, K. A. Kvenvolden, *Geochim. Cosmochim. Acta* **39**, 1571 (1975).
3. M. H. Engel and B. Nagy, *Nature* **296**, 837 (1982); J. L. Bada *et al.*, *ibid.* **301**, 494 (1983).
4. J. R. Cronin and S. Pizzarello, *Science* **275**, 951 (1997).
5. G. Vale *et al.*, *J. Am. Chem. Soc.* **111**, 6828 (1989), and references therein.
6. S. L. Miller and L. E. Orgel, *The Origins of Life on Earth* (Prentice-Hall, River Edge, NJ, 1974), pp. 83–92; Y. Wolman, W. J. Haverland, S. L. Miller, *Proc. Natl. Acad. Sci. U.S.A.* **69**, 809 (1972); E. T. Peltzer, J. L. Bada, G. Schlesinger, S. L. Miller, *Adv. Space. Res.* **4**, 69 (1984); J. R. Cronin, G. W. Cooper, S. Pizzarello, *ibid.* **15**, 91 (1995).
7. J. J. Flores, W. A. Bonner, G. A. Massey, *J. Am. Chem. Soc.* **99**, 3622 (1977).
8. M. Zhao and J. L. Bada, *Nature* **339**, 463 (1989); L. Becker, R. J. Poreda, J. L. Bada, *Science* **272**, 249 (1996).
9. I. L. Karle and P. Balaram, *Biochemistry* **29**, 6747 (1990).

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AGING

# What Makes Us Tick?

Leonard Guarente

What determines how long an animal can live? Some have argued that the life-span of a species is limited by a fixed total metabolic potential that is consumed over a lifetime. This follows from the observation that smaller animals have faster metabolic rates and generally shorter life-spans (*1*). Consistent with this idea, rats or mice that have existed on a diet reduced in calories live longer than animals that were allowed to eat as much as they liked. A corollary of this view is that the "clock" that times aging might be cumulative damage that is generated by toxic by-products of metabolism, such as oxygen radicals. Others have suggested that life-span may be genetically determined and that these genetic factors override any simple metabolic readout. This could explain why bats and mice, mammals of roughly the same size, have life-spans that differ by a factor of 5 to 10. This view also suggests that the clock is a genetic program set at a different rate in each species. The cloning and sequencing of the *clk-1* gene of *Caenorhabditis elegans* reported in this issue (*2*), along with recent findings discussed below, suggests how both of these propositions may be true.

Worms that have a mutant form of *clk-1* enjoy life-spans that are up to 50% longer than those of wild-type worms (*3, 4*) and also display a decreased rate of embryonic

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The author is in the Department of Biology, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. E-mail: leng@mit.edu