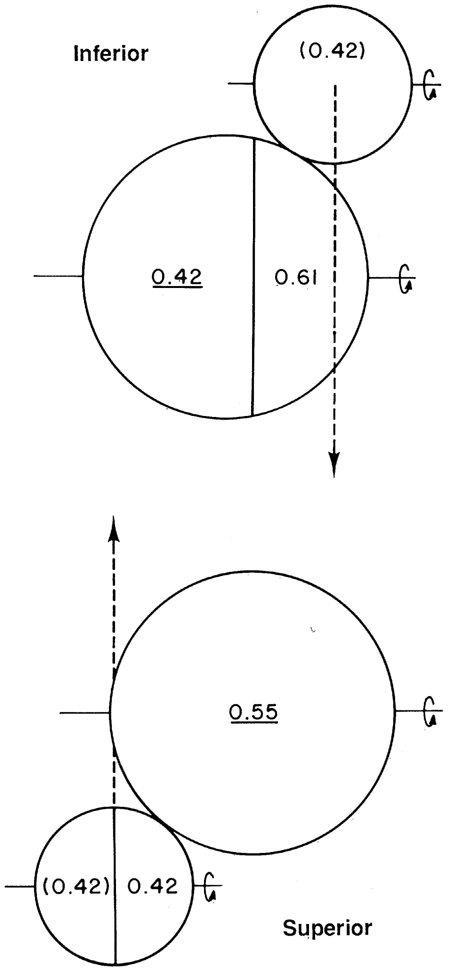

Fig. 2. Surface albedo distribution of the Pluto-Charon system. The unmarked albedo values were determined from the least-squares fit to the observations. If the values in parentheses are assumed, the underlined values can be derived.

system object with strikingly different hemispherically sized geologic units. The existence of this hemispherical color difference does not necessarily imply an albedo difference, which would invalidate the uniform surface albedo assumed earlier, but the possibility does admittedly exist (*9*).

Small-scale surface albedo features on either object should manifest themselves as small deviations from a smooth event light curve. A comparison of the 5 April and 27 June superior events shows a bump early in both events. The relative times of these bumps are shifted slightly, but this effect is expected, because the orientation of the limb of Pluto was different for these two events. The time shift information is essential to localize the albedo feature; given only one event, the location could be anywhere along the intersection of Charon's disk and Pluto's limb at the corresponding time. We feel confident that real albedo features have been detected on Charon. Although similar deviations have been seen in some high-quality inferior event data, which would indicate albedo features on Pluto, these deviations have yet to be confirmed.

In conclusion, we have already learned a great deal about the Pluto system from just the first 2 years of events. The next 2 years are critical for determining the individual radii of Pluto and Charon and the mean density of the system. Total superior events offer the opportunity to study Pluto uncontaminated by the light of Charon with both spectroscopic and colorimetric techniques. Similar observations of the combined light of Pluto and Charon immediately preceding or following a total event can be differenced with the observations of Pluto alone to yield the corresponding information on Charon alone.

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9. New observations obtained by several investigators in 1987 have further confirmed these color findings.
10. We thank the telescope allocations committee at the Institute for Astronomy for their support of this project. Because of the timing of these mutual events, the telescope scheduler faces a difficult task, and we also thank him for his patience. We acknowledge the assistance of F. Cheigh and B. Barnes at the 2.24-m telescope. The work at the University of Hawaii is supported by NASA grant NGL 12-001-057, and that at the University of Texas by NASA grant NGR 44-012-152. A portion of the computations done in the course of this research were performed with the facilities of the San Diego Supercomputer Center, which is supported by the National Science Foundation.

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An Invariance in the Isoheptanes of Petroleum

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Four isoheptanes in petroleum display a remarkable invariance in a ratio of sums of concentrations. The isoheptanes are not at thermodynamic equilibrium, nor are they fixed to some constant composition. The four isomers display coherent change in relative amounts but maintain invariance in the ratio of sums. Within sets of genetically related petroleum samples, invariance reaches levels that approach the limits of our analytical precision. The invariance is inconsistent with a chemical origin that involves the thermal fragmentation of natural products or their derivatives. It suggests a reaction process at steady state, in which relative rates of product formation are constant. A mechanism is proposed in which the four isoheptanes are formed pairwise and sequentially through two intermediates in a catalytic process that operates at steady state.

THIS REPORT FOCUSES ON THE chemical origin of the light hydrocarbons in petroleum. Are light hydrocarbons derived, for example, from biological precursors that were somehow structurally altered in the process of kerogen synthesis? Or are they formed through other chemical processes unrelated to specific organic compounds in the geosphere? The existence of structural precursors to the light hydrocarbons in kerogen and the generation of light hydrocarbons through the thermal breakdown of kerogenous sediments (*1*) is not questioned. Interest is centered on the chemical events that precede thermal generation. The stimulus that directed attention to these questions rests in the structural variations that exist in the light hydrocarbons, their dissimilarities to natural products, and their widespread occurrence in petroleum.

It was suggested nearly 30 years ago that the overall compositional mix of light isoparaffins in petroleum was constant (*2*). However, later work seemed to indicate that this view was only approximate (*3*), and the idea failed to gain currency. In this analysis of the isoheptanes rather strong linear relations have emerged, particularly when certain isomers are analyzed in specific compositional configurations. For example, the isoheptanes display a striking proportionality between the four isomers: 2-methylhexane (2-MH), 3-methylhexane (3-MH), 2,3-dimethylpentane (2,3-DMP), and 2,4-di-

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Table 1. Invariance data for several homologous sets of oils. Means, regression slopes, and root-mean-square errors for the ratio [(2-MH) + (2,3-DMP)]/[(3-MH) + (2,4-DMP)]. The sets are identified in Fig. 2; *n* is the number of oils in each set.

Set	*n*	Mean ± SD	Regression slope ± SE	Root-mean-square error
Sabine	13	1.09 ± 0.02	1.12 ± 0.0053	0.00366
Bee	10	1.12 ± 0.103	1.13 ± 0.02	0.0382
Houston	11	1.09 ± 0.041	1.18 ± 0.029	0.015
Offshore	18	1.07 ± 0.0092	1.08 ± 0.0023	0.0033
Midland	22	0.786 ± 0.023	0.837 ± 0.015	0.01

methylpentane (2,4-DMP). Regardless of their absolute concentrations in oils, their relative amounts are such that the ratio of sums of concentrations

$$\frac{(2\text{-MH}) + (2,3\text{-DMP})}{(3\text{-MH}) + (2,4\text{-DMP})} \simeq 1 \qquad (1)$$

remains approximately one (Fig. 1). The concentrations of these four isoheptanes vary from 0.001% by weight to 10%, with a mean of 0.9% total oil. This database of approximately 2000 oils was constructed without discrimination. Thus it includes samples believed to have experienced some postgeneration form of compositional alteration, such as biodegradation (*4*), thermal cracking, or possibly mineral-catalyzed degradation (*5*).

The proportionality in Fig. 1 relates to all petroleum, regardless of source or degrees of alteration. Unaltered oils believed to be genetically related (referred to as "homologous") can express an extraordinary invariance in the ratio of sums. One example is that of 13 homologous oils from Sabine Parish, Louisiana (Fig. 2 and Table 1). A linear regression of the Sabine oils gives

$$(2\text{-MH}) + (2,3\text{-DMP}) = 1.12\,[(3\text{-MH}) + (2,4\text{-DMP})] \qquad (2)$$

Considering errors in sampling, transport, and analytical procedure, data variance in the Sabine set is within overall analytical error.

The Sabine set reveals two additional characteristics that are significant. The first is a constant value in the ratio of methylhexane to dimethylpentane. A least-squares linear regression of the Sabine data gives

$$(2\text{-MH}) + (3\text{-MH}) = 3.85\,[(2,3\text{-DMP}) + (2,4\text{-DMP})] \qquad (3)$$

Second, although this ratio remains fixed at 3.85, for exponentially increasing isoheptane concentration the logarithms of the ratios (2-MH)/(3-MH) and (2,4-DMP)/(2,3-DMP) increase in concert (Fig. 3). Figure 3 illustrates a fundamental characteristic of invariance within homologous sets, namely, that invariance in the ratio of sums is preserved while the two ratios, (2-MH)/(3-MH) and (2,4-DMP)/(2,3-DMP), undergo coherent change.

The linear relations in the Sabine set take on additional importance in that the isoheptanes are far from thermodynamic equilibrium for all the temperatures that generally occur in subsurface petroleum habitats. The reported equilibrium values for the ratios (2-MH)/(3-MH) and (2,4-DMP)/(2,3-DMP) are 1.99 and 2.48 at 300 K and 1.16 and 0.84 at 500 K, respectively (*6*). In the database of petroleum samples, these ratios range between 0.5 to 1.2 and 0.03 to 0.8, respectively.

Thus invariance in the Sabine set does not reflect some static, fixed distribution of isomers. It indicates a dynamic system that displays two compositional constraints that require explanation:

$$\frac{[(2\text{-MH}) + (3\text{-MH})]}{[(2,3\text{-DMP}) + (2,4\text{-DMP})]} = \text{constant} \qquad (4)$$

$$\ln[(2\text{-MH})/(3\text{-MH})] = m\,\ln[(2,4\text{-DMP})/(2,3\text{-DMP})] + b \qquad (5)$$

The most reasonable pathway to the generation of isoheptanes appears to be the simple thermal fragmentation of natural products or their kerogenous derivatives.

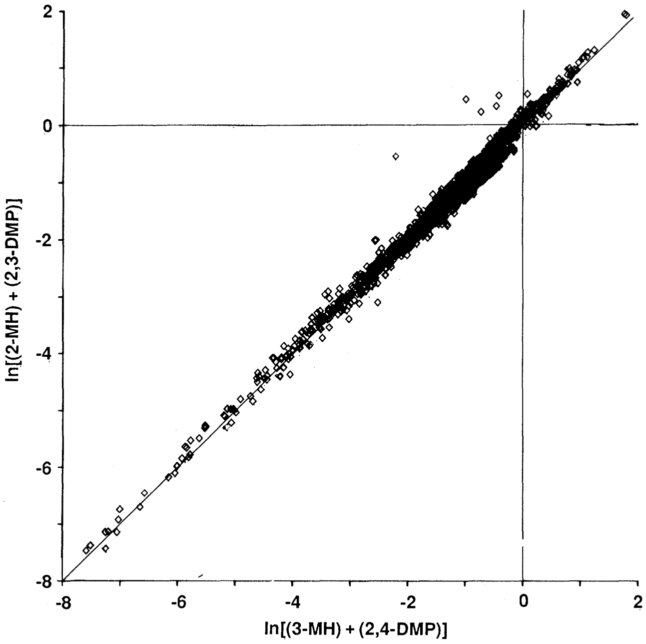


Fig. 1. A plot of ln[(2-MH) + (2,3-DMP)] as a function of ln[(3-MH) + (2,4-DMP)] for the database of 1880 oils. (The unity-slope line, for which the ratio of sums is exactly one, is shown for clarity.) A linear regression of the data gives a slope of 0.978 ± 0.003 SE and intercept of 0.0072 ± 0.006 SE. The mean of the ratio of sums is 1.06 ± 0.336 SD. To construct this database, oil deposits from all of the producing stratigraphic horizons were sampled, from the early Paleozoic to the late Cenozoic. Oil selection included heavy oils, in which the light hydrocarbons were in trace amounts, to light gas condensates, in which they were the major components. Each sample was analyzed by high-resolution gas chromatography by using a procedure that gives baseline resolution of all hydrocarbons that boil below 115°C (*14*).

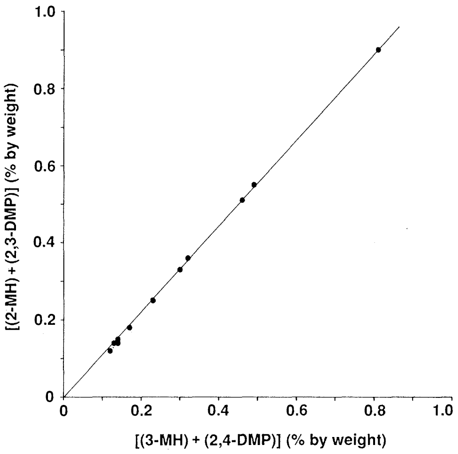


Fig. 2. An invariance plot (percent by weight total oil) of 13 homologous oils from Sabine Parish, Louisiana. These oils, reservoired in the Upper Cretaceous (Saratoga Chalk), were sampled in 1977 from three fields, namely, Pendleton-Many, Fort Jessup, and Zwolle. Four additional samples were taken in 1983, and proved to be compositionally similar to their counterparts sampled in 1977. A significant number of homologous sets have been identified that express invariance as shown here (Table 1). In the Gulf of Mexico, for example, sets from Bee County, south Texas (Eocene) (10 oils), Houston County, east Texas (Eocene) (11 oils), and offshore Louisiana (Upper Tertiary) (18 oils) display Sabine-like invariance, whereas a set (22 oils) from the Midland Basin, Texas (Spraberry, Permian), shows an invariance ratio that is distinct from the Sabine-like sets (*15*).

Likely precursors in the biosphere should contain the C_7 structures as terminal units so that products could be generated through the cleavage of a single carbon–bond. Surprisingly no single family of natural products contains all four isoheptane structures as thermally fragmentable units. The methylhexanes can be generated from the so-called iso- and anteisoheptyl units in the lipid family. Since 3-MH contains the more common head-to-tail isoprene structure, it could also be a cleavage product of the acyclic isoprenoids. However, the 2-methylhexane isomer cannot. Although 2,3-DMP may be a thermal product of certain polycyclic isoprenoids (for example, the 24-methyl- and 24-ethylcholestanes), the 2,4-DMP structure, which is a rare moiety in any family of natural products, cannot. If one of the four isomers were generated to a significant degree from some natural source (for example, 3-MH from phytane), then oils rich in that source should contain disproportionate concentrations of that isomer. However, in the oil set analyzed no such relation was found.

The strongest argument against biological precursors is the proportionality between the four hydrocarbons in virtually all of the petroleum samples analyzed. A similar proportionality should exist in the distribution of their precursors in the biosphere. Moreover, since the invariant isoheptanes represent about 1% of the carbon in petroleum, their precursors must be conspicuous contributors to the sedimentary biomass. Efforts to identify an appropriate family of precursors from the geochemical fossils found in petroleum were not successful.

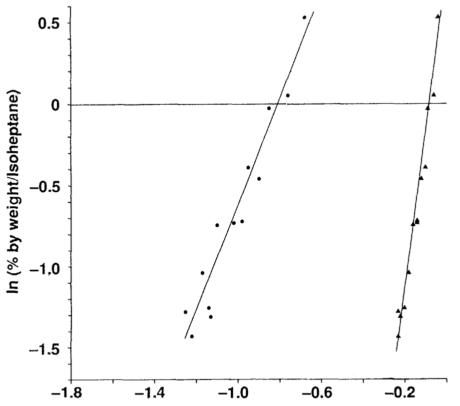


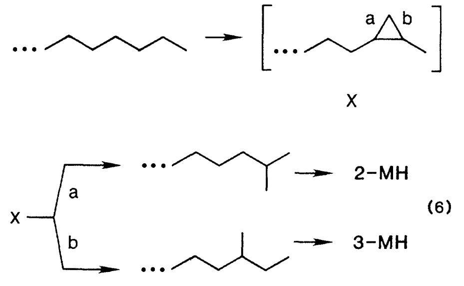
Fig. 3. A plot of ln (percent by weight isoheptane) as a function of ln[(2,4-DMP)/(2,3-DMP)] (●) and ln[(2-MH)/(3-MH)] (▲) for the homologous set of Sabine Parish oils in Fig. 2. Linear regressions give:

$$\ln(\%\ \text{isoC-7}) = 3.26\ \ln[(2,4\text{-DMP})/(2,3\text{-DMP})] + 2.62$$

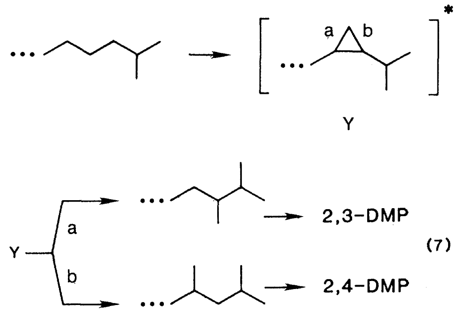
$$\ln(\%\ \text{isoC-7}) = 9.21\ \ln[(2\text{-MH})/(3\text{-MH})] + 0.67$$

When invariance is viewed in Sabine-like sets, the case for biological precursors weakens further. In thermal-cracking models, rates of product formation are controlled by activation energies and reactant concentrations. Irrespective of what the precursors to the isoheptanes might be, their relative amounts at the onset of thermal cracking and the respective activation energies will affect the composition of thermal products over time. For any set of activation energies or initial concentrations, a thermal cracking scheme could not be constructed that over time maintained the distribution of products seen in the Sabine set.

A chemical process that yields an invariant composition of products suggests steady-state kinetics, in which the relative rates of product formation are constant. A catalytic scheme consistent with the Sabine data is shown in Eqs. 6 and 7.



(6)



(7)

This is a generalized scheme that focuses primarily on steady-state kinetics and the requisite rearrangements of carbon chains. No assumptions are made about the possible degrees of unsaturation of the participants or the charge state of the activated intermediates X and Y. Since the catalytic species is unknown, it is left unspecified in the scheme.

Reactions occur in a kerogenous matrix at the end-units of the straight-chain paraffin, which is the hydrocarbon in petroleum that can be traced to biological parents that are abundant throughout the biosphere. Pairwise products are formed sequentially with the 2-methylhexyl unit in Eq. 6 serving as the reactant in Eq. 7 (*7*). Products are generated through the thermal cracking of carbon-carbon bonds, which is the kinetic step that regenerates the end-unit to repeat the catalytic cycle. Reactants (end-units) are continuously regenerated and products are continuously formed to define a catalytic process at steady state.

Cyclopropanes, such as the ring systems in X and Y, are ring-strained, thermally unstable structures that can ring-open along pathways a or b in Eqs. 6 and 7 to give the respective skeletally isomerized products. Catalytic intervention is inferred since skeletal rearrangements like these are generally high-energy processes that are rarely unassisted. Cyclopropanes are invoked because they are reported to intervene under mild conditions in a number of skeletal rearrangements. In acid catalysis, for example, the so-called protonated cyclopropane is the indicated intermediate (*8*). In free-radical systems, cyclopropanes are intermediates in 1,2-vinyl migrations (*9*). Cation radicals, which are generated by irradiating olefins, yield cyclopropanes and skeletally rearranged olefins, and the rearranged structures are very likely products of intermediate cyclopropyl ion radicals (*10*).

At steady state (that is, $d[\text{X}]/dt$ and $d[\text{Y}]/dt$ are both zero) the ratio of intermediates $[X]/[Y]$ will remain fixed to some constant value. Since the four isoheptanes are to a first approximation pairwise proportional to their respective intermediates, their pairwise ratio should remain constant throughout steady state, so that the ratio in Eq. 4 is a constant.

Since the cyclopropanes in X and Y are asymmetric, the energies of bonds a and b may differ. In this case the logarithms of the two ratios of products would become functions of temperature in accordance with the Arrhenius expression $k = A\ \exp(-\Delta E^*/RT)$, where ΔE^* is the activation energy, R is the gas constant, T is the temperature, and A is the preexponential factor. The slopes of the functions will be proportional to the differences in activation energies for ring-opening along the two pathways, namely, $\Delta\Delta E_x^*$ in Eq. 6 and $\Delta\Delta E_y^*$ in Eq. 7. Because of the different structures in X and Y, $\Delta\Delta E_x^*$ should not equal $\Delta\Delta E_y^*$, and thus the logarithms of the two ratios (2-MH)/(3-MH) and (2,4-DMP)/(2,3-DMP) become different linear functions of temperature. If the Sabine oils were generated over a temperature span, then the second requisite to invariance is obtained, namely, that ln(2-MH)/(3-MH) and ln(2,4-DMP)/(2,3-DMP) have increased with temperature (*11*) along different slopes (Eq. 5). In this general kind of model, the changing ratios in Eq. 5 will not significantly alter the invariance in Fig. 2 or the relation in Eq. 4 since any change in the amount of one product is made in concert with a compensating change in the amount of its partner product (*12*).

If the logarithms of the isoheptane ratios are functions of temperature as suggested above, then some relation between these functions and the rate of thermal cracking should exist. The concentration of light hydrocarbons in petroleum has been suggested as an index to the rate of thermal cracking (*13*). As temperature increases, the rate of thermal cracking should increase exponentially. The Sabine oils show the predicted exponential relation between isoheptane concentration and the postulated temperature functions (Fig. 3).

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16. I thank P. R. Mommessin for patient guidance and counsel and P. O. Knigge for aid in data processing and general assistance, and Shell Development Company for its continuing support of this work.

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Guam Amyotrophic Lateral Sclerosis–Parkinsonism–Dementia Linked to a Plant Excitant Neurotoxin

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The decline in the high incidence of amyotrophic lateral sclerosis, parkinsonism, and Alzheimer-type dementia among the Chamorro population of the western Pacific islands of Guam and Rota, coupled with the absence of demonstrable viral and hereditable factors in this disease, suggests the gradual disappearance of an environmental factor selectively associated with this culture. One candidate is seed of the neurotoxic plant *Cycas circinalis* L., a traditional source of food and medicine which has been used less with the Americanization of the Chamorro people after World War II. Macaques were fed the *Cycas* amino acid β-*N*-methylamino-L-alanine, a low-potency convulsant that has excitotoxic activity in mouse brain, which is attenuated by *N*-methyl-D-aspartate receptor antagonists. These animals developed corticomotoneuronal dysfunction, parkinsonian features, and behavioral anomalies, with chromatolytic and degenerative changes of motor neurons in cerebral cortex and spinal cord. In concert with existing epidemiological and animal data, these findings support the hypothesis that cycad exposure plays an important role in the etiology of the Guam disease.

AMYOTROPHIC LATERAL SCLEROSIS (ALS) is a progressive, fatal disorder of adults stemming from degeneration of anterior horn cells in the spinal cord, certain motor nuclei of the brain stem, and neurons in the motor cortex. Elucidation of the etiology of ALS has been sought for over 35 years through intensive longitudinal study of the indigenous (Chamorro) population of the Marianas islands of Guam and Rota, among whom the disease and a parkinsonism-dementia (PD) clinical variant thereof have been remarkably common (*1*). In the 1950s, ALS prevalence ratios and death rates for Chamorro residents of Guam or Rota were 50 to 100 times the estimates for the continental United States and other developed countries (*2*). The decline of ALS after 1955 on Guam (*3*), and the absence of demonstrable inherited (*4*) or viral (*5*) factors in this disease, has led to the search for environmental agents that have been decreasing as the Chamorro population has become Americanized. An early suggestion (*6*) incriminated the highly toxic seed of the false sago palm (*Cycas circinalis* L.), which was used in food and traditional medicine (*7*) until the acculturation of this people after World War II to the contemporary practices of the continental United States led to a decline in cycad use (*8*). Descriptions of a degenerative locomotor disease in animals grazing on cycad species (*9*) fueled interest in the possible etiologic role of this plant in Guam ALS-PD. Laboratory investigation of *C. circinalis* revealed the presence of various glycosides, including cycasin (*10*), and an "unusual" nonprotein amino acid, α-amino-β-methylaminopropionic acid (synonym, β-*N*-methylamino-L-alanine or L-BMAA) (*11*), agents that possessed certain neurotoxic properties but failed to induce an experimental disorder akin to ALS-PD (*12*). Cycad research in relation to Guam ALS-PD was then abandoned (*13*), even though prolonged feeding of "cycasin-free" flour (L-BMAA content unknown) had been noted (*14*) to induce limb muscle atrophy, nonreactive degeneration of anterior horn cells, and degeneration and partial loss of pyramidal neurons of motor cortex in a single rhesus monkey (*Macaca mulatta*). We report here that repeated oral administration of L-BMAA to macaques (*Macaca fascicularis*) produces signs of motor-neuron, extrapyramidal, and behavioral dysfunction, conduction deficits in the central motor pathway, and neuropathological changes of giant Betz cells in motor cortex and of anterior horn cells in spinal cord.

Thirteen 1-year-old male cynomolgus monkeys in six groups received by gavage varying doses of synthetic L-BMAA identical in composition to the natural free amino acid in *C. circinalis* seed (*15*). Treated and control animals were inspected daily, clinically examined weekly, evaluated neurophysiologically before and during the period of treatment (*16*), and subjected to neuro-

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