Valuable information about the possible isotopic behavior of the oceans may be obtained by direct examination of Eq. 4. For example, if A and B are constant, δ_O will approach the value A/B asymptotically as time progresses. Models I and II of Fig. 2 show this kind of behavior. It is commonly assumed that $\delta^{18}O$ of seawater has been constant in the past at its present value of zero. This requires the unlikely coincidence that A, a sum of products of mass transport rates and isotopic shifts, has remained equal to zero throughout geologic time. It is important to emphasize that there is no known buffering process, in the sense of negative feedback, that can hold the $\delta^{18}O$ of the oceans constant. Muehlenbachs (*9*) has presented a model in which the coincidence is observed that $A = 0$ at present. However, he restricted himself to oceanic processes and did not consider the crustal excess of ^{18}O mentioned above. Furthermore, to achieve a balance he had to require that greenstones in layer 2 of the oceanic crust have been depleted in ^{18}O by 0.5 per mil during metamorphism of the parent basaltic material, and that the correspondingly enriched waters have been able to circulate freely and mix back completely into the oceans. Also, the suggested isotopic shift between basalt and greenstone is not demonstrated to be statistically significant. For these reasons we conclude that the balance obtained is invalid. Thus, theoretical considerations and the chert data discussed above both lead us to the conclusion that the $\delta^{18}O$ of seawater has changed with time.

What we consider most important in Fig. 2 is the drastic effect that growth of the oceans has on the calculated $\delta^{18}O$. Model I, with constant mass, starts with a reasonable value of δ_O, -12 per mil, 3.3×10^9 years ago. The corresponding value for model II, with linear outgassing, is a quite unreasonable -519 per mil. We compared other constant-mass models with models in which the oceans grow according to various laws and found that with these paired models ocean growth greater than about 10 percent since early Precambrian results in runaway δ_O behavior. It can be seen from Eq. 4 that the effect is due to the greater sensitivity of a reservoir of small M_O to tendencies for isotopic change expressed in A and B. This limitation on the growth rate of the oceans is only applicable, therefore, if there has been a tendency to change, that is, if A and B have not been zero throughout geologic time. This is probable, so with the constraints imposed by the chert data on the oxygen isotope history of the oceans, it seems likely that their growth in volume has been limited since early Precambrian.

Fanale (*10*) has assembled many lines of evidence on rare gases and other volatiles that indicate a catastrophic early degassing of the earth and early formation of the oceans and atmosphere. Oversby and Ringwood (*11*) deduced from data on lead partitioning in appropriate core compositions that the core of the earth formed very early; this implies an initially molten earth and consequent early degassing. These conclusions are entirely consistent with the results of our models, suggesting that water can recycle through the mantle but that the current distribution between mantle and surficial water is essentially a steady-state one, and involves no significant present growth of the mass of the water in the oceans.

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References and Notes

1. The quantity $\delta^{18}O$ is defined by

$$\delta^{18}O = \left\{ \frac{(^{18}O/^{16}O)_{\mathrm{sample}}}{(^{18}O/^{16}O)_{\mathrm{SMOW}}} - 1 \right\} \times 1000$$

where SMOW is standard mean ocean water [see H. Craig, *Science* **133**, 1833 (1961)].
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5. The unit per mil mole is the product of moles of oxygen involved in a process by the $\delta^{18}O$ shift.
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7. Equation 1 follows from these relationships: M is the number of moles of ^{16}O in the ocean; N is the number of moles of ^{18}O; $\delta_O = 10^3\,[(N/M)/R - 1]$, where R is $^{18}O/^{16}O$ in the standard; $m_{io} = dM/dt$; and $\delta_{io} = 10^3\{[dN/dt)/(dM/dt)]/R - 1\}$.
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Lanthanide Complexes as Nuclear Magnetic Resonance Structural Probes: Paramagnetic Anisotropy of Shift Reagent Adducts

Abstract. *Magnetic anisotropy measurements on single crystals of a series of paramagnetic 8-coordinate lanthanide shift reagent adducts of the type* $Ln[(CH_3)_3CCOCHCOC(CH_3)_3]_3(4\text{-}CH_3C_5H_4N)_2$ *have been made for the following lanthanides: praseodymium, neodymium, samarium, europium, terbium, dysprosium, holmium, erbium, thulium, and ytterbium. The susceptibility tensors are highly anisotropic and nonaxial. Dipolar nuclear magnetic resonance shifts evaluated from the solid-state data are in satisfactory agreement with the solution results.*

The determination of the geometry and conformation of molecules in fluid solution, especially those of biological interest, is a matter of paramount importance. There has been considerable interest in the use of paramagnetic metal ions as nuclear magnetic resonance (NMR) broadening probes (*1*) and lanthanide ions in particular as both broadening and shift probes (*2*). Furthermore, the NMR shifting abilities of certain lanthanide complexes of bulky β-diketonate ligands has been exploited to a considerable extent through their use as shift reagents (SR's) (*3*) introduced by Hinckley (*4*). While it is a generally held view that isotropic NMR shifts observed for substrate protons in lanthanide systems are predominately dipolar in origin, and therefore related to substrate geometry in solution, there has been no direct, independent evidence of this prior to the research reported here.

It was pointed out by one of us (*5*), and verified by independent theoretical work (*6*), that dipolar shifts may be evaluated directly from single-crystal magnetic susceptibility data. This method has been applied to a number of transition metal systems including $Co[C_{10}H_8N_2]_3^{2+}$ (*5*), Co(CH$_3$COCH-

$COCH_3)_2(C_5H_5N)_2$ (*7*), and $M[(C_6H_5)_3P]_2Cl_2$, where M is Co or Ni (*8*); the results agree quite well with dipolar shifts estimated by independent means from NMR data alone. The quantitative relationship between susceptibility anisotropy and dipolar shifts ($\Delta H^{dip}/H$) is given by Eq. 1 (*8*):

$$\frac{\Delta H^{dip}}{H} = -D\left\langle\frac{3\cos^2\Theta - 1}{r^3}\right\rangle - D'\left\langle\frac{\sin^2\Theta\cos 2\Omega}{r^3}\right\rangle \tag{1}$$

where r, Θ, and Ω are the spherical polar coordinates (*9*) of the resonating nucleus, and D and D' are functions of the magnetic anisotropy given by Eq. 2,

$$\begin{aligned} D &= \frac{1}{3N}\left[\chi_z - \frac{1}{2}\left(\chi_x + \chi_y\right)\right] \\ D' &= \frac{1}{2N}\left[\chi_x + \chi_y\right] \end{aligned} \tag{2}$$

where the χ's are the principal molecular susceptibilities and N is Avogadro's number. Under conditions of Curie law magnetic behavior this equation reduces to the more familiar one in terms of g-tensor anisotropy (*10*). For the case of axial symmetry the second term in Eq. 1 vanishes.

The measurement of shifts of a dipolar nature can, in principle, lead to valuable detailed information about ligand geometry in fluid solution. Thus, many workers have attempted to extract geometric information from NMR studies of SR's and other lanthanide complexes. In using such complexes as structural probes in solution the following, usually tacit, assumptions have generally been made.

1) The observed shifts used in the analysis are purely dipolar in origin.

2) Only a single stoichiometric complex species exists in solution in equilibrium with the uncomplexed substrate.

3) Only a single geometric isomer of this complex species is present.

4) This isomer is magnetically axially symmetric so that the shifts are proportional to the geometric factor: $\langle(3\cos^2\Theta - 1)r^{-3}\rangle$ (*11*).

5) The principal magnetic axis has a particular, known orientation with respect to the substrate ligand or ligands.

6) The substrate ligand exists in a single conformation, or an appropriate averaging over internal motions is carried out.

If any of the above conditions are not met, the geometric inferences drawn will not be strictly valid. An x-ray structure determination by us (*12*) on the SR adduct $Ho(dpm)_3(4\text{-picoline})_2$ (*13*) shows this 8-coordinate complex to have only C_2 symmetry in the solid state with no real or approximate axes of threefold or higher symmetry. Nor, with one exception (*14*), do the available solid-state structures (*15, 16*) of related 7- and 8-coordinate lanthanide chelate complexes exhibit real or approximate axial symmetry.

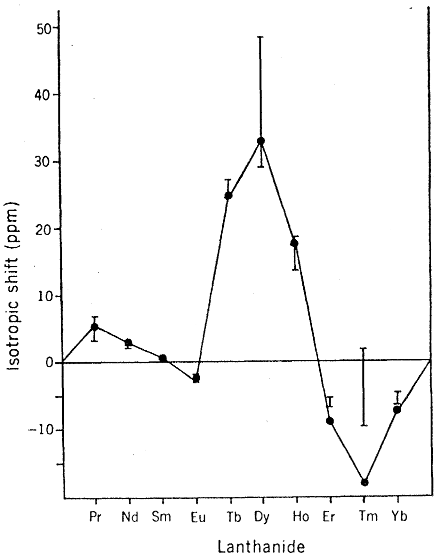

Fig. 1. Comparison of the observed isotropic shifts at 298°K for the 4-CH_3 resonance of 4-picoline (points connected by solid line) in the $Ln(dpm)_3(4\text{-picoline})_2$ systems (*13*) with the dipolar shifts evaluated from single-crystal magnetic anisotropy data for values of the parameter η in the range 2° to 22° (see text). With the exception of the Tb, Er, and Tm systems, for which the opposite is true, the shift of maximum absolute magnitude represents the extreme $\eta = 20°$.

In order to evaluate the dipolar shifts and to assess the degree of magnetic nonaxiality in a SR adduct series we undertook magnetic anisotropy studies of the isomorphous orthorhombic (P_{bcn}) $Ln(dpm)_3(4\text{-picoline})_2$ crystals by using Krishnan's critical torque method (*17*). The principal crystal susceptibilities were converted to molecular susceptibilities via a unitary transformation (*18*). The molecular C_2 (y) and crystal b axes are coincident, but the direction cosines of the molecular x and z axes with respect to the crystal a and c axes are unknown. The required relationship may be expressed by a parameter η, the angle the molecular z axis makes with the crystal a axis. Table 1 gives the molecular susceptibilities derived for $\eta = 18°$, a value in the range of η yielding the best fits for the dipolar shifts of the 4-CH_3 resonance of 4-picoline for the entire series of adducts (see Fig. 1). The marked magnetic nonaxiality of the various adducts is evident. Dipolar shifts for the freely rotating 4-CH_3 group of 4-picoline evaluated (*19*) from the crystal magnetic and structural data by using Eq. 1 for η in the range 2° to 22° are shown in Fig. 1 along with the experimental NMR results (*20*). The quality of the agreement demonstrates the basic dipolar nature of the shifts. With the exception of the Tm system, for which the agreement is poorest, the second term in Eq. 1 contributes less than 15 percent to any of the shifts. This is not expected to be a general result, however, but occurs because the axial geometric factor is greater by a factor of about 26 than the equatorial one in the present case. It should be noted that while the exact value of the parameter η is unknown (the measured crystal susceptibilities are compatible with any η in the range 0° to 36°), the quality of the agreement is not particularly sensitive to its value. Indeed, qualitative agreement (direction of shifts) is achieved for all

Table 1. Magnetic susceptibility and anisotropy data for $Ln(dpm)_3(4\text{-picoline})_2$ complexes at 298°K (*13*). The χ's are the principal molecular susceptibilities in Van Vlecks per mole (*17*), derived from the principal crystal susceptibilities via the equations of (*18*) with $\eta = 18°$. The average susceptibility was obtained by an NMR method (*21*) with a diamagnetic correction of − 447 VVk/mole applied.

Ln	χ_x	χ_y	χ_z	$[\chi_x - \chi_y]$	$[\chi_z - (1/2)(\chi_z + \chi_y)]$
Pr	5,111	6,315	2,533	− 1,204	− 3,180
Nd	4,394	5,903	3,791	− 1,508	− 1,357
Sm	978	1,249	926	− 271	− 188
Eu	4,773	3,610	5,694	1,163	1,502
Tb	26,390	62,210	28,470	− 35,820	− 15,830
Dy	46,540	65,870	31,610	− 19,330	− 24,600
Ho	42,120	54,800	38,460	− 12,680	− 9,995
Er	36,900	27,570	35,890	9,326	3,653
Tm	30,920	9,072	21,820	21,850	1,823
Yb	7,974	3,563	9,221	4,401	3,453

the complexes (save those with Tm) for any η in the range 0° to 30°.

Our results demonstrate the dipolar origin of the proton resonance shifts in SR systems. They further show that magnetic axiality in lanthanide complexes cannot be assumed in general, and suggest that detailed structural inferences based on this assumption must be accepted with reservation.

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$$\chi_a = \chi_z\cos^2\eta + \chi_x\cos^2(90° - \eta);$$
$$\chi_b = \chi_y;$$
$$\chi_c = \chi_z\cos^2(90° - \eta) + \chi_x\cos^2\eta$$
19. The assumption necessarily made here is that the solid-state structure persists in solution, retains its solid-state magnetic properties, and is the only species present. The degree of agreement found suggests that this may be true in large measure. This is further supported by the fact that $Ho(dpm)_3(4\text{-picoline})_2$, and $Eu(dpm)_3(pyridine)_2$ have virtually identical molecular structures although they crystallize in different crystal systems, orthorhombic and triclinic, respectively (*16*).
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Biological Damage from Intranuclear Tritium: DNA Strand Breaks and Their Repair

Abstract. *Isotopic decay in tritiated thymidine in the DNA of frozen (−196°C) Chinese hamster cells causes breaks in DNA strands to accumulate at a rate of 2.1 breaks per decay. After DNA is thawed the tritium-induced breaks repair rapidly with a half-time of 15 minutes at 37°C. In comparison to breakage by x-rays, the efficiency of DNA strand breakage by tritium is equivalent to 0.48 rad per decay. This dose per decay is close to that predicted by simple dosimetric considerations (0.38 rad per decay) for irradiation by the β particles from tritium.*

The biological consequences of radioisotopes located within tissue are of current interest in view of possible human exposure that may result from environmental contamination with industrial waste products, such as the effluent from fission power reactors (*1*). Radioisotopes, particularly tritium (^{3}H), which concentrate within genetic material (DNA), present several practical and theoretical problems (*1*). Tritium in the form of [^{3}H]water is a waste product from fission power reactors, and ^{3}H-labeled nucleosides, particularly [^{3}H]thymidine ([^{3}H]dT), have abundant use in studies of normal and malignant cell proliferation (*1, 2*).

The lethal effect of ^{3}H decays originating in DNA labeled with [^{3}H]dT is greater than that of decays originating elsewhere in a mammalian cell nucleus (*3*), and this is usually attributed to the various dose distributions that result from different sites of ^{3}H incorporation (*1, 3*). Although many experiments in bacteria (*4, 5*) and mammalian cells (*6*) are explicable in terms of energy deposited by β particles from ^{3}H, results that can be ascribed to transmutation processes have been detected in bacterial mutagenesis (*5*) and in inactivation of transforming DNA (*7*). In the latter, ^{3}H decays from [^{3}H]dT-labeled transforming DNA produced 0.3 DNA strand break per decay and only inactivated genetic markers on the strand in which the decay originated (*7*).

We have studied DNA breakage in mammalian cells from ^{3}H decays originating in DNA thymine to determine whether efficiency of breakage is similar to that in transforming DNA. Also we have determined the effective ^{3}H radiation dose in comparison to x-rays and the extent of strand break repair. Chinese hamster V79 cells were labeled with [methyl-^{3}H]dT by growth for one generation time (15 hours) in Eagle's medium plus 10 percent fetal calf serum containing $10^{-5}M$ deoxycytidine and [^{3}H]dT (0.1 to 1 μc/ml, 0.1 to 1 c/mmole) or [methyl-^{14}C]dT (0.3 μc/ml, 55 mc/mmole). Labeled cells suspended in growth medium with or without 5 percent dimethyl sulfoxide were frozen to −196°C at a rate of 1 deg/min and stored for various periods in liquid nitrogen. Portions containing known numbers of cells were washed in 10 percent trichloroacetic acid (TCA) at 5°C and digested in 5 percent TCA (1 hour at 90°C), and radioactivity was counted with the use of a water-miscible counting mixture (Aquasol). Counting efficiencies were determined by channel ratio methods and by the addition of internal [^{3}H]-toluene standards. The specific activity of the cells was calculated as disintegrations per cell per day (standard deviation, 10 percent). Cells labeled with [^{14}C]dT were irradiated with x-rays (300 kv-peak, 750 r/min) while frozen in liquid nitrogen and then stored in liquid nitrogen for later study. The dose rate was determined with the use of lithium fluoride thermoluminescent powder, irradiated at room temperature to avoid the reduction in lithium fluoride response that occurs at − 196°C (*8*). At various times after freezing,