vation, however, that the rate of change of Pb isotopes with time mimics that of oxygen isotopes in the sedimentary record over the last 50 million years—peak by peak, trough by trough—comes as a major surprise. Oxygen isotopes in foraminifera trace both water temperature and the volume of water sequestered in polar ice caps. Lead isotopes tell us a different story. Efficient removal of this element from the ocean implies that the average oceanic lead must adjust almost instantaneously to the isotopic composition of the riverine and eolian input from the continent.

Causes of lead isotopic variations are twofold, and implications for each of them are far-reaching. A first explanation is that the Pb source (forcing) has varied through time and the consistency of the Pb and the oxygen isotopic record necessitates some form of coupling between climate and the nature of the eroded products. Alternatively, the vigor of exchange between the different domains of the ocean (relaxation) has changed along with thermohaline circulation. Not enough is presently known from the broad-scale distribution of Pb isotopes in the modern and ancient oceans to eliminate this ambiguity, but geochemists are aware of where to focus their upcoming efforts in order to build a major increment of understanding on the dynamics of ancient oceans and atmospheres.

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HIGH-PRESSURE PHYSICS

Shocking Matter to Extreme Conditions

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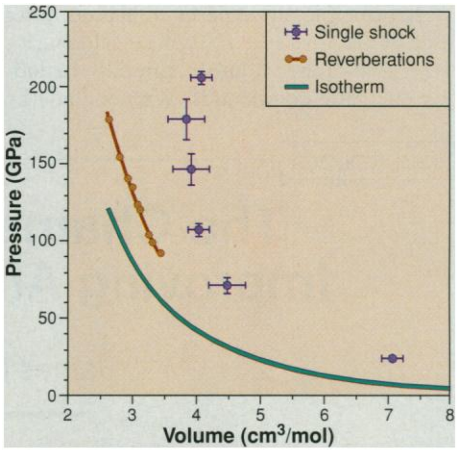
A good understanding of the thermodynamic response of matter at high compression and high energy densities (or temperatures) is important to several areas of physics, including inertial confinement fusion, astrophysics, condensed matter physics, and planetary science. Shock-wave experiments are uniquely suited for obtaining data at extreme conditions because high pressures and temperatures occur naturally in these experiments, and pressure–volume–internal energy (*P-V-E*) states can be determined directly and accurately in the shocked state through the use of mass, momentum, and energy jump conditions (*1*). Depending on the pressure-temperature (*P-T*) conditions, shock-compressed matter can be viewed as a condensed system with or without dissociation, or as a strongly coupled plasma.

Although most of the existing high-pressure and high-temperature data have been obtained with the use of gas guns, high explosives, and nuclear detonations (*2*), the development of high-intensity lasers provides a potentially attractive complement to these methods, particularly for equation of state (EOS) studies at high energy densities (*3*). By focusing a short-pulse, intense laser beam on a sample, a rapidly expanding plasma is created, which, in turn, drives a shock wave into the sample; laser-induced shock-wave experiments to obtain high-pressure EOS data (in excess of a megabar) have been carried out for more than a decade (*4*). However, concerns have existed regarding the accuracy of the data owing to the lack of planarity of the shock front, pre-heating of the material ahead of the shock front, difficulty in determining the steadiness of the wave front because of the small sample size, and the absence of absolute *P-V-E* data. Recent improvements in beam smoothing and other experimental developments have improved the quality of the propagating shock wave (*3*).

The article by Da Silva *et al.* (*5*), published earlier this year, represents an important achievement regarding the use of laser-induced shock waves for EOS studies. In this work, irradiances ranging from 5×10^{12} to 2×10^{14} W/cm^2 were used to generate 8- to 10-ns square pulses in liquid deuterium (D_2). Using a variety of innovative techniques, these authors demonstrated negligible pre-heating of the sample, steady propagation of the shock front, and direct determination of the shock-wave velocity along with particle velocity and density in the shocked state. Because any two of these measurements are sufficient to calculate *P*, *V*, and *E* in the shocked state (*1*), the third measurement provides an internal consistency check. The absolute determination of the thermodynamic variables represents a noteworthy development.

The measurements by Da Silva *et al.* (*5*) along with other recent data on hydrogen and deuterium (*6*, *7*) [there does not appear to be much of an isotopic effect (*7*)] demonstrate that the simplest element in the periodic table is not understood at extreme conditions. Before



Pressure-volume response of deuterium under various conditions. Isotherm from diamond-anvil cell experiments at 300 K (*7*), quasi-isentropic reverberation data of Weir *et al.* (*6*), and single-shock data of Da Silva *et al.* (*5*). Unlike the shock data, the diamond-anvil cell data are for the solid phase.

discussing some of these complexities, we summarize the *P-V* results on hydrogen and deuterium from several methods (see figure). The points from Weir, Mitchell, and Nellis (*6*) represent the calculated values for their reverberation experiments (quasi-isentropic loading) in which they reported the metallization of hydrogen. The considerable differences observed for the three loading conditions are a consequence of temperature differences and their effects on the internal processes.

The *P-V* results from Da Silva *et al.* disagree strongly with model predictions that do not include molecular dissociation. Any dissociation of the molecule results in energy absorption, which reduces temperature and makes the material more compressible. The single-shock data for undissociated D_2 would display a considerably steeper response than

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the points indicated. Dissociation can result from either compression (isothermal) or temperature rise (8). Present modeling of this behavior is phenomenological and is based on treatment of the fluid as an average of pure molecular and monatomic hydrogen equations of state (9). The latter is treated as a metallic fluid with one adjustable parameter designed to reproduce shock data on H_2 and D_2. At present, different theoretical approaches are used to explain the measured isotherm and shock data. A consistent understanding of all available thermodynamic data and the recent conductivity data on H_2 and D_2 under stepwise loading (6) represents an important and exciting scientific challenge.

In principle, the experimental procedures used by Da Silva *et al.* (5) will be valuable for other low–atomic number materials, including energetic compounds. We conclude by noting several important experimental needs: longer pulse durations to examine materials where dissociations or other processes may not be complete in 8 to 10 ns; direct measurements of pressure and particle velocity histories at high energy densities and high compression to provide information about the time evolution of dissociation or other changes; and time-resolved temperature measurements and other spectroscopic data, because these provide important insight into the material processes of interest. For temperature measurements, recent developments using Raman spectroscopy (10) can be used to measure temperatures as low as 1500 K by monitoring the intramolecular vibration in H_2 and D_2.

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IMMUNOLOGY

The Chameleon Within: Improving Antigen Delivery

James L. Madara

The spaces inside the gut and the lungs are continuous with the outside world, exposing the adjacent tissues to toxic and pathogenic threats from the environment. The body protects these tissues by lining the airways and intestines with a single layer of epithelial cells, joined cell to cell by gasketlike intercellular tight junctions. This surface barrier protects the organism, but also prevents the efficient uptake of environmental antigens that is required for successful oral vaccination and immunization. Normally, antigens and pathogens in the gut can only penetrate the barrier through infrequent gateway cells called M cells. Now on page 949 of this issue, Kernéis *et al.* (1) point the way toward manipulating these essential participants of the immunization process. The authors describe how to stimulate the conversion of the epithelial cells that normally line the intestine (enterocytes) to an M cell lineage, which can efficiently transport antigens across the intestinal barrier to the underlying immune system.

Beneath the epithelial lining of the lungs and gut, bits of lymphoid tissue make up the organized mucosa-associated lymphoid tissue. The rare M cells are located over these subepithelial lymphoid follicles, termed Peyer's patches (2). M cells can transport soluble and particulate antigens across their cytoplasm (transcytosis), and use this ability to sample lumenal antigens, which then trigger the induction of secretory immunity—the process by which mucosal surfaces of the gut and lung are bathed with protective antibodies. A basal pocketlike invagination in M cells (see the figure) creates a space in which lymphocytes, macrophages, and possibly dendritic cells gather. Lumenal antigens transcytosed by M cells are thus immediately delivered to these antigen-processing and -presenting cells, which then migrate to antigen-specific lymphocytes in underlying lymphoid follicles and induce their proliferation. This process results in the development of IgA–producing B cells, some of which move into the vasculature and then back to the mucosal surfaces, efficiently seeding specific mucosal immunity (2).

Mechanistic study of this M cell–initiated immune response pathway has been limited, because M cells are scattered and few (<0.1% of epithelial cells). Further, the M cell lin-

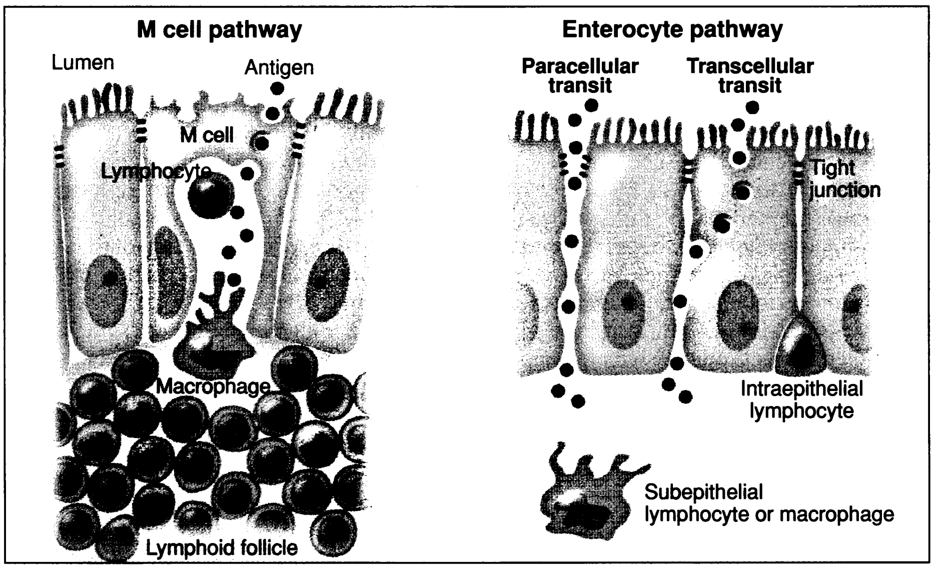

ILLUSTRATION: K. SUTLIFF

Paths across the lining of the gut. Antigens can enter the body from the gut through rare M cells (left), specialized to deliver antigen directly to underlying immune cells, or through the more common enterocytes (right), the epithelial cells that line the gut.

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