clusive enumeration of only articulated remains, and the multifactorial aging of adults all tend to maximize census accuracy at Libben. Yet the $\bar{B}$ (*22*) of the population (.083) is only half the average given by Weiss for anthropological populations (*20*). To raise the Libben figure to the average for these populations would require the undetected loss (nonenumeration) of more than 225 children. Archeologically, this would have been virtually impossible at Libben.

Recent work has demonstrated a marked decrease of adult mortality in cohorts subjected to elevated disease stress in early years (*23*). This is most probably a direct result of intensified selection for "immunological competence." Those with less adequate genomes are removed from the cohort in early childhood, and the more hardy survivors consequently display depressed mortality. This provides a possible solution to the skeletal-ethnographic sampling discrepancy. Modern "anthropological" populations are virtually all contact societies and remain under the selective influence of a battery of novel pathogens. Skeletal series are for the most part remains of smaller and more isolated groups. It is very possible that these two kinds of populations are showing mortality profiles reflective of distinctly different levels of early selection for immunological competence. If so, a major shift in the selective process in human evolution may not have received its due emphasis. This hypothesis will require further examination in future demographic studies of aboriginal populations.

C. OWEN LOVEJOY
Division of Anatomy, Northeast Ohio Universities College of Medicine, Rootstown 44272, and *Department of Anthropology, Kent State University, Kent, Ohio 44242*

RICHARD S. MEINDL
Department of Anthropology, University of Massachusetts, Amherst 01002

THOMAS R. PRYZBECK
Department of Anthropology, Washington University, St. Louis, Missouri 63130

THOMAS S. BARTON
Department of Anthropology, Kent State University

KINGSBURY G. HEIPLE
Department of Orthopaedics, School of Medicine, Case Western Reserve University, Cleveland, Ohio 44106

DAVID KOTTING
Department of Anthropology, Kent State University

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Gravitational Compression of Crystallized Suspensions of Polystyrene Spheres

Abstract. *In a crystallized suspension of polystyrene spheres, the earth's gravitational field, acting on a vertical column of material several centimeters high, produces an elastic deformation that can be readily observed through its effect on the crystal lattice constant. This effect has been used to determine that Young's modulus for the crystalline material ranges from 1 to 3 dynes per square centimeter, depending on the concentration of spheres.*

Spherical polymer particles, suspended in a liquid, can arrange themselves to form a crystal lattice (*1–6*). A typical system is a monodisperse aqueous suspension of polystyrene spheres, 1000 Å in diameter (*5, 6*). Each particle has a bound negative charge, Q, of about 2000 electron charges and a compensating positive charge on protons distributed in the surrounding water. When the suspension is carefully purified to remove other ions, the Debye radius becomes comparable to the distance between polystyrene particles. Each particle then exerts a significant screened Coulomb force on its neighbors, and the array of particles crystallizes under the influence of purely repulsive forces (*1, 5, 6*). The interparticle distance can be as much as eight particle diameters. Well-defined crystallites form and show brilliant Bragg diffraction of visible light. Normally, the lattice is body-centered cubic (*5*). There is a sharp melting temperature that depends on the particle concentration (*6*). Most of the properties normally associated with a crystalline solid are present. However, the dimensions are scaled up from those of the usual crystal by a factor of several thousand. By adjusting the particle concentration, one can vary the crystal lattice constant by more than a factor of 2 without changing the lattice type (*5*). This indicates that the ordering is due to purely repulsive forces. Such repulsive ordering is the central feature of the Wigner crystal (*7*), based on a model of electrons moving in a uniform background of positive charge. For electrons, no experimental system is known that shows such ordering, although it has been proposed that electrons moving on the surface of liquid helium might be an example (*8–12*).

The macroscopic interparticle distances and the unusual ordering force in the system of polystyrene spheres should make elastic properties especially

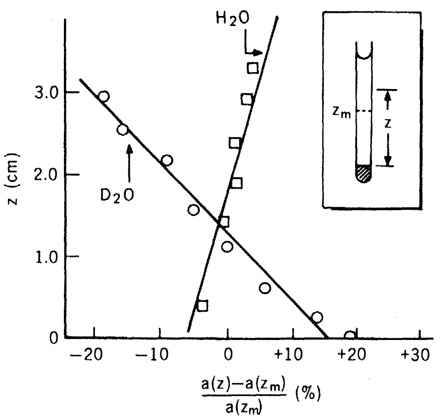

Fig. 1. Lattice constant, $a(z)$, as a function of height. (Inset) Sample contained in a closed vertical cylindrical quartz tube. The shaded area at the bottom is ion-exchange resin. The vertical coordinate is z, and z_m is the altitude of the horizontal midplane. The mean particle concentration was 1×10^{12} per cubic centimeter for the sample in H_2O and 6.6×10^{12} per cubic centimeter for the sample in D_2O.

interesting. We have measured Young's modulus, E, for crystals that form in an aqueous suspension of polystyrene spheres 1000 Å in diameter. From previous work, nothing was known about the magnitude of E. However, one could infer that it must be extraordinarily small because the crystals are easily deformed by anything that stirs the water containing the suspension. This includes effects due to sudden movement of the container or to thermal convection. We estimate the order of magnitude of E by noting that there is a relation between the yield stress of a solid and its heat of fusion (*13*). For a number of metals the low-temperature yield stress is proportional to the heat of fusion per cubic centimeter. Thus it is proportional to the molar heat of fusion times the number of atoms per cubic centimeter. What we need to know is the elastic modulus, not the yield stress. However, we will assume that things scale in the same way. From the melting properties of crystals of polystyrene spheres we have determined the heat of fusion (*6*). The value is around 4 kcal/mole, which is comparable to the molar heat of fusion of many hard metals. The big difference between the two systems is in the number of particles per cubic centimeter, N. For metals N can be as much as 10^{23}, but in our experiments with polystyrene spheres it can be as low as 10^{12}. Since the molar heats of fusion are similar, we assume that E for crystals of polystyrene spheres can be obtained from E for a metal by scaling with the particle densities. For a hard metal, E is around 10^{12} dyne/cm². For a crystal of polystyrene spheres it should be smaller by the factor $10^{12}/10^{23}$. In this way we estimate that our value of E should be around 10 dyne/cm². This is good enough to be useful in designing an experiment to measure E, and, indeed, our results show that it is within an order of magnitude of the actual value.

The suspension of crystals completely fills the water in the container, although, of course, the actual volume of the spheres themselves is only a small fraction of the total volume. In our experiments, to be described here, the volume fraction of the spheres ranges from 5×10^{-4} to 3.5×10^{-3}. The problem is to measure an elastic modulus of 10 dyne/cm² for crystals occupying the same volume as the water, which has a modulus of about 10^{10} dyne/cm². To do this we make use of the gravitational compression of the crystalline material and the associated change in lattice constant. Consider a crystalline suspension, contained in a vertical column of water, as illustrated in Fig. 1. Since the density of the polystyrene spheres is 1.05 g/cm³, they tend to sink in the water and exert a downward force proportional to their effective density, ρ_{eff}, which is 0.05 g/cm³. We will treat this as a vertical column of polycrystalline material supported at its upper and lower ends. As a result of the gravitational forces, the crystal lattice constant, $a(z)$, is smaller at the bottom of the column than at the top. The vertical coordinate, z, is measured from the bottom of the column, and the horizontal midplane is at z_m. Then $a(z)$ is related to $a(z_m)$ by (*14*)

$$\frac{a(z) - a(z_m)}{a(z_m)} = N\left(\frac{\pi d^3}{6}\right)\rho_{eff}\, g(z - z_m)/E \qquad (1)$$

where d is the sphere diameter, N the number of spheres per cubic centimeter, and g the gravitational constant. Equation 1 indicates variations of several percent in $a(z)$ over a height of 1 cm. To verify this we measured the lattice constant as a function of z by using the Bragg diffraction of light from a He-Ne laser. We described the experimental arrangement earlier (*5*).

To prepare crystals, ion-exchange resin was put in the bottom of a cylindrical quartz tube of 4-mm inner diameter. A suspension of polystyrene spheres, diluted with water to the desired concentration, was then added to give a depth of about 4 cm. The tube was clamped in place on a stand and allowed to stand without moving it further. Crystallization takes place as impurity ions in the water diffuse to the ion-exchange resin and are removed. This takes several

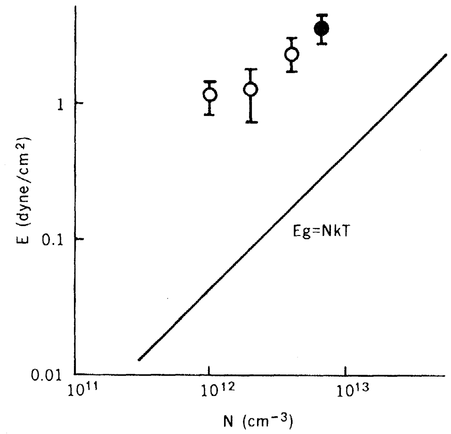

Fig. 2. Young's modulus, E, as a function of N. The points are the measured values of E in (○) H_2O and (●) D_2O. The error bars refer to different measurements on the same sample. The solid line shows E_g, the elastic modulus for an ideal gas at room temperature.

days. (We tried experiments to speed up the crystallization by stirring as it proceeded. This built permanent mechanical distortions into the crystals and masked the effect we were trying to measure.)

We found the expected uniform decrease of lattice constant from top to bottom. To confirm that the trend of lattice constant with z was actually due to gravitational compression and not to an extraneous cause, such as a concentration gradient of ionic impurities in the cell, we made a suspension of spheres in heavy water, D_2O. Since the density of D_2O is 1.1 g/cm³, the spheres, with a density of 1.05 g/cm³, are now lighter than the surrounding fluid. They tend to float rather than sink and ρ_{eff} becomes −0.05 g/cm³. Everything is the same as before except that the lattice should now be compressed at the top of the column and dilated at the bottom. This is what we found. Figure 1 shows the behavior of the lattice constant under gravitational compression in light and heavy water. The trend of the lattice constant with height is comparable in magnitude, but opposite in sign, as we go from light water to heavy water. From the data we derive the numerical value of E, using Eq. 1. It is remarkable that Hooke's law is approximately obeyed over a 40 percent range of variation in the lattice constant. In fact, the lattice would probably not fracture under tensile stress but would melt instead, when the lattice constant moves outside the range of stability of the crystalline phase.

In Fig. 2 we show values of E determined for samples having different concentrations of spheres. As expected, E increases with increasing N since the Coulomb repulsion is larger when the particles are closer together. To get some feeling for the meaning of an elastic modulus of the magnitude that we observe, we compare it with the elastic modulus of what should be a highly compressible material—an ideal gas having the same particle concentration. For an ideal gas the elastic modulus, E_g, is the reciprocal of the compressibility. Thus $E_g = NkT$, where k is the Boltzmann constant and T is temperature. This is shown by the lower line in Fig. 2. For the crystal of polystyrene spheres, E is greater than E_g by an order of magnitude. The difference is due to the Coulomb repulsion between the spheres.

We have shown that a crystallized suspension of polystyrene spheres has an elastic modulus in the usual sense of the term. Elastic forces are propagated over macroscopic distances, as in a normal crystalline solid. The weakness of the elastic forces in this system is due, not to weak interaction between individual particles, but to the small number of particles per unit volume. At metallic densities, even an ideal gas would have an elastic modulus of 4×10^9 dyne/cm^2. The elastic forces may play an important part in crystallized virus systems (*15*), which are similar in particle size and concentration to the system we have studied. Mechanical forces might provide a useful biological function by excluding foreign particles such as antibodies from a crystal. It has recently been shown, for example, that crystals of polystyrene spheres exclude foreign particles during growth (*16*).

RICHARD S. CRANDALL
RICHARD WILLIAMS
RCA Laboratories,
Princeton, New Jersey 08540

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Telecommunication with Neutrino Beams

Abstract. *Collimated neutrino beams in the energy range 1 to 100 gigaelectron volts, now available from high-energy proton accelerators, are proposed as a potential means for telecommunication over global distances. Quantitative estimates of the feasibility of this proposal based on a particular detector configuration are presented.*

Neutrinos have the greatest penetrating power of all the elementary particles. Their weak interaction with matter renders neutrino beams capable of traversing the earth without any significant attenuation up to energies of $\sim 10^3$ Tev (1 Tev = 10^3 Gev = 10^{12} electron volts). Only above this energy will the earth begin to appear less transparent to them. To date, however, man-made neutrino beams have been produced with energies up to only ~ 200 Gev [at the 400-Gev proton accelerator of the Fermi National Accelerator Laboratory (Fermilab), Batavia, Illinois].

This enormous penetrating power makes neutrinos unique candidates for novel types of applications in long-distance telecommunication: specifically, those involving point-to-point, direct line communication through the earth over global distances (10^3 to 10^4 km). Conventional telecommunication over such distances by means of high- or low-frequency electromagnetic waves depends on the reflection of radio waves from the ionosphere, or on retransmission by a satellite relay. For a path directly through the earth, the attenuation is prohibitive even for extremely low frequency electromagnetic waves. The same is true for beams of elementary particles such as muons, which might be used for communication (*1*). Neutrino beams have the further advantages that their propagation cannot be hampered or blocked (unlike that of electromagnetic waves) and they produce no harmful environmental effects (in possible contrast with muon beams).

The possible use of neutrinos for telecommunication was mentioned by Arnold (*1*) in a report mainly concerned with telecommunication by muon beams. A further suggested application of neutrino beams, although advanced for purely scientific reasons, has some relevance to neutrino telecommunication: Mann and Primakoff (*2*) proposed a search for neutrino oscillations (a transition from muon-type to electron-type neutrinos, speculated to occur over large distances) by detecting neutrino reactions over distances of 10^3 km from the neutrino source at Fermilab (*3*).

Telecommunication by means of neutrinos is made difficult by the property that renders them so highly penetrating—namely, their extremely small interaction cross section with matter. Because of this, intense beams and massive detectors are required for any type of neutrino experiment. While the beam quality can probably be improved even at the accelerators that now produce neutrino beams (Fermilab, CERN, Serpukhov, Brookhaven, and Argonne), especially by improving beam collimation and thus increasing flux density, accelerators designed for the production of neutrino beams for telecommunication would be expected to furnish intensities several orders of magnitude higher than the present intensities.

In addition, detector arrangements have to be considered which provide the largest possible detector mass. The approach to this problem proposed here is an extension of one suggested a number of years ago (*4, 5*)—that is, using a large volume of water (for instance, in the ocean or in a deep lake) as a target and detector for neutrino reactions in which a muon is produced (*6*), possibly accompanied by a hadron cascade. All along its path through the water, the muon (and some of the other reaction products) will emit a forward cone of Cerenkov photons, which can be intercepted by a light collector–phototube system to provide a signal of the neutrino reception. The reaction of importance here is

$$\nu_\mu + \mathrm{n} \rightarrow \mu^- + \text{hadrons} \qquad (1)$$

where ν_μ is a muon neutrino, n is a neutron, and μ^- is a muon. This reaction has a measured cross section (up to 200 Gev) of

$$\sigma_\nu \cong 0.58 \times 10^{-38} E_\nu \text{ cm}^2 \qquad (2)$$

where the neutrino energy, E_ν, is measured in gigaelectron volts. Prototype experiments using a Cerenkov detection system in the deep ocean (depth ~ 1 km) have been carried out by Riel and coworkers (*7*). More recent proposals (*8*) for Project DUMAND (deep underwater muon and neutrino detection), designed to detect cosmic neutrinos, are partly based on a similar principle.

Relatively simple Cerenkov light–collecting equipment is capable of surveying water volumes of $\geqslant 10^6$ tons. With such a detector volume, and utilizing a neutrino beam with essentially the characteristics of the present one at Fermi-