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*).

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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-

Table 1. Estimated neutrino event rates for various distances and detector masses, at beam angles of 1 and 3 mrad. The last two rows refer to a planned Fermilab accelerator energy of 1000 Gev.

Accelerator energy (Gev)	θ_ν (mrad)	M (tons)	L (m)	N	$D = 10^3$ km φ (km)	$D = 10^3$ km R (hour^{-1})	$D = 10^4$ km φ (km)	$D = 10^4$ km R (hour^{-1})
400	3	10^6	86	80	3	25	30	0.25
		10^7	200	1,000		250		2.5
		10^8	450	11,400		2,500		25
400	1	10^7	200	1,000	1	2,500	10	25
		10^8	450	11,400		25,000		250
1,000	1	10^7	200	1,000	1	25,000	10	250
		10^8	450	11,400		250,000		2,500

lab, the expected counting rate over distances, D, of 10^3 to 10^4 km approaches the value required for neutrino communications. With accelerators and detector systems specifically designed for neutrino communications, the required counting rates can probably be achieved. Neutrino event rates and background rates in such large water targets are discussed below.

The 400-Gev proton accelerator at Fermilab, using 40 Mw, generates a pulsed beam of $\sim 10^{13}$ protons per pulse at a pulse rate of one in ~ 8 seconds and a pulse length of ~ 20 μsec. Pi- and K-mesons are produced by the protons incident on an aluminum target, focused in a magnetic horn, and passed into a 400-m-long decay tunnel, where they decay into neutrinos by reactions such as

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad (3)$$

where π^+ is a pi-meson. This generates $\sim 10^{10}$ neutrinos per pulse, consisting largely of muon neutrinos, with a spectrum peaked at about $E_\nu \sim 15$ Gev. The neutrino beam emerges from the decay tunnel with a diameter of $\lesssim 1$ m (that is, a full opening angle, θ_ν, of ~ 3 mrad). After a distance of 900 m, in a liquid neon bubble chamber 4 m in diameter, the $\sim$ 4-m-wide neutrino beam generates about one neutrino reaction (Eq. 1) per pulse in the ~ 25 tons of detector material.

We now estimate the rates of neutrino-induced events in a large water Cerenkov counter located 10^3 to 10^4 km from the neutrino source, assumed to be Fermilab in what follows. Muons produced as in Eq. 1 will travel ~ 50 m in water, emitting along their path a 41° forward Cerenkov cone of ~ 200 photons per centimeter in the visible region (4000 to 7000 Å). We propose to collect these photons (*5*) on a clear plastic plate, possibly containing a wavelength shifter, and monitor them with photomultipliers. The horizontal plate could be blackened on top to eliminate some Cerenkov background from downward-traveling cosmic-ray muons; thus it would survey the ocean below it and receive the desired signals from communication neutrinos, which follow a secant through the earth and arrive from below (*9*).

The volume of water surveyed by the light collector depends strongly on the light transmission properties of ocean water. The measured absorption length, l, in clear seawater (*5*) is plotted in Fig. 1 against wavelength, together with the spectrum of Cerenkov light, which increases toward the blue. The maximum overlap lies at about 4500 Å, where $l \sim 30$ m, but we adopt the more conservative estimate $l \sim 20$ m. To take a concrete example of a detector configuration, we now consider a number, N, of detector modules, each consisting of a 1-m^2 downward-looking plate surveyed by one photomultiplier, arranged over a cube of water of side length L and spaced regularly 20 m apart. Table 1 shows the

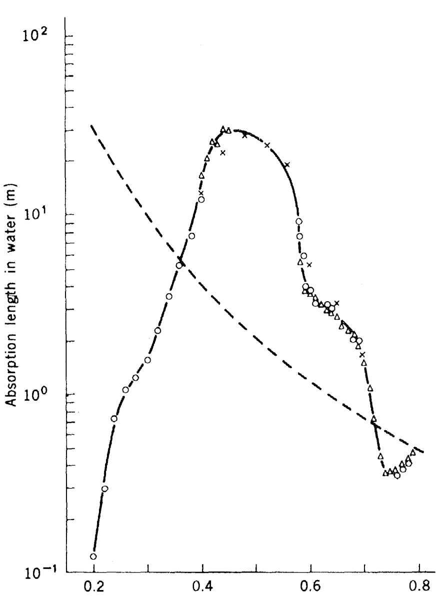

Fig. 1. Absorption length (l) in water as a function of wavelength (1 μm = 10^4 Å). The dashed line shows the Cerenkov spectrum in arbitrary units.

estimated rates, R, of neutrino events (Eq. 1) taking place in detector (water) masses, M, of 10^6 to 10^8 tons. The first three values of R therein correspond to the existing Fermilab neutrino beam. In calculating L and N, account was taken of the fact that an $\sim$ 10-Gev muon traveling toward the detector may be generated ~ 50 m in front of it and still be detected (*10*). At $D = 10^3$ or 10^4 km, detector sizes are always well within the beam diameter, φ, and the event rates can be substantial.

The next two values of R in Table 1 are the expected (increased) event rates for a neutrino beam opening angle of 1 mrad, which appears to be a feasible improvement of the existing beam quality. A further gain would be achieved by increasing the accelerator energy from 400 to 1000 Gev, which is already envisioned for Fermilab. This would result in a proportional increase of neutrino peak energy (and hence cross section), meson multiplicity (hence neutrino intensity), and muon energy, producing a gain in event rates by a factor of about 10, as shown in Table 1.

The neutrino signal generated by the Fermilab accelerator can be transmitted as 20-μsec pulses emitted approximately once every 8 seconds (or 450 times per hour). The communication rate depends on both the signal and the noise. For the following discussion, we assume an accelerator power, transmission range, and detector mass leading to 10^4 neutrino events per hour or approximately 22 events per pulse.

The most important sources of background for the expected signals are the penetration of sunlight through the ocean (*11*) and the Cerenkov light of cosmic-ray muons, which arrive at angles from the vertical with a distribution $\cos^n \theta$ (*12, 13*). Using data in (*11*) and (*12*), we arrive at the following conclusions. Assuming no shielding other than that provided by the ocean, an immersion depth of 400 to 500 m is needed to keep the daylight sensed by the entire array smaller than the Cerenkov signals during the 20-μsec pulse period. However, shielding against sunlight might be used to avoid going to such depths. Also, the cosmic-ray muon background during the pulse is less than the neutrino-induced signal for immersion depths of 300 to 400 m.

Because the expected variation in propagation time from the accelerator to the detector is less than the width of the pulse, synchronous detection techniques can greatly enhance the apparent signal-to-noise ratio for detectors at these depths, provided the propagation time is known in advance and suitable clocks are available at the transmitter and receiver. For example, if 1 bit is to be transmitted per accelerator pulse, bit error rates better than 10^{-3} can be achieved by using suitable demodulators. At greater depths, the signal-to-noise ratio improves, and more than 1 bit could be transmitted per pulse. For example, at a depth of 3 km, pulse position modulation could be used to transmit one 15-bit message per pulse with a message error rate better than 10^{-3}.

We have considered the possibility of neutrino communication with present and future neutrino beams, using a suitable underwater Cerenkov detector for which specific examples have been presented. These concepts could be tested by establishing neutrino communication over a modest distance, such as from Fermilab into Lake Michigan, where the neutrino beam of Fermilab is now directed. In fact, the present Fermilab neutrino experiment already provides an example of "communication" with the bubble chamber detector over a distance of about 1 km.

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Gemmae: A Role in Sexual Reproduction in the Fern Genus Vittaria

Abstract. *Gemmae are generally defined as vegetative propagules. In the shoestring ferns,* Vittaria, *gemmae grown in the presence of mature gametophyte plants or on medium containing gibberellic acid produce antheridia in lieu of vegetative growth. This suggests that antheridial differentiation in* Vittaria *is controlled by a chemical antheridogen system similar to those described in other fern genera. In natural populations of* Vittaria *gametophytes composed primarily of long-lived individuals, gemmae may provide the only source of tissue susceptible to antheridogen action and may have evolved in response to that condition.*

In lower plants such as fungi, liverworts, mosses, and ferns, gemmae are generally considered to be agents of asexual reproduction. They are units of vegetative cells which, when shed from their parental plant, can grow into new individuals. However, gemmae produced by the gametophyte generation of the shoestring ferns, *Vittaria*, in addition to their role in vegetative dispersal and reproduction (*1–3*), may play an important role in sexual reproduction.

Vittaria species are tropical and subtropical epiphytes. Their gametophytes are branching, ribbonlike plants of indeterminate growth which typically form dense, perennial mats. Gemmae, consisting of chains of 4 to 12 cells, form at the ends of aerial branches of the gametophytes (Fig. 1A). After dispersal onto a suitable substrate, the gemmae may develop vegetatively into new gametophytes or, under conditions described herein, may produce antheridia with little or no accompanying vegetative growth (Fig. 1, B to D, and Table 1).

Table 1. Induction of antheridia in *Vittaria* gemmae. Test plants were grown for 6 to 10 weeks on agar blocks opposite living, mature gametophytes (living); on agar substrates containing aqueous extracts from mature gametophyte cultures (extract); on agar substrates from which mature gametophytes were removed (medium); or on agar substrates containing gibberellic acid. The percentage of gemmae forming antheridia is the average response of a minimum of 100 gemmae in each of three or more replications. *Pteridium* extract, at dilutions of 1:2 to 1:10,000, was assayed against 10-day-old gametophytes of *Onoclea sensibilis*, which yielded a 75 to 80 percent response at all concentrations except 1:10,000, where the response dropped to 30 percent.

Source of antheridium-inducing activity	Gemmae forming antheridia (%)
None (control)	0
Vittaria lineata (living)	45
Vittaria lineata (extract)	0
Vittaria lineata (medium)	0
Gibberellic acid (5×10^{-5} g/ml)	49
Pteridium aquilinum (living)	0
Pteridium aquilinum (extract)	0

Earlier descriptions of *Vittaria* gametophytes have noted the frequent occurrence of antheridia on gemmae and very young gametophytes (*1, 4–6*). In stock cultures we have observed that antheridia are produced almost exclusively on recently shed gemmae, and that mature gametophytes usually produce only archegonia. An explanation for this developmental pattern is suggested by the antheridogen system which has been shown to operate in other fern species. In this system a chemical, termed antheridogen, is produced by certain members of a culture population and induces antheridia to form on other members (*7–12*). In *Pteridium aquilinum* (L). Kuhn gametophytes produce antheridogen only after they have reached a developmental stage at which they are insensitive to this chemical (*8*). These gametophytes proceed to form archegonia, but form no antheridia. However, gametophytes in earlier stages of development respond to antheridogen by forming antheridia without concomitant archegonial development and often cease vegetative growth.

Previously described antheridogens show varying degrees of interspecific activity. Antheridogen produced by *P. aquilinum* induces antheridia in many higher ferns, but not in species of the Schizaeaceae (*10, 12*). In contrast, the antheridogen of *Anemia phyllitidis* L. is active only within the family Schizaeaceae (*9, 12*). The chemical structure of the former has not been fully determined. The latter is gibberellin-like and various gibberellins can mimic its effects (*10, 13–15*).

In *Vittaria* we wished to test the hypothesis that gemmae respond to an antheridogen produced by the mature gametophytes. Gemmae of *V. lineata* J. E. Smith were placed in two groups of 100 each, separated by 3 cm, onto petri plates of mineral nutrient agar (*16*). Mature *V. lineata* gametophytes were placed among one group of gemmae on each plate; the other group was left as a control. After 11 weeks, no antheridia