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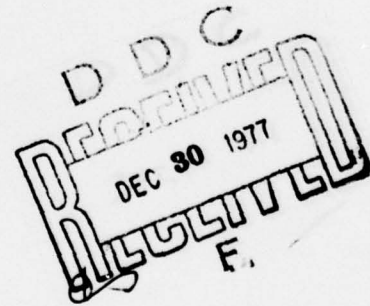
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ACOUSTIC DETECTION OF NEUTRINO INTERACTIONS IN THE
OCEAN: THE 1977 DUMAND SUMMER WORKSHOP, MOSCOW,
26-28 JUNE 1977

A. ROBERTS*

2 NOVEMBER 1977

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This was the third in a series of Workshops to foster the collaboration of high-energy, cosmic-ray, and theoretical physicists, astrophysicists, astronomers, acousticians, computer scientists, geophysicists, oceanographers, ocean engineers, and other assorted enthusiasts, all captivated by the objective to use the ocean as a gigantic neutrino detector.

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ACOUSTIC DETECTION OF NEUTRINO INTERACTIONS
IN THE OCEAN: THE 1977 DUMAND SUMMER WORKSHOP,
MOSCOW, 26-28 JUNE 1977

The 1977 Deep Underwater Muon and Neutrino Detector (DUMAND) Summer Workshop was held under the sponsorship and at the invitation of the Soviet Academy of Sciences. Directly following the Neutrino-77 conference at Elbrus which ended 25 June, the Workshop started on a Sunday to avoid delaying the participants who attended both meetings.

The DUMAND project is not yet an officially established one; it has not as yet the blessing of a funding agency, nor does it as yet boast an annual budget. It is a collaboration of high-energy, cosmic-ray, and theoretical physicists, astrophysicists, astronomers, acousticians, computer scientists, geophysicists, oceanographers, ocean engineers, and other assorted enthusiasts, all captivated by its simple but audacious objective: to use the ocean as a gigantic neutrino detector. The aims are to observe and study cosmic-ray neutrinos (and muons) at energies far above those available from any present or foreseeable accelerator—those neutrinos (and muons) that arise from the interactions of the primary cosmic-ray protons (and heavier nuclei) in the earth's atmosphere, as well as those that impinge upon us directly from extraterrestrial sources. The latter have hitherto not been observed. The detection of the low-energy neutrino bursts that accompany gravitational stellar collapse is also one of its aims; but that has been temporarily shelved until someone devises a less-expensive detection procedure for neutrinos in the 20-MeV region than any now known to us.

Such studies would extend our knowledge of the "weak interaction," the sole mechanism of interaction between neutrinos and the rest of the universe, and they would vastly extend the infant science of neutrino astronomy. One might hope to detect neutrino fluxes from the galactic center, from point sources like expanding supernova shells, and perhaps from remote galaxies whose neutrinos date from an early epoch in which the sources may have been much brighter.

Why the ocean? Because detectors of enormous mass are needed to detect the feeble current of neutrinos, which interact with matter so weakly that on the average they may, if their energies are in the right range, readily penetrate the earth, or even a star, without undergoing a single interaction. The ocean alone offers the requisite mass. Two modes of detection appear possible. The more certain, but probably the more expensive, is optical detection: photomultipliers pick up the Čerenkov light that is generated in transparent media by highly relativistic particles—in this case the secondaries produced by the neutrino interaction. This is a standard laboratory method and is well developed and well understood.

Less certain, but possibly less expensive, is the acoustic method, in which the sound produced by the neutrino interaction is picked up by an array of sensitive hydrophones. The sound results from the pressure pulse generated when the energy of the neutrino, divided among many secondaries, is converted into heat as the particles are brought to rest. This method, first suggested by G. Askarian (Lebedev Inst., Moscow) in the fifties[1] has been shown to work in the laboratory[2,3], but further studies are still necessary to ascertain how well it will work in the ocean at the energies of interest. Its principal advantage is that sound is attenuated in the ocean far less rapidly than light; thus the detectors may be further apart and fewer in number. Early work on these problems is summarized in the *Proceedings of the DUMAND 1976 Summer Workshop*, published by DUMAND, Fermilab, Batavia, Illinois 60510.

Atmospherically generated neutrinos are accompanied by highly penetrating charged muons, whose intensity at sea level is relatively high. To avoid the interference such particles would produce, it is necessary to go to a considerable depth in the ocean; about 5 to 6 km is desirable. Thus the problem for DUMAND engineers is to design an experimental apparatus in which thousands of sensors, distributed through a volume of perhaps 1 to 100 km^3 of ocean, can be accurately located with respect to each other, and will operate continuously, reliably, and smoothly for many years, returning their data to shore by submarine cable as they are accumulated.

The venue of the Moscow conference emphasized the serious and sustained interest of the Soviet scientists, which has been manifest from the beginning of the project about four years ago. In the last year, following the 1976 DUMAND workshop in Honolulu, experimental and organizational progress has been rapid, and the 1977 conference provided an opportunity for meeting to discuss progress and formulate plans. The DUMAND meeting was held at the Lebedev Institute in Moscow; the arrangements were supervised by Prof. G.T. Zatsepin, and the organization of the conference was in the capable hands of Dr. V.S. Berezinsky (both of the Lebedev Institute).

Two previous workshops, in 1975 and 1976, had been concerned with establishing the conceptual feasibility of both the physical measurements and the ocean engineering. With last year's suggestion of acoustic detection, the economics of the project began to look far more favorable, and the notion of detectors of 10^9 tons (1 km^3) or even more, began to appear realistic, and even conservative. This year's workshop was concerned with establishing more clearly the possible extraterrestrial sources of ultra-high-energy (UHE) neutrinos and their probable intensities; and in reviewing the progress to date on acoustic detection, both in the USSR and in the US. Total attendance was approximately 25-30, of which eight were US physicists. Soviet attendees included A.I. Alikhanian, B. Pontecorvo, A.E. Chudakov, V.S. Berezinski, G.T.

Zatsepin, L.M. Ozernoi, B.L. Joffe, G. Askarian, B. Dolgoshoin, A.I.
Petrukhin, and V.D. Volovik, the latter reporting on his pioneering work
on the acoustic detection of particle beams.

The agenda of the three-day meeting, which was conducted on an in-
formal basis (and mostly in English), was varied to suit the interests
and needs of the participants, and to follow the directions in which
the frequently animated discussions led. On the first day, Prof. F.
Reines (Univ. of California, Irvine) described the history of the DUMAND
project and its present status; Prof. G.T. Zatsepin (Lebedev Inst. and
Univ. of Moscow) reviewed the cosmic-ray properties that determined the
conditions for the proposed detection schemes, and discussed what might
be learned; and Prof. D.N. Schramm (Univ. of Chicago) discussed the
astrophysical aspects, particularly with regard to estimating the antici-
pated high-energy extraterrestrial neutrino flux.

The uncertainties in these estimates amount to several orders of
magnitude, and so predictions range from highly pessimistic (no observ-
able signal) to highly optimistic (many high-energy events).

On the second morning I opened the program with a description of
the design of a four-stage prototype 10^9-ton combined optical and acous-
tic detector. This description elicited the objection that the acoustic
threshold of detection (which the Soviet scientists place at about 10^{15} eV,
at least ten times the value favored in the US) would be too high for
the acoustic detectors to be useful on so small a detector; the event
rates would be too low. This was followed by discussions by Ozernoi
and by Berezinski on the probable sources and intensities of extraterres-
trial neutrinos. Berezinsky concluded that with a detector of
3×10^{11} tons (300 km^3) even a pessimistic estimate of the intensity
of neutrinos of 10^{15} eV and above leads to an observed event rate of
10/yr or more.

Prof. L. Sulak (Harvard) discussed the optical detection of high-
energy neutrino interactions and the instrumentation required to extract
maximum information. The content of his paper was taken mainly from
the report of the Neutrino Signature group in the 1976 Summer Study[4].
A purely optical detector is in principle capable of measuring the
Bjorken scaling variables x and y, by determining the energy of the muon
as well as that of the shower; of good accuracy in measuring directions,
and moderate accuracy in energy (25%). It might be capable of distin-
guishing nuclear cascades from electromagnetic showers as well. Given
all these data, one can certainly do a cascade measurement that compares
favorably with those now customary in accelerator-produced neutrinos,
the major difference lying in the inability to determine the signs and
energies of the outgoing muons.

This report was received with some skepticism, both as to whether the measurements could indeed be made with the prescribed accuracy, and as to the possibility of achieving this accuracy at a tolerable cost; the system implies an array of optical detectors in the ocean filling a cubic kilometer in a lattice of 40- to 80-m separation.

Berezinsky then discussed experiments[5] to look for resonant production of W bosons (intermediate-vector bosons postulated as the carrier of the weak interaction). The reaction would be $\bar{\mu}_e + e^- \rightarrow W^- \rightarrow$ anything. The expected mass of the W is about 70 GeV in the Weinberg form of gauge theory, but they might be much heavier. Ioffe commented that the experiment might possibly determine the mass; he also thought it important (as suggested also by D. Cline) to look for the Higgs boson, a postulated scalar boson necessary in gauge theory.

P. Kotzer (Seattle) gave a short description of a proposed experiment to attempt to observe neutrino oscillations, using an optical detector in the ocean near Seattle, and a neutrino beam produced at Fermilab pointing in that direction. Neutrino oscillations are fluctuations in intensity that might be observed if a coherent beam contains two different types of neutrino whose rest masses are slightly different, and which can transform into each other.

Acoustic Detection of Nuclear Cascades. The third and last day of the meeting was devoted mainly to discussions of acoustic-detection possibilities. First B. Dolgoshein (Moscow Physical Engineering Institute) gave a review of the subject and detailed the results of new Monte Carlo calculations, using the MARS program at Serpukhov[6] to calculate the shower distribution from very high-energy hadronic cascades, and the resultant acoustic radiation pattern (see Fig. 1). As we had earlier speculated, the acoustic pattern is not symmetrical about the plane through the maximum of the cascade and normal to the shower axis. It rises more sharply on the side toward the origin (the upstream side) and falls off more slowly on the downstream side. This implies that with sufficiently accurate observation of the acoustic pattern, the sense of motion of the incident particle along the cascade axis can be inferred. Other new results include the prediction of a considerable acoustic radiation flux in the 100-200 kHz region. The direction of the shower can readily be determined to 10 mrad or better.

V.D. Volovik (Univ. of Kharkov) described the acoustic research experiments that have been going on for several years[7] (since 1971), and which, although published, had been unknown to the DUMAND group. He finds that the mechanism of sound production by particle beams is not purely thermoacoustic, but includes bubble or microbubble formation. The theoretical analysis predicts that as the pressure in the liquid increases beyond 200 atm, the bubble formation contribution vanishes; at the pressures to be encountered in DUMAND (500-600 atm) the effect

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becomes pure thermoacoustic, with the exception that dissolved gases, if present, can contribute too.

L. Sulak (Harvard) then presented the results of DUMAND experiments at Brookhaven and Harvard, using proton beams at 150-200 MeV and at 23 GeV. The work of the DUMAND group, which started last October following the suggestion[8] of acoustic detection by Bowen and Dolgoshein at the 1976 Summer Workshop, has now produced significant data[9,10]. The existence of the acoustic signal was readily established. [It had been known for years by Brookhaven technicians, who observed (without amplification) an audible chirp when the 200-MeV linac proton beam was dumped in a large tank of water.] Further efforts were directed at trying to establish the nature of the signal and its threshold of observability. Other experiments concerned the effect of pressure and temperature in the water, dissolved salt, and the question whether the signal was purely thermoacoustic, or whether microbubbles are involved. In the latter case, one would expect different pressure and temperature dependence of the signal. In water, a thermoacoustic signal would be proportional to the parameter β/C_p, where β is the bulk coefficient of thermal expansion and C_p the specific heat at constant pressure. This quantity is particularly small for water, in which the coefficient of expansion changes sign at 4°C (for fresh water, not for sea water) and for which C_p is particularly large.

Volovik's experiments, as he reported, showed no vanishing of the signal in water at 4°C, so he concluded that a mechanism other than thermoacoustic must be responsible. The data reported by Sulak did not agree with Volovik's but did not permit unambiguous interpretation.

Dr. John Learned (Univ. of California, Irvine) presented a new exposition of the theory of thermoacoustic pressure pulses produced by particle beams. It uses a Fourier-transform approach in the time domain. It will shortly be published[12]. Pending this, readers may be interested in a simple and readily understood analysis of the acoustic-effect ionizing particles, by Prof. T. Bowen (Univ. of Arizona). It is given in the appendix[13].

Prof. A. Parvulescu (Institute of Geophysics, Univ. of Hawaii) discussed a few observations on an alternative site for DUMAND, to the west of the Island of Hawaii; and presented some actual spectral analyses of hydrophone recordings made at Barking Sands, Kauai, to show the existence of signals, probably due to porpoises, whose waveforms are remarkably similar to those to be expected from a nuclear cascade.

The meeting closed with expressions of thanks to the organizers, and of hopes for continued and closer cooperation for the future. There are no plans for publishing the proceedings of the workshop.
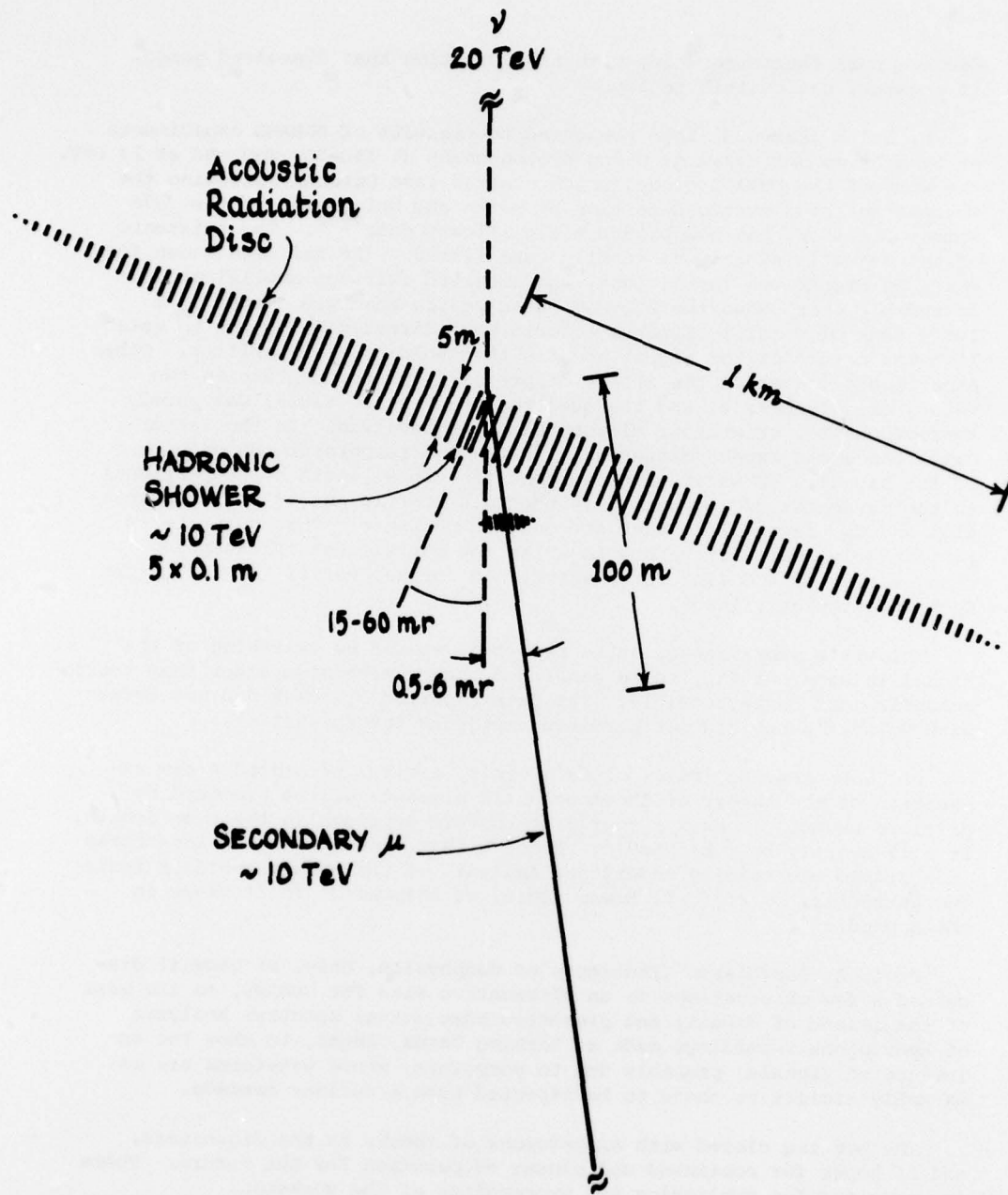
Fig. 1. Acoustic radiation from a neutrino-produced high-energy cascade. The sonic radiation, being produced in phase along a 10-m path only a few cm in diameter, is emitted in a very narrow-angle disc coaxial with the cascade. The total cascade length is ca. 10 m; the width between half-power points is about 5 m, as shown.

APPENDIX

THEORY OF ACOUSTIC RADIATION FROM HIGH-ENERGY
NUCLEAR CASCADES

The theoretical description of the sound waves from particle energy
loss has been extended since the Hawaii Workshop by DUMAND participants
T. Bowen and J. Learned and also by the Soviet members G.A. Askarian
and B.A. Dolgoshein[6]. Bowen and Learned both account[12],[13] for the bi-
polar pulse shapes observed in the Brookhaven experiments and give defi-
nite predictions assuming that the spatial distribution of heat deposi-
tion is known and that other mechanisms, such as bubble formation, can
be neglected. The experimental and theoretical work indicates that par-
ticle cascades in water with energies down to $10^{14} - 10^{15}$ eV should be
detectable at one meter by single hydrophones. The task remains to
acquire acoustic data from typical high-energy particle cascades both
for detailed comparison with theory and for direct use in the design
of underwater detectors.

Factors of 10^3 or more in sensitivity can be achieved by combining
the signals from many hydrophones, so that the detection at distances
up to 1 km of cascades of 10^{14} eV will certainly be possible, at the
expense of some technical complexity and cost; how much is not yet clear.

The following theoretical analysis is that of T. Bowen[13].

The acoustic radiation from high-energy cascades in liquids such
as water is a theoretical problem considerably simpler than the case
of solids, in which shear waves and other complications arise. In liq-
uids the pressure is a scalar quantity, and its propagation is described
by the inhomogeneous wave equation

$$\Delta^2 \phi - \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} = - \frac{\beta_0 e_0(\vec{r})}{\rho_0 c_p} \tag{1}$$

where ϕ is a "displacement potential" defined by the equations:

$$q = -\Delta\phi \tag{2}$$

$$p = \rho_0 \partial^2\phi/\partial t^2 \tag{3}$$

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and q is the displacement of a volume element due to the heat pulse; p is the pressure generated (the acoustic pressure), and

> c = velocity of sound in the medium
> ρ_o = density of the medium,
> β_o = coefficient of thermal expansion of the medium
> C_p = specific heat at constant pressure and
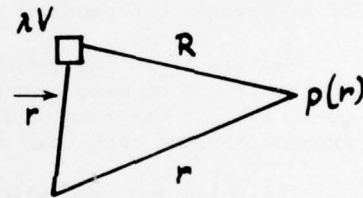> $e_o(\vec{r})$ = heat deposited adiabatically at T = 0 per unit volume at $\vec{r}$.

The solution to this equation is of the form (see, e.g., Morse and Feshbach)

$$\phi(r,t) = \frac{\beta_o}{4\pi\rho_o C_p} \int_{R < Ct} dV \frac{e_o(\vec{r})}{R} \qquad (4)$$

where $\phi(r,t)$ is the retarded potential. The form of ϕ is like this:
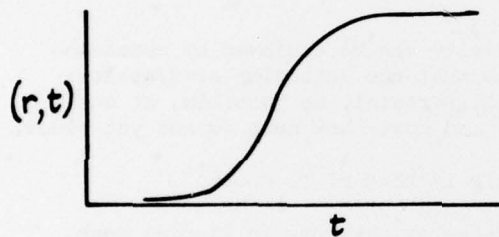
(a)

and that of p is the second time derivative, shown in (b).

(b)
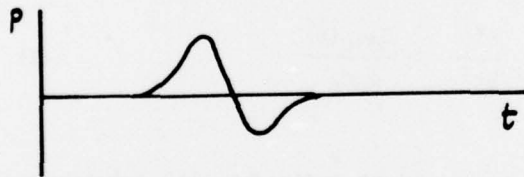
Since ϕ is a constant determined only by the initial heat deposition, we should be able to find a function of p which gives us ϕ, and thus is a constant of the problem. From the relation between p and ϕ (Eq. 4), this can be obtained by two successive integrations:

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$$I_1(t) = \int_0^t p(t')\,dt' = \rho_0 \int_0^t \frac{\partial^2 \phi}{\partial t^2} = \rho_0 \left[\left(\frac{\partial \phi}{\partial t} \right)_t - \frac{\partial \phi}{\partial t}_0 \right]$$

$$= \rho_0 \phi(t), \text{ since the second term is zero; and}$$

$$I_2(t) = \int_0^t I_1(t')\,dt' = \rho_0 \int_0^t \frac{\partial \phi}{\partial t}\,dt = \rho_0 \left[\phi(t) - \phi(o) \right]$$

$$= \rho_0 \phi(t), \text{ the second term again vanishing;}$$

But now $I_2(t \to \infty) = \int_0^\infty I_1(t)\,dt = \rho_0 \phi(t \to \infty)$

$$= \frac{\beta_0}{4\pi C_p} \int_{\substack{\text{heated} \\ \text{region}}} dV\, \frac{e_0(\vec{r})}{R}$$

$$\simeq \frac{\beta_0 E_0}{4\pi C_p} \cdot \frac{1}{R} \tag{5}$$

where E_0 is the total energy deposited, provided R is much larger than the dimensions of the heated region. But now let us evaluate $I_2(t \to \infty)$; we integrate by parts:

$$\text{Let } u = I_1(t) = \int_0^t p(t')\,dt'$$

$$du = p(t)\,dt$$

$$v = t$$

$$dv = dt$$

$$I_2(t \to \infty) = \left[t \int_0^t p(t')\,dt \right]_0^\infty - \int_0^\infty t\, p(t)\,dt$$

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The first term vanishes, since there can be no net change in pressure after the event is over; thus

$$\int_o^\infty p(t) \; dt = - \frac{\beta_o}{4\pi C_p} \int_{\substack{heated \\ region}} dV_d \; \frac{e_o(\vec{r})}{R} \simeq \frac{\beta_o E_o}{4\pi C_p R} \qquad (6)$$

The above treatment implies that a simple integration of the pressure pulse in the time domain will give a constant result, characteristic both of the total energy deposited, E, and of the medium, through the parameter β/C_p. This emphasizes an important feature of this treatment: the mechanism of the signal is assumed to be purely thermoacoustic, with no contributions from microbubbles (as suggested, e.g., by Askarian and Dolgoshein[9]) or ionic expansion (as suggested by Volovik[14]).

In addition, the theory automatically defines the region over which to integrate to get the best signal-to-noise ratio, and also predicts the magnitude of the signal to be observed. A double-integration of the pressure signal, which can be performed with filters, will also give a transformation of the signal into a directly usable output indication of the primary signal strength.

To date, detailed quantitative agreement between theory and observation has not yet been seriously attempted; we believe that the experimentally observed data have uncertainties large enough to cover the discrepancies, which are still of the order of 10 dB. Every effort is being made to diminish these; and since the original discrepancies between theory and experiment were factors of 10^6 or more as recently as last fall, we are optimistic about resolving the remaining discrepancy.

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