NFAC
Neutrino Facilities Assessment Committee

for
National Research Council

Barry Barish
Chair
5-Nov-02
Charge to NFAC

The Neutrino Facilities Assessment Committee will review and assess the scientific merit of IceCube and other proposed U.S. neutrino detectors—neutrino detectors associated with deep underground research laboratories and large volume detectors, such as IceCube—in the context of current and planned neutrino research capabilities throughout the world. Specifically, the study will address the unique capabilities of each class of new experiments and any possible redundancy between these two types of facilities. The review will also include: (1) the identification of the major science problems that could be addressed with cubic-kilometer-class neutrino observatories; (2) the identification of the major science problems that could be addressed with a deep underground science laboratory neutrino detector; and, (3) an assessment of the scientific importance of these problems and the extent to which they can be addressed with existing, soon to be completed, or planned facilities around the world.
NFAC Membership

Barry C. Barish, California Institute of Technology, Chair
Daniel S. Akerib, Case Western Reserve University
Steven R. Elliott, Los Alamos National Laboratory
Patrick D. Gallagher, National Institute of Standards and Technology
Robert E. Lanou, Jr., Brown University
Peter Meszaros, Pennsylvania State University
Hidoshi Murayama, University of California, Berkeley
Angela V. Olinto, University of Chicago
Rene A. Ong, University of California, Los Angeles
R. G. Hamish Robertson, University of Washington
Nicholas P. Samios, Brookhaven National Laboratory
John P. Schiffer, Argonne National Laboratory
Frank J. Sciulli, Columbia University
Michael S. Turner, University of Chicago

NRC Staff
Donald C. Shapero, Director
Joel Parriott, Study Director*
Tim Meyer, Study Director*
Meetings & Schedule

**First meeting:**
June 24-25, 2002
National Research Council –Washington, DC
Begin data gathering

**Second meeting**
July 25-26, 2002
O'Hare Hilton Chicago, IL
Complete data gathering

**Third meeting**
Sept 30 - Oct 1, 2002
Caltech Pasadena, CA
Complete draft report.

**Draft report sent for review**
October, 2002

**Public release of report**
November, 2002
NFAC Committee Process

• Our goal was to answer the charge by doing an assessment of the scientific merits of IceCube and a new deep underground laboratory in the U.S.

• Although the charge specifically singles out “neutrinos,” we assessed the science more broadly

• Our meetings in June (Wash DC) and July (Chicago O’Hare) were primarily information gathering. Open sessions included invited presentations, plus some short presentations from the community.

• Individual inputs from the community were encouraged and were received at our email address: (NFAC@NAS.EDU)
NeSS 2002 is a major international workshop designed to review and integrate the results of recent developments in neutrino, low background and geo-science investigations requiring great subterranean depth.

This workshop is very important to the future of our respective fields. Its genesis is a statement in the fiscal year 2003 budget request for the National Science Foundation submitted by the President to the US Congress. This request includes the following statement pertaining to research on neutrino collectors, including applications for underground research: "Such research, including underground applications, will also be the subject of a major NSF Workshop on neutrino research projects and a National Academy of Sciences’ Report."
NeSS 2002 Working Groups

**Double beta-decay**
- Giorgio Gratta - Stanford
- Wick Haxton - Washington

**Proton decay**
- Hank Sobel - Irvine
- Jogesh Pati - Maryland

**Neutrino Oscillations and Mass, and CP violation**
- Michael Shaevitz - Columbia
- Vernon Barger - Wisconsin

**Dark matter**
- Richard Gaitskell - Brown
- Richard Arnowitt – Texas A&M

**Solar Neutrinos and Stellar Nuclear Processes**
- Michael Wiescher – Notre Dame
- Tomas Bowles - LANL
- M.C. Gonzalez-Garcia - Stonybrook

**Astrophysical and Cosmological Neutrinos**
- David Nygren - LBNL
- Eli Waxman - Weizmann
NeSS 2002 Working Groups (cont)

Geology, Geo-Biology, and Geo Engineering Geomicrobiology
  Tullis Onstott - Princeton

Geochemistry - Petrology
  Steve Kesler - Michigan

Geohydrology & Engineering
  Brian McPherson

Geophysics
  Bill Roggenthen

Geomechanics & Engineering
  Herb Wang - Wisconsin

National Security
  Kem Robinson - LBNL
  Frank Hartmann - MPI

Education & Outreach
  Susan Millar - Wisconsin
NFAC – Important Considerations

• NFAC is asked to address to what extent the science “can be addressed with existing, soon to be completed, or planned facilities around the world.”
  ➢ We had presentations at our meetings to try to understand the global context of the proposed U.S. initiatives.

• NFAC is asked to assess “the unique capabilities of each class of new experiments and any possible redundancy between these two types of facilities.”

• Our study and report are being developed with the full consideration of the recommendations in several recent reports:
  ➢ The NRC Report “Connecting Quarks and the Cosmos: Eleven Science Questions for the New Century,”
  ➢ The NSAC Long Range Report for Nuclear Physics
  ➢ The HEPAP Long Range Report for High Energy Physics
The Birth of Neutrino Astrophysics

- The detection of neutrinos coming from the sun and from an exploding star, discoveries from underground experiments of the past decades, were recognized in the 2002 Nobel physics prize.

\[ {^{37}\text{Cl}} + \nu_\text{e} \rightarrow {^{37}\text{Ar}} + \text{e} \]

Solar Neutrinos
Supernovae 1987a
But, there is an observed deficit in the rate of solar neutrinos ...
High Energy Cosmic Ray Spectrum

- Protons
- Heavy nuclei
- Extra galactic

GZK cutoff
Questions we are now poised to answer

• Why do neutrinos have tiny masses and how do they transform into one another?

• Are the existence and stability of ordinary matter related to neutrino properties?

• Are there additional types of neutrinos?

• What is the mysterious dark matter and how much of it is neutrinos?

• What causes the most powerful explosions in the Universe?

• What role do neutrinos play in the synthesis of the elements in the periodic table?

• How do supermassive black holes produce very high energy gamma rays?

• Is there a deeper simplicity underlying the forces and particles we see?
Science Potential of IceCube
Why High Energy Neutrinos?

• The observation of cosmic high energy neutrinos would open a new window to the most energetic phenomena in the Universe.

• From cosmic- and gamma-ray observations, we know that astrophysical processes accelerate particles to above $10^{20}$ eV and there are good arguments for the production of high-energy neutrinos as well.

• Reasons to detecting such neutrinos:
  – Neutrinos would provide evidence for the cosmic acceleration of hadrons
  – Neutrinos point directly back to their source
  – Neutrinos traverse the diffuse matter in the Universe to reveal the sources.
The Goals of IceCube

The possibility of new discoveries in the very high energy range is the main motivation for building large neutrino detectors such as IceCube. IceCube will be able to address several of the questions we posed:

- What is the mysterious dark matter and how much of it is neutrinos?
- What causes the most powerful explosions in the Universe?
- How do supermassive black holes produce very high energy gamma rays?

IceCube is an exploratory experiment, in that it will search for astrophysical neutrinos in the very high energy range with much greater sensitivity than previous efforts.
Scientific Motivation

• Search for sources of high energy neutrinos
  – *Galactic*: SR, Galactic micro-quasars, diffuse ν’s from CR interactions
  – *Extra-galactic*: GRB, AGN’s, other HE sources

• Mechanisms powering these sources
  – Neutrinos will help in the understanding of the physics of these sources.

• Indirect Search for Dark Matter (relic neutralinos).

• Measurement of neutrino oscillation parameters.

• Search for unexpected phenomena.
Muon detection through Cherenkov light:

\[ \mu \text{ energy from energy loss and range. } \mu \text{ direction from T:O:F.} \]

Angular correlation: \[ \Delta (\theta_{\nu} - \theta_{\mu}) \approx 0.7^\circ / E^{0.6}(\text{TeV}). \]

Expected resolution in \( \nu_\mu \) direction: \( 0.5^\circ \) for ice, \( 0.1^\circ \) for water.
IceCube Detector Concept

- 80 strings
- 4800 PMTs in *Digital Optical Modules* (DOMs)
- 160 IceTop tanks
- 1400 m to 2400 m depth
Neutrino Interactions in IceCube

\[\nu_\mu + N \rightarrow \mu + X\]

\[\nu_e + N \rightarrow e + X\]

\[\nu_\tau + N \rightarrow \tau + X\]
IceCube Sensitivity to WIMPs

Neutralinos may be indirectly detected \textit{indirectly} through their annihilations in the sun. The produced particles subsequently decay and yield high energy neutrinos.

Complementary to Direct Searches

- \textit{Sensitive to higher masses}
- \textit{Sensitive to spin-dependent neutralinos interactions}

Similar sensitivity to direct searches
Extragalactic objects such as active galactic nuclei (AGN) and gamma ray bursts (GRBs) are possible sources.

Galactic sources, such as pulsars and supernovae, are also possible sources.

AGN rates are detectable, assuming substantial fraction of the power accelerates hadrons and the energy spectrum falls slowly ($< E^{-2}$).
Diffuse Sources of High Energy Neutrinos

Whatever the source of the ultra high energy cosmic rays, they are likely to produce a flux of high energy neutrinos.

A number of ultra-high energy astrophysical accelerators, proposed to explain the origin of the highest energy cosmic rays, could be detectable by IceCube.

The Waxman-Bahcall limit is based on the consideration that the energy input into neutrinos cannot exceed the observed cosmic ray flux at high-energies. IceCube can reach fluxes down to one tenth of the W-B limit.
Alternatives to IceCube – Deep Underwater

Deep-water Neutrino Telescope Projects

ANTARES  La-Seyne-sur-Mer, France
          (NEMO  Catania, Italy)

BAIKAL: Lake Baikal, Siberia

DUMAND, Hawaii
(canceled 1995)

NESTOR: Pylos, Greece
Ice vs Water

Light attenuation is less in ice than in water.
  • Attenuation depends on both absorption and scattering.
  • Absorption is smaller (but scattering is larger) in ice than in water.

Ice has higher effective area and potentially better energy resolution than water.
  • Scattering is smaller in water than in ice.
  • Pointing resolution is potentially higher in water than in ice, for both muons and e-m showers.

Test line deployment, Nov 2001

Antares deployment tests
IceCube

Assessment: The planned IceCube experiment can open a new window on the Universe by detecting very high energy neutrinos from objects across the Universe. The science is well motivated and exciting, the detection technique is proven, and the experiment appears ready for construction.

IceCube has completed its R&D, prototyping and conceptual design phases. When the funding is approved, it is ready to transition to the construction phase. This will require putting into place appropriate project management, making final technical and design decisions and ensuring that the collaboration is strong enough to support a project of this importance and magnitude.

IceCube has a head start on its competitors, and so timely deployment of the detector will give it a lead in the exploration of this new window of astrophysics.
Deep Underground Laboratory

Variation of the flux of cosmic-ray muons with overburden.

The horizontal bar indicates the range of depths that would be available for experiments in a multipurpose underground laboratory.
Why Deep Underground?

- A clean, quiet and isolated setting is needed to study rare phenomena free from environmental background. Such a setting can be obtained only deep underground, where we can escape the rain of cosmic rays from outer space.

- Why do neutrinos have tiny masses and how do they transform into one another?
- Are the existence and stability of ordinary matter related to neutrino properties?
- Are there additional types of neutrinos?
- What is the mysterious dark matter and how much of it is neutrinos?
- What role do neutrinos play in the synthesis of the elements in the periodic table?
- Is there a deeper simplicity underlying the forces and particles we see?
One Depth Suits All?

- Cosmic rays create background events that mask the critical events being searched for.
  - It takes two miles of rock to absorb the most energetic of the muons created by cosmic ray protons striking the earth's atmosphere
  - At such great depths, the only backgrounds are made by neutrinos (which easily penetrate the whole earth but, by the same token, interact very seldom) and by local radioactivity in the rock itself
  - Some experiments do not require the greatest depths, while for other experiments there is no option but depth and extreme cleanliness. Only in such an isolated environment can we hope to detect the faintest signals of our Universe.

- A new multipurpose underground laboratory should be able to provide a range of depths for experiments, allowing an optimized cost benefit for each experiment
Deep Underground Laboratory

Variation of the flux of cosmic-ray muons with overburden.

The horizontal bar indicates the range of depths that would be available for experiments in a multipurpose underground laboratory.
Scientific Motivation

• Neutrino Properties
  – Solar Neutrinos
  – Long Baseline Experiments
  – Double Beta Decay

• Dark Matter

• Proton Decay

• Neutrinos, Solar Energy, and the Formation of the Elements
The Sun as seen from SuperKamiokande deep underground

SuperK
SNO shows the deficit is due to neutrino flavor change or “neutrino oscillations”

<table>
<thead>
<tr>
<th>Fluxes</th>
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<tbody>
<tr>
<td>$(10^6 \text{ cm}^{-2} \text{ s}^{-1})$</td>
<td></td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>1.76(11)</td>
</tr>
<tr>
<td>$\nu_{\mu\tau}$</td>
<td>3.41(66)</td>
</tr>
<tr>
<td>$\nu_{\text{total}}$</td>
<td>5.09(64)</td>
</tr>
<tr>
<td>$\nu_{\text{SSM}}$</td>
<td>5.05</td>
</tr>
</tbody>
</table>
Neutrino Oscillations of Solar Neutrinos

Interpretation of flavor transformation as the result of non-zero neutrino mass and mixing in the lepton sector.

Before SNO

After SNO
The Near Term Future

A new solar neutrino experiment, Borexino, and a reactor antineutrino experiment, KamLAND, are now being commissioned to provide tighter constraints on the neutrino mass and mixing parameters responsible for flavor conversion.
Reactor Neutrinos -- KamLAND
Solar Neutrinos – The Future

In the standard solar model the flux from the $pp$ reaction is predicted to an accuracy of 1%. Further, the total flux is related directly to the measured solar optical luminosity.

Such a copious and well-understood source of neutrinos is ideal for precisely determining the neutrino masses and mixings.

It also affords a way to search for hypothesized sterile neutrinos as much as a million times lighter than those explored by present experiments, provided they mixed sufficiently with the active neutrinos.

Unfortunately, the $pp$ neutrinos have very low energies.
Two types of experiment are required, both sensitive to the lowest-energy neutrinos.

- One experiment measures the electron-flavor component by the “charged-current” (CC) reaction
- The other measures a combination of electron, mu and tau neutrinos via elastic scattering from electrons (the ES reaction)
- Large background mitigation required, so deep sites are required.
- Several technologies being pursued – need underground testing

Clean – Liquid Neon

XMASS – Liquid Xenon
Atmospheric Neutrinos

\[ \pi \rightarrow \mu + \nu_\mu \]
\[ \mu \rightarrow e + \nu_\mu + \nu_e \]

predict
\[ N_{\nu_\mu} = 2 N_{\nu_e} \]

but observe
\[ N_{\nu_\mu} \approx N_{\nu_e} \]
Atmospheric Neutrinos

Angular distribution of neutrino events yields neutrino rate vs path length
Angular distributions and deficit both consistent with neutrino oscillation hypothesis and with each other.
Confirm or Reject LSND

MiniBooNE Detector

Signal Region

Veto Region

Fermilab
Long Baseline Neutrino Experiments

MINOS

Main Injector Neutrino Oscillation Search

Fermilab

Soudan

Duluth

MN

WI

Lake Michigan

MO

IA

IL

IN

10 km

730 km

12 km

K2K

CERN

Gran Sasso

CNGS

Opera and Icarus
Neutrino Masses and Admixtures

- Next generation neutrino oscillation experiments aim to determine the admixtures and mass differences but not their absolute scale.
- Experiments on the neutrinoless double beta decay would supply the crucial information on the absolute scale.
- The electron-type component mixed in the 3rd state, called $\theta_{13}$, is not known.
- The potential differences between neutrinos and antineutrinos are also unknown.

The longer term future will involve determination of $\theta_{13}$ and possibly measuring CP violation in the neutrino sector with another generation of long base line experiments.
Concept for Next Generation Proton Decay/Neutrino Oscillation Detector

UNO Baseline Design

Total Mass: 648 kt
Fiducial: 440 kt

For 1 Mtyr exposure (no background)

- \( \tau_{\text{sens}} \sim \frac{1}{4} \epsilon \times 10^{35} \text{ yr} \)
- \( \tau_{90\%} \sim \epsilon \times 10^{35} \text{ yr} \)
Goals: Dirac or Majorana particle?

Majorana: The neutrino is its own antiparticle

Ettore Majorana
Dirac vs Majorana mass

- Majorana mass is measured by double beta decay
  - Use Nuclei stable under normal beta decay, but decay by a double weak interaction process.
    - Changes charge two units
    - Two neutrinos are emitted.
  - If neutrinos have Majorana mass, a vertex with no external neutrinos is possible.
    - unambiguous signal of a Majorana mass.
    - identified from two neutrino double beta decay by electron spectra
Double Beta Decay – The Future

Some models predict very low values for neutrinoless double beta decay, still allowing the physical masses of all neutrinos to be orders of magnitudes larger than the observed limit of effective Majorana mass.

Future Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>nucleid</th>
<th>detector</th>
<th>sensitivity/eV</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENIUS</td>
<td>100-1000 kg 76-Ge</td>
<td>Ge</td>
<td>0.01</td>
<td>2005</td>
</tr>
<tr>
<td>CUORE</td>
<td>225 kg 130-Te</td>
<td>TeO$_2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEMO 3</td>
<td>several, 10 kg</td>
<td>drift chamber</td>
<td></td>
<td>2001</td>
</tr>
<tr>
<td>MOON</td>
<td>Mo</td>
<td></td>
<td></td>
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The start times are only suggestive, and not all proposals have decisive funding. Other proposals exist.
Dark Matter – Direct Searches
• 1400 m rock overburden
• Flat cross-section
• Underground area 18 000 m²
• Support facilities on the surface
Gran Sasso Scientific Program

Neutrinos from CERN (CNGS)
- OPERA
  - Observe $\tau$-decay
  - Em: 36tons, Pb: 2ktons

ICARUS (600ton $\rightarrow$ 3000ton)
- $\mu$ stop and decay in $e$
- (data taken at the surface)

Neutrinos from the atmosphere
- MONOLITH not approved

Neutrinos from the Sun
- GNO
  - Low energy solar neutrino exp with 30ton Ga.

BOREXINO
- Real time measurement of $^7$Be $\nu$.
- It will start soon.

LENS proposal
Gran Sasso Scientific Program

**Neutrinos from Supernovae**
- LVD
- 1kton liq scintillator detector

**Double beta decay experiments**
- Enriched Ge (Heidelberg-Moscow)
- Cryogenic techniques (Cuorecino, TeO₂)

**Search for non baryonic dark matter**
- Several complementary experiments
  - Example: DAMA 100kg NaI detector

**Nuclear reactions (two accelerators, 40 and 400keV)**
- Fusion reactions in the Sun
- Anomalous screening in metals (LUNA-2)

The lab is also used for studies of geology and biology.
Kamioka Observatory

KamLAND
(operated by Tohoku Univ.)

Super-Kamiokande

XMASS R&D

To mine entrance (1.8km from SK)

- 1000 m rock overburden
- The mine is no more active
- Support facilities on the surface

Plot type GW detectors
20m × 20m
100m × 100m (Cryogenic)
SNO Laboratory

- 2000 m rock overburden
- Almost flat surface
- Support facilities on the surface
- Vertical access
- Main cavity ~10,000m³
Future SNO (Approved, expected completion: 2005)

- New exp. Hall (15m × 60m × 15mh)
  - Two major exp's + ...
  - One exp could be: PICASSO DM exp.

- Low B.G. counting facility (8m × 8m × 4mh, general purpose facility)

- Future clean boundaries

- Future SNO upgrade or completely new exp. (under consideration)

- + surface facilities

SNO cavity

Chem. Lab.
Conclusions – Deep Underground Laboratory

• Important future experiments on solar neutrinos, double beta decay, dark matter, long baseline neutrinos, proton decay, and stellar processes are being devised, proposed and discussed.

• We find that a common feature of the future experimentation in this field is the importance of depth. Most of the experiments envisaged require an overburden of about 4500 mwe or more.

• To optimize long baseline studies of neutrino oscillations, a new underground facility should be located at a distance greater than 1000 km from existing, high intensity proton accelerators.

• The breadth and quality of the potential future experimental program requiring an underground location suggests that there is a major opportunity for the United States if it can soon develop a large new underground facility with the ability to meet the requirements of the broad range of proposed experiments.
Deep Underground Laboratory

Assessment: A deep underground laboratory can house a new generation of experiments that will advance our understanding of the fundamental properties of neutrinos and the forces that govern the elementary particles, as well as shedding light on the nature of the dark matter that holds the Universe together. Recent discoveries about neutrinos, new ideas and technologies, and the scientific leadership that exists in the U.S. make the time ripe to build such a unique facility.

It will require considerable strategic and technical guidance, in order to construct a deep underground laboratory expeditiously and in synergy with the research program. Critical decisions that are beyond the scope of this report remain: choosing between several viable site options, defining the scope of the laboratory, defining the nature of the laboratory staff and the management organization, the site infrastructure and the level of technical support that will be resident. Developing sound experimental proposals will require early access to deep underground facilities to perform necessary R&D. Therefore, it is important to complete the process of setting the scope and goals for the laboratory, soliciting and reviewing proposals, and building up the necessary infrastructure, in order to initiate the experimental program in a timely fashion.
Redundancy and Complementarity

The exploratory physics of IceCube and the broad science program for a deep underground laboratory are truly distinct. IceCube concentrates on very high energy neutrinos from astrophysical sources that require a detector of much larger size than is possible in an underground laboratory, while an underground laboratory focuses on experiments, including neutrino experiments, that require the low backgrounds available deep underground. The committee finds essentially no overlap or redundancy in the primary science goals and capabilities of IceCube and that of a deep underground laboratory.