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Nuclear Physics Neutrino PreTown Meeting: Summary and Recommendations

1 Introduction

In preparation for the nuclear physics Long Range Plan exercise, a group of 104 neutrino physicists met in Seattle September 21-23 to discuss both the present state of the field and the new opportunities of the next decade. This group included a substantial fraction of the US nuclear physics neutrino community. The meeting was organized around five working groups: solar neutrinos; supernova neutrinos and the supernova mechanism; reactor and accelerator neutrinos; underground laboratories (including atmospheric and high energy neutrinos); and neutrino mass (double beta decay and tritium beta decay). Plenary speakers summarized the status of field, while the important question of future directions was tackled by the working groups. In the third day of the meeting the working groups presented their conclusions in a plenary session that concluded with a group discussion of future opportunities and priorities.

While discussions were wide ranging, three broad themes surfaced frequently:

- Although nuclear physics has a long tradition in neutrino physics – landmark events include introduction of the neutrino to conserve energy in β decay, the precision β decay tests that contributed to the experimental foundations of the standard model, and the chlorine solar neutrino experiment, which started the field of neutrino astrophysics – now is a time of special opportunity. The neutrino physics done by nuclear physicists lies at the intersection of two major intellectual revolutions. One of these is the nature of physics beyond the standard model. Measurements of the atmospheric

neutrino flux have provided the first clear evidence that the standard model is incomplete. The most naive interpretation of the neutrino mass difference derived from these measurements suggests a seesaw mass of about 10^{15} GeV, remarkably close to the grand unification scale. With SNO and other new solar neutrino experiments, a new generation of massive double beta decay experiments, and opportunities like KamLAND, MiniBooNE, and K2K to probe oscillations with accelerator and reactor neutrinos, the next decade should be a time of rich discovery. The pattern of neutrino masses and mixings should be revealed, thereby guiding the efforts of theorists to formulate a new standard model.

A second revolution is occurring in astronomy and astrophysics: rapid technological advances are allowing observers to probe the universe with increasing precision and in a breadth of wavelengths. Among the problems that may be clarified in the next decade are the nature of dark matter and dark energy; the origin of the elements; the evolution of structure; and the physics of extreme environments, including supernova explosions, neutron stars, and cosmic rays of energy in excess of 10^9 TeV. Neutrino physics is central to much of this physics. The atmospheric neutrino results already demand that neutrinos are as important as the stars in their contribution to the mass of the universe. Neutrino masses will become important cosmological parameters as more precise microwave and large-scale structure maps of the universe are made. Neutrinos control the proton-neutron chemistry of supernova ejecta in which we believe the heavy r-process elements are synthesized, and are directly involved in the synthesis of certain nuclei. Just as solar neutrinos allow us to probe conditions in the solar core, the supernova neutrino “light curve” may help us better understand such stellar explosions, and may carry information on the state of the high-density nuclear matter in the proton-neutron star. High energy neutrinos may allow us to look inside the universe’s most energetic central engines. Conversely, these new environments will extend our tests of basic neutrino physics: matter effects for supernovae neutrinos can dramatically enhance oscillations that would otherwise be unobservable, for example.

Nuclear physics has an opportunity to play major roles in these two revolutions.

- In the last decade decisions to expand the boundaries of nuclear physics – to the substructure of the nucleon (JLab) and to the phases of nuclear matter at extremes of temperature and density (RHIC) – helped to revital-

ize the field. It is important to maintain this momentum by exploring new frontiers in the next decade. A new initiative in nuclear astrophysics, which would encompass the neutrino physics discussed above, is an outstanding opportunity for the field. Such an initiative could include other physics now under discussion in the Long Range Plan process, such as the Rare Isotope Accelerator, with its strong program of laboratory astrophysics. Clearly the impact of future studies of the nuclear structure of the r-process will be enhanced if nuclear physicists can simultaneously understand the supernova neutrino physics that controls the r-process path. Progress on both fronts would hopefully lead to a standard model of the core-collapse supernovae and the associated nucleosynthesis. The analogy with the solar neutrino problem, where the importance of laboratory measurements of pp chain reaction rates was enhanced by efforts on solar neutrino detection and on the standard solar model, is quite striking.

- Despite the interest in and promise of nonaccelerator neutrino physics, US physicists have had to overcome obstacles in mounting major experiments. Important ideas have come from the US community (e.g., SAGE/GALLEX and SNO), but the detectors have been built elsewhere, with US scientists as participants. Similarly, though US physicists are active in the field, no double beta decay experiment is currently running in the US. The reasons for this situation are complex. In the case of SNO, the Canadians owned the heavy water. In the case of SAGE/GALLEX, community recommendations to fund these experiments were not followed. A factor in siting some double beta decay experiments overseas was the quality of available underground sites. Despite this history, there are recent signs that support for the field is increasing: significant agency investments have been made in SNO, Borexino, SAGE/GALLEX, and KamLAND.

Europe and Japan have moved ahead of the US in important respects. Italy's Gran Sasso laboratory was created to foster underground experiments in Europe. It has become a major center, encouraging new ideas in underground physics and drawing experiments from across Europe and elsewhere. It is currently oversubscribed, prompting discussions of expansion. In Japan the Kamioka proton decay experiment, contemporaneous with the US IMB detector, was followed by SuperKamiokande, an effort that has had a profound influence due to its solar and atmospheric neutrino discoveries. There was no US followup to IMB, the first experiment to uncover an anomaly in the atmospheric neutrino flux.

The recent discoveries in neutrino physics provide the US nuclear physics community with an opportunity to rethink its strategy in neutrino physics and related areas of nuclear astrophysics. The benefits to nuclear physics are not confined to the physics results: The field is very popular with students and thus is an important aid to recruitment. The ultimate success of any field depends on the quality of the students it attracts. Physics is also increasingly interconnected, with discoveries in one area affecting progress in others. Neutrino physics is an outstanding example, with relevance to astrophysics, cosmology, and particle physics. Results from experiments like SNO have the potential to influence all of physics, and thus to contribute to the stature of our field.

2 Principal Recommendations

While there are additional recommendations discussed in the working group summaries, the following four could form the basis of a neutrino initiative for the next decade:

The current generation of solar neutrino experiments is expected to produce exciting results, including the first separation of the ^8B neutrino flux into electron and heavy flavors. The next major push in this field must involve active detectors capable of determining the flux and flavor of the low-energy pp and ^7Be neutrinos. Most candidate solutions to the solar neutrino puzzle affect this portion of the spectrum in distinctive ways. Several detectors with the necessary characteristics are well along in development. Remarkable progress in neutrinoless double beta decay over the past two decades – a factor of two increase in lifetime limits every two years – has now reached a fundamental limit, $\sim 10^{25}$ years, imposed by current detector sizes (~ 10 kg). There are now urgent reasons for probing Majorana neutrino masses at the 0.03-0.10 eV level, requiring ton masses of the parent nucleus. Several excellent experiments have been proposed, some of which are technically well developed. Some of these exploit idle Russian enrichment capabilities.

One obstacle to increasingly precise neutrino experiments is the absence of a US deep underground laboratory, isolated from cosmic rays and other background sources. This has forced US experimentalists to mount their experiments elsewhere, or to manage in less than optimal surroundings, such as

active mines. The announced closing of the Homestake Mine in 16 months, coupled with the interest of the state of South Dakota in converting this to a national scientific facility, could provide a very deep (4850-8000 ft) hard-rock site. San Jacinto remains the best studied possibility for creating a site with horizontal access. The Sudbury Neutrino Observatory could be further developed as a multipurpose underground laboratory for North America.

Recommendation #1: Neutrino experiments in nuclear physics are making fundamental contributions to our understanding of the mass, mixing, and charge conjugation properties of neutrinos. The new discoveries are crucial to our field, affecting our understanding of nucleosynthesis, supernovae, and many other phenomena, and to astrophysics, particle physics, and cosmology.

- *Nuclear physics must build on its low energy neutrino successes, fully exploiting the existing detectors, while, at the same time, preparing to undertake the next generation of solar neutrino/supernova neutrino and double beta decay experiments. Several interesting next-generation experiments have been proposed. It is imperative to move these projects quickly through the R&D phase, so that the most promising detectors can be identified and launched as full-scale experiments. The community and agencies should work together to accomplish this goal.*

- *To satisfy the background requirements of new solar/supernova neutrino and double beta decay experiments, the nuclear physics community should spearhead an effort to create a deep underground multipurpose laboratory. Because this national facility could also serve the needs of dark matter and nucleon decay experiments, it is important to involve colleagues from particle and astrophysics. The urgency of one of the proposals (Homestake) requires that the community move now to define the merits and attributes of such a facility.*

The Spallation Neutron Source at Oak Ridge National Laboratory is now under construction. One byproduct of this facility is a stopped pion neutrino source of unusual characteristics: a flux in excess of that achieved at LAMPF, a pulsed time structure similar to that of the ISIS facility at Rutherford Laboratory, and an unusually low contamination of $\bar{\nu}_e$ (important for oscillation tests). The ORLAND collaboration has proposed exploiting this \sim \$1B new accelerator by constructing a neutrino bunker near the beam stop. A variety

of neutrino experiments – new oscillation tests, measurements of neutrino-nucleus cross sections important to supernova physics, tests of isoscalar axial currents – could be tackled with such a facility.

Recommendation #2: Nuclear physics should construct a neutrino bunker at the SNS beam stop so that the pulsed neutrino flux can be exploited in future experiments. It is important that the bunker be situated as close as possible to the beam stop. Such a facility would allow community collaborations to propose detectors and conduct experiments.

A major nuclear astrophysics challenge is to construct and experimentally verify a standard model of core-collapse supernovae. This problem encompasses nuclear theory, astrophysics, and computer science, requiring modeling of the nuclear equation of state up to at least four times nuclear density; of hydrodynamics, convection, and shock wave propagation; and of the neutrino-nucleus microphysics that we believe is crucial to both the explosion mechanism and associated nucleosynthesis. Supernova physics has already been an important stimulus to nuclear structure, motivating a great deal of recent shell model work (for example, finite temperature shell model Monte Carlo studies of Gamow-Teller strength distributions and level densities). A standard supernova model is needed to make full use of the the nuclear structure along the r-process path that RIA will provide. It is also needed to understand detailed abundances patterns that have recently come from Hubble Space Telescope and other studies of metal-poor stars enriched in r-process metals. Finally, it is essential if we are to exploit the next galactic supernova as a laboratory for new neutrino physics: unique kinematic neutrino mass and matter-enhanced oscillation tests are possible with supernova neutrinos.

Recommendation #3: The supernova mechanism is an outstanding computational and theoretical “grand challenge” problem in nuclear physics and astrophysics. A new theory initiative should be launched to make progress toward a multi-dimensional model with realistic neutrino transport and nuclear microphysics. An important component of this effort is improvements in nuclear structure methods for neutrino-nucleus cross sections.

Neutrino physics lies at the intersection of nuclear, particle, and astrophysics. Collaborations often cross subfield lines: the different experimental

skills within these subfields are a source of vitality for neutrino physics. One example is the AMANDA detector (and its proposed successor ICECUBE) for observing high-energy astrophysical neutrinos. AMANDA, which exploits the extensive experience in high energy physics with water Cerenkov detectors, will use neutrinos to probe active galactic nuclei and other astro-particle accelerators, very much as nuclear physicists are using solar neutrinos to probe the solar core. A second example is the next-generation proton decay detector being planned by particle physics: nuclear physics interest might focus on exploiting such a massive detector for solar or supernova neutrino detection. A third example is the proposed neutrino factory. At the time of the next long range plan nuclear physics will need to consider the opportunities for nuclear structure-function measurements this facility might provide. It is important for nuclear physics to have some involvement in these and other similar projects because they are relevant technologically and intellectually to nuclear physics.

Recommendation #4: Nuclear physics should continue to support members of our community who collaborate on relevant neutrino experiments funded primarily by other subfields.

3 Working Group Summaries

The five working groups addressed many of the questions that have been posed to guide the Long Range Plan process. Here the responses are summarized.

3.1 Solar Neutrino Working Group

What scientific questions is this subfield trying to answer?

There are five principal questions driving the field:

- What nuclear physics governs energy production in our sun's core and in other stars? Is our understanding of stellar evolution quantitative?
- What is the origin of the solar neutrino problem?
- Do electron neutrinos oscillate and, if so, to what?
- What constraints on neutrino masses and mixing angles can be extracted from solar neutrino experiments?
- Do neutrinos have other non-standard-model properties, such as magnetic

moments or flavor-changing interactions?

The pattern of solar neutrino fluxes that has emerged from current experiments, combined with the atmospheric neutrino evidence for neutrino mass, strongly suggests that the solar neutrino problem is due to neutrino oscillations. The current interpretation of the SuperKamiokande atmospheric results favors $\nu_\mu \rightarrow \nu_\tau$ oscillations. Thus solar neutrinos may be the best tool for probing the new properties of the first-generation ν_e .

What is the significance of this subfield for nuclear physics and science in general?

- The nuclei we study were created in stars and in stellar explosions. Solving the solar neutrino problem is the first step in demonstrating we understand stellar evolution and nucleosynthesis quantitatively. It opens the door to further studies in more explosive environments, where nuclei exist in conditions not yet found in the laboratory.
- In the past two decades physics has made an extraordinary investment in both accelerator and nonaccelerator experiments to probe the standard model. It now appears that the first sign of new physics involves the neutrino. Nuclear physicists started the field of neutrino astrophysics with the chlorine experiment and are now positioned to contribute to major discoveries in particle physics.
- A knowledge of neutrino masses is crucial to the next generation of precision cosmology experiments. It is already established that neutrinos are an important part of the universe's mass, at least comparable to the visible stars. Neutrino mixing can alter the spectrum of cosmological neutrinos.
- Neutrino properties are crucial to understanding much of nuclear astrophysics, including the supernova mechanism and the r-process.

What are the achievements of this subfield since the last long range plan?

- In 1995 SuperKamiokande was nearing completion. It has now produced results on the ^8B neutrino spectrum of unprecedented accuracy and found very strong evidence of atmospheric neutrino oscillations.
- In 1995 SNO was under construction. Today it is operating, has surpassed its background goals, and has observed the ^8B neutrino spectrum.
- In 1995 no neutrino source of sufficient intensity was available for measuring the responses of solar neutrino detectors. GALLEX and SAGE have now been tested with ^{51}Cr neutrino sources, verifying the nuclear cross sections and the efficiency of the chemistry.

- In 1995 Borexino's Counting Test Facility was under construction. The CTF experiment was successful, and construction of the full detector is now well underway.
- KamLAND, an experiment that can directly probe part of the neutrino oscillation parameter space relevant to solar neutrinos and may also have ^7Be neutrino detection capabilities, is now under construction.
- In 1995 there were still reasonable suggestions for nonstandard solar models that could reduce the solar neutrino discrepancy. Today both the increasing precision of helioseismology and the development of solar-model-independent neutrino analyses appear to rule out any such possibility.

What are the theoretical and experimental challenges facing the field? Identify the new opportunities.

- Definitive proof of oscillations must be obtained. SNO's ability to distinguish charged and neutral current events is the outstanding opportunity to provide such proof.
- Various oscillation scenarios can account for the data, some of which are quite difficult to distinguish unless low energy solar neutrinos can be measured. Can the US take the lead in developing and mounting one of the several promising experiments to measure the flux and flavor of these neutrinos? Among the proposals discussed by the working group were HERON, HELLAZ, MOON, LENS, CLEAN, GaAs, and Cerenkov-triggered radiochemical detectors employing Cl or I. The ideas range from new technology cryogenic detection schemes to hybrid detectors capable of simultaneously measuring solar neutrino reactions and double beta decay.
- The atmospheric neutrino results are consistent with maximal mixing, an unexpected result given the small mixing angles between quark generations. Can theorists, aided by results from SNO and other new experiments, find a compelling explanation for the pattern of masses and mixing angles?
- Can detectors developed for solar neutrino research probe other neutrino sources: atmospheric neutrinos, geophysical neutrinos, supernova neutrinos, and solar thermal neutrinos?

What are the resources required for this field?

There must be continued strong support for the major experiments now underway. SNO appears to be functioning very well, but the continuation of that experiment through the neutral current phase will require sustained effort. Measuring the heavy-flavor component of the solar neutrino flux is

clearly the highest priority. Borexino and KamLAND are tackling the very challenging problem of active detection of ${}^7\text{Be}$ neutrinos. While Italy and Japan have the lead in these efforts, respectively, the US participation is significant and must be continued.

But the principal challenge to US nuclear physics is to assume the lead in developing the next-generation active detector for the lowest energy solar neutrinos. The US currently lacks an effective mechanism for nurturing projects in the R&D phase and for constructing new detectors once the concepts have been proven. This problem is long standing, and has led to lost opportunities such as the gallium experiment. The institutional support available elsewhere - Gran Sasso is the outstanding example - places the US at a disadvantage. Because we lack a facility like Gran Sasso to advocate for the subfield, the community and the funding agencies must be more active in assessing a broad range of developing technologies; in distinguishing promising efforts from others, strongly supporting those R&D directions that make progress; and in mounting major experiments when the development stages have been completed.

Judging from precedents like SNO and Borexino, the typical scale of such major experiments is now in the \$25-50M range.

3.2 Neutrino Mass Working Group

The neutrino mass working group focused on the status and future of double beta decay experiments and tritium beta decay and other direct tests of neutrino mass.

What scientific questions is this subfield trying to answer?

- Is lepton number conserved? The most sensitive and most direct test of this question is provided by neutrinoless double beta decay.
- How does the neutrino transform under charge conjugation? The neutrino, lacking any additive quantum numbers like electric charge, is unique among the known fermions in having an ambiguous behavior under charge conjugation. It may be its own antiparticle (Majorana) or it may have a distinct antiparticle (Dirac). The possibility of both Majorana and Dirac masses is the key to the seesaw mechanism, the most popular theory explaining why neutrinos are so much lighter than their charged partners.
- What is the nature of neutrino mixing? As a virtual process, neutrinoless double beta decay probes aspects of the neutrino mass matrix that, other-

wise, are very difficult to test. It is sensitive not only to very light Majorana masses (below 1 eV), but also to very heavy ones, above a TeV. The mass derived from double beta decay is sensitive to the relative CP eigenvalues of the mass eigenstates. It is also sensitive to CP-violating phases in the mass matrix.

- How does neutrinoless double beta decay probe new phenomena beyond the standard model? Again, as a virtual process, double beta decay is particularly sensitive to new physics, even physics residing at very high energies. Examples include lepton-number-violating right-handed couplings, Majorons, supersymmetry, ...
- What is the absolute scale of neutrino masses? This is the crucial question for cosmology and dark matter searches, yet cannot be answered by either oscillation experiments, which depend on differences in the squares of the masses, or double beta decay, where eigenstates with different CP eigenvalues interfere. It can be measured in kinematic neutrino mass experiments, with tritium beta decay being the outstanding example.

What is the significance of this subfield for nuclear physics and science in general?

- Double beta decay – neutrinoless and two neutrino – is a fundamental nuclear process. It is the only open decay mode for approximately 50 otherwise stable nuclei. It is also the rarest process yet measured in nature. The basic decay process involves a two-nucleon correlation and a nuclear polarizability, and thus is fascinating from the perspective of nuclear structure theory.
- Opportunities to study second-order weak decays in nature are extremely rare. Double beta decay is one of only two such possibilities in particle physics.
- The question of lepton number violation in the early universe is crucial to cosmology. It is connected, in the standard model, to possible mechanisms for baryogenesis. Early universe lepton number asymmetries can trigger oscillations that distort the neutrino distributions, producing warm – not hot – neutrino dark matter.
- The question of the absolute scale of neutrino masses is crucial to dark matter studies, including interpretations of the cosmic microwave background and large scale structure. Tritium beta decay is a direct test of this mass scale.
- Double beta decay (and solar neutrino) experiments are technologically relevant. Low level counting and ultrapure materials have industrial signifi-

cance.

What are the achievements of this subfield since the last long range plan?

- Thirty years of effort was required before the allowed process, two-neutrino double beta decay, was observed in 1987. Today accurate lifetimes are known for approximately 12 nuclei.
- Extraordinary efforts to reduce backgrounds has resulted in a “Moore’s law” for neutrinoless double beta decay: over the past two decades, lifetime limits have improved by a factor of two every two years. The current limit on the Majorana mass is in the range (0.4-1.0) eV, with the spread reflecting nuclear matrix element uncertainties.
- Detector technology has greatly improved in areas such as backgrounds, detector mass, the use of isotopically enriched sources, and cryogenics.
- Double beta decay theory has improved significantly. Shell model methods have been develop to treat the intermediate nuclear Green’s function in two-neutrino decay. Full or nearly full fp-shell diagonalizations have been done. Shell model Monte Carlo methods have been developed and checked against exact shell model results. Virtually all of this work has occurred since the last long range plan.
- Tritium β decay mass limits have reached 2.2 eV (95% c.l.), a bound important to cosmology.
- At the time of the last Long Range Plan, the observation of excess events near the endpoint affected the field’s confidence in tritium β decay mass limits. Recently the Mainz group has traced much of the effect to energy losses due to rough source surfaces. Their latest results (98-99) appear to be free of any problems.

What are the theoretical and experimental challenges facing the field? Identify the new opportunities.

- Radiogenic and cosmogenic backgrounds have been tremendously suppressed by new techniques for refining ultrapure materials and by mounting experiments underground. The most challenging background in many cases is now the high-energy tail of the 2ν process, a serious limitation for detectors lacking excellent electron energy resolution. Thus high resolution detectors must be developed.
- With lifetime limits now above 10^{25} years, the next generation of detectors must employ larger masses to make progress. The counting rate is a fundamental limit at current ~ 10 kg detector masses. Thus much larger masses (

~ 1000 kg) are being planned in future experiments.

- The physically relevant scales for 0ν double beta decay experiments are still unclear. Current theoretical models that explain the solar and atmospheric neutrino results with Majorana neutrinos predict a broad range of double beta decay masses (typically from 1 eV to 10^{-5} eV).
- The goal of future direct ν_e mass searches is a sensitivity below 1 eV. The new ideas include the proposed 7m Karlsruhe spectrometer and a cryogenic calorimeter using Re.

What are the resources required for this field?

The current generation of neutrinoless double beta decay experiments includes the Heidelberg-Moscow and IGEX experiments on ^{76}Ge , the Caltech-Neuchatel effort on ^{136}Xe , and the ELEGANTS and NEMO-3 ^{100}Mo measurements. They have comparable goals (lifetime limits of $\sim 10^{25}$ years) and typically involve parent isotope masses of $\sim 10\text{kg}$. The Heidelberg-Moscow experiment, which has acquired more than 35 kg-years of data, has set a limit of 2×10^{25} years on the ^{76}Ge lifetime. All of these experiments are being conducted outside the US, though several involve US collaborators.

The new large-mass proposals have as their goal Majorana mass limits in the range of 0.03-0.10 eV. This is an important goal since the δm^2 deduced by SuperKamiokande, our first indication of the scale of neutrino masses, is centered around $\sim (0.05 \text{ eV})^2$. There are also strong claims from cosmologists that, once results have been obtained from MAP, PLANCK, and the Sloan Digital Sky Survey, knowledge of neutrino masses in the 0.1-1.0 eV range will be important to their analyses. The proposed experiments include MAJORANA and GENIUS (enriched ^{76}Ge), CUORE (cryogenic detector using ^{130}Te), MOON (^{100}Mo foils with plastic scintillator), EXO (a laser tagged TPC using ^{136}Xe), and CAMEO (^{116}Cd and ^{100}Mo in Borexino's CTF). Some of these detectors are very well developed, while others require considerable R&D. Some of the proposals, such as MAJORANA, GENIUS, MOON, and EXO, depend on Russian isotopic enrichment facilities which are currently available, but may not be so indefinitely.

Among the resources needed are consistent support for R&D in those cases where significant development is necessary; agency help in defining procedures where developed projects can be evaluated and supported; and support for international collaborations (most of the next-generation experiments listed above are international). The anticipated cost of a typical 1000 kg experiment is $\sim \$10\text{M}$, exclusive of isotope enrichment costs (which may

be provided by other agencies). There is need for some redundancy in double beta decay studies because of nuclear matrix element uncertainties and because the ultimate sensitivity of new approaches is often difficult to predict.

A US site for mounting double beta decay experiments is another issue. While the needs of experiments differ, current experiments typically require about 2000 m.w.e. coverage. Thus near-term requirements can be satisfied by sites like WIPP and the Soudan Mine, but deeper sites may be required for some next-generation detectors. Another issue is cosmic ray induced activities: activities such as ^{68}Ge must be allowed to decay away. Thus underground storage of materials, in anticipation of future experiments, is under discussion.

Dual-purpose detectors for solar neutrino and double beta decay are another interesting possibility in the next decade. MOON proponents anticipate solar neutrino rates for pp and ^7Be neutrinos comparable to their neutrinoless $\beta\beta$ decay rate goals. The problems confronting both types of measurements, small rates and troublesome backgrounds, can be solved with highly instrumented detectors that exploit coincidence techniques to isolate the signals of interest.

While shell model treatments of double beta decay have become more sophisticated in the last ten years, fundamental issues still need attention. Probably the most important is the effect of shells in the excluded space: how do these renormalize the shell-model $\beta\beta$ decay operators? The theory is not an experimental show-stopper – any observation of $0\nu\beta\beta$ decay demonstrates lepton number violation – but is important in translating lifetime limits into upper bounds on neutrino masses.

In tritium β decay near-term activity will focus on the Karlsruhe-Mainz-Troitsk project, an effort to push mass limits to ~ 0.5 eV with a massive 7m spectrometer. The estimated cost is \$10-15M. Other groups have been invited to join. Thus support is needed for US collaborators wanting to help in this effort. There are also interesting cryogenic Re calorimeters under development in Genova and Milano. On the longer term, very severe obstacles will have to be overcome to further increase sensitivities to ~ 0.1 eV. Molecular excited state contributions are one of the very troublesome issues at this level.

3.3 Supernova Neutrinos and the Supernova Mechanism Working Group

This working group focused on the theoretical challenge of building realistic models of core-collapse supernovae, the experimental challenge of building and operating neutrino observatories to measure the flux and flavors of neutrinos from the next galactic supernova, and related astrophysics issues.

What scientific questions is this subfield trying to answer?

- What is the mechanism by which a core-collapse supernova ejects its mantle? Can we build a quantitative standard model of the explosion, including neutrino production and associated nucleosynthesis, such as the r-process and the neutrino process?
- What experiments can be done to test such a standard model? Can we use the nucleosynthesis, particularly the pattern of r-process metals, to diagnose the explosion, in analogy with the use of d, ^3He , and $^6,7\text{Li}$ to test the big bang? Can we use the neutrino flux from the next galactic supernova to learn about the explosion mechanism and, possibly, to probe properties of the protoneutron star? Can we measure the gravitational wave signal in LIGO, and supernova gamma rays in INTEGRAL?
- Can we exploit supernovae to search for new phenomena, including neutrino oscillations and neutrino masses?

The supernova mechanism is one of the outstanding challenges in nuclear theory and theoretical astrophysics, involving an extraordinary range of physics. To specify the initial conditions for the explosion the massive progenitor star must be evolved through its various burning stages, to formation of the inert iron core. This problem couples laboratory nuclear astrophysics – including open problems like the $^{12}\text{C} + \alpha$ S-factor – with stellar evolution, and is very much an extension of the program that began with the solar neutrino problem. The description of the core bounce requires us to predict the behavior of bulk nuclear matter at densities and temperatures not otherwise accessible. New phenomena – mixed or quark-matter phases, color superconductivity, kaon condensation – could affect the equation of state. Both the early deleptonization of the star and the subsequent cooling require a detailed treatment of neutrino transport through the nuclear medium, and an understanding of the various processes that determine the opacity. Shock wave propagation through nuclear matter must be under-

stood. The nucleosynthesis depends on relationships between the explosion dynamics, the neutrino physics, and laboratory astrophysics. The explosion determines the timescale for the nucleosynthesis. Neutrino reactions control the isospin of the nuclear matter. Laboratory astrophysics must determine the masses and the β decay lifetimes important to the r-process and other explosive nucleosynthesis.

The neutrino fluxes produced by a supernova provide unique opportunities to learn about neutrino properties. As the neutrinosphere resides at a density $\sim 10^{12}$ g/cm³, supernovae allow us to extend our tests of matter effects on oscillations by 10 orders of magnitude. Thus MSW effects, even for very small mixing angles of 10^{-5} , can distort the neutrino spectra. The entire range of cosmologically interesting masses can be probed in this way. In particular, supernovae may provide our best laboratory for investigating $\nu_e - \nu_\tau$ oscillations. Kinematic tests of neutrino mass can be made by studying arrival times on earth as a function of flavor or energy. In this way it may be possible to greatly reduce mass limits for the ν_τ and ν_μ .

What is the significance of this subfield for nuclear physics and science in general?

- Supernovae are thought to have produced about half of the heavy nuclei found in nature. Nucleosynthesis is a central question for nuclear physics.
- To the extent that we can understand such synthesis, we can predict, given a galactic model, how metallicities evolve. This opens up a wonderful intersection with astronomy, including both abundance determinations and gamma ray astronomy.
- Neutron stars are the only example in nature of the nuclear theorist's test case, bulk nuclear matter. It is very likely that new phenomena exist at neutron star densities. In the next decade precise mass/radii determinations are likely to be made. This will provide a crucial check on our theories of the equation of state of dense nuclear matter.
- Core collapse supernovae (and neutron star merges) may produce detectable gravitational radiation. Accurate modeling of the collapse could help LIGO experimentalists by defining the wave forms that they must find.
- Supernova neutrino detection is a key part of the "supernova watch" program that also involves gravitational wave detectors and optical observatories.
- Supernova modeling is a terascale (and beyond) "grand challenge" problem that requires collaboration between nuclear theorists, astrophysicists,

and computer scientists. Many of the underlying issues, such as radiation transport, hydrodynamics, shock wave propagation, and the mathematical challenge of scalable algorithms for large, sparse, linear systems, are common to problems ranging from medical imaging to climate prediction to internal combustion. Thus the developments from supernova models will benefit many other sciences.

What are the achievements of this subfield since the last long range plan?

- At the time of supernova 1987A, two neutrino detectors were operational and ~ 18 events were recorded. Today there are four operating detectors and three others that should be operational in the next 1-2 years. Approximately 10^4 neutrinos should be counted at the time of the next galactic supernova.
- The first semi-realistic two-dimensional simulations of supernova explosions have been performed. This could be an important step in understanding the mixing apparent in the ejecta of observed supernovae.
- Full Boltzmann neutrino transport has been implemented in one dimensional models.
- Significant progress has been made in descriptions of the progenitor, e.g., multi-D models that account for convection and rotation. Improved electron capture and beta decay rates and improved neutrino opacities have made the input microphysics much more realistic.
- Progress has been made in modeling the r-process, including improved weak interaction rates, a better understanding of the effects of mass formula uncertainties and phenomena such as the vanishing of shell closures, and inclusion of neutrino postprocessing effects.

What are the theoretical and experimental challenges facing the field? Identify the new opportunities.

- The key theoretical challenge is to develop a supernova standard model that incorporates realistic neutrino transport and microphysics. Current 1D models generally fail to explode. This could reflect some flaw in our understanding of the physics, or the importance of doing multi-D simulations.
- Test relevant microphysics input into supernova simulations, such as mass formulas used in r-process synthesis and neutrino-nucleus cross sections important to opacities and nucleosynthesis, by direct laboratory measurements at RIA, ORLAND, and other facilities.
- Test supernova models by comparing predicted supernova neutrino flavor, energy, and time distributions to measurements made in underground neu-

trino detectors.

- Exploit the next galactic supernova to make kinematic tests of neutrino masses. More significant results can be obtained if sharp temporal features in the neutrino flux – the rise time or a sudden termination of ν emission due to black hole formation – can be identified.
- Exploit the next galactic supernova to search for the MSW flavor transformation $\nu_\tau \rightarrow \nu_e$. Because supernova ν_e s are more strongly coupled to the matter, they are predicted to be substantially less energetic than the heavy flavor neutrinos. Thus such a MSW oscillation will produce a distinctive spectral inversion, distorting the angular distribution of events in detectors like SuperKamiokande.

There are many open questions in supernova modeling that could be addressed by a “grand challenge” effort. A variety of physics – neutrino heating, convection, rotation, magnetic fields, general relativity – are inadequately modeled in current multi-D simulations. It is not known which of these effects may be essential to successful explosions. Nor is it clear how dependent (or independent) explosions may be on the class of progenitor star.

What are the resources required for this field?

One of the fundamental difficulties for the field is the low rate of galactic supernovae, estimated to be $\sim 1/30$ years. This corresponds to a timescale that exceeds some (though not all) neutrino detector lifetimes. The challenge, then, is to begin to view neutrino detectors as observatories, rather than experiments. Some compromises may be required because highly instrumented, high maintenance detectors become more costly, both in dollars and in the human investment, when operated over decades. Thus there is some merit to arguments that low-tech, flavor-specific experiments, such as the radiochemical detectors Cl, I, and SAGE/GNO, have a role to play.

When possible, it is clearly preferable to exploit detectors built for other purposes – SuperKamiokande, SNO, or a next-generation proton decay detector like UNO – as supernova observatories. This allows the physicists involved with the detector to do other physics while waiting for a rare supernova. Yet there are proposals for dedicated experiments, such as OMNIS, that are designed to minimize manpower requirements.

If supernova observatories are exclusively multipurpose detectors, then in some sense they monitor the galaxy for free. But to ignore the supernova physics in designing and operating such detectors is clearly a mistake. It is

essential that detectors with the requisite capabilities monitor the galaxy at all times, to avoid missing a once-in-a-lifetime opportunity. This is a theme of the supernova watch. In the case of SN1987A, we measured supernova $\bar{\nu}_e$ s. The goal, at the time of the next supernova, should be to measure separately the properties of the ν_e , $\bar{\nu}_e$, and heavy flavor fluxes. Water Cerenkov detectors have excellent capabilities for $\bar{\nu}_e$ s; the charge current reaction in SNO provides a clean signal for ν_e s. But SNO may operate for only a decade, and neither SNO nor SuperKamiokande has a 100% duty cycle. While there are strategies for extracting a neutral current (and thus dominately heavy flavor) signal from SuperKamiokande, the deuteron breakup reaction in SNO, which will produce about 800 events for a supernova at the galactic center, appears to be the better monitor of this flux. Scintillation detectors, such as KamLAND and Borexino, are also interesting neutral current detectors because neutrinos will excite the 15.11 MeV M1 transition in ^{12}C .

Clearly the nuclear physics community needs to be highly involved in supernova watch plans. Decisions to turn off detectors must take into consideration whether supernova capabilities are being lost. This also applies to scheduled maintenance.

The arguments for a theory initiative in supernova physics are very strong. This modeling is central not only to neutrino physics, but also to other major nuclear physics initiatives, such as RIA. The development of multi-D models with realistic neutrino transport and microphysics is possible at this time. Presuming that terascale machines are made available, the primary resource needed is person power: the groups currently involved in supernova theory are greatly understaffed. A reasonable starting budget for such an initiative is \$2.0M/year, most of which should be invested in young scientists who would attack the neutrino transport, hydrodynamics, and computer science issues associated with supernova modeling, as well as critical issues involving the underlying microphysics, such as the nuclear structure important to neutrino-nucleus scattering and other weak interactions, the nuclear equation of state at high density, and neutrino opacities.

3.4 Underground Laboratories Working Group

The underground laboratories working group considered not only underground sites, but also interdisciplinary experiments, such as those on atmospheric neutrinos or neutrinos produced by high-energy astrophysical sources, conducted in such sites.

What scientific questions is this subfield trying to answer?

- What type of environment, isolated from both cosmic ray and natural radioactivity backgrounds, can be provided to optimize the success of future background-sensitive experiments? How should such a facility (or facilities) be operated to meet the needs not only of nuclear physics, but of physics and science in general?
- What can be learned by extending the program of astrophysical neutrino detection to higher energies? In analogy with solar neutrinos and supernova neutrinos, could such a program allow us to probe the structure of active galactic nuclei and other high-energy objects?
- What contributions can nuclear physics make to the atmospheric neutrino problem and to proton decay and other searches for physics beyond the standard model?

What is the significance of this subfield for nuclear physics and science in general?

- Despite early leadership in the field of underground science, the US has fallen behind Europe and Japan in providing facilities for such experiments. The US community is largely engaged in overseas projects. The few efforts within the US, such as the Homestake solar neutrino program, manage in active mines. The shortage of suitable underground sites is a concern for proton decay, dark matter, and similar searches for new physics, projects important to our colleagues in particle and astrophysics.
- Atmospheric neutrinos are another tool to probe the physics of neutrino mass and mixing of interest to the nuclear physics community. SNO will have significant capabilities for atmospheric neutrinos. As the source distance varies from the height of the atmosphere to the diameter of the earth, very clean tests of oscillations can be made with atmospheric neutrinos if the oscillation length lies in this range.
- Many phenomena in astrophysics – such as 10^{21} eV cosmic rays and gamma ray bursts corresponding to isotropic sources of energy 10^{53} ergs – involve extraordinary scales of energy and particle acceleration. Even in our own galaxy there are hints, from AGASA, of 10^{18} eV events. The detection of neutrinos produced by such natural accelerators might help us understand the acceleration mechanism and pinpoint the source. Nuclear physics can contribute to such high-energy astrophysics questions because of our interest in water Cerenkov and other neutrino detection schemes.

What are the achievements of this subfield since the last long range plan?

- SNO has been constructed and has surpassed its background specifications, demonstrating that a clean-room environment can be maintained at great depth, even in an active mine.
- WIPP, the waste isolation facility in New Mexico, has offered to host scientific experiments. This provides a US laboratory site at moderate depth (~ 2000 m.w.e.). The depth is comparable to that of the Soudan Mine, but access is easier. Because it is located in a salt formation, U and Th background levels are low.
- SuperKamiokande has measured with very good statistics a distinctive zenith angle dependence in the ratio of electron to muon events. There are very strong arguments attributing this to $\nu_\mu \rightarrow \nu_\tau$ oscillations with a nearly maximal mixing angle. Most experts accept this result as the first demonstration of physics (nonzero neutrino masses, flavor mixing) beyond the standard model.
- AMANDA, the high-energy neutrino detector located 1500-2000m below the surface of the Antarctic ice sheet, was commissioned in February, 1997. The experimentalists have observed atmospheric neutrinos and are searching for astronomical sources.

What are the theoretical and experimental challenges facing the field? Identify the new opportunities.

- There are outstanding opportunities to create a deep underground national laboratory that will serve the next generation of solar neutrino, double beta decay, dark matter, atmospheric neutrino, and proton decay experiments. Deep sites are also important to accelerator measurements of astrophysical S-factors, and potentially interesting for other sciences and industry.

The model for such a national laboratory is Gran Sasso, located at an average depth of 4300 m.w.e. and with horizontal access off a highway excavated through the Gran Sasso d'Italia. The laboratory has been in existence since the early 1980's. Gran Sasso comprises 3 halls (~ 100 m \times 18m \times 18m), external offices, a computing center, technical and engineering services, electronics and chemical laboratories, a machine shop, library, conference room, and stockroom. The competition for space is keen. The laboratory currently hosts a broad program of experiments: the GNO successor to the GALLEX solar neutrino experiment; Borexino; the dark matter search DAMA; the Heidelberg-Moscow ^{76}Ge double beta decay experiment; the EASTOP air

shower array for cosmic ray physics (and for coincidence with underground detectors), located on top of the mountain; the ICARUS liquid Ar detector; LVD, a 1.6 kton liquid scintillator detector; MACRO, a large monopole detector; and LUNA, a low-energy accelerator for nuclear astrophysics.

The Kamioka laboratory, located in a mine in the Japanese alps, is also becoming a multipurpose facility. Activities include SuperKamiokande, KamLAND, a gravity wave detector under construction, and double beta decay.

There has been serious discussion in the US of a deep underground national laboratory since the early 1980s. The question has become very urgent with the announcement that the Homestake Mine, in South Dakota, will close in 16 months. Homestake is a deep, hardrock mine with a large shaft (15 \times 20 ft) running to 4850 ft; additional levels exist every 150 ft, to 8000 ft. The State of South Dakota, in combination with the South Dakota School of Mines, has expressed interest in taking on the operations, management, and liability burdens that would be associated with an underground laboratory. The mine has considerable infrastructure (pumps, power, air exhaust systems, multiple shafts). But significant investments are needed to produce an above-ground campus comparable to that at Gran Sasso; to install modern lifts that utilize the full dimensions of the shafts; to produce large halls of the type existing at Gran Sasso; and to engineer areas for cryogenics and other facilities where safety is a concern.

There is also a proposal for constructing a horizontal access laboratory by tunneling beneath Mt. San Jacinto, near Palm Springs. A laboratory located at the end of a 2.5 mile tunnel would provide 6000 ft of rock overburden. Although this requires construction of a laboratory and its infrastructure from scratch, the plan offers the advantages of horizontal access and proximity to a number of physics laboratories in California.

The Sudbury Neutrino Observatory is a third possible deep site in North America. Though an active mine, the success of SNO construction demonstrates that science requiring a clean-room environment can be done there. The SNO site is quite deep, 2039 m.

These possibilities for deep sites, together with the existing shallower sites at the Soudan Mine and WIPP, should be the starting point for a community discussion of how to prepare for the next generation of underground experiments. These sites have complementary aspects: different radioactivities, access, depth potentials, etc. The community has an opportunity to consider which facility or combination of facilities will help the next generation of experiments reach their potential. As Gran Sasso has proved, both the

underground site and the supporting infrastructure are important in facilitating new experiments.

- The successful commissioning of AMANDA opens up the possibility of large Antarctic arrays to do high energy neutrino astronomy. AMANDA has given the US leadership in this area. The next generation detector, ICE-CUBE, is designed to map the neutrino sky from GeV to PeV energies, determining both the diffuse flux from galactic and extra-galactic sources and point sources, such as active galactic nuclei or gamma ray bursters. High energy neutrinos are unique tracers of high energy protons and nuclei that we know are accelerated to extraordinary energies somewhere in the cosmos. The behavior of nuclei at very high energies and their interactions with the interstellar medium are topics of interest to nuclear physicists.

What are the resources required for this field?

The creation of a national deep underground laboratory is a major investment, the largest discussed in this report. In the case of Homestake, there is a large investment already made by the miners: the value of the existing mile-long 15×20 ft shaft is considerably in excess of \$100M. The additional investment that will be needed from scientific agencies to convert Homestake into a suitable national facility may be smaller, but is still significant. The costs include improved lifts, the experimental halls, and the above-ground facilities of the type provided by Gran Sasso. The cost of the experimental program of such a facility, extrapolating from Gran Sasso, is likely in the \$20-25M/year range. There are important efficiencies in such a laboratory because experiments can make use of a common infrastructure.

The construction costs of an ab initio laboratory like San Jacinto are more difficult to estimate. A reasonable extrapolation of the estimates made in the early 1980s, when the proposal was first discussed, yields \sim \$100M.

The construction and operations costs of such a facility presumably would be shared between nuclear and particle physics: dark matter searches and proton decay experiments are among the candidate experiments requiring significant cover. It is unlikely that the use of such a laboratory would be confined to nuclear and particle physics: isolated environments are also of interest to geophysicists, the electronics industry, biologists, and gravity wave experimentalists.

3.5 Reactor and Accelerator Neutrinos

What scientific questions is this subfield trying to answer?

- Can neutrino oscillations be observed under controlled laboratory conditions?
- Can neutrinos provide new information on the structure of nucleons and nuclei, such as strangeness content?
- Can laboratory neutrino sources be exploited to test our understanding of neutrino-nucleus cross sections important to supernovae and to the solar neutrino problem?

What is the significance of this subfield for nuclear physics and for science in general?

- Despite the strong evidence for neutrino oscillations from atmospheric and solar neutrino studies, the underlying physics issues are so important that confirmation of oscillations in the laboratory is crucial. The use of known neutrino sources and the ability to adjust the source-target distance are among the advantages of accelerator and reactor neutrinos. Disappearance and appearance measurements can be made.
- Neutrinos are potentially interesting as probes of strangeness in the nucleon and nucleus, with simpler radiative corrections. If some of the suggested experiments can be done, the results complement similar studies done at JLab and elsewhere.
- There are very few quantitative tests of the accuracy of calculated neutrino-nucleus cross sections. The renormalization of the effective shell model axial vector coupling g_A is known from β decay, while muon capture probes first-forbidden weak responses for time-like four-momenta. But apart from these constraints, most of the nuclear physics used in describing supernova neutrino-nucleus cross sections (space-like four-momentum transfers, important allowed and first forbidden transitions) has not been subjected to detailed experimental tests. Yet many aspects of supernova physics, including nucleosynthesis, require accurate cross sections.

What are the achievements of this subfield since the last long range plan?

- LSND was completed in 1998, and KARMEN II has reported three years of data (2/97-3/00). Evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ has been found in the LSND experiment. KARMEN has found no evidence for oscillations, though a portion of the LSND allowed range, corresponding to small mixing angles and masses,

is not ruled out.

- The Chooz and Palo Verde reactor $\bar{\nu}_e$ oscillation experiments constrained δm^2 to below 10^{-3} eV² in the disappearance channel at maximum mixing angle. This became an important constraint on the interpretation of the SuperKamiokande atmospheric neutrino results.
- Early results from the K2K long-baseline oscillation experiment disfavor the no oscillation hypothesis at about the two standard deviation level. This is the first hint that the SuperKamiokande atmospheric neutrino results may have laboratory confirmation.
- LSND and KARMEN obtained ¹²C exclusive charge current cross sections for exciting the ground state of ¹²N. The results are in good agreement with theory. Inclusive charge current cross sections were also obtained. KARMEN measured neutral current neutrino excitation of the 15.11 MeV state in ¹²C. These results are the first obtained for complex nuclei.
- FermiLab's MiniBooNE, the followup experiment to LSND, and KamLAND, the first reactor/accelerator neutrino experiment to address part of the oscillation parameter space relevant to solar neutrinos, are under construction.

What are the theoretical and experimental challenges facing the field? Identify the new opportunities.

- The completion of MiniBooNE is very important. If both the atmospheric and solar neutrino problems are attributed to neutrino oscillations, and if the LSND results are correct, then a good fit to the data can only be obtained by hypothesizing a fourth light neutrino with sterile interactions. Thus confirming or ruling out the LSND results has important consequences for interpretations of the neutrino data. If the LSND results are confirmed by MiniBooNE, it will be important to build a second detector at a different distance in order to define the oscillation parameters precisely.
- The KamLAND reactor antineutrino experiment now under construction will break exciting new ground: it will be the first laboratory experiment to probe δm^2 values directly relevant to the solar neutrino problem. The projected sensitivity covers all of the large mixing angle solar neutrino solution. Thus completion of this experiment must be a very high priority for nuclear physics.
- Similarly, accelerator oscillation experiments testing the atmospheric neutrino parameter space are crucial. K2K, which already has very interesting data, and MINOS must be completed.

- The Spallation Neutron Source now under construction at Oak Ridge will, as a byproduct of operations, produce an intense source of neutrinos with a pulsed time structure (similar to that of ISIS/KARMEN) and with a very favorable $\bar{\nu}_e/\bar{\nu}_\mu \sim 3 \times 10^{-4}$ ratio. This will be the most intense, pulsed, intermediate energy neutrino source available. An interesting program of possible experiments has been discussed, some of which exploit the similarities between the SNS neutrino spectrum and that from a supernova. The opportunity to build a neutrino bunker – a shielded room in which experiments can be mounted – should be seized. It is important to situate the room as close as possible to the SNS mercury beam stop. This facility (ORLAND) will stimulate the community to propose detectors and experiments: the possibilities include oscillation experiments, searches for isoscalar axial charge transitions, and the continuation of the neutrino-nucleus cross section program begun by KARMEN and LSND.
- Much of the underlying physics of ORLAND, the supernova mechanism, and other problems discussed here involves nuclear structure theory. The US nuclear theory program is currently quite weak in this area. Neutrino physics has strong student appeal and, because it involves many nuclear structure issues, provides an opportunity for training students in an area of some national importance.

What are the resources required for this field?

It is important to continue nuclear physics support for the MiniBooNE and KamLAND efforts. These experiments focus directly on issues of importance to nuclear physics: checking the LSND claims and probing neutrino oscillation parameters relevant to the solar neutrino problem.

The SNS bunker requires a significant investment, perhaps \$15M. The additional cost of detectors for the experimental program has been estimated to be \sim \$45M.

Two of the long range plan initiatives now under consideration – the neutrino program outlined here and the Rare Isotope Accelerator – have important links to nuclear structure theory. There are very few US nuclear structure theorists of age \lesssim 40 years occupying tenure track university or national laboratory positions. (Interestingly, those few all seem to have close connections to weak interactions and neutrino physics, particularly neutrino astrophysics.) It is important, for the success of the experimental part of the LRP program, to enhance the nuclear theory program in the relevant areas of nuclear structure and nuclear astrophysics. The creation of 20 entry-

level university nuclear theory/nuclear astrophysics positions over a period of 5 to 10 years would require an increase in the theory budget of about \$3M/year. This \$3M investment could be used initially to fund tenure-track bridge positions, then gradually rolled over to provide continuing research support (summer salary, graduate students, and postdocs) once the bridges are completed.

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The success of the workshop is due to the enthusiastic participation of the neutrino physics community. The talks presented at the workshop can be found at

int.phys.washington.edu

(click on talks online, then on Neutrino Workshop). The organizing committee, working group convenors, and workshop participants are listed in the following pages.

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