Forty years after the first direct detection of neutrino interactions with matter, the three neutrino types $\nu_e$, $\nu_\mu$ and $\nu_\tau$ (and their antiparticles) are known to carry linear and angular momentum and an assigned quantum number to specify the family to which they belong. All other fundamental properties, e.g., mass, charge, magnetic dipole moment, and whether they mix with one another, are known only by their limiting values. Indeed, it is not known whether the neutrino is a Dirac particle with a distinct antiparticle or a Majorana particle, i.e., its own antiparticle. In the search for physics beyond the standard particle physics model, new information in the neutrino sector is most likely to make an important, perhaps vital, contribution. In particular, most theories of what underlies the standard model predict nonzero neutrino masses at some level.

In our report we have addressed the particular question of neutrino mass and mixing, which in recent years has become a focus of attention for many scientists, not only from the discipline of particle physics, but nuclear physics, astrophysics, and cosmology as well.

In the cosmological Big Bang Model, neutrinos decoupled relatively early in the evolution of the Universe, which guarantees that they should have a substantial relic abundance today, if they are stable and do not annihilate. Their intrinsic properties are constrained by their cosmological consequences, and, in turn, improved knowledge of neutrino properties would constrain cosmological models of the early Universe. If neutrinos are massive with masses in the electron-volt region, they may contribute to the empirically indicated but not yet identified dark matter, and even significantly to the total mass of the Universe.

In astrophysics, neutrinos probe the interior of stars early and late in their lifetimes. They are the coolant of neutron stars resulting from supernovae and a potential thermometer to provide a precision measurement of the temperature of the solar core. Neutrino astrophysics has become a recognized discipline in the last decade.

The next generation of underground neutrino detectors could determine a neutrino mass in the 15 to 100 eV range if there is a galactic core-collapse supernova. Depending upon one's confidence in the predictive power of supernova burst models, the lower end of this range might be pushed down to

5 eV. It has been estimated that such a supernova should occur every $31 \pm 7$ years. Hence, over the next decade the probability of such an occurrence is ~20-30%, sufficiently high to motivate strong efforts to capitalize upon the physics associated with such an event.

There is presently no fundamental theoretical reason why neutrinos cannot have mass. In the past few years, direct tritium decay measurements placing limits on the mass of the electron-neutrino in the region of electron-volts have been made. A common feature of all of these experimental results is an anomalous excess of events near the endpoint of the spectrum. The anomaly is indicative of a misconception—perhaps a serious one—on our part, and experiments to probe its nature and pursue the hint it offers are crying to be done. Speculations on new physics include tachyonic neutrinos, capture from a (very dense) relic cosmic sea of neutrinos which would produce a monoenergetic peak at or above the endpoint, and admixture of a massive neutrino with strong final-state interactions that would produce a bump at or below the endpoint. Such possibilities are exciting, even if unlikely, and demand that improved experiments be performed to verify or reject them.

Compelling direct measurements of double beta decay involving two neutrinos have been made for the first time in the past few years. These measurements set the stage for incisive attempts to observe neutrinoless double beta decay and possibly settle the question of the Majorana identity of the neutrino once and for all.

For the first time since the suggestion in the 1960s that neutrino oscillations might take place and serve to measure neutrino mass and mixing, there are reliable data indicating the possible occurrence of resonant and vacuum neutrino oscillations.

Solar neutrino results from four operating detectors indicate serious departures from expectations of astrophysical calculations. Not only are the rates considerably lower than the expectations of the standard solar model, but also comparison of the results of the four experiments suggests that the largest suppression is in the middle of the spectrum. This is hard to accomodate by any astrophysical or nuclear physics mechanism, suggesting that even highly nonstandard solar models cannot by themselves explain the data.

Neutrino oscillations, particularly of the MSW sort, provide an attractive solution that fits all the data, and the implications of neutrino mass are strong. Three possible parameter ranges are viable, all below $\Delta m^2 = 10^{-5}$ $eV^2$. Truly conclusive proof will require a physics signature that is independent of astrophysical arguments, and there are 3 such signatures:

- a ratio of flux in neutral currents to charged currents greater than unity
- distortions of the shape of the $^8$B electron-neutrino spectrum
- time dependence in the charged-current neutrino rate.

The next generation of solar-neutrino detectors, the Sudbury Neutrino Observatory and SuperKamiokande, will be able to look for all of these signatures.

Measurements of the flavor content of atmospheric neutrinos gives a ratio of muon to electron flavor closer to 1 than to the expected value of 2. If neutrino oscillations are responsible, long-baseline accelerator and reactor experiments can provide conclusive evidence in the interesting range of parameter space, $0.001 \leq \Delta m^2 \leq 0.01$ $eV^2$ and $0.5 \leq \sin^2 2\theta \leq 1$. Such experiments, which could come on line and begin taking data within the next five years are proposed for the Fermilab and Brookhaven accelerators. Experiments at the San Onofre and Chooz reactors will shortly begin to explore this region of parameter space for the channel $\overline{\nu_e}$ to $X$.

A third piece of suggestive evidence for neutrino oscillations comes from the Los Alamos experiment LSND. Recently reported data suggest conversion of $\nu_\mu$ to $\nu_e$ and $\overline{\nu_\mu}$ to $\overline{\nu_e}$ in the region of parameter space $0.7 \leq \Delta m^2 \leq 6$ $eV^2$, and $0.005 \leq \sin^2 2\theta \leq 0.01$. A neutrino of sufficient mass to be of cosmological importance would be implied.

Of the three light neutrinos now known to exist, the tau neutrino is arguably the least well understood. Not only has it never been directly observed, but the limits on its mass are orders of magnitude less stringent than those on its electron and muon neutrino cousins. Meanwhile, from both theoretical models and the experimental "smoking guns" motivating the search for massive neutrinos it emerges as the most likely candidate for a "heavy" neutrino. Accelerator based oscillation searches, which can produce neutrino beams of energy sufficiently above the threshold for tau lepton production, have the unique opportunity to discover neutrino oscillations in the channel $\nu_\mu \rightarrow \nu_\tau$. Such experiments are presently underway at CERN and are planned for Fermilab, and if the tau neutrino is a significant component of the dark matter they have a strong probability of a positive result.

There are strong hints for nonzero neutrino masses and mixings from theory, cosmology, solar and atmospheric neutrinos, and LSND. These results point to well-defined regions of parameters, which the next generation of planned and proposed experiments should be able to conclusively explore.

As is apparent from this brief summary, the field of neutrino physics, by its nature, is diverse and carried out non-centrally in self-contained experiments in university laboratories, deep underground sites, and accelerators. In part for this reason, it appears to involve a small community with few needs. But in truth, it is a world-wide effort pursued by many physicists, and requires in some experiments well-instrumented, massive apparatus, and in others adequate long term support. In any distribution of resources for the support of research which properly weighs the physics potential of the areas of present-day physics research, neutrino physics would deserve and receive support beyond the level at which it now functions.

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