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Questions of Identity

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Abstract

As an introduction to νFact '99, the ICFA/ECFA Workshop on Neutrino Factories Based on Muon Storage Rings, I place the issues of neutrino properties and neutrino oscillations in the broader context of fermion flavor.

Key words: NUFACT99 ; neutrino ; oscillations ; Lyon ; flavor

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1 Introduction

Our colleagues working to assess the feasibility of very-high-energy muon colliders [1] have given us the courage to think that it may be possible, not too many years in the future, to accumulate 10^{20-21} (or even 10^{22}) muons per year. It is very exciting to think of the possibilities that millimoles of muons would raise for studies in fundamental physics [2–4], and indeed that is why we have come together today in Lyon.

From the perspective of a muon collider, the 2.2-μs lifetime of the muon presents a formidable challenge. But if the challenge of producing, capturing, storing, and replenishing many unstable muons can be met, the decays

$$\mu^- \to e^-\nu_\mu\bar{\nu}_e\ , \qquad \mu^+ \to e^+\bar{\nu}_\mu\nu_e \tag{1}$$

offer delicious possibilities for the study of neutrino interactions and neutrino properties [5–8]. In a *Neutrino Factory*, the composition and spectra of intense neutrino beams will be determined by the charge, momentum, and polarization of the stored muons. At the energies best suited for the study of neutrino oscillations—tens of GeV, by our current estimates—the muon storage ring is compact. We could build it at one laboratory, pitched at a deep angle, to

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illuminate a laboratory on the other side of the globe with a neutrino beam whose properties we can control with great precision. By choosing the right combination of energy and destination, we can tune future neutrino-oscillation experiments to the physics questions we will need to answer, by specifying the ratio of path length to neutrino energy and determining the amount of matter the neutrinos traverse. Although we can use each muon decay only once, and we will not be able to select many destinations, we may be able to illuminate two or three well-chosen sites from a muon-storage-ring neutrino source. That possibility—added to the ability to vary the muon charge, polarization, and energy—may give us just the degree of experimental control it will take to resolve the outstanding questions about neutrino oscillations.

2 Some Issues for the Workshop

As we begin this workshop, it seems to me that we should keep in mind four essential questions:

> Is a Neutrino Factory feasible?
>
> At what cost?
>
> How soon?
>
> What R&D must we do to learn whether we can make the neutrino factory a reality?

The answers to these questions will be influenced by what we want the neutrino factory to be. To decide that, we need to consider another set of questions:

> What do we want to know about neutrino masses and mixings now ... in five years ... in ten years?
>
> Is a neutrino factory the best way—or the only way—to provide this information?
>
> What (range of) beam parameters should the neutrino factory offer?
>
> What detectors are needed to carry out the physics program of a neutrino factory? It seems that distant detectors must weigh several kilotonnes and ideally should identify electrons, muons, and taus—and measure their charges. Are all these characteristics essential? How should the prospect of a neutrino factory influence the detectors we build now?

We need to consider the scientific issues with an eye to both the intrinsic interest in neutrino properties and interactions and also the evolving place of neutrino physics within contemporary particle physics. I find it useful to organize the goals of particle physics at the millennium in terms of three broad themes. The first theme is *symmetry,* with the attendant ideas of symmetry breaking. One of the great campaigns of particle physics over the next decade will be—must be—the quest for a complete understanding of electroweak symmetry breaking through an exploration of the 1-TeV scale. The second theme is *unity.* By unity I understand, of course, the hope that we can unify quarks and leptons and thus achieve a comprehensive theory of the strong, weak, and electromagnetic interactions with its consequent coupling constant unification. But I also include the grander goals of unifying constituents and force particles, incorporating gravity into our theories of fundamental interactions, and reconciling quantum theory and relativity. The third theme I call *identity,* which incorporates the mystery of fermion masses and mixings, the origin and understanding of CP violation that we hope to gain through studies of the K and B systems, and the phenomenology of neutrino oscillations. The problem of identity is as simple to state as this: what makes an electron an electron and a top quark a top quark?

Our current understanding of flavor and family—of identity—is not so well developed as the visions we have for symmetry and unity. I believe that the question of identity is an essential part of the physics that will determine the machine beyond the Large Hadron Collider. As we master, or at least gain a more mature understanding of, symmetry and unity, I expect that the questions of identity will increasingly define the agenda of particle physics. Neutrino physics is at the center of those questions and has an indispensable role to play in guiding our future.

3 Ten Timely Questions in the Physics of Neutrino Oscillations

We need answers to many questions in order to unravel the puzzle of neutrino physics. The first question, to which the presumed answer motivates much of the current interest in neutrino physics, is . . .

3.1 Do neutrinos oscillate?

Many experiments have now used natural sources of neutrinos, neutrino radiation from fission reactors, and neutrino beams generated in particle accelerators to look for evidence of neutrino oscillation. The positive indications for neutrino oscillations fall into three classes [9]:

(1) Five solar-neutrino experiments report deficits with respect to the predictions of the standard solar model: Kamiokande and Super-Kamiokande using water-Cherenkov techniques, SAGE and GALLEX using chemi-

cal recovery of germanium produced in neutrino interactions with gallium, and Homestake using radiochemical separation of argon produced in neutrino interactions with chlorine. These results suggest the oscillation $\nu_e \to \nu_x$.

(2) Five atmospheric-neutrino experiments report anomalies in the arrival of muon neutrinos: Kamiokande, IMB, and Super-Kamiokande using water-Cherenkov techniques, and Soudan II and MACRO using sampling calorimetry. The most striking result is the zenith-angle dependence of the ν_μ rate reported last year by Super-K [10,11]. These results suggest the oscillation $\nu_\mu \to \nu_\tau$ or ν_s.

(3) The LSND experiment [12] reports the observation of $\bar{\nu}_e$-like events is what should be an essentially pure $\bar{\nu}_\mu$ beam produced at the Los Alamos Meson Physics Facility, suggesting the oscillation $\bar{\nu}_\mu \to \bar{\nu}_e$. This result has not yet been reproduced by any other experiment.

A host of experiments have failed to turn up evidence for neutrino oscillations in the regimes of their sensitivity. These results limit neutrino mass-squared differences and mixing angles. In more than a few cases, positive and negative claims are in conflict, or at least face off against each other. Over the next five years, many experiments will seek to verify, further quantify, and extend these claims.

Explanations other than neutrino oscillations have been advanced for some of these phenomena. These include flavor-changing interactions [13], neutrino decay [14], violations of special relativity [15], and reservations about the standard solar model. However, the most graceful interpretation of the oscillation evidence is that neutrinos have mass and neutrino flavors mix.

If neutrinos do oscillate, . . .

3.2 What are the neutrino masses?

No one has ever weighed a neutrino. The best kinematical determinations we have set upper bounds [16] on the dominant neutrino species emitted in nuclear beta decay ($m_{\nu_e} \lesssim 15\ \mathrm{eV}/c^2$), $\pi^\pm$ decay ($m_{\nu_\mu} < 0.19\ \mathrm{MeV}/c^2$ at 90% CL), and τ decay ($m_{\nu_\tau} < 18.2\ \mathrm{MeV}/c^2$ at 95% CL). Although there are prospects for improving these bounds [17]—and the measurement of a nonzero mass would constitute a real discovery—they are sufficiently large that it is of interest to consider indirect (nonkinematic) constraints from other quarters.

If neutrino lifetimes are greater than the age of the Universe, the requirement that neutrino relics from the Big Bang not overclose the Universe leads to a constraint on the sum of neutrino masses. For relatively light neutrinos

($m_\nu \lesssim$ a few MeV/c^2), the total mass in neutrinos,

$$m_{\mathrm{tot}} = \sum_i \tfrac{1}{2} g_i m_{\nu_i} \ , \tag{2}$$

where g_i is the number of spin degrees of freedom of ν_i plus $\bar{\nu}_i$, sets the scale of the neutrino contribution to the mass density of the Universe, $\varrho_\nu = m_{\mathrm{tot}} n_\nu \approx 112 m_{\mathrm{tot}}$ cm^{-3}. If we measure ϱ_ν as a fraction of the critical density to close the Universe, $\varrho_c = 1.05 \times 10^4 h^2$ eV/c^2 cm^{-3}, where h is the reduced Hubble parameter, then

$$\Omega_\nu \equiv \frac{\varrho_\nu}{\varrho_c} = \frac{m_{\mathrm{tot}}}{94 h^2 \ \mathrm{eV}/c^2} \ . \tag{3}$$

An assumed bound on $\Omega_\nu h^2$ then implies a bound on m_{tot}. A very conservative bound results from the assumption that $\Omega_\nu h^2 < 1$: it is that $m_{\mathrm{tot}} < 94$ eV/c^2.

Recent observations [18] suggest that the total matter density is considerably smaller than the critical density, so that $\Omega_m \approx 0.3$. If we fix $\Omega_\nu < \Omega_m$ and choose the plausible value $h^2 = 0.5 \pm 0.15$, then we arrive at the still generous upper bound $m_{\mathrm{tot}} \lesssim 19$ eV/c^2. Taking into account the best (and model-dependent) information about the hot- and cold-dark-matter cocktail [19], it seems likely that cosmology limits $m_{\mathrm{tot}} \lesssim$ a few eV/c^2. It is worth remarking that the cosmological desire for hot dark matter has been on the wane.

If neutrinos do have mass, . . .

3.3 Is neutrino mass a sign of physics beyond the standard model?

Until we have additional evidence, I believe that the right answer to this question is, “It depends.” All fermion masses and mixings are mysterious—by which I mean not calculable—within the standard model. The gauge-boson masses are predicted in terms of the weak mixing parameter $\sin^2\theta_W$:

$$\begin{aligned} M_W^2 &= \frac{g^2 v^2}{2} = \frac{\pi\alpha}{G_F\sqrt{2}\sin^2\theta_W} \\ M_Z^2 &= \frac{M_W^2}{\cos^2\theta_W} \ , \end{aligned} \tag{4}$$

where $v = (G_F\sqrt{2})^{-1/2} = 246$ GeV sets the electroweak scale. On the other hand, each fermion mass involves a new, unknown, Yukawa coupling. For example, the term in the electroweak Lagrangian that gives rise to the electron mass is

$$\mathcal{L}_{\text{Yuk}} = -\zeta_e \left[\bar{\mathsf{R}}(\varphi^\dagger \mathsf{L}) + (\bar{\mathsf{L}}\varphi)\mathsf{R} \right] \; , \tag{5}$$

where φ is the (complex) Higgs field and the left-handed and right-handed fermions are specified as

$$\mathsf{L} = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_{\text{L}} \; , \quad \mathsf{R} = e_{\text{R}} \tag{6}$$

When the electroweak symmetry is spontaneously broken, the electron mass emerges as

$$m_e = \zeta_e v/\sqrt{2} \; . \tag{7}$$

The Yukawa couplings that reproduce the observed quark and lepton masses range over many orders of magnitude, from $\zeta_e \approx 3 \times 10^{-6}$ for the electron to $\zeta_t \approx 1$ for the top quark. Their origin is unknown.

In one sense, therefore, *all fermion masses involve physics beyond the standard model.* If we find that the electron neutrino has a Dirac mass reproduced by a Yukawa coupling $\zeta_{\nu_e} \approx 10^{-10}$, perhaps nothing fundamentally new would be involved—though the mystery of fermion masses would still be a mystery. We would still want to explain why neutrino masses are so small compared with charged-fermion masses.

It is worth remarking on another manifestation of the logical separation between the origin of gauge-boson masses and the origin of fermion masses. The observation that a fermion mass is different from zero ($m_f \neq 0$) implies that the electroweak gauge symmetry $SU(2)_L \otimes U(1)_Y$ is broken, but electroweak symmetry breaking is only a necessary, not a sufficient, condition for the generation of fermion mass. The separation is complete in simple technicolor [20], the theory of dynamical symmetry breaking modeled on the Bardeen–Cooper–Schrieffer theory of the superconducting phase transition.

When we try to make sense of the Yukawa couplings ζ_i, it is useful—probably essential—to keep in mind that according to unified theories, the pattern of fermion masses simplifies on high scales. A theory based on $SU(5)$ with a specific symmetry-breaking pattern leads to simple quark-lepton mass relations at the unification scale, while an embedding of $SU(5)$ in $SO(10)$ reconciles a large ν_μ-ν_τ mixing with the small quark mixing [21].

3.4 Does the evidence require more than three neutrino species?

Measurements of the invisible decay rate of the Z-boson, $\Gamma(Z^0 \to \text{invisible})$, tell us with considerable precision that there are three light neutrinos with normal weak interactions: $N_\nu = 2.994 \pm 0.011$ [16]. The restriction to three light neutrinos does not preclude the existence of a "sterile" neutrino, ν_s, that couples very feebly (so that $\Gamma(Z^0 \to \nu_s\bar{\nu}_s) \ll \Gamma(Z^0 \to \nu_e\bar{\nu}_e)$) or not at all (so that $Z^0 \not\to \nu_s\bar{\nu}_s$) to the Z^0. With a little stretching of error bars, a three-neutrino scenario can account for all the oscillation signals [22], but *at least four neutrinos* seem required to fit the central values quoted by the experiments [23].

A simple argument indicates the necessity for more than three neutrino flavors. If there are three mass eigenstates (ν_1, ν_2, ν_3), then the sum of the squares of the mass differences, suitably defined, must vanish:

$$\sum \delta M^2_{ij} = (M_3^2 - M_2^2) + (M_2^2 - M_1^2) + (M_1^2 - M_3^2) = 0. \tag{8}$$

However, experiments that study solar neutrinos, atmospheric neutrinos, and accelerator-generated muon antineutrinos seem to require three very different values of δM^2:

$$\begin{aligned} |\delta M^2|_{\text{solar}} &\approx 10^{-10}\ \text{eV}^2 \text{ or } 10^{-5}\ \text{eV}^2\ ; \\ |\delta M^2|_{\text{atm}} &\approx 10^{-3}\ \text{-}\ 10^{-2}\ \text{eV}^2\ ; \\ |\delta M^2|_{\text{LSND}} &\approx 10^{-1}\ \text{-}\ 10^{1}\ \text{eV}^2\ . \end{aligned} \tag{9}$$

No choice of signs allows us to sum these three scales of δM^2 to zero. For the moment, the conclusion that there must be more than three neutrino species is not a robust result, because the LSND anomaly has not (yet!) been confirmed by an independent experiment, and the determination of the preferred range of $|\delta M^2|$ has an impressionistic quality in all experiments [24]. It is, however, a conclusion lingering on the horizon that we cannot entirely ignore. Many theorists, motivated by their convictions about mass patterns, or their doubts about the LSND experiment, or their fear of opening Pandora's box, choose to put aside for the moment the conclusion that we require at least four neutrino species. It is fine to wait and see, but we must also be ready to take the evidence as it comes.

If the evidence from mass differences remains inconclusive, . . .

3.5 Can we find evidence for (or against) a sterile neutrino?

If a neutrino oscillates, it is essential that we learn what it oscillates into. For the moment, it is common practice to suppose that each oscillation effect is governed—in first approximation—by a single transition. The best way of confirming an oscillation between two $SU(2)_L$ flavors is by observing the *appearance* of a species not in the initial beam. Until now, the only appearance experiment we have is the unconfirmed LSND observation. In view of the suspicion [25] that the atmospheric neutrino anomaly reflects a $\nu_\mu \to \nu_\tau$ transition, it is very important to carry out long-baseline experiments capable of observing τ appearance. A comparison of the neutral-current / charged-current ratio—or a measurement of an exclusive neutral-current rate—at a far detector gives information about the total flux of $SU(2)_L$ flavors. It can be a valuable tool to discriminate between flavor-flavor oscillations and flavor-sterile oscillations, and is the goal of many experiments in the next round.

If there is one sterile neutrino—which must be light enough to mix with the $SU(2)_L$ neutrinos—why shouldn't there be (at least) three? What do we need to know about a sterile neutrino? What sort of experiments can tell us?

3.6 Could neutrino masses be special?

Alone among the known fermions, the neutral neutrino can be its own antiparticle. This fact opens the possibility of several varieties of neutrino masses. Let us begin by making a chiral decomposition of the neutrino's Dirac spinor,

$$\psi = \tfrac{1}{2}(1-\gamma_5)\psi + \tfrac{1}{2}(1+\gamma_5)\psi \equiv \psi_{\mathrm{L}} + \psi_{\mathrm{R}} \; , \tag{10}$$

and remarking that the charge conjugate of a right-handed field is left-handed:

$$\psi^c_{\mathrm{L}} \equiv (\psi^c)_{\mathrm{L}} = (\psi_{\mathrm{R}})^c \; . \tag{11}$$

What are the possible forms that neutrino mass terms might take?

A Dirac mass term connects the left-handed and right-handed components of the same field. It is represented by the Lagrangian term

$$\mathcal{L}_D = D(\bar{\psi}_{\mathrm{L}}\psi_{\mathrm{R}} + \bar{\psi}_{\mathrm{R}}\psi_{\mathrm{L}}) = D\bar{\psi}\psi \; , \tag{12}$$

which implies a mass eigenstate $\psi = \psi_{\mathrm{L}} + \psi_{\mathrm{R}}$. The Dirac mass eigenstate is invariant under the global phase rotation $\nu \to e^{i\theta}\nu$, $\ell \to e^{i\theta}\ell$, so that lepton number is conserved.

Majorana mass terms connect the left-handed and right-handed components of conjugate fields. They are represented by the Lagrangian terms

$$\begin{aligned} -\mathcal{L}_{MA} &= A(\bar{\psi}^c_{\rm R}\psi_{\rm L} + \bar{\psi}_{\rm L}\psi^c_{\rm R}) = A\bar{\chi}\chi \\ -\mathcal{L}_{MB} &= B(\bar{\psi}^c_{\rm L}\psi_{\rm R} + \bar{\psi}_{\rm R}\psi^c_{\rm L}) = B\bar{\omega}\omega \; , \end{aligned} \tag{13}$$

for which the mass eigenstates are

$$\begin{aligned} \chi &\equiv \psi_{\rm L} + \psi^c_{\rm R} = \chi^c = \psi_{\rm L} + (\psi_{\rm L})^c \; , \\ \omega &\equiv \psi_{\rm R} + \psi^c_{\rm L} = \omega^c = \psi_{\rm R} + (\psi_{\rm R})^c \; . \end{aligned} \tag{14}$$

The coupling of conjugate fields in the Majorana mass terms violates lepton number by two units. Accordingly, Majorana neutrinos can mediate neutrinoless double-beta decays ($\beta\beta_{0\nu}$) in heavy nuclei,

$$(Z, A) \rightarrow (Z + 2, A) + e^- + e^- \; . \tag{15}$$

Detection of neutrinoless double-beta decay would offer decisive evidence for the Majorana nature of the neutrinos [26].

The Heidelberg–Moscow experiment has recently set the most stringent limit on a *Majorana* neutrino mass [27]. Their lower limit on the half-life for neutrinoless double-beta decay of ^{76}Ge, $t_{1/2}^{\beta\beta_{0\nu}} \geq 5.7 \times 10^{25}$ yr at 90% CL, restricts an effective Majorana neutrino mass to be $\lesssim 0.2$ eV/c^2.

With both Dirac and Majorana mass terms, the neutrino mass contribution to the Lagrangian is

$$\begin{aligned} -\mathcal{L}_{DM} &= \tfrac{1}{2}D(\bar{\chi}\omega + \bar{\omega}\chi) + A\bar{\chi}\chi + B\bar{\omega}\omega \\ &= (\bar{\chi}, \bar{\omega}) \begin{pmatrix} A & \tfrac{1}{2}D \\ \tfrac{1}{2}D & B \end{pmatrix} \begin{pmatrix} \chi \\ \omega \end{pmatrix} \; , \end{aligned} \tag{16}$$

which has mass eigenvalues

$$M_{2,1} = \frac{A + B \pm \sqrt{(A - B)^2 + D^2}}{2} \; , \tag{17}$$

which is to say two Majorana mass eigenstates.

A favorite realization of the Dirac–Majorana mass alternative is the so-called see-saw mechanism [28], which offers the prospect of a connection to high-scale physics, and thus an opening to true physics beyond the standard model. Let us assume that the Dirac mass D takes a typical value of a lepton mass in the electroweak theory. If the left Majorana mass $A \approx 0$ is negligible, and the right Majorana mass $B \gg |D|$, then the two mass eigenvalues are given by

$$M_{2,1} = \frac{B \pm \sqrt{B^2 + D^2}}{2} \; . \tag{18}$$

To excellent approximation, we have

$$M_2 = B, \quad M_1 = -\frac{D^2}{4B} \; . \tag{19}$$

Because M_1 is small compared with the typical lepton mass D, this scheme offers a “natural” explanation for the observed strong inequality, $m_\nu \ll m_e$. It also leads naturally to a sterile neutrino; but notice that the sterile neutrino is heavy, not the light sterile neutrino needed to accommodate all the hints of neutrino oscillation.

3.7 How could light sterile neutrinos arise?

If the data do lead us to consider mixing between the $SU(2)_L$ neutrinos and a sterile neutrino, what are the mechanisms that might produce a light sterile neutrino, and what other implications would they have for neutrino physics and beyond. Among sources of light scalar neutrinos that have been investigated, are the radiative generation of m_ν and induced masses that arise through R-parity violation in supersymmetry. If neutrino masses are generated through loop diagrams, neutrinoless double-beta decay does not arise in general. R-parity–violating supersymmetry has a great number of potentially observable consequences. It would be useful to focus on these—and other—mechanisms for light scalar neutrinos, to understand what demands they would put on a neutrino factory’s performance.

3.8 Are neutrino mixing angles large? maximal?

Although two of the favored interpretations for the solar-neutrino deficit feature large mixing angles, the possibility of resonant conversion within the varying matter profile of the Sun allows a small-mixing-angle solution. The density profile of the Earth does not naturally allow resonant conversion of atmospheric neutrinos over a broad range of energies, and so it is generally accepted that large mixing is required to account for the atmospheric neutrino anomaly. This conclusion and the existence of the large-angle solar solutions discourage the formerly traditional belief that the structure of the neutrino mixing matrix should be similar to that of the familiar quark mixing matrix.

If the mixing among neutrino flavors that accounts for the atmospheric neutrino anomaly is large—or, indeed, maximal—should we interpret it as large flavor-sterile mixing, or as large flavor-flavor mixing? In either case, it seems natural to take the large mixing as an important clue to neutrino properties [29].

3.9 Do neutrino masses probe large extra dimensions?

It is a longstanding dream of string theory that string modes in the dimensions beyond the known $3+1$ spacetime dimensions might determine the properties of the quarks and leptons. On this interpretation, the structure of the Calabi–Yau manifolds in the small dimensions is reflected in the spectrum of what we take, at our limited resolution, to be elementary particles. It offers a novel approach to the problem of identity.

Over the past eighteen months, the apparently preposterous idea that some of the extra spatial dimensions might be perceivably large has shown itself to be not at all easy to rule out, and both entertaining and informative to consider. A number of authors have suggested that the physics of extra dimensions might give rise to neutrino properties and oscillations [30]. How can we test these mechanisms?

3.10 Can we detect CP *violation in neutrino mixing?*

Using the beams available at a neutrino factory, it will be of great interest to compare

$$\begin{aligned}
&\nu_e \to \nu_\mu \;\; vs. \;\; \nu_\mu \to \nu_e \;, \\
&\nu_e \to \nu_\mu \;\; vs. \;\; \bar{\nu}_\mu \to \bar{\nu}_e \;, \\
&\nu_e \to \nu_\mu \;\; vs. \;\; \bar{\nu}_e \to \bar{\nu}_\mu \;.
\end{aligned} \tag{20}$$

Although oscillation probabilities are insensitive to the signs of δM^2, matter effects do depend on the ordering of neutrino masses, so the observation of Earth matter effects could help us determine the pattern of neutrino masses completely. Matter effects can mimic some of the unequal rates induced by CP violation, so it is essential to understand them for engineering purposes.

In representative scenarios for the pattern of neutrino masses, what constitutes a definitive program of measurements to separate matter effects from

CP violation? What implications does that program have for the capabilities of detectors and for muon energy and the ability to manipulate muon polarization? The discovery of CP violation in the neutrino system would have profound implications for questions of identity, and is worth pursuing aggressively, if the pattern of mixing makes it a plausible target. Introductions to the problem can be found in References [7,31].

4 Concluding Remarks

I commend the workshop organizers and our Lyonnais hosts for putting together a stimulating and enjoyable program. I particularly want to thank Serguey Petcov and Belen Gavela for their indispensable contributions to the theory working group. I am grateful to the CERN Theoretical Studies Division for warm hospitality following νFact '99. Fermilab is operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy.

Now, let us get down to work to set out our physics goals and understand what a neutrino factory should be. As we do that, I would like to return to one of my opening questions: Is a neutrino factory the only way—or the best way—to provide information we so urgently need about neutrinos, flavor, and identity?

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