FROM A desperate REMEDY
to a profound ENIGMA —

CAN THE FUTURE of NEUTRINO PHYSI
COMPARE to Its PAST?

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THE DESPERATE REMEDY

1930 · Pauli, in his famous letter, cuts himself on Ockham's Razor — he tries to solve two problems with one new particle. the statistics problem + continuous β spectrum.

1932 · Neutrons discovered. Heisenberg proposes N & P form a doublet, and that these particles are the nuclear constituents.
· Positrons are discovered. Pairs can be created.

1933 · Pauli publically presents his remedy at the Solvay Conference, where
· Fermi renames P's particle the NEUTRINO

1934 · Fermi develops a theory of β decay, (rejected by Nature). The electron and neutrino are created in β decay.
· The Joliot-Curies discover β^+ decay.
· Dirac renames P's particle ANTINEUTRINO, (so lepton no. can be conserved).

1937 Majorana suggests that ν and $\bar{\nu}$ may be identical to one another. (then mysteriously vanishes)

DOUBTS & REGRETS

PAULI: "I have done something terrible. I have predicted an undetectable particle."

BETHE: "There is no possible way of observing the neutrino." (1934)

GAMOW: "A beam of νs would go through... several light-years of lead. No wonder they escape from any poss observation" (1945)

Updike: "Neutrinos, they are very small
They have no charge and have no mass
And do not interact at all..." (1959)

NEUTRINOS ARE SEEN!

Clyde Cowan and Fred Reines thought they would use an atomic bomb as an antineutrino source, but settled for the Savannah River nuclear power plant.

Anti-ν's would induce $\bar{\nu} + p \rightarrow n + e^+$ in their instrumented water tank. The e^+ annihilation and subseq. neutron capture wd. provide a unique signal.

By 1956, "The quest was completed, the challenge met!" Pauli was delighted that his particle was found 25 yrs later: "Everything comes to he who knows how to wait." But the waiting was not over.

Fred would win the Nobel Prize for this work 40 years afterward, but sadly, Clyde could not wait so long.

WAS MAJORANA RIGHT?

While C&R were observing neutrinos, Ray Davis was only a few meters away. Instead of water, their target was perchlorethylene or C_2Cl_2. The reaction

$$\bar{\nu} + {}^{37}Cl_{17} \rightarrow \bar{e} + {}^{37}A_{18}$$

could take place iff $\nu \equiv \bar{\nu}$. Davis saw no signal, thus confirmed that neutrinos and antineutrinos are different, and that nuclear beta decay conserves lepton number. And then...

Aided and abetted by theorist John Bahcall, Ray set out to detect and measure solar neutrinos with a much larger chlorine detector. The exp't began in 1967

25 years later, Davis had collected 2200 detected A atoms. The news was good and bad. What had gone wrong?

The experiment ?
The solar model?
or was there something weird about neutrinos ?

Again, we would have to wait.

AND THEN THERE WERE TWO

In 1957, I began my thesis on E-W unification while Gary Feinberg showed that $\mu \not\rightarrow e\gamma$ meant $\nu_\mu \neq \nu_e$ in any such theory.

So I was not so much surprised as delighted by the 1963 bombshell of Lederman, Schwartz & Steinberger.

EVOLUTION

Paulis Neutron became
Fermis Neutrino, then
Dirac's Antineutrino, now
the electron antineutrino

And with the development of neutrino beams, neutrinos became a powerful new tool of discovery.

Neutrinos Become Powerful tools for Discovery

- 1964 First Ω^- observed, confirming unitary symmetry.
- 1972 Deep inelastic ν scatt. "provide astonishing verification of the quark model" (Don Perkins)
- 1973 Neutral Currents are seen at CERN, then Fermilab, confirming the E.W. model.
- 1975 First charmed baryon observed, thus confirming the charm hypothesis.

Some Neutrino Discoveries of the Past Decade

1994 The surprising and anomalous indications of the LSND experiment should *not* be included in this list for two reasons. The experiment did not take place in the past decade and its result has not been confirmed.

1998 Super-Kamiokande dramatically resolves the apparent atmospheric neutrino anomaly first noted by MACRO, IMB and Kamiokande. The electrifying announcement at Takayama of decisive evidence for neutrino mass and atmospheric oscillations is met by a standing ovation.

1999 CHOOZ sets the current upper bound to the subdominant mixing angle θ_{13} associated with 3–family neutrino oscillations. This important parameter constrains the size of CP-violating effects in the neutrino sector.

2000 DONUT (at Fermilab) is the first experiment to provide *direct* evidence for the existence of tau neutrinos. (Of course, we all knew it had to be there.)

2003 SNO decisively solves the solar neutrino problem (and confirms the standard solar model) by measuring the neutral-current interactions of all the neutrinos coming from the Sun.

2003 KAMLAND observes the disappearance of electron antineutrinos from relatively distant nuclear reactors.

2005 KAMLAND reports the detection of antineutrinos from natural sources within the earth (geoneutrinos).

Some Neutrino Awards from the Past Decade

1995 Fred Reines wins the Nobel Prize for his detection of the neutrino (with Clyde Cowan, since deceased) for work done 40 years earlier!

2000 Ray Davis and Masatoshi Koshiba share the Wolf Prize for their observations of neutrinos of astrophysical origin.

2001 Ray Davis is awarded the National Medal of Science for his lifelong contributions to neutrino physics.

2002 Nick Samios wins the Pontecorvo Prize for discovering, via neutrino interactions, the Ω^- particle and the first charmed baryon.

2003 John Bahcall wins the Dan David Prize for his contributions to neutrino astrophysics.

2002 Ray Davis and Koshiba share the Nobel Prize for the detection of cosmic neutrinos.

2002 Koshiba, Totsuka and Kajita share the Panofsky Prize for their compelling evidence for neutrino oscillations.

2003 John Bahcall and Ray Davis share the Fermi Prize for work leading to a revolution in the understanding of the properties of neutrinos.

2003 Art McDonald is awarded the Hertzberg Medal for developing and exploiting the Sudbury Neutrino Observatory.

2003 Tom Bowles, V. Gavrin and V. Kuzmin share the Markov Prize for their radiochemical research on the solar neutrino problem.

2005 Art NcDonald wins the Pontecorvo Prize for his work at the Sudbury Neutrino Observatory.

What Have We learned about Neutrinos?

- We are virtually certain that there are exactly three active (*i.e.*, weak doublet) neutrino states, at least two of which have mass.

- Their masses and mixings seem to be well-described by a minimal model: a 3 × 3 neutrino mass matrix involving precisely six observable parameters, all but one either roughly measured or constrained. These are three angles: θ_{12} (solar), θ_{23} (atmospheric), and θ_{13} (subdominant), one CP-violating phase δ, and two squared-mass differences: $\Delta_{\rm solar}$ and $\Delta_{\rm atm}$.

- No experiment (save LSND) suggests or requires the mixing of active neutrinos with sterile light singlet states. Stronger constraints on sterile states can and must be set.

- Neutrino masses may be 'Majorana' (lepton-number violating) or 'Dirac' (lepton-number conserving). Intermediate possibilities, such as would require sterile neutrinos, are disfavored.

- Despite hundreds of published papers, little is known of the origin of neutrino masses, and nothing at all about why the various parameters are what they are. The latter question is analogous to the mystery of quark masses and mixings.

- Neutrino experiments have enabled the most sensitive searches for Lorentz violation in the neutrino sector. The relevant dimensionless parameters are known to be less than 10^{-25}.

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CHALLENGES FOR THE FUTURE

(I) **Geoneutrinos,** *pour rendre une politesse*

By geoneutrinos is meant those antineutrinos produced by naturally radioactive elements in the crust, mantle and core of our planet. I placed the investigation of these particles at the top of my list because it is timely, and because a version of this talk was first presented at the recent Geoneutrino Workshop in Honolulu, a most unusual gathering of neutrino physicists, geochemists and geologists. But why on Earth is the study of geoneutrinos interesting?

- Because their precise measurement is a daunting and difficult challenge for experimenters, who thrive on doing the near impossible.
- Because theorists have written (and will write) lots of papers about geoneutrinos, such as Eder and Marx in the 1960s and at least 13 others (including me) in the 1980s.
- To determine how uranium and thorium are distributed within the Earth, and (optimistically) to see if potassium has migrated to the core, thus helping power the geomagnetic dynamo.
- To test the wild notion of a natural nuclear reactor within Earth's core.
- Additional motivations to investigate geoneutrinos are likely to be found in the Proceedings of Geoneutrinos-2005.

(II) The Quest for Neutrinoless Double Beta Decay

- If this process is decisively observed, we will *know* that lepton number is not conserved in nature. Such a discovery would be comparable in importance to those of parity and CP violation.

- The existence of neutrinoless $\beta\beta$ decay would show that neutrinos are likely to have Majorana masses. Conversely, if it be shown that the process is absent at an appropriate level, then neutrino masses are likely to be Dirac, although there are more exotic possibilities (such as VSR neutrino masses).

- If the process is both seen and measured, we will have a quantitative test of our 3×3 matrix model of neutrino masses and mixings, and as well, an estimate of the absolute size of neutrino mass (which oscillation experiments cannot provide).

- In 2001, Klapdor *et al.* claimed 'Evidence for No-Neutrino Double Beta Deacay' [Mod. Phys. Lett. A16, 2409]. However, Aabeth *et al.* responded that 'there is no basis' to this claim [*Ibid.* A17, 1475]. And so?

- While one future experiment may suffice in principle to establish the existence of no-ν $\beta\beta$ decay, several positive results will be necessary to clinch the case: "Extraordinary claims require extraordinary proof!" Furthermore, several positive experiments are essential to pin down the neutrino parameter M_{ee}, because the relevant nuclear matrix elements are (and are likely to remain) poorly known.

(III) Setting the Parameters of the Minimal Model

- The subdominant angle θ_{13} must be measured (and not be too small) if we are to see CP violation in the neutrino sector. The present (CHOOZ) limit is roughly $\sin^2 2\theta_{13} < 0.2$ (I say 'roughly' because the constraint depnds strongly on $\Delta_{\rm atm}$. We can do better: Minos-Numi may achieve 0.06; Double-CHOOZ aims for 0.03; while the (not yet funded) Daya Bay project targets 0.01.

- Aside from learning how far θ_{13} departs from zero, we must determine how far θ_{23} departs from $\pi/4$, and how far θ_{12} departs from $\pi/6$.

- The squared-mass differences are roughly known: $\Delta_{\rm atm} \simeq 3 \pm 1 \times 10^{-3}$ eV^2, and $\Delta_{\rm sol} \simeq 8 \pm 1 \times 10^{-5}$ eV^2. More accuracy is needed, especially for the atmospheric difference. Of equal importance is the resolution to the mass hierarchy dichotomy, to be addressed by long baseline off-axis experiments.

- It would be wonderful, but difficult, to detect and measure CP violation in the neutrino sector. JParc (for example) may succeed if θ_{13} is not too small and δ is nearly maximal.

- Finally, the big question: Are all aspects of neutrino propagation correctly described by the six parameters of the minimal model? In particular, can we convince ourselves that there is no need to invoke sterile neutrino states or other exotic contrivances? If not, great! We will be challenged. But if so, what more can neutrino experimenters do? Will they have completed their appointed task?

(IV) What about LSND?

This experiment alleges to see $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ with a small mixing angle and large (0.1–10 eV^2) squared-mass difference. This result is unique in that it cannot be explained by the otherwise triumphant minimal (3-state) model, senza steriles. Hundreds of theorists are in hot pursuit of models that can deal with this snomaly, , but I am not yet persuaded to join the chase. It is the intent of the long-running MiniBoone experiment to confirm or refute the LSND experiment, but its result has not yet been announced. While a decisive refutation would put this issue to rest, I fear that theorists will be permitted to play their games for many years to come.

(V) To Catch a Supernova

We observed a total of 18 events from supernova 1987a at IMB and Kamioka, thereby confirming our understanding of core-collapse supernovæ. How wonderful it would be to detect and measure thousands of neutrinos from the next relatively nearby supernova. So much the better if our ever-ready detector could (like SNO) distinguish charged-current and neutral-current events. This device (with some cooperation from Nature) could tell us a lot about both neutrinos and supernovæ. I would assign a high priority to the indefinite maintenance of such a facility.

(VI) Absolute Neutrino Masses

Oscillation phenomena depend on differences of squared neutrino masses, not their absolute values. At present, we have only a weak lower bound to their size from oscillation experiments:

$$\sum m_i > 0.05 \text{ eV}/c^2 ,$$

and a surprisingly strong upper bound from our more astrophysical colleagues:

$$\sum m_i < 1 \text{ eV}/c^2 .$$

In addition, studies of the tritium beta-decay endpoint provide a relatively weak (but improveable?) constraint on the 'electron neutrino' mass: $m_{\nu_e} < 2.2 \text{ eV}/c^2$.

These constraints may someday converge. Indeed, Sheng Wang *et al.* suggest that an ambitious study of weak lensing by galactic clusters "could tighten the upper bound... to a level of 0.03 eV." If this level of sensitivity is achieved, the scale of neutrino masses would be set!

If neutrino masses are lepton-number violating (Majorana), the detection of neutrinoless double beta decay can provide an alternative estimate of the neutrino mass scale, but one complicated by the possible appearance of 'Majorana phases.'

I should mention that better *direct* limits on the masses of the muon and tau neutrinos can and will be set, but these improvements are unlikely to be relevant to the issue at hand.

(VII) Cosmic Ray Neutrinos?

We've seen and studied extra-terrestrial neutrinos: from our Sun, from a supernova, and as tertiary products of cosmic-ray impacts. But what about neutrinos as primary cosmic rays?

- As point sources in the sky?
- As transient sources such as GRBs?
- As ultra-high energy neutrinos?
- From W-bursts via the Glashow resonance?
- From wimp anihillation within the Earth or Sun?

We do not know if ever there will be a true science of neutrino astronomy, but we shall never know if we do not look, whether on land, under the sea or beneath the polar ice.

(VIII) Surprises?

Who knows what Nature has in store for us?

Sterile neutrinos,
Mass-Varying Neutrinos,
Lorentz Violation,
Effects due to Extra Dimensions,
Neutrino Magnetic Moments,
Decaying Neutrinos,
Departures from Flavor Universality,
What about $N_\nu = 2.984 \pm 0.008$, a 2-σ discrepency?

Or will there be something even more interesting,
Because, as always, She will call the shots.