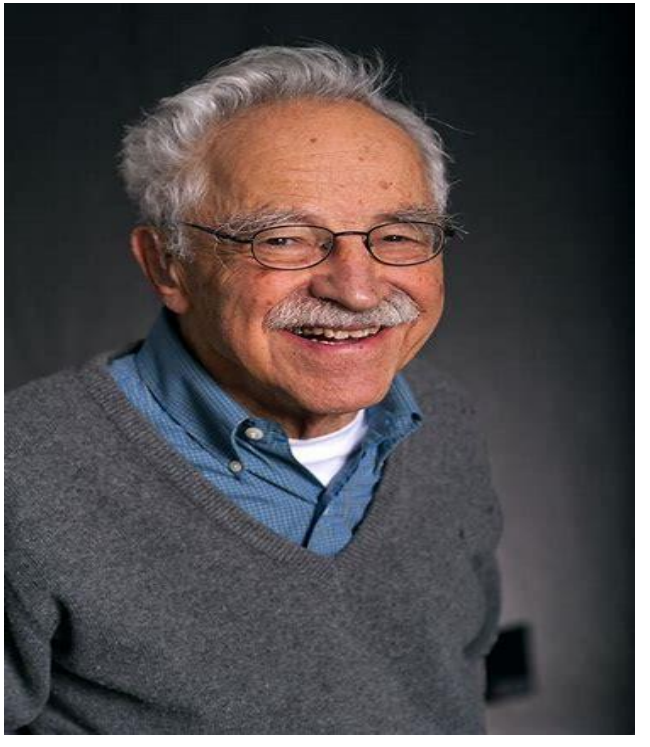
Ernest Henley: Friend and Mentor



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Introductory Remarks (1)

I want to tell you about one of the most memorable and productive scientific collaborations of my career. The collaboration with Ernest extended over about 30 years, led to fourteen published articles, and resulted in many unpublished manuscripts. Topics dealt entirely with novel aspect of symmetry.

In addition to Ernest, the other principal members of this collaboration were Leonard Kisslinger and Pauchy Hwang.

Woei-Yann Pauchy Hwang

1948-2018

Introductory Remarks (2)

The four of us decided to focus on the general areas of cosmology and astrophysics. Ernest suggested we focus on symmetry violation, directing our attention to early universe (electroweak and quark-gluon) phase transitions, unresolved issues in neutrino oscillations, and in the the creation of neutron stars, along with a list of insightful publications. I will give you examples of the ones that were especially meaningful to me.

This collaboration extended over a period of about 20 years.

deep insights and friendship, which he generously extended to all of us, was essential in many ways.

Timeline: 1991 to 2003

1991 to 2003: Ernest, Leonard, and I meet numerous times with Pauchy in Taiwan and Los Alamos. In Taiwan, Pauchy arranges lively retreats. These retreats were also attended by other NTU visitors

1991 to 1999: The primary focus of our collaboration: application of QCD Sum Rules

1999: Pauchy suggests that Cosmology & Astrophysics might be an interesting and productive line of research

Timeline: 2003 to 2016

2003: Our initial work on these topics was presented at Pauchy's second CosPA conference

2003 to 2016: Leonard, Ernest, and I meet in Los Alamos, Pittsburg, and Seattle to work on Seattle to work on problems involving cosmology, astrophysics, and neutrinos that Ernest thought were ripe for new ideas.

2016: Ernest withdrew from our collaboration because of illness

Taiwan: 1991-2003

Ernest, Leonard, and I met numerous times at informal meetings and retreats arranged by Pauchy in Taiwan. I remember well lengthy discussions with Ernest about a paper by Coleman shortly after it was published [*Aspects of Symmetry* (Cambridge, 1995), Ch 7] regarding second-order phase transitions. This paper laid the foundation of several papers the four of us published on symmetry-breaking early universe phase transitions.

1999: Dynamics of neutron stars (pulsar kicks)

Pulsars are observed to move with speeds up to 1500 Km/sec, making them the fastest stellar objects in our galaxy. How do pulsars get these kicks?

Pulsars have large magnetic fields (3x10^13 to 10^15 Gauss)

Asymmetric neutrino emission occurs in standard beta decay (n to p + e + antineutrino: “URCA” process) in the presence of magnetic fields

Detailed balance (high temperature and short mean free path) washes out asymmetric neutrino emission.

Our contribution

Inside the neutrino-sphere of a collapsing star, $T < 10^{10}$ K, and asymmetric neutrino emission can occur because n, p, and electrons are confined to levels of momentum $p < P_f$ (a degenerate Fermi gas)

For $T < 10^{10}$ K, two neutrino beta decay (n + n to n + p + electron + anti-neutrino: modified URCA) dominate the URCA process.

Result: Pulsar kicks up to 1000 Km/sec can be obtained from asymmetric neutrino emission at the surface of a proto-neutron star in the 10 to 20 sec time interval

2003 – 2016: Neutrino oscillations

See “Propagation of Neutrinos in Matter,” Mikkel Johnson, The Universe, Vol. 4, No. 4 (2016)

A complete list of the neutrino physics publications of E. M. Henley, L. S. Kisslinger, and M. B. Johnson is given in the talk of Leonard Kisslinger presented at this symposium

Neutrino Hamiltonian

$$\hat{\bar{\bar{H}}}_{\nu} = \hat{\bar{\bar{H}}}_{0v} + \hat{H}_1$$

- The neutrino vacuum Hamiltonian (dimensionless)

$$\hat{\bar{\bar{H}}}_{0v} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Neutrino interaction with matter (dimensionless)

$$\hat{H}_1 = U^{-1} \begin{pmatrix} \hat{A} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} U$$

- Here, U is a unitary matrix, the neutrino analog of the CKM matrix.
- U connects neutrino states of good flavor and neutrino mass eigenstates.

Time-Evolution Operator S(t' - t)

$$S(t', t) = e^{-iH_\nu(t'-t)}$$

Total Oscillation Probability

$$\boxed{\mathcal{P}(\nu_a \to \nu_b) = |S^{ab}(L)|^2 \equiv P^{ab}(L)}$$

Issues

- A credible error analysis requires calibrating the accuracy of expressions for the oscillation probability.

- Techniques used to determine the accuracy of the oscillation probability had not been previously examined.

- The lack of a credible theoretical error analysis initiated our search for an alternative formulation.

The Standard Neutrino Model

The ratio of two neutrino masses squared:

$$\alpha \equiv \frac{\delta m^2_{21}}{\delta m^2_{31}} = 3.17 \times 10^{-2},$$

The Mixing angles: θ_{ij}

The strength of the neutrino interaction with matter: $\hat{A}$
where $\hat{A} = \pm 6.50\ 10^{-2} \frac{Z}{N}\ E[\mathrm{GeV}]\rho[\mathrm{gm/cm}^3]$

with $\rho[\mathrm{gm/cm}^3]$ the density of matter through which the beam passes, and Z/N is the ratio of the proton to total nucleon number.

Formulation

Use the Lagrange interpolation formula to evaluate the time-evolution operator $S(L) = \sum_{\ell} F_\ell \exp^{-i\hat{\hat{E}}_\ell \Delta_L}$,

where $\Delta_L \approx 3.05 \times 10^{-3} \frac{L[\mathrm{Km}]}{E[\mathrm{GeV}]}$,

with $L[\mathrm{Km}]$ being the baseline, $E[\mathrm{GeV}]$ the beam energy, and $F_\ell \equiv \Pi_{j \neq \ell} \frac{U \hat{\hat{H}}_\nu U^{-1} - \mathbf{1} \hat{\hat{E}}_j}{\hat{\hat{E}}_\ell - \hat{\hat{E}}_j}$.

Simplifying the Oscillation Probability

(1) Expand the oscillation probabilities in the small parameters of the Standard Neutrino Model
(2) Retain only the dominant terms
(3) The neutrino eigenvalues must be expanded with caution
(4) In the complex plane, neutrino eigenvalues are found to have branch points
(5) Small-parameter expansions do not converge near branch points

Branch Points

- The branch point of the α -expanded eigenvalues occur at $\hat{A} = 0$

- The branch point of the $\sin^2\theta_{13}$ -expanded eigenvalues occur near the atmospheric resonance, $\hat{A} = \hat{A}_0 \equiv \dfrac{1-\alpha}{1-\alpha\cos^2\theta_{12}} \approx 1$

Simplifying the Oscillation Probability

we find, for $\hat{A} > 0.35$,

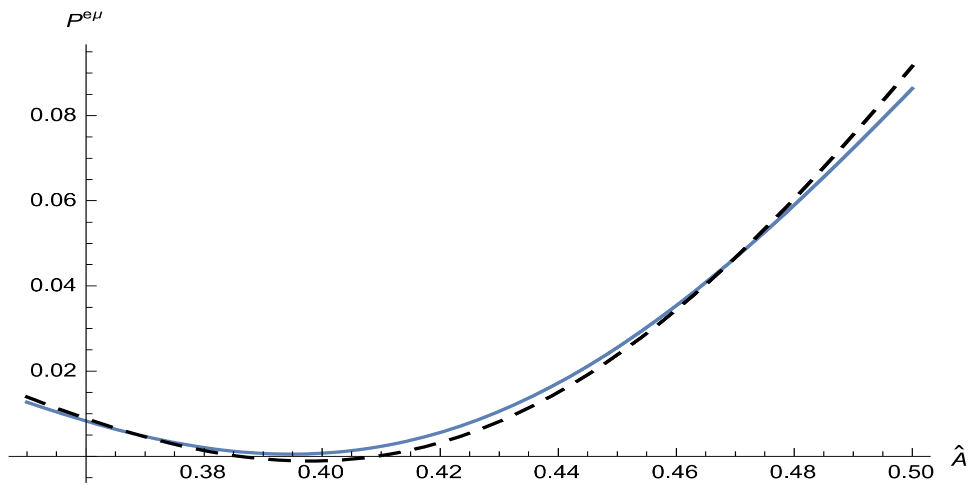
$$P^{+ab}(\Delta_L, \hat{A}) = \frac{4\Delta_L^2}{\hat{\hat{D}}}(\hat{\hat{w}}_0^{ab}[1] + D\hat{\hat{w}}_0^{e\mu}[1])j_0^2(\Delta_L \Delta\hat{\hat{E}}[1])$$

Here, $D\hat{\hat{w}}_0^{e\mu}[1] = 0$ and $\hat{\hat{w}}_0^{e\mu}[1] = -\frac{\alpha R_p}{C_\alpha} s_{23}^2(\hat{A}\tilde{A}^2 + \alpha(4R_p - \tilde{A}(s_{12}^2 + 8R_p)))$

except near the atmospheric resonance. In this small region,

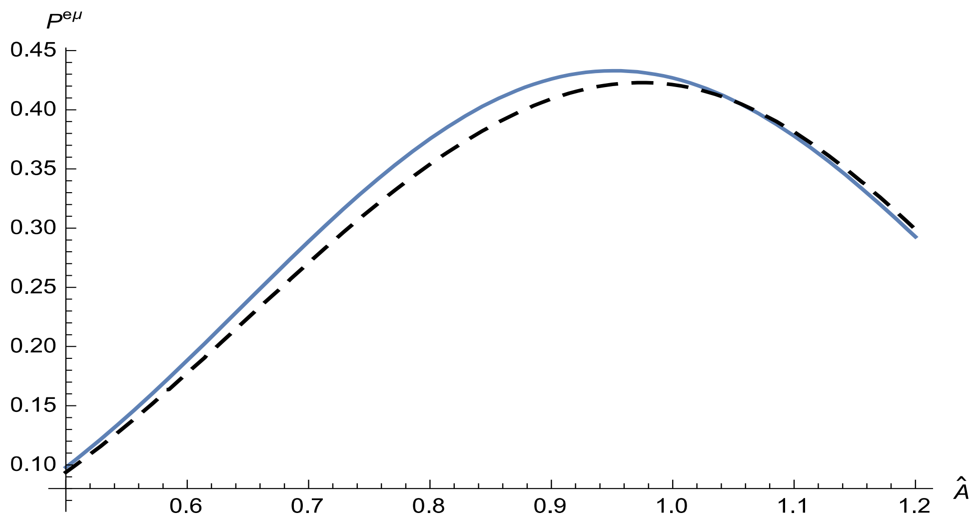
$$D\hat{\hat{w}}_0^{e\mu}[1] = \frac{2\alpha^2 R_p^2}{\hat{C}_\alpha} s_{23}^2(3c_{12}^2 + 4R_p)$$

$\nu_e \to \nu_\mu$ Oscillation Probability



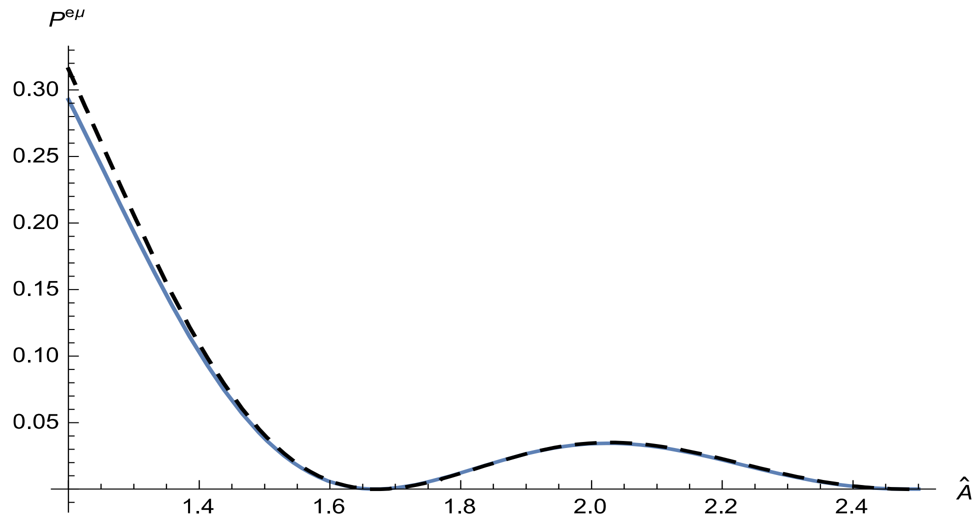
Approximate oscillation probability (dashed) compared to exact (solid) for $0.35 < \hat{A} < 0.50$

$\nu_e \rightarrow \nu_\mu$ Oscillation Probability (near the Atmospheric Resonance)



Approximate oscillation probability (dashed) compared to exact(solid) for 0.5 < $\hat{A}$ < 1.2

$\nu_e \to \nu_\mu$ Oscillation Probability



Approximate oscillation probability (dashed) compared to exact (solid) for $1.2 < \hat{A} < 2.6$

Concluding Remarks

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