Neutrinos

Ramon Miquel (ICREA / IFAE Barcelona)
(with input from Maury Goodman and Petr Vogel)

- Productive period. About 75 new measurements (from 24 reviewed papers, 30 (!) with relevant data)
  Moved to the precision-measurements mode ("mature")
- Many structural changes in previous year 2004 → 2006
- Basically no changes in 2008. Consolidation of big 2006 changes.
- A few extra changes foreseen for 2010

Cast

Maury Goodman	Encoding of accelerator neutrino papers
Don Groom	Overseer emeritus
Boris Kayser	“Neutrino Mass, Mixing, and Flavor Change”
Dean Karlen	“Number of Light Neutrinos”
Ramon Miquel	Overseer
Hitoshi Murayama	Mega-plot with current oscillation parameters
Kenzo Nakamura	Encoding of extraterrestrial neutrino papers
	“Solar Neutrinos”
Keith Olive	Encoding of Astrophysical papers
Andreas Piepke	Encoding of Nuclear Physics papers
&	“Introduction to the Neutrino Properties Listings”
Petr Vogel	“Note on Neutrinoless Double-Beta Decay”

+ consultants, referees, verifiers…

In Numbers

- # of pages (in web edition --- haven't seen the book yet)
  - Summary table: 1
  - Sports section: 25
  - Listings (including mini-reviews): 101

  Neutrinos badly underrepresented in summary tables!

- # of new measurements (papers):
  - Properties: 15 (12)
  - # of neutrino types: 5 (5)
  - $0\nu\beta\beta$ decays: 21 (5)
  - Mixing: 34 (8)
  - Searches for Heavy Neutral Leptons: 0 (0)

SUM OF THE NEUTRINO MASSES, m_{tot}

(Defined in the above note), of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary, we have generalized the results reported so they apply to m_{tot}. For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

VALUE (eV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 0.17–2.3		[54] FOGLI 07	COSM	
< 0.66		[55] SPERGEL 07	COSM	
< 0.63–2.2		[56] ZUNCKEL 07	COSM	
< 0.24	95	[57] CIRELLI 06	COSM	
< 0.62	95	[58] HANNESTAD 06	COSM	
< 0.52	95	[59] KRISTIANSEN 06	COSM	
< 1.2		[60] SANCHEZ 06	COSM	
< 0.17	95	[57] SELJAK 06	COSM	
< 2.0	95	[61] ICHIKAWA 05	COSM	
< 0.75		[62] BARGER 04	COSM	
< 1.0		[63] CROTTY 04	COSM	
< 0.7		[64] SPERGEL 03	COSM	WMAP
< 0.9		[65] LEWIS 02	COSM	
< 4.2		[66] WANG 02	COSM	CMB
< 2.7		[67] FUKUGITA 00	COSM	
< 5.5		[68] CROFT 99	ASTR	Ly α power spec
<180		SZALAY 74	COSM	
<132		COWSIK 72	COSM	
<280		MARX 72	COSM	
<400		GERSHTEIN 66	COSM	

Most of these papers were missed by our literature searchers : JCAP, MNRAS..

Found by Keith Olive

Double-β Decay

OMITTED FROM SUMMARY TABLE

A REVIEW GOES HERE – Check our WWW List of Reviews

Half-life Measurements and Limits for Double-β Decay

In most cases the transitions (Z,A) $\rightarrow$ (Z−2,A) + $2e^-$ + (0 or 2) $\overline{\nu}_e$ to the 0^+ ground state of the final nucleus are listed. However, we also list transitions that increase the nuclear charge ($2e^+$, e^+/EC and ECEC) and transitions to excited states of the final nuclei (0_i^+, 2^+, and 2_i^+). In the following Listings, only best or comparable limits or lifetimes for each isotope are reported. For 2ν decay, which is well established, only measured half-lives are reported.

$t_{1/2}(10^{21}$ yr)	CL%	ISOTOPE		TRANSITION	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>0.004	90	^{64}Zn	0ν	2K	$ZnWO_4$ scint.	1 BELLI	08
>0.22	90	^{64}Zn	0ν		$ZnWO_4$ scint.	2 BELLI	08
$0.57^{+0.13}_{-0.09} \pm 0.08$	68	^{100}Mo	2ν	$0^+ \rightarrow 0_1^+$	NEMO-3	3 ARNOLD	07
>89	90	^{100}Mo	0ν	$0^+ \rightarrow 0_1^+$	NEMO-3	4 ARNOLD	07
>1.1	90	^{100}Mo	2ν	$0^+ \rightarrow 2^+$	NEMO-3	5 ARNOLD	07
>160	90	^{100}Mo	0ν	$0^+ \rightarrow 2^+$	NEMO-3	6 ARNOLD	07
>0.0019	90	^{74}Se	0ν+2ν		γ in Ge det.	7 BARABASH	07
>0.0055	90	^{74}Se	0ν+2ν	$0^+ \rightarrow 2_2^+$	γ in Ge det.	8 BARABASH	07
$>(1.9–6.0)\ 10^{-4}$	90	^{120}Te	0ν		γ in Ge det.	9 BARABASH	07B
$>1.9 \times 10^{-4}$	90	^{120}Te	0ν+2ν		γ in Ge det.	10 BARABASH	07B
$>7.5 \times 10^{-4}$	90	^{120}Te	0ν+2ν	$0^+ \rightarrow 2^+$	γ in Ge det.	11 BARABASH	07B
$>1.19 \times 10^{-4}$	90	^{64}Zn	0ν		CdZnTe calorim.	12 BLOXHAM	07
$>1.21 \times 10^{-4}$	90	^{120}Te	0ν		CdZnTe calorim.	13 BLOXHAM	07
$>2.68 \times 10^{-6}$	90	^{120}Te	0ν		CdZnTe calorim.	14 BLOXHAM	07
$>9.72 \times 10^{-6}$	90	^{120}Te	0ν	$0^+ \rightarrow 2_1^+$	CdZnTe calorim.	15 BLOXHAM	07
22300^{+4400}_{-3100}	68	^{76}Ge	0ν		Enriched HPGe	16 KLAPDOR-K...	06A
>1800	90	^{130}Te	0ν		Cryog. det.	17 ARNABOLDI	05

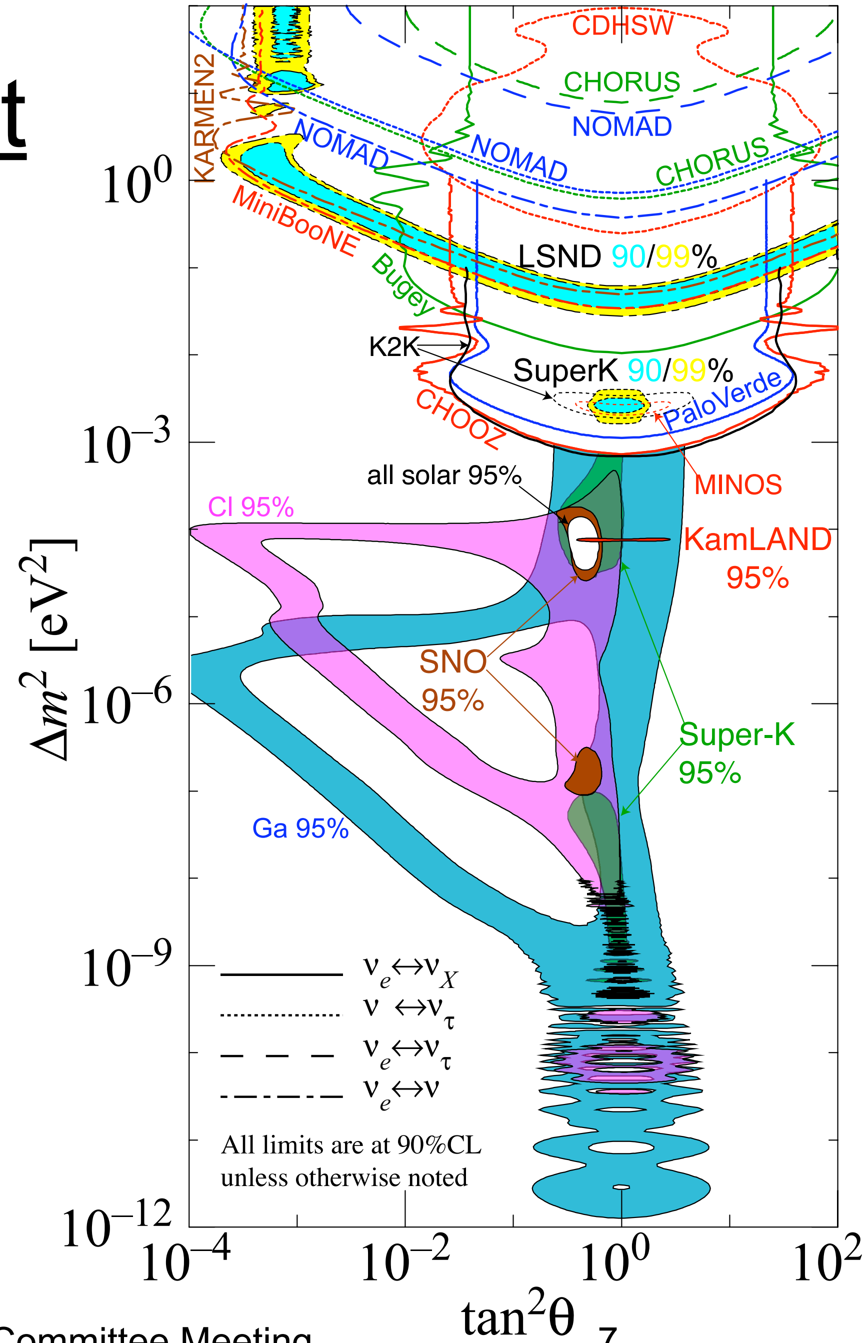
Lots of papers with several measurements (2v, 0v, excited states) each.

Reviews

- Revised mass and mixing review by Kayser.
- Revised intro to neutrino properties review by Vogel and Piepke.
- Revised neutrinoless double-beta decay review by Vogel and Piepke.
- Revised solar neutrino review by Nakamura.

Oscillation Plot

- By Hitoshi Murayama.
- Combines all two-flavor oscillation data in one figure.
- Solar, atmospheric, reactor and accelerator results available at a glance.
- Included in Boris Kayser's review on neutrino mass and mixing.



http://hitoshi.berkeley.edu/neutrino

The 2006 Revolution

- The 2006 revisions in the neutrino mixing sections added nodes on θ's and Δm^2, and eliminated (many more) nodes on probabilities of oscillations.
  - This has been regarded as useful and successful

- The revisions in the neutrino properties sections eliminating misleading names like "ν_e mass" and removing duplicate structures have been considered successful, although some degree of fine-tuning may be useful.

[Presented at 11/04 PDG] Summary of Workshop on 11/12/04 (I)

- Mixing
  - Introduce new "nodes" with measurements of θ_{12}, θ_{23}, θ_{13}, Δm^2_{12}, Δm^2_{23} in the 3-neutrino scenario, including mini-review explaining how it is done, assumptions, etc.
  - Remove Don's two-flavor mini-review which focuses on understanding limits.
  - Keep solar fluxes, atmospheric flux ratios, reactor flux ratios. Add accelerator flux ratios.
  - Remove obsolete oscillation limits in Δm^2 regions we now know are irrelevant.
  - Keep LSND-related limits from $\nu_\mu \leftrightarrow \nu_e$ oscillation searches.

Mixing Formalism:

Pontecorvo-Maki-Nakagawa-Sakata Matrix

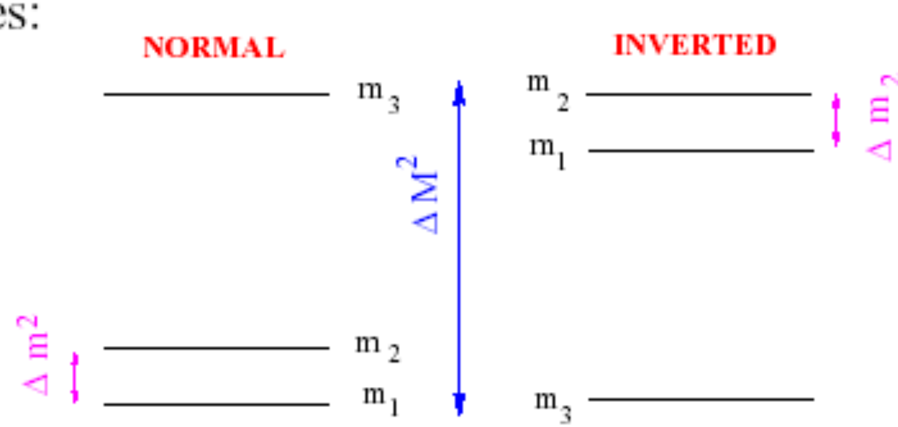
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

– U: 3 angles, 1 CP-phase + (2 Majorana phases)

c_{12}

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

– Two schemes:



- Results “relevant” to LSND were kept
- Since we didn’t know what LSND measured, if it was right, this was not 100% straightforward
- This was done in conjunction with MiniBooNE spokespersons

(C) Other neutrino mixing results

The LSND collaboration reported in AGUILAR 01 a signal which is consistent with $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations. In a three neutrino framework, this would be a measurement of θ_{12} and Δm^2_{21}. This does not appear to be consistent with the interpretation of other neutrino data, particularly solar neutrino experiments. If the LSND anomaly is correct, a more complicated framework is required, perhaps involving one or more sterile neutrinos, or even CPT violation. The following listings include results which might be relevant towards understanding or ruling out the LSND observations. They include searches for $\nu_\mu \rightarrow \nu_e$, $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$, sterile neutrino oscillations, and CPT violation.

Mixing Results (PDG'08)

- $|\Delta m^2_{32}|$ = $(1.9 - 3.0) \times 10^{-3}$ eV^2 Super-K
- Δm^2_{21} = $(8.0 \pm 0.3) \times 10^{-5}$ eV^2 KamLAND + Solar
- $\sin^2(2\theta_{23}) > 0.92$ Super-K
- $\sin^2(2\theta_{12}) = 0.86^{+0.03}_{-0.04}$ KamLAND + Solar
- $\sin^2(2\theta_{13}) < 0.19$ CHOOZ (+Super-K)

Mixing Results (PDG'06)

- $|\Delta m^2_{32}|$ = $(1.9 - 3.0) \times 10^{-3}$ eV^2 Super-K
- Δm^2_{21} = $(8.0\ ^{+0.4}_{-0.3}) \times 10^{-5}$ eV^2 KamLAND + Solar
- $\sin^2(2\theta_{23}) > 0.92$ Super-K
- $\sin^2(2\theta_{12}) = 0.86\ ^{+\,0.03}_{-\,0.04}$ KamLAND + Solar
- $\sin^2(2\theta_{13}) < 0.19$ CHOOZ (+Super-K)

Issues: Reviews

- The listings state and assume $\Delta m^2_{atm} \approx \Delta m^2_{31} \approx \Delta m^2_{32}$
- This is appropriate for now.
- However, there is a great deal of interesting physics at the next level, and the reviews allude to this in ways that are not totally consistent.
- They need to be carefully re-edited with this in mind

Issues: Listings

- The double beta decay section should be revised:
  - Separating the 0ν and 2ν results
  - Hiding the excited states
- As a result of the MiniBooNE results, the "Other Neutrino Mixing Results" section should probably be hidden in 2010.
- We should be on the watch for what new nodes (if any) may be needed for new paradigms ($>3\nu$, etc.)

Issues: Encoding

- Growing number of “cosmo” papers dealing with neutrino mass and number of neutrinos published in journals we do not follow: JCAP, MNRAS...

- Papers are assigned to encoders according to our old categories: reactor (Vogel and Piepke), accelerator (Goodman), solar + atmospheric (Nakamura), cosmic (Olive). It may be time to revise this.

Issues: Change Neutrino Names?

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Issues: Personnel

- I'm currently planning to leave PDG after the 2010 edition.
- A new overseer for the neutrino sections will be needed.

Conclusions

- Neutrino physics has entered a mature phase.
- RPP has adapted well to the changes in our understanding of neutrino physics.
- Great reviews help the reader follow this rather complicated subject.
- Minor changes in the listings will be applied for 2010.
- Future changes may depend on the outcome of new experiments: Double Chooz, T2K, Katrin, Daya Bay, Nova, etc.