Some aspects of neutrino phenomenology

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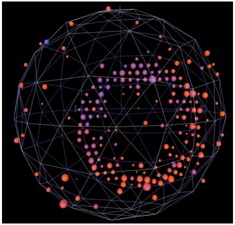


Section

Some unanswered questions on neutrinos

- Are neutrinos Majorana particles? $\nu = \bar{\nu}$? ν spinor unknown!
- The neutrino spectrum: Hierarchical or degenerate? Normal/Inverted?
- Are there sterile neutrinos? How many $(1, 2, \ldots, \infty)$?
- Why $m_\nu << m_{lep,q}$?
- Is there $\not{CP}$ in the leptonic sector?
- What is θ_{13} ? Is it non-zero?
- Can we observe the COH el. νN scattering ? And the CνB?
- Why are V_{CKM} and U_{PMNS} so different?
- Can we detect ultra high-energy cosmic neutrinos?

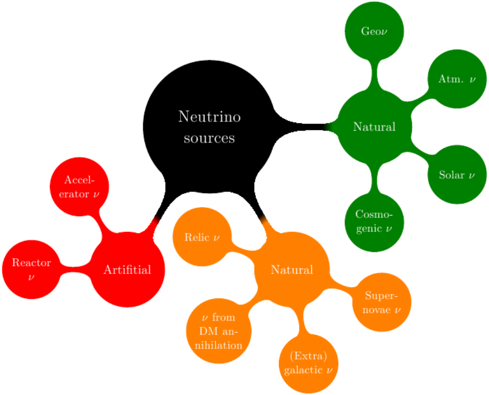
Why νN scattering and ν phenomenology?

- σ_ν for νN scatterings are not so precisely known as for leptonic reactions. Cause: nuclear form factors.
- νN interactions are essential to determine the Majorana or Dirac character of neutrinos via $\beta\beta$ decay.
- νN interactions and the SM framework. νN are SM tests. New physics?
- Some νN are found to be the important background events involved in DM experiments.
- Neutrino mixing($m_\nu \neq 0!$)$\Rightarrow \exists$ New Physics! Current and future high statistics measurements of oscillation parameters.

Section

Neutrino sources

We find neutrinos everywhere...



Some neutrino estimates and numbers

- From current cosmological theories:
  $n_\nu \approx 330\text{cm}^{-3} = 330 \cdot 10^6\text{m}^{-3}$. Compare with $n_p \sim 0.5\text{m}^{-3}$ and $n_\gamma \approx 411 \cdot 10^6\text{m}^{-3}$. $n_\nu / n_p \sim 10^9$, $n_\gamma / n_\nu \sim 1.2$
- How many neutrino interactions coming, e.g. from atmospheric neutrinos are we going to expect in our time-life?

$$\sigma \sim 10^{-38}\text{cm}^2 \cdot E_\nu(\text{GeV})$$

then, since the neutrino flux around 1 GeV is isotropic about 1 neutrino per square centimer per second, we get

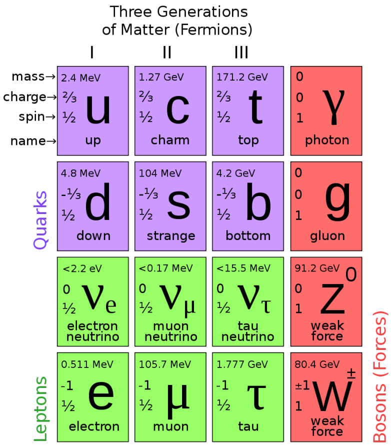
$$\frac{1\nu}{\text{cm}^2 s} \frac{10^{-38}\text{cm}^2}{N} \frac{6 \cdot 10^{32} N}{kT} \frac{3 \cdot 10^7\text{s}}{yr} \frac{75yr(hum)}{\text{life}} \frac{70\text{kg}}{(hum)} \sim 1\nu \frac{int.}{\text{hum life}}$$

The Standard Model(SM)

The most elaborated theory of subatomic particles. Recipe:

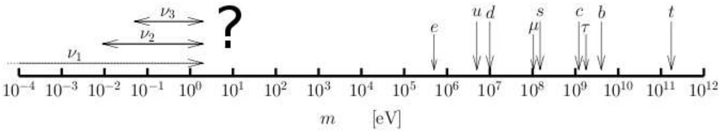
- Electroweak theory: Local Gauge Group $SU(2)_L \times U(1)_Y$ invariance(massless fields)
- Unified weak and electromagnetic forces through $W^{\pm}, Z, \gamma$ bosons.
- SSB and Higgs mechanism to generate mass of gauge bosons and fermions.(Higgs particle still missing)
- QCD lagrangian and V-A lagrangian (CC/NC) to describe, e.g., β decay of nuclei, μ decay,π decay,...

SM spectrum and the unknown ν absolute mass scale(I)



SM spectrum and the unknown ν absolute mass scale(II)

Then, we have to hunt the neutrino masses YET! (Not only the Higgs mass is unknown, provided it exists at Nature!)



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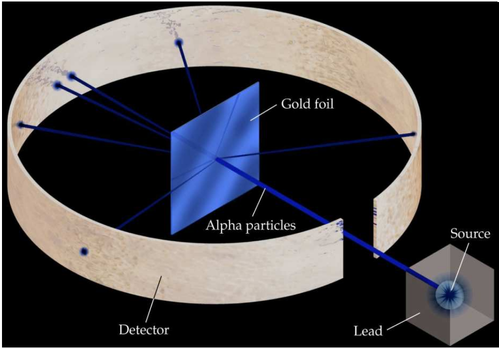
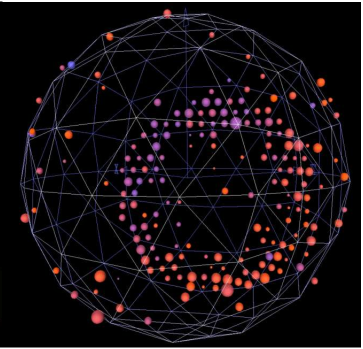
Why cross-sections? 1911 vs. 2011, α^{2+}vs.ν probes

$$N_\nu(E) \sim \epsilon \phi_\nu(E) \sigma_\nu(E)$$



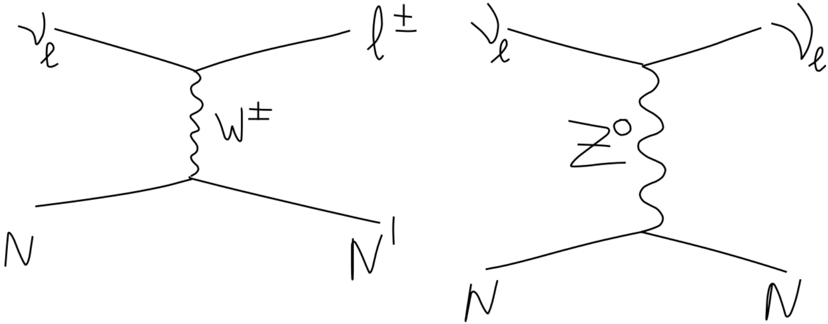


General background: SM interactions νN

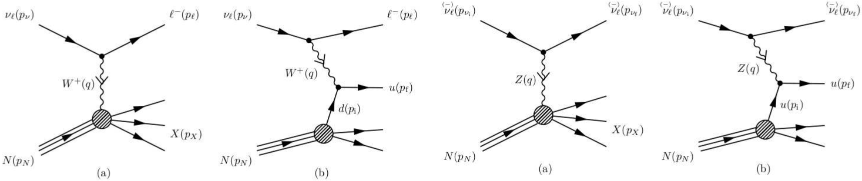
The SM establishes 4 kind of interactions νN, CC and NC.

- **Quasielastic/Elastic scattering** (CCQE/NCE). $E \sim 100$MeV to $E \sim 1$GeV. CC:$\nu_l + n \to p^+ + l^-$. NC:$\nu + N \to \nu + N$
- **Resonant channel scattering** (mainly one pion, Δbarion,...).$E \sim 100$MeV to $E \sim 1$GeV
- **CC/NC Deep Inelastic scattering**. $E \sim 100$MeV to $E \sim 100$GeV. Dominant at high energies. Based on the parton model. Cross sections are proportional to the parton distribution functions(PDFs).
- **Coherent scattering νN**. Diffractive process. νN as a whole. Low energy, less than $E \sim 100$MeV.

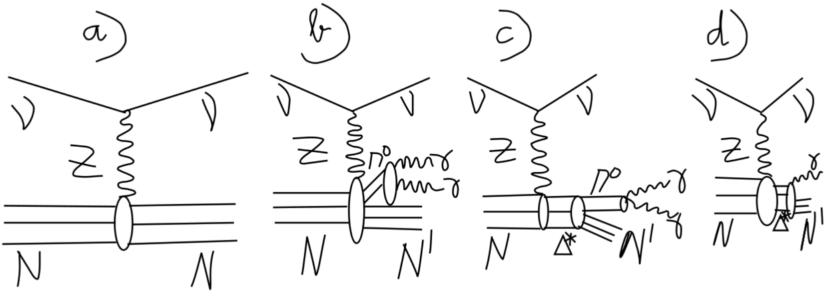
Feynman graph(I): Quasilastic and Elastic



Feynman graph(II): DIS



Feynman graph(III): NC Resonant and Coherent scattering



CCQE cross-section

CCQE

$$\frac{d\sigma_{CC}^{\nu_l n,\bar{\nu}_l p}}{dQ^2} = \frac{G_F^2 m_N^4}{8\pi E_\nu^2}\left[A(Q^2) \pm B(Q^2)\frac{(s-u)}{m_N^2} + C(Q^2)\frac{(s-u)^2}{m_N^4}\right]$$

Put it in numbers:

CCQE in numbers

$$\sigma_{CC}^{\nu_l n,\bar{\nu}_l p} \simeq 1.601 \times 10^{-44}\,(1+3g_A^2)\left(\frac{E_\nu}{\text{MeV}}\right)^2 \text{cm}^2$$

NCE cross-section

NCE

$$\frac{d\sigma_{CC}^{\nu_l N,\bar{\nu}_l N}}{dQ^2} = \frac{G_F^2 m_N^4}{8\pi E_\nu^2}\left[A_N(Q^2) \pm B_N(Q^2)\frac{s-u}{m_N^2} + C_N(Q^2)\frac{(s-u)^2}{m_N^4}\right]$$

Put it in numbers:

NCE in numbers

$$\sigma_{NC}^{\nu_l p,\bar{\nu}_l p} \simeq \frac{G_F^2}{4\pi}\left[\left(1-4\sin_w^2\right)^2 + 3g_A^2\right]E_\nu^2 \approx 6.0\cdot 10^{-46}\ \text{cm}^2\,\frac{E_\nu^2}{\text{MeV}^2}$$

$$\sigma_{NC}^{\nu_l n,\bar{\nu}_l n} \simeq \frac{G_F^2}{4\pi}\left[1 + 3g_A^2\right]E_\nu^2 \approx 9.3\cdot 10^{-44}\ \text{cm}^2\,\frac{E_\nu^2}{\text{MeV}^2}$$

What are $A(Q^2), B(Q^2), C(Q^2), g_A, \ldots$?

Answer: certain "complicated" functions depending on

$$F_1(Q^2) = \frac{1+\tau(1+\mu_p-\mu_n)}{(1+\tau)\left(1+\frac{Q^2}{M_V^2}\right)^2} \quad F_2(Q^2) = \frac{(\mu_p-\mu_n)}{(1+\tau)\left(1+\frac{Q^2}{M_V^2}\right)^2}$$

$$G_A(Q^2) = \frac{g_A}{\left(1+\frac{Q^2}{M_A^2}\right)^2} \quad G_P(Q^2) = \frac{2m_N^2}{M_\pi^2+Q^2} G_A \quad \tau = Q^2/4m_N^2$$

Here, $g_A = -1.25$, $M_V = 0.84\text{GeV}$ is the vector mass and $M_A = 1.03$ is the axial mass, M_π is the pion mass and μ_p, μ_n are the anomalous magnetic moments for the proton and the neutron.

Resonant νN cross-section: the Rein-Sehgal model

It describes $\nu, \bar{\nu}$ induced pion processes using one unified formalism. All non-strange resonant states below 2 GeV (18 resonances, usually the Δ exchange being the dominant mode) are combined, even interference terms, to produce the single pion channels. In addition, a small isospin $1/2$ non-resonant background is generally added incoherently to improve the agreement with data.

Resonant RS CS

$$\frac{\partial\sigma}{\partial Q^2 \partial E_q} = \frac{1}{128\pi^2} \sum_{spins} |T(\nu N \to l N^*)|^2 \frac{\Gamma}{(W - M_{N^*})^2 + \Gamma^2/4}$$

where M_{N^*} is the resonance mass, with width Γ and observed invariant mass W.

Deep Inelastic Scattering CS

CC DIS CS

$$\frac{d^2\sigma_{CC}^{\nu N,\bar{\nu}N}}{dxdy} = \sigma_{CC}^0 \left[xy^2 F_1 + (1-y) F_2 \pm xy \left(1 - \frac{y}{2}\right) F_3 \right]$$

NC DIS CS

$$\frac{d^2\sigma_{NC}^{\nu N,\bar{\nu}N}}{dxdy} = \sigma_{NC}^0 \left[xy^2 F_1^{ZN} + (1-y) F_2^{ZN} \pm xyF_3^{ZN} \right]$$

Note:

$$\sigma_{CC}^0 \simeq \frac{G_F^2}{\pi} m_N E_\nu \simeq 1.58 \times 10^{-38} \left(\frac{E_\nu}{\text{GeV}}\right) \text{cm}^2 \underbrace{\simeq}_{Q^2 << m_N^2} \sigma_{NC}^0 \sim G_F^2 s$$

Coherent νN cross-section(I): coherence conditions

- The transferred momentum to every nucleon is small enough that the nucleon remains bound in the nucleus.
- There is no transference of any quantum number, since it would spoil coherence otherwise.
- For scattering angles $\theta > 0$, processes are suppressed by $\sin^2\theta \leq (R\nu)^{-2}$, with $\nu = E - E'$ the difference energy before and after the coherent scattering.
- For convenience, a coherence length is introduced to be

$$l_c = \Delta t_c \simeq \frac{2\nu}{Q^2 + m^2}$$

where m is the real hadron state mass. Note that if this coherence length is greater than the nucleus radius target, the weak current will behave like a real hadron current.

Coherent νN cross-section(II): NC elastic case

NC elastic CS

$$\sigma^{coh}_{SM,total} = \frac{G_F^2}{4\pi} E_\nu^2 \left[Z(1 - 4\sin^2\theta_w) - N\right]^2 |f(q)|^2$$

NC elastic CS in numbers

$$\sigma^{coh}_{total} \approx \frac{G_F^2 E_\nu^2}{4\pi} N^2 |f(q)|^2 = 4.2 \cdot 10^{-45} N^2 \left(\frac{E_\nu}{1\text{MeV}}\right)^2 |f(q)|^2 \text{cm}^2$$

Coherent νN cross-section(III): coherent pion models

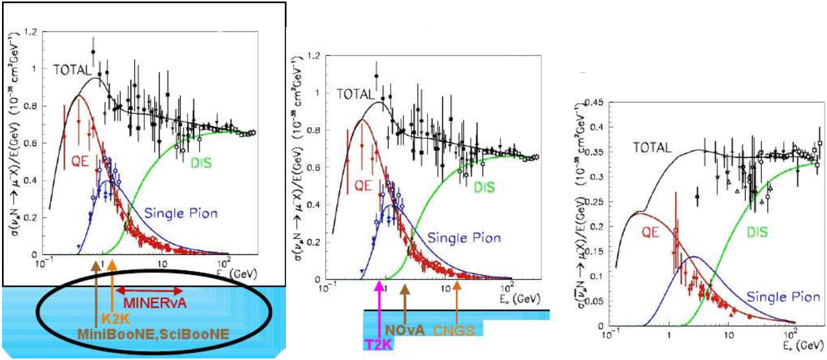
Rein-Sehgal COHπ

$$\frac{d^3\sigma}{dxdydt} = \frac{G_F^2 f_\pi^2 m_N E_\nu}{2\pi^2}(1-y)A^2\left(\frac{m_A^2(1+r^2)}{Q^2+m_A^2}\right)\frac{\left(\sigma_{tot}^{\pi N}\right)^2}{16\pi}e^{-b|t|}F_{abs}$$

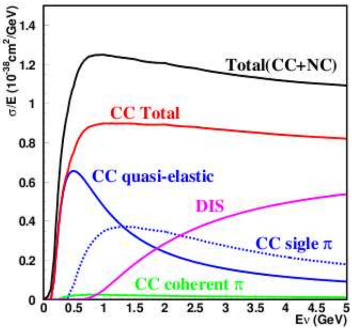
Belkov-Kopeliovich COHπ

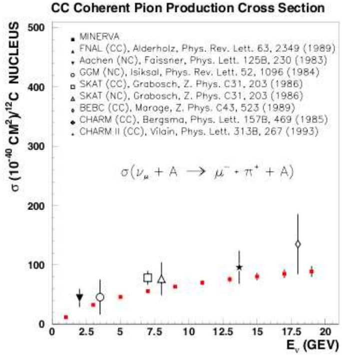
$$\frac{d^3\sigma}{dxdydt} = \frac{G_F^2 A^2 f_\pi^2 m_N E_\nu}{2\pi^2}(1-y)\frac{m_A^2(1+r^2)}{Q^2+m_A^2}\frac{\left(\sigma_{tot}^{\pi A}\right)^2}{16\pi}e^{-B_T|t'|}e^{-B_L|t_{min}|}$$

Some Plots


TOTAL
QE
DIS
Single Pion
$\sigma(\nu_\mu N \to \mu^- X)/E(GeV)$ $(10^{-38}$ cm^{2}GeV$^{-1})$
E_ν (GeV)
MINERvA
K2K
MiniBooNE,SciBooNE
NOvA
CNGS
T2K
$\sigma(\bar{\nu}_\mu N \to \mu^+ X)/E(GeV)$ $(10^{-38}$ cm^{2}GeV$^{-1})$

Some Plots(II)





Prospects in νN CS experiments

- CCQE and NCE CS are well understood and provide useful information. Nuclear form factors are the problem.
- Resonance models and COH pion processes are less understood. Elastic NC COH events have not been observed yet.
- RS fails to produce good fits at low energy beams and light nuclei. Theoretical challenge to build new models!
- Recently, SciBooNE reported:

$$\sigma_{CC}^{coh\pi}/\sigma_{NC}^{coh\pi} = 0.14^{+0.30}_{-0.28}$$

PCAC naturally produces a ratio $1.5 \sim 2$ from the isospin factor. SciBooNE claimed no known model can reproduce the data.

Section

Neutrino mixing/Neutrino oscillations

Fact and experimental well established phenomenon:
flavor eigenstates $\neq$ mass eigenstates$\rightarrow$ neutrino mixing!

Mixing matrix

$$\nu_{lL}(x) = \sum_i U_{li}\nu_{iL}(x)$$

Parameters: $N_\theta = \dfrac{n(n-1)}{2}, n_\phi^D = \dfrac{(n-1)(n-2)}{2}, n_\phi^M = \dfrac{n(n-1)}{2}$
Types of oscillation: oscillations in vacuum, oscillations in matter.
Oscillation amplitudes: $A(x,t) \rightarrow P(x,t) = |A(x,t)|^2$

PMNS standard parametrization

The PDG uses the mixing matrix decomposition:

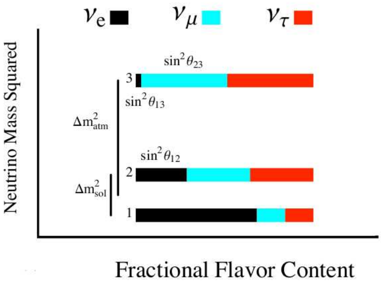
$$U^D = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Including the Majorana phases:

$$U = U^D S^M(\alpha) = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

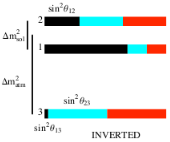
$$S^M(\alpha) = diag(e^{i\alpha_1}, e^{i\alpha_2}, e^{i\alpha_3})$$

The neutrino spectrum: mass squared vs. flavor content plots



central values θ_{12}, θ_{23}
max. for θ_{13}
and $|\sin\delta| = 1$

or



Oscillations in vacuum(I): basic quantities

$$E_k = \sqrt{p^2 + m_k^2} \simeq E_k + \frac{m_k^2}{2p} \rightarrow \Delta E = E_k - E_i \simeq \frac{\Delta m_{ki}^2}{2E}$$

$$\Delta m_{ki}^2 = m_i^2 - m_k^2 \rightarrow (E_k - E_i)\, t \simeq \frac{\Delta m_{ki}^2}{2}\frac{L}{E} = \frac{\Delta m_{ki}^2}{2E} L$$

$$\frac{\Delta m_{ji}^2}{2E} L = \frac{c^4}{\hbar c}\frac{\Delta m_{ji}^2}{2E} L = 1.267 \frac{\Delta m_{ji}^2}{1\text{eV}^2}\frac{L}{1\text{km}}\frac{1\text{GeV}}{E} = 1.267 \frac{\Delta m_{ji}^2}{1\text{eV}^2}\frac{L}{1\text{m}}\frac{1\text{MeV}}{E}$$

Oscillation length:

$$L_{osc} = \lambda_{osc} = 4\pi \frac{E}{\Delta m^2} = 4\pi \frac{E\hbar c}{c^4 \Delta m^2} = 2.47 \frac{E}{\Delta m^2}\ \text{m}$$

Oscillations in vacuum(II): some common formulae

Atmospheric neutrino formula:

$$P(\nu_\mu \to \nu_\mu) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2_{23}}{4E}L\right)$$

Solar neutrino formula:

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{12}}{4E}L\right)$$

Reactor neutrino formula:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}}{4E}L\right)$$

Accelerator formula:

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}}{4E}L\right) + O\left(\frac{\Delta m^2_{12}}{\Delta m^2_{23}}\right)$$

Oscillations in matter with constant density

- In the presence of matter, neutrinos acquire effective masses and exhibit particularly interesting oscillation patterns(MSW effect).
- Oscillations in matter distinguish complementary oscillation angles and show resonance effect(oscillation amplitude can be maximal whatever the mixing angle in vacuum is).
- Importance: $\theta_{13} > 0$ implies that the resonance condition is relevant for atmospheric neutrinos

$$\sqrt{2}G_F N_e \mp \frac{\Delta m^2}{2E}\cos 2\theta = 0 \Longrightarrow \sin^2\theta_m = 0 \rightarrow \Delta m_m^2 = \Delta m^2 \sin 2\theta$$

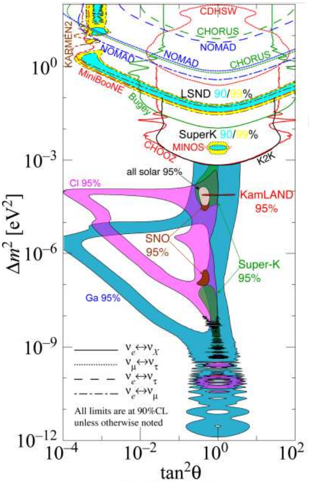
$$\text{Resonance energy:}\quad E_\nu \sim \frac{\Delta m^2}{\sqrt{2}G_F N_e} = 3\text{GeV}\frac{\Delta m^2}{10^{-3}\text{eV}^2}\frac{1.5\text{g/cm}^3}{\rho Y_e}$$

Neutrino oscillation data

- From **KAMLAND and a solar neutrino** global fit, we get:
  $\sin^2(2\theta_{12}) = 0.861^{+0.026}_{-0.022}$,
  $\Delta m^2_{12} = \Delta m^2_{solar} = 7.59^{+0.20}_{-0.21} \cdot 10^{-5}\text{eV}^2$
- **Atmospheric neutrino** yields (sign of Δm^2_{23} is unknown):
  $\sin^2(2\theta_{23}) > 0.92$, $CL = 90\%$
  $\Delta m^2_{23} = \Delta m^2_{atm} = 2.43 \pm 0.13 \cdot 10^{-3}\text{eV}^2 \quad CL = 68\%$
- **Reactor neutrino** provides: $\sin^2(2\theta_{13}) < 0.15$, $CL = 90\%$

The absolute scale of neutrino masses or their Majorana character are also unknown from neutrino oscillation results. Hints of a non-zero θ_{13} have appeared in T2K and MINOS, this year 2011.

Bounds on oscillation parameters (2010 data)



Section

$\beta\beta$ basics

SM double beta decay

$$(Z, A) \rightarrow (A, Z+2) + e^- + e^- + \nu_e + \nu_e$$

If the neutrino is a Majorana particle, then neutrinoless double beta decay:

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$
$$(A, Z) \rightarrow (A, Z+2) + 2e^- + \mathcal{M}$$
$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\mathcal{M}$$

Neutrinoless double beta decay and effective mass

$$K^+ \to \pi^- + \mu^+ + \mu^+ \;, K^+ \to \pi^- + e^+ + e^+ \;, K^+ \to \pi^- + \mu^+ + e^+$$
$$\mu^- + (A, Z) \to (A, Z-2) + e^+$$
$$\tau^- \to e^+ + \pi^- + \pi^-, \tau^- \to \mu^+ + \pi^- + \pi^-, \tau^- \to e^+ + \pi^- + K^-$$

$\beta\beta 0\nu$ decay rate

$$\Gamma^{\beta\beta 0\nu} = \frac{1}{T_{1/2}^{\beta\beta 0\nu}} = |m_{\beta\beta}|^2 |M^{\beta\beta 0\nu}|^2 G^{\beta\beta 0\nu}(Q, Z)$$

Effective mass:

$$m_{\beta\beta} = \sum_i U_{ei}^2 m_i$$

Why is $\beta\beta$ decay useful?

- Complementary information to neutrino oscillation experiments.
- Required to determine the mass spectrum kind under certain conditions (both theory and experiment).

For NH:

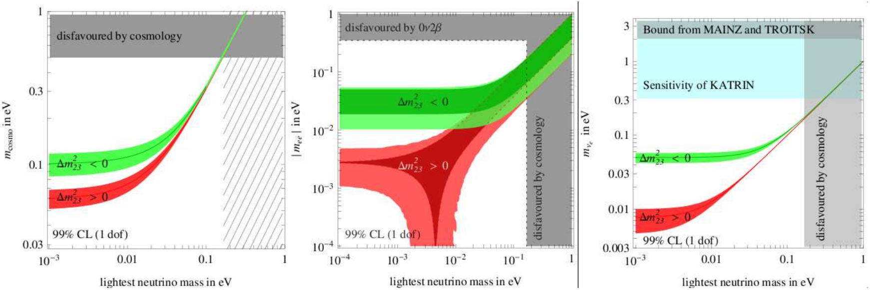
$$|m_{\beta\beta}| \simeq \left| \sin^2\theta_{12}\sqrt{\Delta m^2_{12}} + \sin^2\theta_{13}\sqrt{\Delta m^2_{23}} \right| \lesssim 5.3\cdot 10^{-3}\text{eV}$$

For IH: $1.8\cdot 10^{-2} \leq |m_{\beta\beta}| \leq 4.9\cdot 10^{-2}$ eV

β_{0ee} and absolute mass bounds

- The most known bound for the electron neutrino mass is the one from the Mainz and Troitsk data. It yields: $m_e < 2.2$eV. The double beta decay $\beta\beta 0\nu$ measurement is very hard and challenging. It is also highly dependent from the chosen method and isotope.
- From IGEX (^{76}Ge):$|m_{\beta\beta}| < 0.3 - 1.2$eV $CL = 90\%$.
  From CUORICINO(^{130}Te):$|m_{\beta\beta}| < 0.19 - 0.68$eV $CL = 90\%$
  From
  Heidelberg-Moscow(^{76}Ge):$|m_{\beta\beta}| < 0.3 - 1.3$eV $CL = 90\%$.
- From NEMO-3 (^{96}Zr) we get the 2010 bound:
  $|m_{\beta\beta}| < 7.2 - 19.5$eV $CL = 90\%$.

β_{0ee} and absolute mass plots



Section

The neutrino window(I)

Neutrino physics has a promising present and future. Some ideas for present an future νN scattering:

- CC events are sensitive to the nucleon axial mass M_A. MINERνA plans to improve its precision.
- NC events can probe the strangeness content of the nucleon. Neutrino as ideal probes of nuclear structure and structure functions.
- Nuclear effects (FSI, correlations, two-body currents,...) must be well understood and it is a highly non trivial task. Some models are in tension with data (e.g.: SciBooNe).
- Low energy CS (around 1 GeV and below) are important to study (SM model predictions and MC are not fully tested there in the neutrino sector). Interface with other searches.

The neutrino window(II):forthcoming future

- Reactor: Double CHOOZ, Daya Bay, RENO.
- Accelerator: T2K, MINOS (MiniBooNE,SciBooNE,...NuSonG?).
- Atmospheric/Solar/Neutrino telescopes: IceCube, KM3NET, ANTARES, NESTOR,...
- Supernovae neutrinos, UHECRν: Pierre Auger,...
- Double beta decay: CUORE, GERDA, MAJORANA, EXO and superNEMO or KATRIN.
- Develop and research: low energy particle detectors, neutrino superbeams, beta beams, neutrino factories(related to muon colliders...),...

The neutrino window(III):anomalies

- NuTeV
- Reactor
- LSND
- OPERA?
- ...

Ghostly, evasive, light, "dark", anomalous,ubiquitous...neutrinos

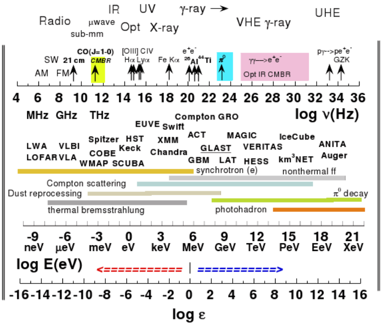
Neutrinos are so interesting because we do not know them well enough. We love them because they are so mysterious!

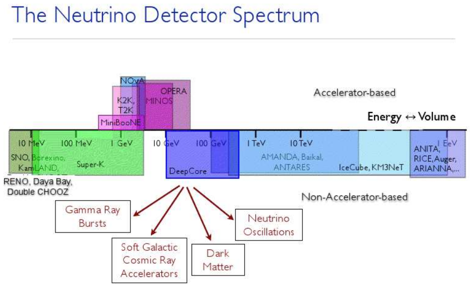
THANK YOU!

EXTRA SLIDES

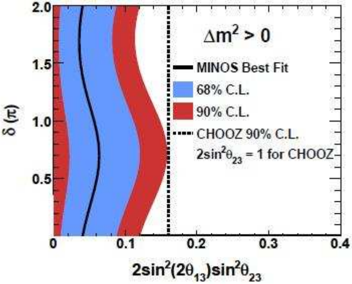
BACK-UP SLIDES

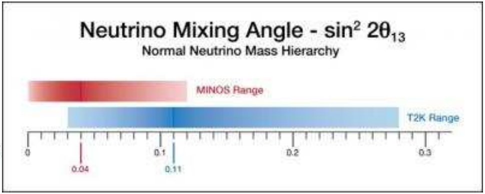
Neutrino detectors/Experiments and energy





Hints of θ_{13}



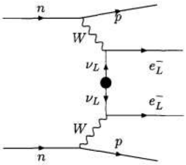


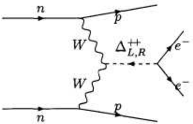
Mohapatra on double beta decay and neutrino masses

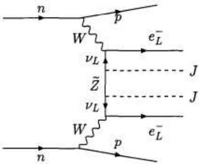
☞ Sign of Δm^2, $\beta\beta_{0\nu}$ and KATRIN result can tell us a lot:

$\beta\beta_{0\nu}$	Δm^2_{32}	KATRIN	Conclusion
yes	> 0	yes	Degenerate, Majorana
yes	> 0	No	Degenerate, Majorana or normal or heavy exchange
yes	< 0	no	Inverted, Majorana
yes	< 0	yes	Degenerate, Majorana
no	> 0	no	Normal, Dirac or Majorana
no	< 0	no	Dirac
no	< 0	yes	Dirac
no	> 0	yes	Dirac

β_{0ee} graphs $\sim G_F^2$







Decay effects in oscillations

$$P^{det}_{\nu_\alpha} = \langle \nu_\alpha | \rho(t) | \nu_\alpha \rangle = \sum_\beta w_\beta \sum_{j,k} U_{\beta j} U^*_{\beta k} U_{\alpha k} U^*_{\alpha j} e^{+i\frac{\Delta m^2_{kj}}{2E}t} e^{-\frac{\Gamma_j + \Gamma_k}{2}}$$

$$P^{det}_{\nu_\alpha} = \sum_j |U_{\alpha j}|^2 e^{-\Gamma_j t} \sum_\beta w_\beta |U_{\beta j}|^2 \rightarrow P^{det}_{\nu_\alpha} = \frac{1}{3} \sum_j |U_{\alpha j}|^2 e^{-\Gamma_j t}$$

Cosmological bound on neutrino masses

Cosmology and neutrinos

$$\frac{\sum m_\nu}{94\text{eV}} = \Omega_{DM} h^2 \lesssim 0.23 \cdot 0.7^2 \rightarrow \sum m_\nu \lesssim 10\text{eV}$$

GZK, Zevatrons, Z bursts in UHECR

Z-burst dip in UHECR spectroscopy
$\nu_{UHE} + \nu_{C\nu B} \rightarrow Z \rightarrow$ hadrons (resonance)

$$E_\nu^R = \frac{M_Z^2}{2m_\nu} \approx 4.2 \cdot 10^{21} \left(\frac{\text{eV}}{m_\nu}\right) \text{eV}$$

GZK(Greisen-Zatsepin-Kuzmin) cutoff $p + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^0$

$$E_\nu^{GZK} \simeq 5.0 \cdot 10^{20} \text{GeV}$$

Paschos-Wolfenstein DIS formulae

Paschos-Wolfenstein relationships(NuTeV)

$$R^- = \frac{\sigma^{\nu}_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar{\nu}}_{CC}} = \frac{1}{2} - \sin^2\theta_w$$

$$R^+ = \frac{\sigma^{\nu}_{NC} + \sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC} + \sigma^{\bar{\nu}}_{CC}} = \frac{1}{2} - \sin^2\theta_w + \frac{10}{9}\sin^4\theta_w$$

Seesaw formulae I,II,III

- Type I:

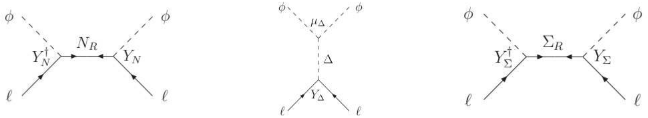
$$m_\nu = -M_D M_N^{-1} M_D^T$$

- Type II:

$$m_\nu = \sqrt{2}\mathcal{Y}_\nu v_3 = \frac{\mathcal{Y}_\nu \mu_D v_2^2}{M_\Delta^2}$$

- Type III:

$$m_\nu = -M_D^T M_\Sigma^{-1} M_D$$



KOIDE formulae and generalizations

Koide formula

$$Q = \frac{m_e + m_\mu + m_\tau}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2} = \frac{2}{3}$$

- $\frac{1}{3} < Q < 1$. Mysterious precision. Origin: preonic models.
- $\frac{1}{3Q}$ as the squared cosine of the angle between $(\sqrt{m_e}, \sqrt{m_\mu}, \sqrt{m_\tau})$ and $(1,1,1)$.

Koide formula for neutrinos (Brannen)

$$\frac{\left(-\sqrt{m_{\nu_e}} + \sqrt{m_{\nu_\mu}} + \sqrt{m_{\nu_\tau}}\right)^2}{m_{\nu_e} + m_{\nu_\mu} + m_{\nu_\tau}} = \frac{3}{2}$$

NEUTRINOS IN FICTION-SCIENCE, YET!

Neutrino Propulsion for Interstellar Spacecraft

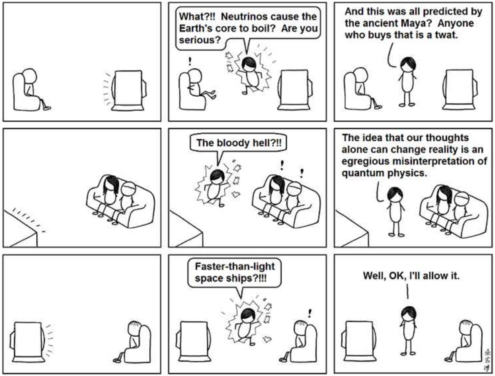
J. A. Morgan
The Aerospace Corporation, El Segundo, CA 90009, U. S. A.

July 3,1997

Abstract

An exotic spacecraft propulsion technology is described which exploits parity violation in weak interactions. Anisotropic neutrino emission from a polarized assembly of weakly interacting particles converts rest mass directly to spacecraft impulse.

Neutrino jokes in the www: abstruse goose



NEW RULE:
All science fiction DVDs must now include audio commentary by Brian Cox.

Neutrino jokes in the www: abstruse goose(II)