Experimental Neutrino Physics in Brazil

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Cosmic Rays and Chronology Department – DRCC
Outline

● Physics Challenges
  ● History and facts
  ● The context of neutrino experiments in the frontier of Physics

● Experiments
  ● Where are the Brazilians researchers/institutions within this scenario?

● Conclusion
History: the beta decay puzzle

Neutrinos were born in 1930, when Wolfgang Pauli tried a saving operation of "the energy conservation principle"

The famous Pauli's letter for radioactive ladies and gentlemen can be found at: http://lappweb.in2p3.fr/neutrinos/aplettre.html

Expected beta-particle energy

Original papers on neutrino first detection:


### Neutrino: a building block

Fermions

#### Leptons, spin = 1/2

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_L$</td>
<td>$(0-0.13) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>electron</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_M$</td>
<td>$(0.009-0.13) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_H$</td>
<td>$(0.04-0.14) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$\tau$</td>
<td>1.777</td>
<td>-1</td>
</tr>
</tbody>
</table>

#### Quarks, spin = 1/2

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$</td>
<td>0.002</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$</td>
<td>0.005</td>
<td>-1/3</td>
</tr>
<tr>
<td>$c$</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s$</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$t$</td>
<td>173</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$</td>
<td>4.2</td>
<td>-1/3</td>
</tr>
</tbody>
</table>
Neutrinos: some facts

- **Neutrinos are super abundant.** Neutrinos are the second most abundant particle in the universe.
  - If we were to take a snapshot, we’d see that every cubic centimeter has approximately 1,000 photons and 300 neutrinos.
  - The nuclear fusion reactions in the Sun sends 65 billion neutrinos per second per square centimeter to Earth, they are crossing us all the time.

- **Neutrinos are almost massless.** The three types of neutrinos in the standard model are the lightest particles with a non-zero mass ever discovered. The upper limit on the mass of the heaviest neutrino is still more than 4 million times lighter than the electron, the next lightest particle.

- **Neutrinos may have altered the course of the universe.** Why we have predominance of matter over antimatter? Cosmologists think that at the start of the universe there were equal parts of matter and antimatter.
  - Neutrino interactions may have tipped this delicate balance, enabling the formation of galaxies, stars and planets like our own Earth.

- **Neutrinos are the key particle in the heavy-element forges of the universe:** neutrinos dissipate more than 99 percent of a supernova’s energy. Supernovae eject heavy elements to the cosmos in a recycling matter mechanism.
  - “Core collapse” supernovae end as either a black hole or a neutron star. Neutrinos are key particles to understand how supernovae explode and tell us more about other astronomical objects like active galactic nuclei.

Do they deserve a careful and comprehensive study ???
Neutrino Theory of Stellar Collapse

G. Gamow, George Washington University, Washington, D. C.
M. Schoenberg,* University of São Paulo, São Paulo, Brazil
(Received February 6, 1941)

At the very high temperatures and densities which must exist in the interior of contracting stars during the later stages of their evolution, one must expect a special type of nuclear processes accompanied by the emission of a large number of neutrinos. These neutrinos, penetrating almost without difficulty the body of the star, must carry away very large amounts of energy and prevent the central temperature from rising above a certain limit. This must cause a rapid contraction of the stellar body ultimately resulting in a catastrophic collapse. It is shown that energy losses through the neutrinos produced in reactions between free electrons and oxygen nuclei can cause a complete collapse of the star within the time period of half an hour. Although the main energy losses in such collapses are due to neutrino emission which escapes direct observation, the heating of the body of a collapsing star must necessarily lead to the rapid expansion of the outer layers and the tremendous increase of luminosity. It is suggested that stellar collapses of this kind are responsible for the phenomena of novae and supernovae, the difference between the two being probably due to the difference of their masses.
Physics Challenges

The Intensity Frontier

- “Measurements of the mass and other properties of neutrinos are fundamental to understanding physics beyond the Standard Model and have profound consequences for the understanding of the evolution of the universe.” (PG. 3)

- “Recent striking discoveries make the study of the properties of neutrinos a vitally important area of research. Measurements of the properties of neutrinos are fundamental to understanding physics beyond the Standard Model and have profound consequences for the evolution of the universe. The latest developments in accelerator and detector technology make possible promising new scientific opportunities in neutrino science as well as in experiments to measure rare processes.” (PG. 10)

The panel recommends a world-class neutrino program as a core component of the US program (PG. 3)
Building for Discovery
Strategic Plan for U.S. Particle Physics in the Global Context

The P5 report recommends a prioritized and time-ordered list of experiments to address the five science Drivers optimally. These opportunities are at the small, medium, and large investment scales that, together, produce a continuous flow of major scientific results throughout a twenty-year timeframe.

- Large projects, in time order, include the Muon g-2 and Muon-to-electron Conversion (Mu2e) experiments at Fermilab, strong collaboration in the high-luminosity upgrades to the Large Hadron Collider (HL-LHC), and a U.S.-hosted Long Baseline Neutrino Facility (LBNF) that receives the world's highest intensity neutrino beam from an improved accelerator complex (PIP-II) at Fermilab.

Small changes in yearly budgets have large impacts on the timeline and capability of the U.S. particle physics program. A very large return on investment is ensured by the relatively small increment in funding between the constrained budget scenarios given in the P5 charge:

- A small limited-time funding increment to ensure support of the Dark Energy Spectroscopic Instrument (DESI) would yield scientific returns with high impact.
- World-leading accelerator and instrumentation development research would be retained.
- U.S. research capability would be maintained, including a
Physics Challenges: scientific motivations

- Neutrino Physics is one of the most active field in the advanced frontier of “Big Science”
- Offers an unique opportunity to stay tuned with technological and scientific progress in worldwide scale
  - For sure Brazilian scientists have interest in be part of it.
Figures about BR-HEP

- ~ 100 Institutes
- ~ 600 faculty

- Field Theory: 37.5%
- Cosmology & Gravitation: 17.8%
- Phenomenology: 17.2%
- HEP-exp: 13.1%
- Astrop.: 5.2%
- Nuclear: 2.4%
- Other: 6.7%
Figures about BR-HEP: by subarea

- **hep-exp**
  - 5800 papers
  - 242 technological products
  - 211 supervision works in progress
  - 1080 concluded

- **Particle Physics**
  - 3900 papers
  - 218 technological products
  - 259 supervision works in progress
  - 1379 concluded

- **Field Theory**
  - 6800 papers
  - 375 technological products
  - 534 supervision works in progress
  - 3476 concluded

- **cosmology**
  - 3000 papers
  - 308 technological products
  - 318 supervision works in progress
  - 1352 concluded

- **Lattes data base (from CNPq)**
- Sampled from ENFPC (2013)
- Caution: there are “contaminations”
Neutrino experiments: some examples

Near Detector at NuMI
FERMILAB Illinois

Neutrino beam diverges

Far Detector
SOUDAN MINE Minnesota
Iron Mountains

MINOS detector

Experimental setup...

Chooz Reactors
Power: 8.5GW_{th}
(N4s: very powerful)

Imagem artística de SN2006gy - NASA
Where? : Experiments with BR teams

- **Neutrino Properties:**
  - *oscillations*
    - DUNE
    - Double Chooz
    - NOvA
    - MINOS
      - MINOS+

- **Neutrino Interactions:**
  - *nuclear scattering and NSI*
    - DUNE
    - MINERVA
    - CONNIE

- **Astrophysical Neutrinos**
  - DUNE
  - LVD
  - Pierre Auger Observatory

- **Neutrino Applied Physics**
  - Neutrinos-ANGRA
Where? : Experiments with BR teams

- Neutrino Properties:
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- Astrophysical Neutrinos
  - DUNE
  - LVD
  - Pierre Auger Observatory

- Neutrino Applied Physics
  - Neutrinos-ANGRA

Most of Brazilian neutrino scientists have joined DUNE collaboration:
1) a more efficient participation
2) a very attractive experiment
What? : activities from BR teams

• R&D
  – Detectors development, integration, prototype tests

• Experiment construction
  – Installation, commissioning

• Monitoring
  – Data analysis for detector characterization
    • Performance and systematics studies

• Data Analysis

• Management
  – Scientific boards and task leading
  – Administrative boards and tasks
Experiments: Double Chooz

**Near**
- \( <L> \) 400m
- 400kV/day
- 120mwe
- Target: 8.2t
- End of 2012

**Far**
- \( <L> \) 1050m
- 50kV/day
- 300mwe
- Target: 8.2t
- March 2011

**Chooz Reactors**
- Power: 8.5GW\(_{th}\)
- (N4s: very powerful)
Experiments: Double Chooz

Detector Layout

engineer's view

MC's (G4)view

The Real Detector
Experiments: Double Chooz

\[
\sin^2(2\theta_{13}) = 0.085 \\
\pm 0.029 \text{ (stat)} \\
\pm 0.042 \text{ (syst)} \quad \Delta m^2_{\odot} = 2.35 \times 10^{-3} \text{eV}^2
\]
Experiments: MINOS
Experiments: MINOS

- The detectors are made of steel plates interleaved with scintillators.
- We identify the neutrinos through the trajectory of the particles they generate.
- The number of muon neutrinos measured in the detector is far less than expected based on the near detector if there was no oscillation.
Experiments: MINERVA

Goals for (Quasi)-Elastic Scattering at MINERvA

- MINERvA was designed in large part to map out features of quasi-elastic cross-sections at moderate energies across a wide range of $Q^2$.
  - Broad range of energies, target nuclei

<table>
<thead>
<tr>
<th>Target</th>
<th>LE $\nu_\mu$</th>
<th>LE $\bar{\nu}_\mu$</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scint. (CH)</td>
<td>58.0K</td>
<td>34.1K</td>
<td>6.4t</td>
</tr>
<tr>
<td>Helium</td>
<td>2.6K</td>
<td>1.3K</td>
<td>0.25t</td>
</tr>
<tr>
<td>Graphite (C)</td>
<td>1.5K</td>
<td>0.8K</td>
<td>0.17t</td>
</tr>
<tr>
<td>Water (H$_2$O)</td>
<td>3.2K</td>
<td>2.2K</td>
<td>0.4</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>9.5K</td>
<td>4.3K</td>
<td>0.97t</td>
</tr>
<tr>
<td>Lead</td>
<td>11.4K</td>
<td>3.7K</td>
<td>0.98t</td>
</tr>
</tbody>
</table>

8 March 2011

K. McFarland, Quasi-Elastic @ MINERvA
Experiments: MINERVA

MINERvA’s Prospects

- To illustrate our aspirations, here are our design-era simulation results for measurements with our full low energy data set.
Experiments: MINERVA

MINERvA’s Prospects

- To illustrate our aspirations, here are our design-era simulation results for measurements with our full low energy data set.

\[ \nu + n \rightarrow p + \mu^-, \text{MINERvA, Low Energy Beam} \]

Statistical and resolution errors. No flux error.

8 March 2011

K. McFarland, Quasi-Elastic @ MINERvA
Experiments: Large Volume Detector - LVD

THE LVD NEUTRINO OBSERVATORY

Supported by INAF-IESI-To & INFN
Experiments: Large Volume Detector - LVD

Inverse beta decay (double signature)

\[ \nu_e + p \rightarrow e^+ + n \]

1. Positron detection followed by ...

2. Gamma (2.2 MeV) from neutron capture \((\tau = 185 \mu s)\)

Neutron capture efficiency = 60% (from \(^{252}\text{Cf}\) measurement)
Experiments: Large Volume Detector - LVD

SN Signal / background

High threshold
average rate = 1 Hz

Low threshold
average rate = 120 Hz

\( \nu_e \) signature
Neutron capture efficiency = 60%

300 events burst
burst due to background:
300 \times (120 \text{ Hz}) \times (6 \times 10^{-4} \text{ s})
= 22 \pm 5
low en. pulses expected

Normalized to same number of events!

In a 10 s burst, 10 events expected from background with high threshold cut
Conclusions from LVD (presentation in 20 years of SN1987A - Hawaii - Feb/2007)

Leaving to a further study the detailed time structure, the energy spectrum, the flavor content and the topological distribution of signals inside the detector,

LVD is able to identify (at 90 % c.l.) on-line neutrino bursts from gravitational stellar collapses occurring in the whole Galaxy (D≤20 kpc).

Such a sensitivity is preserved even if the detector is running with only one third of its total mass in operation, with a severe noise rejection factor (1 fake event every 100 year).

LVD has been monitoring the Galaxy since 1992, for ~ 5000 days and with a duty cycle > 90%.

Since 2001 is running in the final configuration, $M_{act}$ always > 600 tons and duty cycle > 99.5%

$\rightarrow R < 0.18 \text{ event/year 90\% c.l.}$

Gd loaded scintillator in the future?
Experiments: Pierre Auger Observatory

Pierre Auger Observatory
studying the universe’s highest energy particles
Experiments: Pierre Auger Observatory

The Auger Collaboration

Participating Countries

Argentina
Australia
Bolivia*
Brazil
Czech Republic
France
Germany
Italy

Mexico
Netherlands
Poland
Portugal
Slovenia
Spain
United Kingdom
USA
Vietnam*

*Associate

17 countries, 63 Institutions, 369 Collaborators
The Observatory Lay-Out

Surface Array
1600 detector stations
1.5 km spacing
3000 km²

Fluorescence Detectors
4 Telescope enclosures
6 Telescopes per enclosure
24 Telescopes total

Experiments: Pierre Auger Observatory
The Hybrid Design
Surface detector array + Air fluorescence detectors
A unique and powerful design

- Nearly calorimetric energy calibration of the fluorescence detector transferred to the event gathering power of the surface array.
- A complementary set of mass sensitive shower parameters.
- Different measurement techniques force understanding of systematic uncertainties.
- Determination of the angular and core position resolutions.
Experiments: Pierre Auger Observatory

The Surface Array
Detector Station

- Communications antenna
- GPS antenna
- Solar panels
- Electronics enclosure
- Battery box
- Plastic tank with 12 tons of water
- 3 - nine inch photomultiplier tubes

The fluorescence telescope

- 440 PMT camera
- 1.5° per pixel
- Corrector lens (aperture x 2)
- - aperture box
- - shutter
- - filter UV pass
- - safety curtain

30 deg x 30 deg view per telescope

Segmented spherical mirror (d = 3.4 m)
Experiments: Pierre Auger Observatory

Neutrinos in Auger

Tau-neutrinos coming soon...
Experiments: Neutrinos-ANGRA

Development of new techniques for nuclear reactor monitoring
Experiments: Neutrinos-ANGRA

World map of nuclear reactors
Experiments: Neutrinos-ANGRA

Neutrinos & Non-proliferation

- ~438 reactors worldwide:
  The International Atomic Energy Agency - IAEA inspects nuclear installations under safeguards

- ~200kg plutonium produced in each fuel cycle (~1.5 years)
  ~90 tons of Plutonium produced every year worldwide

- IAEA is the verification authority of the Non Proliferation Treaty (NPT). IAEA has to keep track of all this material.
Experiments: Neutrinos-ANGRA

NEUTRINOS ANGRA Project

23/09/2008

containter: 1st laboratory in Angra
Experiments: Neutrinos-ANGRA

Focused Workshop on Antineutrino Detection for Safeguards Applications

28-30 October 2008
IAEA Headquarters, Vienna

Agenda

Tuesday, 28 October

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:00 – 09:45</td>
<td>Introductory Talk for Agency Personnel on Neutrinos (A. Bernstein, LLNL, USA)</td>
</tr>
<tr>
<td>10:00 – 10:15</td>
<td>Welcoming Address (M. Zande, Acting Director SGTS, IAEA)</td>
</tr>
<tr>
<td>10:15 – 10:45</td>
<td>Introduction of participants (all)</td>
</tr>
<tr>
<td></td>
<td>• Objectives of meeting (L. Whippelio, AEA)</td>
</tr>
<tr>
<td></td>
<td>• Elect Chairperson and rapporteur</td>
</tr>
<tr>
<td>10:45 – 11:00</td>
<td>Coffee Break</td>
</tr>
<tr>
<td>11:00 – 11:20</td>
<td>IAEA Safeguards Presentation (A. Monteith, SGTS, IAEA)</td>
</tr>
<tr>
<td>11:20 – 11:50</td>
<td>Antineutrino Flux from a Research and Isotope Producing Facility - A Case Study for Determining Detector Requirements (G. Jonkman, AECL, Canada)</td>
</tr>
<tr>
<td>11:50 – 12:20</td>
<td>The Nucler Neutrino Detector for Thermal Power Measurement and Non Proliferation (Th. Lasserre, CEA, France)</td>
</tr>
<tr>
<td>12:20 – 13:15</td>
<td>Lunch</td>
</tr>
<tr>
<td>13:15 – 13:50</td>
<td>Reactor Neutrino Spectra and Nuclear Reactor Simulations for Unravelling Diversion Scenarios (C. Lhullier, CEA, France / M. Fallot, Subatech, France)</td>
</tr>
<tr>
<td>13:50 – 14:25</td>
<td>Direction-Sensitive Monitoring of Nuclear Power Plants (F. de Meijer, Stichting SARTII foundation)</td>
</tr>
<tr>
<td>14:25 – 15:00</td>
<td>Finnish know-how, Infrastructure and Activities Relevant to the Development of Antineutrino Detection Technologies for Safeguards Purposes (M. Traska, Univ. of Jyvaskyla, Finland)</td>
</tr>
<tr>
<td>15:00 – 15:15</td>
<td>Coffee Break</td>
</tr>
<tr>
<td>15:15 – 15:50</td>
<td>The Angra Neutrino Project: Present Status (J. dos Anjos, CBPF, Brazil)</td>
</tr>
<tr>
<td>15:50 – 16:20</td>
<td>Study of Neutrino Detection from Fast Research Reactor (F. Suukane, Tohoku Univ., Japan)</td>
</tr>
</tbody>
</table>
Experiments: DUNE design

34 kt fiducial mass
single-phase LAr TPC
Depth = 4300 m.w.e.

1.2 MW Proton Beam (PbP-II)
Upgradeable to ≥ 2.4 MW

Magnetized, low-density
fine-grained tracker
Experiments: DUNE design

Experiments: DUNE design

LBNE Liquid Argon TPC
Volume: 15m x 23m x 62m x 2
Total Liquid Argon Mass: ~50,000 tonnes

mm-scale resolution!

ArgoNeuT
DUNE: current efforts

- Hardware development
  - Light collectors based on dopped fibers
    - (DRCC + Special Fibers Lab)
  - Simulations:
    - Light propagation and light collections efficiency
    - Calculations on detector sensitivity
      - Supernovae, non-standard interactions, quantum effects

- Unicamp + UFABC + UFAL + UFG + UESB
Conclusions

- Brazilian experimentalists on neutrino science are well inserted
- There are many opportunities both for new collaborators and students
- Future is also promising

Thank you!
Physics Challenges

• The Intensity Frontier

  • “Measurements of the mass and other properties of neutrinos are fundamental to understanding physics beyond the Standard Model and have profound consequences for the understanding of the evolution of the universe.” (PG. 3)

  • “Recent striking discoveries make the study of the properties of neutrinos a vitally important area of research. Measurements of the properties of neutrinos are fundamental to understanding physics beyond the Standard Model and have profound consequences for the evolution of the universe. The latest developments in accelerator and detector technology make possible promising new scientific opportunities in neutrino science as well as in experiments to measure rare processes.” (PG. 10)

The panel recommends a world-class neutrino program as a core component of the US program (PG. 3)
3.2 The Intensity Frontier: Neutrino Physics and Precision Measurements

At the Intensity Frontier, precision measurements of the properties of leptons and quarks can lead the way to resolving some of the universe’s deepest mysteries.

3.2.1 Neutrino physics

Neutrino physics has had a long and distinguished history, ... We outline an ambitious vision that builds on that strong scientific tradition to capture the unique scientific opportunities of neutrino science. Results of recent experiments have revolutionized and brought renewed excitement to this field.

They have shown that neutrinos have nonzero masses, mix with one another, and oscillate among the neutrino flavor states.

Cosmology tells us that the neutrino masses are very small, less than one millionth of the electron’s mass.

Oscillation studies find tiny nonzero neutrino mass differences between generations, but large values of two of the three mixing angles, $\theta_{23} \sim 45^\circ$ and $\theta_{12} \sim 32^\circ$. Currently we only have an upper limit of about $10^\circ$ on the third angle, $\theta_{13}$.

Collectively, these advances in neutrino physics have opened the first crack in the Standard Model of particle physics. They have significantly changed our view of neutrinos and the special role they play in elementary particle physics, astrophysics and cosmology.

In the coming years, neutrino physics presents exciting opportunities:
• the measurement of the mixing angle between the heaviest and lightest neutrinos,
• determination of the hierarchy of neutrino masses,
• the search for matter-antimatter asymmetry (CP violation) in neutrino mixing, and lepton number violation.

These opportunities are fundamental to the science of particle physics and have profound consequences for the understanding of the evolution of the universe.
Physics Challenges

Questions for the future

1) Do neutrino oscillations violate CP?
   - CP violation drive a matter-antimatter asymmetry (leptogenesis)?
   - What is the value of the CP violating phase?
   - CP violation among neutrinos related to CP violation in the quark sector?

2) What are the relative masses of the three known neutrinos?
   - Are they “normal,” \( m_3 > m_2 > m_1 \) or “inverted” hierarchy \( m_2 > m_1 > m_3 \)?
   - The ordering has important consequences for interpreting the results of neutrinoless double beta decay
   - Origin and pattern of masses in a more fundamental way

3) Is \( \theta_{23} \) maximal \( (45^\circ) \)? if so, why?
   - Will the pattern of neutrino mixing provide insights regarding unification of the fundamental forces?
   - Will it indicate new symmetries or new selection rules?

4) Are neutrinos their own antiparticles?
   - Lepton number violation, or leptogenesis, in the early universe?
   - Observable: neutrinoless double beta decay in nuclei

5) What can we learn from supernovae neutrinos?
   - Can we observe the neutrino remnants of all supernovae that have occurred since the beginning of time?

6) What can neutrinos tell us about new physics? Beyond the Standard Model, dark energy, extra dimensions? Do sterile neutrinos exist?
Among these people there are those interested in neutrinos (obs.: only main research interest, not accounted researchers working occasionally with neutrinos)

- 24 (faculty) = 13 (exp) + 11 (theo)
- 11 Institutions (number of people):
  - UNICAMP (4), USP (2), UFABC (3), IFT (2) (SP state)
  - UFG (1) (GO state)
  - CBPF (3), UFRJ (1) , PUC-Rio (1) (RJ state)
  - UFAL (1), UFJF (1) (MG state)
  - UFBA (2), UEFS (1) (BA state)
  - UFPR (1) (PR state)
  - UFPB (1) (PB state)
Who ?: countries

- Latin American Countries in neutrino experiments
  - Argentina: Auger, CONNIE, ANDES
  - Brazil: LBNE, DC, Auger, MINOS(+), NOvA, CONNIE, NUCLEAR, ANGRA, ANDES
  - Chile: ANDES
  - Colombia: NEXT
  - Paraguay: CONNIE
  - Peru: MINERvA
  - Mexico: Auger, MINERvA, ANDES
Experiments: MINOS