Future Neutrino Oscillation Facilities
A. the status and CP violation

B. Beyond the approved program:
   options in Europe and elsewhere
   B1 Elsewhere
      B1.1 in Japan
      B1.2 In the US
   B2. in Europe
      B1.1 LAGUNA and liquid detectors
      B1.2 EURONU future neutrino facility and the SPL
      B1.3 Super-beam options
      B1.4 Beta beam
      B1.5 Neutrino Factory

C. Conclusions and outlook
Status of neutrino oscillations in a few words

1. We know that there are three families of active, light neutrinos (LEP)
2. Solar neutrino oscillations are established
   (Homestake+Gallium+Kam+SuperK+!SNO(2002)!+KamLAND)
3. Atmospheric neutrino (\(\nu_\mu \rightarrow \nu_\mu\)) oscillations are established
   (IMB+Kam+Macro+Sudan +!SuperK(1998)!+K2K+MINOS)
3. At that frequency, electron neutrino oscillations are small (CHOOZ)

4. Indication of possible higher frequency oscillation (LSND) is not confirmed (miniBooNe)

This allows a consistent picture with 3-family oscillations
\[
\theta_{12} \sim 34^0 \quad \Delta m_{12}^2 \sim 7.6 \times 10^{-5} eV^2, \quad \theta_{23} \sim 45^0, \quad \Delta m_{23}^2 \sim \pm 2.4 \times 10^{-3} eV^2, \quad \theta_{13} < 10^0
\]
with 3 unknown \(\theta_{13}\), phase \(\delta\), sign of \(\Delta m_{13}^2\)

BUT many basics full scheme and unitarity still untested:
=> an exciting experimental program for at least 25 years *)
   including leptonic CP & T violations

*) to set the scale: CP violation in quarks was discovered in 1964
and there is still an important program (LHCb, K0pi0, superB, Neutron EDM, NA63....)
to go on for 10+ years...i.e. a total of ~50+ yrs. and we have not discovered leptonic CP violation yet

5. Several experiments are prepared/starting to go further:
   OPERA, T2K, D-CHOOZ, RENO, Daya Bay, NOvA
   and the future program is being discussed
The neutrino mixing matrix: 3 angles and a phase $\delta$

$\theta_{23}$ (atmospheric) = 45$^0$, $\theta_{12}$ (solar) = 32$^0$, $\theta_{13}$ (Chooz) $< 13^0$

$\Delta m^2_{23} = 2.4 \times 10^{-3} \text{eV}^2$
$\Delta m^2_{12} = 7.6 \times 10^{-5} \text{eV}^2$

$\begin{bmatrix}
\sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin \theta_{13} e^{i\delta} \\
\sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\
\sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2}
\end{bmatrix}$

Unknown or poorly known $\theta_{13}$, phase $\delta$, sign of $\Delta m^2_{13}$

$\mu$
KamLAND+Solar: $\Delta m^2 = 7.59^{+0.21}_{-0.21} \times 10^{-5} \text{ eV}^2$, $\tan^2 \theta = 0.47^{+0.06}_{-0.05}$
\[ \sin^2 \theta_{23} = 0.50^{+0.07}_{-0.06} \]

\[ |\Delta m^2_{31}| = 2.40^{+0.12}_{-0.11} \times 10^{-3} \text{ eV}^2 \]
There are today **THREE** compelling and firmly established observational facts that the Standard Model fails to account for:

-- neutrino masses  
-- the existence of dark matter  
-- the baryon asymmetry of the universe  

The fact that neutrino have masses and mix is established by neutrino oscillations

The neutrino masses offer a chance to explain the baryon asymmetry in the most natural way via

*** LEPTOGENESIS ***

by a combination of
-- fermion number violation  (authorized by neutrino masses and GUT)  
-- three families of neutrinos  ==> leptonic CP violation  
(authorized by the mixing of three families with large mixing angles)

Fermion number violation  $\rightarrow$ neutrino less double beta decay  
CP violation  $\rightarrow$ neutrino oscillations (today)
\[ P(\nu_e \rightarrow \nu_\mu) = |A|^2 + |S|^2 + 2A\,S\,\sin\delta \]

\[ P(\overline{\nu}_e \rightarrow \overline{\nu}_\mu) = |A|^2 + |S|^2 - 2A\,S\,\sin\delta \]

\[
\frac{P(\nu_e \rightarrow \nu_\mu) - P(\overline{\nu}_e \rightarrow \overline{\nu}_\mu)}{P(\nu_e \rightarrow \nu_\mu) + P(\overline{\nu}_e \rightarrow \overline{\nu}_\mu)} = A_{\text{CP}} \frac{\sin\delta \, \sin (\Delta m^2_{12} L/4E) \, \sin \theta_{12} \sin \theta_{13}}{\sin^2 2\theta_{13} + \text{solar term}}
\]

... need large values of \( \sin \theta_{12}, \Delta m^2_{12} \) (LMA-- we have it!) but *not* large \( \sin^2 \theta_{13} \)

... need APPEARANCE ... \( P(\nu_e \rightarrow \nu_e) \) is time reversal symmetric (reactors or sun are out)

... can be large (100\%) for suppressed channel (one small angle vs two large)

at wavelength at which ‘solar’ = ‘atmospheric’ and for \( \nu_e \rightarrow \nu_\mu, \nu_\tau \)

... asymmetry is opposite for \( \nu_e \rightarrow \nu_\mu \) and \( \nu_e \rightarrow \nu_\tau \)
Asymmetry can be very large.

Stat. sensitivity in absence of bkg is \( \sim \) independent of \( \theta_{13} \) down to \( \sin^2 2\theta_{13} = 10^{-3} \)

Asymmetry changes sign from one max. to the next.

Sensitivity at low values of \( \theta_{13} \) is better for short baselines, sensitivity at large values of \( \theta_{13} \) is better for longer baselines (2d max or 3d max.)

Optimal experiment depends on \( \theta_{13} \)

\[ \text{Max. Asymmetry} \]

\[ \text{Stat. error with no background} \]

\[ \text{First step: what is the value of } \theta_{13} \text{?} \]
<table>
<thead>
<tr>
<th>Future project</th>
<th>$\sin^2 2\theta_{13}, \text{sign} (\Delta m^2_{13})$</th>
<th>CP</th>
<th>methods</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DCHOOZ (2010)</strong></td>
<td>0.03 - 0.01 no no</td>
<td></td>
<td>Reactor + scintillator</td>
</tr>
<tr>
<td><strong>RENO</strong></td>
<td>0.03 - 0.01 no no</td>
<td></td>
<td>Near + far (1km) baselines up to 1.8km</td>
</tr>
<tr>
<td><strong>DAYA BAY (2012)</strong></td>
<td>0.02-0.008 no no</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>T2K (2010)</strong></td>
<td>0.01 no no</td>
<td></td>
<td>Near (scint. + TPC) Far (Water Ckov)50kt</td>
</tr>
<tr>
<td><strong>T2K+</strong></td>
<td>0.001? Yes? ?</td>
<td></td>
<td>Far= 250-500 kt WC a/o 100kt Larg TPC?</td>
</tr>
<tr>
<td><strong>3. NOvA (2012)</strong></td>
<td>0.01 W/T2K? no</td>
<td></td>
<td>Active Scintillator</td>
</tr>
<tr>
<td><strong>4. DUSEL</strong></td>
<td>0.001 Yes? ?</td>
<td></td>
<td>WC, (TASD, Larg)?</td>
</tr>
<tr>
<td><strong>5. CERN</strong></td>
<td>Combination allows 0.001 no? yes</td>
<td></td>
<td>SB or BB + 500 kt WC or Larg?</td>
</tr>
<tr>
<td>-- SB to ?F-lab</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-- BB to ?F-lab</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>-- neutrino factory</strong></td>
<td>0.0001 Yes Yes</td>
<td></td>
<td>muon decay beam magnetized Fe Mag MECC/Larg/TASD</td>
</tr>
</tbody>
</table>
The quest for $\sin^2 2\theta_{13}$

**MINOS 2009**

- **MINOS**
- **OPERA**
- **World limit**
- **Double Chooz**
- **T2K**
- **Daya Bay**
- **NOvA**

90% CL sensitivity
Computed with:
$\delta_{CP} = 0$
$\text{sign}(\Delta m^2) = +1$
Situation after approved program if $\sin^2 \theta_{13}$ is close to present limit:

Very scant possibility of $2\sigma$ if both $\sin \delta$ and $\sin^2 \theta_{13}$ are at the limit.
Otherwise nothing is known! Obviously we must go beyond this and prepare for it!
Beyond the Approved program
Neutrino Intensity Upgrade
Quest for the Origin of Matter Dominated Universe

One of the Main Subject of KEK Roadmap

T2K (2009~)
Discover $\nu_e$ app.

Neutrino
Anti-Neutrino meas.

Intensity Upgrade

Detector R&D

Tech. Choice

Huge det. Construction

CPV search
Proton decay

Possible Timeline

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac (400MeV)</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>?</td>
<td>400MeV</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>T2K</td>
<td>4</td>
<td>4</td>
<td>?</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>MR Intensity Upgrade</td>
<td>4</td>
<td>4</td>
<td>?</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Detector R&amp;D</td>
<td>?</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Presented by KEK DG at KEK Roadmap Review Committee 9, 10-March 2008
First Protons on Target!

Image in proton beam position monitor 30 cm before target

• First **protons on target** April 24, 2009!

Signal in Muon Monitor at end of decay volume
Three Possible Scenario Studied at NP08 Workshop

Korea  Okinoshima  Kamioka

1000km  658km  295km
1 deg. Off-axis  0.8 deg. Off-axis  2.5 deg. Off-axis

NP08 is The 4th International Workshop on Nuclear and Particle Physics at J-PARC
http://j-parc.jp/NP08
Fermilab in 2020?

- NuMI (NOvA)
- DUSEL (2 MW)
- 8 GeV neutrinos
- 8 GeV SC Linac (or Synchrotron?)
- Tevatron FT
- Low energy program (350-2000 kW)
- 8 GeV SC Linac
• An opportunity exists for the U.S. to become a world leader at the Intensity Frontier
  • Central is an intense neutrino beam and large underground long-based line detector
  • Building on infrastructure at Fermilab and partnering with NSF
  • Develops infrastructure that positions the U.S. to regain Energy Frontier (Muon Collider)

• HEP at its core is an accelerator based experimental science
  • Accelerator R&D develops technologies needed by the field and that benefit the nation

*as reported by Dennis Kovar at the Fermilab Users’ Meeting, June 2008
Possibilities in EUROPE

1. The community

the active participants in
- CNGS (OPERA + ICARUS)
- T2K (250 = about half of the collaboration)
- MINOS
- DCHOOZ
- R&D for future neutrino beams and detectors
  (MICE MERIT, EUROnu, LAGUNA, ISS...)
- Ancillary experiments such as HARP, NA61

This represents of the order of >~ 500 European physicists.
Diverse but very motivated!

2. CNGS

OPERA is THE neutrino accelerator experiment in Europe today.
Design limitations:
  - Intensity due to SPS and due to radiation environement
  - No near detector.
  - High energy suitable for tau appearance but far from osc. maximum requires redesign
Proposals exist (MODULAR, 20 kton liquid argon TPC) and should be evaluated

3. Advanced neutrino beams
References and Links

Original ideas in 1970's (Amaldi, Budker)

Neutrino Beams From Muon Storage Rings: Characteristics And Physics Potential

Prospective study of muon storage rings at CERN, ECFA-CERN CERN 99-02 (1999)

Study IIA Neutrino Factory and Beta Beam Experiments and Development,
C. Albright et al, BNL-72369-2004, FNAL-TM-2259, LBNL-55478,

ECFA-CERN study of a Neutrino Factory Complex

ISS (ECFA supported) reports
Accelerator design concept for future neutrino facilities. arXiv:0802.4023

ISS study
-- Performed comparison between proposed facilities
-- defined the baseline parameters.
to be followed-up quantitatively (R&D, feasibility, cost) ➔ International Design Study
Towards a high-intensity neutrino programme

EP2010:
« pursue an internationally coordinated, staged program in neutrino physics »

CERN-SG:
Studies of the scientific case for future neutrino facilities and the R&D into associated technologies are required to be in a position to define the optimal neutrino programme based on the information available in around 2012; Council will play an active role in promoting a coordinated European participation in a global neutrino programme.
LAGUNA: considered underground sites

Example: baselines from CERN
Detectors envisaged in Laguna

- Large Water Cherenkov (160 kton per tank)
- Giant Liquid Argon TPC (100 kton)
- 30ton Liquid Scintillator à la Borexino

Non magnetic. Suitable for superbeam and/or Beta beam, but not with neutrino factory. Synergy with proton decay and astropysical neutrinos.
Steps towards GLACIER

Small prototypes ⇒ ton-scale detectors ⇒ 1 kton ⇒ ?

- LEM readout on 1x1 m² scale, UHV, cryogenic system at ton scale, cryogenic pump for recirculation, PMT operation in cold, light reflector and collection, very high-voltage systems, feed-throughs, industrial readout electronics, safety (in Collab. with CERN)

- ArDM ton-scale

- direct proof of long drift path up to 5 m

- we are here

- Application of LAr LEM TPC to neutrino physics: particle identification (200-1000 MeV electrons), optimization of readout and electronics, cold ASIC electronics, possibility of neutrino beam exposure

- Test beam 1 to 10 ton-scale

- full engineering demonstrator for larger detectors, acting as near detector for neutrino fluxes and cross-sections measurements, ...
superbeam (pion decay)

Neutrino Factory (muon decay)

Can any of this be at CERN? Elsewhere in Europe?
Main possibilities connected to LHC injector upgrade

LP-SPL: Low Power-Superconducting Proton Linac (4 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
sLHC: “Super-luminosity” LHC (up to $10^{35}$ cm$^{-2}$s$^{-1}$)
DLHC: “Double energy” LHC (1 to ~14 TeV)

Main requirements of PS2 on its injector:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2 x ultimate brightness with nominal emittances</td>
<td>Injection energy</td>
<td>4 GeV</td>
</tr>
<tr>
<td></td>
<td>Nb. of protons / cycle for LHC (180 bunches)</td>
<td>$6.7 \times 10^{13}$</td>
</tr>
<tr>
<td>Single pulse filling of SPS for fixed target physics</td>
<td>Nb. of protons / cycle for SPS fixed target</td>
<td>$1.1 \times 10^{14}$</td>
</tr>
</tbody>
</table>
The preferred possibility for high power: the SPL SC-linac (160 MeV → 4 GeV) with ejection at intermediate energy

Elliptical 5 cell bulk Niobium cavities (e.g.: $\beta=0.47$)

<table>
<thead>
<tr>
<th>Beam characteristics at 4 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy (GeV)</td>
</tr>
<tr>
<td>Beam power at 4 GeV (MW)</td>
</tr>
<tr>
<td>Repetition period (s)</td>
</tr>
<tr>
<td>Protons/pulse ($\times 10^{14}$)</td>
</tr>
<tr>
<td>Average pulse current (mA)</td>
</tr>
<tr>
<td>Pulse duration (ms)</td>
</tr>
</tbody>
</table>

Low Power - SPL

Medium $\beta$ cryomodule
- $9 \times 6$ $\beta=0.65$ cavities

High $\beta$ cryomodules
- $5 \times 8$ $\beta=1$ cavities

Ejection
- $14 \times 8$ $\beta=1$ cavities

High $\beta$ cryomodules

Debunchers

Length: ~430 m
SPL Architecture
High Power proton beams (HP-SPL)

- Replacement of klystron power supplies, upgraded infrastructure (cooling & electricity, etc.)
- Addition of 5 high $\beta$ cryomodules to accelerate up to 5 GeV ($\pi$ production for $\nu$ Factory)

SC-linac (160 MeV $\rightarrow$ 5 GeV) with ejection at intermediate energy

- Medium $\beta$ cryomodule
  - 0 m
  - 0.16 GeV
  - 9 x 6
  - $\beta=0.65$ cavities

- High $\beta$ cryomodules
  - 110 m
  - 0.73 GeV
  - 11 x 8
  - $\beta=1$ cavities

- Ejection
  - 291 m
  - 2.5 GeV
  - 13 x 8
  - $\beta=1$ cavities

- To EURISO

- High $\beta$ cryomodules
  - 500 m
  - 5 GeV

- Debunchers

- To PS2 and Accumulator

Length: $\sim$500 m

- Up to 4MW at BOTH 2.5 GeV (For EURISOL, L.E. muons etc.)
  and 5 GeV (for neutrino production)

A formidable power-horse!
### Beam characteristics of the main options

<table>
<thead>
<tr>
<th></th>
<th>Option 1</th>
<th>Option 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>2.5 or 5</td>
<td>2.5 and 5</td>
</tr>
<tr>
<td>Beam power (MW)</td>
<td>2.25 MW (2.5 GeV)</td>
<td>4 MW (2.5 GeV)</td>
</tr>
<tr>
<td></td>
<td>or</td>
<td>and</td>
</tr>
<tr>
<td></td>
<td>4.5 MW (5 GeV)</td>
<td>4 MW (5 GeV)</td>
</tr>
<tr>
<td>Rep. frequency (Hz)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Protons/pulse ($\times 10^{14}$)</td>
<td>1.1</td>
<td>2 (2.5 GeV) + 1 (5 GeV)</td>
</tr>
<tr>
<td>Av. Pulse current (mA)</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Pulse duration (ms)</td>
<td>0.9</td>
<td>0.8 (2.5 GeV) + 0.4 (5 GeV)</td>
</tr>
</tbody>
</table>

Faster rep. rate ⇒ new power supplies, more cooling etc.

2 × beam current ⇒ 2 × nb. of klystrons etc.
SPL Super-Beam Project

- H- linac 2.2, 3.5 or 5 GeV, 4 MW
- Target
- Accumulator ring + bunch compressor
- Magnetic horn capture (collector)
- Proton driver
- Decay tunnel
- Hadrons
- ν, µ
- ~300 MeV νµ beam to far detector

To be studied in EUROν WP2
To be studied by LAGUNA

ECFA session EPS Cracow 18-07-2009 Alain Blondel
SUPERBEAM at SPL? 50 Hz 4 MW 4-5 GeV LINAC

High beam power required (~4MW or more if possible)

Short duty cycle => accumulator ring is necessary

Pulsed Magnetic horns require duty cycle typically <10-3 (thermal constraint)
At 50 Hz operation this requires beam delivery within <20 microseconds.

Single Target? Liquid Hg target difficult to integrate in horn. Solid/powder target?

Proton Beam energy?
On axis pion decay Neutrino energy is typically < 10-15% of proton beam energy
SPL superbeam=> 400-500 MeV neutrino beam energy.
This is a good energy for the Water Cherenkov also in search of proton decay.

First oscillation maximum is situated at <250 km.
Second oscillation maximum at < 750 km.
(useful if \(\sin^2 2\theta_{13}\) is small?)

Probably not very interesting if considered in isolation.
Advocated to be Interesting/important/necessary if considered in conjunction to beta-beam.
Recall of Beta Beam scenario, EURISOL

Proton Driver
SPL

Ion production
ISOL target & Ion source

Beam preparation
pulsed ECR

Ion acceleration
Linac, 0.4 GeV

Acceleration to medium energy
RCS, 1.7 GeV

β-emitters of suitable lifetime

Existing!!!

SPS
93 GeV

8.7 GeV

Decay ring
$B_p = 1000 \text{ Tm}$
$B = \sim 6 \text{ T}$
$C = \sim 6900 \text{ m}$
$L_{ss} = \sim 2500 \text{ m}$

$^6\text{He}: \gamma = 100$
$^{18}\text{Ne}: \gamma = 100$

SPS

8.7 GeV

Detector in the Frejus tunnel

ECFA session E 26/3 2009
Combination of beta beam with super beam

Combines CP and T violation tests

\[
\begin{align*}
\nu_e &\rightarrow \nu_\mu \quad (\beta^+) \\
\bar{\nu}_e &\rightarrow \bar{\nu}_\mu \quad (\beta^-) \\
\nu_\mu &\rightarrow \nu_e \quad (\pi^+) \\
\bar{\nu}_\mu &\rightarrow \bar{\nu}_e \quad (\pi^-)
\end{align*}
\]

In addition, one beam provides cross-sections and topologies for the other in the near detector.
Beta-beams

Original concept for the ion production is based on the SPL: successful for $^6\text{He}$, well established production mechanism.

Spallation production of $^6\text{He}$ on a BeO target from a powerful proton source ($\sim 200$ kw per target station)

For $^{18}\text{Ne}$ initial considerations using the same technique lead to a deficit of a factor $> 10$ wrt to physics demands. ($8 \times 10^{11}/s$).

Direct production using high power $^3\text{He}$ gun needed. Demonstration needed!

With SPS as final accelerator, typical maximal energy for (anti) neutrinos is 400–600 MeV (i.e. can be matched to the SPL superbeam)

$\rightarrow$EUROnu DS will investigate new production mechanisms using high Q isotopes: $^8\text{Li}$, $^8\text{B}$ (C. Rubbia et al) which are less demanding on the proton source.

Higher energy neutrinos (factor 4–5) but correspondingly higher number of ions will be required for same event rates. Flux goes as $1/Q^2$ and cross-section as $Q$.

Exciting possibility also with e-capture ions (Dy for instance) $\text{N}+e \rightarrow \text{N}'+\nu_e$ which produce monochromatic electron neutrino beams.

Spallation production; really needs high power SPL.

These new ion production schemes are object of the EUROnu design study.
A monochromatic neutrino beam

Electron Capture: $N + e^- \rightarrow N' + e$$_\nu$

<table>
<thead>
<tr>
<th>Decay</th>
<th>$T_{1/2}$</th>
<th>BR$_\nu$</th>
<th>$E_{C/\nu}$</th>
<th>$I_{EC}^\beta$</th>
<th>$B$(GT)</th>
<th>$E_{GR}$</th>
<th>$\Gamma_{GR}$</th>
<th>$Q_{EC}$</th>
<th>$E_\nu$</th>
<th>$\Delta E_\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{148}$Dy$\rightarrow^{148}$Tb$^*$</td>
<td>3.1 m</td>
<td>1</td>
<td>0.96</td>
<td>0.96</td>
<td>0.46</td>
<td>620</td>
<td>2682</td>
<td>2062</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{150}$Dy$\rightarrow^{150}$Tb$^*$</td>
<td>7.2 m</td>
<td>0.64</td>
<td>1</td>
<td>1</td>
<td>0.32</td>
<td>397</td>
<td>1794</td>
<td>1397</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{152}$Tm2$\rightarrow^{152}$E$^*_T$</td>
<td>8.0 s</td>
<td>1</td>
<td>0.45</td>
<td>0.50</td>
<td>0.48</td>
<td>4300</td>
<td>520</td>
<td>8700</td>
<td>4400</td>
<td>520</td>
</tr>
<tr>
<td>$^{150}$Ho2$\rightarrow^{150}$Dy$^*$</td>
<td>72 s</td>
<td>1</td>
<td>0.77</td>
<td>0.56</td>
<td>0.25</td>
<td>4400</td>
<td>400</td>
<td>7400</td>
<td>3000</td>
<td>400</td>
</tr>
</tbody>
</table>

This has been advocated as a good way to perform oscillation measurements...

Unfortunately the decay rate of these isotopes is very long, and the number of stored ions correspondingly lower => intensities likely to be too small for oscillation experiments.

Tunable monochromatic beam for cross-section measurements in near detector!
neutrino factory: accelerate muons and store to produce neutrinos
Intense nucl. and hadr. physics
Intense Low-E muons
Neutrino Factory
Higgs(es) Factory(ies)
Energy Frontier \( \rightarrow \) 5 TeV

Possible layout of a muon complex on the CERN site.
Unique: High energy electron neutrinos, spectrum extends up to ~nuon energy above tau production threshold (3.5 GeV) and matter resonance (~12 GeV).

Flux well known (10^{-3})

Appearance oscillation signal: wrong sign muons:

Golden channel:

\[ \nu_e \rightarrow \nu_\mu; \nu_\mu + N \rightarrow \mu^- + X \]

vs

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu; \bar{\nu}_\mu + N \rightarrow \mu^+ + X \]

Detection « easy »: LARGE (100kton) magnetized iron neutrino detector (MIND) baseline detector.

More difficult:

Silver channel:

\[ \nu_e \rightarrow \nu_\tau; \nu_\tau + N \rightarrow \tau^- + X \]

Platinum channel:

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e; \bar{\nu}_e + N \rightarrow e^+ + X \]

require emulsion or fine grain (Larg or TASD) detector in magnetic field - a challenge!
Explore neutrino factory or muon collider as an option for the future. Feasibility, cost.

Long baseline detectors: Magnetized Iron, emulsions, liquid argon.
Good baselines are: ~3000-5000 depending on muon threshold + 7500 km.
Major challenges tackled by R&D expts

- High-power target
  - 4MW
  - good transmission
- MERIT experiment (CERN)
- Fast muon cooling
- MICE experiment (RAL)
- Fast, large aperture accelerator (FFAG)
- EMMA (Daresbury)

Proton Driver

Hg Target Capture Drift Buncher

Bunch Rotation Cooling

Accelerator Linac 0.2 – 0.9 GeV

Storage Ring

μ⁺

μ⁻

FFAG 25–50 GeV (optional) Acceleration

μ⁺

μ⁻

FFAG 12.6–25 GeV

ν beam

ν beam

Dogbone RLAs 0.9 – 3.6 GeV 3.6 – 12.6 GeV

ISS baseline
MERIT EXPERIMENT at CERN
BNL, MIT, ORNL, Princeton University CERN, RAL

Splash velocity
– 24 GeV beam

<table>
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<th>Time (ms)</th>
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<td>t=0.375</td>
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</tbody>
</table>

Demonstrated liquid mercury jet technology for neutrino factory and muon collider up to 8MW on target Oct22-Nov12 2007
- Model of muon FFAG accelerator(s) in NF – v. imp. R&D project
- Proof-of-principle non-scaling FFAG – variety of applications:
  - proton & light ion cancer therapy
  - ADSR
  - muon production for slow muons
  - etc
- Will study:
  - ns dynamics
  - large acceptance, 30ºm mrad
  - bucketless acceleration
  - fast resonance crossing
  - very large momentum compaction
  - etc
- Comparison with tracking codes
- Parameters:
  - electrons, 10-20MeV
  - 42 cells, doublet lattice, 1.3GHz RF
  - cell length 40cm → 16.5m circumference
Neutrino factory is the most powerful device for neutrino CP violation, matter effects, universality, precise measurements of Neutrino mixing parameters.
Overall comparisons from ISS

\[ \theta_{13} \]

\[ \text{sign } \Delta m^2_{13} \]

NuFACT does it all... (+ univ. test etc...) but when can it do it and at what cost?
International Design Study of the Neutrino Factory

Steering Group
A. Blondel, K. Long (chair), M. Zisman, Y. Kuno

Physics and Performance Evaluation:
A. Donini, P. Huber, S. Pascoli, W. Winter

Accelerator:
S. Berg, Y. Mori, C. Prior, J. Pozimski

Detector:
A. Bross, A. Cervera, N. Mondal, P. Soler

Aim: produce CDR for 2012

'CDR' implies:
Physics performance of costed scenario
Conceived as input to cost/performance comparison required at C.E.R.N.
Council Strategy Group 2012 decision point

EU component is part-funded via EUROnu

https://www.ids-nf.org
Muon beams for rare muon decay physics

Rare decays searches: $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+ee$, $\nu \rightarrow e^-N$ are sensitive probes of Models with FCNC's. (SU-SY in particular). Very fundamental experiments!

Leading experiment $\mu \rightarrow e\gamma$, MEG at PSI aims at $10^{-13}$ sensitivity.
1.5 MW proton beam at 590 MeV, 4% transmission target, surface muons.
(PSI Main user of protons is spallation source SINQ and low energy neutron source)

Can one gain 3 orders of magnitude over MEG?
Progress needed both on detector side and on beam intensity.

As was pointed out in early studies the SPL with accumulator ring provides (using an internal target of completely open design)
a very convenient DC beam for DC muon production. $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+ee$,

It can also provide en excellent pulsed proton beam with short pulses using
a target on the neutrino beam transfer line or its own fast extraction beam line. $\nu \rightarrow e^-N$

No succesful idea (yet) to use the muons from the neutrino factory front end.
Conclusions -- outlook

Neutrino Oscillation physics attracts a growing community on a step-wise programme

The ultimate goal is precision measurements of neutrino oscillation parameters with important potential for discoveries along the way. Leptonic CP violation, mass hierarchy, unitarity etc..

NEUTRINO PHYSICS IS NEW, FUNDAMENTAL PHYSICS that is complementary to the high energy frontier but cannot be addressed by it.

Substantial efforts are underway both on detectors and accelerators to establish feasibility of future steps; but the CERN involvement has remained marginal. The date of 2012 for deciding the next step is taken seriously.

Several options, many issues... and the way forward

-- How do we come to an agreed program?
-- How can efforts be optimized and enhanced where (sometimes badly) needed?

WILL BE EXPOSED AND DISCUSSED AT THE UPCOMING WORKSHOP

European Strategy for Neutrino physics -- 1-3 Oct09 at CERN
References and Links

Original ideas in 1970's (Amaldi, Budker)

*Neutrino Beams From Muon Storage Rings: Characteristics And Physics Potential*

Prospective study of muon storage rings at CERN, ECFA-CERN CERN 99-02 (1999)

*Study IIA Neutrino Factory and Beta Beam Experiments and Development*,
C. Albright et al, BNL-72369-2004, FNAL-TM-2259, LBNL-55478,

ECFA-CERN study of a Neutrino Factory Complex

ISS reports
*Accelerator design concept for future neutrino facilities.* arXiv:0802.4023

ISS study
-- Performed comparison between proposed facilities
-- defined the baseline parameters.
to be followed-up quantitatively (R&D, feasibility, cost) ➔ International Design Study

ECFA session EPS Cracow 18-07-2009 Alain Blondel