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Neutrino beam design

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The measurements of the parameters of the neutrino mixing matrix in the oscillation experiments at accelerators are presented with the perspectives for new high intensity neutrino facilities as SuperBeams, BetaBeams and Neutrino Factories. Emphasis is on the determination on the presently unknown θ_{13} mixing angle and on the CP violating phase δ .

1. Introduction

The experimental evidences for neutrino oscillations collected in the last six years measuring solar and atmospheric neutrinos represent a major discovery in modern particle physics.

Solar neutrino oscillations were observed in Homestake [1], Gallex-GNO [2], Sage [3], Super-Kamiokande [4] and SNO [5] experiments allowing then convincing evidence of ν_{μ} , ν_{τ} appearance and a first precise determination of the solar oscillation parameters.

A clear signal of ν_{μ} disappearance of atmospheric neutrinos, and an anomalous value of the ratio of electron to muon neutrino events were reported by the Super-Kamiokande experiment [6], then confirmed by Soudan2 [7] and Macro [8] experiments. Super-Kamiokande provided an indirect evidence of ν_{τ} appearance ruling out at 99% C.L. pure oscillations into sterile neutrinos [9,10].

The measurement of the neutrino oscillation parameters can be addressed by long-baseline oscillation experiments with suitable neutrino beams produced at accelerators, since this technique can offer a better control of the neutrino flux compared to the atmospheric and cosmic sources. Of particular interest will be the detection and measurement of sub-leading $\nu_{\mu} \rightarrow \nu_{e}$ oscillations in the atmospheric neutrino oscillations, which are the link between the solar and the atmospheric regimes and can offer the possibility to discover the CP violation in the lepton sector.

2. Present status of neutrino oscillations

In the standard scenario of three neutrino generations, the observed neutrino flavor oscillations can be described by a mixing matrix U which connects the mass eigenstates to the flavor ones. Six independent parameters have to be experimentally measured: three mixing angles $\theta_{12} \ \theta_{13} \ \theta_{23}$, two mass-squared differences $\Delta m_{12}^2 \ \Delta m_{23}^2$, where $\Delta m_{ij}^2 = m_i^2 - m_j^2$, and a CP violating phase δ . In vacuum the oscillation probability between two neutrino flavors α , β is:

$$P(\nu_{\alpha} \to \nu_{\beta}) = -4 \sum_{k>j} Re[W_{\alpha\beta}^{jk}] \sin^2 \frac{\Delta m_{jk}^2 L}{4E_{\nu}}$$
$$\pm 2 \sum_{k>j} Im[W_{\alpha\beta}^{jk}] \sin^2 \frac{\Delta m_{jk}^2 L}{2E_{\nu}} \tag{1}$$

where $\alpha = e, \mu, \tau, j = 1, 2, 3$ and the coefficients $W_{\alpha\beta}^{jk}$ depend on the mixing matrix elements $U_{\alpha j}$ as $W_{\alpha\beta}^{jk} = U_{\alpha j} U_{\beta j}^* U_{\alpha k}^* U_{\beta k}$. Therefore the neutrino energy E_{ν} and the baseline L (distance of the neutrino source from the detector), combined in the oscillation formula into the L/E_{ν} ratio, are the experimental parameters. Oscillations are perturbed if neutrinos propagate in matter [11] depending on sign(Δm_{23}^2) [12], its measurement can fix the order with which mass eigenstates are coupled to flavor eigenstates (neutrino mass hierarchy).

A combined data analysis of solar neutrino experiments and of KamLAND [13] long-baseline reactor experiment running at the solar Δm^2

Table	1					
Main [•]	parameters	for	present	long-baseline	neutrino	beams.

-	1 0			
Neutrino facility	Proton momentum (GeV/c)	L (km)	E_{ν} (GeV)	$pot/yr (10^{19})$
KEK PS	12	250	1.5	2
FNAL NUMI	120	735	3	$20 \div 34$
CERN CNGS	400	732	17.4	$4.5 \div 7.6$

scale constrains the solar mixing angle and mass splitting to $|\Delta m_{12}^2| = 7.9^{+0.6}_{-0.5} \cdot 10^{-5} \text{ eV}^2$, $\tan \theta_{12} = 0.40^{+0.10}_{-0.07}$ [14].

An almost pure $\nu_{\mu} \rightarrow \nu_{\tau}$ transition, connected with the m_2 and m_3 mass eigenstates, with parameters $1.5 \cdot 10^{-3} \text{eV}^2 < |\Delta m_{23}^2| < 3.4 \cdot 10^{-3} \text{eV}^2$, $\sin^2 2\theta_{23} > 0.92$ at 90 % C.L. [15] resulted in the atmospheric neutrinos measurements. A first rough confirmation was obtained in the longbaseline experiment K2K which observed a ν_{μ} disappearance in a 1.5 GeV mean energy neutrino beam sent to the Super-Kamiokande detector (L = 250 km) measuring $1.9 \cdot 10^{-3} < |\Delta m_{23}^2| < 3.6 \cdot 10^{-3} \text{ eV}^2$ at 90 % C.L. [16].

The θ_{13} mixing angle represents the link between the solar and the atmospheric neutrino oscillations: both solar and atmospheric neutrino data are compatible with $\theta_{13} = 0$ within the experimental sensitivity. The best experimental constraint $\sin^2 2\theta_{13} \leq 0.14$ at 90 % C.L. for $|\Delta m_{23}^2| = 2.5 \cdot 10^{-3} \text{ eV}^2$, comes from the reactor experiment Chooz [17].

The three neutrino oscillation scheme will result a bit more complicated, requiring nonstandard explanations, if the $\overline{\nu}_{\mu} \rightarrow \overline{\nu}_{e}$ signal with $|\Delta m^{2}|$ of $0.3-20 \text{ eV}^{2}$ observed by LSND [18] will be confirmed by the MiniBooNE experiment at FNAL looking to $\nu_{\mu} \rightarrow \nu_{e}$ transitions [19]. However a large part of the allowed region of the oscillation parameters was already excluded by KAR-MEN [20] experiment and NOMAD experiment at CERN SPS-WANF [21].

3. Present long-baseline experiments

Over the next five years the present generation of oscillation experiments at accelerators with long-baseline ν_{μ} beams (Table 1), K2K at KEK [16], MINOS [22] at the NUMI beam from FNAL [23] and ICARUS [24] and OPERA [25] at the CNGS beam from CERN [26] are expected to confirm the atmospheric neutrino oscillations and measure $\sin^2 2\theta_{23}$ and $|\Delta m_{23}^2|$ within $10 \div 15 \%$ of accuracy if $|\Delta m_{23}^2| > 10^{-3} \text{ eV}^2$.

Table 2

The expected 90% C.L. sensitivity on θ_{13} measurements for the present long-baseline experiments with conventional ν_{μ} beams for $\Delta m_{23}^2 = 2.5 \cdot 10^{-3} \text{ eV}^2$ ($\delta = 0$). The 90% C.L. limit from the reactor experiment Chooz is also shown as comparison.

Experiment	fid. mass (kt)	$\sin^2 2\theta_{13}$	θ_{13}
MINOS	5.0	0.08	8.1°
ICARUS	2.4	0.04	5.8°
OPERA	1.8	0.06	7.8°
Chooz	0.012	0.14	11°

K2K and MINOS are looking for neutrino disappearance by measuring the ν_{μ} survival probability as a function of neutrino energy while ICARUS and OPERA will search for evidence of ν_{τ} interactions in a ν_{μ} beam, the final proof of $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillations. K2K has already completed its data taking, while MINOS has started data taking in 2005. CNGS neutrino beam is expected to start operations in the second half of 2006.

In all these facilities conventional muon neutrino beams are produced through the decay of π and K mesons generated by a high energy protons hitting needle-shaped light targets. Positive (negative) mesons are sign-selected and focused (defocused) by large acceptance magnetic lenses into a long evacuated decay tunnel where ν_{μ} 's ($\overline{\nu}_{\mu}$'s) are generated.

In case of positive charge selection, the ν_{μ} beam has typically a contamination of $\overline{\nu}_{\mu}$ at few per-



Figure 1. CNGS neutrino beam line (top) and the expected ν_{μ} and ν_{e} flux spectra at the Gran Sasso (bottom).

cent level (from the decay of the residual $\pi^-, K^$ and K^0) and ~ 1% of ν_e and $\overline{\nu}_e$ coming from three-body K^{\pm} , K_0 decays and μ decays. The precision on the evaluation of the intrinsic ν_e to ν_{μ} contamination is limited by the knowledge of the π and K production in the primary proton beam target. Hadroproduction measurements at 400 and 450 GeV/c performed with the NA20 [27] and SPY [28] experiments at the CERN SPS provided results with $5 \div 7\%$ systematic uncertainties. The CNGS ν_{μ} beam (Fig. 1) has been optimized for the $\nu_{\mu} \rightarrow \nu_{\tau}$ appearance search. The beam-line design was accomplished on the basis of the previous experience with the WANF beam at CERN SPS [29]. The expected muon neutrino flux at the Gran Sasso site will have an average energy of 17.4 GeV and ~ 0.6% ν_e contamination for $E_{\nu} < 40$ GeV. Due to the long-baseline (L=732 Km) the contribution to neutrino beam from the K^0 and the mesons produced in the reinteraction processes will be strongly reduced with respect to the WANF [30]: the ν_e/ν_μ ratio is expected to be known within $\sim 3\%$ systematic uncertainty [31].

Current long-baseline experiments with conventional neutrino beams can look for $\nu_{\mu} \rightarrow \nu_{e}$ even if they are not optimized for θ_{13} studies (Tab. 2 and in Fig. 2). MINOS at NuMI is expected to reach a sensitivity of $\sin^2 2\theta_{13} = 0.08$ [22] integrating $14 \cdot 10^{20}$ protons on target (pot) in 5 years according to the FNAL proton plan evolution [32]. ICARUS and OPERA [24,25] can reach a 90% C.L. combined sensitivity $\sin^2 2\theta_{13} = 0.03$ $(\Delta m_{23}^2 = 2.5 \cdot 10^{-3} \text{ eV}^2$, convoluted to CP and matter effects), a factor ~ 5 better than Chooz for five years exposure to the CNGS beam at nominal intensity (shared operation $4.5 \cdot 10^{19}$ pot/yr) [33]. Depending on the δ value and matter effects $(sign(\Delta m_{23}^2))$, these sensitivities can be reduced by $\sim 30\%$ [34]. According to the CERN PS and SPS upgrade studies [35], the CNGS beam intensity could be improved by a factor ~ 1.5 , allowing for more sensitive neutrino oscillation searches for ICARUS and OPERA experiments.



Figure 2. The expected 90 % C.L. sensitivity on θ_{13} mixing angle (matter effects and CP violation effects not included) for MINOS, ICARUS and OPERA combined at nominal CNGS and for the next T2K experiment, compared to the Chooz exclusion plot.

Clearly the sensitivity on θ_{13} measurement of the current long-baseline experiments is limited by the power of the proton source which determines the neutrino flux and the event statistics, by the not optimized L/E_{ν} and by the presence of the ν_e intrinsic beam contamination and its related systematics. To overcome the kinematic threshold for τ production and to detect the τ decay products, the CNGS average neutrino energy is ~ 10 times higher than the optimal value for θ_{13} searches.

4. Sub-leading $\nu_{\mu} \rightarrow \nu_{e}$ oscillations: the future challenge

The unknown parameters of the mixing matrix U, the angle θ_{13} , the sign (Δm_{23}^2) and δ which generates the CP violation in the neutrino oscillations, can be extracted by measuring sub-leading $\nu_{\mu} \rightarrow \nu_{e}$ oscillations at accelerators. Reactor experiments on $\overline{\nu}_{e}$ disappearance are only sensitive to θ_{13} mixing angle. Accounting for all the contri-

butions and not knowing a priori the size of θ_{13} , all the six parameters of the mixing matrix are involved in the appearance probability for electron neutrino in a muon neutrino beam which can be parameterized as [36]:

$$P(\nu_{\mu} \rightarrow \nu_{e}) = 4c_{13}^{2} s_{13}^{2} s_{23}^{2} \sin^{2}(\frac{\Delta m_{13}^{2} \cdot L}{4E_{\nu}}) + 8c_{13}^{2} s_{12} s_{13} s_{23} (c_{12} c_{23} \cdot \cos \delta - s_{12} s_{13} s_{23}) \cdot \cos \frac{\Delta m_{23}^{2} L}{4E_{\nu}} \cdot \sin \frac{\Delta m_{13}^{2} L}{4E_{\nu}} \cdot \sin \frac{\Delta m_{12}^{2} L}{4E_{\nu}} - 8c_{13}^{2} c_{12} c_{23} s_{12} s_{13} s_{23} \cdot \sin \delta \cdot \sin \frac{\Delta m_{23}^{2} L}{4E_{\nu}} \cdot \sin \frac{\Delta m_{13}^{2} L}{4E_{\nu}} \cdot \sin \frac{\Delta m_{12}^{2} L}{4E_{\nu}} + 4s_{12}^{2} c_{13}^{2} \cdot (c_{13}^{2} c_{23}^{2} + s_{12}^{2} s_{23}^{2} s_{13}^{2}) - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cdot \cos \delta) \cdot \sin^{2} \frac{\Delta m_{12}^{2} L}{4E_{\nu}} - 8c_{12}^{2} s_{13}^{2} s_{23}^{2} \cdot \cos \frac{\Delta m_{23}^{2} L}{4E_{\nu}} \cdot \sin \frac{\Delta m_{13}^{2} L}{4E_{\nu}}$$
(2)

where s_{ij} : $\sin \theta_{ij}$, c_{ij} : $\cos \theta_{ij}$, $a \simeq 7.6 \cdot 10^{-5}$ $eV^2 \rho[g/cm^3] E_{\nu}[GeV].$

The first term, which has the largest contribution, is θ_{13} driven, while the fourth is driven by the solar neutrino regime. The second term is CP-even and the third as well the last-one, which account for the matter effects on the neutrino propagation as developed at the first order, result CPodd. The CP odd term and matter effects change sign by changing neutrinos with antineutrinos.

The $\nu_{\mu} \rightarrow \nu_{e}$ transitions are dominated by the solar term; at the distance defined by the Δm_{23}^2 parameter, they are driven by the θ_{13} term which is proportional to $\sin^2 2\theta_{13}$. Below $\sin^2 2\theta_{13} \simeq 10^{-3}$ the "solar neutrino oscillation regime" will be again the dominant transition mechanism, limiting further improvements of the experimental sensitivity to θ_{13} . Moreover, $P(\nu_{\mu} \rightarrow \nu_{e})$ could be strongly influenced by the unknown value of δ and sign (Δm_{23}^2) .

The θ_{13} measurement represents the first necessary ingredient for the investigation of the CP leptonic violation in the $\nu_{\mu} \rightarrow \nu_{e}$ transitions and for the mass hierarchy determination. The detection of the δ phase will require a major experimental effort because of the intrinsic difficulty of disentangling the several contributions to $\nu_{\mu} \rightarrow \nu_{e}$ oscillation probability. The leptonic direct CP violation can be detected looking for the asymmetry of electron neutrino and antineutrino appearance probabilities in a ν_{μ} and $\overline{\nu}_{\mu}$ beam respectively through the amplitude:

$$A_{CP}(\delta) = \frac{P(\nu_{\mu} \to \nu_{e}, \delta) - P(\overline{\nu}_{\mu} \to \overline{\nu}_{e}, \delta)}{P(\nu_{\mu} \to \nu_{e}, \delta) + P(\overline{\nu}_{\mu} \to \overline{\nu}_{e}, \delta)}$$
$$\simeq \frac{\Delta m_{12}^{2} L}{4E_{\nu}} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta.$$
(3)

Since the $\nu_{\mu} \rightarrow \nu_{e}$ leading oscillation probability is proportional to $\sin^{2} \theta_{13}$ and $A_{CP} \sim 1/\sin \theta_{13}$ a strong interplay between δ and θ_{13} is envisaged. The richness of the $\nu_{\mu} \rightarrow \nu_{e}$ transition is also its weakness because it will be very difficult to extract all the parameters unambiguously in presence of correlations between θ_{13} and δ [37]. In absence of information about the sign of Δm_{23}^{2} [38,40] and the approximate [$\theta_{23}, \pi/2 - \theta_{23}$] symmetry for the atmospheric angle [39], additional clone solutions appear. In general, the measurement of $P(\nu_{\mu} \rightarrow \nu_{e})$ and $P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e})$ will result in eight allowed regions of the parameter space, the so-called eightfold-degeneracy [40].

Measuring the subleading $\nu_{\mu} \rightarrow \nu_{e}$ transitions one looks for experimental evidence of ν_e appearance in excess to what expected from the solar terms. These measurements will be experimentally hard because the Chooz limit on the $\overline{\nu}_e$ disappearance, $\theta_{13} < 11^{\circ}$ for $|\Delta m_{23}^2| \simeq 2.5 \cdot 10^{-3}$ eV^2 , translates into a $\nu_{\mu} \rightarrow \nu_e$ appearance probability less than 10% at the appearance maximum in a high energy ν_{μ} beam. Furthermore, as already pointed out, the $\nu_{\mu} \rightarrow \nu_{e}$ experimental sensitivity with conventional ν_{μ} beams is limited by an unavoidable ν_e beam contamination of about 1%. The ν_{μ} to ν_{τ} oscillations, with E_{ν} above the τ mass production threshold, generate background due to a significant number of ν_{τ} charged current interactions where a large fraction of τ 's decay into electrons. Finally, neutral pions in both neutral current or charged current interactions can fake an electron providing also a possible background for the ν_e 's. Therefore the measurement of θ_{13} mixing angle and the investigation of the leptonic CP violation will require:

- neutrino beams with high performance in terms of intensity, purity and low associated systematics. Event statistics, background rates and systematic errors will play a decisive role in detecting ν_e appearance;
- the use of detectors of unprecedented mass, granularity and resolution. Again event statistics is the main concern, while high detector performances are necessary to keep the backgrounds (as π° from ν_{μ} neutral current interactions, mis-identified as ν_e events) as low as possible. Different detection techniques of neutrino interactions based on water Cerenkov, liquid Argon, and calorimetry are available to build very massive detectors according to the intrinsic neutrino beam characteristics, energy and composition.

The improved control of the systematic errors will demand for ancillary experiments to measure the meson production for a better neutrino beam knowledge and the neutrino cross-sections especially below 1 GeV. The Harp [41] hadroproduction experiment at CERN PS took data for primary protons between 3 and 14.5 GeV/c in 2001 and 2002 with different target materials. These data are expected to contribute to a future proton driver optimization, to the determination of the K2K and MiniBooNE neutrino beam fluxes and to the study of atmospheric neutrino interaction rates.

5. New facilities for next generation of neutrino oscillation experiments

Different options for neutrino beams of novel conception are presently under study for the next generation of the long-baseline neutrino oscillation experiments. The intrinsic limitations of conventional beams are overcome if the neutrino parents can be fully selected, collimated and accelerated to a given energy. This can be realized with muons or selected beta decaying ions. The neutrino beams as obtained from their decays would then be pure and perfectly predictable. The first approach brings to the Neutrino Factories [42], the second to the BetaBeams [47]. However, the technical difficulties associated with developing and building these novel conception neutrino beams suggest for the middle term to improve the conventional beams by new high intensity proton machines, optimizing the beams for the $\nu_{\mu} \rightarrow \nu_{e}$ oscillation searches, the SuperBeams [36].

5.1. Neutrino Factories

The neutrino production by muon decay from a pure muon beam has been considered since 1998 [42]: this is indeed a perfectly well known weak process and the μ beam can be well measured in momentum and intensity.

In the CERN present layout for a Neutrino Factory (νF) [43] a 4 MW proton beam is accelerated up to 2.2 GeV by the Super Conducting Proton Linac (SPL) to produce low energy π 's in a liquid mercury target, which are collected by a solenoid. Muons produced from the π -decay are then cooled and phase rotated before acceleration through a recirculating Linac system up to 50 GeV. These muons of well defined charge and momentum are injected in the μ accumulator where they will circulate until they decay, delivering along the two main straight sections two pure ν beams whose intensity is expected more than 100 times the one in conventional beams. Both muon signs can be selected. The decay $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu \ (\mu^- \to e^- \overline{\nu}_e \nu_\mu)$ produces a pure well collimated neutrino beam with equal numbers of $\overline{\nu}_{\mu}, \nu_{e} \quad (\nu_{\mu}, \overline{\nu}_{e})$ allowing to extend the baseline to several thousand kilometers.

The optimal beam energy at the ν F, $E_{\mu} = 50$ GeV ($E_{\nu} \sim 34$ GeV), will be as large as possible accounting for the difficulties and the technical challenge for the construction of such a muon accelerator complex. In fact the neutrino flux ϕ_{ν} grows like E_{ν}^2 (in the conventional neutrino beams ϕ_{ν} is proportional to E_{ν}); the number of charged current neutrino events from the oscilla-



Figure 3. Expected layout for a Neutrino Factory at CERN (top) and corresponding energy spectra of neutrino beams for ν^+ beam (bottom).

tions (N_{osc}) , measured by a detector at a distance L, will be proportional to E_{ν} :

$$N_{osc} \propto \phi_{\nu} \cdot \sigma_{\nu} \cdot P_{osc} \propto \frac{E_{\nu}^{3}}{L^{2}} \cdot \sin^{2} \frac{L}{E_{\nu}} \simeq E_{\nu}$$
(4)

where $\sigma_{\nu} \propto E_{\nu}$ is the corresponding neutrino interaction cross-section and P_{osc} is the oscillation probability.

Furthermore, the ν intensity can be precisely determined from the measurement of the monochromatic μ current circulating in the storage ring (absolute normalization at 1% level). An accurate determination of μ momentum allows for the measurement of the neutrino energy spectra at the detector site.

The νF lends itself naturally to the exploration of neutrino oscillations between ν flavors with high sensitivity to small mixing angles and small mass differences. The detector should be able to perform both appearance and disappearance experiments, providing lepton identification and charge discrimination which is a tag for the initial flavor and of the oscillation. In particular the search for $\nu_e \rightarrow \nu_\mu$ transitions ("golden channel") appears to be very attractive at νF , because this transition can be studied in appearance mode looking for μ^- (appearance of wrong-sign μ) in neutrino beams where the neutrino type that is searched for is totally absent (μ^+ beam in νF). With a 40 kton magnetic detector (MINOS like) exposed to both polarity beams and 10^{21} muon decays, it will be possible to explore the θ_{13} angle down to 0.1° opening the possibility to measure the δ phase if $\Delta m_{12}^2 \geq 5 \cdot 10^{-4} \text{ eV}^2$ (systematic errors not accounted for) [37,44]. As discussed in Section 4, the determination of (θ_{13}, δ) is not free of ambiguities which can be solved by using a combination of different neutrino beams as SuperBeams and BetaBeams [45]. More details on the physics performances of a νF toward a precision measurement of neutrino oscillation parameters can be found in Refs. [43, 46].

5.2. BetaBeams

According to the BetaBeams (β B) concept [47] a pure, well collimated and intense ν_e ($\overline{\nu}_e$) beams can be generated by producing, collecting, accelerating radioactive ions and storing them in a decay ring in 10 ns long bunches. The resulting βB would be virtually background free containing a single flavor neutrinos which fluxes and energy spectrum, could be easily computed by the properties of the beta decay of the parent ion and by its Lorentz boost factor γ . The best ion candidates so far are ¹⁸Ne and ⁶He for ν_e and $\overline{\nu}_e$ respectively.



Figure 4. A schematic layout of the BetaBeam complex. At left, the low energy part is largely similar to the EURISOL project [54]. The central part (PS and SPS) uses existing facilities. At right, the decay ring has to be built.

As for Neutrino Factories close detectors are not necessary to normalize the fluxes. Both neutrino and anti-neutrino beams can be produced with a comparable flux. Moreover the energy of neutrinos depends on the γ factor: the ion accelerator can be tuned to optimize the sensitivity of the experiment. Similarly to Neutrino Factory, experiments search for $\nu_e \rightarrow \nu_{\mu}$ transitions with BetaBeams require detectors capable to identify muons from electrons. Moreover, since the beam does not contain ν_{μ} or $\bar{\nu}_{\mu}$ in the initial state, magnetized detectors are not needed.

A baseline study for a βB complex (Fig. 4) has been carried out at CERN [48]. The SPS could accelerate ⁶He ions at a maximum γ value of $\gamma_{^{6}He} = 150$ and ^{18}Ne ions up to $\gamma_{^{18}Ne} =$ 250. In this scenario the two ions circulate in the decay ring at the same time provided that their γ are in the ratio $\gamma_{^{6}He}/\gamma_{^{18}Ne} = 3/5$, i.e. $\gamma_{^{6}He} = 60, \ \gamma_{^{18}Ne} = 100$. The expected neutrino fluxes at 130 Km of distance for 2.9·10¹⁸ ^{6}He and 1.1·10¹⁸ ^{18}Ne decays/yr are displayed in Fig. 5. The corresponding physics potential computed with a Cerenkov water detector of 440 kton fiducial mass, showed a 90 % C.L. sensitivity $\sin^{2}2\theta_{13} \sim 0.0007$ and a CP violation signal at 3 σ if $|\delta| \geq 35^{\circ}$ and $\theta_{13} \geq 1.0^{\circ}$ [49]. Sensitivities accounting all the parameter degeneracies and ambiguities have been computed in [50].

Novel developments, suggesting the possibilities of running the two ions separately both at $\gamma =$ 100 [51] can allow to push the investigation of $\sin^2 2\theta_{13}$ down to 0.0002, and the CP violation search down to $\delta \geq 25^\circ$ for $\theta_{13} \geq 1.0^\circ$ [52,53].

In principle all the necessary machinery has been already developed at CERN for the heavy ion physics programme. However the required improvement by about 3 orders of magnitude of the presently available ion fluxes will require submegawatt 1-2 GeV Linacs, new target developments for heavy ion production, ion collection and acceleration system including the CERN PS and SPS and a novel decay ring [54]. Accounting for the technical challenges involved in the new facilities, the expected timescale of βB is expected to exceed the next ten years.

BetaBeam capabilities for ions accelerated at higher energies than those allowed by SPS have been considered [53,55,56]: studies to define realistic neutrino fluxes as a function of γ are in progress [51]. It is worth noting that if a high intensity BetaBeam with $\gamma \sim 300 \div 500$ (requiring a new Super-SPS [57]) can be built, a 40 kton iron calorimeter located at the Gran Sasso Laboratory will have the possibility to discover a non vanishing δ if above 20° for $\theta_{13} \geq 2^{\circ}$ (99% C.L.) and measure the sign of Δm_{23}^{23} [55].

5.3. Near-term experiments with Super-Beams

According to the present experimental situation, conventional neutrino beams can be improved and optimized for the $\nu_{\mu} \rightarrow \nu_{e}$ searches. The design of a such new SuperBeam facility for a very high intensity and low energy ν_{μ} flux will demand:

- a new higher power proton driver, exceeding the megawatt, to deliver more intense proton beams on target;
- a tunable L/E_{ν} in order to explore the $|\Delta m_{23}^2|$ parameter region as indicated by the previous experiments with neutrino beams and atmospheric neutrinos;
- narrow band beams with $E_{\nu} \sim 1 \div 2 \text{ GeV};$
- a lower intrinsic ν_e beam contamination which can be obtained suppressing the K^+ and K^0 production by the primary proton beam in the target.

The realization of such neutrino SuperBeams will require the development of high power proton Linacs or Rapid Cycling Synchrotrons, expected to happen in the next decade, and the development of a target able to survive to megawatt power proton beams, whose R&D studies have already started [58].

An interesting option for the SuperBeams is the possibility to tilt the beam axis a few degrees with respect to the position of the far detector (Off-Axis beams) [59,60]. According to the two body π -decay kinematics, all the pions above a given momentum produce neutrinos of similar energy at a given angle $\theta \neq 0$ with respect to the direction of parent pion (contrary to the $\theta = 0$ case where the neutrino energy is proportional to the pion momentum). These neutrino beams are narrower, with lower energy and a smaller ν_e contamination (since they mainly come from three body decays) with respect to their corresponding On-Axis ones, although the neutrino flux is significantly smaller.

In the JHF project Phase I (T2K experiment [59]) a 50 GeV proton beam of 0.75 MW from a PS will produce an intense π and K beam tilted by $\theta = 2^{\circ}$ with respect to the position of Super-Kamiokande detector at 295 Km of distance. The first beam is expected to start in 2009 with a reduced intensity: a 0.7 MW power is foreseen in 2012. The resulting 700 MeV ν_{μ} beam (Fig. 6) with 0.4% ν_{e} contamination will allow a 90 % C.L. sensitivity $\sin^{2} 2\theta_{13} \sim 0.006$ in five years ($\delta = 0$),



Figure 5. Left: neutrino flux of βB ($\gamma_{^6He} = 60$, $\gamma_{^{18}Ne} = 100$, shared mode) and CERN-SPL SuperBeam, 2.2 GeV, at 130 Km of distance. Right: the same for $\gamma_{^6He} = 100$, $\gamma_{^{18}Ne} = 100$, (non shared mode, that is just one ion circulating in the decay ring) and a 3.5 GeV SPL SuperBeam.



Figure 6. T2K neutrino beam energy spectrum for different off-axis angle θ with 50 GeV, 0.75 MW proton driver.

a factor 20 better than the current limit set by Chooz, see Fig. 7. T2K will also measure Δm_{23}^2 and $|\sin^2 2\theta_{23}|$ with ~ 2% precision via ν_{μ} disappearance. A possible machine upgrade to 4 MW (JHF-II), in conjunction with the construction of Hyper-Kamiokande water Cerenkov detector of 0.54 Mton fiducial mass will allow to investigate $\sin^2 2\theta_{13}$ down to $6 \cdot 10^{-4}$ at 90 % C.L. in 5 year run, while with 2 years of ν_{μ} and 6 years of $\overline{\nu}_{\mu}$ operations, it will discover the CP violation at a 3σ level or better if $|\delta| > 20^{\circ}$ and $\sin^2 2\theta_{13} \sim 0.01$ [61].

The NO ν A experiment using an upgraded NuMI Off-Axis neutrino beam, $E_{\nu} \sim 2$ GeV with a ν_e contamination less than 0.5% at a baseline of 810 Km (12 km off-axis), was recently proposed at FNAL with the aim to explore the $\nu_{\mu} \rightarrow \nu_e$ oscillations with a sensitivity 10 times better than MINOS. The NuMI target will receive a 120 GeV proton flux with an expected intensity of $6.5 \cdot 10^{20}$ pot/yr ($2 \cdot 10^7$ s/year are considered available to NuMI operations while the other beams are normalized to 10^7 s/yr). The experiment will use a near and a far detector, both liquid scintillator. In 5 years of data taking, with a 30 kton active mass far detector a sensitivity on $\sin^2 2\theta_{13}$ slightly better than T2K, as well as a precise measurement of $|\Delta m_{23}^2|$ and $\sin^2 2\theta_{23}$, can be achieved. NO ν A can also allow to solve the mass hierarchy problem for a limited range of the δ and sign (Δm_{23}^2) parameters [62]. As a second phase, a new proton driver of 8 GeV and 2 MW, could increase the NuMI beam intensity to $17.2 \div 25.2 \cdot 10^{20}$ pot/yr, improving the experimental sensitivity by a factor two and initiating the experimental search for the CP violation.



Figure 7. Expected sensitivity on θ_{13} mixing angle (CP violation and matter effects not included) for a 20 GeV high intensity PS proton beam from CERN to Gran Sasso (PS++) and for ICARUS 2.25 kton at the CNGS-L.E. neutrino beam compared to T2K experiment.

A longer term experiment has been proposed at BNL for a different long-baseline neutrino beam [63]. The AGS 28 GeV PS should be upgraded to 1 MW and a neutrino beam with $\langle E_{\nu} \rangle \simeq 1.5$ GeV should be fired into a megaton water Cerenkov detector at a baseline of 2540 km (second oscillation maximum). The comparison of ν_{μ} disappearance and ν_e appearance at the first and second oscillation maximum could allow a better control of degeneracies. A 90 % C.L. sensitivity $\sin^2 2\theta_{13} \simeq 0.003$ ($\delta = 0$) could be reached in five years.

In Table 3 the features of the different options for the next generation of SuperBeams and of BetaBeams are reported, rescaling the maximum source power at 4 MW and the useful time machine to 10⁷ s per year (see also Refs. [64]). For an appropriate choice of the L/E_{ν} well matched to the Δm_{23}^2 value, the figure of merit of the neutrino beam is determined by the ν_{μ} -CC/kton/yr event rate and also by the ν_e/ν_{μ} natural beam contamination.

5.3.1. European SuperBeam projects

Many ideas and approaches have been developed for neutrino long-baseline experiments in Europe after the CNGS ν_{τ} appearance programme aiming to improve and develop existing infrastructures and detectors or considering new neutrino beams and detectors.

A general proton driver optimization study for θ_{13} -driven $\nu_{\mu} \rightarrow \nu_{e}$ oscillations with a new generation of low energy and high intensity Super-Beams was recently done [65]. In this study a systematic analysis of the experimental sensitivity on $\sin^2 2\theta_{13}$ as a function of the proton energy E_p , from 2.2 to 400 GeV, and of the required power of the proton driver, was performed. In the calculation the optimal base-line distance L^* was considered in the 130 \div 800 km range according to the resulting neutrino energy with $E_{\nu}/L^* \propto \Delta m^2_{23} \sim 2.5 \cdot 10^{-3} \text{ eV}^2$. In term of proton economics, minimizing the required driver power factor $W = E_p \times pot$, i.e. the proton energy multiply for the required number of protons on target, the optimum beam energy turns out to be around 20 GeV for a ν_{μ} beam with 1.6 GeV of mean energy well matched to a 732 Km of baseline (i.e. CERN - Gran Sasso). A $\sin^2 2\theta_{13} \simeq 0.005$ sensitivity at 90 % C.L., slightly better than T2K, is reached for $2 \cdot 10^{22}$ pot/yr in 5 years exposure of 2.35 kton ICARUS liquid Argon detector ($\delta = 0$ and no matter effects).

The request proton number is about two orders

Table 3

Different future LBL options with L/E_{ν} matching the $\Delta m_{23}^2 = 2.5 \cdot 10^{-3} \text{ eV}^2$. All the experiments are normalized to 5 years data taking considering a neutrino beam time operation of 10^7 s per year. J-Parc II $\sin^2 2\theta_{13}$ sensitivity is extrapolated from T2K phase I. Numbers quoted for NO ν A refer to the standard and the proton driver options (see text). SPL numbers are for the $E_P = 2.2 \text{GeV}$ (the 3.5 GeV performances are in parentheses). The β B column is computed for the $\gamma = 60, 100$ option (the $\gamma = 100, 100$ performances are in parentheses); the ν CC of β B indicates the $\nu_e^{CC} + \overline{\nu}_e^{CC}$ rate. Detector legenda: H₂O (water Cerenkov), LAr (liquid Argon), LScint (liquid scintillator).

	T2K	J-Parc II	$NO\nu A$	BNL	PS++	SPL(3.5)	$\beta B \left(\beta B_{100,100}\right)$
p-driver (MW)	0.75	4	0.8(2)	1	4	4	0.4
p beam energy (GeV)	50	50	120	28	20	2.2(3.5)	1-2.2
$\langle E(\nu) \rangle$ (GeV)	0.7	0.7	2	1.5	1.6	0.27(0.29)	0.3(0.4)
L (Km)	295	295	810	2540	732	130	130
Off-Axis beam	2°	2°	0.8°	-	-	-	-
$\nu {\rm CC}$ no osc. $(1/kt/yr)$	100	500	80 (200)	11	450	37(122)	38 (56)
ν contamination (%)	0.4	0.4	0.5	0.5	1.2	0.4(0.7)	0
Detect. Fid. Mass (kt)	22.5	540	30	440	3.8	440	440
Material	H_2O	H_2O	LScint	${\rm H}_2{\rm O}$	LAr	H_2O	H_2O
Signal efficiency $(\%)$	40	40	24	25	100	70	60(70)
$\sin^2 2\theta_{13} \cdot 10^4 $ (90% C.L.)	60	6	38(24)	30	50	18(8)	7(2)

of magnitude higher than the intensity deliverable by the current CERN-PS. The performance of this facility, indicated as PS++, has been computed for a power source corresponding to 6.5 MW accounting for a useful beam time operation of 10^7 s per year: the same sensitivity can be reached in 5 years with 4 MW power if a LNGS hall is fully occupied by ICARUS, about 4 kton mass (Table 3).

In this framework study both the 2.2 and 400 GeV energies of the protons appear marginals because the proton energy limits for opposite reasons the neutrino flux and the $\nu_{\mu} \rightarrow \nu_{e}$ oscillation sensitivity. In fact at 2.2 GeV the meson production is too low and the focusing too much difficult due to the low energy of the pions which are produced with a transversal momentum similar to the longitudinal one. On the contrary at 400 GeV the meson production is really effective at high energy but not enough pion flux per proton on target is produced at low energy for the low energy neutrino flux. In both the cases the detector mass has

to be properly increased to compensate the low neutrino flux. These general considerations have been confirmed with more detailed studies for a possible upgrade of the existing CNGS beam-line or for a new low energy proton driver at CERN.

The possibility to improve the CERN to Gran Sasso neutrino beam performances for θ_{13} searches even with the present SPS proton beam, $E_p = 400 \text{ GeV}$ and $4.5 \cdot 10^{19} \text{ pot/yr}$ was investigated (CNGS-L.E.) [66]. The low energy neutrino flux can be increased by a factor 5 with respect to the current CNGS beam by an appropriate optimization of the target (a compact 1 m carbon rod) and of the focusing system. The reduction of the decay tunnel to 350 m can also allow to install a near detector useful for beam composition studies. With this low energy CNGS-L.E. neutrino beam, $E_{\nu_{\mu}} \sim 1.8$ GeV, the sensitivity to $\sin^2 2\theta_{13}$ can be increased by a factor 7 with respect to Chooz, $\sin^2 2\theta_{13} < 0.02$ at 90% C.L. (not accounting for CP and matter effects) in 5 vears exposition of ICARUS detector (2.35 kton fiducial mass) for $\Delta m_{23}^2 = 2.5 \cdot 10^{-3} \text{ eV}^2$, Fig. 7. A second study considered again a low energy neutrino beam (1.5 GeV mean energy) fired into a detector made of 44,000 phototubes deployed in the Golfo di Taranto at 1000 m depth, 1200 km from CERN (CNGT), 2° degrees off-axis, equipping 2 Mton of water [67]. The detector would be placed at the second oscillation maximum and if movable it could take data both at the minimum and at the maximum of oscillation probability. Sensitivity would be marginally worse than T2K in a 5 years data taking [67].

As opposite alternative the CERN-SPL Super-Beam [68,69,43] based on the 4MW SPL (Superconducting Proton Linac) 2.2 GeV proton beam hitting a Hg target was investigated. The intense π^+ (π^-) beam focused by a magnetic horn in a short decay tunnel will produce an intense ν_{μ} beam mainly via the π -decay, providing a flux $\phi \sim 3.6 \cdot 10^{11} \nu_{\mu} / \text{yr/m}^2$ at 130 Km of distance with an average energy of 0.27 GeV (Fig. 5). The $\nu_e/\nu_\mu \sim 0.4\%$ contamination, completely from ν^+ decay being K contribution suppressed by threshold effects, will be known within 2% error. The use of a near and far detector (the latter at L = 130 Km of distance in the Frejus area) will allow for both ν_{μ} -disappearance and $\nu_{\mu} \rightarrow \nu_{e}$ appearance studies. The physics potential with a water Cerenkov far detector with 440 kton of fiducial mass having fixed $\Delta m_{23}^2 = 2.5 \cdot 10^{-3} \text{ eV}^2$ was extensively studied [69]. The 90 % C.L. sensitivity on $\sin^2 2\theta_{13}$ is 0.002 ($\delta = 0, 5$ years ν_{μ} beam, see Tab. 3), with a 3σ CP violation discovery potential (2 years with ν_{μ} beam and 8 years with the reversed polarity $\overline{\nu}_{\mu}$ beam) for $\delta > 40^{\circ}$ and $\sin^2 2\theta_{13} > 0.02.$

The SPL SuperBeam performance could be improved by rising the proton energy to 3.5 GeV [70], to produce more copious secondary mesons and to focus them more efficiently, using new status of the art RF cavities [71]. In this upgraded configuration with a 40 m long and 4 m diameter decay tunnel neutrino flux could be increased by a factor 3 but with twice ν_e contamination with respect to the 2.2 GeV configuration, reaching a sensitivity to $\sin^2 2\theta_{13}$ 8 times better than T2K and allowing to discover CP violation (at 3 σ level) if $\delta \geq 25^{\circ}$ and $\theta_{13} \geq 1.4^{\circ}$ [52].

The SPL can be used as injector for a BetaBeam, requiring at most 10% of its protons. This will can allow a simultaneous βB and SPL SuperBeam exploitation, the two neutrino beams having similar neutrino energies (see also Fig. 5). The same detector at 130 km of distance could then be exposed to 2×2 beams (ν_{μ} and $\overline{\nu}_{\mu} \times \nu_{e}$ and $\overline{\nu}_{e}$) having access to CP, T and CPT violation searches in the same run. A 90 % C.L. sensitivity to $\sin^{2} 2\theta_{13}$ 35 times better than T2K and a 3 σ sensitivity to CP violation if $|\delta| \geq 18^{\circ}$ and $\theta_{13} \geq 0.55^{\circ}$ can be reached [52].

6. Conclusions

The investigation of the neutrino oscillations allows to measure fundamental parameters of the Standard Model, to provide the first insight beyond the electroweak scale and to explore for the first time CP violation in the leptonic sector. The precise measurements of the oscillation parameters and in particular of θ_{13} , $\operatorname{sign}(\Delta m_{23}^2)$ and δ CP violating phase in the subleading $\nu_{\mu} \rightarrow \nu_{e}$ oscillations are needed.

The exploration of the θ_{13} angle beyond the Chooz limit with the present neutrino beams, NuMI and CNGS, is limited by the power and the purity of these conventional beams, where neutrinos are generated mainly by pion and kaon decays in a wide range of momenta.

New high intensity proton accelerator facilities (in the MWatt regime) are required to produce neutrino beams with an intensity and purity much higher than the conventional neutrino beams. Novel concepts of neutrino beams, like BetaBeams and Neutrino Factories, where neutrinos are produced by the decay of radioactive ions and muons respectively, suitable accelerated to a selected momentum, can allow to explore the neutrino oscillation world with high accuracy. However a long R&D phase and study due to the different intrinsic difficulties involved in the projects and in the constructions is required. Accounting that no prediction exists for the θ_{13} angle that drives all the new phenomena, SuperBeam facilities, conventional neutrino beams improved in flux and purity and tuned to $\nu_{\mu} \rightarrow \nu_{e}$ transitions, appear the most suitable for the next generation

experiments. Moreover, due to the intrinsic difficulties and complexity of the three flavor neutrino oscillations, a single world facility will not probably be sufficient to measure in a firm way all the elements of the neutrino mixing matrix.

The T2K experiment at J-Parc using Super-Kamiokande as far detector, is expected to deliver full intensity at 0.7 MW in 2012. A second phase J-Park II with improved beam intensity and detector mass has been considered.

The NO ν A experiment at FNAL can be a competitor to T2K experiment for the θ_{13} investigation as well as the BNL SuperBeam project.

The option CERN to Gran Sasso neutrino SuperBeam PS++ based on improved synchrotron seems to be equivalent to J-Parc phase II, as far as concerns neutrino fluxes, except for ν_e level due to the off-axis alignment of J-Parc. However, a high resolution and granularity detector with a good efficiency for electron measurement, like ICARUS liquid Argon, with a fiducial mass exceeding 30-50 kton is required to complement it and to exploit its physics potential beyond the T2K sensitivity.

The SPL-SuperBeam at CERN, complemented with a megaton water Cerenkov detector, seems to require a too big effort compared with its physics output due to the too low proton energy, even if the 3.5 GeV option improves its discovery potential.

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