NEUTRINO PHYSICS

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Abstract

Progress in neutrino physics in the last 20 years especially on understanding of masses and mixings is summarized.

INTRODUCTION

Twenty years ago, when the SN1987A was observed by Kamiokande and IMB, the neutrinos were the least known matter particle. Since then, the understanding of neutrino properties has been greatly improved by various discoveries and measurements of many neutrino experiments.

Amazingly, the neutrinos, which has long been assumed to be massless and hence to have no flavor mixing in the framework of standard model, has now been shown to have finite masses and large flavor mixing.

However, now in 2007, neutrino is still least known matter particle. There are many unanswered fundamental questions on the neutrino properties many of which could have essential impact on understanding of nature, such as baryon number asymmetry in the universe. Many new experiments to attack those questions are planned or being constructed.

In this paper, the development of the neutrino physics during the last 20 years, especially focusing on the neutrino mixings and masses, the remaining questions and the future projects are summarized.

$\nu_e \rightarrow \nu_x$ OSCILLATION

The Homestake experiment started to observe solar neutrino flux in 1970 using a reaction $^{37}\mathrm{Cl} + \nu_e \rightarrow^{37} \mathrm{Ar} + e^-$ in 615 tons of C_2Cl_4. The observed event rate $\phi(Homestake) = 2.56 \pm 0.16(stat.) \pm 0.16(sys.)$ SNU was significantly lower than the Standard Solar Model (SSM) prediction of 8.5±1.8 SNU, where SNU is 10^{-36}captures/atom/sec [1]. This observation was the beginning of the long-standing “Solar Neutrino Problem”.

Since then, several experiments with different technologies and energy threshold had observed solar neutrino flux such as two ^{71}Ga radiochemical experiments SAGE and GALLEX/GNO, Kamiokande Water Cherenkov detector. All experiments before Super-Kamiokande (SK) have observed significantly lower flux than SSM predictions [2].

In 1996, Super-Kamiokande, 50kton Water Cherenkov detector [3] had become operational in Kamioka, Japan and started accumulating solar neutrino data with drastically higher statistics than ever before. SK detect solar neutrino through the elastic scattering (ES), $\nu_x + e^- \rightarrow \nu_x + e^-$, which gives the flux $\Phi^{ES} = \Phi_e + 0.15(\Phi_\mu + \Phi_\tau)$. The observed flux in SK-I period, which is before the SK accident in 2001, is $\phi^{ES}_{SK-I} = 2.35 \pm 0.02(\text{stat.}) \pm 0.08(\text{sys.}) \times 10^6/\mathrm{cm}^2/\mathrm{sec}$, which is 30$\sigma$ lower than SSM prediction [4].

The 1,000ton D_2O Water Cherenkov detector, SNO in Canada had operated from 1999 to 2006. Most striking feature of SNO is the ability to measure total neutrino flux regardless of the flavors through detection of neutral current (NC) interactions $\nu_x + d \rightarrow p + n + \nu_x$. SNO also measures ν_e flux with CC reaction Φ^{CC} and Φ^{ES}. The measured fluxes in SNO are [5]

$$\begin{aligned} \Phi^{CC}_{SNO} &= 1.68 \pm 0.06(\text{stat.})^{+0.08}_{-0.09}(\text{sys.}) \times 10^6/\mathrm{cm}^2/\mathrm{sec} \\ \Phi^{ES}_{SNO} &= 2.35 \pm 0.22(\text{stat.})^{+0.15}_{-0.15}(\text{sys.}) \times 10^6/\mathrm{cm}^2/\mathrm{sec} \\ \Phi^{NC}_{SNO} &= 4.94 \pm 0.21(\text{stat.})^{+0.38}_{-0.34}(\text{sys.}) \times 10^6/\mathrm{cm}^2/\mathrm{sec} \end{aligned} \quad (1)$$

The ν_e flux Φ^{CC} is significantly smaller than the total flux Φ^{NC} which proves the existence of neutrinos other than ν_e, namely ν_μ or ν_τ. Combining flux measurements of SK and SNO, finite $\nu_\mu + \nu_\tau$ flux is measured as shown in Fig. 1

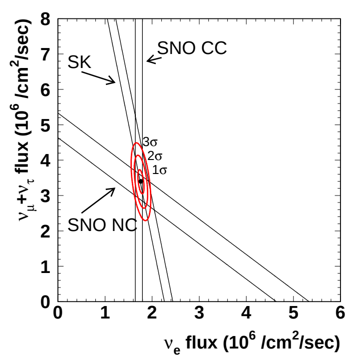

Figure 1: Flux constraints from flux measurements by SK and SNO. Each band shows $\pm1\sigma$ constraint from each measurement. The circles show 1σ, 2σ and 3σ constraints obtained by combining SK-I and SNO data.

The observations of all the solar neutrino experiments are consistently reproduced by assuming the neutrino oscillation from ν_e to other flavors, with the allowed oscillation parameter region shown in Fig 2 (Left) [4]

The KamLAND experiment, 1200 m^3 liquid scintillator detector took different approach to settle the solar neutrino problem; searching for disappearance of reactor $\bar{\nu}_e$ after long distance flight. There are commercial reactors distributed at 130-220 km distance from KamLAND which generate 70 GW_{th} in total and neutrinos from those reactors contribute to 80% of the neutrino flux at the KamLAND site. The observed number of events from Mar.

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2002 to Jan. 2004 was 258 where 365.2 ± 23.7 $\bar{\nu}_e$ signals (w/o oscillation) and 17.8 ± 7.3 backgrounds are expected [6]. Clear deficit is observed with the significance of 99.9998%. Spectrum distortion of 99.6% significance is also observed. Combining the rate and shape, no-oscillation is excluded at 99.999995%. Allowed oscillation parameter region by KamLAND is overlaid on solar neutrino results in Fig. 2 (Right).

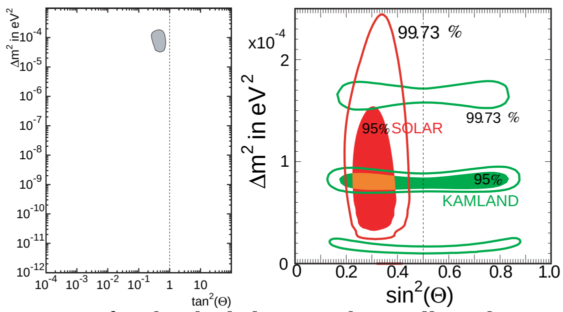

Figure 2: Left: The shaded region shows allowed region of oscillation parameters with 95% C.L. obtained by SK and SNO combined analysis. Right: Red regions show allowed oscillation parameter regions obtained by combining all solar experiments with 95% C.L.(filled red) and 99.73% (red line). Green regions show results from KamLAND reactor neutrinos [6] with 95% C.L.(filled green) and 99.73% (green line).

Now solar neutrino problem is solved and is understood as caused by the neutrino oscillation.

$\nu_\mu \rightarrow \nu_x$ OSCILLATIONS

Atmospheric Neutrino Anomaly

Atmospheric neutrinos are generated in the decays of secondaries (π, K and μ) produced by primary cosmic-ray interactions in the atmosphere. The flux ratio $\nu_\mu + \overline{\nu}_\mu$ over $\nu_e + \overline{\nu}_e$ has a value of about 2 for energies less than a few GeV, because a π-decay produces a ν_μ and a μ; the μ when it decays, produces another ν_μ and a ν_e.

The Kamiokande reported in 1988 the significantly lower μ/e ratio compared with the Monte Carlo prediction. A supporting result was reported in the early 1990's from the IMB experiment. On the other hand, fine grained iron calorimeter experiments did not observe significantly small μ/e ratio within their limited statistical precisions. Hence, the situation was unclear in the early 1990's [7]. In addition, the data from Kamiokande showed that the deficit of multi-GeV μ-like events depended on the neutrino arrival direction [8]. Those results hinted neutrino oscillations.

Evidence of neutrino oscillation from Super-Kamiokande

Super-Kamiokande reported the results of observation in 1998 with substantially higher statistics than previous experiments. The μ-like data have exhibited a strong deficit of upward-going events, while no significant deficit has been observed in the e-like data as shown in Fig. 3 [9]. The oscillation hypothesis is tested by fitting the prediction with $\nu_\mu \rightarrow \nu_\tau$ oscillation to the observed data. The best fit oscillation predictions reproduce the observed distributions very well. The allowed region of oscillation parameters are drawn in Fig. 4. The oscillation parameters are determined as; $\sin^2 2\theta > 0.93$ and $1.9 \times 10^{-3} < \Delta m^2 < 3.1 \times 10^{-3}$eV^2 at 90% C.L..

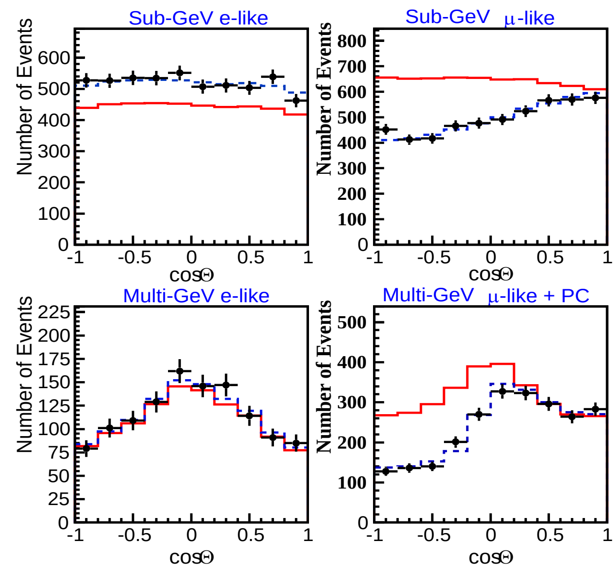

Figure 3: Zenith angle distributions for contained atmospheric neutrino events observed in Super-Kamiokande (top, middle) [9]. The histograms show the prediction with and without $\nu_\mu \rightarrow \nu_\tau$ oscillations.

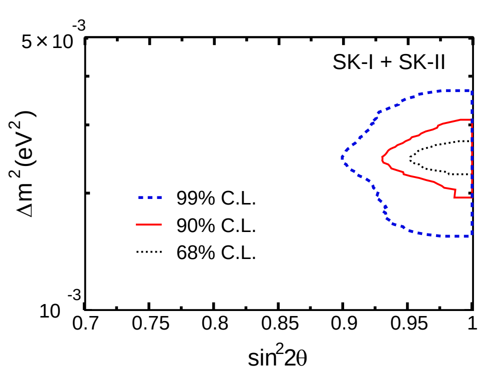

Figure 4: 68, 90 and 99% C.L. allowed oscillation parameter regions for 2-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations obtained by the zenith-angle analysis from Super-K-I+II [9].

The appearance of ν_τ is also searched for using ν_τ enhanced sample of atmospheric neutrino data. Signal excess of 2.4 σ beyond background is observed [9].

Definite confirmation by accelerator experiments

To confirm the SK results, several accelerator based long baseline (LBL) neutrino oscillation experiments were (are being) conducted.

K2K is the first accelerator-based LBL experiment where ν_μ beam of $\langle E_\nu \rangle \sim 1.3$ GeV is produced using 12-GeV KEK-PS and detected by SK at 250km distance. The expriment started taking data in 1999 and finished in 2004. Observed number of events 112 during the whole period is signifiantly smaller than the expected 158.1 $^{+9.2}_{-8.6}$ events without oscillation. Distortion of energy spectrum which is consistent with oscillation hypothesis is also observed as in Fig. 5. Combining the event deficit and spectrum shape distortion, the non-oscillation is excluded at 4.3σ level (99.9985%) [10].

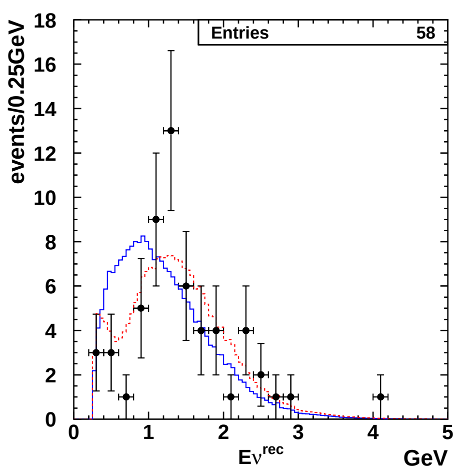

Figure 5: The reconstructed E_ν distribution observed in K2K. The histogram with solid line is the expected spectrum shape without oscillation, which is normalized by the number of observed events. The histogram with dotted line is the one with best fit oscillation parameters.

MINOS experiment produces ν_μ of around 3 GeV with FNAL MI 120-GeV proton beam and detects by 5.4 kt MINOS detector in Soudan mine at 735km from the neutrino production point. Data taking started in 2005 and the first results are publised in 2006 [11]. Observed number of ν_μ CC events of 215 is significantly smaller than the expected number of events without oscillation of 336.0±14.4. Also observed energy spectrum is distorted from expected one without oscillation and agrees well with the oscillated one as shown in Fig. 6.

In order to detect ν_τ events oscillated from ν_μ, OPERA experiment produces high energy ν_μ beam of $\langle E_\nu \rangle \sim$ 17 GeV with CERN 400-GeV SPS and detect by an emulsion-based fine grained tracker with 1.8ton target mass [12]. Commissioning of the CERN Neutrino to Gran Sasso (CNGS) beam line [13] has been done in Aug. 2006 and more than 300 neutrino induced events were detected

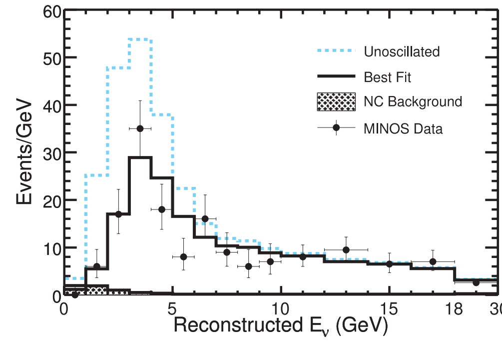

Figure 6: Observed spectrum of reconstructed neutrino energy E_ν in MINOS with the expected spectrum at the best-fit oscillation parameters (solid) and the one without oscillation (dashed) [11]. The hatched area indicate NC background contribution.

by the electronic part of the detector. Expected number of ν_τ CC events in 5 years is 10.4 at oscillation parameters $\Delta m^2_{23} = 2.4 \times 10^{-3}\ eV^2$ and $\sin^2 2\theta_{23} = 1$ with a background of 0.7.

Summary

The atmospheric neutrino anomaly before early '90 is solved by the discovery of oscillation in atmospheric neutrino observation by Super-Kamiokande. The results are definitely confirmed by different systematics experiments, ie, accelerator LBL experiments K2K and MINOS. Allowed regions of oscillation parameters for those experiments are overlaid in Fig. 7. All those results point to same parameter region.

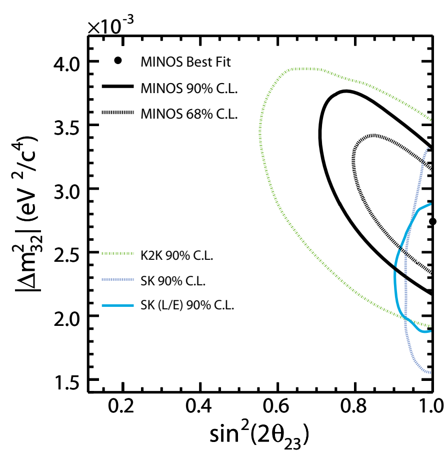

Figure 7: Allowed regions of oscillation parameters[11]

LSND/MINIBOONE ISSUE

The LSND experiment[14] reported the evidence of $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations. The experiment observed an excess of 22 electron-like events with the predicted background of 4.6 ± 0.6 events in a 167 tons of dilute liquid scintillator detector located at 30 m from the $\overline{\nu}_\mu$ source by μ^+ decay at rest. If the LSND results is true, there are three different Δm^2, namely, Solar, Atmospheric and LSND which requires the fourth light neutrino. Since the impact of the consequences is considerable, decisive confirmation was necessary and MiniBooNE experiment is proposed to address this issue with higher statistics and different sources of systematic errors.

In the MiniBooNE experiment a ν_μ beam is produced by 8 GeV proton beam from Booster at FNAL and detected at 541m from the neutrino source by a 800ton, 610cm radius ring imaging Cherenkov detector filled with pure mineral oil viewed by 1280 8-inch PMTs. The first beam was delivered in 2002 and the first results based on the data of $(5.58 \pm 0.12) \times 10^{20}$ protons on target collected from 2003 to 2005 is released in April 2007. No excess of ν_e signal event beyond the expected background is observed. Most of the parameter region suggested by LSND is rejected by the MiniBooNE experiment as shown in Fig. 8 [15].

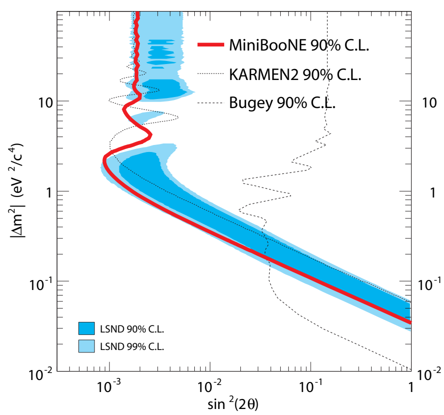

Figure 8: MiniBooNE 90% CL upper limit together with the limits from the KARMEN [16] and Bugey [17] experiments. The shaded areas show the 90% and 99% CL allowed regions from the LSND experiment.

SUMMARY OF PRESENT KNOWLEDGE AND UNANSWERED QUESTION

In the framework of 3 flavor mixing, flavor and mass eigenstates are connected by an unitary mixing matrix called Maki-Nakagawa-Sakata (MNS) matrix which frequently parametrized by 3 real mixing angles and 1 CP violating phase as

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (2)$$

where s and c stand for $\sin\theta$ and $\cos\theta$. The neutrino oscillation can be described by those 4 parameters and $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$ where m_i is the mass of i-th mass eigenstate. Within this picture, the knowledge on neutrino accumulated so far are summarized as follows;

- $\theta_{12} \sim 33°, \Delta m_{21}^2 \sim 7.9 \times 10^{-5} eV^2$ from Solar and KamLAND experiments
- $\theta_{23} \sim 45°, |\Delta m_{23}^2| \sim 2 - 3 \times 10^{-3} eV^2$ from Atmospheric and accelerator experiments
- Upper limit $\theta_{13} \lesssim 8.5°$ from CHOOZ experiment. No direct measurement on Δm_{13}^2 although it is considered to be close to Δm_{23}^2.
- Sign of Δm_{23}^2 is unknown
- No information on δ.

Remaining questions on fundamental properties of neutrinos include (1) Size of θ_{13}, (2) Sign of Δm_{23}^2, (3) CP is violated?, (4) Absolute mass?, (5) Majorana or Dirac neutrino? Since CP violation and sign of Δm_{23}^2 can be probed in ν_e appearance in accelerator LBL or atmospheric neutrino experiments, the size of θ_{13}, which control the size of the ν_e appearance signal, will be critical. Therefore as a next step, the most important and urgent issue is the determination of θ_{13}.

The accelerator LBL ν_e appearance experiments can cover the first three issues because ν_e appearance probability depend on all three parameters. Reactor $\bar{\nu}_e$ disappearance experiments can only probe θ_{13} since the probability does not contain other two parameters. Several accelerator and reactor experiments are planned for those purposes as briefly summarized in the following section. Future atmospheric ν_e appearance can have a possibility to determine θ_{13} for some parameter regions.

The last two issues are to be studied by neutrino-less double beta decay experiments. Absolute neutrino mass can also be probed by spectrum measurements of a beta decay.

FUTURE PROJECTS

Accelerator LBL experiments

As next generation high sensitivity experiments, T2K in Japan and NOνA experiment in US are being prepared. Main goal of the experiments is the discovery of ν_e appearance.

T2K experiment [18] produces ν_μ beam using high intensity (750 kW) 50 GeV PS in J-PARC [19] at Tokai, Japan and detect the neutrino by Super-Kamiokande. Intense narrow energy spectrum beam tuned at the oscillation maximum is produced by the off-axis method to maximize the sensitivity. Expected number of ν_μ CC interactions without oscillation is 1600/yr in 22.5kt fiducial mass. Sensitivity on $\sin^2 2\theta_{13}$ is 0.008 (90%CL) when $\delta = 0$ in 5 years of design intensity running. The commissioning of J-PARC 50-GeV PS will be from May 2008 and T2K experiment will start from April 2009. Also in T2K, $\sin^2 2\theta_{23}$ and Δm_{23}^2 can be measured to 1% and 10^{-4} eV^2 precision, respectively in the ν_μ disappearance measurement. Furthermore, if ν_e appearance is discovered, possibility to discover CP violation in the future with upgraded beam power and detector is opened.

The NOνA experiment proposed to construct a new 20-kt total mass segmented liquid scintillator tracker on off-axis of the FNAL NuMI beam at ~810 km from FNAL.

At ~15 mr off-axis, a narrow-band neutrino beam with the peak energy of ~ 2 GeV is produced. Over the six-year run with 60×10^{20} POT, the 3-sigma discovery sensitivity for $\sin^2 2\theta_{13}$ is expected to be approximately 0.01 which is comparable with T2K. If $\sin^2 2\theta_{13} \sim 0.1$, NO$\nu$A has a chance to resolve the mass hierarchy through matter effect. It is planned to start the far detector construction in 2009 and to take the first data in late 2010 with a partial detector of 5 kt.

Reactor Experiments

Another approach to measure the finite θ_{13} is to search for disappearance of $\bar{\nu}_e$ from reactors at a distance of ~1 km. Several experiments, Double Chooz, RENO, Daya Bay and ANGRA are planned aiming the final sensitivities on $\sin^2 2\theta_{13}$ of 0.025, 0.03, 0.008 and 0.0055, respectively [20]. Since the disappearance signal is expected to be very small, the experiment will be systematic limited and all those experiments will prepare identical near and far detectors to reduce the systematic errors.

Tritium beta decay experiment

Absolute mass of neutrino can be probed by precise measurements of beta decay energy spectrum. The effect of the finite neutrino mass appears as the shift of spectrum end point from the Q value of the beta decay. The tritium beta decay experiments of Mainz and Troitsk gave an upper limit of $m(\nu_e) < 2.2$ eV/c^2 (95 % C.L.)[21]. The KATRIN experiment[22] with a sensitivity of 0.3eV/c^2(3σ discovery) is being constructed at Karlsruhe, Germany.

Neutrinoless Double Beta Decay Experiments

Another probe to search for absolute neutrino mass is neutrinoless double beta decay($0\nu\beta\beta$). The $0\nu\beta\beta$ decay occur only when neutrino is massive and Majorana type. Experiments with a sensitivity of several tens to 100 meV are proposed using ton-class ^{76}Ge (Majorana, Genius, Gerda), ^{130}Te (Cuore), ^{136}Xe (EXO, XMASS), ^{48}Ca (Candles, Carvel), ^{82}Se (Supernemo), ^{100}Mo (Moon-3), and ^{150}Nd (Dcba-2). Details of those experiments are discussed in ref.[23].

SUMMARY

During the last 20yrs, remarkable developments in understanding of neutrino properties have been made. Evidence of neutrino oscillations have been found and now neutrinos are known to be massive and have large flavor mixings. Both Solar neutrino problem and Atmospheric neutrino anomaly are now understood as caused by the oscillations. These are the first experimental facts which the standard model does not account for. However still there are many unanswered fundamental questions such as absolute mass and CP violation which, in quark sector, have been answered long ago. In this sense, understanding of neutrino is far from satisfactory and we could say that we are just on a starting point of "flavor physics" in neutrino sector, which has been studied for last 40 years for quarks.

Many new projects are planned and under preparation aiming to understand whole nature of neutrinos. The field of neutrino physics must continue to be exciting for at least coming several ten years.

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