

## "Neutrino Studies in the OPERA Experiment"

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Abstract:

In 2021, the OPERA Collaboration has finally completed the analysis of the experimental data by publishing the last paper. Here we present the papers, published during the experiment, the participation of JINR group in the preparation of which was significant or decisive. A brief summary of the papers is given below.

The aim of the OPERA experiment was to prove the oscillations of  $\nu_\mu \rightarrow \nu_\tau$  by direct observation of the appearance of tau neutrinos in a muon neutrino beam at a distance from the neutrino source. Such oscillations would explain the observed deficit of muon neutrinos in the atmospheric showers. This task was very relevant in the late 90s, when the existence of the effect of neutrino oscillations was officially recognized, but their mechanism and parameters were poorly studied yet.

However, the registration of tau neutrinos is an extremely difficult task, for the first time it was done only in 2001 by the DONuT Collaboration at Fermilab using a special emulsion detector ("Emulsion Cloud Chamber" - ECC). The search for tau neutrinos in the OPERA experiment was even more difficult, since it was necessary to register neutrinos at a distance of 730 km from their source at CERN, where their flux is significantly weakened. In the early 2000s, the OPERA collaboration was formalized and the creation of a hybrid detector with a target part (ECC) and electronic detectors had started. In parallel, a new neutrino beam – CNGS (CERN Neutrinos to Gran Sasso) was created at CERN. In 2006, it was launched, and the first muon neutrinos were registered in the OPERA detector in the Gran Sasso underground laboratory in Italy. The detector had unprecedented characteristics: with a mass of about 1200 tons, exceptionally high spatial and angular resolution (less than 1 micrometer and less than 0.5 mrad, respectively) was achieved, which made it possible to effectively recognize charged current tau-neutrino interactions, i.e. direct registration of tau lepton production and its decay. The main data were collected from 2008 to 2012, in total about 20,000 neutrino events were registered in the detector. From these events, using special selection criteria and analysis methods, including those based on a neural network, tau neutrino interaction events were recognized [3,5,8,12]. In the last paper devoted to the search for tau neutrinos [3], 10 events were identified using multivariate analysis, which, taking into account the estimated background of 2 events, meant the significance of tau neutrino registration at a level exceeding 6 sigma. Thus, the oscillations of muon neutrinos to tau neutrinos were discovered by observing their appearance in an initially pure beam of  $\nu_\mu$ , and the main goal of the experiment has been successfully achieved. This result was an important addition to the studies of neutrino oscillations in the "disappearance" mode conducted in other experiments.

The cross section of the tau-neutrino interaction and the oscillation parameters in the "atmospheric" sector in the "appearance" mode were also estimated [2,3].

The OPERA detector could also efficiently register electron neutrinos. However, there were no oscillations observed in the kinematic region to which the experiment was tuned, the number of the detected electron neutrinos corresponded to their level in the CNGS beam. Nevertheless, the analysis of data with electron neutrinos, in which the JINR group was directly involved, allowed establishing restrictions on the existence of sterile neutrinos in the appearance mode [4,9].

The JINR group actively participated in the creation of the Target Tracker (TT) detector: the production of scintillator strips, the assembly of the modules and their calibration in France, the assembly of the entire detector in Gran Sasso. More than 20 people from the DLNP and other

laboratories took part in these activities. The total area of the TT detector was 6200m<sup>2</sup>, 63488 PMT channels [14,15].

After the TT detector was launched, the JINR group created its own data processing software package to search for event vertices in the OPERA detector [7]. The JINR software turned out to be more efficient, compared to the one created by other groups, allowed to do the analysis much faster, and the interface included in it (“event-display”) was much more informative and functional. The JINR group was responsible for the TT data analysis and searching for the vertices of neutrino events throughout almost the entire experiment [11,13].

In 2011, a group from Lyon estimated the time of neutrino flight in a CNGS beam. Due to a number of technical errors, the result had a large systematic error, leading to a paradoxical result regarding the neutrino velocity. Through the efforts of other groups participating in OPERA, it was possible to quickly detect the source of the error related to electronics. At the same time, the JINR group proposed a more accurate method for measurement of the neutrino interaction time in TT, which additionally eliminated a systematic error of about 7 ns from the result obtained by the French group. This method was applied in the analysis led to the final results of measuring the neutrino velocity, published in 2012 [10].

The exceptional spatial resolution of emulsion detectors makes the analysis of events in them very clear and understandable. As part of the CERN Open Data project (<http://opendata.cern.ch>), data on the most interesting events and tools for their analysis were made publicly available, so that everyone (including teachers, students) could try to process the information and get a result. The last article of the OPERA Collaboration published in 2021 is devoted to this project, implemented largely thanks to the JINR group [1].

JINR group members have presented the results of the OPERA experiment 15 times at international conferences.

Members of the group participated in the management of the experiment: Gornushkin Yu.A. and Dmitrievsky S.G. were members of the Executive Committee of OPERA.

Gornushkin Yu.A. is a Deputy Spokesperson of the OPERA Collaboration since 2012.

List of publications:

1. OPERA tau neutrino charged current interactions

OPERA Collaboration • N. Agafonova (Moscow, INR) et al. (Aug 12, 2021)

Published in: Sci.Data 8 (2021) 1, 218 – 0 citations (S.Dmitrievsky – corresponding author)

2. Final results on neutrino oscillation parameters from the OPERA experiment in the CNGS beam

OPERA Collaboration • N. Agafonova (Moscow, INR) et al. (Apr 11, 2019)

Published in: Phys.Rev.D 100 (2019) 5, 051301 • e-Print: 1904.05686 [hep-ex] - 9 citations

3. Final Results of the OPERA Experiment on  $\nu_\tau$  Appearance in the CNGS Neutrino Beam

OPERA Collaboration • N. Agafonova (Moscow, INR) et al. (Apr 13, 2018)

Published in: Phys.Rev.Lett. 120 (2018) 21, 211801, Phys.Rev.Lett. 121 (2018) 13, 139901

(erratum) • e-Print: 1804.04912 [hep-ex] - 116 citations (Yu.Gornushkin – internal referee)

4. Final results of the search for  $\nu_\mu \rightarrow \nu_e$  oscillations with the OPERA detector in the CNGS beam

OPERA Collaboration • N. Agafonova (Moscow, INR) et al. (Mar 30, 2018)  
Published in: JHEP 06 (2018) 151 • e-Print: 1803.11400 [hep-ex] - 21 citations  
(S.Vasina – corresponding author)

5. Discovery of  $\tau$  Neutrino Appearance in the CNGS Neutrino Beam with the OPERA Experiment

OPERA Collaboration • N. Agafonova (Moscow, INR) et al. (Jul 6, 2015)  
Published in: Phys.Rev.Lett. 115 (2015) 12, 121802 • e-Print: 1507.01417 [hep-ex]  
- 199 citations

6. Limits on muon-neutrino to tau-neutrino oscillations induced by a sterile neutrino state obtained by OPERA at the CNGS beam

OPERA Collaboration • N. Agafonova (Moscow, INR) et al. (Mar 6, 2015)  
Published in: JHEP 06 (2015) 069 • e-Print: 1503.01876 [hep-ex]- 37 citations

7. Locating the neutrino interaction vertex with the help of electronic detectors in the OPERA experiment

Yu.A. Gornushkin (Dubna, JINR), S.G. Dmitrievsky (Dubna, JINR), A.V. Chukanov (Dubna, JINR) (Jan7, 2015) Published in: Phys.Part.Nucl.Lett. 12 (2015) 1, 89-99 - 5 citations

8. Evidence for appearance  $\nu_\mu \rightarrow \nu_\tau$  in the CNGS neutrino beam with the OPERA experiment

OPERA Collaboration • N. Agafonova (Moscow, INR) et al. (Jan 9, 2014)  
Published in: Phys.Rev.D 89 (2014) 5, 051102 • e-Print: 1401.2079 [hep-ex]- 130 citations

9. Search for oscillations  $\nu_\mu \rightarrow \nu_e$  with the OPERA experiment in the CNGS beam

OPERA Collaboration • N. Agafonova (Moscow, INR) et al. (Mar 16, 2013)  
Published in: JHEP 07 (2013) 004, JHEP 07 (2013) 085 (addendum) • e-Print: 1303.3953 [hep-ex] - 168 citations (Yu.Gornushkin – an internal referee)

10. Measurement of the neutrino velocity with the OPERA detector in the CNGS beam

OPERA Collaboration • T. Adam (Louis Pasteur U., Strasbourg I) et al. (Sep, 2011)  
Published in: JHEP 10 (2012) 093 • e-Print: 1109.4897 [hep-ex] - 429 citations

11. Study of neutrino interactions with the electronic detectors of the OPERA experiment

OPERA Collaboration • N. Agafonova (Moscow, INR) et al. (Feb, 2011)  
Published in: New J.Phys. 13 (2011) 053051 • e-Print: 1102.1882 [hep-ex]  
- 74 citations

12. Observation of a first candidate  $\nu \tau$  in the OPERA experiment in the CNGS beam

OPERA Collaboration • N. Agafonova (Moscow, INR) et al. (Jun, 2010)  
Published in: Phys.Lett.B 691 (2010) 138-145 • e-Print: 1006.1623 [hep-ex] - 358 citations

13. Measurement of the atmospheric muon charge ratio with the OPERA detector

OPERA Collaboration • N. Agafonova (Moscow, INR) et al. (2010)  
Published in: Eur.Phys.J.C 67 (2010) 25-37 • e-Print: 1003.1907 [hep-ex]  
- 67 citations

14. The OPERA experiment in the CERN to Gran Sasso neutrino beam

R. Acquafredda (INFN, Naples), T. Adam (Strasbourg, IPHC), N. Agafonova (Moscow, INR), P. Alvarez-Sanchez (CERN), M. Ambrosio (INFN, Naples) et al. (Apr, 2009)

Published in: JINST 4 (2009) P04018 - 289 citations

15. The OPERA experiment target tracker

T. Adam (Strasbourg, IPHC), et al. (Jan, 2007)

Published in: Nucl.Instrum.Meth.A 577 (2007) 523-539 • e-Print: physics/0701153 [physics]

- 93 citations