Nomination of the paper series
"Quantum Field Theory of Neutrino Oscillations"

Authors: D. V. Naumov (DLNP), V. A. Naumov (BLTP), D. S. Shkirmanov (BLTP).
The "Theoretical Physics" section.

The series of papers [1–6] considers the quantum-field theory of neutrino oscillations within a covariant formalism with relativistic wave packets as asymptotically free in- and out-states. These states correspond to particles involved in the processes of the neutrino production in the "source" and absorption in the "detector". The source and the detector are vertices of a connected Feynman diagram conjoint by a propagator of neutrino with a definite mass. Flavour transformations at macroscopic space-time distances between the source and the detector are treated as a result of the interference of the contributions to the full amplitude from the macrodiagrams containing virtual neutrinos with different masses.

The detailed theory is elaborated by the authors in Ref. [1]. In Ref. [2], the theorem is proved that extends an important result by Grimus and Stockinger about asymptotic behaviour of the neutrino propagator at large spatial distances between the vertices of the macrodiagram. Refs [3, 4] cover different aspects of the covariant wave packet theory used in the formalism. The first experimental data analysis for verification of some predictions of the developed theory has been performed by the Daya Bay collaboration under the leadership of one of the authors [5]. In Ref. [6], the statements and consequences of the quantum-mechanical and quantum-field-theoretical approaches to neutrino oscillations are presented in detail. Also, a number of new physical and mathematical results of the theory are obtained.

The relevance of the papers [1-6] arises from incompleteness and inconsistency of the widely used neutrino oscillation theory based on the quantum-mechanical plane-wave model. The neutrino oscillation phenomenon, intriguing on itself as the only example of the of lepton numbers preserved with high precision in all other processes, plays the crucial role in measuring the fundamental parameters of the Standard Model (mixing angles and neutrino mass-squared differences, CP violation phases) and also in studying physics beyond the Standard Model (non-standard neutrino interactions with matter, sterile neutrinos, etc). Along with coherent and collective scattering, neutrino oscillations in vacuum and matter are of great value for research of neutrino fluxes from astrophysical sources (from the Sun to active galactic nuclei) and for understanding of dynamics of some astrophysical processes (supernovae, latent high-energy particle sources). That is why discrepancies in the plane-wave neutrino oscillation theory should not be ignored. The theory elaborated by the authors is self-consistent. It addresses all the problems of the standard quantum-mechanical approach, outlines the domain of its applicability (a rather wide one) and predicts a number of new effects allowing for experimental testing.

The new results are:

I. Covariant wave packet (WP) formalism of a general form, the detailed research of the WP evolution and its general properties, including the mean values of kinematic characteristics of WPs and properties of the multipacket states. Research of asymptotic WP behaviour at long distances. The analysis of the simplest models of the covariant WPs — relativistic Gaussian WP and asymmetric true Gaussian WP, dependent on the "hidden parameters" (momenta of particles involved in the WP production process). Specification of the WP quasi-stability requirements.

II. Formula for the cross-section of interaction of relativistic WPs elastically scattered off each other with a non-zero impact parameter. Calculation of the geometric suppression of the WP interaction probability in non-collinear collisions.

III. Formulation of Feynman rules for WP scattering and calculation of the connected diagram of sufficiently general form with macroscopically separated vertices — the "source" and the "detector", near which charged leptons are produced.

IV. Proof of the theorem of hadronic block factorization at long distances between the vertices of the macrodiagram.

V. Proof of the extended Grimus— Stockinger theorem for the generalized neutrino propagator (containing the factors depending on the external WP parameters). The theorem predicts corrections to the classical inverse-square law at short (macroscopic) distances, L. The corrections are derived as an asymptotic expansion of the extended neutrino propagator in inverse powers of L.

VI. Formulation of the method for macroscopic averaging of the squared Feynman macrodiagram and derivation of a general formula for the number of events in the detector, including kinematic and dynamic particle interaction characteristics (phase spaces, squared matrix elements), particle distribution functions in the physical source and the detector, and also a factor generalizing the well-known expression for quantum-mechanical flavour transition probability, depending on the space-time distance between the macrodiagram vertices and containing both the standard oscillatory multiplier (with a few corrections) and decoherence factors.

VII. Detailed examination of the general properties of the overlap tensors (defining space-time interaction domains of the external in and out WPs) and determination of their explicit form for basic reactions of neutrino production and absorption needed for practical calculations of decoherence effects.

VIII. Demonstration of duality of features of the generalized neutrino propagator and an effective neutrino WP at long spatial distances.

IX. Examination of the dependence of the effective 4-momentum of a virtual neutrino on the 4-momentum transfer between the macrodiagram vertices in the most general case, as well as in ultra-relativistic and non-relativistic limits.

X. Analysis of the generalized flavour transition probability considering longitudinal dispersion of the effective neutrino WP and finite-time intervals of activity of the physical source and detector for synchronized measurements. Prediction of a number of novel and potentially observable effects in terrestrial and astrophysical experiments studying neutrino oscillations, in particular, a new oscillation regime at ultra-long baselines. Determination of conditions for reaching the non-oscillatory regime as a result of narrowing of the overlap region of the effective neutrino WPs propagating with different group velocities (due to different neutrino masses).

XI. Formulation of the problem and analysis of the reactor experimental data performed by the Daya Bay collaboration resulting in obtaining the first experimental restrictions to the effective neutrino WP dispersion and decoherence effect scale predicted within the quantum-field theory of neutrino oscillations.

Practical significance of the papers [1-6] is elaborating the self-consistent covariant formalism for neutrino oscillation description considering the influence of particle interaction kinematics in the source and the detector and particularly predicting the existence of non-oscillatory regime in well defined experimental conditions. These results permit outlining the area of applicability of the standard quantum-mechanical formalism and ensure the data analysis tool for precision measurement of the fundamental parameters of the Standard Model in future neutrino oscillation experiments. They can be used for measuring the form of the neutrino wave function and will be helpful for physical interpretation of the results from astrophysical high-energy neutrino experiments.

The results of Refs [1-6] were widely presented at international and national conferences, public lectures and seminars.

List of publications:

1. D.V. Naumov, V.A. Naumov, A Diagrammatic treatment of neutrino oscillations. J. Phys. G **37** (2010) 105014; arXiv:1008.0306 [hep-ph].
2. V.A. Naumov, D.S. Shkirmanov, Extended Grimus-Stockinger theorem and inverse square law violation in quantum field theory, Eur. Phys. J. C **73** (2013) 2627, arXiv: 1309.1011 [hep-ph].
3. D.V. Naumov, On the theory of wave packets, Письма в ЭЧАЯ **10** (2013) 1055-1070 [Phys. Part. Nucl. Lett. **10** (2013) 642-650]; arXiv: 1309.1717 [quant-ph].
4. V.A. Naumov, D.S. Shkirmanov, Mod. Phys. Lett. A **30** (2015) 1550110; arXiv:1409.4669 [hep-ph].
5. Feng Peng An, ..., D.V. Naumov,... (Daya Bay Collaboration), Study of the wave packet treatment of neutrino oscillation at Daya Bay, Eur. Phys. J. C **77** (2017) 606; arXiv: 1608.01661 [hep-ex].
6. D.V. Naumov, V.A. Naumov, Quantum Field Theory of Neutrino Oscillations, ЭЧАЯ **51** (2020) 5-209 [Phys. Part. Nucl. **51** (2020) 1-106].