
Neutrino oscillations reveal Dirac's form of interaction

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Abstract – We consider neutrino oscillations in both instant and point forms of Dirac's dynamics. Interacting generators of symmetry transformations are constructed explicitly and shown to satisfy Poincaré commutators exactly. Thus, our solutions for flavor probabilities conform to all requirements of relativistic invariance. Instant form calculations agree with experimental data but point form results are unacceptable: oscillation period shrinks as particle energy increases. We interpret this as an indication that neutrino mixing is controlled by the instant form of Dirac's dynamics.

Introduction. – Neutrino flavor mixing and oscillations [1] is now a well established fact. In the simplest case of two neutrino ($\nu_\mu \rightarrow \nu_\tau$) mixing, time-dependent flavor probabilities contain a characteristic sinusoidal factor

$$\rho(t) \sim \sin^2 \frac{(m_2^2 - m_1^2)c^4 t}{4E\hbar}, \quad (1)$$

where m_2, m_1 are neutrino mass eigenvalues and E is particle energy. Early derivations [2] of this formula lacked relativistic rigor. Nevertheless, this result seemed satisfactory, not only because it agreed with experiments [3], but also because it reproduced the special-relativistic “time dilation” effect by exhibiting the direct proportionality between oscillation period T and particle energy

$$T \propto E \propto 1/\sqrt{1 - v^2/c^2}. \quad (2)$$

According to Wigner-Dirac relativistic quantum theory [4–6], Hilbert space \mathcal{H} of any isolated system (including oscillating neutrinos) carries a representation of the 10-dimensional Poincaré Lie algebra by means of Hermitian operators, which are identified with observables of total energy H , total linear momentum \mathbf{P} , total angular momentum \mathbf{J} and total boost momentum \mathbf{K} . In non-relativistic theories, the full interacting Hamiltonian H may be formed by adding “potential energy” V to the Hamiltonian H_0 of free particles

$$H = H_0 + V.$$

However, in the relativistic case such a construction violates Poincaré commutation relations. Dirac found out

that in order to preserve relativistic invariance, interaction terms have to be added to generators of other inertial transformations as well [5]. For example, in Dirac's instant form of dynamics a “potential boost momentum” should be added to the non-interacting generator of boosts \mathbf{K}_0 . In the point form dynamics, a “potential linear momentum” should be added to the non-interacting generator of space translations \mathbf{P}_0 . The question is what are observable effects, if any, of these relativistic interaction terms? Is it possible to distinguish various Dirac's forms of dynamics in experiments?

Sokolov and Shatnii proved that different forms of Dirac's dynamics are scattering equivalent [7, 8]. So, for S -matrix calculations we are allowed to choose any form of dynamics, as convenient. The canonical formulation of QFT was done in the instant form of dynamics [9], but Dirac's front form [10] and point form [11] also gained popularity in nuclear and particle physics.

In order to apply scattering theory to neutrino oscillations, Kleister and Polyzou [12] modified the standard S -matrix approach by considering two spatially separated scattering events (associated with neutrino production and neutrino detection), so that the oscillating neutrino was regarded as a virtual particle transmitting momentum-energy between these two vertices. By using instant form of Dirac's dynamics, the authors were able to reproduce the standard formula (1). They also inferred that the same result will hold in other forms as well. This conclusion was supported by Glazek and Traviński [13] who obtained formula (1) in the front form of modified scattering theory.

In this work we will approach neutrino oscillations from a different perspective. Instead of resorting to the S -

From Dirac To Neutrino Oscillations

Yoichiro Suzuki



From Dirac To Neutrino Oscillations:

From Dirac to Neutrino Oscillations Tino Ahrens, 2000-07-31 This text is meant to be a view of the quantum mechanical formalism as it develops with the successive introduction of different types of transformations. In particular it is meant to help the readers with three tasks: acquainting themselves with a general and direct approach to the quantum mechanics of spin one half and spin one particles primarily leptons, photons and massive vector bosons and to some extent quarks; finding out what some of the related areas of current research interest are; and last and foremost trying to understand the subject beginning with and stressing the principles involved. The exposition is based on finite dimensional representations of the homogeneous Lorentz group and the subsequent introduction of gauge transformations of the Abelian and non Abelian varieties. Reference to classical mechanics is avoided. Acting on the simple basis spinors and vectors, Lorentz transformations generate wave and field functions. Equations are obtained by the relativistic generalization of the addition of angular momenta, the wave or field functions being the solutions. For zero mass the equations may be obtained as the limits of the equations for the massive cases or by the application of the Euclidian group in two dimensions. The latter approach is illuminating in that it uncovers a loss in generality resulting from the former. Identifying momenta as eigenvalues of translations demonstrates covariance under the inhomogeneous Lorentz or Poincare group. Various representations of wave and field functions are given.

Neutrino Oscillations Fumihiko Suekane, 2015-03-23 Neutrino oscillation (N O) is the only firm evidence of the physics beyond the Standard Model of particle physics and is one of the hottest topics in elementary particle physics today. This book focuses on the N O from its history to the future prospects, from the basic theories to the experiments. Various phenomena of N O are described intuitively with thorough explanations of the fundamental physics behind well known formulations. For example, while many textbooks start with a discussion of the mixing matrix, this book stresses that N O is caused by the transition amplitudes between different neutrino flavors and that the purpose of N O experiments is to measure transition amplitudes and think of its origin. The current understanding of neutrino oscillation is also summarized using the most up to date measurements, including the recently measured neutrino mixing angle θ_{13} and the future prospects of N O studies are described as well. The level of this book makes it a bridge between introductory textbooks and scientific papers.

The Third International Workshop on Neutrino Oscillations and Their Origin Yoichiro Suzuki, 2002

Neutrino Oscillations And Their Origin, Proceedings Of The Third International Workshop Yoshiyuki Fukuda, T Mori, Masayuki Nakahata, Yoichiro Suzuki, Y Takeuchi, T Yoshida, 2002-12-30 Contents: Solar Neutrinos: The Latest Solar Neutrino Results in Super Kamiokande; Y Koshio: Weak Current in Deuterium; T Sato: Solar Neutrino Phenomenology and Future Solar Neutrino Oscillations; M C Gonzalez Garcia: The Status of Resonant Spin Flavor Precession; C S Lim: Atmospheric Neutrinos: Status of the Atmospheric Neutrino Studies; M D Messier: Cosmic Ray Measurements for Atmospheric Neutrino with BESS TeV; K Abe: Oscillation Phenomenology; I: Calculations of the Atmospheric Fluxes; P Lipari: Three Flavor Analysis of

Atmospheric and Solar Neutrinos A Marrone Absolute Neutrino Mass Neutrinoless Double Beta Decay and Neutrino Oscillations H V Klapdor Kleingrothaus Accelerator Neutrinos CPV The MINOS Experiment M D Messier The JHF Kamioka Neutrino Project T Kajita Models and GUTs Proton Decay in the Semi Simple Unification Model T Watari Leptogenesis via LHu Flat Direction M Fujii Lepton Flavor Violation Probing Physics Beyond the Standard Model from Lepton Sector J Hisano Oscillation Phenomenology II Four Puzzles of Neutrino Mixing S M Barr Supernova Neutrinos Supernova Neutrinos J F Beacom and other papers Readership Researchers in high energy physics Keywords Solar Neutrinos Atmospheric Neutrinos Oscillation Phenomenology Neutrino Mass Accelerator Neutrinos CP Violation GUTs Lepton Flavor Violation Supernova Neutrinos

Massive Neutrinos: Flavor Mixing Of Leptons And Neutrino Oscillations Harald Fritzsch, 2015-08-28

Since the discovery of neutrino oscillations neutrino physics has become an interesting field of research in physics They imply that neutrino must have a small mass and that the neutrinos coupled to the charged leptons are mixtures of the mass eigenstates analogous to the flavor mixing of the quarks The mixing angles for the quarks are small but for the leptons two of the mixing angles are large The masses of the three neutrinos must be very small less than 1 eV but from the oscillation experiments we only know the mass differences the absolute masses are still unknown Also we do not know if the masses of the neutrinos are Dirac masses as the masses of the charged leptons and of the quarks or whether they are Majorana masses In this volume an overview of the present state of research in neutrino physics is given by well known experimentalists and theorists The contents originated from talks and discussions at a recent conference addressing some of the most pressing open questions in neutrino physics range from the oscillation experiments to CP violation for leptons to texture zero mass matrices and to the role of neutrinos in astrophysics and cosmology

A Search for Muon Neutrino to Electron Neutrino Oscillations in the MINOS Experiment Juan Pedro Ochoa-Ricoux, 2011-04-11

The centerpiece of the thesis is the search for muon neutrino to electron neutrino oscillations which would indicate a non zero mixing angle between the first and third neutrino generations 13 currently the holy grail of neutrino physics The optimal extraction of the electron neutrino oscillation signal is based on the novel library event matching LEM method which Ochoa developed and implemented together with colleagues at Caltech and at Cambridge which improves MINOS Main Injector Neutrino Oscillator Search reach for establishing an oscillation signal over any other method LEM will now be the basis for MINOS final results and will likely keep MINOS at the forefront of this field until it completes its data taking in 2011 Ochoa and his colleagues also developed the successful plan to run MINOS with a beam tuned for antineutrinos to make a sensitive test of CPT symmetry by comparing the inter generational mass splitting for neutrinos and antineutrinos Ochoa s in depth creative approach to the solution of a variety of complex experimental problems is an outstanding example for graduate students and longtime practitioners of experimental physics alike Some of the most exciting results in this field to emerge in the near future may find their foundations in this thesis

Neutrino Oscillations And Their Origin, Proceedings Of The 4th International

Workshop Masayuki Nakahata,Y Itow,Masato Shiozawa,Y Obayashi,Yoichiro Suzuki,2004-05-24 The discovery of neutrino oscillations in 1998 initiated efforts to form a group to work on the detailed study of the phenomenon this study is now supported by a grant in aid in the specific field of neutrinos from the Japanese Ministry of Education Culture and Sports The aim of this working group is to put together the efforts from various fields necessary for understanding neutrino oscillations in detail from both the experimental and the theoretical point of view The 4th International Workshop on Neutrino Oscillations and Their Origin was held to discuss recent progress in both experimental and theoretical study *The Fourth International Workshop on Neutrino Oscillations and Their Origin* Y. Suzuki,Y. Itow,M. Nakahata,Y. Obayashi,M. Shiozawa,2004 Annotation Contents Status and Future Prospects of Reactor Neutrinos Solar Neutrinos and Supernova Neutrinos Status and Future Prospects of Long Baseline Neutrino Experiments Atmospheric Neutrinos Dark Matter Searches and Double Beta Decays Lepton Number Violated Muon Decays Proton Decay Searches Neutrino Phenomenology and Model Building *Neutrino Oscillations* Jennifer A. Thomas,Patricia L. Vahle,2008 This book reviews the status of a very exciting field neutrino oscillations at a very important time The fact that neutrinos have mass has only been proved in the last few years and the acceptance of that fact has opened up a whole new area of study to understand the fundamental parameters of the mixing matrix The book summarizes the results from all the experiments which have played a role in the measurement of neutrino oscillations and briefly describes the scope of some new planned experiments Contributions include a theoretical introduction by Stephen Parke from FNAL as well as articles from all the major experimental groups who have been pivotal in uncovering the nature of the neutrino mass **Physics of Neutrinos** Masataka Fukugita,Tsutomu Yanagida,2013-06-29 This book aims to provide a survey of the current state of research in the physics of neutrinos which has undergone dramatic development during the last decade in a form accessible to the nonspecialist and the graduate student The major issue during the last two decades has been the neutrino mass whereas the interaction of neutrinos was well understood within the framework of the standard theory which was established in the 1970s In 1994 we published a textbook format review article Physics 01Neutrinos in Physics and Astrophysics 01 Neutrinos in anticipation that the mass of the neutrino would be found in the near future It was indeed found thanks to the Super Kamiokande experiment four years after that book was written and a flurry of activity followed in the phenomenology of the neutrino mass From the theoretical point of view the importance of this discovery stems from the fact that it probably indicates the presence of a new energy scale beyond the standard theory At the same time the formalism for massive neutrinos and the techniques to find the neutrino mass have now realistic importance and have become the subject of standard physics On the other hand experiment revealed that the pattern of the neutrino mass and mixing among generations appears in a way different from what has been speculated on the basis of existing theoretical models Proceedings of the Conference in Honour of Murray Gell-Mann's 80th Birthday H. Fritzsch,2010 The Conference on Quantum Mechanics Elementary Particles Quantum Cosmology and Complexity was held in

honour of Professor Murray Gell Mann's 80th birthday in Singapore on 24-26 February 2010. The conference paid tribute to Professor Gell Mann's great achievements in the elementary particle physics. This notable birthday volume contains the presentations made at the conference by many eminent scientists including Nobel laureates C. N. Yang, G. 't Hooft and K. Wilson. Other invited speakers include G. Zweig, N. Samios, M. Karliner, G. Karl, M. Shifman, J. Ellis, S. Adler and A. Zichichi. **Neutrinos in Particle Physics, Astronomy and Cosmology** Zhizhong Xing, Shun Zhou, 2011-06-08. Neutrinos in Particle Physics, Astronomy and Cosmology provides a comprehensive and up to date introduction to neutrino physics, neutrino astronomy and neutrino cosmology. The intrinsic properties and fundamental interactions of neutrinos are described as is the phenomenology of lepton flavor mixing, seesaw mechanisms and neutrino oscillations. The cosmic neutrino background, stellar neutrinos, supernova neutrinos and ultrahigh energy cosmic neutrinos together with the cosmological matter-antimatter asymmetry and other roles of massive neutrinos in cosmology are discussed in detail. This book is intended for researchers and graduate students in the fields of particle physics, particle astrophysics and cosmology. Dr Zhizhong Xing is a professor at the Institute of High Energy Physics, Chinese Academy of Sciences, China. Dr Shun Zhou is currently a postdoctoral fellow at the Max Planck Institute for Physics, Germany. *Measurement of Neutrino Interactions and Three Flavor Neutrino Oscillations in the T2K Experiment* Tatsuya Kikawa, 2015-09-18. This book is based on the author's work in the T2K long baseline neutrino oscillation experiment in which neutrinos are generated by a proton beam and are detected by near and far neutrino detectors. In order to achieve the precise measurement of the neutrino oscillation, an accurate understanding of the neutrino beam and the neutrino interaction is essential. Thus the author measured the neutrino beam properties and the neutrino interaction cross sections using a near neutrino detector called INGRID and promoted a better understanding of them. Then the author performed a neutrino oscillation analysis using the neutrino beam and neutrino interaction models verified by the INGRID measurements. As a result, some values of the neutrino CP phase are disfavored at the 90% confidence level. If the measurement precision is further improved, we may be able to discover the finite CP phase which involves the CP violation. Thus this result is an important step towards the discovery of CP violation in the lepton sector which may be the key to understanding the origin of the matter-antimatter asymmetry in the universe. *Particle Physics - Proceedings Of The 1999 Summer School* Goran Senjanovic, Anatoly Yuri Smirnov, 2000-05-24. In this volume, precision tests of the Standard Model and a wide spectrum of physics beyond it, such as supersymmetry, grand unification and the fermion mass problem are covered. The emphasis is on the areas where new experimental results will lead to significant progress in neutrino physics, CP violation and B physics. The articles written by top level experts in the fields give a comprehensive view of the state of the art of modern particle physics. *Commemorating the Past and Looking Towards the Future* Ngee-pong Chang, Hon Ming Lai, Cheuk-Yin Wong, 2002. OCPA 2000 provided a forum for researchers from the various subfields of physics to broaden their knowledge horizons. It promoted friendship among ethnic Chinese physicists from all the continents and fostered a sense of

belonging to a community with a strong tradition of scholarship and heritage Ethnic Chinese physicists gathered to review past accomplishments and to consider making further contributions to the world of physics

Introduction to the Physics of Massive and Mixed Neutrinos Samoil Bilenky, 2010-09-02 For many years neutrino was considered a massless particle The theory of a two component neutrino which played a crucial role in the creation of the theory of the weak interaction is based on the assumption that the neutrino mass is equal to zero We now know that neutrinos have nonzero small masses In numerous experiments with solar atmospheric reactor and accelerator neutrinos a new phenomenon neutrino oscillations was observed Neutrino oscillations periodic transitions between different flavors of neutrinos are possible only if neutrino mass squared differences are different from zero and small and flavors of neutrinos are mixed The discovery of neutrino oscillations opened a new era in neutrino physics an era of investigation of neutrino masses mixing magnetic moments and other neutrino properties After the establishment of the Standard Model of the electroweak interaction at the end of the seventies the discovery of neutrino masses was the most important discovery in particle physics Small neutrino masses cannot be explained by the standard Higgs mechanism of mass generation For their explanation a new mechanism is needed Thus small neutrino masses is the first signature in particle physics of a new beyond the Standard Model physics It took many years of heroic efforts by many physicists to discover neutrino oscillations After the first period of investigation of neutrino oscillations many challenging problems remained unsolved One of the most important is the problem of the nature of neutrinos with definite masses Are they Dirac neutrinos possessing a conserved lepton number which distinguish neutrinos and antineutrinos or Majorana neutrinos with identical neutrinos and antineutrinos Many experiments of the next generation and new neutrino facilities are now under preparation and investigation There is no doubt that exciting results are ahead

The Physics of Ettore Majorana Salvatore Esposito, 2015 A unique volume exploring Majorana's work for graduate students and researchers interested in the history of science

The Physics of the Standard Model and Beyond T. Morii, C. S. Lim, S. N. Mukherjee, 2004 This book provides a unified description of elementary particle interactions and the underlying theories namely the Standard Model and beyond The authors have aimed at a concise presentation but have taken care that all the basic concepts are clearly described Written primarily for graduate students in theoretical and experimental particle physics The Physics of the Standard Model and Beyond conveys the excitement of particle physics centering upon experimental observations new and old and a variety of ideas for their interpretation Contents Weak Interaction Symmetries and the Gauge Theories The Standard Model of Electroweak Interactions Quantum Chromodynamics Neutrino Masses and Neutrino Oscillations Supersymmetry Precision Test of Electroweak Radiative Corrections and New Physics Flavor Physics and CP Violation Appendices Notation and Useful Relations Cross Sections and Feynman Rule Basics of the Group Theory C P and T Transformation The Quark Model Readership Graduate students experimentalists and theorists in high energy physics

Particle And Astroparticle Physics, Gravitation And Cosmology: Predictions, Observations And New Projects -

Proceedings Of The Xxx-th International Workshop On High Energy Physics Roman Anatolievich Ryutin,Vladimir Alexeevich Petrov,2015-06-16 This unique volume captures the content of the XXXth International Workshop on High Energy Physics The scope of this volume is much wider than just high energy physics it actually concerns and includes materials from all the most fundamental areas of modern physics research high energy physics proper gravitation and cosmology Presentations embrace both theory and experiment *Neutrinos in High Energy and Astroparticle Physics* Jose Wagner Furtado Valle,Jorge Romao,2015-02-02 This self contained modern textbook provides a modern description of the Standard Model and its main extensions from the perspective of neutrino physics In particular it includes a thorough discussion of the varieties of seesaw mechanism with or without supersymmetry It also discusses schemes where neutrino mass arises from lighter messengers which might lie within reach of the world s largest particle accelerator the Large Hadron Collider Throughout the text the book stresses the role of neutrinos due to the fact that neutrino properties may serve as a guide to the correct model of unification hence for a deeper understanding of high energy physics and because neutrinos play an important role in astroparticle physics and cosmology Each chapter includes summaries and set of problems as well as further reading

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