FROM CP VIOLATION TO ARROWS OF TIME: A VOYAGE THROUGH STRANGENESS AND BEAUTY

L.M. Sehgal

1. SOME HISTORY, SOME NOSTALGIE

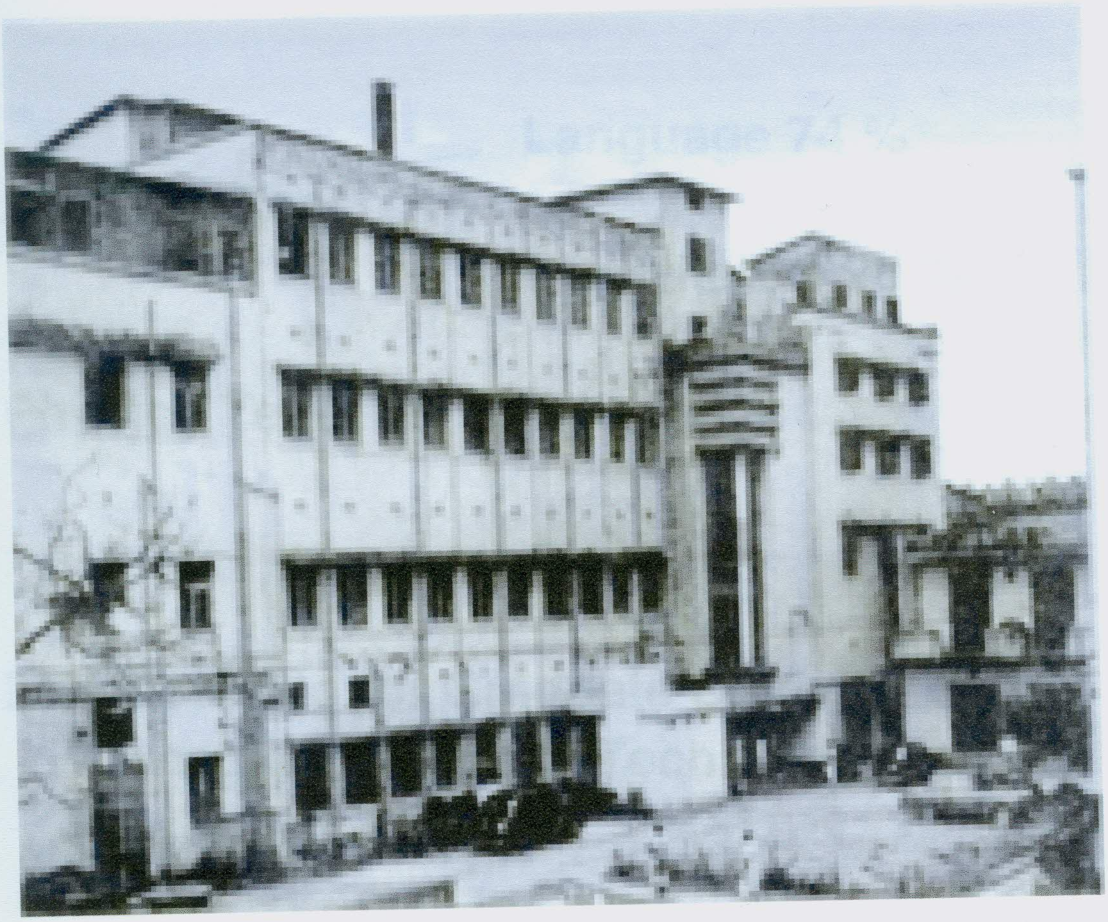
2. UNDERSTANDING CP VIOLATION: TRIUMPH OF CKM HYPOTHESIS

2. CP VIOLATION AND ARROWS OF TIME

CHANDIGARH 1961-62

Physics Department, Panjab University

CALCUTTA 1962-63



Saha Institute of Nuclear Physics

1963: A Year of Good Tidings

1. Graduate Record Exam

Aptitude Test → Language 74 %
Aptitude Test → Quantitative 99 %

Physics Test : 99 %

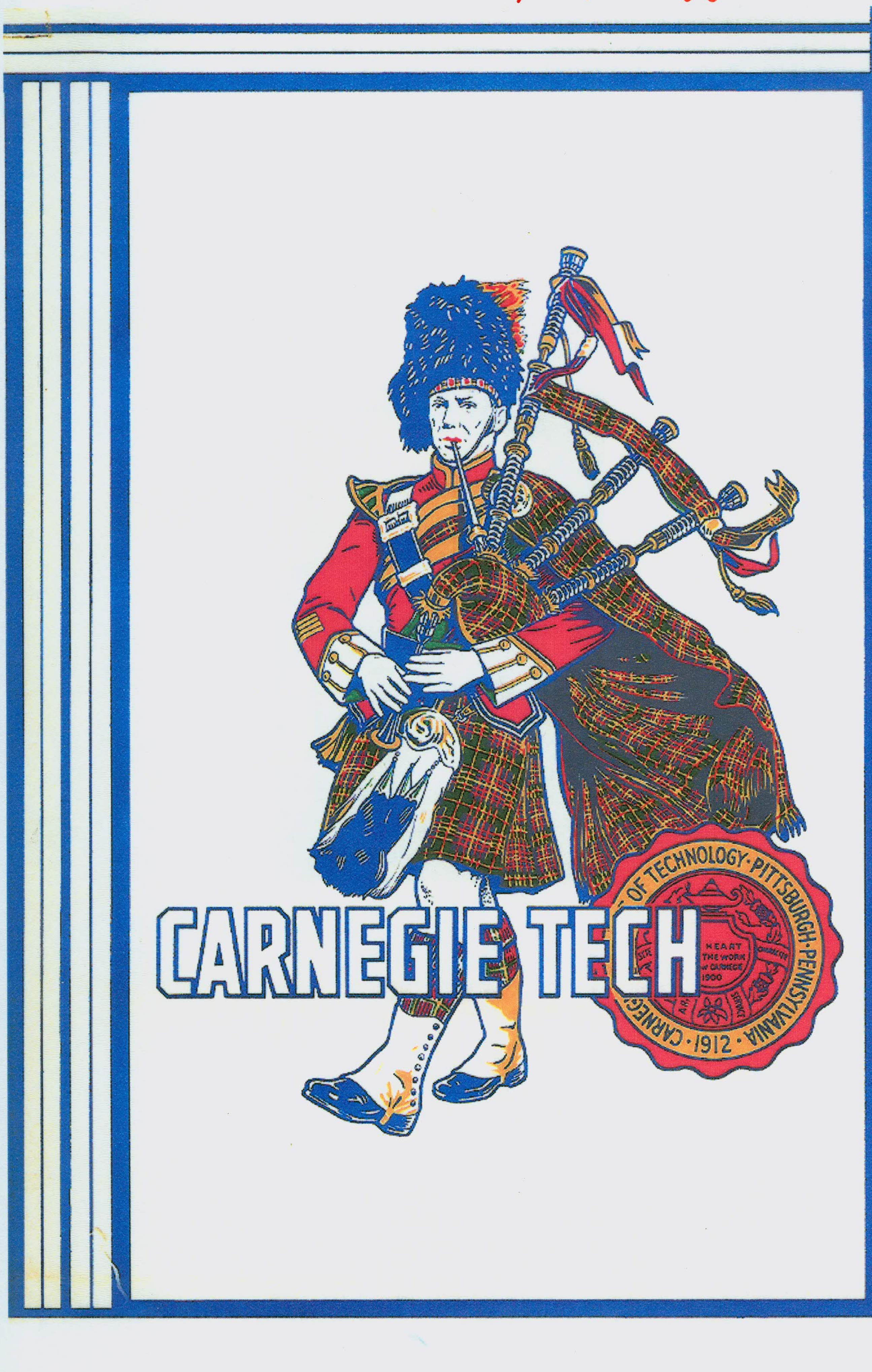
2. Fellowship for Graduate Study:
   Carnegie Institute of Technology,
   Pittsburgh

3. Fulbright award for travel to U.S.A.

BOMBAY, July 27, 1963

SS ORSOVA

PITTSBURGH, 1963-68



Sergio De Benedetti

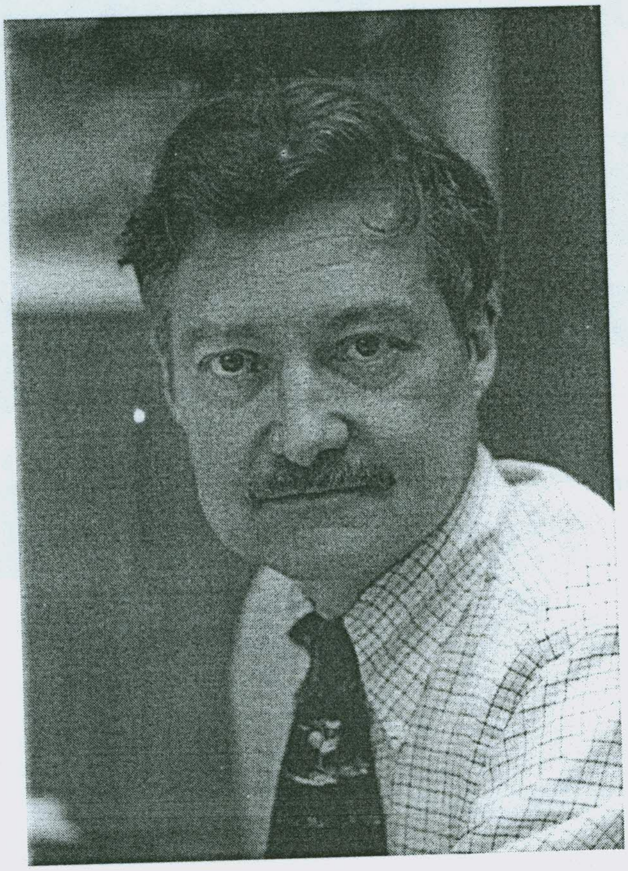
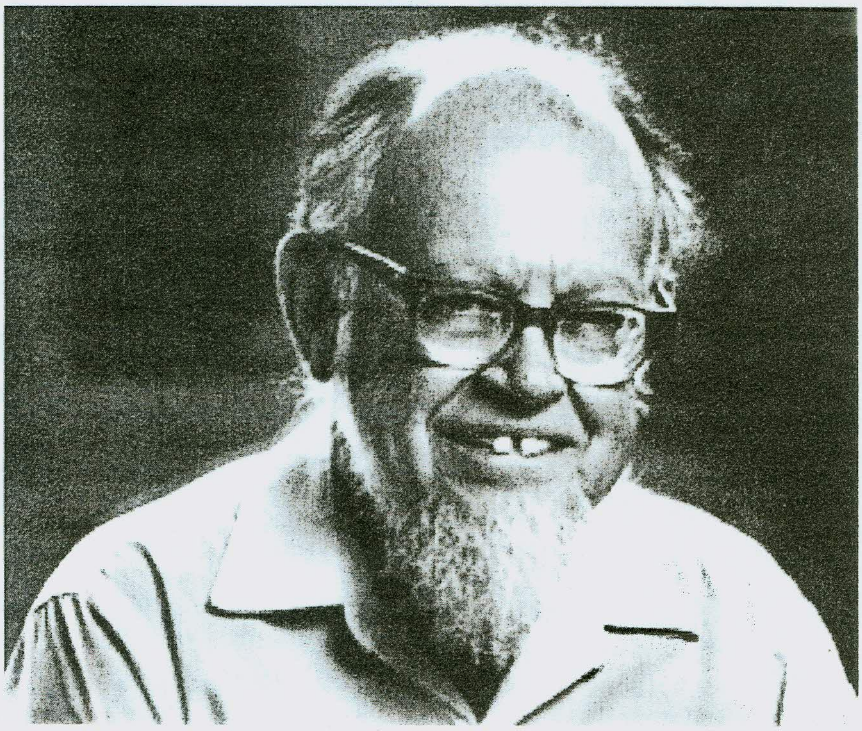


Figure 1: R. Cutkosky



Lincoln Wolfenstein

1968-71: Tata Institute of Fundamental Research

BOMBAY

[T. Das, N. Mukunda, P. Divakaran, G. Rajasekaran, K.V.L. Sarma, V. Singh, V. Gupta, S.M. Roy, D. Sankaranarayan, J. Pasupathy, L.K. Pandit, and many others.]

LMS : Papers 1968-71

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IMPLICATIONS OF UNEQUAL CHARGE ASYMMETRY IN $K_L^0 - \pi^\pm e^\mp \nu$ AND $K_L^0 - \pi^\pm \mu^\mp \nu$

L. M. Sehgal
Tata Institute of Fundamental Research, Bombay, India
(Received 10 June 1968)

The possibility is considered that the charge asymmetries δ_e and δ_μ in the decays $K_L^0 - \pi^\pm e^\mp \nu$ and $K_L^0 - \pi^\pm \mu^\mp \nu$ might turn out to be different. Some implications, including a test of CPT, are pointed out.

Tests of CP and CPT Invariance in the Decay $K_L \to l\bar{l}$

L. M. SEHGAL
Tata Institute of Fundamental Research, Bombay, India
(Received 29 January 1969)

Pais and Treiman have studied the implications of CP and CPT invariance for the decay $K_L \to l\bar{l}$. We indicate how their results are modified when account is taken of the possibility of real intermediate states in this decay.

Electromagnetic Contribution to the Decays $K_S \to l\bar{l}$ and $K_L \to l\bar{l}$*

L. M. SEHGAL
Tata Institute of Fundamental Research, Bombay, India
(Received 5 March 1969)

Using a model in which the decays $K_{S,L} \to l\bar{l}$ occur through a two-photon intermediate state, and considering only the absorptive part of the amplitudes, we obtain lower bounds on the ratios Rate$(K_{S,L} \to l\bar{l})$/ Rate$(K_{S,L} \to \gamma\gamma)$.

$\mu{:}e$ RATIO IN $\eta^0 - \pi^0 l^+ l^-$ AND $X^0 - \eta^0 l^+ l^-$ AS A TEST OF ELECTROMAGNETIC C NONINVARIANCE

L. M. Sehgal
Tata Institute of Fundamental Research, Bombay, India
(Received 23 April 1969)

If the decays $\eta^0 - \pi^0 l^+ l^-$ occur via a C-nonconserving (isovector) electromagnetic interaction, the ratio $\Gamma(\eta^0 - \pi^0 e^+ e^-)/\Gamma(\eta^0 - \pi^0 \mu^+ \mu^-)$ should be 3.3. Similarly, if the decays $X^0 - \eta^0 l^+ l^-$ are induced by a C-nonconserving (isoscalar) interaction, the ratio $\Gamma(X^0 - \eta^0 e^+ e^-)/\Gamma(X^0 - \eta^0 \mu^+ \mu^-)$ should be 2.9.

ELECTROMAGNETIC CORRECTIONS TO THE COHERENT K_L-K_S REGENERATION AMPLITUDE IN HYDROGEN

K. V. L. SARMA and L. M. SEHGAL
Tata Institute of Fundamental Research, Bombay 5, India

Received 8 February 1971

Abstract: Electromagnetic corrections to the coherent K_L-K_S regeneration amplitude from protons, $f_{21} = f(0) - \bar{f}(0)$ are estimated in a model based on elastic unitarity and Regge behaviour. The correction to Im f_{21}/k is found to vanish asymptotically as $(\ln s)^{-2}$. The correction to Re f_{21}/k, assuming additivity of the Coulomb- and strong-phase shifts, is also finite. Numerical values are given at a typical energy.

T, P, and C Symmetries in $K_{L,S} \to \gamma\gamma$

L. M. Sehgal
Tata Institute of Fundamental Research, Bombay 5, India
(Received 8 February 1971)

The Bernstein-Michel analysis of $\pi^0 - \gamma\gamma$ is applied to the decays $K_{L,S} - \gamma\gamma$. It is shown that, in contrast to the situation in $\pi^0 - \gamma\gamma$, a hypothetical violation of CP invariance in $K_{L,S} - \gamma\gamma$ can, in principle, be detected by a measurement of the circular polarization of *one* of the two photons.

Sept. 1971 : RWTH Aachen

H. Faissner, K. Schultze, J. von Krogh, J. Morfin, H. Reithler, E. Radermacher, K. Eggert, A. Böhm, F. Hasert, H. Weerts, D. Lanske et al

Theorie: R. Rodenberg, D. Rein, G. Köpp, B.R. Kim

June 1972 : Balatonfüred , Neutrino '72

R.P. Feynman , T.D. Lee , R. Marshak, V. Weisskopf, B. Pontecorvo , Y. Zeldovich , V. Gribov , V. Telegdi , F. Reines , R. Davis , J. Bahcall , B. Barish , D. Cline, C. Baltay et al

TIFR/TH/72-9

YANG-MILLS FIELDS AND THEORY OF WEAK INTERACTIONS

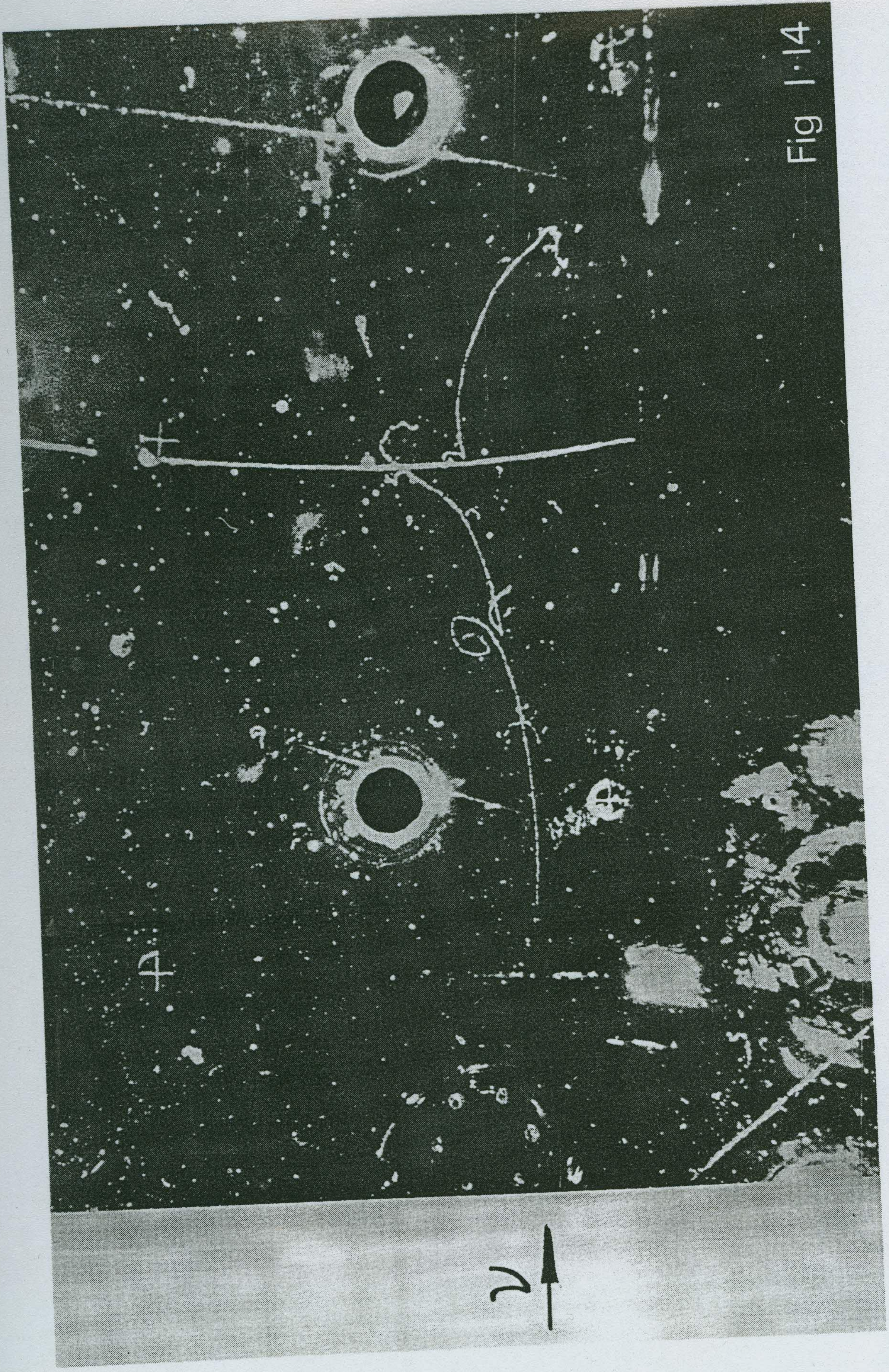
G. RAJASEKARAN
Tata Institute of Fundamental Research
BOMBAY - 5

LECTURES GIVEN AT
SAHA INSTITUTE OF NUCLEAR PHYSICS
92, Acharya Prafulla Chandra Road
CALCUTTA-9

(JUNE, 1971)

(This was previously issued as a Saha Institute Report. The present version incorporates some minor corrections and an addendum.)

Dec. 1972 : Aachen Event



First Observation of $\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$

III. Physikalisches Institut

der Rheinisch-Westfälischen Technischen Hochschule

Aachen

PITHA-(1973) NR 68

Unified Theories of Weak and Electromagnetic Interactions: An Elementary Introduction

L.M. Sehgal

III. Physikalisches Institut
Technische Hochschule Aachen

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geneva 12.4.1973 our telex ref 4018 15.25 mh

dr lm sehgal
physikalisches institut
technische hochschule

could you kindly send us 85 additional copies of your report pitha-(1973)nr 68, ''unified theories of weak and electromagnetic interactions: an elementary introduction.

thank you

b.e. josephy cernlab / library

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TELEX TELEX TELEX

Nuclear Physics B65 (1973) 141–157. North-Holland Publishing Company

PREDICTIONS OF THE WEINBERG MODEL FOR NEUTRAL CURRENTS IN INCLUSIVE NEUTRINO REACTIONS*

L.M. SEHGAL
III. Physikalisches Institut, Technische Hochschule Aachen, Aachen, W-Germany

Received 19 June 1973

Abstract: We investigate the consequences of the Weinberg theory for neutral current reactions of the type $\nu(\bar{\nu})$ + nucleon → $\nu(\bar{\nu})$ + hadrons, using a quark parton model. The total cross section ratios $R = \sigma(\nu \to \nu)/\sigma(\nu \to \mu^-)$ and $\bar{R} = \sigma(\bar{\nu} \to \bar{\nu})/\sigma(\bar{\nu} \to \mu^+)$ are obtained as functions of the Weinberg angle θ, and have the minimum values $R_{\min} = 0.17$, $\bar{R}_{\min} = 0.37$. An approximate relation between R and $\bar{R}$ is obtained, which is independent of the Weinberg angle: $\frac{1}{2}(1-3R+\bar{R}) = [\frac{27}{40}(\bar{R}-R)]^{\frac{1}{2}}$. Predictions are made for the average ν and average Q^2 in comparison to those in charged current reactions. Preliminary results of the Gargamelle experiment are compared with the theory.

1. Introduction

The Weinberg model unifying weak and electromagnetic interactions predicts the existence of neutral lepton and neutral hadron currents in weak processes [1]. The coupling of such currents to each other should produce observable effects such as semi-leptonic reactions which are distinguished from the normal weak reactions by the fact that no charge is transferred from the lepton to the hadron system. Of particular interest is the prediction of neutrino induced reactions of the type $\nu(\bar{\nu}) + \mathrm{N} \to \nu(\bar{\nu})$ + hadrons (N = nucleon) which differ from the normal reactions $\nu(\bar{\nu}) + \mathrm{N} \to \mu^-(\mu^+)$ + hadrons by the absence of a charged lepton in the final state. It was shown by Pais and Treiman [2] and by Paschos and Wolfenstein [3] that the inclusive cross sections for such neutral current reactions have, in the Weinberg model, lower limits which are quite large, and which therefore make these reactions suitable for an experimental test of the model.

The purpose of this paper is to examine closely the quantitative predictions of the Weinberg theory for neutral currents in inclusive neutrino reactions. We assume that the neutral current process, like its charged current counterpart, shows a scaling behaviour at high energies, and adopt a parton model for the description of the deep inelastic scattering [4–6]. The parton model employed is one which affords a satis-

* Work supported by the German Bundesministerium für Technologie and Wissenschaft.

1974: A Busy Year

January:	- Seminar in Rutherford Lab - Seminar in Trinity College, Dublin
February:	- Plenary talk, DPG Tagung Hamburg
March:	- Visit to CERN (met Wolfenstein)
May:	- Seminar in Liége
June:	- Seminar in Karlsruhe
September:	- Talk in Weak Interaction Meeting, Strobl (got to know Pais)

+

Nine papers written !

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ANL-HEP-PR-75-45

PHENOMENOLOGY OF NEUTRINO REACTIONS

L. M. Sehgal

III. Physikalisches Institut
Technische Hochschule Aachen
Aachen, W. Germany

(Lectures given at Argonne National Laboratory, August 1975)

HIGH ENERGY PHYSICS DIVISION

ARGONNE NATIONAL LABORATORY
ARGONNE, ILLINOIS

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
SIEGE: GENÈVE/SUISSE

CERN LABORATOIRE I

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1211 GENÈVE 23
SUISSE / SWITZERLAND

27/2/76

Dear Sehgal:

I have been studying your notes with great profit to myself. They are clear and precise and to the point. I have also suggested, without success, that you be asked to give the lectures, since you know the material much better and will be there anyway, but they (Weyers) insist on an experimenter. I will, of course, try to stay as much as possible with experiment. But may I ask if it would be possible for you to have a copy of your Argonne lectures for every student?

Sincerely yours

J Steinberger

1976 : Another Busy Year

January:	- Seminar in Mainz
February:	- Seminar in Strasbourg
March:	- Seminar in Orsay
May:	- Seminar in Bielefeld
June:	- CERN School of Physics, Wepion (Tutor to Jack Steinberger) - Neutrino Conference, Aachen
July:	- Seminar in Siegen
August:	- Gordon Conference, Tilton, NH (talk) - Seminar in Brookhaven
September:	- Minerva Symposium, Kleinwalsertal (talk)
November:	- Seminar in Heidelberg - Seminar in Dortmund - Seminar im CERN
December:	- Seminar in Bonn - Seminar in Wuppertal

Neutrino Conference Aachen
1976

Highlights

1. Neutral Currents (Sakurai, Gourdin)
2. Charm (De Rujula, Gaillard)
3. τ-Lepton (Perl)
4. CP Violation (Wolfenstein)
5. Reactor Neutrinos (Reines)
6. Proposal: $\bar{p}p$ Collider (Rubbia)
7. Summary (B. W. Lee)

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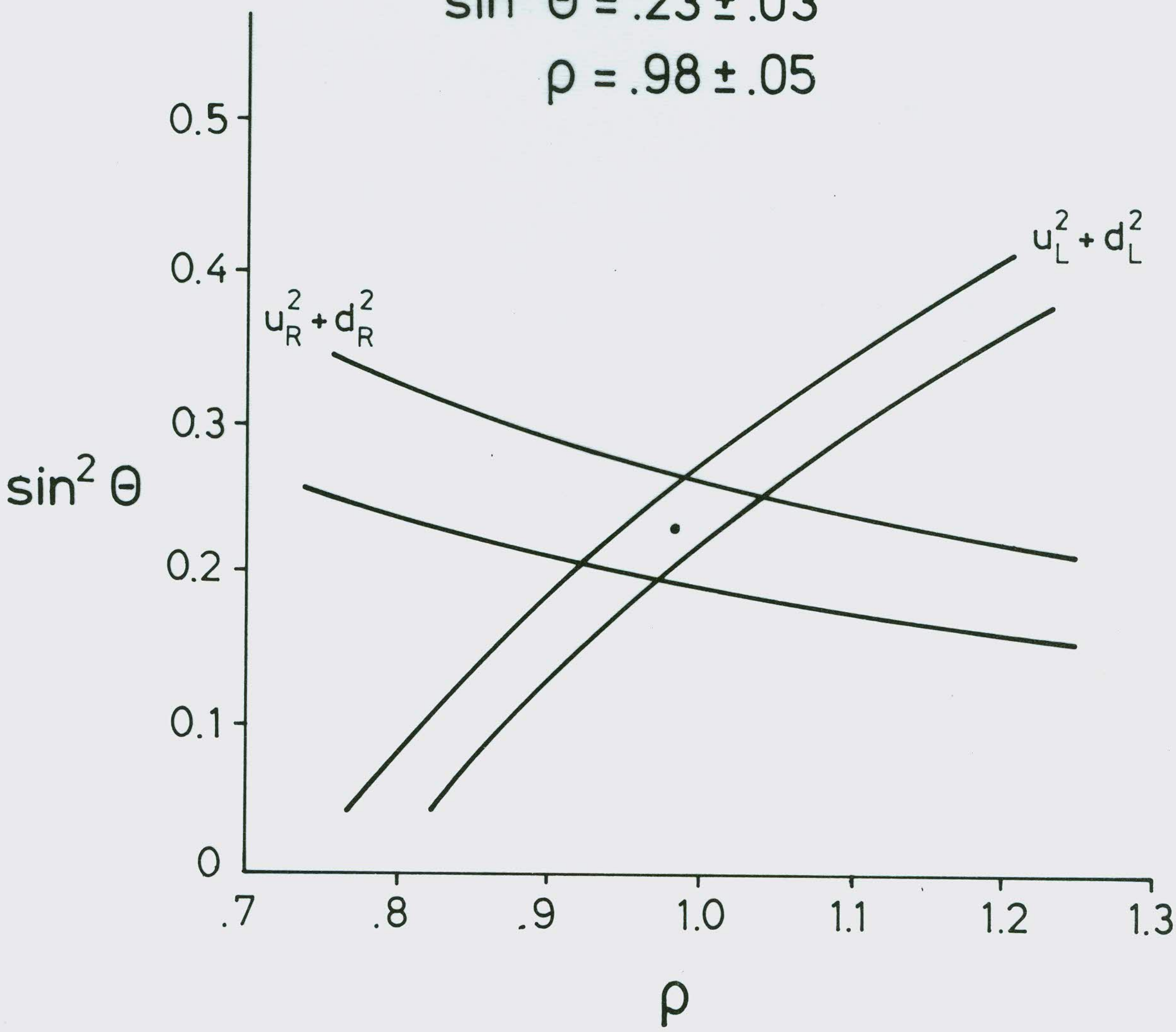
Neutrino '78 Conference
Purdue

$\sin^2\Theta = .23 \pm .03$
$\rho = .98 \pm .05$



A Salaam To A. Salam

THIS article is a salute, a salaam, to Abdus Salam, who was awarded the Nobel Prize in Physics recently for his work on the unification of two forces of nature in one mathematical scheme.

He was born in Jhang town of the Punjab in undivided India on January 29, 1926, and is now a citizen of Pakistan although he has lived and worked outside it for the last 25 years. Salam belongs to the Ahemediya sect founded by Mirza Ghulam Ahmed, who died in Qadian near Amritsar in 1908. It is of topical interest to know that Ahmed proclaimed himself as the Mahdi as well as the Messiah, and he interpreted Jehad as striving for righteousness and inspired his followers to seek knowledge and serve others.

Pakistan in its peculiar penchant for the purity of Islam, however, declared Ahmediyas as "non-Muslims", a few years ago. Salam is as good a Muslim as any; he wears a Fez sometimes and comes out of conferences to do the decreed devotions (Namaz) regularly. He attributed the Nobel award to the Grace of Allah and has donated the prize money, which is perhaps all that he would have had, for the benefit of Pakistan's children —alas! only one-third of the prize which is $ 60,000, since he shares it with the Americans, Weinberg and Glashow.

Salam, took a masters' degree from Lahore in 1946, but failed to get a job at the Delhi University. A similar situation arose later when Hargobind Khorana could not find employment in India; Prof. Thacker was said to have told him that he had already too many molecular biologists in India.

Salam got a "small farmer's son's" scholarship from the Punjab, went to England and took a Ph.D. from Cambridge, in 1952, after which he worked for three years as the head of the mathematics department at the Lahore University. He had to abandon this post, however, because he found it impossible to establish a school of research. Yet, he was connected with scientific activities in Pakistan until he was declared a "non-Muslim". Interestingly, he has co-authored a report entitled, "Persecution of Admediyas in Pakistan."

Salam was elected Fellow of the Royal Society of London in 1959, at the age of 33. This society also awarded him with two of its medals, Hughes in 1964 and Royal in 1978. (Raman was given the Hughes medal and Chandrasekhar the Royal Medal). At present Salam is a Professor of Physics at the Imperial College of Science and Technology in London and concurrently Director of the International Centre for Theoretical Physics, at Trieste in Italy, where he has invited a number of promising physicists of developing countries in the spirit of a true Admediya.

What was the work that Salam did which won him a Nobel? Well, it is for a theory which claims to unify weak and electromagnetic interactions (or forces). Actually not less than three dozen physicists have contributed materially to the work which has culminated in the crowning theory of Glashow, Salam and Weinberg (G-S-W). The path-breaking steps were taken by Enrico Fermi in 1934 and E.C.G. Sudershan (with Marshak) in 1957. And G-S-W theory could not simply have taken off without the crucial recent work of P. W. Higgs and of the self-effacing young G't Hooft of Utrecht. Nor can one, in all fairness, leave out in the cold the experimental physicists and engineers without whose efforts the new theory would have remained only a morbid mathematical symbolism.

The first experimental verification of a significant prediction of the theory came from the Gargamelle detector in Italy, in 1973, named after the mother of the gluttonous giant, Gargantua, offspring of the fertile mind of Rabelais. And a veritable glutton it is. Fifty-five scientists hailing from six countries were needed to perform the experiment. However, two pages sufficed for the report, proving eloquently that brevity is the soul of wisdom! But the Mother saw to it that no less a number than 290,000 pictures were taken before she yielded the anticipated information about interactions, in which some of the participating particles can never be made visible. (Wait, a man cannot yet be made from these particles!) Incidentally, an Indian scientist, L. M. Sehgal, working in Germany, made the most detailed analysis of the Gargamelle results to show that they strongly corroborate the new theory of weak interactions.

I am sure the Nobel committee was in a fix. The physics prizes have usually been given to one person, sometimes to two and rarely to three for the same work. I think the committee must revise their ideas. Science is becoming more and more of a democratic process requiring the will, wits and work of many. I should also add, with regret, that there are only three communities with enormous machines, tons of money and facilities for joint research, which can possibly win the prizes in sciences in future. (U.S.A. including Japan, Western Europe and Eastern Europe). The large gargantuan facilities in these countries must be opened up to the whole world. It is a fit challenge to the U.N.

Let us return to the subject of the prize. What are these weak interactions and why are we bothered about these weak ones? And what is the big thing about these unifications?

Well, physics is very concerned with unifications. It is constantly endeavouring to reduce the number of principles required for the explanation of physical changes, the ultima thule, like the Brahman of the Vedantists, being a single white and eternal law, so that the physicist could say with Shelley:

The One remains, the many change and pass,
Heaven's light forever shines Earth's shadows fly;
Life, like a dome of many-coloured glass,
Stains the white radiance of Eternity,

Believe it or not, physics has proceeded so far as to claim that it needs just four principles or laws to explain its entire mysteries, and the Glashow-Salam-Weinberg theory makes a bold bid to amalgamate two principles reducing the ultimate laws to a trinity.

All physics can be explained in terms of the laws of certain interactions or forces, which describe how things will happen. The four interactions are: gravitational, electromagnetic, strong, and weak. And now let us explain them briefly.

The law of gravitation, according to legend, was discovered by Newton when he saw an apple falling on the earth and he extended this idea to the orb of the planets. Incidentally, the force exerted by the earth on the apple is precisely the same as that of the small apple on the earth. Einstein later showed that the geometry of space and working of clocks are affected by gravitating bodies, and thus Newton's theory received a modification. But even Einstein's theory is not clear as to how gravitational effects are propagated.

The second type of interaction is electromagnetic. It was Faraday who showed through experiments that electric and magnetic forces are connected with each other. He demonstrated this first to his wife on Christmas morning in 1821, when he showed her the revolution of a magnetic needle around an electric current.

Maxwell put the laws of electromagnetic interactions into equations so marvellous that when the great German physicist, Boltzmann, saw them he exclaimed, "Who was the God who wrote these signs?" Planck and Einstein showed that electromagnetic actions are carried by quanta now known as photons. But efforts to unify gravity and electromagnetism have not yet succeeded. Einstein attempted unification of these two forces for more than 25 years but he confessed that he had failed. A little before his death, he told his son that he wished he knew more mathematics. The electrical forces between, say, two electrons or protons are enormously greater than the gravitational forces. The above two forces sufficed to explain all of physics until about 50 years ago. But when the interior of the atom began to be explored, and new types of fundamental particles even smaller than the smallest atom were discovered, things changed.

Let us now come to the third force or the strong nuclear force. The nucleus is surrounded by electrons which are much lighter than the proton but each electron has the same charge as the more massive proton but of the opposite sign. There is a lot of empty space between the nucleus and the electrons but the two sets of positive and negative charges are equal and the atom as a whole is electrically neutral and stable.

The following question now arises. How does the nucleus by itself remain stable? Why does it not break up due to the well-known repulsion of like electrical charges on the protons? The theory to explain this stability is expressed in mathematics so ob-ture that thoughts desert me in a race! The physical idea is roughly this: A new type of powerful attractive force exists at short distances between protons and neutrons. This force is propagated by particles called pi mesons. The proton and neutron are supposed to be essentially identical particles exchanging these mesons, a neutron becoming proton and then again a neutron, in a see-saw game which ensures stability. This then is the third (strongly interacting) force, set at very short distances between nuclear particles, which is larger than the electrical force.

The fourth force or interaction called the weak interaction, forced itself on the physicists when it was found that nuclei of some atoms and some fundamental particles like neutrons and mesons, by themselves spontaneously break up. This happens in radium for example. Such atoms and particles have fixed "half-lives". Let me explain this concept of "half-life". The half-life of a neutron is about 10-1|2 minutes; that is to say, in this period half of the neutrons present at the beginning of the period would break up or decay; in another period of 10-1|2 minutes, half of the remainder would decay, leaving one-quarter and so on. This law of half-lives looks simple but it really violates causality because there is no way of telling which neutrons will decay earlier. It is a matter of chance. The half-life of radium atoms is 1,662 years.

Neutrons left to themselves break up at the rate stated above, one neutron yielding a proton, an electron (also called a beta particle) and a neutrino. This neutrino is an illusive entity, having no mass or electric charge, but travelling with the velocity of light, having half a unit of spin and carrying any amount of energy. When Pauli postulated it, he bet a bottle of champagne that the neutrino will never be found. He did not realise that he could never claim his bottle of champagne in any case, unless he waited till eternity. In the event, he had to give a bottle. It was the above mentioned neutrino-yielding reaction which poured the contents of a Pandora's box into physics. Salam's work is connected with this phenomena of the chance decay of various particles. How are the half-lives to be worked out? What are the forces that hold a particle together before it breaks up? What is the carrier of these interactions? The answer to the first question was given by Fermi in 1934. The interaction was later named as weak, because it was less than even the electro-magnetic interaction.

Nearly 20 years elapsed before any significant development occurred. Suffice it to say here that Sudershan and Salam both made fundamental contributions in 1957, the former by his principle of the chiral-invariance, as it is called, and the latter by his two-component theory of the neutrino. These ideas developed in the hands of "a throng of theoreticians" including Glashow, Salam and Weinberg, (G-S-W), who have now presented a theory which brings under one umbrella, the electromagnetic and weak interactions.

A new theory must go beyond itself and predict new phenomena not put into the theory, or known earlier. The G-S-W theory predicts the exchange of currents of neutral particles in addition to currents of charged particles in weak interactions. This prediction was verified by the Gargamelle experiment mentioned earlier.

I might end with possible objections to the theory, the human aspects of such highly competitive endeavours, and some sociological issues that emerge. The reader may bear with the following somewhat technical paragraph or skip it. The objections range from the philosophical to the technical. Indeed, one of the winners of the prize, Glashow, is reported to have said that the Nobel Committee had taken a risk in giving the prize for the work in question.

Some gratuitous assumptions have been made in the theory; for example, "spontaneous breaking of symmetry" which is regarded by some as a mere "clever trick". While the parity principle is valid for electromagnetic interactions, it does not hold for weak interactions and yet the new theory is called a unified theory. Indeed, the coupling constants of weak and electromagnetic interactions remain different and their unification is only formal. It is not impossible to devise a mathematical scheme wide enough to embrace two disparate phenomena which are not naturally connected. Most important, the weightiest predictions of the theory about the masses of the new charged and uncharged particles which are the carriers of the interaction and of Higgs spinless particle, have not yet been found, since machines powerful enough to show them up will be available only in 1981. These particles within the smallest of atoms are supposed to have masses as high as that of the zinc atom! The science journal 'Nature' while announcing the awards, therefore, rightly said that the severest test of the theory is yet to come. The neutral and charged current tests cannot be regarded as experimentum crucis. Also there is an essential difference between the unification of weak and electromagnetic interactions by Salam and others, and of electric and magnetic interactions by Faraday and Maxwell. Physically, magnetic and electric fields are related but not the weak and electromagnetic fields between themselves. Incidentally, is it much comfort to unify two interactions and then add a few more particles to the list of fundamental entities?

Let me comment on the question of priority. Even first-rate scientists are human, all too human. For many years American physicists would not credit Salam who had developed his ideas in lectures at the Imperial College in London but had not published them before Weinberg did in 1967. But Salam's lecture at the Nobel Symposium in 1968 clearly showed how deeply he had worked on the theory. Yet it was only in 1972, at the Rochester Conference, in the presence of Weinberg, that Salam's simultaneous formulations of 1967 were conceded after a battle royal.

Salam has always been a good friend. As I said earlier, some ice-breaking steps towards an understanding of weak interactions had been taken by E.C.G. Sudarashan. So, when a mutual friend visited Salam after the award, he sent a friendly message to Sudershan, who is five years younger to Salam, not to lose heart.

Since Salam's name had come up for the award of the Nobel Prize even earlier, it is said that he was very concerned lately and made anxious inquiries from Stockholm before the award was announced.

Finally, I must mention the sociological aspects of current research in physics. First-rate work is now possible only in a certain milieu. This means sophisticated and costly equipment and stimulus from men working at the threshold of discovery. Excepting a few centres in India, notably TIFR, Indian scientists are far, far away from this milieu. It is upto our government to make it possible for Indians to participate in large numbers in the massive common programmes available for the European community and similar programmes of the U.S.A. Our embassies abroad should interest themselves in these matters.

It is well-known that the Indian (or Pakistani) scientists working abroad, mostly through their own initiative, have acquitted themselves gloriously. S. Chandrasekhar, H. G. Khorana, A. Salam, E.C.G. Sudershan, J. R. Tata, K. Nandy, S. M. Shah, Harish Chandar, C.K.N. Patel, A. B. Bhatia, and H. C. Choudhury, all fellows of the Royal Society of London or Edinburgh or Canada, or members of the National Academy of Sciences of U.S.A., are examples. My point is that these examples could be multiplied many times over, our scientists in India were given opportunities to flower under the full gaze of the world.

A TOAST TO SCIENCE: Abdus Salam at the banquet-table with Queen Silvia of Sweden. The dinner to honour this year's Nobel Laureates was held at Stockholm's town-hall on December 10.

The verification of the new theory for which Abdus Salam, the Pakistani physicist, shares the Nobel Prize with two Americans, was based on the efforts of a multitude of scientists. Though there is no dearth of able scientists in India, we have neither the equipment nor an environment which can stimulate original contributions, says G. H. KESHWANI, a Jawaharlal Nehru fellow.

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CERN

Cours/Lecture Series

1982-1983 ACADEMIC TRAINING PROGRAMME

Title	"Electroweak Interactions"
Lecturer	L.M. SEHGAL (Institute of Physics, RWTH, Aachen)
Dates	November 18, 19, 22, 23, 24, 25 & 26, 1982
Time	11h to 12h
Place	Auditorium

Abstract

We shall review the theoretical foundations and empirical status of the standard model of weak and electromagnetic interactions.

The following topics will be covered (tentative) :

1. Theoretical Perspective
2. Charged Currents
3. Neutral Currents
4. Forbidden Reactions
5. Vector Quanta (Intermediate Bosons)
6. Scalar Quanta (Higgs Particles)
7. Problems on the Frontier

Distr.: int. + ext.

Training & Education Service
Secretariat: Tel. 2844
PE/ED/TE

SIS/M/345

DISCOVERY OF W

27

Volume 122B, number 1 PHYSICS LETTERS 24 February 1983

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland

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We report the results of two searches made on data recorded at the CERN SPS Proton–Antiproton Collider: one for isolated large-E_T electrons, the other for large-E_T neutrinos using the technique of missing transverse energy. Both searches converge to the same events, which have the signature of a two-body decay of a particle of mass ~80 GeV/c^2. The topology as well as the number of events fits well the hypothesis that they are produced by the process $\bar{p} + p \to W^{\pm} + X$, with $W^{\pm} \to e^{\pm} + \nu$; where $W^{\pm}$ is the Intermediate Vector Boson postulated by the unified theory of weak and electromagnetic interactions.

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2. Understanding CP Violation:

Kobayashi - Maskawa Hypothesis ('73)

Essential Idea: $SU(2) \times U(1)$ theory with 3 quark doublets

Opened up new vistas for exploration of CP violation.

$\not{CP}$ no longer a dead-end street.

Focus moved from

K-mesons to B-mesons,

from

Strangeness to Beauty

Thirty-five years later, the K-M hypothesis had passed all crucial experimental tests.

$\Rightarrow$ Nobel prize 2008

(3rd major triumph of the $SU(2) \times U(1)$ theory)

1973 : Kobayashi - Maskawa

CP-violation in framework of $SU(2) \times U(1)$ gauge theory.

With two doublets of quarks, charged current interaction is

$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} \, \overline{u}\ \overline{c} \, \gamma_\mu \frac{1-\gamma_5}{2} \, U \begin{pmatrix} d \\ s \end{pmatrix} W^\mu$$

$$U = 2 \times 2 \text{ unitary matrix}$$

$$= \begin{pmatrix} U_{ud} & U_{us} \\ U_{cd} & U_{cs} \end{pmatrix}$$

Effective Hamiltonian for $\Delta S = 1$ interaction

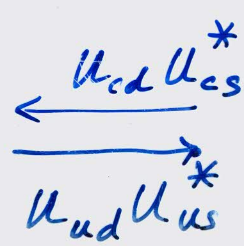
$$H_{eff}(s \to d) \sim U_{ud} U_{us}^* \, (\bar{d} u)(\bar{u} s)$$
$$+ U_{cd} U_{cs}^* \, (\bar{d} c)(\bar{c} s)$$

CP Violation requires a relative phase between $U_{ud} U_{us}^*$ and $U_{cd} U_{cs}^*$

However, unitarity $\Rightarrow$

$$U_{ud} U_{us}^* + U_{cd} U_{cs}^* = 0$$

$\Rightarrow$ CP violation impossible.

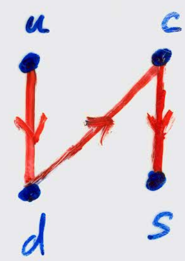


This can also be understood as follows:
The most general 2×2 unitary matrix is

$$U = \begin{pmatrix} \cos\theta\, e^{i\alpha} & \sin\theta\, e^{i\beta} \\ -\sin\theta\, e^{i\gamma} & \cos\theta\, e^{i\delta} \end{pmatrix}$$

$U^\dagger U = U U^\dagger = 1 \Rightarrow \alpha + \delta = \beta + \gamma \Rightarrow$ 4 real par.

Choose 3 relative phases among 4 quarks such that $\alpha = \beta = \gamma = 0$



Unitarity $\Rightarrow \delta = 0$.

$$\Rightarrow \quad U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

= Cabibbo matrix (real, orthogonal).

With three quark doublets

$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} \left(\bar{u}\ \bar{c}\ \bar{t} \right) \gamma_\mu \frac{1-\gamma_5}{2} V \begin{pmatrix} d \\ s \\ b \end{pmatrix} W^\mu$$

V = 3×3 unitary matrix

$$= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{td} \end{pmatrix}$$

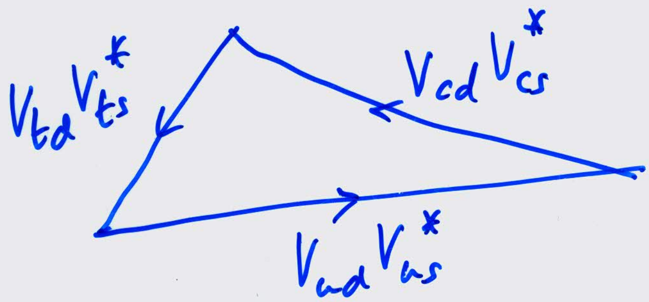
Effective Hamiltonian for $\Delta S = 1$ transitions now has the form

$$H_{eff}(s \to d) \sim V_{ud} V_{us}^* (\bar{d} u)(\bar{u} s) + V_{cd} V_{cs}^* (\bar{d} c)(\bar{c} s) + V_{td} V_{ts}^* (\bar{d} t)(\bar{t} s)$$

Unitarity condition:

$$V_{ud} V_{us}^* + V_{cd} V_{cs}^* + V_{td} V_{ts}^* = 0$$

This is a closed triangle in the complex plane:



(F1)

Conclusion: $H_{eff}(s \to d)$ contains terms whose coefficients are complex relative to one another $\Longrightarrow$ CP Violation!

The above figure (F1) is an example of a Unitarity Triangle.

Properties of Unitarity Triangles

(i) There are <u>six triangles</u> corresponding to the effective Hamiltonians $H_{eff}(s\to d)$, $H_{eff}(b\to d)$, $H_{eff}(b\to s)$, $H_{eff}(t\to u)$, $H_{eff}(t\to c)$ and $H_{eff}(c\to u)$.

The relevant equations are

$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0 \qquad (s\to d)$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{td}^* = 0 \qquad (b\to d)$$

etc.

(ii) <u>All unitarity triangles have the same area.</u>

Reason: $\mathrm{Im}\,(V_{\alpha j}V_{\beta k}V_{\alpha k}^* V_{\beta j}^*) = \pm J$

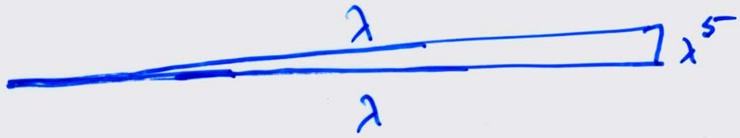
$$\beta \neq \alpha$$
$$j \neq k$$

The parameter J is a universal measure of CP violation in all flavour-changing interactions. Area of triangle $= \frac{1}{2}J$.

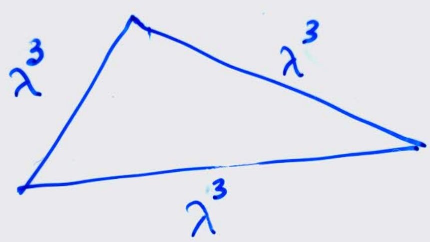
(iii) <u>Different unitarity triangles have different shapes</u>. Reason: hierarchical structure of quark mixing matrix:

$$|V| \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad \lambda \sim 0.2$$

Consequence : UT for $s \to d$ transitions has the shape



while that for $b \to d$ has the form



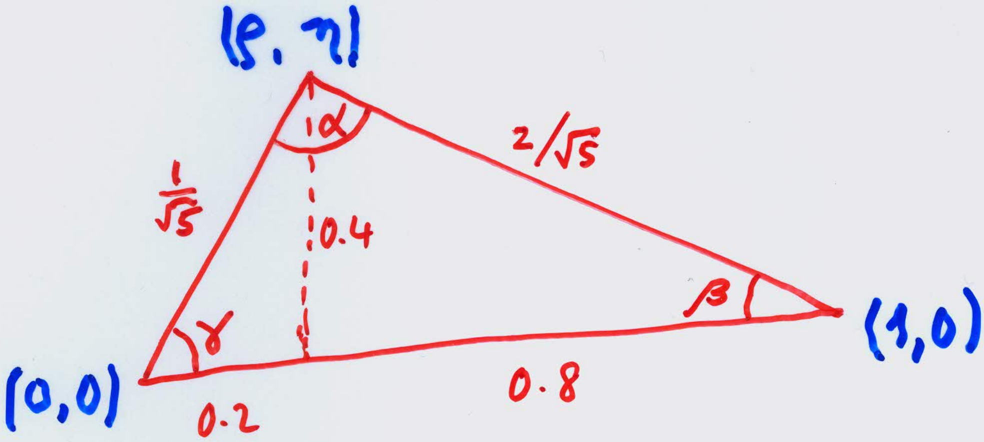
This accounts for the diversity of CP-viol. effects in various sectors, even though the areas of all triangles are universal.

(iv) Sides of a triangle are determined by the moduli $|V_{ij}|$, which can be measured in CP-conserving processes. Knowledge of sides fixes the angles of the triangle, which (if $\neq 0, \pi$) are measures of CP violation. Example of unification of CP-violating and CP-conserving phenomena.

Rough dimensions of Unitarity Triangle:

ca. 2000

$$\rho = 0.2 \,, \quad \eta = 0.4$$



$$\alpha = 90^\circ$$

$$\beta = \tan^{-1}\left(\tfrac{1}{2}\right) \sim 25^\circ$$

$$\gamma = \tan^{-1}(2) \sim 65^\circ$$

Status 2011

$$\rho = 0.144^{+.027}_{-.018} \qquad \alpha = 89 \pm 4^\circ$$

$$\beta = 21 \pm 1^\circ$$

$$\eta = 0.343^{+0.014}_{-0.014} \qquad \gamma = 68 \pm 13^\circ$$

Date: Wed, 15 Oct 1997 11:30:06 -0400
From: cox@uvahep.phys.virginia.edu
To: sehgal@physik.rwth-aachen.de
Subject: Questions concerning asymmetries in K0L->pipiee

Dear Professor Sehgal,

I attempted to get in touch with you in August and am trying again. Please let me know if you get this message.

My group has observed the K0l->pipiee decay in the data that we recent took in the KTEV experiment run at Fermilab. We have much greater sensitivity than previous experiments and see this mode quite easily. I expect to have between two and three thousand events eventually when the entire data sample is process from several months of running for rare K decays.

The bottom line is that we see very clearly the CP violating asymmetry in the angle between the normals to the e+e- and the pi+pi- planes that you predicted in PR D46 of August 1992. My problem is that we would like to have the non-integrated matrix element for our acceptance calculations rather than experession (16) of that paper which is already integrated over the angle of the positron in the e+e- center of mass with respect to the dirction of the pi+pi- system in the e+e- frame of reference and the angle of the positive pi with respect to the direction of the e+e- in the pi+pi- frame of reference. Is a non integrated expression available? It would help greatly if we could obtain this from you.

With a few thousand events, we are beginning to look at the other angles in the decay (other than the angle between the normals to the e+e- and the pi+pi- plane in the K0L CMS) to see if there is any hint of an asymmetry which would indicate an unusual source of direct CP violation. We have been using your PR D48 article with Heiliger as a guide to the search for such anomalous direct CP violation. However, there is a question concenring the coordinate systems. You give a description in words of the angle theta (essentially what I used above when describing the angle of the positron in the e+e- center of mass). However, you give a second definition in terms of cross products at a slightly later point in the paper. The two definitions appear to be different. Can you reiterate the definition of the angle theta for us?

I hope to hear from you soon. It would be good to get this result out. The data is very pretty and agrees with your predictions very well.

Brad Cox

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CP violation in the decay $K_L \to \pi^+\pi^-e^+e^-$

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Direct and indirect *CP* violation in the decay $K_L \to \pi^+\pi^-e^+e^-$

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(Received 10 May 1993)

The decay $K_L \to \pi^+\pi^-e^+e^-$ is analyzed in a model containing (i) a *CP*-conserving amplitude associated with the $M1$ transition in $K_L \to \pi^+\pi^-\gamma$, (ii) an indirect *CP*-violating amplitude related to the bremsstrahlung part of $K_L \to \pi^+\pi^-\gamma$, and (iii) a direct *CP*-violating term associated with the short-distance interaction $s\bar{d} \to e^+e^-$. Interference of the first two components produces a large *CP*-violating asymmetry ($\sim 14\%$) in the distribution of the angle Φ between the e^+e^- and $\pi^+\pi^-$ planes. The full angular distribution contains two further *CP*-violating observables. Effects of direct *CP* violation are found to be numerically small.

PACS number(s): 13.20.Eb, 11.30.Er

I. INTRODUCTION

The decay $K_L \to \pi^+\pi^-e^+e^-$ can be envisaged, in the first instance, as a conversion process related to the decay $K_L \to \pi^+\pi^-\gamma$. The latter is empirically known to contain two components: a bremsstrahlung piece related to the *CP*-violating decay $K_L \to \pi^+\pi^-$ and a *CP*-conserving magnetic dipole component. Interference of these terms produces a *CP*-violating circular polarization of the photon in $K_L \to \pi^+\pi^-\gamma$. The conversion process $K_L \to \pi^+\pi^-e^+e^-$ may be viewed as a means of probing this polarization by studying the correlation of the e^+e^- plane relative to the $\pi^+\pi^-$ plane.

In a recent paper [1], a calculation of the decay $K_L \to \pi^+\pi^-e^+e^-$ was carried out in which the amplitude was determined by the two empirically known components of the radiative decay [2]. In addition, a virtual photon component $K_L \to \pi^+\pi^-\gamma^*$ (absent for a real photon) was introduced, in the form of a K^0 charge-radius contribution. The branching ratio was determined to be $\sim 3\times10^{-7}$. A significant *CP*-violating asymmetry was found in the Φ distribution of the process, Φ being the angle between the e^+e^- and $\pi^+\pi^-$ planes:[1]

$$\mathcal{A} = \frac{\int_0^{\pi/2}\frac{d\Gamma}{d\Phi}d\Phi - \int_{\pi/2}^{\pi}\frac{d\Gamma}{d\Phi}d\Phi}{\int_0^{\pi/2}\frac{d\Gamma}{d\Phi}d\Phi + \int_{\pi/2}^{\pi}\frac{d\Gamma}{d\Phi}d\Phi} = 15\% \sin[\Phi_{+-} + \delta_0(m_K^2) - \bar{\delta}_1] \approx 14\% \,. \quad (1)$$

Here Φ_{+-} is the phase of the *CP*-violating parameter η_{+-}, $\delta_0(M_K^2)$ is the $I=0$ $\pi\pi$ s-wave phase shift at $s_\pi = M_K^2$, and $\bar{\delta}_1$ is an average $\pi\pi$ p-wave phase shift in the domain $0 < s_\pi < M_K^2$. The result (1) represents one of the largest calculable *CP*-violating effects in the decays of the K^0-$\bar{K}^0$ system.

The effect found in Ref. [1] arose entirely from the bremsstrahlung decay of the K_1 admixture in the K_L wave function. In this sense, it is an example of "indirect" *CP* violation. One of the purposes of the present paper is to examine the consequences of a "direct" *CP*-violating amplitude[2] in $K_L \to \pi^+\pi^-e^+e^-$ associated with the short-distance interaction $s\bar{d} \to e^+e^-$. In addition, we extend the analysis of Ref. [1], by looking at the complete angular distribution of the final state. This enables us to identify two further *CP*-violating observables. The method of calculation adopted here is quite different from that followed in Ref. [1], and permits an independent check of the results presented there.

II. MATRIX ELEMENT

The decay amplitude of

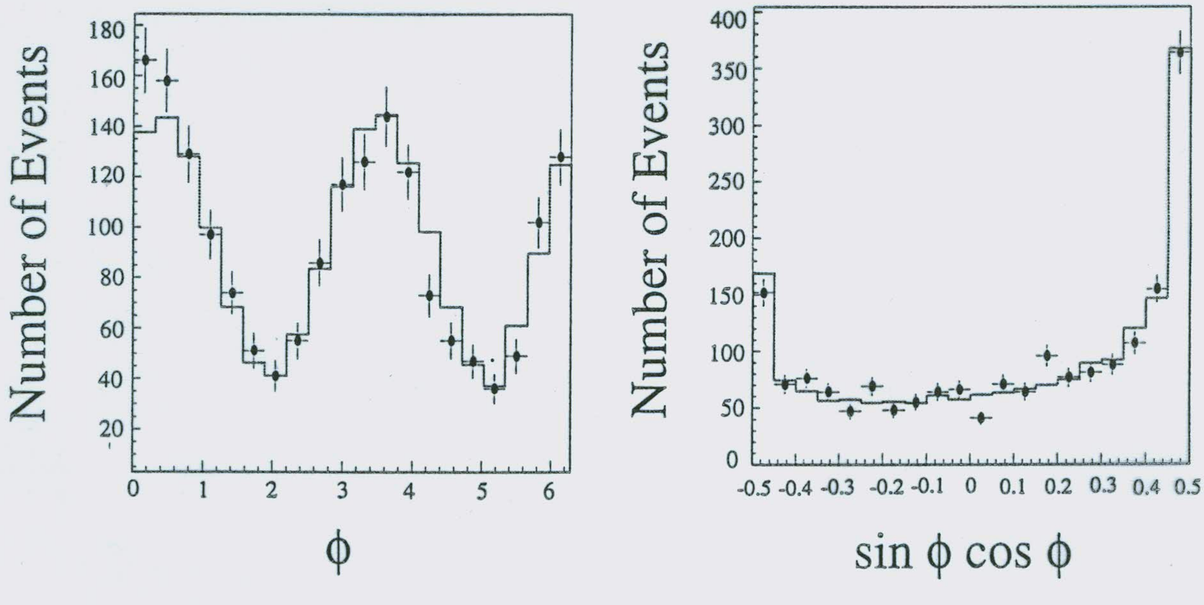
$$K_L(\mathcal{P}) \to \pi^+(p_+)\pi^-(p_-)e^+(k_+)e^-(k_-)$$

in our model has the form

$$\mathcal{M}(K_L \to \pi^+\pi^-e^+e^-) = \mathcal{M}_{\rm br} + \mathcal{M}_{\rm mag} + \mathcal{M}_{\rm CR} + \mathcal{M}_{\rm SD}^{V,A} \,, \quad (2)$$

Measured Angular Asymmetry in $K_L \to \pi^+\pi^-e^+e^-$ Decays

Black points are KTeV data
Red line is Monte Carlo prediction



$$\text{Asymmetry} = (14.6 \pm 2.3\ (\text{stat}) \pm 1.1\ (\text{syst}))\ \%$$

(preliminary)

Agrees with prediction by Sehgal and Wanninger of the fossils. "Everybody would say yes, these are small shellies," agrees paleontologist Douglas Erwin of the National Museum of Natural History in Washington, D.C., who has seen Azmi's paper. The question is what they mean for the age of the tracks.

In the early 1980s, Azmi found similar fossils in another Indian basin, boosting its accepted age by 400 million years into the Cambrian. He thinks the new fossils hold a similar message about the sandstone layer they overlie. As he argues in a letter on page 627, there's not much rock separating the 540-million-year-old fossils from Seilacher's trace fossils—implying that the tracks must be about 600 million, not 1.1 billion, years old. That would make them no older than other known traces of early animals.

Azmi and others add that the radiometric dates aren't as impressive as they might seem. As geochronologist Samuel Bowring of the Massachusetts Institute of Technology notes, the dates might accurately reflect the age of individual mineral grains, but those grains may have formed long before they eroded from parent rock and washed into the sea to become part of the Vindhyan sedimentary rocks. Indeed, the radiometric dates of grains from the formation containing the Cambrian fossils are also about 1.1 billion years old, suggesting that the dates may not reflect the age of the rock layer itself.

Seilacher, Pflüger, and their colleague Pradip Bose of Jadavpur University in Calcutta are just now seeing the details of Azmi's paper, but they already have some reservations. Pflüger speculates that perhaps Azmi's Cambrian fossils are not close in time to the trace fossils after all. Thick layers of sediment may be laid down in one place but not in another, and rocks can be eroded away before the next layer is laid down, making it look as if little time has passed when in fact hundreds of millions of years have gone by. Pflüger also notes that Azmi's fossils come from a part of the basin different from the one that contained the tracks, increasing the chances that fracturing and jumbling of rock layers could confuse interpretations.

And Indian researchers, including paleontologists Anshu Sinha of the Birbal Sahni Institute of Paleobotany in Lucknow and B. S. Venkatachala of the Wadia Institute, say that they are reluctant to adopt a young age for Vindhyan rocks, given the radiometric dates. They also report signs of pre-Cambrian single-celled algae and other fossils in the rocks. To prove the age of the Vindhyan, geologists may have to find and date rocks such as volcanic ash layers, which offer secure dates because they are deposited as soon as they're formed. Until then, the age of the first animals remains in question.

–RICHARD A. KERR

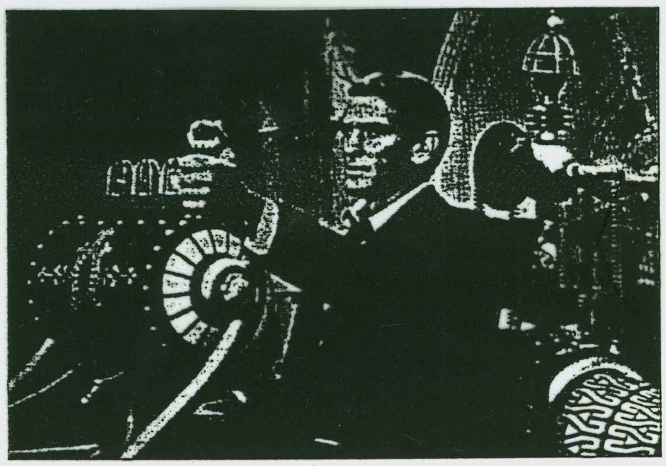
With reporting from India by Pallava Bagla.

PHYSICS

Particle Decays Reveal Arrow of Time

In the everyday world, time is a one-way street. Unlike characters in Martin Amis's novel *Time's Arrow*, we never exit a taxi and salute while it retreats down the street or awake in the evening and see our clothes come flying from the corners of the room. The microscopic level where particles collide and decay, however, has seemed indifferent to the direction of time. But two groups of researchers, at Fermi National Accelerator Laboratory (Fermilab) in Illinois and CERN in Switzerland, have now directly detected the forward march of time in the decays of subatomic particles.

Physicists once thought that the equations of the subatomic world would look the same if time were reversed. A movie of an atom decaying into bits, when run in reverse, would show a process that—although unlikely—still obeys the laws of physics: the bits converging to form a full atom. But they also knew that this time-reversal symmetry was part of a larger, more powerful package known as CPT (for charge, parity, and time reversal) symmetry, which sits at the heart of modern physics: Swap antimatter for matter, view the universe (essentially) in a mirror, and reverse the direction of time, and all the experiments should come out the same way they do in the real world. The CPT theorem (which has now been tested to an impressive 18 decimal places) meant that time-reversal symmetry could hold only if charge-parity (CP) symmetry holds as well.



Only in the movies. New findings would leave H. G. Wells's time machine (here, in a 1960 version) with nowhere to go.

CREDIT: MGM/THE KOBAL COLLECTION

In 1964, physicists found that it doesn't. They noted that neutral particles called kaons occasionally decayed in a way that blatantly violated CP symmetry. The CPT theorem could be saved only if making time flow backward changed things in a way that canceled out the CP asymmetry. No one could gather enough data to isolate the rare decays that would show this directly, however.

Now two groups have finally managed this feat, by measuring the rate of a particular decay and showing that it differs from the rate of the same process done in reverse. "I think it's truly spectacular work," says Alan Kostelecky of Indiana University, Bloomington. "This is the most important experimental advance since" 1964 for testing time symmetry.

One of the groups, the CPLEAR collaboration at CERN, collided antiprotons and hydrogen atoms to make kaons and their antimatter counterparts, antikaons. As they travel, antikaons can transform into kaons and vice versa. In results to appear in an upcoming issue of *Physics Letters B*, the team used a large tracking chamber to count the kaons and antikaons as they decayed—each to an electron, a pion, and a neutrino. The charge of the electron revealed which type of kaon had decayed. The team found that the rate for antikaons transforming into kaons was a fraction of a percent higher than for what would be the time-reversed process—kaons becoming antikaons. "This shows that you can't turn the clock backward" and always get the same results, says CPLEAR spokesperson Panagiotis Pavlopoulos.

The other group, the KTeV collaboration at Fermilab, also studied kaons, but watched for much rarer events—the 1-in-10-million decay of a single kaon into pairs of electrons and pions. The team, which presented its results at a Fermilab workshop earlier this month, mapped out the directions of the electrons and pions. Here, time asymmetry revealed itself in a subtler way. Because reversing time also reverses a particle's momentum, the team looked for time asymmetries by comparing the rates of some decays to others where the direction of the emerging particles looked as they would if time had been reversed. The rates differed by about 13%. "It's a huge effect," says Fermilab physicist and KTeV collaborator Vivian O'Dell.

Both experiments observe time asymmetry at about the level that would compensate for the CP asymmetry first observed over 3 decades ago. "I don't think anyone is sur-

3. CP Violation & Arrows of Time

(i) Conundrum :

Excluding CP-viol. interactions, Hamiltonian of universe (grav, em, strong, weak) is time-symmetric

$$T H T^{-1} = H$$

∴ All physical phenomena (other than CP viol) should be symmetric with respect to forward and backward directions in time.

Future and Past should be symmetric

This contradicts everyday experience:

Time seems to flow from past to future.

Unstable systems decay, don't rejuvenate.

Time has a direction (arrow)

⇒ River of time

(ii) Standard Explanations :

Entropy ? Cosmic Expansion ?

No one knows for sure !

(iii) Present investigation: Role of CP violation in Evolution of Elementary systems (K, B ...)

- Consider observables that are monotonic (unidirectional) in time, when CP is conserved.

- Investigate in what way this unidirectionality is affected when CP viol. is switched on.

- We give examples where a system makes a transition from monotonic to non-monotonic behaviour when the strength of CP violation exceeds a critical value.

Reference:

Ch. Berger & L.M. Sehgal
Phys. Rev. D76, 036003 (2007)
Phys. Rev. D83, 037901 (2011)

Density Matrix of $K^0, \bar{K}^0$

$$\rho(t) = \frac{1}{2} N(t) \left[\mathbb{1} + \vec{\zeta}(t) \cdot \vec{\sigma} \right]$$

$$N(t) = \mathrm{Tr}\, \rho(t)$$

$$\zeta_i(t) = \mathrm{Tr}\, \rho(t)\sigma_i / \mathrm{Tr}\, \rho(t) \qquad i = 1,2,3$$

Initial State : 1 : 1 incoh. mixture

$$N(0) = 1 \quad , \quad \vec{\zeta}(0) = 0$$

$$\rho(0) = \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Evolution :

$$K^0 \underset{t}{\rightarrow} \psi(t) = \frac{1}{2p} \left[K_S e^{-\lambda_S t} + K_L e^{-\lambda_L t} \right]$$

$$\bar{K}^0 \underset{t}{\rightarrow} \bar{\psi}(t) = \frac{1}{2q} \left[K_S e^{-\lambda_S t} - K_L e^{-\lambda_L t} \right]$$

where $K_{L,S} = p\, K^0 \mp q\, \bar{K}^0$

$$|p|^2 + |q|^2 = 1$$

Eigenvalues $\lambda_{L,S} = \frac{1}{2} \gamma_{L,S} + i\, m_{L,S}$

$$\delta \equiv \langle K_L | K_S \rangle = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} = 3.27 \times 10^{-3}$$

Same formalism applies to $B^0 - \bar{B}^0$

Solution

$$N(t) = \frac{1}{2(1-\delta^2)}\left[e^{-\gamma_S t} + e^{-\gamma_L t} - 2\delta^2 \cos\Delta m t \cdot e^{-(\gamma_L+\gamma_S)t/2}\right]$$

$$|\vec{\zeta}(t)| = \left[1 - \frac{1}{N(t)^2}\, e^{-(\gamma_S+\gamma_L)t}\right]^{1/2}$$

N.B. $\det \rho = \frac{1}{4} N^2 (1 - |\vec{\zeta}|^2)$

$$= \frac{1}{4} e^{-(\gamma_L+\gamma_S)t}$$

(Monotonic, since $\gamma_{L,S} > 0$: macroscopic arrow of time)

Eigenvalues of ρ are

$$\lambda_{1,2} = \frac{N}{2}(1 \pm \zeta), \quad \zeta \equiv |\vec{\zeta}|$$

Question : Are $N(t)$, $\zeta(t)$ monotonic functions of t ? Is there a phase transition as CP-violating parameter δ is varied ?

Note: as $t \to \infty$, $N(t) \to 0$ (state decays)

$\zeta(t) \to 1$ (state becomes pure K_L)

Phase transition in N(t)?

Monotonic for

$$\delta^2 \leq \left[\frac{\gamma_S \gamma_L}{(\gamma_S+\gamma_L)^2/4 + \Delta m^2}\right]^{1/2}$$

$$= \left[\frac{r}{(1+r)^2/4 + \mu^2}\right]^{1/2}, \quad r = \gamma_L/\gamma_S, \quad \mu = \Delta m/\gamma_S$$

Stronger bound if one requires monotonic behaviour for norm of a pure state $|\psi\rangle = \alpha|K_L\rangle + \beta|K_S\rangle$

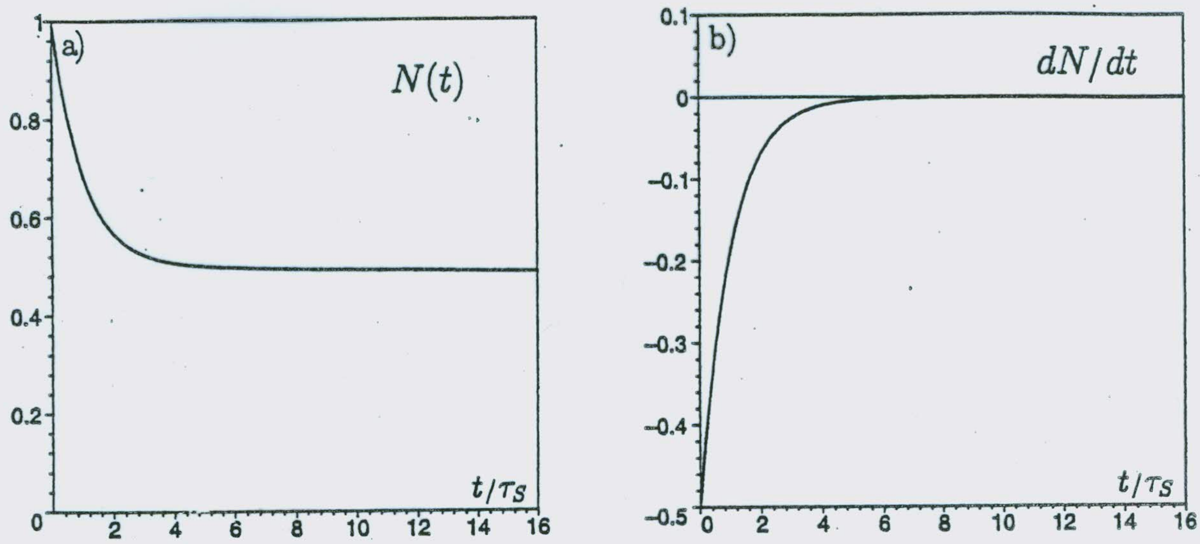
$$\delta^2_{unit} \leq \frac{r}{(1+r)^2/4 + \mu^2}$$

Called **unitarity** bound (derived by **Lee & Wolfenstein**, **Bell & Steinberger**)

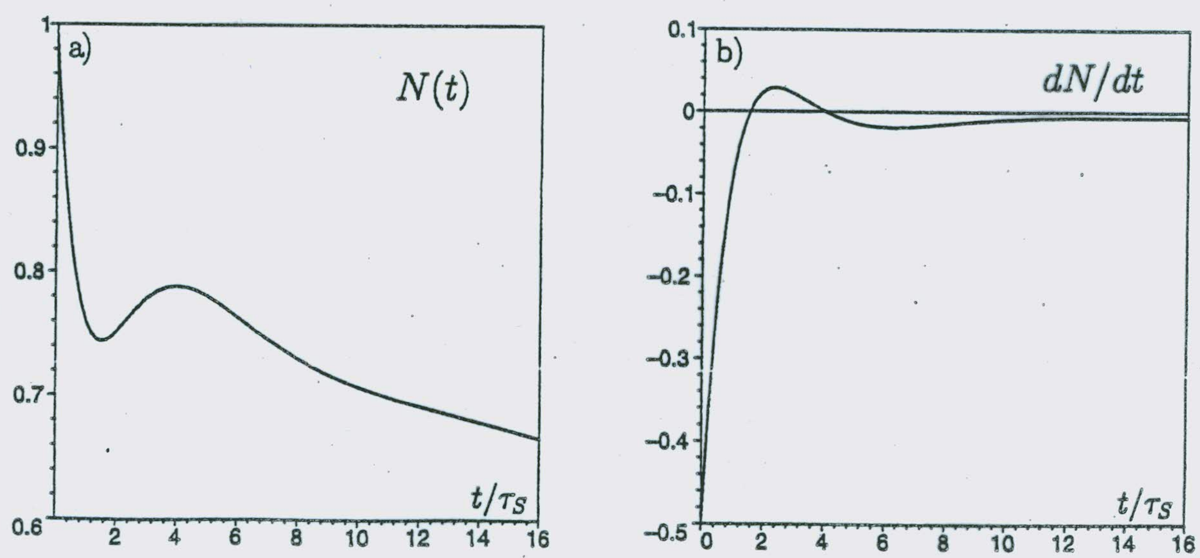
Transition from monotonic to non-monotonic behaviour **if δ exceeds this bound**.

Empirical values for $K^0-\bar{K}^0$, $B^0-\bar{B}^0$, $B_s-\bar{B}_s$ satisfy this bound.

$\delta \ll \delta_{crit}$



$\delta \gg \delta_{crit}$



Phase transition in $\zeta(t)$?

Require $d\zeta(t)/dt > 0$

$$\Rightarrow \quad \delta^2 < \frac{1}{2}\left(\frac{1-\lambda}{\mu}\right)\sinh\left(\frac{3\pi}{4}\,\frac{1-\lambda}{\mu}\right)$$

Quite stringent for $B^0-\bar{B}^0$, since $\lambda = \gamma_L/\gamma_S$ close to one!

In view of $\Delta\gamma/\Delta m \ll 1$, approximate result is

$$\delta < \sqrt{\frac{3\pi}{8}}\left|\frac{\Delta\gamma}{\Delta m}\right|$$

For $B_d-\bar{B}_d$ system, this gives

$$\delta < 0.0155$$

Empirical value is $\delta_{exp} = 0.005 \pm 0.005$, just below bound

For $B_s-\bar{B}_s$ system, monotonicity of Stokes parameter $\zeta(t)$ requires

$$\delta < 0.0038$$

Present data from D^0-experiment violate this bound by factor 2 !

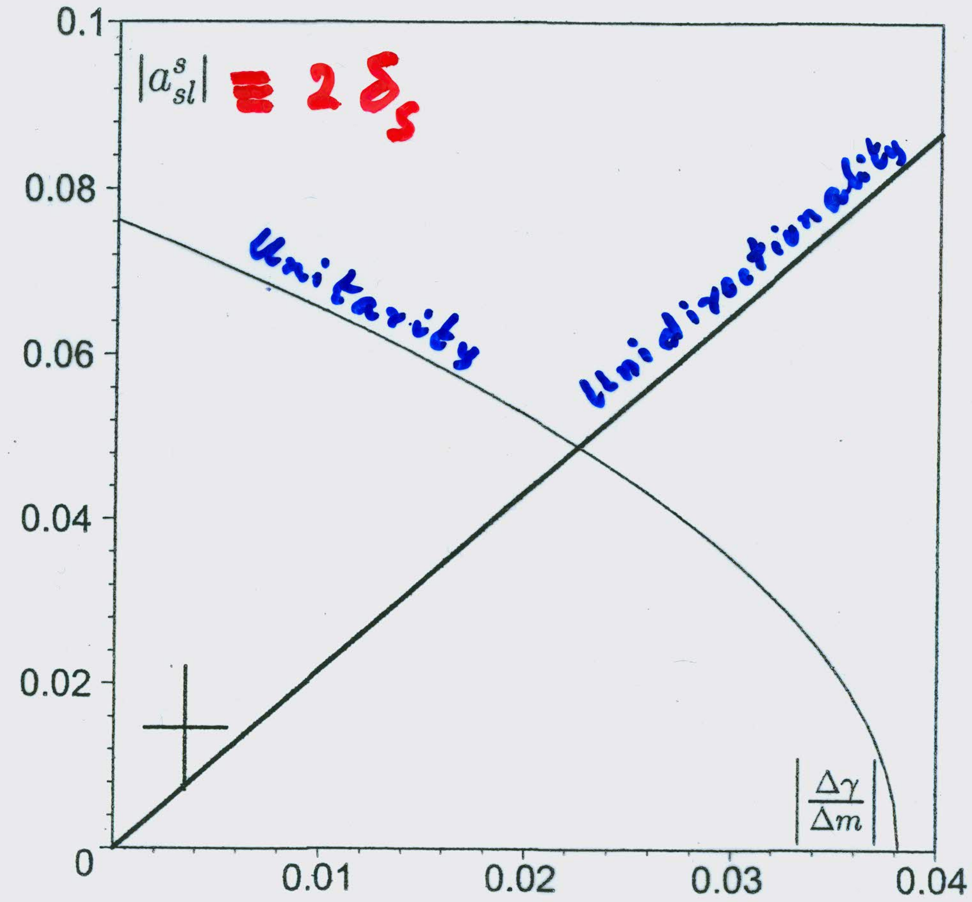


Figure 1: Constraints on $|a_{sl}^s|$ in the $|a_{sl}^s| - |\Delta\gamma/\Delta m|$ plane resulting from unitarity and monotonicity of $|\zeta(t)|$ for the $B_s^0 - \bar{B}_s^0$ system. The thin line represents the unitarity bound (7) with $\Delta m/\gamma_S = 26.2$ and the thick line our new bound evaluated from (8). The cross represents the experimental result of the D0 experiment for $|a_{sl}^s|$ with the horizontal error bar indicating the uncertainty of $|\Delta\gamma/\Delta m|$

bound following from (8). In this case the D0 result – if true – implies the existence of a new type of quantum mechanical oscillation.

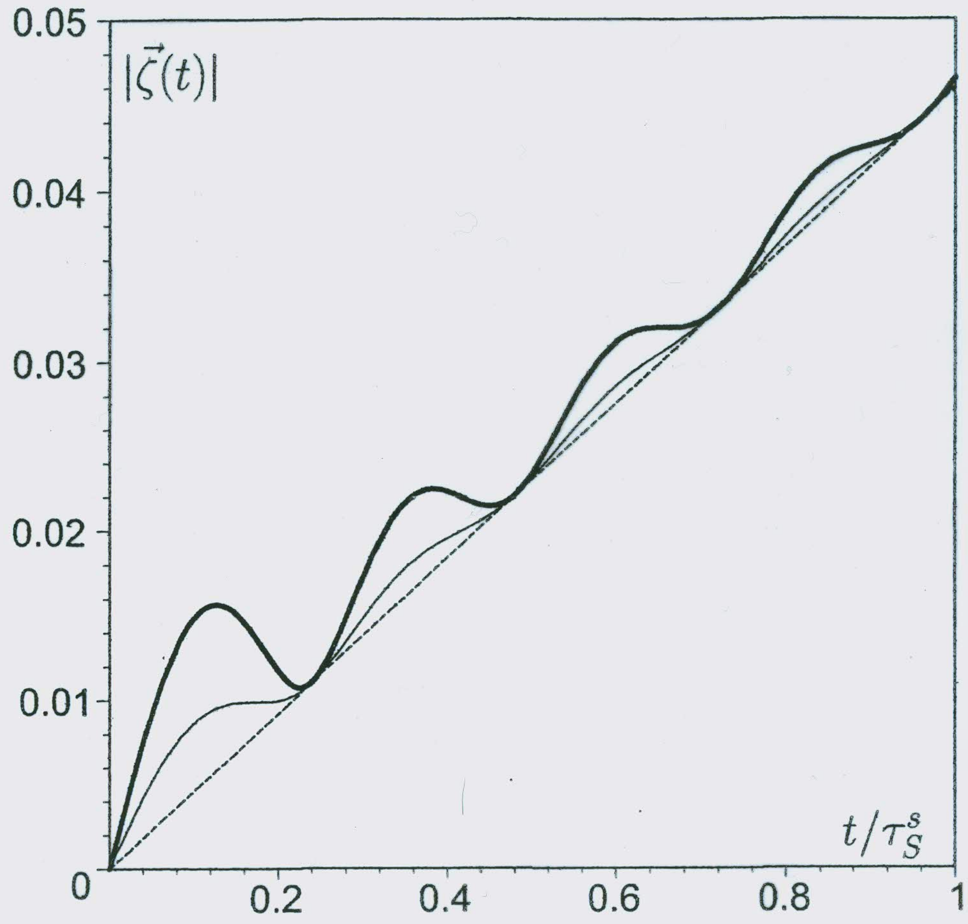


Figure 2: Plot of $|\vec{\zeta}(t)|$ versus t in units of the lifetime τ_S^s. The thick line is calculated for the nominal D0 value of $\delta = 0.0073$. The strictly monotonic dashed line is obtained for the standard model value of δ. The thin line represents the behaviour of $|\vec{\zeta}(t)|$ at the critical value $\delta_{\text{crit}} = 0.0038113$ i.e. the transition between monotonic and nonmonotonic regimes.

Phase Transition in $|\vec{\zeta}(t)|$

Alternative to Stokes Parameter $\zeta(t)$:

Define "Entropy" (similar to von Neumann Entropy):

$$\text{"Entropy"} = -p_1 \log p_1 - p_2 \log p_2$$

$$p_{1,2} \equiv \frac{\lambda_{1,2}}{\lambda_1 + \lambda_2}$$

$\lambda_{1,2}$ = eigenvalues of density matrix $\rho(t)$:

$$\lambda_{1,2} = \frac{N(t)}{2}\left(1 \pm \zeta(t)\right)$$

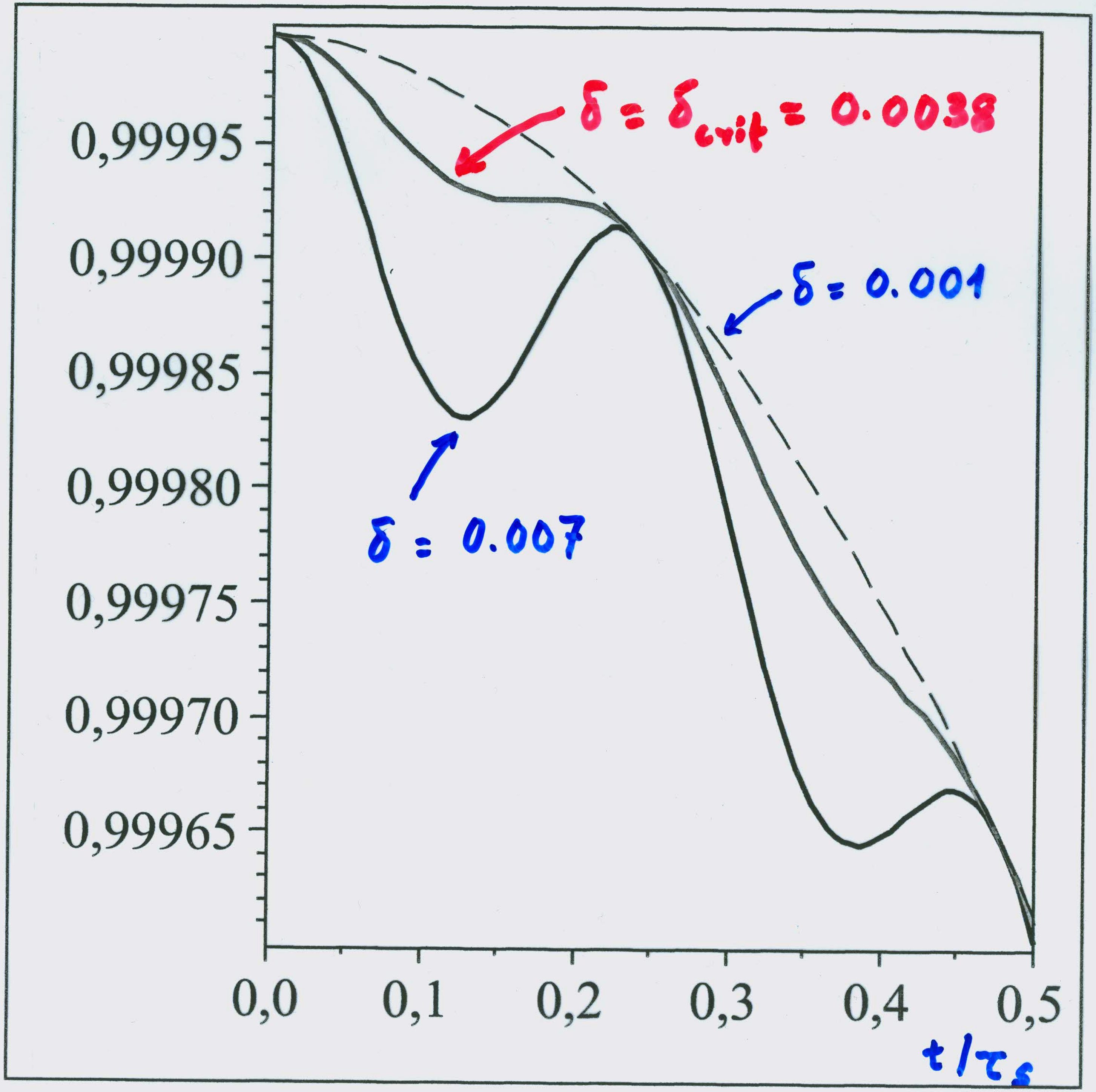
Maximal mixing ($p_1 = p_2 = 1/2$)

$\Rightarrow$ "Entropy" = 1

Minimal mixing (pure state)

$\Rightarrow$ "Entropy" = 0

"Entropy" of $B_s - \bar{B}_s$ decreases from one to zero.



Phase Transition in "Entropy"

Implication for $B_s - \bar{B}_s$ System :

- Violation of Monotonicity of $\zeta(t)$?
- Evolution of Coherence in a $B_s - \bar{B}_s$ mixture not unidirectional ?
- Does the river of time have eddies ?
- Is the macroscopic arrow of time dented in microscopic processes, as a consequence of CP violation ?
- Is the $B_s - \bar{B}_s$ system special ?

Is the CP violating parameter δ an order parameter ?

Contemplating Strange Beauty

$B_s^0 = s\bar{b}$, $\bar{B}_s^0 = \bar{s}b$

Mass = 5366 ± 0.6 MeV

Mean life τ = 1.47 ps

Two lifetimes : $\frac{\Delta\Gamma}{\Gamma} \sim 10\%$

Δm = 17.77 ± 0.12 ps^{-1}

Oscillates between B_s^0 and $\bar{B}_s^0$
26 times before disappearing
in a cloud of quarks and leptons!

"There is no excellent beauty
that hath not some strangeness
in the proportion."

Francis Bacon
1561–1626