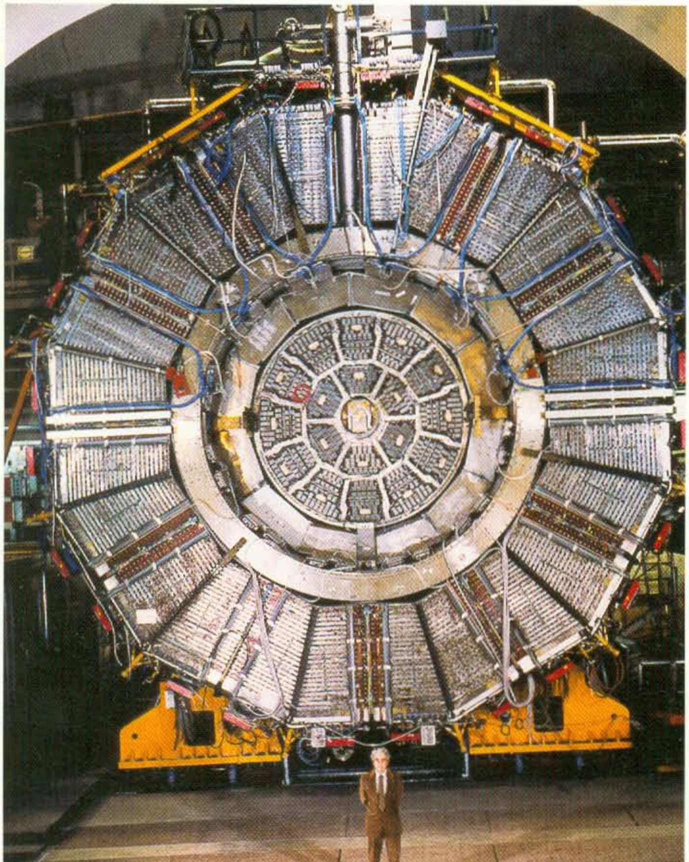
JACK STEINBERGER
DOCTOR HONORIS CAUSA



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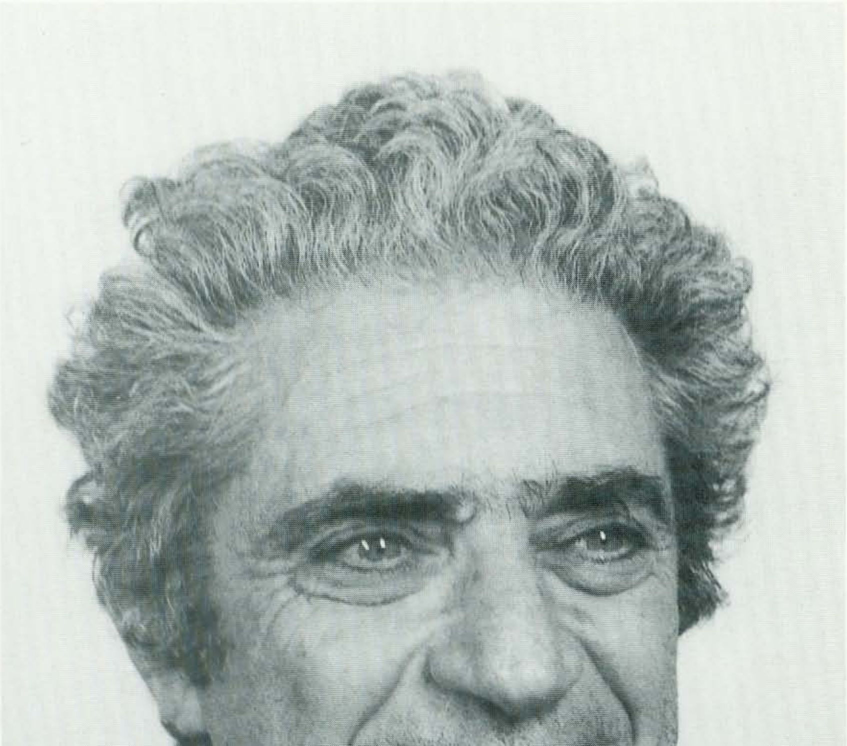

UNIVERSITAT AUTÒNOMA DE BARCELONA

DOCTOR
HONORIS CAUSA

JACK STEINBERGER

DISCURS LLEGIT A LA CERIMÒNIA
D'INVESTIDURA CELEBRADA A LA SALA
D'ACTES DEL RECTORAT
EL DIA 8 DE MAIG DE 1992

BELLATERRA, 1992

La conferència pronunciada pel professor Jack Steinberger s'ha reproduït directament de l'original del mateix autor.

EDITAT PEL
SERVEI DE PUBLICACIONS
DE LA
UNIVERSITAT AUTÒNOMA DE BARCELONA
08193 Bellaterra (Barcelona)

IMPRÈS PER GRÁFICAS UNIÓN
Prim, 6 baixos. Terrassa (Barcelona)

Dipòsit legal: B. 41.412-1992

Imprès a Espanya

PRESENTACIÓ

DE

JACK STEINBERGER

PER

ENRIQUE FERNÁNDEZ

Excel·lentíssim i Magnífic Senyor Rector,
Digníssimes Autoritats,
Benvolguts Col·legues,
Senyores i Senyors,

En aquest acte, la Facultat de Ciències de la Universitat Autònoma de Barcelona, a proposta dels grups de Física d'Altes Energies i de Física Teòrica, demana a l'Excel·lentíssim i Magnífic Sr. Rector la investidura com a doctor *honoris causa* del professor Jack Steinberger.

Ja fa alguns anys que els membres dels esmentats grups teníem pensat realitzar aquesta proposta. Això és degut en primer lloc a la preeminència científica del professor Steinberger, àmpliament reconeguda entre la comunitat científica de tot el món. Però també és degut en gran manera al paper que ha tingut el professor Steinberger en el desenvolupament i en la consolidació del grup experimental de Física d'Altes Energies existent en aquesta universitat.

El fet que el professor Steinberger accepti aquesta distinció, i que estableixi, per tant, una relació formal amb la nostra institució, és per a tots nosaltres un motiu d'orgull i de satisfacció.

El professor Steinberger nasqué a Alemanya l'any 1921. El 1934 ell i el seu germà més gran emigraren als Estats Units i s'establiren a Xicago, on més tard, el 1938, hi anà la resta de la família. El 1942 va acabar una diplomatura en química a la Universitat de Xicago. Estant a l'exèrcit durant la Segona Guerra Mundial, fou enviat al laboratori de radiacions del MIT, on entrà en contacte amb la física.

Després de la guerra va reprendre els estudis de física a la Universitat de Xicago. Aquesta universitat era aleshores, i encara ho és, un centre de prestigi. Crec que és suficient anomenar alguns dels professors i companys de Steinberger per adonar-se de quina devia ser l'atmosfera que hi regnava. Entre els professors hi havia Enrico Fermi, Edward Teller, Gregor Wentzel... Entre els estudiants, a més a més de Steinberger, hi havia Lee, Yang, Goldberger, Rosenbluth, Garwin, Chamberlain, Wolfenstein, Chew... Noms tots ells prou familiars i que no necessiten presentació per a molts físics.

Per a la seva tesi doctoral, Jack Steinberger treballà, seguint un suggeriment de Fermi, en un problema que s'havia posat de manifest en experiments previs, i que el va portar a la mesura de l'espectre de desintegració d'electrons produïts en desintegracions de muons còsmics aturats en la matèria. Aquesta mesura, completada el 1948, establí que el muó decau en tres partícules: un electró i presumiblement dos neutrins. Aquest resultat fou força fonamental en el sentit que va ajudar a establir el concepte d'una interacció dèbil universal, concepte que és una de les pedres angulars del nostre coneixement de les interaccions fonamentals.

Vull remarcar la paraula fonamental. La majoria de nosaltres, treballant en aquest camp avui en dia, estaríem molt satisfets de fer una o dues mesures d'aquest estil al llarg de les nostres carreres. Per a Jack Steinberger, aquest fou tan sols el començament d'una sèrie, de les quals esmentaré tan sols alguns exemples. Clarament, els anys en què Jack Steinberger va començar la seva carrera, al final dels anys quaranta i començament dels cinquanta, van ser molt especials per al camp de la física de partícules. En aquest període van començar a funcionar els primers acceleradors; això portà a un nivell d'experimentació sense precedents, i, conseqüentment, a un alt nivell de coneixement del camp. Malauradament, molts de nosaltres hem de mirar aquest període des d'una perspectiva històrica. Jack Steinberger és un dels protagonistes d'aquesta història.

Després d'un any a l'Institut d'Estudis Avançats de Princeton, la tardor de 1949, Steinberger anà a la Universitat de Califòrnia, a Berkeley, convidat pel professor Wick per ser el seu ajudant. Allà, al Laboratori Lawrence Berkeley, va tenir l'oportunitat de treballar amb els acceleradors més importants del món que estaven en funcionament en aquell moment, el sincrotró d'electrons de 330 meV i el ciclotró de 335 meV. Amb un muntatge experimental relativament senzill, que era pioner en l'ús de centellejadors, Steinberger contribuí a tres experiments, altre cop fonamentals, en tan sols un any: la mesura acurada de l'espectre dels p^+ fotoproduïts, que portà la primera indicació de la natura pseudoescalar de la interacció pió-nucleó; la mesura de la vida mitjana del p^+, amb una exactitud sorprenent; l'observació de la desintegració d'un mesó neutre, de massa similar a la dels mesons carregats ja observats, en dos fotons, i per tant establint l'existència de pió neutre.

Tanmateix, la carrera a Berkeley s'acabà en menys d'un any, a causa del que avui dia es coneix per maccarthisme. En refusar de signar el «jurament de lleialtat anticomunista» requerit als membres de la plantilla de la Universitat de Califòrnia, es denegà a Steinberger l'autorització per treballar al LBL. Afortunadament per a la física, Steinberger anà com a professor ajudant a la Universitat de Colúmbia, el 1950, on va poder continuar la seva carrera experimental, primer en el ciclotró Nevis de 380 meV i després en el cosmotró i en el sincrotó de gradient alternat del Laboratori Nacional de Brookhaven.

El Departament de Física de la Universitat de Colúmbia ja era força prestigiós, i Jack Steinberger contribuí en gran manera a aquest prestigi en els anys següents. Hi ha, als Estats Units, tota una escola de físics experimentals d'altes energies formats a Colúmbia en els anys cinquanta i seixanta. Que aquests anys degueren de ser molt especials i excitants científicament es pot deduir no tan sols estudiant els resultats científics, sinó també parlant amb aquells que hi foren, Jack Steinberger entre ells. L'excitació perdura encara avui en dia. Foren anys realment molt especials.

M'agradaria resumir molt breument alguns dels treballs de Jack Steinberger durant els anys cinquanta. Molts experiments es realitzaren per estudiar les propietats dels mesons, cosa que fou possible gràcies a la disponibilitat d'un feix extern de pions a Nevis. Una altra sèrie completa d'experiments encaminats a l'estudi de les propietats de les partícules estranyes es va fer al cosmotró de Brookhaven fent servir cambres de bombolles. Jack Steinberger fou, de fet, un dels pioners en la utilització d'aquest dispositiu, que va ser una de les eines fonamentals de la física de partícules durant quasi dues dècades.

Una millora crucial en la tècnica de la cambra de bombolles, que havia estat inventada per Glaser, fou portada a terme per Steinberger i tres estudiants (Leitner, Samios i Schwartz) ja l'any 1954. Consistia en una ràpida recompressió, uns deu mil·lisegons després de l'expansió, que impedia que les bombolles pugessin a la part superior de la cambra, i així era possible treballar a un ritme ràpid. Entre altres resultats importants obtinguts per Steinberger i col·laboradors seus hi ha la demostració de la violació de paritat en la desintegració de la lambda, la determinació de la paritat del pió neutre i la demostració de la regla $\Delta S = \Delta Q$ en la desintegració de K^0 i de l'hiperó.

Un experiment molt important en la carrera de Jack Steinberger es va fer a Brookhaven el 1961-1962, i fou conegut amb el nom d'experiment dels dos neutrins. La importància de l'experiment fou reconeguda, 26 anys més tard, amb la concessió del premi Nobel a Lederman, Schwartz i Steinberger. Aquest experiment fou molt important per diverses raons. Primerament establia la tècnica per formar feixos de neutrins d'alta energia, que s'ha utilitzat fins avui. En segon lloc, era capdavanter en l'ús de detectors de gran àrea, anomenats cambres *spark* de capes múltiples, que tot just s'havien acabat d'inventar. I, sobretot, provava que els neutrins produïts juntament amb muons en les desintegracions de mesons produïen muons en interaccionar amb la matèria. Aquest resultat fou un pas crucial per entendre que les partícules elementals s'agrupen en famílies, un fet encara no explicat a un nivell bàsic.

L'any 1965, durant una estada sabàtica al CERN, Jack Steinberger començà a treballar en una sèrie d'experiments basats en l'estudi de la violació de CP en el sistema $K^0, \bar{K}^0$. L'experiment dut a terme al CERN mostrà entre altres coses que la dependència temporal de la desintegració del $K^0{}_0$s'explicava per la interferència entre les amplituds del K_s i el K_l, un efecte de la violació de CP.

El 1968 es va fer membre del CERN i continuà amb l'estudi de la violació de CP, aquesta vegada amb dos detectors idèntics, un al CERN i un altre a Brookhaven, exposats a dos feixos diferents de K^0. Per als experiments es va fer servir la tècnica de les cambres de fils proporcionals, inventada aleshores recentment per Charpak. Alguns dels resultats d'aquests experiments foren mesures precises d'alguns dels paràmetres de la violació CP.

Simultàniament als experiments de CP del CERN, que duraren fins al final dels anys setanta, Jack Steinberger liderà un gran esforç, iniciat el 1972, encaminat a construir un detector de 1.200 tones per estudiar les interaccions dels neutrins d'alta energia amb un feix obtingut a partir del nou gran accelerador del CERN, el SPS. Aquest és el famós experiment CDHS que adquirí dades des del 1977 fins al 1983. Dic «famós» perquè aleshores jo treballava com a estudiant, en física de neutrins, a Fermilab, i inevitablement sentia moltes històries sobre la preparació del CDHS. Aquell era «l'experiment» de neutrins d'aleshores, una amenaça real per a tots els que treballàvem en aquell camp. Recordo que un dels meus col·laboradors, un antic estudiant de Steinberger de Colúmbia, em portà un *preprint* de Steinberger titulat «Experiments amb feixos de neutrins d'alta energia». L'article tenia una dedicatòria escrita a mà: «Amb els meus millors desitjos», signada «Jack». Encara tinc una còpia d'aquest *preprint*.

L'experiment provà que, en efecte, era una amenaça real: va dur a terme un bon nombre de mesures definitives i precises de les interaccions de neutrins, tant en corrents neutres com carregats. En particular va mesurar l'evolució en Q^2 de les funcions d'estructura del nucleó, que estaven d'acord amb les prediccions de la teoria de QCD. A més, també refutà un cert nombre de pretesos, però no conclusius, resultats en el camp de la física de neutrins.

Al començament dels anys vuitanta, quan va ser aprovat l'accelerador LEP, Jack Steinberger liderà una altra vegada una gran col·laboració d'uns tres-cents físics, per preparar un experiment encaminat a l'estudi de les col·lisions e^+e^- a l'energia de la partícula Z. Aquest és l'experiment Aleph, que actualment s'està duent a terme al CERN i del qual som una institució col·laboradora. Fins ara amb aquest experiment s'han fet mesures precises d'alguns dels paràmetres fonamentals del model estàndard, com ara l'amplada i la massa de la Z. La mesura de l'amplada dóna una indicació clara que hi ha tres i només tres tipus de neutrins, un bon resultat que també podem titllar de fonamental.

Ara parlaré de l'important paper que va tenir el professor Steinberger en el desenvolupament del grup experimental d'aquesta universitat. Això va passar arran de la nostra incorporació a l'experiment Aleph, i, atesa la meva part de responsabilitat en aquesta incorporació, explicaré com va començar.

Vaig venir aquí per primera vegada la primavera del 1984, convidat per l'aleshores rector d'aquesta universitat, el professor Antoni Serra Ramoneda. Espanya s'havia tot just reincorporat al CERN i molta gent d'aquí i de la Universitat de Barcelona, els professors Ramon Pascual, Pere Pascual i Rolf Tarrach entre altres, volien tenir a Barcelona un grup experimental de física d'altes energies. Hi havia un físic experimental a la Universitat Autònoma de Barcelona, el professor Crespo, i alguns estudiants novells, entre ells els doctors Garrido, Martínez i Mató, que havien estat enviats al CIEMAT de Madrid per tal de començar la seva formació en física experimental d'altes energies. M'oferiren de venir aquí i dirigir aquest grup que s'estava formant. Vaig prendre la decisió de venir durant l'estiu de 1984, encara que no m'hi vaig traslladar fins a la primavera següent.

Després de prendre aquesta decisió, una de les meves tasques principals fou escollir un experiment en el qual poguéssim participar d'una manera adient. Vaig llegir amb deteniment les propostes de LEP i vaig parlar amb col·legues que em podien orientar en aquest aspecte. El que va simplificar les coses fou el fet que el professor Steinberger donés una xerrada al Stanford Linear Accelerator Center sobre el detector Aleph, a la qual vaig assistir. Em vaig quedar molt impressionat per la simplicitat i la claredat de la presentació. El que també em va plaure molt va ser l'entusiasme amb què Jack Steinberger va explicar els problemes físics i la tecnologia escollida per Aleph. No em va quedar cap dubte de quin era l'experiment en el qual volia participar. Vaig comunicar-ho a Barcelona i el professor Steinberger fou convidat a venir aquí la tardor de 1984. Va expressar el desig d'Aleph de rebre el nou grup i entrarem oficialment a formar part d'Aleph pocs mesos més tard.

Per a un grup que tot just començava com ara el nostre, no va ser fàcil d'esdevenir una part rellevant d'una gran col·laboració de la importància d'Aleph. Des de bon començament l'encoratjament per part de Steinberger fou per a nosaltres molt important. Sempre ha tingut paraules amables per a aquest grup, i venint d'ell, això ha estat per a tots nosaltres una font de motivació. Però, més que això, ha estat el seu guiatge el que ha tingut un paper vital en el desenvolupament d'aquest grup. Steinberger té una gran habilitat per anar a l'essència d'un problema d'una manera clara i senzilla; per distingir el que és rellevant del que no ho és, el que importa del que no és important. Parlant amb ell sobre qualsevol cosa, sigui o no de física, la seva primera pregunta, formulada sempre de manera directa i clara, és normalment la més difícil, potser l'única pregunta. Potser és per això que treballar amb ell és un privilegi i ha tingut una gran importància per a tots nosaltres. Avui som aquí per agrair-li aquest privilegi.

Per això, tenint en consideració i exposats tots aquests fets, sol·licito que s'atorgui i confereixi al professor Jack Steinberger el grau de doctor *honoris causa* per aquesta universitat.

WHAT DO WE KNOW ABOUT NEUTRINOS?
WHAT DO WE LEARN FROM NEUTRINOS?

PER

JACK STEINBERGER

WHAT DO WE KNOW ABOUT NEUTRINOS?
WHAT DO WE LEARN FROM NEUTRINOS?

J. Steinberger

Talk given at Barcelona, May 8, 1992

Each type of particle, by definition, is special. The special property of neutrinos is that they are penetrating. This has made their discovery and the understanding of their properties elusive, but it has also made them a useful tool in the study of particles and their interactions. In astrophysics, on account of this property, they provide an important means for energy transfer and permit insight into the interior of stars hidden to other radiation. The special conditions in space permit, in turn, the study of neutrino properties not possible in the laboratory.

The written history of the neutrino begins with Pauli's (fig. 1) delicious letter of 1930 to his "Liebe Radioaktive Damen und Herren" (fig. 2)* . He timidly suggests a new particle to solve two outstanding problems: the apparent violation of energy conservation in β decay, and the "wrong" statistics of certain nuclei, for example nitrogen 14, but he does not dare to publish it until three years later[1)]. In the meantime, the name he proposed for it (neutron) was eaten up by the discovery by Chadwick of the neutral partner of the proton, the discovery which also solved the statistics problem. At the time the nuclear energy levels were so uncertain that Pauli could only restrict the mass of his proposed neutral particle to less than .01 proton masses. The present upper limit is lower by the factor 10^8, about ten electron volts, on the basis of measurements on the tritium β spectrum near its end point. For all we know today, the neutrino mass may very well be zero.

Figure 1: Pauli.

* Following (see Appendix) is an english translation, courtesy the CERN translation service, as revised by M. Schmelling, R. Wanke and B. Wolf.

original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Figure 2: 1930 Letter of Pauli to the Tübingen congress, suggesting the neutrino.

In 1934 Fermi proposed a theory of β-decay[2], which incorporated the neutrino, and was remarkably simple, successful and long-lived. With the Fermi theory, the neutrino became a particle like the others. As muon capture and decay became understood in the late forties, the Fermi theory became the universal theory of weak interactions. It was superseded in the early seventies by the beautiful electroweak gauge theory which unified the weak and electromagnetic interactions, but it still survives as a useful approximation.

The direct detection of neutrinos was not possible at the time, because of the very small interaction rates, as correctly predicted by the Fermi theory. Neutrinos are the only particles with only weak interaction. No experiment to detect them could be imagined until the advent of the atomic age. The first observation of a neutrino induced process, the inverse β decay reaction $\nu + p \rightarrow n + e^+$, had to wait until 1956[3], for the development of the hydrogen bomb and the Savannah River tritium producing reactors, which could generate a sufficiently large flux of neutrinos. The target was a water tank with some cadmium salt dissolved in it. The reaction was identified on the basis of the signal from the gamma rays emitted in the capture by the cadmium of the slowed down neutron, these gamma rays in delayed coincidence with the gamma rays resulting from the annihilation of the positron with an electron (fig. 3).

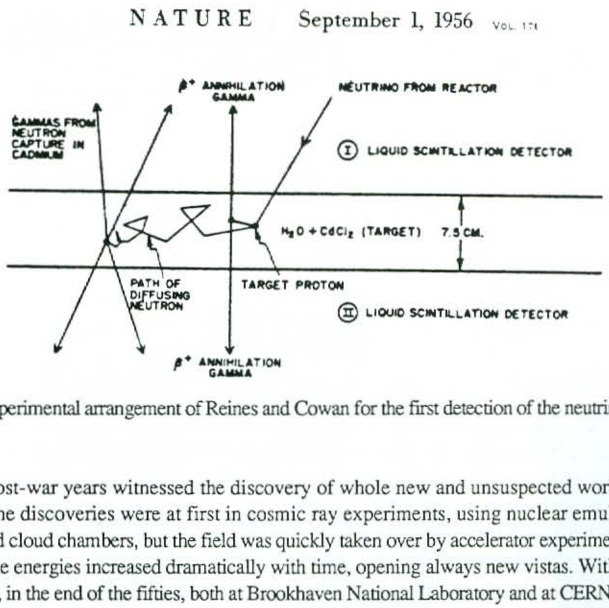

Figure 3: Experimental arrangement of Reines and Cowan for the first detection of the neutrino.

The post-war years witnessed the discovery of whole new and unsuspected worlds of particles. The discoveries were at first in cosmic ray experiments, using nuclear emulsion detectors and cloud chambers, but the field was quickly taken over by accelerator experiments. The available energies increased dramatically with time, opening always new vistas. With the construction, in the end of the fifties, both at Brookhaven National Laboratory and at CERN, of proton accelerators in the range of 30 billion electron volts, it became possible to contemplate the production of high energy neutrino beams of sufficient intensity to perform experiments[4]. The accelerator energy is doubly important for neutrino beam experimentation: the cross-sections increase linearly with energy, and the beams are more collimated and therefore more intense at higher energy. Neutrino experiments opened entirely new possibilities in the study of particle properties and the weak interaction[5].

The first high energy neutrino experiment was performed at Brookhaven in 1962[6]. The hadrons produced on a target inside the AGS accelerator were allowed to enter a 17 meter long decay region (fig.4). The dominant source of neutrinos is the decay of the pion to a muon and a neutrino, and to a somewhat smaller extend, but with higher neutrino energy, the decay of the kaon to the same final state. The decay region was followed by a thick iron shield and a ten ton detector consisting of 2.5 cm thick aluminum plates separated by spark gaps. The target doubles as particle detector, a feature of almost all subsequent neutrino experiments, which is necessitated by the smallness of the neutrino cross-sections. The sparks are photographed ; energetic particles traverse several plates and can be recognized as tracks.

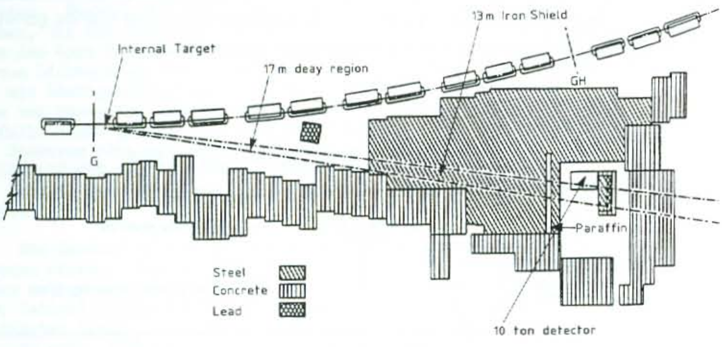

Figure 4: Arrangement of the first accellerator neutrino experiment, which found the separate identity of the muon neutrino.

After some months of running, a few dozen events were obtained, and it could be demonstrated that these are due to neutrinos. One of these is reproduced in fig. 5. The most striking feature of the events was that the large majority contained a muon, recognized on the basis of its large penetration in the aluminum. The muon track can be seen clearly in fig. 5, the other sparks are due to hadronic debris. No events containing a high energy electron could be identified. This demonstrated that the neutrinos produced in pion and kaon decay, in association with muons, are not the same as the neutrinos originating in β–decay, in association with electrons. The latter would necessarily produce electrons in their interaction with matter[7]. So, already the first neutrino experiment observed a fundamental, important result. This pairing of neutrinos with charged leptons into families is one of the basic features of the electroweak theory. Fig. 6 reproduces a contemporary photo of the experimental team.

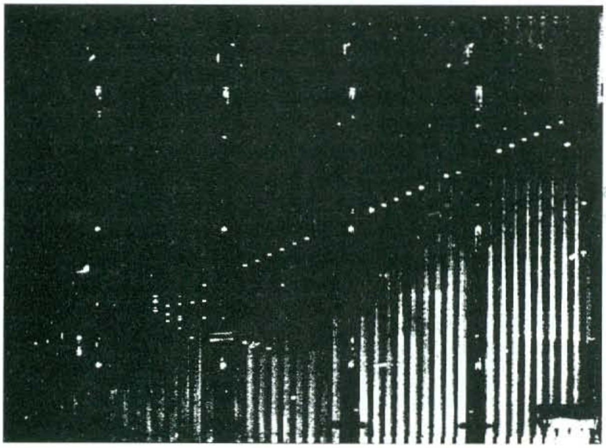

Figure 5: One of the events. The upper track is the muon, the lower sparks are due to the hadronic debris.

Figure 6: The "two neutrino" collaboration. From right to left: M. Schwartz, L.M. Lederman, W. Hayes, G. Danby, N. Mistry, J.M. Gaillard, K. Goulianos, and myself.

High energy neutrino experiments have been pursued actively since that time, until the present. Probably the most important result was the discovery in 1973 of a new weak interaction, the "neutral current". In the late sixties and early seventies the electroweak theory took form. The theory represented an enormous step forward in our formal understanding of particles. It unified two of the three particle interactions, and offered, for the first time, the possibility of calculating weak interaction processes in higher order perturbation theory, something not possible in the Fermi theory.

It was not immediately clear that the new theory is correct. All known manifestations of the weak interaction, almost all of them particle decays, could already be quantitatively understood in terms of the old Fermi theory. The new theory agreed with the old on these processes, but it also predicted two entirely new phenomena: the "neutral current" and the existence of the vector bosons, particles of a vastly greater mass than had been seen before. The first of these predictions to be verified was the "neutral current". This discovery established the new theory beyond any doubt. The vector bosons were discovered ten years later, also at CERN. Until the "Gargamelle"—that was the name of the detector—experiment, all observed neutrino interactions, as best one knew, involved the emission of a charged lepton, a muon or electron, in the final state: one can think of it as the conversion of the neutrino into the other lepton member of its "family". The "neutral current" permits the scattering of the neutrino, with its reappearance in the final state.

Gargamelle was a large bubble chamber constructed at the Paris Ecole Polytechnique and exposed in a neutrino beam at CERN (fig. 7). It was four meters long, two meters in diameter, inside a large magnet producing 2 tesla, and filled with a heavy liquid, freon. "Muonless" events were searched for and several hundred were found, both in neutrino and in antineutrino beams. Such an event is shown in fig. 8. Both of the outgoing particles are identified: one is a kaon, the other is a lambda hyperon, there is no muon. The non hadronic nature of the beam particle was demonstrated by the distribution in depth along the chamber, shown in fig. 9. The distribution is consistent with being independent of depth, as expected for neutrinos. Neutrons, on the other hand, would be attenuated with an exponential constant roughly equal to one-quarter of the total depth of the chamber.

The ratio of rates relative to the more numerous "charged current" events gave a first measure of the weak mixing angle, an important free constant in the theory. The ratio of antineutrino to neutrino neutral current cross-sections was predicted by the theory. The measured result, in agreement with the theoretical prediction, constituted additional, quantitative confirmation of the theory.

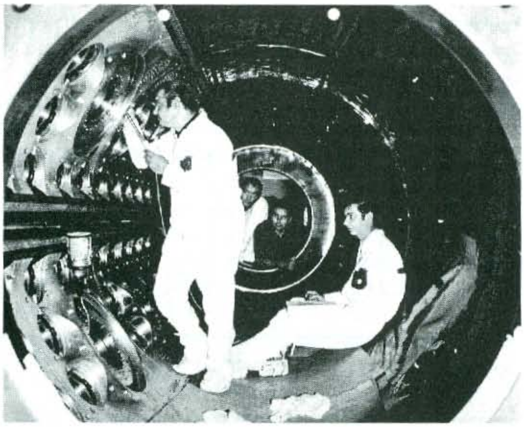

Figure 7: Inside the Gargamelle bubble chamber.

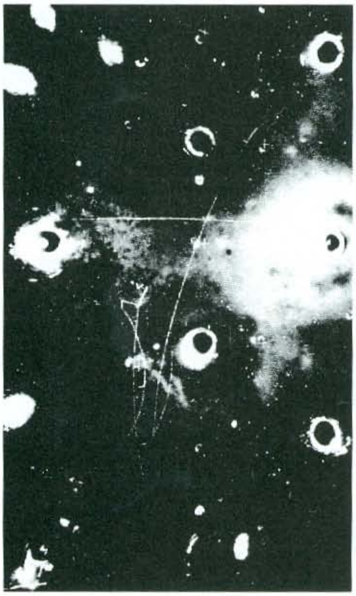

Figure 8: One of the original Gargamelle neutral current events. The neutrinos are coming from the bottom. At the interaction point a neutral particle and a single charged track are produced. The charged particle identifies itself as a positive kaon by its decay, after scattering in the chamber. The V which points to the production vertex is a lambda particle, decaying to a proton and a negative pi meson. There is no muon.

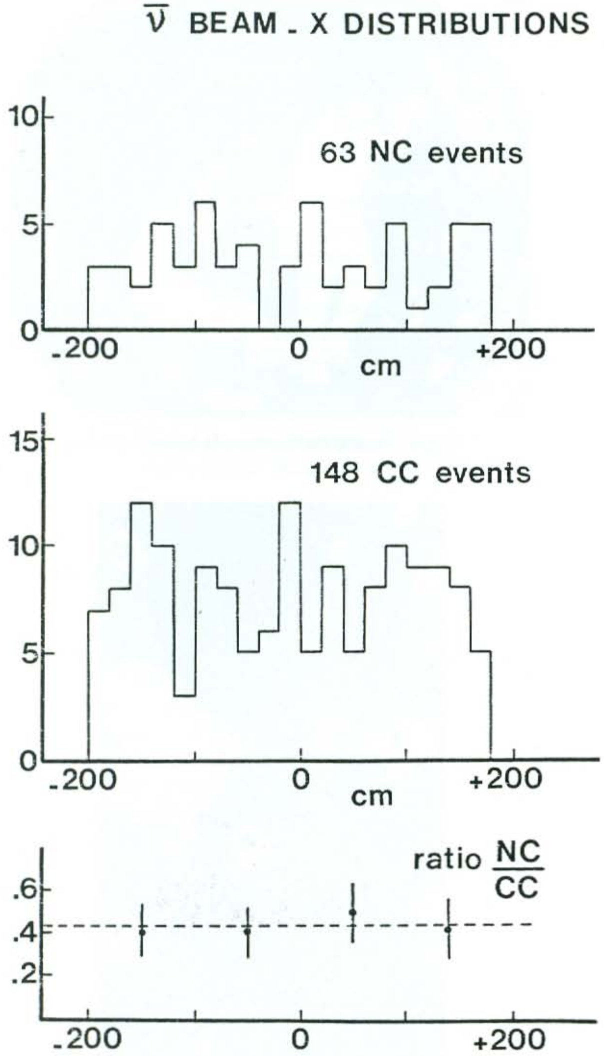

Figure 9: The distribution of the events in the chamber, along the beam direction, shows that the neutral current (non muonic) events, the top histogram, are not produced by neutrons (see text).

In the years 1969 to 1972 the inelastic scattering of high energy electrons on protons and deuterons (neutrons) at SLAC revealed a pointlike constituency of the nucleon. This was a capital discovery. Nucleons were no longer elementary. Subsequently, neutrinos proved to be excellent projectiles for complementary studies on the nature of the structure of the nucleon. On account of the weakness of their interaction, neutrinos penetrate the nucleon, and the nature of their interaction with the quarks, the primary candidates for the elementary constituency of nuclear matter, was already predicted by the electroweak theory.

Experiments were carried out with a new generation of massive, electronic neutrino detectors, at the new 400 GeV proton synchrotron at CERN. A photograph of the 1000 ton CDHS apparatus is shown in fig. 10. On account of the more massive detector, the higher beam energy, and the more sophisticated beam optics, millions of events were now obtained in comparison with the handful of the first neutrino experiment, and each event contained more detailed and precise information on the scattering than had been possible before. A typical event is shown in fig. 11. The results, in conjunction with the SLAC electron scattering results, demonstrated the quark nature (quarks had been postulated as particles of spin 1/2 and of 1/3 integral electric charge, interacting strongly with each other) of the nuclear constituency.

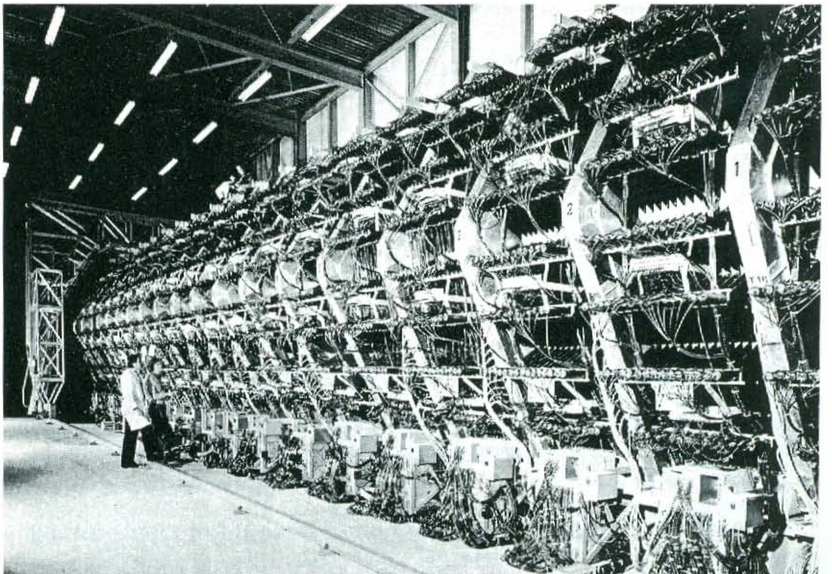

Figure 10: The CDHS 1200 ton electronic neutrino detector at CERN.

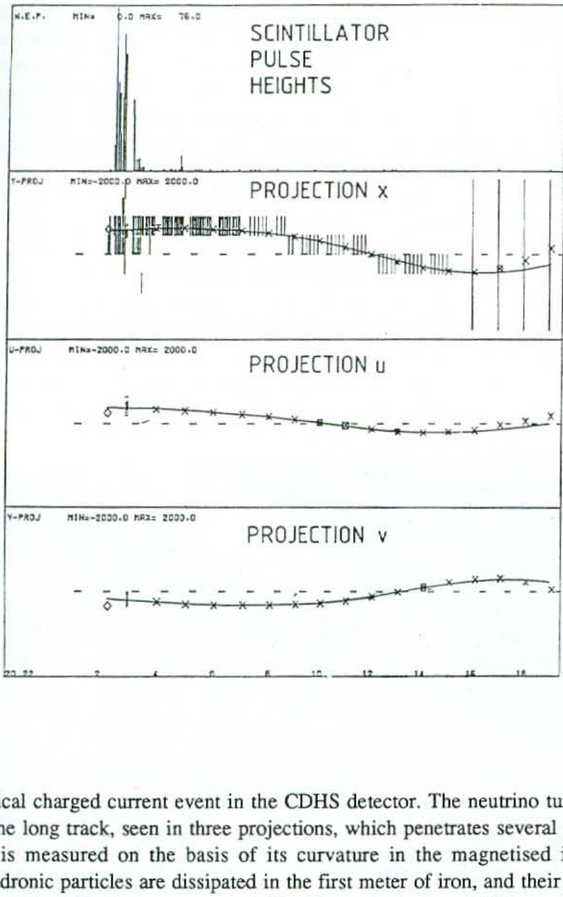

Figure 11: A typical charged current event in the CDHS detector. The neutrino turns into a muon, which is the long track, seen in three projections, which penetrates several meters of iron. Its energy is measured on the basis of its curvature in the magnetised iron. The accompanying hadronic particles are dissipated in the first meter of iron, and their energy is measured by means of scintillation counters sandwiched between the 5cm thick iron plates.

An additional important result of these neutrino studies was their contribution to the experimental confirmation of the now universally accepted theory of the strong quark forces, the Quantum Chromo-Dynamics. This theory predicted small, calculable deviations from the simple point-like scattering which was expected in the "naive" quark model, and which results in cross-sections independent of the momentum transfer called "scaling". Scaling was the basic element of the SLAC discovery, but it is only approximately true. The neutrino experiments[8,9] confirmed the scaling violations predicted by QCD, as shown in fig. 12, and so gave important experimental support to the QCD theory.

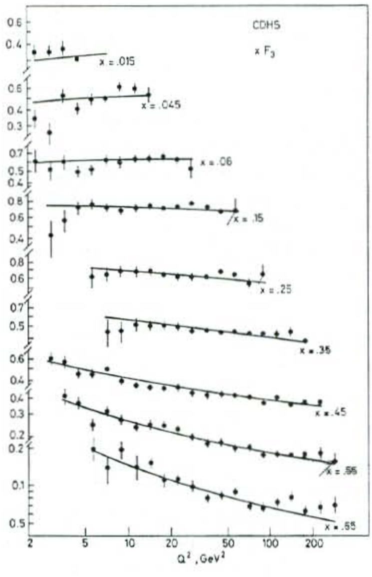

Figure 12: CDHS results which show the violation of "scaling". The observed event rates are converted to "structure functions" of two variables, x and Q^2. The variable x can be identified with the fraction of the nucleon's momentum carried by the quark which was struck, Q^2 is the square of the momentum transfer. For small x, the scattering increases with Q^2, for large x it decreases. The result confirmed the QCD theory which predicted this behaviour, as shown by the solid lines.

Neutrinos continue to be an important tool in the study of nucleon structure and the properties of the weak interaction.

Recently neutrinos played an indirect, but important role in establishing the *number of fermion families* which constitute matter. In the Standard Model—the Standard Model is the sum of the electroweak and the QCD theories—"families" consist of four elementary particles: a charged lepton and its associated neutrino, plus a pair of quarks of electric charges 2/3 and -1/3 respectively. Two of these families are known entirely, in the third family the "top" quark is still missing, presumably because its mass is too large to have been produced in sufficient quantity for detection so far. The general belief is that it will soon be found. The Standard Model does not predict how many families there should be. With the possible exception of the neutrinos, whose masses are smaller than could so far be measured, the masses of the members of succeeding families increase rapidly, by a factor of the order of one hundred from one family to the next. If additional families existed, they might be out of the reach of present accelerators because of the large possible masses of their constituents. But based only on the assumption that the masses of the neutrino members of possible higher mass families would also be small, recent experiments at the LEP electron-positron collider have been able to demonstrate that there are three families of matter and no more.

The LEP result uses the measurement of the resonance line shape of the Z. The Z, the particle with the highest mass yet discovered, about one hundred times heavier than the proton, decays into many different final states. Each of these consists of a fermion -anti fermion pair. A typical Z decay, here into a quark-antiquark pair, is shown in fig. 13. All fermion species contribute, with probabilities predicted in the Standard Model. The width of the resonance curve therefore is the sum of the contributions from all fermions accessible on energetic grounds, that is, whose mass is less than one-half the Z mass. The neutrino member of a higher mass family would contribute, provided only that its mass is less than one-half the very heavy Z mass. The resonance curve has been very accurately measured at LEP[10]), as shown in fig. 14. The width is known now with a precision of 0.4%, and is precisely the width expected for the known three families of matter. The neutrino of a possible fourth family is excluded with a precision of one twentieth of the expected contribution of such a neutrino to the width.

Let us turn now to what we have learned about stars using neutrino radiation, and, in turn what we might learn about neutrinos from those which arrive on our earth from far away. We will touch on three topics: neutrinos from the sun, neutrinos from supernova, and neutrinos during the big bang. This is not my own subject of experimentation, so I am afraid this discussion will be superficial.

We see the sun dominantly by means of the visual spectrum. This thermal energy takes about 10^6 years and 10^{30} collisions from the time of its creation to get out of the sun, and is modified in the process so that it cannot tell us much about the conditions which created it. Neutrinos however typically traverse the sun without collision. Although the solar neutrino flux on earth is far from negligible: $\sim 10^{11}$ solar neutrinos arrive here per cm^2 per second, with an energy flux as large as several percent of the sun's thermal energy, which sustains our life, nevertheless, just because the neutrino interaction cross-section is so small, their detection has been a big challenge.

The first experiment to detect solar neutrinos, and the only one until just a few years ago, dates to 1970[11]). It is still running. Neutrinos are detected by the inverse β-decay interaction on chlorine: $^{37}Cl + \nu \rightarrow {}^{37}Ar + e^-$. The reaction is observed by means of the argon β-decay, which has a lifetime of 35 days. The chlorine is in the form of 400 cubic meters (133 tons) of perchloretylene, 1500 meters underground, to get away from background produced by cosmic radiation, in the Homestake gold mine in the US. About one of the 10^{30} chlorine atoms per day is expected to be converted to argon by the solar neutrino radiation! Every couple of months the radioactive argon is flushed out by means of a small amount of non radioactive argon isotope, and counted. The results, which have taken much patience to accumulate, have been consistently below the expectations of models of nuclear energy production in the sun. They now stand at 0.4 ± 0.06 atoms per day, about one third of the rate predicted by detailed models of solar nuclear energy production.

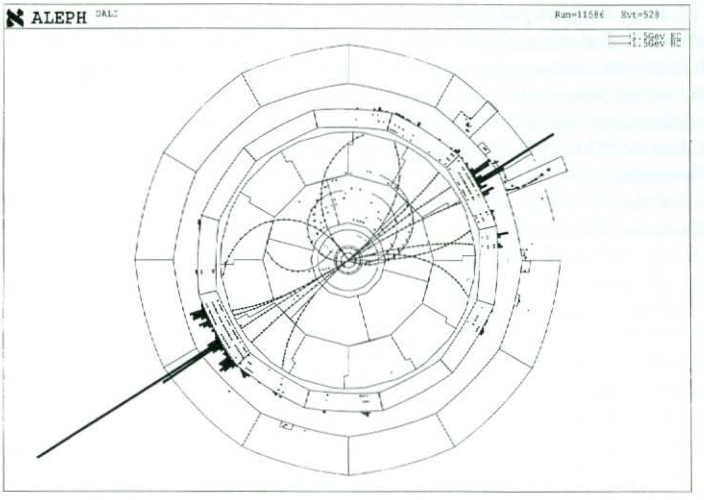

Figure 13: Decay of a Z into a quark-antiquark pair as seen in the ALEPH detector at LEP. The quark and antiquark materialize as jets, which are typically composed of a dozen or so hadrons. The momenta of the charged particles are measured by the stiffness (inverse curvature) of their tracks. The neutral particles are measured by means of the "calorimeters" which surround the track chambers.

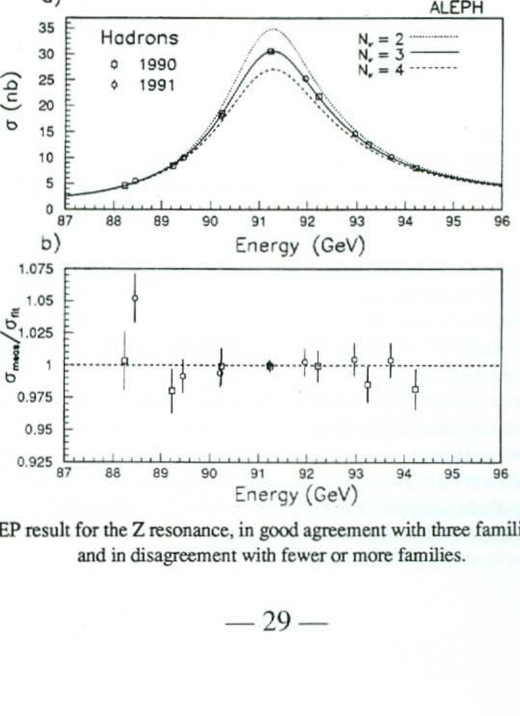

Figure 14: LEP result for the Z resonance, in good agreement with three families of neutrinos, and in disagreement with fewer or more families.

In the last years, this depletion has been confirmed by an experiment using a radically different method of detection[12]. The basic reaction is the elastic scattering of the neutrinos on electrons, with the observation of the recoil electron. The detector is a large tank of water, about 20m on each side, which is viewed by an array of photomultipliers. These measure the energy and direction of the little recoil electron on the basis of emitted Cerenkov light. Again, the detector is shielded from cosmic rays in a deep mine, the Kamiokande mine in Japan. Fig.15 shows the distribution in the angle of the recoil electron with respect to the sun for data obtained in 1040 days of running. The results, which are very clear, correspond to 0.46 ± 0.05 times the expectations of the solar models.

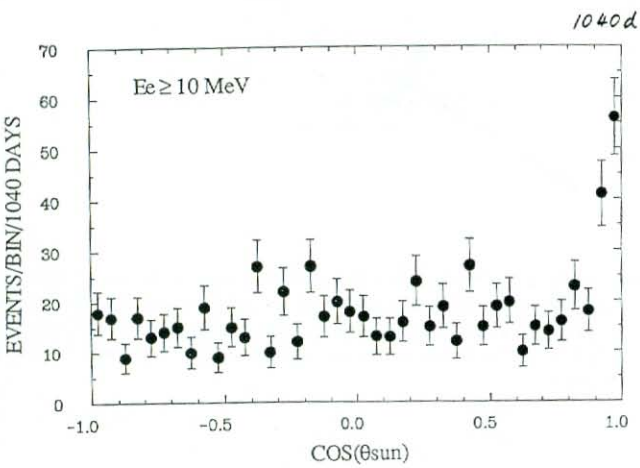

Figure 15: Kamiokande results on solar neutrinos. The plot shows the observed event rate for electron recoils with energy in excess of 10 MeV, as function of the angle of the track with respect to the sun. There is a large background; the signal is the peak at small angles.

The deviation from the expectations of the standard solar model of the combined result of the two solar neutrino experiments, by a factor of the order of 1/3 to 1/2, the "solar neutrino puzzle", is of great interest, since the process of nuclear energy production in the sun is believed to be adequately understood. To keep the experimental result in perspective, it should be kept in mind that on the one hand the experiments are difficult, and on the other both experiments are sensitive only to the relatively rare high energy component of the expected solar neutrino flux, essentially only to the decay of ^8B, since the neutrino energy threshold is 0.814 Mev for the chlorine reaction, and about 7.5 MeV for the Kamiokande detector. The experiments are insensitive to the lower energy neutrinos from the reaction $p + p \rightarrow d + \nu + e^+$, which accounts for the large bulk of solar neutrinos. There is a larger theoretical uncertainty for this high energy tail of the solar neutrino spectrum than for the pp component.

For this reason two new experiments are now underway, using the gallium reaction $^{71}Ga + \nu \rightarrow {}^{71}Ge + e^-$ which is sensitive to the pp reaction neutrinos: an American- Russian collaboration at Baksan in the Caucasus as well as a European collaboration in the Grand Sasso tunnel in Italy. No positive results have as yet been given by either experiment, but initial results of the Baksan experiment[13)] fall well below the expectations of the standard solar model. .

Perhaps it is too early to get exited about this new negative result, but if it were confirmed it would be a demonstration of new physics in the properties of neutrinos. Pontecorvo[14)] was the first to note the possibility of neutrino flavor oscillation, Wolfenstein[15)] pointed out that neutrino oscillations would be markedly affected by matter, and Mikheyev and Smirnov[16)] used this mechanism to provide a possible explanation of the "solar neutrino puzzle". For neutrino masses much less than one electron volt, it is expected that in dense matter, the electron neutrino, in virtue of its charged current scattering on electrons, will have a higher effective mass than the muon neutrino, even if its "free" mass is slightly lower. An electron neutrino born in the center of the sun would then, if there is adequate mixing between the flavors, leave the sun as a muon neutrino, impotent to perform inverse β decay. If both the present experiments as well as the standard solar model calculations are correct, then the parameter space of neutrino mass differences and mixing angles is very tightly limited to mass differences in the range of a few thousandth of an electron volt and a substantial mixing angle. The end of this story is not yet told, but it is a nice example of the symbiotic relationship between particle physics and astronomy.

Another interesting example of this relationship was the detection of neutrinos from the supernova SN1987A. Neutrinos are the dominant (99%) mechanism by which supernovae are expected to dissipate the energy released in the gravitational collapse of its core into a neutron star. Prior to the event of 1987 it was calculated that in a typical supernova more than 10^{53} ergs should be radiated in the form of neutrinos. These are thermal neutrinos with typical energies of the order of 10 MeV. On march 23rd of 1987, at 7:35 U.T., 11 and 8 events respectively, of such low energy neutrino events were registered in the Kamiokande[17)] and IMB[18)] large underground water Cerenkov detectors. The time distribution of the burst, of the order of 10 seconds duration, shown in fig. 16, was in line with the expectations of the supernova collapse models, as was the energy distribution and the overall rate. The observation was useful in establishing a new level of confidence in the present understanding of the theory of supernovae.

The observations were serendipitous in the sense that these detectors were built to study an entirely different process, the possibility of the decay of the nucleon. They also provided new information on the properties of neutrinos, since the time coherence of the events, despite the energy differences of the individual neutrinos, permits an upper limit of 25 electron volts on the electron neutrino mass. Other neutrino properties which follow from the observation were a lower bound of $1.6*10^5$ years on the electron neutrino lifetime based on the time of flight from the supernova, as well as an upper bound on its electric charge of 10^{-17} electron charges, and an upper bound on its magnetic moment 10^{-11} times smaller than the electron magnetic moment, both based on the passage of the neutrinos through the matter of the supernova.

The energy density of neutrinos as well as the energy transfer by neutrinos played an important role in the dynamics of the early universe. The competition between the expansion rate (or the cooling time) and the neutron decay time is determinant in the formation of the primordial helium after the temperature has decreased to about 1 MeV, and the weak interaction has frozen out of thermal equilibrium. From the measured cosmic abundances of Deuterium, Helium and Lithium7 relative to Hydrogen, it has been deduced that there should have been of the order of three families of neutrinos, in agreement with the particle physics result. If one of families would have a mass of the order of ten to twenty electron volts, the remnants of these neutrinos from the big bang would be possible candidates for the "dark matter" which is known to dominate the universe.

I hope that these examples make it comprehensible why some people spend their time in the study of the most evasive of known particles: the neutrinos.

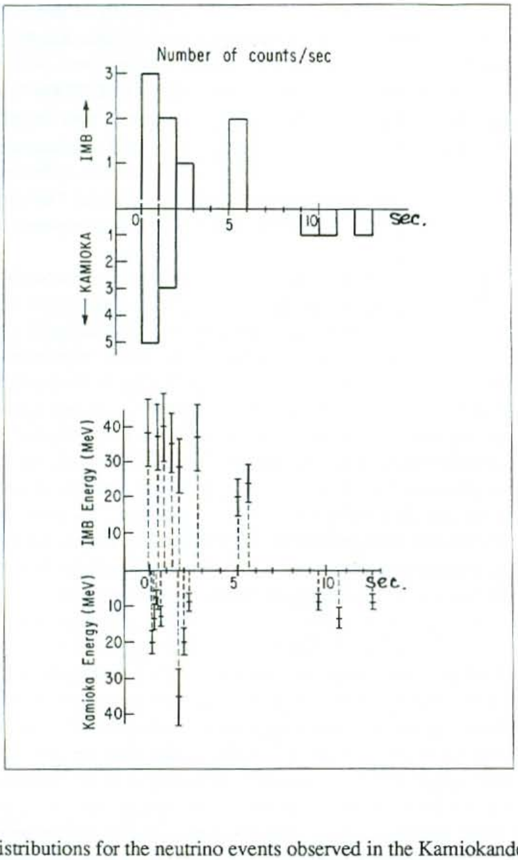

Figure 16: Time distributions for the neutrino events observed in the Kamiokande and IMB underground water cerenkov detectors, and attributed to the Supernova SN1987A. For the neutrinos, it was all finished in ten seconds.

Appendix

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Dear Radioactive Ladies and Gentlemen.

As the bearer of these lines, to whom I ask you to lend most graciously your ears, will explain in greater detail, I have hit, in view of the "false" statistics of the N and Li-6 nuclei and of the continuous β–spectrum, upon a desperate expedient for saving the "Wechselsatz"† of statistics and energy conversation. This is the possibility that electrically neutral particles, which I shall call neutrons, might exist in the nucleus, having spin 1/2 and obeying the exclusion principle. In addition they differ from light quanta in that they do not travel at the speed of light. The mass of the neutron should be of the same order of magnitude as that of the electron and in any event no greater than 0.01 of the proton mass. The continuous β–spectrum would then be comprehensible on the assumption that on β–decay a neutron is emitted with the electron in such a way that the sum of the neutron and the electron energy is constant.

Furthermore the question arises which forces act on the neutron. For reasons of wave mechanics (the bearer of these lines knows more about this) the likeliest model for the neutron seems to me to be, that the neutron at rest is a magnetic dipole with a certain moment μ. Experiments apparently demand that the ionising effect of such a neutron is no greater than that of a γ–ray, in which case μ should be no greater than e $(10^{-13}$ cm).

For the moment I would not venture to publish anything on this notion and should like first of all to turn trustingly to you, dear Radioactives, with the question concerning the prospects for experimental verification of the existence of such a neutron if it were to have the same or perhaps a 10 times greater penetrating power às a γ–ray.

I admit that my expedient may seem rather improbable from the first, because if neutrons existed they would have been discovered long since. Nevertheless, nothing ventured nothing gained, and the seriousness of the situation with the continuous β–spectrum is illustrated by a statement by my esteemed predecessor in office, Mr. Debye, who recently told me in Brussels: "Oh, it's better to ignore that completely, just like the new taxes". We should therefore be seriously discussing every path to salvation. So, dear Radioactives, consider and judge. Unfortunately I cannot come to Tübingen in person since my presence here is essential as a result of a ball held on the night of 6th to 7th December in Zürich.

With kind regards to all of you and Mr. Back, I remain,
your humble servant,

(signed) W. Pauli

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† This states: Fermi statistics and half-numbered spin for nuclei with an odd total number of particles; Bose statistics and integer spin for nuclei with an even total number of particles.

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CURRICULUM VITAE

DE

JACK STEINBERGER

CURRICULUM VITAE

Jack Steinberger

Born: Bad Kissingen, Germany, 25-05-1921

Father: Ludwig Steinberger, cantor in the synagogue, religious teacher.

Mother: Berta Steinberger (born May), language teacher, housewife.

Education:

1927-1931:	Volksschule, Bad Kissingen.
1931-1934:	Realshule, Bad Kissingen.
1934:	Emmigration to US, thanks to generosity of American-Jewish charities.Foster father Barnet Faroll, Winnetka IL.
1935-1938:	New Trier Township High Scholl, Wilmetter IL.
1938-1940:	Armour Institute of Technology, Chicago, IL., subject: Chemical engineering.
1941-1942:	University of Chicago, subject: Chemistry. B.S. Degree 1942.
1946-1948:	University of Chicago, subject: Physics. Ph. D. Sponsor: E. Fermi, Ph. D. Degree 1948.

Employment:

1940-1941:	Bottle washer, G.D. Searle Co., Chicago.
1943-1945:	Radiation Laboratory, MIT, Cambridge, MA, wartime development of radar bomb sights, first chance to study some physics, part time, at MIT, with Lazlo Tisza.
1945-1946:	US Army, Signal Corps, Pfc.

1948-1949:	Member, Institute for Advanced Study, Princeton
1949-1950:	Assistant to G.C. Wick, University of California, Berkeley, CA.
1950-1968:	Columbia University, starting as assistant professor, ending up as Higgens Professor.
1956:	Sabatical at Rome, Bologna Universities.
1964:	Sabatical at University of California, San Diego.
1965-1966:	Sabatical at CERN, Geneva.
1968-1986:	Physicist, CERN, Geneva, 1969-1972: Director, physics department.
1986:	Visiting professor, Scuola Normale Superiore, Pisa.

Civil status:

1943-1962:	Married to Joan Beauregard, two children, Joseph 1944, Richard Ned 1948.
1962:	Married to Cynthia Eva Alff, two children, Julia Karen 1974, John Paul 1977.

Selection of research papers:

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Honors:

US National Medal of Science, 1988.
Nobel prize for Physics (with L.M. Lederman and M. Schwartz), 1988.
Mateuzzi medal, Società Italiana delle Science, 1991.
Guggenheim fellow.
Sloan fellow.

Doctor Honoris Causa:

Illinois Institute of Technology
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Universitat Dortmund
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Member:

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US National Academy of Science
American Academy of Arts and Sciences
Academia Europea

EXCLÒS DEL PRÉSTEC