<u>Chasing Neutrinos Around The</u> <u>World: A Personal History</u>



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Kavli IPMU Colloquium Kashiwa July 17, 2019 I'm going to tell you all about trying to detect neutrinos, and in the process you will hear tales of:





boundless ambition



catastrophic failure

and just a touch of madness



triumphant discovery

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

Abschrift.

Physikalisches Institut der Eidg. Technischen Hochschule Zurich

Zirich, 4. Des. 1930 Cloriastrasse

Liebe Radioaktive Damen und Herren.

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinendersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen versweifelten Ausweg verfallen um den "Wechselsats" (1) der Statistik und den Energiesats su retten. Nämlich die Möglichkeit, es könnten elektrisch neutrals Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und den von Lichtquanten musserden noch dadurch unterscheiden. dass sie mieht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen finste von derselben Grossenordnung wie die Elektronenwasse sein und jesenfalls nicht grösser als 0,01 Protonenmasse.- Das kontimuierliche bate- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem blektron jeweils noch ein Neutron emittiert Mird. derart. dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter derum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir sus wellenwechenischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Meutron ein magnetischer Dipol von einem gewissen Moment A ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, sis die eines gamma-Strahls und darf dann A4 wohl nicht grösser sein als $e \cdot (10^{-13} \text{ cm})$.

Ich traue mich vorläufig aber nicht, etwas über diese Idee su publisieren 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 Lonal grösseres Durchdringungsverwögen besitsen wurde, wie ein Strahl.

Ich gebe su, dass mein Ausweg vielleicht von vornherein Wanig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon lingst geschen hatte. Aber nur wer wagt, ingt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Aussprech meines verehrten Vorgängers im Ante, Harrn Debye, beleuchtet, der mir Mirslich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg sur Rettung ernstlich diskutieren --Also, liebe Radioaktive, prufet, und richtet .- Leider kann ich nicht personlich in Tübingen erscheinen, da sch infolge eines in der Nacht vom 6. sum 7 Des. in Zurich stattfindenden Balles hier unabkömmlich bin .- Mit vielen Grüssen an Buch, sowie an Herrn Back. Buer untertanigster Diener

Absohrift/15.12. (a very good place to start):



Wolfgang Pauli's famous 1930 letter in which the neutrino - called the "neutron" until Fermi renamed it in 1934 – was first proposed.

Dear Radioactive Ladies and Gentlemen,

...I have hit upon a desperate remedy to save the...law of conservation of energy...there could exist...electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light.

I agree that my remedy could seem incredible... But only the one who dare can win... ...dear radioactive people, look and judge.

> Your humble servant W. Pauli

Pauli thought this idea was so crazy he didn't publish it!

Twenty years later, along came the first really serious, but still crazy, proposal to detect neutrinos.

It was suggested by a 32 year old named Frederick Reines, a protégé of an even younger (well, 63 days younger) Richard Feynman.



However, this proposal probably <u>isn't</u> the experiment you're thinking of right now.



So, essentially Fred asked for his very own, private above-ground atomic test, and was told,

"Well, sure, you go right ahead. We'll set aside a nuclear bomb just for you."

Ah, the 1950's!





= "man made"





Hey... they forgot one! \rightarrow



After over sixty years, this is still an unobserved source of neutrinos, because Fred suddenly thought of a better way.

It took Fred and his team several more years and a few approved experiments until they finally managed to detect neutrinos. These pictures are from an <u>unsuccessful</u> experiment at the Hanford reactor in 1953.





At last, success! The first certain neutrino detection took place in 1956 at the Savannah River nuclear reactor in South Carolina.

39 long years later, Reines would finally be given the 1995 Nobel Prize in physics for this discovery.





Now that the neutrino had been discovered, it was time to consider other sources and look for them, too.

One likely candidate: cosmic rays



[Slide by F. Reines] -22-

ATMOSPHERIC VR

protons cosmic roy (cosmic roy primary) Extraterrestrial Atmospheric sources (stors, supernovae, TIMINIMATINA black holes?...) Atmosphere Eorth \mathcal{V}_{μ} produced . ere The Case-Wits Experiment produced in interaction here interaction Figure 18 » sources, terrestrial and extraterrestrial. Cosmic ray protons interact with earth's atmosphere producing particles (K, $\pi, ...$) whose decay yields various v types. Shown is the interaction of a vy with the earth to produce a µ. SOURCES TERRESTRIAL

& EXTRA-TERRESTIAL



So, if you want to look for neutrinos from cosmic ray interactions in the atmosphere, you have to go deep. Really deep.

And this is as deep as it gets:



The East Rand gold mine in South Africa, circa 1964

Extends 3585 meters below ground! So, Fred Reines (a professor at Case Western Institute in Cleveland, Ohio) and his crew headed off to apartheid-era South Africa.









The Case Western Irvine/South Africa Neutrino Detector [CWI/SAND]

> Boxes of liquid scintillator viewed with Two 5-inch PMT's on each end



Digging out the experimental space, circa 1964

"Putty,"an explosives expert employed by the mine, was killed during the course of the experiment









Downward-going Muon (background) Horizontal Muon (neutrino signal)





THIS DISCOVERY TOOK PLACE IN A LABORATORY SITUATED TWO MILES BELOW THE SURFACE OF THE EARTH ON 76 LEVEL OF EAST RAND PROPRIETARY MINE, MANNED BY A CROUP OF PHYSICISTS FROM THE CASE INSTITUTE OF TECHNOLOCY U.S AND THE UNIVERSITY OF THE WITWATERSRAND JOHANNESBURC.

THE PROJECT WAS SPONSORED BY :-UNITED STATES ATOMIC ENERCY COMMISSION E.R.P.M. AND RAND MINES CROUP CASE INSTITUTE OF TECHNOLOCY UNIVERSITY OF THE WITWATERSRAND TVL. & O.F.S. CHAMBER OF MINES AND CONVERTED FROM PROPOSAL TO REALITY WITH THE HELP OF THE OFFICIALS AND MEN OF THE HERCULES SHAFT OF E.R.P.M. 6¹⁰¹ DECEMBER 1967

SCIENTIFIC TEAM : F.REINES J.P.E.SELLSCHOP M.E.CROUCH MD LI JENEINS W.R.KROPP H.S.CURR B.MEYER A.A.HRUSCHKA B.M.SHOFENFI Fred Reines and his team had done it again!

EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

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Case Institute of Technology, Cleveland, Ohio

and

J. P. F. Sellschop and B. Meyer

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The flux of high-energy neutrinos from the decay of K, π , and μ mesons produced in the earth's atmosphere by the interaction of primary cosmic rays has been calculated by many authors.¹ In addition, there has been some conjecture¹ as to the much rarer primary flux of high-energy neutrinos originating outside the earth's atmosphere. We present here evidence² for the interactions of "natural" high-energy neutrinos obtained with a large area liquid scintillation detector (110 m^2) located at a depth of 3200 m (8800 meters of water equivalent, average $Z^2/A \simeq 5.0$) in a South African gold mine.

The essential idea of the present experiment³ is to detect the energetic muons produced in neutrino interactions in a mass of rock by means of a large area detector array imbedded in it. Backgrounds are reduced by the large overburden and by utilizing the fact that the angular distribution of the residual muons from the earth's atmosphere is strongly peaked in the vertical direction at this depth. The angular distribution of the muons produced by neutrino interactions should show a slight peaking in the horizontal direction.¹

The detector array, shown schematically in Fig. 1, consists of two parallel vertical walls made up of 36 detector elements. The array is grouped into 6 "bays" of 6 elements each. Each detector element, Fig. 2, is a rectangular box of Lucite of wall area 3.07 m² containing 380 liters of a mineral-oil based liquid scintillator,⁴ and is vièwed at each end by two 5-in. photomultiplier tubes. The array constitutes a hodoscope which gives a rough measurement of the zenith angle of a charged particle passing through it. In addition, the event is located along the detector axis by the ratio of the photomultiplier responses at the two ends. The sum of the responses then pro-

FIG. 1. Schematic of detector array.

They saw the very first atmospheric neutrino, but theirs was not the first publication.

This time, they had competition.



The next chapter in underground neutrino physics opened in the late 1970's.

Unified field theories had become popular, and one in particular, SU(5), made testable predictions on the proton lifetime.

Of course, it was still a pretty high number (around 10²⁹ years or so) and so would require observing a lot of protons to prove.

If you want a lot of protons and you want to be able to look at all of them without spending too much money, a great big tank of clear water is your best bet. Because they were looking for proton decay, which emits around 1 GeV of energy in a specific pattern, the shielding requirements were less severe for the new generation of experiments than they had been for SAND.

One no longer had to find the deepest mine in the world to do your work. Instead of 8 km.w.e., 2 km.w.e. would be okay.

The Reines group, now based at the University of California, Irvine, joined forces with groups from the University of Michigan and Brookhaven National Laboratory, to build the IMB experiment in the Morton Salt Mine in Cleveland, Ohio. Proposal Submitted to DoE May 31st, 1979

> Proposal Approved November 28th, 1979

> Excavation Began November 30th, 1979

PROPOSAL FOR A NUCLEON DECAY DETECTOR IRVINE/MICHIGAN/BROOKHAVEN



IMB was the first largescale water Cherenkov detector: 7000 tons H_2O

Relativistic charged particles would make rings of light on the inner wall of the detector. The rings would then be imaged by photomultiplier tubes.



This detector was going to be very big – a cube about 20 meters on a side. To save money, a salt mine was used, since it's easier to excavate salt than hard rock.

Also, there was no big metal tank holding the water. A plastic liner kept the water away from the salt.





September, 1981

Full of water, with 5-inch PMT's

Late 1982

They had really expected to – and had told the funding agency that they would – find proton decay right away.

But after only 80 days of running, and no proton decay candidates observed, the proton lifetime had to be over 5 X 10 ³¹ years.

 \rightarrow By April of 1983, minimal SU(5) was dead! \leftarrow

However, by the summer of 1983 a strange effect had been noticed in the observed atmospheric neutrinos (the main background to the proton decay search).


There should have been about two muon-type events for every electron-type event.

But there seemed to be too few muons.

A detector upgrade was proposed and approved, perhaps in part because by then they had serious competition from a new player in the game.



A professor at the University of Tokyo, Masatoshi Koshiba, had convinced his friend and UTokyo classmate (and now the head of Hamamatsu **Photomultiplier Tube** Company) to try and make a tube an unbelievable 20" in diameter.

"He was one day younger than me, so he had to do as I said."



Institute of Physics



Incredibly, Hamamatsu did it!

Here's a publicity shot announcing the technological breakthrough.

It was so unwieldy the process could not be easily automated.

Every tube was made out of hand-blown glass.

Equipped with his powerful new tool, Koshiba also had his sights set on discovering proton decay.

By 1983 he and his team were busy building the Kamiokande detector, in rural, mountainous central Japan.

It was about 1/2 the size of IMB, but more sensitive.







Kamiokande also noticed something strange going on with the atmospheric muon neutrinos.

They tended to use the ratio-of-ratios approach to discuss the data. Eventually this became standard.

$$(v_{\mu}/v_{e})^{data}$$

R = ------
 $(v_{\mu}/v_{e})^{Monte}$ Carlo

But then, at 07:35:41 UT on February 23rd, 1987, both IMB and Kamiokande got a nice surprise:



This was 22 years to the day since the first atmospheric neutrino was seen in South Africa.











Supernova 1987A re-energized the neutrino field, and (at least in my opinion) did a lot to help make the next generation of detectors a reality.

They were also driven by important neutrino findings coming out of an upgraded Kamiokande:



First proof neutrinos are made by the Sun.

But here, not enough $v_e!$



In Japan neutrinos were (and are) quite popular.

In the late 1980's there started serious talk of building something called <u>Super-Kamiokande</u>.

But something important had changed in a decade...

Kamiokande = Kamioka Nucleon Decay Experiment

Super-Kamiokande = Super Kamioka Neutrino Detection Experiment

Neutrinos – atmospheric, solar, and supernova – were now the stars of the show!

By 1990 things were looking pretty good (if a bit confusing – where were the missing nu's?) for atmospheric and solar neutrinos in both the US and Japan.

But IMB's luck was about to run out...



Over Easter weekend in 1991, the plastic bag holding IMB's 7000 tons of water sprang a leak.

This had actually happened before, and each time divers had been quickly sent in to patch the leaks.

Acting fast was important, because behind the plastic liner and a thin layer of concrete was nothing but salt.

But this was a long holiday weekend, and they could not get into the mine!



By the time they did, it was too late...



By the time they did, it was too late...



The laboratory dissolved... and that was the salty end of IMB.



Meanwhile, in Japan, construction had begun on Super-Kamiokande.

Super-Kamiokande

4 4

41

40m

50000 tons ultra-pure water 22500 tons fiducial volume 1 km overburden = 2700 m.w.e.

mm

-

Koshiba had been forced to retire (due to turning 60) right after SN1987A, and so the leader of Super-K was to be the senior member of the Kamiokande team, Yoji Totsuka.





After a proposal to the DoE to rebuild IMB was turned down, senior members of the collaboration (Reines had also retired by then) traveled to Japan to see if joining Super-K was a possibility.

Although there was some initial resistance, Totsuka graciously welcomed them aboard.

It was agreed that the US would provide the veto counter for Super-K. They used 1885 8" PMT's salvaged from the wreckage of IMB to instrument it.

The additional manpower was needed, too, as the Super-K construction surged ahead.



Kamiokande was still taking data during this period. In 1994, they put out a very important result.



I September 1994



PHYSICS LETTERS B

Physics Letters B 335 (1994) 237-245

Atmospheric ν_{μ}/ν_{e} ratio in the multi-GeV energy range

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> Received 27 June 1994 Editor: L. Montanet

Abstract

Data from the Kamiokande detector were used to study the atmospheric $(\nu_{\mu} + \overline{\nu}_{\mu})/(\nu_{e} + \overline{\nu}_{e})$ ratio in the multi-GeV energy range. The observed ratio of μ -like to e-like events relative to the calculated ratio, $(\mu/e)_{det}/(\mu/e)_{MC} = 0.57 \stackrel{10.08}{-0.07} \pm 0.07$, suggests that the atmospheric $(\nu_{\mu} + \overline{\nu}_{\mu})/(\nu_{e} + \overline{\nu}_{e})$ ratio is smaller than expected for these neutrino energies. Also studied was the zenith-angle dependence of the above ratio. Results of an analysis of neutrino oscillations are presented.





But this was new



And this!

Higher statistics data was eagerly awaited... and there wouldn't be long to wait.

Fig. 5. 90% C.L. allowed neutrino-oscillation parameters as obtained from the multi-GeV data (thick curves). 90% C.L. allowed regions as obtained from the updated sub-GeV data are also shown by thick-dotted curves. The allowed regions as obtained by combining the sub- and multi-GeV data are also shown (shaded region). The best-fit values are also shown by dash-crosses (sub-GeV data), full-crosses (multi-GeV data) and stars (suband multi-GeV data combined). The 90% C.L. excluded regions from the other experiments are also shown [15,16,18–21].



June 1995







September 1995





September 1995, two weeks after that



October 1995



I've been a part of Super-K (and wearing brightly-colored shirts) from its very early days...



January 1996




January 1996



January 1996

After half a decade of construction, data taking began precisely on schedule at 00:00 JST on April 1, 1996



12 MeV solar v

Result of v-e elastic scattering: points back in solar direction



603 MeV atmospheric <u>muon</u> v

Note sharp edge of ring from muon produced by v_{μ} -nucleon interaction



492 MeV atmospheric <u>electron</u> v

Note diffuse edge of ring from electron produced by v_e -nucleon interaction Because Super-K has 22X the fiducial volume of Kamiokande, it quickly surpassed the old data set... in many cases, in just two or three months!

Two years after turning on, Super-K hosted the Neutrino 1998 conference in Takayama, Japan.

The Japanese head of the atmospheric neutrino analysis group, Takaaki Kajita, was ready to



make a big announcement.

"The discovery of neutrino oscillations has been confirmed."



Kajita's key transparency from his Neutrino 98 presentation

One person in particular was most interested...

Super-K ran another three years before being drained for refurbishment in July 2001

SK-I

1489 days of data

SK-I





⁸B flux = $2.35 \pm 0.02 \pm 0.08$ [x10⁶/cm²/s]

Data / $SSM_{BP2004} = 0.406 \pm 0.004(stat.) + 0.014 - 0.013 (syst.)$

Data / $SSM_{BP2000} = 0.465 \pm 0.005(stat.) + 0.016 - 0.015 (syst.)$



Picture of the Sun in neutrino "light."

We worked all summer in 2001, draining the water out and replacing the few percent of PMT's which had failed during five years of continuous operation.

Then we started to refill the tank.

The tank was about 2/3rd full on November 12, 2001...





November 12, 2001



November 12, 2001

Spokesman Toksuka's November 13th, 2001 Announcement to His Grieving Collaboration



"We will rebuild the detector. There is no question." Special implosion-proof housings were developed for the Super-K PMT's

We cleaned up the tank, rearranged the surviving inner PMT's, replaced the outer PMT's, and 13 months after the disaster we were taking data again!



We were back in the neutrino business just in time to watch Koshiba to receive his Nobel Prize for SN1987A.

December 10, 2002



Eventually, half of the 2015 Nobel Prize in physics (shared with SNO's Art McDonald) went to Takaaki Kajita for Super-K's 1998 discovery of neutrino oscillations.



October 6, 2015





SK-I: 40% PMT Coverage



SK-II: 19% PMT Coverage



April 1996 → July 2001

December 2002 → September 2005

SK-III/IV: 40% PMT Coverage



April 2006 \rightarrow September 2008 \rightarrow May 2018

Wait... what happened to Super-K in May 2018?

Well, on July 30th, 2002, at ICHEP2002 in Amsterdam, Yoichiro Suzuki, then the newly appointed head of SK, said to me during a coffee break,

"We must find a way to get the new physics."





Inspired by this call to action, theorist John Beacom and I wrote the original GADZOOKS! (Gadolinium Antineutrino Detector Zealously

Outperforming Old Kamiokande, Super!) paper.

It proposed loading big WC detectors, specifically Super-K, with water soluble gadolinium, and evaluated the physics potential and backgrounds of a giant antineutrino detector. [Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004] (364 citations → one every 15 days for fifteen years)



Here's the very first transparency (i.e., what we older folks used before PowerPoint but after glass slides) I ever showed on the topic... over sixteen years ago.

Please note the subtitle:

"A Serious SK Upgrade Suggestion" After many years of testing and study - and about \$10M in equipment - no technical showstoppers have been encountered. And so...

June 27, 2015: The Super-Kamiokande Collaboration approved the addition of gadolinium sulfate to the detector, pending discussions with T2K.

January 30, 2016: The T2K Collaboration approved addition of gadolinium sulfate to Super-Kamiokande, with the precise timing to be jointly determined based on the needs of both projects.



July 26, 2017: The official start time of draining the SK tank to prepare for Gd loading was decided \rightarrow June 1, 2018.



Main jobs to get ready for Gd loading: 1) Fix SK leak 2) Clean up interior 3) Replace dead PMTs 4) Augment internal plumbing

Entering Super-K for the first time since 2006; June 1st, 2018

From March 2018 → October 2018, 2683 person-days of work were required!

Inside Super-K veto region (top); June 6th, 2018



Applying special low-background MineGuard sealant

Super-K veto region (side) with floating floor; June 23rd, 2018







Following ~3000 persondays of refurbishment work, as of Feb. 2019 the detector is now refilled with pure water and taking data, ready for the addition of gadolinium!

"Currently we do not observe any water leakage from the SK tank within the accuracy of our measurement, which is less than 0.017 tons per day. This is less than 1/200th of the leak rate observed before the 2018/2019 tank refurbishment."





Leak sealing work is a success!

Expected timeline for SK-Gd



Gd-H₂O: Everybody's Doing It, Man...

UTS CADLATE	Name	Location	Main Goal	Water Volume	Loaded with Gd ₂ (SO ₄) ₃
	EGADS	Kamioka	Gd R&D, SN Watch	200 tons	Since 2013
ALLTHE DETECTORSI	ANNIE	Fermilab	High-E Neutron Multiplicity	26 tons	2019
	Super-K-VI	Kamioka	DSNB, SN Burst, PDK, ATM/Solar/LB Neutrinos	50 ktons	2020
ALL THE DETECTORS!	XENONnT Water Shield	Gran Sasso	Dark Matter Detection	700 tons	2020
LETS CADIATE	WATCHMAN	Boulby	Nuclear Non- proliferation Demonstrator	6 ktons	2024
ALL THE DETECTORS!	Hyper-K(-II)	Kamioka	DSNB, SN Burst, PDK, ATM/Solar/LB Neutrinos	258 ktons	2028(?)

How did I learn all of this history, hear all of these stories? Well, I exist in a superposition state between the US and Japan.

I even have an office in <u>Reines Hall at UCI,</u> and sometimes teach in <u>Koshiba Hall at UTokyo.</u>



MATHEMATICS OF THE UNIVERSE
<u>I am currently</u> in the middle of <u>my 253rd</u> trip to Japan!

Apparently neutrinos are not the only massive things that oscillate.

So until next time... sayonara, dudes!

