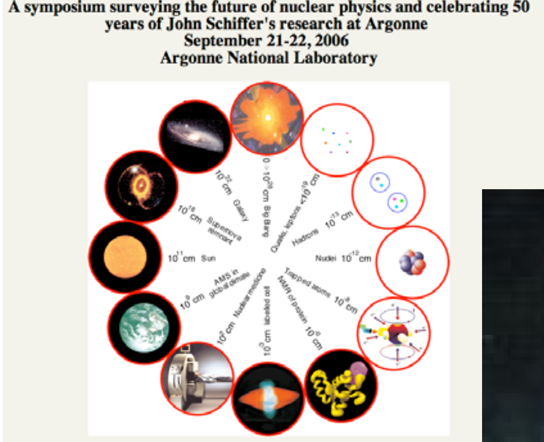


"I am not very happy about this!" and the search for exotica in Science

(with apologies)

Stuart Freedman
UC Berkeley / LBNL*

(*ANL Physics Division from 1982 until 2003
when I was forced to retire by the the Division Director)

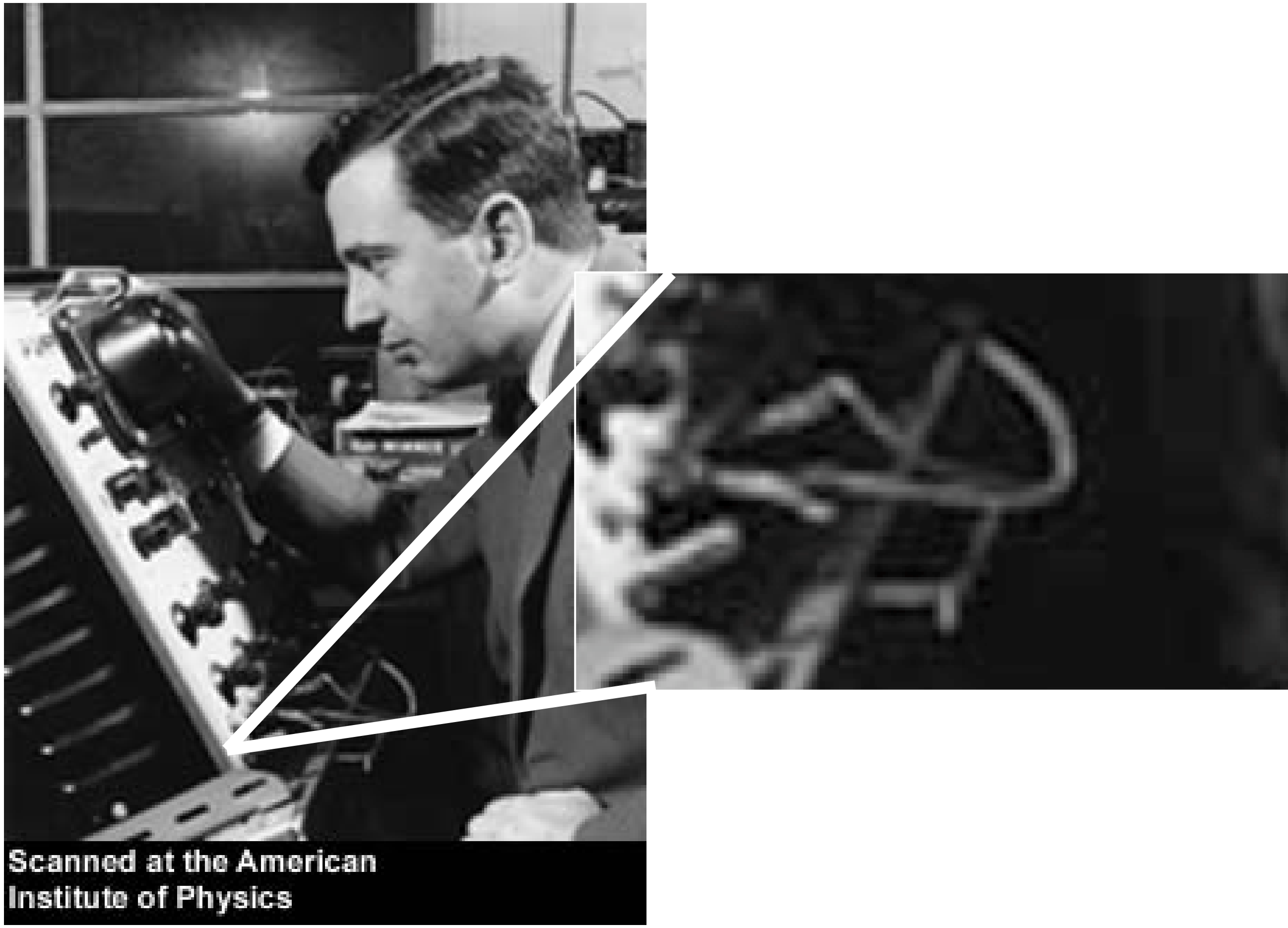
Research Interests

My primary interests have been in trying to understand the single-particle structure and effective interactions that underlie the structure of structure of atomic nuclei. This entails calibrating reaction mechanisms to best extract the relevant information. Some of this work was done a long time ago - and some recently - particularly with a focus on how these nuclear properties might change as nuclei move further away from stability.

An additional interest of mine has been to investigate 'exotic' phenomena that are associated with nuclear physics. Among these (and the only one that turned out to be real) was the Mössbauer effect. When I first heard of it (a small effect in 191Ir) we were incredulous but then Argonne was were the first to repeat this successfully. Shortly after this I came across 57Fe, and from this a whole industry emerged; I worked on relativistic red-shift measurements. After quarks were first proposed by Gell-Mann, I spent a fair amount of effort in looking for stable fractional charges in Nature - including sea water, the atmosphere, meteorites, and moon dust, and on trying to reproduce some positive experiments in this regard - we found none. After that came the 'GSI positron lines' reported from the collisions between very heavy nuclei, and our work with APEX could not confirm the reported phenomena. I did some work on cold fusion. Recently the reported 'triggered decay' of an isomer in Hf by x-rays, lead to speculations about new method of airplane propulsion and of other uses. We found no such effect. We also set a limit on helium-like strangelets in nature.

I am currently involved with a number of measurements with unstable light nuclei that are of interest both for nuclear structure and related to microscopic ab origine theoretical predictions of nuclear properties and for astrophysical interests. I have proposed a new scheme for charged-particle detection from reactions in inverse kinematics (that is required with radioactive beams) a technique that could overcome many of the current difficulties encountered in such measurements. The scheme requires a large super-conducting solenoid and methods of obtaining such a solenoid and detector array are being pursued.

An interest that grew out of nuclear physics is in the simulation of very cold plasmas such as can be obtained in ion traps and storage rings and the properties of such plasmas properties associated with crystallization.



John and I have nothing in common!

We share an appreciation for null experiments.

Search for Exclusive Free-Quark Production in e^+e^- Annihilation

A. Marini, I. Peruzzi, M. Piccolo, and F. Ronga
Laboratori Nazionali di Frascati dell' Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Roma, Italy

and

D. M. Chew,[a] R. P. Ely, T. P. Pun, and V. Vuillemin[b]
Lawrence Berkeley Laboratory, Berkeley, California 94720

and

R. Fries,[c] B. Gobbi, W. Guryn, Donald H. Miller, and M. C. Ross
Northwestern University, Evanston, Illinois 60201

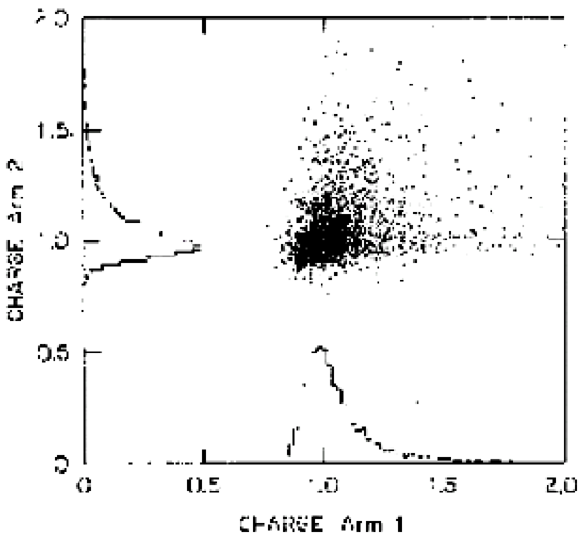
and

D. Besset, S. J. Freedman, A. M. Litke, J. Napolitano, and T. C. Wang[d]
Stanford University, Stanford, California 94305

and

Frederick A. Harris, I. Karliner,[e] Sherwood Parker, and D. E. Yount
University of Hawaii, Honolulu, Hawaii 96822
(Received 5 April 1982)

The products of e^+e^- annihilation at 29-GeV center-of-mass energy have been searched for free fractionally charged particles produced in exclusive two-body final states. No evidence for fractionally charged quarks was found and the upper limits on the ratio $R_{q\bar{q}} = \sigma_{q\bar{q}}/\sigma_{\mu\bar{\mu}}$ are below 1% for quarks with charges $\frac{1}{3}e$ or $\frac{2}{3}e$ and masses below about 14 GeV/c^2. This is the first reported limit for charge $\frac{1}{3}e$. Long-lived fractionally charged leptons are definitely ruled out over a significant range of masses.



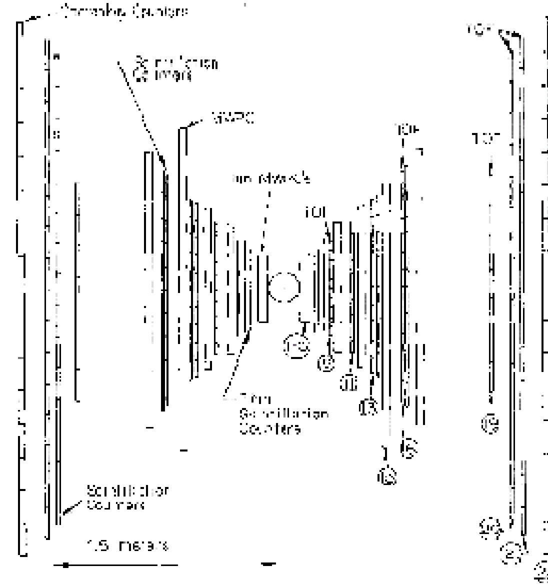


FIG. 1. Elevation view of the detector as viewed along the beam pipe. The elements are numbered sequentially from 1 to 22 moving outward from the IR (some of the layers are numbered in the figure). The "thin" MWPC's (layers 1 to 5) are not shown individually. Scintillation layers 9, 16, 19, 20, and 21 are equipped with TOF electronics.

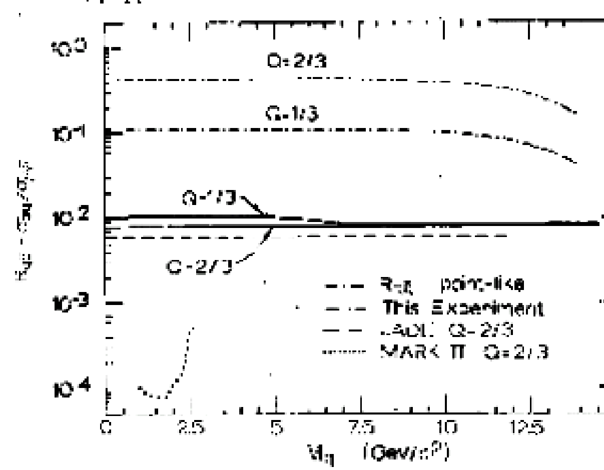
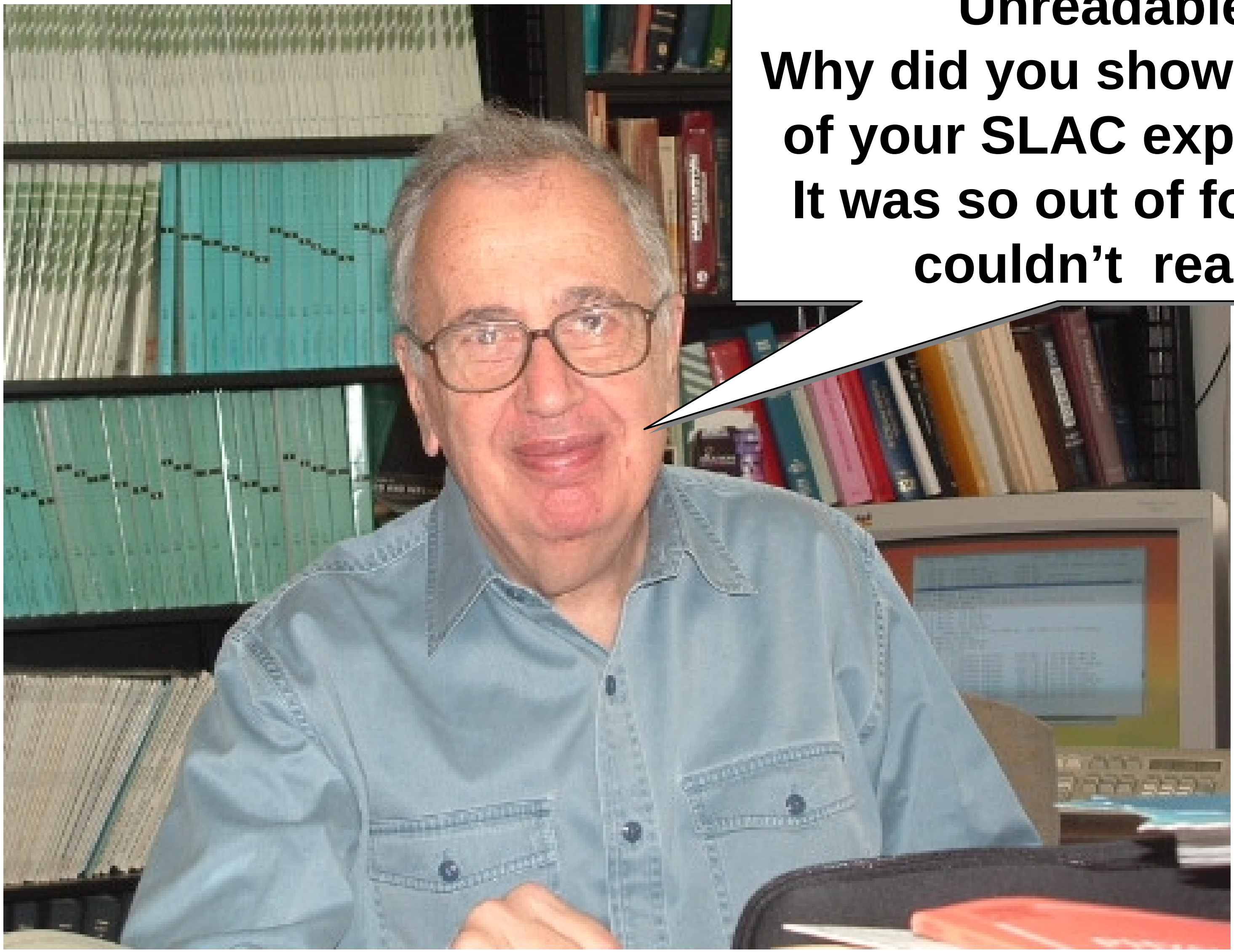
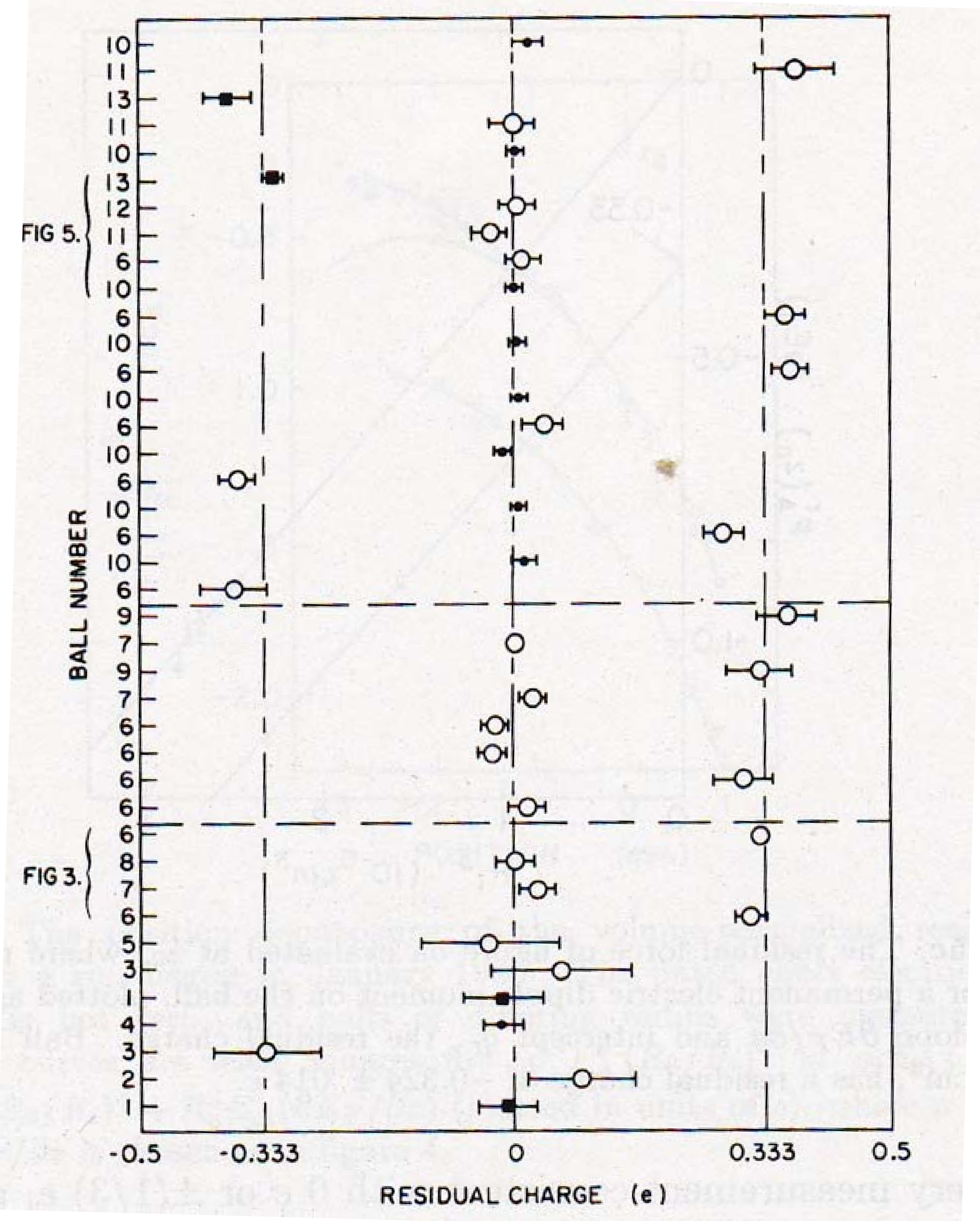


FIG. 3. Limits (90% confidence level) on exclusive quark production in e^+e^- annihilation. The limits for JADE are from Ref. 3 and the limits from Mark II are


Unreadable!!
Why did you show that slide
of your SLAC experiment?
It was so out of focus you
couldn’t read it!

Positive evidence for free quarks from Stanford

Fairbank et al.



EXPERIMENTAL SEARCH FOR STABLE, FRACTIONALLY CHARGED PARTICLES*

W. A. Chupka, J. P. Schiffer, and C. M. Stevens
Argonne National Laboratory, Argonne, Illinois
(Received 23 May 1966)

Various samples of matter were examined to search for stable quarks, particles of charge $\frac{1}{3}e$ or $\frac{2}{3}e$. The three materials examined were iron meteorites, air, and sea water; the concentrations of quarks were less than 10^{-17}, 5×10^{-27}, and 3×10^{-29} per nucleon.

Following a suggestion by Gell-Mann[1] that particles with fractional charges (quarks) may be the basic constituents of nucleons and that some form of quarks would be stable, we have tried a series of experiments designed to observe such particles in nature. Most experiments reported so far in the literature have attempted to recognize such particles immediately after their production, by the anomalously small ionization they would cause in the relativistic limit. Experiments using accelerators[2] and cosmic rays[3] can be summarized as setting a probable limit $M_q \gtrsim \mathrm{BeV}/c^2$ on the quark mass. The present experiment is an effort to exploit the stability of quarks, and the property of fractional charges that they cannot be neutralized in ordinary substances. In particular, negative quarks of charge $-\frac{1}{3}e$ would be captured in ordinary atoms in a Bohr orbit, which for such a heavy particle would be inside the nucleus. Such atoms then would be fractionally charged and remain so indef-

would have an ionization potential of 6.04 eV, would exist as a hydrated ion in water solution, and under most conditions would evaporate predominantly in a tight association with an electron or a negative ion; the $+\frac{2}{3}$ quark thus is probably best sought as a negatively charged species. Our experiments have been concentrated on these.

It is amusing to note that Millikan, in his first published report on measurements of the electron charge on water droplets in a cloud chamber, remarks: "In the third place I have discarded one uncertain and unduplicated observation apparently upon a single charged drop, which gave a value of the charge on the drop some 30% lower than the final value of e."[4] It may even be argued that later measurements of the electron charge with oil drops were less likely to turn up quarks because oil-bearing strata are at such depths as to be shielded from any quarks produced by cosmic rays, and that the chemical properties of a fractionally charged

From the Magazine | Science

The Hunting of the Quark

Argonne National Laboratory physicists have also examined iron meteor ites, air and sea water in a vain attempt to find quarks that had combined with stable atoms. Instead of being electrically neutral, they reasoned, such atoms would have fractional charges imparted by the quarks—enabling scientists to separate them out in an electric field and analyze them. Because quarks would more likely combine with heavier atoms, one scientist has suggested looking for quark-bearing atoms in oysters, which tend to concentrate the heavier elements in the seas.

hope some day to restore order by finding a truly elemental particle — one out of which all the others are made.

Collaborations with John

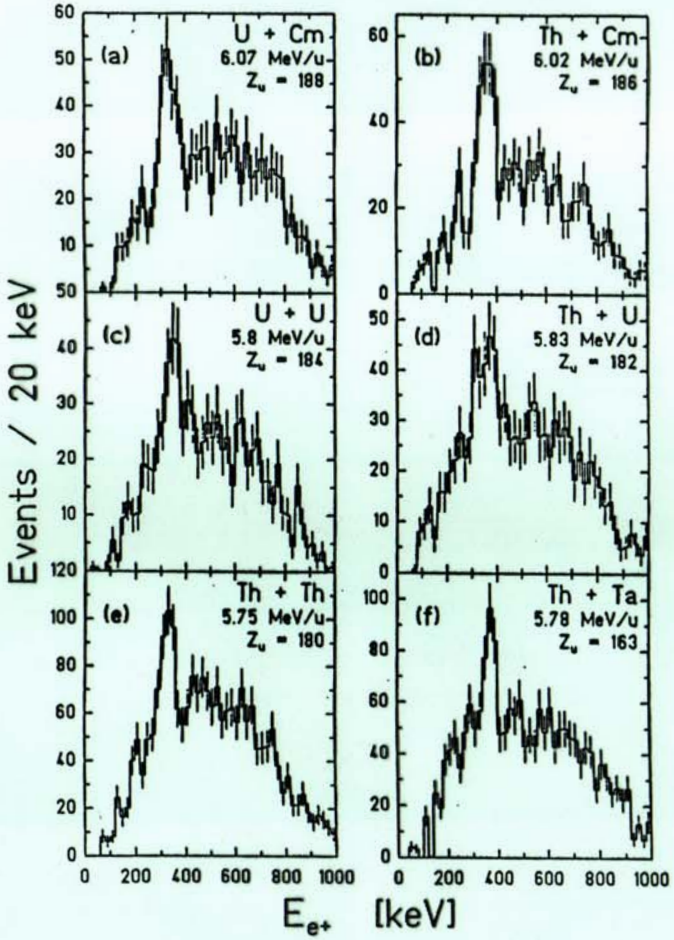
Evidence against a 17-keV neutrino from S-35 beta decay. J.L. Mortara, I. Ahmad, K.P. Coulter, S.J. Freedman, B.K. Fujikawa, J.P. Greene, J.P. Schiffer, W.H. Trzaska, A.R. Zeuli Phys.Rev.Lett.70:394-397,1993

Search for narrow sum energy lines in electron positron pair emission from heavy ion collisions near the Coulomb barrier. I. Ahmad et al. Phys.Rev.Lett.75:2658-2661,1995

β^+ Decay Partial Half-Life of ^{54}Mn and Cosmic Ray Chronometry A. H. Wuosmaa et al Phys. Rev. Lett. 80, 2085–2088 (1998)

Determination of the ^{8}B neutrino spectrum. W.T. Winter et al. Phys.Rev.Lett.91:252501,2003

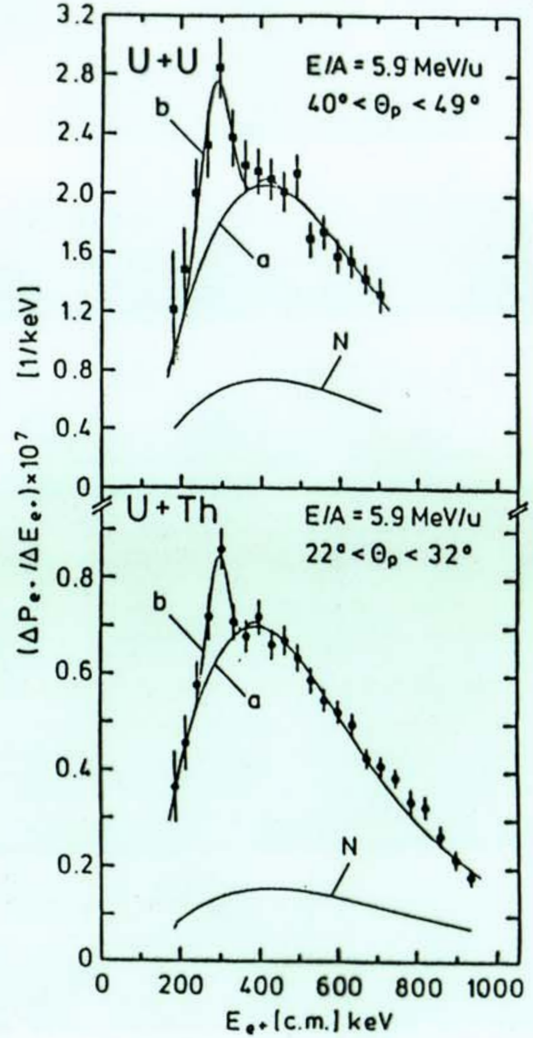
EPOS



T. Cowan *et al.*

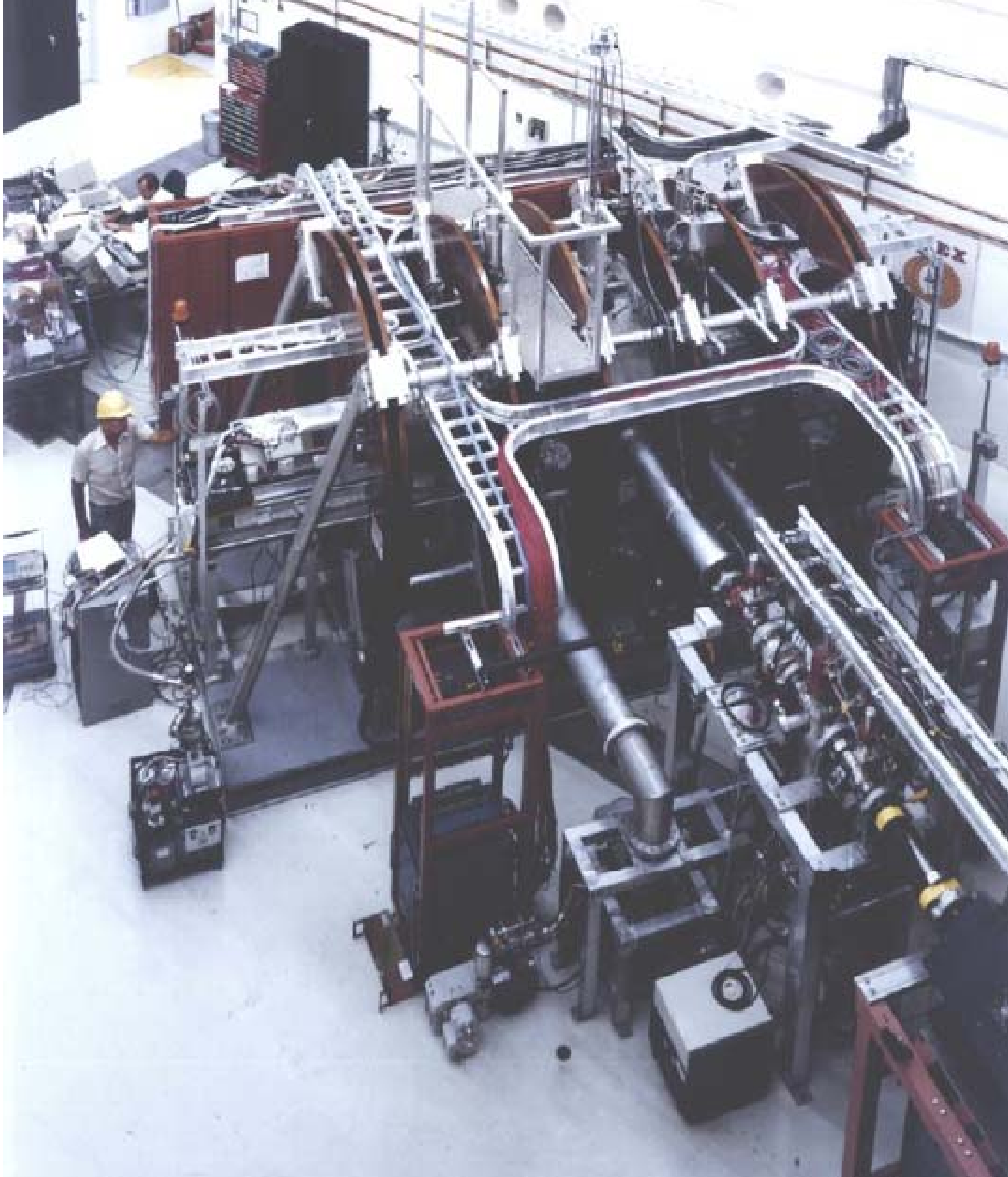
Phys. Rev. Lett. **54**, 1761 (1985)

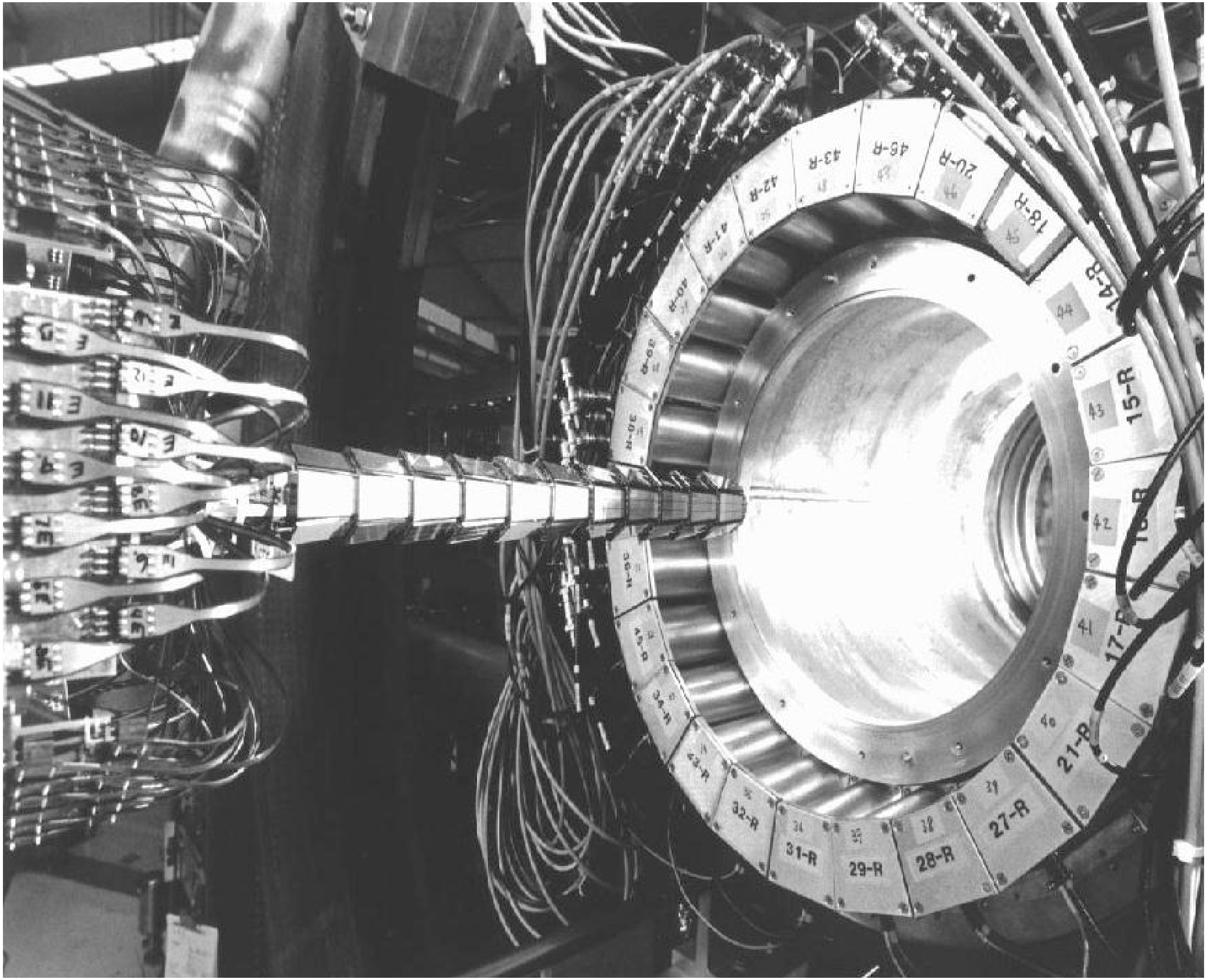
ORANGE



M. Clemente *et al.*

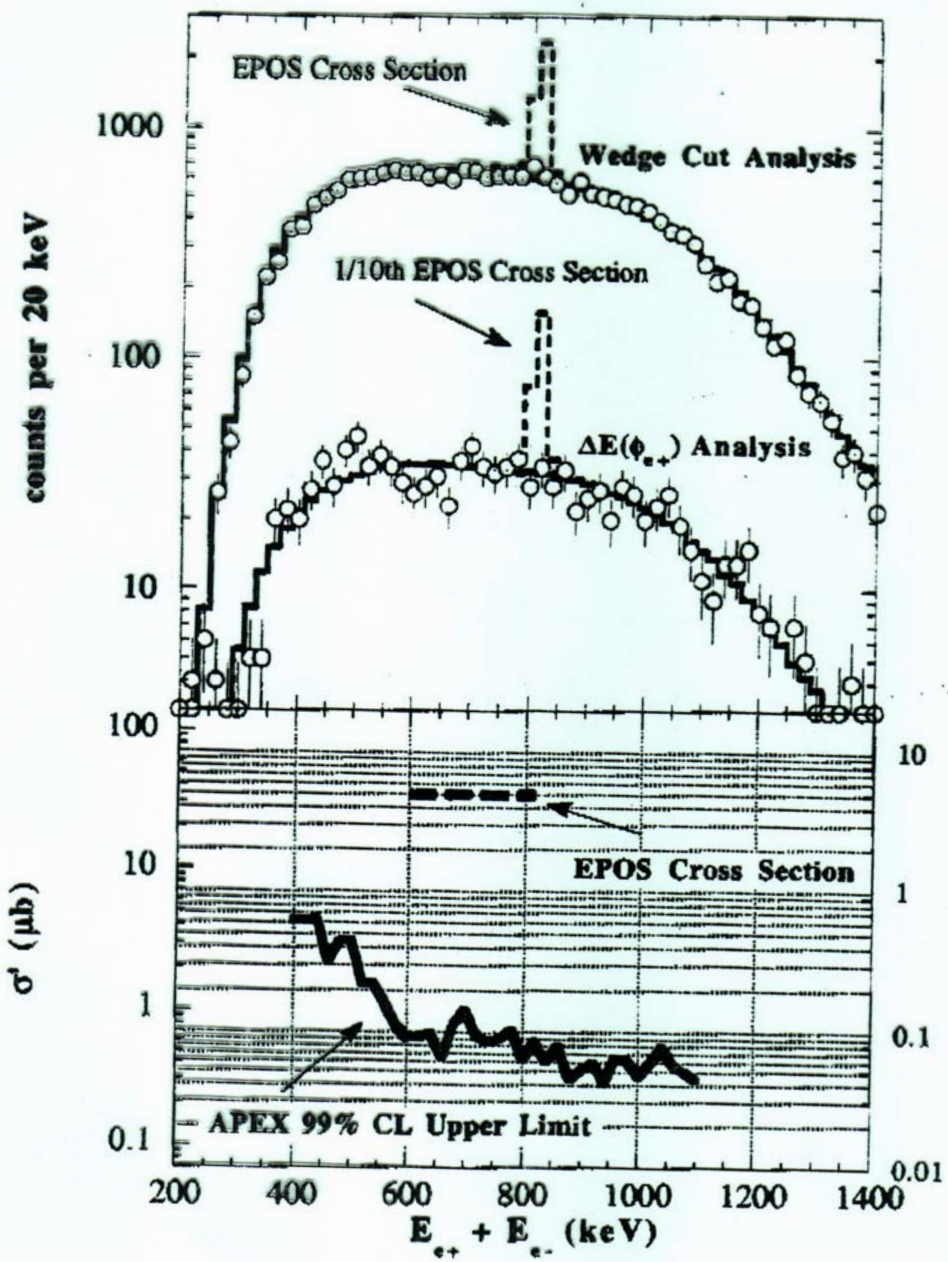
Phys. Lett. **137B**, 41 (1984)




15-R
21-R
27-R
28-R
29-R
31-R
32-R

$^{238}U + ^{232}Th$ at 5.95 MeV/u

EPOS Cross Section and APEX Upper Limit, $X^{\circ} \rightarrow e^{+}e^{-}$



Research News

Is There a Massive Neutrino?

Three far-flung labs say yes, triggering an avalanche of sp... how theories f... the Standard Model to the Big Bang might need to be...

SCIENCE

'Fourth' neutrino upsets the theories

"Many people say if we see it, it's true, and if we don't, they are in trouble."

SCIENCE WATCH

The universe is saved!

The universe faces two possible fates, de... enough gravity-producing matter...

Physics theory faces challenge

...entist throws doubt ...or explaining atoms

SCIENCE NEWS of the week

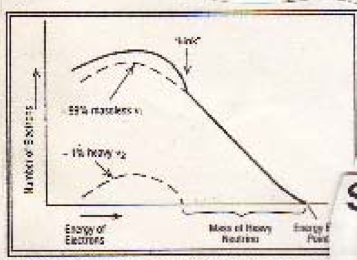
New Evidence of a Heavy Neutrino

Sometimes you see it; sometimes you ... The ghostly neutrino has again ... the heavy neutrino exists, "there must..."

BAY AREA/...

FRIDAY, APRIL 19, 1991

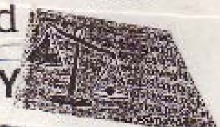
Physicists All Agog Over Neutrinos



Kinky stuff. *A "kink" 17KeV below the endpoint o... emitted electron's energy spectrum in beta-decay wa... first clue to a possible massive neutrino.*

FOUR OF FIVE NEW EXPERIMENTS CLAIM EVIDENCE FOR 17-keV NEUTRINOS

Neutrino Debate Revived

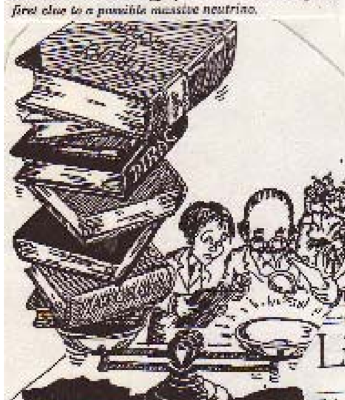


SCIENCE AND TECHNOLOGY

Weighing up the neutrino

"There is definitely something interesting going on that is still unexplained."
—Thomas Bowles

The little neutrino could cause big problems for the physicists' pic... the universe



Physicists Close in on a Weighty Quarry

After a year of sightings, the Great (Heavy) Neutrino Hun... seems about to capture the beast—or prove it a chimera

Littlest things mean a lot to physicists

Heavy dude. John Simpson of the University of Guelph.

SCIENCE PHYSICS

Elusive, Upstart Particles May Be Tipping the Scales of the Cosmos

By Curt Suplee

The fate of the cosmos, not to mention the future of the physics...

CARBON 14

WHAT IS A NEUTRINO?

F. Shape of Energy and Momentum Spectrum

Equation IV.17 for P, the probability of emission of an electron in the momentum range dp depends on p through the factor $\left[\left(\sqrt{m^2c^4+p_{max}^2c^2}-\sqrt{m^2c^4+p^2c^2}\right)^2 p^2\right]$ which has the form:

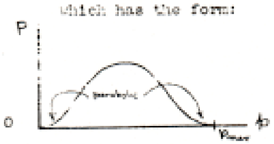


FIG. IV.8

The curve approaches P = 0 parabolically at 0, since there the expression $\left(\sqrt{\ \ } - \sqrt{\ \ }\right)^2$ is almost constant. It approaches P = 0 parabolically at $p = p_{max}$ because there p^2 is almost constant and a Taylor expn. of the 2nd term about p_{max} gives

$$c\sqrt{m^2c^2+p^2} = c\sqrt{m^2c^2+p_{max}^2} + c\frac{(p-p_{max})p_{max}}{\sqrt{m^2c^2+p_{max}^2}} + \cdots$$

$$\text{So} \lim_{p\to p_{max}} \left(\sqrt{\ \ } - \sqrt{\ \ }\right)^2 = \frac{c^2(p-p_{max})^2}{m^2c^2+p_{max}^2} p_{max}^2$$

This plot must be corrected for the perturbation of the electron or positron wave function by the nuclear charge. $\Psi_{\beta-}$ is larger than for Z = 0; $\Psi_{\beta+}$ is smaller. The correction is greater for low energies. For negative electrons the correction near p = 0 is roughly proportional to 1/p; thus the corrected curve for negative electrons is linear near p = 0 (FIG. IV.9). For positrons the correction is in the other direction.

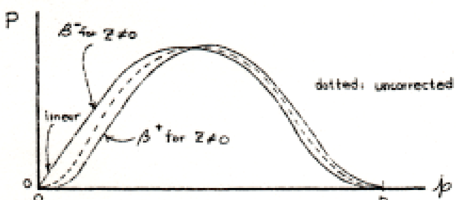


FIG. IV.9

The corresponding plot against energy is given in FIG. IV.10.*

$$\left(\sqrt{m^2c^4+p_{max}^2c^2}-\sqrt{m^2c^4+p^2c^2}\right)^2 p^2 dp \propto \left(E_\beta^{max}-E\right)^2\sqrt{E}\,dE \qquad \text{IV.26}$$

For $E \ll mc^2$ (E stands for kinetic energy here)

since $p^2dp = 1/2\ p\ d(p^2) \propto \sqrt{E}\ dE$.

The curves corrected for non-zero nuclear charge are shown. The corrected negative electron curve has the form near E = 0 of $(E_\beta^{max} - E)^2\ dE \sim$ constant x dE, therefore the curve has finite ordinate at E = 0.

G. Experimental Verification.

There has always been uncertainty in the experimental results for the low energy part of the spectrum. Improvement in experimental technique has so far improved the agreement between experiment and theory.

*Some forbidden β decays have a different spectrum shape. These forbidden spectra have been experimentally verified.

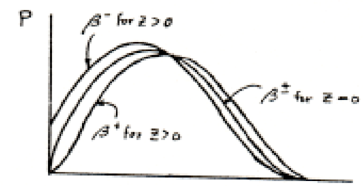


FIG. IV.10

The theoretical shape of the curve near E_β^{max} depends on the mass of the neutrino. For neutrino mass 0, there is second order contact; for neutrino mass $\neq$ 0 the curve has a vertical tangent at the point of contact. See Bethe A, p. 191.

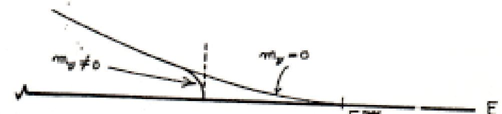


FIG. IV.11

Within experimental error, the curve for neutrino mass 0 is correct. The mass is certainly small, less than 10 Kev, in energy units.

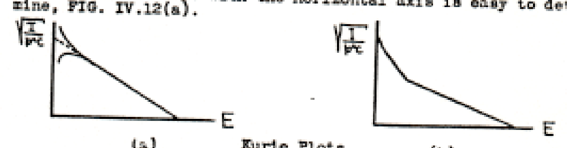
The point at which the curve reaches the horizontal axis is difficult to determine experimentally because the curve is tangent to the axis there. It is therefore difficult to determine E_β^{max} directly. More accurate determination of E_β^{max} is made possible by the Kurie plot. From equation IV.15, the intensity of emission at p is

$$I(p) = \left(E_\beta^{max}-E\right)^2 p^2 C(Z,p) \qquad \text{IV.27}$$

where C(Z,p) includes the constants and also the dependence on nuclear charge. This can be written

$$\left(E_\beta^{max}-E\right) = \sqrt{\frac{I(p)}{p^2 C(Z,p)}} \qquad \text{IV.28}$$

Now the plot of the radical against energy should be a straight line whose intercept with the horizontal axis is easy to determine, FIG. IV.12(a).



Kurie Plots
FIG. IV.12

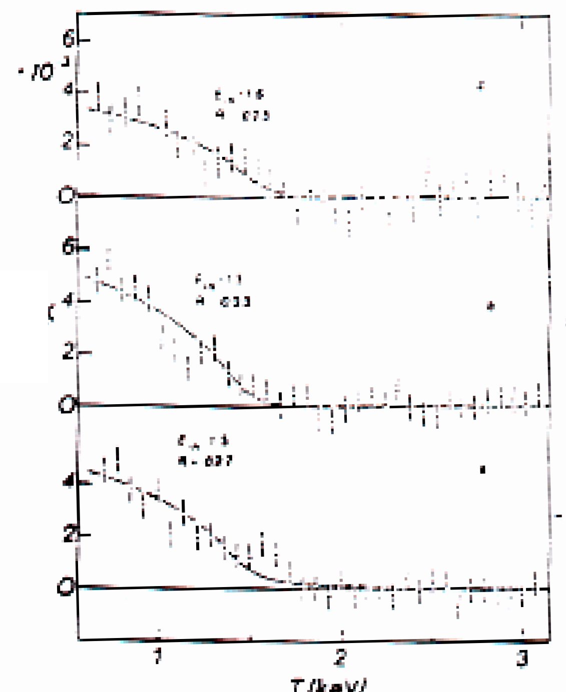
Evidence of Heavy-Neutrino Emission in Beta Decay

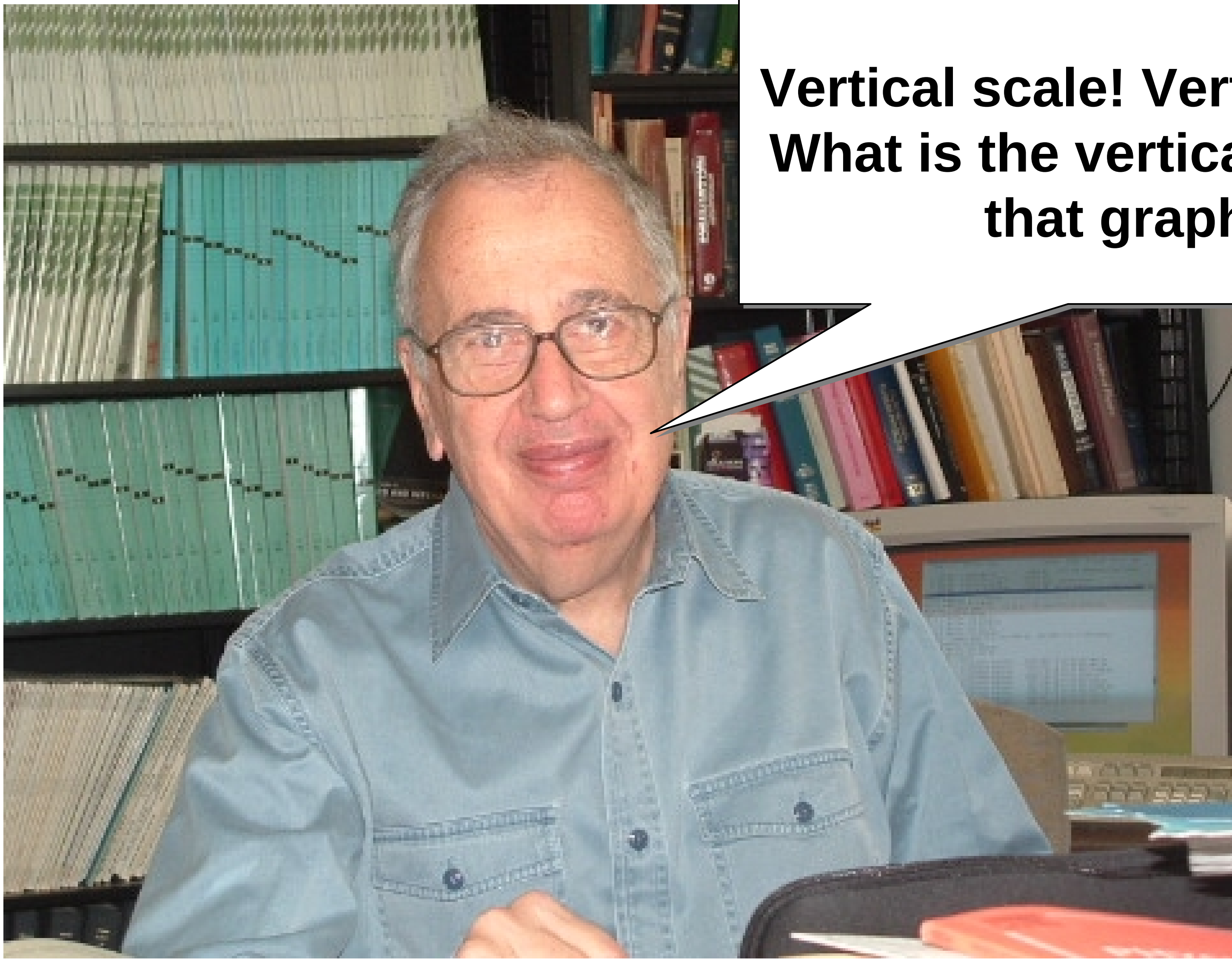
J. J. Simpson
Department of Physics and Guelph-Waterloo Program for Graduate Work in Physics, University of Guelph, Guelph, Ontario N1G 2W1, Canada

(Received 18 February 1985)

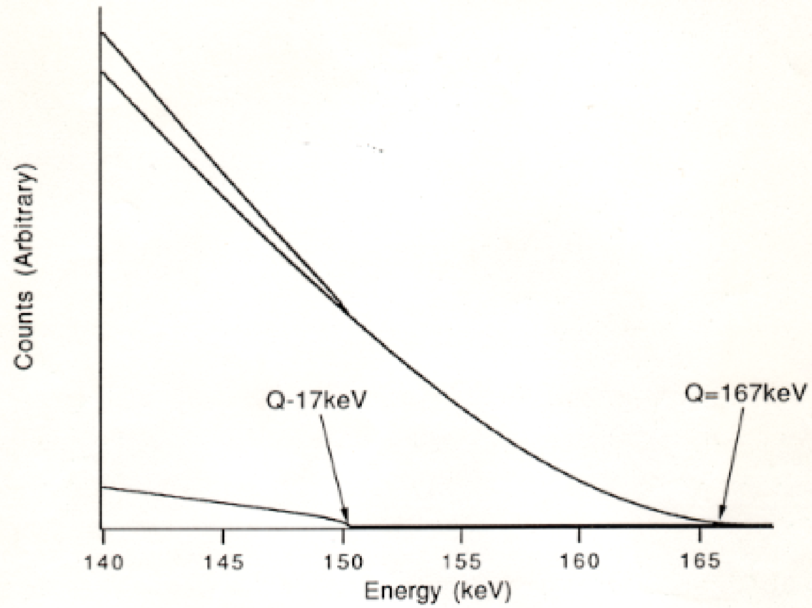
The observation of a distortion of the β spectrum of tritium is reported. This distortion is consistent with the emission of a neutrino of mass about 17.1 keV and a mixing probability of 3%.

PACS numbers: 23.40.Bw, 14.60.Gh, 27.10.+h

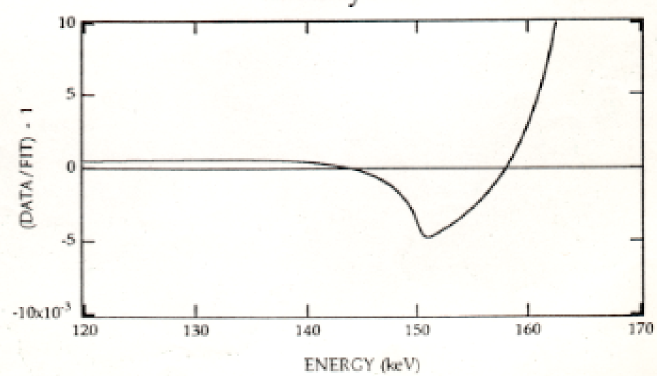


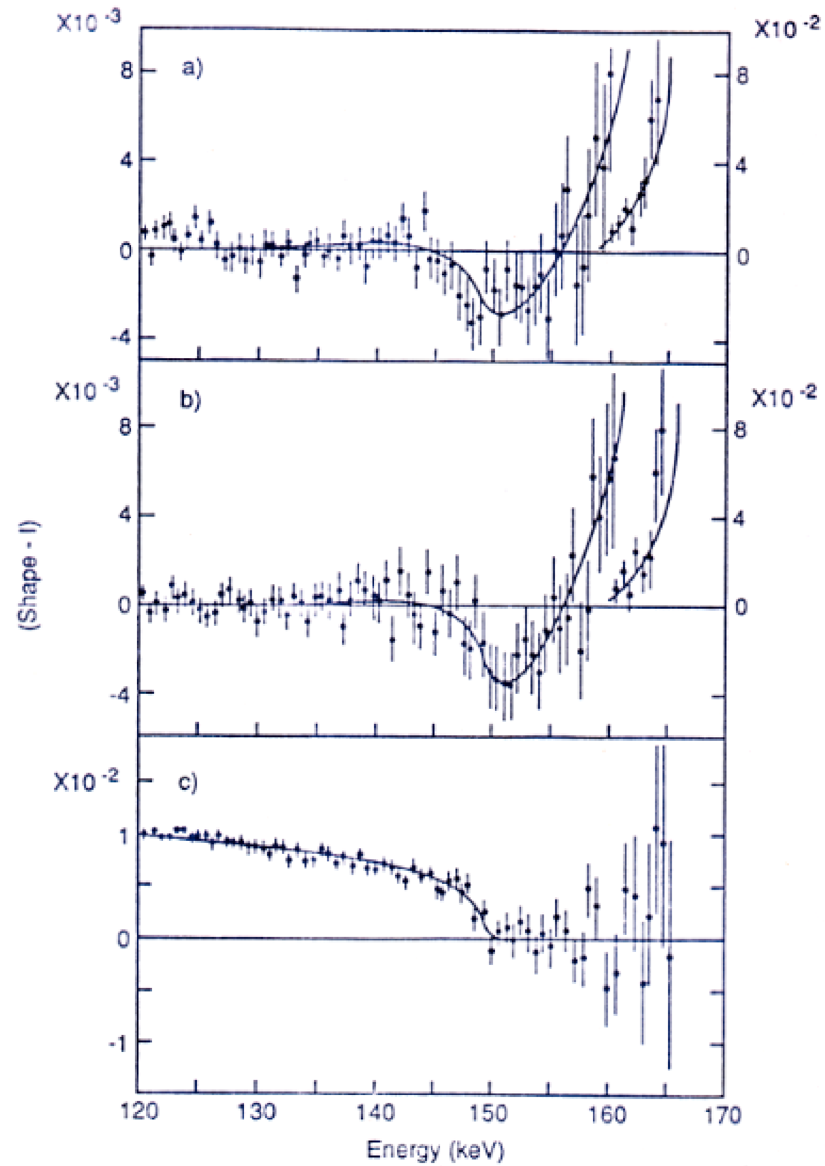

Vertical scale! Vertical scale! What is the vertical scale on that graph?

^{35}S with m_ν=17keV and 10% mixing



Shape factor plotted for 1% mixture of heavy neutrino





X10 -3
a)
8
4
0
-4
X10 -2
8
4
0
X10 -3
b)
8
4
0
-4
X10 -2
8
4
0
(Shape - I)
X10 -2
c)
1
0
-1
120
130
140
150
160
170
Energy (keV)

Hime & Jelley

SUMMARY OF POSITIVE RESULTS

SOURCE	$SIN^2\Theta$	M_ν	EXPERIMENT TYPE
^3H	1.10 +/- 0.30	17.07 +/- 0.09	Implanted source
^3H	1.11 +/- 0.14	16.93 +/- 0.07	Implanted source
^{14}C	1.40 +/- 0.45	17.00 +/- 2.00	Implanted source
^{71}Ge	1.60 +/- 0.74	17.20 +/- 1.30	IBEC
^{55}Fe	0.85 +/- 0.45	21.00 +/- 2.00	IBEC
^{35}S	0.73 +/- 0.11	16.90 +/- 0.40	External source
^{35}S	0.84 +/- 0.08	17.00 +/- 0.40	External source
^{63}Ni	0.99 +/- 0.12	16.75 +/- 0.35	External source

The massive neutrino would “violate every theoretical prejudice we have in particle physics, astrophysics, and cosmology,” says Michael Turner, a University of Chicago expert on cosmology.

“It’s a true surprise. If it’s true, then it’s pointing us in a different direction than previous physics suggests.” adds John Bahcall of the Institute for Advanced Study at Princeton.

Is There a Massive Neutrino?

Three far-flung labs say yes, triggering an avalanche of speculation about how theories from the Standard Model to the Big Bang might need to be revised

EVEN BY THE STANDARDS OF PARTICLE physics, the subatomic particle called the neutrino is a shadowy commodity. It can pass through the entire Earth without leaving a trace, and it's immune to many of the forces that bind matter together, including the electromagnetic force. Until recently, it was even thought to be without mass—or at least without much. But now, dramatic evidence has begun to emerge from laboratories in Oxford, Czechoslovakia, and Berkeley that the neutrino does have mass—and lots of it, thousands of times more than predicted by current theories. Sheldon Glashow, Nobel Prize–winning physicist at Harvard, who's seen the recent results (which are speeding around the physics community in preprint form) calls them "quite spectacular." In fact, he says "it's the kind of thing Nobel Prizes are awarded for."

If the results hold up, and there is a Nobel Prize for the "massive neutrino," the award would likely go to John Simpson, a physicist not in one of the three labs that have claimed recent successes but at the University of Guelph in Ontario. It was Simpson who, in 1985, first presented evidence for a neutrino with a mass as heavy as 17,000 electron-volts (keV, the units of energy that are interchangeable with mass). If Simpson is correct, his discovery will send shock waves through not merely the high-energy physics community but through astrophysics and cosmology as well—indeed it would fundamentally alter physicists' views of the universe.

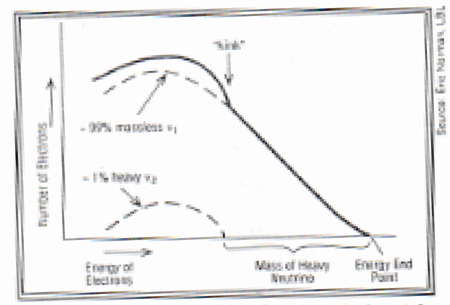
A massive neutrino would "violate every theoretical prejudice we have in particle physics, astrophysics, and cosmology," says Michael Turner, a University of Chicago expert on cosmology. Adds astrophysicist John Bahcall of the Institute for Advanced Study at Princeton: "It's a true surprise. If it's true, then it's pointing us in a different direction than previous physics suggested."

That new direction would actually include a number of major course corrections. Elegant theories purporting to explain why neutrinos are so light would crumble. Overarching conceptions, like the "Standard Model" of particle physics—which unifies the so-called weak force and the electromagnetic force and for which Glashow received his Nobel Prize—would need embellishing. (Glashow has already rushed into print with what he calls "various crazy models" in an attempt to patch his notions up.) And there might be a profound impact even on the Big Bang theory.

All this assumes that the latest discovery isn't just an experimental artifact—something difficult to be sure of in an area where experimental results can be deceptive and prey to perturbations. Although the recent work from the far-flung labs is suggestive, many feel it won't hold up. "My attitude toward this 17keV neutrino," says Bahcall, "is, if you're thinking of skating on a lake which you're not sure is frozen and you see a sign posted on the lake [reading] 'There is suggestive evidence that the ice is safely thick,' I wouldn't skate on that ice, and I wouldn't invest much of my reputation on the likelihood that this 17keV neutrino is real."

Felix Boehm, a respected experimentalist at the California Institute of Technology who has tried and failed to find evidence for a massive neutrino, acknowledges being "a little biased." But Boehm, who has seen the new results, argues that "there is nothing"—the massive neutrino doesn't exist. Even he admits, however, that the case isn't closed: He's still looking for conclusive evidence one way or the other.

The reason for the current excitement is that it is the first time results confirming Simpson's hypothesis have come from outside his own laboratory. In 1985, Simpson, already a world-renowned neutrino physicist, began table-top experiments aimed at measuring the energy of electrons emitted from tritium (heavy hydrogen) in the radioactive process called beta-decay. Although Simpson's interest was in the nearly invisible neutrino (which is spit out alongside the electron), he couldn't observe the neutrino directly. Instead, he measured the effect of the neutrino on the electron.

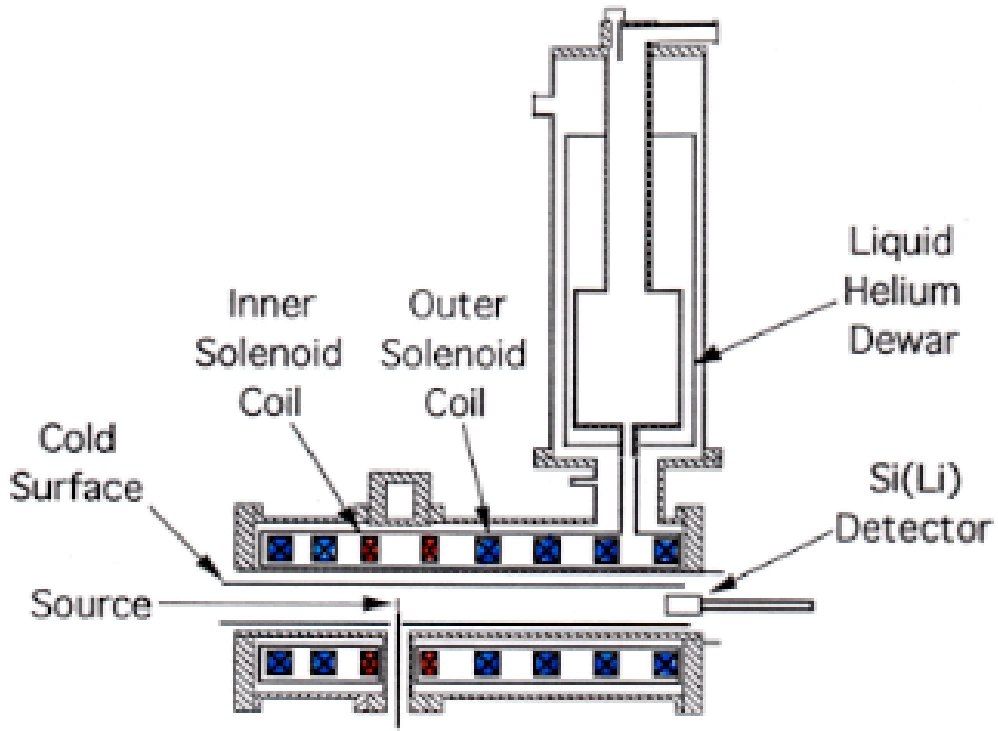


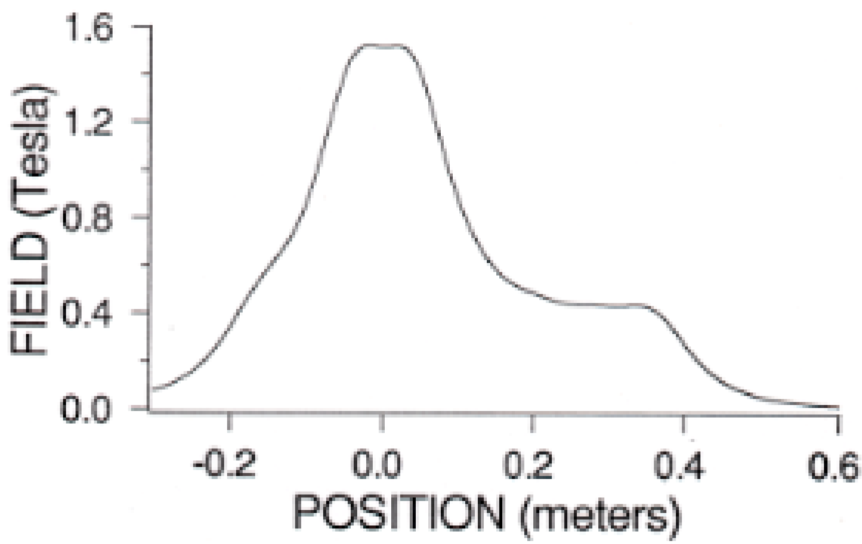
Kinky stuff. *A "kink" 17KeV below the endpoint of the emitted electron's energy spectrum in beta-decay was the first clue to a possible massive neutrino.*

Ordinarily in beta-decay the electron and the neutrino share the energy of the reaction. Under those conditions, the energy of the emitted electrons appears as a spectrum varying smoothly from zero to a maximum called the "endpoint" energy. But in Simpson's mid-'80s work, he observed a small "kink," or disturbance, of the smooth spectrum corresponding to an energy 17keV below the endpoint.

Published in *Physical Review Letters*, this result startled physicists, who have studied beta-decay for decades without seeing the 17keV anomaly. The kink, Simpson argued, came from the occasional emission of a massive neutrino, which was "stealing" energy from the electron and changing its energetic spectrum. But the kink was small: 97% of the time, the electron associated with the ordinary, massless neutrino was found, and only 3% of the time did the electron paired with the massive newcomer show up.

Those early results triggered a feverish hunt aimed at confirming them—or proving that they weren't valid. If the kink was real and was caused by a massive neutrino, experimentalists reasoned, it should appear not just in tritium but also in other nuclei that undergo beta-decay. Moreover, although the endpoint of the electron's spectrum varies from nucleus to nucleus, if there is indeed a 17keV neutrino, the kink should appear 17keV below the endpoint in each case. Eight different groups, including two led by such notables as Caltech's Boehm and Princeton's Frank Calaprice, attempted to find that kink

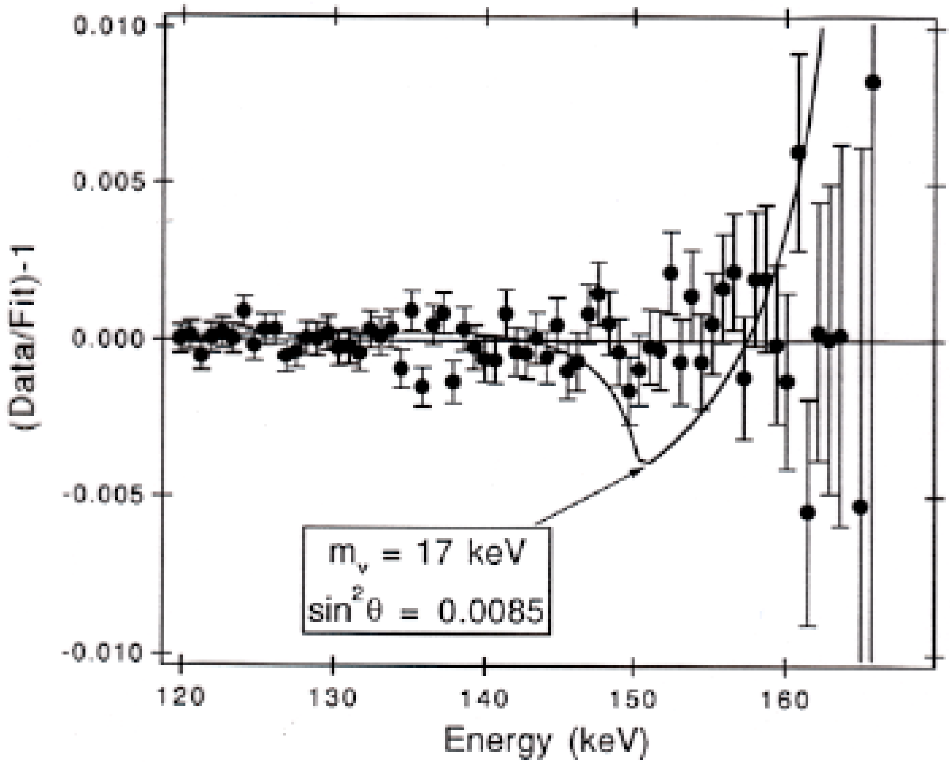




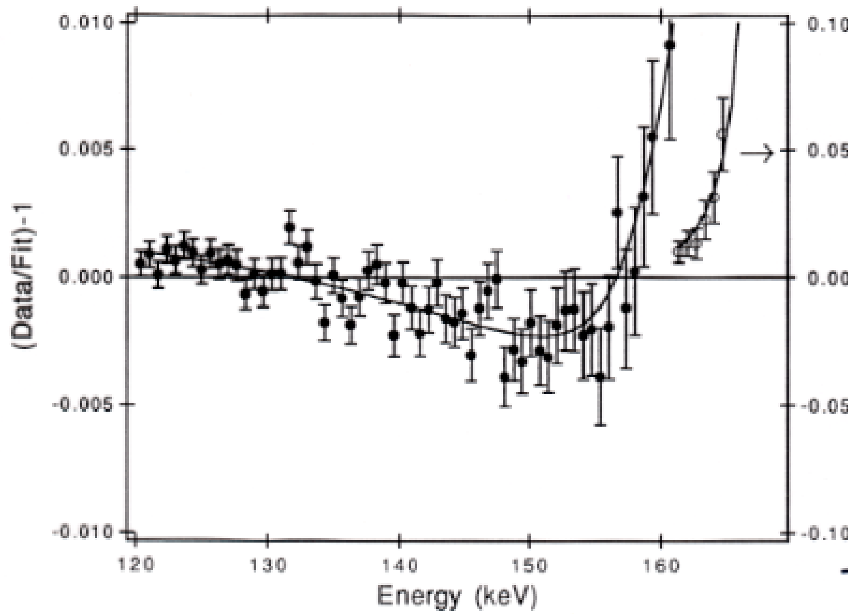
Collaborators:
ANL/BERKELEY

I. AHMAD
K. Coulter
B. Fujikawa
J. Mortara*
J. Schiffer
A. Zeuli
+ Grabowski + Traska

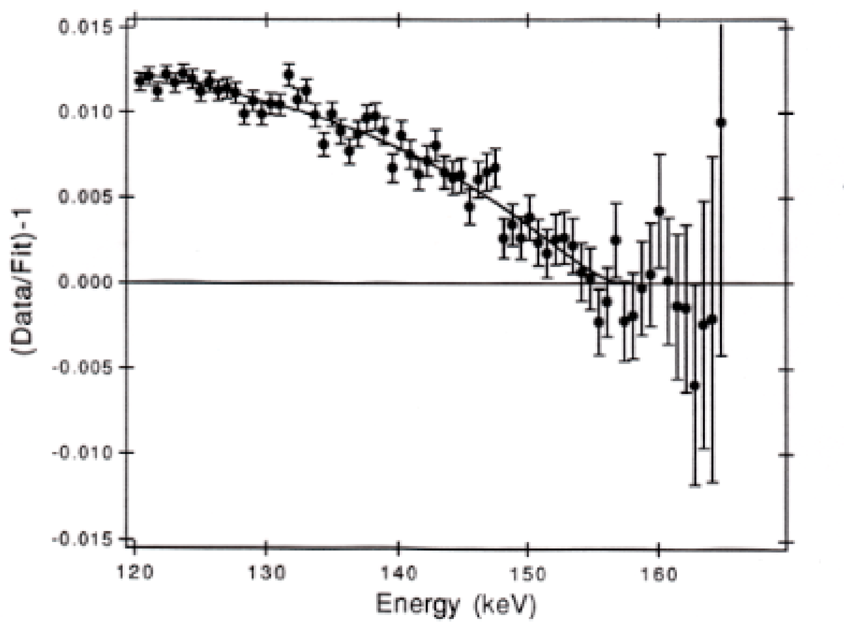
^{35}S Data


0.010
0.005
0.000
-0.005
-0.010
(Data/Fit)-1
120
130
140
150
160
Energy (keV)
m_ν = 17 keV
sin²θ = 0.0085

^{35}S + ^{14}C Data



1.34% "^{14}C" put in, 1.4±0.1% measured



Evidence Against a 17 keV Neutrino from ^{35}S Beta Decay

J.L. Mortara[(1),(4),(a)], I. Ahmad[(1)], K.P. Coulter[(1)], S.J. Freedman[(1),(2),(3),(4)], B.K. Fujikawa[(1),(2)], J.P. Greene[(1)], J.P. Schiffer[(1),(4)], W.H. Trzaska[(5),(b)] and A.R. Zeuli[(1)]

[(1)] *Argonne National Laboratory, Argonne IL 60439*
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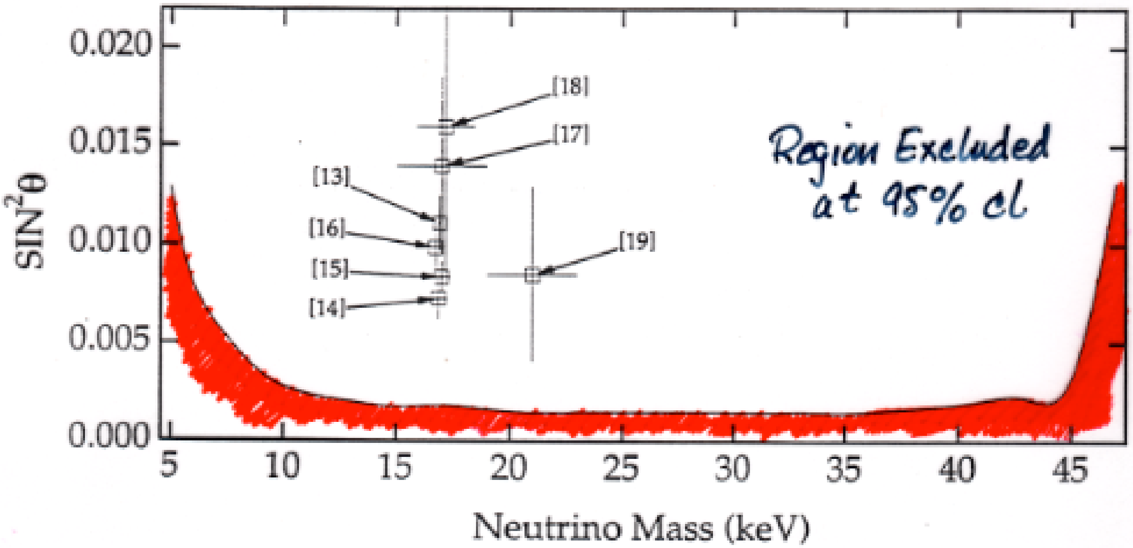
[(4)] *University of Chicago, Chicago IL 60637*
[(5)] *Texas A&M University, College Station TX 77843*

(Received Sept 25, 1992

We have searched for the effect of a 17 keV/c^2 - mass neutrino in the beta decay of ^{35}S with an apparatus incorporating a high-resolution solid-state detector and a superconducting solenoid. The experimental mixing probability, $\sin^2\theta = -0.0004 \pm 0.0008$ (stat.) ± 0.0008 (syst), is consistent with zero, in disagreement with several previous experiments. Our sensitivity to neutrino mass is verified by measurements with a mixed source of ^{35}S and ^{14}C which artificially produces a distortion in the beta spectrum similar to that expected from the massive neutrino.

PACS numbers: 14.60.Gh, 23.40.Bw

Published January 25, 1993



For $m_\nu c^2 = 17$ keV

$$\sin^2\theta = -0.0004 \pm 0.0008 \pm 0.0008$$

Progress

Nature **366**, 29 - 32 (04 November 1993); doi:10.1038/366029a0

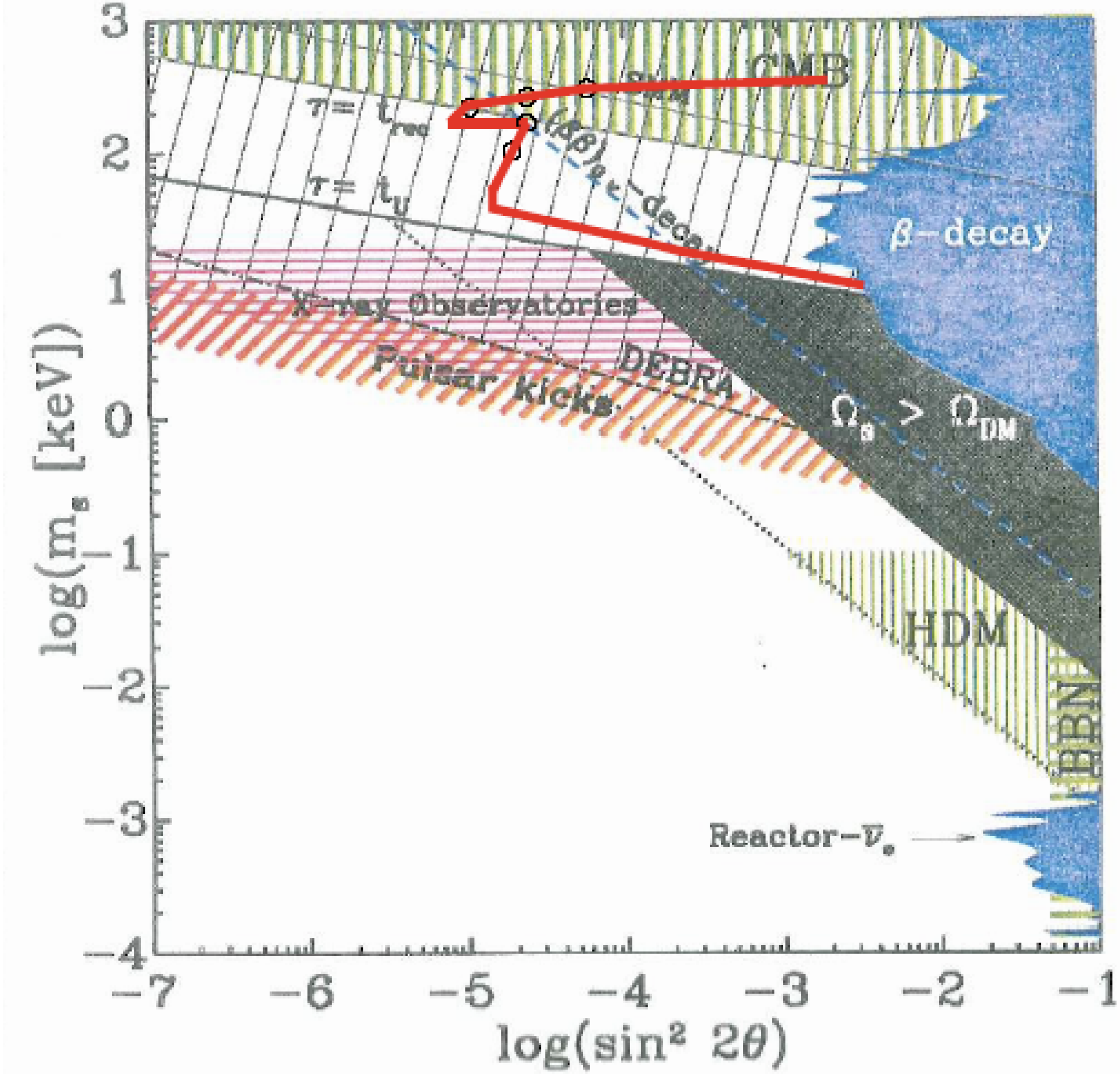
The rise and fall of the 17-keV neutrino

DOUGLAS R. O. MORRISON

CERN, CH-1211 Geneva, Switzerland.

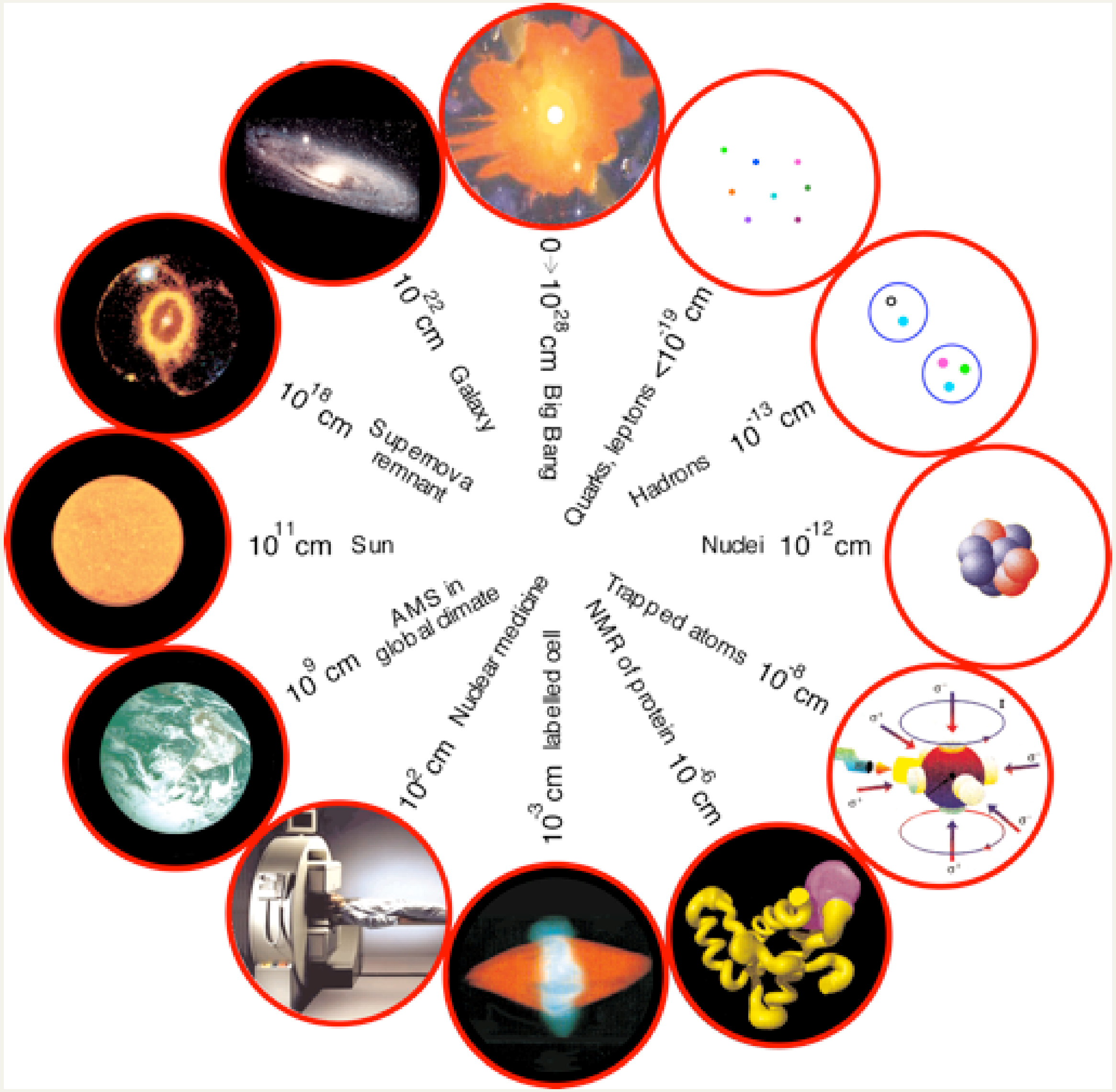
Experiments showing evidence for a heavy neutrino with a mass of 17 keV launched the new particle on an erratic eight-year career, during which it raised questions about the Standard Model of particle physics and about cosmological theories, stimulated many theoretical papers and pushed experimental techniques to their limit. Its demise provides grounds for faith in the efficacy of the scientific method.

Gelmini PRL 93 80312 (2004) "low reheating" T<<100 MeV

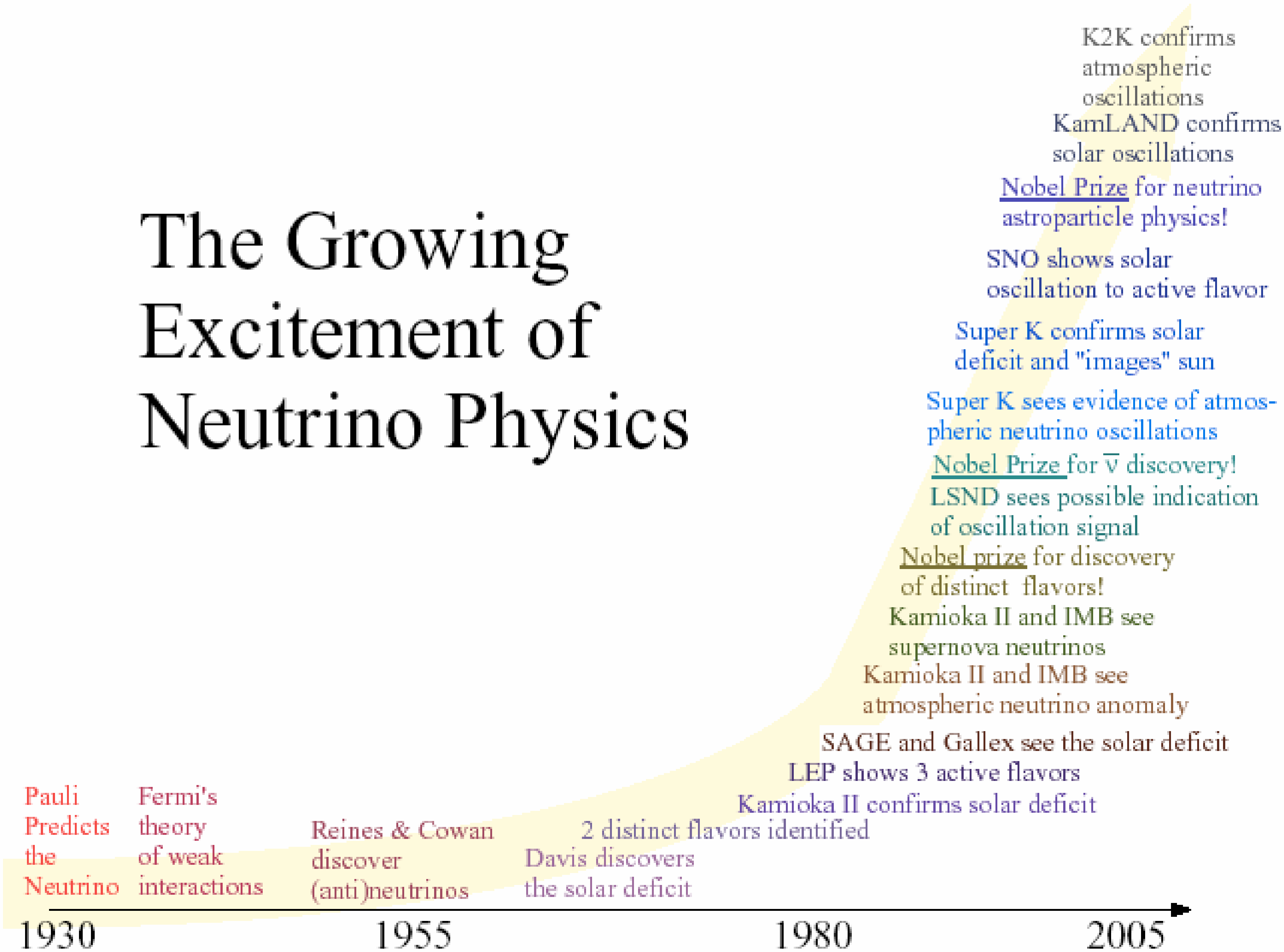


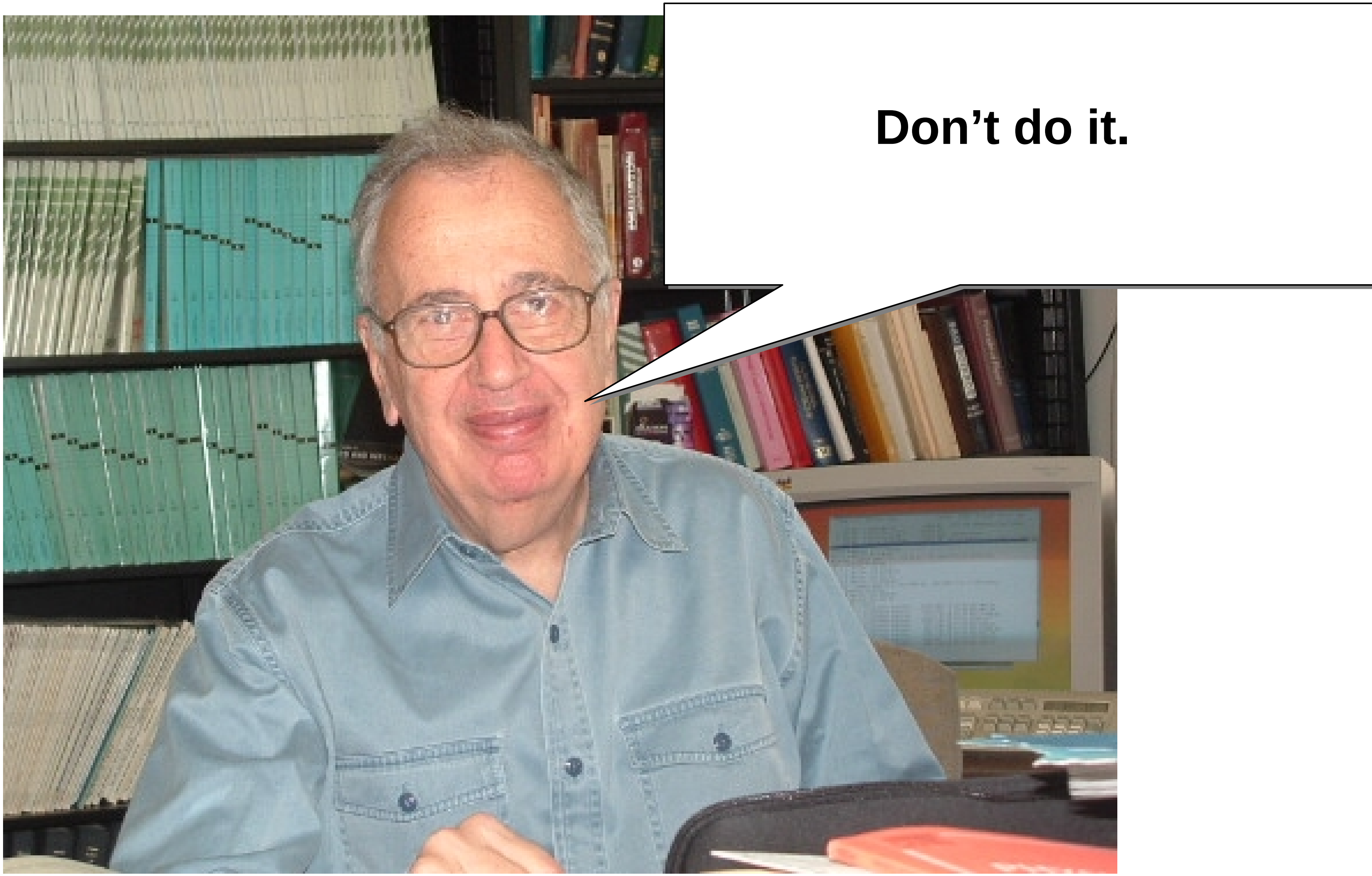
Boyarsky astro-ph/512509 plots Ω_s $\sin^2 2\theta$

A symposium surveying the future of nuclear physics and celebrating 50 years of John Schiffer's research at Argonne
September 21-22, 2006
Argonne National Laboratory



The Growing Excitement of Neutrino Physics




Don’t do it.

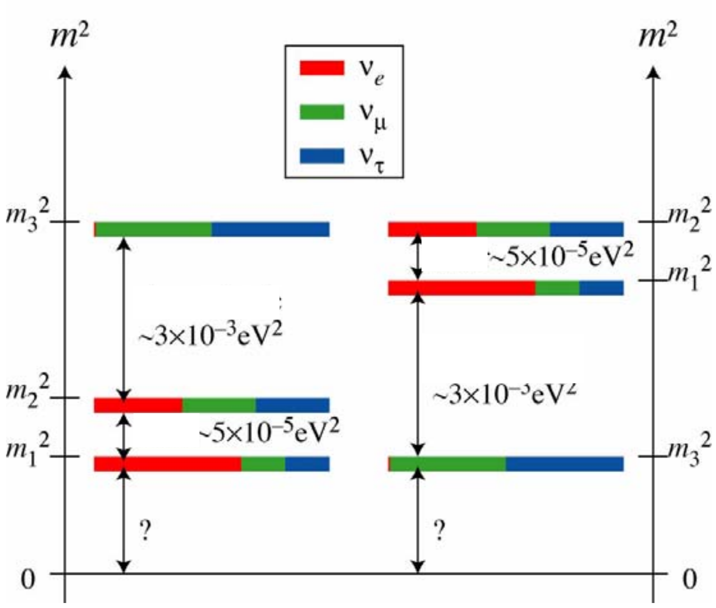
U_{MNSP} Matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

$\theta_{23} \sim 45°$ $\tan^2\theta_{13} < 0.03$ at 90% CL $\theta_{12} \sim 32°$

Mass Hierarchy



Essentials of Neutrino Oscillations

m_2c^2

m_1c^2

$$|\nu_e\rangle = |\psi_{\nu_e}(0)\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\psi_{\nu_e}(t)\rangle = \cos\theta\, e^{-\frac{im_1c^2t}{\hbar}}\,|\nu_1\rangle + \sin\theta\, e^{-\frac{im_2c^2t}{\hbar}}\,|\nu_2\rangle$$

$$P_{ee}(t) = \left|\langle\psi_{\nu_e}(0)|\psi_{\nu_e}(t)\rangle\right|^2 = \left|\cos^2\theta\, e^{-\frac{im_1c^2t}{\hbar}} + \sin^2\theta\, e^{-\frac{im_2c^2t}{\hbar}}\right|^2$$

$$P_{ee}(t) = 1 - \sin^2 2\theta \sin^2\left(\frac{(m_2-m_1)c^2}{2\hbar}t\right)$$

$$t = \frac{t_{lab}}{\gamma} \approx \frac{L}{\gamma c} \qquad \gamma = \frac{E}{mc^2} \qquad m = \frac{m_1+m_2}{2}$$

$$P_{ee}(t) = 1 - \sin^2 2\theta \sin^2\left(\frac{(m_2^2-m_1^2)c^4}{4\hbar c}\frac{L}{E}\right)$$

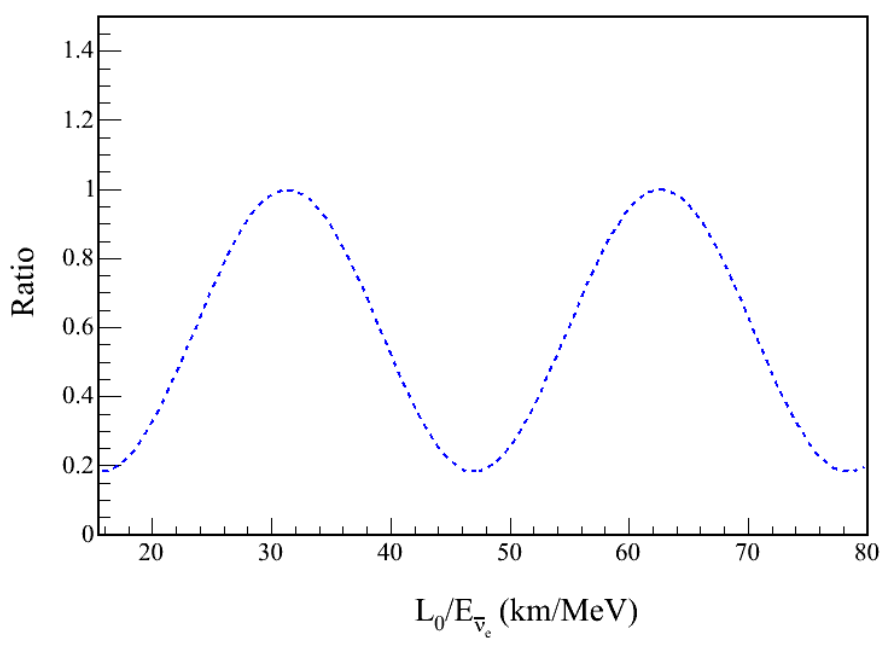
$$P_{ee}(t) = 1 - \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

Looking for the oscillation effect

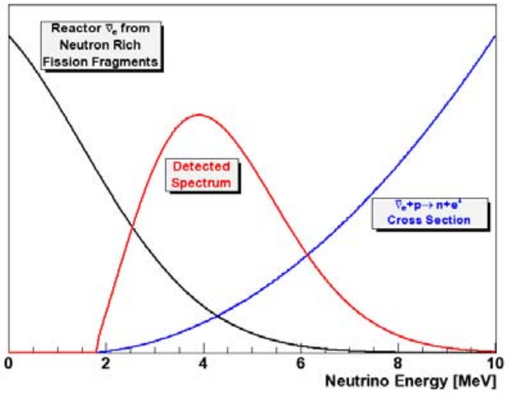
$$\left|\left\langle \psi_{\nu_e}(t) \middle| \psi_{\nu_e}(0) \right\rangle\right|^2 = 1 - \sin^2(2\theta)\sin^2\left(\frac{(m_2 - m_1)c^2}{2\hbar} t\right)$$

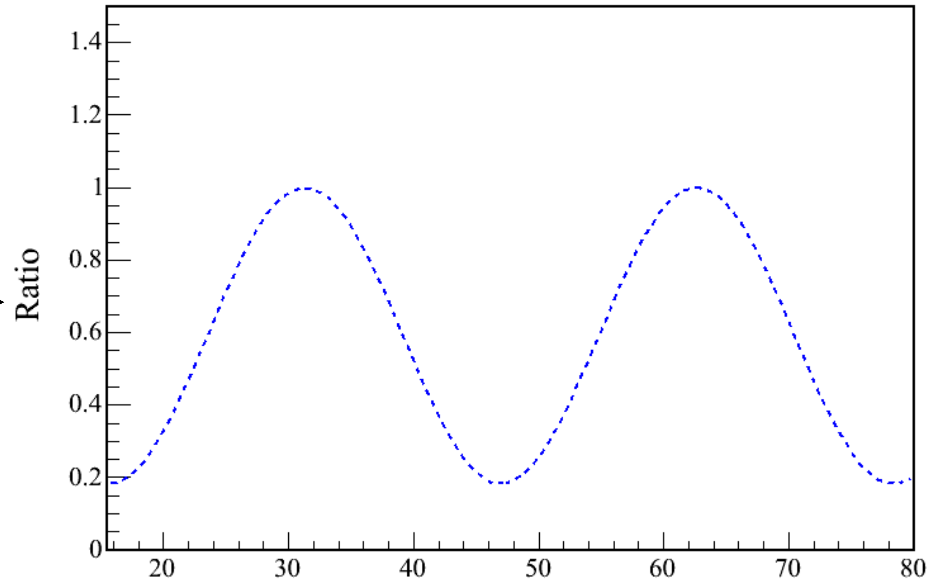
$$P_{ee} = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{(m_2^2 - m_1^2)L}{E}\right)$$

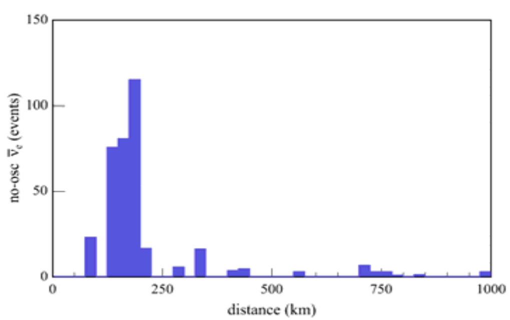
$$L = c \bullet t_{lab} \qquad t_{restframe} = \frac{t_{lab}}{\gamma} = \frac{m}{E} t_{lab}$$

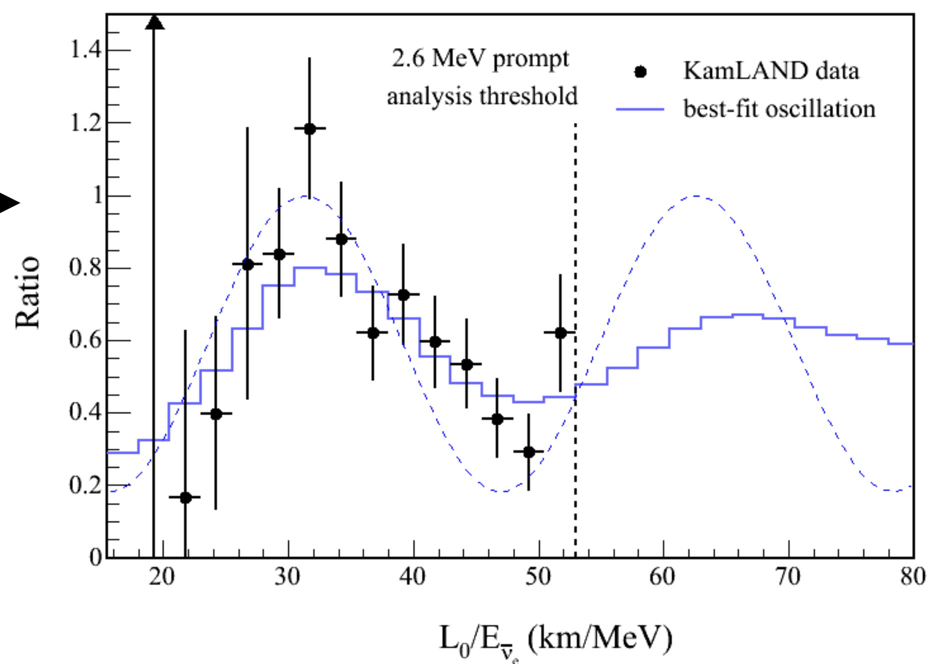


Observing the oscillations in the neutrino rest frame

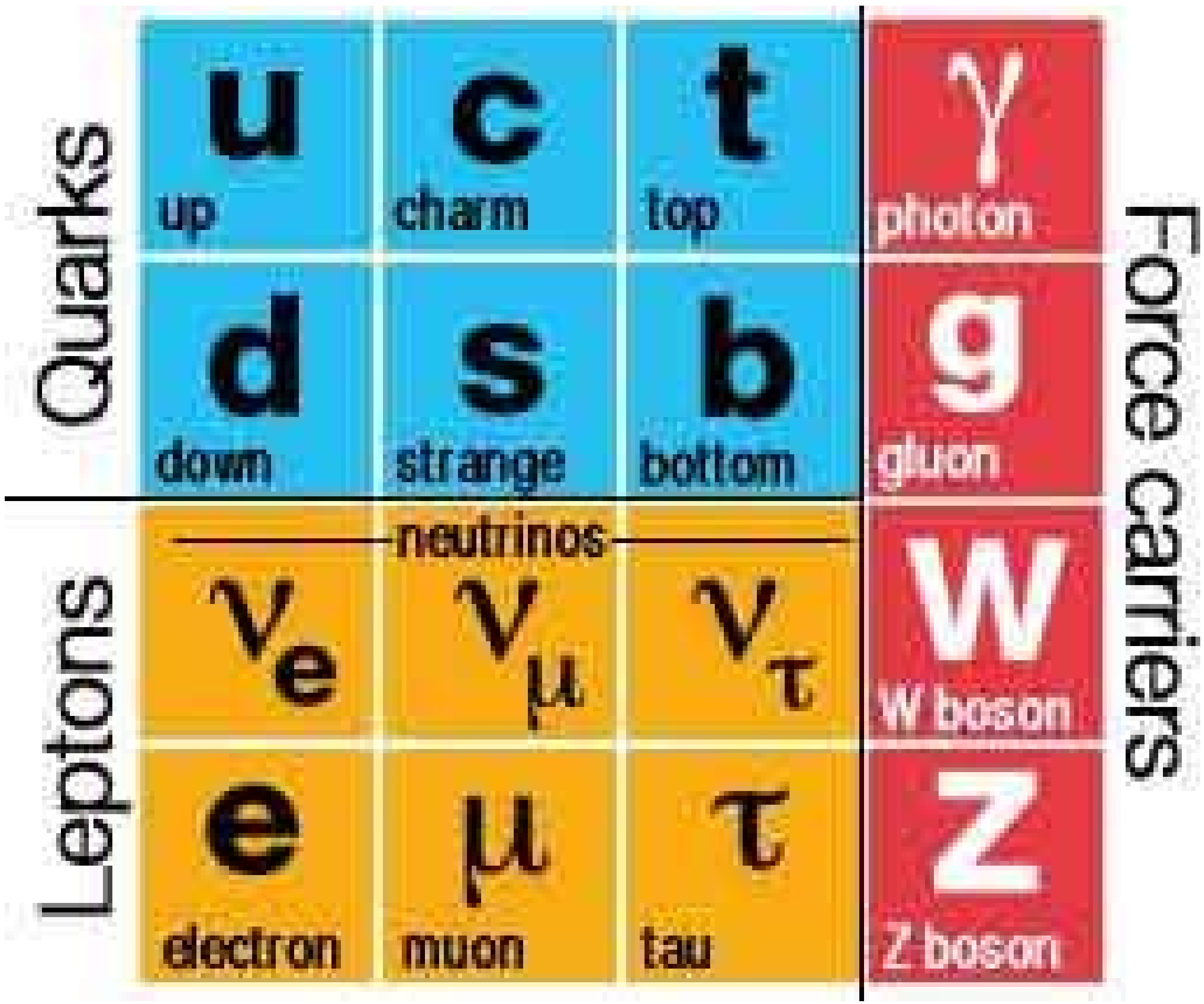




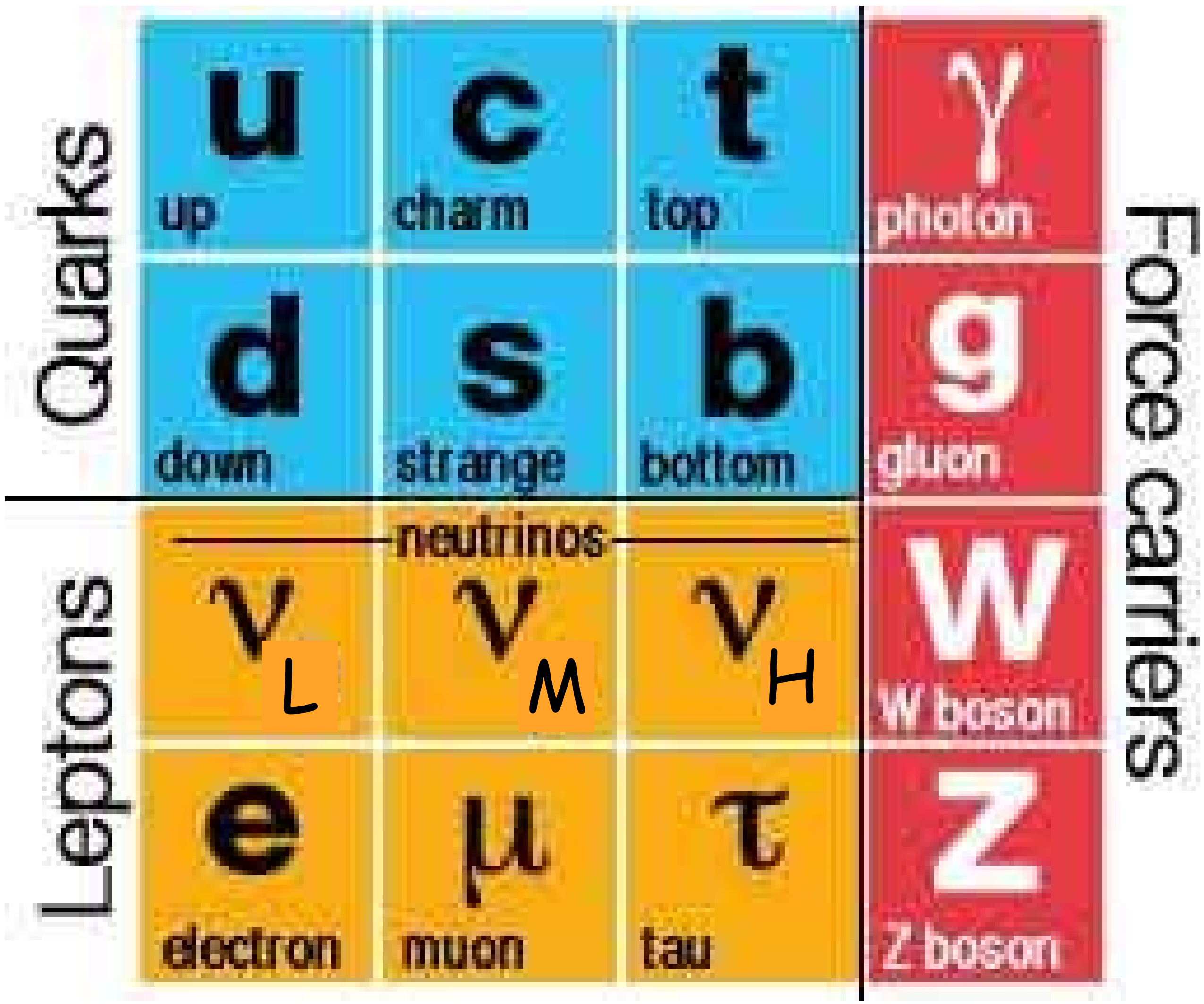




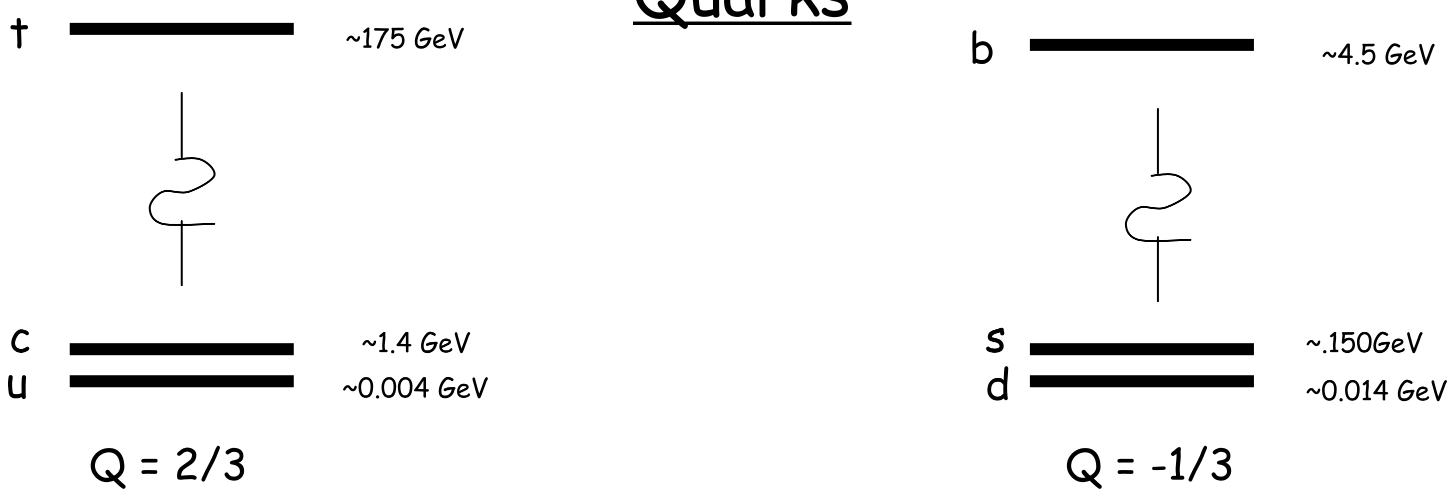
The Standard Model of Quarks and Leptons



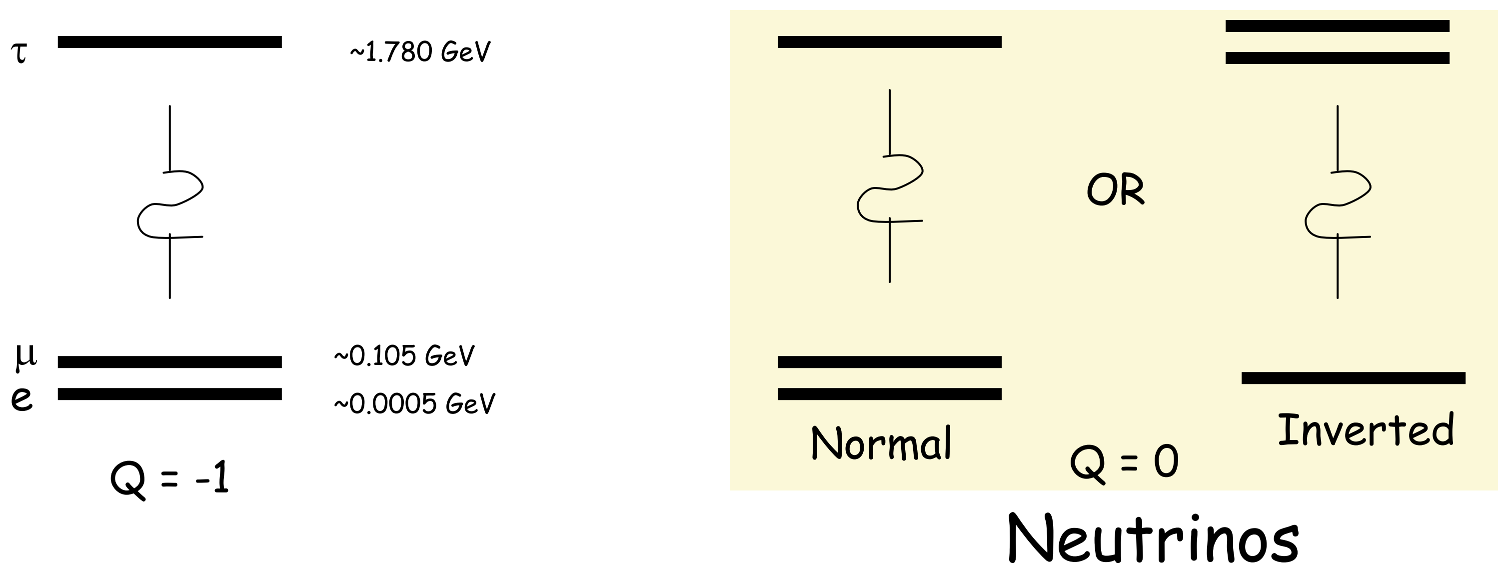
The Standard Model of Quarks and Leptons



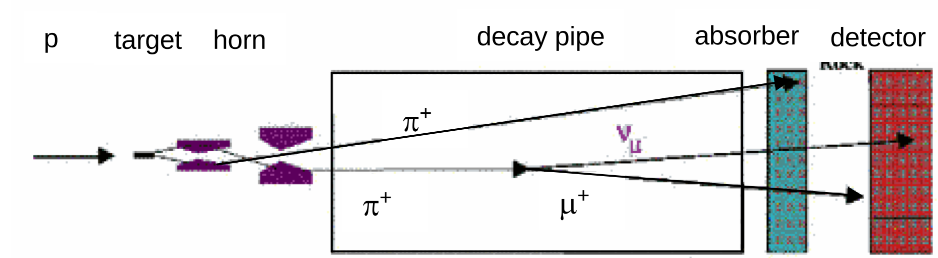
Quarks



Leptons



Measuring the rest: θ_{13},δ_{CP}

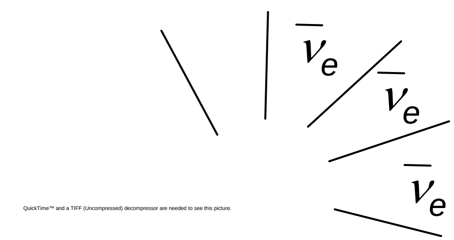


Method 1: Accelerator Experiments

$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu} + \ldots$$

- appearance experiment $\nu_\mu \rightarrow \nu_e$
- measurement of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ yields θ_{13},δ_{CP}
- baseline *O(100 -1000 km),* matter effects present

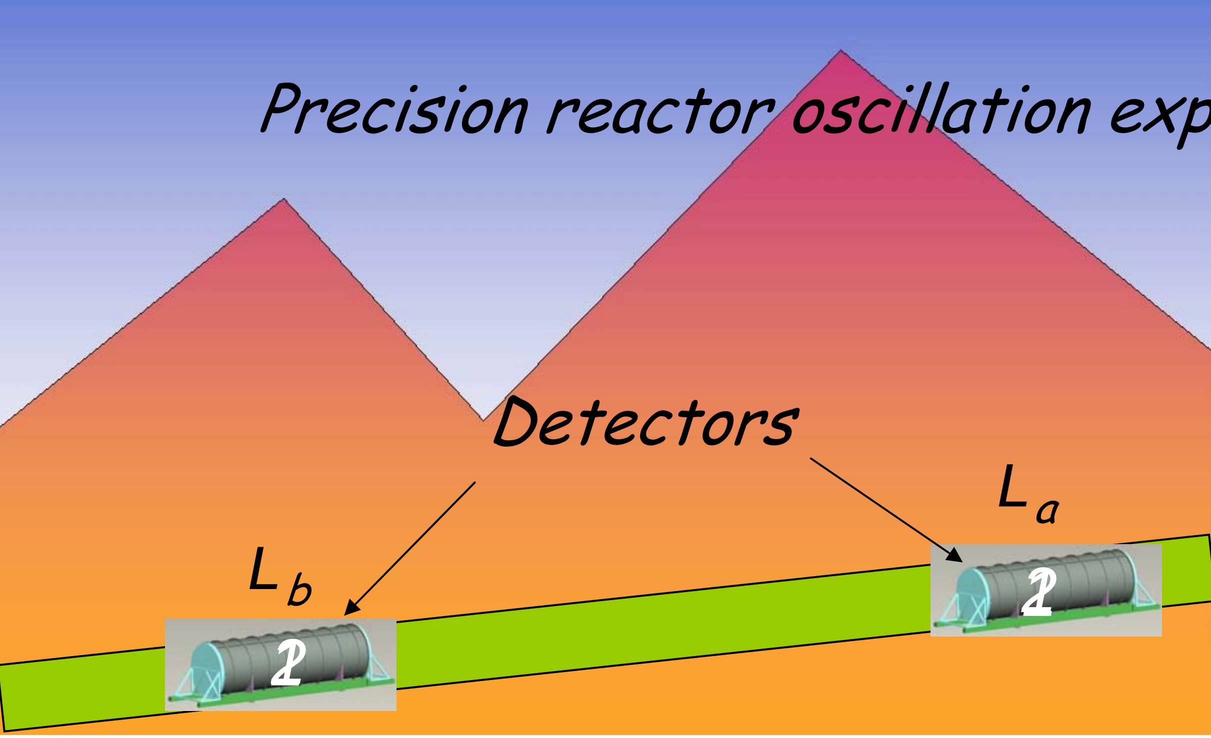
Method 2: Reactor Neutrino Oscillation Experiment

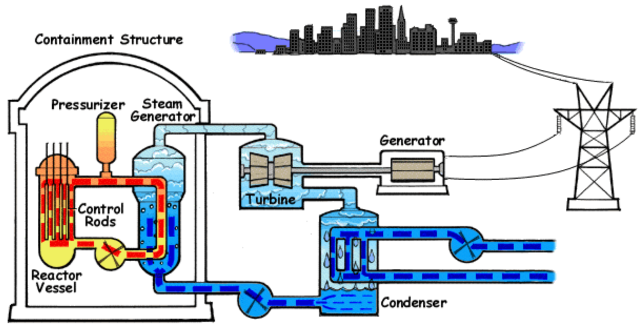


$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

- disappearance experiment $\bar{\nu}_e \rightarrow \bar{\nu}_e$
- look for rate deviations from $1/r^2$ and spectral distortions
- observation of oscillation signature with 2 or multiple detectors
- baseline *O(1 km),* no matter effects

Precision reactor oscillation experiment



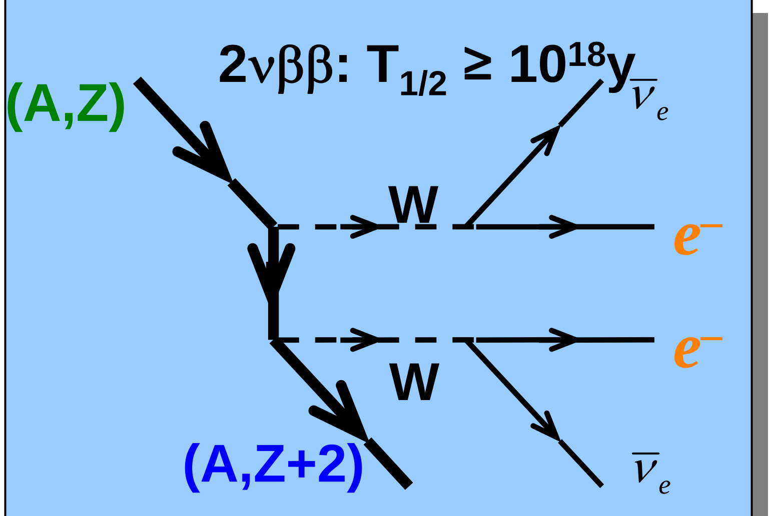


Reactor

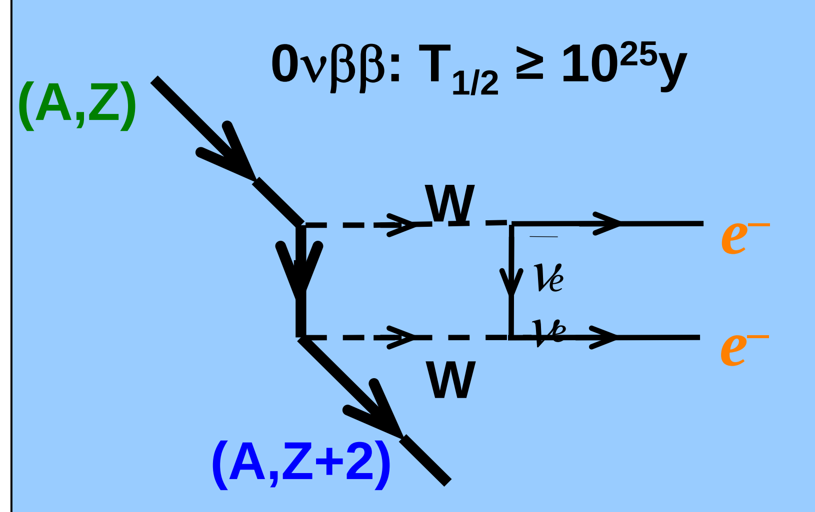
$$R_{1aA} = \frac{F_A}{4\pi L_a^2}\varepsilon_1(1-\delta_a)$$

$$\frac{R_{1aA}}{R_{2bA}}\frac{R_{2aB}}{R_{1bB}} = \frac{L_b{}^4}{L_a{}^4}\frac{(1-\delta_a)^2}{(1-\delta_b)^2} \approx \frac{L_b{}^4}{L_a{}^4}[1-2(\delta_a-\delta_b)]$$

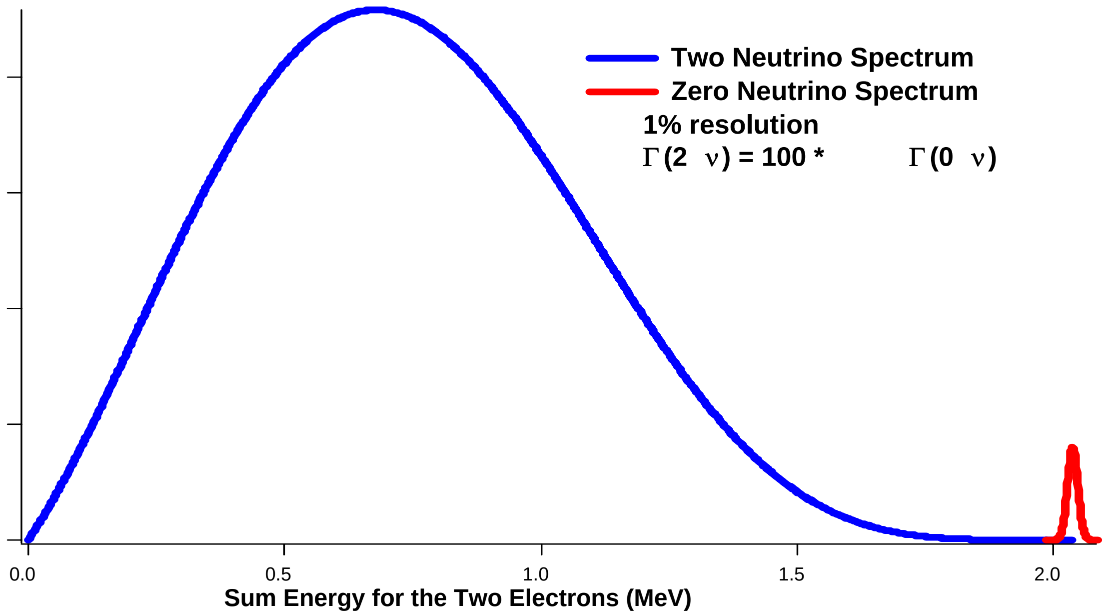
$$(\delta_a-\delta_b) \approx \sin^2(2\theta_{13})\left[\sin^2(1.27\frac{\Delta m_{13}^2 L_a}{E}) - \sin^2(1.27\frac{\Delta m_{13}^2 L_b}{E})\right]$$



$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\ \bar{\nu}_e$

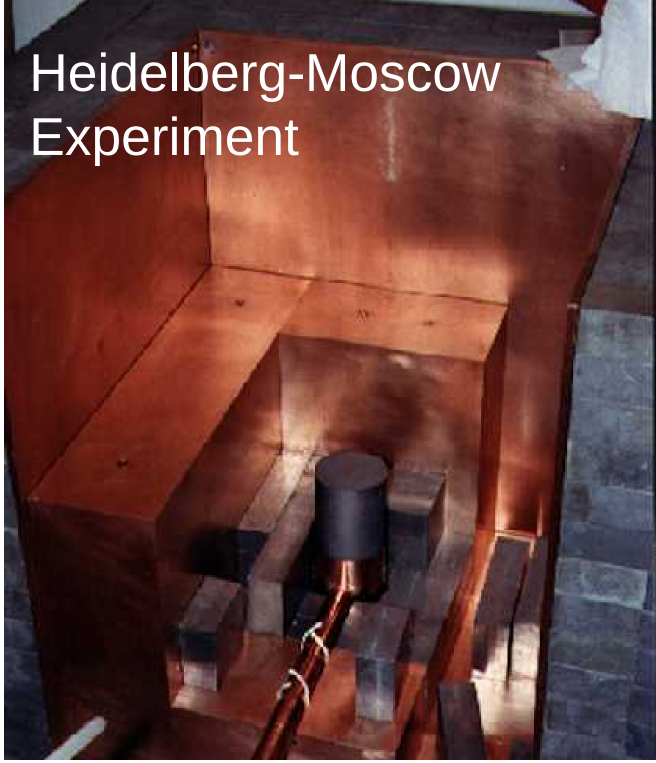


$(A,Z) \rightarrow (A,Z+2) + 2e^-$



$$\Gamma_{0\nu} = G_{0\nu}(Q,Z)\ |M_{nucl}|^2\ m_\nu^{\ 2}$$

Claimed Observation of 0νββ in ^{76}Ge



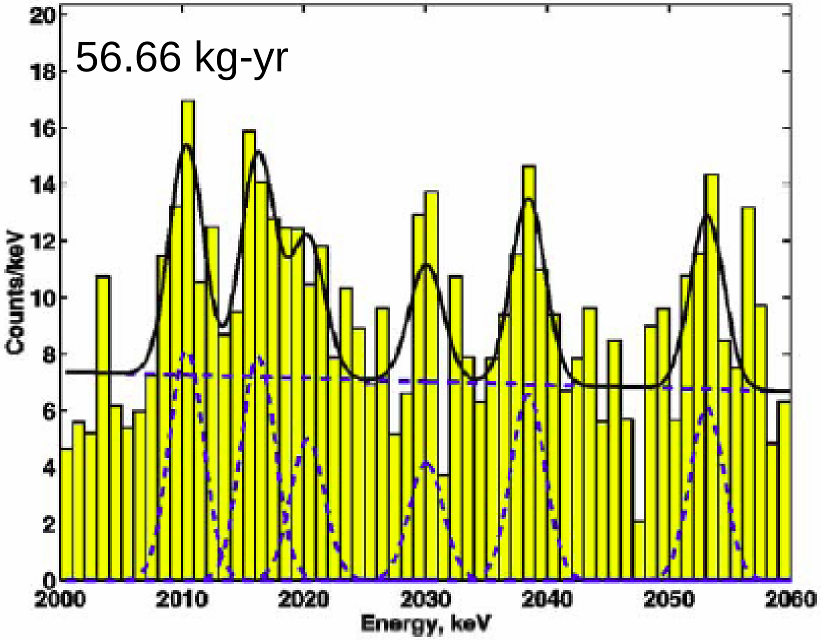
5 detectors of overall 10.96 kg enriched to 86%.
Most sensitive to date.

$T_{1/2}$ = (0.67 - 4.45) x 10^{25} *years* (99.73% *C.L.)*

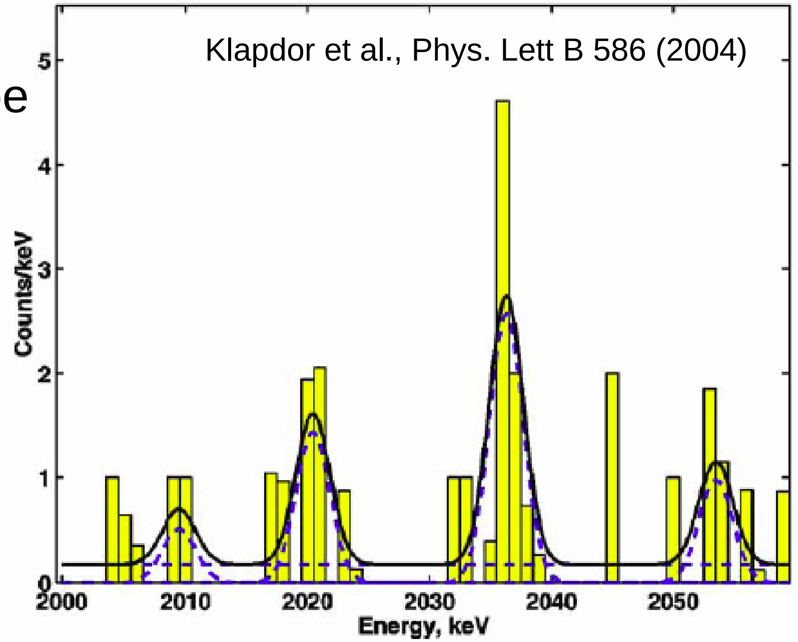
Majorana ν Mass

$\langle m_{\beta\beta} \rangle$ = (0.1 - 0.9) eV (99.73% *C.L.*)

$\langle m_{\beta\beta} \rangle_{\text{best}}$ = 0.45 *eV*



Pulse-shape selection



QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

MOON

CUORE

Candidate Experiments

$\sin^2 2\theta_{13}$

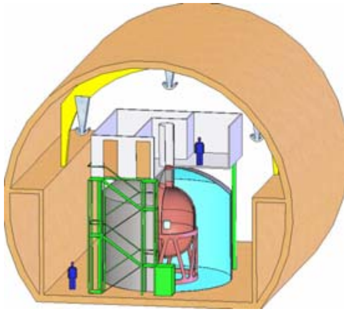
Experiment	Nucleus	Detector
NEMO III	^{100}Mo et al	10 kg of enrich. Isotopes -tracking
Cuoricino	^{130}Te + etc.	40 kg of TeO_2 bolometers (nat)
CUORE	^{130}Te + etc.	750 kg of TeO_2 bolometers (nat)
EXO	^{136}Xe	200kg - 1 t Xe TPC
GERDA	^{76}Ge	30 Š 40 kg Š 1t Ge diodes in LN
Majorana	^{76}Ge	180 kg - 1t Ge diodes
MOON	^{100}Mo	nat.Mo sheets in plastic sc.
DCBA	^{150}Nd	20 kg Nd-tracking
CAMEO	^{116}Cd	1 t $CdWO_4$ in liquid scintillator
COBRA	^{116}Cd , ^{130}Te	10 kg of CdTe semiconductors
Candles	^{48}Ca	Tons of CaF_2 in liquid scintillators
GSO	^{116}Cd	2 t Gd_2SiO_5:Ce scintill.in liquid sc.
Xe	^{136}Xe	1.56 Xenon in liquid scintillator.
Xmass	^{136}Xe	1 t of liquid Xe

Majorana

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

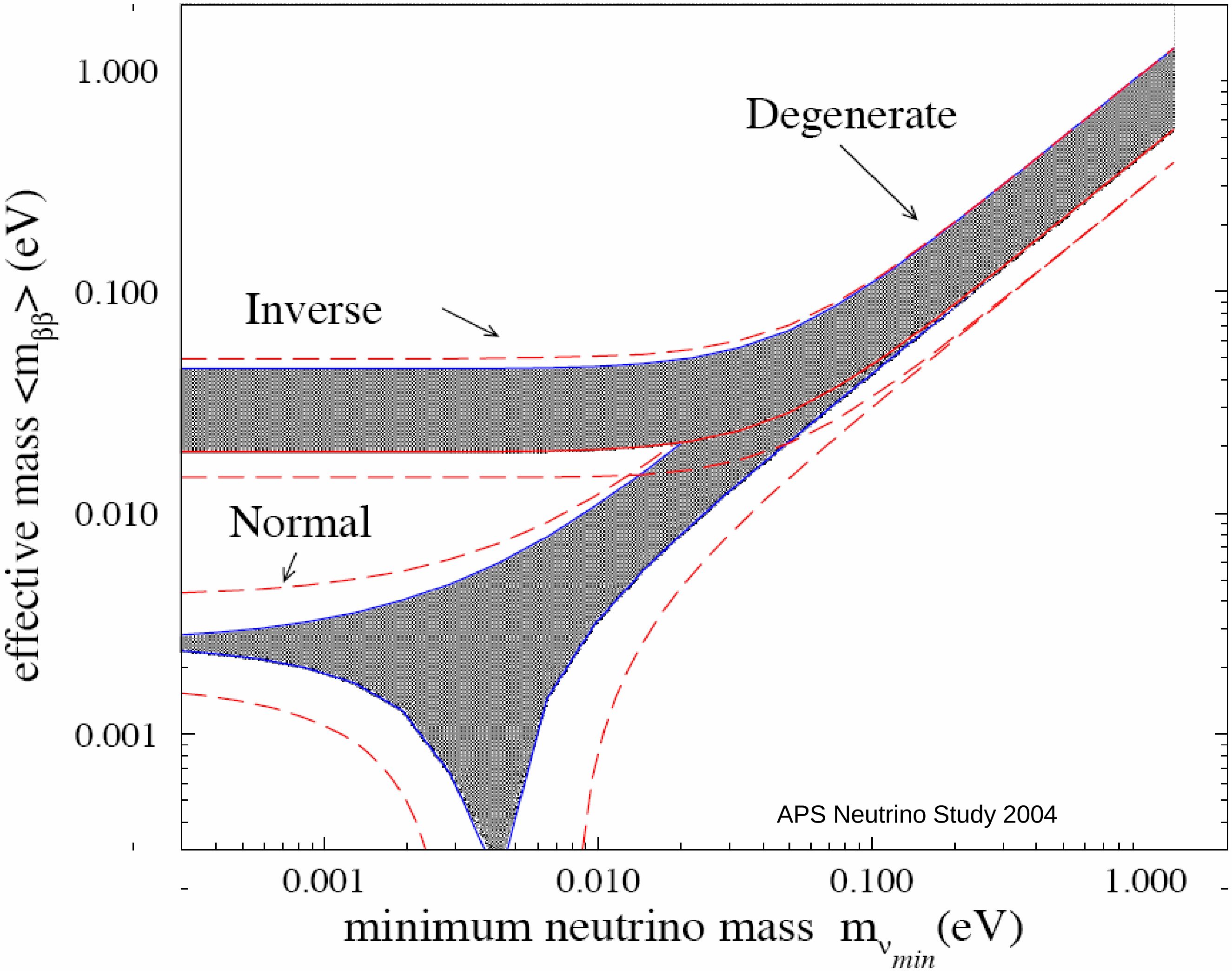
NEMO



GERDA

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

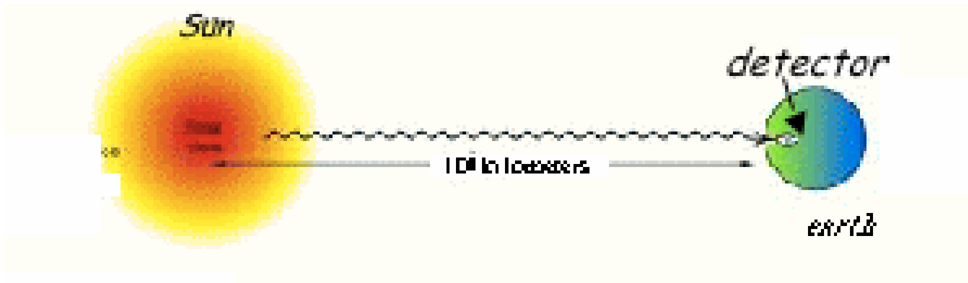
EXO

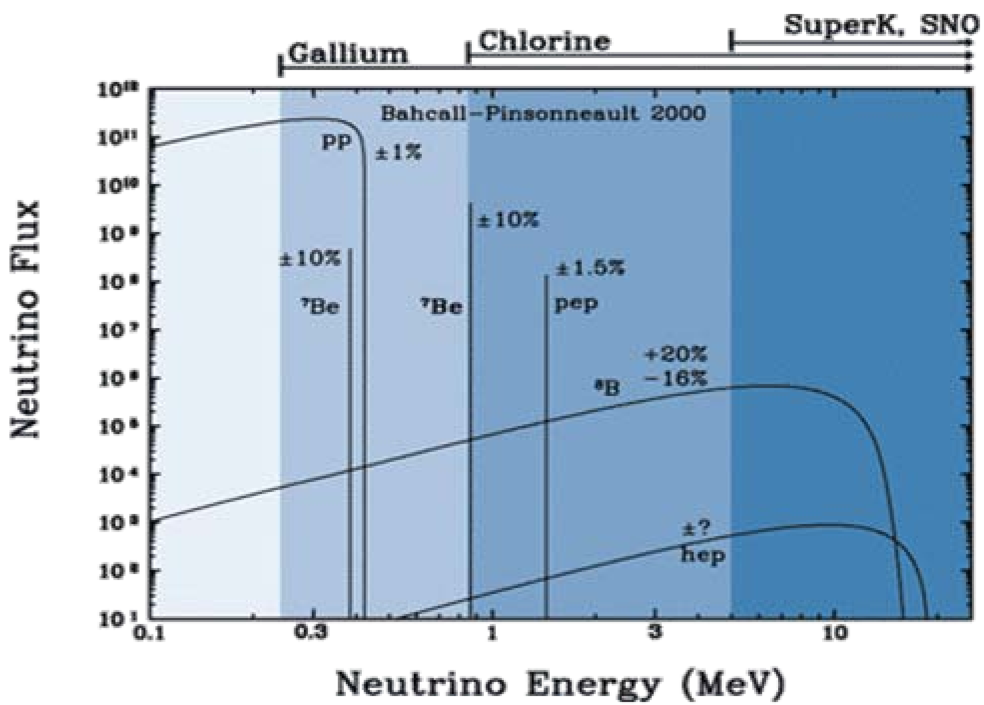


$$\Gamma_{0\nu} = G_{0\nu}(Q,Z)\ |M_{nucl}|^2 \langle m_{\beta\beta}\rangle^2$$

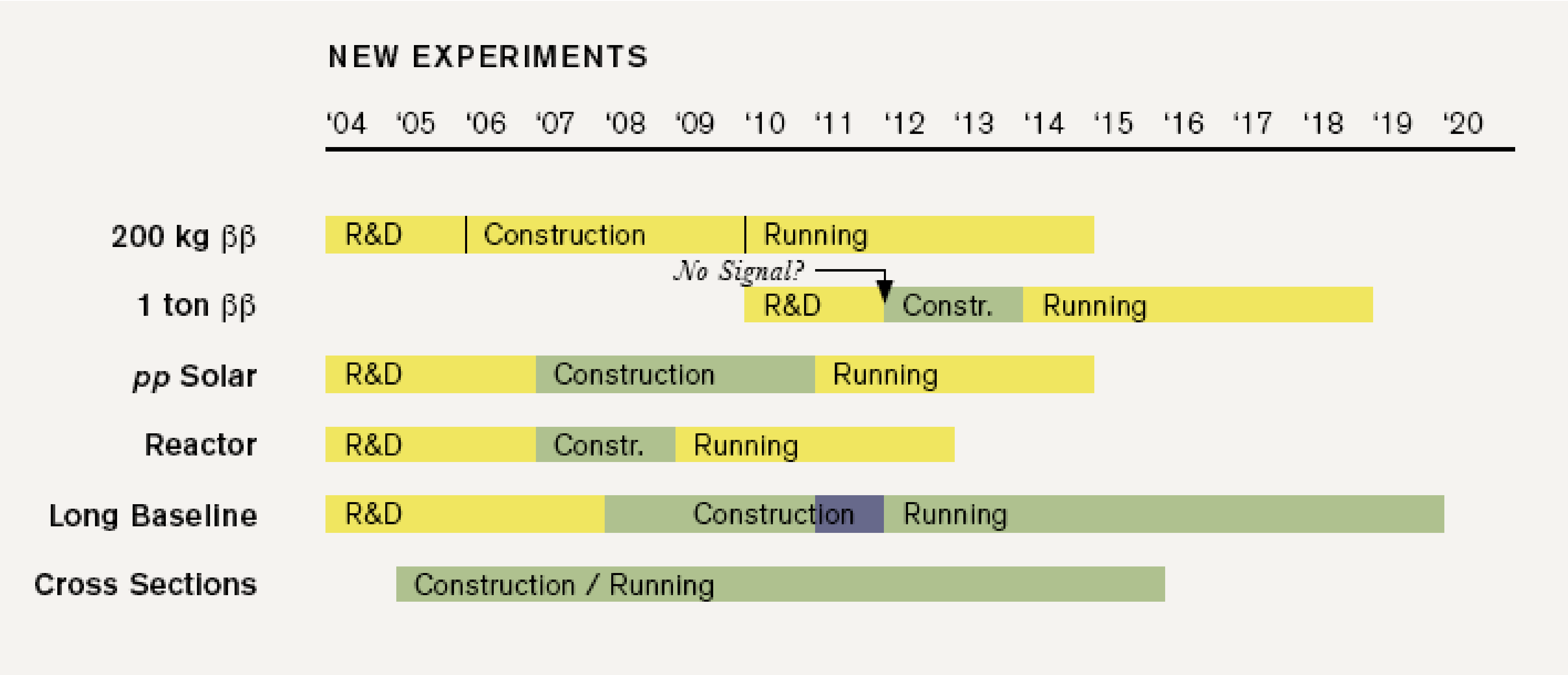
$$\left\langle m_{\beta\beta} \right\rangle = \sum_{i=1}^{3} \left| U_{ei} \right|^2 m_i \varepsilon_i$$

Solar Neutrino
Exotic to Established





APS Multidivisional Neutrino Study



I wonder if John liked my talk.