PHYS 575A/C/D

Autumn 2015

# Radiation and Radiation Detectors

**Course home page:**
**http://depts.washington.edu/physcert/radcert/575website/**

## 2: Radioactivity; fundamental interactions

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# Course calendar

Tonight

| week | date | day | topic | text |
|---|---|---|---|---|
| 1 | 10/1/15 | Thurs | Introduction, review of basics, radioactivity, units for radiation and dosimetry | Ch. 1, notes |
| 2 | 10/6/15 | Tues | Radioactive sources; decay processes; | Ch. 1, notes |
| 3 | 10/13/15 | Tues | Photomultiplier tubes and scintillation counters; Counting statistics | Chs. 3, 8, 9 (I-V) |
| 3 | 10/15/15 | Thurs | **LAB: Room B248** Scopes, fast pulses; PMTs and scintillation counters; standard electronics modules | Chs. 4, 9, 16, 17 |
| 4 | 10/20/15 | Tues | Overview of charged particle detectors | Ch. 4 |
| 4 | 10/22/15 | Thurs | **LAB: Room B248** Coincidence techniques; nanosec time measurement, energy from pulse area | Chs. 17, 18 |
| 5 | 10/27/15 | Tues | Interaction of charged particles and photons with matter | Ch. 2 |
| 6 | 11/3/15 | Tues | Other photodetectors; gas and solid-state detectors | Chs. 5, 6, 7<br>Chs. 11, 12, 13 |
| 7 | 11/10/15 | Tues | Detecting neutral particles; Data acquisition methods | Ch. 14, 15, 18 |
| 8 | 11/17/15 | Tues | Cherenkov detectors; Case studies: neutrino detectors (Super-K) | Ch. 19, Notes |
| 9 | 11/24/15 | Tues | Case studies: classic detectors (cloud and bubble chambers, nuclear emulsion), high energy accelerators | Ch. 19 |
| 10 | 12/1/15 | Tues | Case studies: contemporary leading-edge detectors (ATLAS, Auger) | Notes |
| 11 | 12/8/15 | Tues | Student presentations | - |
| 11 | 12/10/15 | Thurs | Student presentations | |

Last time:

# Radioactive decay math

- Radioactive decay law represents the differential equation

$$dN/dt = -\lambda N,$$

*where* $\lambda$ *is the decay constant,*

*which has the solution*

$$N(t) = N_0 \exp(-\lambda t) = N_0 \exp(-t/\tau)$$

- *Where* $\tau = 1/\lambda$ = *Mean lifetime*
- Half-life $T_{1/2}$ = time when $N/N_0 = ½$ → $½ = \exp(-T_{1/2}/\tau)$
- So $T_{1/2} = (\ln 2)\tau = 0.693\tau$
- Units for decay rate:

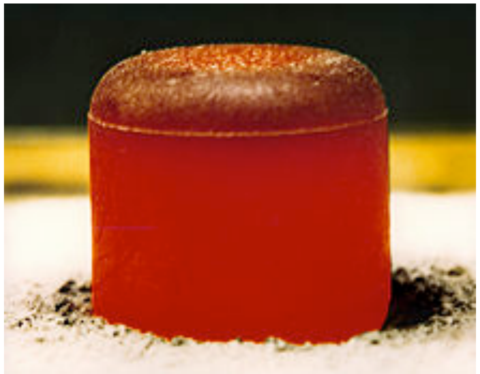
One becquerel (Bq) = 1 nuclear disintegration per second

One curie (Ci) = $3.7 \times 10^{10}$ decays per second = $3.7 \times 10^{10}$ Bq

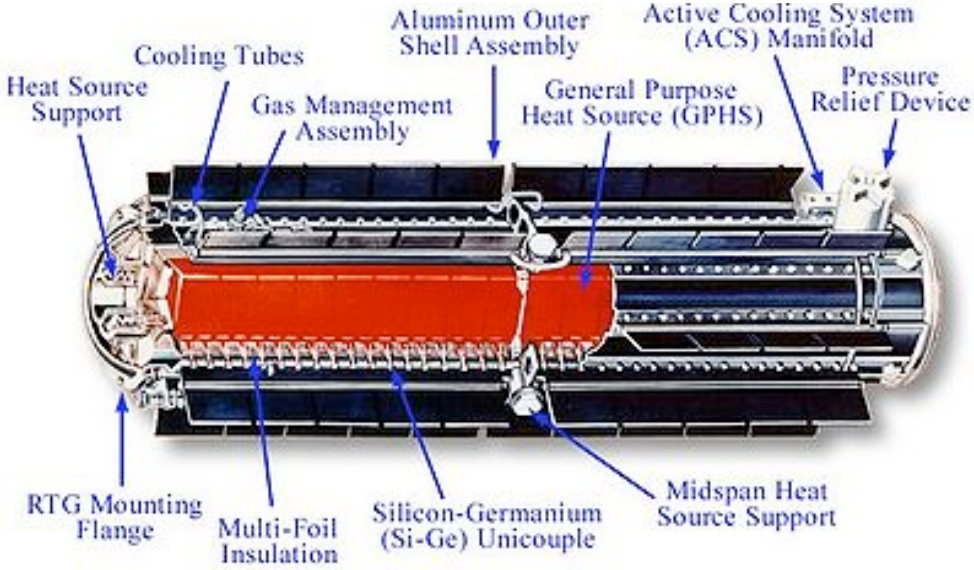
# “Hot” can mean hot!

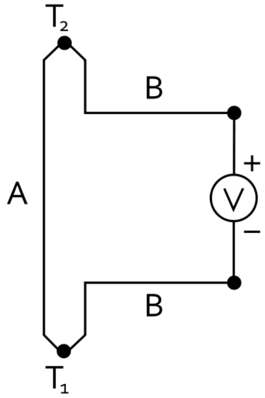
- High SA can create significant thermal energy
  - Example: plutonium power sources for spacecraft

Plutonium pellet:
red hot from its own radiation



Cassini spacecraft’ s Pu power source





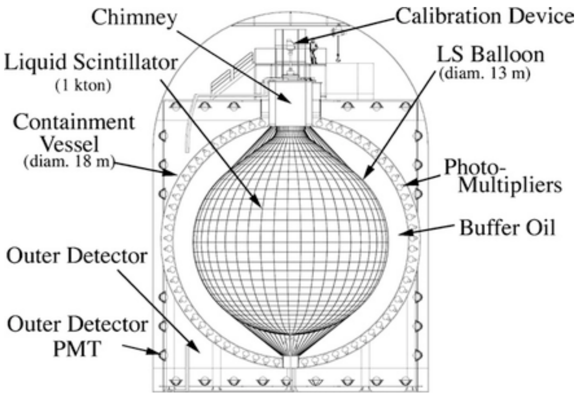
Thermoelectric generator:
Electric current from junctions of dissimilar metals (A, B) at different temperatures

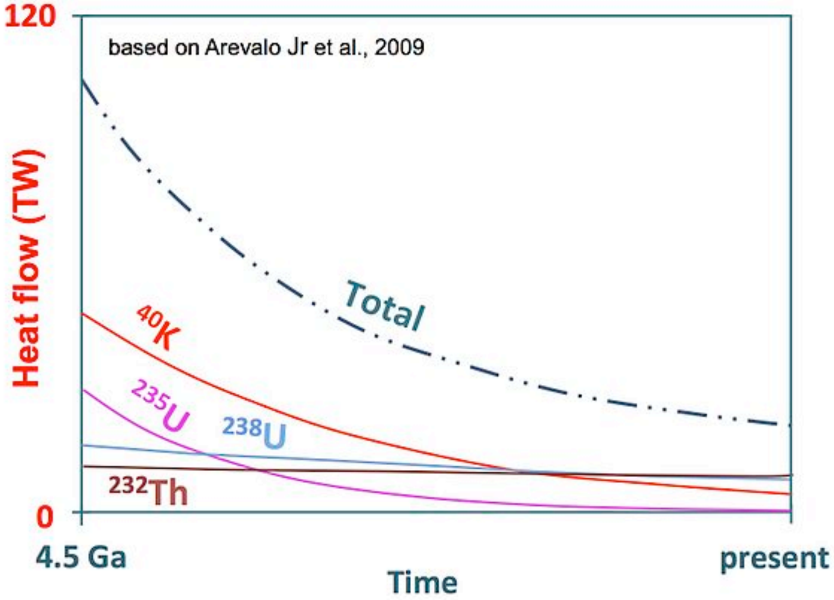
# Heat from the earth’s core

- Radioactivity in earth’s core generates heat
- Total heat from earth is 43~49 TW (poorly known)
  - Primordial heat = remaining from earth’s formation
  - Radiogenic heat = mainly U and Th in core
  - Little is known about mantle below 200 km, and core
- Geoneutrinos
  - From U and Th decays
  - Recent data from surface particle physics detectors

    → “x-ray the earth”

KamLAND
Antineutrino
detector





# Example: Compare activity of radium and uranium

- The rate of *nuclear decays per second* = Activity

  $\lambda N = |dN/dt|$ = *activity A* *(in Bq)*
- Specific Activity = activity per unit mass: $SA = \lambda N / m$

  where sample mass in grams $m = (N M / N_{AV})$, N=# molecules,

  M=grams /mole ( ~ atomic mass number), $N_{AVOG}$= Avogodro's no. = nuclei / mole

  $SA = \lambda N_{AVOG}/M$, for a pure sample (no other substances mixed)
  - So large SA for large $\lambda$ = small half-life:

    $T_{1/2} / (\ln 2) = \tau = 1 / \lambda$ ; $\lambda = (\ln 2) / T_{1/2}$
- How many grams of U-238 has the same activity as 1 gram of Ra-226?
  - Ra-226 has $T_{1/2} = 1.6 \times 10^3$ y = $49.6 \times 10^9$ sec,

    $\lambda_{Ra} = 0.693 / T_{1/2} = 1.4 \times 10^{-11}$ /sec
  - SA(Ra) = ($1.4 \times 10^{-11}$ /nucleus/sec)( $6.02 \times 10^{23}$ nuclei/mole) / (226 g/mole)

    = $3.7 \times 10^{10}$ /g/sec ( = 1 Bq – not surprising; that is the definition!)
  - U-238 has $T_{1/2} = 4.5 \times 10^9$ y = $1.4 \times 10^{17}$ sec, $\lambda_U = 5 \times 10^{-18}$ /sec
  - SA(U) = ($5 \times 10^{-18}$ /nucleus/sec)( $6.02 \times 10^{23}$ nuclei/mole) / (238 g/mole)

    = $1.25 \times 10^{4}$ /g/sec : 1 gram of Ra = 3 million grams of U, for activity

    (or: just take ratio of $( T_{1/2} M)_U / ( T_{1/2} M)_{Ra}$

# Radioactive decay: daughter products

- Suppose we have a decay chain

1 (parent nuclide) → 2 (daughter nuclide) → 3 (grand-daughter)

- Nuclides 1, 2, 3 decay with *decay constants* $\lambda_1, \lambda_2, \lambda_3$

  so $dN_1/dt = -\lambda_1 N_1$,

  but $dN_2/dt = +\lambda_1 N_1 - \lambda_2 N_2$, (parent *adds to* $N_2$ )

For initial conditions $N_1 = N_0, \; N_2 = N_3 = 0$ (only parent at t=0)

Solutions for $N_i$ (t) are: $N_1(t) = N_0 \exp(-\lambda_1 t)$

$$N_2(t) = N_0 \; \{ \lambda_1 / (\lambda_2 - \lambda_1) \} \; \{ \exp(-\lambda_1 t) - \exp(-\lambda_2 t) \}$$

Consider 4 scenarios:

- *Case 1: nuclide 2 is relatively stable,* $\lambda_2 \sim 0$

  then $N_2(t) = N_0 \; \{ 1 - \exp(-\lambda_1 t) \}$

# Radioactive decay chains

- *Case 2: nuclide 2 has much shorter half-life than nuclide 1,*

  $\lambda_2 >> \lambda_1 \Rightarrow exp(-\lambda_1 t) \sim 1$

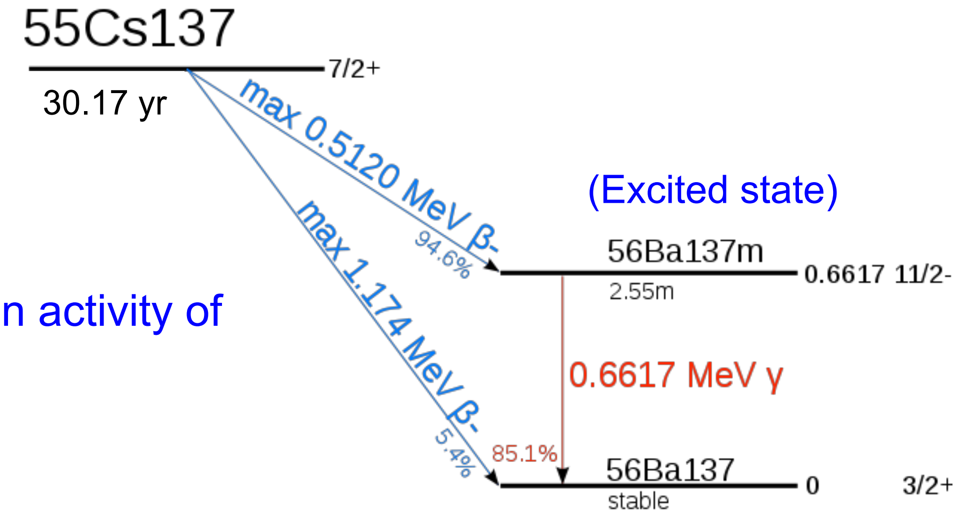
  $N_2(t) = N_0 \; (\lambda_1 / \lambda_2) \; \{ 1 - exp(-\lambda_2 t) \}$

- *Then at large t,* $N_2 \lambda_2 \sim N_0 \lambda_1$

  (recall: $\lambda N = |dN/dt|$ = *activity A* )

  – "Secular equilibrium" – nuclide 2 decays at same rate as it gets made: $N_2$ = constant

Example: Cs-137 → Ba-137



One gram of cesium-137 has an activity of 3.2 terabecquerel (TBq) !

# Radioactive decay chains

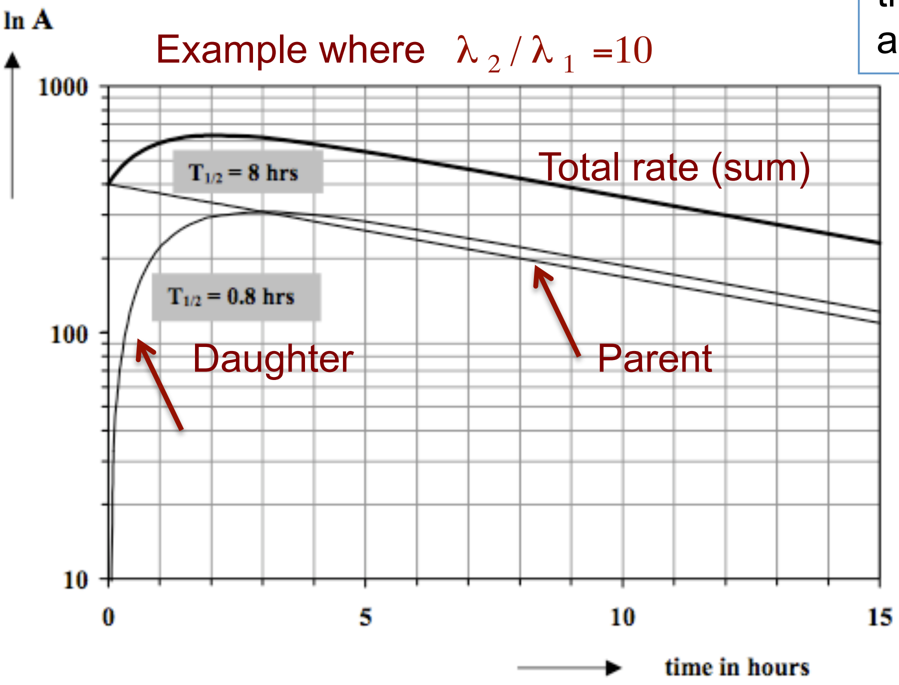
- *Case 3:* $\lambda_1 < \lambda_2$ *but* **not** *negligible in comparison ( X10)*

$$\frac{A_2}{A_1} = \frac{\lambda_2 N_2}{\lambda_1 N_1} = \frac{\lambda_2}{\lambda_2 - \lambda_1}\left\{1 - \exp\left[\left(\lambda_2 - \lambda_1\right)t\right]\right\}$$

$$as \quad t \rightarrow \infty, \quad \frac{A_2}{A_1} \rightarrow \frac{\lambda_2}{\lambda_2 - \lambda_1} = const$$

**"Transient equilibrium" –**
Daughter population increases at first, then briefly in equilibrium, later drops off according to parent's decay rate

Example where $\lambda_2 / \lambda_1 = 10$



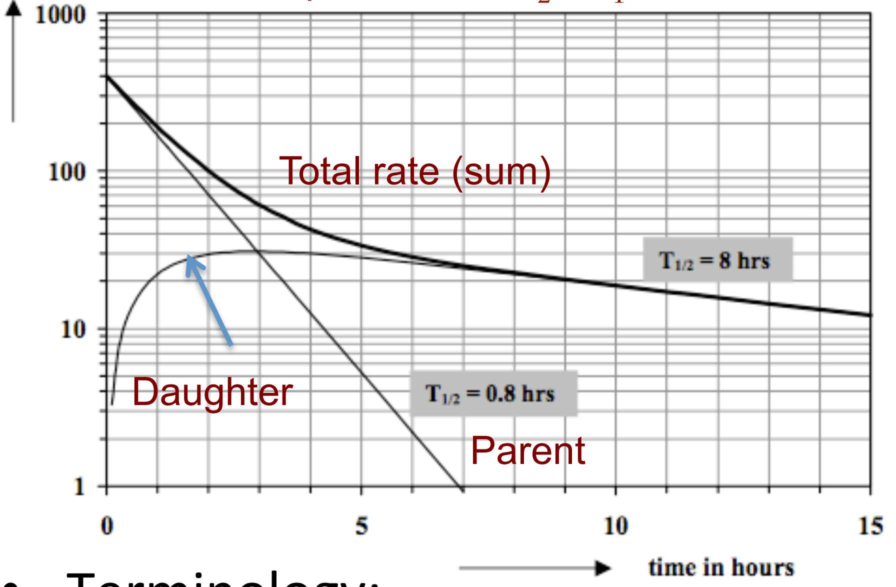
Example: Mo-99 → Tc-99
$T_{1/2}$ = 6hr 66hr
Max A $_{Tc}$ occurs after ~ 24 hr

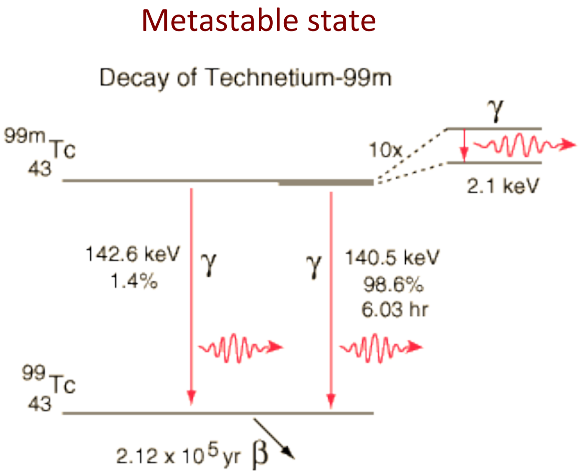
Graph: www-naweb.iaea.org/napc/ih/documents/global_cycle/Environmental Isotopes in the Hydrological Cycle Vol 1.pdf

# Radioactive decay chains

- *Case 4:* $\lambda_1 > \lambda_2$ (no equilibrium)
  - Parent decays away quickly
  - Daughter activity rises, then falls according to its own decay rate

Example where $\lambda_2 / \lambda_1 = 0.1$



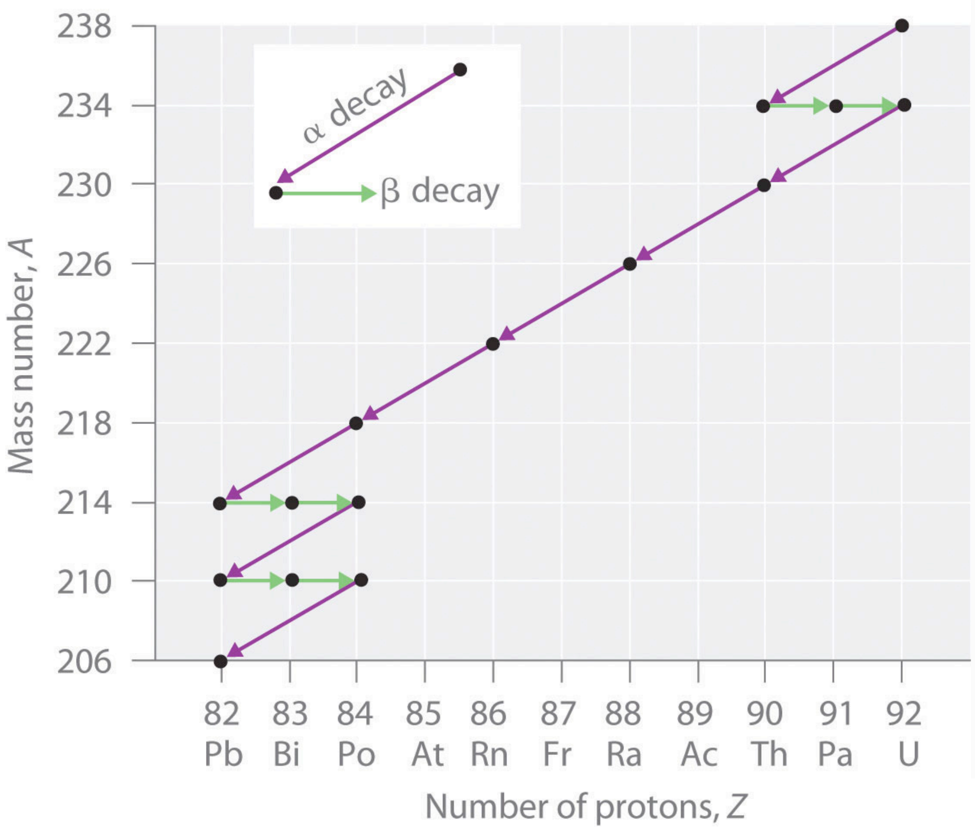


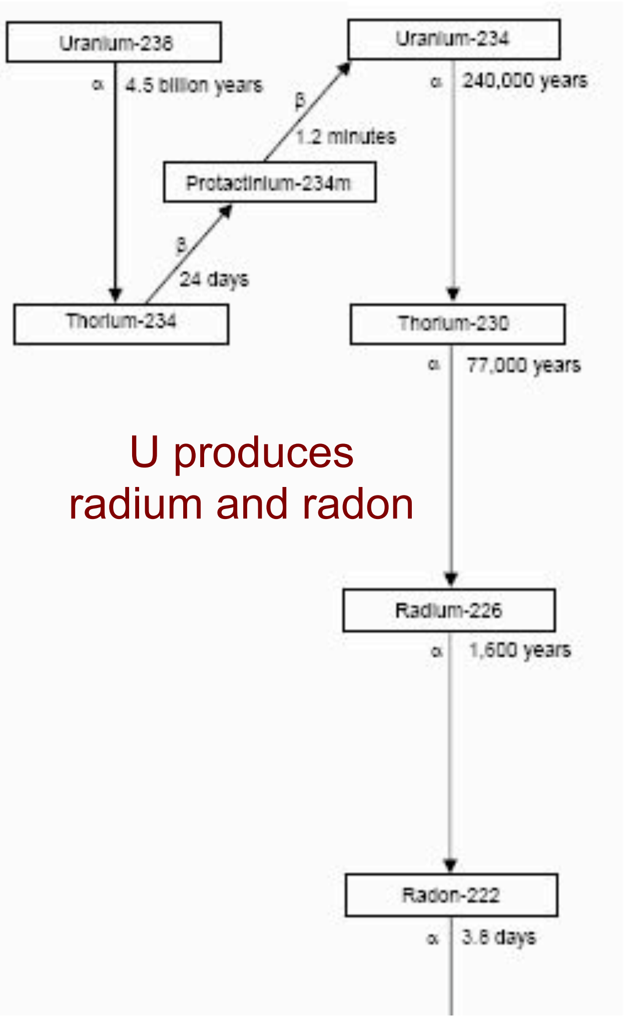
- Terminology:
  - Isobaric decay: Atomic number is constant (beta decay or e capture)
  - Metastable state: intermediate nuclear state with relatively long lifetime (example: $Tc^{99m}$ )

# A famous decay chain: Ra (or U) series

- Important natural decay chain is

  U-238… Ra …Rn … Po… Pb
  - U is more abundant than silver,
  - Natural uranium metal is 99% U-238



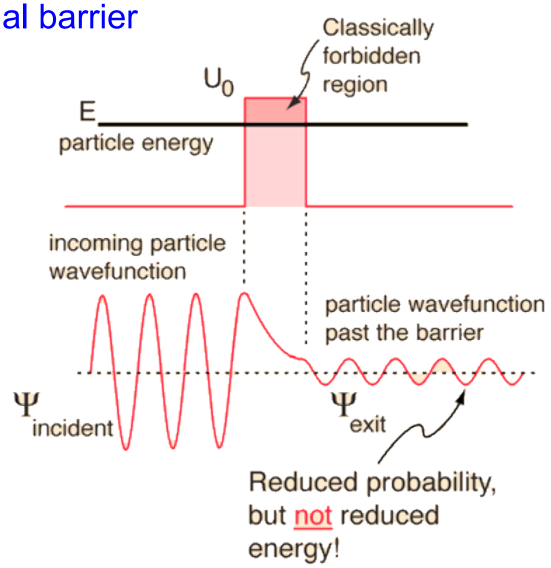


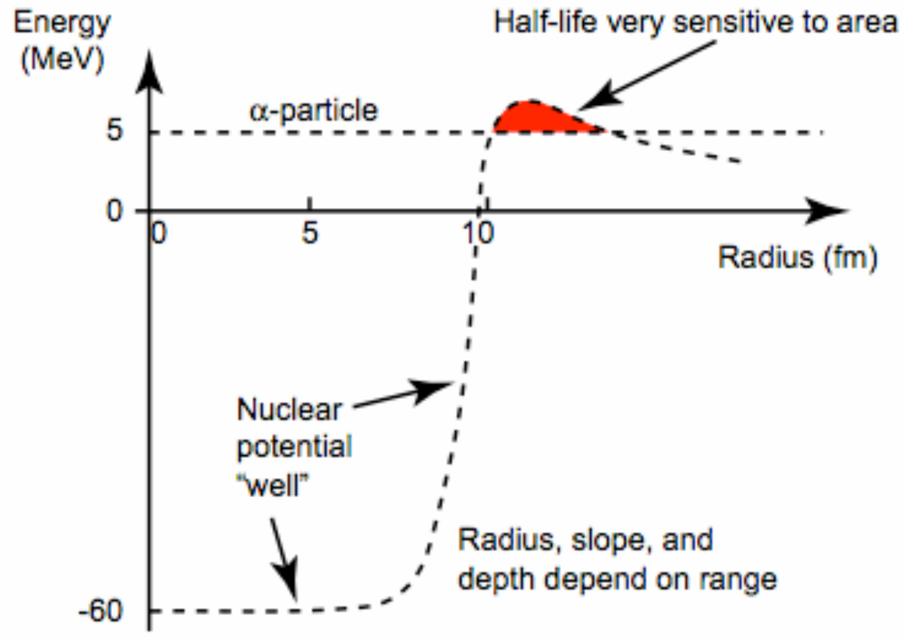
U produces
radium and radon

# Nuclear structure and binding energy

- Nuclear potential energy vs range, and alpha-decay
  - Alpha (He nucleus) is very stable, relatively light “cluster” of nucleons
  - Quantum tunneling concept applied by George Gamow, Ronald Gurney and Edward Condon (1928) to explain alpha decay.

Wavefunction tunneling through a potential barrier





# Nuclear structure and binding energy

- Semi-empirical mass formula - Estimates nuclear mass and binding energy with fair accuracy

$$M(Z,A) = Z\, m(^1\mathrm{H}) + N\,(m_n) - B(Z,A)/c^2\ ,$$

where

$$B = a_V A - a_s A^{2/3} - a_c Z^2/A^{1/3} - a_a (N-Z)^2/A + \Delta$$

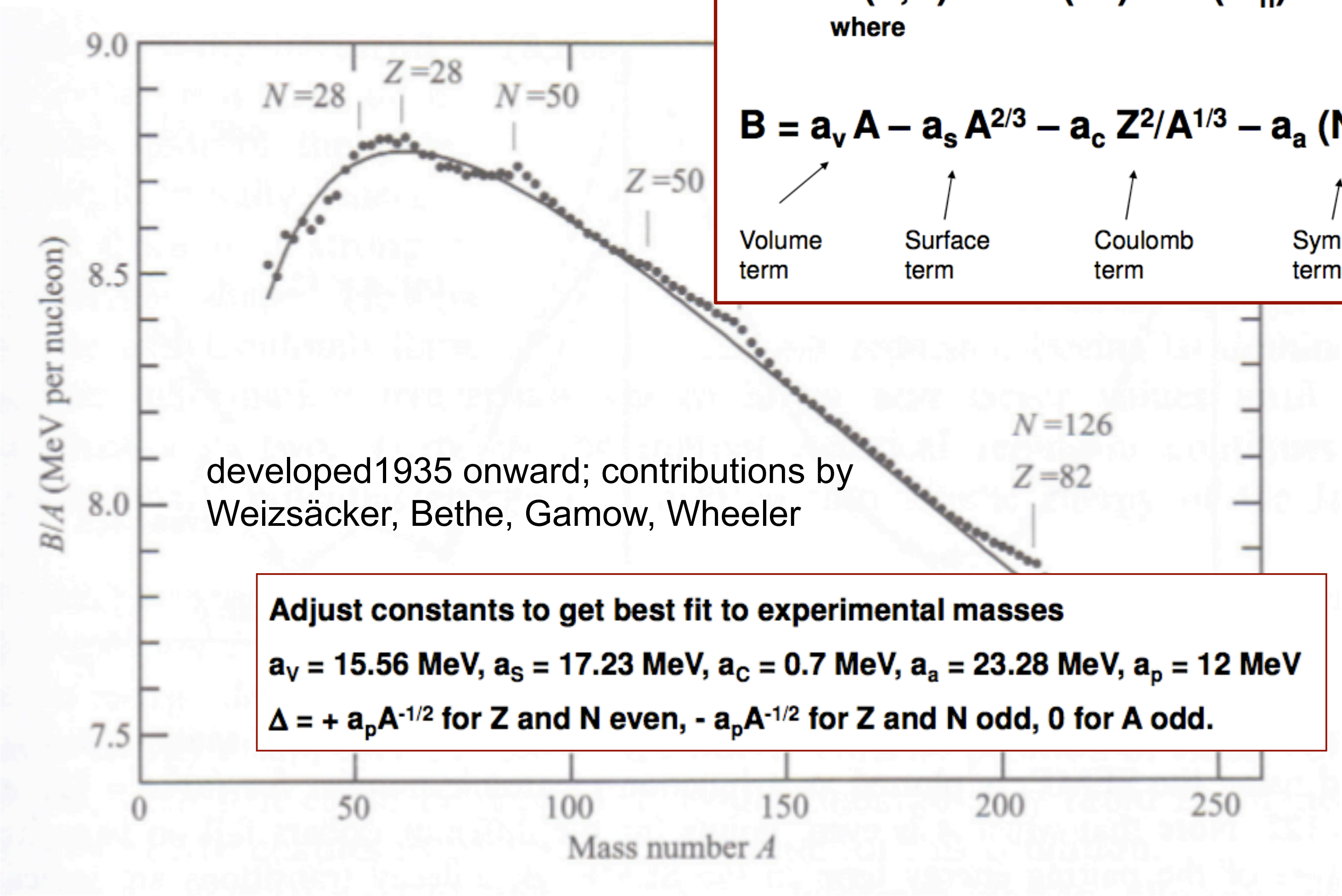
Volume term

Surface term

Coulomb term

Symmetry term

Pairing term



developed1935 onward; contributions by Weizsäcker, Bethe, Gamow, Wheeler

**Adjust constants to get best fit to experimental masses**

**$a_V$ = 15.56 MeV, $a_S$ = 17.23 MeV, $a_C$ = 0.7 MeV, $a_a$ = 23.28 MeV, $a_p$ = 12 MeV**

**$\Delta = + a_p A^{-1/2}$ for Z and N even, $- a_p A^{-1/2}$ for Z and N odd, 0 for A odd.**

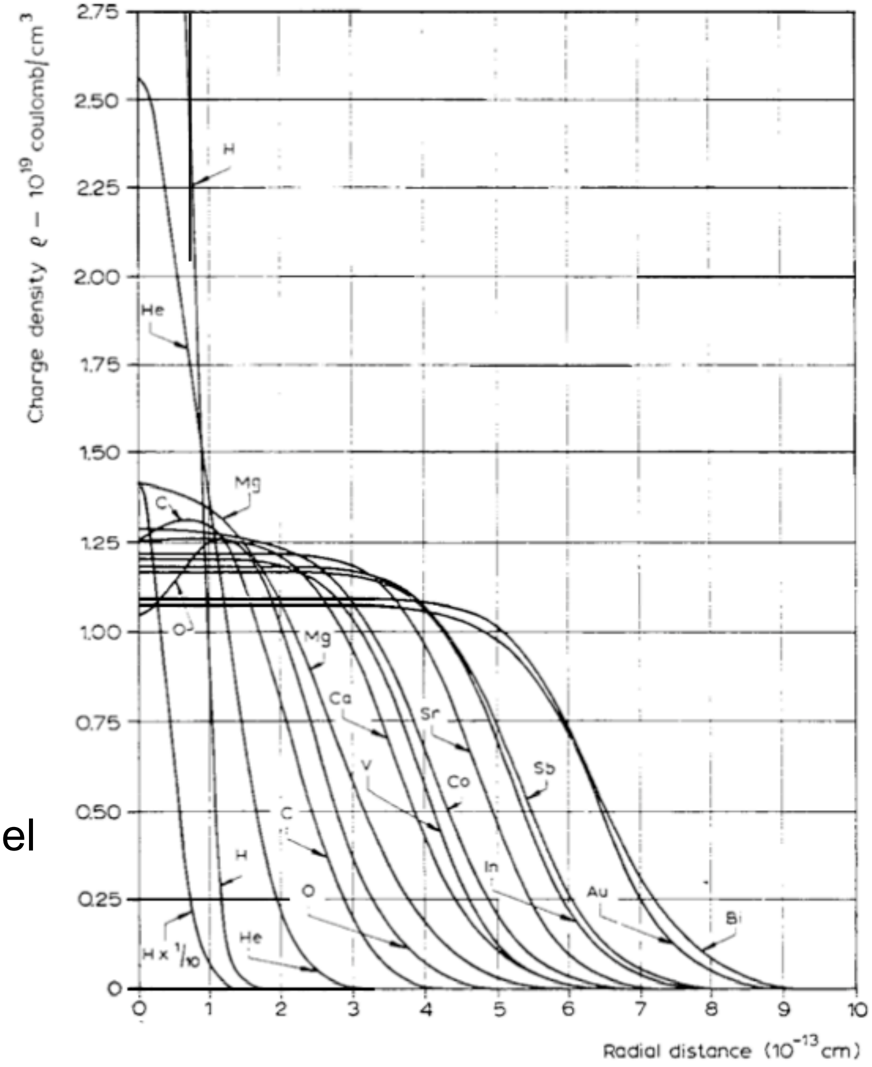
# Nuclear radii

- Scattering experiments (from Rutherford 1911 onward!) show

  $R_A = r_0 A^{1/3}$ ,

  with nucleon ‘size’

  $r_0 = 1.25$ fm



From R. Hofstadter, 1961 Nobel Prize lecture

# Robert Hofstadter

- Father of Douglas Hofstadter (Godel-Escher-Bach author)

- Pioneering electron-beam experiments at Stanford (SLAC) in 1950s and early 1960s
- Nobel prize 1961

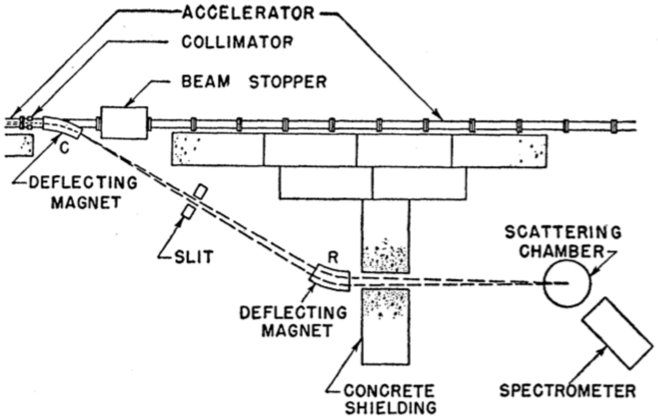


FIG. 14. The general layout of the equipment at the halfway point and the accelerator. Experiments, limited by the spectrometer to 190 Mev, are carried out in this area.

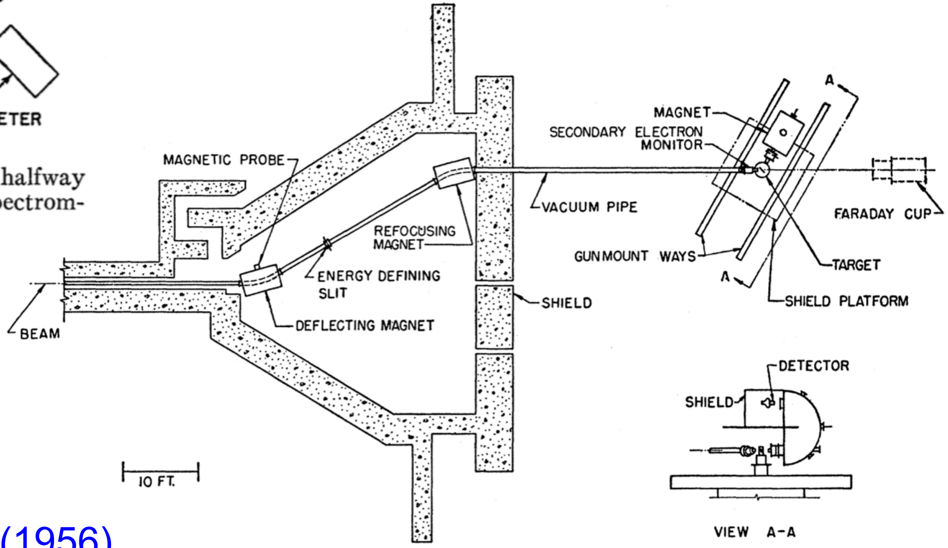


FIG. 18. The experimental installation of the 550-Mev spectrometer.

Hofstadter, Rev.Mod.Phys. 28:214 (1956)

# Explore for further info:
# Nuclear/particle data websites

- LBNL Isotopes Project     http://ie.lbl.gov/toi.html
- Periodic Table linked to decay data
  for known isotopes of each element

  http://ie.lbl.gov/toi/perchart.htm
- Particle Data Group (LBL):

  http://pdg.lbl.gov/

# Fundamental forces

- In practice, we leave string theory and Grand Unified Theory* to the theorists, and still talk about 4 fundamental forces:

| **Force** | **Carrier / mass** | **Range** | **Theory** |
|---|---|---|---|
| Gravity | Graviton / 0 | infinite | Newton, Einstein |
| Electromagnetic | Photon / 0 | infinite | QED (Feynman) |
| Weak nuclear | Point interaction<br>$W^+$, $W^-$ / 80 GeV, $Z^0$ / 91 GeV | 0<br>0.001 fm | Fermi Theory (1934)<br>Electroweak (Glashow, Salam, Weinberg) |
| Strong nuclear | Quark scale: Gluon / 0<br>Nuclear scale: Pion / 140 MeV | < 1 fm<br>O(1 fm) | QCD (Gell-Mann et al)<br>Yukawa et al |

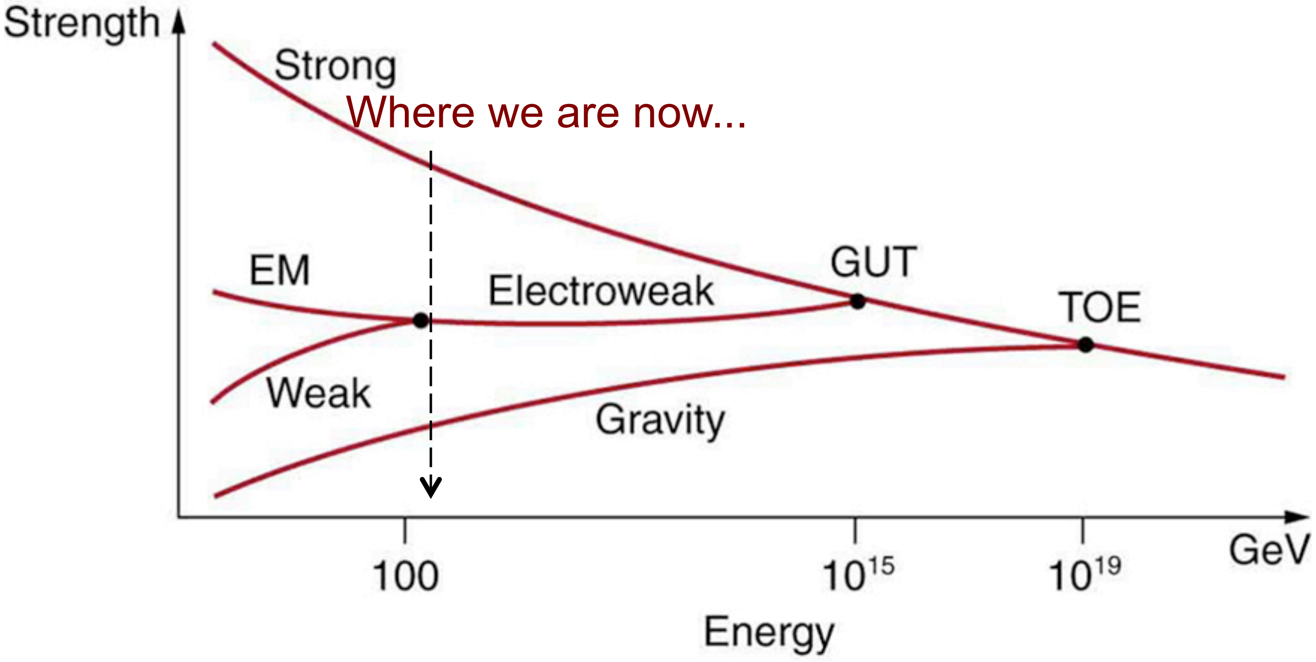
- Electroweak theory unified QED and weak interactions

* Holy grail: unify strong, electroweak, and gravity = GUT

# GUT and TOE

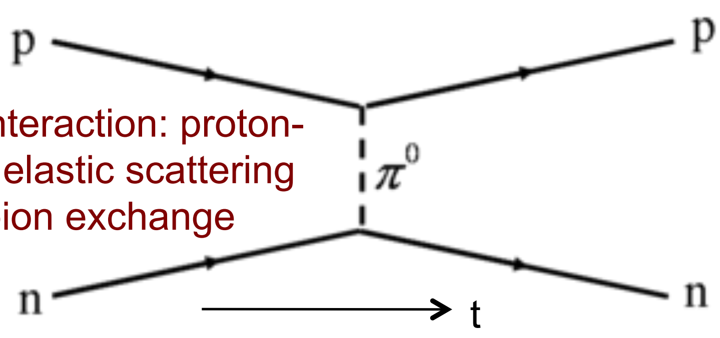
- Electromagnetic and weak force have already been unified by Glashow, Weinberg and Salam

  see www.nobelprize.org/nobel_prizes/physics/laureates/1979/
- Relative strength of strong and electro-weak forces (scale parameters) appear to intersect at a GUT energy scale around $10^{25}$ eV
- Perhaps we can then unify GUT with gravity (estimated scale: $10^{28}$ eV) to get a Theory of Everything (TOE)

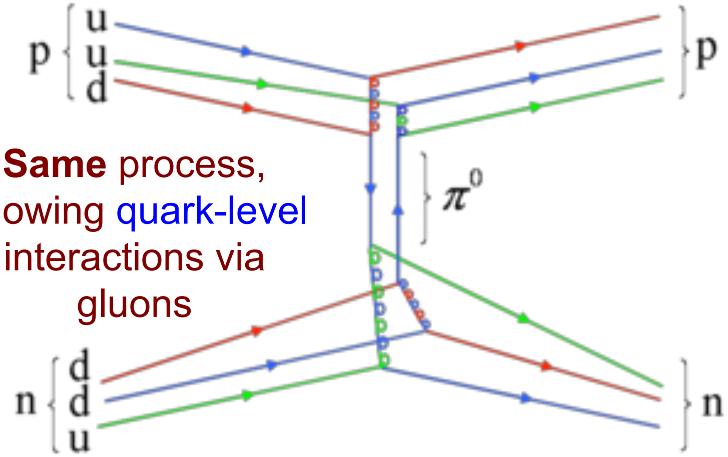


# Picturing fundamental interactions

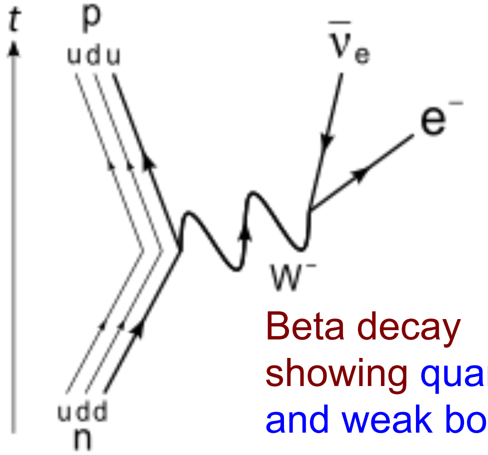
- Feynman diagrams (c. 1948)
- *Space-time diagrams,* with each component connected to an element in the probability calculation



Strong interaction: proton-neutron elastic scattering via pion exchange

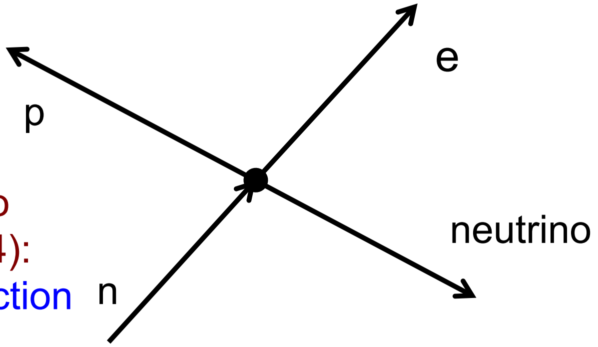


**Same** process, showing quark-level interactions via gluons



Beta decay showing quarks and weak boson

Beta decay according to Fermi (1934): point interaction



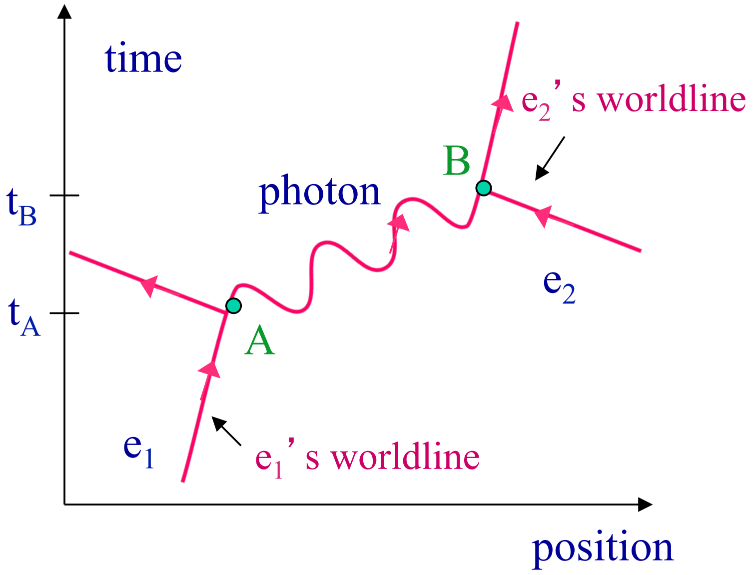
# More about Feynman's space-time diagrams

- Feynman's diagrams of a fundamental particle interactions seem simple, but have a lot of content!

*Feynman Diagram:* electron 1 emits a photon, which hits electron 2.

Case 1: energy of photon = energy lost by electron 1 (so energy is conserved at spacetime event A)
Photon is "real" and delivers its energy to electron 2 (spacetime event B).

Case 2: energy is not conserved at A: photon may carry **more** energy than $e_1$ gave up!
Photon is "virtual", because it carries "borrowed energy".
When it interacts with $e_2$ at B it must settle its energy accounts!
During the time $t_A$ to $t_B$, energy conservation is temporarily violated.



How can energy conservation be violated?
W. Heisenberg (1927): Uncertainty principle

$$\Delta E \, \Delta t \sim h$$

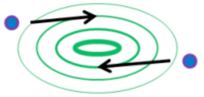
Energy "borrowed"

Duration of "loan"

very tiny number (Planck's constant)

# Terminology: Real/virtual – on-shell/off-shell

- Special Relativity tells us the energy/momentum relation for particle with mass m: $E^2 - |\vec{p}|^2 c^2 = m^2 c^4$
- Values of E and p that satisfy this equation form a 4D hyper-surface ("mass shell") in energy-momentum space
  - Real particles are "on-shell" (or, "on the mass shell")
  - Virtual particles are "off-shell"
- So what is the difference?
  - Real particle has a worldline, and can be located in space and time (within uncertainty principle limits) until it is destroyed
  - "Virtual particle" is just shorthand for "a disturbance in the field" (E-M field for photon, gravity field gravitons, etc) which dies away after some time
  - Required by mathematics of QM – but not really subject to our intuitive understanding!



Virtual photon exchange
(Matt Strassler, 2011)

# Example of strong force in action:
# Fission reactions / chain reactions

- Two isotopes of U (element 92) are involved:
  - 99.3 % of natural U metal is U-238, only 0.7% is U-235
  - These are isotopes of the same element: *chemically identical,* cannot be separated by methods of chemistry

$^{235}$U + neutron ➔ 2 or more neutrons + ~ 200 MeV energy (+ debris)

How to get "fissionable material" from ordinary uranium metal?

Method 1: separate U-235 (=fissionable material) from natural U

Hard: have to use physics instead of chemical engineering!

a) vaporize uranium, ionize it, then bend ion paths in magnetic field (slow and inefficient)

b) Run U vapor through a series of *filters*: diffusion rate depends upon atomic mass, but only a 1% difference! Takes thousands of diffusion steps. (WW-II method, Oak Ridge Nat'l Lab)

c) Run vapor through *centrifuges* to separate a tiny amount a a time (Iranian method!)

Another idea: use U to make *another element* that is fissionable

$^{238}$U + neutron ➔ $^{239}$U ➔ $^{239}$Pu (plutonium, new element not found in nature)

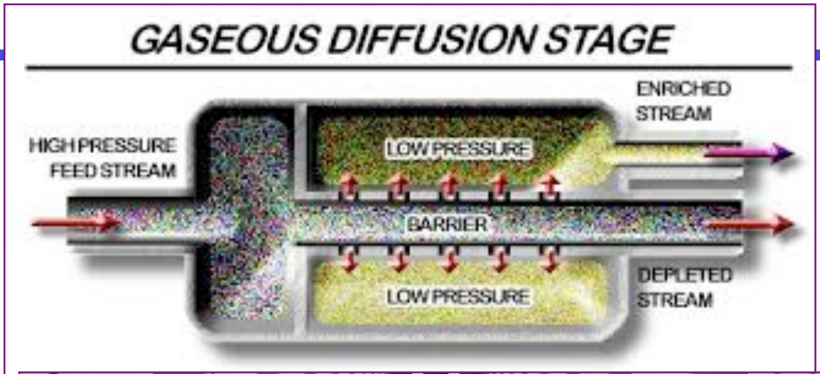
$^{239}$Pu has good characteristics for fission too, so

Method 2: build a nuclear reactor and generate Pu-239 (which can then be extracted by well-developed industrial chemical engineering methods)

Also difficult: Pu is extremely poisonous (chemically), and mixed in with highly radioactive residues in reactor fuel rods

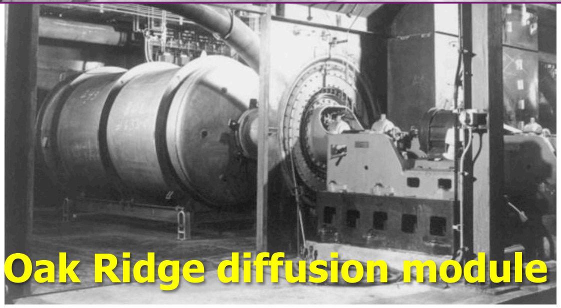
Neutrons must be slowed down to cause fission efficiently, so U fuel blocks were surrounded by carbon as a *moderator* in the 1942 U. Chicago experimental reactor

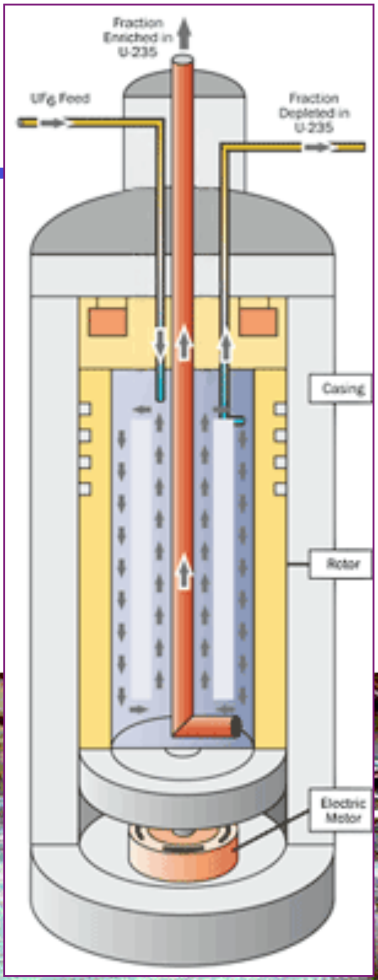
# Separating U-235: Centrifuges vs diffusion




Manhattan Project, WW-II

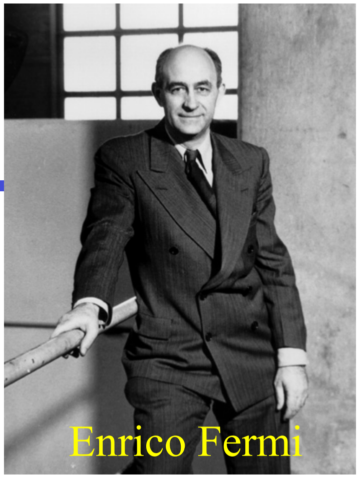
Workers at Oak Ridge, 1943


Oak Ridge diffusion module




Centrifuge arrays

# Nuclear power


Enrico Fermi

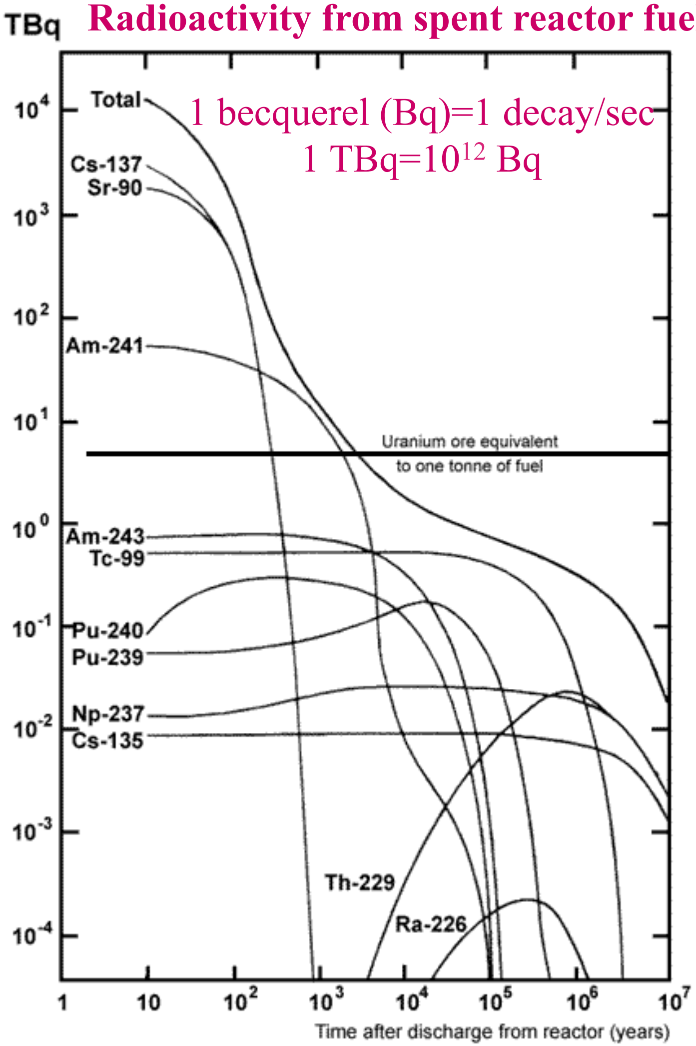
- First nuclear reactor was built in December, 1942
  (under football stands at U. of Chicago!)
  - Pile of uranium and carbon blocks (obsolete term: “nuclear pile”)
  - Historical context
    - 1938: nuclear fission reaction is discovered in Germany
    - 1940: Enrico Fermi theorizes it may be possible to create a “self-sustaining fission reaction”
      - Each fission produces neutrons which trigger others: chain reaction
      - Might be possible to get fast reaction = explosion ($10^6$ X chemical E)


First reactor, 1943

- 1941: Leo Szilard persuades Einstein (among others) to write President Roosevelt pointing out danger if Germany develops this first
- 1942: Manhattan District of US Army Corps of Engineers is assigned to conduct R&D and if possible develop nuclear weapons (“Manhattan Project”)
  - Labs built at Los Alamos, NM (physics research), Oak Ridge, TN (industrial-scale separation of U-238 from natural U) and Hanford, WA (reactors for Pu production)
  - These all still exist as “national laboratories” belonging to US Dept of Energy: LANL, ORNL, PNNL

# Safety issues

- Radioactive waste
  - Fuel elements from fission reactors are highly dangerous
  - No firm plan in place for storing them long-term in USA!
    - Most (40,000 tons) high-level waste now stored in water tanks on reactor sites
    - Significant problem from leakage of WW-II era waste containers at Hanford, WA –
      - USA just put off settling this, problem, once again…
    - Need long-term storage ($10^4$ yr!)
  - Fuel rods can be processed to extract Pu and other isotopes
    - Nuclear security / proliferation concern !



Radioactivity from spent reactor fuel

1 becquerel (Bq)=1 decay/sec
1 TBq=$10^{12}$ Bq

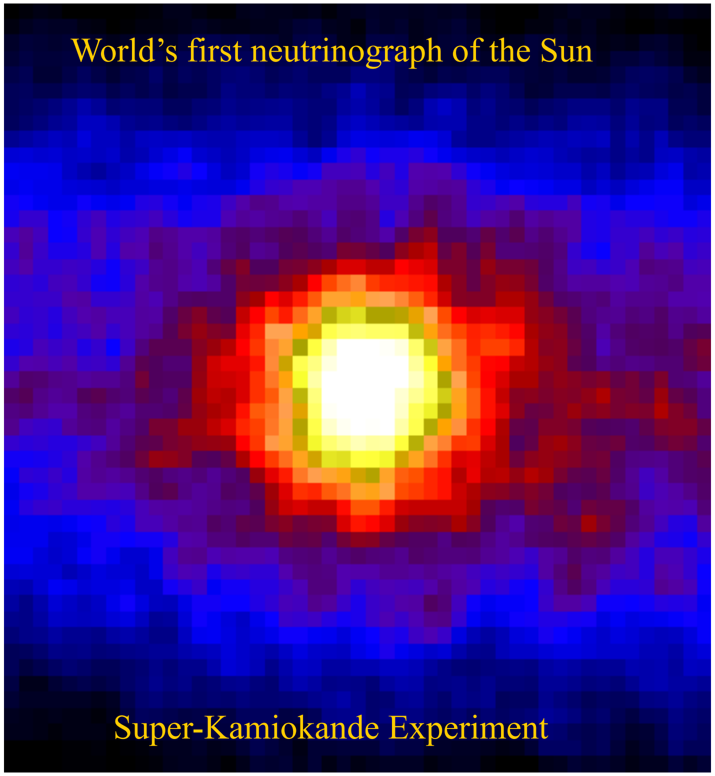
Activity of high-level waste from one tonne of spent fuel

Source: IAEA, 1992 - radioactive waste management.

# Weak force

- Force responsible for radioactive decays
  - Very short range, due to high mass of W, Z force carriers
- Also involved in nuclear fusion processes
  - Study of neutrinos is intimately connected with our understanding of weak interactions

- We can study neutrinos from several sources:
  - Man-made (particle accelerators, or reactors)
  - The Sun (fusion reactions)
  - Earth's atmosphere (cosmic ray interactions)
  - Distant astrophysical objects like Active Galactic Nuclei
    - Not yet observed
  - Super-Novae


World's first neutrinograph of the Sun

Super-Kamiokande Experiment

# So: What are neutrinos?

Symbol: υ
(Greek letter nu)

- Neutrinos = subatomic particles with:
  - zero electric charge
  - (almost) zero mass
  - They only interact with matter via weak nuclear force
    - Makes them very hard to observe: hardly ever interact, and most particle detectors respond only to charged particles

That doesn't sound very interesting! But…

  - neutrinos are created in (almost) every radioactive decay
  - neutrinos are as abundant as photons in the Universe
    - Several hundred per cm$^3$ everywhere in the Universe
      - even though they are nearly massless, they make up a noticeable (but not significant) fraction of the mass in the Universe!
    - You are emitting ~ 4,000 neutrinos/sec right now
      - Your blood ~ seawater – contains radioactive potassium-40
    - Neutrinos can penetrate the entire Earth (or Sun) without interacting
      - maybe we can study earth's core with neutrinos? (UW Prof. N. Tolich)
      - astronomical window into places we can't observe with light (me)

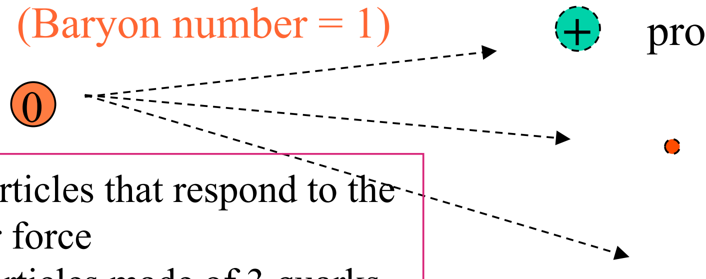
# Other kinds of "charge": *quantum numbers*

(subatomic properties that have no "macro world" analogues)

- Radioactive decays = weak nuclear force in action
  - Example: *beta decay* of neutron

    Charge, B, and L must balance before and after:

lepton number L is a conserved property (like a new kind of 'charge') that only leptons have.
Baryon number B: ditto, for protons and neutrons.



neutron (Lepton number = 0)
(Baryon number = 1)

proton (Lepton number = 0)
(Baryon number = 1)

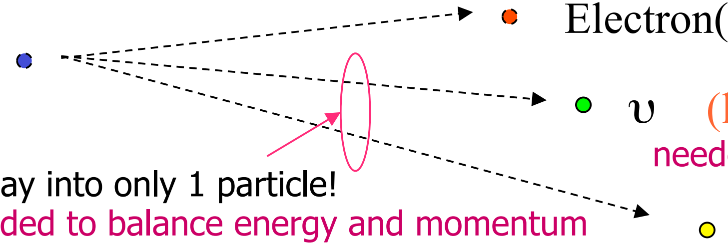
Electron(-) (lepton number = +1)
needed to balance electric charge

anti-υ (lepton number = -1)
needed to balance lepton number
(must be *anti* to balance lepton #)

Leptons = particles that respond to the weak nuclear force
Baryons = particles made of 3 quarks

  - another example: muon decay

$\mu^-$ (lepton number = +1)



Electron(-) (lepton number = +1)

υ (lepton number = +1)
needed to balance energy and momentum

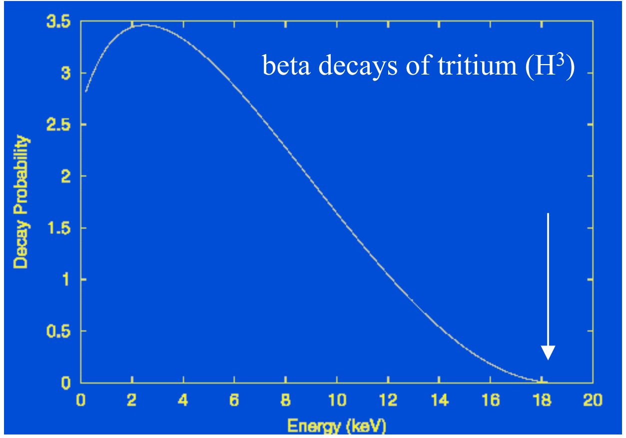
anti-υ (lepton number = -1)
(must be *anti* to balance lepton #)

Newton: can't decay into only 1 particle!
2 or more are needed to balance energy and momentum

# Neutrinos: Who said we need them?

- Wolfgang Pauli, c. 1931~33

Electron energies observed in decays. Nuclear energy released is 18 keV. But usually the electron carries away much less!!



Pauli (with Heisenberg and Fermi)

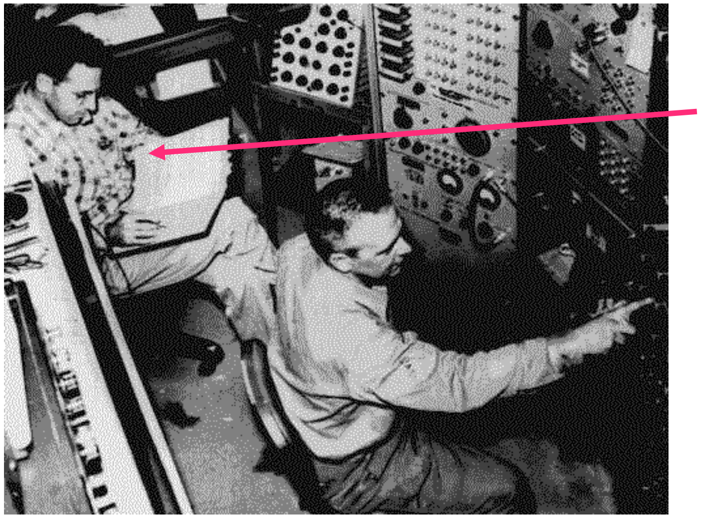
  – Beta decay of nuclei produced only 1 detectable* particle (electron), and seemed to violate conservation of energy and momentum!
    - Observed electrons can have *any* energy up to maximum allowed by conservation of energy ($E_{MAX}$ = [parent mass - daughter mass]*$c^2$)
    - There must be a neutral, almost massless, extra particle emitted
      – Pauli called it a *neutron*, not realizing Chadwick had used that name!
      – Fermi suggested the name 'neutrino' = "little neutral one"

* Only charged particles are easily observed

> "I've done a terrible thing - I've invented a particle that can't be detected!" - Pauli

# Neutrinos: How were they first ‘seen’?

- Fred Reines and Clyde Cowan, 1956
  - υ source: Nuclear reactor in Hanford, WA (later they moved to even more powerful Savannah River reactor in South Carolina)



**Nobel Prize in Physics 1995**

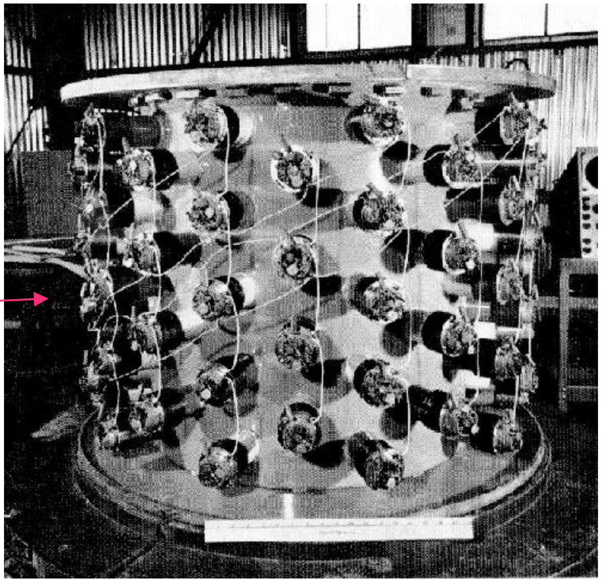
**Awarded to Fred Reines "for pioneering experimental contributions to lepton physics"**

Detector: water with chlorine salts, viewed by many *photomultiplier tubes*

- *inverse* beta decay: $\bar{\nu} + p \rightarrow n + e^+$

$e^+$ quickly hits meets atomic $e^-$ and they annihilate

Reines & Cowan looked for light flashes from $e^+$ $e^-$ annihilation, followed by later decay of neutron

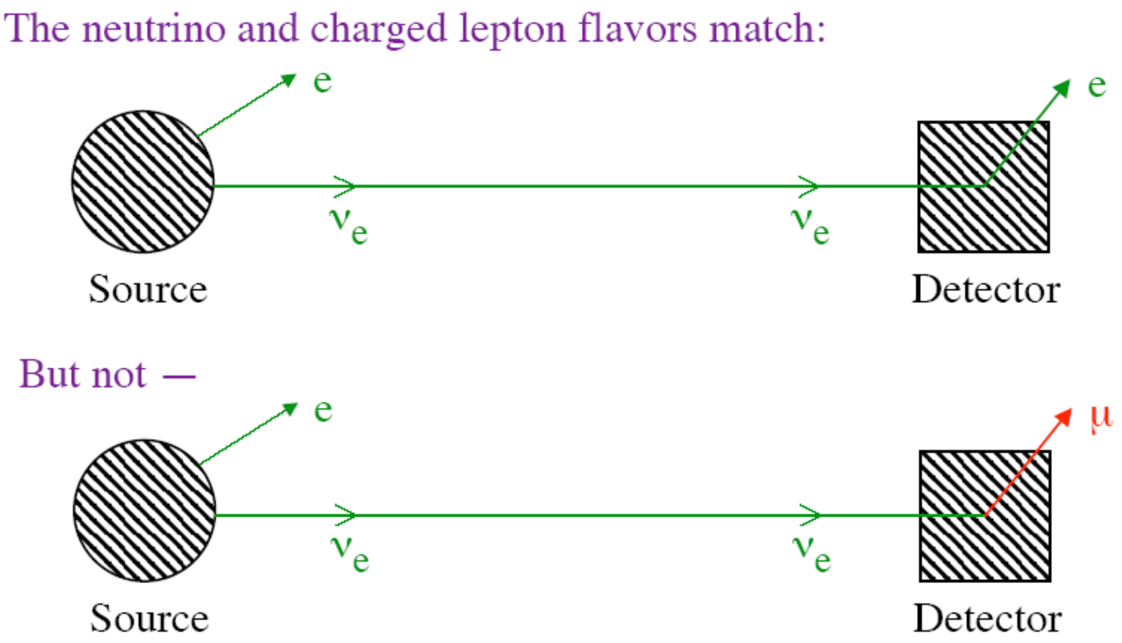


# Q: how do we tell a neutrino’s *flavor*?

- We detect and identify neutrinos by observing the *charged leptons* they produce when they interact:

  $\nu_e$ + proton → e + other stuff

  $\nu_\mu$ + proton → $\mu$ + other stuff
- The states $|\nu_\tau\rangle$, $|\nu_\mu\rangle$ , $|\nu_e\rangle$ are called neutrino “flavor” states.



The neutrino and charged lepton flavors match:

But not —

# Do neutrinos have mass? Applied Quantum Mechanics

- You too can be a quantum mechanic ! Basic ideas:

1. Particles also behave like waves *(Wave-Particle Duality)*
   - Wavelength depends on *momentum* (deBroglie, 1924)
2. All information about a particle is contained in its *wave* (*state*) *function* $\Psi(x,t)$
3. Probability of finding particle at position x at time t is $|\Psi(x,t)|^2$
   - Wave function itself is *not* a measurable physical quantity
4. Quantum states *evolve* with time:

E = energy = $mc^2$

$$\Psi(x,t) = \Psi(x,0) \cdot e^{-iEt/\hbar}$$

5. Quantum states can be described as a mixture of other states

$$\Psi_{FLAVOR}(x,t) = \Psi_{MASS-1}(x,t) + \Psi_{MASS-2}(x,t) + \Psi_{MASS-3}(x,t)$$

Neutrino flavor state
is a *mixture*...

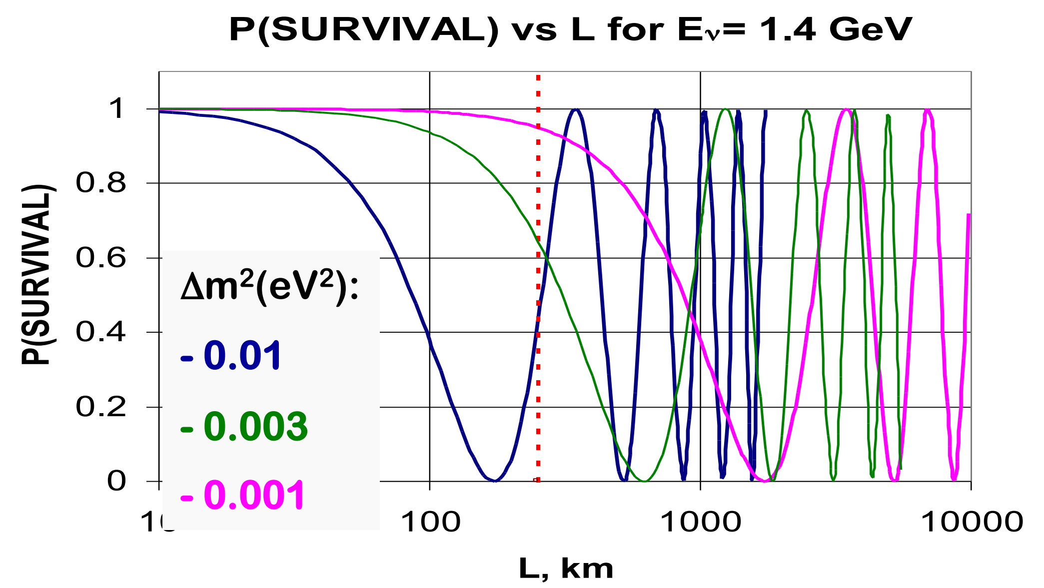
...of neutrino mass states
(and vice-versa)

# Q: What are neutrino “oscillations”?

- If neutrinos can change flavor, they must also have mass states
  - Flavor changes are observed
- If we start out with a given flavor = mixture of *mass* states,
  - Probability that a neutrino is detected as the same flavor *oscillates*
  - The relative proportion of each *flavor* will change with time
    - t = *time* on neutrino’s clock ~ distance travelled from production point

Fraction of muon neutrinos *remaining* vs distance from production point

$$P = 1 - \sin^2 2\theta \sin^2\left(1.2\Delta m^2 \frac{L}{E}\right)$$



L = distance traveled (in km)

E = neutrino energy in GeV

dm$^2$ = ( m2 – m1 )$^2$

P = probability of remaining same flavor

# Neutrino experiments we work on here: Super-Kamiokande and T2K

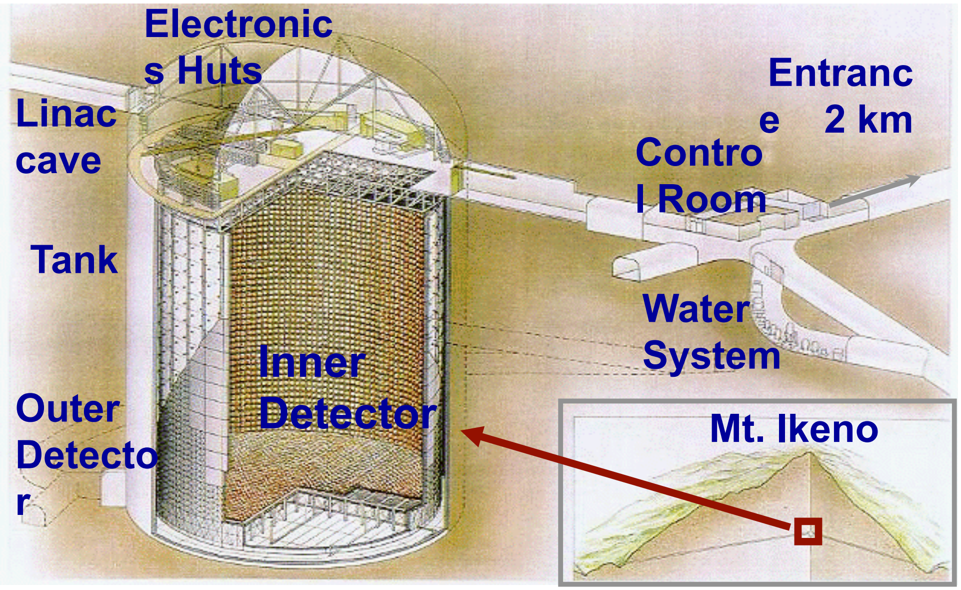
Super-Kamiokande Underground Neutrino Observatory

- In Mozumi mine of Kamioka Mining Co, near Toyama City
- Detects natural (solar, atmospheric) and artificial (K2K) neutrinos

T2K (Tokai to Kamiokande) long baseline experiment

- Neutrino beam is generated and sampled at Tokai (particle physics lab, near Tokyo)
- Beam goes through the earth to Super-K, 300 km away

# Super-Kamiokande



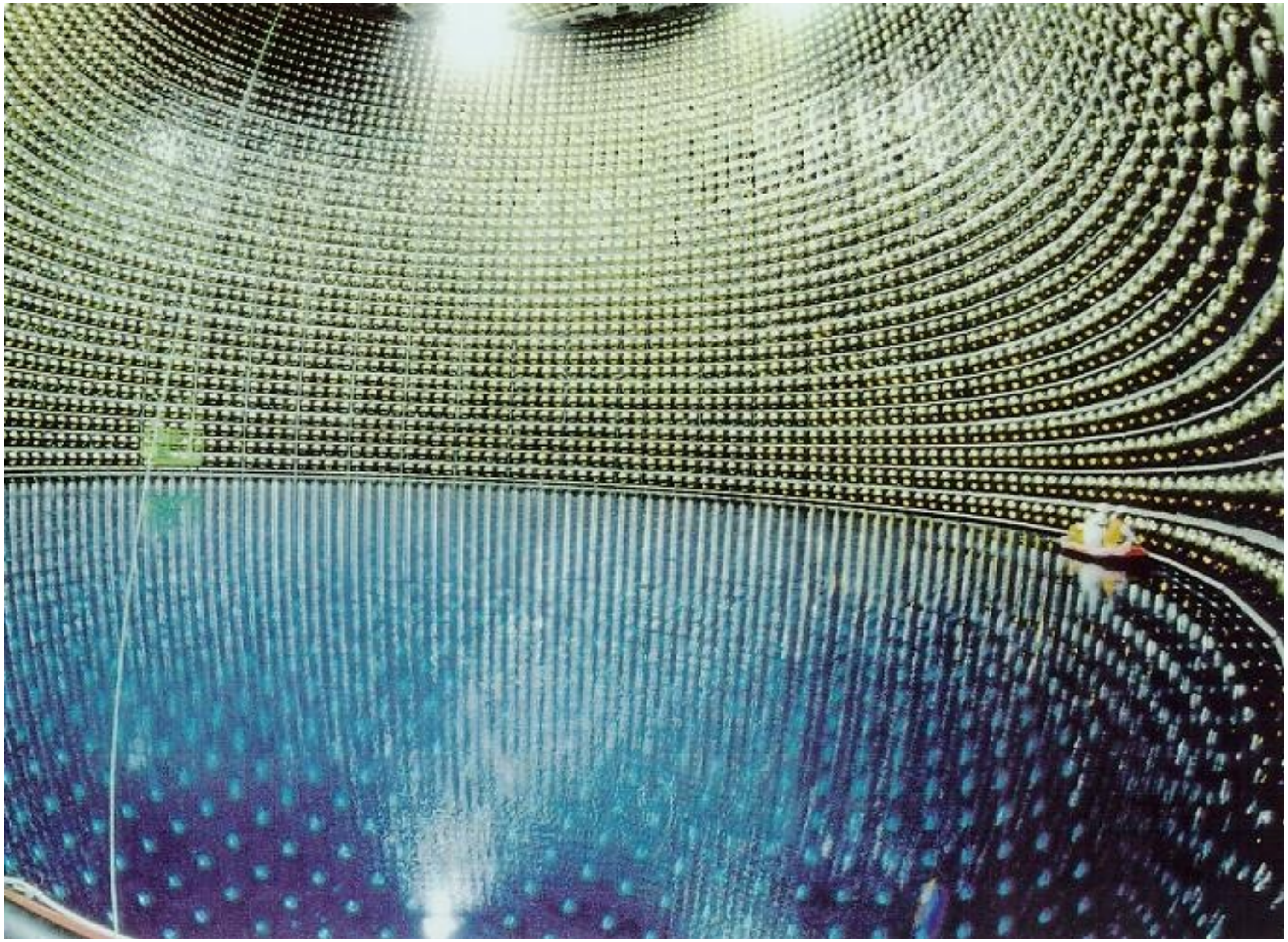
- US-Japan collaboration
- (~100 physicists)
- 1000 m of rock overhead to block cosmic ray particles
- 50,000 ton ring-imaging water Cherenkov detector
- Inner Detector: 11,146 phototubes*, 20” diameter
- Outer Detector: 1,885 phototubes, 8” diameter

- Began operation in April, 1996
- Published first evidence for neutrino mass in June, 1998
- Typically records about 15 neutrino events per second

See website for more info: http://www.phys.washington.edu/~superk/

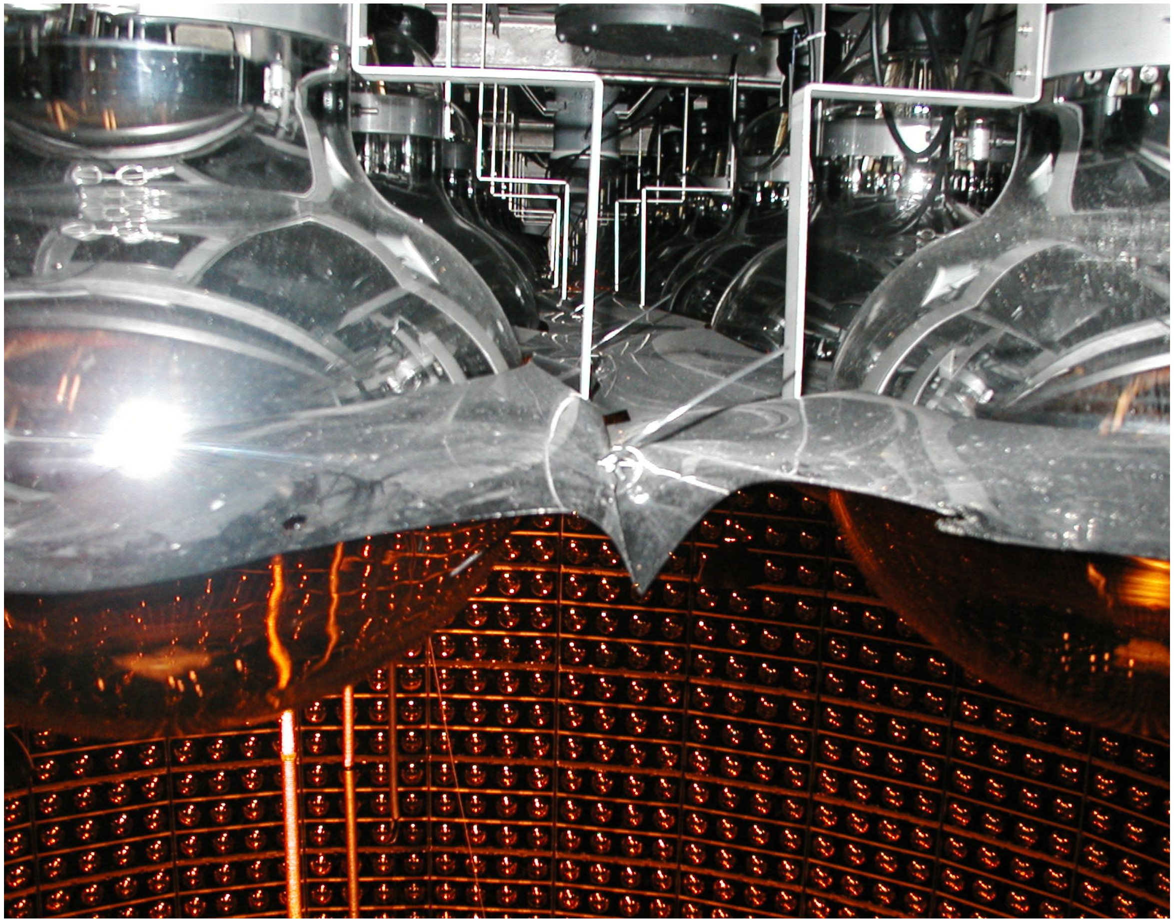
# Just how big is Super-K?

- Checking photomultiplier tubes by boat as the tank fills (1996)



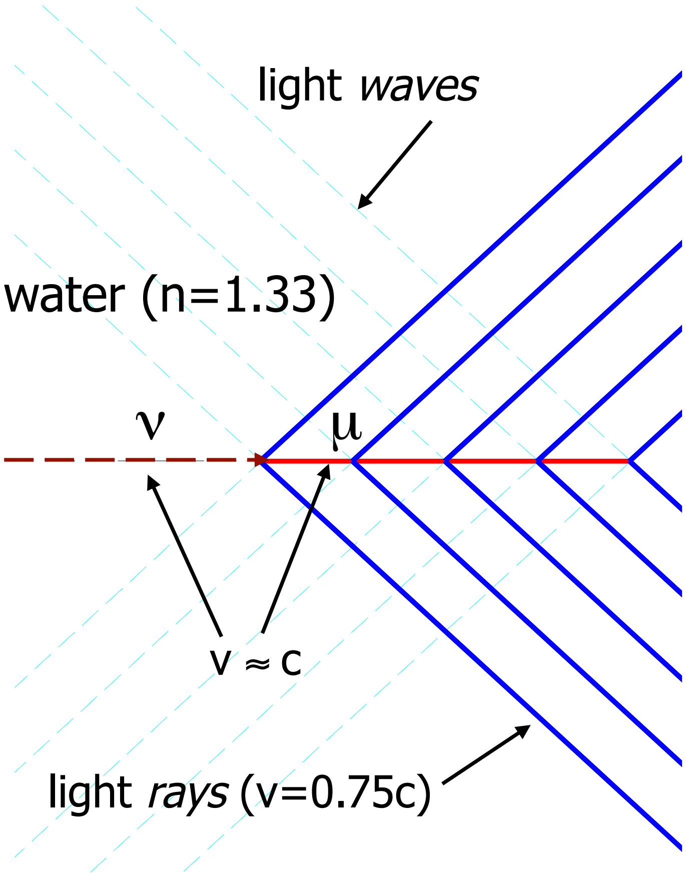
# View into Super-K from tank top

- Each photomultiplier tube is 20 inches in diameter!



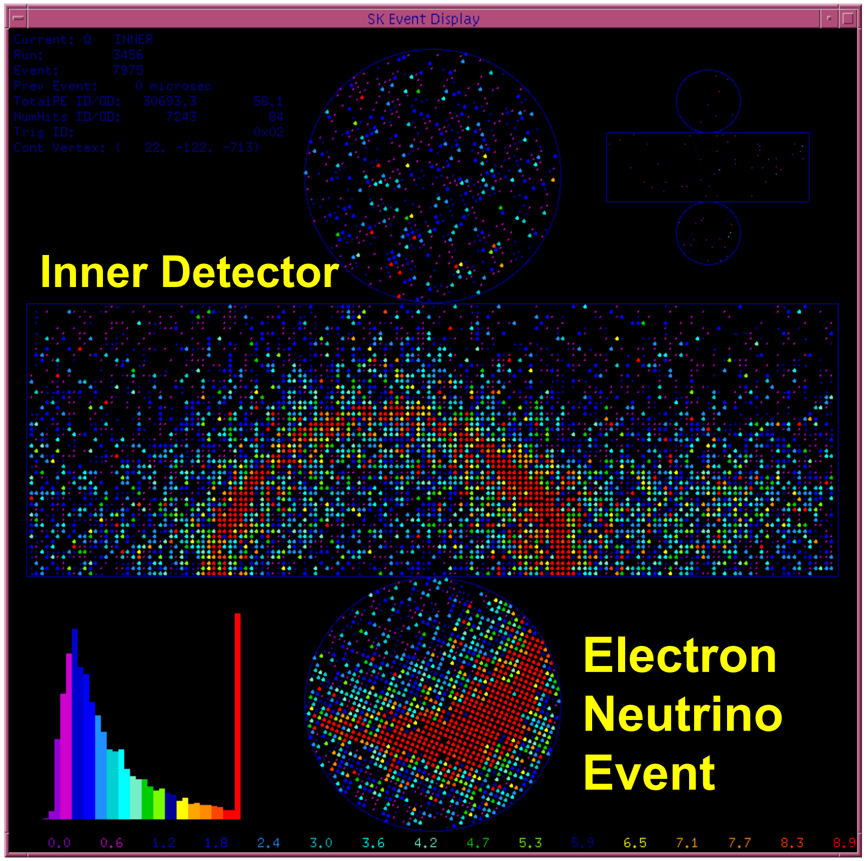
# Cherenkov light in water

- Neutrino interacts in a nucleus in the water (oxygen or hydrogen)
- Produces a charged muon or electron, which carries an electromagnetic field
  - Tau neutrinos produce a tau which immediately decays into muons and e's
    - Super-K can't identify tau neutrinos
- Muon is going faster than its field can travel in water: "shock wave" builds up
- Cherenkov light is emitted in characteristic 42° rings around the particle direction
- Cherenkov 'rings' are fuzzy for electrons and sharp for muons
  - electrons scatter in the water
  - heavier muons travel in straight paths until very nearly stopped



# Neutrino “events”: $\nu_e$ and $\nu_\mu$

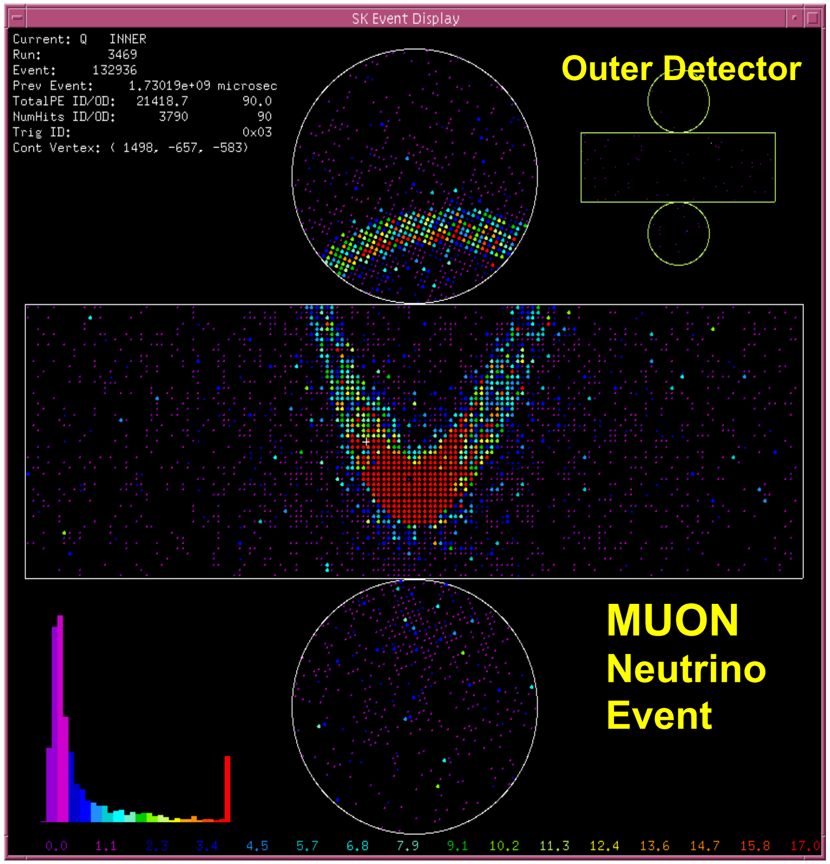
Electrons scatter in water and produce fuzzy Cherenkov rings;
Muons travel in straight lines and produce sharp rings



```
Current: Q   INNER
Run:          3456
Event:        7975
Prev Event:      0 microsec
TotalPE ID/OD:  30693.3        58.1
NumHits ID/OD:     7243          84
Trig ID:                       0x02
Cont Vertex: (   22, -122, -713)
```

**Inner Detector**

**Electron Neutrino Event**



```
Current: Q   INNER
Run:          3469
Event:      132936
Prev Event:     1.73019e+09 microsec
TotalPE ID/OD:  21418.7        90.0
NumHits ID/OD:     3790          90
Trig ID:                       0x03
Cont Vertex: ( 1498, -657, -583)
```

**Outer Detector**

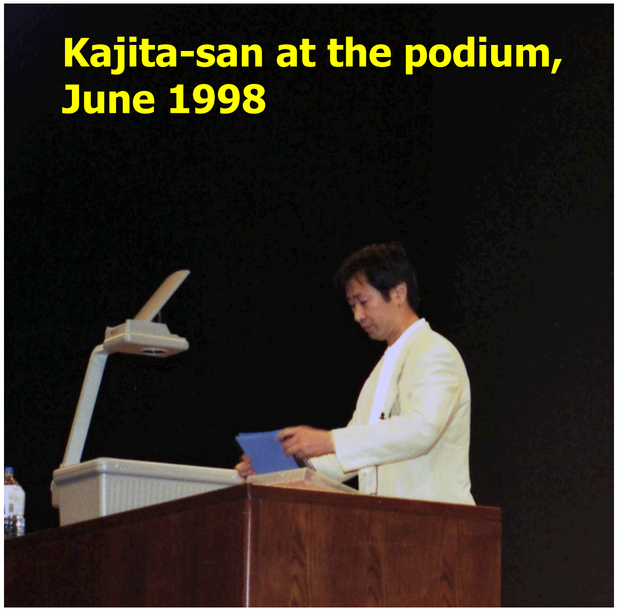
**MUON Neutrino Event**

# UW participation

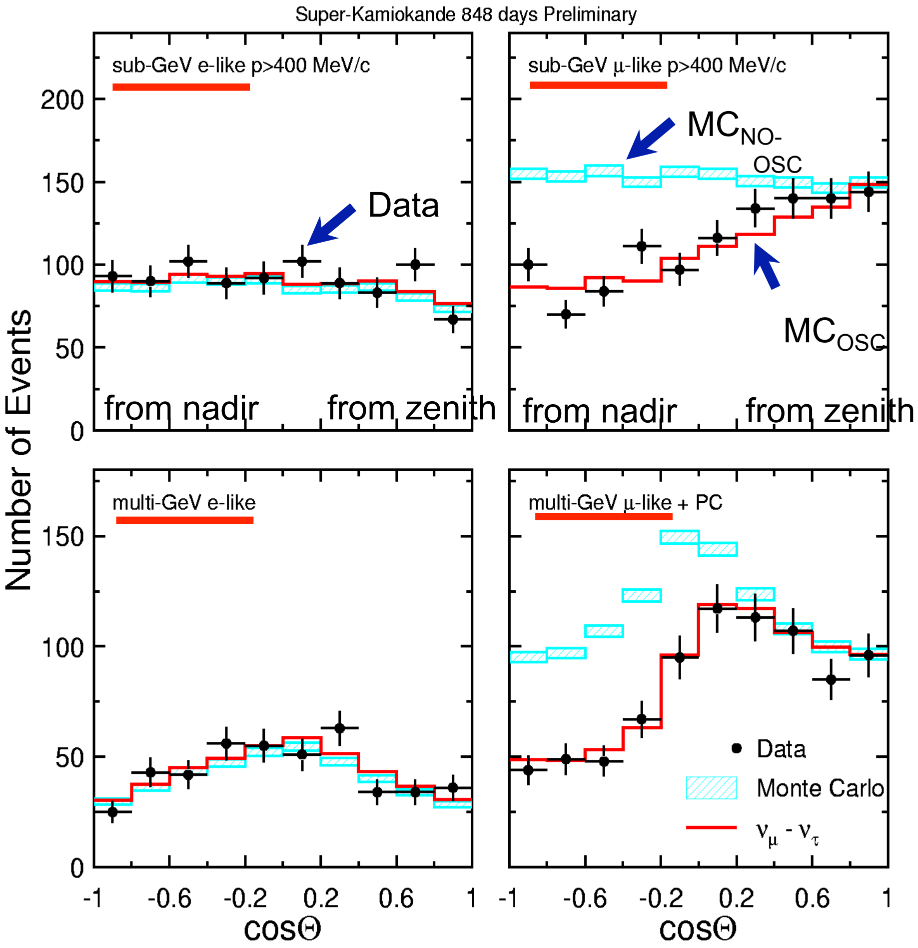
- 1994: Ken Young and J. Wilkes join Super-K collaboration (200 people in USA and Japan), with our 3 grad students
- 1996: first operation of Super-K detector – runs continuously (up and collecting data about 90% of the time) thereafter
- UW group joins “atmospheric neutrino analysis group”
  - Separate, competing groups on US and Japanese sides (blind until done)
  - Compare results only when done: nice check for errors or biases
- Focus: “atmospheric neutrino puzzle”: should be 2x as many muon as electron neutrinos, but we see about equal numbers overall
  - What don’t we understand about weak force / radioactive decay?
- By early 1998 we have a clear indication that
  - Downward going neutrinos (traveled ~15 km from production) have correct proportion of muon neutrino flavors
  - Upward going neutrinos (traveled 13,000 km through the Earth after production) have a deficit of muon-flavored
  - Only explanation that experimental conditions allow: neutrinos change flavor given sufficient time: flavor oscillations → neutrinos must have mass > 0
- Both US and Japan working groups agree within estimated uncertainties

# Neutrino 1998 conference

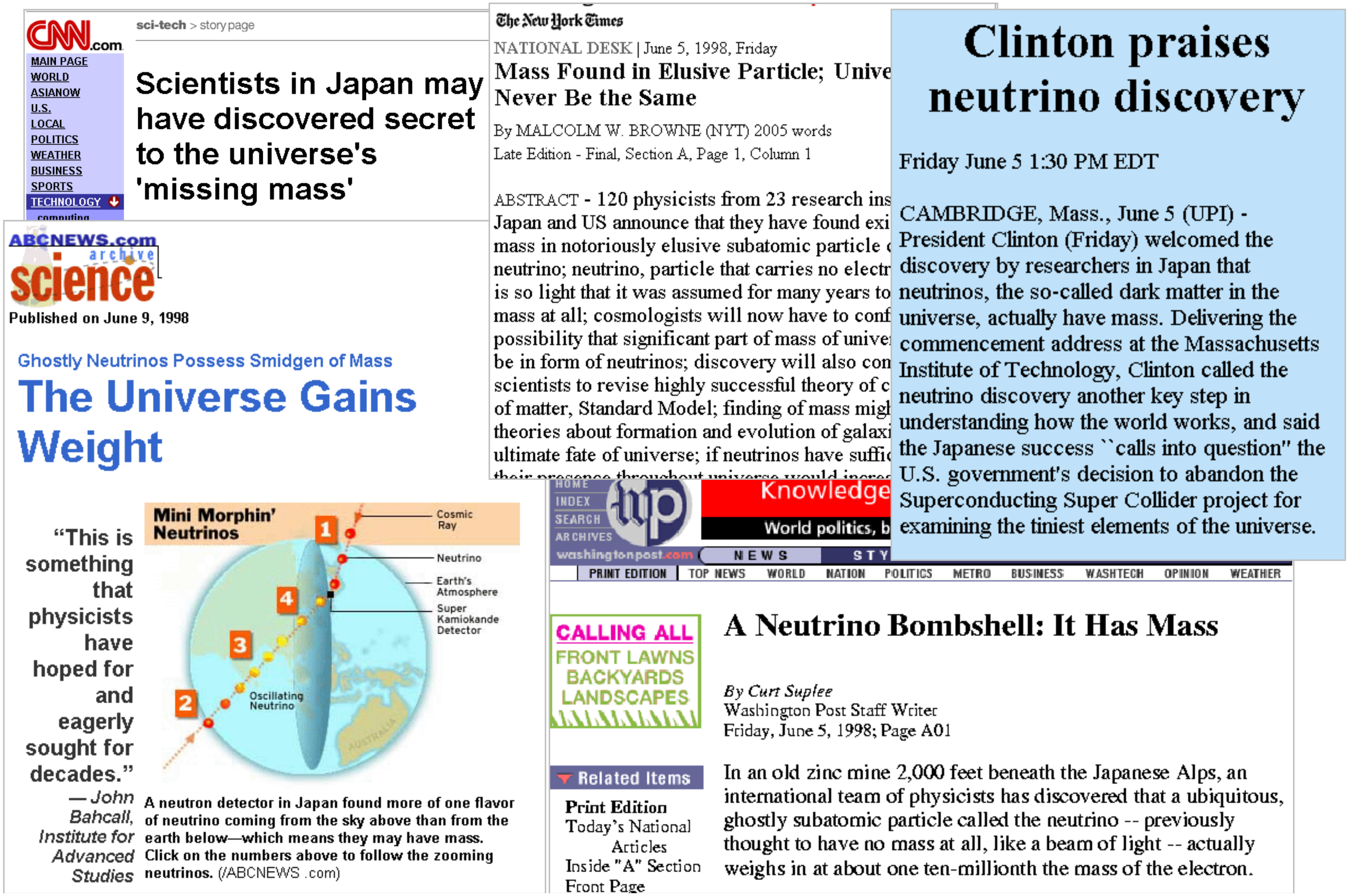
- Ready to present atm-nu results before a critical audience of experts
- Takaaki Kajita (leader of Japanese atm analysis subgroup) is chosen to make the presentation (everyone helps)



**Kajita-san at the podium, June 1998**



# June 5, 1998: Press clippings…



**Scientists in Japan may have discovered secret to the universe's 'missing mass'**

The New York Times

NATIONAL DESK | June 5, 1998, Friday

**Mass Found in Elusive Particle; Unive**
**Never Be the Same**

By MALCOLM W. BROWNE (NYT) 2005 words
Late Edition - Final, Section A, Page 1, Column 1

ABSTRACT - 120 physicists from 23 research ins
Japan and US announce that they have found exi
mass in notoriously elusive subatomic particle c
neutrino; neutrino, particle that carries no electr
is so light that it was assumed for many years to
mass at all; cosmologists will now have to conf
possibility that significant part of mass of unive
be in form of neutrinos; discovery will also con
scientists to revise highly successful theory of c
of matter, Standard Model; finding of mass migh
theories about formation and evolution of galaxi
ultimate fate of universe; if neutrinos have suffic

**Clinton praises neutrino discovery**

Friday June 5 1:30 PM EDT

CAMBRIDGE, Mass., June 5 (UPI) - President Clinton (Friday) welcomed the discovery by researchers in Japan that neutrinos, the so-called dark matter in the universe, actually have mass. Delivering the commencement address at the Massachusetts Institute of Technology, Clinton called the neutrino discovery another key step in understanding how the world works, and said the Japanese success ``calls into question'' the U.S. government's decision to abandon the Superconducting Super Collider project for examining the tiniest elements of the universe.

Published on June 9, 1998

Ghostly Neutrinos Possess Smidgen of Mass

**The Universe Gains Weight**

"This is something that physicists have hoped for and eagerly sought for decades."
— *John Bahcall, Institute for Advanced Studies*

A neutron detector in Japan found more of one flavor of neutrino coming from the sky above than from the earth below—which means they may have mass. Click on the numbers above to follow the zooming neutrinos. (/ABCNEWS .com)

**A Neutrino Bombshell: It Has Mass**

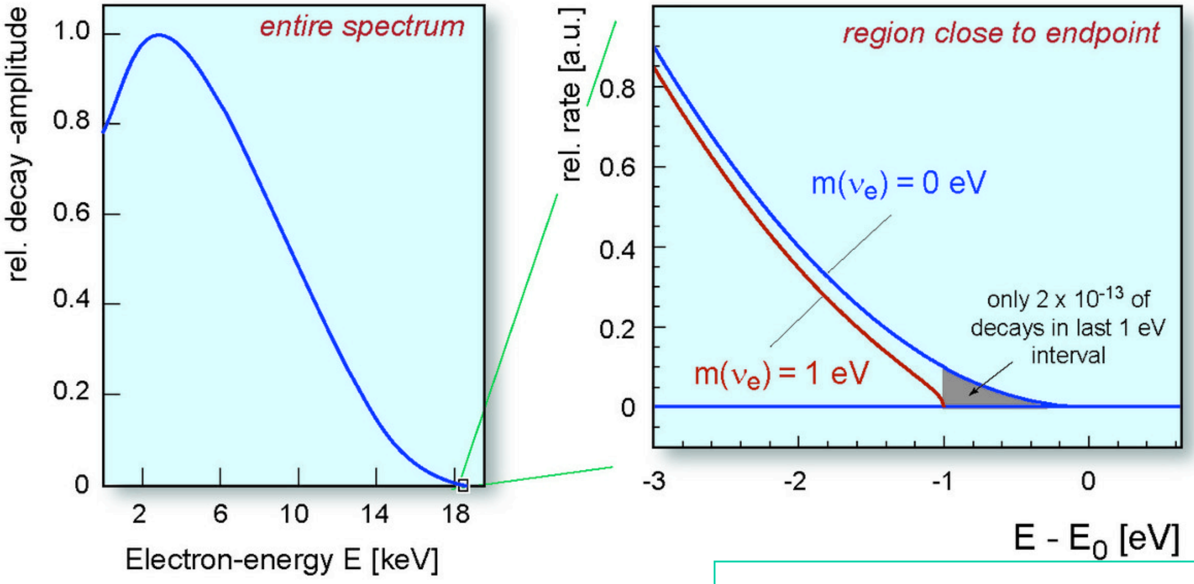
*By Curt Suplee*
Washington Post Staff Writer
Friday, June 5, 1998; Page A01

In an old zinc mine 2,000 feet beneath the Japanese Alps, an international team of physicists has discovered that a ubiquitous, ghostly subatomic particle called the neutrino -- previously thought to have no mass at all, like a beam of light -- actually weighs in at about one ten-millionth the mass of the electron.

# $\beta$ spectrum endpoint → neutrino mass

- Direct measurement of electron neutrino mass by decay kinematics
- Endpoint observation is very difficult!

  Only one decay in $10^{13}$ is near the endpoint



Spectrometer en route to lab

KATRIN experiment to measure endpoint (UW participants)