Reactor Neutrinos I: Physics

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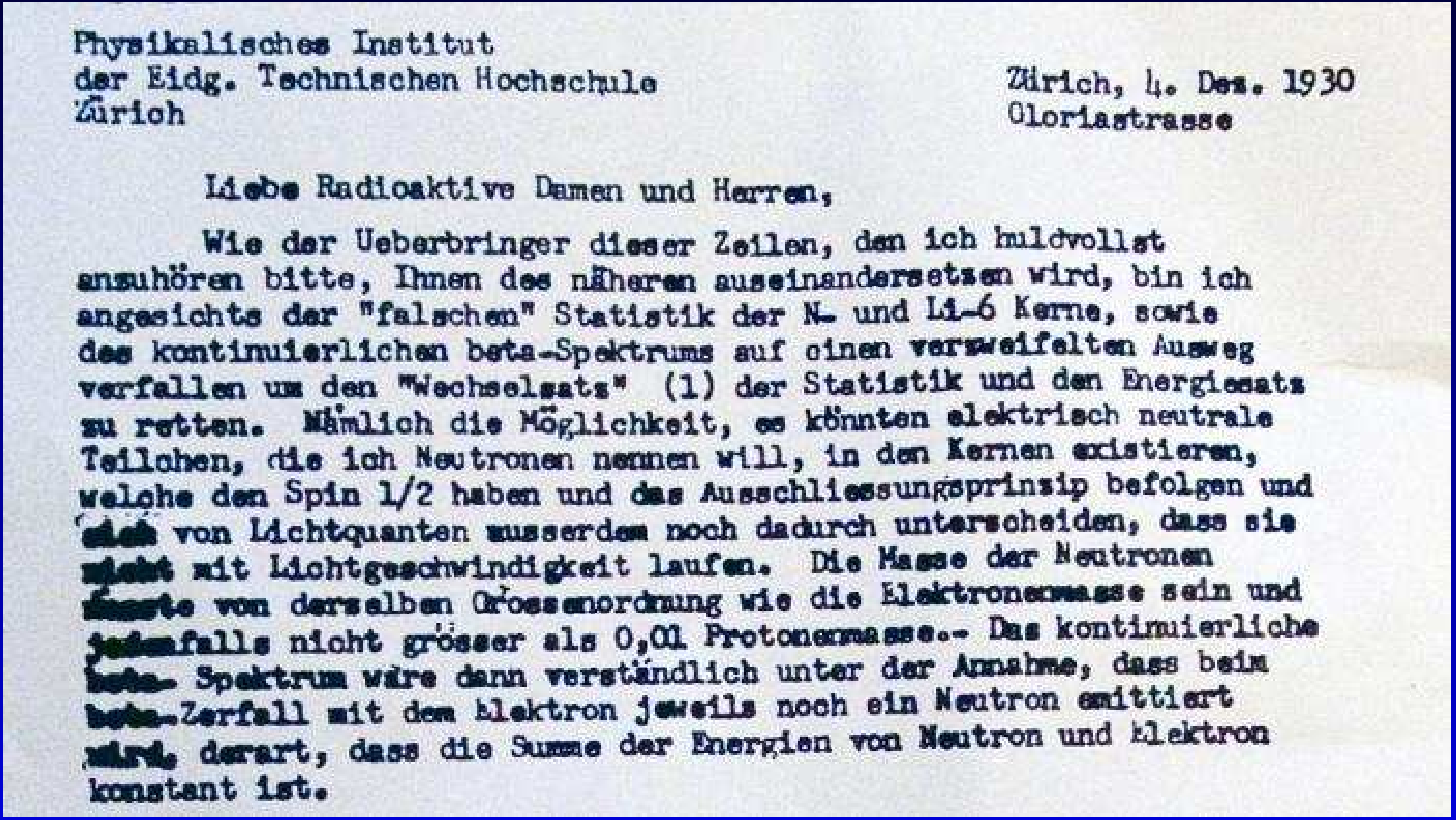
Enter – the neutrino

The neutrino was first proposed by Wolfgang Pauli



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

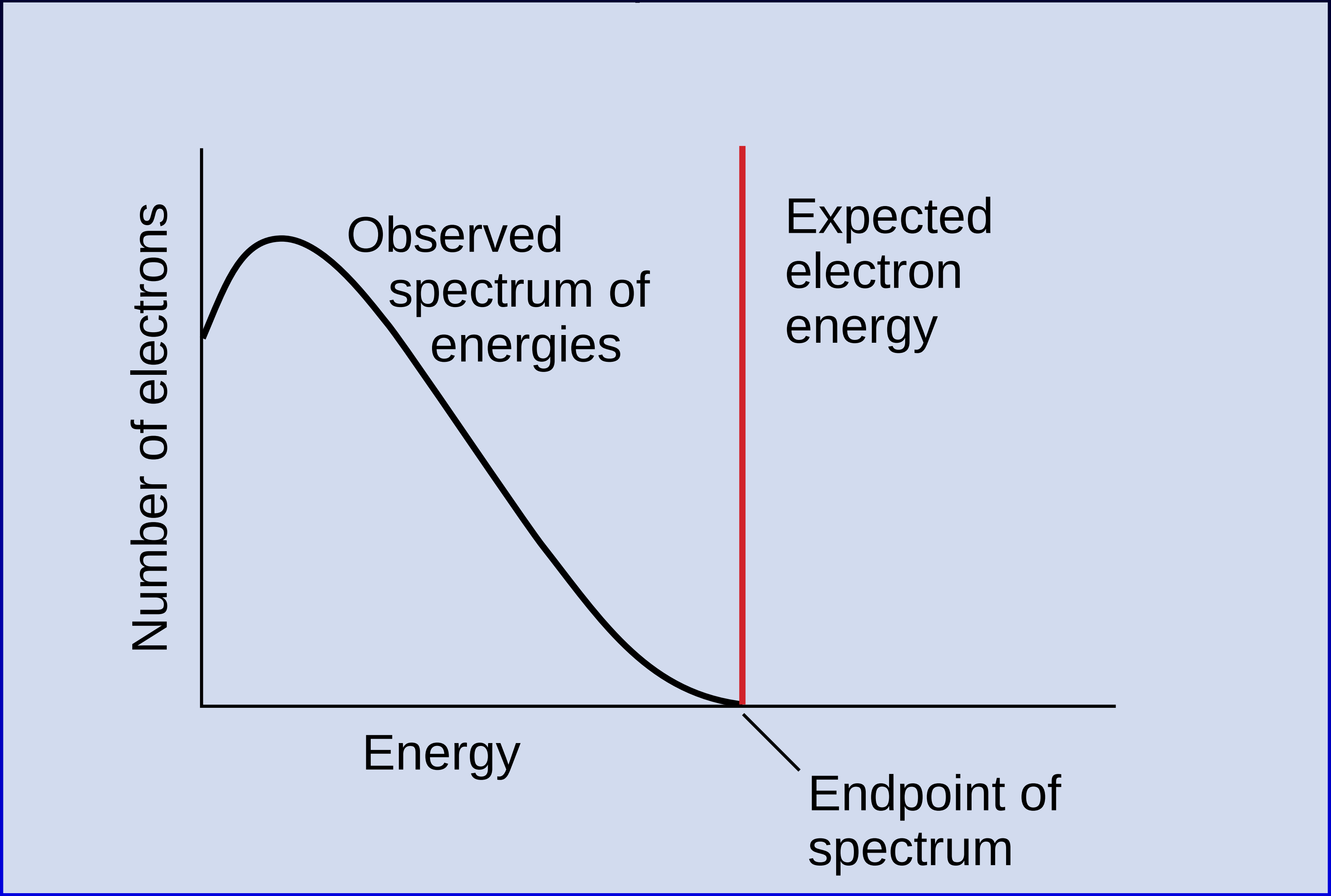
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

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

He postulates a neutral, very light, spin 1/2 particle inside the nucleus.

What was the problem?



Beta decay 101

Fermi would take this idea and develop a first theory of beta decay (1934):

$$n \to p + e^- + \nu$$

or in a nuclear bound state

$$(Z, A) \to (Z+1, A) + e^- + \nu$$

Fermi's Golden Rule (invented for this problem) reads as, with **O** being the operator for weak interactions

$$\frac{dP}{dt} \propto \underbrace{|\langle \psi_f | \mathbf{O} | \psi_i \rangle|^2}_{\text{matrix element } \mathcal{H}_{fi}} \quad \underbrace{\rho(E)}_{\text{phase space density}} \quad dE$$

Beta decay 101 – cont'd

$$d\Gamma = \int \frac{\mathbf{p}_e}{(2\pi)^3} \frac{\mathbf{p}_\nu}{(2\pi)^3} |\mathcal{H}_{fi}|^2 2\pi \delta(E_0 - E_e - E_\nu)$$

assuming $|\mathcal{H}_{fi}|^2$ is independent of momentum transfer this becomes for $m_\nu = 0$ and $M_N \to \infty$

$$d\Gamma = |\mathcal{H}_{fi}|^2 p_e E_e (E_0 - E_e)^2 dE_e$$

The electron wave function is not a plane wave, but an unbound solution of the hydrogen atom, yielding a correction term

$$|\psi_e(r = 0)|^2 =: F(Z, E_e)$$

so called Fermi function.

Beta decay 101 – cont'd

Cleaning up our notation (and make it compatible with modern literature)

$$|\mathcal{H}_{fi}|^2 = F(Z,E_e)\frac{G_F^2|V_{ud}|^2}{2\pi^3}|\mathcal{M}_{fi}|^2$$

Fermi used the solution to the relativistic, point-like, infinitely heavy hydrogen atom to compute $F(Z,E_e)$. $|\mathcal{M}_{fi}|^2$ incorporates all the nuclear bound state physics and the assumption that it is independent of momentum transfer implies that we approximate the nucleus as a point. Transitions for which this approximation is valid are called "allowed".

Beta decay 101 – cont'd

Now the lifetime is given by

$$\frac{1}{\tau} = \Gamma = \frac{G_F^2 |V_{ud}|^2}{2\pi^3} |\mathcal{M}_{fi}|^2 \underbrace{\int_{m_e}^{E_0} dE_e \, F(Z, E_e) p_e E_e (E_0 - E_e)^2}_{=: f(Z, E_0)}$$

or

$$ft := \log 2 f \tau = \frac{2\pi^3 \log 2}{G_F^2 |V_{ud}|^2} |\mathcal{M}_{fi}|^{-2}$$

The ft-value of more often $\log ft$-value is a measure of the nuclear matrix element.

Inverse beta decay

Now that we can describe

$$n \to p + e^- + \nu$$

what about the inverse beta decay

$$\nu + p \to n + e^+ \,?$$

Bethe and Peirls in 1934 estimate the cross section to be (neutron decay was not yet discovered!)

$$\sigma \simeq \frac{\hbar^3}{m^3 c^4 \tau} (E_\nu / mc^2)^2 \simeq E_\nu^2 \, 10^{-43} \, \mathrm{cm}^2$$

and conclude: “there is no practically possible way of observing the neutrino.”

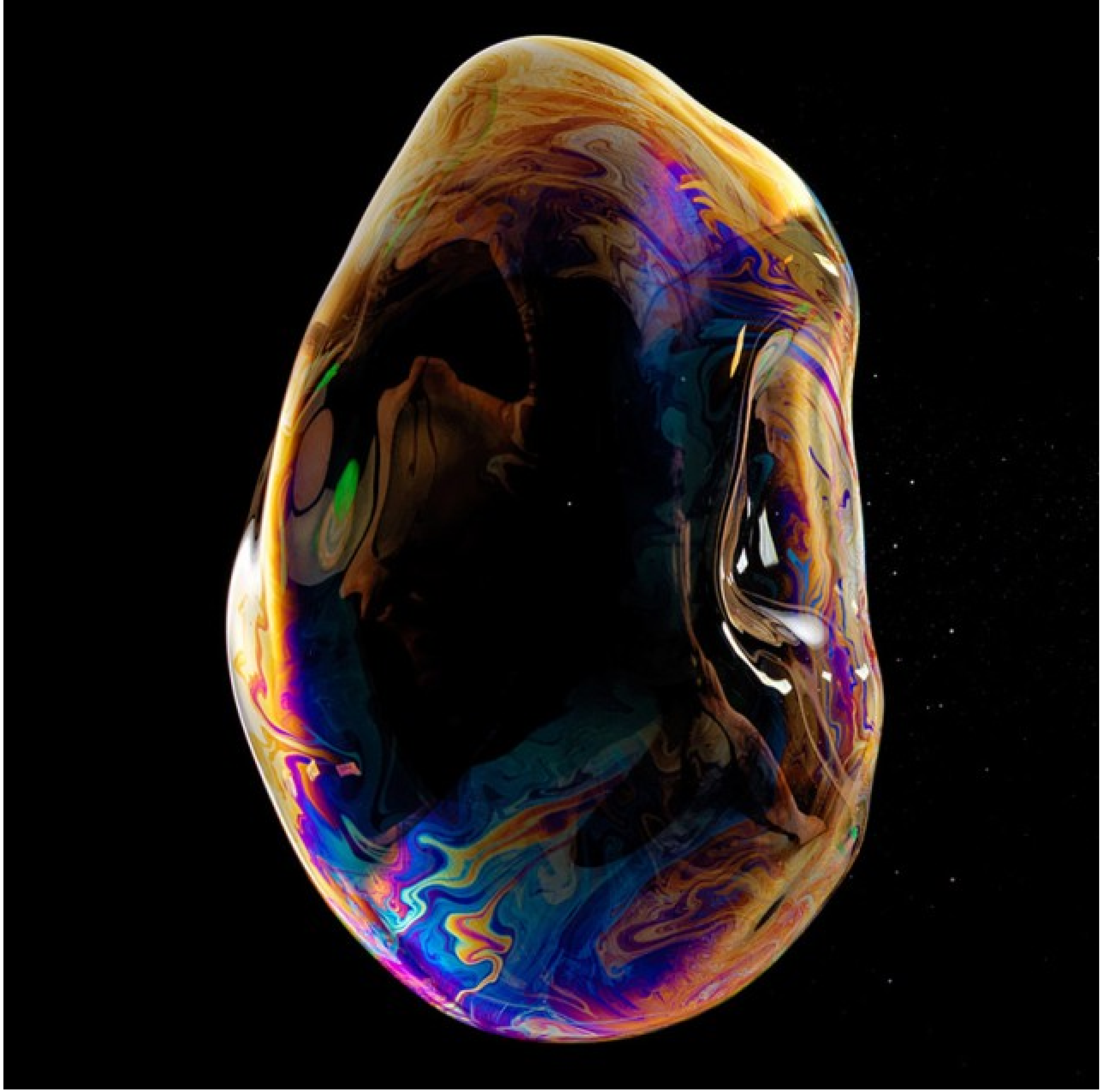
Avogadro's number

Using a cross section of around $10^{-42}\mathrm{cm}^2\ldots$

We can get a factor 10^{24} from Avogadro's number but that still leaves us with 10^{18} neutrinos to see anything.

Where do we get 10^{18} neutrinos?

$\rightarrow$ digression on nuclear fission



Physics of Fission

Lab table of Otto Hahn and Fritz Strassmann
Deutsches Museum, München, Germany

Discovery of Fission

In 1938 Hahn and Strassmann used slow neutrons to irradiate Natural uranium and found that this resulted in the production barium.

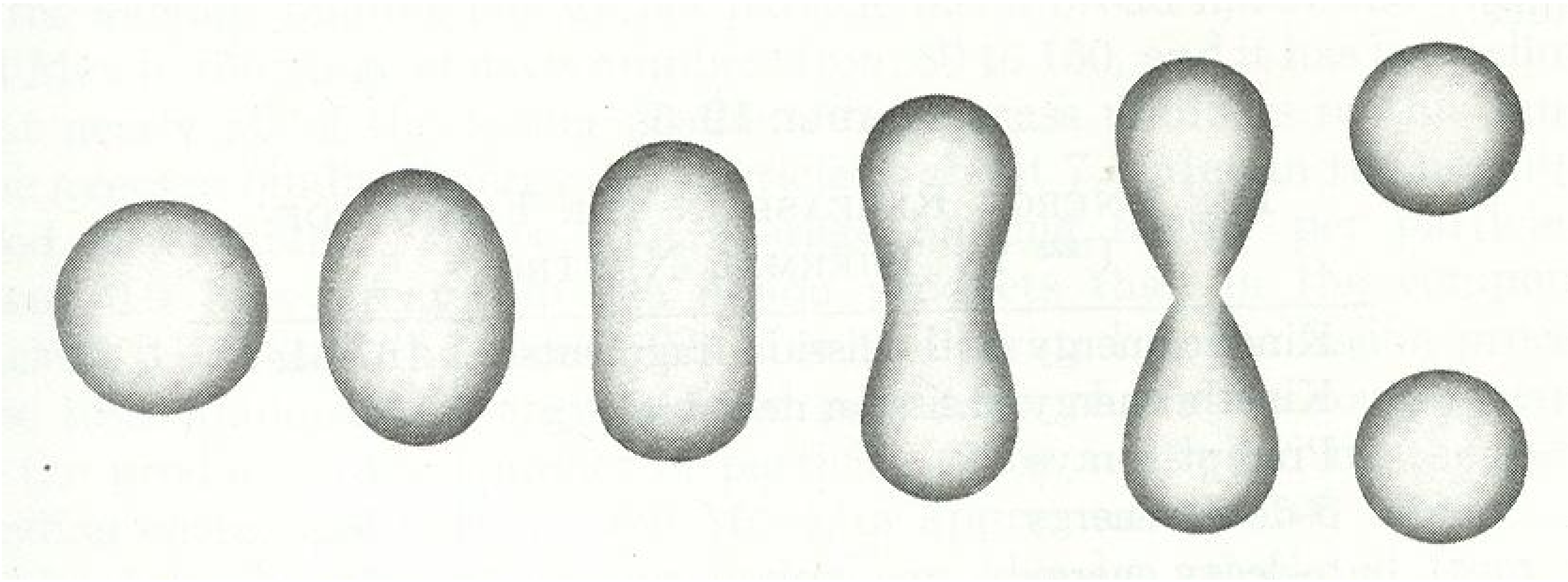
$$\text{uranium (92 protons, 143 neutrons) + neutron}$$
$$\downarrow$$
$$\text{barium (56 protons, \textasciitilde 80 neutrons) + ?}$$

Hahn was a chemist and the chemistry of uranium and barium is sufficiently different that a mistake was basically excluded. Also there was no barium prior to irradation.

What had happened?

Liquid drop

The explanation was provided in 1939 by
Lise Meitner and Otto Frisch



The uranium nucleus can be described as a charged, liquid drop of fixed volume and under certain conditions such a drop can lower its energy by splitting into two smaller drops.

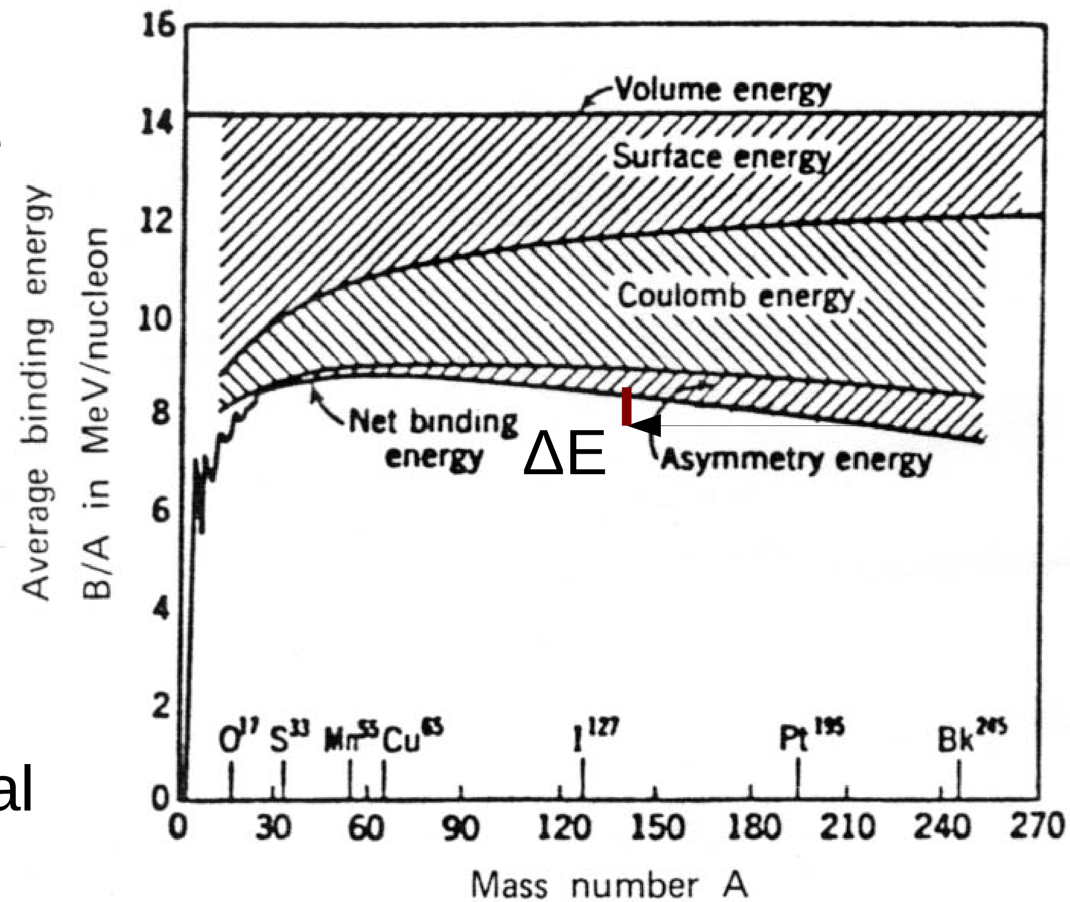
Balance of energy

The energy of a liquid drop has various contributions, some are proportional to the volume, others to the surface etc.

All terms except for the asymmetry energy have an analog in classical mechanics.

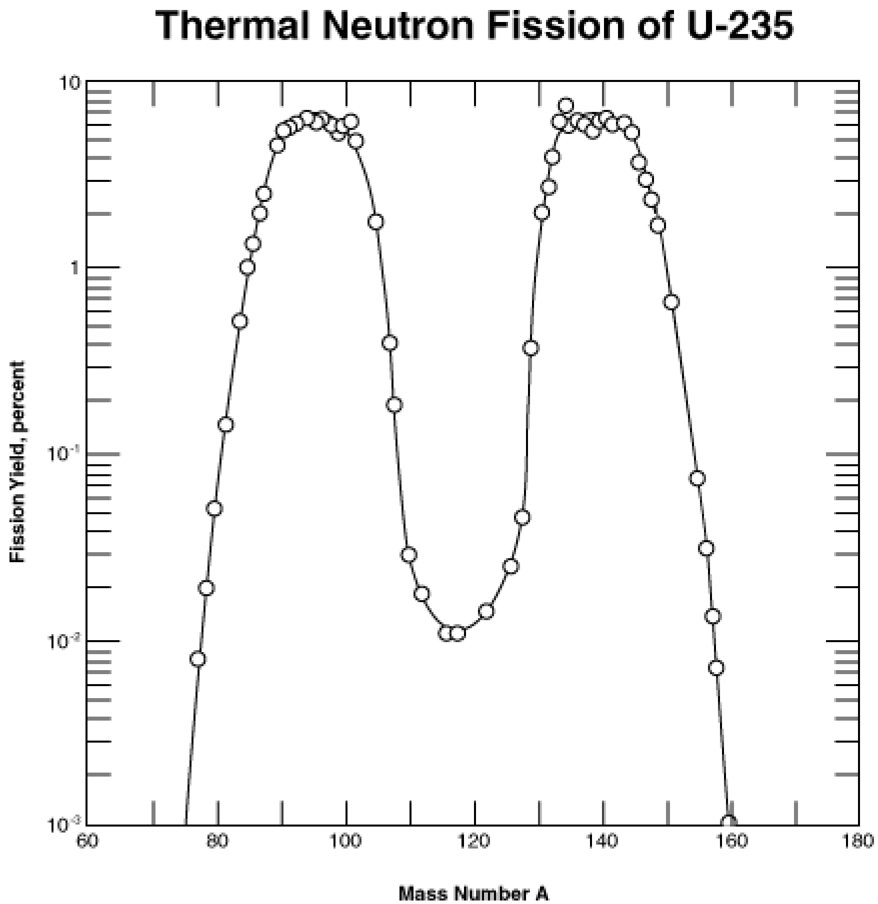
energy release = number of nucleons x ΔE = 200 x 1 MeV = 200 MeV

For comparison chemical reactions release 10eV



Fission yields

Fission does not always produce the same two pieces, barium and krypton, instead it yields a range of fission fragments.



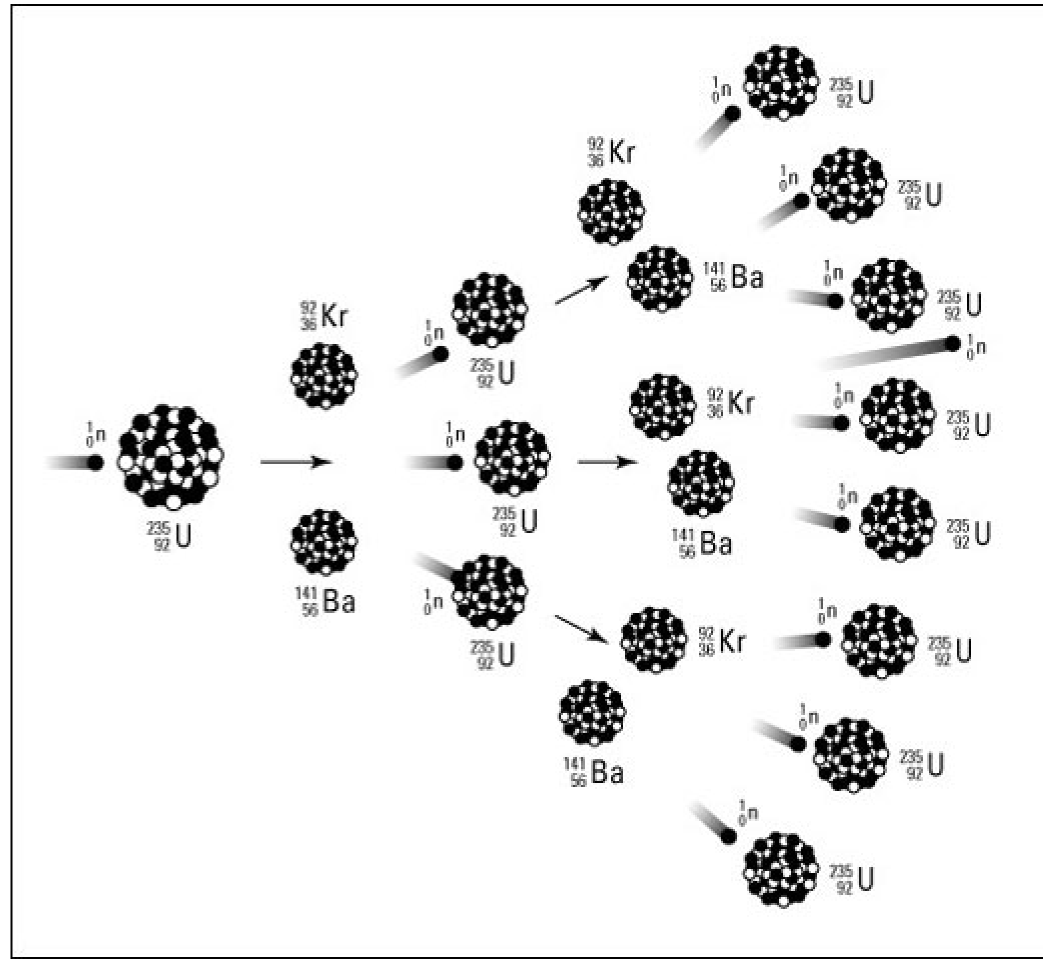
Many of these fission fragments are highly radioactive, like cesium-137 or strontium-90.

Most of them will have decayed away after 1,000-10,000 years.

Chain reaction

Later in 1939 Leo Szillard realized that if neutrons should be among the fission products a chain reaction might be possible – resulting in an exponetial increase in the number of fission with time.

Assuming that there are 2 neutrons per fission, each generation would have twice as many fissions as the previous one.



After 81 generations all uranium in 1kg would be fissioned!

Energy release

The energy released in the complete fission of 1kg of uranium

E=energy per fission x number or uranium atom in 1kg
= 200 MeV x 2.5E23 = 8.2E13 J

For these very large quantities of energy another unit is

1 kiloton TNT equivalent (kt) = 4E12 J

The energy from fissioning 1kg uranium corresponds to 20kt
this is as little as 1g converted to energy.

Fissile isotopes

We call an isotope fissile if it can sustain a nuclear chain reaction.

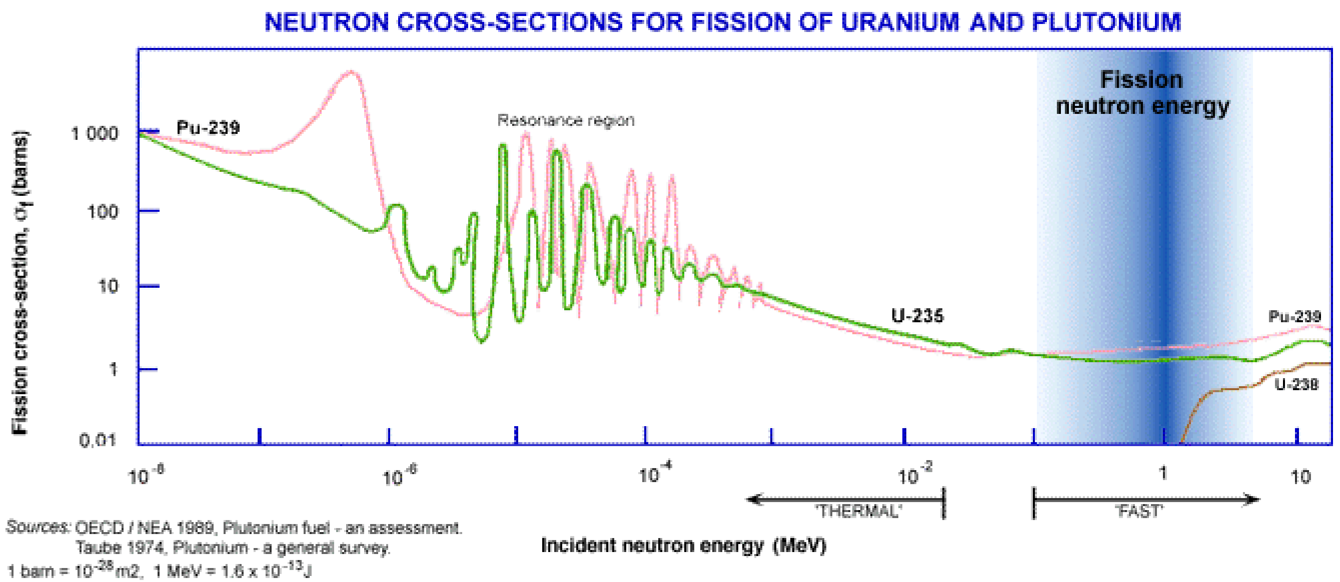
The most important fissile isotopes are

Isotope	235U	233U	239Pu	241Pu
Half-life	700 Million years	160,000 years	24,000 years	14 years
Natural abundance	0.72%	0%	0%	0%

Only 235U occurs naturally, all other fissile isotopes are man-made.

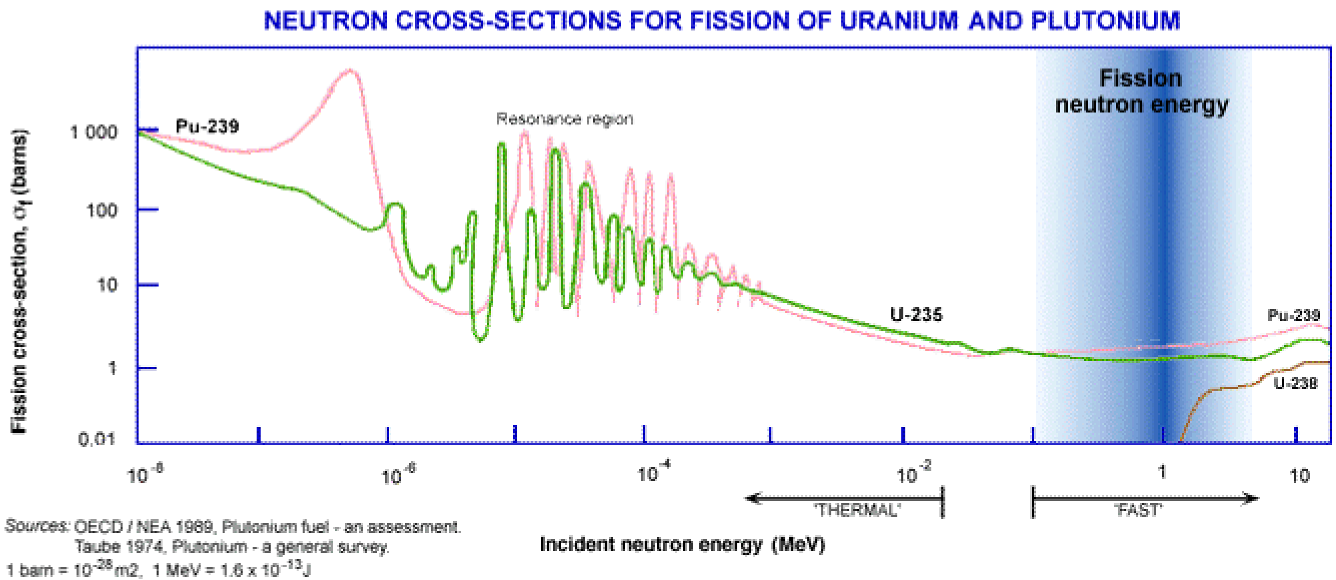
An isotope is called fissionable if it can be fissioned by a neutron of any energy. Many heavy isotopes are fissile, in particular, the naturally occuring 238U with an abundance of 99.28%.

Degrees of fissionable



To be fissile, the neutrons released in fission have to be able to cause another fission – which is true for 235U and 239Pu but not for 238U.

Two types of fission

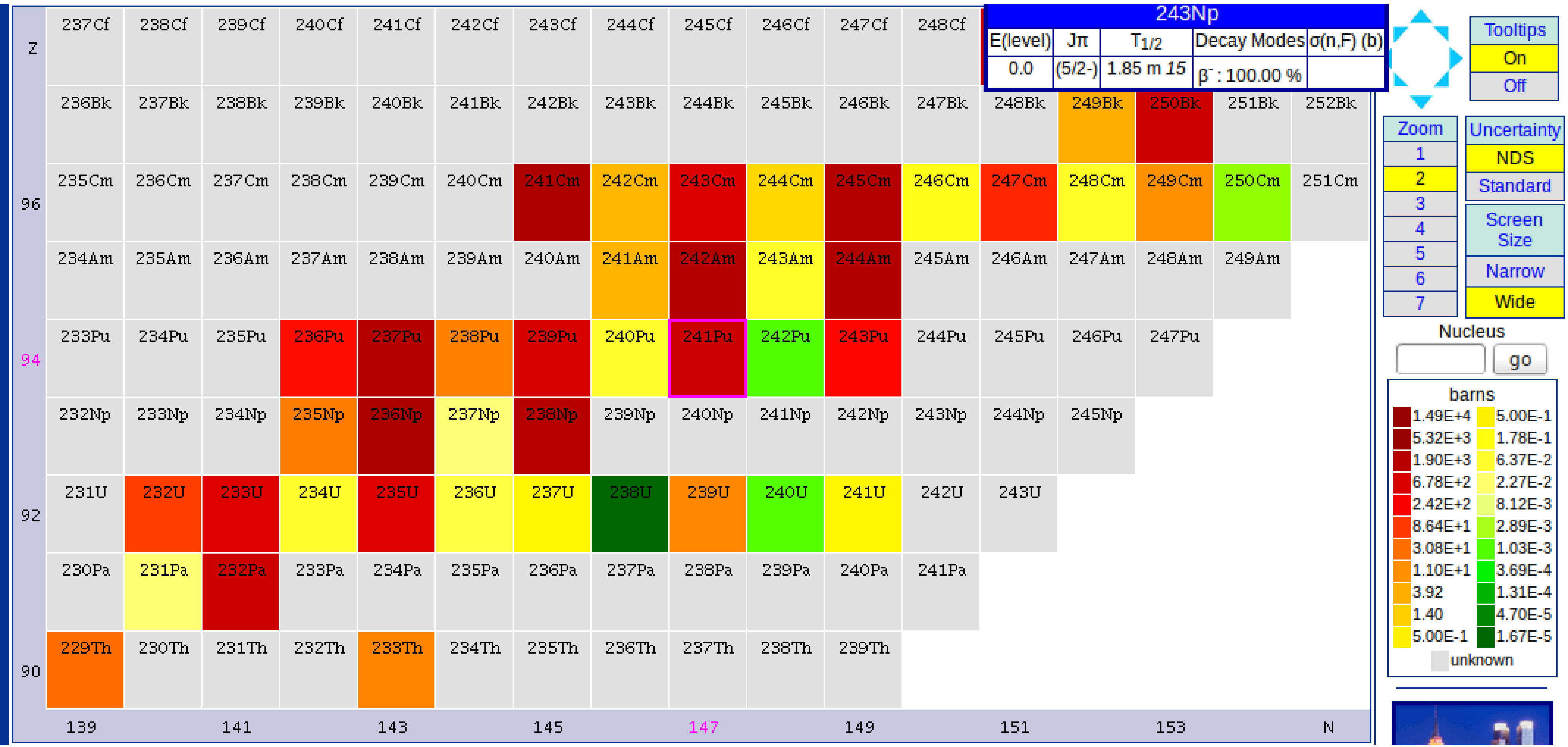


A chain reaction can be sustained by either

- fast neutrons, which are directly released in fission
- thermal neutrons, which are fission neutrons which have been slowed down by interactions in the medium or moderated

Since the fission cross section is 100-1000 times larger for thermal neutrons, it should be easier to maintain a chain reaction that way.

Thermal fission x-sections

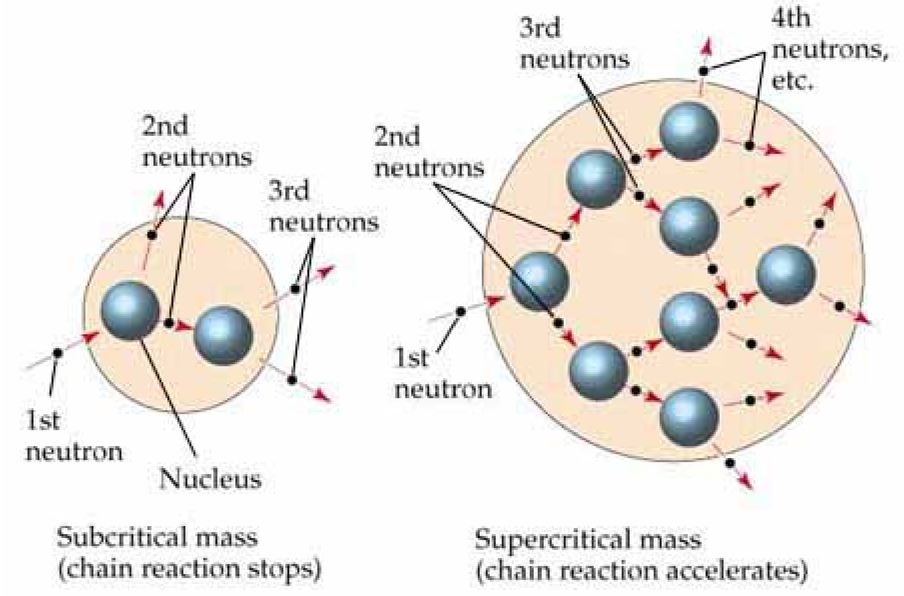


Odd-mass nuclei have larger thermal fission cross-sections

Fast & furious

Fast fission is indeed fast and one generation in a fast chain reactions takes about 10ns or 100 generations take 1μs – this is the key to nuclear explosions.

Not every arbitrary small quantity of fissile material will explode, there is minium amount called a critical mass. If you have one critical mass each fission will cause exactly one new fission and the second neutron is lost through the surface of your material before it can cause a fission.



Critical mass

The critical mass is determined by a balance of neutron production through fission and neutron losses and thus sensitively depends on

- surface to volume ratio
- density
- the purity of the material
- presence of a neutron reflector
- fission cross section

The following table lists critical mass at the natural density of the pure isotope, for a bare sphere, i.e. without a neutron reflector

Isotope	235U	233U	239Pu	241Pu
Critical mass [kg]	52	15	10	12
Diameter [cm]	17	11	10	10.5

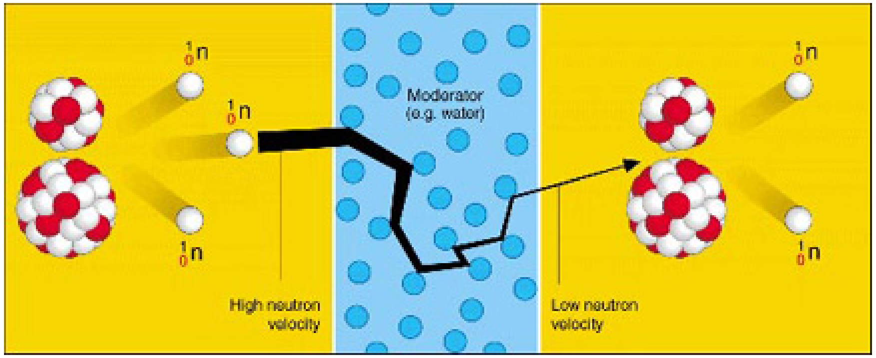
Nuclear explosives can be made with less than 1/2 of that quantity!

Moderation

For a thermal chain reaction the trick is to slow down fission neutrons by roughly a factor 1000 without losing them – this is achieved using a moderator.

The key to moderate neutrons is elastic scattering of neutrons, the closer the mass of the atoms in the moderator is to a neutron the more effective the moderator and the smaller is the risk to loose the neutron by absorption.

Good moderators are for example



- water
- heavy water
- graphite

They all can be made very pure so that they do not absorb neutrons and they are available in large quantities.

Moderating ratio

The logarithmic energy loss

$$\xi = \ln \frac{E_0}{E} = 1 + \frac{(A-1)^2}{2A} \ln\left(\frac{A-1}{A+1}\right)$$

The moderating ratio measures the ratio of energy loss length to neutron absorption length

Material	H2O	D2O	Helium	Beryllium	Boron	Carbon
ξ	0.927	0.510	0.427	0.207	0.171	0.158
Collisions to thermal	19	35	42	86	105	114
Moderating ratio	62	4830	51	126	1e-3	216

D2O and carbon (graphite) allow chain reactions using natural uranium

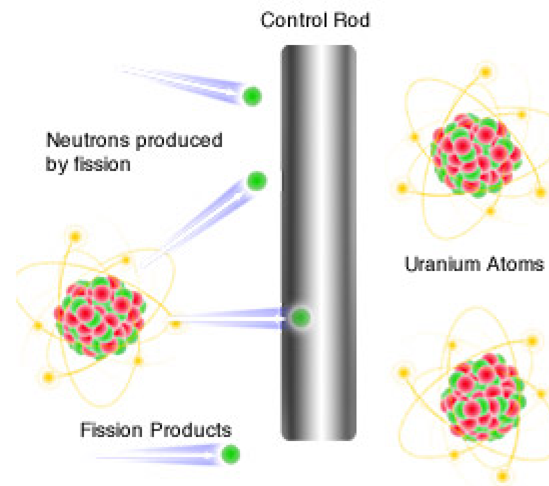
Controlled chain reaction

In a chain reaction sustained by thermal neutrons there are two features which allow to maintain a steady state reaction and which prevent explosions

no moderator = no fission	since moderatored neutrons are so much more efficient in causing fissions, a loss of moderator will end the chain reaction.
delayed fission neutrons	A small number ~1% of fission neutrons are released with a delay of ~1s. The trick is to keep the number of fissions cause by prompt neutrons just below critical and to use the delayed ones to reach steady state

More control

Beyond the inherent safety offered by moderation and delayed neutrons, in practice, one also adds movable neutron absorbers –
control rods

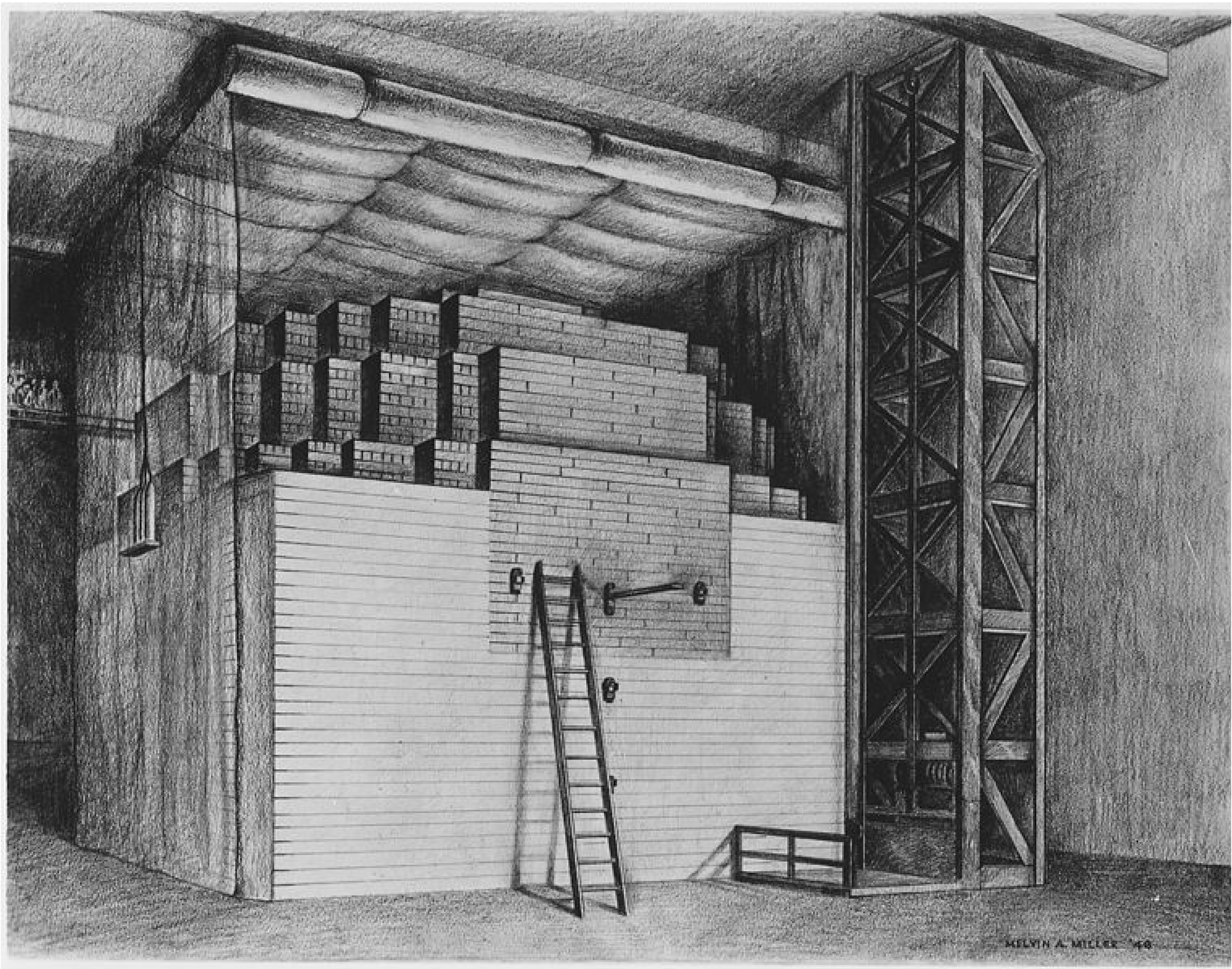


Control rods are made of materials with a very high absorption for thermal neutrons – cadmium and boron are common.

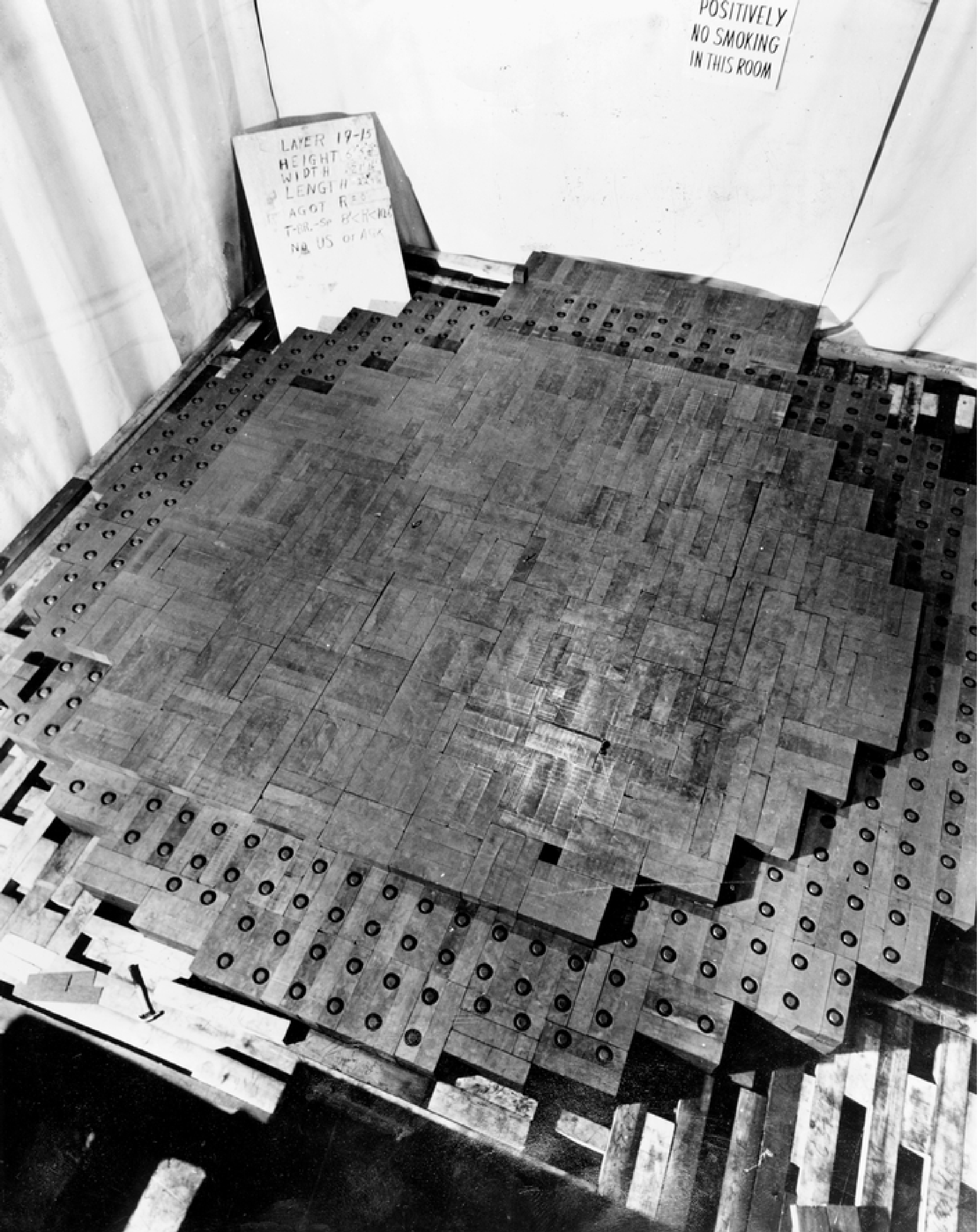
SCRAM – safety control rod axe man

Chicago Pile 1

Went critical at 3:25pm on Dec 2, 1942 on the campus of the University of Chicago and was shut down 28 min later.



The Italian Navigator was Enrico Fermi



Compton:

The Italian navigator has landed in the New World

Conant:

How were the natives?

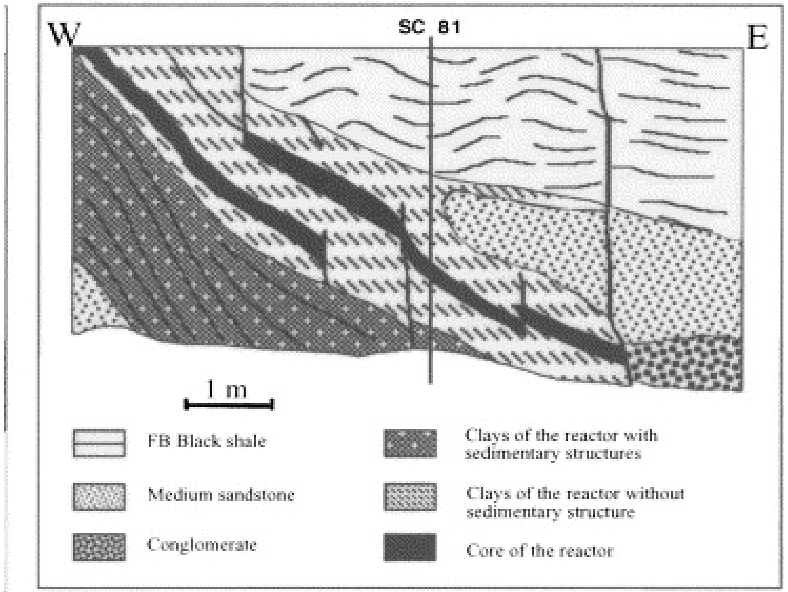
Compton:

Very friendly.

Was Fermi the first one?

About 2 billion years ago there was a natural nuclear reactor at Oklo (Gabon).

This was discovered in 1970s since uranium ore from there showed a reduced abundance of 235U – it was fissioned away.

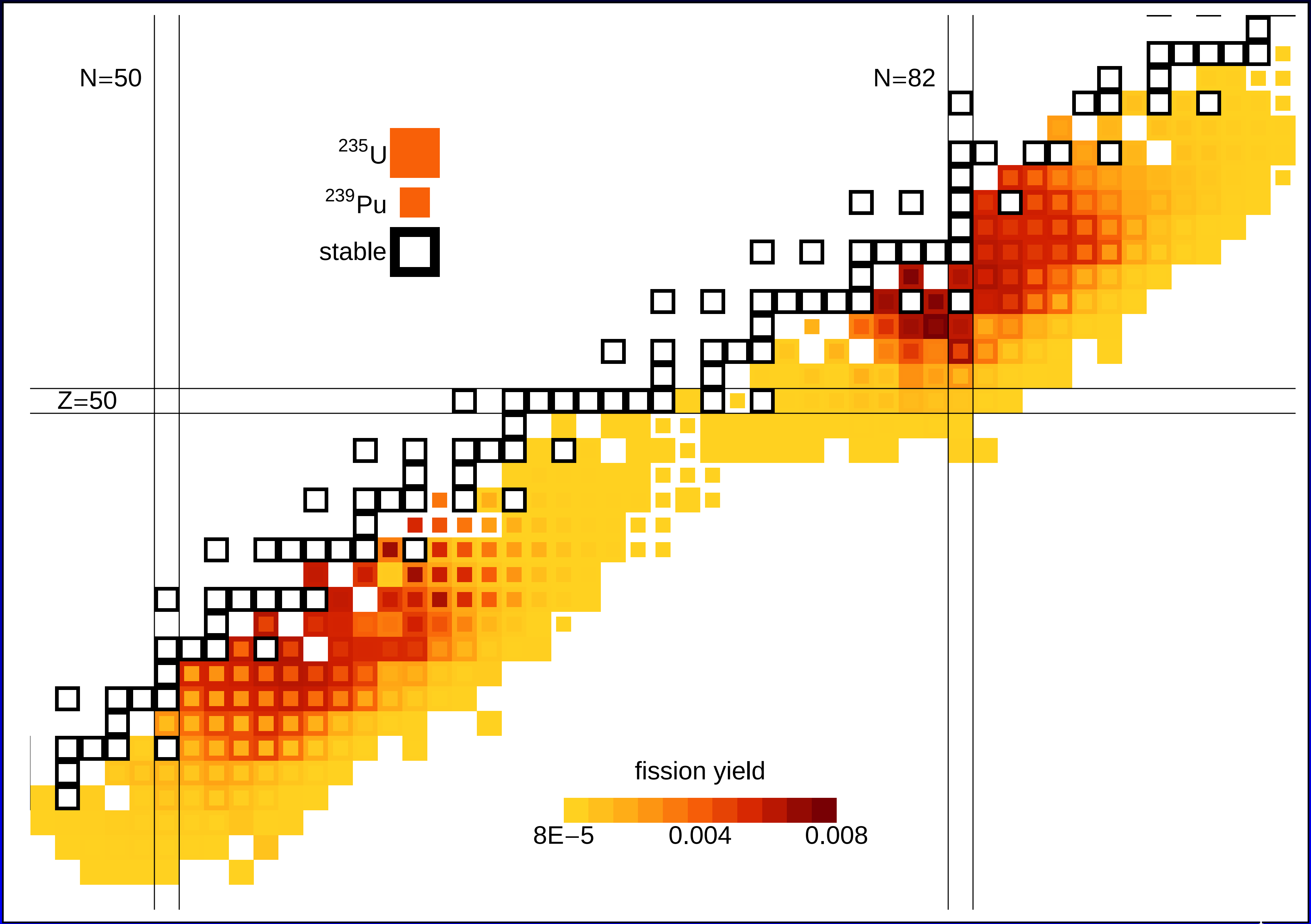


Further reading

http://oklo.curtin.edu.au/

Highly recommended lasts about 15 minutes!
http://www.youtube.com/watch?v=1E2GftIaSas

Neutrinos from fission



How many?

$$^{235}U + n \to X_1 + X_2 + 2n$$

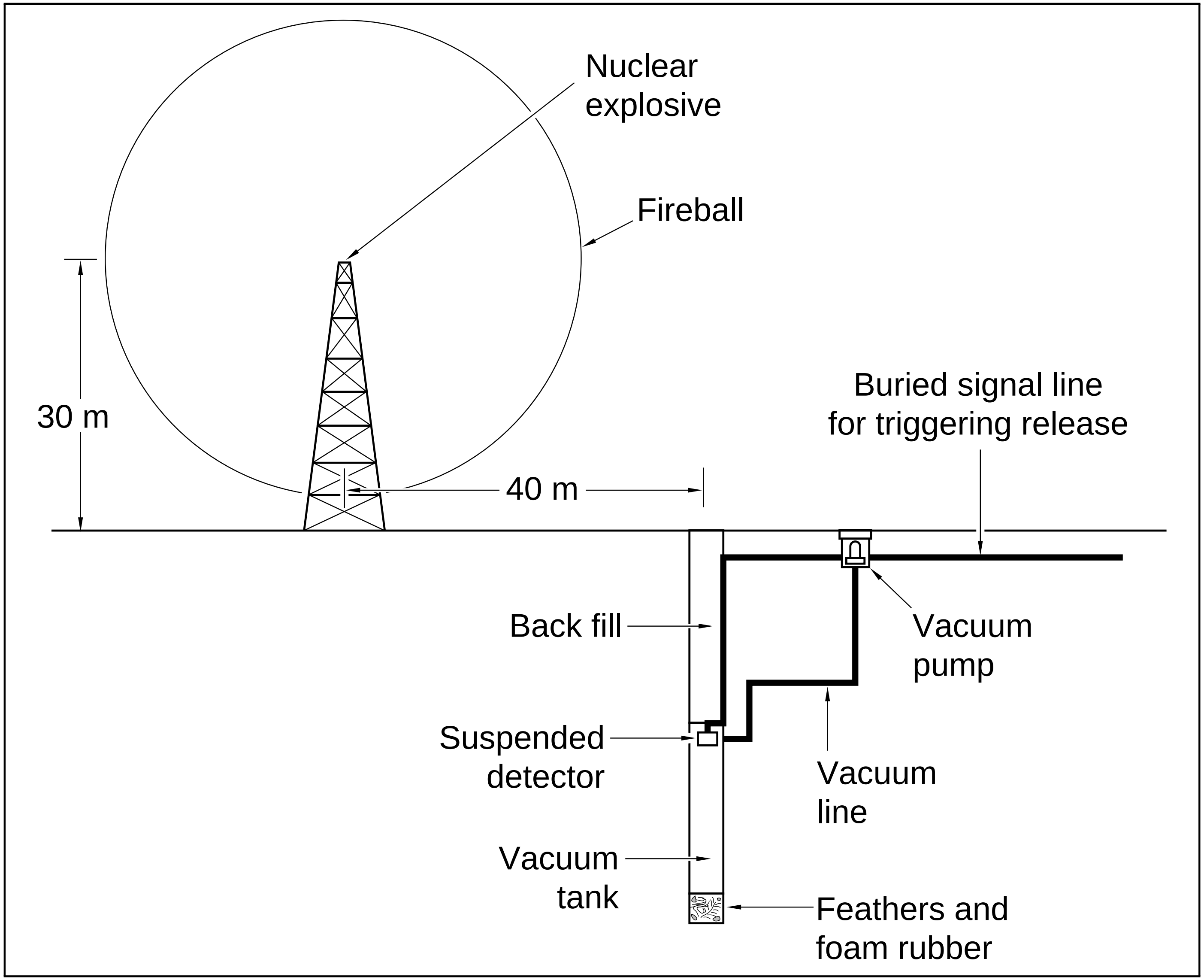
with average masses of X_1 of about A=94 and X_2 of about A=140. X_1 and X_2 have together 142 neutrons.

The stable nuclei with A=94 and A=140 are $^{94}_{40}Zr$ and $^{140}_{58}Ce$, which together have only 136 neutrons.

Thus 6 β-decays will occur, yielding 6 $\bar{\nu}_e$.

Fissioning 1kg of 235U gives 10^{24} neutrinos, or at distance of 50 m about $10^{16}\,\mathrm{cm}^{-2}$.

Ca. 1951



Fred Reines and Glen Cowan

Reines & Cowan's day job was to instrument nuclear weapons tests.

Bethe and Fermi thought this was a good idea and thus, not surprisingly their A-bomb proposal was approved.

What really happened

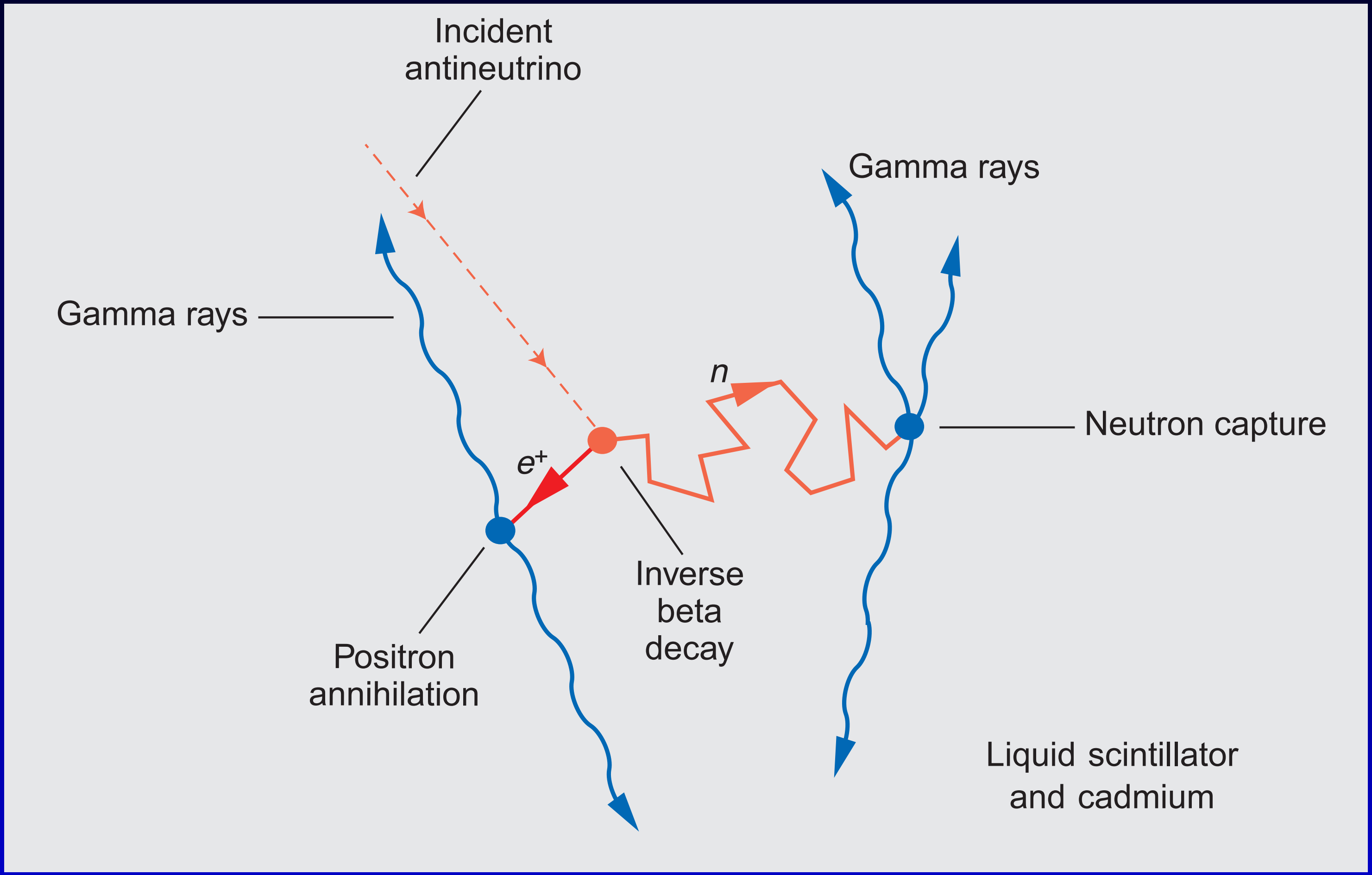
In the fall of 1952 Reines & Cowan revisited the idea of using a reactor:

number of fissions per second = thermal reactor power / energy per fission

$$\frac{300\,\mathrm{MW}}{200\,\mathrm{MeV}} \simeq 10^{19}\,\mathrm{s}^{-1}$$

so 10^5 seconds yields the same fluence, 10^{24} as a $20\,\mathrm{kt}$ explosion.

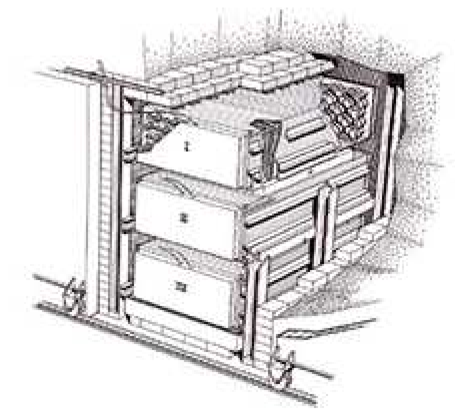
Delayed coincidence

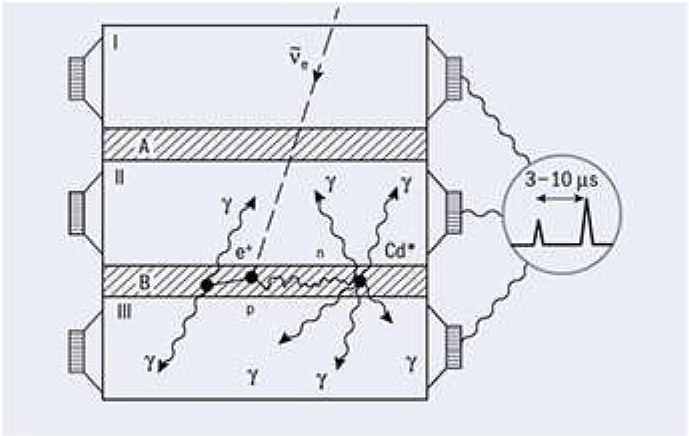


This is the basis for all reactor neutrino experiments since then.

Savannah River

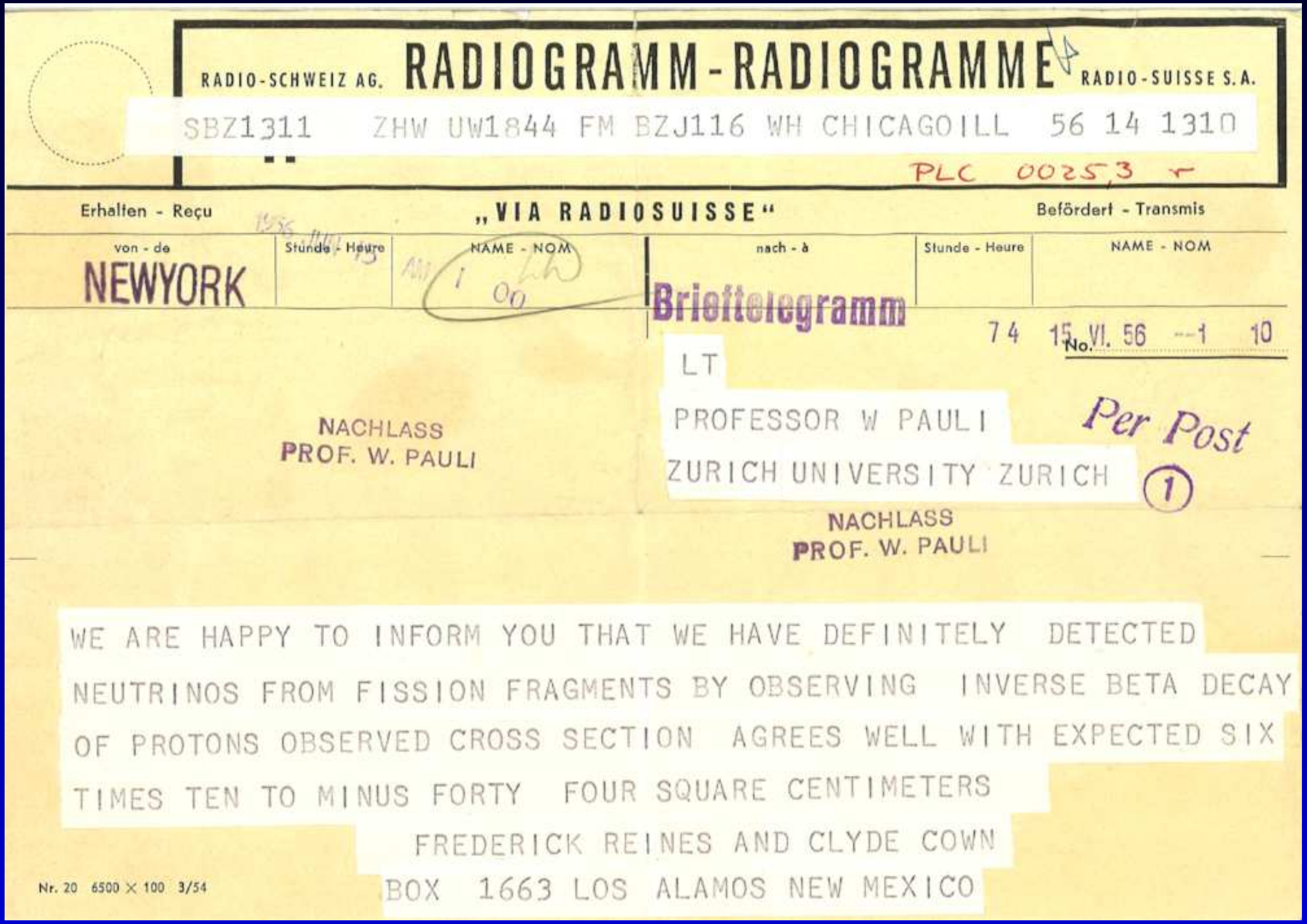
P-reactor became operational in Feb 1954, initially rated for less than 500MW, heavy water cooled, plutonium production reactor.





Note, positron energy is NOT observed.

1956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LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

1

NACHLASS
PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

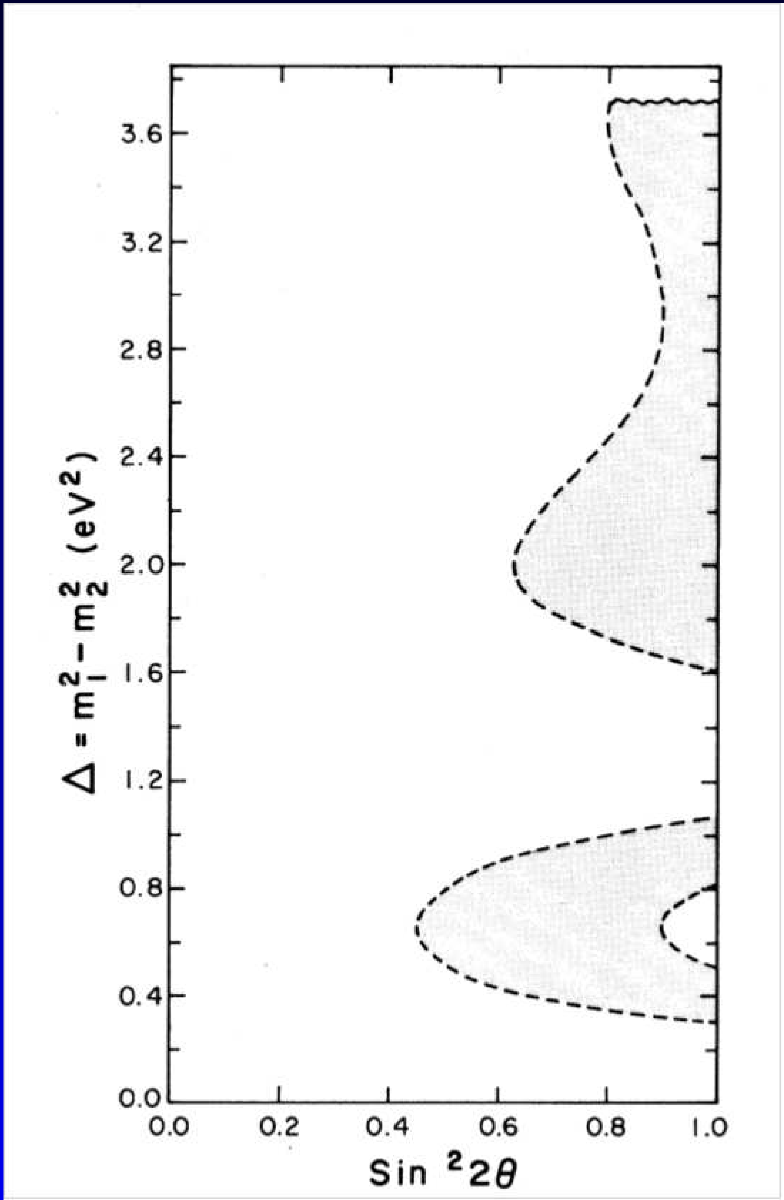
FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 × 100 3/54

They report a cross section (!) of $6 \times 10^{-44}\,\mathrm{cm}^{-2}$.

Reines' D2O experiment



Reines, Sobel, Pasierb in 1970 study the ratio of the rate for

$$\bar{\nu}_e + d \to n + n + e^+$$

$$\bar{\nu}_e + d \to n + p + \bar{\nu}_e$$

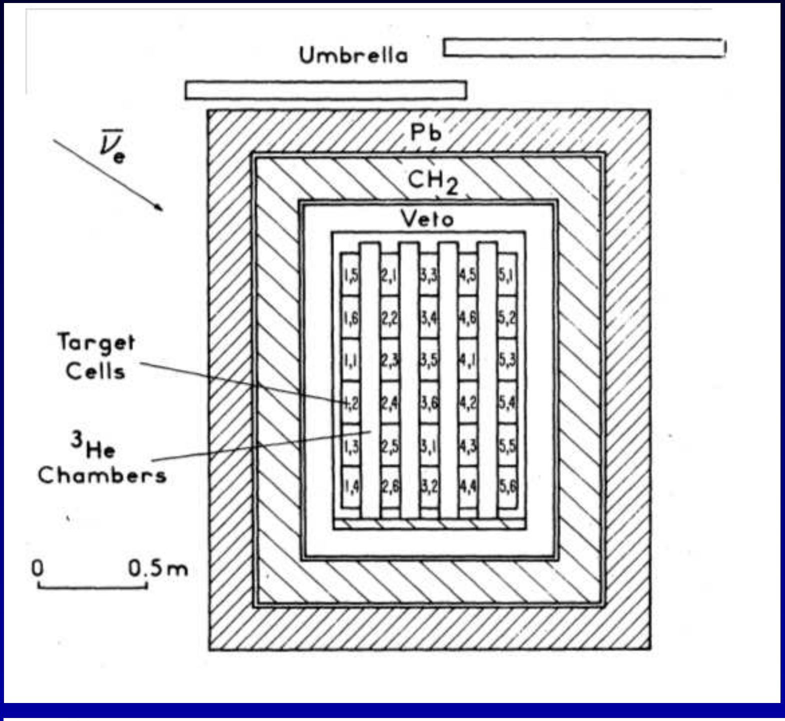
and found indication for oscillation.

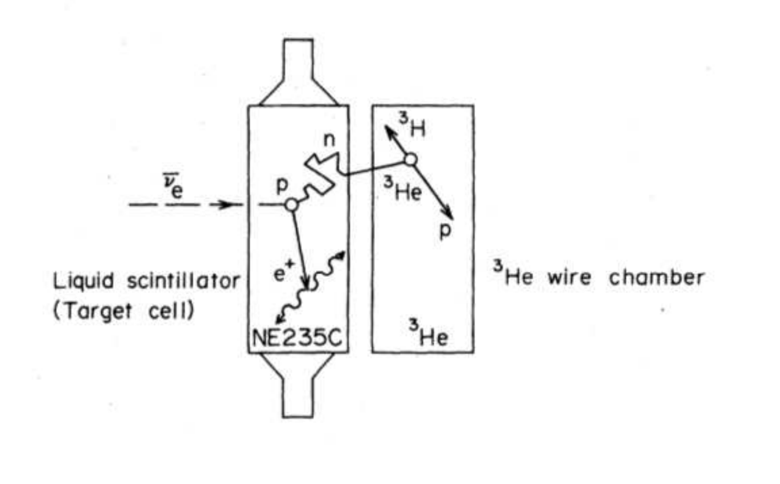
Long list of SBL experiments

a	Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	$R^{\text{exp}}_{a,\text{SH}}$	σ^{exp}_a [%]	σ^{cor}_a [%]	L_a [m]
1	Bugey-4	0.538	0.078	0.328	0.056	0.932	1.4	1.4	15
2	Rovno91	0.606	0.074	0.277	0.043	0.930	2.8		18
3	Rovno88-1I	0.607	0.074	0.277	0.042	0.907	6.4	3.8	18
4	Rovno88-2I	0.603	0.076	0.276	0.045	0.938	6.4		18
5	Rovno88-1S	0.606	0.074	0.277	0.043	0.962	7.3	2.2	18
6	Rovno88-2S	0.557	0.076	0.313	0.054	0.949	7.3	3.8	25
7	Rovno88-2S	0.606	0.074	0.274	0.046	0.928	6.8		18
8	Bugey-3-15	0.538	0.078	0.328	0.056	0.936	4.2		15
9	Bugey-3-40	0.538	0.078	0.328	0.056	0.942	4.3	4.0	40
10	Bugey-3-95	0.538	0.078	0.328	0.056	0.867	15.2		95
11	Gosgen-38	0.619	0.067	0.272	0.042	0.955	5.4		37.9
12	Gosgen-46	0.584	0.068	0.298	0.050	0.981	5.4	2.0	45.9
13	Gosgen-65	0.543	0.070	0.329	0.058	0.915	6.7	3.8	64.7
14	ILL	1	0	0	0	0.792	9.1		8.76
15	Krasnoyarsk87-33	1	0	0	0	0.925	5.0	4.1	32.8
16	Krasnoyarsk87-92	1	0	0	0	0.942	20.4		92.3
17	Krasnoyarsk94-57	1	0	0	0	0.936	4.2	0	57
18	Krasnoyarsk99-34	1	0	0	0	0.946	3.0	0	34
19	SRP-18	1	0	0	0	0.941	2.8	0	18.2
20	SRP-24	1	0	0	0	1.006	2.9	0	23.8
21	Nucifer	0.926	0.061	0.008	0.005	1.014	10.7	0	7.2
22	Chooz	0.496	0.087	0.351	0.066	0.996	3.2	0	≈ 1000
23	Palo Verde	0.600	0.070	0.270	0.060	0.997	5.4	0	≈ 800
24	Daya Bay	0.561	0.076	0.307	0.056	0.946	2.0	0	≈ 550
25	RENO	0.569	0.073	0.301	0.056	0.946	2.1	0	≈ 410
26	Double Chooz	0.511	0.087	0.340	0.062	0.935	1.4	0	≈ 415

Giunti 2016

ILL experiment – 1981

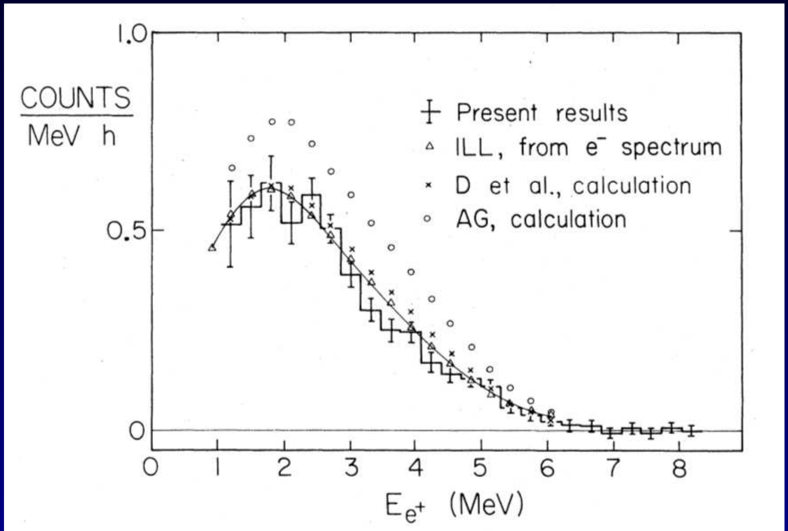


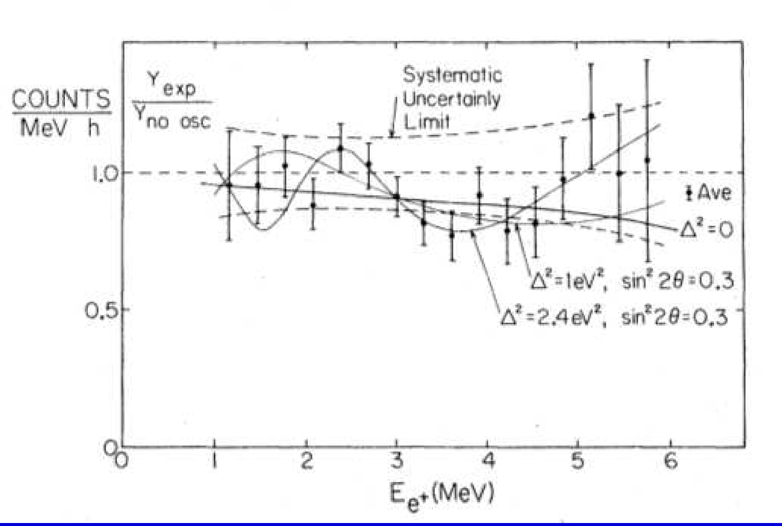


Institut Laue Langevin

57 MW reactor
8.6 m from reactor core

ILL experiment – 1981





Measurement of the positron spectrum

Comparison to theoretical calculations

Comparison to so-called ILL spectrum (more about this later)

Oscillation in the ratio of measured to predicted

SBL reactors summary

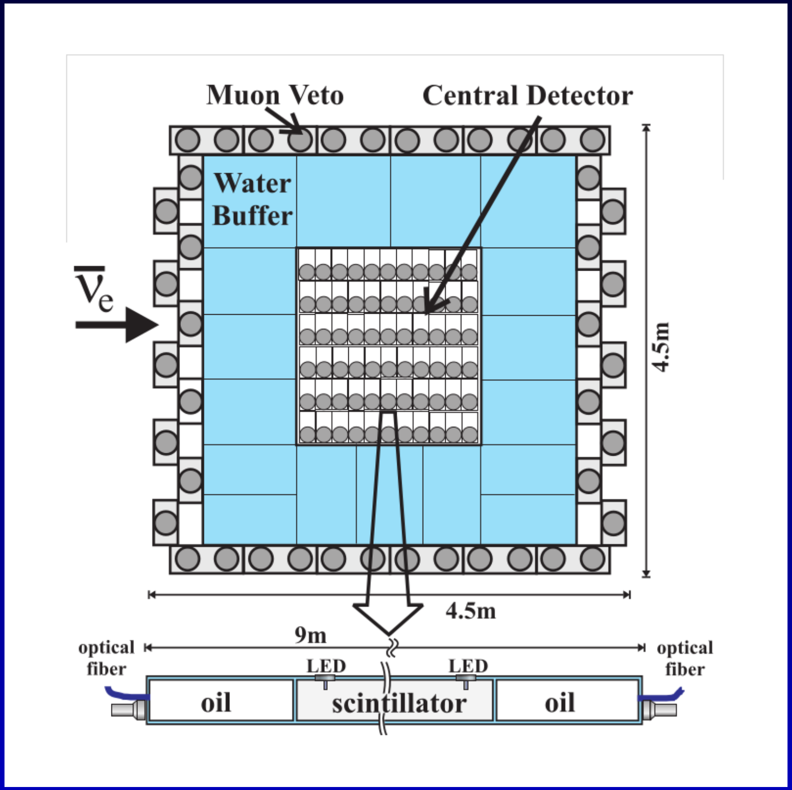
Technological achievements:

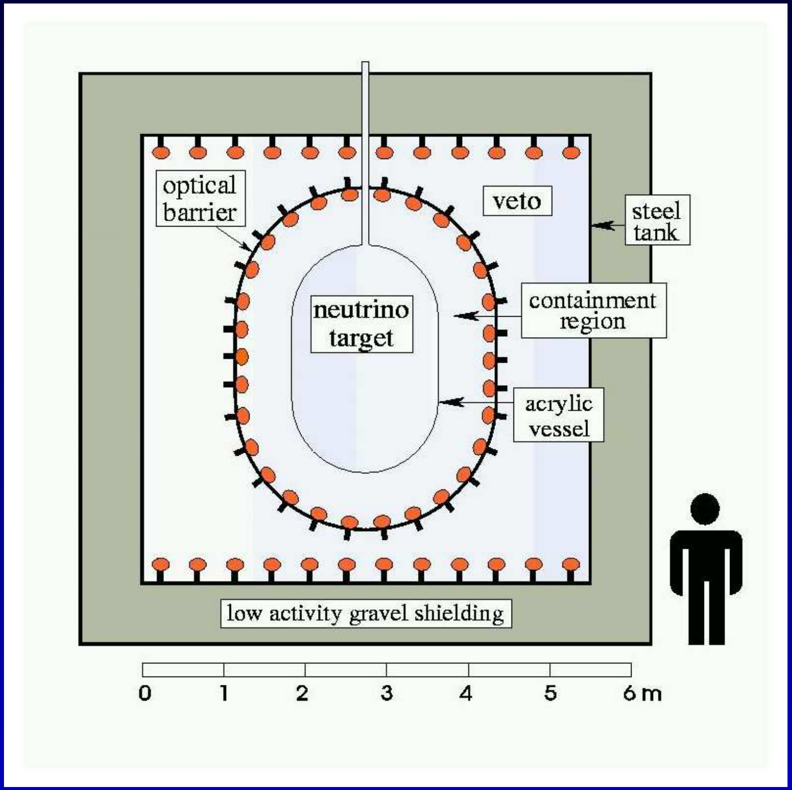
large liquid scintillator detectors
target and detector are one, *cf.* original Reines/Cowan detector
single volume and segmented detectors
many different neutron tagging concepts
Gd-doped scintillators

Science results as of 2011: In the baseline range from 7 – 93 m all results are consistent with NO oscillation.

Palo Verde & CHOOZ

Late 1990's inspired by KamiokaNDE



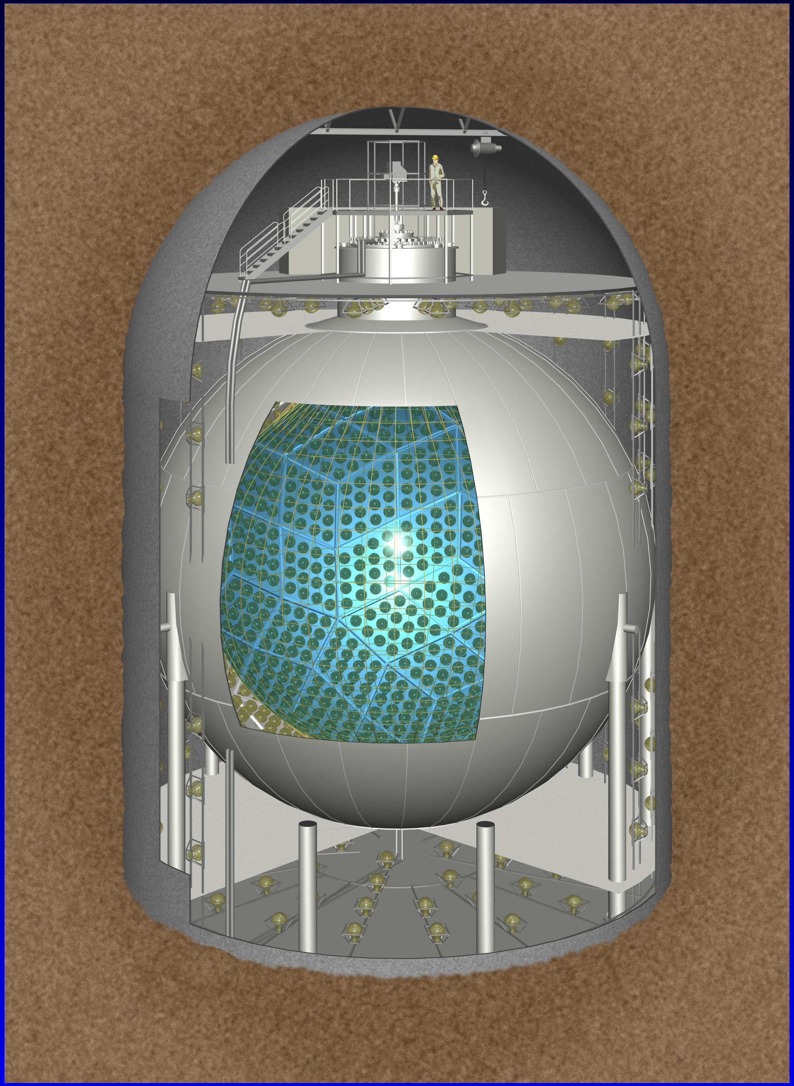


800 m from a commercial reactor

1100 m from a commercial reactor

Null result in both.

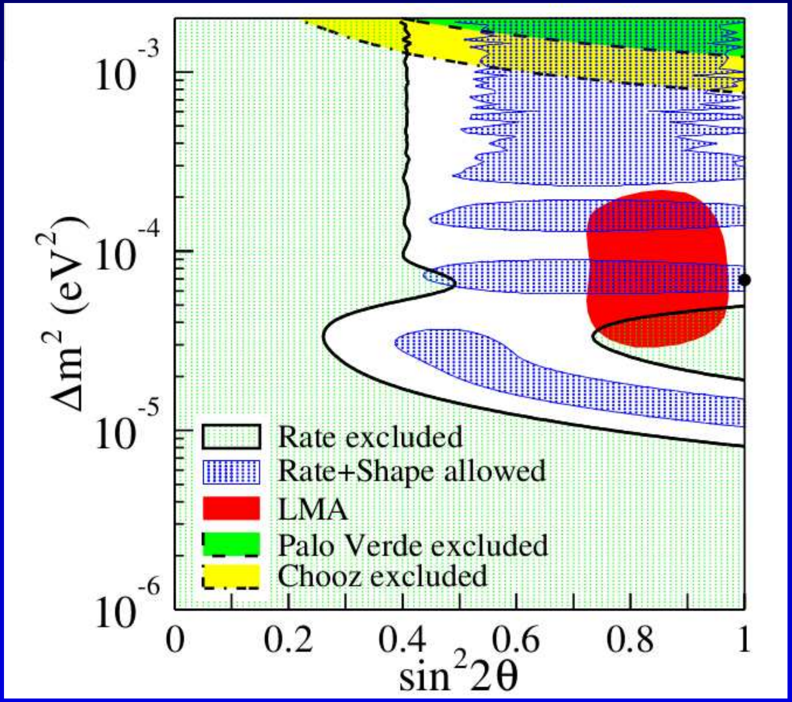
KamLAND – 2002

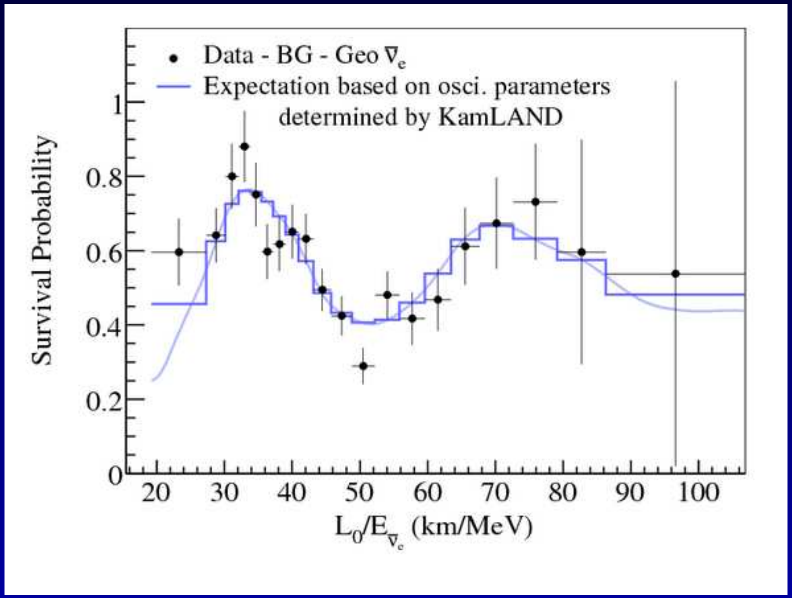


1000 t of liquid organic scintillator, undoped, deep underground.

KamLAND – results

KamLAND confirmed the oscillation interpretation of the solar neutrino results and "picked" the so-called LMA solution.

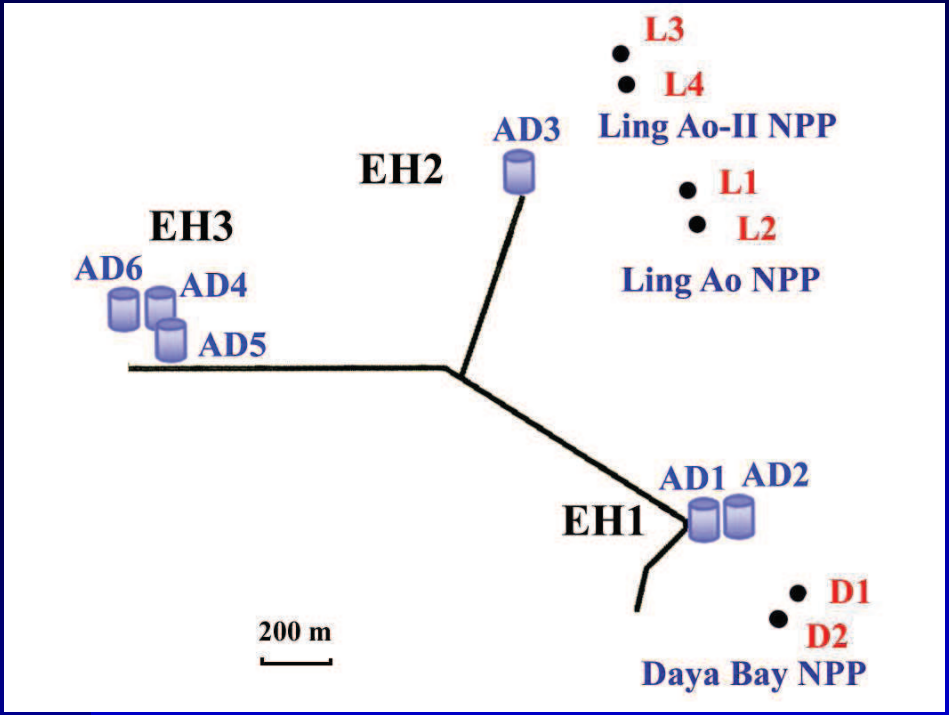




Later it was the first experiment to see an oscillatory pattern.

Daya Bay – 2011

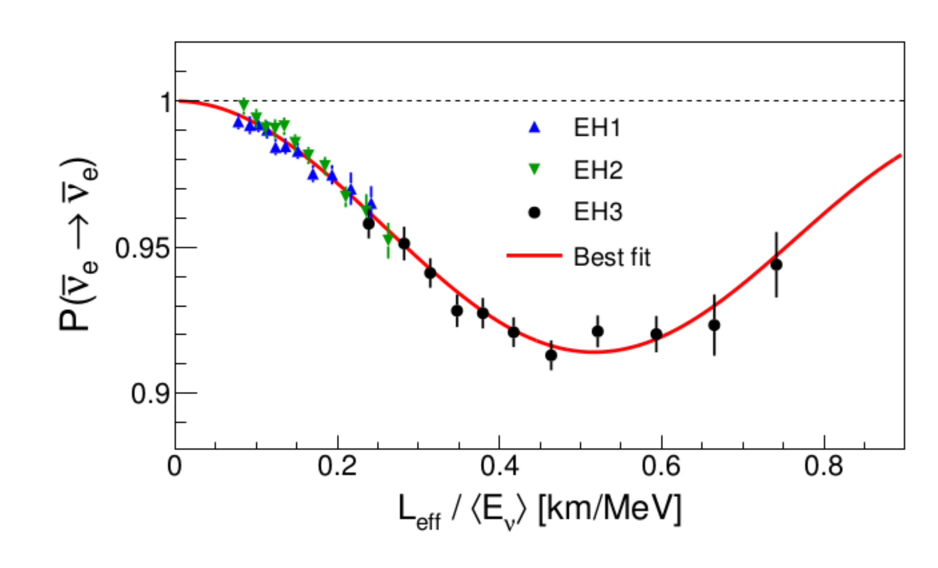
In a 1 reactor, 2 detector setup all flux related errors cancel completely in the near-to-far ratio.

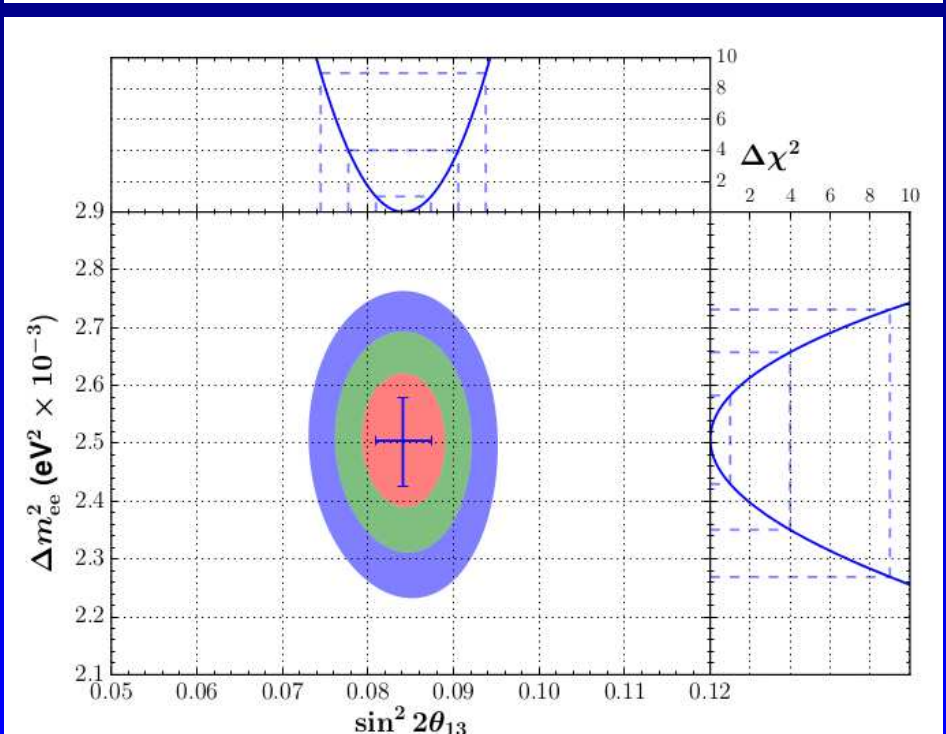


A careful choice of detector locations mitigates the complexity of the Daya Bay layout.

AD3 sees the same ratio of Ling Ao I to Ling Ao II events as do the far detectors.

Daya Bay – results





More than 2.5 million IBD events.

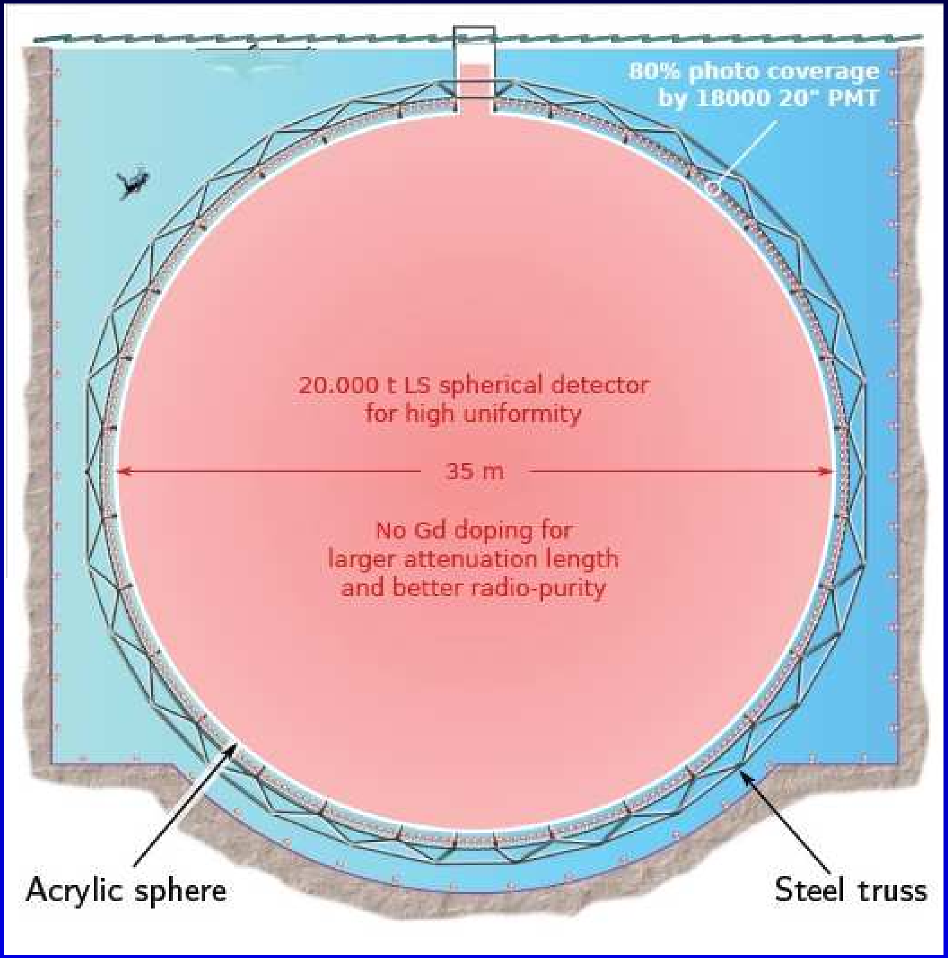
Most precise measurement of θ_{13}

Precise measurement of Δm^2_{32}

RENO and Double Chooz are very similar in concept and results between agree very well.

JUNO – under construction

JUNO – Jiangmen Underground Neutrino Observatory

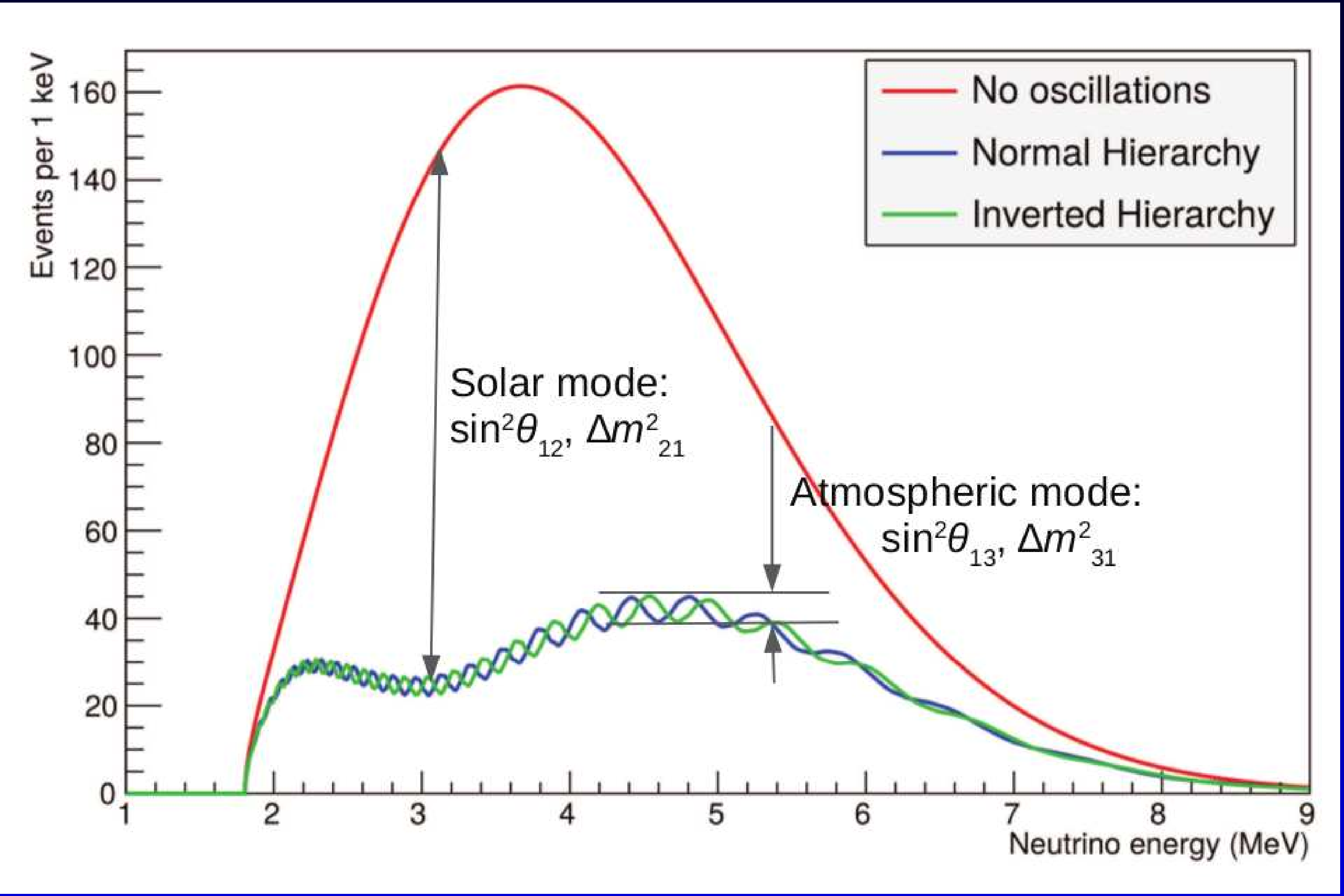


20,000 ton undoped liquid scintillator

53 km from two powerful reactor complexes, 18 GW each

Start of data taking $\sim$ 2020.

JUNO – physics goals



Measurement of mass hierarchy w/o matter effects
1% level measurement of solar mixing parameters

Summary

- Reactors as neutrino source have been a driving force since the 1950's.
- Early oscillation searches, KamLAND and Daya Bay have shapped our understanding of neutrino properties
- Detectors have evolved significantly, allowing for very precise measurements.
- JUNO will pin down solar oscillation parameters.

NuFact 2018

We invite you to NuFact 2018, August 13–18, at Virginia Tech, Blacksburg, VA.

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