The 100th Anniversary of Enrico Fermi

Out of Africa:
A 2 billion year old nuclear reactor

2001 July Lecture

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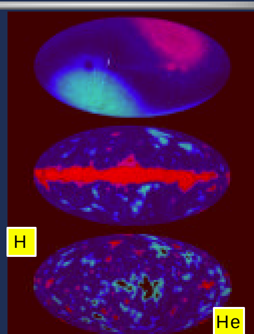
Outline

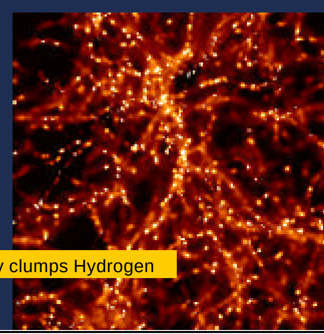
- In the beginning…
  - The Big Bang
  - Stellar nucleosynthesis
  - Formation of the Earth and solar system
- On the Nucleus, Isotopes and the Strong Nuclear Force
- Nuclear fission
- Enrico Fermi and the first artificial nuclear reactor 58 y BP
- No really, the first nuclear reactor: The Oklo phenomenon 2 Gy BP
- Implications for the future

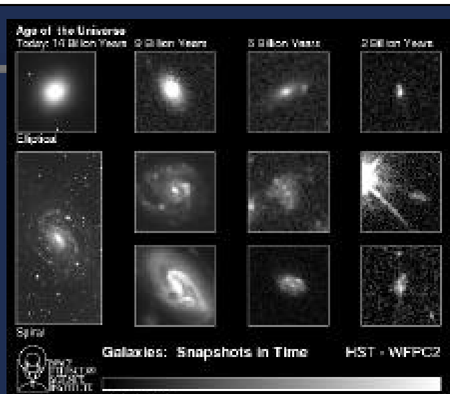
In the Beginning...



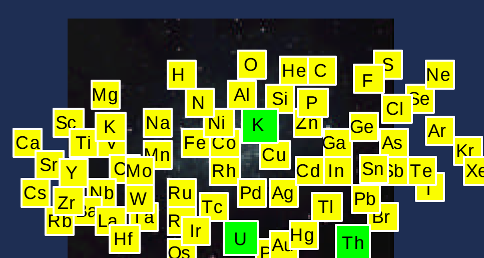
Echoes of the Big Bang

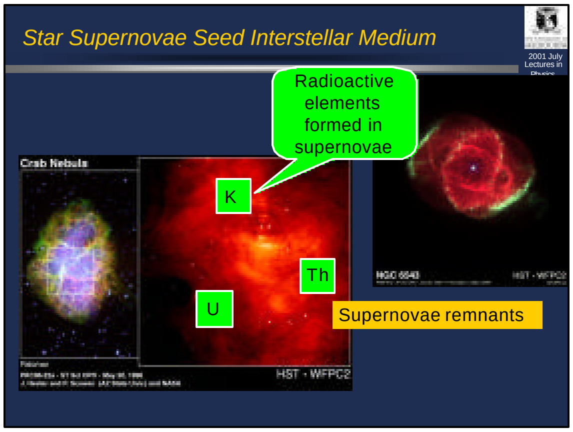
Clumping into Stars & Galaxies





Nucleosynthesis builds Elements




Star Supernovae Seed Interstellar Medium
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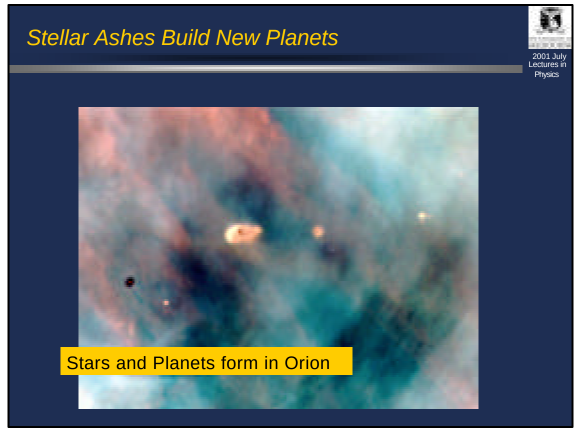
Radioactive elements formed in supernovae
Crab Nebula
K
Th
U
NGC 6543
HST · WFPC2
Supernovae remnants
HST · WFPC2


Stellar Ashes Build New Planets
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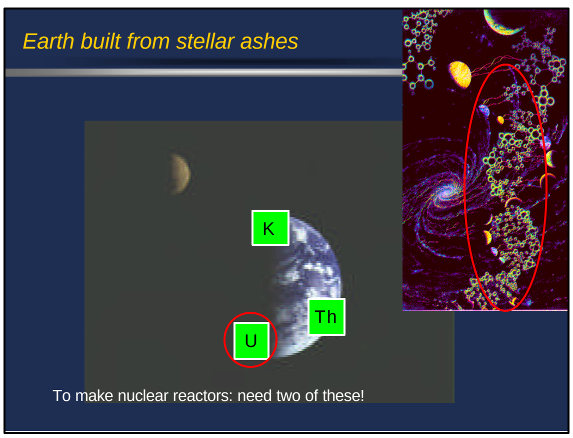
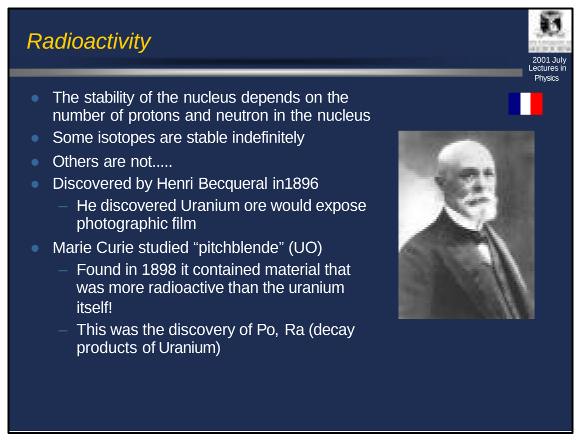
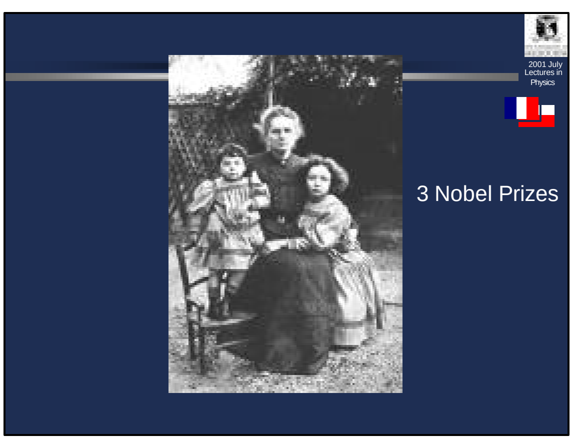
Stars and Planets form in Orion


Earth built from stellar ashes
K
Th
U
To make nuclear reactors: need two of these!


Radioactivity
2001 July Lectures in Physics
The stability of the nucleus depends on the number of protons and neutron in the nucleus
Some isotopes are stable indefinitely
Others are not.....
Discovered by Henri Becqueral in1896
– He discovered Uranium ore would expose photographic film
Marie Curie studied "pitchblende" (UO)
– Found in 1898 it contained material that was more radioactive than the uranium itself!
– This was the discovery of Po, Ra (decay products of Uranium)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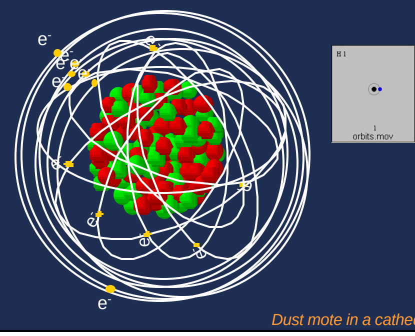
3 Nobel Prizes


Enrico Fermi
History of neutron experiments
Rn/Be neutron tubes
The goldfish pond experiment
Migration to the USA
Start of WW2
The experiments in Chicago
The German reactor project
(The Manhattan project)
ATOMS IN THE FAMILY
My Life with Enrico Fermi
by LAURA FERMI

Isotopes

- An atom consists of a nucleus surrounded by a cloud of electrons
- The nucleus consists of a bunch of protons (+ charge) and neutrons (no charge) bound together
- The chemical characteristics of the atom are determined by the number of protons in the nucleus
- An atom can have a number of different isotopes that differ only in the number of neutrons

Heavy atom (artist's impression)



Dust mote in a cathederal

Isotope names

Number of nucleons (protons + neutrons)

Chemical symbol (defines number of protons, 19 in this case)

^{40}K

Data:

- Of all the potassium atoms in the Earth:
  - 93.1% are ^{39}K (stable)
  - 0.01% are ^{40}K (unstable, half life 1.3 billion years)
  - 6.9% are ^{41}K (stable)

Isotope names

Number of nucleons (protons + neutrons)

Chemical symbol (defines number of protons, 6 in this case)

^{12}C

Data:

- Of all the carbon atoms in the biosphere of Earth:
  - 98.89 % are ^{12}C (stable)
  - 1.11 % are ^{13}C (stable)
  - 1.5×10^{-10} % are ^{14}C (unstable, half life 5730 years)
- (except petrol - no ^{14}C)

Natural Radioactive elements

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															

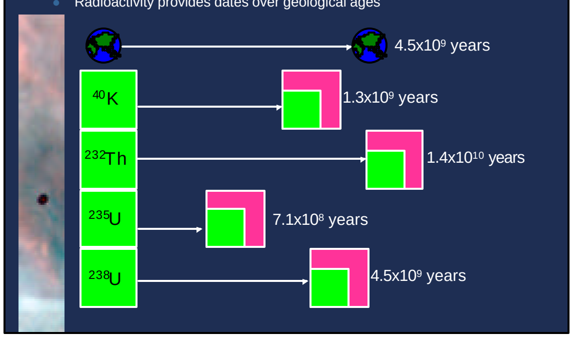
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

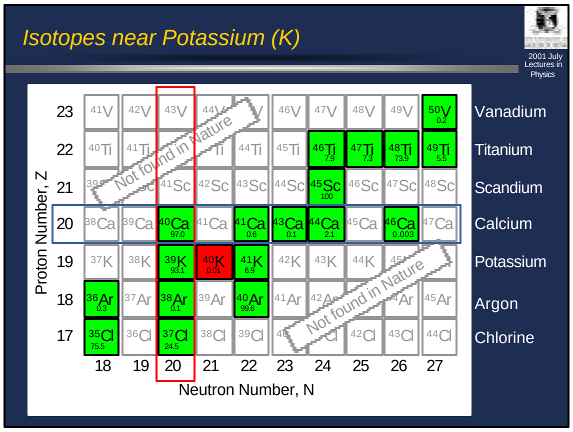
U Radioactive elements

Tc Elements not presently found in nature

Radioactive elements decay (slowly)

- Radioactivity provides dates over geological ages




Isotopes near Potassium (K)
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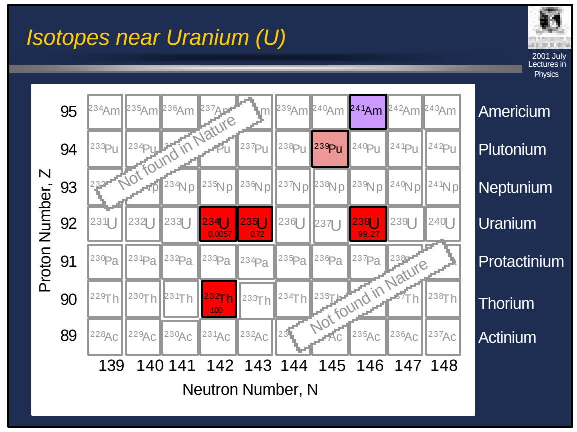
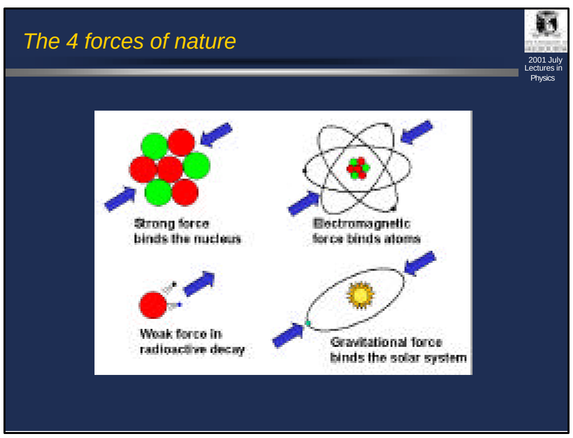
Proton Number, Z
Neutron Number, N
Not found in Nature
Not found in Nature
Vanadium
Titanium
Scandium
Calcium
Potassium
Argon
Chlorine
23
22
21
20
19
18
17
18 19 20 21 22 23 24 25 26 27


Isotopes near Uranium (U)
2001 July Lectures in Physics
Proton Number, Z
Neutron Number, N
Not found in Nature
Not found in Nature
Americium
Plutonium
Neptunium
Uranium
Protactinium
Thorium
Actinium
95
94
93
92
91
90
89
139 140 141 142 143 144 145 146 147 148


The 4 forces of nature
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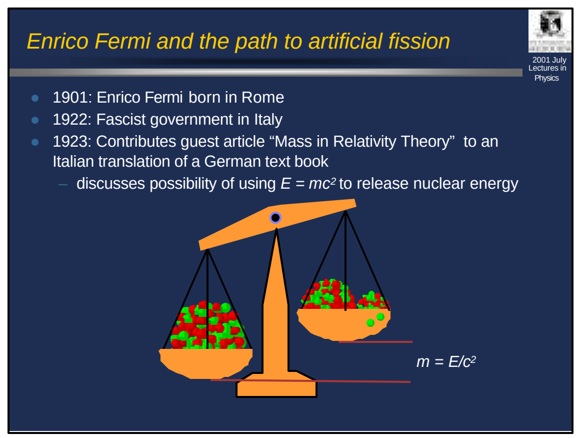
Strong force binds the nucleus
Electromagnetic force binds atoms
Weak force in radioactive decay
Gravitational force binds the solar system


Enrico Fermi and the path to artificial fission
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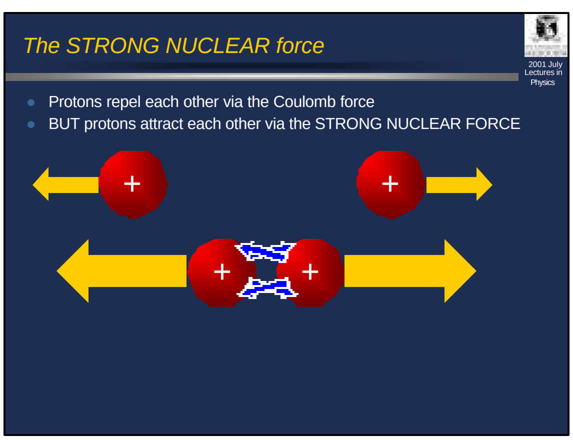
1901: Enrico Fermi born in Rome
1922: Fascist government in Italy
1923: Contributes guest article "Mass in Relativity Theory" to an Italian translation of a German text book
– discusses possibility of using $E = mc^2$ to release nuclear energy
$m = E/c^2$


The STRONG NUCLEAR force
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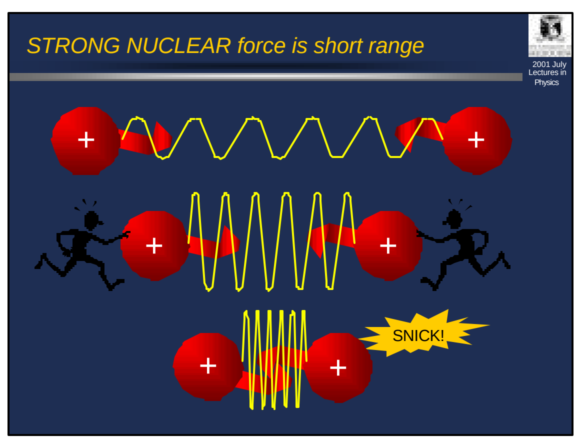
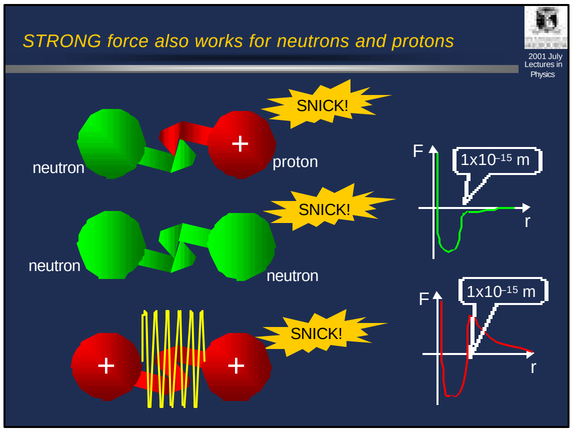
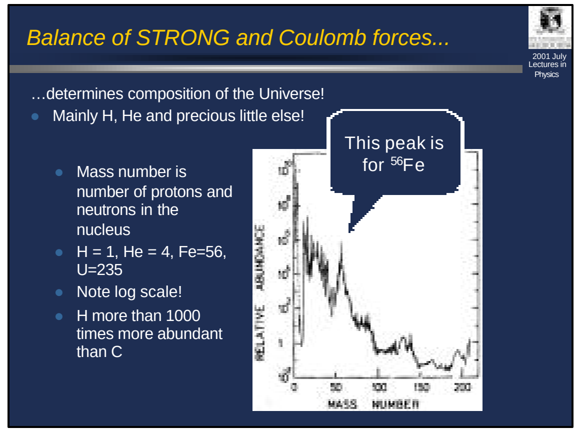
Protons repel each other via the Coulomb force
BUT protons attract each other via the STRONG NUCLEAR FORCE
+
+
+
+


STRONG NUCLEAR force is short range
2001 July Lectures in Physics
SNICK!


STRONG force also works for neutrons and protons
2001 July Lectures in Physics
neutron
proton
SNICK!
neutron
neutron
SNICK!
SNICK!
F
r
1x10-15 m
F
r
1x10-15 m


Balance of STRONG and Coulomb forces...
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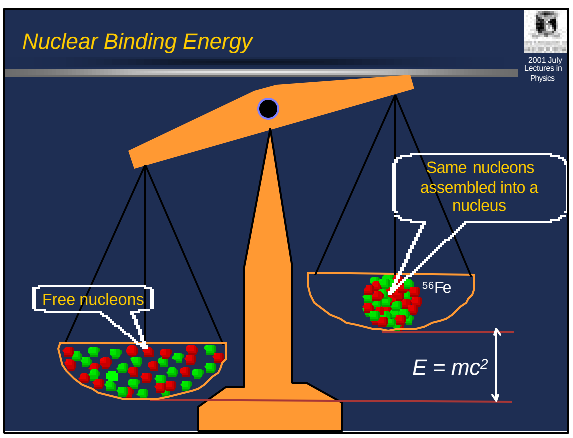
...determines composition of the Universe!
Mainly H, He and precious little else!
Mass number is number of protons and neutrons in the nucleus
H = 1, He = 4, Fe=56, U=235
Note log scale!
H more than 1000 times more abundant than C
This peak is for 56Fe
RELATIVE ABUNDANCE
MASS NUMBER


Nuclear Binding Energy
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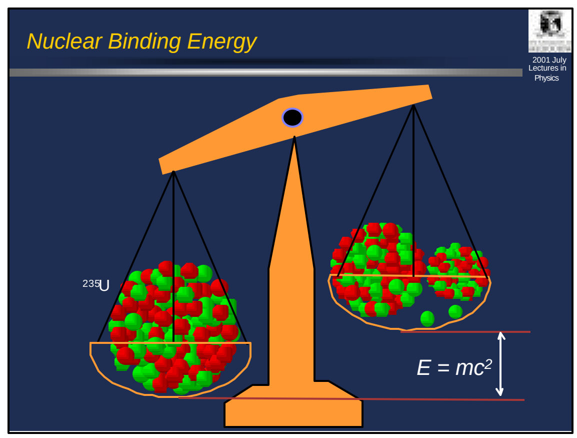
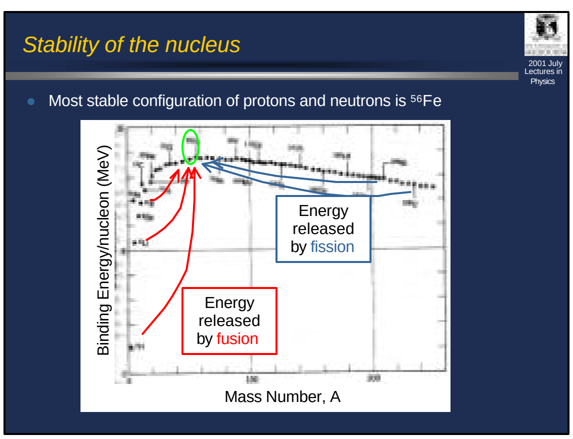
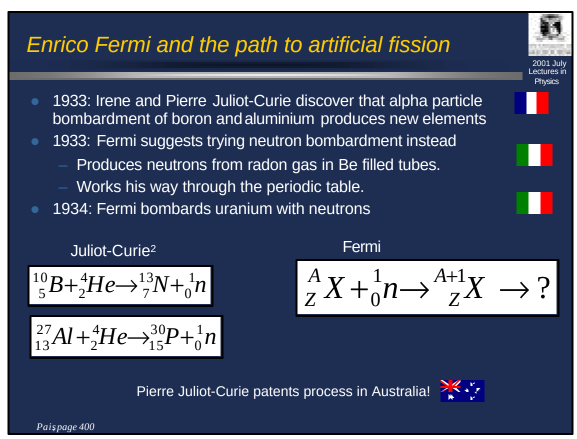
Same nucleons assembled into a nucleus
56Fe
Free nucleons
E = mc2


Nuclear Binding Energy
2001 July Lectures in Physics
235U
E = mc2


Stability of the nucleus
2001 July Lectures in Physics
Most stable configuration of protons and neutrons is 56Fe
Binding Energy/nucleon (MeV)
Energy released by fission
Energy released by fusion
Mass Number, A


Enrico Fermi and the path to artificial fission
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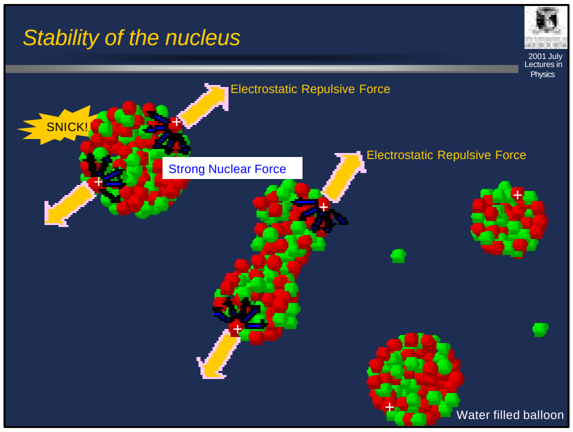
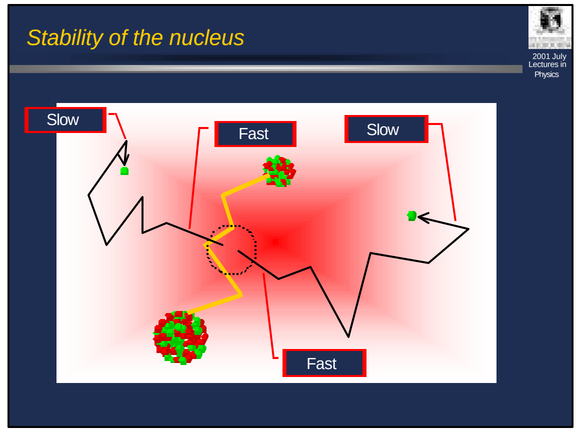
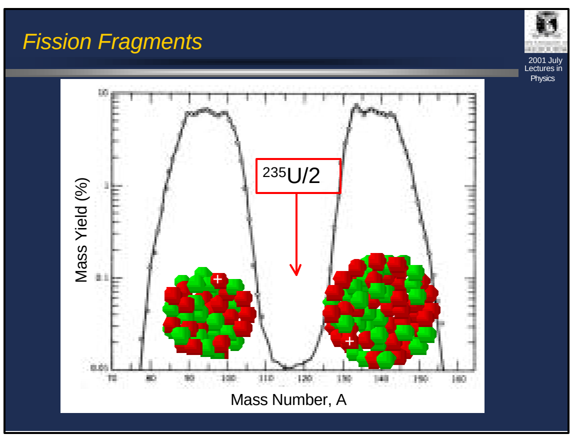
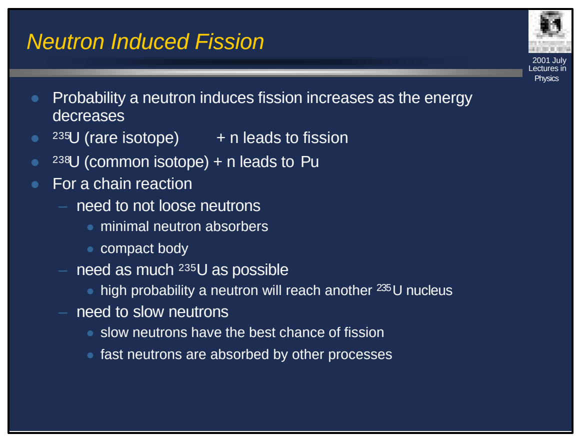
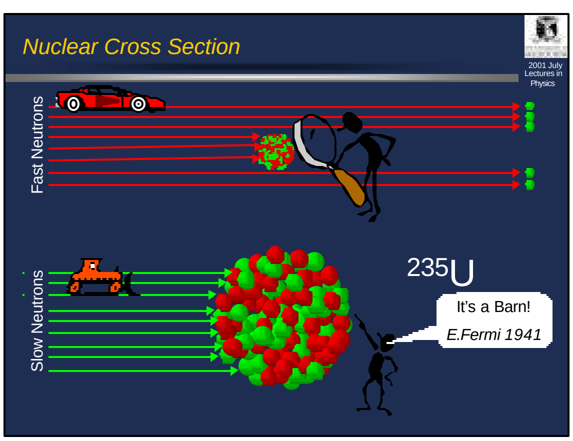
1933: Irene and Pierre Juliot-Curie discover that alpha particle bombardment of boron and aluminium produces new elements
1933: Fermi suggests trying neutron bombardment instead
Produces neutrons from radon gas in Be filled tubes.
Works his way through the periodic table.
1934: Fermi bombards uranium with neutrons
Juliot-Curie2
$^{10}_{5}B+^{4}_{2}He \rightarrow ^{13}_{7}N+^{1}_{0}n$
$^{27}_{13}Al+^{4}_{2}He \rightarrow ^{30}_{15}P+^{1}_{0}n$
Fermi
$^{A}_{Z}X+^{1}_{0}n \rightarrow ^{A+1}_{Z}X \rightarrow ?$
Pierre Juliot-Curie patents process in Australia!
Pais page 400

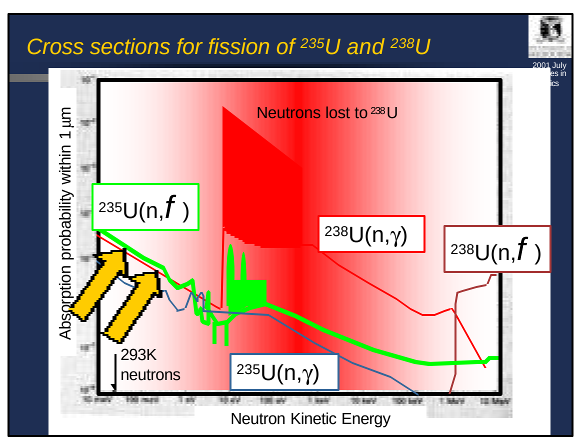

Stability of the nucleus
Electrostatic Repulsive Force
SNICK!
Strong Nuclear Force
Electrostatic Repulsive Force
Water filled balloon


Stability of the nucleus
Slow
Fast
Slow
Fast


Fission Fragments
Mass Yield (%)
235U/2
Mass Number, A


Neutron Induced Fission
Probability a neutron induces fission increases as the energy decreases
235U (rare isotope) + n leads to fission
238U (common isotope) + n leads to Pu
For a chain reaction
need to not loose neutrons
minimal neutron absorbers
compact body
need as much 235U as possible
high probability a neutron will reach another 235U nucleus
need to slow neutrons
slow neutrons have the best chance of fission
fast neutrons are absorbed by other processes

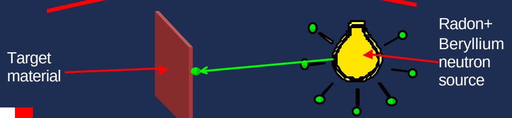

Nuclear Cross Section
Fast Neutrons
Slow Neutrons
235U
It's a Barn!
E.Fermi 1941


Cross sections for fission of 235U and 238U
Neutrons lost to 238U
235U(n,f)
238U(n,γ)
238U(n,f)
Absorption probability within 1 μm
293K neutrons
235U(n,γ)
Neutron Kinetic Energy

1934: The failure to discover fission

- Fermi's mentor, Corbino, announces that neutron bombardment of U produces even heavier elements, Fermi skeptical
- Press announces discovery of element 93!
  - Government trumpets triumph of fascist inspired research
  - Tabloids announce jar of fascist element 93 presented to queen (fable)

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U \rightarrow ^{239}_{93}Mu + b^{-} + \bar{n}$$



1934: The failure to discover fission

- 1934 June: Nature paper "Possible production of elements of atomic number higher than 92"
- 1934 September : Ida Noddack (chemist, discoverer of Rhenium) criticises Fermi's paper - should consider the production of lighter elements
- Fermi recalculates, uses wrong mass* for He - dismisses Noddack's criticisms.
- (*not his fault)
- c.i.f. "*con intuito formidable*"

The discovery of slow neutrons

- 1934: Wooden tables give better results than marble tables!
- October 1934: Discovers a paraffin filter greatly amplifies the effect
- Water also works
  - the goldfish pond experiment
- Use of slow neutrons for transmutation patented
- 1938 Dec 10: Nobel prize for slow neutron work
  - departure for USA after ceremony

The failure to discover fission

- 1938 Dec 22: Fission of uranium by neutrons discovered by Otto Hahn, Fritz Strassman (in Germany) and Lise Meitner (Strassman's aunt - in exile in Sweden)
  - eclipse of German science

The rare isotope ^{235}U and fission

- 1939 January: "A little bomb like that (cupping hands) and it would all disappear" (Fermi, referring to Manhattan visible out the window)
- 1939 January: Leo Szilard saw the future better than anyone - tried to pursuade Fermi and others to suppress uranium work
- "Nuts" E. Fermi to Szilard 1939
- 1939 February: Bohr and Fermi deduce role of ^{235}U
  - ^{238}U + n leads to an odd-numbered neutron isotope
  - ^{235}U + n leads to an even numbered neutron isotope
    - Neutrons like to be in pairs
    - making ^{235}U + n liberates binding energy sufficient to fission the nucleus
    - Barrier to fission is about 6 MeV
    - Adding 1 neutron liberates about 5.3 MeV
    - Adding 1 neutron and pairing it liberates about 6.3 MeV

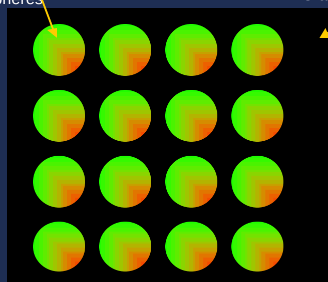
Einstein and the chain reaction

- 1939 July: Szilard tells Einstein about possibility of nuclear chain reaction:
- "Daran habe ich gar nicht gedacht!" I never thought of that! A. Einstein.
- 1941 December: Fermi joins "Metallurgical laboratory", U. Chicago
- 1941 April: First carbon moderated pile built at Columbia
- "So the physicists on the 7th floor of Pupin Laboratories started looking like coal miners and the wives to whom these physicists came back tired each night were wondering what was happening" E. Fermi
- 1942 December : First reactor goes critical

Fermi's Reactor

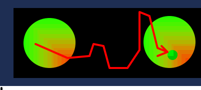
U, UO spheres

Graphite moderator

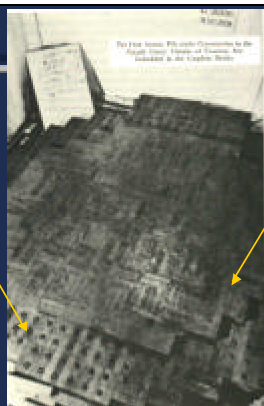


Other moderators

- Properties of materials used as moderators

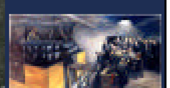


Material	Absorption cross section for thermal neutrons	Average slowing down length from fast to thermal (cm)	
H_2O	0.664	5.3	Oklo
D_2O	0.001	11.2	CANDU
C	0.0045	19.1	Fermi

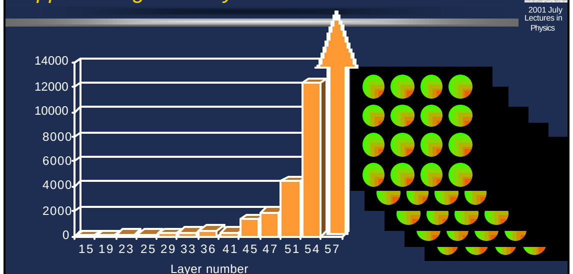


Graphite moderator

U, UO spheres

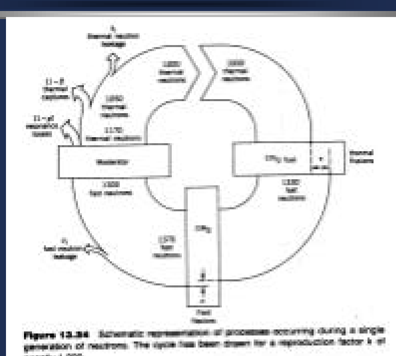


Approaching criticality



- Layer 57 caused pile to "go critical" - reaction became self sustaining
- Elaborate precautions taken to prevent run-away

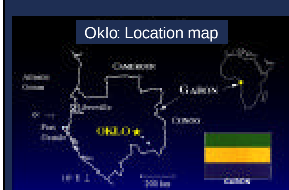
Neutron "generations" in a critical reactor



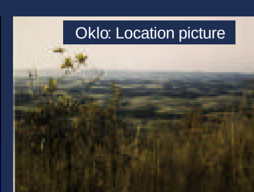
Out of Africa

- The very rich uranium mines in Gabon
- Assays of uranium ore shipped to France in 1972
- Anomalous depletion of ^{235}U: 0.4% instead of 0.72%
- Closer investigation discovered fossil nuclear reactors

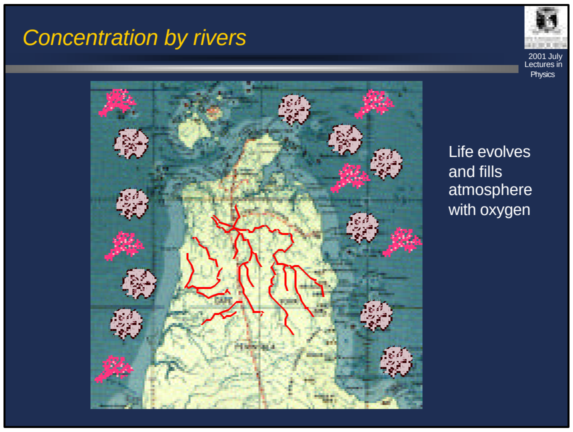
Oklo: Location map



Oklo: Location picture



From Robert Loss' Oklo website: http://www.curtin.edu.au/curtin/centre/waisrc/OKLO


Concentration by rivers
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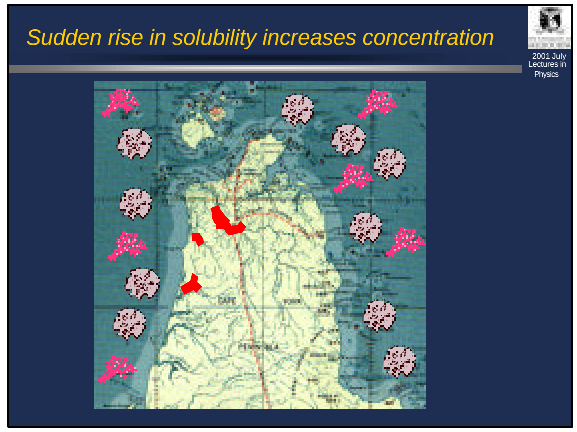
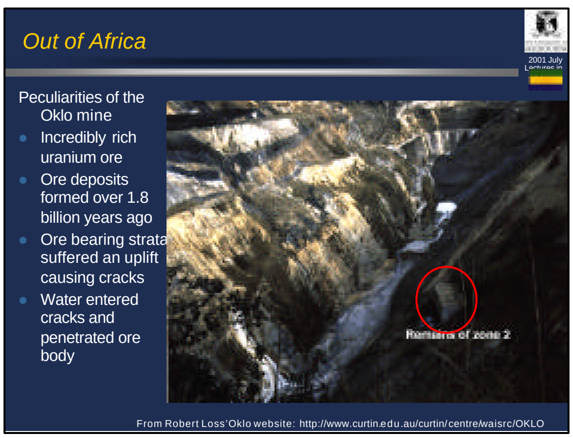
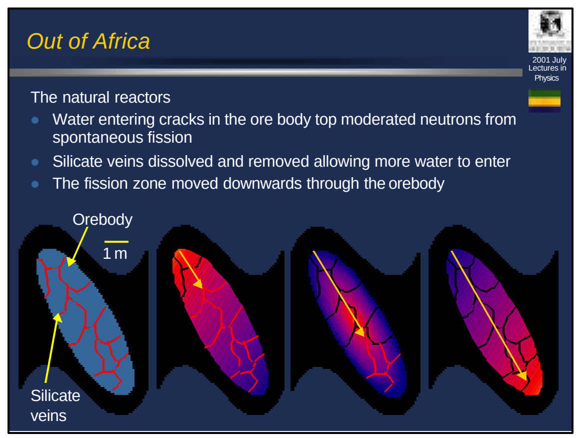
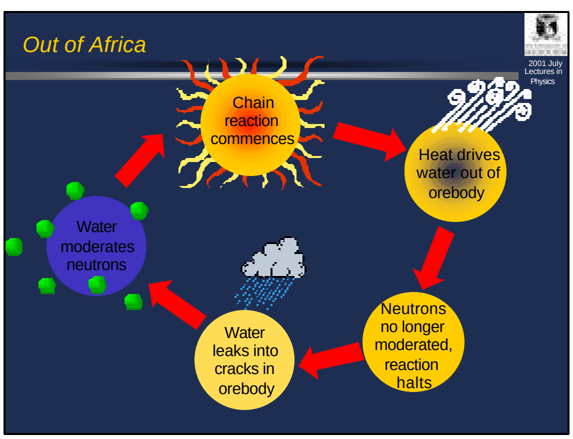
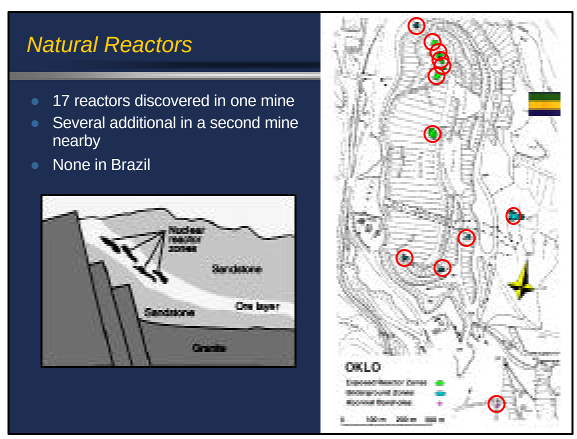
Life evolves and fills atmosphere with oxygen


Sudden rise in solubility increases concentration
2001 July Lectures in Physics


Out of Africa
Peculiarities of the Oklo mine
Incredibly rich uranium ore
Ore deposits formed over 1.8 billion years ago
Ore bearing strata suffered an uplift causing cracks
Water entered cracks and penetrated ore body
Remains of zone 2
From Robert Loss' Oklo website: http://www.curtin.edu.au/curtin/centre/waisrc/OKLO


Out of Africa
2001 July Lectures in Physics
The natural reactors
Water entering cracks in the ore body top moderated neutrons from spontaneous fission
Silicate veins dissolved and removed allowing more water to enter
The fission zone moved downwards through the orebody
Orebody
1 m
Silicate veins

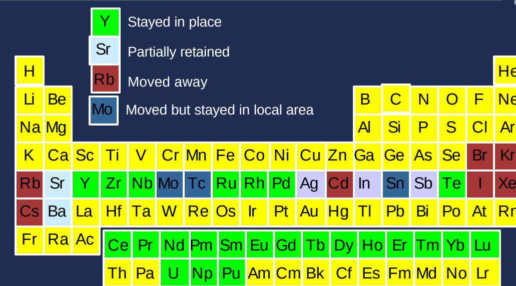

Out of Africa
2001 July Lectures in Physics
Chain reaction commences
Heat drives water out of orebody
Neutrons no longer moderated, reaction halts
Water leaks into cracks in orebody
Water moderates neutrons


Natural Reactors
17 reactors discovered in one mine
Several additional in a second mine nearby
None in Brazil
Nuclear reactor zones
Sandstone
Ore layer
Sandstone
Granite
OKLO

Inside the natural reactors

From Robert Loss' Oklo website: http://www.curtin.edu.au/curtin/centre/waisrc/OKLO

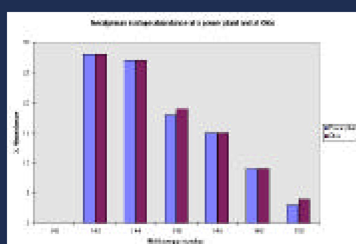
2 Billion years of weathering



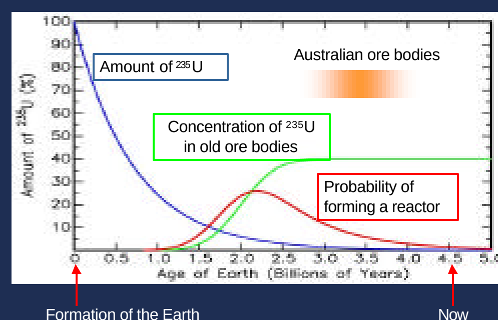
Adapted from Robert Loss' Oklo website: http://www.curtin.edu.au/curtin/centre/waisrc/OKLO

Out of Africa

- Cycle continues until ^{235}U consumed



Conditions for the Oklo Phenomenon



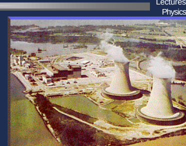
Conclusion

Fermi's "pile" (as in heap):

- 6 tonnes of natural uranium (0.72% ^{235}U)
- produced 200 W of power
- used graphite as the moderator

Oklo reactors:

- generated 15,000 GW/years (large nuclear plant for 4 years)
- produced 100 kW of power
- operated for 150,000 years
- consumed 6 tonnes of uranium (3% ^{235}U)
- Used water as the moderator
- Laws of Physics same then as now
- Retained many waste products (including Pu) in place for 2 Gy



The *Fermi II* nuclear plant, near Detroit, USA: 1.14GW

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