Lecture 1 - Neutron Sources

1. The Production of Neutrons

a. Radioactive sources
b. Fission Reactors
c. Accelerated Particle sources

2. Modern Neutron Sources

a. The Quest for High Intensities
b. The Institut Laue Langevin High Flux Reactor
c. ISIS at the Rutherford Appleton Laboratory
d. The SNS and J-PARC

1. The Production Of Neutrons

a. Natural Radioactive Sources

(α,n) reaction

Chadwick 1932

Po^{210} beryllium

α

5.3 MeV

neutrons

$He^4 + Be^9 = C^{12} + n^1 + 5.7$ MeV

The last neutron is weakly bound

Radium-beryllium Laboratory source

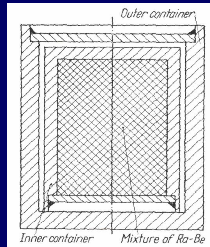


Fig. 2.2.2. Cross section through a typical (Ra—Be) source

Radium bromide + beryllium mixture

Practical Use: Setting up detectors

The Discovery of the Neutron

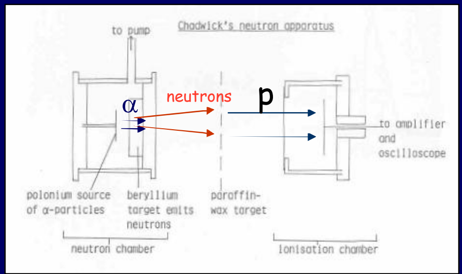
Chadwick 1932

Po^{210} beryllium

α 5.3 MeV → neutrons

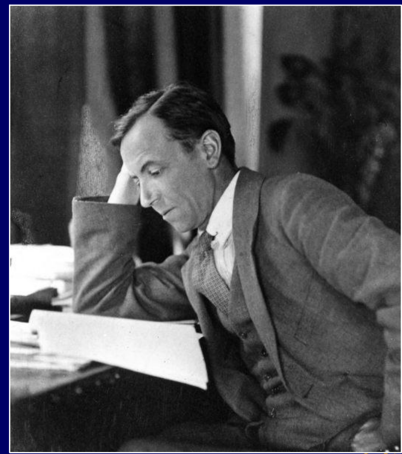
$$He^4 + Be^9 = C^{12} + n^1 + 5.7\ MeV$$

The last neutron is weakly bound

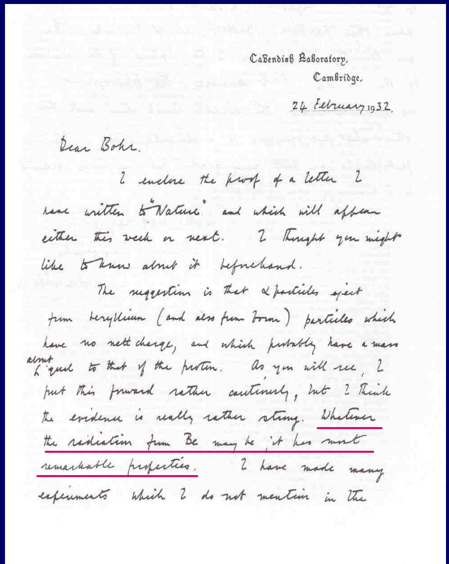


The Discovery of the Neutron

Chadwick 1932



"Whatever the radiation from Be may be, it has most remarkable properties"

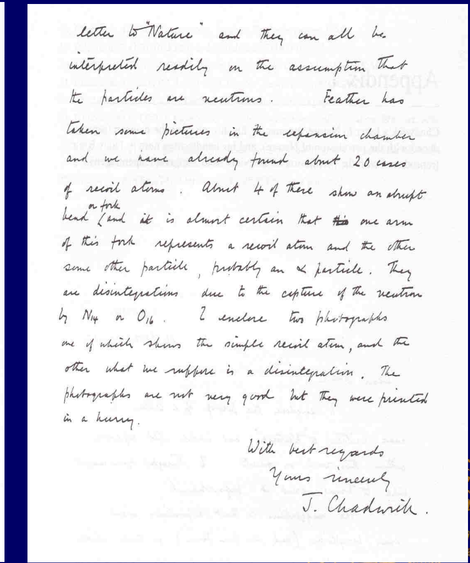


Cavendish Laboratory,
Cambridge.
24 February 1932.

Dear Bohr,

I enclose the proof of a letter I have written to "Nature" and which will appear either this week or next. I thought you might like to know about it beforehand.

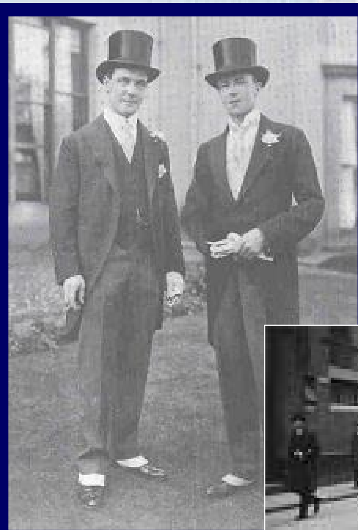
The suggestion is that α particles eject from beryllium (and also from boron) particles which have no nett charge, and which probably have a mass about equal to that of the proton. As you will see, I put this forward rather cautiously, but I think the evidence is really rather strong. Whatever the radiation from Be may be, it has most remarkable properties. I have made many experiments which I do not mention in the



letter to "Nature" and they can all be interpreted readily on the assumption that the particles are neutrons. Feather has taken some pictures in the expansion chamber and we have already found about 20 cases of recoil atoms. About 4 of these show an abrupt bend or fork and it is almost certain that one arm of this fork represents a recoil atom and the other some other particle, probably an α particle. They are disintegrations due to the capture of the neutron by N_{14} or O_{16}. I enclose two photographs one of which shows the simple recoil atom, and the other what we suppose is a disintegration. The photographs are not very good but they were printed in a hurry.

With best regards
Yours sincerely
J. Chadwick.

"Whatever the radiation from Be may be, it has most remarkable properties"



a. Natural Radioactive Sources… continued

(γ,n) reaction

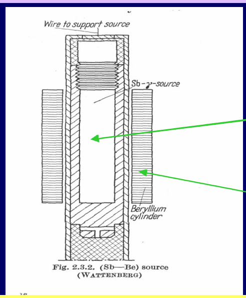
antimony $\xrightarrow{\gamma}$ beryllium → neutrons

$Sb^{124} \xrightarrow{\beta^-} Te^{124}$

$\longrightarrow \gamma \longrightarrow Be^9 = Be^{9*} = Be^8 + n^1 - 1.66$ MeV

The last neutron is weakly bound

Antimony Beryllium Laboratory source



Solid Antimony γ source

Beryllium cylinder

Advantage: *Can be switched off*

The Production Of Neutrons - (ii) Fission

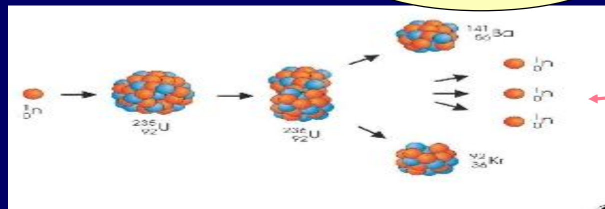
$n^1 + U^{235} \longrightarrow$ 2 fission fragments + $2.5n^1$ + 200 MeV

thermal

1 neutron to maintain chain reaction

1 neutron escapes & is available for use

0.5 neutrons absorbed



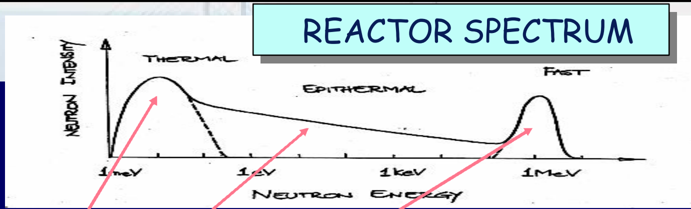
2 to 3 neutrons per fission

Example: 20 MW Research Reactor

No. of fissions/sec $= \dfrac{20 \times 10^6 \text{ watts}}{200 \text{ MeV/fission}}$ $\boxed{= 6 \times 10^{17} \text{ fissions/second}}$

generates 1.5×10^{18} neutrons/sec in the whole reactor volume

REACTOR SPECTRUM



THERMAL E< 200 meV

$$\Phi(E)dE = \Phi_{th} \frac{E}{k_B T} \exp\left(-\frac{E}{k_B T}\right).dE$$

Maxwell-Boltzmann Region

EPITHERMAL 200 meV < E< 500 keV

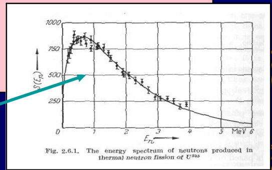
$$\Phi(E)dE = \frac{\Phi_{epi}}{E}.dE$$

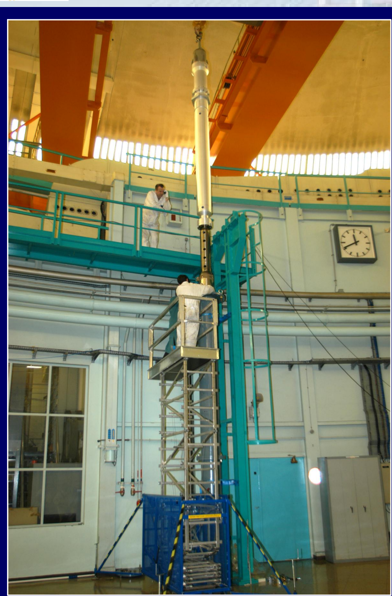
Slowing Down or 1/E Region

FAST E > 500 keV & extending to ~ 10 MeV

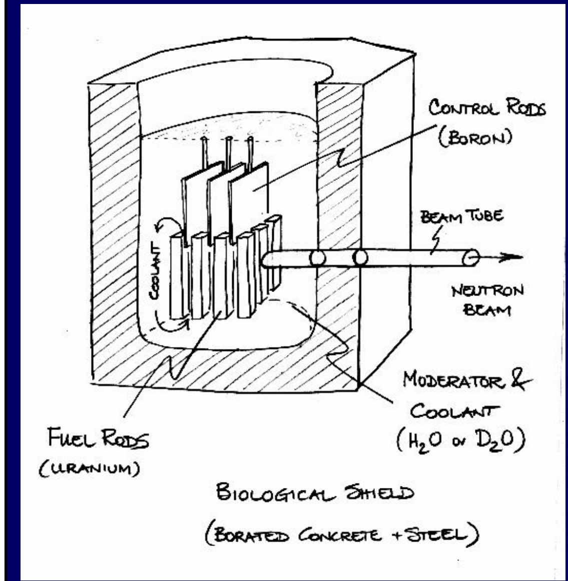
$$\Phi(E)dE = \Phi_f \exp(-E) \sinh(2E)^{1/2} dE$$

Fission Spectrum





SWIMMING POOL REACTOR



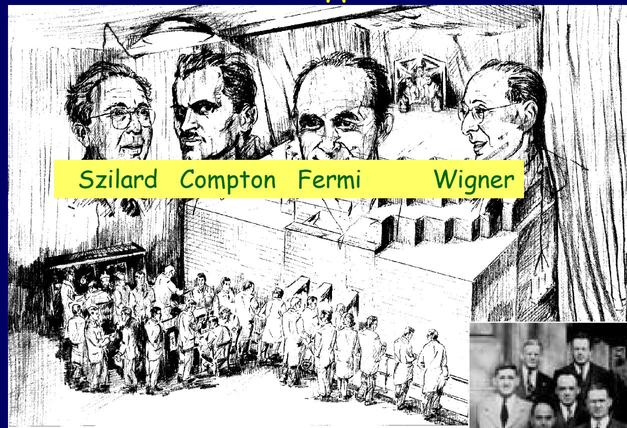
Thermal Neutron Fission

$\nu \sim 2.5$

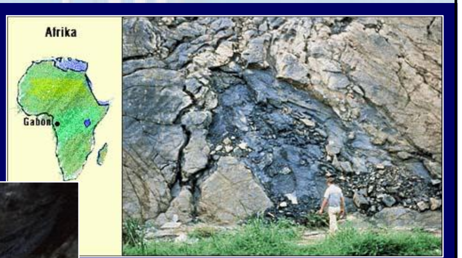
1.5×10^{18} fast neutrons/sec generated at 20 MW

Man-made

December 2nd 1942 First sustainable fission reaction Chicago

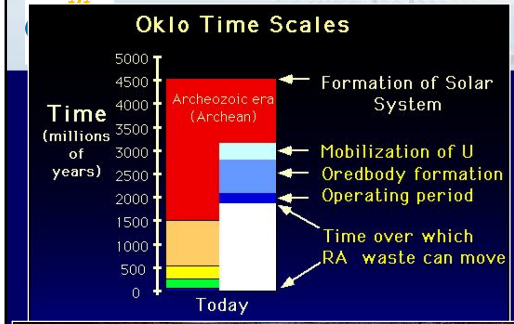


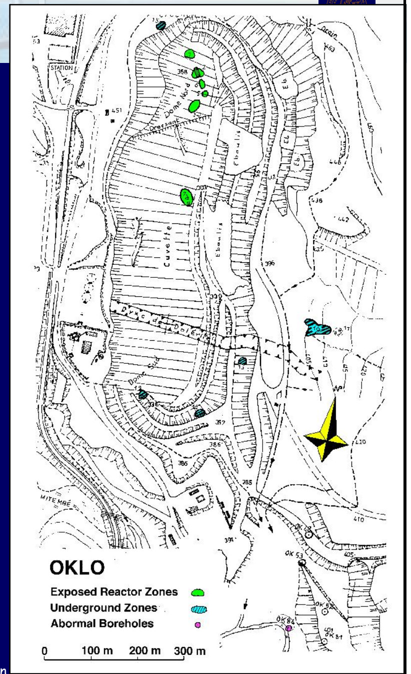
The Oklo reactor in Gabon Africa

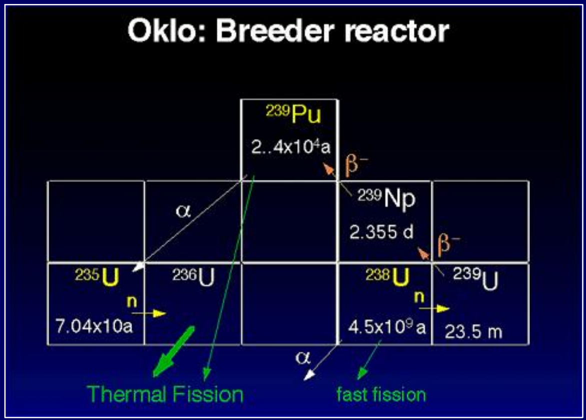


$T_{\frac{1}{2}}$ U^{235} =
$7.1*10^8$ years
$T_{\frac{1}{2}}$ U^{238} =
$4.51*10^9$ years

The ratio of U^{235} to U^{238}
was higher 2000 million years ago – 0.720 % nowadays







20 MW Research Reactor

1.5×10^{18} Fast neutrons/sec generated.
Typically these neutrons distribute themselves in different proportions dependent on the fuel and moderator used

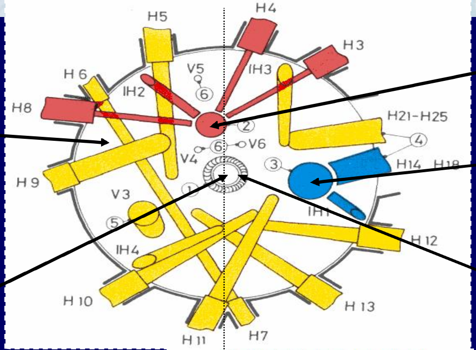
Fuel & Moderator	Thermal Flux n/cm²/sec	Epithermal Flux n/cm²/sec	Fast Flux n/cm²/sec	Gamma Flux γ/cm²/sec
Natural Uranium + D_2O	6×10^{13}	2×10^{12}	4×10^{12}	2×10^{12}
Enriched Uranium + H_2O	2×10^{14}	2×10^{13}	2×10^{14}	1×10^{13}

N.B. ENRICHED URANIUM + D_2O
Higher Reactivity
& More Compact Core

Higher Power Density
Higher Neutron Flux

The Neutron flux can be Maximised in the Reflector where the beam tubes sit

Flux Distribution around ILL Core



58MW
93% U^{235}
Thermal
$1.5\ 10^{15}$ n/cm^2/s
Epithermal
$8\ 10^{13}$ n/cm^2/s
Fast
$2.5\ 10^{14}$ n/cm^2/s

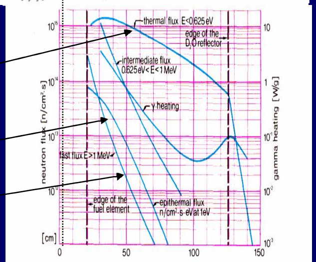
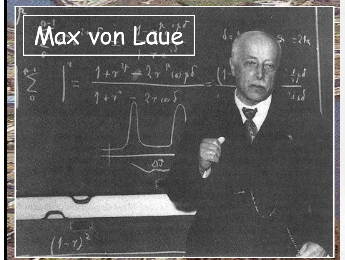
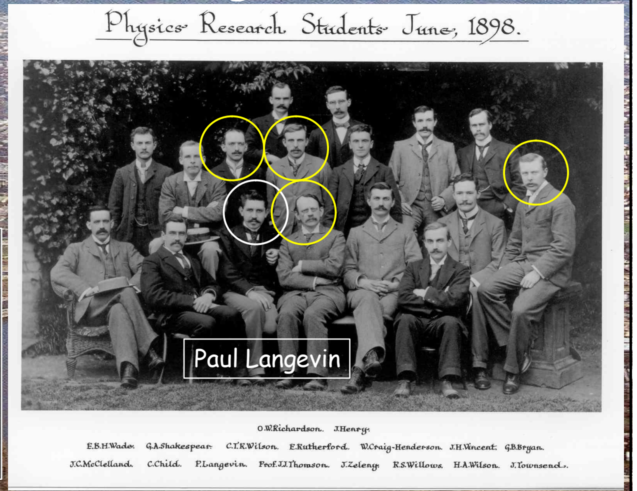
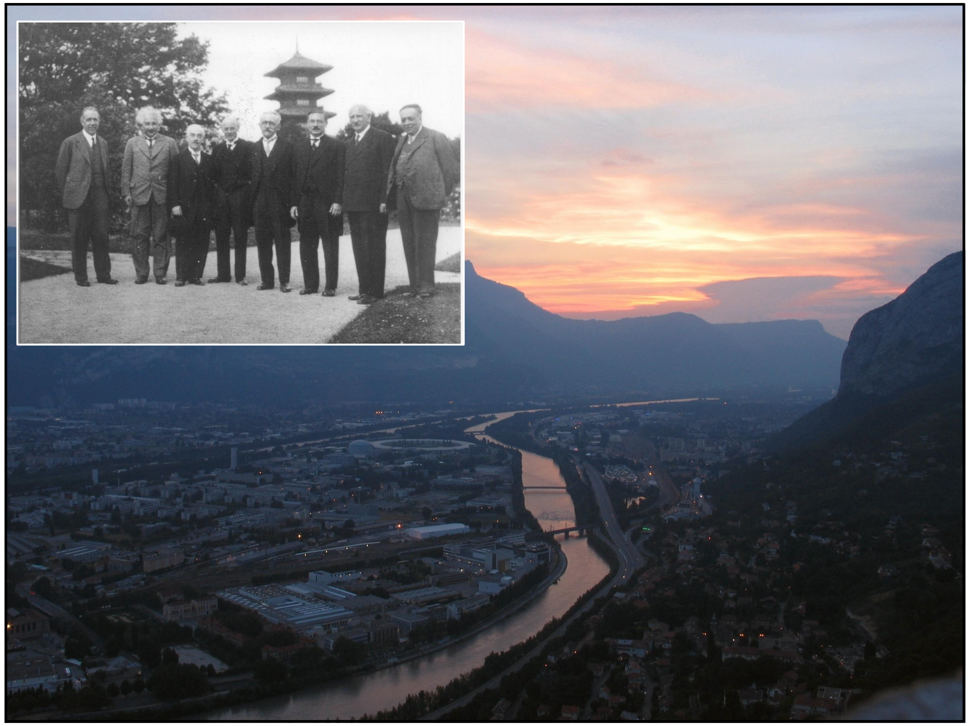


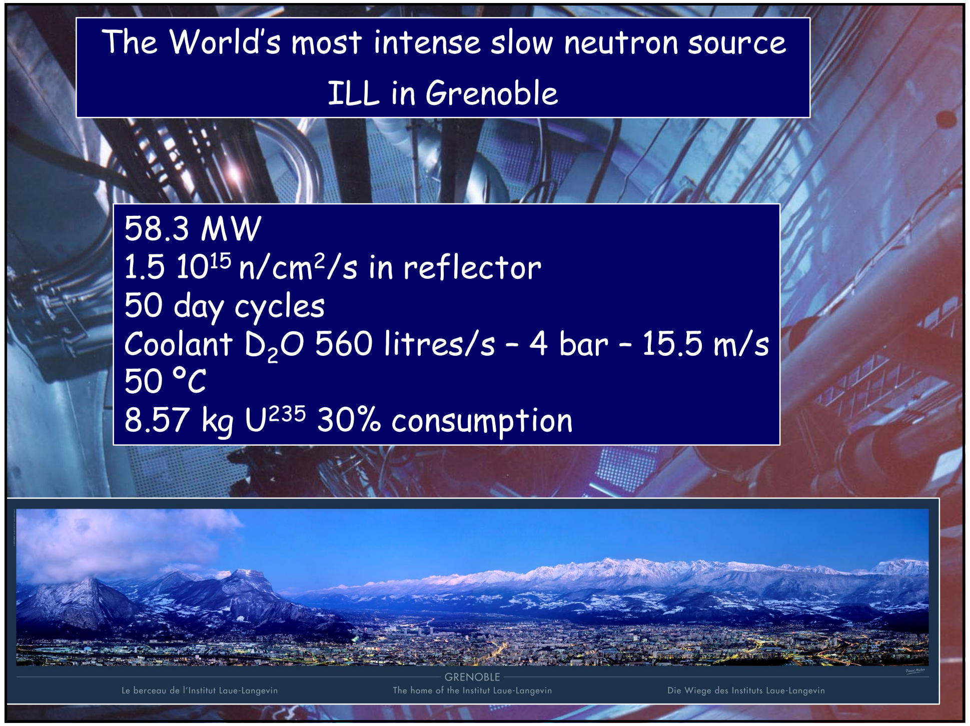
Fig. 2. Local flux distribution of the HFR as a function of the distance from the core axis.

Institut Laue Langevin

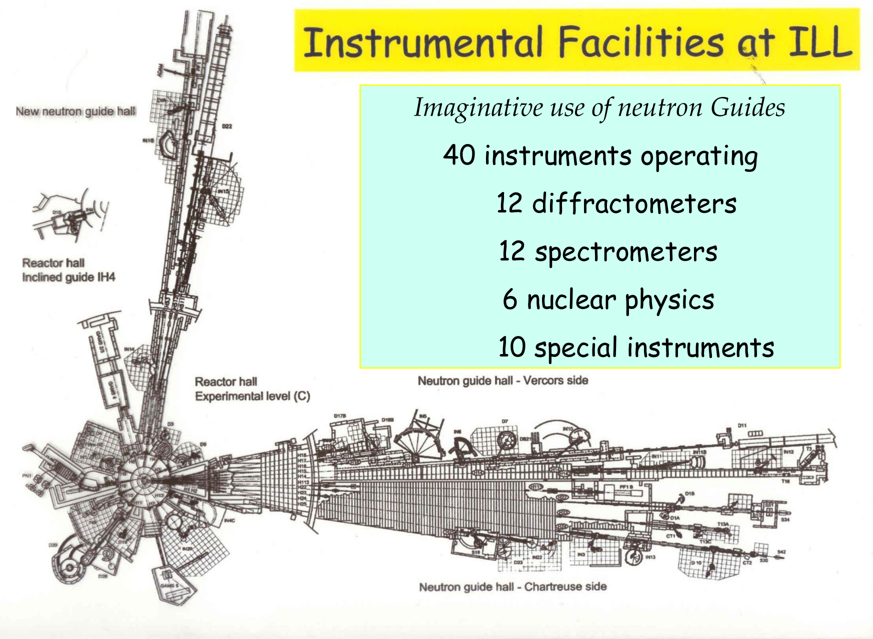







The World's most intense slow neutron source
ILL in Grenoble
58.3 MW
1.5 10^{15} n/cm^2/s in reflector
50 day cycles
Coolant D_2O 560 litres/s – 4 bar – 15.5 m/s
50 °C
8.57 kg U^{235} 30% consumption
GRENOBLE
Le berceau de l'Institut Laue-Langevin
The home of the Institut Laue-Langevin
Die Wiege des Instituts Laue-Langevin

Instrumental Facilities at ILL



Imaginative use of neutron Guides

40 instruments operating

12 diffractometers

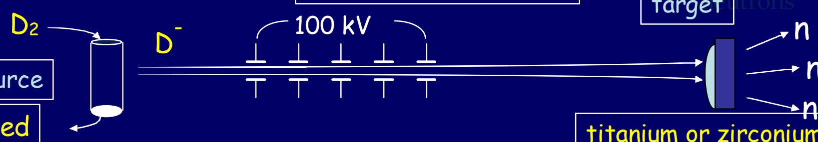
12 spectrometers

6 nuclear physics

10 special instruments

c. Accelerated Particles

(D,T) Fusion Reaction



accelerating electrodes

target

ion source

heated nickel tube

titanium or zirconium loaded with tritium

$H^2 + H^3 = He^4 + n^1 + 17.6$ Mev

Deuterium ions at 100 kV

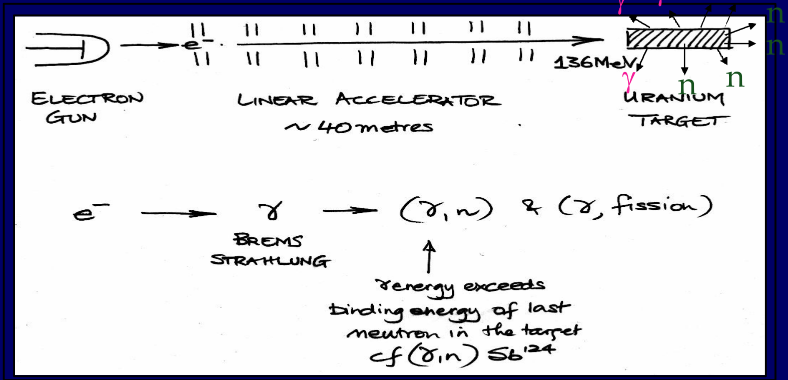
Tritium Target

14.1 MeV

gives ~ 10^{11} neutrons/sec continuous

Uses: Reactor Physics Experiments
e.g. Thermalisation in Graphite

Bremsstrahlung from Electron Accelerators



frequency & pulse width easily adjusted

uses: neutron scattering

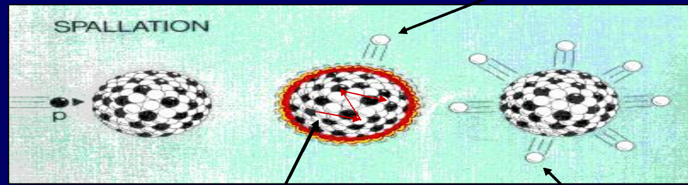
e.g. Lisone at Frascati

disadvantage: high γ - background

Spallation with Protons

What is Spallation?

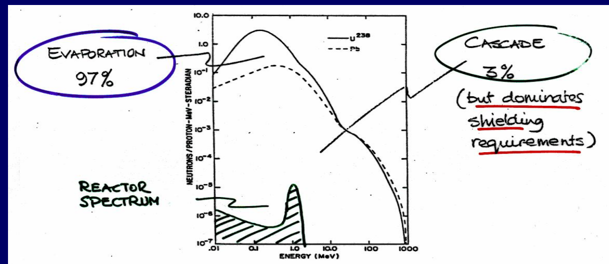
2. Inter Nuclear Cascade



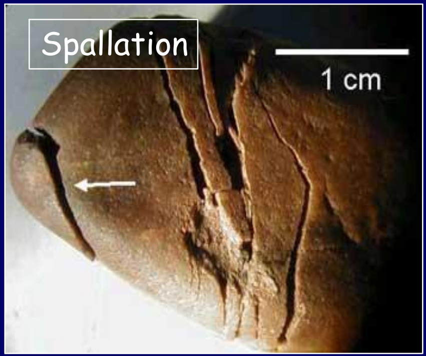
1. Internal Cascade

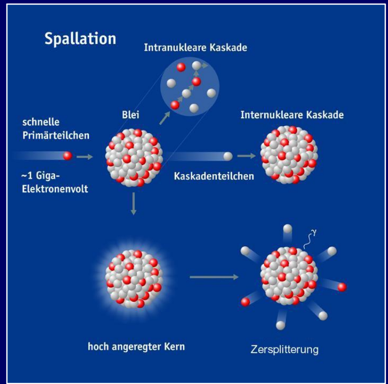
3. Evaporation

Up to 30 neutrons per incident proton



What is Spallation ?

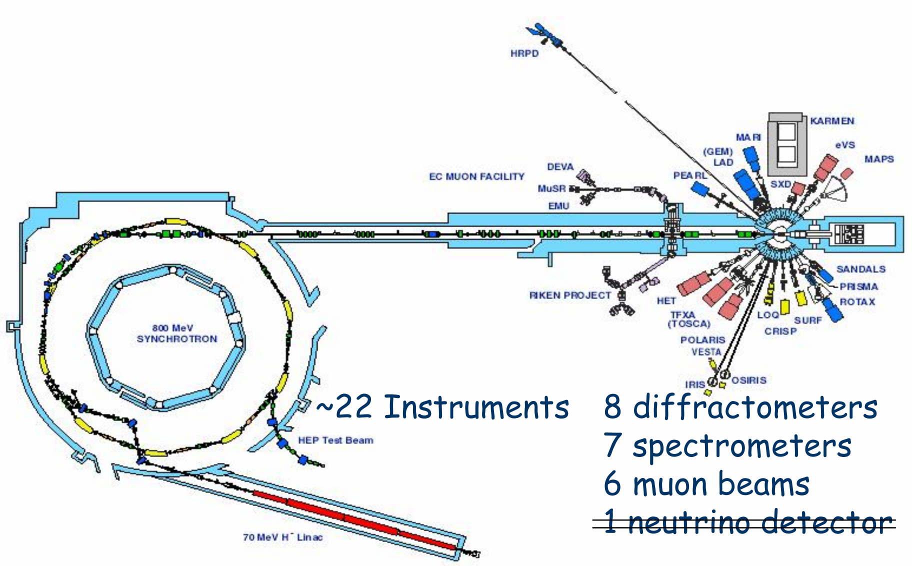




Up to 30 neutrons per proton produced

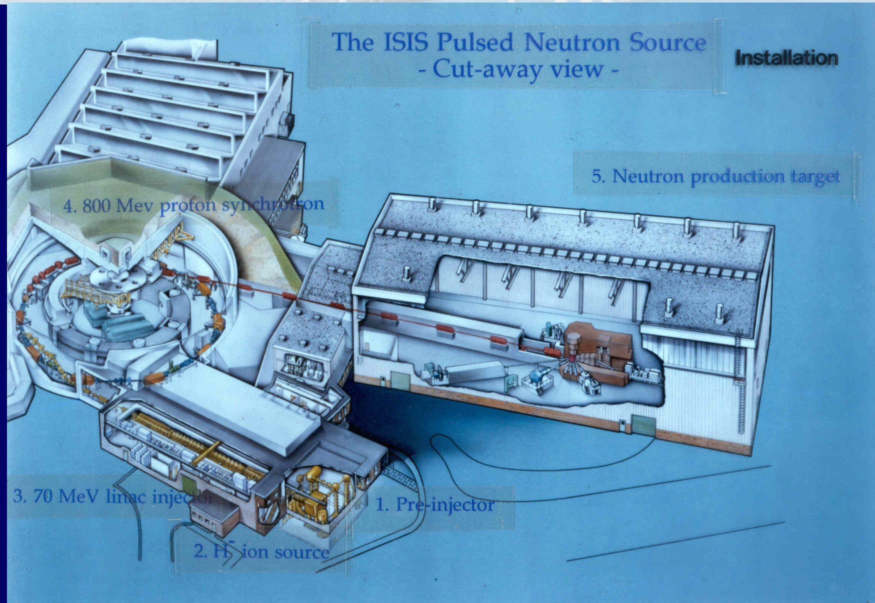
A bird's eye view of ISIS as it was built

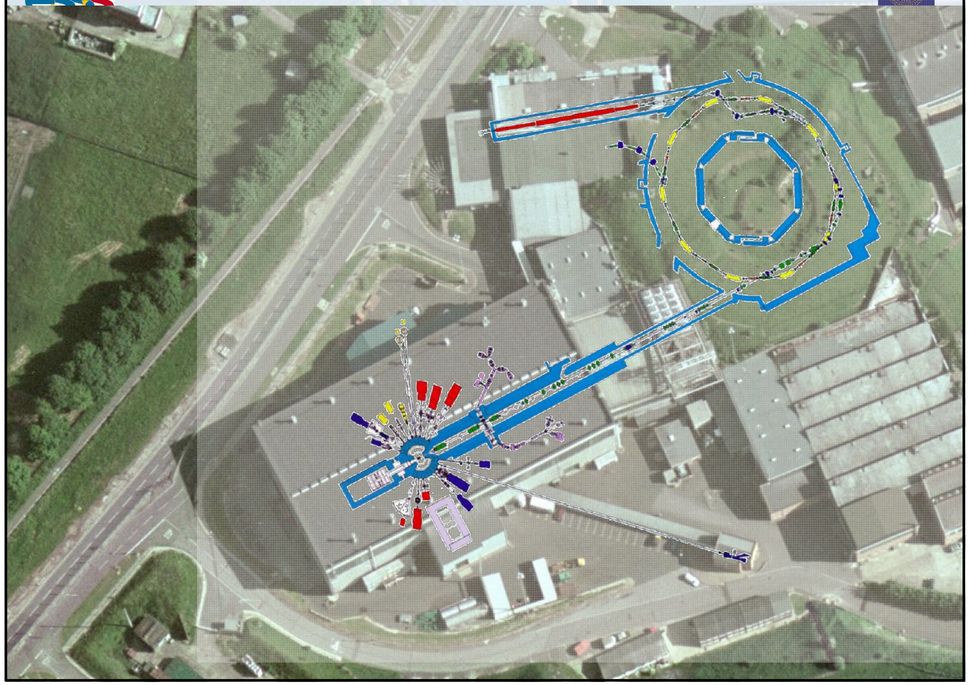
The ISIS Instrument Suite



~22 Instruments

8 diffractometers
7 spectrometers
6 muon beams
~~1 neutrino detector~~



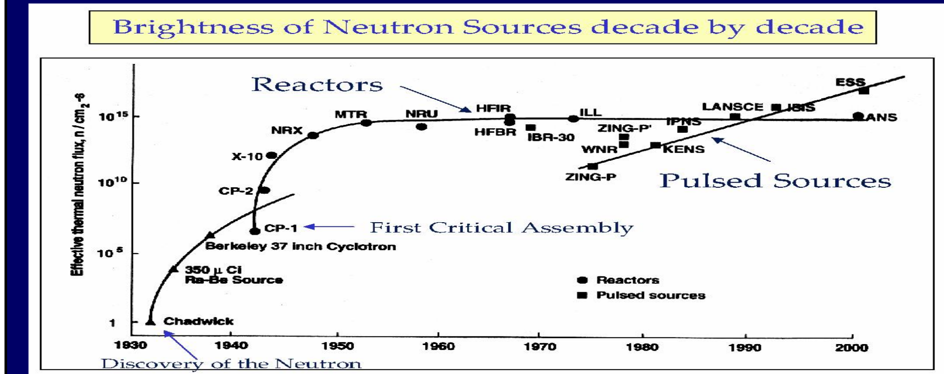


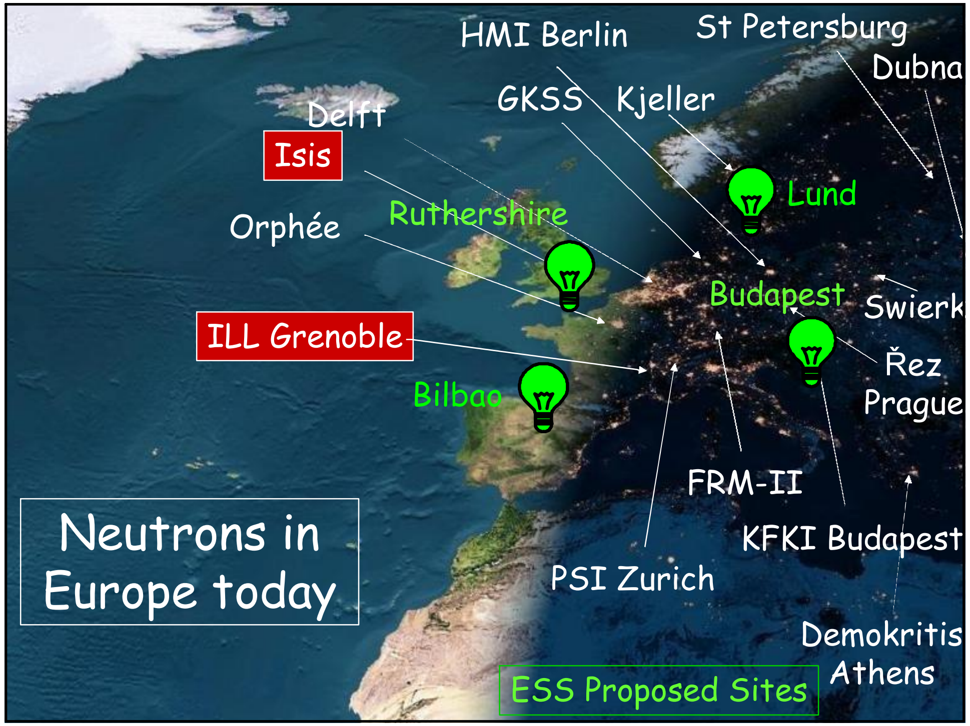
2. Modern Neutron Sources

a. The Quest for Higher Intensities

Reactors have reached the limit at which heat can be removed from the core

Pulsed sources have not yet reached that limit and hold out the promise of higher intensities





Neutron Sources today

Continuous Sources:

Operating: ILL 58MW; LLB Saclay Paris; HMI Berlin;
NIST USA; FRMII Munich; JRRIIIm Tokai;
KRR Serpong; HFIR Oak Ridge;
ARRII Lucas Heights Australia
SINQ 1MW continuous spallation

In build: CRRII China

Pulsed Sources:

Operating: ISIS 160kW; Los Alamos 90kW;
IPNS Argonne 20kW; KENS Tsukuba 5kW;
SNS Oak Ridge 90kW to 1.4MW
IBR2 Dubna 1MW pulsed reactor

In build: J-PARC Tokai 1MW; ISIS ts2

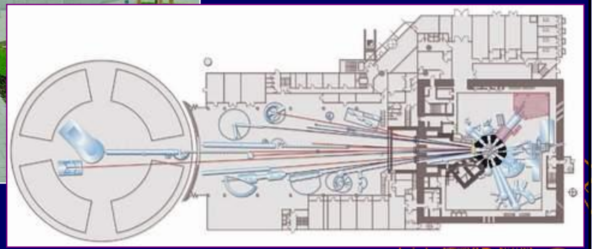
Projects: ESS 5MW

ILL – the world's leading neutron facility

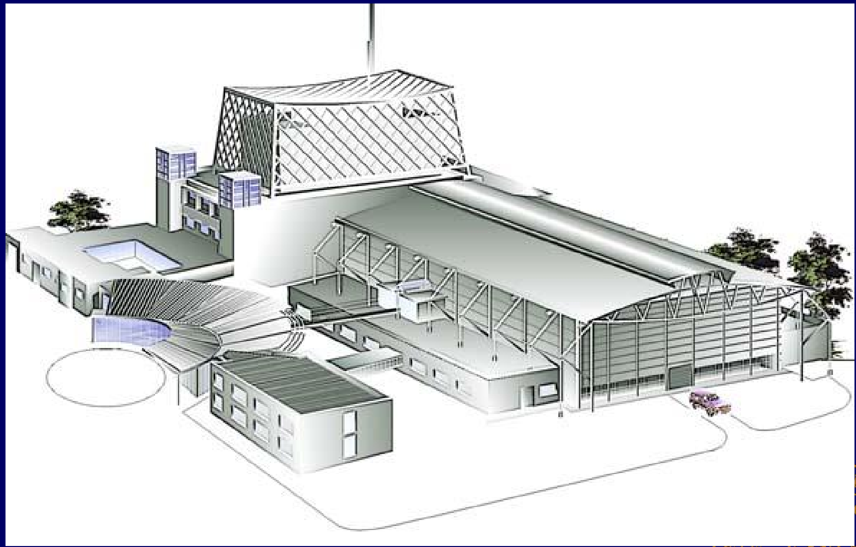
FRM-II Munich

High Fluxes
Nice Instruments

Operational at 20 MW
since summer 2004

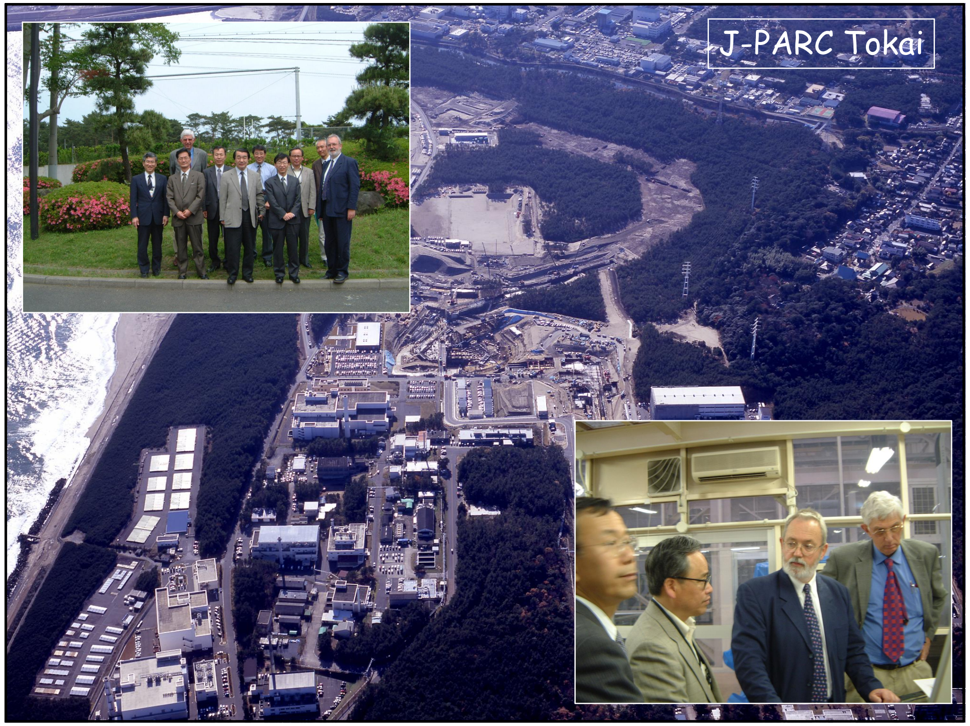


ARR-II Australia 15MW - Operational since 2006

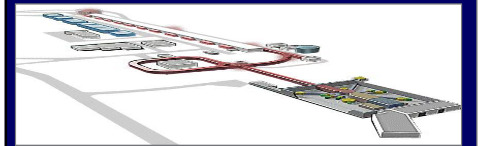


Finally, the USA got itself together

The US Spallation Neutron Source – a 1.4 MW pulsed source



USA commissioning 1.4 MW SNS $1.4B +

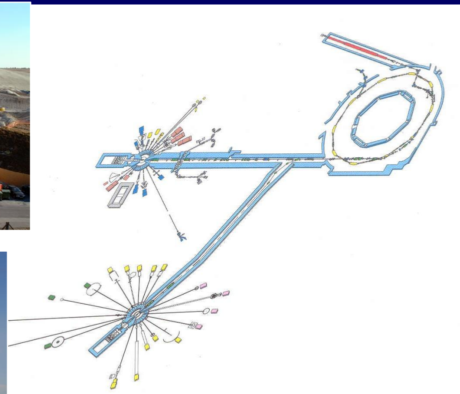


Commissioning	*2007/9*
Science	*2007 on*
Source at 6x ISIS	*2010*
Full Instrument suite	*2014*

Japan building 1 MW J-PARC $1.8B

Commissioning	*2008/10*
Science	*2009*
Source ~ 4x ISIS	*2011*
Full Instrument suite	*2015*

ISIS and its Second Target Station

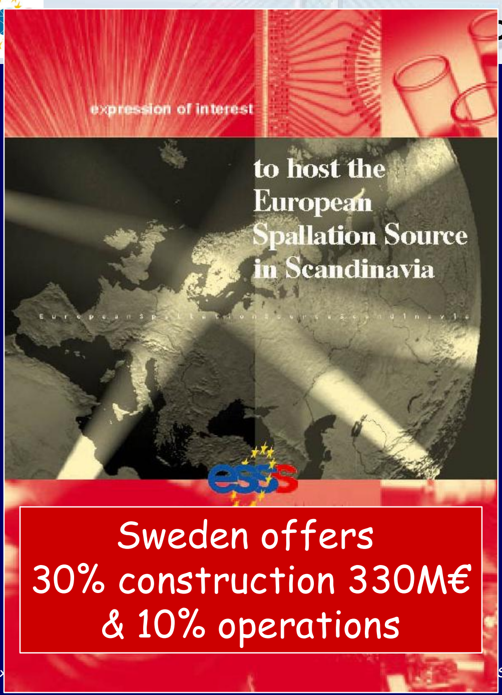


ISIS and its Second Target Station

ESS – the leading site contender - Lund

The European Spallation Source, Lund in Sweden

ontender - Lund



The European Spallation Source –

A 5 MW long-pulse Spallation source

Protons of 1.0 GeV current ~ 5 mA

ESS-S proposes to build ESS in Lund, with the Scandinavian countries as host countries

ESS in a Nutshell

- A 623 m long Proton linear accelerator at 1.0 GeV
- A liquid metal target (mercury or lead/bismuth)
- 22 neutron instruments
- Supports a 500-strong user community
  800 experiments per year
  600 papers per year
- 500 staff
- Capital cost 1.2 B€ - (9 BDKKr)
- Operating Cost 90 M€ p.a.
- First neutrons 2017

International Collaboration is the only way ahead

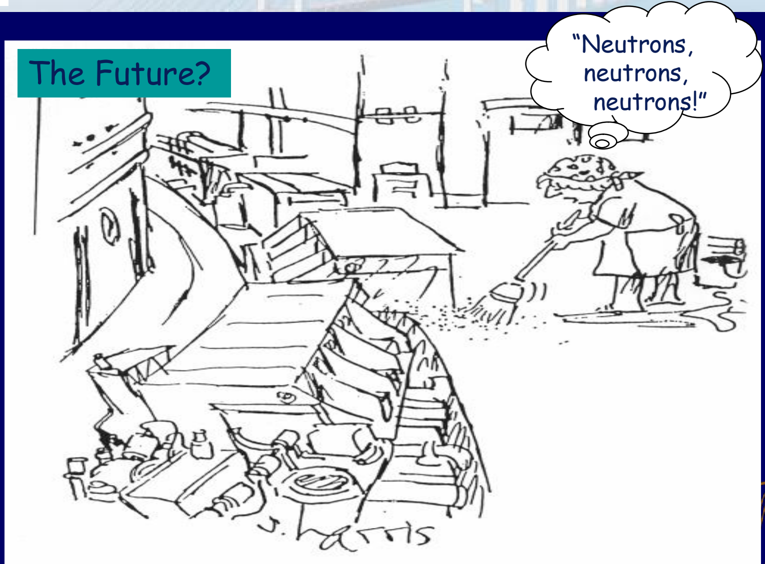
A Comparison of Reactors and Pulsed Sources

Pulsed Sources	Reactors
1. More High Energy Neutrons	1. More Low Energy Neutrons
2. Produce neutrons in bursts Measure when source is off Lower backgrounds	2. Easier to shield against fission neutrons Lower backgrounds
3. Pulsed Operation	3. Continuous Operation

If $\phi_{peak} \sim \phi_{average}$ then data rates are "equal"

Pulsed Sources	Reactors
4. Higher ϕ_{peak} possible	4. Higher $\phi_{average}$ difficult
5. Sharp pulses give high resolution	5. Resolution can be adapted to problem
6. Pulse shape asymmetric - resolution function asymmetric	6. Resolution function gaussian
7. Must use Time of Flight methods	7. Flexibility possible
8. Horizons still to be explored.	8. Mainly tried & tested techniques
9. Seen as environmentally friendly	9. Seen as environmentally unfriendly

The Future?



"Neutrons, neutrons, neutrons."

Further Reading

Neutron Physics K H Beckurts & K Wirtz
Springer-Verlag (1964)

The Elements of Nuclear Reactor Theory
S Glasstone & M C Edlund
Van Nostrand (1952)

Pulsed Spallation Neutron Sources for Slow Neutrons
J M Carpenter
Nuclear Instruments & Methods
(1977) 145, 91-113

The Neutron & the bomb
Andrew Brown
Oxford University Press (1998)