7th International Topical Meeting on Neutron Radiography (ITMNR-7)

The neutron's discovery – 80 years on

John Rogers

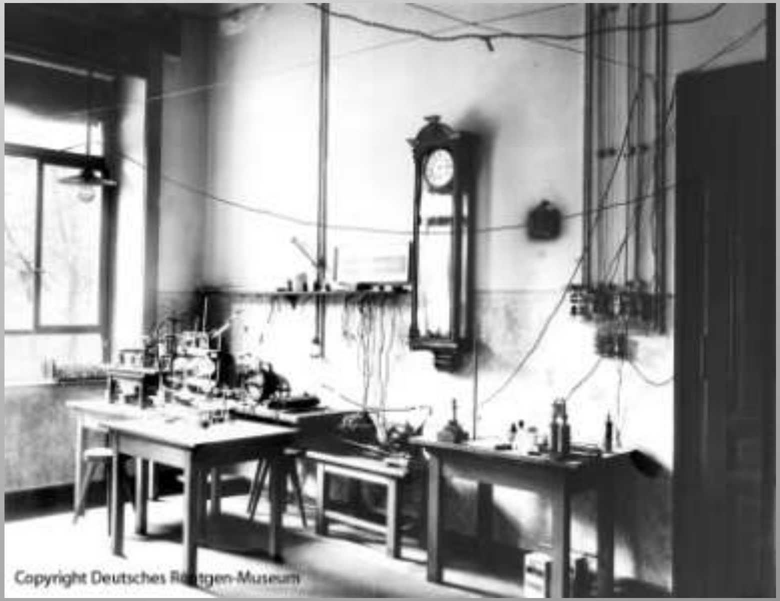
RadSci Consultancy Ltd

U.K.

Kingston, Ontario, Canada 16 – 24 June 2012

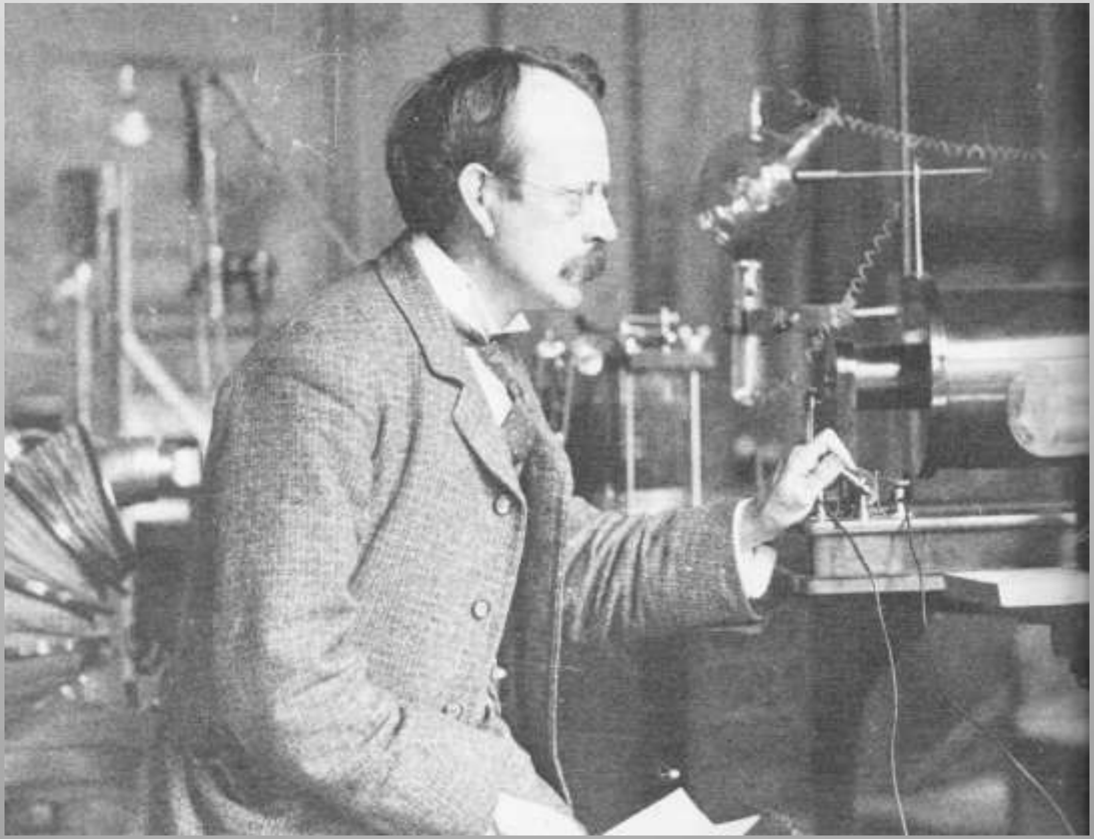
The start of the modern physics era

1895 – Wilhelm Röntgen discovered X-rays



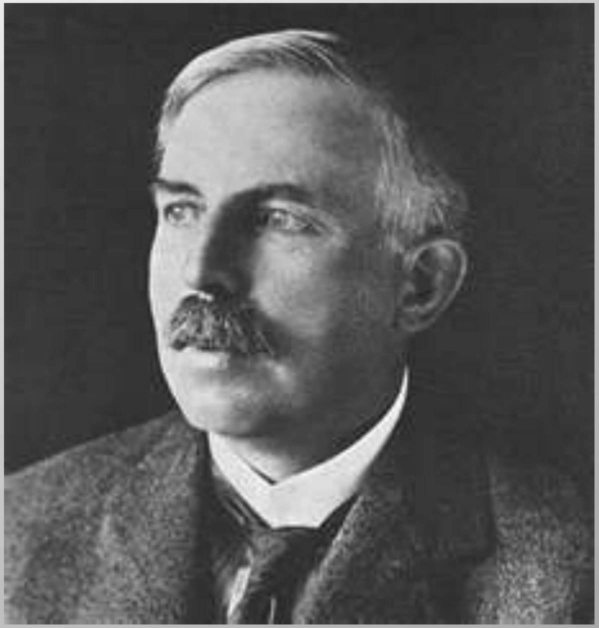
1896 - Henri Becquerel identified natural radioactivity in his studies of uranium salts

1897 - JJ Thomson discovered the electron in his studies of cathode rays



Ernest Rutherford

- After completing his studies at Cambridge University under JJ Thomson, he became a professor of physics at McGill University, Montreal, Canada in 1898.



Rutherford and Soddy at McGill University 1898 - 1907

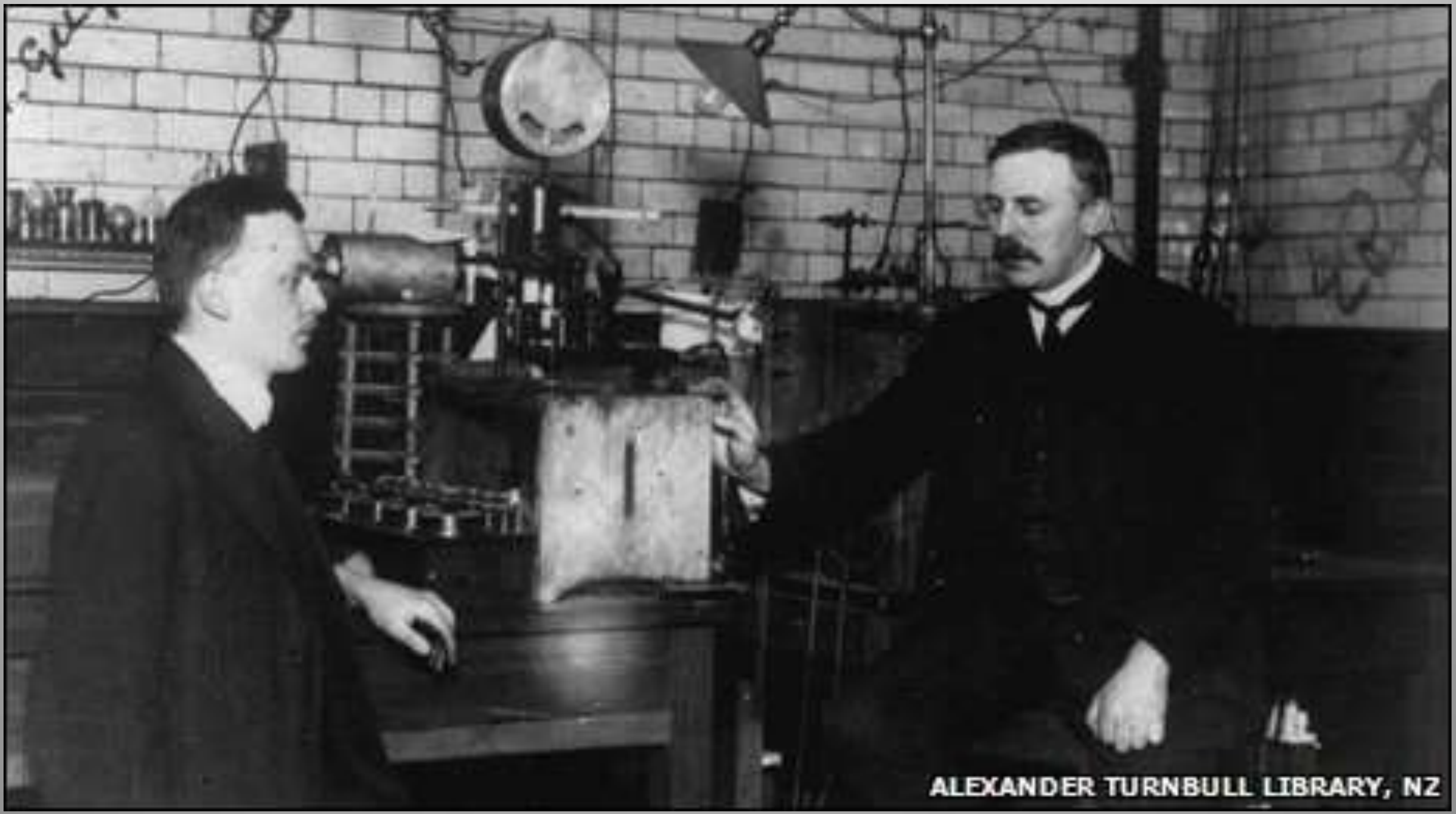
With Frederick Soddy, a chemist, Rutherford:-

- identified and named the alpha and beta particles
- determined the radioactive changes in the radium, thorium and actinium series
- derived the exponential nature of radioactive decay

Rutherford at Manchester University

1907 - 1919

Rutherford and Geiger



Rutherford’s Atom

- A series of classic experiments on the scattering of alpha particles was carried out by Hans Geiger and Ernest Marsden in 1913
- Rutherford deduced from the results that the atom contained a heavy positively charged nucleus
- Hantaro Nagaoka of Tokyo University had earlier (in 1904) proposed a nuclear model of a central nucleus with rings of orbiting electrons but this was never accepted because electrons would be expected to lose energy and collapse into the central nucleus

James Chadwick at Manchester University

- Chadwick was born and lived near Manchester
- Aged 16, he gained a scholarship to Manchester University in 1908
- Although he wanted to study maths, by mistake he was enrolled into the physics department

Chadwick

- Final year project - a test method for accurate inter-comparisons of Ra sources (after international agreement to define the Curie in terms of the radiation emission from 1 gm of Ra)
- Completed M.Sc. In 1912
- Awarded research scholarship in 1913
- Moved to Berlin to work with Geiger
- Chadwick was interned at the start of the war

1st World War

- Geiger and many other scientists on both sides were enlisted to fight at the front line
- Henry Moseley, who had measured the X-ray spectra of the elements and associated the increase in energy with increasing atomic number, was killed in the fighting in the Dardanelles in 1915

Niels Bohr at Manchester

- Niels Bohr obtained leave of absence from Copenhagen University to work with Rutherford as a post-doc
- He applied the quantum theory that had been proposed by Max Planck (in 1900) to Rutherford’s model of the atom and published in 1913 that atomic electrons could only occupy certain discrete orbits around a nucleus with each level at a certain energy
- Bohr later made another important contribution to nuclear physics with the concept of the compound nucleus in 1936

Rutherford

- In 1919, Rutherford discovered that light elements such as nitrogen disintegrated under alpha particle irradiation and a particle that he later named the proton emitted
- This was later proven to be the transmutation of nitrogen into oxygen in cloud chamber measurements carried out by Patrick Blackett at Cambridge University

Rutherford moves to Cambridge University

- Rutherford becomes professor of physics at the Cavendish Laboratory of Cambridge University in 1919
- He asked Chadwick, who had returned to Manchester after his internment, to go with him
- Chadwick becomes Assistant Director of the Laboratory and Rutherford’s right hand man

Cavendish Laboratory Staff and Research Students in 1933

Lewis, Walton
Chadwick, Thomson, Rutherford, Wilson, Blackett

Wilfrid Lewis – the father of CANDU

- Lewis was an expert in electronics
- After completing his PhD at the Cavendish Laboratory he continued there as a research staff member
- In the 2nd World War, he worked in a senior scientific role at the UK government's Telecommunications Research Laboratory.
- He was later appointed a Director of the Canadian NRC's Atomic Energy Division – now known as AECL.
- He pushed forward the development of the heavy water-natural uranium power reactor project, coming to be regarded as the father of CANDU.
- He became a professor of physics at Queen's University, Kingston.

Theoretical Atomic Physics Developments

The steady stream of experimental discoveries from the different laboratories stimulated the development of theoretical atomic physics by, among others,

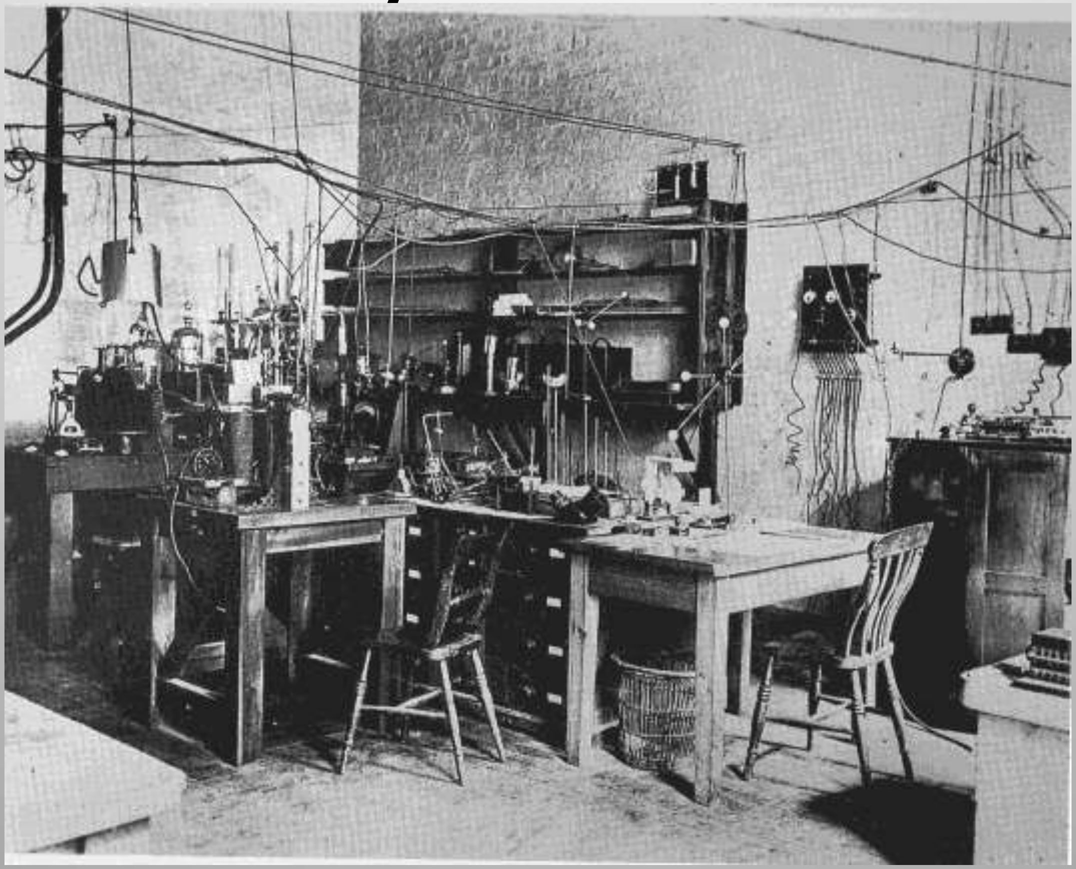
- Bohr in Copenhagen
- Lois de Broglie in Paris (who had proposed the wave theory of matter in 1924)
- Heisenberg in Berlin who proposed the new quantum physics in 1925 based on the mathematical description of observable quantities
- Schrodinger who announced his new wave mechanics principles in 1926

Discovery of the Neutron

In 1930, Walther Bothe and Herbert Becker bombarded beryllium, boron and lithium with alpha particles and discovered an intense form of radiation

The Joliot-Curies repeated these experiments and showed that if the radiation passed through paraffin wax, the intensity increased

Discovery of the Neutron

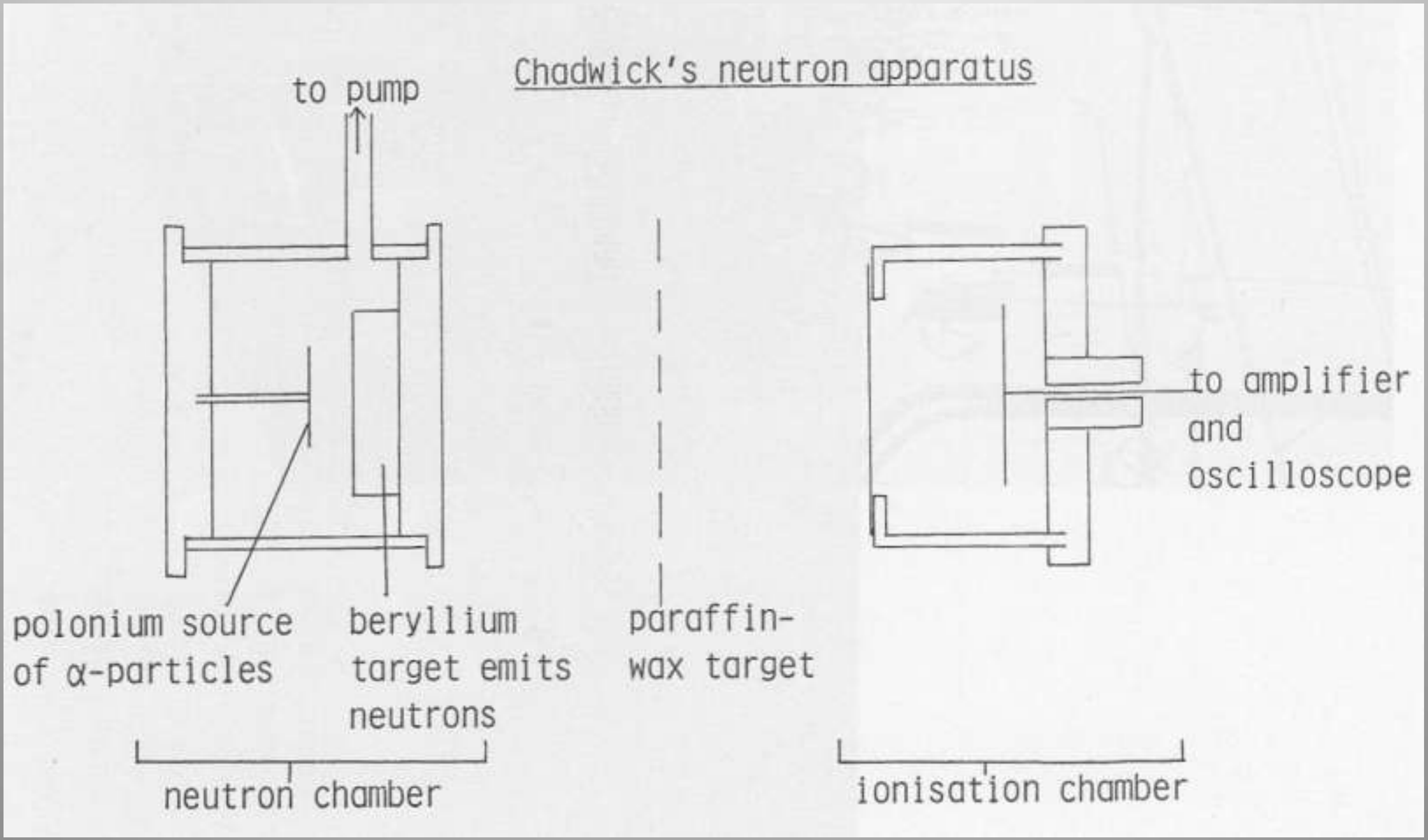


What would a modern Health and Safety officer have to say about Chadwick's Lab?!!

After reading the Joliot-Curies' paper in 1931, Chadwick immediately realised that, for energy and momentum to be conserved, a neutral particle must be being emitted

Chadwick’s vacuum chamber

Drawing of Chadwick's apparatus



Letter in Nature on the neutron's discovery Feb 27 1932

Letters to the Editor

[The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, nor to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. *No notice is taken of anonymous communications.]*

Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly 3×10^9 cm. per sec. They suggested that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50×10^6 electron volts.

I have made some experiments using the valve counter to examine the properties of this radiation excited in beryllium. The valve counter consists of a small ionisation chamber connected to an amplifier, and the sudden production of ions by the entry of a particle, such as a proton or α-particle, is recorded by the deflexion of an oscillograph. These experiments have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about $3 \cdot 2 \times 10^9$ cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

If we ascribe the ejection of the proton to a Compton recoil from a quantum of 52×10^6 electron volts, then the nitrogen recoil atom arising by a similar process should have an energy not greater than about 400,000 volts, should produce not more than about 10,000 ions, and have a range in air at N.T.P. of about 1·3 mm. Actually, some of the recoil atoms in nitrogen produce at least 30,000 ions. In collaboration with Dr. Feather, I have observed the recoil atoms in an expansion chamber, and their range, estimated visually, was sometimes as much as 3 mm. at N.T.P.

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons. The capture of the α-particle by the Be^9 nucleus may be supposed to result in the formation of a C^{12} nucleus and the emission of the neutron. From the energy relations of this process the velocity of the neutron emitted in the forward direction may well be about 3×10^9 cm. per sec. The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view. Moreover, I have observed that the protons ejected from hydrogen by the radiation emitted in the opposite direction to that of the exciting α-particle appear to have a much smaller range than those ejected by the forward radiation. This again receives a simple explanation on the neutron hypothesis.

If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts. It is difficult to make such a quantum responsible for the effects observed.

It is to be expected that many of the effects of a neutron in passing through matter should resemble those of a quantum of high energy, and it is not easy to reach the final decision between the two hypotheses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

J. CHADWICK.

Cavendish Laboratory,
Cambridge, Feb. 17.

The Oldoway Human Skeleton

A LETTER appeared in NATURE of Oct. 24, 1931, signed by Messrs. Leakey, Hopwood, and Reck, in which, among other conclusions, it is stated that "there is no possible doubt that the human skeleton came from Bed No. 2 and not from Bed No. 4". This must be taken to mean that the skeleton is to be considered as a natural deposit in Bed No. 2, which is overlaid by the later beds Nos. 3 and 4, and that all consideration of human interment is ruled out.

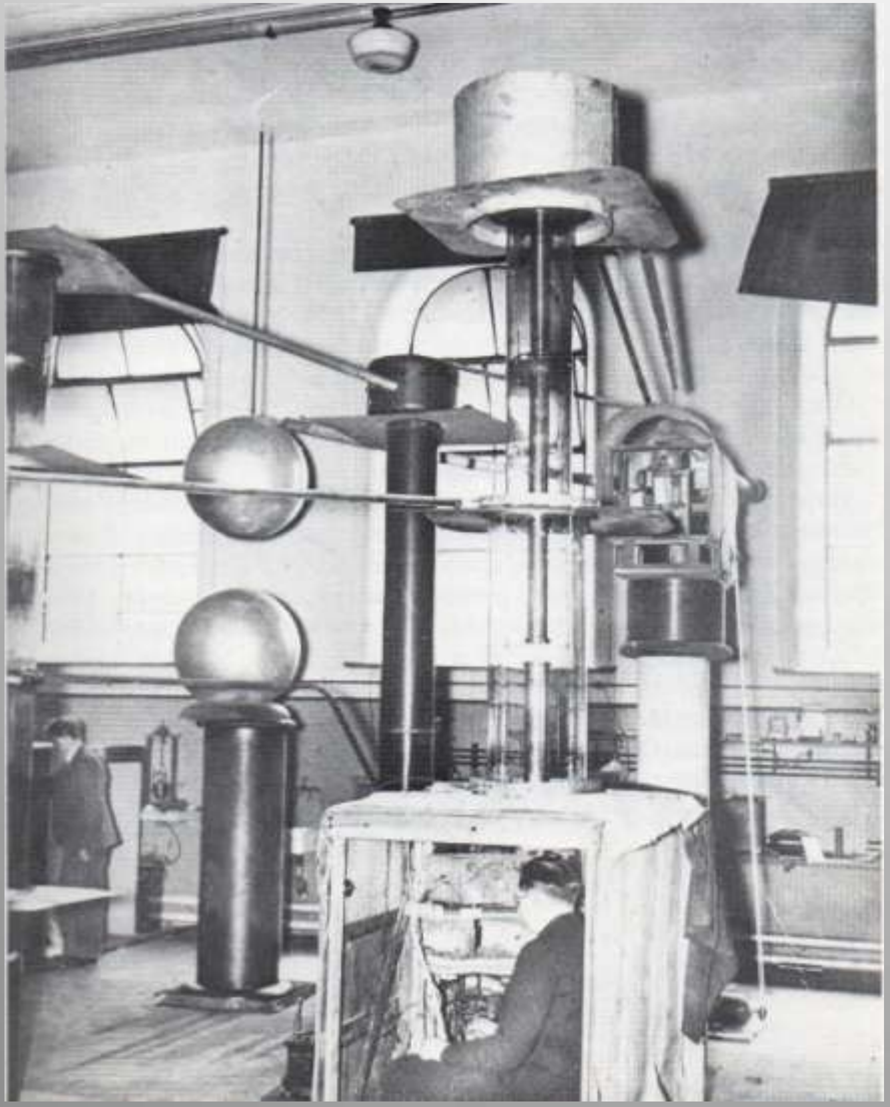
If this be true, it is a most unusual occurrence. The skeleton, which is of modern type, with filed teeth, was found completely articulated down even to the phalanges, and in a position of extraordinary contraction. Complete mammalian skeletons of any age are, as field palæontologists know, of great rarity. When they occur, their perfection can usually be explained as the result of sudden death and immediate covering by volcanic dust. Many of the more or less perfect skeletons which may be seen in museums have been rearticulated from bones found somewhat scattered as the result of death from floods, or in the neighbourhood of drying water-holes. We know of no case of a perfect articulated skeleton being found in company with such broken and scattered remains as appear to be abundant at Oldoway. Either the skeletons are all complete, as in the *Stenomylus* quarry at Sioux City, Nebraska, or are all scattered and broken in various degrees, as in ordinary bone beds. The probability, therefore, that the Oldoway skeleton represents an artificial burial is thus one that will occur to palæontologists.

The skeleton was exhumed in 1913, and published photographs show that the excavation made for its disinterment was extensive. It is, therefore, very difficult to believe that in 1931 there can be reliable evidence left at the site as to the conditions under which it was deposited. If naturally deposited in Bed No. 2, the skeleton is of the highest possible importance, because it would be of pre-Mousterian age, and would be in the company of *Pithecanthropus* and the Piltdown, Heidelberg, and Peking men, all of whose remains are fragmentary to the last degree. Of the few other human remains for which such antiquity is claimed, the Galley Hill skeleton and the Ipswich skeleton are, or apparently were, complete. The first of these was never seen *in situ* by any trained observer, and the latter has, we believe, been withdrawn by its discoverer. The other fragments, found long ago, are entirely without satisfactory evidence as to their mode of occurrence.

Ettore Majorana

- Majorana was an Italian theoretical physicist who made important contributions in nuclear particle studies and worked with Heisenberg and Bohr
- It is reported that Majorana, on reviewing the Joliot-Curie's results, also came to the conclusion that a neutral particle was being generated
- Fermi told him that he should publish his conclusions but he did not do this
- Majorana disappeared in 1938 after withdrawing all the money in his bank

1932 Cockcroft-Walton



Cockroft and Walton demonstrated nuclear transmutation in the Cavendish Laboratory by accelerating protons at 125 kV in a linear accelerator on to a lithium target and using a zinc sulphide screen to detect the alpha particles produced

Lawrence's Cyclotron

The first model cyclotron operated in 1931 was a 10cm diameter brass device operating at 2kV and accelerating protons to 80 kV

Ernest Lawrence took out a patent on the design in 1934

Werner Heisenberg

Within 3 weeks of the publishing of the neutron's discovery, Heisenberg wrote the first of three papers outlining the nuclear structure in which the principal components were protons and neutrons

Heisenberg

One day, Heisenberg decided to go for a drive. He accelerated in his fast car down the highway but was stopped by a policeman.

Policeman: “Herr Professor, have you any idea of the speed you were driving?”
Heisenberg: “Nein, but I know EXACTLY where I am!”

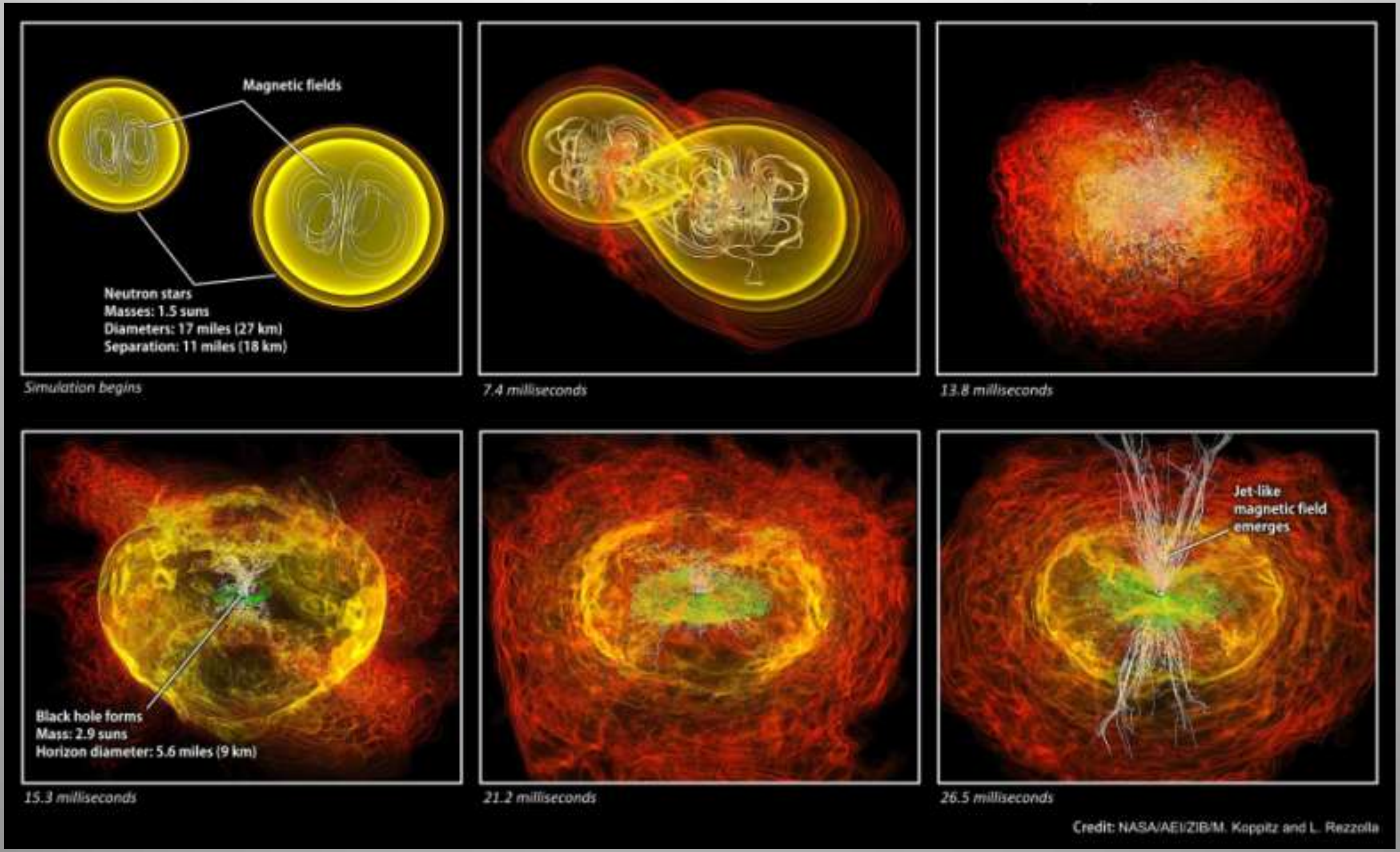
Neutron Stars

- In 1933, Walther Baade and Fritz Zwicky (astrophysicists working in California) identified supernovae as a new category of astronomical objects.
- In the following year (1934), they proposed the formation of neutron stars in supernovae.
- Zwicky also determined the gravitational mass of galaxies in a galaxy cluster and came to the conclusion that there was an unseen dark matter making up the bulk of the known universe

Pulsars

- In 1967, Jocelyn Bell and Anthony Hewish at Cambridge University detected a regular radio pulse emission from a distance source. The period of the first source they observed was very precise – 1.3373011 secs
- Thomas Gold identified this pulsar in 1968 as being an isolated, rotating neutron star

Neutron Stars and Gamma Bursts



NASA modelling of the black hole and gamma ray burst created by two colliding neutron stars

Neutron Chain Reaction

- In 1933, Leo Szilard realised that a neutron interaction with a nucleus could result in two or more neutrons being produced leading to the possibility of a nuclear chain reaction but he did not have his own laboratory to carry out this work

The nuclear force

Hideki Yukawa, whilst at Osaka University, published his meson theory in 1935 which explained the proton – neutron interaction in the nucleus. This involved the exchange of massive charged particles (~ 100 MeV) between n and p

The π meson was discovered by C Powell , Bristol University, in cosmic rays using nuclear film emulsions

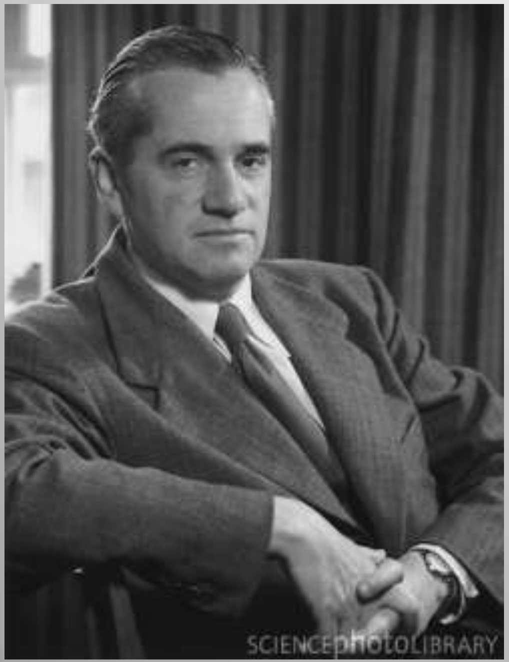
Enrico Fermi

- Fermi developed the theory of beta decay in 1934, incorporating the neutrino ideas of Pauli
- Following the discovery of artificial radioactivity published by the Joliot-Curies, he demonstrated nuclear transmutation in many of the elements
- Importantly, he discovered the increased interaction probability of slow neutrons
- He emigrated to the USA in 1938

Nuclear Fission

Otto Hahn and Fritz Strassman carried out some very elegant chemistry on the products of neutron reactions with different elements and for uranium, in 1939, they discovered the presence of barium in the break up of the nucleus

Nuclear Fission



Lise Meitner had been kept up to date with results of their work by her collaborators Hahn and Strassman. With Otto Frisch, Meitner identified and named the process as being one of fission.

Nuclear Chain Reaction

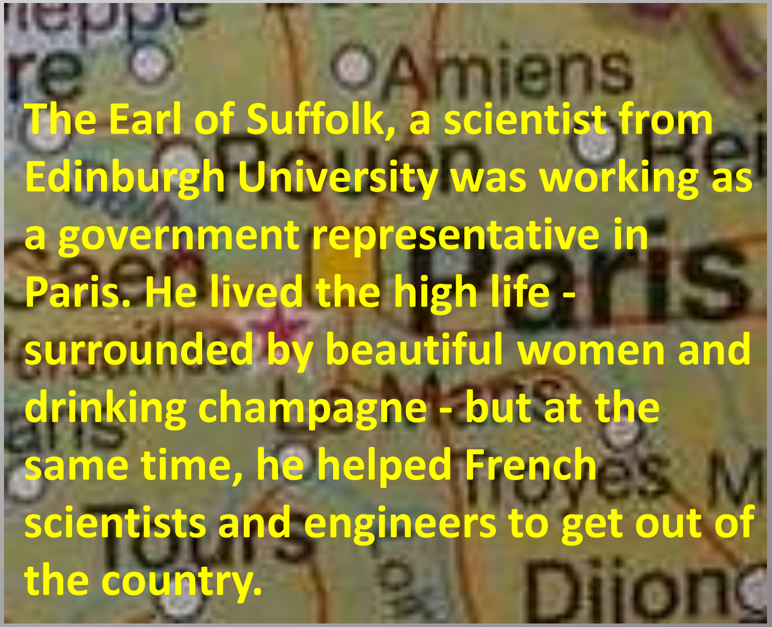
- Many laboratories were now studying the generation of energy from fission
- Ludwik Kowalski and Frederick Joliot-Curie measured the number of neutrons emitted in the fission of U-235
- Joliot-Curie took out a patent in 1940 for a heavy water moderated reactor
- Fermi carried out many experiments that would lead to building the first “atomic pile”(CP-1) in a rackets court in Chicago

The Heavy Water Saga
1940

The French had obtained 200 kg of heavy water from Norway via Scotland but, with the fall of France imminent, this material was removed from Joliot-Curie's laboratory to be shipped to Britain.

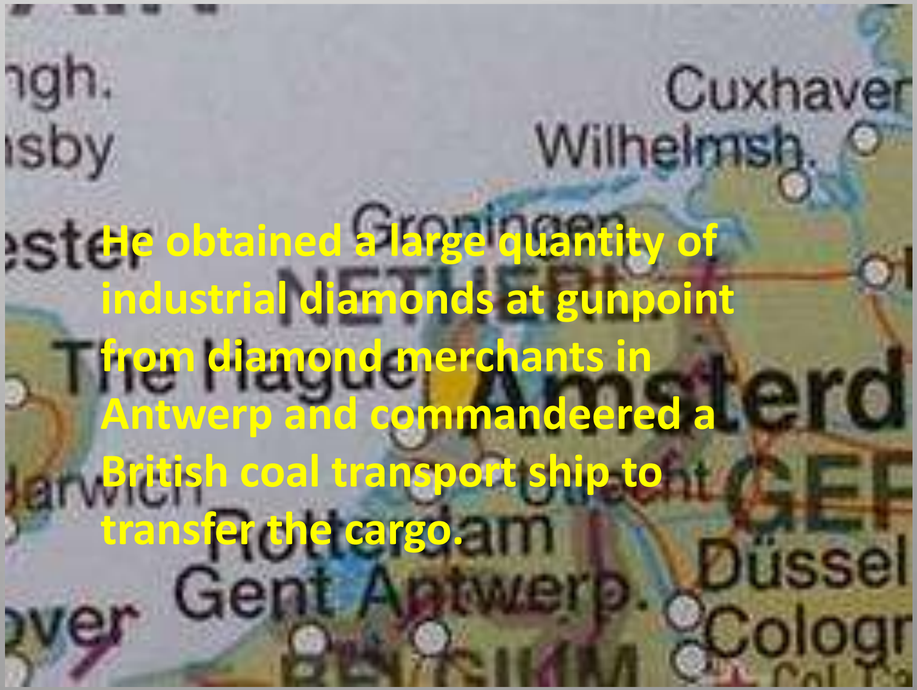
1940 – in Paris

Earl of Suffolk



The Earl of Suffolk, a scientist from Edinburgh University was working as a government representative in Paris. He lived the high life - surrounded by beautiful women and drinking champagne - but at the same time, he helped French scientists and engineers to get out of the country.

Industrial diamonds for the move



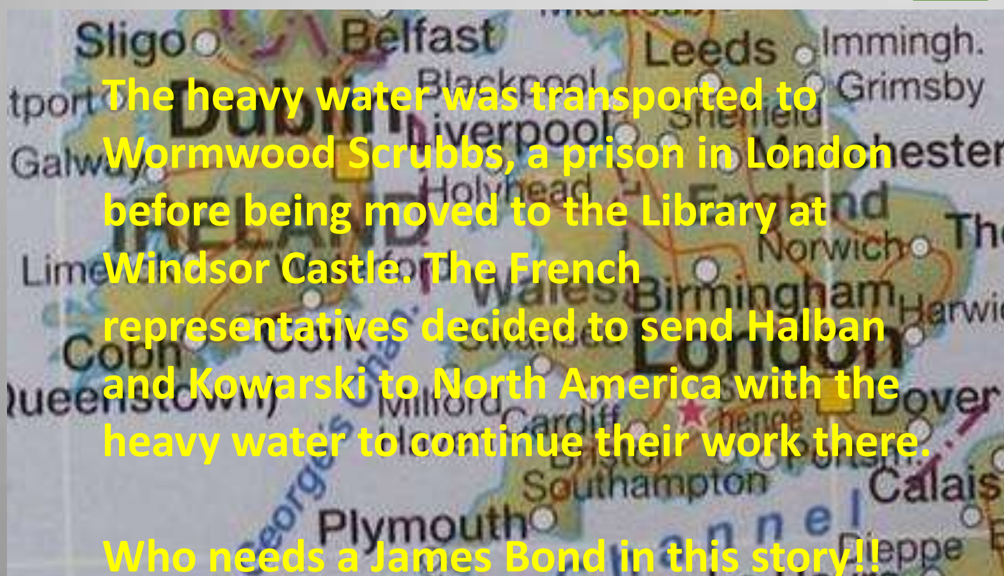
He obtained a large quantity of industrial diamonds at gunpoint from diamond merchants in Antwerp and commandeered a British coal transport ship to transfer the cargo.

The 26 cans of heavy water plus about 25 French scientists (including Hans von Halban and Kowarski, who worked in Joliot-Curie's laboratory and had co-authored an important paper on nuclear fission in 1939 with him) sailed to Britain in June 1940. Joliot-Curie himself did not want to leave France.

Arrival in England

To North America

Windsor Castle Library



The heavy water was transported to Wormwood Scrubbs, a prison in London before being moved to the Library at Windsor Castle. The French representatives decided to send Halban and Kowarski to North America with the heavy water to continue their work there.

Who needs a James Bond in this story!!

200 kg Heavy Water

Wormwood Scrubbs Prison

Nuclear Data

- Accurate nuclear data is important for theoretical modelling of multiplying and non-multiplying media
- Data was mainly acquired confidentially by each country
- 1955 First Geneva Conference on Peaceful Uses of Atomic Energy opened up a new era of international data interchange and cooperation

Data Compilation Centres

- National Nuclear Data Centre (Brookhaven, USA)
- Nuclear Data Bank (OECD, Paris, France)
- Nuclear Data Section (IAEA, Vienna, Austria)
- Centre for Nuclear Data (Obninsk, Russia)

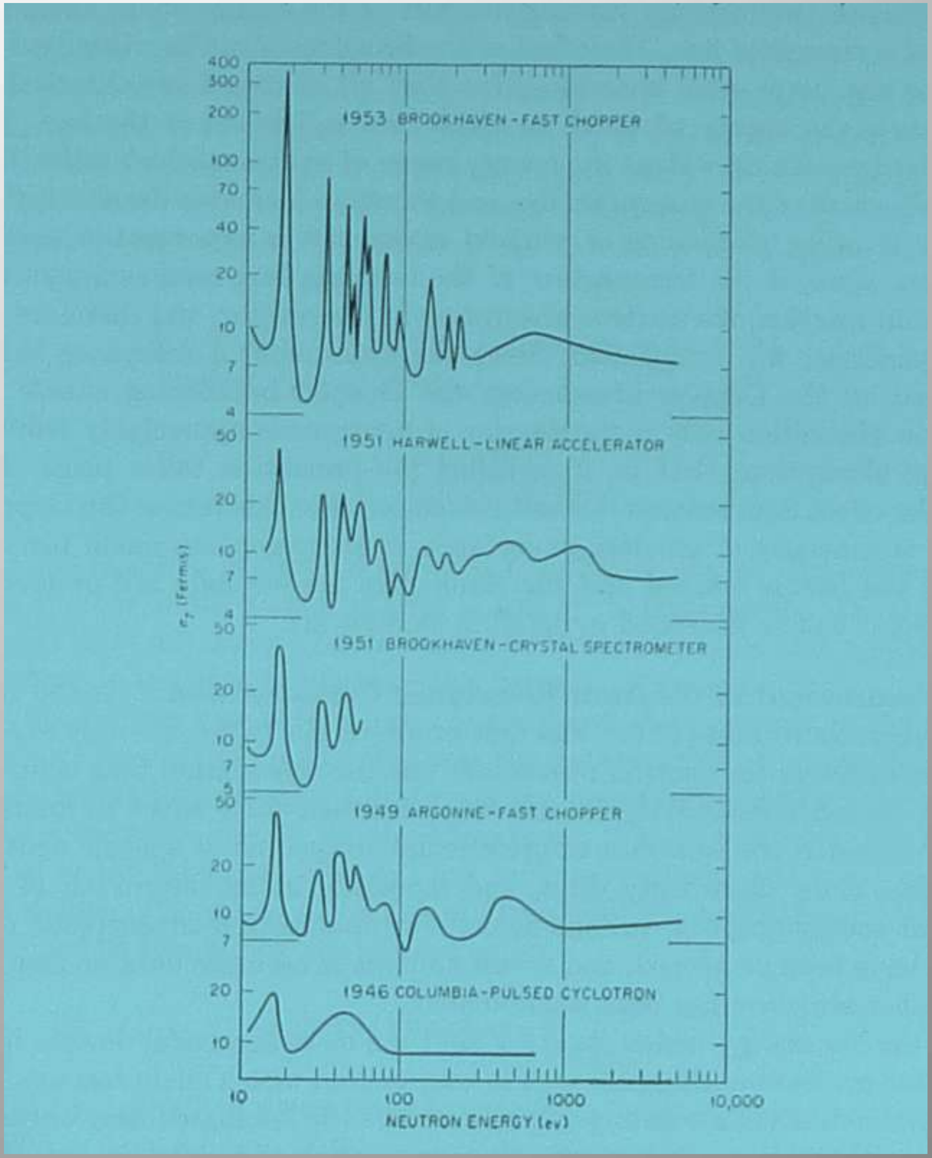
The Barn Book (BNL-325)

Improvement in Cross-section Measurements

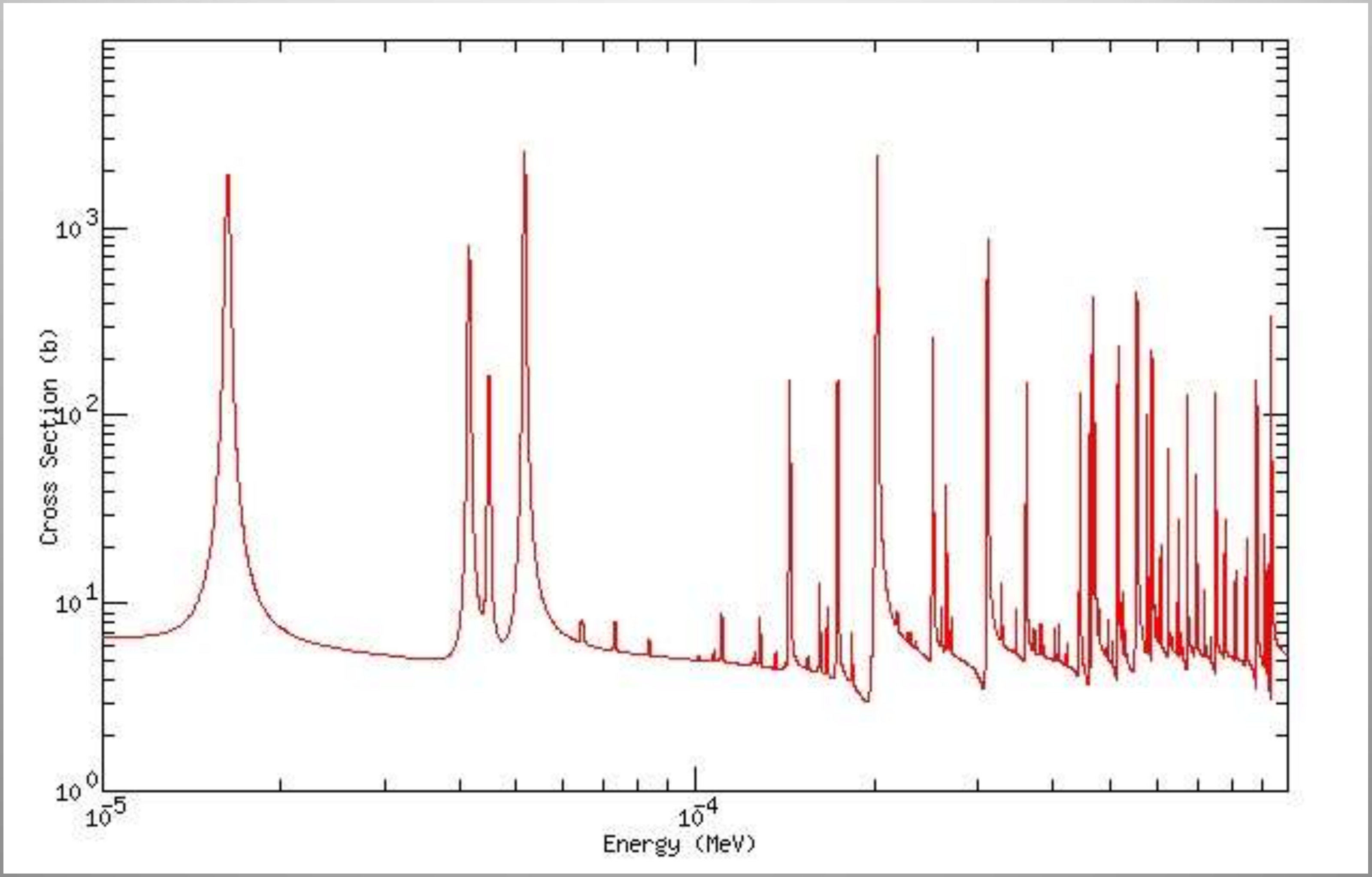
Neutron total cross-section for silver

Ref:

“The Physical Theory of Neutron Chain Reactors” Alvin Weinberg and Eugene Wigner, University of Chicago Press, 1958.



ENDF/B-VII σ-total data for silver



Evaluated Nuclear Databases

• ENDF/B-VII.1	(USA 2011)
• JEFF-3.1	(Europe 2005)
• JENDL-4.0	(Japan 2010)
• CENDL-3.1	(China 2009)
• ROSFOND	(Russia 2010)

Brockhouse Triple-Axis Spectrometer

- Brockhouse joined the AECL in 1950, working at the Chalk River Nuclear Laboratories
- He began to study the inelastic scattering of slow neutrons using the NRX (National Research Experimental) reactor, which at the time had the world's highest flux beam intensity

Brockhouse Triple-Axis Spectrometer

- In 1952, Brockhouse constructed a triple-axis spectrometer to measure energy and momentum transfers in solid and liquid media
- This instrument has become one of the most versatile instruments for measuring excitations in solids via neutron scattering
- In 1962, he became a professor of physics at McMaster University
- He was awarded the Nobel prize for Physics in 1994, jointly with Clifford Shull, who had started his pioneering work on the neutron diffraction technique in 1946 at the Oak Ridge National Laboratory

The Westcott Convention

- Carl Westcott was one of Rutherford’s last PhD students – receiving his degree in 1936 for studies of the processes involved in the neutron’s interactions with matter
- In 1944, he transferred to the British/Canadian Atomic Energy Project at the National Research Laboratories in Montreal and then to the Chalk River Nuclear Laboratory where he specialised in nuclear data acquisition and use

Westcott

- The “Westcott Convention” was used to easily and accurately estimating neutron reaction rates in thermal neutron reactors with spectra well defined by the Maxwell-Boltzmann distribution
- Tabulated g and r cross-section functions for different activation materials at different neutron temperatures were produced
- These could be used to determine reaction rates including cadmium ratios and for calculating neutron temperatures using thin activation foils

Neutron Sources

- High flux reactors
- Spallation neutron sources
- Other accelerator sources

Many of the first generation multi-beam accelerator and reactor sources have now been de-commissioned.

Today, very diverse neutron physics experiments are carried out mainly at spallation neutron source centres or at high flux reactors.

Neutron Radiography Meetings

Neutron radiography research has been well documented at the following meetings:-

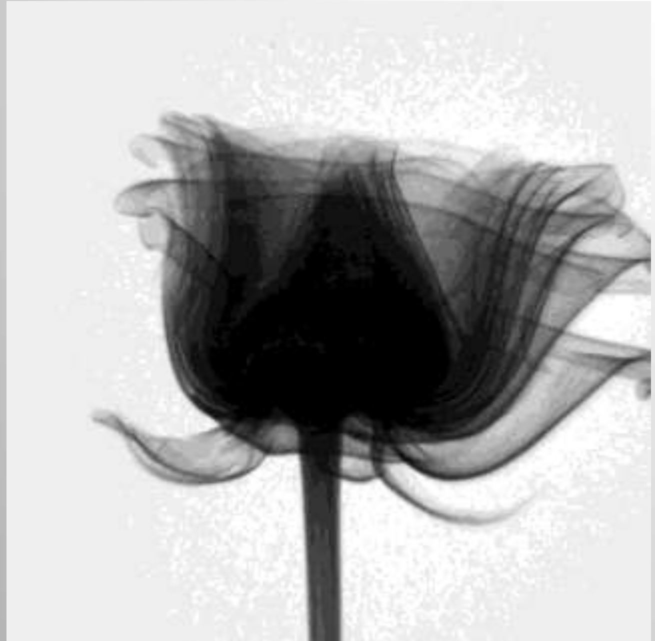
- Transactions of the American Nuclear Society in 1971
- Radiography with Neutrons – University of Birmingham in 1973
- World Conference on Neutron Radiography Series in 1981, 1986, 1989, 1992, 1996, 1999, 2002, 2006, 2010
- International Technical Meetings on Neutron Radiography in 1990, 1995, 1998, 2001, 2004, 2008, 2012
- NeuWave in 2008, 2009, 2011

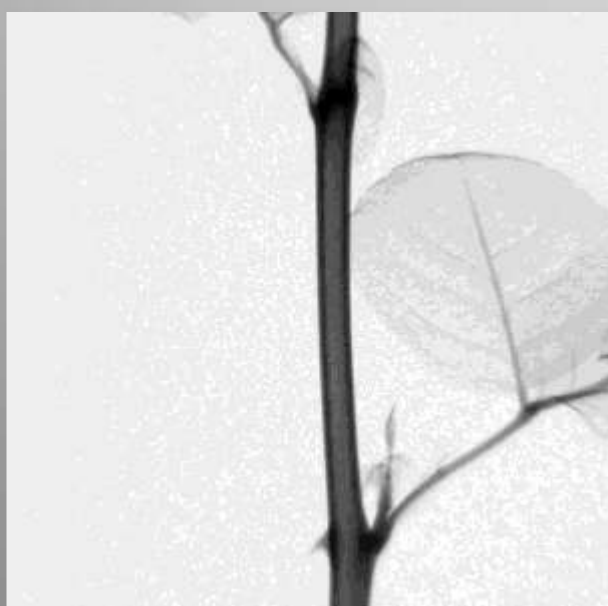
References

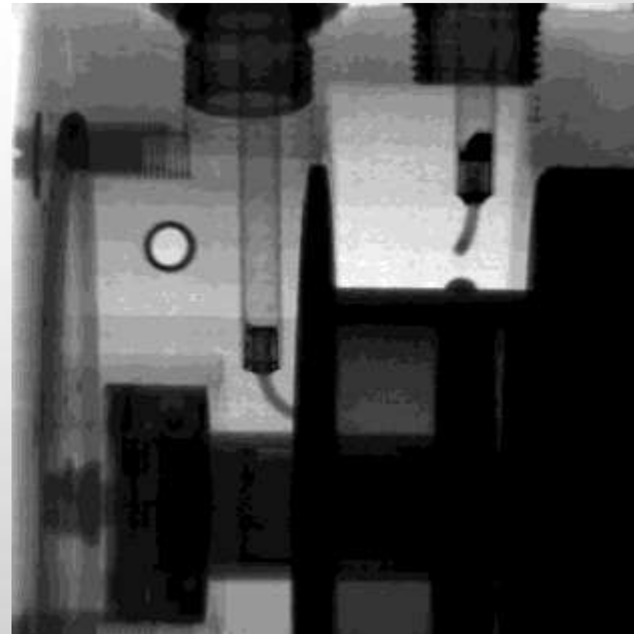
- Evans RD. *The atomic nucleus.* New York: McGraw Hill; 1955.
- Birks JB, editor. *Rutherford at Manchester.* London: Heywood; 1962.
- Brown A. *The neutron and the bomb.* Oxford: OUP; 1997.
- Weinberg AM and Wigner EP. *The physical theory of neutron chain reactors*. Chicago: University of Chicago; 1958.
- Crowther JG. *The Cavendish Laboratory 1874 - 1974.* London: Macmillan; 1974.
- Chadwick J. Possible existence of a neutron. *Nature 1932*; 129: p312.
- Schofield P, editor. *The neutron and its applications, 1982.* London: IoP; 1983.
- Chadwick L and Goldhaber M. A nuclear photo-effect: disintegration of the diplon by gamma rays. *Nature 1934; 134:237-238.*
- Rhodes R. *The making of the atomic bomb*. New York: Simon & Schuster; 1986.
- Fischer C-O. The history of the first neutron radiographs in Berlin, 1935 - 1944. *Neutron Radiography (4) Proceedings of the Fourth World Conference. Gordon and Breach; 1992.*
- Berger H. *Neutron radiography methods, capabilities and applications.* Amsterdam: Elsevier; 1965.
- de Beer F, editor. Proceedings of the 9th World Conference on Neutron Radiography. Nucl. Instr. and Meth. 2011; A651: 1: p1-336.

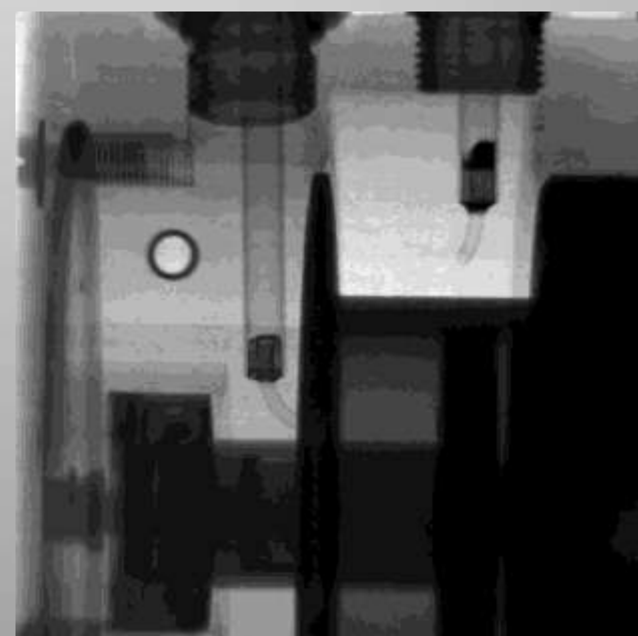
Acknowledgements

- Thanks to Les Bennett, Emeritus Professor at the Royal Military College of Canada and to students Herbert Lam and Dannielle Whittier, students at the Queen’s University, Kingston for allowing me to use some of the bibliographic material that they had researched.









RadSci Consultancy Ltd and SCITEK Consultants Ltd at PSI