What was known about NSE in 1932?

Retracing Chadwick’s discovery of the neutron

X-rays – Roentgen – Nov. 8, 1895

Wilhelm Roentgen

1st x-ray, 1895

Better x-ray, 1896

Image sources: Wikimedia Commons, “Roentgen” (Public domain)

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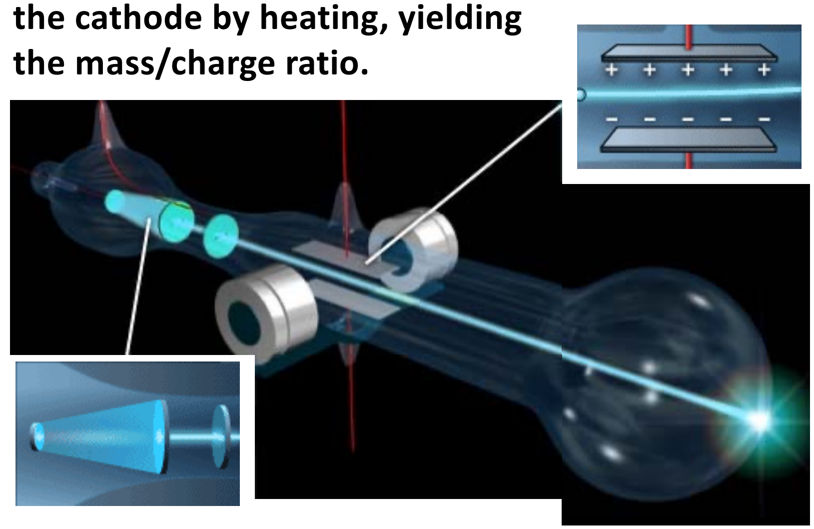
J. J. Thompson – The Electron (1897)

Sir Joseph John Thomson

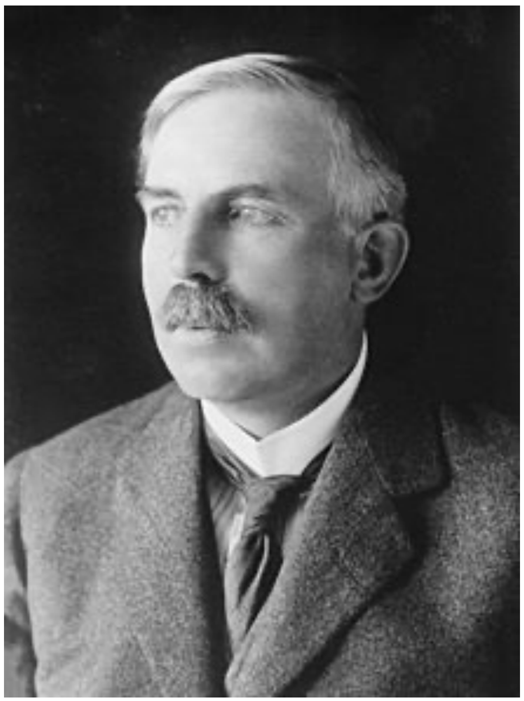
Image: Wikimedia Commons (Public domain)

Illustration of the cathode ray tube that led to the electron discovery. Charged plates bent a beam of "cathode rays," liberated from the cathode by heating, yielding the mass/charge ratio.



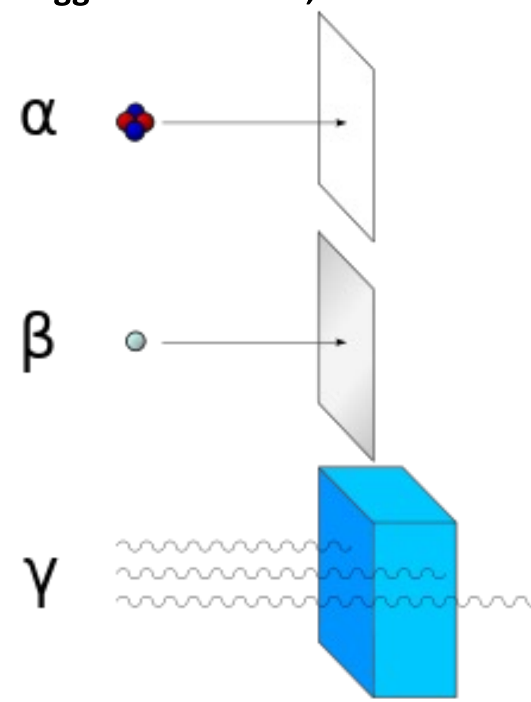
Rutherford and Villard – α-Particles (1900)

Ernest Rutherford



Paul Villard

A-particles were defined by Rutherford to have the lowest penetrating power of all emitted particles. Mass/charge ratio suggested He-ions, later confirmed.



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So… what did Chadwick see?

Possible Existence of a Neutron

James Chadwick
Nature, p. 312 (Feb. 27, 1932)

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 been 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.

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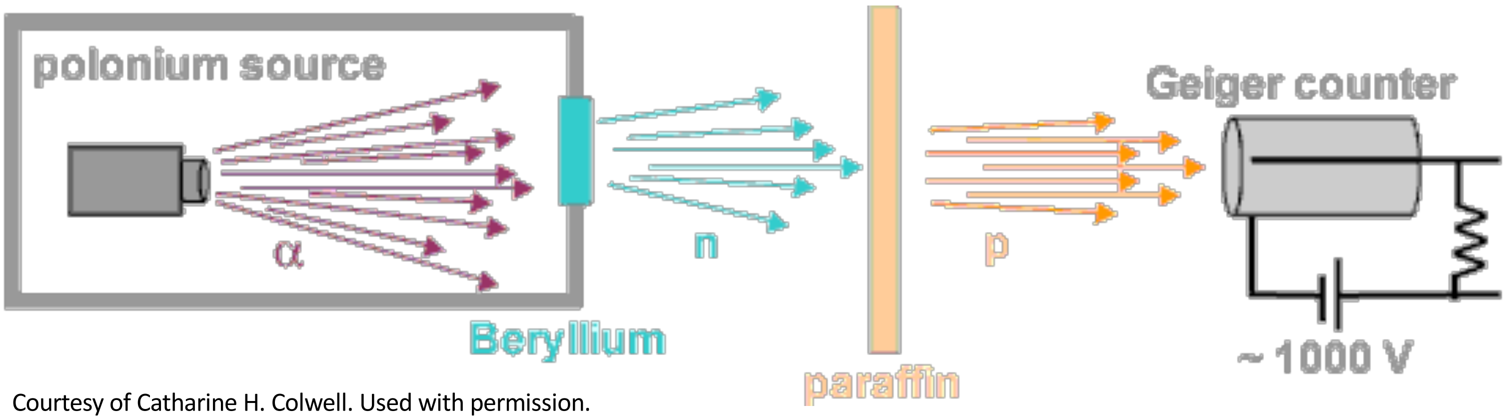

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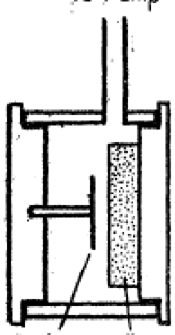


Chadwick's Po source, ionization chamber, and oscillograph

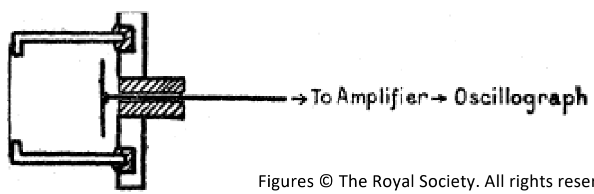


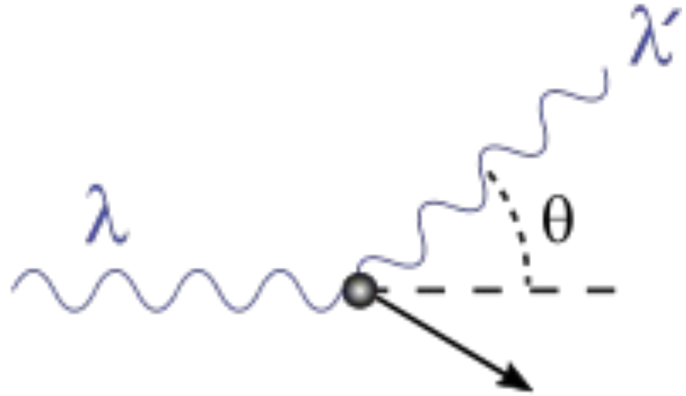
FIG. 1.

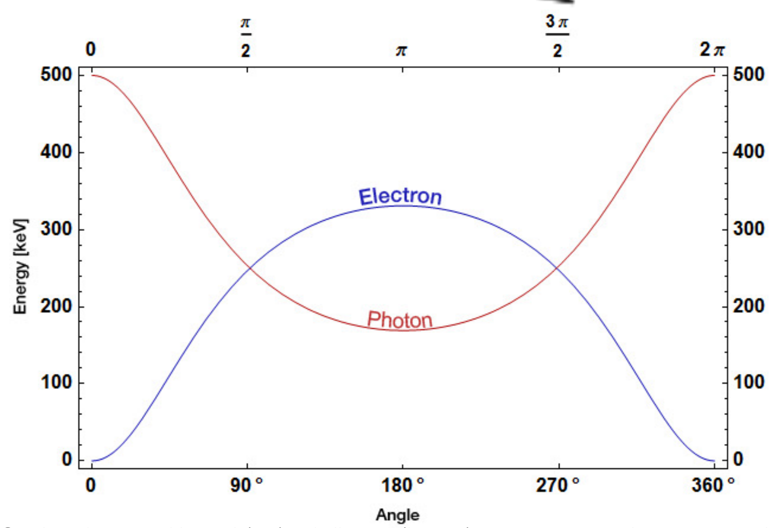
J. Chadwick, "The Existence of a Neutron," *Royal Soc. Pub. A*, p. 692 (1932)

Compton Scattering – Photon-Electron Collisions (1923)

Arthur Holly Compton

Image sources: Wikimedia Commons (Public domain)





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 3.2×10^9 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 the 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 of 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.

§ 1. It was shown by Bothe and Becker* that some light elements when bombarded by α-particles of polonium emit radiations which appear to be of the γ-ray type. The element beryllium gave a particularly marked effect of this kind, and later observations by Bothe, by Mme. Curie-Joliot† and by Webster‡ showed that the radiation excited in beryllium possessed a penetrating power distinctly greater than that of any γ-radiation yet found from the radioactive elements.

There are two grave difficulties in such an explanation of this phenomenon. Firstly, it is now well established that the frequency of scattering of high energy quanta by electrons is given with fair accuracy by the Klein-Nishina formula, and this formula should also apply to the scattering of quanta by a proton. The observed frequency of the proton scattering is, however, many thousand times greater than that predicted by this formula. Secondly, it is difficult to account for the production of a quantum of 50×10^6 electron volts from the interaction of a beryllium nucleus and an α-particle of kinetic energy of 5×10^6 electron volts. The process which will give the greatest amount of energy available for radiation is the capture of the α-particle by the beryllium nucleus, Be^9, and its incorporation in the nuclear structure to form a carbon nucleus C^{13}. The mass defect of the C^{13} nucleus is known both from data supplied by measurements of the artificial disintegration of boron B^{10} and from observations of the band spectrum of carbon; it is about 10×10^6 electron volts. The mass defect of Be^9 is not known, but the assumption that it is zero will give a maximum value for the possible change of energy in the reaction $Be^9 + \alpha \rightarrow C^{13}$ + quantum. On this assumption it follows that the energy of the quantum emitted in such a reaction cannot be greater than about 14×10^6 electron volts.

When a sheet of paraffin wax about 2 mm. thick was interposed in the path of the radiation just in front of the counter, the number of deflections recorded by the oscillograph increased markedly. This increase was due to particles

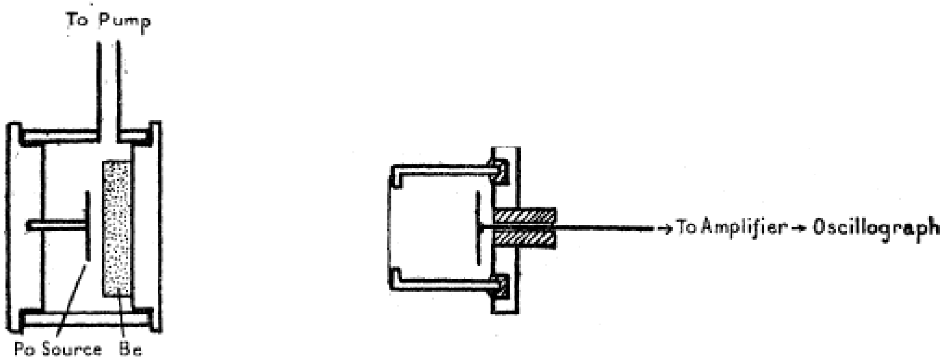


FIG. 1.

ejected from the paraffin wax so as to pass into the counter. By placing absorbing screens of aluminium between the wax and the counter the absorption curve shown in fig. 2, curve A, was obtained. From this curve it appears that the particles have a maximum range of just over 40 cm. of air, assuming that an Al foil of 1·64 mg. per square centimetre is equivalent to 1 cm. of air. By comparing the sizes of the deflections (proportional to the number of ions produced in the chamber) due to these particles with those due to protons of about the same range it was obvious that the particles were protons. From the range-velocity curve for protons we deduce therefore that the maximum velocity imparted to a proton by the beryllium radiation is about $3{\cdot}3 \times 10^9$ cm. per second, corresponding to an energy of about $5{\cdot}7 \times 10^6$ electron volts.

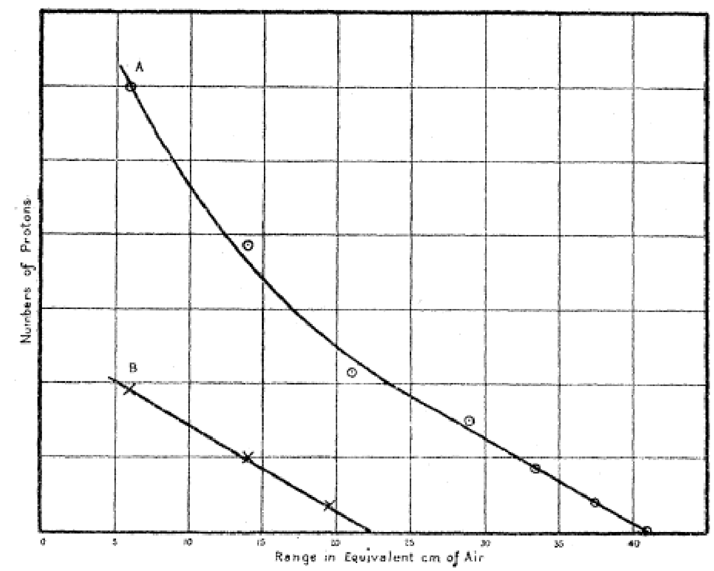


FIG. 2.

J. Chadwick, "The Existence of a Neutron,"
Royal Soc. Pub. A, p. 692 (1932)

It has been shown that protons are ejected from paraffin wax with energies up to a maximum of about $5 \cdot 7 \times 10^6$ electron volts. If the ejection be ascribed to a Compton recoil from a quantum of radiation, then the energy of the quantum must be about 55×10^6 electron volts, for the maximum energy which can be given to a mass m by a quantum $h\nu$ is $\frac{2}{2 + mc^2/h\nu} \cdot h\nu$.

§ 3. *The Neutron Hypothesis.*—It is evident that we must either relinquish the application of the conservation of energy and momentum in these collisions or adopt another hypothesis about the nature of the radiation. If we suppose that the radiation is not a quantum radiation, but consists of particles of mass very nearly equal to that of the proton, all the difficulties connected with the collisions disappear, both with regard to their frequency and to the energy transfer to different masses. In order to explain the great penetrating power of the radiation we must further assume that the particle has no net charge. We may suppose it to consist of a proton and an electron in close combination, the " neutron " discussed by Rutherford* in his Bakerian Lecture of 1920.

It is, however, easy to show that such a process fits the experimental facts. We have

$$\mathrm{Be}^9 + \mathrm{He}^4 + \text{kinetic energy of } \alpha$$
$$= \mathrm{C}^{12} + n^1 + \text{kinetic energy of } \mathrm{C}^{12} + \text{kinetic energy of } n^1.$$

If we assume that the beryllium nucleus consists of two α-particles and a neutron, then its mass cannot be greater than the sum of the masses of these particles, for the binding energy corresponds to a defect of mass. The energy equation becomes

$$(8{\cdot}00212 + n^1) + 4{\cdot}00106 + \text{K.E. of } \alpha > 12{\cdot}0003 + n^1 + \text{K.E. of } \mathrm{C}^{12} + \text{K.E. of } n^1$$

or

$$\text{K.E. of } n^1 < \text{K.E. of } \alpha + 0{\cdot}003 - \text{K.E. of } \mathrm{C}^{12}.$$

Since the kinetic energy of the α-particle of polonium is $5{\cdot}25 \times 10^6$ electron volts, it follows that the energy of emission of the neutron cannot be greater than about 8×10^6 electron volts. The velocity of the neutron must therefore be less than $3{\cdot}9 \times 10^9$ cm. per second. We have seen that the actual maximum velocity of the neutron is about $3{\cdot}3 \times 10^9$ cm. per second, so that the proposed disintegration process is compatible with observation.

$$B^{11} + He^4 \rightarrow N^{14} + n^1.$$

The energy equation of the process is

$$\text{Mass of } B^{11} + \text{mass of } He^4 + \text{K.E. of } He^4$$
$$= \text{mass of } N^{14} + \text{mass of } n^1 + \text{K.E. of } N^{14} + \text{K.E. of } n^1.$$

The masses are $B^{11} = 11{\cdot}00825 \pm 0{\cdot}0016$; $He^4 = 4{\cdot}00106 \pm 0{\cdot}0006$; $N^{14} = 14{\cdot}0042 \pm 0{\cdot}0028$. The kinetic energies in mass units are α-particle $= 0{\cdot}00565$; neutron $= 0{\cdot}0035$; and nitrogen nucleus $= 0{\cdot}00061$. We find therefore that the mass of the neutron is $1{\cdot}0067$. The errors quoted for the mass measurements are those given by Aston. They are the maximum errors which can be allowed in his measurements, and the probable error may be taken as about one-quarter of these.* Allowing for the errors in the mass measurements it appears that the mass of the neutron cannot be less than $1{\cdot}003$, and that it probably lies between $1{\cdot}005$ and $1{\cdot}008$.

Actual neutron mass: 1.0087 ***amu***

Such a value for the mass of the neutron is to be expected if the neutron consists of a proton and an electron, and it lends strong support to this view. Since the sum of the masses of the proton and electron is 1·0078, the binding energy, or mass defect, of the neutron is about 1 to 2 million electron volts. This is quite a reasonable value. We may suppose that the proton and electron form a small dipole, or we may take the more attractive picture of a proton embedded in an electron. On either view, we may expect the "radius" of the neutron to be a few times 10^{-13} cm.

§ 5. *The Passage of the Neutron through Matter.*—The electrical field of a neutron of this kind will clearly be extremely small except at very small distances of the order of 10^{-12} cm. In its passage through matter the neutron will not be deflected unless it suffers an intimate collision with a nucleus.

Summary.

The properties of the penetrating radiation emitted from beryllium (and boron) when bombarded by the α-particles of polonium have been examined. It is concluded that the radiation consists, not of quanta as hitherto supposed, but of neutrons, particles of mass 1, and charge 0. Evidence is given to show that the mass of the neutron is probably between 1·005 and 1·008. This suggests that the neutron consists of a proton and an electron in close combination, the binding energy being about 1 to 2×10^6 electron volts. From experiments on the passage of the neutrons through matter the frequency of their collisions with atomic nuclei and with electrons is discussed.