The Mass of the Neutron and the Stability of Heavy Hydrogen

The different calculations of the mass of the neutron (n^1) show rather large discrepancies. Chadwick's value[1] 1.0067 was based on the assumed process

$${}_5B^{11}+{}_2He^4\rightarrow{}_7N^{14}+{}_0n^1.$$

Curie and Joliot,[2] by bombarding boron with α-particles from polonium, discovered that positive electrons (positrons) were produced in this process, besides neutrons, protons and γ-rays. They assume that not B^{11}, but B^{10}, is transformed and that either a proton or a neutron plus a positron (ϵ^+) are produced.[3] In combining these two possible processes, they find 1.012 for the neutron mass without making use of the different atomic masses besides the proton. They take as mass of the positive electron the same as that of the negative electron (0.0005_5), 0.0045 as the sum of the kinetic energies (k.e.) of neutrons and positrons (in mass units), and 0.0094 as that of the protons. This value corresponds to the largest range (74 cm) of protons observed in this process. If one uses the shorter range (33 cm) corresponding to 0.0054, one gets 1.0076 as neutron mass. An upper limit for this mass, namely 1.0093, can be calculated according to Chadwick[4] from the process

$${}_3Li^7+{}_2He^4\rightarrow{}_5B^{10}+{}_0n^1,$$

assuming that the k.e. of the neutrons be zero; it is known to be small (of the order of 0.0005). Dunning and Pegram[5] calculate this mass from the maximum k.e. of the neutrons emitted from a very strong radon-Be source. Assuming that the process is

$${}_4Be^9+{}_2He^4\rightarrow{}_6C^{12}+{}_0n^1$$

and that these neutrons are produced by the α-rays of Ra C′, they get 1.0066 as the neutron mass.

Further values can be calculated from the transformation of Li and other nuclei by artificially accelerated H-nuclei, especially in combining the two processes (according to reports from the Cavendish Laboratory):

$${}_3Li^7+{}_1H^1\rightarrow 2{}_2He^4+T_1;\quad {}_3Li^7+{}_1H^2\rightarrow 2{}_2He^4+{}_0n^1+T_2.$$

The k.e. of the α-particles produced in the first process T_1 is accurately known:[6] 0.0184. The k.e. of the particles produced in the second process is a little doubtful. According to the assumption of Oliphant, Kinsey and Rutherford,[7] the fastest α-particles observed correspond to the mode that the two α-particles are emitted in opposite directions, the neutron getting no energy. Then $T_2=0.01775$, and the neutron mass comes out to be[8] 1.0066, the mass of H^1 and of H^2 being respectively 1.0072 and 2.0131. But the fastest α-particle would be produced if one of them goes off in a direction opposite to that in which the other α-particle and the neutron are emitted, although this mode has a rather small probability. From the equations of conservation of momentum and energy it is easily calculated that in this case T_2 is only nine-tenths of the value mentioned above.[8] The corresponding neutron mass is 1.0083.

A totally different value is calculated by Lawrence, Livingston and Lewis[9] and by Livingston, Henderson and Lawrence[10] from the assumption that the heavy hydrogen isotope H^2, called deuton, when hitting various targets, breaks up into a proton and a neutron. By accelerating the deutons with 1.2 million volts (MV) they always find protons of 18 cm range corresponding to a k.e. of 3.6 MV. They assume that the deuton was disintegrated as a result of nuclear collision with atoms of the various targets and that the proton and the neutron each acquire 2.4 MV from inner energy. They confirm their result in different ways, especially by observing neutrons of the expected yield. From these experiments they calculate the neutron mass as the difference between the masses of the deuton and the proton minus the energy of 4.8 MV released in the disintegration process, and get the value 1.0006, i.e., very near to unity.

So we have the following values today:

1^a 1.0067; 1^b 1.012; 1^c 1.0076 (transformation of B by α-particles
2 1.0093 (upper limit; transformation of Li)
3 1.0066 (transformation of Be)
4^a 1.0066; 4^b 1.0083 (disintegration of Li by H^1 and H^2)
5 1.0006 (disintegration of H^2)

The first four values lie very near to the proton mass, whereas the last one is about 0.006 unit smaller. If it was the right value, one could obviously expect the H^2 nucleus to be unstable, although the natural lifetime was difficult to foresee. Then one could also suppose that the Be nucleus was unstable assuming that it consists of two He-nuclei and one neutron—but it seems to be very stable.[11]

Quite independently of such theoretical considerations, it is rather interesting to see if any radioactivity of the heavy hydrogen can be detected or rather to determine the lower limit of its natural lifetime.

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[1] Chadwick, Proc. Roy. Soc. **A136**, 692 (1932).

[2] Curie and Joliot, Comptes Rendus **196**, 1885; **197**, 237 (1933).

[3] But it should not be overlooked that the positron could, in this case, also be produced, together with an electron, by internal conversion of a γ-ray emitted by the B-nucleus.

[4] Chadwick, Proc. Roy. Soc. **A142**, 1 (1933) gives the value 1.0070; but the data he uses lead to the value given above. If γ-rays were involved in this process, the neutron mass would come out correspondingly lower.

[5] Dunning and Pegram, Bull. Am. Phys. Soc. Boston Meeting, 1933, No. 54.

[6] Cockcroft and Walton, Proc. Roy. Soc. **A137**, 229 (1932).

[7] Oliphant, Kinsey and Rutherford, Proc. Roy. Soc. **A141**, 722 (1933).

[8] Provided that no γ-rays are involved in this process.

[9] Lawrence, Livingston and Lewis, Phys. Rev. **44**, 56 (1933).

[10] Livingston, Henderson and Lawrence, Phys. Rev. **44**, 781 (1933).

[11] Compare Evans and Henderson, Phys. Rev. **44**, 59 (1933) and others.

For the first experiments I used a Geiger point counter which gave only about 1 stray count in 5 minutes. It was controlled by use of a very weak polonium source of known activity. Recoil protons of a few centimeters range in air could easily be counted. Heavy water (80 percent) in a cup of about 1 cm^2 surface did certainly not give 0.05 count per minute more than ordinary water.[12] For instance, the mean value of counts per minute over 6 hours was $0.20_5 \pm 0.02$ for heavy and $0.19_4 \pm 0.02$ for ordinary distilled water. If protons of 2.4 MV, corresponding to a range of about 11 cm in air, were given off from H^2, they could penetrate a layer of about 90 microns of water. Then the experiments show that the constant of transformation of H^2 would be: $\lambda < 2 \cdot 10^{-23}$ and its "period" $T > \cdot 10^{15}$ years.[13] An ionization chamber with linear amplifier which can probably detect a hundred times smaller yield will be used in the near future.

Of course such experiments cannot prove that the neutron mass is not so small as Livingston, Henderson and Lawrence assume, but it appears now more improbable that it is so small. Perhaps another explanation for their experiments can be found.

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[12] Professor H. C. Urey and Dr. J. R. Dunning have kindly informed me that they have carried out similar experiments; it is probable that such experiments have also been done elsewhere.

[13] Such a lifetime for a nucleus which emits spontaneously a proton would only be possible, if the potential barrier of a reasonable thickness (5×10^{-13} cm) had a height of some billion volts—provided that the Gurney-Condon-Gamow theory of α-ray disintegration is applicable.

On the Interior Magnetic Field in Iron

In an effort to determine the magnitude of the deflecting field in magnetized iron, the following experiment was recently performed: Beta-rays from radium C ($H\rho = 5900$) were focussed in a field of 1900 gauss, and after passing through 0.36 mm of transformer iron, were registered on a photographic film, 1.53 mm from the latter. Both the iron sheet and the film were parallel to the direction of the field, and normal to the incident beta-rays. To prevent darkening of the film due to the continuous spectrum, and to secondary and scattered beta-rays from the walls of the spectrograph, a sheet of brass 2 mm thick was placed 1.88 mm above the film. A 1 mm slit in this sheet allowed the beta-rays to strike the iron, which was waxed to its lower side, only in a definite line, parallel to the radon tube which was used as the source of beta-rays. The brass sheet was soldered to two pieces of brass, which rested directly on the film. One of these supporting pieces was pierced with a thin slit, through which some of the beta-rays passed to darken the plate in a line parallel to the source. The sharp edge of this line served as a fiducial mark.

Photographs were taken with the apparatus as described, and with an equal thickness of copper in place of the iron. The field was kept constant to within less than one percent with the aid of a ballast lamp. Small variations in the field could not shift the line on the plate, since its position was determined by the stationary slit. Exposures of 110 millicurie hours gave maximum contrast as measured by a Mohl microphotometer. The shape of the microphotometer traces was very nearly the same for the copper and iron photographs, and agreed very well with a curve calculated on the basis of the theory of beta-ray scattering.[1]

If the field in the iron were assumed to be equal to the induction B, which in this case was 17,000 gauss, the point of maximum density on an iron photograph should have been 0.15 mm further from the fiducial mark than the corresponding point on a copper photograph. (The induction was calculated from the magnetization curve of the iron used, after allowing for the demagnetizing effect of the free poles developed at the ends of the sheet,[2] and was later measured with a fluxmeter.) Since it was difficult to locate the maximum point with precision, the shift could be more easily detected at a point 1/3 of the distance down from the peak of the microphotometer trace. Here the trace was quite smooth, and in addition, the expected shift was considerably increased because of the greater distance from iron to film, the inclination of the film to the beta-rays, and the greater path in the iron. 1/3 down on the trace (corresponding to a point on the film 1.2 mm from the center of the line), the expected shift was 0.27 mm. The traces were measured on a comparator equipped with micrometer screws at right angles, and similar curves were plotted with the aid of the readings obtained in this manner. All measurements were made on these enlarged traces (×5); the shift 1/3 down should have been 0.92 cm. Points on these curves could be reproduced to within 1 mm.

Fig. 1 shows the distance from the mean abscissa of a trace to the fiducial mark, as a function of the half width of the curve at the corresponding ordinate. The curves in this figure are essentially the center lines of the microphotometer traces, corrected for variations in exposure time. Their inclination is due to the "straggling" of the beta-rays by the metal sheets. The dotted lines show the calculated positions of iron curves for various values of the interior field.

The data obtained so far are in definite disagreement with the classical theory of magnetism, which postulates an interior field $= B$. The experimental results indicate that the deflecting field in iron is less than 1/3 of B. This is

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[1] Rutherford, Chadwick and Ellis, *Radiations from Radioactive Substances*, 219 (1930).

[2] DuBois, *The Magnetic Circuit*, 34, 41 (1896).