used by Oliphant, Kinsey and Rutherford was, as far as we know, the same (about 0.2×10^6 e.v.), and hence cancels. The ranges of the α-particles resulting from the two reactions are nearly the same (7.8 and 8.4 cm, respectively) and since only the difference in energy is made use of, any systematic error in the measurements or in the conversion from range to energy tends to cancel out. Using $E_1=16.6\times 10^6$ e.v. and $E_2=17.5\times 10^6$ e.v., the difference of which is equivalent to 0.0010 mass units, we obtain for the mass of the neutron 1.0068. This we believe to be the best value on the basis of the data here discussed, and it is in agreement with the value found by Chadwick.

It is interesting, and perhaps of some significance, that γ-rays are produced in the disintegration of lithium by protons but not in the disintegration of lithium by deutons. This would lead one to suspect that the γ-ray quantum is not associated with an excitation level in the α-particle, since α-particles with high energy are produced in both instances. A solution which seems very plausible is to associate the γ-ray quantum with excited He^3 in the reaction[3]

$$Li^6+H^1\rightarrow He^4+He^3+\gamma.$$

Oliphant, Kinsey and Rutherford have observed short range particles produced in the disintegration of lithium by protons having ranges 0.65 cm and 1.15 cm. If we assume that the longer of the two ranges corresponds to He^3 and the shorter to He^4, we find that the energies† corresponding to those ranges are 1.6 and 2.1×10^6 e.v., respectively, which are just in the ratio 3 to 4, as would be expected from momentum considerations. Taking into account the γ-ray, and solving the equation for the mass of He^3, we obtain 3.0146, which is in good agreement with that to be expected from the upper branch of Aston's packing fraction curve.

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† The energy of He^3 was obtained from the range-energy curve for α-particles, and corrected for the difference in mass.

The Energy Distribution of the Neutrons from Fluorine

From experiments on the ionization currents in hydrogen produced by neutrons from Be, B and F, Bonner[1] concluded that the neutrons from fluorine must have a considerably smaller average energy than those from beryllium or from boron. Curie and Joliot,[2] on the other hand, concluded that fluorine neutrons must be of high energy since they found them to be weakly absorbed by lead. Accordingly, it was desirable to make, if possible, a direct measurement of the energy of the fluorine neutrons.

It appeared that the methods of energy measurement which have been used for beryllium and boron neutrons were not especially suitable, since the intensity of the fluorine radiation is so small. It seemed entirely impractical to use recoil protons from paraffin, observed with either a counter or a cloud chamber. Indeed it seemed not feasible to observe recoil atoms with any arrangement of an ordinary cloud chamber on account of the excessively large number of photographs which would be necessary to record a reasonable number of tracks. In order to increase this number a special cloud chamber was constructed which allowed the gas pressure to be increased by a factor of more than ten. In this experiment it was used with hydrogen at a pressure of 12.9 atmospheres, so that more than a tenfold increase in sensitivity was attained. The experiment then consisted in measuring by the usual method the range of the recoil protons produced in the gas.

The source of neutrons consisted of a ten millicurie polonium source of α-particles bombarding a piece of fluorite. It was placed near the side wall of the chamber. The tracks were photographed with the usual stereoscopic camera arrangement and were reconstructed by projection.

About 9000 pairs of photographs were taken, on which 205 recoil protons were found. The ranges of these protons were measured and were then converted to air-equivalent by making use of the differential stopping-power data obtained by Gurney.[3] The number of observed recoil protons as a function of the range is shown in the curve of Fig. 1. From the curve it appears that the maximum range

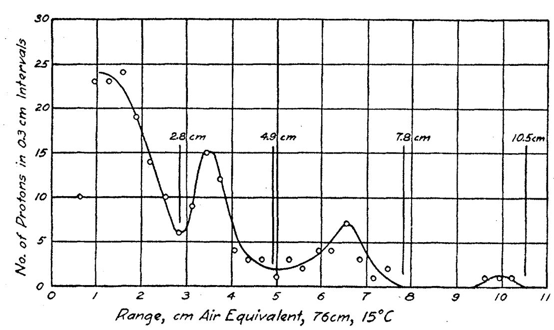

FIG. 1. Range distribution of the recoil protons from fluorine neutrons.

of the recoil protons is about 10.5 cm of air, giving the maximum energy of fluorine neutrons to be 2.5×10^6 e.v. This value is considerably less than the maximum energy of neutrons from beryllium and confirms Bonner's result.

It is seen that the curve shows distinct peaks which we believe definitely means that the neutrons are emitted with

[1] T. W. Bonner (to appear in the May 1st Physical Review).

[2] I. Curie and F. Joliot, J. de Phys. et le Rad. **4**, 278 (1933).

[3] R. W. Gurney, Proc. Roy. Soc. **A107**, 340 (1925).

discrete energies, rather than with a continuous distribution. The values of the maximum range for these groups are given in Table I and are indicated in Fig. 1. The velocity and energy corresponding to these ranges are given in succeeding columns of this table.

TABLE I.

Proton Emission from Fluorine (Chadwick and Constable)				*Neutron Emission from Fluorine*				
Rp (cm)	$Ep/10^6$ e.v.	ΔEp	$R\alpha$ (cm)	Rn (cm)	$Vn/10^9$ cm/sec.	$En/10^6$ e.v.	ΔEn	$R\alpha$ (cm)
56	6.55		3.9	10.5	2.20	2.54		3.9 (assumed)
		0.42					0.43	
47	6.13		3.9	7.8	2.01	2.11		3.9 (assumed)
		0.55					0.52	
40	5.58		2.7	4.9	1.74	1.59		2.7 (assumed)
		0.51					0.49	
33.5	5.07		2.2	2.8	1.45	1.10		2.3
		0.30						
30.5	4.77		2.7	—	—	—	—	—
		0.51						
25	4.26		2.2	—	—	—	—	—

Rp = Range of disintegration protons
Ep = Energy of protons.
ΔEp = Energy difference between proton groups.
$R\alpha$ = Range of α-particles producing disintegration.
Rn = Maximum range of recoil protons.
Vn = Neutron velocity.
En = Neutron energy.
ΔEn = Energy difference between neutron groups.

Since the α-particles producing the disintegrations have a continuous range of energy from their maximum to zero (because a thick target was used) it seems probable that the discrete energy groups in the neutron emission are produced by the penetration of the α-particle into the nucleus through resonance levels. Such a resonance phenomenon has been observed in the other type of disintegration of fluorine where a proton is emitted. The latest work on this subject is that of Chadwick and Constable.[4] Since both types of disintegration depend on the entrance of the α-particle into the fluorine nucleus, it was expected that the resonance levels should be the same in both cases. Accordingly, we have looked for a correlation between the proton groups and the neutron groups. It cannot be expected that the actual energies of the groups shall be the same in both cases since the disintegration reactions are entirely different. However, the energy differences between successive groups should be the same if the same resonance levels are involved. The energy differences for both cases are given in Table I. The corresponding differences for the two cases are seen to agree as well as could be expected. It will be noted that the two groups of lowest energy for the neutron disintegration are missing. It is probable that they exist but have not been found because of poor resolving power at the shorter ranges. Further evidence that the same resonance levels are effective comes from the fact that the emission of neutrons from fluorine begins when the α-particle has a range of 2.3 cm.[5] This value agrees with the range of 2.2 cm corresponding to the lowest resonance level which Chadwick and Constable observed in the proton disintegration.

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[4] J. Chadwick and J. E. R. Constable, Proc. Roy. Soc. **A135**, 48 (1932).
[5] T. W. Bonner, Phys. Rev. **45**, 425 (1934).

Disintegration of Li^6 by Protons and Deutons

In a recent letter to *Nature*, Oliphant, Shire and Crowther[1] reported the results of the disintegration of the separate isotopes of lithium by protons and deutons. The results for Li^7 are well understood, the nuclear reactions being:

$$Li_3^7 + H_1^1 \rightarrow 2\ He_2^4 \tag{1}$$

$$Li_3^7 + H_1^2 \rightarrow 2\ He_2^4 + n_0^1 \tag{2}$$

as shown by Cockroft, Walton,[2] Oliphant, Kinsey and Rutherford.[3] In case (1) the α-particles have a sharp range of 8.4 cm, in case (2) all ranges up to 8 cm are observed.

On bombarding ordinary Li with protons two other groups of α-particles in addition to the 8.4 cm group were observed,[3] having ranges of 6.5 mm and 11.5 mm. The experiments of Oliphant, Shire and Crowther show that the 11.5 mm group is due to Li_3^6. The group of 6.5 mm could not be observed because the screen had a stopping power of about 6 mm. Perhaps it may also be ascribed to Li_3^6. If this is the case one can try to explain these two groups by assuming the reaction:

$$Li_3^6 + H_1^1 \rightarrow He_2^4 + He_2^3 \tag{3}$$

as already suggested by Oliphant, Kinsey and Rutherford.[3] We must assume then further that the 11.5 mm group is really He_2^3. Neglecting the impulse of the proton, the velocity of He_2^4 would then be three-fourths the velocity of He_2^3. Taking tentatively[4] the range of two equally charged particles as proportional to mv^3 one obtains for the range of He_2^4 $(\frac{3}{4})^2 \times 11.5 = 6.47$ mm, in agreement with the observed value. The kinetic energy of an α-particle of 6.5 mm range is 1.6×10^6 e.v. and hence the kinetic energy of the He_2^3 would be 2.1×10^6 e.v. If we use for the values of the nuclear masses $Li_3^6 = 6.0129$, $H_1^1 = 1.0072$, $He_2^4 = 4.0011$ and take for the kinetic energy of the protons 0.0002 M.U., the mass of He_2^3 comes out to be 3.0152. With the value 1.0065 for the mass of the neutron the binding energy of He_2^3 would be 0.0057 or about 5×10^6 e.v. This is a quite

[1] Oliphant, Shire and Crowther, Nature **133**, 377 (1934).
[2] Cockroft and Walton, Proc. Roy. Soc. **A137**, 229 (1932).
[3] Oliphant, Kinsey and Rutherford, Proc. Roy. Soc. **A141**, 722 (1933).
[4] Comp. Blackett, Proc. Roy. Soc. **A135**, 132 (1932); Duncanson, Proc. Camb. Phil. Soc. **30**, 102 (1934).