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The Emission of Protons from Light Nuclei on Bombardment with α-Particles of Short Range

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The expansion chamber method is used to obtain tracks of protons ejected in 67 disintegrations of fluorine and 121 disintegrations of neon while both gases are under α-particle bombardment. The energetics of the reaction are in good agreement with the mass data, and protons corresponding to transitions to the ground state of the residual nuclei are found with both elements. No disintegrations are detected until the energies of the α-particles reach 3.7 and 4.4 Mev in fluorine and neon, respectively. These are the only energy levels recorded.

The ranges of the protons from fluorine vary within wide limits (an indication of several excited states of the residual nucleus), while those from neon show only one range corresponding to the ground state. In all cases the angular distribution of the ejected protons is anisotropic, and evidence is given that the low energy α-particles responsible for the disintegrations all make off-center collisions and therefore possess angular momentum about the nuclear center. A simple model of the collision process is suggested to account for these results and also for the relative yields which are in the ratio 1:0.5:2 for nitrogen, fluorine, and neon, respectively. A possible cause of the apparent disintegration of nitrogen by α-particles of very low energy is discussed.

I. INTRODUCTION

A CONSIDERABLE quantity of data is now available on the proton emission accompanying the disintegration of light nuclei by α-particle bombardment.[1] Most of the experiments have hitherto been performed with α-particles of 5- to 8-Mev energy using electrical methods of recording. We have now applied the expansion chamber method to examine the disintegration of the three elements, nitrogen, fluorine, and neon by α-particles of energies 0–5 Mev.

The information which could be derived from such experiments would ideally comprise (1) establishment of resonance levels and a measurement of their energy and breadth, (2) demonstration of the existence and the nature of the selection rules governing nuclear disintegration, and (3) measurement of the absolute yield of the disintegration process. The quantities measured experimentally are the numbers and ranges of the emitted protons and of the incident α-particles, together with the angular distribution of the direction of ejection of the protons with respect to the direction of the incident α-particles. We have already presented[2] some results for nitrogen which showed that the angular distribution of the group of protons emitted, when the remaining range R_α of the incident α-particles in air at S.T.P. was 2.1 cm, had a pronounced maximum when $\theta \approx 90°$, where θ is the angle between the direction of emission of the proton and the direction of the incident α-particle. While disintegration experiments with nitrogen have been undertaken with success by several workers, the disintegration of fluorine and neon by α-particle bombardment has not hitherto been demonstrated by the expansion chamber method.

II. EXPERIMENTAL METHOD

The expansion chamber used was larger than in the previous experiment with nitrogen for it was now 16.5 cm in diameter and about 4 cm high. It enclosed a thin cylinder of Cellophane mounted coaxially and of diameter 10 cm. The stopping power of the Cellophane was about 3 cm of air. Such an arrangement allowed the estimation of the range of protons which would otherwise have been uncertain because of their passage out of the expansion chamber. This improvement was only partially successful for it introduced straggling up to 1 cm because the protons passed through the cylinder at varying angles. Uncertainties also arose from possible inhomogeneity in thickness of the Cellophane and condensation of water vapor on the Cellophane surface.

[1] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys 9, 299 (1937).
[2] F. Champion and R. Roy, Proc. Roy. Soc. A191, 269 (1947).

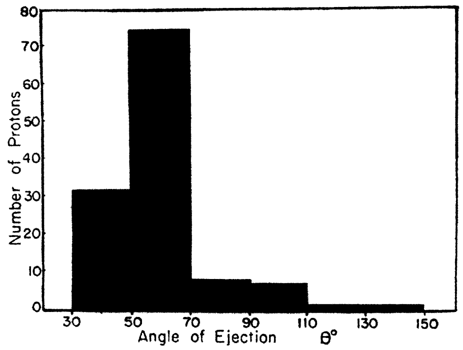

FIG. 1. Angular distribution of protons ejected from neon under α-particle bombardment.

The slit and shutter system were also improved with a view to obtaining a finer and more rectangular beam of condensation, but certain difficulties still remain which can only be remedied by the construction of a chamber working at lower pressure. For example, the fact that the neon was contaminated with 20 percent helium and also that the fluorine, in the form of carbon tetrafluoride, had to be diluted with helium in order to give a suitable stopping power resulted in a broadening of the condensation beam even more than in the previous experiment with nitrogen. This was partly caused by the greater mobility of the ions in helium, but it resulted mainly from the long ranges of the projected helium nuclei and the α-particles scattered by the various nuclei present. To avoid including projected protons arising from possible hydrogen contamination, protons ejected with $\theta < 30°$ were neglected. This precaution at small angles, together with the mechanical interference at large angles produced by the presence of the slit system on back-projected protons, restricted the effective angular range of examination to between 30° and 120°.

III. RESULTS

A. Fluorine

In 1775 photographs in 25 percent carbon tetrafluoride and 75 percent helium, with minor impurities of not more than 2 percent nitrogen, carbon dioxide, fluorine oxide, and oxygen, 67 disintegrations were obtained. In the only other expansion chamber experiment on record,[3] a much weaker source of α-particles was used and no disintegrations were found in 6265 photographs. The ranges of the ejected protons had all values from 8 cm upwards, with 19 examples in which the range exceeded the confines of the expansion chamber. No disintegrations were found for $R_\alpha < 1.9$ cm and all those registered lay between this limit and $R_\alpha = 2.3$ cm. The angular distribution of the whole 67 tracks of all ranges was roughly isotropic over the angular range 30° to 120°. No effective separation of the protons into discrete groups was possible with the resolution available. However, the angular distribution of the 19 protons which passed out of the expansion chamber was examined separately and found to show a preponderance at the smaller angles.

B. Neon

In 1200 photographs in about 80 percent neon, 20 percent helium, and less than 2 percent nitrogen, 121 disintegrations were recorded. The protons were all of range 8 cm with a spread of about 1 cm. This spread may be due to more than one energy of emission of the protons but the resolving power of the apparatus is too poor to establish this. All protons were emitted soon after the α-ray beam emerged from the slit system when R_α lay between 2.6 and 3 cm. The angular distribution is shown in Fig. 1.

IV. DISCUSSION

According to the mass data,[4] the fluorine reaction is exothermic for the ground state with $Q = +1.57$ Mev. From our observations with $R_\alpha = 2.3$ cm corresponding to $E_\alpha = 3.7$ Mev, the maximum range of the protons emitted should be about 35 cm. These could correspond to the 19 examples where the range of the protons exceeded the size of the expansion chamber. Those of smaller range would correspond to a number of excited levels of the residual nucleus formed in the reaction. Several of them are known to exist from the reports of other workers.[1]

With neon, the mass data indicate a value of $Q = -1.7$ Mev. From our observations, the energy of the protons emitted is about 2.1 Mev

[3] N. Feather, Proc. Roy. Soc. **A141**, 194 (1933).

[4] G. Mattauch, *Nuclear Physics Tables* (Interscience Publishers, Inc., New York, 1946).

and of the α-particles responsible for the disintegration $E_\alpha = 4.4$ Mev. We therefore conclude that we are observing the protons from the ground state. Apart from the initial report,[5] the only other experiment[6] on the disintegration of neon used electrical methods of recording. With α-particles of up to 8-Mev energy, these workers found a value of $Q = -2.54$ Mev, which indicated an excited state of the residual nucleus. These faster α-particles passed over the top of the potential barrier whereas our protons come from a resonance disintegration. The results clearly support the view that the ground state of the nucleus is more likely to be in evidence the lower the energy of the bombarding particles.

The angular distribution of all the protons ejected from fluorine is approximately isotropic when examined as a whole. It is difficult to extract as much information as is desirable in this case because of our inability to resolve the energies of the individual proton groups. However, some interesting conclusions can be drawn if attention is confined to the long-range protons possibly corresponding to the ground state. The distribution of these 19 protons shows a maximum at the smallest angle, that is at 30°, and then shows a gradual decrease at larger angles, no protons being recorded for $\theta > 60°$. In this group, therefore, the distribution is anisotropic and, since the total distribution of all the ranges is approximately isotropic, by subtraction one at least of the remaining groups must also be anisotropic. With neon, Fig. 1 shows that the angular distribution has a pronounced maximum at $\theta \approx 60°$. The relatively large number which also occurs at angles close to 30° should almost certainly be reduced, for some of these tracks were on the short-range side and were probably protons projected from hydrogen contamination. A few tracks were recorded at high angles but, as has already been explained, the present experimental arrangement is not very suitable for reliable recording of protons ejected at much more than 90°. Therefore, we are unable to state definitely that the theoretically fundamental requirement for resonance disintegrations from a single level is fulfilled, namely, that the angular distribution should be symmetrical in the forwards and backwards direction. The results in nitrogen have been shown to be in fair agreement with this requirement but as the distribution rose rather sharply to a maximum at $\theta \approx 90°$ in that case, the evidence is not entirely conclusive. Our general impression with fluorine is that there are fewer particles emitted in the backward than in the forward direction, but this may be explicable in terms of interference effects resulting from a complex level system.[7]

Attempts which we have made to explain the results in terms of an α-particle substructure of the nuclei concerned have been completely unsuccessful. In our last paper we suggested that nuclei containing equal numbers of neutrons and protons possessed symmetrically arranged nucleons with the protons closer to the nuclear surface than the neutrons. Off-center collisions by α-particles possessing angular momentum with respect to the nuclear center would then result in impact on a particular proton, which would leave the nucleus after a time sufficient to allow appreciable nuclear rotation to occur, according to the principle of the conservation of angular momentum. Such a simple picture would predict a rotation in neon somewhat less than in nitrogen for incident α-particles of the same impulse. Consequently, ejection would occur at smaller angles in neon than in nitrogen; the experimental results show $\theta = 60°$ and 90°, respectively. For fluorine which contains ten neutrons and nine protons the symmetry is lacking, and the protons are likely to be less close to the nuclear surface. For proton emission, therefore, an α-particle must make a nuclear collision which is relatively less off-center and, consequently, less angular momentum should be imparted to the nucleus. Less rotation should result and, in agreement with experiment, protons should be ejected mainly at smaller angles. We are aware that such a picture is not easy to reconcile with present theoretical views of nuclear disintegration, according to which the incident particle is completely absorbed in the nucleus for an appreciable time before disintegration occurs and according to which the nu-

[5] E. Rutherford, J. Chadwick, and C. Ellis, *Radiations from Radioactive Substances* (Cambridge University Press, Teddington, 1930), p. 293.

[6] E. Pollard and C. J. Brasefield, Phys. Rev. **51**, 8 (1937).

[7] S. Rubin, Phys. Rev. **72**, 1176 (1947).

cleon which is first struck bears no relation to the nucleon which is finally emitted. We wish to emphasize that more data are required on the back-projected protons before a final decision can be reached on this point.

The strength of the polonium source in these experiments was 4 mc and an approximate comparison of the yields with the three elements shows them to be in the ratio 1:0.5:2 for nitrogen, fluorine, and neon, respectively. The high yield with neon is perhaps surprising but several factors could account for this. For example, the energy of the α-particles responsible for the neon disintegration is somewhat higher than with the other two elements. On the other hand, the smaller yield with fluorine is explicable by the simple picture that we have suggested, in which the protons are less close to the nuclear surface and hence the nucleus presents an effectively smaller cross section for proton emission resulting from the impact of α-particles which have made off-center collisions.

It is interesting to note that all the angular distributions recorded are anisotropic and the implication is that probably none of the disintegrations produced by these low energy α-particles corresponds to an s-state. Earlier evidence[8] has been given in this respect in that the width of the resonance levels in fluorine have been shown to require disintegration from a p-level when α-particles of low energy are used.

One outstanding difference exists between the observations in nitrogen and the other two gases. With fluorine and neon no disintegrations were observed when the α-particle range fell below 2 cm, whereas in nitrogen several such cases were found. We have explained that the intense source of α-particles which was used resulted in a condensation beam of some breadth and this limited the accuracy with which R_α could be determined, unless $\theta=90°$. However, under this ideal condition, three cases were found where $R_\alpha<1.4$ cm. Now from the mass data it follows that if energy and momentum are conserved in all disintegrations, it is impossible for protons of range such as that shown in our previous paper, Fig. 7, Plate 19, to be produced by α-particles with $R_\alpha<1.4$ cm. Previous workers[1] have, on many occasions, found Q values for nitrogen much larger than that calculated from the mass data. In particular, technically good photographs[9] have recorded a value as high as $+0.94$ Mev, whereas the value calculated from the mass data is -1.2 Mev. The suggestion made to account for this discrepancy was that the recoil nucleus made an unresolved collision with another nucleus, although the chances against such an event were 200:1. We too can explain our anomaly in a similar fashion. For example, the anomalous protons might be those liberated in a forward direction within the collimating slits by α-particles of high energy. At some point of their path, before they emerge from the end of the condensation beam, these protons might be deflected by a nuclear encounter and emerge from the beam at a high angle at some point close to the end of the range of the α-particles. They would thus give the appearance of having been generated close to the end of the range. It seems only reasonable to point out, however, that if this explanation is the correct one, it is difficult to understand why such behavior is not found with fluorine and neon.

V. ACKNOWLEDGMENTS

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[8] J. Chadwick and J. Constable, Proc. Roy. Soc. **A135**, 49 (1932).

[9] P. Blackett and D. Lees, Proc. Roy. Soc. **A136**, 325 (1932).

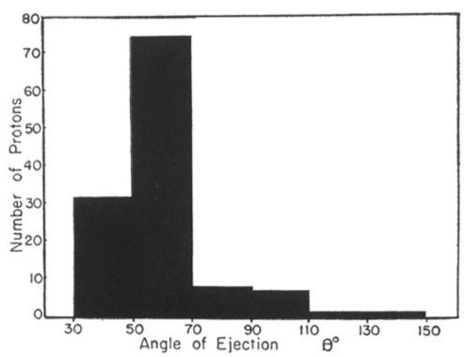

FIG. 1. Angular distribution of protons ejected from neon under α-particle bombardment.